Climate Change Reconsidered

2011 Interim Report of the Nongovernmental International Panel on Climate Change

CENTER FOR THE STUDY OF CARBON DIOXIDE
AND GLOBAL CHANGE

SCIENCE AND ENVIRONMENTAL
POLICY PROJECT

Climate Change Reconsidered

2011 Interim Report

Lead Authors

Craig D. Idso (USA), Robert M. Carter (Australia), S. Fred Singer (USA)

Contributors

Susan Crockford (Canada)
Joseph D'Aleo (USA)
Indur Goklany (USA)
Sherwood Idso (USA)
Madhav Khandekar (Canada)
Anthony Lupo (USA)
Willie Soon (USA)
Mitch Taylor (Canada)

Editors

Joseph L. Bast (USA), S.T. Karnick (USA), Diane Carol Bast (USA)

Published for the Nongovernmental International Panel on Climate Change (NIPCC)

The Heartland INSTITUTE

From reviews of *Climate Change Reconsidered* 2009:

“With its emphasis on natural variability as a cause for the recent climate changes, it is a must-have for serious climate scientists who should not just rely on the IPCC Fourth Assessment Report alone to get the full picture of our current state of knowledge (and what is not known) about climate and climate change.”

Anthony R. Lupo, Ph.D.
University of Missouri-Columbia

“Their scholarly analysis brings some much-needed realism (and good old-fashioned common sense) to the climate change debate. Highly informative, *Climate Change Reconsidered* ought to be required reading for scientists, journalists, policymakers, teachers and students. It is an eye-opening read for everyone else (concerned citizens, taxpayers, etc.). In short ... this book is highly recommended!”

William Mellberg
Author, *Moon Missions*

“I’ve been waiting for this book for twenty years. It was a long wait, but I’m not disappointed. *Climate Change Reconsidered* is a tour de force. It takes on all the alleged evidences of catastrophic, manmade global warming and demonstrates, patiently and clearly, why they fail to support the conclusion.”

E. Calvin Beisner, Ph.D.
Cornwall Alliance for the Stewardship of Creation

“I strongly recommend this book to any individual who seriously wants to understand the science of climate, the effects of climate change on human health, or who needs to make decisions about policy related to greenhouse gas regulations. It should be in every library for education on these questions, as it is the best and most complete work on these subjects of its type.”

Howard Maccabee, Ph.D., M.D.
Alamo, California

“One of the most significant climate science documents ever produced. Coming to conclusions diametrically opposed to those of the Intergovernmental Panel on Climate Change (IPCC), the new Nongovernmental International Panel on Climate Change (NIPCC) report is essential reading for all politicians, or at least those who want to develop policies that actually benefit their countries and the environment.”

Tom Harris
International Climate Science Coalition

“The reports of the NIPCC and of the IPCC are very important reading for the public.... The former, an independent assessment of the claims of the latter, appears to be based on sound interpretations of solid scientific observations. One doctor is telling us that we have cancer and there is no hope (unless we kill ourselves to stop it). The other doctor has a second opinion which says maybe the symptoms are being misinterpreted; maybe we should pay more attention to actual observations and alternative explanations based on sound principles. *Climate Change Reconsidered* is must reading.”

Ronald A. Wells, Ph.D.
University of California, Berkeley (retired)

Climate Change Reconsidered

2011 Interim Report

Published by THE HEARTLAND INSTITUTE
19 South LaSalle Street #903
Chicago, Illinois 60603 U.S.A.
phone +1 (312) 377-4000
fax +1 (312) 377-5000
www.heartland.org

Opinions expressed are solely those of the authors. Nothing in this report should be construed as reflecting the views of the Science and Environmental Policy Project, Center for the Study of Carbon Dioxide and Global Change, or The Heartland Institute, or as an attempt to influence pending legislation. Additional copies of this book are available from the Science and Environmental Policy Project, The Heartland Institute, and Center for the Study of Carbon Dioxide and Global Change at the following prices:

1-10 copies	$79 per copy
11-50 copies	$63 per copy
51-100 copies	$49 per copy
101 or more	$39 per copy

Please use the following citation for this report:

NIPCC-IR1 (2011)
Craig D. Idso, Robert M. Carter, and S. Fred Singer, Eds.
Climate Change Reconsidered: 2011 Interim Report of the
Nongovernmental Panel on Climate Change (NIPCC), Chicago, IL: The Heartland Institute, 2011.

ISBN-13 – 978-1-934791-36-3
ISBN-10 – 1-934791-36-9

September 2011

1 2 3 4 5 6

Foreword

The Heartland Institute is pleased to partner once again with the Science and Environmental Policy Project and the Center for the Study of Carbon Dioxide and Global Change on a report that makes a serious contribution to the global debate over the causes and consequences of climate change.

Events since our last collaboration, the publication of *Climate Change Reconsidered* in 2009 (hereafter NIPCC-1), have made this new report necessary while also making the earlier report look prescient. This foreword briefly recaps how the global warming debate has changed in just the past two years.

Recanting Alarmists, Climategate

Mike Hulme (2009), a professor of climate change in the School of Environmental Sciences at the University of East Anglia and a contributor to the Intergovernmental Panel on Climate Change (IPCC), published in 2009 a book that contained admissions of uncertainty rarely voiced by insiders of the climate change research community. Hulme wrote, "the three questions examined above—What is causing climate change? By how much is warming likely to accelerate? What level of warming is dangerous?—represent just three of a number of contested or uncertain areas of knowledge about climate change" (p. 75).

Hulme also admitted, "Uncertainty pervades scientific predictions about the future performance of global and regional climates. And uncertainties multiply when considering all the consequences that might follow from such changes in climate" (p. 83). On the subject of the IPCC's credibility, he admitted it is "governed by a Bureau consisting of selected governmental representatives, thus ensuring that the Panel's work was clearly seen to be serving the needs of government and policy. The Panel was not to be a self-governing body of independent scientists" (p. 95).

These are all basic "talking points" of global warming realists, which invariably result in charges of "denial" and "industry shill" when expressed by someone not in the alarmist camp. To see them written by Hulme reveals how the debate has changed.

Just months after Hulme's book was released, a large cache of emails was leaked by someone at the Climatic Research Unit at the University of East Anglia. "Climategate," as it has come to be known, revealed deliberate efforts by leading scientific supporters of the IPCC, and of climate alarmism more generally, to hide flaws in their evidence and analysis, keep "skeptics" from appearing in peer-reviewed journals, and avoid sharing their data with colleagues seeking to replicate their results (Bell, 2011; Sussman, 2010; Montford, 2010). The emails reveal that important data underlying climate policy are missing or have been manipulated.

In February 2010, the BBC's environment analyst Roger Harrabin posed a series of written questions to Philip D. Jones, director of the Climatic Research Unit (CRU) at the University of East Anglia and the person responsible for maintaining the IPCC's all-important climate temperature records (BBC, 2010). Jones appeared to back away from many of the foundational positions of the IPCC, admitting for example:

- The rates of global warming from 1860–1880, 1910–1940 and 1975–1998, and 1975–2009 "are similar and not statistically significantly different from each other."

- The temperature trend for the period 1995 to 2009 “is positive, but not significant at the 95% significance level.”

- When asked, “When scientists say “the debate on climate change is over”, what exactly do they mean – and what don’t they mean?” Jones replied, “It would be supposition on my behalf to know whether all scientists who say the debate is over are saying that for the same reason. I don’t believe the vast majority of climate scientists think this. This is not my view. There is still much that needs to be undertaken to reduce uncertainties, not just for the future, but for the instrumental (and especially the palaeoclimatic) past as well.”

Climategate was followed by a series of revelations that many of the key “findings” of the Fourth Assessment Report of the IPCC (IPCC-AR4) relied on non-peer-reviewed sources, sometimes little more than the newsletters of environmental advocacy groups. As a result, IPCC had to retract claims about Amazon rain forests, African crop harvests, Himalayan glaciers, trends in disaster losses, flooding in Bangladesh, and more. Evidence of these errors and more could be readily found in *Climate Change Reconsidered,* but the British media apparently preferred to “discover” and announce the errors in their own way. The media also ignored an excellent audit of all 18,531 references cited in the AR4 that found 5,587—nearly one-third—were not peer-reviewed (Laframboise et al., 2008).

Global Warming Politics

The Climategate affair was followed by the messy global conference in Copenhagen in December 2009. It became evident that there was no political will to continue drastic restrictions on greenhouse gas emissions after the Kyoto Protocol expires in 2012. Developing nations, led by China and India, made it clear they did not intend to hamstring their economies by energy restrictions based on uncertain scientific justifications. Of course, smaller developing countries are quite happy to receive further financial subsidies from industrialized nations for the sake of “saving the climate.” This drive for subsidies will continue even if there is no successor to Kyoto.

Political leaders in European nations continue to mouth support for climate alarmism, but that support appears to be crumbling in the face of a financial crisis, the high price and small impact of renewable energy sources, and the refusal by the United States, China, and India to participate in an emissions control regime. Japan, Canada, and Russia are abandoning negotiations for a future Kyoto Protocol, while there is still uncertainty in Australia. But one thing is certain: The Kyoto Protocol is dead.

At national and state levels in the United States, there have been major changes since 2009. The United States has never ratified the Kyoto Protocol, but there have been unilateral efforts to impose similar mandates. Those efforts peaked in 2009 when a Democrat-controlled House of Representatives passed a cap-and-trade bill. The November 2009 elections, however, put an end to Democratic control of the House, and more.

Republicans gained more seats in the House than in any election since 1938, leaving Democrats with the party’s fewest seats in the House since 1946. Even more important in terms of its impact on climate change policy were Republican gains at the state level. A record number of freshmen state legislators—1,765 out of 7,300—were elected. Republicans replaced Democrats in eight governors’ mansions and at least 675 seats in state legislatures. The number of Republican governors rose from 22 to 29, and the number of states with Republican majorities in both houses rose from 14 to 26.

The political realignment in the United States, combined with the slowest economic recovery among the world’s developed countries, means there is little chance of passing cap-and-trade legislation or a treaty for the coming two years, and probably longer. The White House and Environmental Protection Agency (EPA) seek to impose equivalent restrictions on the economy by the Clean Air Act, but EPA’s “endangerment finding,” necessary if the agency is to proceed in its regulatory efforts, is being challenged in the courts on the grounds that it is based on faulty IPCC science. Appeals are likely to continue into 2012. Meanwhile, the Republican majority in the House is doing what it can to restrict appropriations to EPA that would be used to implement greenhouse gas regulations.

InterAcademy Council Audit of IPCC

In 2010, the Amsterdam-based InterAcademy Council (IAC), a scientific body composed of the heads of national science academies around the world, revealed crippling flaws in the IPCC’s peer-review process. The IAC reported (InterAcademy Council, 2010) that IPCC lead authors fail to give “due consideration … to properly documented alternative views" (p. 20), fail to "provide detailed written responses to the most significant review issues identified by the Review Editors" (p. 21), and are not "consider[ing] review comments carefully and document[ing] their responses" (p. 22).

The IAC found "the IPCC has no formal process or criteria for selecting authors" and "the selection criteria seemed arbitrary to many respondents" (p. 18). Government officials appoint scientists from their countries and "do not always nominate the best scientists from among those who volunteer, either because they do not know who these scientists are or because political considerations are given more weight than scientific qualifications" (p. 18).

The rewriting of the Summary for Policy Makers by politicians and environmental activists—a problem called out by global warming realists for many years, but with little apparent notice by the media or policymakers—is plainly admitted, perhaps for the first time by an organization in the "mainstream" of alarmist climate change thinking. "[M]any were concerned that reinterpretations of the assessment's findings, suggested in the final Plenary, might be politically motivated," the auditors wrote, and the scientists they interviewed commonly found the Synthesis Report "too political" (p. 25).

Note especially this description by the IAC of how the "consensus of scientists" is actually obtained by the IPCC:

> Plenary sessions to approve a Summary for Policy Makers last for several days and commonly end with an all-night meeting. Thus, the individuals with the most endurance or the countries that have large delegations can end up having the most influence on the report (p. 25).

Another problem documented by the IAC that was noted in NIPCC-1 is the use of phony "confidence intervals" and estimates of "certainty" in the Summary for Policy Makers (pp. 27–34). We knew this was make-believe, almost to the point of a joke, when we first saw it in 2007. Work by J. Scott Armstrong (2006) on the science of forecasting makes it clear scientists cannot simply gather around a table and vote on how confident they are about some prediction, and then affix a number to it such as "80% confident." Yet this is how the IPCC proceeds. The IAC authors say it is "not an appropriate way to characterize uncertainty" (p. 34), a huge understatement. Unfortunately, the IAC authors recommend an equally fraudulent substitute, called "level of understanding scale," which is mush-mouth for "consensus."

The IAC authors warn, also on p. 34, that "conclusions will likely be stated so vaguely as to make them impossible to refute, and therefore statements of 'very high confidence' will have little substantive value."

Finally, in a discussion of conflict of interest and disclosure, the IAC noted, "the lack of a conflict of interest and disclosure policy for IPCC leaders and Lead Authors was a concern raised by a number of individuals who were interviewed by the Committee or provided written input … about the practice of scientists responsible for writing IPCC assessments reviewing their own work. The Committee did not investigate the basis of these claims, which is beyond the mandate of this review" (p. 46). Too bad, because these are both big issues and their presence in the report is an admission of more structural problems with the IPCC.

New Survey of Climate Scientists

German scientists Dennis Bray and Hans von Storch (2010) released their latest international survey of climate scientists in 2010. The survey, which was actually conducted in 2007, consisted of 120 questions. Typical is question 11a, which asked scientists to rank "data availability for climate change analysis" on a scale from 1 ("very inadequate") to 7 ("very adequate"). More respondents said "very inadequate" (1 or 2) than "very adequate" (6 or 7), with most responses ranging between 3 and 5. About 40 percent scored it a 3 or less. This single question and its answers imply that we need to know more about how climates actually work before we can predict future climate conditions.

The roughly bell-shaped distribution of answers is repeated for about a third of the 54 questions addressing scientific issues (as opposed to opinions about the IPCC, where journalists get their information, personal identification with environmental causes, etc.). Answers to the other questions about science were divided almost equally between distributions that lean toward skepticism and those that lean toward alarmism. What this means is that for approximately two-thirds of the questions asked, scientific opinion is deeply divided, and in half of those cases, most scientists disagree with positions that are at the foundation of the alarmist case. This survey certainly shows no consensus on the science behind the global warming scare.

The questions for which most scientists give alarmist answers are those that ask for an opinion about the "big picture," such as "How convinced are you that climate change poses a very serious and dangerous threat to humanity?" These questions ask about beliefs and convictions, not discrete scientific facts or knowledge. When asked questions about narrower scientific matters, scientists seem quick to admit their uncertainty.

This survey, like previous ones done by Bray and von Storch, provided a fascinating look at cognitive dissonance in the scientific community. When asked, majorities of climate scientists say they do not believe the scientific claims that underlie the theory and predictions of catastrophic anthropogenic climate change, yet large majorities of those same scientists say they nevertheless believe in the theory and its predictions. This cognitive dissonance gives rise to and sustains a popular mass delusion.

Acknowledgements

Climate change is an interdisciplinary topic, and so it draws on the work of people in widely divergent fields of study. We have been honored to be able to work with many of the leading thinkers in the fields of physics, geology, climatology, biology, and economics. We extend our thanks and appreciation to the many scientists, economists, and other experts who helped write this report and its precursor, and to those who conducted the original research that is summarized and cited.

Funding for this effort comes from two family foundations, both requesting anonymity, and neither having any commercial interest in the topic. We thank them for their generosity. No government or corporate funds were solicited or received to support this project.

J Bast

Joseph L. Bast
President
The Heartland Institute

Sam Karnick

S.T. Karnick
Research Director
The Heartland Institute

Diane Carol Bast

Diane Carol Bast
Executive Editor
The Heartland Institute

References

Armstrong, J.S. 2006. Findings from evidence-based forecasting: Methods for reducing forecast error. *International Journal of* Forecasting **22:** 583–598.

BBC. 2010. Q&A: Professor Phil Jones**,** http://news.bbc.co.uk/2/hi/science/nature/8511670.stm, posted on February 13, 2010.

Bell, L. 2011. *Climate of Corruption: Politics and Power Behind the Global Warming Hoax*. Austin, TX: Greenleaf Book Group Press.

Bray, D. and von Storch, H. 2010. GKSS-Report 2010/9: CliSci2008: A Survey of the Perspectives of Climate Scientists Concerning Climate Science and Climate Change.

Hulme, M. 2009. *Why We Disagree About Climate Change.* New York, NY: Cambridge University Press.

Idso, C. and Singer. S.F. 2009. *Climate Change Reconsidered: The 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

InterAcademy Council. 2010. Review of the Processes and Procedures of the IPCC.

IPCC-AR4. 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press.

Laframboise, D. et al. 2009. *UN's Climate Bible Gets 21 'F's on Report Card*, NoConsensus.org. http://www. noconsensus.org/ipcc-audit/findings-main-page.php.

Montford, A.W. 2010. *The Hockey Stick Illusion: Climategate and the Corruption of Science*. London:, UK: Stacey International.

Sussman, B. 2010. *Climategate.* Washington, DC: WorldNetDaily.

Preface

This *2011 Interim Report* from the Nongovernmental International Panel on Climate Change (hereafter NIPCC-IR 2011) presents an overview of research on climate change that has appeared since publication of *Climate Change Reconsidered: The 2009 Report of the Nongovernmental International Panel on Climate Change* (Idso and Singer, 2009, hereafter NIPCC-1). Research published before 2009 is included if it did not appear in the 2009 report or provides context for the new research. Nearly all of the research summarized here appeared in peer-reviewed science journals.

The current report was coauthored by a team of scientists recruited and led by Craig D. Idso, Robert M. Carter, and S. Fred Singer. Significant contributions were provided by the lead authors and contributors identified on the title page. This team of scientists has been working since the release of NIPCC-1 on a new report currently scheduled for release in 2013. A second interim report, similar to the current report, is planned for 2012.

Being an interim compilation of research rather than a comprehensive assessment, this volume has not been formally peer reviewed. Peer review, as it has come to be exercised in the climate change debate, is controversial and difficult to define (Wegman et al., 2006). The InterAcademy Council (2010), for example, documented shortcomings in the process used by the Intergovernmental Panel on Climate Change (IPCC) for peer review of its Fourth Assessment Report (2007) (AR4), yet the IPCC continues to claim its reports were peer-reviewed. We will not make a similar mistake.

About NIPCC

NIPCC is what its name suggests: an international panel of *nongovernment* scientists and scholars who have come together to understand the causes and consequences of climate change. Because we are not predisposed to believe climate change is caused by human greenhouse gas emissions, we are able to look at evidence the IPCC ignores. Because we do not work for any governments, we are not biased toward the assumption that greater government activity is necessary.

Our motivation remains the same as we reported in the preface to NIPCC-1:

> We donated much of our time and best efforts to produce this report out of concern that the IPCC was provoking an irrational fear of anthropogenic global warming based on incomplete and faulty science. … While there is nothing wrong with initiatives to increase energy efficiency or diversify energy sources, they cannot be justified as a realistic means to control climate. Neither does science justify policies that try to hide the huge cost of greenhouse gas controls, such as cap and trade, a “clean development mechanism,” carbon offsets, and similar schemes that enrich a few at the expense of the rest of us.
>
> Seeing science clearly misused to shape public policies that have the potential to inflict severe economic harm, particularly on low-income groups, we choose to speak up for science at a time when too few people outside the scientific community know what is happening, and too few scientists who know the truth have the will or the platforms to speak out against the IPCC.

NIPCC began as an informal “Team B” of persons who attended a meeting in Milan in 2003 organized by S. Fred Singer and the Science and Environmental Policy Project (SEPP). Their purpose was to produce an independent evaluation of the available scientific evidence in anticipation of the release of the IPCC’s

AR4. The organization was activated after the AR4 "Summary for Policy Makers" appeared in February 2007, and it organized an international climate workshop in Vienna in April 2007.

In 2008, SEPP partnered with The Heartland Institute to publish *Nature, Not Human Activity, Rules the Planet* (Singer 2008). In 2009, SEPP and The Heartland Institute partnered with the Center for the Study of Carbon Dioxide and Global Change to produce NIPCC-1, the first comprehensive rebuttal of the IPCC's previous reports. That report, with contributions by 37 scientists and spanning the entire breadth of issues addressed by the IPCC, marked a decisive turning point in the global debate over climate change.

The three organizations that now constitute NIPCC decided so much new research was being produced, much of it critical of the alleged "consensus" in favor of belief in catastrophic anthropogenic global warming, that annual "interim reports" would be necessary prior to the release of NIPCC-2. Hence, the appearance of the current volume.

New Science

The Executive Summary, which follows the Table of Contents, briefly summarizes the contents of the ten chapters of this report. On the most important issue, the IPCC's claim that "most of the observed increase in global average temperatures since the mid-twentieth century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations [emphasis in the original]," we once again reach the opposite conclusion, that natural causes are very likely to be dominant. Once again, we stress that we are not saying anthropogenic greenhouse gases (GHG) *cannot* produce some warming or have not in the past. Our conclusion is that the evidence shows they are not playing a substantial role.

On the related question of the effects global warming might have on human health and the natural environment, we find the latest available research shows a warmer world would be a safer and healthier world for humans and wildlife alike. Climate change will continue to occur, regardless of whether human emissions contribute to the process, and some of those effects may be positive and some negative for human health and wildlife in different areas of the world. But the *net* effect of continued warming and rising carbon dioxide concentrations in the atmosphere is most likely to be beneficial to humans, plants, and wildlife.

Looking Ahead

Since NIPCC-1 was published in 2009, scientific opinion, politics, and informed public opinion have shifted toward the realism presented in that volume. Other factors, including the lack of global warming and the economic recession in the United States, have contributed to growing skepticism about the scientific claims made by the IPCC.

One should not underestimate, however, the resources or momentum of the powerful interest groups that knowingly or unknowingly exaggerate the human role in climate. Some of these groups have financial stakes in maintaining climate alarmism—they include investors in "renewable energy" (solar and wind), producers of biofuels such as ethanol, financial houses and analysts, and of course environmental advocacy groups.

Our hope is that this report will help policymakers and politicians make rational decisions on climate policy and energy policy based on real science, not all-night plenary sessions. We are confident such decisions will advance economic development, expand job creation, and improve standards of living for all nations.

Bob Carter S. Fred Singer

Craig D. Idso, Ph.D.
Chairman, Center for the
Study of Carbon Dioxide and
Global Change

Robert M. Carter, Ph.D.
Adjunct Research Fellow
James Cook University
Queensland, Australia

S. Fred Singer, Ph.D.
President
Science and Environmental
Policy Project

References

Idso, C. and Singer. S.F. 2009. *Climate Change Reconsidered: The 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

Singer, S.F. 2008. *Nature, Not Human Activity, Rules the Climate.* Chicago, IL: The Heartland Institute.

Wegman, E., Scott, D.W. and Said, Y. 2006. Ad Hoc Committee Report to Chairman of the House Committee on Energy & Commerce and to the Chairman of the House sub-committee on Oversight & Investigations on the Hockey-stick Global Climate Reconstructions. Washington, DC: U.S. House of Representatives.

Table of Contents

Executive Summary

This volume presents an overview of the research on climate change that has appeared since publication of *Climate Change Reconsidered: The 2009 Report of the Nongovernmental International Panel on Climate Change* (Idso and Singer, 2009, hereafter NIPCC-1). Research published before 2009 is included if it did not appear in the 2009 report or provides context for the new research. Nearly all of the research summarized here appeared in peer-reviewed science journals.

The current report was coauthored by a team of scientists recruited and led by Craig D. Idso, Robert Carter, and S. Fred Singer. Significant contributions were provided by the lead authors and contributors identified on the title page. This team of scientists has been working since the release of NIPCC-1 on a new comprehensive report currently scheduled for release in 2013. Being an interim compilation of research rather than a comprehensive assessment, this volume has not been formally peer-reviewed.

On the most important issue, the IPCC's claim that "most of the observed increase in global average temperatures since the mid-twentieth century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations [emphasis in the original]," we once again reach the opposite conclusion, that natural causes are very likely to be dominant. Once again, we stress we are not saying anthropogenic greenhouse gases (GHG) *cannot* produce some warming or have not in the past. Our conclusion is that the evidence shows they are not playing a substantial role.

On the related question of the effects global warming might have on human health and the natural environment, we find the latest available research shows a warmer world would be a safer and healthier world for humans and wildlife alike. Climate change will continue to occur, regardless of whether human emissions contribute to the process, and some of those effects may be positive and some negative for human health and wildlife in different areas of the world. But the *net* effect of continued warming and rising carbon dioxide concentrations in the atmosphere is most likely to be beneficial to humans, plants, and wildlife.

The report is divided into ten chapters that are briefly summarized here, and then more fully described in the remainder of this summary.

Chapter 1 describes problems that may be intrinsic to the global climate modeling exercise, followed by more detailed documentation of model shortcomings involving precipitation, temperature, El Niño/Southern Oscillation (ENSO), and soil moisture. We find evidence that the models over-estimate the amount of warming that occurred during the twentieth century, fail to incorporate chemical and biological processes that may be as important as the physical processes employed in the models. The models often diverge so greatly in their assumptions and findings that they cannot be said to validate each other, nor can such discordant projections be combined to produce meaningful averages.

Chapter 2 summarizes the latest research on what is known about forcings and feedbacks. While rising levels of atmospheric carbon dioxide (CO_2) would increase global temperatures through its thermal radiative properties, all else being equal, all else is not equal. More CO_2 promotes more plant growth both on land and throughout the surface waters of the world's oceans, and this vast assemblage of plant life has the ability to affect Earth's climate in several ways, almost all of them tending to counteract the heating effects of CO_2's thermal radiative forcing.

Chapter 3 reviews the latest research on paleoclimatology and recent temperatures, finding new evidence that the Medieval Warm Period of approximately 1,000 years ago, when there was about 28 percent less CO_2 in the atmosphere than there is currently, was both global and warmer than today's world. Research also reveals a significant period of elevated air temperatures that immediately preceded the Little Ice Age, during a time that has come to be known as the Little Medieval Warm Period. Other researchers have documented a decade-long cooling period following the record heat of 1998.

Chapter 4 reports the latest observations on changes in the cryosphere, oceans, precipitation, and rivers and streamflow, comparing those observations to projections made by the IPCC. The new research finds less melting of ice in the Arctic, Antarctic, and on mountaintops than previously feared, no sign of acceleration of sea-level rise in recent decades, no trend over the past 50 years in changes to the Atlantic meridional overturning circulation (MOC), and no changes in precipitation patterns or river flows that could be attributed to rising CO_2 levels.

Chapter 5 compares observations concerning extreme weather, such as floods, droughts, storms, and hurricanes, to projections made by the IPCC. Researchers have found extreme and destructive rainfall events were more common in many parts of the world during the Little Ice Age than they have been subsequently, contradicting the forecasts of the IPCC. Regional climate models of North America generate predictions that vary considerably among models and extend well beyond the realm of reality. Similarly, the frequency and severity of floods, droughts, and hurricanes all appear to be determined by natural processes other than anthropogenic climate change.

Chapter 6 compares observations regarding the fate of terrestrial animals to projections made by the IPCC. The IPCC assumes temperatures will rise so rapidly that many animal species will not be able to migrate poleward in latitude or upward in elevation rapidly enough to avoid extinction. New research and observational data contradict this assumption, finding instead that amphibians, birds, butterflies, other insects, lizards, mammals, and even worms benefit from global warming and its myriad ecological effects.

Chapter 7 reviews new research on the effects of rising temperatures and atmospheric CO_2 concentrations on plants and soils. It confirms NIPCC's earlier finding that plants benefit from both trends and increase the amount of carbon they sequester in woody tissue and root systems. Rising temperatures and atmospheric CO_2 concentrations, by increasing crop yields, will play a major role in averting hunger and ecological destruction in the future.

Chapter 8 examines research on the effects of rising temperature and atmospheric CO_2 concentrations on aquatic life. While some corals exhibit a propensity to bleach and die when sea temperatures rise, others exhibit a positive relationship between calcification, or growth, and temperature. The latest research suggests corals and other forms of aquatic life have effective adaptive responses to climate change enabling them to flourish despite or even because of climate change.

Chapter 9 finds global warming is more likely to improve rather than harm human health because rising temperatures lead to a greater reduction in winter deaths than the increase they cause in summer deaths. The result is a large net decrease in human mortality. Climate plays a relatively small role in the spread of viral and vector-borne diseases, which suggests continued warming would not increase the incidence of diseases. Higher atmospheric CO_2 concentrations tend to increase the production of plant nutrients with direct medicinal value, such as antioxidants that protect cells from the damaging effects of oxidation.

Chapter 10 presents data on the economic effects of the global warming of the twentieth century, errors in how the IPCC conducts its impact analyses, and recent studies concerning biofuels and the relationship between climate and war and social unrest. It finds decades-long empirical trends of improving human well-being according to measures that are climate-sensitive, such as hunger, poverty rates, and deaths due to extreme weather events. The IPCC systematically underestimates society's adaptive capacity by failing to take into account the greater wealth and technological advances that will be present at the time for which impacts are to be estimated. Even in worst-case scenarios, mankind will be much better off in the year 2100 than it is today, and therefore able to adapt to whatever challenges climate change presents.

Key Findings By Chapter

Chapter 1. Climate Models and Their Limitations

- Climate models over-estimate the amount of warming that occurred during the twentieth century, fail to incorporate chemical and biological processes that may be as important as the physical processes employed in the models, and often diverge so greatly in their assumptions and findings that they cannot be said to validate each other.

- Climate models fail to correctly simulate future precipitation due to inadequate model resolution on both vertical and horizontal spatial scales, a limitation that forces climate modelers to parameterize the large-scale effects of processes that occur on smaller scales than their models are capable of simulating. This is particularly true of physical processes such as cloud formation and cloud-radiation interactions.

- The internal variability component of climate change is strong enough to overwhelm any anthropogenic temperature signal and generate global cooling periods (between 1946 and 1977) and global warming periods (between 1977 and 2008), yet models typically underestimate or leave out entirely this component, leading to unrealistic values of climate sensitivity.

- Climate models fail to predict changes in sea surface temperature and El Niño/Southern Oscillation (ENSO) events, two major drivers of the global climate. There has been little or no improvement to the models in this regard since the late-1990s.

- Climate models typically predict summer desiccation of soil with higher temperatures, but real-world data show positive soil moisture trends for regions that have warmed during the twentieth century. This is a serious problem since accurate simulation of land surface states is critical to the skill of weather and climate forecasts.

- While climate models produce a wide range of climate sensitivity estimates based on the assumptions of their builders, estimates based on real-world measurements find that a doubling of the atmosphere's CO_2 concentration would result in only a 0.4° or 0.5° C rise in temperature.

Chapter 2. Forcings and Feedbacks

- All else being equal, rising levels of atmospheric CO_2 would increase global temperatures through its thermal radiative properties. But CO_2 promotes plant growth both on land and throughout the surface waters of the world's oceans, and this vast assemblage of plant life has the ability to affect Earth's climate in several ways, almost all of them tending to counteract the heating or cooling effects of CO_2's thermal radiative forcing.

- The natural environment is a major source of atmospheric aerosols, the output of which varies with temperature and CO_2 concentrations. Aerosols serve as condensation nuclei for clouds, and clouds affect Earth's energy budget through their ability to reflect and scatter light and their propensity to absorb and radiate thermal radiation. The cooling effect of increased emissions of aerosols from plants and algae is comparable to the warming effect projected to result from increases in greenhouse gases.

- Similarly, warming-induced increases in the emission of dimethyl sulfide (DMS) from the world's oceans would offset much or all of the effects of anthropogenic warming.

- New evidence points to a larger role for solar forcing than the IPCC has acknowledged. Likely mechanisms include perturbation of ocean currents, tropospheric zonal mean-winds, and the intensity of cosmic rays reaching the Earth.

- The IPCC underestimated the warming effect of chloroflourocarbons (CFCs) prior to their gradual removal from the atmosphere following the implementation of the Montreal Protocol in 2000. This could mean CO_2 concentrations played a smaller role in the warming prior to that year, and could help explain the global cooling trend since 2000.

- Other forcings and feedbacks about which little is known (or acknowledged by the IPCC) include stratospheric water vapor, volcanic and seismic activity, and enhanced carbon sequestration.

Chapter 3. Paleoclimate and Recent Temperature

- Evidence of a Medieval Warm Period (MWP) approximately 1,000 years ago, when there was about 28 percent less CO_2 in the atmosphere than there is currently, would show there is nothing unusual, unnatural, or unprecedented about recent temperatures. Such evidence is now overwhelming.

- New evidence not reported in NIPCC-1 finds the Medieval Warm Period occurred in North America, Europe, Asia, Africa, South America, Antarctica, and the Northern Hemisphere. Despite this evidence, Mann et al. (2009) continue to understate the true level of warming during the MWP by cherry-picking proxy and instrumental records.

- Research from locations around the world reveals a significant period of elevated air temperatures that immediately preceded the Little Ice Age, during a time that has come to be known as the Little Medieval Warm Period.

- Recent reconstructions of climate history find the human influence does not stand out relative to other, natural causes of climate change. While global warming theory and models predict polar areas would warm most rapidly, the warming of Greenland was 33 percent greater in magnitude in 1919–1932 than it was in 1994–2007, and Antarctica cooled during the second half of the twentieth century.

- Perlwitz et al. (2009) reported “a decade-long decline (1998–2007) in globally averaged temperatures from the record heat of 1998” and noted U.S. temperatures in 2008 “not only declined from near-record warmth of prior years, but were in fact colder than the official 30-year reference climatology … and further were the coldest since at least 1996.”

- New research disputes IPCC’s claim that it has ferreted out all significant influences of the world’s many and diverse urban heat islands from the temperature databases they use to portray the supposedly unprecedented warming of the past few decades.

Chapter 4. Observations and Projections: Cryosphere, Ocean Dynamics, and Hydrology

- The continent-wide snow and ice melting trend in Antarctica since 1979, when routine measurement of the phenomenon via space-borne passive microwave radiometers first began, has been negligible. New research also shows the West Antarctic Ice Sheet (WAIS) is more stable than previously thought.

- After doubling during the early 2000s, annual ice discharge from the Greenland Ice Sheet slowed dramatically beginning in 2006, the result of negative feedback that mitigates against fast loss of ice in a warming climate. Scientists have concluded present-day melting rates “are not exceptional within the last 140 years” and “are not necessarily the result of anthropogenic-related warming” (Wake et al., 2009).

- Glaciers on mountaintops and in mountain valleys have been retreating since the end of the Little Ice Age and there is little evidence the rate of their retreat increased in the twentieth century. Scientists have ruled out any role for rising local air temperature in the loss of ice from the top of Mt. Kilimanjaro, identifying changes in atmospheric moisture due to logging and agriculture at the foot of the mountain as the cause.

- Mean sea level has risen at a constant rate over the past 114 years, even though the air’s CO_2 concentration rose about 3.8 times faster over the second half of that period as during the first half. The aerial fertilization effect of CO_2 stimulates biogenic contributions to marsh elevation, counterbalancing sea-level rise. Other studies find “no evidence of large-scale reductions in island area” and “reef islands are geomorphically resilient landforms that thus far have predominantly remained stable or grown in area over the last 20–60 years” (Webb and Kench, 2010).

- No trend has been found over the past 50 years in changes to the Atlantic meridional overturning circulation (MOC), despite predictions by the IPCC that warming would disrupt this important system of heat transportation through ocean basins.

- No changes in precipitation patterns, snow, monsoons, or river flows that might be considered harmful to human well-being or plants or wildlife have been observed that could be attributed to rising CO_2 levels. What changes have been observed tend to be beneficial.

Chapter 5. Observations and Projections: Extreme Weather

- Researchers have found extreme and destructive rainfall events were more common in many parts of the world during the Little Ice Age than they have been subsequently, contradicting the forecasts of the IPCC. Regional climate models of North America generate predictions that vary considerably among models and extend well beyond the realm of reality.

- Flood frequency and severity in many areas of the world were higher historically during the Little Ice Age and other cool eras than during the twentieth century. Climate change ranks well below other contributors, such as dikes and levee construction, to increased flooding.

- Droughts are not becoming more frequent, more severe, or longer-lasting. For example, droughts in the central U.S. since 1895 have not been as severe or as long as earlier droughts, with three of the top ten most severe droughts occurring in the late sixteenth century.

- Hurricane frequency does not fluctuate linearly with global temperatures. Researchers find "no significant [tropical cyclone] trend remains using either an 1878 or a 1900 starting point" (Landsea et al., 2009). Hurricane frequency during the Medieval Warm Period was equivalent to or even greater than that of the recent past.

- Similarly, wildfire frequency and intensity does not increase linearly with global temperatures. The incidence of large forest fires has decreased during the past 150 years in Canada and Russia. Human adaptation during the industrial age appears to have overpowered any natural tendency toward increased wildfires.

Chapter 6. Terrestrial Animals

- The basis of the IPCC's forecasts of impending extinctions and range retractions is an assumption that temperatures will rise so rapidly that many animal species will not be able to migrate poleward in latitude or upward in elevation rapidly enough to avoid extinction. New research and observational data contradict this assumption.

- The shortcomings associated with models predicting the impact of climate on distributions of species "are so numerous and fundamental that common ecological sense should caution us against putting much faith in relying on their findings for further extrapolations" (Dormann, 2007).

- Empirical data on amphibians, birds, butterflies, other insects, lizards, mammals, and even worms find global warming and its myriad ecological effects more often expand than contract animal habitats, ranges, and populations. Many species thrive with warmer temperatures, and while southern borders of ranges may remain stable, northern borders move poleward into previously uninhabitable regions.

- The net effect of climate change on the spread of parasitic and vector-borne diseases is complex and likely to be unpredictable. Rising temperatures increase the mortality rates as well as the development rates of many parasites of veterinary importance, and temperature is only one of many variables that influence the range of viruses and other sources of diseases.

Chapter 7. Terrestrial Plants and Soils

- "The IPCC's failure to report the beneficial effects of rising CO_2 concentrations is surprising when literally thousands of peer-reviewed journal articles exist on the subject. It is also a major defect of the IPCC report and one reason why it is not a reliable summary of the science of climate change" (NIPCC-1).

- Extensive research shows plants sequester greater amounts of carbon in woody biomass, including roots, as CO_2 concentrations rise. For most species studied and in most conditions, this sequestration does not slow or stop with the passage of time. Old-growth forests, for example, can sequester carbon for multiple centuries.

- Higher atmospheric CO_2 concentrations benefit plant growth-promoting microorganisms that help land plants overcome drought conditions, a potentially negative aspect of future climate change. Continued atmospheric CO_2 enrichment should prove to be a huge benefit to plants by directly enhancing their growth rates and water use efficiencies.

- Increased plant growth leads to higher emissions of isoprene, a highly reactive non-methane hydrocarbon that is responsible for the production of tropospheric ozone, which in turn is harmful to plant and animal life. Between 1901 and 2002, climate change at the global scale was responsible for a 7 percent increase in isoprene emissions. However, rising atmospheric CO_2 caused a more-than-offsetting 21 percent *reduction* in those emissions. Combined with anthropogenic cropland expansion, global isoprene emissions fell 24 percent during the twentieth century (Lathiere et al., 2010).

- Rising temperatures and atmospheric CO_2 concentrations, by increasing crop yields, will play a major role in averting hunger without the taking of new land and water from nature. For a nominal doubling of the air's CO_2 concentration, for example, the productivity of Earth's herbaceous plants rises by 30 to 50 percent and the productivity of its woody plants rises by 50 to 80 percent or more. In addition, atmospheric CO_2 enrichment typically increases plant nutrient and water use efficiency.

Chapter 8. Aquatic Life

- While some corals exhibit a propensity to bleach and die when sea temperatures rise, others exhibit a positive relationship between calcification, or growth, and temperature. "Such variable bleaching susceptibility implies that there is a considerable variation in the extent to which coral species are adapted to local environmental conditions" (Maynard et al., 2008).

- The latest research suggests corals have effective adaptive responses to climate change, such as symbiont shuffling, that allow reefs in some areas to flourish despite or even because of rising temperatures. Coral reefs have been able to recover quickly from bleaching events as well as damage from cyclones.

- Bleaching and other signs of coral distress attributed to global warming are often due to other things, including rising levels of nutrients and toxins in coastal waters caused by runoff from agricultural activities on land and associated increases in sediment delivery.

- The IPCC expresses concern that rising atmospheric CO_2 concentrations are lowering the pH values of oceans and seas, a process called acidification, and that this could harm aquatic life. But the drop in pH values that could be attributed to CO_2 is tiny compared to natural variations occurring in some ocean basins as a result of seasonal variability, and even day-to-day variations in many areas. Recent estimates also cut in half the projected pH reduction of ocean waters by the year 2100 (Tans, 2009).

- Real-world data contradict predictions about the negative effects of rising temperatures, rising CO_2 concentrations, and falling pH on aquatic life. Studies of algae, jellyfish, echinoids, abalone, sea urchins, and coral all find no harmful effects attributable to CO_2 or acidification.

Chapter 9. Human Health Effects

- Global warming is more likely to improve rather than harm human health because rising temperatures lead to a greater reduction in winter deaths than the increase they cause in summer deaths. The result is a large net decrease in human mortality.

- Climate plays a relatively small role in the spread of viral and vector-borne diseases, which suggests continued warming would not increase the incidence of diseases. Much bigger players include population growth (of both humans and domestic animals), armed conflicts, displaced populations, urbanization, and lack of reliable water systems.

- Higher atmospheric CO_2 concentrations tend to increase the production of plant nutrients with direct medicinal value, such as antioxidants that protect cells from the damaging effects of oxidation. This effect has been found in wheat, Chinese broccoli, spinach, grapes, and thyme.

Chapter 10. Economic and Other Policy Implications

- Decades-long empirical trends of climate-sensitive measures of human well-being, including the percent of developing world population suffering from chronic hunger, poverty rates, and deaths due to extreme weather events, reveal dramatic improvement during the twentieth century, notwithstanding the historic increase in atmospheric CO_2 concentrations.

- The magnitude of the impacts of climate change on human well-being depends on society's adaptability (adaptive capacity), which is determined by, among other things, the wealth and human resources society can access in order to obtain, install, operate, and maintain technologies necessary to cope with or take advantage of climate change impacts. The IPCC systematically underestimates adaptive capacity by failing to take into account the greater wealth and technological advances that will be present at the time for which impacts are to be estimated.

- Even accepting the IPCC's and Stern Review's worst-case scenarios, and assuming a compounded annual growth rate of per-capita GDP of only 0.7 percent, reveals that net GDP per capita in developing countries in 2100 would be double the 2006 level of the U.S. and triple that level in 2200. Thus, even developing countries' future ability to cope with climate change would be much better than that of the U.S. today.

- The IPCC's embrace of biofuels as a way to reduce greenhouse gas emissions was premature, as many researchers have found "even the best biofuels have the potential to damage the poor, the climate, and biodiversity" (Delucchi, 2010). Biofuel production consumes nearly as much energy as it generates, competes with food crops and wildlife for land, and is unlikely to ever meet more than a small fraction of the world's demand for fuels.

- The notion that global warming might cause war and social unrest is not only wrong, but even backwards – that is, global cooling has led to wars and social unrest in the past, whereas global warming has coincided with periods of peace, prosperity, and social stability.

References

Delucchi, M.A. 2010. Impacts of biofuels on climate change, water use, and land use. *Annals of the New York Academy of Sciences* **1195**: 28–45.

Dormann, C.F. 2007. Promising the future? Global change projections of species distributions. *Basic and Applied Ecology* **8**: 387–397.

Idso, C.D. and Singer, S.F. 2009. *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

Landsea, C.W., Vecchi, G.A., Bengtsson, L., and Knutson, T.R. 2009. Impact of duration thresholds on Atlantic tropical cyclone counts. *Journal of Climate* **23**: 2508–2519.

Lathiere, J., Hewitt, C.N., and Beerling, D.J. 2010. Sensitivity of isoprene emissions from the terrestrial biosphere to 20th century changes in atmospheric CO_2 concentration, climate, and land use. *Global Biogeochemical Cycles* **24**: 10.1029/2009GB003548.

Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R.S., Hughes, M.K., Shindell, D., Ammann, C., Faluvegi, G., and Ni, F. 2009. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science* **326**: 1256–1260.

Maynard, J.A., Baird, A.H., and Pratchett, M.S. 2008. Revisiting the Cassandra syndrome; the changing climate of coral reef research. *Coral Reefs* **27**: 745–749.

Perlwitz, J., Hoerling, M., Eischeid, J., Xu, T., and Kumar, A. 2009. A strong bout of natural cooling in 2008. *Geophysical Research Letters* **36**: 10.1029/2009GL041188.

Tans, P. 2009. An accounting of the observed increase in oceanic and atmospheric CO_2 and an outlook for the future. *Oceanography* **22**: 26–35.

Wake, L.M., Huybrechts, P., Box, J.E., Hanna, E., Janssens, I., and Milne, G.A. 2009. Surface mass-balance changes of the Greenland ice sheet since 1866. *Annals of Glaciology* **50**: 176–184.

Webb, A.P. and Kench, P.S. 2010. The dynamic response of reef islands to sea-level rise: evidence from multi-decadal analysis of island change in the Central Pacific. *Global and Planetary Change* **72**: 234–246.

1

Climate Models and Their Limitations

Introduction

To commemorate the publication of the 100th volume of the journal *Climatic Change*, Norman Rosenberg (Rosenberg, 2010) was asked to contribute an overview paper on progress that had occurred since the journal's inception in the interrelated areas of climate change, agriculture, and water resources. Rosenberg accepted, and at the valedictory age of 80, he did it quite admirably.

He began by noting the "overarching concern" of the volumes he edited was "to gain understanding of how climatic change affects agricultural production, unmanaged ecosystems and water resources; how farmers, foresters and water managers can strengthen these sectors against the negative impacts of climatic change and capitalize on positive impacts if any; how they can adapt to impacts that cannot be so modified or ameliorated and how they can contribute directly or indirectly to mitigation of anthropogenic climatic change—as, for example, through soil carbon sequestration and the production of biomass to substitute in part for the fossil fuels that are adding CO_2 to the atmosphere."

Rosenberg wrote in his closing paragraph, "it seems difficult to say with assurance that the 'state-of-the-art' in projecting climatic change impacts on agriculture and water resources and unmanaged ecosystems is, today, that much better than it was 30 years ago," noting that "the uncertainty and lack of agreement in GCMs [global climate models] is still too great." He reported, "much can and has been learned about *possible* outcomes," but "for actual planning and policy purposes we are still unable to assure those who need to know that we can forecast where, when and how much agriculture (as well as unmanaged ecosystems and water resources) will be affected by climatic change."

A similarly pessimistic commentary on the state of climate modeling appeared in 2010 in *Nature Reports Climate Change*. Kevin Trenberth, head of the Climate Analysis Section of the National Center for Atmospheric Research in Boulder, Colorado (USA), wrote that one of the major objectives of upcoming climate modeling efforts will be to develop "new and better representations of important climate processes and their feedbacks." The new work, Trenberth wrote, should increase "our understanding of factors we previously did not account for ... or even recognize."

In expressing these sentiments, Rosenberg and Trenberth gave voice to the concerns of many scientists who are skeptical of the reliability of GCMs. This is not "denial." Trenberth, at least, would deny being a "skeptic" of the theory of anthropogenic global warming. It is, rather, the humility of true scientists who—attempting to comprehend the complexity of the world of nature and its innermost workings—are well aware of their own limitations and those of all seekers of such truths. Although much has been learned, as Rosenberg and Trenberth outline in their respective essays, what is known pales in comparison to what is required "for actual planning and policy purposes," as Rosenberg describes it, or "certainty" as Trenberth puts it.

This sense of humility is no more, and no less, than what the authors of this chapter seek to communicate. The first section briefly describes problems that may be intrinsic to the global climate modeling exercise. It is followed by more detailed documentation of model shortcomings involving precipitation, temperature, El Niño/Southern Oscillation (ENSO), and soil moisture. We remind the reader that this is only a compilation of recent research on these topics, and little effort has been expended to make sustained arguments.

References

Rosenberg, N.J. 2010. Climate change, agriculture, water resources: what do we tell those that need to know? *Climatic Change* **100**: 113–117.

Trenberth, K. 2010. More knowledge, less certainty. *Nature Reports Climate Change*: 10.1038/climate.2010.06.

1.1 Intrinsic Problems with Models

To introduce the topic of intrinsic problems with GCMs, consider a paper that fails to recognize any such problems. Published in the *Proceedings of the National Academy of Sciences of the United States of America* and written by Susan Solomon (a cochair of the IPCC's Working Group 1 when AR4 was produced) and three coauthors, it claims to show that "climate change that takes place due to increases in carbon dioxide concentration is largely irreversible for 1,000 years after emissions stop" (Solomon et al., 2009). In the virtual world of computer-run climate models, that may be the case, but that need not be true of the real world.

The four scientists set forth three criteria they say should be met by the modeled climatic parameters they study: "(i) observed changes are already occurring and there is evidence for anthropogenic contributions to these changes, (ii) the phenomen[a] [are] based upon physical principles thought to be well understood, and (iii) projections are available and are broadly robust across models."

Real-world data provide little or no support for the first criterion. The global warming of the past few decades was part of a much longer warming trend that began in many places throughout the world a little over three centuries ago (about 1680) with the dramatic "beginning of the end" of the Little Ice Age (LIA, see Figure 1.1 below), well before there was any significant increase in the air's CO_2 content. This observation suggests a continuation of whatever phenomenon—or combination of phenomena—may have caused the greater initial warming may have caused the lesser final warming, the total effect of which has been to transport the Earth from the chilly depths of the Little Ice Age into the relative balminess of the Current Warm Period.

Climate history will be discussed in greater detail in Chapter 3, but it is useful to note here that Earth's current temperature is no higher now (and may be slightly less) than it was during the peak warmth of the Medieval Warm Period (MWP), when there was more than 100 ppm less CO_2 in the air than there is today. Consequently, since the great MWP-to-LIA cooling occurred without any significant change in the atmosphere's CO_2 concentration, the opposite could occur just as easily, and the planet could warm, and by an equal amount—just as it actually did over the past three centuries—without any help from an increase in the atmosphere's CO_2 content.

Regarding Solomon et al.'s second criterion, the studies reported in this chapter will show that there are non-modeled chemical and biological principles that may be equally as important as the physical principles employed in the models. The phenomena are simply not as "well understood" as Solomon et al. claim. A highly selective reading of the literature is required to miss the repeated admissions by leading researchers of the uncertainty and outright ignorance of underlying processes that undermine the reliability of GCMs.

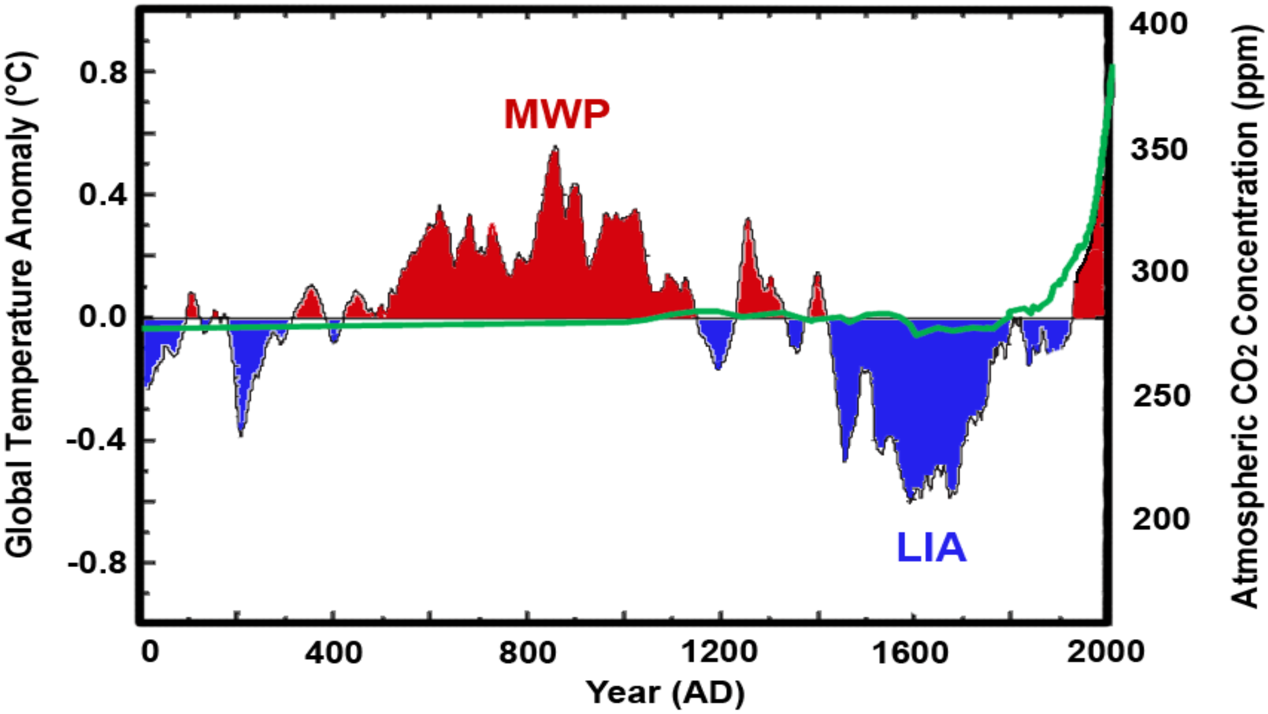


Figure 1.1. The mean relative temperature history of the Earth (blue, cool; red, warm) over the past two millennia—adapted from Loehle and McCulloch (2008)—highlighting the Medieval Warm Period (MWP) and Little Ice Age (LIA), together with a concomitant history of the atmosphere's CO_2 concentration (green).

Regarding Solomon et al.'s third criterion, many computer model projections are indeed "available and are broadly robust across models." But these models often diverge so greatly in their assumptions and in their specific spatial and temporal findings that they cannot be said to validate each other, nor can such discordant projections be combined to produce meaningful averages. Many studies have found that real-world data contradict what the models say should be occurring. To say such models are "robust" is wishful thinking.

A good example of an admission of the wide range of uncertainty that undermines GCMs appears in Woollings (2010):

> The spread between the projections of different models is particularly large over Europe, leading to a low signal-to-noise ratio. This is the first of two general reasons why European climate change must be considered especially uncertain. The other is the long list of physical processes which are very important for defining European climate in particular, but which are represented poorly in most, if not all, current climate models.

Woollings cites several examples of key atmospheric processes affecting the climate of Europe that models currently do not simulate well, noting that (1) the location of the jet stream over northern Europe in most models diverges from reality, (2) zonal flow is biased too far south in most models, (3) the models can't simulate or explain the North Atlantic Oscillation with sufficient magnitude to match historical data, and (4) heat waves and droughts, such as the summer 2010 Moscow heat wave and fires, are caused by blocking, which is a process the models are currently unable to simulate.

In addition, for several key processes the models produce widely varying predictions. The atmospheric circulation response to warming in climate models, for example, is highly variable, as is the change in storm intensity, the projected change in the jet stream, and changes in temperature. And it is particularly noteworthy that Europe is predicted to warm less than most Northern Hemisphere sites due to the slowing of the Gulf Stream providing reduced northward heat transport. As a result of such findings it is easy to recognize that current climate models are unable to achieve the degree of accuracy in the details of atmospheric circulation that are critical to replicating current weather events, such as droughts, heat waves, and major storms in Europe. Thus, any assertion that these events can be forecast 100 years in the future under a changed climate is simply false, and claims about negative impacts of climate change in Europe are based upon no specific modeling skill.

The rest of this section presents four specific problems that may be intrinsic to GCMs: their treatment of aerosols, atmospheric blocking, chaotic systems, radiation, and tropospheric humidity, and how to reconcile divergent models.

References

Idso, S.B. 1998. CO_2-induced global warming: a skeptic's view of potential climate change. *Climate Research* **10**: 69–82.

Loehle, C. and McCulloch, J.H. 2008. Correction to: A 2000-year global temperature reconstruction based on non-tree ring proxies. *Energy & Environment* **19**: 93–100.

Solomon, S., Plattner, G.-K., Knutti, R., and Friedlingstein, P. 2009. *Proceedings of the National Academy of Sciences USA* **106**: 1704–1709.

Woollings, T. 2010. Dynamical influences on European climate: an uncertain future. *Philosophical Transactions of the Royal Society A* **368**: 3733–3756.

1.1.1 Aerosols

The treatment of aerosols by GCMs is a major limitation on their reliability. Mishchenko et al. (2009) write, "because of the global nature of aerosol climate forcings, satellite observations have been and will be an indispensable source of information about aerosol characteristics for use in various assessments of climate and climate change," and "there have been parallel claims of unprecedented accuracy of aerosol retrievals with the moderate-resolution imaging spectroradiometer (MODIS) and multi-angle imaging spectroradiometer (MISR)."

If both aerosol retrieval systems are as good as they have been claimed to be, they should agree on a pixel-by-pixel basis as well as globally. Consequently, and noting that "both instruments have been flown for many years on the same Terra platform, which provides a unique opportunity to compare fully collocated pixel-level MODIS and MISR aerosol retrievals directly," Mishchenko et al. decided to see how they compare in this regard by analyzing eight years of such data.

The six scientists from NASA's Goddard Institute for Space Studies report finding what they describe as "unexpected significant disagreements at the pixel level as well as between long-term and spatially averaged aerosol properties." In fact, they write, "the only point on which both datasets seem to fully agree is that there may have been a weak increasing tendency in the globally averaged aerosol optical thickness (AOT) over the land and no long-term AOT tendency over the oceans." As a result, the bottom line for the NASA scientists is quite succinct: "Our new results suggest that the current knowledge of the global distribution of the AOT and, especially, aerosol microphysical characteristics remains unsatisfactory." And since this knowledge is indispensable "for use in various assessments of climate and climate change," it would appear that current assessments of greenhouse gas forcing of climate made by the very best models in use today are deficient.

In a contemporaneous study, Haerter et al. (2009) write that future projections of climate "have been—for a given climate model—derived using a 'standard' set of cloud parameters that produce realistic present-day climate." However, they write, "there may exist another set of parameters that produces a similar present-day climate but is more appropriate for the description of climate change," and, "due to the high sensitivity of aerosol forcing (F) to cloud parameters, the climate projection with this set of parameters could be notably different from that obtained from the standard set of parameters, even though the present-day climate is reproduced adequately." This state of affairs suggests that replication of the present-day climate is no assurance that a climate model will accurately portray Earth's climate at some future time.

To get a better idea of the magnitude of uncertainty associated with this conundrum, Haerter et al. used the ECHAM5 atmospheric general circulation model (GCM), which includes parameterizations of direct and first indirect aerosol effects, to determine what degree of variability in F results from reasonable uncertainties associated with seven different cloud parameters. These are the entrainment rate for shallow convection, the entrainment rate for penetrative convection, the cloud mass flux above the non-buoyancy level, the correction to asymmetry parameter for ice clouds, the inhomogeneity parameter for liquid clouds, the inhomogeneity parameter for ice clouds, and the conversion efficiency from cloud water to precipitation. When they had completed their analyses, the four researchers reported "the uncertainty due to a single one of these parameters can be as large as 0.5 W/m^2" and "the uncertainty due to combinations of these parameters can reach more than 1 W/m^2." As for the significance of their findings, they write, "these numbers should be compared with the sulfate aerosol forcing of -1.9 W/m^2 for the year 2000, obtained using the default values of the parameters."

Due to these large parametric uncertainties, we apparently do not know the mean sulfate aerosol forcing component of Earth's top-of-the-atmosphere radiative budget to within anything better than ± 50%. In addition, Haerter et al. note that structural uncertainties, such as "uncertainties in aerosol sources, representation of aerosols in models, parameterizations that relate aerosols and cloud droplets to simulate the indirect aerosol effect, and in cloud schemes" lead to an overall uncertainty in F of approximately ± 43%, as per the most recent IPCC estimates. In reality, therefore, we probably do not know the current atmosphere's aerosol radiative forcing to anything better than ± 100%, which does not engender confidence in our ability to simulate earth's climate very far into the future with state-of-the-art climate models.

References

Haerter, J.O., Roeckner, E., Tomassini, L., and von Storch, J.-S. 2009. Parametric uncertainty effects on aerosol radiative forcing. *Geophysical Research Letters* **36**: 10.1029/2009GL039050.

Mishchenko, M.I., Geogdzhayev, I.V., Liu, L., Lacis, A.A., Cairns, B., and Travis, L.D. 2009. Toward unified satellite climatology of aerosol properties: What do fully compatible MODIS and MISR aerosol pixels tell us? *Journal of Quantitative Spectroscopy & Radiative Transfer* **110**: 402–408.

1.1.2 Atmospheric Blocking

A phenomenon that is not often discussed in climate change studies is atmospheric blocking, a situation that develops when there is a stationary ridge of high pressure in the mid-latitude jet stream. This phenomenon is typically associated with unusually warm and dry weather in areas where these high-pressure ridges form, and cooler or wetter conditions upstream and downstream of where they occur. Some recent examples of blocking and its impact on regional weather are: (1) the Western European heat wave of 2003, (2) the extreme heat in Russia in 2010 and the downstream flooding in Pakistan, and (3) the cold temperatures over most of North America and Europe during December 2010.

In investigating this phenomenon, Kreienkamp et al. (2010) used National Centers for Atmospheric Research re-analyses to examine the occurrence of blocking events over Europe since the 1950s, using a well-known blocking index (Tibaldi and Molteni, 1990). They then employed the atmospheric general circulation model (ECHAM) used by the IPCC in an effort to determine how well the models were able to simulate such blocking. Lastly, they examined two climate warming scenarios (A1B and B1) for the twenty-first century in order to infer whether blocking will become more or less common in the twenty-first century based on model projections.

With respect to the re-analysis data, Kreienkamp et al. found little evidence of a statistically significant trend over the period 1951–2007 apart from a weak decrease in the European region, which decrease suggests extreme weather events caused by blocking events have probably also declined. With respect to model simulations, they found the models showed little change in the frequency, seasonality, or interannual variability of blocking for the Atlantic/European region as a whole but a significant decrease in Central European region frequency.

Although we are cautious about placing too much emphasis on model projections, this finding is also good news, for it suggests the number of heat waves and/or cold waves that can be attributed to atmospheric blocking will not increase for the Atlantic/European region during the twenty-first century. In fact, the model output suggests fewer of these occurrences and/or a shorter duration of such events.

References

Kreienkamp, F., Spekat, A., and Enke, W. 2010. Stationarity of atmospheric waves and blocking over Europe—based on a reanalysis dataset and two climate scenarios. *Theory of Applied Climatology* **102**: 205–212.

Tibaldi, S. and Molteni, F. 1990. On the operational predictability of blocking. *Tellus* **42A**: 343–365.

1.1.3 Climate as a Chaotic System

The ability of atmosphere-ocean GCMs to predict the climatic effects of human alterations of greenhouse gases and other factors cannot be tested directly with respect to a point in time a hundred years in the future. However, it is still possible to ask—and determine—whether those models can in principle make such predictions to a reasonable degree of accuracy. One way to evaluate this ability is to consider the effects of errors in system initial values. If a system is well-behaved, small initial errors will lead to small future errors, or even damped responses. In a chaotic system, on the other hand, small initial errors will cause trajectories to diverge over time; and for such a system (or model), true predictability is low to nonexistent.

In a study addressing initial value errors, Collins (2002) used the HadCM3 model, the output of which at a given date was used as the initial condition for multiple runs in which slight perturbations of the initial data were used to assess the effect of a lack of perfect starting information, as can often occur in the real world. The results of the various experimental runs were then compared to those of the initial control run, assuming the degree of correlation of the results of each perturbed run with those of the initial run is a measure of predictability.

As a result of these operations, Collins found "annual mean global temperatures are potentially predictable one year in advance" and "longer time averages are also marginally predictable five to ten years in advance." In the case of ocean basin sea surface temperatures, it was additionally found that coarse-scale predictability ranges from one year to several years. But for land surface air temperature and precipitation, and for the highly populated northern land regions, Collin concludes, "there is very little sign of any average potential predictability beyond seasonal lead times."

Reference

Collins, M. 2002. Climate predictability on interannual to decadal time scales: the initial value problem. *Climate Dynamics* **19**: 671–692.

1.1.4 Radiation

Eisenman et al. (2007) used two standard thermodynamic models of sea ice to calculate equilibrium Arctic ice thickness based on simulated Arctic cloud cover derived from 16 different general circulation models (GCMs) that were evaluated for the IPCC's Fourth Assessment Report. Their results indicated there was a 40 Wm^{-2} spread among the 16 models in terms of their calculated downward long-wave radiation, for which both sea ice models calculated an equilibrium ice thickness ranging from 1.0 to more than 10.0 meters. However, they note that the mean 1980–1999 Arctic sea ice thickness simulated by the 16 GCMs ranged from only 1.0 to 3.9 meters, a far smaller inter-model spread. Hence, they say they were "forced to ask how the GCM simulations produce such similar present-day ice conditions in spite of the differences in simulated downward longwave radiative fluxes."

Answering their own question, the three researchers observe that "a frequently used approach" to resolving this problem "is to tune the parameters associated with the ice surface albedo" to get a more realistic answer. "In other words," they continue, "errors in parameter values are being introduced to the GCM sea ice components to compensate simulation errors in the atmospheric components."

In consequence of the above findings, the three researchers conclude, "the thinning of Arctic sea ice over the past half-century can be explained by minuscule changes of the radiative forcing that cannot be detected by current observing systems and require only exceedingly small adjustments of the model-generated radiation fields" and, therefore, "the results of current GCMs cannot be relied upon at face value for credible predictions of future Arctic sea ice."

In another pertinent study, Andronova et al. (2009) "used satellite-based broadband radiation observations to construct a continuous 1985–2005 record of the radiative budget components at the top of the atmosphere (TOA) for the tropical region (20°S–20°N)" and then (1) "derived the most conservative estimate of their trends" and (2) "compared the interannual variability of the net radiative fluxes at the top of the tropical atmosphere with model simulations from the Intergovernmental Panel on Climate Change fourth assessment report (AR4) archive available up to 2000."

The three researchers found "the tropical system became both less reflective and more absorbing at the TOA" and, "combined with a reduction in total cloudiness (Norris, 2007), this would mean the tropical atmosphere had recently become more transparent to incoming solar radiation, which would allow more shortwave energy to reach earth's surface." Second, they found "none of the models simulates the overall 'net radiative heating' signature of the earth's radiative budget over the time period from 1985–2000."

With respect to the first of their findings and the associated finding of Norris (2007), Andronova et al. state these observations "are consistent with the observed near-surface temperature increase in recent years," which provides an independent validation of the TOA radiation measurements. With respect to their second finding, however, the failure of all of the AR4 climate models to adequately simulate the TOA radiation measurements discredits the models. The combination of these two conclusions suggests the historical rise in the air's CO_2 content has likely played a next-to-negligible role in the post-Little Ice Age warming of the world.

References

Andronova, N., Penner, J.E., and Wong, T. 2009. Observed and modeled evolution of the tropical mean radiation budget at the top of the atmosphere since 1985. *Journal of Geophysical Research* **114**: 10.1029/2008JD011560.

Eisenman, I., Untersteiner, N., and Wettlaufer, J.S. 2007. On the reliability of simulated Arctic sea ice in global climate models. *Geophysical Research Letters* **34**: 10.1029/2007GL029914.

Norris, J.R. 2007. Observed interdecadal changes in cloudiness: Real or spurious? In *Climate Variability and Extremes During the Past 100 Years*, edited by S. Broennimann et al., 169–178. New York, NY: Springer.

1.1.5 Tropospheric Humidity

Paltridge et al. (2009) write, "water vapor feedback in climate models is large and positive" and "the various model representations and parameterizations of convection, turbulent transfer, and deposition of latent heat generally maintain a more-or-less constant relative humidity (i.e., an increasing specific humidity *q*) at all levels in the troposphere as the planet warms," and that this "increasing *q* amplifies the response of surface temperature to increasing CO_2 by a factor or 2 or more." Consequently, knowledge of how *q* responds to atmospheric warming is of paramount importance to the task of correctly predicting how air temperatures respond to increasing CO_2 concentrations. Paltridge et al. explored this important subject by determining trends in relative and specific humidity at various levels in the atmosphere based on reanalysis data of the National Centers for Environmental Prediction (NCEP) for the period 1973–2007.

The three researchers report, "the face-value 35-year trend in zonal-average annual-average specific humidity *q* is significantly negative at all altitudes above 850 hPa (roughly the top of the convective boundary layer) in the tropics and southern midlatitudes and at altitudes above 600 hPa in the northern midlatitudes." Given these findings, Paltridge et al. conclude "negative trends in *q* as found in the NCEP data would imply that long-term water vapor feedback is negative—that it would reduce rather than amplify the response of the climate system to external forcing such as that from increasing atmospheric CO_2."

Reference

Paltridge, G., Arking, A. and Pook, M. 2009. Trends in middle- and upper-level tropospheric humidity from NCEP reanalysis data. *Theoretical and Applied Climatology* **98**: 351–359.

1.1.6 Reconciling Divergent Models

Reifen and Toumi (2009) note, "with the ever increasing number of models, the question arises of how to make a best estimate prediction of future temperature change." That is to say, which model should one use? With respect to this question, they note, "one key assumption, on which the principle of performance-based selection rests, is that a model which performs better in one time period will continue to perform better in the future." In other words, if a model predicts past climate fairly well, it should predict future climate fairly well. The principle sounds reasonable enough, but is it true?

Reifen and Toumi examined this question "in an observational context" for what they describe as "the first time." Working with the 17 climate models employed by the IPCC in its Fourth Assessment Report, they determined how accurately individual models, as well as various subsets of the 17 models, simulated the temperature history of Europe, Siberia, and the entire globe over a selection period (such as 1900–1919) and a subsequent test period (such as 1920–1939), asking whether the results for the test period are as good as those of the selection period. They followed this procedure while working their way through the entire twentieth century at one-year time-steps for not only 20-year selection and test intervals but also for 10- and 30-year intervals.

The two researchers could find "no evidence of future prediction skill delivered by past performance-based model selection," noting, "there seems to be little persistence in relative model skill." As for why this was so, they speculated, "the cause of this behavior is the non-stationarity of climate feedback strengths," which they explain by stating "models that respond accurately in one period are likely to have the correct feedback strength at that time," but "the feedback strength and forcing is not stationary, favoring no particular model or groups of models consistently."

Given such findings, the U.K. physicists conclude their analysis of the subject by stating, "the common investment advice that 'past performance is no guarantee of future returns' and to 'own a portfolio' appears also to be relevant to climate projections."

Reference

Reifen, C. and Toumi, R. 2009. Climate projections: Past performance no guarantee of future skill? *Geophysical Research Letters* **36**: 10.1029/2009GL038082.

1.2. Precipitation

Correctly simulating future precipitation has proved an extremely difficult task for modelers. One reason for the lack of success in this area is inadequate model resolution on both vertical and horizontal spatial scales, a limitation that forces climate modelers to parameterize the large-scale effects of processes that occur on smaller scales than their models are capable of simulating. This is particularly true of physical processes such as cloud formation and cloud-radiation interactions.

A good perspective on the cloud-climate conundrum was provided by Randall et al. (2003), who state at the outset of their review of the subject that "the representation of cloud processes in global atmospheric models has been recognized for decades as the source of much of the uncertainty surrounding predictions of climate variability." Yet despite what they called the "best efforts" of the climate modeling community, they had to acknowledge that "the problem remains largely unsolved." What is more, they suggested that "at the current rate of progress, cloud parameterization deficiencies will continue to plague us for many more decades into the future," which has important implications for predicting precipitation-related events such as floods and droughts.

In describing some of these deficiencies, Randall et al. stated, "our understanding of the interactions of the hot towers [of cumulus convection] with the global circulation is still in a fairly primitive state," and not knowing all that much about what goes up, it's not surprising the climate modelers don't know much about what comes down, as they report "downdrafts are either not parameterized or crudely parameterized in large-scale models."

The situation is no better with respect to stratiform clouds. Randall et al. describe the modelers' parameterizations as "very rough caricatures of reality." The models do not account for interactions between convective and stratiform clouds. During the 1970s and '80s, Randall et al. report, "cumulus parameterizations were extensively tested against observations without even accounting for the effects of the attendant stratiform clouds." Even at the time of their study (2003), in fact, they had to report that the concept of cloud detrainment was "somewhat murky" and that conditions that trigger detrainment are "imperfectly understood." Hence it should come as no surprise that at the time of their review they had to admit that "no existing GCM [includes] a satisfactory parameterization of the effects of mesoscale cloud circulations."

Randall et al. additionally noted, "the large-scale effects of microphysics, turbulence, and radiation should be parameterized as closely coupled processes acting in concert," but they reported only a few GCMs had attempted to do so. As they described it, "the cloud parameterization problem is overwhelmingly complicated," and "cloud parameterization developers," as they referred to them, were still "struggling to identify the most important processes on the basis of woefully incomplete observations." To drive this point home, they wrote, "there is little question why the cloud parameterization problem is taking a long time to solve: It is very, very hard." In fact, the four scientists concluded that "a sober assessment suggests that with current approaches the cloud parameterization problem will not be 'solved' in any of our lifetimes."

In spite of such a sobering assessment, the climate-modeling community places hope in what Randall et al. call "cloud system-resolving models," or CSRMs, which can be compared with single-column models or SCMs that can be "surgically extracted from their host GCMs." These advanced models, as they describe them, "have resolutions fine enough to represent individual cloud elements, and space-time domains large enough to encompass many clouds over many cloud lifetimes." Of course, these improvements mean "the computational cost of running a CSRM is hundreds or thousands of times greater than that of running an SCM." Nevertheless, in a few more decades, according to Randall et al., "it will become possible to use such global CSRMs to perform century-scale climate simulations, relevant to such problems as anthropogenic climate change." In the interim, they remain far from ready for prime time, as evidenced in a study conducted four years later by Zhou et al. (2007) and one three years later by Schliep et al. (2010).

In the first of these two studies, Zhou et al. acknowledged CSRMs "still need parameterizations on scales smaller than their grid resolutions and have many known and unknown deficiencies." To stimulate progress in these areas, they compared the cloud and precipitation properties observed by instruments deployed in the Clouds and Earth's Radiant Energy System (CERES) and Tropical Rainfall Measuring Mission (TRMM) systems against simulations obtained from the three-dimensional Goddard Cumulus Ensemble (GCE) model during the South China Sea Monsoon Experiment (SCSMEX) field campaign of 18 May–18 June 1998. As a result of that analysis, the nine researchers reported the following: (1) "the GCE rainfall spectrum includes a greater proportion of heavy rains than PR (Precipitation Radar) or TMI (TRMM Microwave Imager) observations," (2) "the GCE model produces excessive condensed water loading in the column, especially the amount of graupel as indicated by both TMI and PR observations," (3) "the model also cannot simulate the bright band and the sharp decrease of radar reflectivity above the freezing level in stratiform rain as seen from PR," (4) "the model has much higher domain-averaged OLR (outgoing longwave radiation) due to smaller total cloud fraction," (5) "the model has a more skewed distribution of OLR and effective cloud top than CERES observations, indicating that the model's cloud field is insufficient in area extent," (6) "the GCE is ... not very efficient in stratiform rain conditions because of the large amounts of slowly falling snow and graupel that are simulated," and finally, in summation, (7) "large differences between model and observations exist in the rain spectrum and the vertical hydrometeor profiles that contribute to the associated cloud field."

In the second of the two studies, Schleip et al. (2010) compared the results of six regional climate models (RCMs) that were forced with a common set of reanalysis data, which was created by running a climate model that was fed real-world data for a 20-year simulation period. The area analyzed was North America, where winter precipitation was the response variable and the 100-year extremum of daily winter precipitation was the test statistic, extreme values of which were estimated by fitting a tailed distribution to the data, taking into account their spatial aspects.

The results of this exercise indicated the six RCMs maintained similar general spatial patterns of extrema across North America, with the highest extremes in the Southeast and along the West Coast. However, when comparing absolute levels, which are most relevant to risk forecasts, the models exhibited strong disagreement. The lowest-predicting model was low almost everywhere in North America compared to the mean of the six models; and, similarly, the highest-predicting model was above the mean almost everywhere. In fact, the difference between the two models was almost 60mm of daily precipitation (for the 100-year extreme event) over much of the United States. The other four models showed greatly differing spatial patterns of extremes from each other, which differences were found to be statistically significant by an F-test. The researchers speculate that when driven by multiple GCMs rather than reanalysis data, the range of extreme outcomes would only increase.

Other studies have continued to demonstrate the difficulties models have in simulating precipitation properties and trends. Kiktev et al. (2007), for example, analyzed the abilities of five global coupled climate models that played important roles in the IPCC's Fourth Assessment Report to simulate temporal trends over the second half of the twentieth century for five annual indices of precipitation extremes. Their results revealed "low skill" or an "absence" of model skill.

Two years later, Lavers et al. (2009) examined the predictive skill of eight seasonal climate forecast models developed at various European climate centers. Specifically, they assessed the predictability of monthly precipitation "retrospective forecasts" or hindcasts, which were composed of multiple nine-month projections initialized during each month of the year over the period 1981–2001. They compared the projections against real-world precipitation values obtained from Global Precipitation Climatology Center data. In addition, they conducted a virtual-world analysis, where the output of one of the models was arbitrarily assumed to be the truth and the average of the rest of the models was assumed to be the predictor.

The results of these exercises indicated that in the virtual world of the climate models, there was quite good skill over the first two weeks of the forecast, when the spread of ensemble model members was small, but that there was a large drop off in predictive skill in the second 15-day period. Things were even worse in the real world, where they say the models had negligible skill over land at a 31-day lead time, which they described as being "a relatively short lead time in terms of seasonal climate prediction." In light of these findings, therefore, the three researchers concluded that given the lack of real-world skill demonstrated by state-of-the-art models, "it appears that only through significant model improvements can useful long-lead forecasts be provided that would be useful for decision makers," a quest they frankly state "may prove to be elusive."

More of the same was reported by O'Gorman and Schneider (2009), who assessed "how precipitation extremes change in simulations with 11 different climate models in the World Climate Research Program's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) archive." Based on their findings, as well as those of others, O'Gorman and Schneider report, "in simulations with comprehensive climate models, the rate of increase in precipitation extremes varies widely among models, especially in the tropics (Kharin et al., 2007)." They also note, in this regard, "the variations among models in the tropics indicate that simulated precipitation extremes may depend sensitively on the parameterization of unresolved and poorly understood processes," citing the work of Wilcox and Donner (2007). In fact, they state, "climate models do not correctly reproduce the interannual variability of precipitation extremes in the tropics (Allan and Soden, 2008), or the frequency and intensity distribution of precipitation generally (Wilcox and Donner, 2007; Dai, 2006; Sun et al., 2006)." Thus the two researchers concluded, "current climate models cannot reliably predict changes in tropical precipitation extremes," noting "inaccurate simulation of the upward velocities may explain not only the intermodal scatter in changes in tropical precipitation extremes but also the inability of models to reproduce observed interannual variability."

In another study, based on real-world data pertaining to the onset, end, and total rainfall of the South American Monsoon System (SAMS)—as characterized by precipitation data for the period 1979–2006, which they derived from the Global Precipitation Climatology Project—Bombardi and Carvalho (2009) evaluated the ability of ten IPCC global coupled climate models (with distinct physics and resolutions) to simulate real-world SAMS characteristics. They report that over northern South America the annual precipitation cycle "is poorly represented by most models," and more specifically, "most models tend to underestimate precipitation during the peak of the rainy season." In addition, they say "the misrepresentation of the Inter-Tropical Convergence Zone and its seasonal cycle seems to be one of the main reasons for the unrealistic out-of-phase annual cycles simulated near the equator by many GCMs" and "poor representation of the total monsoonal precipitation over the Amazon and northeast Brazil is observed in a large majority of the models." As a consequence, they note, "simulations of the total seasonal precipitation, onset and end of the rainy season diverge among models and are notoriously unrealistic over [the] north and northwest Amazon for most models."

Roesler and Penner (2010) used a microphysical model to explore the impact of the chemical composition and size of aerosols on the concentration of cloud droplets over the United States, noting aerosols are important because they can affect energy budgets in the atmosphere and because they also serve as condensation nuclei for cloud formation. Clouds, as we know, affect Earth's energy budget through their ability to reflect and scatter light and to absorb and reradiate long-wave radiation.

The results Roesler and Penner obtained by this approach indicate that as vertical motion increased in their model, the number of cloud droplets increased. They also found that larger aerosols, though fewer in number, were more soluble as they formed cloud droplets, as opposed to smaller, less-soluble aerosols that were more numerous. Thus the larger aerosols were found to be better at producing cloud droplets. In addition, they found that the size of the aerosols depended on their chemical composition, which could vary by region across the United States, and by season.

Considering these results, it is clear that in order to model cloud forcing in a GCM, which ultimately impacts the ability of the model to capture climate or climate change, the chemical composition of the condensation nuclei that form the clouds must be known. And in this regard, Roesler and Penner state in closing, "A global model using an empirical relationship based on regional measurements could over or under predict droplet concentrations when applied to other regions depending on differences in composition."

Also in 2010, Zhang et al. wrote as background for their study that different representations of clouds and their feedback processes in Global Climate Models (GCMs) have been identified as major sources of differences in model climate sensitivities, stating, "contemporary GCMs cannot resolve clouds and highly simplified parameterizations are used to represent the interactions between clouds and radiation." In conducting their own study of the subject, therefore, they combined cloud profiling radar data from the CloudSat satellite with lidar data from the CALIPSO satellite to obtain 3D profiles of clouds and precipitation regimes across the tropics. Some of these profiles corresponded to well-known weather features, such as low clouds, thin cirrus, cirrus anvils, etc., and they were compared to output obtained from the Community Atmosphere Model version 3 (CAM3.1).

The results of this exercise revealed the model "overestimates the area coverage of high clouds and underestimates the area coverage of low clouds in subsidence regions." And what was particularly striking, in the words of Zhang et al., was "the model overestimate of the occurrence frequency of deep convection and the complete absence of cirrus anvils," plus the fact that "the modeled clouds are too reflective in all regimes."

Since incoming and outgoing radiation are strongly affected by the 3D spatial pattern of clouds of various types, a model that gets the "right" current global temperature with the wrong pattern of clouds must have errors in its radiation and/or heat transfer parameterizations. In addition, the manner in which future climate scenarios achieve amplification of the direct radiative effect of increased greenhouse gases (the assumed positive feedback) is also not likely to be correct if the 3D pattern of simulated clouds is as far off as shown in this study. What is more, the pattern of clouds also reflects convective processes that distribute heat and water vapor in the atmosphere, and the results of Zhang et al. point to deficiencies in the handling of this aspect of atmospheric dynamics as well. Climate modelers' claims of physical realism in their models are not supported by detailed comparisons with the real world, and the basic radiative physics they employ, as parameterized at the grid scale, is probably faulty.

In another study, Anagnostopoulos et al. (2010) compared observed versus modeled precipitation values over the twentieth century for 55 locations across the globe. Their results indicated the six models investigated (three from the IPCC's Third Assessment and three from its most recent Fourth Assessment) reproduce only poorly the observed precipitation values over the period of study, and in far too many instances the models showed a rise in precipitation when observed values actually fell, or vice versa. The models fared worse when a similar analysis was conducted in the aggregate for the entire conterminous United States. Model output differed "substantially" from the observed time series, with annual precipitation values overestimating observed values by up to 300 mm, or 40 percent. What is more, the authors indicate the results from the three models used in the IPCC's Fourth Assessment Report were "no better" than the three models used in the IPCC's Third Assessment Report.

In one final study comparing model observations with real-world observations, Stephens et al. (2010) write in introducing their work that in prior studies of the subject "land surface observations of the daily-accumulated rainfall intensities of rates >1 mm/day were compiled from the Global Historical Climatology Network by Sun et al. (2006) and compared to analogous model accumulated precipitation," and they report that "as in other studies (e.g., Dai and Trenberth, 2004), the Sun et al. comparison revealed a general overestimate in the frequency of modeled precipitation and an associated underestimate of intensity," while noting that "Wilcox and Donner (2007) reached a similar conclusion."

To further examine the issue—and to extend the scope of its relevance—Stephens et al. focused on the much larger portion of the planet that is occupied by oceans, where they used "new and definitive measures of precipitation frequency provided by CloudSat [e.g., Haynes et al., 2009]" to assess the realism of global model precipitation via an analysis that employed five different computational techniques representing "state-of-the-art weather prediction models, state-of-the-art climate models, and the emerging high-resolution global cloud 'resolving' models."

Stephens et al. determined "the character of liquid precipitation (defined as a combination of accumulation, frequency, and intensity) over the global oceans is significantly different from the character of liquid precipitation produced by global weather and climate models," noting "the differences between observed and modeled precipitation are larger than can be explained by observational retrieval errors or by the inherent sampling differences between observations and models." More specifically, they say for the oceans as a whole, "the mean model intensity lies between 1.3 and 1.9 times less than the averaged observations" and occurrences "are approximately twice the frequency of observations." They also say the models "produce too much precipitation over the tropical oceans" and "too little mid-latitude precipitation." And they indicate the large model errors "are not merely a consequence of inadequate upscaling of observations but indicative of a systemic problem of models more generally."

In concluding their study, the nine U.S., U.K., and Australian researchers say their results imply that state-of-the-art weather and climate models have "little skill in precipitation calculated at individual grid points" and "applications involving downscaling of grid point precipitation to yet even finer-scale resolution has little foundation and relevance to the real earth system." That is not too encouraging a result, considering it is the "real earth system" in which we live and for which we have great concern. Given these findings and the many others previously cited, it is difficult to conceive how today's state-of-the-art computer models can be claimed to produce reliable precipitation forecasts decades and centuries into the future.

References

Allan, R.P. and Soden, B.J. 2008. Atmospheric warming and the amplification of precipitation extremes. *Science* **321**: 1481-1484.

Anagnostopoulos, G.G., Koutsoyiannis, D., Christofides, A., Efstradiadis, A., and Mamassis, N. 2010. A comparison of local and aggregated climate model outputs with observed data. *Hydrological Sciences Journal* **55**: 1094-1110.

Bombardi, R.J. and Carvalho, L.M.V. 2009. IPCC global coupled model simulations of the South America monsoon system. *Climate Dynamics* **33**: 893-916.

Dai, A. 2006. Precipitation characteristics in eighteen coupled climate models. *Journal of Climate* **19**: 4605-4630.

Dai, A. and Trenberth, K.E. 2004. The diurnal cycle and its depiction in the Community Climate System Model. *Journal of Climate* **17**: 930-951.

Haynes, J.M., L'Ecuyer, T.S., Stephens, G.L., Miller, S.D., Mitrescu, C., Wood, N.B., and Tanelli, S. 2009. Rainfall retrieval over the ocean with spaceborne W-band radar. *Journal of Geophysical Research* **114**: 10.1029/2008JD009973.

Kharin, W., Zwiers, F.W., Zhang, X., and Hegerl, G.C. 2007. Changes in temperature and precipitation extremes in the IPCC ensemble of global coupled model simulations. *Journal of Climate* **20**: 1419-1444.

Kiktev, D., Caesar, J., Alexander, L.V., Shiogama, H., and Collier, M. 2007. Comparison of observed and multimodeled trends in annual extremes of temperature and precipitation. *Geophysical Research Letters* **34**: 10.1029/2007GL029539.

Lavers, D., Luo, L., and Wood, E.F. 2009. A multiple model assessment of seasonal climate forecast skill for applications. *Geophysical Research Letters* **36**: 10.1029/2009GL041365.

O'Gorman, P.A. and Schneider, T. 2009. The physical basis for increases in precipitation extremes in simulations of 21st-century climate change. *Proceedings of the National Academy of Sciences, USA* **106**: 14,773-14,777.

Randall, D., Khairoutdinov, M., Arakawa, A., and Grabowski, W. 2003. Breaking the cloud parameterization deadlock. *Bulletin of the American Meteorological Society* **84**: 1547-1564.

Roesler, E.L. and Penner, J.E. 2010. Can global models ignore the chemical composition of aerosols? *Geophysical Research Letters* **37**: L24809, doi:10.1029/2010GL044282.

Schliep, E.M., Cooley, D., Sain, S.R., and Hoeting, J.A. 2010. A comparison study of extreme precipitation from six different regional climate models via spatial hierarchical modeling. *Extremes* **13**: 219-239.

Stephens, G.L., L'Ecuyer, T., Forbes, R., Gettlemen, A., Golaz, J.-C., Bodas-Salcedo, A., Suzuki, K., Gabriel, P., and Haynes, J. 2010. Dreary state of precipitation in global models. *Journal of Geophysical Research* **115**: 10.1029/2010JD014532.

Sun, Y., Solomon, S., Dai, A., and Portmann, R.W. 2006. How often does it rain? *Journal of Climate* **19**: 916-934.

Wilcox, E.M. and Donner, L.J. 2007. The frequency of extreme rain events in satellite rain-rate estimates and an atmospheric General Circulation Model. *Journal of Climate* **20**: 53-69.

Zhang, Y., Klein, S.A., Boyle, J., and Mace, G.G. 2010. Evaluation of tropical cloud and precipitation statistics of Community Atmosphere Model version 3 using CloudSat and CALIPSO data. *Journal of Geophysical Research* **115**: doi:10.1029/2009JD012006.

Zhou, Y.P., Tao, W.-K., Hou, A.Y., Olson, W.S., Shie, C.-L., Lau, K.-M., Chou, M.-D., Lin, X., and Grecu, M. 2007. Use of high-resolution satellite observations to evaluate cloud and precipitation statistics from cloud-resolving model simulations. Part I: South China Sea monsoon experiment. *Journal of the Atmospheric Sciences* **64**: 4309-4329.

1.3 Temperature

How much of the warming of the past 100 years is due to human activity? When multiple forcings are varying and poorly characterized, and there is also internal variation, this question becomes even more difficult to answer. Nevertheless, several studies have attempted to do so, including DelSole et al. (2010), who began by using a set of climate models run in "control" or unforced mode to develop a 300-year dataset of spatial ocean temperature data, where it was found that an internal pattern, detectable using a spatial fingerprinting technique, could be identified in the simulated data. This spatial pattern of ocean temperature anomalies was labeled the Internal Multidecadal Pattern (IMP); it was found to be highly coherent with the Atlantic Multidecadal Oscillation (AMO), suggesting the models were able to match the internal dynamics of the real-earth system reasonably well.

Proceeding from this point, the researchers next extracted, also by means of discriminant fingerprinting, the forced component of the spatial patterns produced in the absence of the IMP as an orthogonal function, which they demonstrated has only a minor effect (less than 1/7 the amplitude) on the IMP, after which they used historical sea surface temperature data to evaluate the relative importance of the forced vs. IMP components of change from 1850.

In considering the latter portion of the record (1946–2008), the researchers' results indicated the internal variability component of climate change (the IMP) operated in a cooling mode between 1946 and 1977, but switched to a warming mode thereafter (between 1977 and 2008), suggesting the IMP is strong enough to overwhelm any anthropogenic signal. That led them to state, "the trend due to only the forced component is statistically the same in the two 32-year periods and in the 63-year period." That is to say, the forced part was not accelerating. Taken together, these results imply that the observed trend differs between the periods 1946–1977 and 1977–2008 not because the forced response accelerated but because "internal variability led to relative cooling in the earlier period and relative warming in the later period." Thus their results suggest that simple extrapolations of rates of warming from 1980 onward overestimate the forced component of warming, and that using this period without factoring out internal variability will likely lead to unrealistic values of climate sensitivity.

In an earlier study, Lean and Rind (2008) performed "a robust multivariate analysis using the best available estimates of each together with the observed surface temperature record from 1889 to 2006" in an effort "to distinguish between simultaneous natural and anthropogenic impacts on surface temperature, regionally as well as globally." Their results indicated that "contrary to recent assessments based on theoretical models (IPCC, 2007) the anthropogenic warming estimated directly from the historical observations is more pronounced between 45°S and 50°N than at higher latitudes," which finding, in their words, "is the approximate inverse of the model-simulated anthropogenic plus natural temperature trends ... which have minimum values in the tropics and increase steadily from 30 to 70°N." Furthermore, as they continue, "the empirically-derived zonal mean anthropogenic changes have approximate hemispheric symmetry whereas the mid-to-high latitude modeled changes are larger in the Northern Hemisphere." And as a result, the two researchers concluded that "climate models may therefore lack—or incorrectly parameterize—

fundamental processes by which surface temperatures respond to radiative forcings."

Lavers et al. (2009), in a study also described previously in Section 1.2, assessed the predictability of monthly "retrospective forecasts," or hindcasts, which were composed of multiple nine-month projections initialized during each month of the year over the period 1981-2001, comparing the projections against real-world air temperatures obtained from ERA-40 reanalysis data. In addition, they conducted a virtual-world analysis where the output of one of the models was arbitrarily assumed to be the truth and the average of the rest of the models was assumed to be the predictor.

Lavers et al. report that in the virtual world of the climate models, there was quite good skill over the first two weeks of the forecast, when the spread of ensemble model members was small, but that there was a large drop off in predictive skill in the second 15-day period. Things were even worse in the real world, where they say the models had negligible skill over land at a 31-day lead time, which they described as being "a relatively short lead time in terms of seasonal climate prediction." Based on these results, the three researchers concluded that given the real-world skill demonstrated by the state-of-the-art models, "it appears that only through significant model improvements can useful long-lead forecasts be provided that would be useful for decision makers," a quest they state "may prove to be elusive."

Chylek et al. (2009) state, "one of the robust features of the AOGCMs [Atmosphere-Ocean General Circulation Models] is the finding that the temperature increase in the Arctic is larger than the global average, which is attributed in part to the ice/snow-albedo temperature feedback." More specifically, they say "the surface air temperature change in the Arctic is predicted to be about two to three times the global mean," citing the IPCC (2007). In conducting their own study of this feature, the authors utilized Arctic surface air temperature data from 37 meteorological stations north of 64°N in an effort to explore the latitudinal variability in Arctic temperatures within two belts—the low Arctic (64°N-70°N) and the high Arctic (70°N-90°N)—comparing them with mean global air temperatures over three sequential periods: 1910–1940 (warming), 1940–1970 (cooling), and 1970–2008 (warming).

In harmony with state-of-the-art AOGCM simulations, the five researchers report "the Arctic has indeed warmed during the 1970–2008 period by a factor of two to three faster than the global mean." More precisely, the Arctic amplification factor was 2.0 for the low Arctic and 2.9 for the high Arctic. But that is the end of the real world's climate-change agreement with theory. During the 1910–1940 warming, for example, the low Arctic warmed 5.4 times faster than the global mean, while the high Arctic warmed 6.9 times faster. Even more out of line with climate model simulations were the real-world Arctic amplification factors for the 1940–1970 cooling: 9.0 for the low Arctic and 12.5 for the high Arctic. Such findings constitute another important example of the principle described (and proven to be correct) by Reifen and Toumi (2009), that a model that performs well in one time period will not necessarily perform well in another period.

Also studying the Arctic, Liu et al. (2008) "assessed how well the current day state-of-the-art reanalyses and CGCMs [coupled global climate models] are reproducing the annual mean, seasonal cycle, variability and trend of the observed SAT [surface air temperature] over the Arctic Ocean for the late twentieth century (where sea ice changes are largest)." According to the authors, the results indicate that "large uncertainties are still found in simulating the climate of the twentieth century," and on an annual basis, "almost two thirds of the IPCC AR4 [Fourth Assessment Report] models have biases that [are] greater than the standard deviation of the observed SAT variability." What is more, Liu et al. additionally note (1) the models "can not capture the observed dominant SAT mode variability in winter and seasonality of SAT trends," (2) "the majority of the models show an out-of-phase relationship between the sea ice area and SAT biases," and (3) "there is no obvious improvement since the IPCC Third Assessment Report."

Anagnostopoulos et al. (2010) compared observed versus modeled temperature values over the twentieth century for 55 locations across the globe, finding that although the six models (three from the IPCC's Third Assessment and three from its most recent Fourth Assessment) could reproduce the seasonal variations in temperature fairly well, they fared far worse, or "poor," at the annual time scale, where "some model outputs [had] enormous differences from reality (up to 6 °C in temperature)." What is more, the authors note, there were many instances where the models showed a rise in temperature when observed values actually fell, or vice versa.

Not much changed when the five researchers conducted a similar analysis in the aggregate for the conterminous United States. Model output differed "substantially" from the observed time series. For example, the observed annual mean temperature of the conterminous USA "gradually rose between 1890 and 1940, then had a falling trend until 1970, and from 1970 until today it had a slight upward trend." Yet "none of the model outputs fit these fluctuations of the annual mean temperature; most indicate a constant increase that becomes steeper in the last decades of the twentieth century." What is more, the authors indicate the results from the three models used in the IPCC's Fourth Assessment Report were "no better" than the three models used in the IPCC's Third Assessment Report, noting that in some, "the annual mean temperature of the USA is overestimated by about 4–5 °C." Given such findings, they conclude by stating, "we think that the most important question is not whether GCMs can produce credible estimates of future climate, but whether climate is at all predictable in deterministic terms."

Christy et al. (2010) focused on the upper atmosphere, where models suggest the presence of a tropical tropospheric "hotspot" that warms faster than the surface under conditions of enhanced greenhouse gas forcing, and where previous studies had produced disagreement over whether data were consistent with models on this question. In conducting their analysis, Christy et al. (2010) made several advances by doing the following: (1) enhancing the data for surface trends, (2) extending the data to a 31-year period, (3) evaluating the wind-based temperature estimates, and (4) clarifying the meaning of "best estimate" multi-data warming trends from data and models.

Two prior studies had derived tropospheric temperature trends from the Thermal Wind Equation (TWE)—which uses radiosonde measurements of wind speed to calculate temperature—on the theoretical basis that warmer air should move faster than cooler air. They found there were biases in the data for this type of calculation. For example, particularly for older radiosonde observations, on days when the upper wind was stronger, the balloons would tend to blow out of receiver range. This created a bias by causing missing data for high winds for older observations, leading to a spurious warm trend over time. Overall, the TWE-based trends were three times greater than trends derived from all other types of data. In addition, they did not agree with other wind data and were based on much sparser data. This type of data was therefore not used in the authors' analysis, which also identified a small warm bias in the RSS satellite data that was explained by Christy and his colleagues.

The next innovation was to use the Scaling Ratio (SR), which is the ratio of atmospheric temperature trend to surface temperature trend. The SR attempts to factor out the effect of the lack of actual (historic) El Niños or other oscillations in climate model runs, and such simulated events in different computer runs. In doing so, the nine researchers found that the SR for real-world data was 0.8 ± 0.3, whereas the model simulations had a SR of 1.38 ± 0.08 (a significant difference). That is, the data show a lower rate of warming for the lower troposphere than for the surface (though not statistically different), whereas the models show amplification. The SR value for the middle troposphere data was 0.4, which is even more different from the model predictions. Only the SR for RSS data, which has a documented warming bias, overlaps with any model SR results. Given these findings, this study suggests that current state-of-the-art climate models have something fundamentally wrong with how they represent Earth's atmosphere.

Solomon et al. (2010) write "the trend in global surface temperatures has been nearly flat since the late 1990s despite continuing increases in the forcing due to the sum of the well-mixed greenhouse gases (CO_2, CH_4, halocarbons, and N_2O), raising questions regarding the understanding of forced climate change, its drivers, the parameters that define natural internal variability, and how fully these terms are represented in climate models." Therefore, in an effort to better our understanding of climate forcing, Solomon et al. used observations of stratospheric water vapor concentration obtained over the period 1980–2008, together with detailed radiative transfer and modeling information, in order to calculate the global climatic impact of this important greenhouse gas and compare it with trends in mean global near-surface air temperature observed over the same time period.

According to the seven scientists, stratospheric water vapor concentrations decreased by about 10 percent after the year 2000; and their analysis indicates this decrease should have slowed the rate of increase in global near-surface air temperature between 2000 and 2009 by about 25 percent compared to what would have been expected (on the basis of climate model calculations) due to measured increases in carbon dioxide and other greenhouse gases over the same time period. In addition, they found "more limited data suggest that stratospheric water vapor probably increased between 1980 and 2000, which would have enhanced the decadal rate of surface warming during the 1990s by about 30% [above what it would have been without the stratospheric water vapor increase]."

In their concluding paragraph, Solomon et al. thus write it is "not clear whether the stratospheric water vapor changes represent a feedback to global average climate change or a source of decadal variability." In either case, their findings elucidate an important phenomenon that was not included in any prior analyses of global climate change. They also write that current climate models do not "completely represent the Quasi Biennial Oscillation [which has a significant impact on stratospheric water vapor content], deep convective transport [of water vapor] and its linkages to sea surface temperatures, or the impact of aerosol heating on water input to the stratosphere."

In light of Solomon et al.'s specific findings, their listing of what current climate models do not do (which they should do), and the questions they say are raised by the flat-lining of mean global near-surface air temperature since the late 1990s, it is premature to conclude that current climate models correctly simulate the intricate workings of Earth's climate regulatory system.

References

Anagnostopoulos, G.G., Koutsoyiannis, D., Christofides, A., Efstradiadis, A., and Mamassis, N. 2010. A comparison of local and aggregated climate model outputs with observed data. *Hydrological Sciences Journal* **55**: 1094–1110.

Christy, J.R., Herman, B., Pielke Sr., R., Klotzbach, P., McNider, R.T., Hnilo, J.J., Spencer, R.W., Chase, T., and Douglass, D. 2010. What do observational datasets say about modeled troposphere temperature trends since 1979? *Remote Sensing* **2**: 2148–2169.

Chylek, P., Folland, C.K., Lesins, G., Dubey, M.K., and Wang, M. 2009. Arctic air temperature change amplification and the Atlantic Multidecadal Oscillation. *Geophysical Research Letters* **36**: 10.1029/2009GL038777.

DelSole, T., Tippett, M.K., and Shukla, J. 2010. A significant component of unforced multidecadal variability in the recent acceleration of global warming. *Journal of Climate* **24**: 909–926.

Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by S. Solomon, et al. Cambridge, UK: Cambridge University Press.

Lavers, D., Luo, L., and Wood, E.F. 2009. A multiple model assessment of seasonal climate forecast skill for applications. *Geophysical Research Letters* **36**: 10.1029/2009GL041365.

Lean, J.L. and Rind, D.H. 2008. How natural and anthropogenic influences alter global and regional surface temperatures: 1889 to 2006. *Geophysical Research Letters* **35**: 10.1029/2008GL034864.

Liu, J., Zhang, Z., Hu, Y., Chen, L., Dai, Y., and Ren, X. 2008. Assessment of surface air temperature over the Arctic Ocean in reanalysis and IPCC AR4 model simulations with IABP/POLES observations. *Journal of Geophysical Research* **113**: 10.1029/2007JD009380.

Reifen, C. and Toumi, R. 2009. Climate projections: Past performance no guarantee of future skill? *Geophysical Research Letters* **36**: 10.1029/2009GL038082.

Solomon, S., Rosenlof, K., Portmann, R., Daniel, J., Davis, S., Sanford, T., and Plattner, G.-K. 2010. Contributions of stratospheric water vapor to decadal changes in the rate of global warming. *Sciencexpress*: 10.1126/science.1182488.

1.4 El Niño/Southern Oscillation

Computer model simulations have given rise to three claims regarding the influence of global warming on El Niño/Southern Oscillation (ENSO) events: (1) global warming will increase the *frequency* of ENSO events, (2) global warming will increase the *intensity* of ENSO events, and (3) weather-related disasters will be exacerbated under El Niño conditions. In this section we highlight findings that suggest the virtual world of ENSO, as simulated by state-of-the-art climate models, is at variance with reality, beginning with several studies that described the status of the problem a decade ago.

In a comparison of 24 coupled ocean-atmosphere climate models, Latif et al. (2001) reported, "almost all models (even those employing flux corrections) still have problems in simulating the SST [sea surface temperature] climatology." They also noted "only a few of the coupled models simulate the El Niño/Southern Oscillation in terms of gross equatorial SST anomalies realistically." And they stated, "no model has been found that simulates realistically all aspects of the interannual SST variability." Consequently, because "changes in sea surface temperature are both the cause and consequence of wind fluctuations," according to Fedorov and Philander (2000), and because these phenomena figure prominently in the El Niño-La Niña oscillation, it is not surprising that the latter researchers concluded climate models near the turn of the century did not do a good job of determining the potential effects of global warming on ENSO.

Human ignorance likely also played a role in those models' failure to simulate ENSO. According to Overpeck and Webb (2000), there was evidence that "ENSO may change in ways that we do not yet understand," which "ways" had clearly not yet been modeled. White et al. (2001), for example, found that "global warming and cooling during earth's internal mode of interannual climate variability [the ENSO cycle] arise from fluctuations in the global hydrological balance, not the global radiation balance," and they noted that these fluctuations are the result of no known forcing of either anthropogenic or extraterrestrial origin, although Cerveny and Shaffer (2001) made a case for a lunar forcing of ENSO activity, which also was not included in any climate model of that time.

Another example of the inability of the most sophisticated of late twentieth-century climate models to properly describe El Niño events was provided by Landsea and Knaff (2000), who employed a simple statistical tool to evaluate the skill of 12 state-of-the-art climate models in real-time predictions of the development of the 1997–98 El Niño. In doing so, they found the models exhibited essentially no skill in forecasting this very strong event at lead times ranging from zero to eight months. They also determined no models were able to anticipate even one-half of the actual amplitude of the El Niño's peak at a medium-range lead time of six to 11 months. Hence, they stated, "since no models were able to provide useful predictions at the medium and long ranges, there were no models that provided both useful and skillful forecasts for the entirety of the 1997–98 El Niño."

Given the inadequacies listed above, it is little wonder that several scientists criticized model simulations of ENSO behavior at the turn of the century, including Walsh and Pittock (1998), who concluded, "there is insufficient confidence in the predictions of current models regarding any changes in ENSO," and Fedorov and Philander (2000), who wrote, "at this time, it is impossible to decide which, if any, are correct."

So what's happened subsequently? Have things improved since then?

Huber and Caballero (2003) introduced their contribution to the subject by stating, "studies of future transient global warming with coupled ocean-atmosphere models find a shift to a more El Niño-like state," although they also reported the "permanent El Niño state"—which has been hyped by some climate alarmists—"is by no means uniformly predicted by a majority of models." To help resolve this battle of the models, they worked with still another model, plus real-world data pertaining to the Eocene, which past geologic epoch—having been much warmer than the recent past—provided, in their words, "a particularly exacting test of the robustness of ENSO." More specifically, they used the Community Climate System Model of the National Center for Atmospheric Research, which they said yielded "a faithful reproduction of modern-day ENSO variability," to "simulate the Eocene climate and determine whether the model predicts significant ENSO variability." In addition, they compared the model results against middle Eocene lake-sediment records from two different regions: the Lake Gosiute complex in Wyoming and Eckfield Maar in Germany.

In describing their findings, Huber and Caballero report the model simulations showed "little change in ... ENSO, in agreement with proxies." They also note other studies "indicate an ENSO shutdown as recently as ~6000 years ago, a period only slightly warmer than the present." Hence, they concluded, "this result contrasts with theories linking past and future 'hothouse' climates with a shift toward a permanent El Niño-like state." This conclusion represents a significant setback to climate alarmists who have used this unsubstantiated (and now invalidated) theory to induce unwarranted fear of global warming among the general public.

Three years later, Joseph and Nigam (2006) evaluated several climate models "by examining the extent to which they simulated key features of the leading mode of interannual climate variability: El Niño -Southern Oscillation (ENSO)"—which they described as "a dominant pattern of ocean-atmosphere variability with substantial global climate impact"—based on "the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4) simulations of twentieth-century climate." This evaluation indicated that different models were found to do well in some respects but not so well in many others. For example, they found climate models "are still unable to simulate many features of ENSO variability and its circulation and hydroclimate teleconnections.” In fact, they found the models had only “begun to make inroads in simulating key features of ENSO variability.”

According to Joseph and Nigam, “climate system models are not quite ready for making projections of regional-to-continental scale hydroclimate variability and change.” Indeed, the study raises the question of whether they are ready to make any valid projections about anything. As Joseph and Nigam conclude, “predicting regional climate variability/change remains an onerous burden on models.”

One year later, L’Ecuyer and Stephens (2007) asked how well state-of-the-art climate models reproduced the workings of real-world energy and water cycles, noting “our ability to model the climate system and its response to natural and anthropogenic forcings requires a faithful representation of the complex interactions that exist between radiation, clouds, and precipitation and their influence on the large-scale energy balance and heat transport in the atmosphere,” while further stating “it is also critical to assess [model] response to shorter-term natural variability in environmental forcings using observations.”

The two researchers used multi-sensor observations of visible, infrared, and microwave radiance obtained from the Tropical Rainfall Measuring Mission satellite for the period January 1998 through December 1999, in order to evaluate the sensitivity of atmospheric heating (and the factors that modify it) to changes in east-west SST gradients associated with the strong 1998 El Niño event in the tropical Pacific, as expressed by the simulations of nine general circulation models of the atmosphere that were utilized in the IPCC’s AR4. This protocol, in their words, “provides a natural example of a short-term climate change scenario in which clouds, precipitation, and regional energy budgets in the east and west Pacific are observed to respond to the eastward migration of warm sea surface temperatures.”

L’Ecuyer and Stephens report “a majority of the models examined do not reproduce the apparent westward transport of energy in the equatorial Pacific during the 1998 El Niño event.” They also discovered “the intermodel variability in the responses of precipitation, total heating, and vertical motion [was] often larger than the intrinsic ENSO signal itself, implying an inherent lack of predictive capability in the ensemble with regard to the response of the mean zonal atmospheric circulation in the tropical Pacific to ENSO.” In addition, they found “many models also misrepresent the radiative impacts of clouds in both regions [the east and west Pacific], implying errors in total cloudiness, cloud thickness, and the relative frequency of occurrence of high and low clouds.” In light of these much-less-than-adequate findings, they conclude, “deficiencies remain in the representation of relationships between radiation, clouds, and precipitation in current climate models,” while further stating these deficiencies “cannot be ignored when interpreting their predictions of future climate.”

Paeth et al. (2008) compared 79 coupled ocean-atmosphere climate simulations derived from 12 different state-of-the-art climate models forced by six different IPCC emission scenarios with observational data in order to evaluate how well they reproduced the spatio-temporal characteristics of ENSO over the twentieth century, after which they compared the various models’ twenty-first-century simulations of ENSO and the Indian and West African monsoons to one another. With respect to the twentieth century, this work revealed that “all considered climate models draw a reasonable picture of the key features of ENSO.” With respect to the twenty-first century, on the other hand, they say that “the differences between the models are stronger than between the emission scenarios,” while “the atmospheric component of ENSO and the West African monsoon are barely affected.” Their “overall conclusion” was that “we still cannot say much about the future behavior of tropical climate.” Indeed, they considered their study to be merely “a benchmark for further investigations with more recent models in order to document a gain in knowledge or a stagnation over the past five years.”

Jin et al. (2008) investigated the overall skill of ENSO prediction in retrospective forecasts made with ten different state-of-the-art ocean-atmosphere coupled general circulation models with respect to their ability to hindcast real-world observations for the 22 years from 1980 to 2001. They found almost all models have problems simulating the mean equatorial SST and its annual cycle. They write, “none of the models we examined attain good performance in simulating the mean annual cycle of SST, even with the advantage of starting from realistic initial conditions.” They also note that “with increasing lead time, this discrepancy gets worse,” and that “the phase and peak amplitude of westward propagation of the annual cycle in the eastern and central equatorial Pacific are different from those observed." What is more, they found, "ENSO-neutral years are far worse predicted than growing warm and cold events," and "the skill of forecasts that start in February or May drops faster than that of forecasts that start in August or November." They and others call this behavior "the spring predictability barrier," which gives an indication of the difficulty of what they were attempting to do. Jin et al. conclude that "accurately predicting the strength and timing of ENSO events continues to be a critical challenge for dynamical models of all levels of complexity."

McLean et al. (2009) quantified "the effect of possible ENSO forcing on mean global temperature, both short-term and long-term," using Southern Oscillation Index (SOI) data provided by the Australian government's Bureau of Meteorology. This parameter is defined as "the standardized anomaly of the seasonal mean sea level pressure difference between Tahiti and Darwin, divided by the standard deviation of the difference and multiplied by 10." The temperature data employed in this endeavor were "the University of Alabama in Huntsville lower-tropospheric (LT) temperature data based on measurements from selected view angles of Microwave Sounding Unit (MSU) channel LT 2" for the period December 1979 to June 2008, supplemented by "balloon-based instrumentation (radiosondes)." More specifically, in the case of the latter data going back in time to 1958, they employed the Radiosonde Atmospheric Temperature Products for Assessing Climate (RATPAC) product (A) of the U.S. National Climatic Data Center, which represents the atmospheric layer between approximately 1500 and 9000 meters altitude.

When their work was completed, McLean et al. found "change in SOI accounts for 72% of the variance in GTTA [Global Tropospheric Temperature Anomalies] for the 29-year-long MSU record and 68% of the variance in GTTA for the longer 50-year RATPAC record," as well as "81% of the variance in tropospheric temperature anomalies in the tropics," where they say ENSO "is known to exercise a particularly strong influence." In addition, they determined that "shifts in temperature are consistent with shifts in the SOI that occur about 7 months earlier." Consequently, the three researchers state as their final conclusion, "natural climate forcing associated with ENSO is a major contributor to variability and perhaps recent trends in global temperature, a relationship that is not included in current global climate models."

Noting that "coral records closely track tropical Indo-Pacific variability on interannual to decadal timescales," Ault et al. (2009) employed 23 coral δ^{18}O records from the Indian and Pacific Oceans to extend the observational record of decadal climate variability back in time to cover the period of AD 1850–1990. In so doing they identified "a strong decadal component of climate variability" that "closely matches instrumental results from the twentieth century." In addition, they report the decadal variance they uncovered was much greater between 1850 and 1920 than it was between 1920 and 1990. As for what this observation means, the researchers say they "infer that this decadal signal represents a fundamental timescale of ENSO variability," which has an enhanced variance in the early half of the record that "remains to be explained."

In conclusion, there remain multiple unknowns with respect to ENSO and long-term climate change, and many of these unknowns raise serious questions about the ability of current climate models to adequately anticipate the multiplicity of climatic effects that the ongoing rise in the air's CO_2 content may or may not impose on Earth's atmospheric and oceanic environments.

References

Ault, T.R., Cole, J.E., Evans, M.N., Barnett, H., Abram, N.J., Tudhope, A.W., and Linsley, B.K. 2009. Intensified decadal variability in tropical climate during the late 19th century. *Geophysical Research Letters* **36**: 10.1029/2008GL036924.

Cerveny, R.S. and Shaffer, J.A. 2001. The moon and El Niño. *Geophysical Research Letters* **28**: 25–28.

Fedorov, A.V. and Philander, S.G. 2000. Is El Niño changing? *Science* **288**: 1997–2002.

Huber, M. and Caballero, R. 2003. Eocene El Niño: Evidence for robust tropical dynamics in the "Hothouse." *Science* **299**: 877–881.

Jin, E.K., Kinter III, J.L., Wang, B., Park, C.-K., Kang, I.-S., Kirtman, B.P., Kug, J.-S., Kumar, A., Luo, J.-J., Schemm, J., Shukla, J., and Yamagata, T. 2008. Current status of ENSO prediction skill in coupled ocean-atmosphere models. *Climate Dynamics* **31**: 647–664.

Joseph, R. and Nigam, S. 2006. ENSO evolution and teleconnections in IPCC's twentieth-century climate simulations: Realistic representation? *Journal of Climate* **19**: 4360–4377.

Landsea, C.W. and Knaff, J.A. 2000. How much skill was there in forecasting the very strong 1997–98 El Niño? *Bulletin of the American Meteorological Society* **81**: 2107–2119.

Latif, M., Sperber, K., Arblaster, J., Braconnot, P., Chen, D., Colman, A., Cubasch, U., Cooper, C., Delecluse, P., DeWitt, D., Fairhead, L., Flato, G., Hogan, T., Ji, M., Kimoto, M., Kitoh, A., Knutson, T., Le Treut, H., Li, T., Manabe, S., Marti, O., Mechoso, C., Meehl, G., Power, S., Roeckner, E., Sirven, J., Terray, L., Vintzileos, A., Voss, R., Wang, B., Washington, W., Yoshikawa, I., Yu, J., and Zebiak, S. 2001. ENSIP: the El Niño simulation intercomparison project. *Climate Dynamics* **18**: 255–276.

L'Ecuyer, T.S. and Stephens, G.L. 2007. The tropical atmospheric energy budget from the TRMM perspective. Part II: Evaluating GCM representations of the sensitivity of regional energy and water cycles to the 1998–99 ENSO cycle. *Journal of Climate* **20**: 4548–4571.

McLean, J.D., de Freitas, C.R., and Carter, R.M. 2009. Influence of the Southern Oscillation on tropospheric temperature. *Journal of Geophysical Research* **114**: 10.1029/2008JD011637.

Overpeck, J. and Webb, R. 2000. Nonglacial rapid climate events: Past and future. *Proceedings of the National Academy of Sciences USA* **97**: 1335–1338.

Paeth, H., Scholten, A., Friederichs, P. and Hense, A. 2008. Uncertainties in climate change prediction: El Niño-Southern Oscillation and monsoons. *Global and Planetary Change* **60**: 265–288.

Walsh, K. and Pittock, A.B. 1998. Potential changes in tropical storms, hurricanes, and extreme rainfall events as a result of climate change. *Climatic Change* **39**: 199–213.

White, W.B., Cayan, D.R., Dettinger, M.D., and Auad, G. 2001. Sources of global warming in upper ocean temperature during El Niño. *Journal of Geophysical Research* **106**: 4349–4367.

1.5 Soil Moisture

Climate models have long indicated that CO_2-induced global warming will increase evapotranspiration, causing decreases in soil moisture content that may offset modest increases in continental precipitation and lead to greater aridity in water-limited natural ecosystems and lands devoted to agriculture (Manabe and Wetherald, 1986; Rind, 1988; Gleick, 1989; Vlades et al., 1994; Gregory et al., 1997; Komescu et al., 1998). In the following pages we examine this model-based claim.

In a turn-of-the century evaluation of how climate modelers had progressed in their efforts to improve simulations of soil moisture content over the prior few years, Srinivasan et al. (2000) examined "the impacts of model revisions, particularly the land surface representations, on soil moisture simulations, by comparing the simulations to actual soil moisture observations." In summarizing their findings, they stated, "the revised models do not show any systematic improvement in their ability to simulate observed seasonal variations of soil moisture over the regions studied." They also concluded, "there are no indications of conceptually more realistic land surface representations producing better soil moisture simulations in the revised climate models." In addition, they reported a "tendency toward unrealistic summer drying in several models," which they noted was "particularly relevant in view of the summer desiccation projected by GCMs considered in future assessments of climate change."

Although Srinivasan et al. note that "simpler land-surface parameterization schemes are being replaced by conceptually realistic treatments" as the climate-modeling enterprise moves ever forward, they state that "improvements gained by such changes are ... not very apparent." Thus at the time of their study there had been no real progress in this area, only attempted progress.

Robock et al. (2000) developed a massive collection of soil moisture data for more than 600 stations from a wide variety of climatic regimes within the former Soviet Union, China, Mongolia, India, and the United States. In describing these datasets they also stated an important ground rule. Sometimes, they said, "the word 'data' is used to describe output from theoretical model calculations, or values derived from theoretical analysis of radiances from remote sensing." However, as they put it, "we prefer to reserve this word for actual physical observations," noting that "all the data in our data bank are actual *in situ* observations."

This distinction is important, for one of the illuminating analyses Robock et al. performed with their data was to check summer soil moisture trends simulated by the Geophysical Fluid Dynamics Laboratory's general circulation model of the atmosphere as forced by transient CO_2 and tropospheric sulfate aerosols for specific periods and regions for which they had actual soil moisture data.

What they learned from this exercise, in their words, was that "although this model predicts summer desiccation in the next century, it does not in general reproduce the observed upward trends in soil moisture very well." That is an understatement, when one considers that the predictions and observations go in opposite directions.

Robock et al. add, "in contrast to predictions of summer desiccation with increasing temperatures, for the stations with the longest records, summer soil moisture in the top 1 m has increased while temperatures have risen." Given that the model predictions and actual measurements failed to coincide, or actually diverged, Robock et al. offer their hope that the real-world data they assembled in their databank might help "improve simulations of the recent past so we may have more confidence in predictions for the next century."

Five years later, Robock et al. (2005) noted "most global climate model simulations of the future, when forced with increasing greenhouse gases and anthropogenic aerosols, predict summer desiccation in the midlatitudes of the Northern Hemisphere (e.g., Gregory et al., 1997; Wetherald and Manabe, 1999; Cubasch et al., 2001)," and they stated, "this predicted soil moisture reduction, the product of increased evaporative demand with higher temperatures overwhelming any increased precipitation, is one of the gravest threats of global warming, potentially having large impacts on our food supply."

Therefore, with the explicit purpose "to evaluate these model simulations," the three American and two Ukrainian scientists presented "the longest data set of observed soil moisture available in the world, 45 years of gravimetrically-observed plant available soil moisture for the top 1 m of soil, observed every 10 days for April-October for 141 stations from fields with either winter or spring cereals from the Ukraine for 1958–2002." And as they described it, "the observations show a positive soil moisture trend for the entire period of observation, with the trend leveling off in the last two decades," noting that "even though for the entire period there is a small upward trend in temperature and a downward trend in summer precipitation, the soil moisture still has an upward trend for both winter and summer cereals."

As a result of these real-world observations, Robock et al. noted that "although models of global warming predict summer desiccation in a greenhouse-warmed world, there is no evidence for this in the observations yet, even though the region has been warming for the entire period." In attempting to explain this dichotomy, they say the real-world increase in soil moisture content possibly may have been driven by a downward trend in evaporation caused by the controversial "global dimming" hypothesis (Liepert et al., 2004). Alternatively, it may have been driven by the well-known anti-transpirant effect of atmospheric CO_2 enrichment, which tends to conserve water in the soils beneath crops and thereby leads to enhanced soil moisture contents, as has been demonstrated in a host of experiments conducted in real-world field situations.

One especially outstanding study in this regard was that of Zaveleta et al. (2003), who tested the hypothesis that soil moisture contents may decline in a CO_2-enriched and warmer world, in a two-year study of an annual-dominated California grassland at the Jasper Ridge Biological Preserve, Stanford, California, USA. They delivered extra heating to a number of free-air CO_2-enriched (FACE) plots (enriched with an extra 300 ppm of CO_2) via infrared heat lamps suspended over the plots, which warmed the surface of the soil beneath them by 0.8–1.0°C.

The individual effects of atmospheric CO_2 enrichment and soil warming were of similar magnitude, and acting together they enhanced mean spring soil moisture content by about 15 percent over that of the control treatment. The effect of CO_2 was produced primarily as a consequence of its ability to cause partial stomatal closure and thereby reduce season-long plant water loss via transpiration. In the case of warming, there was an acceleration of canopy senescence, which further increased soil moisture by reducing the period of time over which transpiration losses occur, all without any decrease in total plant production.

Zaveleta et al. note their findings "illustrate the potential for organism-environment interactions to modify the direction as well as the magnitude of global change effects on ecosystem functioning." Indeed, whereas for the past two decades climate alarmists have predicted that vast reaches of agricultural land will dry up and be lost to profitable production in a CO_2-enriched world of the future, this study suggests just the opposite could occur. As the six researchers describe it, "we suggest that in at least some ecosystems, declines in plant transpiration mediated by changes in phenology can offset direct increases in evaporative water losses under future warming."

Guo and Dirmeyer (2006) compared soil moisture simulations made by 11 different models within the context of the Second Global Soil Wetness Project (a multi-institutional modeling research activity intended to produce a complete multi-model set of land surface state variables and fluxes by using current state-of-the-art land surface models driven by the ten-year period of data provided by the International Satellite Land Surface Climatology Project Initiative II) against real-world observations made on the top meter of grassland and agricultural soils located within parts of the former Soviet Union, the United States (Illinois), China, and Mongolia that are archived in the Global Soil Moisture Data Bank.

According to the two researchers, "simulating the actual values of observed soil moisture is still a challenging task for all models" and "both the root mean square of errors (RMSE) and the spread of RMSE across models are large." They conclude "the absolute values of soil moisture are poorly simulated by most models," and they find that "within regions there can be tremendous variations of any model to simulate the time series of soil moisture at different stations."

How serious are these large errors and tremendous variations? It would appear they are very serious, based on a number of explanatory statements made by Guo and Dirmeyer. First, the two researchers say "the land surface plays a vital role in the global climate system through interactions with the atmosphere." Second, they state that "accurate simulation of land surface states is critical to the skill of weather and climate forecasts." Third, they write that soil moisture "is the definitive land surface state variable; key for model initial conditions from which the global weather and climate forecasts begin integrations, and a vital factor affecting surface heat fluxes and land surface temperature."

Lastly, Li et al. (2007) compared soil moisture simulations derived from the IPCC's Fourth Assessment climate models (which were driven by observed climate forcings) for the period 1958–1999 with actual measurements of soil moisture made at more than 140 stations or districts in the mid-latitudes of the Northern Hemisphere, which were averaged in such a way as to yield six regional results: one each for the Ukraine, Russia, Mongolia, Northern China, Central China, and Illinois (USA).

According to the three researchers, the models showed realistic seasonal cycles for the Ukraine, Russia, and Illinois but "generally poor seasonal cycles for Mongolia and China." In addition, they report that the Ukraine and Russia experienced soil moisture increases in summer "that were larger than most trends in the model simulations." They write, "only two out of 25 model realizations show trends comparable to those observations," and they note the two realistic model-derived trends were "due to internal model variability rather than a result of external forcing," which means the two reasonable matches were actually accidental. Noting further that "changes in precipitation and temperature cannot fully explain soil moisture increases for [the] Ukraine and Russia," Li et al. write, "other factors might have played a dominant role on the observed patterns for soil moisture." In this regard they mention solar dimming as well as the fact that in response to elevated atmospheric CO_2 concentrations, "many plant species reduce their stomatal openings, leading to a reduction in evaporation to the atmosphere," so that "more water is likely to be stored in the soil or [diverted to] runoff," reporting that this phenomenon was detected by Gedney et al. (2006) in continental river runoff data.

Given these findings, the climate models employed in the IPCC's AR4 appear to be deficient in their ability to correctly simulate soil moisture trends, even when applied to the past and when driven by observed climate forcings. In the words of Li et al., "global climate models should better integrate the biological, chemical, and physical components of the earth system." Essentially all climate models employed to date have erred with respect to what Robock et al. (2005) describe as "one of the gravest threats of global warming."

References

Cubasch, U., Meehl, G.A., Boer, G.J., Stouffer, R.J., Dix, M., Noda, A., Senior, C.A., Raper, S. and Yap, K.S. 2001. Projections of future climate change. In *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J.T. Houghton, et al., 525–582. Cambridge, NY: Cambridge University Press.

Gedney, N., Cox, P.M., Betts, R.A., Boucher, O., Huntingford, C., and Stott, P.A. 2006. Detection of a direct carbon dioxide effect in continental river runoff records. *Nature* **439**: 835–838.

Gleick, P.H. 1989. Climate change, hydrology and water resources. *Reviews of Geophysics* **27**: 329–344.

Gregory, J.M., Mitchell, J.F.B., and Brady, A.J. 1997. Summer drought in northern midlatitudes in a time-dependent CO_2 climate experiment. *Journal of Climate* **10**: 662–686.

Guo, Z. and Dirmeyer, P.A. 2006. Evaluation of the Second Global Soil Wetness Project soil moisture simulations: 1. Intermodel comparison. *Journal of Geophysical Research* **111**: 10.1029/2006JD007233.

Komescu, A.U., Eikan, A., and Oz, S. 1998. Possible impacts of climate change on soil moisture availability in the Southeast Anatolia Development Project Region (GAP): An analysis from an agricultural drought perspective. *Climatic Change* **40**: 519–545.

Li, H., Robock, A., and Wild, M. 2007. Evaluation of Intergovernmental Panel on Climate Change Fourth Assessment soil moisture simulations for the second half of the twentieth century. *Journal of Geophysical Research* **112**: 10.1029/2006JD007455.

Liepert, B.G., Feichter, J., Lohmann, U., and Roeckner, E. 2004. Can aerosols spin down the water cycle in a warmer and moister world? *Geophysical Research Letters* **31**: 10.1029/2003GL019060.

Manabe, S. and Wetherald, R.T. 1986. Reduction in summer soil wetness induced by an increase in atmospheric carbon dioxide. *Science* **232**: 626–628.

Rind, D. 1988. The doubled CO_2 climate and the sensitivity of the modeled hydrologic cycle. *Journal of Geophysical Research* **93**: 5385–5412.

Robock, A., Mu, M., Vinnikov, K., Trofimova, I.V., and Adamenko, T.I. 2005. Forty-five years of observed soil moisture in the Ukraine: No summer desiccation (yet). *Geophysical Research Letters* **32**: 10.1029/2004GL021914.

Robock, A., Vinnikov, K.Y., Srinivasan, G., Entin, J.K., Hollinger, S.E., Speranskaya, N.A., Liu, S., and Namkhai, A. 2000. The global soil moisture data bank. *Bulletin of the American Meteorological Society* **81**: 1281–1299.

Srinivasan, G., Robock, A., Entin, J.K., Luo, L., Vinnikov, K.Y., Viterbo, P., and Participating AMIP Modeling Groups. 2000. Soil moisture simulations in revised AMIP models. *Journal of Geophysical Research* **105**: 26,635–26,644.

Vlades, J.B., Seoane, R.S., and North, G.R. 1994. A methodology for the evaluation of global warming impact on soil moisture and runoff. *Journal of Hydrology* **161**: 389–413.

Wetherald, R.T. and Manabe, S. 1999. Detectability of summer dryness caused by greenhouse warming. *Climatic Change* **43**: 495–511.

Zavaleta, E.S., Thomas, B.D., Chiariello, N.R., Asner, G.P., Shaw, M.R., and Field, C.B. 2003. Plants reverse warming effect on ecosystem water balance. *Proceedings of the National Academy of Science USA* **100**: 9892–9893.

1.6. Climate Sensitivity

"We still can't predict future climate responses at low and high latitudes, which constrains our ability to forecast changes in atmospheric dynamics and regional climate." Thus states the subtitle of a paper by NASA Senior Scientist David Rind of the Goddard Institute for Space Studies (Rind, 2008). Rind begins his review and analysis of this important subject by noting Charney et al. (1979) concluded global temperature sensitivity to a doubling of the atmosphere's CO_2 concentration was "between 1.5° and 4.5°C," while noting since that time "we have not moved very far from that range." In addition, he reports uncertainty in our assessment of high- and low-latitude climate sensitivity "is also still as great as ever, with a factor of 2 at both high and low latitudes."

Rind lists a number of separate problems. For one thing, whether the water vapor response to warming employed by climate models "is realistic is hard to assess," as he puts it, "because we have not had recent climate changes of the magnitude forecast for the rest of this century" to test against. Closely associated are low-latitude difficulties related to modeling both low- and high-level clouds in the tropics and the physics and dynamics associated with them, plus high-latitude difficulties associated with cryosphere feedbacks related to sea ice and snow cover.

One approach to dealing with these uncertainties has been to suggest, in Rind's words, that "we can have greater confidence in the multi-model mean changes than in that of any individual model for climate change assessments." However, he writes, "it is doubtful that averaging different formulations together will end up giving the 'right' result," because "model responses (e.g., tropical land precipitation) can often be of different signs, and there can be little confidence that averaging them together will produce a better result."

Rind thus concludes, "at this point, we cannot determine the low- and high-latitude sensitivities, and we have no real way of obtaining them." These unknowns, in his opinion, "affect the confidence we can have in many of our projections of atmospheric dynamic and hydrologic responses to global warming."

Rind states, "forecasting even the large-scale response to climate change is not easy given the current uncertainties," and "regional responses may be the end result of varying influences in part due to warming in different tropical and high-latitude regions."

As to what Rind's analysis of the climate-modeling enterprise suggests about the future, he writes, "real progress will be the result of continued and newer observations along with modeling improvements based on these observations," which observations must provide the basis for evaluating all model implications. So difficult will this task be, however, that he says "there is no guarantee that these issues will be resolved before a substantial global warming impact is upon us." However, because of the large uncertainties—and unknowns—that surround many aspects of Earth's complex climate system, there is also no guarantee there even will be any "substantial global warming impact" from a doubling or more of the air's CO_2 content.

Lindzen and Choi (2009), two Massachusetts Institute of Technology scientists, used the National Centers for Environmental Prediction's 16-year (1985–1999) monthly record of sea surface temperature (SST), together with corresponding radiation data from the Earth Radiation Budget Experiment, to estimate the sign and magnitude of climate feedback over the oceanic portion of the tropics and thus obtain an empirical evaluation of Earth's thermal sensitivity, as opposed to the model-based evaluation employed by the IPCC.

According to Lindzen and Choi, all 11 models employed in the IPCC's analysis "agree as to positive feedback," but they find that they all *disagree*—and disagree "very sharply"—with the real-world observations that Lindzen and Choi utilized, which imply that negative feedback actually prevails. Moreover, the presence of that negative feedback reduces the CO_2-induced propensity for warming to the extent that their analysis of the real-world observational data yields only a mean SST increase "of ~0.5°C for a doubling of CO_2."

How does one decide which of the two results is closer to the truth? Real-world data would be the obvious standard against which to compare model-derived results, but since Lindzen and Choi's results are indeed based on real-world measurements, the only alternative we have is to seek other real-world results. Fortunately, there are several such findings, many of which are summarized by in Idso (1998), who describes eight "natural experiments" that he personally employed in prior studies to determine "how earth's near-surface air temperature responds to surface radiative perturbations."

The eight natural experiments used by Idso were (1) the change in the air's water vapor content that occurs at Phoenix, Arizona with the advent of the summer monsoon, (2) the naturally occurring vertical redistribution of dust that occurs at Phoenix between summer and winter, (3) the annual cycle of surface air temperature caused by the annual cycle of solar radiation absorption at the Earth's surface, (4) the warming effect of the entire atmosphere caused by its mean flux of thermal radiation to the surface of the Earth, (5) the annually averaged equator-to-pole air temperature gradient that is sustained by the annually averaged equator-to-pole gradient of total surface-absorbed radiant energy, (6) the mean surface temperatures of Earth, Mars, and Venus relative to the amounts of CO_2 contained in their atmospheres, (7) the paradox of the faint early sun and its implications for Earth's thermal history, and (8) the greenhouse effect of water vapor over the tropical oceans and its impact on sea surface temperatures.

These eight analyses, in the words of Idso, "suggest that a 300 to 600 ppm doubling of the atmosphere's CO_2 concentration could raise the planet's mean surface air temperature by only about 0.4°C," which is right in line with Lindzen and Choi's deduced warming of ~0.5°C for a nominal doubling of the air's CO_2 content. Hence, there would appear to be strong real-world data that argue against the overinflated CO_2-induced global warming predicted by state-of-the-art climate models.

References

Charney, J.G. et al. 1979. *Carbon Dioxide and Climate: A Scientific Assessment.* National Academy of Sciences. Washington, DC (USA).

Idso, S.B. 1998. CO_2-induced global warming: a skeptic's view of potential climate change. *Climate Research* **10**: 69–82.

Lindzen, R.S. and Choi, Y.-S. 2009. On the determination of climate feedbacks from ERBE data. *Geophysical Research Letters* **36**: 10.1029/2009GL039628.

Rind, D. 2008. The consequences of not knowing low- and high-latitude climate sensitivity. *Bulletin of the American Meteorological Society* **89**: 855–864.

2

Forcings and Feedbacks

2. Forcings and Feedbacks

Introduction

In a paper that appeared in the 15 October 2010 issue of *Science*, Lacis et al. (2010) claim atmospheric CO_2 is the "principal control knob governing earth's temperature." Using models that employ only physical principles, they profess to have proven that carbon dioxide—not water vapor—should hold the title of "principal controller of earth's temperature" because water vapor, being a condensable greenhouse gas at current temperatures, is a "fast responder" to temperature changes induced by variations in both solar radiation intensity and non-condensable greenhouse gas concentrations, the most significant of which is CO_2. Therefore, by meekly "following in the footsteps" of CO_2 (decreasing in concentration when the atmosphere's CO_2 content drops and air temperatures cool), water vapor's potential role as an instigator of climate change is essentially preempted.

All else being equal, their conclusion might be correct. However, "all else being equal" is rarely the case in the real world, and in the case in point CO_2 affects Earth's climate in several more ways than through its thermal radiative properties. CO_2 promotes plant growth both on land and throughout the surface waters of the world's oceans, and this vast assemblage of plant life has the ability to affect Earth's climate in several ways, almost all of them tending to counteract the heating or cooling effects of CO_2's thermal radiative forcing as its concentration either rises or falls, thereby helping to maintain Earth's temperature within a range that is conducive to the continued existence and indeed flourishing of the planet's myriad life forms.

For example, Earth's plants—ranging from unicellular algae in the sea to grasses, shrubs, and majestic trees on land—emit copious quantities of gases that are converted to particles in the atmosphere, forming aerosols that reflect significant amounts of incoming solar radiation back to space, thereby cooling the planet, or that serve as condensation nuclei for cloud droplets that create more numerous, more extensive, longer-lasting, and brighter clouds that also cool the globe. Therefore, depending on whether the air's CO_2 content is increasing or decreasing, these phenomena result in changes in global radiative forcing similar in magnitude, but generally opposite in sign, to the direct thermal forcing induced by the increases or decreases in the atmosphere's CO_2 concentration.

Many of these phenomena are discussed in detail in *Climate Change Reconsidered*, the 2009 report of the Nongovernmental International Panel on Climate Change (Idso and Singer, 2009). In the subsections that follow, we provide brief reviews of related research that has subsequently been conducted on these and other climate forcing and feedback phenomena.

References

Idso, C.D. and Singer, S.F. 2009. Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC). Chicago, IL: The Heartland Institute.

Lacis, A.A., Schmidt, G.A., Rind, D., and Ruedy, R.A. 2010. Atmospheric CO_2: Principal control knob governing earth's temperature. *Science* **330**: 356–359.

2.1. Aerosols

Aerosols are an important factor in global temperature because they serve as condensation nuclei for clouds; clouds are important because they affect Earth's energy budget through their ability to reflect and scatter light and their propensity to absorb and radiate thermal radiation.

Roesler and Penner (2010) employed a microphysical model to explore how the chemical composition and size of aerosols affects the concentration and size of cloud droplets over the United States (using aerosol composition measurements from 1988–2004), while varying the strength of atmospheric vertical motions lifting initially saturated air parcels over a distance of about 300 meters in order to induce cloud formation. As vertical motion increased in their model, the number of cloud droplets increased. In addition, they found that larger aerosols, though fewer in number, were more soluble as they formed cloud droplets, as opposed to smaller, less-soluble aerosols that were more numerous, the end result being that the larger aerosols were better at producing cloud droplets than were the smaller aerosols. As an added complexity, they found the all-important size of the aerosols depended on their chemical composition, which varied by region and by season. Consequently, the two scientists concluded, "a global model using an empirical relationship based on regional measurements could over or under predict droplet concentrations when applied to other regions depending on differences in [aerosol] composition," thus demonstrating the great need for complex time- and location-dependent empirical data regarding the physical and chemical characteristics of aerosols as input to general circulation models (GCMs).

In a contemporaneous study of aerosols, Carslaw et al. (2010) write, "the natural environment is a major source of atmospheric aerosols, including dust, secondary organic material from terrestrial biogenic emissions, carbonaceous particles from wildfires, and sulphate from marine phytoplankton dimethyl sulphide emissions." These aerosols "have a significant effect on many components of the Earth system, such as the atmospheric radiative balance and photosynthetically available radiation entering the biosphere, the supply of nutrients to the ocean, and the albedo of snow and ice. With this background in mind, the authors reviewed "the impact of these natural systems on atmospheric aerosols based on observations and models, including the potential for long term changes in emissions and feedbacks on climate."

Based on their review, the seven scientists report, "the number of drivers of change is very large and the various systems are strongly coupled," noting "there have therefore been very few studies that integrate the various effects to estimate climate feedback factors." However, they add, "available observations and model studies suggest that the regional radiative perturbations are potentially several watts per square meter due to changes in these natural aerosol emissions in a future climate," which is equivalent to the magnitude of climate forcing projected to result from increases in greenhouse gases but typically of the opposite sign.

Arriving at their ultimate conclusion, therefore, Carslaw et al. state, "the level of scientific understanding of the climate drivers, interactions and impacts is very low." This is difficult to reconcile with the great degree of confidence the IPCC attaches to the conclusions it reaches about Earth's climatic future.

Some scientists believe aerosols could have a warming effect. Kiendler-Scharr et al. (2009) "present evidence from simulation experiments conducted in a plant chamber that isoprene can significantly inhibit new particle formation." The significance of this finding derives from the fact that "the most abundant volatile organic compounds emitted by terrestrial vegetation are isoprene and its derivatives, such as monoterpenes and sesquiterpenes," and the fact, as described in the "This Issue" abstract section of the *Nature* issue in which the paper appeared (p. 311), that "these compounds are involved in the formation of organic aerosols [the 'new particles' mentioned by them], which act as 'seeds' for cloud formation and hence as cooling agents via an effect on radiative forcing." Ziemann (2009), in a "News & Views" article that discusses the Kiendler-Scharr et al. paper, writes that "clouds formed at higher CCN [cloud condensation nuclei] concentrations have more and smaller drops than those formed at lower concentrations, and so reflect more sunlight and are longer-lived—effects that, at the global scale, enhance the planetary cooling that counteracts some of the warming caused by greenhouse gases." Thus, if vegetative isoprene emissions were to increase, driven directly by rising temperatures and/or indirectly by warming-induced changes in the species composition of boreal forests (as further suggested by Ziemann), the resulting decrease in CCN concentrations "could lead to increased global-warming trends," as suggested by Kiendler-Scharr in a "Making the Paper" article in the same issue of *Nature* (p. 313).

The rather convoluted story propounded by these four related items may sound like a blow to those familiar with data showing negative feedbacks are likely to maintain the temperature of the planet within bounds conducive to its own continued existence. However, and almost as an afterthought, Ziemann writes that some consideration should also be given to what he describes as "the potential suppression of terpene emissions by elevated carbon dioxide concentrations." When this is done, it is readily evident, as demonstrated by the multiple sets of observational data plotted in Figure 2.1, that rising atmospheric CO_2 concentrations will *decrease* isoprene emissions and thus *increase* CCN concentrations and lead to a cooling of the planet. These facts have yet to be sufficiently addressed by the IPCC.

References

Carslaw, K.S., Boucher, O., Spracklen, D.V., Mann, G.W., Rae, J.G.L., Woodward, S., and Kulmala, M. 2010. A review of natural aerosol interactions and feedbacks within the Earth System. *Atmospheric Chemistry and Physics* **10**: 1701–1737.

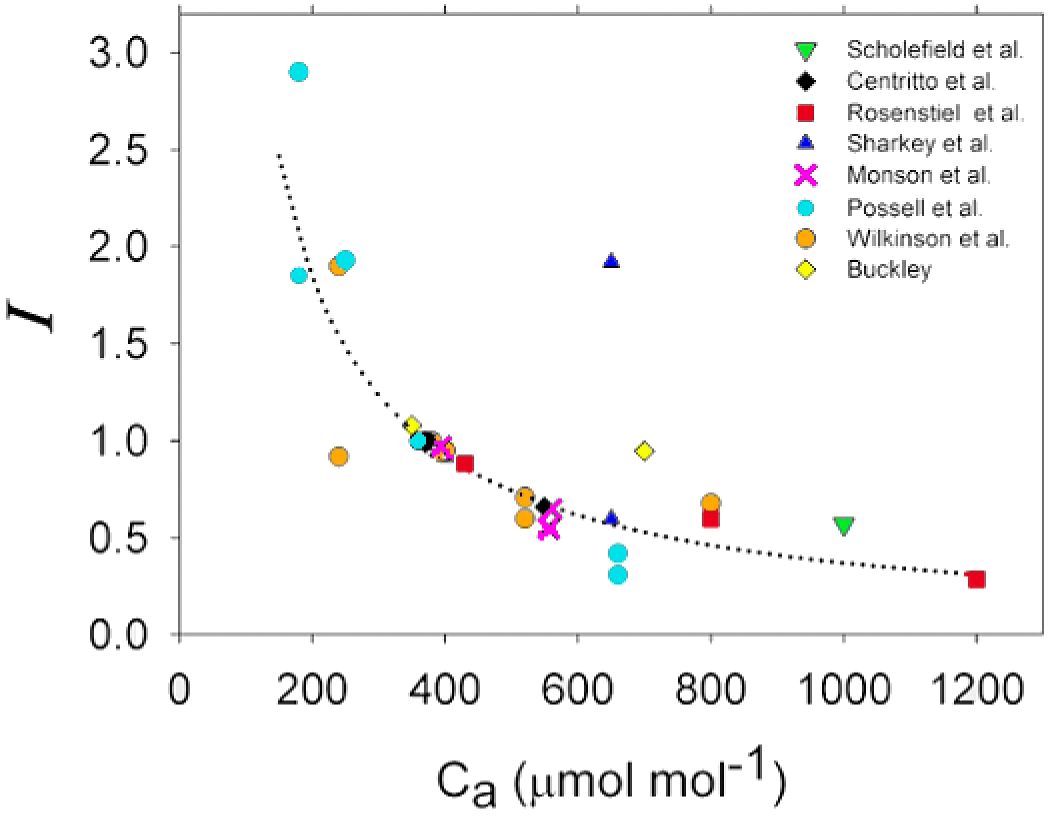


Figure 2.1. Field and laboratory observations of leaf isoprene emissions from plants grown in a variety of atmospheric CO_2 concentrations (Ca), normalized to a value of unity at Ca = 370 µmol mol^{-1} (= 370 ppm). Adapted from Young et al. (2009).

Kiendler-Scharr, A., Wildt, J., Dal Maso, M., Hohaus, T., Kleist, E., Mentel, T.F., Tillmann, R., Uerlings, R., Schurr, U., and Wahner, A. 2009. New particle formation in forests inhibited by isoprene emissions. *Nature* **461**: 381–384.

Roesler, E.L. and Penner, J.E.. 2010. Can global models ignore the chemical composition of aerosols? *Geophysical Research Letters* **37**: L24809, doi:10.1029/2010GL044282.

Young, P.J., Arneth, A., Schurgers, G., Zeng, G., and Pyle, J.A. 2009. The CO_2 inhibition of terrestrial isoprene emission significantly affects future ozone projections. *Atmospheric Chemistry and Physics* **9**: 2793–2803.

Ziemann, P.J. 2009. Thwarting the seeds of clouds. *Nature* **461**: 353–354.

2.2. Dimethyl Sulfide

In the 2009 NIPCC report, Idso and Singer (2009) discussed the plausibility of a multistage negative feedback process whereby warming-induced increases in the emission of dimethyl sulfide (DMS) from the world's oceans tend to counteract any initial impetus for warming. The basic tenet of this hypothesis is that the global radiation balance is significantly influenced by the albedo of marine stratus clouds (the greater the cloud albedo, the less the input of solar radiation to the Earth's surface). The albedo of these clouds, in turn, is known to be a function of cloud droplet concentration (the more and smaller the cloud droplets, the greater the cloud albedo and the reflection of solar radiation), which is dependent upon the availability of cloud condensation nuclei on which the droplets form (the more cloud condensation nuclei, the more and smaller the cloud droplets). And in completing the negative feedback loop, the cloud condensation nuclei concentration often depends upon the flux of biologically produced DMS from the world's oceans (the higher the sea surface temperature, the greater the sea-to-air flux of DMS).

Since the publication of the 2009 NIPCC report, additional empirical evidence has been found to support the several tenets of the DMS feedback process. Qu and Gabric (2010), for example, introduce their contribution to the subject by stating, "dimethylsulfide (DMS) is the main volatile sulfur [species] released during the formation and decay of microbial ocean biota" and "aerosols formed from the atmospheric conversion of DMS to sulfate and methanesulfonic acid can exert a climate cooling effect directly by scattering and absorbing solar radiation and indirectly by promoting the formation of cloud condensation nuclei and increasing the albedo of clouds, thus reflecting more solar radiation back into space."

Working with climate and DMS production data from the region of the Barents Sea (70–80°N, 30–35°E) obtained over the period 1998 to 2002, Qu and Gabric employed a genetic algorithm to calibrate chlorophyll-a measurements (obtained from SeaWiFS satellite data) for use in a regional DMS production model. Then, using GCM temperature outputs for the periods 1960–1970 (pre-industry CO_2 level) and 2078–2086 (triple the pre-industry CO_2 level), they calculated the warming-induced enhancement of the DMS flux from the Barents Sea region.

The two researchers report, "significantly decreasing ice coverage, increasing sea surface temperature and decreasing mixed-layer depth could lead to annual DMS flux increases of more than 100% by the time of equivalent CO_2 tripling (the year 2080)." In commenting on their findings, they state, "such a large change would have a great impact on the Arctic energy budget and may offset the effects of anthropogenic warming that are amplified at polar latitudes." What is more, they write, "many of these physical changes will also promote similar perturbations for other biogenic species (Leck et al., 2004), some of which are now thought to be equally influential to the aerosol climate of the Arctic Ocean." Thus it can be appreciated that DMS production in a warming world—especially when augmented by analogous biogenic phenomena—may provide a large moderating influence on the primary impetus for warming that is produced by mankind's emissions of CO_2 and other greenhouse gases.

Kim et al. (2010) write that DMS "represents 95% of the natural marine flux of sulfur gases to the atmosphere (Bates et al., 1992; Liss et al., 1997)," and they say it "may be oxidized to form non sea-salt sulfate aerosols, which are known to act as cloud condensation nuclei and thereby exert a cooling effect by absorbing or scattering solar radiation." They cite Charlson et al. (1987), who first described the intriguing and important chain of events. They also note "DMS is generated by intracellular or extracellular enzymatic cleavage of DMSP [dimethylsulfoniopropionate] by DMSP-lyase, which is synthesized by algae and bacteria, following DMSP secretion from producer cells or release following autolysis or viral attack," while noting that "grazing activity can also result in DMSP conversion to DMS if DMSP and DMSP-lyase are physically mixed following grazing," citing Stefels et al., 2007, and Wolfe and Steinke, 1996.

Working in the coastal waters of Korea from 21 November to 11 December 2008, the 14 Korean scientists utilized 2,400-liter mesocosm enclosures to simulate, in triplicate, three sets of environmental conditions—an ambient control (~400 ppm CO_2 and ambient temperature), an acidification treatment (~900 ppm CO_2 and ambient temperature), and a greenhouse treatment (~900 ppm CO_2 and ~3°C warmer-than-ambient temperature)—and within these mesocosms they initiated phytoplankton blooms by adding equal quantities of nutrients to each mesocosm on day 0. For 20 days thereafter they measured numerous pertinent parameters within each mesocosm. This work revealed, as they describe it, that "total accumulated DMS concentrations (integrated over the experimental period) in the acidification and greenhouse mesocosms were approximately 80% and 60% higher than the values measured in the control mesocosms, respectively," which they attribute to the fact that, in their experiment, "autotrophic nanoflagellates (which are known to be significant DMSP producers) showed increased growth in response to elevated CO_2" and "grazing rates [of microzooplankton] were significantly higher in the treatment mesocosms than in the control mesocosms." In the concluding paragraph of their paper, they write, "the key implication of our results is that DMS production resulting from CO_2-induced grazing activity may increase under future high CO_2 conditions," concluding that "DMS production in the ocean may act to counter the effects of global warming in the future."

References

Bates, T.S., Lamb, B.K., Guenther, A., Dignon, J., and Stoiber, R.E. 1992. Sulfur emissions to the atmosphere from natural sources. *Journal of Atmospheric Chemistry* **14**: 315–337.

Charlson, R.J., Lovelock, J.E., Andreae, M.O., and Warren, S.G. 1987. Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate. *Nature* **326**: 655–661.

Idso, C.D. and Singer, S.F. 2009. Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC). Chicago, IL: The Heartland Institute.

Kim, J.-M., Lee, K., Yang, E.J., Shin, K., Noh, J.H., Park, K.-T., Hyun, B., Jeong, H.-J., Kim, J.-H., Kim, K.Y., Kim, M., Kim, H.-C., Jang, P.-G., and Jang, M.-C. 2010. Enhanced production of oceanic dimethylsulfide resulting from CO_2-induced grazing activity in a high CO_2 world. *Environmental Science & Technology* **44**: 8140–8143.

Leck, C., Tjernstrom, M., Matrai, P., Swietlicki, E., and Bigg, E.K. 2004. Can marine micro-organisms influence melting of the Arctic pack ice? *EOS, Transactions, American Geophysical Union* **85**: 25–36.

Liss, P.S., Hatton, A.D., Malin, G., Nightingale, P.D., and Turner, S.M. 1997. Marine sulphur emissions. *Philosophical Transactions of the Royal Society London B* **352**: 159–169.

Qu, B. and Gabric, A.J. 2010. Using genetic algorithms to calibrate a dimethylsulfide production model in the Arctic Ocean. *Chinese Journal of Oceanology and Limnology* **28**: 573–582.

Stefels, J., Steinke, M., Turner, S., Malin, G., and Belviso, S. 2007. Environmental constraints on the production and removal of the climatically active gas dimethylsulphide (DMS) and implications for ecosystem modeling. *Biogeochemistry* **83**: 245–275.

Wolfe, G.V. and Steinke, M. 1996. Grazing-activated production of dimethyl sulfide (DMS) by two clones of *Emiliania huxleyi*. *Limnology and Oceanography* **41**: 1151–1160.

2.3. Solar Forcing of Climate

Solar forcing of climate during the Current Warm Period has long been discounted by climate alarmists and the IPCC as being of insufficient magnitude to cause the observed rise in late twentieth and early twenty-first century temperatures. In contrast, the 2009 NIPCC report (Idso and Singer, 2009) made a strong case for solar forcing. In this section we present findings of additional papers that support a significant influence of this celestial body on Earth's climate, beginning with a discussion of the study of Helama et al. (2010).

The study of sun-climate connections long has been plagued by the lack of suitably extensive and continuous data for solar activity and climatic variables. Helama et al. (2010), however, overcame some of those difficulties by examining the sun-climate relationship in unprecedented detail from the Mid- to Late-Holocene, beginning a new exploration of sun-climate co-variations on bimillennial and millennial timescales. In conducting their study, for example, they produced a well-dated and annually resolved tree-ring proxy temperature reconstruction from 5500 BCE to 2004 CE, which was representative of the high Arctic region of Northern Lapland, Finland, and Norway (68–70°N, 20–30°E), after which they employed the reconstructed sunspot series for the past 11,000 years that was developed by Solanki and colleagues in 2004 as a proxy for their solar activity index. Although Helama et al. were able to confirm relevant temperature oscillations on centennial and bicentennial timescales, they chose to focus their study on bimillennial and millennial timescale variations.

Figure 2.3.1 shows the band-pass filtered (900–1100 years) millennial-scale variations of the sunspot number series and reconstructed tree-ring temperature series are very well correlated if one introduces a time lag of about 70 years. The statistical correlations between the two sun-climate variables change with time but become more significant during the last 2,000 years with r = 0.796 and p = 0.0066. In contrast, the authors cannot demonstrate similar positive or significant correlations for the sun-climate variables for bimillennial (band-pass filtering of 1,150 to 3,000 years) scale variations for the last two thousand years (late Holocene), but stronger correlations (with r = 0.877 and p = 0.0121) were shown to exist between sunspot activity and temperatures at high-latitude Lapland for the Mid Holocene interval at the bimillennial timescale (not shown).

Helama et al. (2010) suggest the statistical correlations for the sun and temperature series on millennial timescales depicted in the figure above are probably realistic and physically meaningful, especially if one takes into account the time lag of 60–80 years. They explain that the probable scenario for explaining this relationship would be that solar activity could have driven the advection of cold surface waters southward and eastward in the subpolar North Atlantic and that cold water

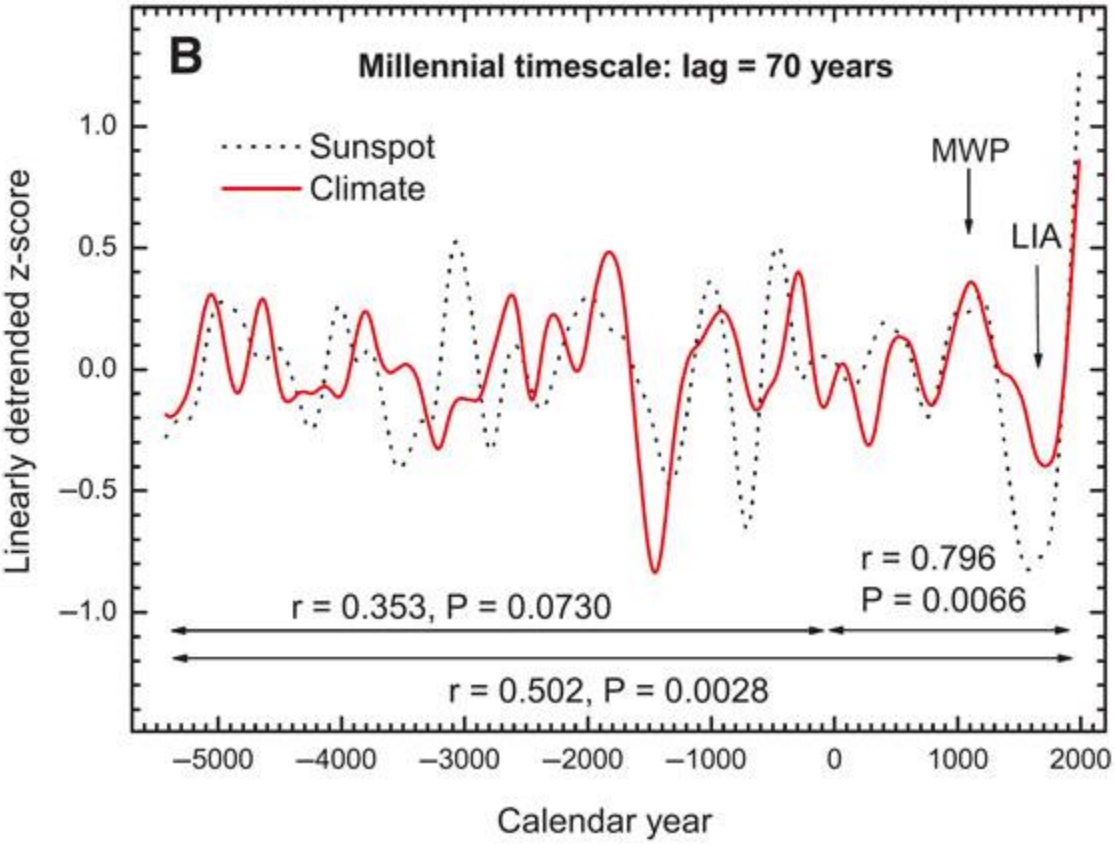


Figure 2.3.1. Band-pass filtered (900–1100 years) millennial-scale variations of the sunspot number series and reconstructed tree-ring temperature series lagged by 70 years. From Helama et al. (2010).

perturbation may ultimately influence the production of the North Atlantic deep water down to a depth of 2,000 meters. This chain of processes would probably need to include a time delay for actions within the high Arctic to propagate further south to affect the formation and working of the famous North Atlantic oceanic flywheel known as the North Atlantic Meridional Overturning Circulation. It also should be noted that such physical time delays, although in a shorter time range of five to 30 years, have been pointed out to be necessary for a physical connection between changes in the Sun and climatic conditions around Europe and North and tropical Atlantic regions by Eichler et al. (2010) and Soon (2009).

The authors also provide a brief discussion of plausible sun-climate mechanisms through the atmosphere, invoking changing tropospheric-stratospheric temperature gradients. But they ultimately conclude that a pathway and mechanism involving the ocean for both memory and redistribution of heat are probably needed to explain what they observed for bimillennial and millennial temperature variations during the Mid to Late Holocene in the high Arctic.

Finally, it is important to note Helama et al.'s observation that "the near-centennial delay in climate in responding to sunspots indicates that the Sun's influence on climate arising from the current episode of high sunspot numbers [which are the most pronounced of the entire record] may not yet have manifested itself fully in climate trends," and "if neglected in climate models, this lag could cause an underestimation of twenty-first-century warming trends."

Examining the sun-climate connection on a much-reduced time scale were Le Mouel et al. (2010a). The team of Professors Jean-Louis Le Mouel, Vincent Courtillot, and colleagues has been particularly inspired and productive of late in publishing papers revealing more evidence and information about how the sun's variable magnetic activity may affect various terrestrial phenomena, including weather and climate (see for example Kossobokov et al. 2010; Le Mouel et al. 2010b). And their 2010 publication (Le Mouel et al. 2010a) adds even more remarkable evidence and insight to the topic.

Figure 2.3.2, for example, displays some rather unexpected and surprising correlations between the long-term variation in the amplitude (A) of the solid Earth rotation parameter (here they have adopted its well-detected semiannual variation) called length-of-day, and two candidate solar activity measures: sunspot number (SN) and neutron count (NC, a proxy for incoming galactic cosmic rays), obtained from a station in Moscow, Russia. They point out that A and NC are inversely correlated with SN, the solar activity index, which leads A by about one year. And since galactic cosmic rays are also inversely related to sunspot number with a delay of one to two years or so, A is directly correlated to NC.

Le Mouel et al. (2010a) explain the correlations in the figure above as being due to a plausible physical link of the 11-year solar activity cycle to a systematic modulation of tropospheric zonal wind (since winds above 30 km contribute less than 20 percent of Earth's angular momentum, as proxied by A). They also make the important point that although the IPCC and others usually rule out the role of solar irradiance impact on terrestrial climate because of the small interannual changes in the solar irradiance, such an argument does not apply to the plausible link of the large seasonal incoming solar radiation in modulating the semiannual oscillations in the length-of-day amplitude. Therefore, Le Mouel et al. (2010a) say their paper "shows that the Sun can (directly or indirectly) influence tropospheric zonal mean-winds over decadal to multidecadal time scales." And noting "zonal mean-winds constitute an important element of global atmospheric circulation," they go on to suggest, "if the solar cycle can influence zonal mean-winds, then it may affect other features of global climate as well, including oscillations such as the NAO and MJO, of which zonal winds are an ingredient." Thus, "the cause of this forcing," as they describe it, "likely involves some combination of solar wind, galactic cosmic rays, ionosphere-Earth currents and cloud microphysics."

Contemporaneously, Scafetta (2010) investigated lesser-explored solar-planetary interactions and how they might also be capable of influencing Earth's climate. Using the pattern of perturbations of the sun's motion relative to the center of the solar system as a measure of the internal gravitational interactions of the sun-planet system, he identified—via spectral analysis and other means—a number of clear periodic signals. A spectral decomposition of Hadley Centre climate data shows similar spectra, with the results of a spectral coherence test of the two histories being highly significant. On the other hand, the spectral pattern of climate model simulations does not match the solar and climatic variability patterns, whereas the

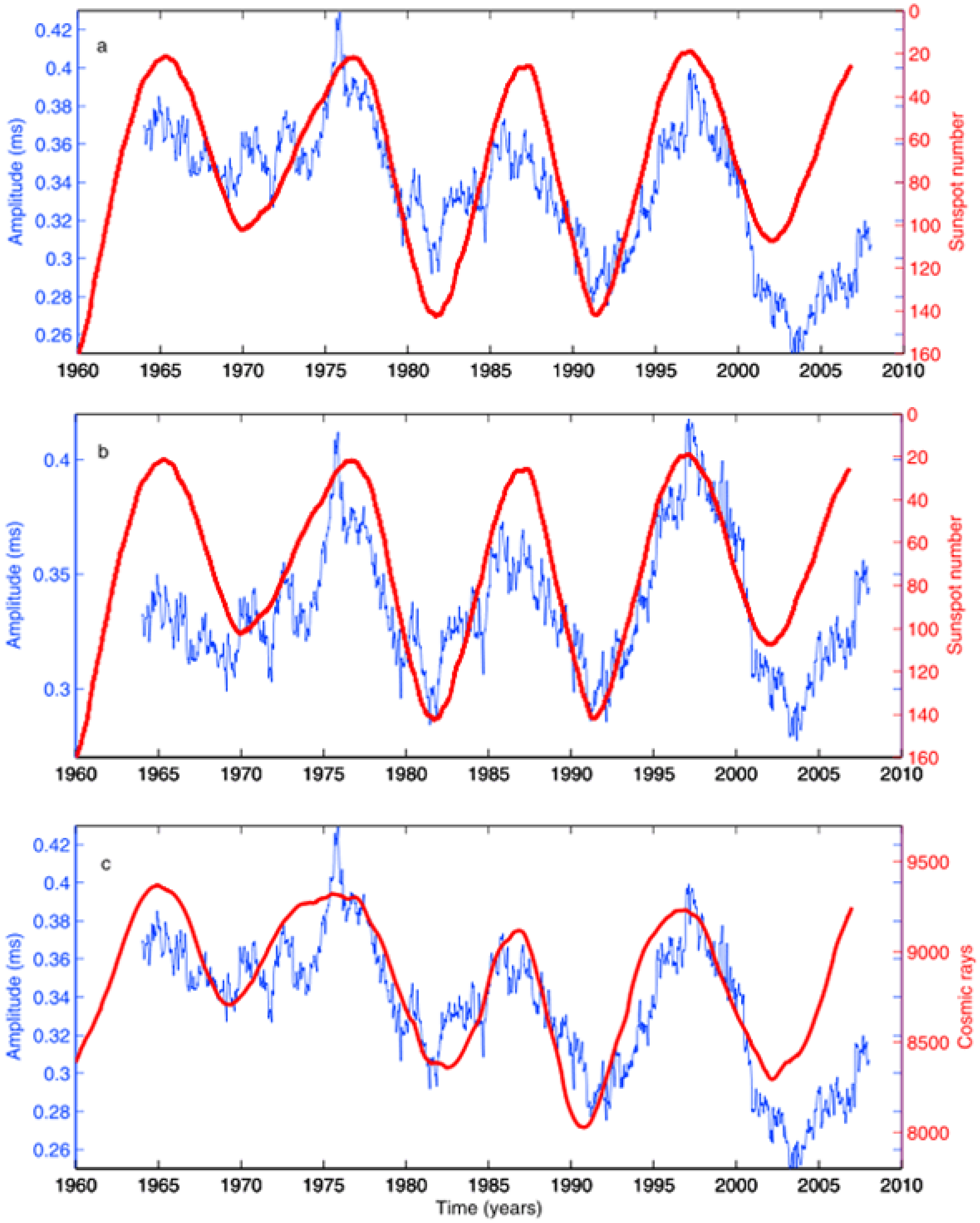


Figure 2.3.2. Correlation between the amplitude of the semiannual oscillation in length-of-day (blue curves with middle panel as detrended data with both top and bottom panels as original data) and various solar activity measures (sunspot numbers and proxy for galactic cosmic rays: red curves) from 1962–2009. A four-year moving-average filter was used to smooth the data series. Adapted from Le Mouel et al. (2010).

output of a model based on astronomically forced cycles does match global temperature data well, and it matches ocean temperature data even better.

The mechanism behind the newly discovered suite of relationships appears to be a combination of planetary gravitational effects upon the sun that influence both direct solar irradiance and the sun's magnetic field, plus an interaction of the magnetic fields of the other planets with Earth's magnetic field and the solar wind. Through these means the solar-terrestrial magnetic field experiences oscillations of several different frequencies that each exert an influence on the intensity of cosmic rays reaching the Earth and the subsequent generation of climate-changing clouds. As for the significance of the hypothesized sun-planets-Earth-(and moon) interactions, Scafetta notes failure to include these natural cyclical components of climate in current state-of-the-art climate models has resulted in at least a 60 percent overestimate of the degree of anthropogenic-induced greenhouse warming between 1970 and 2000.

Further examining the cosmic ray/climate hypothesis, Shaviv (2008) writes as background for his study, "climatic variations synchronized with solar variations do exist, whether over the solar cycle or over longer time-scales," citing numerous references in support of this fact. However, it is difficult for some scientists to accept the logical derivative of this fact, that solar variations are driving major climate changes, the prime problem being that measured or reconstructed variations in total solar irradiance seem far too small to be able to produce the observed climatic changes.

One potential way of resolving this dilemma would be to discover some type of amplification mechanism, but most attempts to identify one have been fraught with difficulty and met with much criticism. In this particular instance, however, Shaviv makes a good case for at least the existence of such an amplifier, and he points us in the direction of a sensible candidate to fill this role.

Shaviv "use[d] the oceans as a calorimeter to measure the radiative forcing variations associated with the solar cycle" via "the study of three *independent* records: the net heat flux into the oceans over 5 decades, the sea-level change rate based on tide gauge records over the 20th century, and the sea-surface temperature variations," each of which can be used "to consistently derive the same oceanic heat flux."

In pursuing this path, Shaviv demonstrates "there are large variations in the oceanic heat content together with the 11-year solar cycle." He also reports the three independent datasets "consistently show that the oceans absorb and emit an order of magnitude more heat than could be expected from just the variations in the total solar irradiance," thus "implying," as he describes it, "the necessary existence of an amplification mechanism, although without pointing to which one."

Finding it difficult to resist pointing, however, Shaviv acknowledges his affinity for the solar-wind modulated cosmic ray flux (CRF) hypothesis, suggested by Ney (1959), discussed by Dickinson (1975), and championed by Svensmark (1998). Based on "correlations between CRF variations and cloud cover, correlations between non-solar CRF variations and temperature over geological timescales, as well as experimental results showing that the formation of small condensation nuclei could be bottlenecked by the number density of atmospheric ions," this concept, according to Shaviv, "predicts the correct radiation imbalance observed in the cloud cover variations" that are needed to produce the magnitude of the net heat flux into the oceans associated with the 11-year solar cycle. Shaviv thus concludes the solar-wind modulated CRF hypothesis is "a favorable candidate" for primary instigator of many climatic phenomena.

Moving the hypothesis forward one year later, Knudsen and Riisager (2009) proposed the galactic cosmic ray (GCR) climate theory involves a solar forcing of the climate that significantly amplifies the forcing owing to solar irradiance. Noting "the GCR flux is also modulated by earth's magnetic field," they speculated, "if the GCR-climate theory is correct, one would expect not only a relatively strong solar-climate link, but also a connection between earth's magnetic field and climate." Thus, they went on to "compare a new global reconstruction of the Holocene geomagnetic dipole moment (Knudsen et al., 2008) with proxy records for past low-latitude precipitation (Fleitmann et al., 2003; Wang et al., 2005)," the first of which proxy records was derived from a speleothem $\delta^{18}O$ record obtained from stalagmite Q5 from Qunf cave in southern Oman, and the second of which was derived from a similar record obtained from stalagmite DA from Dongge cave in southern China.

The two researchers report the various correlations they observed over the course of the

Holocene "suggest that the Holocene low-latitude precipitation variability to some degree was influenced by changes in the geomagnetic dipole moment." More particularly, they say the general increase in precipitation observed over the past 1,500 years in both speleothem records "cannot be readily explained by changes in summer insolation or solar activity," but that it "correlates very well with the rapid decrease in dipole moment observed during this period." This relationship is largely explained by the fact that "a higher dipole moment leads to a lower cosmic ray flux, resulting in reduced cloud coverage and, ultimately, lower precipitation."

Knudsen and Riisager also state, "in addition to supporting the notion that variations in the geomagnetic field may have influenced earth's climate in the past," their study provides support for a link "between cosmic ray particles, cloud formation, and climate, which is crucial to better understand how changes in solar activity impact the climate system."

In an intriguing paper published in *Physics Reports*, Qing-Bin Lu (2009)—who is associated with three different departments of Canada's University of Waterloo (physics and astronomy, biology, and chemistry)—injects a new dimension into the debate over what has been the cause of late twentieth-century global warming and its apparent early twenty-first-century cessation.

The bulk of Lu's paper is dedicated to describing the new cosmic-ray-driven electron-induced reaction mechanism—or CRE model—of ozone depletion, which he contrasts with the conventional photochemical model of ozone depletion. Near the end of his discussion of this other important subject, however, he makes some original observations about the possible effects of chlorofluorocarbons (CFCs) and cosmic-ray-driven ozone depletion on global climate change. This subsidiary analysis gives one reason to suspect the IPCC has long been focused on the wrong greenhouse gas, CO_2.

Lu begins by noting ozone-depleting CFCs are also greenhouse gases but that the IPCC has considered them to provide only about 13 percent of the total radiative forcing produced by all of the atmosphere's well-mixed greenhouse gases. He then goes on to challenge the low value of this assessment, stating emphatically (as indicated by his use of italics), "*these conclusions were based on climate model simulations rather than direct observations*." He then proceeds to describe and consider certain real-world measurements in ways that have not been done before.

In plotting yearly mean global temperature deviations (ΔT, relative to the 1980 mean value) vs. equivalent effective stratospheric chlorine concentrations (EESC, normalized to their 1980 value) over the period 1970–2008, for example, Lu found the former parameter was a well-defined function of the latter, as may be seen in Figure 2.3.3, where the correlation coefficient (R) of the linear relationship between the two parameters is 0.89 at a probability level (P) of < 0.0001.

Of course, correlation does not prove causation, as must also be admitted to be the case when examining the similar relationship between ΔT and the atmosphere's CO_2 concentration over the latter part of the twentieth century and early part of the twenty-first century. However, Lu makes an important point in noting that following the implementation of the Montreal Protocol, the total halogen level in the lower atmosphere was observed to peak in 1994, while the EESC over Antarctica was estimated to peak around the year 2000, after which it actually began to decline, as did global temperature, as shown in Figure 2.3.4. And based on the estimated trend of EESC over the next four decades, Lu's analysis suggests the Earth could well continue to cool—as it has been gradually doing for the past decade—until the middle of the current century or more.

As for what it all means, Lu states in the concluding paragraph of his lengthy treatise that the "observed data point to the possibility that the global warming observed in the late 20th century was dominantly caused by CFCs, modulated by CRE-driven ozone depletion" and "with the decreasing emission of CFCs into the atmosphere, global cooling may have started since 2002." Lu does not contend this must be the case; he states only that "this is likely a subject deserving close attention." The question now is: Will other scientists and the IPCC provide that close attention?

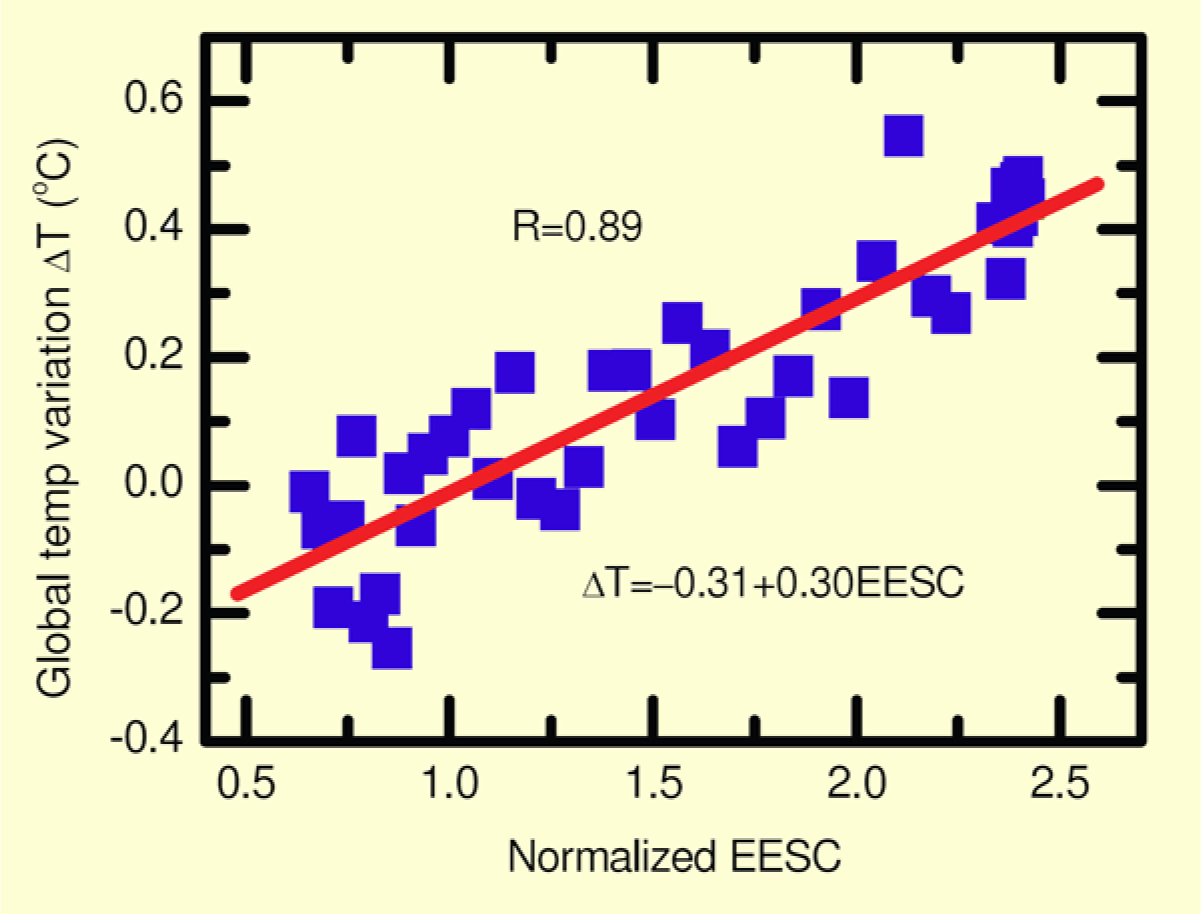


Figure 2.3.3. Yearly global temperature relative to its 1980 value (ΔT) vs. yearly equivalent effective stratospheric chlorine concentrations (EESC) normalized to its 1980 value. Adapted from Lu (2009).

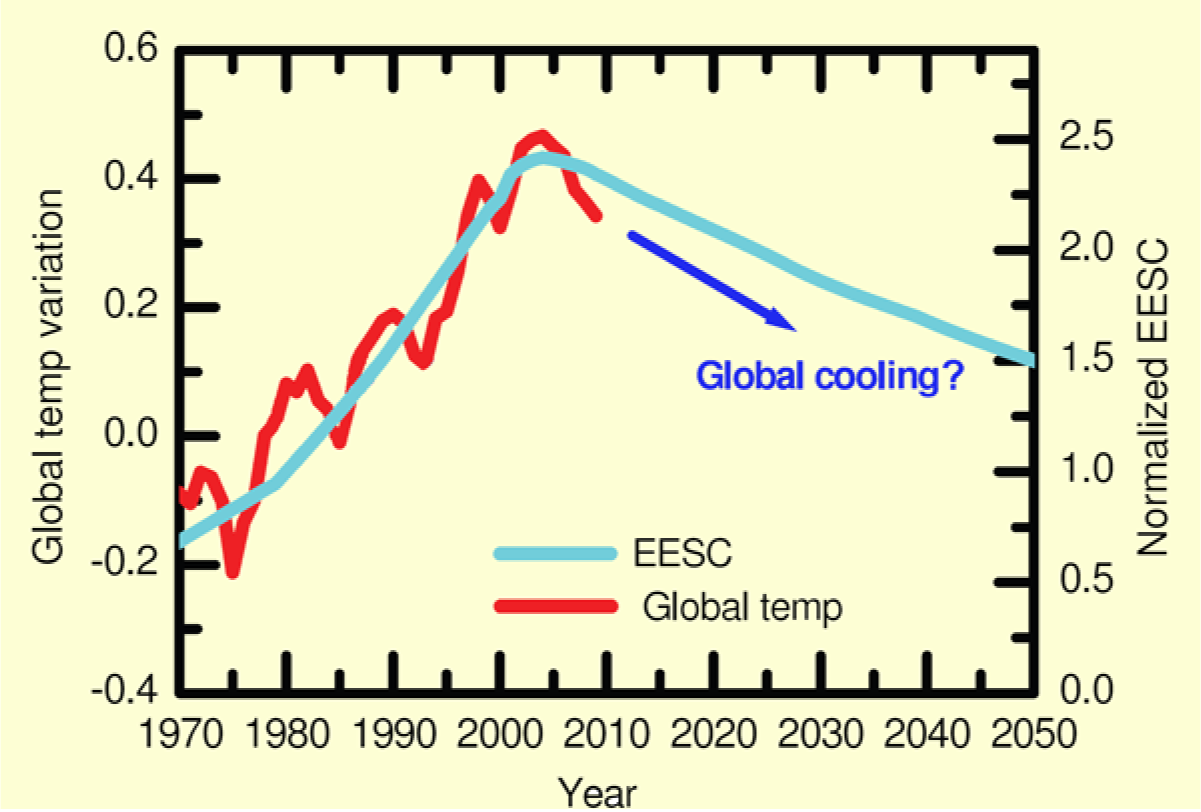


Figure 2.3.4. Yearly global temperature relative to its 1980 value (ΔT) and yearly EESC normalized to its 1980 value vs. time. Adapted from Lu (2009).

References

Dickinson, R.E. 1975. Solar variability and the lower atmosphere. *Bulletin of the American Meteorological Society* **56**: 1240–1248.

Eichler, A., Olivier, S., Henderson, S.K., Laube, A., Beer, J., Papina, T., and Gaggler, H.W. 2010. Sub-Milankovitch solar forcing of past climates: Mid and late Holocene perspectives. *Geological Society of America Bulletin* **122**: 1981–1988.

Fleitmann, D., Burns, S., Mudelsee, M., Neff, U., Kramers, U., Mangini, A., and Matter, A. 2003. Holocene forcing of the Indian monsoon recorded in a stalagmite from southern Oman. *Science* **300**: 1737–1739.

Helama, S., Fauria, M.M., Mielikainen, K., Timonen, M., and Eronen, M. 2010. Sub-Milankovitch solar forcing of past climates: Mid and late Holocene perspectives. *Geological Society of America Bulletin* **122**: 1981–1988.

Idso, C.D. and Singer, S.F. 2009. Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC). Chicago, IL: The Heartland Institute.

Knudsen, M.F. and Riisager, P. 2009. Is there a link between earth's magnetic field and low-latitude precipitation? *Geology* **37**: 71–74.

Knudsen, M.F., Riisager, P., Donadini, F., Snowball, I., Muscheler, R., Korhonen, K., and Pesonen, L.J. 2008. Variations in the geomagnetic dipole moment during the Holocene and the past 50 kyr. *Earth and Planetary Science Letters* **272**: 319–329.

Kossobokov, V., Le Mouel, J.-L., and Courtillot, V. 2010. A statistically significant signature of multi-decadal solar activity changes in atmospheric temperatures at three European stations. *Journal of Atmospheric and Solar-Terrestrial Physics* **72**: 595–606.

Le Mouel, J.-L., Blanter, E., Shnirman, M., and Courtillot, V. 2010a. Solar forcing of the semi-annual variation of length-of-day. *Geophysical Research Letters* **37**: 2010GL043185.

Le Mouel, J.-L., Kossobokov, V., and Courtillot, V. 2010b. A solar pattern in the longest temperature series from three stations in Europe. *Journal of Atmospheric and Solar-Terrestrial Physics* **72**: 62–76.

Lu, Q.-B. 2009. Cosmic-ray-driven electron-induced reactions of halogenated molecules adsorbed on ice surfaces: Implications for atmospheric ozone depletion and global climate change. *Physics Reports* **487**: 141–167.

Ney, E.P. 1959. Cosmic radiation and weather. *Nature* **183**: 451.

Scafetta, N. 2010. Empirical evidence for a celestial origin of the climate oscillations and its implications. *Journal of Atmospheric Solar-Terrestrial Physics*: 10.1016/j.jastp.2010.04.015.

Shaviv, N.J. 2008. Using the oceans as a calorimeter to quantify the solar radiative forcing. *Journal of Geophysical Research* **113**: 10.1029/2007JA012989.

Solanki, S.K., Usoskin, I.G., Kromer, B., Schüssler, M., and Beer, J. 2004. Unusual activity of the Sun during recent decades compared to the previous 11,000 years. *Nature* **431**: 1084–1087.

Soon, W.W.-H. 2009. Solar Arctic-mediated climate variation on multidecadal to centennial timescales: Empirical evidence, mechanistic explanation, and testable consequences. *Physical Geography* **30**: 144–184.

Svensmark, H. 1998. Influence of cosmic rays on earth's climate. *Physical Review Letters* **81**: 5027–5030.

Wang, Y.J., Cheng, H., Edwards, R.L., He, Y.Q., Kong, X.G., An, Z.S., Wu, J.Y., Kelly, M.J., Dykoski, C.A., and Li, X.D. 2005. The Holocene Asian monsoon: Links to solar changes and North Atlantic climate. *Science* **308**: 854–857.

2.4. Other Forcings and Feedbacks

Researchers have identified other forcings and feedbacks about which little is currently known (or acknowledged by the IPCC), but which may ultimately prove to be important drivers of climate change. In this section we examine some of those phenomena that have been described in the peer-reviewed scientific literature.

2.4.1 Stratospheric Water Vapor

Solomon et al. (2010) write, "the trend in global surface temperatures has been nearly flat since the late 1990s despite continuing increases in the forcing due to the sum of the well-mixed greenhouse gases (CO_2, CH_4, halocarbons, and N_2O), raising questions regarding the understanding of forced climate change, its drivers, the parameters that define natural internal variability, and how fully these terms are represented in climate models." In an effort to improve our understanding of climate forcing, they used observations of stratospheric water vapor concentration obtained over the period 1980–2008, together with detailed radiative transfer and modeling information, to calculate the global climatic impact of this important greenhouse gas and compare it with trends in mean global near-surface air temperature observed over the same time period.

According to the seven scientists, stratospheric water vapor concentrations decreased by about 10 percent after the year 2000, and their analysis indicates this decrease should have slowed the rate of increase in global near-surface air temperature between 2000 and 2009 by about 25 percent compared to what would have been expected on the basis of climate model calculations due to measured increases in carbon dioxide and other greenhouse gases over the same period. In addition, they found, "more limited data suggest that stratospheric water vapor probably increased between 1980 and 2000, which would have enhanced the decadal rate of surface warming during the 1990s by about 30% [above what it would have been without the stratospheric water vapor increase]."

In their concluding paragraph, Solomon et al. thus write it is "not clear whether the stratospheric water vapor changes represent a feedback to global average climate change or a source of decadal variability." In either case, their findings elucidate a hugely important phenomenon not previously included in any prior analyses of global climate change. They also write that current climate models do not "completely represent the Quasi Biennial Oscillation [which has a significant impact on stratospheric water vapor content], deep convective transport [of water vapor] and its linkages to sea surface temperatures, or the impact of aerosol heating on water input to the stratosphere." Consequently, in light of (1) Solomon et al.'s specific findings, (2) their listing of what current climate models do not do (which they should do), and (3) the questions they say are raised by the flat-lining of mean global near-surface air temperature since the late 1990s, it is premature to conclude that current state-of-the-art models know enough to correctly simulate the intricate workings of Earth's climate regulatory system.

2.4.2 Volcanic and Seismic Activity

Tuffen (2010) writes, “there is growing evidence that past changes in the thickness of ice covering volcanoes have affected their eruptive activity.” He states, “the rate of volcanic activity in Iceland accelerated by a factor of 30–50 following the last deglaciation at approximately 12 ka (Maclennan et al., 2002)” and “analyses of local and global eruption databases have identified a statistically significant correlation between periods of climatic warming associated with recession of ice and an increase in the frequency of eruptions (Jellinek et al., 2004; Nowell et al., 2006; Huybers and Langmuir, 2009).” Thus he asks the next logical question: “Will the current ice recession provoke increased volcanic activity and lead to increased exposure to volcanic hazards?”

In response to his self-interrogation, Tuffen—a researcher at the Lancaster Environment Centre of Lancaster University in the United Kingdom—proceeds to “analyze our current knowledge of how ice thickness variations influence volcanism” and to “identify several unresolved issues that currently prevent quantitative assessment of whether activity is likely to accelerate in the coming century.”

At the conclusion of his review and analysis, Tuffen finds “ice unloading may encourage more explosive eruptions” but “melting of ice and snow may decrease the likelihood and magnitude of meltwater floods.” On the other hand, he writes, there is (1) “uncertainty about the time scale of volcanic responses to ice unloading,” (2) “poor constraint on how ice bodies on volcanoes will respond to twenty-first century climate change,” (3) “lack of data on how past changes in ice thickness have affected the style of volcanic eruptions and associated hazards,” and he notes (4) “the sensitivity of volcanoes to small changes in ice thickness or to recession of small glaciers on their flanks is unknown,” (5) “it is not known how localized ice withdrawal from stratovolcanoes [tall, conical volcanoes with many layers (strata) of hardened lava, tephra, and volcanic ash] will affect shallow crustal magma storage and eruption,” and (6) “broader feedbacks between volcanism and climate change remain poorly understood.”

The U.K. researcher concludes, “in order to resolve these problems, both new data and improved models are required.” In the data area, he states, “existing databases of known volcanic eruptions need to be augmented by numerous detailed case studies of the Quaternary eruptive history of ice-covered volcanoes.” Regarding models, he writes, “improved physical models are required to test how magma generation, storage and eruption at stratovolcanoes are affected by stress perturbations related to the waxing and waning of small-volume ice bodies on what is commonly steep topography.” Last, he suggests “feedbacks between the mass balance of ice sheets and glaciers and volcanic activity need to be incorporated into future earth-system models.” Hence, it is clear that much is known about the subject, but it is equally clear that much is still to be learned.

O. Molchanov (2010) of the Russian Academy of Sciences’ Institute of the Physics of the Earth, headquartered in Moscow, Russia, makes a case for the hypothesis that, at least partially, global climate changes and corresponding activity indices such as the ENSO phenomenon are induced by similar variations in seismicity. Molchanov (1) calculates the cumulative annual seismic energy released by large earthquake events originating from depths of 0 to 38 km, based on data archived by the U.S. Geological Survey for the 35-year time interval of 1973–2008 for various earthquake activity zones spread across the tropical and western Pacific—including the Chilean subduction zone; the Tonga-Kermadec zone; the Sunda, Philippine, and Solomon Sea zones; and the Mariana, Japan, and Kuril-Kamchatka zones—and (2) compares the then-evident periodicity of seismic energy production with that of sea surface temperature oscillations that occurred over the same 35-year period within the Niño zones 1+2 (0–10°S, 90–80°W), 3 (5°N–5°S, 150–90°W), and 4 (5°N–5°S, 160°E–150°W).

It was first determined that the “climate indices show expected ENSO variation” and “amazingly,” as Molchanov describes it, the earthquake indices demonstrate “similar quasi-ENSO variations.” So the next question was obviously: which is the action and which is the reaction? From a number of other factors, the Russian researcher concludes it is “more probable” that earthquake activity is “forcing the ENSO variation in the climate” than vice versa.

In concluding his paper, Molchanov states, “trends in the climate and seismic variations are similar to each other” and “it is rather probable that the climate ENSO effect is at least partially induced by seismicity with a time lag of about 1.5 years,” leaving it up to others to further study and debate the issue.

2.4.3 Carbon Sequestration

Lin et al. (2010) observe that "most models predict that climate warming will increase the release of carbon dioxide from the terrestrial biosphere into the atmosphere, thus triggering positive climate-terrestrial carbon feedback which leads to a warmer climate." However, they state the "stimulation of biomass accumulation and net primary productivity of terrestrial ecosystems under rising temperature (Rustad et al., 2001; Melillo et al., 2002; Luo et al., 2009) may enhance carbon sequestration and attenuate the positive feedback between climate warming and the terrestrial biosphere."

In an effort to find out which view is correct, Lin et al. conducted a meta-analysis of pertinent data from 127 individual studies published before June 2009, in order to determine whether the overall impact of a substantial increase in the air's CO_2 concentration on terrestrial biomass production would likely be positive or negative.

The three scientists report that for the totality of terrestrial plants included in their analysis, "warming significantly increased biomass by 12.3%" and there was a "significantly greater stimulation of woody (+26.7%) than herbaceous species (+5.2%)." They also found the warming effects on plant biomass production "did not change with mean annual precipitation or experimental duration" and "other treatments, including CO_2 enrichment, nitrogen addition, drought, and water addition, did not alter warming responses of plant biomass." Given such findings, the Chinese researchers conclude, "results in this and previous meta-analyses (Arft et al., 1999; Rustad et al., 2001; Dormann and Woodin, 2002; Walker et al., 2006) have revealed that warming generally increases terrestrial plant biomass, indicating enhanced terrestrial carbon uptake via plant growth and net primary productivity." Thus, we can logically expect that (1) the ongoing rise in the air's CO_2 content will soften its own tendency to increase global temperatures, while simultaneously (2) enhancing Earth's terrestrial vegetation with greater growth rates and biomass production, both in the agricultural arena and throughout the planet's many natural ecosystems.

In another study, Geibert et al. (2010) write, "the Southern Ocean (SO) plays a key role in modulating atmospheric CO_2 via physical and biological processes," but "over much of the SO, biological activity is iron-limited," which restricts the SO's ability to do its job in this regard. However, they note "new in situ data from the Antarctic zone south of Africa in a region centered at ~20°E–25°E reveal a previously overlooked region of high primary production." They sought to learn the cause of this anomalous production, which is an integral part of the globe's deep-ocean carbon transferal system, whereby massive quantities of CO_2-carbon recently absorbed from the atmosphere are photosynthetically incorporated into phytoplanktonic biomass, which either directly or indirectly—via marine food chains—is transported to the bottom layers of the sea, where it experiences long-term separation from the atmosphere.

Based on data obtained from expedition ANT XX/2 to the Weddell Gyre (WG) that took place from 24 November 2002 to 23 January 2003—carried out on the icebreaker RV *Polarstern*—Giebert et al. acquired "an in situ biogeochemical data set to complement indirect information from modeling and remote sensing techniques." This dataset included multiple water samples for analyses of nutrients, oxygen, phytoplankton species identification and pigment and chlorophyll-a concentration, as well as for measurements of particulate matter, temperature, salinity, and the radionuclides ^{234}Th and ^{238}U.

The 11 researchers—from Germany, New Zealand, South Africa, and the United Kingdom—determined that "sea ice together with enclosed icebergs is channeled by prevailing winds to the eastern boundary of the WG," where a sharp transition to warmer waters causes melting of ice that contains significant amounts of iron previously deposited upon it by aeolian transport of iron-rich dust. As the larger icebergs penetrate deeper into the sea, the researchers note, "they are exposed to warmer waters even during winter, when sea ice is present and growing," which means the "continuous melting of icebergs in winter will lead to rising fresher and potentially iron-enriched waters from below, in the immediate vicinity of icebergs," which meltwater "would spread under the sea ice as a thin lens of fresher water, where it can refreeze due to its comparatively low salinity, and it can undergo processes of sorption and biological uptake." This hypothesis, in their words, "is consistent with maxima of iron concentrations in the lowermost parts of sea ice prior to the onset of spring melting (Lannuzel et al., 2007)." Thus, they conclude, "this melting hot spot causes an enhanced input of iron and salinity-driven stratification of the surface waters," which are the ideal conditions for sustaining the "intense phytoplankton blooms" that characterize the waters they studied.

With respect to the significance of their work, Geibert et al. state their findings "imply that future changes in sea-ice cover and dynamics could have a significant effect on carbon sequestration in the SO." If those changes included enhanced melting of Antarctic sea ice and icebergs, such as climate alarmists claim will occur, the planet's deep-ocean carbon transferal system would shift into a higher gear and effectively sequester greater amounts of CO_2-carbon from the atmosphere, reducing its rate of rise and thereby reducing the strength of the CO_2 greenhouse effect.

Janssens et al. (2010) write that "atmospheric deposition of reactive nitrogen, originating mainly from fossil-fuel burning and artificial fertilizer applications, has increased three- to five-fold over the past century" and "in many areas of the globe, nitrogen deposition is expected to increase further." This phenomenon stimulates plant growth and the uptake of carbon from the atmosphere, contributing to climate change mitigation. They state that Magnani et al. (2007) demonstrated nitrogen deposition to be "the dominant driver of carbon sequestration in forest ecosystems," although there has been what they describe as "intense debate" about the magnitude and sustainability of the phenomenon and its underlying mechanisms.

In an effort designed to further explore the subject, Janssens et al. conducted "a meta-analysis of measurements in nitrogen-addition experiments, and a comparison of study sites exposed to elevated or background atmospheric nitrogen deposition." The work of the 15 scientists revealed, in their words, that "nitrogen deposition impedes organic matter decomposition, and thus stimulates carbon sequestration, in temperate forest soils where nitrogen is not limiting microbial growth." What is more, they find "the concomitant reduction in soil carbon emissions is substantial," being "equivalent in magnitude to the amount of carbon taken up by trees owing to nitrogen fertilization."

For those worried about the prospect of CO_2-induced global warming, these findings should be good news, for in the concluding sentence of their paper, Janssens et al. state, "the size of the nitrogen-induced inhibition of below-ground respiration is of the same order of magnitude as the forest carbon sink." And in the concluding sentence of their paper's introduction, they state, "this effect has not been included in current carbon-cycle models," suggesting that when it is included, it will contribute much to "climate change mitigation."

In one final study of note, Blok et al. (2010) write of "fears" that if Earth's permafrost thaws, "much of the carbon stored will be released to the atmosphere," as will great quantities of the greenhouse gas methane (further exacerbating warming), as is claimed is already happening—and at an accelerating rate—by many climate alarmists, such as Al Gore in his 21 March 2007 testimony before the United States Senate's Environment & Public Works Committee and Michael Mann and Lee Kump (2008) in their *Dire Predictions* book. Quite to the contrary, Blok et al. say "it has been demonstrated that increases in air temperature sometimes lead to vegetation changes that offset the effect of air warming on soil temperature," citing the studies of Walker et al. (2003) and Yi et al. (2007) as specific examples of the phenomenon.

Thus, in an attempt to explore the subject within the context of real-world experimentation, Blok et al. conducted a study within the Kytalyk nature reserve in the Indigirka lowlands of northeastern Siberia (Russia), where they measured the thaw depth or active layer thickness (ALT) of the soil, the ground heat flux, and the net radiation in 10-meter-diameter plots either possessing or not possessing a natural cover of bog birch (*Betula nana*) shrubs, the latter of which set of plots had all *B. nana* shrubs removed from their native tundra vegetation in 2007.

The Dutch, Swiss, and Russian researchers report, "experimental *B. nana* removal had increased ALT significantly by an average of 9% at the end of the 2008 growing season, compared with the control plots," which implies reduced warming in the shrub-dominated plots, and "in the undisturbed control plots with varying natural *B. nana* cover, ALT decreased with increasing *B. nana* cover," also "showing a negative correlation between *B. nana* cover and ALT," which again implies reduced warming in the more shrub-dominated plots.

Blok et al. say their results suggest "the expected expansion of deciduous shrubs in the Arctic region, triggered by climate warming, may reduce summer permafrost thaw" and the "increased shrub growth may thus partially offset further permafrost degradation by future temperature increases." The six scientists write (1) permafrost temperature records "do not show a general warming trend during the last decade (Brown and Romanovsky, 2008), despite large increases in surface air temperature," (2) during the decade before that, "data from several Siberian Arctic permafrost stations do not show a discernible trend between 1991 and 2000 (IPCC, 2007)," and (3) "a recent discovery of ancient permafrost that survived several warm geological periods suggests that vegetation cover may help protect permafrost from climate warming (Froese et al., 2008)." Last, they note this phenomenon "could feedback negatively to global warming, because the lower soil temperatures in summer would slow down soil decomposition and thus the amount of carbon released to the atmosphere."

References

Arft, A.M., Walker, M.D., Gurevitch, J., Alatalo, J.M., Bret-Harte, M.S., Dale, M., Diemer, M., Gugerli, F., Henry, G.H.R., Jones, M.H., Hollister, R.D., Jonsdottir, I.S., Laine, K., Levesque, E., Marion, G.M., Molau, U., Molgaard, P., Nordenhall, U., Raszhivin, V., Robinson, C.H., Starr, G., Stenstrom, A., Stenstrom, M., Totland, O., Turner, P.L., Walker, L.J., Webber, P.J., Welker, J.M., and Wookey, P.A. 1999. Responses of tundra plants to experimental warming: meta-analysis of the international tundra experiment. *Ecological Monographs* **69**: 491–511.

Blok, D., Heijmans, M.M.P.D., Schaepman-Strub, G., Kononov, A.V., Maximov, T.C., and Berendse, F. 2010. Shrub expansion may reduce summer permafrost thaw in Siberian tundra. *Global Change Biology* **16**: 1296–1305.

Brown, J. and Romanovsky, V.E. 2008. Report from the International Permafrost Association: state of permafrost in the first decade of the 21st century. *Permafrost and Periglacial Processes* **19**: 255–260.

Dormann, C.F. and Woodin, S.J. 2002. Climate change in the arctic: using plant functional types in a meta-analysis of field experiments. *Functional Ecology* **16**: 4–17.

Froese, D.G., Westgate, J.A., Reyes, A.V., Enkin, R.J., and Preece, S.J. 2008. Ancient permafrost and a future, warmer Arctic. *Science* **321**: 1648.

Geibert, W., Assmy, P., Bakker, D.C.E., Hanfland, C., Hoppema, M., Pichevin, L.E., Schroder, M., Schwarz, J.N., Stimac, I., Usbeck, R., and Webb, A. 2010. High productivity in an ice melting hot spot at the eastern boundary of the Weddell Gyre. *Global Biogeochemical Cycles* **24**: 10.1029/2009GB003657.

Huybers, P. and Langmuir, C. 2009. Feedback between deglaciation, volcanism, and atmospheric CO_2. *Earth and Planetary Science Letters* **286**: 479–491.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by S. Solomon, et al. Cambridge, UK: Cambridge University Press.

Jellinek, A.M., Manga, M., and Saar, M.O. 2004. Did melting glaciers cause volcanic eruptions in eastern California? Probing the mechanics of dike formation. *Journal of Geophysical Research* **109**: 10.1029/2004JB002978.

Janssens, I.A., Dieleman, W., Luyssaert, S., Subke, J.-A., Reichstein, M., Ceulemans, R., Ciais, P., Dolman, A.J., Grace, J., Matteucci, G., Papale, D., Piao, S.L., Schulze, E.-D., Tang, J., and Law, B.E. 2010. Reduction of forest soil respiration in response to nitrogen deposition. *Nature Geoscience* **3**: 315–322.

Lannuzel, D., Schoemann, V., de Jong, J., Tison, J.L., and Chou, L. 2007. Distribution and biogeochemical behavior of iron in the East Antarctic sea ice. *Marine Chemistry* **106**: 18–32.

Lin, D., Xia, J., and Wan, S. 2010. Climate warming and biomass accumulation of terrestrial plants: a meta-analysis. *New Phytologist* **188**: 187–198.

Luo, Y.Q., Sherry, R., Zhou, X.H., and Wan, S.Q. 2009. Terrestrial carbon-cycle feedback to climate warming: experimental evidence on plant regulation and impacts of biofuel feedstock harvest. *Global Change Biology Bioenergy* **1**: 62–74.

Maclennan, J., Jull, M., McKenzie, D.P., Slater, L., and Gronvold, K. 2002. The link between volcanism and deglaciation in Iceland. *Geochemistry, Geophysics, Geosystems* **3**: 10.1029/2001GC000282.

Magnani, F., Mencuccini, M., Borghetti, M., Berbigier, P., Berninger, F., Delzon, S., Grelle, A., Hari, P., Jarvis, P.G., Kolari, P., Kowalski, A.S., Lankreijer, H., Law, B.E., Lindroth, A., Loustau, D., Manca, G., Moncrieff, J.B., Rayment, M., Tedeschi, V., Valentini, R., and Grace, J. 2007. The human footprint in the carbon cycle of temperate and boreal forests. *Nature* **447**: 848–850.

Mann, M.E. and Kump, L.R. 2008. *Dire Predictions: Understand Global Warming.* New York, NY: DK Publishing Inc.

Melillo, J.M., Steudler, P.A., Aber, J.D., Newkirk, K., Lux, H., Bowles, F.P., Catricala, C., Magill, A., Ahrens, T., and Morrisseau, S. 2002. Soil warming and carbon-cycle feedbacks to the climate system. *Science* **298**: 2173–2176.

Molchanov, O. 2010. About climate-seismicity coupling from correlation analysis. *Natural Hazards and Earth System Sciences* **10**: 299–304.

Nowell, D., Jones, C., and Pyle, D. 2006. Episodic quaternary volcanism in France and Germany. *Journal of Quaternary Science* **21**: 645–675.

Rustad, L.E., Campbell, J.L., Marion, G.M., Norby, R.J., Mitchell, M.J., Hartley, A.E., Cornelissen, J.H.C., Gurevitch, J., and GCTE-NEWS. 2001. A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. *Oecologia* **126**: 543–562.

Solomon, S., Rosenlof, K., Portmann, R., Daniel, J., Davis, S., Sanford, T., and Plattner, G.-K. 2010. Contributions of stratospheric water vapor to decadal changes in the rate of global warming. *Science* **327**: 1219-1223.

Tuffen H. 2010. How will melting of ice affect volcanic hazards in the twenty-first century? *Philosophical Transactions of the Royal Society A* **368**: 2535–2558.

Walker, D.A., Jia, G.J., Epstein, H.E., Raynolds, M.K., Chapin III, F.S., Copass, C., Hinzman, L.D., Knudson, J.A., Maier, H.A., Michaelson, G.J., Nelson, F., Ping, C.L., Romanovsky, V.E., and Shiklomanov, N. 2003. Vegetation-soil-thaw-depth relationships along a low-arctic bioclimate gradient, Alaska: synthesis of information from the ATLAS studies. *Permafrost and Periglacial Processes* **14**: 103–123.

Walker, M.D., Wahren, C.H., Hollister, R.D., Henry, G.H.R., Ahlquist, L.E., Alatalo, J.M., Bret-Harte, M.S., Calef, M.P., Callaghan, T.V., Carroll, A.B., Epstein, H.E., Jonsdottir, I.S., Klein, J.A., Magnusson, B., Molaug, U., Oberbauer, S.F., Rewan, S.P., Robinson, C.H., Shaver, G.R., Suding, K.N., Thompson, C.C., Tolvanen, A., Totland, O., Turner, P.L., Tweedie, C.E., Webber, P.J., and Wookey, P.A. 2006. Plant community responses to experimental warming across the tundra biome. *Proceedings of the National Academy of Sciences USA* **103**: 1342–1346.

Yi, S., Woo, M., and Arain, M.A. 2007. Impacts of peat and vegetation on permafrost degradation under climate warming. *Geophysical Research Letters* **34**: 10.1029/2007GL030550.

3

Paleoclimate and Recent Temperatures

Introduction

The Intergovernmental Panel on Climate Change (IPCC) claims average Northern Hemisphere temperatures during the second half of the twentieth century were "likely the highest in at least the past 1,300 years" (IPCC 2007). Later in its report, the IPCC again states "it is likely that the 20th century was the warmest in at least the past 1.3 kyr."

In the 2009 report of the Nongovernmental International Panel on Climate Change (NIPCC), Idso and Singer (2009) contested the IPCC claims by presenting "a thorough examination of temperature records around the world" illustrating the global presence of a significant Medieval Warm Period (MWP) during which temperatures exceeded those of the twentieth century. The book cited hundreds of scientific papers documenting the MWP in Africa, Antarctica, the Arctic, Asia, Europe, North America, and South America. The authors also reported satellite temperature data showing a much more modest warming trend in the last two decades of the twentieth century and a dramatic decline in the warming trend in the first decade of the twenty-first century.

In this chapter, we cover this ground once again, highlighting papers not addressed in the 2009 NIPCC report or published after its preparation. After reviewing new evidence of a global MWP, we present evidence of a "Little Medieval Warm Period" that began sometime in the early 1400s, and then address two issues specific to the global temperature debate.

References

Idso, C.D. and Singer, S.F. 2009. *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by S. Solomon, et al. Cambridge, UK: Cambridge University Press.

3.1. Medieval Warm Period

The Medieval Warm Period (MWP) is the name typically used to describe a period of warmth in Earth's history that occurred approximately 1,000 years ago. The degree of warmth during that time varied from region to region, and hence its consequences were manifested in a variety of ways. The IPCC has downplayed or ignored the MWP because its existence threatens its core hypothesis of CO_2-induced global warming.

If it can be shown that approximately 1,000 years ago, when there was about 28 percent less CO_2 in the atmosphere than there is currently, temperatures throughout much of the world were just as high as (or even higher than) they were over the latter part of the twentieth century (and continuing to the present), then there is nothing unusual, unnatural, or unprecedented about the current level of Earth's warmth. The warming of the late twentieth/early twenty-first century would more logically be viewed as the recurrence of whatever natural cyclical phenomenon created the equal or even greater warmth of the MWP and other warm periods that preceded it.

3.1.1. North America

McGann (2008) analyzed a sediment core retrieved from the western portion of South Bay near San Francisco International Airport (37°37.83'N, 122°21.99'W) for the presence of various foraminifers as well as oxygen and carbon stable isotopes and numerous trace elements found in the tests of *Elphidium excavatum*. She found "the climate of south bay has oscillated numerous times between warm and dry, and cool and wet conditions over the past 3870 years" and "both the Medieval Warm Period and the Little Ice Age are evident." More specifically, she identifies the MWP as occurring from AD 743 to 1343 and the LIA as occurring in two stages: AD 1450 to 1530 and AD 1720 to 1850. In addition, she states the timing of the MWP "correlates well with records obtained for Chesapeake Bay (Cronin et al., 2003), Long Island Sound (Thomas et al., 2001; Varekamp et al., 2002), California's Sierra Nevada (Stine, 1994), coastal northernmost California (Barron et al., 2004), and the San Francisco Bay estuary in north bay at Rush Ranch (Byrne et al., 2001), and south bay at Oyster Point (Ingram et al., 1996)." As for the more recent past, McGann notes "near the top of the core" foraminiferal abundances suggest, "once again, regional warming has taken place." However, that warming does not appear to have returned the region to the level of sustained warmth it enjoyed during the peak warmth of the MWP.

Moving north to Alaska, Clegg et al. (2010) conducted a high-resolution analysis of midge assemblages found in the sediments of Moose Lake (61°22.45'N, 143°35.93'W) in the Wrangell-St. Elias National Park and Preserve in the south-central portion of the state, producing a record of reconstructed mean July temperatures (T_{July}) for the past six thousand years. In examining the latter half of that record, as portrayed in Figure 3.1.1, from 2,500 cal BP to the present, there is a clear multi-centennial oscillation, with its peaks and valleys defining the temporal locations of the Roman Warm Period, the Dark Ages Cold Period, the Medieval Warm Period, the Little Ice Age—during which the coldest temperatures of the entire interglacial or Holocene were reached—and, finally, the start of the Current Warm Period, which is still not expressed to any significant degree compared to the Medieval and Roman Warm Periods.

In discussing their results, the seven scientists write, "comparisons of the T_{July} record from Moose Lake with other Alaskan temperature records suggest that the regional coherency observed in instrumental temperature records (e.g., Wiles et al., 2008; Gedalof and Smith, 2001; Wilson et al., 2007) extends broadly to at least 2000 cal BP," while noting that climatic events such as the LIA and the MWP occurred "largely synchronously" between their T_{July} record from Moose Lake and a $\delta^{18}O$-based temperature record from Farewell Lake on the northwestern foothills of the Alaska Range.

In considering these findings, it is instructive to note that even with the help of the supposedly unprecedented anthropogenic-induced increase in the atmosphere's CO_2 concentration that occurred over the course of the twentieth century, the Current Warm Period has not achieved the warmth of the MWP or RWP, which suggests the climatic impact of the twentieth-century increase in the air's CO_2 content has been negligible. The warming that defined the Earth's recovery from the global chill of the LIA—which should have been helped by the concurrent increase in the air's CO_2 content—appears no different from the non-CO_2-induced warming that brought the planet out of the Dark Ages Cold Period and into the Medieval Warm Period.

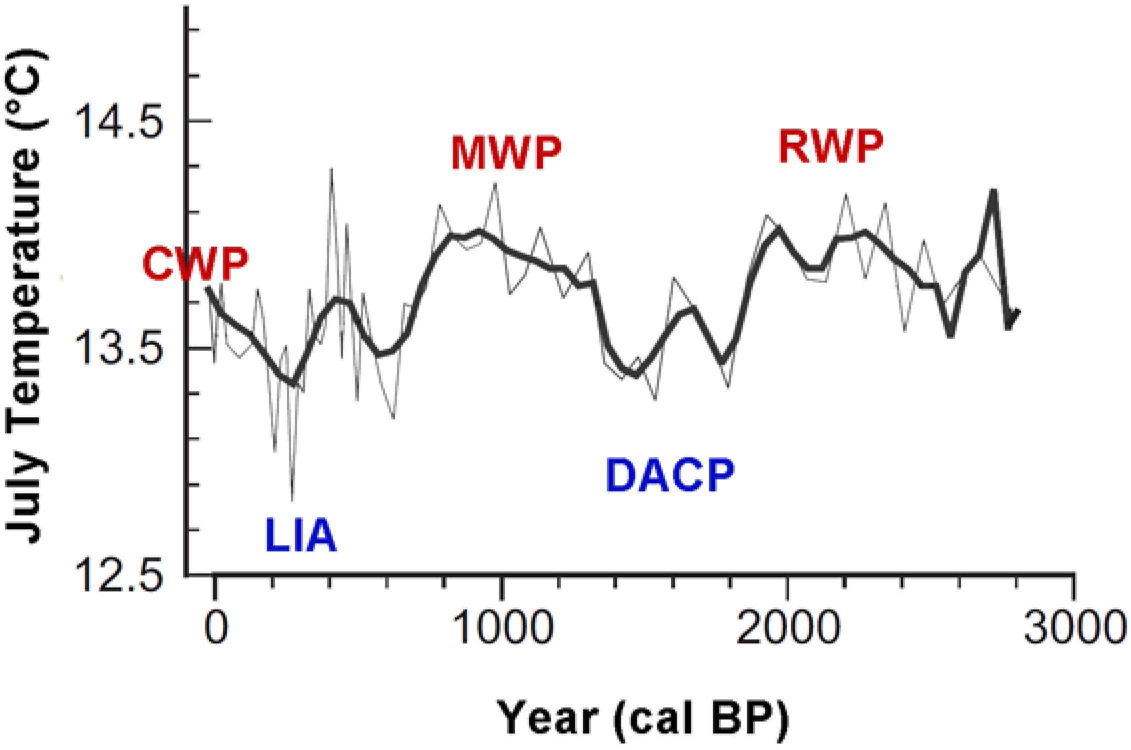


Figure 3.1.1. Mean July near-surface temperature (°C) vs. years before present (cal BP) for south-central Alaska (USA). Adapted from Clegg et al. (2010).

Working nearby in Canada, Edwards et al. (2008) wrote, "Northern Hemisphere climate is believed to have fluctuated from being generally mild on average in the early millennium (the classic Medieval Warm Period) to being cool and variable during the subsequent Little Ice Age, followed by recent warming." To see to what extent western Canada had followed this basic pattern over the past thousand years, they employed a coupled isotope response-surface model "to resolve multi-dimensional patterns of climate variability using carbon- and water-isotope time series developed from tree-ring cellulose," based on "16 subfossil snags and living-tree sequences of *Picea engelmannii* (Engelmann spruce) from upper alpine treeline sites near Athabasca Glacier and subfossil material from the forefield of Robson Glacier plus living and snag material of *Pinus albicaulis* (whitebark pine) adjacent to Bennington Glacier, spanning AD 951–1990."

The results of this climate reconstruction revealed that "high inferred winter temperatures ~AD 1100–1250 stand out in particular, corresponding with the Medieval Climate Anomaly," with the four researchers adding the "climate shifted broadly in western Canada from warm in winter and atmospherically moist during the growth season during medieval times to being cool in winter and atmospherically dry during the growth season in the subsequent Little Ice Age." Nevertheless, they note "independent proxy hydrologic evidence suggests that snowmelt sustained relatively abundant streamflow at this time in rivers draining the eastern Rockies," while during the Medieval Warm Period there was "evidence for reduced discharge in rivers draining the eastern Rockies and extensive hydrological drought in neighboring western USA." Finally, they write, "declining streamflow in rivers draining the eastern Rockies over the past century (Rood et al., 2005) may indicate that conditions are in the process of returning to a similar state," which suggests the Current Warm Period has not yet achieved the more extreme climatic status of the Medieval Warm Period.

Edwards et al.'s results thus delineate the classic cycling of climate that brought the Earth the Medieval Warm Period and subsequent Little Ice Age as well as the twentieth-century transition to the Current Warm

Period, all independent of the air's CO_2 content. Edwards et al.'s data clearly indicate that both the minimum temperature of winter and the yearly average of the winter minimum and summer maximum temperature were greater during the Medieval Warm Period than they were during the late twentieth century, between which times the air's CO_2 concentration rose by approximately 100 ppm and still could not force a temperature increase equal to that of a thousand years ago.

Whitlock et al. (2008) analyzed "geochemical, stable-isotope, pollen, charcoal, and diatom records" further south in North America, from high-resolution cores obtained from Crevice Lake (45.000°N, 110.578°W), with the goal of reconstructing "the ecohydrologic, vegetation, and fire history of the watershed for the last 2650 years to better understand past climate variations at the forest-steppe transition" in "the canyon of the Yellowstone River in northern Yellowstone National Park [YNP]." Their results indicated the Crevice Lake region experienced "a warm interval with dry winters between AD 600 and 850, followed by less dry but still warm conditions between AD 850 and 1100." In addition, they write, "other studies in YNP indicate that trees grew above present-day treeline and fires were more frequent in the Lamar and Soda Butte drainages between AD 750 and 1150," citing Meyer et al. (1995).

As for the modern period, the seven researchers say their data indicate "the last 150 years of environmental history since the formation of YNP have not been anomalous within the range of variability of the last 2650 years, and many of the proxy indicators suggest that 19th and twentieth century variability at Crevice Lake was moderate compared with earlier extremes." In fact, they note that with the possible exception of the charcoal record, "all of the data show greater variability in the range of ecosystem conditions prior to the establishment of the YNP in 1872."

In another study, based on isotopic soil carbon measurements made on 24 modern soils and 30 buried soils scattered between latitudes 48 and 32°N and longitudes 106 and 98°W, Nordt et al. (2008) developed a time series of C_4 vs. C_3 plant dynamics for the past 12,000 years in the mixed and shortgrass prairie of the U.S. Great Plains. They did this because, as they describe it, the percent of soil carbon derived from C_4 plants corresponds strongly with summer temperatures as reflected in the soil carbon pool, citing the work of Nordt et al. (2007) and von Fischer et al. (2008). As a result, they were able to devise a history of the relative warmth of the climate of the region over this protracted period. This history suggested the region of study was slightly warmer during parts of both the Medieval and Roman Warm Periods than it has yet been in modern times, and that it was significantly warmer during a sizeable portion the mid-Holocene Thermal Maximum or Climatic Optimum, as it is sometimes called.

Other studies have documented a Medieval Warm Period in Greenland. Norgaard-Pedersen and Mikkelsen (2009), for example, measured and analyzed several properties of a sediment core retrieved from the deepest basin of Narsaq Sound (60°56.200'N, 46°09.300'W) in southern Greenland from which they were able to infer various "glacio-marine environmental and climatic changes" that had occurred over the prior 8,000 years. Their results revealed the existence of two periods (2.3–1.5 ka and 1.2–0.8 ka) that "appear to coincide roughly with the 'Medieval Warm Period' and 'Roman Warm Period'" and they identified the colder period that followed the Medieval Warm Period as the Little Ice Age and the colder period that preceded it as the Dark Ages Cold Period.

Citing the works of Dahl-Jensen et al. (1998), Andresen et al. (2004), Jensen et al. (2004), and Lassen et al. (2004), the two Danish scientists said "the cold and warm periods identified in [those researchers' studies] appear to be more or less synchronous to the inferred cold and warm periods observed in the Narsaq Sound record," providing even more evidence for the reality of the naturally occurring phenomenon that governs this millennial-scale oscillation of climate that has been identified throughout the world.

A little closer to the present, Vinther et al. (2010) introduced the report of their study by writing, "during the past 10 years studies of seasonal ice core $\delta^{18}O$ records from the Greenland ice sheet have indicated, that in order to gain a firm understanding of the relationships between Greenland $\delta^{18}O$ and climatic conditions in the North Atlantic region, it is important to have not only annually resolved, but seasonally resolved ice core $\delta^{18}O$ data." Therefore, working with 20 ice core records from 14 different sites, all of which stretched at least 200 years back in time, as well as near-surface air temperature data from 13 locations along the southern and western coasts of Greenland that covered approximately the same time interval (1784–2005), plus a similar temperature dataset from northwest Iceland (said by them to be employed "in order to have some data indicative of climate east of the Greenland ice sheet"), Vinther et al. proceeded to demonstrate that winter δ^{18}O was "the best proxy for Greenland temperatures."

Based on that determination, plus three longer ice core δ^{18}O records (DYE-3, Crete, and GRIP), the seven scientists developed a temperature history extending more than 1,400 years back in time. From that history they determined "temperatures during the warmest intervals of the Medieval Warm Period," which they defined as occurring "some 900 to 1300 years ago, "were as warm as or slightly warmer than present day Greenland temperatures."

Last, Kobashi et al. (2010) write, "in Greenland, oxygen isotopes of ice (Stuiver et al., 1995) have been extensively used as a temperature proxy, but the data are noisy and do not clearly show multi-centennial trends for the last 1,000 years, in contrast to borehole temperature records that show a clear 'Little Ice Age' and 'Medieval Warm Period' (Dahl-Jensen et al., 1998)." However, they note nitrogen (N) and argon (Ar) isotopic ratios—^{15}N/^{14}N and ^{40}Ar/^{36}Ar, respectively—can be used to construct a temperature record that "is not seasonally biased, and does not require any calibration to instrumental records, and resolves decadal to centennial temperature fluctuations." Kobashi et al. further describe the development of such an approach, after which they use it to construct a history of the past thousand years of central Greenland surface air temperature, based on values of isotopic ratios of nitrogen and argon previously derived by Kobashi et al. (2008) from air bubbles trapped in the GISP2 ice core that had been extracted from central Greenland (72°36'N, 38°30'W).

Figure 3.1.2 depicts the researchers' reconstruction of central Greenland's surface temperature history. As best as can be determined from this representation, the peak temperature of the latter part of the Medieval Warm Period—which actually began some time before the start of their record, as demonstrated by the work of Dansgaard et al. (1975), Jennings and Weiner (1996), Johnsen et al. (2001), and Vinther et al. (2010)—was about 0.33°C greater than the peak temperature of the Current Warm Period and about 1.67°C greater than the temperature of the last decades of the twentieth century. In addition, it is worth noting that between

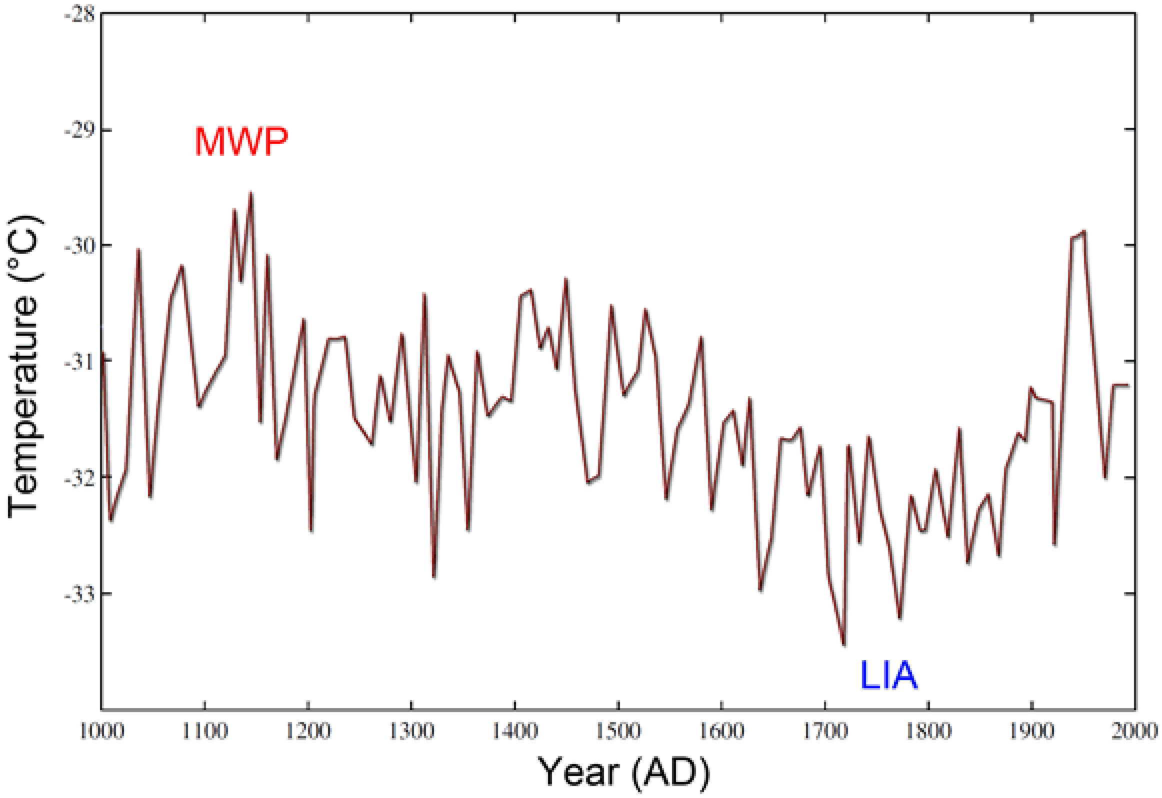


Figure 3.1.2. Central Greenland surface temperature reconstruction for the last millennium. Adapted from Kobashi et al. (2010).

about 1400 and 1460 there was also a period of notable warmth in Kobashi et al.'s temperature reconstruction, which aligns well with the Little Medieval Warm Period, the peak temperature of which was about 0.9°C greater than the temperature of the last decades of the twentieth century and the first decade of the twenty-first century.

These findings, in the words of Kobashi et al., "show clear evidence of the Medieval Warm Period and Little Ice Age in agreement with documentary evidence," and those data clearly show that the Medieval Warm Period in North America was at times considerably warmer than the Current Warm Period has been to date, and that even the Little Medieval Warm Period was considerably warmer than the last decades of the twentieth century and first decade of the twenty-first century.

References

Andresen, C.S., Bjorck, S., Bennike, O., and Bond, G. 2004. Holocene climate changes in southern Greenland: evidence from lake sediments. *Journal of Quaternary Science* **19**: 783–793.

Barron, J.A., Heusser, L.E., and Alexander, C. 2004. High resolution climate of the past 3,500 years of coastal northernmost California. In *Proceedings of the Twentieth Annual Pacific Climate Workshop*, edited by S.W. Starratt and N.L. Blumquist, 13–22. U.S. Geological Survey.

Byrne, R., Ingram, B.L., Starratt, S., Malamud-Roam, F., Collins, J.N., and Conrad, M.E. 2001. Carbon-isotope, diatom, and pollen evidence for late Holocene salinity change in a brackish marsh in the San Francisco estuary. *Quaternary Research* **55**: 66–76.

Clegg, B.F., Clarke, G.H., Chipman, M.L., Chou, M., Walker, I.R., Tinner, W., and Hu, F.S. 2010. Six millennia of summer temperature variation based on midge analysis of lake sediments from Alaska. *Quaternary Science Reviews* **29**: 3308–3316.

Cronin, T.M., Dwyer, G.S., Kamiya, T., Schwede, S., and Willard, D.A. 2003. Medieval Warm Period, Little Ice Age and 20th century temperature variability from Chesapeake Bay. *Global and Planetary Change* **36**: 17–29.

Dahl-Jensen, D., Mosegaard, K, Gundestrup, N., Clew, G.D., Johnsen, S.J., Hansen, A.W., and Balling, N. 1998. Past temperatures directly from the Greenland ice sheet. *Science* **282**: 268–271.

Dansgaard, W., Johnsen, S.J., Reech, N., Gundestrup, N., Clausen, H.B., and Hammer, C.U. 1975. Climatic changes, Norsemen and modern man. *Nature* **255**: 24–28.

Edwards, T.W.D., Birks, S.J., Luckman, B.H., and MacDonald, G.M. 2008. Climatic and hydrologic variability during the past millennium in the eastern Rocky Mountains and northern Great Plains of western Canada. *Quaternary Research* **70**: 188–197.

Gedalof, Z. and Smith, D.J. 2001. Interdecadal climate variability and regime scale shifts in Pacific North America. *Geophysical Research Letters* **28**: 1515–1518.

Ingram, B.L., Ingle, J.C., and Conrad, M.E. 1996. Stable isotope record of late Holocene salinity and river discharge in San Francisco Bay, California. *Earth and Planetary Science Letters* **141**: 237–247.

Jennings, A.E. and Weiner, N.J. 1996. Environmental change in eastern Greenland during the last 1300 years: evidence from foraminifera and lithofacies in Nansen Fjord, 68°N. *The Holocene* **6**: 179–191.

Jensen, K.G., Kuijpers, A., Koc, N., and Heinemeier, J. 2004. Diatom evidence of hydrographic changes and ice conditions in Igaliku Fjord, South Greenland, during the past 1500 years. *The Holocene* **14**: 152–164.

Johnsen, S.J., Dahl-Jensen, D., Gundestrup, N., Steffensen, J.P., Clausen, H.B., Miller, H., Masson-Delmotte, V., Sveinbjörnsdottir, A.E., and White, J. 2001. Oxygen isotope and palaeotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland and NorthGRIP. *Journal of Quaternary Science* **16**: 299–307.

Kobashi, T., Severinghaus, J.P., Barnola, J.-M., Kawamura, K., Carter, T., and Nakaegawa, T. 2010. Persistent multi-decadal Greenland temperature fluctuation through the last millennium. *Climatic Change* **100**: 733–756.

Kobashi, T., Severinghaus, J.P., and Kawamura, K. 2008. Argon and nitrogen isotopes of trapped air in the GISP2 ice core during the Holocene epoch (0–11,600 B.P.): methodology and implications for gas loss processes. *Geochimica et Cosmochimica Acta* **72**: 4675–4686.

Lassen, S.J., Kuijpers, A., Kunzendorf, H., Hoffmann-Wieck, G., Mikkelsen, N., and Konradi, P. 2004. Late Holocene Atlantic bottom water variability in Igaliku Fjord, South Greenland, reconstructed from foraminifera faunas. *The Holocene* **14**: 165–171.

McGann, M. 2008. High-resolution foraminiferal, isotopic, and trace element records from Holocene estuarine deposits of San Francisco Bay, California. *Journal of Coastal Research* **24**: 1092–1109.

Meyer, G.A., Wells, S.G., and Jull, A.J.T. 1995. Fire and alluvial chronology in Yellowstone National Park: climatic and intrinsic controls on Holocene geomorphic processes. *Geological Society of America Bulletin* **107**: 1211–1230.

Nordt, L., von Fischer, J., and Tieszen, L. 2007. Late Quaternary temperature record from buried soils of the North American Great Plains. *Geology* **35**: 159–162.

Nordt, L., von Fischer, J., Tieszen, L., and Tubbs, J. 2008. Coherent changes in relative C_4 plant productivity and climate during the late Quaternary in the North American Great Plains. *Quaternary Science Reviews* **27**: 1600–1611.

Norgaard-Pedersen, N. and Mikkelsen, N. 2009. 8000 year marine record of climate variability and fjord dynamics from Southern Greenland. *Marine Geology* **264**: 177–189.

Rood, S.B., Samuelson, G.M., Weber, J.K., and Wyrot, K.A. 2005. Twentieth-century decline in streamflows from the hydrographic apex of North America. *Journal of Hydrology* **306**: 215–233.

Stine, S. 1994. Extreme and persistent drought in California and Patagonia during Medieval time. *Nature* **369**: 546–548.

Stuiver, M., Grootes, P.M., and Brazunias, T.F. 1995. The GISP2 $\delta^{18}O$ climate record of the past 16,500 years and the role of the sun, ocean, and volcanoes. *Quaternary Research* **44**: 341–354.

Thomas, E., Shackeroff, J., Varekamp, J.C., Buchholtz Ten Brink, M.R., and Mecray, E.L. 2001. Foraminiferal records of environmental change in Long Island Sound. *Geological Society of America, Abstracts with Program* **33**(1), A–83.

Varekamp, J.C., Thomas, E., Lugolobi, F., and Buchholtz Ten Brink, M.R. 2002. The paleo-environmental history of Long Island Sound as traced by organic carbon, biogenic silica and stable isotope/trace element studies in sediment cores. *Proceedings of the 6th Biennial Long Island Sound Research Conference*. Groton, CT.

Vinther, B.M., Jones, P.D., Briffa, K.R., Clausen, H.B., Andersen, K.K., Dahl-Jensen, D., and Johnsen, S.J. 2010. Climatic signals in multiple highly resolved stable isotope records from Greenland. *Quaternary Science Reviews* **29**: 522–538.

von Fischer, J.C., Tieszen, L.L., and Schimel, D.S. 2008. Climate controls on C_3 vs. C_4 productivity in North American grasslands from carbon isotope composition of soil organic matter. *Global Change Biology* **14**: 1–15.

Whitlock, C., Dean, W., Rosenbaum, J., Stevens, L., Fritz, S., Bracht, B., and Power, M. 2008. A 2650-year-long record of environmental change from northern Yellowstone National Park based on a comparison of multiple proxy data. *Quaternary International* **188**: 126–138.

Wiles, G.C., Barclay, D.J., Calkin, P.E., and Lowell, T.V. 2008. Century to millennial-scale temperature variations for the last two thousand years inferred from glacial geologic records of southern Alaska. *Global and Planetary Change* **60**: 115–125.

Wilson, R., Wiles, G., D'Arrigo, R., and Zweck, C. 2007. Cycles and shifts: 1300 years of multi-decadal temperature variability in the Gulf of Alaska. *Climate Dynamics* **28**: 425–440.

3.1.2. Europe

We begin our examination of Europe with the study of Axford et al. (2009), who note "the idea of a widespread and spatially coherent 'Medieval Warm Period' (MWP) has come under scrutiny in recent years," while "it remains a viable hypothesis that a period of relative warmth in northwestern Europe and the northern North Atlantic region helped facilitate Norse expansion across the North Atlantic from the ninth to thirteenth centuries, including settlement of Iceland and Greenland" and "subsequent cooling contributed to the demise of the Norse settlements on Greenland." To further explore the subject, they developed a regional climatic record from a sediment core retrieved from Lake Stora Vioarvatn in northeast Iceland (66°14.232'N, 15°50.083'W) in the summer of 2005, based on chironomid assemblage data—which were well correlated with nearby measured temperatures over the 170-year instrumental record—and total organic carbon, nitrogen, and biogenic silica content. This work revealed the occurrence of "warm temperatures in the tenth and eleventh centuries, with one data point suggesting temperatures slightly warmer than present." They also discovered "temperatures were higher overall and more consistently high through much of the first millennium AD."

In discussing their findings, the Icelandic, U.K., and U.S. scientists state, "the historical perception of a significant medieval climate anomaly in Iceland may be primarily a reflection of the human perspective," in that "Iceland was settled ca. AD 870, during a period of relative warmth that was followed by many centuries of progressively colder and less hospitable climate," that "had the Norse settled Iceland 1000 years earlier, the MWP might be viewed only as a brief period of climatic amelioration, a respite from a shift to colder temperatures that began in the eighth century," near the end of several centuries of even greater warmth. In any event, and viewed from either perspective, it is clear there is nothing unusual or unnatural about the region's present-day temperatures, which the researchers say "do not show much recent warming."

In another significant study, Bonnet et al. (2010) developed a high-resolution record of ocean and climate variations during the late Holocene in the Fram Strait (the major gateway between the Arctic and North Atlantic Oceans, located north of the Greenland Sea)—based on detailed analyses of a sediment core recovered from a location (78°54.931'N, 6°46.005'E) on the slope of the western continental margin of Svalbard—that permitted the reconstruction of sea surface temperature (SST) conditions in both summer and winter. These histories were nearly identical and showed oscillations between -1°C and 5.5°C in winter and between 2.4°C and 10.0°C in summer; their graphical results indicate that between 2,500 and 250 years before present (BP), the mean SSTs of summers were warmer than those of the present about 80 percent of the time, while the mean SSTs of winters exceeded those of current winters approximately 75 percent of the time, with the long-term (2,250-year) means of both seasonal periods averaging about 2°C more than current means. The highest temperatures, however, were recorded during a warm interval that persisted from about AD 500 to 720, during the very earliest stages of the Medieval Warm Period, when the peak summer and winter temperatures of the MWP both exceeded the peak summer and winter temperatures of the first several years of the twenty-first century by about 3°C.

Moving to Finland, Haltia-Hovi et al. (2010) constructed detailed chronological histories of several magnetic properties of two sediment cores taken from Finland's Lake Lehmilampi (63°37'N, 29°06'E), as well as a history of their total organic carbon content. Based on their analyses, they discovered a "conspicuous occurrence of fine magnetic particles and high organic concentration" evident around 4,700–4,300 Cal. yrs BP. This time interval, in their words, "is broadly coincident with glacier contraction and treelines higher than present in the Scandinavian mountains according to Denton and Karlen (1973) and Karlen and Kuylenstierna (1996)." They report from that time on toward the present, there was a "decreasing trend of magnetic concentration, except for the slight localized enhancement in the upper part of the sediment column at ~1,100–900 Cal. yrs BP," where the year zero BP = AD 1950.

Changes of these types in prior studies have been attributed to magnetotactic bacteria (e.g. *Magnetospirillum* spp.), which Haltia-Hovi et al. describe as "aquatic organisms that produce internal, small magnetite or greigite grains" used "to navigate along the geomagnetic field lines in search of micro or anaerobic conditions in the lake bottom," as described by Blakemore (1982) and Bazylinski and Williams (2007). They further state the studies of Snowball (1994), Kim et al. (2005), and Paasche et al. (2004) "showed magnetic concentration enhancement, pointing to greater metabolic activity of these aquatic organisms in the presence of abundant organic matter." This is also what Haltia-Hovi et al. found in their study; they report the "concentration of organic matter in the sediment is highest, together with fine magnetic grain sizes, in the time period 1,100–900 Cal. years BP." This time interval, they say, "is associated with warmer temperatures during the Medieval Climate Anomaly according to the varve parameters of Lake Lehmilampi," citing the precise core-dating by varve-counting work of Haltia-Hovi et al. (2007). Taken together, these observations strongly suggest the peak warmth of the Medieval Warm Period (about AD 850–1050) was very likely somewhat greater than that of the Current Warm Period.

In another study, Larocque-Tobler et al. (2010) write that to better describe the amplitude of temperature change during the past millennium, "new records to increase the geographic coverage of paleoclimatic information are needed" and "only by obtaining numerous high-resolution temperature records will it be possible to determine if the 20th century climate change exceeded the natural pre-industrial variability of European climate." To help achieve this important goal, they proceeded to obtain another such temperature record based on an analysis of fossil chironomids (non-biting midges) identified and quantified in four sediment cores extracted from the bed of Lake Silvaplana (46°26'56"N, 9°47'33"E) in the Upper Engadine (a high-elevation valley in the eastern Swiss Alps). This analysis produced a detailed history of that region's mean July air temperature over the last millennium.

The results of this effort indicate, as the five researchers describe it, "at the beginning of the record, corresponding to the last part of the 'Medieval Climate Anomaly' (here the period between *ca.* AD 1032 and 1262), the chironomid-inferred mean July air temperatures were 1°C warmer than the climate reference period (1961–1990)," which would also make them warmer than most subsequent temperatures. And in looking at their graphs of 20- and 50-year running means, it can be seen that the peak warmth of the Medieval Warm Period exceeded that of the Current Warm Period by approximately 0.5°C in the case of 20-year averages and 1.2°C in the case of 50-year averages. Consequently, Larocque-Tobler et al. conclude, "there is no evidence that mean-July air temperature exceeded the natural variability recorded during the Medieval Climate Anomaly in the 20th century at Lake Silvaplana." They note similar results "were also obtained in northern Sweden (Grudd, 2008), in Western Europe (Guiot et al., 2005), in a composite of Northern Hemisphere tree-ring reconstructions (Esper et al., 2002) and a composite of tree rings and other archives (Moberg et al., 2005)."

A few years earlier in Italy, Frisia et al. (2005) developed a 17,000-year record of speleothem calcite $\delta^{18}O_C$ data they obtained from a cave stalagmite located at the southeast margin of the European Alps (45°37'05" N, 13°53'10" E), which they calibrated against "a reconstruction of temperature anomalies in the Alps" developed by Luterbacher et al. (2004) for the last quarter of the past millennium. This work revealed—among several other things (due to the great length of time involved)—the occurrence of the Roman Warm Period and a Medieval Warm Period that was broken into two parts by an intervening central cold period. The five researchers say both portions of the Medieval Warm Period were "characterized by temperatures that were similar to the present."

Also working in Italy, Giraudi (2009) examined "long-term relations among glacial activity, periglacial activity, soil development in northwestern Italy's alpine River Orco headwaters, and downvalley floods on the River Po," based on "studies carried out by means of geological and geomorphologic surveys on the glacial and periglacial features," including a sampling of soils involved in periglacial processes that "provided a basis for development of a chronological framework of late Holocene environmental change" and an analysis of "a stratigraphic sequence exposed in a peat bog along the Rio del Nel" about 1 km from the front edge of the Eastern Nel Glacier. Among several interesting findings, these undertakings allowed Giraudi to determine that between about 200 BC and AD 100—i.e., during the Roman Warm Period—"soils developed in areas at present devoid of vegetation and with permafrost," indicative of the likelihood that temperatures at that time "probably reached higher values than those of the present." He also concluded "analogous conditions likely occurred during the period of 11th–12th centuries AD, when a soil developed on a slope presently characterized by periglacial debris," while noting "in the 11th–12th centuries AD, frost weathering processes were not active and, due to the higher temperatures than at present or the longer duration of a period with high temperatures, vegetation succeeded in colonizing the slope."

These several studies from Europe provide evidence for the millennial-scale oscillation of climate that has operated throughout glacial and interglacial periods alike, producing century-scale periods when temperatures were as warm as they are at present, or even warmer, even though the air's CO_2 content was much lower at those earlier times than it is today.

References

Axford, Y., Geirsdottir, A., Miller, G.H., and Langdon, P.G. 2009. Climate of the Little Ice Age and the past 2000 years in northeast Iceland inferred from chironomids and other lake sediment proxies. *Journal of Paleolimnology* **41**: 7–24.

Bazylinski, D.A. and Williams, T.J. 2007. Ecophysiology of magnetotactic bacteria. In *Magnetoreception and Magnetosomes in Bacteria*, edited by D. Schuler, 37–75. Berling, Germany: Springer.

Blakemore, R.P. 1982. Magnetotactic bacteria. *Annual Review of Microbiology* **36**: 217–238.

Bonnet, S., de Vernal, A., Hillaire-Marcel, C., Radi, T., and Husum, K. 2010. Variability of sea-surface temperature and sea-ice cover in the Fram Strait over the last two millennia. *Marine Micropaleontology* **74**: 59–74.

Denton, G.H. and Karlen, W. 1973. Holocene climatic variations—their pattern and possible cause. *Quaternary Research* **3**: 155–205.

Esper, J., Cook, E.R., and Schweingruber, F.H. 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* **295**: 2250–2253.

Frisia, S., Borsato, A., Spotl, C., Villa, I.M., and Cucchi, F. 2005. Climate variability in the SE Alps of Italy over the past 17,000 years reconstructed from a stalagmite record. *Boreas* **34**: 445–455.

Giraudi, C. 2009. Late Holocene glacial and periglacial evolution in the upper Orco Valley, northwestern Italian Alps. *Quaternary Research* **71**: 1–8.

Grudd, H. 2008. Tornetrask tree-ring width and density AD 500-2004: a test of climatic sensitivity and a new 1500-year reconstruction of north Fennoscandian summers. *Climate Dynamics* **31**: 843–857.

Guiot, J., Nicault, A., Rathgeber, C., Edouard, J.L., Guibal, F., Pichard, G., and Till, C. 2005. Last-Millennium summer-temperature variations in Western Europe based on proxy data. *The Holocene* **15**: 489–500.

Haltia-Hovi, E., Nowaczyk, N., Saarinen, T., and Plessen, B. 2010. Magnetic properties and environmental changes recorded in Lake Lehmilampi (Finland) during the Holocene. *Journal of Paleolimnology* **43**: 1–13.

Haltia-Hovi, E., Saarinen, T., and Kukkonen, M. 2007. A 2000-year record of solar forcing on varved lake sediment in eastern Finland. *Quaternary Science Reviews* **26**: 678–689.

Karlen, W. and Kuylenstierna, J. 1996. On solar forcing of Holocene climate: evidence from Scandinavia. *The Holocene* **6**: 359–365.

Kim, B., Kodama, K., and Moeller, R. 2005. Bacterial magnetite produced in water column dominates lake sediment mineral magnetism: Lake Ely, USA. *Geophysical Journal International* **163**: 26–37.

Larocque-Tobler, I., Grosjean, M., Heiri, O., Trachsel, M., and Kamenik, C. 2010. Thousand years of climate change reconstructed from chironomid subfossils preserved in varved lake Silvaplana, Engadine, Switzerland. *Quaternary Science Reviews* **29**: 1940–1949.

Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M., and Wanner, H. 2004. European seasonal and annual temperature variability, trends, and extremes since 1500. *Science* **303**: 1499–1503.

Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., and Karlen, W. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* **433**: 613–617.

Paasche, O., Lovlie, R., Dahl, S.O., Bakke, J., and Nesje, E. 2004. Bacterial magnetite in lake sediments: late glacial to Holocene climate and sedimentary changes in northern Norway. *Earth and Planetary Science Letters* **223**: 319–333.

Snowball, I. 1994. Bacterial magnetite and the magnetic properties of sediments in a Swedish lake. *Earth and Planetary Science Letters* **126**: 129–142.

3.1.3. Asia

Arid Central Asia (ACA, an inland zone in central Asia from the Caspian Sea in the west to the southern Mongolian Plateau in the east), according to Chen et al. (2010), is "a unique dry-land area whose atmospheric circulation is dominated today by the westerlies" and is "one of the specific regions that are likely to be strongly impacted by global warming," which could greatly impact its hydrologic future. In an attempt to understand such potential impacts, Chen et al. evaluated the "spatial and temporal patterns of effective moisture variations," using 17 different proxy records in the ACA and synthesizing a decadal-resolution moisture curve for this region over the past millennium, employing five of the 17 records based on their having "reliable chronologies and robust proxies."

The nine researchers report that the effective moisture (precipitation) in the ACA has a generally inverse relationship with the temperature of the Northern Hemisphere, as portrayed by Moberg et al. (2005); China, as portrayed by Yang et al. (2002); and Central Asia, as portrayed by Esper et al. (2007). That is to say, as they describe it, the "wet (dry) climate in the ACA correlates with low (high) temperature." Stating it in yet another way, they indicate the ACA "has been characterized by a relatively dry Medieval Warm Period (MWP; the period from ~1000 to 1350 AD), a wet little Ice Age (LIA; from ~1500–1850 AD)," and "a return to arid conditions after 1850 AD," which has been slightly muted—but only "in some records"—over the past 20 years by an increase in humidity.

Given such findings, Chen et al. propose that "the humid LIA in the ACA, possibly extending to the Mediterranean Sea and Western Europe, may have resulted from increased precipitation due to more frequent mid-latitude cyclone activities as a result of the strengthening and equator-ward shift of the westerly jet stream ... coupled with a decrease in evapotranspiration caused by the cooling at that time," a cooling brought about by the gradual demise of the Medieval Warm Period. This in turn speaks volumes about the great significance of that centuries-long period of much-lower-than-present atmospheric CO_2 concentration but of equivalent or even greater warmth than that of the Current Warm Period. This ultimately suggests the twentieth-century increase in the air's CO_2 content may have had little, or maybe even nothing, to do with twentieth-century global warming.

Also exploring the Medieval Warm Period in China, Hong et al. (2009) indicate that "because it is a distinct warm period nearest to the modern warming period and happened before the Industrial Revolution, it naturally becomes a [source of] comparison with modern warming." And in this regard, they add, "a universal concern in academic circles is whether it also existed outside the European region and whether it is a common phenomenon." In a study designed to broach both questions, they extracted cores of peat from a location close to Hani Village, Liuhe County, Jilin Province, China (42°13'N, 126°31'E) and used those cores to develop, as they describe it, "a peat cellulose $\delta^{18}O$ temperature proxy record proximately existing for 14,000 years."

Their efforts revealed, first, that the MWP had indeed held sway on the Chinese mainland over the period AD 700–1400, peaking at about AD 900. And the eight researchers report that phenological data from east China (Ge et al., 2006) and tree-ring records from west China (Yang et al., 2000) also indicate "the temperature on the Chinese mainland was distinctly warmer during the MWP." In fact, they say MWP temperatures were as much as "0.9–1.0°C higher than modern temperatures (Zhang, 1994)."

With respect to the entire 14,000-year period, Hong et al. write, "sudden cooling events, such as the Older Dryas, Inter-Allerod, Younger Dryas, and nine ice-rafted debris events of the North Atlantic"—which are described by Stuiver et al. (1995) and Bond et al. (1997, 2001)—"are almost entirely reiterated in the temperature signals of Hani peat cellulose $\delta^{18}O$." They state, "these cooling events show that the repeatedly occurring temperature cooling pattern not only appeared in the North Atlantic Region in the high latitudes, but also in the Northwest Pacific Region in the middle latitudes," indicating the recurring cooling and warming pattern did indeed occur "outside the European region" and that this climatic oscillation was "a common phenomenon."

Several years earlier, Hong et al. (2000) had used a 6,000-year peat cellulose $\delta^{18}O$ record derived from nearby Jinchuan Town, Huinan County, Jilin Province, China (42°20'N, 126°22'E) to identify $\delta^{18}O$ periodicities of 86, 93, 101, 110, 127, 132, 140, 155, 207, 245, 311, 590, 820 and 1,046 years, which they described as being "similar to those detected in solar excursions," and which they considered to be "further evidence for a close relationship between solar activity and climate variations on timescales of decades to centuries." These findings were highly praised by Fairbridge (2001), who noted "almost identical equivalents are seen in solar emission periodicities and their harmonics, e.g., 86.884 years = 40 x 2.172 year Quasi Biennial Oscillation (QBO) as well as in the lunar tidal/apsides beat frequency (17.3769 years) which also matches closely with most of the longer spectral peaks, e.g., 140 (139) years, 207 (208.5), 311 (312.8), 590 (590.8) and 1046 (1042.6) years." And for these spectacular spectral findings, Fairbridge wrote, "Hong et al. deserve the appreciation of the entire Holocene community."

In another significant study, Liu et al. (2005) compared Ge et al.'s (2003) reconstructed winter half-year temperature anomalies in the central region of eastern China (25–40°N, east of 105°E) for the last 1,000 years with simulated anomalies of the same parameter, which they obtained from the ECHO-G global atmosphere-ocean coupled climate model that was driven by time-varying external forcings, including solar radiation, volcanic eruptions, and greenhouse gas concentrations (CO_2 and CH_4) for the same time period. And in conducting their analysis, they report, "the Medieval Warm Period (MWP) during 1000–1300 A.D., the Little Ice Age (LIA) during 1300–1850 A.D. and the modern warming period after 1900 A.D. are all recognizable from both the simulated and reconstructed temperatures." In addition, they indicate the anomalies associated with the LIA and the modern warming simulated by the model are "in good consistency" with their reconstructed counterparts. However, they note that "in the earlier MWP, significant discrepancies exist between the simulation and the reconstruction." More specifically, they say, "the simulated temperature anomaly in the 20th century is higher than that of the Medieval Warm Period, while the reconstructed temperature in the 20th century is lower."

The seven scientists say the two different results "provide two different interpretations regarding the amplitude of recent global warming," noting "one states that the 20th century warming has exceeded the normal range of the climate change, and it will result in catastrophic impact on human beings if warming continues," whereas the other suggests "the current climate change has not yet exceeded the range of natural climate change in the past millennium." As the real-world evidence for a warmer-than-present Medieval Warm Period continues to accumulate, it is becoming increasingly difficult to support the claim that current temperatures are unnaturally high due to rising anthropogenic CO_2 emissions.

In one final study of China, Ge et al. (2010) developed three regional composite temperature reconstructions that extended back in time a full two millennia (Northeast, Tibet, Central East), one that extended back approximately 950 years (Northwest), and one that went back about 550 years (Southeast). With respect to the three reconstructions that extended through the Medieval Warm Period and the one that extended into but not through it, the six scientists report: (1) in the Northeast there was a warm period "between approximately 1100 and 1200 that exceeded the warm level of the last decades of the 20th century"; (2) in Tibet there was a "warming period of twenty decadal time steps between the 600s and 800s" that was "comparable to the late 20th century"; (3) in the Central East there were two warm peaks (1080s–1100s and 1230s–1250s) that had "comparable high temperatures to the last decades of the 20th century," although the graph of their data indicates these two periods were in fact warmer than the last decades of the twentieth century; and (4) in the Northwest, "comparable warm conditions in the late 20th century are also found around the decade 1100s." These findings make it clear there is nothing unusual, unnatural, or unprecedented about China's current level of warmth.

From China we proceed to Japan, where Aono and Saito (2010) "investigated documents and diaries from the ninth to the fourteenth centuries to supplement the phenological data series of the flowering of Japanese cherry (*Prunus jamasakura*) in Kyoto to improve and fill gaps in temperature estimates based on previously reported phenological data." They then "reconstructed a nearly continuous series of March mean temperatures based on 224 years of cherry flowering data, including 51 years of previously unused data, to clarify springtime climate changes." In addition, they estimated still other cherry full-flowering dates "from phenological records of other deciduous species, adding further data for six years in the tenth and eleventh centuries by using the flowering phenology of Japanese wisteria (*Wisteria floribunda*)."

Their temperature reconstruction "showed two warm temperature peaks of 7.6°C and 7.1°C, in the middle of the tenth century and at the beginning of the fourteenth century, respectively," and they say "the reconstructed tenth century temperatures [AD 900–1000] are somewhat higher than present temperatures after subtracting urban warming effects." Finally, they note "the general pattern of change in the reconstructed temperature series in this study is similar to results reported by previous studies, suggesting a warm period in Asia corresponding to the Medieval Warm Period in Europe."

In a separate study, Daimaru et al. (2002) wrote, "in snowpatch grasslands, plant distributions follow the contours of the snowmelt gradient around summer snowpatches," producing "similarly steep gradients in plant productivity and topsoil (e.g. Billings and Bliss, 1959; Helm, 1982; Kudo, 1991; Stanton et al., 1994.)" In fact, they note "in the subalpine zone of northeastern Japan, sites where the snow cover disappears after July are usually occupied by 'snowpatch bare grounds' with extremely poor vegetation cover" that is "encircled by snowpatch grassland," citing Yamanaka (1979). As a result, they write, "litter fall and the organic content in topsoil decrease toward the center of a snowpatch because the period for plant growth becomes shorter with delay in the time of snow disappearance," so that in current "snowpatch grasslands, peaty topsoil is restricted to sites where snowmelt comes early." And as a result of this, the unique situation provided by a snowpatch often can provide a good opportunity for paleoclimatic reconstructions based on vertical profiles of soil characteristics at various locations along transects moving outwards from summer snowpatches.

Consequently, working in a snowpatch grassland within a shallow depression of landslide origin on the southeastern slope of Japan's Mt. Zarumori (~39.8°N, 140.8°E), Daimaru et al. dug 27 soil pits at various locations in and around the central location of the snowpatch, carefully examining what they found and determining its age based on ^{14}C dating and tephrochronology. They state, "peaty topsoils were recognized at seven soil pits in the dense grassland, whereas sparse grassland lacked peaty topsoil" and "most of the buried peat layers contained a white pumice layer named 'To-a' that fell in AD 915." This observation, plus their ^{14}C dating, led them to conclude the buried peat layers in the poor vegetation area indicate "warming in the melt season" as well as "a possible weakened winter monsoon in the Medieval Warm Period," which their data suggest prevailed at the site they studied throughout the tenth century, AD 900–1000. They write, "many studies have reported climatic signals that are correlated with the Medieval Warm Period from the 9th to 15th centuries in Japan," suggesting the possibly weakened winter monsoon of AD 900–1000 also may have been a consequence of the warmer temperatures of that period.

In a Japanese study using sediment cores from Lakes Ni-no-Megata (39°57’N, 139°43’E) and San-no-Megata (39°56’N, 139°42’E) located on the Oga Peninsula of northeastern Japan, Yamada et al. (2010) measured several sediment properties, including sulfur content and coarse mineral grains. The former served as a proxy for paleo-Asian summer monsoon activity, and the latter was a proxy for paleo-Asian winter monsoon activity over the last two millennia. Upon examining these data, Yamada et al. found evidence for a cold/dry interval stretching from AD 1 to 750, a warm/humid interval from AD 750 to 1200, and another cold/dry interval from AD 1200 to the present. These intervals could represent, respectively, as they describe them, “the Dark Ages Cold Period (DACP), the Medieval Warm Period (MWP) and the Little Ice Age (LIA).”

In further discussing their findings, the six scientists say they complement those of Kitagawa and Matsumoto (1995), whose study of tree-ring records in southern Japan “suggested the existence of one warm interval at AD 750-1300 and two cold intervals at AD 200-750 and AD 1600-1800,” as well as the findings of Sakaguchi (1983), whose study of the pollen record of peaty sediments in central Japan revealed “an unusual warm interval (AD 700-1300) and a cool interval (ca. AD 250-700).” In addition, they write, the “strong summer monsoon and weak winter monsoon at Lakes Ni-no-Megata and San-no-Megata from AD 750–1200 correlates with the lower δ^{18}O values from Wangxiang Cave (Zhang et al., 2008) and lower values of minerogenic clastic content (Chu et al., 2009).”

References

Aono, Y. and Saito, S. 2010. Clarifying springtime temperature reconstructions of the medieval period by gap-filling the cherry blossom phenological data series at Kyoto, Japan. *International Journal of Biometeorology* **54**: 211–219.

Billings, W.D. and Bliss, L.C. 1959. An alpine snowbank environment and its effects on vegetation, plant development and productivity. *Ecology* **40**: 388–397.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G. 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and Glacial climate. *Science* **278**: 1257–1266.

Chen, F.-H., Chen, J.-H., Holmes, J., Boomer, I., Austin, P., Gates, J.B., Wang, N.-L., Brooks, S.J., and Zhang, J.-W. 2010. Moisture changes over the last millennium in arid central Asia: A review, synthesis and comparison with monsoon region. *Quaternary Science Reviews* **29**: 1055–1068.

Chu, G., Sun, Q., Gu, Z., Rioual, P., Liu, Q., Wang, K., Han, J., and Liu, J. 2009. Dust records from varved lacustrine sediments of two neighboring lakes in northeastern China over the last 1400 years. *Quaternary International* **194**: 108–118.

Daimaru, H., Ohtani, Y., Ikeda, S., Okamoto, T., and Kajimoto, T. 2002. Paleoclimatic implication of buried peat layers in a subalpine snowpatch grassland on Mt. Zarumori, northern Japan. *Catena* **48**: 53–65.

Esper, J., Frank, D.C., Wilson, R.J.S., Buntgen, U., and Treydte, K. 2007. Uniform growth trends among central Asian low- and high-elevation juniper tree sites. *Trees—Structure and Function* **21**: 141–150.

Fairbridge, R.W. 2001. Six millennia in Chinese peats, relating to planetary-solar-luniterrestrial periodicities: a comment on Hong, Jiang, Liu, Zhou, Beer, Li, Leng, Hong and Qin. *The Holocene* **11**: 121–122.

Ge, Q., Zheng, J., Fang, X., Man, Z., Zhang, X., Zhang, P., and Wang, W.-C. 2003. Winter half-year temperature reconstruction for the middle and lower reaches of the Yellow River and Yangtze River, China, during the past 2000 years. *The Holocene* **13**: 933–940.

Ge, Q.S., Zheng, J.-Y., Hao, Z.-X., Shao, X.-M., Wang, W.-C., and Luterbacher, J. 2010. Temperature variation through 2000 years in China: An uncertainty analysis of reconstruction and regional difference. *Geophysical Research Letters* **37**: 10.1029/2009GL041281.

Ge, Q.S., Zheng, J.Y., and Liu, J. 2006. Amplitude and rhythm of winter half-year temperature change in eastern China for the past 2000 years. *Advances in Climate Change Research* **2**: 108–112.

Helm, D. 1982. Multivariate analysis of alpine snow-patch vegetation cover near Milner Pass, Rocky Mountain National Park, Colorado, U.S.A. *Arctic and Alpine Research* **14**: 87–95.

Hong, Y.T., Jiang, H.B., Liu, T.S., Zhou, L.P., Beer, J., Li, H.E., Leng, X.T., Hong, B., and Qin, X.G. 2000. Response of climate to solar forcing recorded in a 6000-year δ^{18}O time-series of Chinese peat cellulose. *The Holocene* **10**: 1–7.

Hong, B., Liu, C.-Q., Lin, Q.-H., Yasuyuki, S., Leng, X.-T., Wang, Y., Zhu, Y.-X., and Hong, Y.-T. 2009.

Temperature evolution from the $\delta^{18}O$ record of Hani peat, Northeast China, in the last 14000 years. *Science in China Series D: Earth Sciences* **52**: 952–964.

Kitagawa, H. and Matsumoto, E. 1995. Climate implications of $\delta^{13}C$ variations in a Japanese cedar (*Cryptomeria japonica*) during the last two millennia. *Geophysical Research Letters* **22**: 2155–2158.

Kudo, G. 1991. Effects of snow-free period on the phenology of alpine plants inhabiting snow patches. *Arctic and Alpine Research* **23**: 436–443.

Liu, J., Storch, H., Chen, X., Zorita, E., Zheng, J., and Wang, S. 2005. Simulated and reconstructed winter temperature in the eastern China during the last millennium. *Chinese Science Bulletin* **50**: 2872–2877.

Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., and Karlen, W. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low and high-resolution proxy data. *Nature* **433**: 613–617.

Sakaguchi, Y. 1983. Warm and cold stages in the past 7600 years in Japan and their global sea level changes and the ancient Japanese history. *Bulletin of Department of Geography, University of Tokyo* **15**: 1–31.

Stanton, M.L., Rejmanek, M., and Galen, C. 1994. Changes in vegetation and soil fertility along a predictable snowmelt gradient in the Mosquito Range, Colorado, U.S.A. *Arctic and Alpine Research* **26**: 364–374.

Stuiver, M., Grootes, P.M., and Braziunas, T.F. 1995. The GISP2 $\delta^{18}O$ climate record of the past 16,500 years and the role of the sun, ocean, and volcanoes. *Quaternary Research* **44**: 341–354.

Yamada, K., Kamite, M., Saito-Kato, M., Okuno, M., Shinozuka, Y., and Yasuda, Y. 2010. Late Holocene monsoonal-climate change inferred from Lakes Ni-no-Megata and San-no-Megata, northeastern Japan. *Quaternary International* **220**: 122–132.

Yamanaka, H. 1979. Nivation hollows on the southeast slope of Mt Onishi, Iide Mountains, northeast Japan. *Annals of the Tohoku Geographical Association* **31**: 36–45.

Yang, B., Braeuning, A., Johnson, K.R., and Shi, Y.F. 2002. General characteristics of temperature variation in China during the last two millennia. *Geophysical Research Letters* **29**: 10.1029/2001gl014485.

Yang, B., Kang, X.C., and Shi, Y.F. 2000. Decadal climatic variations indicated by Dulan tree-ring and comparison with other proxy data in China of the last 2000 years. *Chinese Geographical Science* **10**: 193–201.

Zhang, D.E. 1994. Evidence for the existence of the Medieval Warm Period in China. *Climatic Change* **26**: 293–297.

Zhang, P.Z., Cheng, H., Edwards, R.L., Chen, F.H., Wang, Y.J., Yang, X.L., Liu, J., Tan, M., Wang, X.F., Liu, J.H., An, C.L., Dia, Z.B., Zhou, J., Zhang, D.Z., Jia, J.H., Jin, L.Y., and Johnson, K.R. 2008. A test of climate, sun, and culture relationships from an 1810-year Chinese cave record. *Science* **322**: 940–942.

3.1.4. Africa

Working with the vertical sediment profile of Ocean Drilling Program Hole 658C, which was cored off Cap Blanc, Mauritania (20°45’N, 18°35’W) at a water depth of 2,263 meters, DeMenocal et al. (2000) analyzed samples of two centimeters’ length (equivalent to 50 to 100 years resolution) for various parameters, including planktonic foraminiferal assemblage census counts, from which they calculated warm- and cold-season sea surface temperatures throughout the entire Holocene, based on transfer functions derived from faunal analyses of 191 other Atlantic core tops. This work revealed a series of abrupt millennial-scale cooling events followed by compensatory warming events that “appear to have involved the entire North Atlantic basin (O’Brien et al., 1995; Keigwin, 1996; Bond et al., 1997; Bianchi and McCave, 1999; Bond et al., 1999), recurred with a ~1500 ± 500 year period throughout glacial and interglacial intervals (O’Brien et al., 1995; Bond et al., 1997; Bianchi and McCave, 1999; Bond et al., 1999), were accompanied by terrestrial climate changes (COHMAP Members, 1988; Gasse and Van Campo, 1994), and involved large-scale ocean and atmosphere reorganizations that were completed within decades or centuries (Alley et al., 1993).” The four researchers remark, “these climate perturbations continue to persist during ‘our time’.” With respect to the MWP, they state it was “marginally warmer than present.”

References

Alley, R.B., Meese, D.A., Shuman, C.A., Gow, A.J., Taylor, K.C., Grootes, P.M., White, J.C.W., Ram, M., Waddington, E.D., Mayewski, P.A., and Zielinski, G.A. 1993. Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event. *Nature* **362**: 527–529.

Bianchi, G.G. and McCave, I.N. 1999. Holocene periodicity in North Atlantic climate and deep-ocean flow south of Iceland. *Nature* **397**: 515–517.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G. 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and Glacial climate. *Science* **278**: 1257–1266.

Bond, G., Showers, W., Elliot, M., Evans, M., Lotti, R., Hajdas, I., Bonani, G., and Johnson, S. 1999. The North Atlantic's 1–2 kyr Climate Rhythm: Relation to Heinrich Events, Dansgaard/Oeschger Cycles, and the Little Ice Age. In *Mechanisms of Global Climate Change at Millennial Scales*, edited by P.U. Clark, R.S. Webb, and L.D. Keigwin, 35–58. Washington, DC: American Geophysical Union.

COHMAP Members. 1988. Climatic changes of the last 18,000 years: Observations and model simulations. *Science* **241**: 1043–1052.

DeMenocal, P., Ortiz, J., Guilderson, T., and Sarnthein, M. 2000. Coherent high- and low-latitude climate variability during the Holocene warm period. *Science* **288**: 2198–2202.

Gasse, F. and Van Campo, E. 1994. Abrupt post-glacial climate events in West Asia and North Africa monsoon domains. *Earth and Planetary Science Letters* **126**: 435–456.

Keigwin, L.D. 1996. The Little Ice Age and Medieval Warm Period in the Sargasso Sea. *Science* **274**: 1504–1507.

O'Brien, S.R., Mayewski, P.A., Meeker, L.D., Meese, D.A., Twickler, M.S., and Whitlow, S.E. 1995. Complexity of Holocene climate as reconstructed from a Greenland ice core. *Science* **270**: 1962–1964.

3.1.5. South America

Sepulveda et al. (2009) write, "deciphering climate variability in the Southern Hemisphere and particularly from southern South America—the only continental land mass lying between 38°S and the Antarctic Circle—is crucial for documenting the inter-hemispheric synchronicity of recent abrupt climate changes and thereby determining their ultimate cause(s)," as well as for "predicting future abrupt climate changes." Thus, they conducted what they describe as "a high-resolution multi-proxy study including the elemental and isotopic composition of bulk organic matter, land plant-derived biomarkers, and alkenone-based sea-surface temperature (SST) from a marine sedimentary record obtained from the Jacaf Fjord in northern Chilean Patagonia [44°20.00'S, 72°58.15'W]," in order to develop "a detailed reconstruction of continental runoff, precipitation and summer SST spanning the last 1750 years."

The Chilean, German, and U.S. scientists report their work revealed two distinct climatic conditions: "a relatively dry/warm period before 900 cal yr BP (higher runoff and average SST 1°C warmer than present day) and a wet/cold period after 750 cal yr BP (higher runoff and average SST 1°C colder than present day)," which they associated with the Medieval Warm Period and Little Ice Age, respectively.

In commenting on their findings, Sepulveda et al. write, "the reasonably good correlation between our results (particularly SST) and other continental and marine archives from central-south Chile, Peru, and Antarctica ... confirms the occurrence of globally important climatic anomalies such as the Medieval Warm Period and the Little Ice Age." In addition, their SST data indicate the current level of warmth in that part of the world still has a long way to go before equaling the warmth experienced there a thousand and more years ago, suggesting the region's current level of warmth is neither unprecedented nor unnatural, and that it therefore need not be CO_2-induced.

Working in the same area but one year earlier, Rebolledo et al. (2008) analyzed changes in marine productivity and terrestrial input in a study of sediment cores retrieved from the Jacaf Channel (44°S, 72°W) of Chilean Northern Patagonia that represented the past 1,800 years. The results they obtained clearly depicted two productivity/climate modes. The first period—prior to 900 cal yr BP and including the Medieval Warm Period—was characterized by "decreased marine productivity and a reduced continental signal, pointing to diminished precipitation and runoff," while the second period—between 750 cal yr BP and the late 1800s, and including the Little Ice Age—was characterized by "elevated productivity and an increased continental signal, suggesting higher precipitation and runoff." In addition, their data clearly showed the MWP and LIA were "separated by a relatively abrupt transition of ~150 years."

In addition to providing another demonstration of the reality of the MWP and LIA in Earth's Southern Hemisphere, the Chilean, German, and U.S. scientists say the good correspondence between their record and "other paleoclimate studies carried out in South America and Antarctica demonstrates that the Chilean fjord area of Northern Patagonia is not just sensitive to local climatic variability but also to regional and possibly global variability."

In another study from South America, Kellerhals et al. (2010) write, "to place recent global warming into a longer-term perspective and to understand the mechanisms and causes of climate change, proxy-derived temperature estimates are needed for time periods prior to instrumental records and regions outside instrumental coverage," noting, in this regard, that "for tropical regions and the Southern Hemisphere ... proxy information is very fragmentary."

To help fill this data void, the six scientists developed what they describe as "a reconstruction of tropical South American temperature anomalies over the last ~1600 years ... based on a highly resolved and carefully dated ammonium record from an ice core that was drilled in 1999 on Nevado Illimani [16°37'S, 67°46'W] in the eastern Bolivian Andes," noting "studies from other remote ice core sites have found significant correlations between NH_4^+ concentration and temperature for Siberia and the Indian subcontinent for preindustrial time periods," citing the work of Kang et al. (2002) and Eichler et al. (2009). As for calibrating and validating the NH_4^+-to-°C transfer function, they say they used "the Amazon Basin subset of the gridded HadCRUT3 temperature data set," which is described by Brohan et al. (2006).

In describing their results, Kellerhals et al. state "[1] the most striking features in the reconstruction are the warm temperatures from ~1050 to ~1300 AD [the MWP] compared to the preceding and following centuries, [2] the persistent cooler temperatures from ~1400 to ~1800 AD [the LIA], and [3] the subsequent rise to warmer temperatures [of the Current Warm Period] which eventually seem to exceed, in the last decades of the 20th century, the range of past variation." Consequently, and although the MWP in this particular instance was found to be slightly cooler than it is currently, they add, the "relatively warm temperatures during the first centuries of the past millennium and subsequent cold conditions from the 15th to the 18th century suggest that the MWP and the LIA are not confined to high northern latitudes," but that they "also have a tropical signature." These observations add to the growing body of evidence that demonstrates the global extent of the millennial-scale oscillation of climate that produced both the MWP and the LIA, and which has likely been responsible for the bulk of the warming that has established the Current Warm Period.

References

Brohan, P., Kennedy, J.J., Harris, I., Tett, S.F.B., and Jones, P.D. 2006. Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. *Journal of Geophysical Research* **111**: 10.1029/2005JD006548.

Eichler, A., Brutsch, S., Olivier, S., Papina, T., and Schwikowski, M. 2009. A 750-year ice core record of past biogenic emissions from Siberian boreal forests. *Geophysical Research Letters* **36**: 10.1029/2009GL038807.

Kang, S.C., Mayewski, P.A., Qin, D., Yan, Y., Zhang, D., Hou, S., and Ren, J. 2002. Twentieth century increase of atmospheric ammonia recorded in Mount Everest ice core. *Journal of Geophysical Research* **107**: 10.1029/2001JD001413.

Kellerhals, T., Brutsch, S., Sigl, M., Knusel, S., Gaggeler, H.W., and Schwikowski, M. 2010. Ammonium concentration in ice cores: A new proxy for regional temperature reconstruction? *Journal of Geophysical Research* **115**: 10.1029/2009JD012603.

Rebolledo, L., Sepulveda, J., Lange, C.B., Pantoja, S., Bertrand, S., Hughen, K., and Figueroa, D. 2008. Late Holocene marine productivity changes in Northern Patagonia-Chile inferred from a multi-proxy analysis of Jacaf channel sediments. *Estuarine, Coastal and Shelf Science* **80**: 314–322.

Sepulveda, J., Pantoja, S., Hughen, K.A., Bertrand, S., Figueroa, D., Leon, T., Drenzek, N.J., and Lange, C. 2009. Late Holocene sea-surface temperature and precipitation variability in northern Patagonia, Chile (Jacaf Fjord, 44°S). *Quaternary Research* **72**: 400–409.

3.1.6. Antarctica

Hall et al. (2010) write, "over the past 50 years, the Antarctic Peninsula warmed ~2°C" and resultant rapid ice breakups "have destroyed several small, thin ice shelves fringing the Antarctic Peninsula (i.e., Cook and Vaughan, 2009, and references therein)," leading them to ask, "is the recent warming of the Antarctic Peninsula unique in the Holocene?"

In an effort to place the current ice recession in a broader context, the three researchers "examined organic-rich sediments exposed by the recent retreat of the Marr Ice Piedmont on western Anvers Island near Norsel Point," where glaciers "have been undergoing considerable retreat in response to the well-documented warming." There, they "obtained moss and reworked marine shells from natural sections within 26 meters of the present ice front," as well as "both peat and reworked shells from sediments exposed in a tunnel beneath the residual ice mass," samples of which were radiocarbon-dated and the results converted to calendar years.

The results they obtained by these means indicated peat from the overrun sediments dated to between 707 ± 36 and 967 ± 47 cal. yr B.P.," which led them to conclude, "ice was at or behind its present position at ca. 700–970 cal. yr B.P. and during at least two earlier times, represented by the dates of shells, in the mid-to-late Holocene." Then, in language pure and simple, the three researchers say their findings imply "the present state of reduced ice on the western Antarctic Peninsula is not unprecedented." This leads them to pose another important question: "How widespread is the event at 700–970 cal. yr B.P.?"

In answering their own query, the researchers respond that (1) "Khim et al. (2002) noted a pronounced high-productivity (warm) event between 500 and 1000 cal. yr B.P. in magnetic susceptibility records from Bransfield Basin," (2) "dates of moss adjacent to the present ice front in the South Shetland Islands (Hall, 2007) indicate that ice there was no more extensive between ca. 650 and 825 cal. yr B.P. than it is now," (3) "evidence for reduced ice extent at 700–970 cal. yr B.P. is consistent with tree-ring data from New Zealand that show a pronounced peak in summer temperatures (Cook et al., 2002)," (4) "New Zealand glaciers were retracted at the same time (Schaefer et al., 2009)," and (5) their most recent findings "are compatible with a record of glacier fluctuations from southern South America, the continental landmass closest to Antarctica (Strelin et al., 2008)." In light of these several observations, it would appear much of the southernmost portion of the Earth likely experienced a period of significantly enhanced warmth within the broad timeframe of the planet's global MWP. This interval of warmth occurred when there was far less CO_2 and methane in the atmosphere than there is today.

References

Cook, A.J. and Vaughan, D. 2009. Overview of areal changes of the ice shelves on the Antarctic Peninsula over the past 50 years. *The Cryosphere Discussions* **3**: 579–630.

Cook, E., Palmer, J., and D'Arrigo, R. 2002. Evidence for a "Medieval Warm Period" in a 1100-year tree-ring reconstruction of past austral summer temperatures in New Zealand. *Geophysical Research Letters* **29**: 10.1029/2001GL014580.

Hall, B. 2007. Late-Holocene advance of the Collins Ice Cap, King George Island, South Shetland Islands. *The Holocene* **17**: 1253–1258.

Hall, B.L., Koffman, T., and Denton, G.H. 2010. Reduced ice extent on the western Antarctic Peninsula at 700–907 cal. yr B.P. *Geology* **38**: 635–638.

Khim, B-K., Yoon, H.I., Kang, C.Y., and Bahk, J.J. 2002. Unstable climate oscillations during the Late Holocene in the Eastern Bransfield Basin, Antarctic Peninsula. *Quaternary Research* **58**: 234–245.

Schaefer, J., Denton, G., Kaplan, M., Putnam, A., Finkel, R., Barrell, D.J.A., Andersen, B.G., Schwartz, R., Mackintosh, A., Chinn, T., and Schluchter, C. 2009. High-frequency Holocene glacier fluctuations in New Zealand differ from the northern signature. *Science* **324**: 622–625.

Strelin, J., Casassa, G., Rosqvist, G., and Holmlund, P. 2008. Holocene glaciations in the Ema Glacier valley, Monte Sarmiento Massif, Tierra del Fuego. *Palaeogeography, Palaeoclimatology, Palaeoecology* **260**: 299–314.

3.1.7. Northern Hemisphere

In the 27 November 2009 issue of *Science*, Michael Mann and eight coauthors (Mann et al., 2009) describe how they used a global climate proxy network consisting of data derived from ice core, coral, sediment, and various other records to reconstruct a Northern Hemispheric surface air temperature history covering the past 1,500 years for the purpose of determining the characteristics of the Little Ice Age and Medieval Warm Period. They used Mann's "*Nature* trick" of Climategate fame, truncating the reconstructed temperature history near its end and replacing it with modern-day instrumental data, so the last part of the record cannot be validly compared with the earlier portion.

This subterfuge is unwarranted. And in its current application, it's not just from 1981 or 1961 onwards that the ruse is applied; it's applied all the way from 1850 to 1995, the period of overlap between the proxy and instrumental records that was used to calibrate the proxy data. Therefore, since the proxy data were available to 1995, the reconstructed near-surface air temperature history should also have been plotted to 1995, in order to be able to make valid quantitative comparisons between the degree of warmth of the Current and Medieval Warm Periods.

So why wasn't this clearly superior method of data analysis employed? Perhaps to hide the decline in the reconstructed temperature history that was evident in the latter decades of some of the proxy data. And why was that done? Perhaps to get rid of the Medieval Warm Period, because knowledge of the existence of higher temperatures during the MWP makes it much more difficult for most rational people to believe the planet's current level of warmth is due to its high atmospheric CO_2 concentration.

Even with the greatly biased "apples and oranges" comparison utilized by Mann et al., the nine researchers were forced to acknowledge that the warmth over a large part of the North Atlantic, Southern Greenland, the Eurasian Arctic, and parts of North America during the Medieval Warm Period was "comparable to or exceeds that of the past one-to-two decades in some regions."

Nevertheless, the "*Nature* trick" of Mann et al. allows climate alarmists to continue to underestimate the true level of warmth of the MWP, allowing the IPCC and United Nations to continue to contend Earth's current temperatures are the greatest the planet has experienced over the past millennium or more, when the vast majority of real-world data clearly show otherwise.

To see what the record shows as having happened over the Northern Hemisphere if "apples and apples" are compared, we turn to the study of Fredrik Ljungqvist (2010) of Stockholm University's Department of History, who developed a 2,000-year temperature history of the extra-tropical portion of the Northern Hemisphere (the part covering the latitudinal range 30–90°N) (see Figure 3.1.3) based on 30 temperature-sensitive proxy records with annual to multidecadal resolution, including two historical documentary records, three marine sediment records, five lake sediment records, three speleothem $\delta^{18}O$ records, two ice-core $\delta^{18}O$ records, four varved thickness sediment records, five tree-ring width records, five tree-ring maximum latewood density records, and one $\delta^{13}C$ tree-ring record, but not employing tree-ring width records from arid and semi-arid regions, because they may have been affected by drought stress and may not show a linear response to warming if higher summer temperatures significantly reduced the availability of water, as is

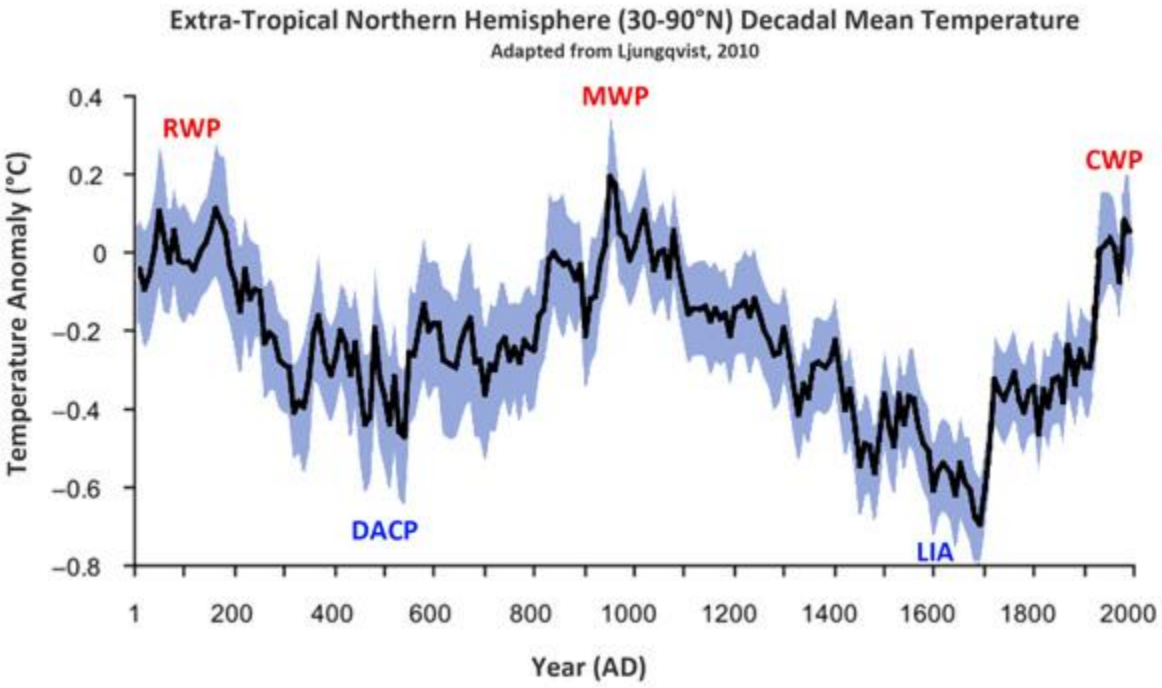


Figure 3.1.3. Reconstructed extra-tropical (30–90°N) mean decadal temperature relative to the 1961–1990 mean of the variance-adjusted 30–90°N CRUTEM3+HadSST2 instrumental temperature data of Brohan et al. (2006) and Rayner et al. (2006). Adapted from Ljungqvist (2010).

suggested by the work of D'Arrigo et al. (2006) and Loehle (2009).

In discussing this temperature history, Ljungqvist states it depicts "a Roman Warm Period *c.* AD 1–300, a Dark Age Cold Period *c.* AD 300–800, a Medieval Warm Period c. AD 800–1300 and a Little Ice Age c. AD 1300–1900, followed by the twentieth-century warming." These alternating warm/cold periods, in his words, "probably represent the much discussed quasi-cyclical *c.* 1470 ± 500-year Bond Cycles (Bond and Lotti, 1995; O'Brien et al., 1995; Bond et al., 1997, 2001; Oppo, 1997)," which "affected both Scandinavia and northwest North America synchronically (Denton and Karlen, 1973)" and have "subsequently also been observed in China (Hong et al., 2009a,b), the mid-latitude North Pacific (Isono et al., 2009) and in North America (Viau et al., 2006), and have been shown to very likely have affected the whole Northern Hemisphere during the Holocene (Butikofer, 2007; Wanner et al., 2008; Wanner and Butikofer, 2008), or even been global (Mayewski et al., 2004)."

Ljungqvist also notes "decadal mean temperatures in the extra-tropical Northern Hemisphere seem to have equaled or exceeded the AD 1961–1990 mean temperature level during much of the Roman Warm Period and the Medieval Warm Period" and "the second century, during the Roman Warm Period, is the warmest century during the last two millennia." He adds, "the highest average temperatures in the reconstruction are encountered in the mid to late tenth century," which was during the Medieval Warm Period. He warns the temperature of the last two decades "is possibly higher than during any previous time in the past two millennia," but he adds "this is only seen in the instrumental temperature data and not in the multi-proxy reconstruction itself," which is akin to saying this possibility presents itself only if one applies Michael Mann's "*Nature* trick" of comparing "apples and oranges," which is clearly not valid.

This new study of Ljungqvist is especially important because it utilizes, in his words, "a larger number of proxy records than most previous reconstructions" and "substantiates an already established history of long-term temperature variability." All of these facts, taken together, clearly demonstrate there is nothing unusual, unnatural, or unprecedented about the planet's current level of warmth.

References

Bond, G. and Lotti, R. 1995. Iceberg discharges into the North Atlantic on millennial time scales during the last glaciation. *Science* **267**: 1005–1010.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G. 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and Glacial climate. *Science* **278**: 1257–1266.

Brohan, P., Kennedy, J., Harris, I., Tett, S.F.B., and Jones, P.D. 2006. Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. *Journal of Geophysical Research* **111**: 10.1029/2005JD006548.

Butikofer, J. 2007. Millennial Scale Climate Variability During the Last 6000 Years—Tracking Down the Bond Cycles. Diploma thesis, University of Bern, Bern, Switzerland.

D'Arrigo, R., Wilson, R. and Jacoby, G., 2006: On the long-term context for late 20th century warming. *Journal of Geophysical Research* **111**: D3, D03103.

Denton, G.H. and Karlen, W. 1973. Holocene climatic variations—their pattern and possible cause. *Quaternary Research* **3**: 155–205.

Hong, Y.T., Hong, B., Lin, Q.H., Shibata, Y., Zhu, Y.X., Leng, X.T., and Wang, Y. 2009a. Synchronous climate anomalies in the western North Pacific and North Atlantic regions during the last 14,000 years. *Quaternary Science Reviews* **28**: 840–849.

Hong, B., Liu, C., Lin, Q., Yasuyuki, S., Leng, X., Wang, Y., Zhu, Y., and Hong, Y. 2009b. Temperature evolution from the δ^{18}O record of Hami peat, Northeast China, in the last 14,000 years. *Science in China Series D: Earth Sciences* **52**: 952–964.

Isono, D., Yamamoto, M., Irino, T., Oba, T., Murayama, M., Nakamura, T., and Kawahata, H. 2009. The 1500-year climate oscillation in the mid-latitude North Pacific during the Holocene. *Geology* **37**: 591–594.

Loehle, C. 2009. A mathematical analysis of the divergence problem in dendroclimatology. *Climatic Change* **94**: 233–245.

Ljungqvist, F.C. 2010. A new reconstruction of temperature variability in the extra-tropical northern hemisphere during the last two millennia. *Geografiska Annaler* **92A**: 339–351.

Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R.S., Hughes, M.K., Shindell, D., Ammann, C., Faluvegi, G., and Ni, F. 2009. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science* **326**: 1256–1260.

Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlen, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G. Rack, F., Staubwasser, M., Schneider, R.R., and Steig, E.J. 2004. Holocene climate variability. *Quaternary Research* **62**: 243–255.

O'Brien, S.R., Mayewski, P.A., Meeker, L.D., Meese, D.A., Twickler, M.S., and Whitlow, S.E. 1995. Complexity of Holocene climate as reconstructed from a Greenland ice core. *Science* **270**: 1962–1964.

Oppo, D. 1997. Millennial climate oscillations. *Science* **278**: 1244–1246.

Rayner, N.A., Brohan, P., Parker, D.E., Folland, C.K., Kennedy, J.J., Vanicek, M., Ansell, T., and Tett, S.F.B. 2006. Improved analyses of changes and uncertainties in marine temperature measured in situ since the mid-nineteenth century: the HadSST2 dataset. *Journal of Climate* **19**: 446–469.

Viau, A.E., Gajewski, K., Sawada, M.C., and Fines, P. 2006. Millennial-scale temperature variations in North America during the Holocene. *Journal of Geophysical Research* **111**: 10.1029/2005JD006031.

Wanner, H. and Butikofer, J. 2008. Holocene Bond cycles: real or imaginary? *Geografie-Sbornik CGS* **113**: 338–350.

Wanner, H., Beer, J., Butikofer, J., Crowley, T., Cubasch, U., Fluckiger, J., Goosse, H., Grosjean, M., Joos, F., Kaplan, J.O., Kuttel, M., Muller, S., Pentice, C., Solomina, O., Stocker, T., Tarasov, P., Wagner, M., and Widmann, M. 2008. Mid to late Holocene climate change—an overview. *Quaternary Science Reviews* **27**: 1791–1828.

3.1.8. Other Temperature Records

Four additional studies that don't fall under the previous seven sections of this chapter shed light on temperature reconstructions of the Medieval Warm Period.

In a lengthy review paper (Wanner et al., 2008), 18 climate scientists—from 13 research institutions in Switzerland, Germany, the United Kingdom, Belgium, and Russia—developed what they describe as "a general framework for understanding climate changes during the last 6000 years," and they ended their analysis of the several hundred papers they cited with a summary consisting of two main points, the second of which is most germane to the topic of the Medieval Warm Period.

Wanner et al. concluded, "at decadal to multi-century timescales, climate variability shows a complex picture with indications of a possible role for (i) rapid changes of the natural forcing factors such as solar activity fluctuations and/or large tropical volcanic eruptions, (ii) internal variability including ENSO [El Niño Southern Oscillation] and NAO [North Atlantic Oscillation], (iii) changes of the thermohaline circulation, and (iv) complex feedback mechanisms between ocean, atmosphere, sea ice and vegetation." They also report "notable swings occurred between warm and cold periods, especially the hemispheric-scale warming leading into the Medieval Warm Period and subsequent cooling into the Little Ice Age." The latter period, they note, "appears at least to be a hemispheric phenomenon." Finally, they say model simulations support the inference that the Little Ice Age "may have been brought about by the coincidence of low Northern Hemisphere orbital forcing during the Late Holocene with unusually low solar activity and a high number of major volcanic events."

Continuing consideration of the sun as a cause for millennial-scale climate perturbations were Dergachev and Raspopov (2010a,b), who analyzed the degree of harmony among earlier reconstructions, as well as their individual correlations with various indices of solar activity. Following this protocol, they initially demonstrated that climate reconstructions that rely heavily on tree-ring data do not agree very well with each other; and when they are compared to ice core data they appear to lose much of the low-frequency signal that is preserved in that other medium.

The Russian researchers next noted a detailed 750-year temperature reconstruction from an ice core in Siberia agrees well with measures of solar modulation based on sunspot number and carbon-14 and Be-10 estimates, and that the agreement is remarkable at multidecadal time scales. They then examined borehole thermometry data, noting that although such data lose annual- and decadal-scale detail, the temperature history thereby derived agrees well over recent decades with local instrumental data. In addition, they found that multiple boreholes from around the world agree with each other on the scale of the last millennium, which shows borehole-derived temperatures are a valid and consistent representation of reality.

Finally, the two scientists compared the solar indices of the past millennium with the borehole temperature reconstructions, demonstrating the borehole data and solar indices agree on the long-term temperature pattern of the past thousand years. Thus the two parameters imply the existence of a solar-induced Medieval Warm Period (MWP) around AD 1000 to 1300 and a Little Ice Age (LIA) in the 1600s to 1700s. Their study confirms the existence of a global MWP and demonstrates the link between the MWP-LIA oscillation and solar activity. In addition, it indicates the MWP was roughly as warm as—or warmer than—it has been to date during the Current Warm Period.

We note that in past IPCC reports, temperature reconstructions by scientists such as Mann, Bradley, Hughes, Jones, and Esper are claimed to be "remarkably consistent." Bürger (2010) decided this opinion needed to be more rigorously evaluated, and to do so he analyzed the data contained in Figure 3.1.4.

Working with eight graphs from the IPCC and adding two more, he determined the calibration process during the instrumental period would bias the degree of agreement because the graphs were all fixed to largely agree during this period. Therefore, he examined only the period before 1850. In order to examine the shapes of the curves rather than arbitrary offsets, he rescaled them all to unit variance and centered them on zero, after which he computed the spectral coherence of each pair, and then—from the similarity matrix—he conducted a clustering analysis.

Five clusters were formed by the 10 reconstructions, with three in the largest and one in the smallest cluster. Members within a cluster were similar at the 95 percent confidence level, based on standard tests. All of the clusters, however, were significantly incoherent with each other, not merely at some points but at virtually all timescales of fluctuation, from decadal to centennial oscillations. Thus, it is not meaningful to speak of somehow "averaging" the different reconstructions, whether by eye or numerically, because the incoherence will lead to a canceling out of the supposed climate signals in each, leaving merely a close-to-flat line.

This incoherence means one cannot claim that the different temperature reconstructions are all "right" or "agree" in any sense of the word, and attempts to use these reconstructions for attribution studies or to calibrate climate models will give different results for any particular choice of reconstruction. The results of Bürger's work suggest the reconstructions differ so much that there is no way to draw meaningful conclusions from them, nor can it be determined which one or ones is or are right.

References

Bürger, G. 2010. Clustering climate reconstructions. *Climate of the Past Discussions* **6**: 659–679.

Dergachev, V.A. and Raspopov, O.M. 2010a.

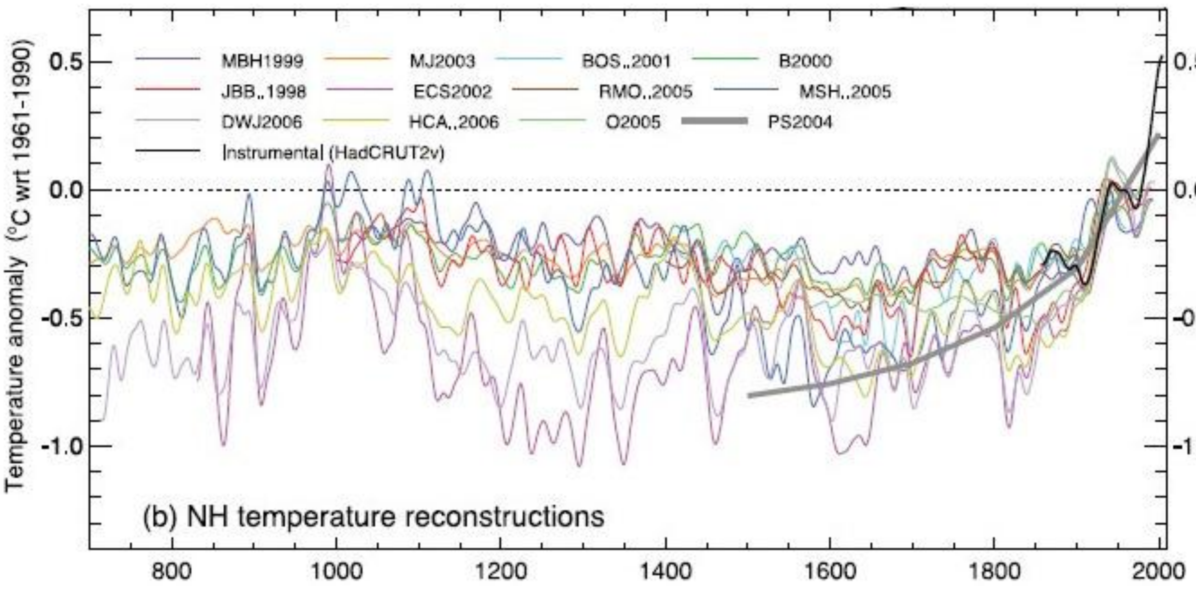


Figure 3.1.4. IPCC spaghetti graph from Fig. 6.10 of Working Group 1.

Reconstruction of the Earth's surface temperature based on data of deep boreholes, global warming in the last millennium, and long-term solar cyclicity. Part 1. Experimental data. *Geomagnetism and Aeronomy* **50**: 383–392.

Dergachev, V.A. and Raspopov, O.M. 2010b. Reconstruction of the Earth's surface temperature based on data of deep boreholes, global warming in the last millennium, and long-term solar cyclicity. Part 2. Experimental data analysis. *Geomagnetism and Aeronomy* **50**: 393–402.

Wanner, H., Beer, J., Butikofer, J., Crowley, T.J., Cubasch, U., Fluckiger, J., Goosse, H., Grosjean, M., Joos, F., Kaplan, J.O., Kuttel, M., Muller, S.A., Prentice, I.C., Solomina, O., Stocker, T.F., Tarasov, P., Wagner, M., and Widmann, M. 2008. Mid- to Late Holocene climate change: an overview. *Quaternary Science Reviews* **27**: 1791–1828.

3.2. The Little Medieval Warm Period

Research from locations around the world reveal a significant period of elevated air temperatures that immediately preceded the Little Ice Age, during a time that has come to be known as the Little Medieval Warm Period. A discussion of this topic was not included in the 2009 NIPCC report, but we include it here to demonstrate the existence of another set of real-world data that do not support the IPCC's claim that temperatures of the past couple of decades have been the warmest of the past one to two millennia.

In one of the more intriguing aspects of his study of global climate change over the past three millennia, Loehle (2004) presented a graph of the Sargasso Sea and South African temperature records of Keigwin (1996) and Holmgren et al. (1999, 2001) that reveals the existence of a major spike in surface air temperature that began sometime in the early 1400s. This abrupt and anomalous warming pushed the air temperatures of these two records considerably above their representations of the peak warmth of the twentieth century, after which they fell back to pre-spike levels in the mid-1500s, in harmony with the work of McIntyre and McKitrick (2003), who found a similar period of higher-than-current temperatures in their reanalysis of the data employed by Mann et al. (1998, 1999).

In another study that reveals the existence of this period of higher-than-current warmth, D'Arrigo et al. (2004) developed a maximum latewood density (MXD) chronology for the period 1389 to 2001, based on cores obtained from white spruce trees growing near the treeline on the eastern Seward Peninsula of Alaska, a portion of which data (1909–1950) were calibrated against May–August temperatures measured at Nome and then used to convert the entire MXD chronology to warm-season temperatures. They found a two-decade period of close-to-twentieth-century-warmth in the mid-1500s that was preceded by a decade of warmth, greater than that of the mid-twentieth century, in the latter part of the 1400s.

In a subsequent study from the same region, D'Arrigo et al. (2005) derived a new tree-ring width dataset from 14 white spruce chronologies covering the years 1358–2001. These data were then combined with additional tree-ring-width chronologies from northwest Alaska to produce two versions of a much longer data series that extended to AD 978. The first chronology was created using traditional methods of standardization (STD), which do not perform well in capturing multidecadal or longer climate cycles, while the second chronology utilized the regional curve standardization (RCS) method, which better preserves low-frequency variations at multidecadal time scales and longer. With respect to the STD- and RCS-derived temperature histories, each of them revealed, in the words of D'Arrigo et al., "several intervals of persistent above-average growth that broadly coincide with the timing of the late Medieval Warm Period." The warming is much more pronounced in the RCS chronology, where the greatest warmth occurred in the early to middle 1200s, with lesser peaks in the early to middle 1100s and early 1400s (the Little Medieval Warm Period).

Additional evidence for this previously unheralded warm period was obtained by Silenzi et al. (2004). Working with Vermetid reefs on the northwest coast of Sicily, they obtained oxygen isotopic data they interpreted in terms of sea surface temperature (SST) variations. These data indicated that in the early to mid-1500s, SSTs in this region were warmer than they are currently. Likewise, Gray et al. (2004) developed a reconstruction of the leading mode of low-frequency North Atlantic (0–70°N) SST variability, known as the Atlantic Multidecadal Oscillation (AMO), for the period 1567–1990. Based on tree-ring records from regions known to border on strong centers of AMO variability, including eastern North America, Europe, Scandinavia, and the Middle East, this record too displayed an intense warm phase, in this case between 1580 and 1596, the unmatched strength of which is clearly evident in reconstructed North Atlantic SST anomalies.

Many other studies have found much the same thing. Helama et al. (2002), for example, reconstructed midsummer temperatures for the last 7,500 years using the long Scots pine ring-width chronology from northern Finland derived by Eronen et al. (2002). Their record revealed the twentieth century was indeed warm compared to the mean of the entire period (about 0.6°C warmer). However, there were three other hundred-year periods that were warmer still, the last of which (AD 1500–1600) falls within the general time frame of what we call the Little Medieval Warm Period.

In a novel paper published in *Nature*, Chuine et al. (2004) used recorded dates of grape harvests in Burgundy, France to reconstruct mean spring–summer (April–August) air temperatures for that location on a yearly basis from 1370 to 2003, employing what they call "a process-based phenology model developed for the Pinot Noir grape." The resulting temperature history is significantly correlated with mean summer air temperatures deduced from tree rings in central France, the Burgundy portion of a spatially distributed multi-proxy temperature reconstruction, and observed summer air temperatures in Paris, central England, and the Alps. The thermal interconnectedness of these sites gives the new temperature history an important regional significance, the most intriguing aspect of which is the existence of much warmer-than-present air temperatures at various times in the past, most notably from the late 1300s through the early 1400s and over a large portion of the 1600s.

In another pertinent paper, Bartholy et al. (2004) meticulously codified and analyzed historical records collected by Antal Rethly (1879–1975), a Hungarian meteorologist who spent the greater portion of his long professional career assembling more than 14,000 historical records related to the climate of the Carpathian Basin. With respect to the temperature history they thereby derived, they report "the warm peaks of the Medieval Warm Epoch and colder climate of the Little Ice Age followed by the recovery warming period can be detected in the reconstructed temperature index time series." In addition, they write, "a warm episode in the 16th century [was] detected in both annual- and seasonal-scale analysis of the 50-year distribution of warm and cold conditions," which would again be the Little Medieval Warm Period.

Regarding North America, Luckman and Wilson (2005) updated a regional temperature history, originally developed in 1997, using new tree-ring data from the Columbia Icefield region of the Canadian Rockies. The update also employed different standardization techniques, including the regional curve standardization method that better captures low-frequency variability (centennial- to millennial-scale) than that reported in the initial study. In addition, the new dataset added more than one hundred years to the chronology, which now covers AD 950–1994. This tree-ring record was found to explain 53 percent of May–August maximum temperature variation observed in the 1895–1994 historical data and was thus considered a good proxy indicator of such temperatures. Based on this relationship, the record showed considerable decadal- and centennial-scale temperature variability, where generally warmer conditions prevailed about 1350–1450 (the Little Medieval Warm Period). Of more than passing interest is that the warmest summer of this record occurred in 1434, when it was 0.23°C warmer than the next warmest summer, which occurred in 1967.

Focusing on a different climate parameter, but one that is highly correlated with temperature, Blundell and Barber (2005) utilized plant macrofossils, testate amoebae, and degree of humification as proxies for environmental moisture conditions to develop a 2,800-year "wetness history" from a peat core extracted from Tore Hill Moss, a raised bog in the Strathspey region of Scotland. The most clearly defined and longest interval of sustained dryness of this entire record stretches from about AD 850 to AD 1080, coincident with the well-known Medieval Warm Period, and the most extreme wetness interval occurred during the depths of the last stage of the Little Ice Age, which was one of the coldest periods of the Holocene. Of most interest to the subject of this section, however, is the period of relative dryness centered on about AD 1550, which corresponds to the Little Medieval Warm Period and implies the existence of significant warmth at that time.

In a somewhat different study, Munroe (2003) replicated and analyzed six photographs taken in 1870 near the subalpine forest-alpine-tundra ecotone in the northern Uinta Mountains of Utah, USA, in an attempt to quantify the redistribution of vegetation that occurred there between the end of the Little Ice Age and the Current Warm Period. After achieving this objective, he used his findings to infer the nature of regional climate change over the past 130 years. Before concluding, however, he directed his attention to what he describes as "downed logs, *in situ* stumps, and upright delimbed boles on the north side of Bald Mountain [that] indicate a treeline up to 60 m higher than the modern level," which he determined, on the basis of the modern atmospheric lapse rate, "corresponds to an increase of mean July temperature of 0.4°C."

With respect to these subfossil relics, Munroe writes, many of them "have been severely abraded by windblown ice, giving the impression of considerable antiquity," noting "similar wood from elsewhere in the Rocky Mountains has been taken as evidence of higher treeline during the early Holocene climatic optimum, or 'altithermal' (Carrara et al., 1991)." However, he reports, a sample cut from one of the stumps was radiocarbon-dated to only about 1550, and "the actual germination of the tree may have occurred a century or more before AD 1550." That places the warm period indicated by the subfossil wood in approximately the same time interval as the warm periods identified in all the prior studies we have discussed. In addition, Munroe remarks, "a higher treeline in the northern Uintas shortly before AD 1550 is consistent with contemporaneous evidence for warmer-than-modern climates in the southwestern United States (Dean, 1994; Petersen, 1994; Meyer et al., 1995; Pederson, 2000)."

In yet another study that provides indirect evidence for the existence of this century-scale Little Medieval Warm Period, Fleitmann et al. (2004) developed a stable isotope history from three stalagmites in a cave in Southern Oman that provided an annually resolved 780-year record of Indian Ocean monsoon rainfall. Over the last eight decades of the twentieth century, when global temperatures rose dramatically as the Earth emerged from the Little Ice Age and entered the Current Warm Period, this record reveals Indian Ocean monsoon rainfall declined dramatically. It further indicates the other most-dramatic decline coincided with the major temperature spike that is evident in the temperature histories discussed above.

Pla and Catalan (2005) analyzed chrysophyte cyst data collected from 105 lakes in the Central and Eastern Pyrenees of northeast Spain to produce a Holocene history of winter/spring temperatures in that part of the world. Their work revealed a significant oscillation in winter/spring temperatures in which the region's climate alternated between warm and cold phases over the past several thousand years. Of particular note were the Little Ice Age, Medieval Warm Period, Dark Ages Cold Period, and Roman Warm Period. The warmest of these intervals was the Medieval Warm Period, which started around AD 900 AD and was about 0.25°C warmer than it is currently. After the Medieval Warm Period, temperatures fell to their lowest values of the entire record (about 1.0°C below present), and then they began to warm but remained below present-day values until the early nineteenth and twentieth centuries—with one exception. A significant warming was observed between 1350 and 1400, when temperatures rose a full degree Celsius to a value about 0.15°C warmer than the present, during the Little Medieval Warm Period.

In a contemporaneous study, Chen et al. (2005) studied the chemical composition of sediments deposited in Lake Erhai (25°35'–25°58'N, 100°05'–100°17'E), the largest fault lake in the western Yunnan Province of China. They applied Principal Component Analysis to the concentrations of 21 major and minor elements found in the sediments, thereby deriving historical variations in temperature and precipitation over the period AD 1340–1990. In doing so, they found an initial period (1340–1550) of relatively high temperature and low rainfall—the Little Medieval Warm Period.

Also in China, but working several years earlier with the top 2 cm of a 20-cm-long stalagmite collected from Shihua Cave near Beijing, Ku and Li (1998) obtained annually resolved δ^{18}O data covering the past five centuries. Based on their analyses of these and other pertinent data, they determined that fluctuations of the δ^{18}O data over periods of less than ten years "reflect changes in precipitation, whereas on coarser time scales (>50 years), the stalagmite δ^{18}O records temperature variations." This finding led them to conclude "the period AD 1620–1900 was cold and periods 1520–1620 and 1900–1994 were warm." From their graphical representations of these two warm periods, it appears the earlier period—the Little Medieval Warm Period—was probably just a tad warmer than it was over the last two decades of the twentieth century.

Sharma et al. (2005) used δ^{13}C values of sphagnum remains from peat deposits located along a sequence of beach ridges of Lake Superior in North America to reconstruct changes in regional water balance from about 1,000 to 3,500 years BP, after which they compared their findings with water-level reconstructions of adjacent Lake Michigan derived by Baedke and Thompson (2000) from sedimentological studies. In doing so they found maxima of sphagnum δ^{13}C values in peat deposits developed from 3,400 to 2,400 years BP and from 1,900 to 1,400 years BP, which closely match two periods of Lake Michigan high-water stands evident in the lake level record of Baedke and Thompson. These two periods coincide with the cooler climatic conditions that prevailed on either side of the Roman Warm Period, the most recent of which is the well-known Dark Ages Cold Period. This latter cold high-water period was then followed by a period of low water and declining δ^{13}C values, which coincides with the well-known Medieval Warm Period that ultimately gave way to the Little Ice Age. Thereafter, there are no more δ^{13}C data, but the lake level data reveal a third low-level stand of Lake Michigan from about 600 to 500 years BP, which coincides with the Little Medieval Warm Period.

Using the regional curve standardization technique applied to ring-width measurements of both living trees and relict wood, Büntgen et al. (2005) developed a 1,052-year summer (June–August) temperature proxy from high-elevation Alpine environments in Switzerland and the western Austrian Alps (between 46°28’ to 47°00’N and 7°49’ to 11°30’E). This exercise revealed the presence of warm conditions from the beginning of the record in AD 951 up to about AD 1350, which the authors associated with the Medieval Warm Period. Thereafter, temperatures declined and an extended cold period known as the Little Ice Age ensued and persisted until approximately 1850—with one brief exception. For a few short decades in the mid- to late-1500s, there was an uncharacteristically warm episode, the temperatures of which were exceeded only at the beginning and end of the 1,052-year record, during the Medieval and Current Warm Periods. This warm episode was the Little Medieval Warm Period.

Holzhauser et al. (2005) “for the first time,” in their words, presented high-resolution records of variations in glacier size in the Swiss Alps together with lake-level fluctuations in the Jura mountains, the northern French Pre-Alps, and the Swiss Plateau in developing a 3,500-year climate history of west-central Europe, beginning with an in-depth analysis of the Great Aletsch glacier, the largest glacier in the European Alps.

Near the beginning of the time period studied, the three researchers report, “during the late Bronze Age Optimum from 1350 to 1250 BC, the Great Aletsch glacier was approximately 1000m shorter than it is today.” They note “the period from 1450 to 1250 BC has been recognized as a warm-dry phase in other Alpine and Northern Hemisphere proxies (Tinner et al., 2003).” Then, after an intervening cold-wet phase, when the glacier grew in both mass and length, they note, “during the Iron/Roman Age Optimum between c. 200 BC and AD 50,” perhaps better known as the Roman Warm Period, the glacier again retreated and “reached today’s extent or was even somewhat shorter than today.”

Next came the Dark Ages Cold Period, which they say was followed by “the Medieval Warm Period, from around AD 800 to the onset of the Little Ice Age around AD 1300.” The latter cold-wet phase was “characterized by three successive [glacier length] peaks: a first maximum after 1369 (in the late 1370s), a second between 1670 and 1680, and a third at 1859/60,” after which the glacier began its latest and still-ongoing recession in 1865. They note written documents from the fifteenth century AD indicate that at some time during that hundred-year interval “the glacier was of a size similar to that of the 1930s,” which latter period in many parts of the world was as warm as today or even warmer, in harmony with the increasing body of evidence suggesting a Little Medieval Warm Period manifested itself during the fifteenth century within the broader expanse of the Little Ice Age.

Weckstrom et al. (2006) developed a high-resolution quantitative history of temperature variability over the past 800 years, based on analyses of diatoms found in a sediment core retrieved from a treeline lake (Lake Tsuolbmajavri) located in Finnish Lapland. The result, in their words, “depicts three warm time intervals around AD 1200–1300, 1380–1550 and from AD 1920 until the present.” Of these intervals, they “associate the warmth of the 13th century with the termination phase of the Medieval Warm Period and the rapid post-1920 temperature increase with the industrially induced anthropogenic warming,” the last decade of which climate alarmists typically tout as having been the warmest such period of the last two millennia. Most interestingly, however, Weckstrom et al.’s data indicate the peak warmth of the AD 1200–1300 termination phase of the MWP was about 0.15°C warmer than the peak warmth of the post-1920 period. Even more interesting is that the peak warmth of the AD 1380–1550 period—the Little Medieval Warm Period—was warmer still, at 0.25°C above the peak warmth of the post-1920 period.

Working with a sediment core extracted from the northeastern slope of the Cariaco Basin (10°45.98'N, 64°46.20'W), Black et al. (2007) derived an 800-year Mg/Ca history of the planktic foraminifer *Globigerina bulloides*, which they correlated with spring (March–May) sea surface temperatures (SSTs) measured between AD 1870 and 1990. This ultimately allowed them to reconstruct an 800-year SST history of the region. A plot of their findings is reproduced in Figure 3.2.1. As may readily be seen, it reveals dramatic twentieth-century warming, the prior Little Ice Age, and (at the beginning of the plot) what they describe as "the end of the Medieval Warm Period." What stands out most boldly of all, however, is the remarkable rise and fall of the region's SST that occurred between the Medieval Warm Period and the Little Ice Age, during the Little Medieval Warm Period.

Barron and Bukry (2007) derived high-resolution records of diatoms and silicoflagellate assemblages spanning the past 2,000 years from analyses of sediment cores extracted from three sites on the eastern slope of the Gulf of California. In all three cores the relative abundance of *Azpeitia nodulifera* (a tropical diatom whose presence suggests higher sea surface temperatures) was found to be far greater during the Medieval Warm Period than at any other time over the 2,000-year period studied. In addition, the first of the cores exhibited elevated *A. nodulifera* abundances from the start of the record to about AD 350 (during the latter part of the Roman Warm Period) and between AD 1520 and 1560 (during what we have denominated the Little Medieval Warm Period). By analyzing radiocarbon production data, Barron and Bukry also determined the changes in climate they identified likely were driven by solar forcing.

Two years later, Richey et al. (2009) derived two decadal-resolution foraminiferal Mg/Ca sea surface temperature (SST) records covering the past six to eight centuries from two locations in the northern Gulf of Mexico—the Fisk Basin (27°33.0'N, 92°10.1'W) and the Garrison Basin (26°40.5'N, 93°55.5'W)—which they compared with the earlier Pigmy Basin (27°11.6'N, 91°24.5'W) Mg/Ca SST record of Richey et al. (2007). The results for all three Gulf of Mexico locations were pretty much the same: all revealed the occurrence of Little Ice Age temperatures in the mid-1700s that were 2–3°C cooler than present-day temperatures, in harmony with the results obtained by the various temperature

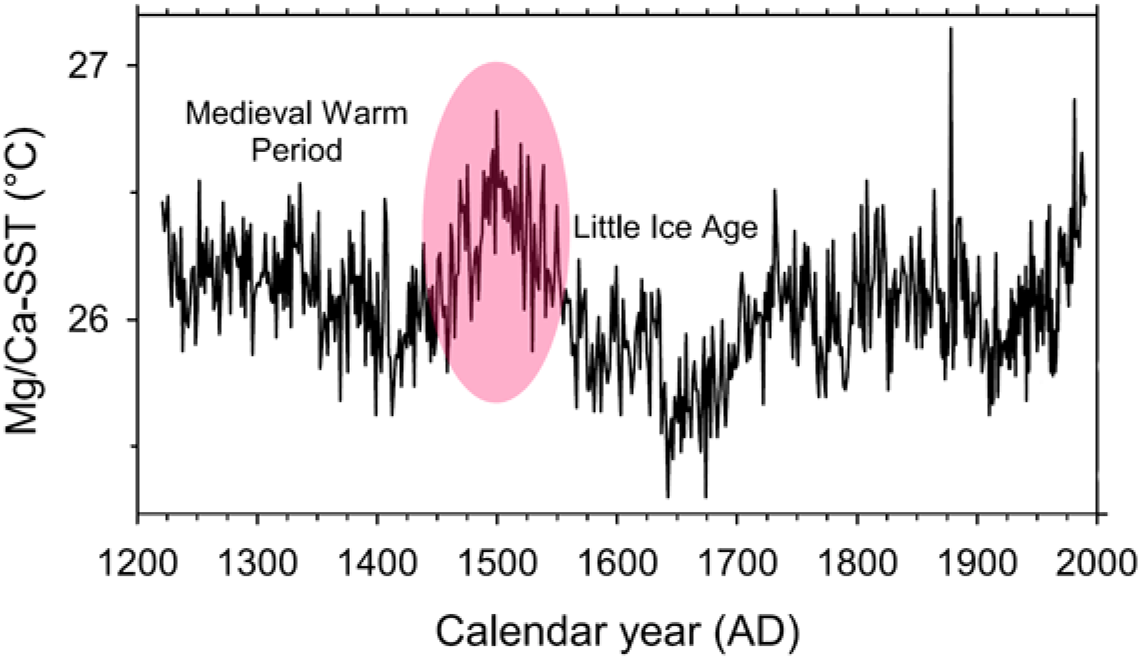


Figure 3.2.1. The 800-year Mg/Ca-derived SST history of the northeastern slope of the Cariaco Basin. Adapted from Black et al. (2007).

reconstruction techniques employed in the other studies they cited. More germane to the topic at hand, the authors found "Little Ice Age cooling in all three Gulf of Mexico Mg/Ca records is preceded by an interval of warmth in which Mg/Ca is as high or higher than the mean Gulf of Mexico core-top value." This warm interval, which falls between about AD 1450 and 1600, represents the region's Little Medieval Warm Period.

Also in 2009, Siklosy et al. conducted a complex trace element and stable carbon and oxygen isotope analysis of a stalagmite recovered from a cave (Kiskohat Shaft) located in northeast Hungary at the southern rim of the Bukk Highland (48°4.086'N, 20°29.422'E), with dating provided by 12 ^{230}Th-^{234}U determinations made along the growth direction of the stalagmite. Results indicated the highest oxygen isotope values occurred around AD 1000–1150, which they identified as the Medieval Warm Period, while the coldest years, which they associated with the Little Ice Age, prevailed from about AD 1550 to 1700. With respect to the Little Medieval Warm Period, their results revealed a 50-year period of approximately AD 1450–1500, which was almost as warm as the MWP.

In another study, Saenger et al. (2009) developed an absolutely dated and annually resolved record of sea surface temperature (SST) from the Bahamas (25.84°N, 78.62°W), based on a 440-year time series (1552–1991) of coral (*Siderastrea siderea*) growth rates, which they found to possess "an inverse correlation with instrumental SST," a relationship verified by "applying it to an *S. siderea* colony from Belize (17.50°N, 87.76°W)." This work revealed that "temperatures were as warm as today from about 1552 [where their record begins, somewhere in the midst of the Little MWP] to 1570."

A year later, Yang et al. (2010) developed a tree-ring-width history spanning AD 1377–1998 from Tibetan juniper (*Cupressus gigantea*) trees growing at a site (29°22'N, 94°16'E) just north of the deep gorge of the Yarlung Tsangbo River of southeast Tibet, from which they developed a linear regression model between ring-width and mean January–June temperature that accounts for 35 percent of the variance of this parameter over the period 1961–1998. According to the authors, the tree ring history revealed a number of relatively warmer and cooler intervals throughout its 622-year record, among the former of which were several that exceeded late twentieth-century warmth. The two most striking of these short-term warm periods were 1443–1466 and 1482–1501, and as best as can be determined from the graphical representations of their data, annual temperatures during the second of these two warm periods exceeded those of the late twentieth century by as much as 0.75°C, while 11-year smoothed temperatures of the first of the two warm periods exceed those of the late twentieth century by as much as 0.3°C.

From a broad sediment shelf at a water depth of 56 meters in the main basin of Loch Sunart—a fjord on the northwest coast of Scotland (56°40.20'N, 05°52.22'W)—Cage and Austin (2010) extracted several sediment cores from which they developed a continuous record of various physical and chemical properties of the sediment, which spanned the last millennium and extended to AD 2006. Of particular interest are the δ^{18}O measurements made on the shells of the benthic foraminifer *Ammonia beccarii*, because prior such data—when operated upon by the palaeotemperature equation of O'Neil et al. (1969)—yielded bottom-water temperatures that had been judged by Cage and Austin (2008) to be "the most realistic water temperature values for infaunal benthic foraminifera from Loch Sunart."

The results of the two researchers' most recent efforts revealed the most distinctive feature of the Loch Sunart temperature record was an abrupt warming at AD 1540 that led to a temperature anomaly of 1.1°C above the long-term mean from AD 1540–1600. This period was preceded within the interval AD 1445–1495 by some of the coldest temperatures of the past 1,000 years.

Noting "the rate and magnitude of the inferred warming at AD 1540 ... is similar to the rate of change and magnitude observed during the late twentieth century," Cage and Austin (2010) concluded "changes in twentieth century marine climate cannot yet be resolved from a background of natural variability over the last millennium," which is another way of saying that late twentieth-century warming—which has not further manifested itself over the first decade of the twenty-first century—was not unusual enough to validly ascribe it to the concomitant increase in the air's CO_2 content.

It is clear that the Medieval Warm Period and the earlier Roman Warm Period were not the only eras to exhibit surface air temperatures that equaled or eclipsed those of the twentieth century. These warmer-than-present eras achieved their higher temperatures without any help from elevated atmospheric CO_2 concentrations, which were fully 100 ppm less than they are today. Consequently, whatever caused the warmth of those prior eras could be maintaining the warmth of the present era, relieving CO_2 of that undeserved responsibility.

References

Baedke, S.J. and Thompson, T.A. 2000. A 4700-year record of lake level and isostasy for Lake Michigan. *Journal of Great Lakes Research* **26**: 416–426.

Barron, J.A. and Bukry, D. 2007. Solar forcing of Gulf of California climate during the past 2000 yr suggested by diatoms and silicoflagellates. *Marine Micropaleontology* **62**: 115–139.

Bartholy, J., Pongracz, R., and Molnar, Z. 2004. Classification and analysis of past climate information based on historical documentary sources for the Carpathian Basin. *International Journal of Climatology* **24**: 1759–1776.

Black, D.E., Abahazi, M.A., Thunell, R.C., Kaplan, A., Tappa, E.J., and Peterson, L.C. 2007. An 8-century tropical Atlantic SST record from the Cariaco Basin: Baseline variability, twentieth-century warming, and Atlantic hurricane frequency. *Paleoceanography* **22**: 10.1029/2007PA001427.

Blundell, A. and Barber, K. 2005. A 2800-year palaeoclimatic record from Tore Hill Moss, Strathspey, Scotland: the need for a multi-proxy approach to peat-based climate reconstructions. *Quaternary Science Reviews* **24**: 1261–1277.

Büntgen, U., Esper, J., Frank, D.C., Nicolussi, K., and Schmidhalter, M. 2005. A 1052-year tree-ring proxy for Alpine summer temperatures. *Climate Dynamics* **25**: 141–153.

Cage, A.G. and Austin, W.E.N. 2008. Seasonal dynamics of coastal water masses in a Scottish fjord and their potential influence on benthic foraminiferal shell geochemistry. In: Austin, Cage, A.G. and Austin, W.E.N. 2010. Marine climate variability during the last millennium: The Loch Sunart record, Scotland, UK. *Quaternary Science Reviews*: 10.1016/j.quascirev.2010.01.014.

Carrara, P.E., Trimble, D.A., and Rubin, M. 1991. Holocene treeline fluctuations in the northern San Juan Mountains, Colorado, U.S.A., as indicated by radiocarbon-dated conifer wood. *Arctic and Alpine Research* **23**: 233–246.

Chen, J., Wan, G., Zhang, D.D., Chen, Z., Xu, J., Xiao, T., and Huang, R. 2005. The 'Little Ice Age' recorded by sediment chemistry in Lake Erhai, southwest China. *The Holocene* **15**: 925–931.

Chuine, I., Yiou, P., Viovy, N., Seguin, B., Daux, V., and Le Roy Ladurie, E. 2004. Grape ripening as a past climate indicator. *Nature* **432**: 289–290.

D'Arrigo, R., Mashig, E., Frank, D., Jacoby, G., and Wilson, R. 2004. Reconstructed warm season temperatures for Nome, Seward Peninsula, Alaska. *Geophysical Research Letters* **31**: 10.1029/2004GL019756.

D'Arrigo, R., Mashig, E., Frank, D., Wilson, R., and Jacoby, G. 2005. Temperature variability over the past millennium inferred from Northwestern Alaska tree rings. *Climate Dynamics* **24**: 227–236.

Dean, J.S. 1994. The Medieval Warm Period on the southern Colorado Plateau. *Climatic Change* **25**: 225–241.

Eronen, M., Zetterberg, P., Briffa, K.R., Lindholm, M., Merilainen, J., and Timonen, M. 2002. The supra-long Scots pine tree-ring record for Finnish Lapland: Part 1, chronology construction and initial inferences. *The Holocene* **12**: 673–680.

Fleitmann, D., Burns, S.J., Neff, U., Mudelsee, M., Mangini, A., and Matter, A. 2004. Palaeoclimatic interpretation of high-resolution oxygen isotope profiles derived from annually laminated speleothems from Southern Oman. *Quaternary Science Reviews* **23**: 935–945.

Gray, S.T., Graumlich, L.J., Betancourt, J.L., and Pederson, G.T. 2004. A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D. *Geophysical Research Letters* **31**: 10.1029/2004GL019932.

Helama, S., Lindholm, M., Timonen, M., Merilainen, J., and Eronen, M. 2002. The supra-long Scots pine tree-ring record for Finnish Lapland: Part 2, interannual to centennial variability in summer temperatures for 7500 years. *The Holocene* **12**: 681–687.

Holmgren, K., Karlen, W., Lauritzen, S.E., Lee-Thorp, J.A., Partridge, T.C., Piketh, S., Repinski, P., Stevenson, C., Svanered, O., and Tyson, P.D. 1999. A 3000-year high-resolution stalagmite-based record of paleoclimate for northeastern South Africa. *The Holocene* **9**: 295–309.

Holmgren, K., Tyson, P.D., Moberg, A., and Svanered, O. 2001. A preliminary 3000-year regional temperature reconstruction for South Africa. *South African Journal of Science* **99**: 49–51.

Holzhauser, H., Magny, M., and Zumbuhl, H.J. 2005. Glacier and lake-level variations in west-central Europe over the last 3500 years. *The Holocene* **15**: 789–801.

Keigwin, L.D. 1996. The Little Ice Age and Medieval Warm Period in the Sargasso Sea. *Science* **274**: 1504–1508.

Ku, T.L. and Li, H.C. 1998. Speleothems as high-resolution paleoenvironment archives: Records from northeastern China. *Proceedings of the Indian Academy of Science (Earth and Planetary Science)* **107**: 321–330.

Loehle, C. 2004. Climate change: detection and attribution of trends from long-term geologic data. *Ecological Modelling* **171**: 433–450.

Luckman, B.H. and Wilson, R.J.S. 2005. Summer temperatures in the Canadian Rockies during the last millennium: a revised record. *Climate Dynamics* **24**: 131–144.

Mann, M.E., Bradley, R.S., and Hughes, M.K. 1998. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* **392**: 779–787.

Mann, M.E., Bradley, R.S., and Hughes, M.K. 1999. Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.

McIntyre, S. and McKitrick, R. 2003. Corrections to the Mann *et al*. (1998) proxy data base and Northern Hemispheric average temperature series. *Energy and Environment* **14**: 751–771.

Meyer, G.A., Wells, S.G., and Jull, A.J.T. 1995. Fire and alluvial chronology in Yellowstone National Park: climatic and intrinsic controls on Holocene geomorphic processes. *Geological Society of America Bulletin* **107**: 1211–1230.

Munroe, J.S. 2003. Estimates of Little Ice Age climate inferred through historical rephotography, Northern Uinta Mountains, U.S.A. *Arctic, Antarctic, and Alpine Research* **35**: 489–498.

O'Neil, J.R., Clayton, R.N., and Mayeda, T. 1969. Oxygen isotope fractionation in divalent metal carbonates. *Journal of Chemical Physics* **51**: 5547–5558.

Pederson, J.L. 2000. Holocene paleolakes of Lake Canyon, Colorado Plateau: paleoclimate and landscape response from sedimentology and allostratigraphy. *Geological Society of America Bulletin* **112**: 147–158.

Petersen, K.L. 1994. A warm and wet Little Climatic Optimum and a cold and dry Little Ice Age in the southern Rocky Mountains, U.S.A. *Climatic Change* **26**: 243–269.

Pla, S. and Catalan, J. 2005. Chrysophyte cysts from lake sediments reveal the submillennial winter/spring climate variability in the northwestern Mediterranean region throughout the Holocene. *Climate Dynamics* **24**: 263–278.

Richey, J.N., Poore, R.Z., Flower, B.P., and Quinn, T.M. 2007. 1400 yr multiproxy record of climate variability from the northern Gulf of Mexico. *Geology* **35**: 423–426.

Richey, J.N., Poore, R.Z., Flower, B.P., Quinn, T.M., and Hollander, D.J. 2009. Regionally coherent Little Ice Age cooling in the Atlantic Warm Pool. *Geophysical Research Letters* **36**: 10.1029/2009GL040445.

Saenger, C., Cohen, A.L., Oppo, D.W., Halley, R.B., and Carilli, J.E. 2009 . Surface-temperature trends and variability in the low-latitude North Atlantic since 1552. *Nature Geoscience* **2**: 492–495.

Sharma, S., Mora, G., Johnston, J.W., and Thompson, T.A. 2005. Stable isotope ratios in swale sequences of Lake Superior as indicators of climate and lake level fluctuations during the Late Holocene. *Quaternary Science Reviews* **24**: 1941–1951.

Siklosy, Z., Demeny, A., Szenthe, I., Leel-Ossy, S., Pilet, S., Lin, Y., and Shen, C.-C. 2009. Reconstruction of climate variation for the last millennium in the Bukk Mountains, northeast Hungary, from a stalagmite record. *Quarterly Journal of the Hungarian Meteorological Service* **113**: 245–263.

Silenzi, S., Antonioli, F., and Chemello, R. 2004. A new marker for sea surface temperature trend during the last centuries in temperate areas: Vermetid reef. *Global and Planetary Change* **40**: 105–114.

Tinner, W., Lotter, A.F., Ammann, B., Condera, M., Hubschmied, P., van Leeuwan, J.F.N., and Wehrli, M. 2003. Climatic change and contemporaneous land-use phases north and south of the Alps 2300 BC to AD 800. *Quaternary Science Reviews* **22**: 1447–1460.

Weckstrom, J., Korhola, A., Erasto, P., and Holmstrom, L. 2006. Temperature patterns over the past eight centuries in Northern Fennoscandia inferred from sedimentary diatoms. *Quaternary Research* **66**: 78–86.

Yang, B., Kang, X., Brauning, A., Liu, J., Qin, C., and Liu, J. 2010. A 622-year regional temperature history of southeast Tibet derived from tree rings. *The Holocene* **20**: 181–190.

3.3. Recent Temperature Trends

Has the global warming of the past century, and especially of the past few decades, been as dramatic as the IPCC claims it has been, leading to unprecedented high temperatures and unsurpassed temperature variability? In the prior two sections of this chapter we evaluated this claim as it pertained to the past thousand years, with specific focus on the Medieval Warm Period (approximately 800–1200

AD) and the Little Medieval Warm Period (approximately 1400–1550 AD). Here, we evaluate it with respect to temperatures of the past few decades, once again limiting our discussion to papers published after the 2009 NIPCC report.

Wood et al. (2010) constructed a two-century (1802–2009) instrumental record of annual surface air temperature within the Atlantic-Arctic boundary region, using data obtained from "recently published (Klingbjer and Moberg, 2003; Vinther et al., 2006) and historical sources (Wahlen, 1886)" that yielded "four station-based composite time series" that pertain to Southwestern Greenland, Iceland, Tornedalen (Sweden) and Arkhangel'sk (Russia). This operation added 76 years to the previously available record, the credibility of which result, in Wood et al.'s words, "is supported by ice core records, other temperature proxies, and historical evidence." In examining the record, the U.S. and Icelandic researchers found "an irregular pattern of decadal-scale temperature fluctuations over the past two centuries," of which the early twentieth-century warming (ETCW) event—which they say "began about 1920 and persisted until mid-century"—was by far "the most striking historical example."

Wood et al. write, "as for the future, with no other examples in the record quite like the ETCW, we cannot easily suggest how often—much less when—such a comparably large regional climate fluctuation might be expected to appear." Nevertheless, they say that if past is prologue to the future, "it would be reasonable to expect substantial regional climate fluctuations of either sign to appear from time to time," and therefore "singular episodes of regional climate fluctuation should be anticipated in the future." This implies any rapid warming that may subsequently occur within the Atlantic-Arctic boundary region need not be due to rising greenhouse gas concentrations, as it could be caused by the same unknown factor that caused the remarkable ETCW event.

Wood and Overland (2010) write, "the recent widespread warming of the earth's climate is the second of two marked climatic fluctuations to attract the attention of scientists and the public since the turn of the 20th century," and that the first of these—"the major early 20th century climatic fluctuation (~1920–1940)"—has been "the subject of scientific enquiry from the time it was detected in the 1920s." In addition, they write, "the early climatic fluctuation is particularly intriguing now because it shares some of the features of the present warming that has been felt so strongly in the Arctic."

To learn more about the nature of both warmings, Wood and Overland reviewed what is known about the first warming through what they describe as "a rediscovery of early research and new assessments of the instrumental record," which allowed them to compare what they learned about the earlier warming with what is known about the most recent one.

With respect to the first of the two warmings, the U.S. researchers say "there is evidence that the magnitude of the impacts on glaciers and tundra landscapes around the North Atlantic was larger during this period than at any other time in the historical period." In addition, they report, "the ultimate cause of the early climatic fluctuation was not discovered by early authors and remains an open question," noting "all of the leading possibilities recognized today were raised by the 1950s, including internal atmospheric variability, anthropogenic greenhouse gas (CO_2) forcing, solar variability, volcanism, and regional dynamic feedbacks (e.g. Manley, 1961)." However, they note, "greenhouse gas forcing is not now considered to have played a major role (Hegerl et al., 2007)." Thus they suggest "the early climatic fluctuation was a singular event resulting from intrinsic variability in the large-scale atmosphere-ocean-land system and that it was likely initiated by atmospheric forcing."

Wood and Overland conclude the "early climatic fluctuation is best interpreted as a large but random climate excursion imposed on top of the steadily rising global mean temperature associated with anthropogenic forcing." However, it could just as easily be concluded that the steadily rising global mean temperature was Earth's natural recovery from the global chill of the Little Ice Age.

White et al. (2010) published a comprehensive review of past climate change in Earth's north polar region. They began their work by describing how "processes linked with continental drift have affected atmospheric circulation, ocean currents, and the composition of the atmosphere over tens of millions of years" and how "a global cooling trend over the last 60 million years has altered conditions near sea level in the Arctic from ice-free year-round to completely ice covered." They also report "variations in Arctic insolation over tens of thousands of years in response to orbital forcing have caused regular cycles of warming and cooling that were roughly half the size of the continental-drift-linked changes" and that, in turn, this glacial-interglacial cycling "was punctuated by abrupt millennial oscillations, which near the North Atlantic were roughly half as large as the glacial-interglacial cycles." Finally, they note "the current interglacial, the Holocene, has been influenced by brief cooling events from single volcanic eruptions, slower but longer lasting changes from random fluctuations in the frequency of volcanic eruptions, from weak solar variability, and perhaps by other classes of events."

In comparing the vast array of past climate changes in the Arctic with what the IPCC claims to be the "unprecedented" anthropogenic-induced warming of the past several decades, White et al. conclude, "thus far, human influence does not stand out relative to other, natural causes of climate change." In fact, they state, the data "clearly show" that "strong natural variability has been characteristic of the Arctic at all time scales considered," and they reiterate the data suggest "that the human influence on rate and size of climate change thus far does not stand out strongly from other causes of climate change."

Ladd and Gajewski (2010) evaluate the position of the Arctic front—defined as "the semi-permanent, discontinuous front between the cold Arctic air mass and the intermediate Polar air mass, bounded in the south by the Polar Front (Oliver and Fairbridge, 1987)"—based on gridded data obtained from the National Center for Environmental Prediction/National Center for Atmospheric Research reanalysis (NNR) for each July between 1948 and 2007, and from 1958 to 2002 using data from the European Centre for Medium-Range Weather Forecasts ERA-40, as well as the period 1948-1957 "for comparison with the results of Bryson (1966)."

The two researchers report "the position of the July Arctic front varies significantly through the period 1948–2007," but they find it does so "with a mean position similar to that found by Bryson (1966)," which "close similarity," as they describe it, "is striking, given that the Bryson study was completed over 40 years ago." Indeed. This front is in the part of the world that theory and computer models predict should be warming faster than nearly all other parts of the globe. If the IPCC's claim were true that the Earth warmed at a rate and to a level that was unprecedented over the past two millennia, it is highly unlikely the Arctic front would have remained stationary for more than four decades.

Box et al. (2009), using "a set of 12 coastal and 40 inland ice surface air temperature records in combination with climate model output," identified "long-term (1840–2007) monthly, seasonal, and annual spatial patterns of temperature variability over a continuous grid covering Greenland and the inland ice sheet." They then compared "the 1919–32 and 1994–2007 warming episodes" and made "a comparison of Greenland ice sheet surface air temperature temporal variability with that of the Northern Hemisphere average," obtaining the near-surface air temperature history of Greenland reproduced Figure 3.3.1, along with the corresponding history of Northern Hemispheric near-surface air temperature.

Based on the results depicted in the figure, the four researchers determined "the annual whole ice sheet 1919–32 warming trend is 33% greater in magnitude than the 1994–2007 warming," and "in contrast to the 1920s warming, the 1994–2007 warming has not surpassed the Northern Hemisphere anomaly." They note, "an additional 1.0°–.5°C of annual mean warming would be needed for Greenland to be in phase with the Northern Hemisphere pattern." Thus there does not appear to be anything unusual, unnatural, or unprecedented about the nature of Greenland's 1994–2007 warming episode. It is much less impressive than the 1919–1932 warming, and it is even less impressive when it is realized that the atmosphere's CO_2 concentration rose by only about 5 ppm during the earlier period of stronger warming but by fully 25 ppm (five times more) during the later period of weaker warming.

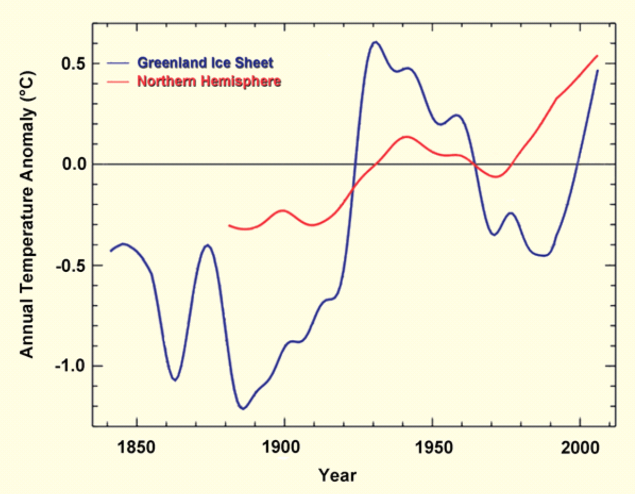


Figure 3.3.1 Low-pass-filtered Greenland and Northern Hemispheric near-surface air temperature anomalies with respect to the 1951-1980 base period vs. time. Adapted from Box et al. (2009).

A long succession of climate models has consistently suggested that anthropogenic-induced global warming should be significantly amplified in Earth's polar regions and that the first signs of man's expected impact on the world's weather should be manifest in that part of the planet. Yet research on Antarctic climate just prior to 2009 found the Antarctic Peninsula was warming rapidly but the rest of Antarctica was not (Chapman and Walsh, 2007; Monaghan et al., 2008). While the warming of the peninsula was deemed to be a "canary in the coal mine" by alarmists, the lack of warming over the rest of the continent posed a difficult challenge in reconciling observational data with model projections of CO_2-induced global warming. However, the sparseness of weather stations across this huge continent left great uncertainty about these conclusions.

Against this backdrop, Steig et al. (2009) provided a method to increase the density of data by utilizing Advanced Very High Resolution Radiometer (AVHRR) satellite data to provide spatial and temporal data infilling. Their analysis claimed to show warming was in fact spread over much of West Antarctica, a result that would be in harmony with theory and climate models. Their result was featured on the cover of *Nature* magazine and widely covered in the press as "proof" that warming in Antarctica was worse than thought. But was it?

O'Donnell et al. (2011) investigated the Steig et al. paper, finding they made statistical and analytical mistakes, including (a) improper calibration, (b) spatial structure differences between the infilling operation and recovery of gridded estimates, and (c) suboptimal determination of regularization parameters. The net effect of these errors was to improperly model spatial correlation of the data, which produced a spurious warming in West Antarctica and altered other spatial patterns and trend statistics. Specifically, O'Donnell et al. say "our results—including the strong Peninsula warming, insignificant cooling to neutral trend in the Ross region, and generally insignificant trends elsewhere on the continent—compare more favorably to Chapman & Walsh (2007) and Monaghan et al. (2008) than [Steig et al.]," which leaves the majority of Antarctica showing very little trend, or in other words, no discernible response to rising greenhouse gas concentrations.

In a paper titled "A strong bout of natural cooling in 2008" published in *Geophysical Research Letters*, Perlwitz et al. (2009) discuss the "precipitous drop in North American temperature in 2008, commingled with a decade-long fall in global mean temperatures." The authors begin their narrative by noting there has been "a decade-long decline (1998–2007) in globally averaged temperatures from the record heat of 1998," citing Easterling and Wehner (2009). In further describing this phenomenon, they note U.S. temperatures in 2008 "not only declined from near-record warmth of prior years, but were in fact colder than the official 30-year reference climatology (-0.2°C versus the 1971–2000 mean) and further were the coldest since at least 1996."

With respect to the geographical origin of this "natural cooling," as they describe it, the five researchers point to "a widespread coolness of the tropical-wide oceans and the northeastern Pacific," focusing on the Niño 4 region, where they report "anomalies of about -1.1°C suggest a condition colder than any in the instrumental record since 1871."

The researchers then push ahead in search of the cause of the global and U.S. coolings that sparked their original interest, seeking out what connects them with other more primary phenomena, the anomalous and significant oceanic coolings. Perlwitz et al. first discount volcanic eruptions, noting "there were no significant volcanic events in the last few years." Next, they write that solar forcing "is also unlikely," because its radiative magnitude is considered to be too weak to elicit such a response. And these two castaway causes thus leave them with "coupled ocean-atmosphere-land variability" as the "most likely" cause of the anomalous coolings.

In regard to Perlwitz et al.'s dismissal of solar forcing, however, the jury is still out with respect to the interaction of the solar wind with the influx of cosmic rays to Earth's atmosphere and their subsequent impact on cloud formation, which may yet prove to be substantial (as discussed earlier in this chapter). And with respect to their final point, the suite of real-world ocean-atmosphere-land interactions is highly complex and also not fully understood. Indeed, there may even be important phenomena operating within this realm of which the entire scientific community is ignorant. Some of those phenomena may be strong enough to compensate for anthropogenic-induced increases in greenhouse gas emissions, so that other natural phenomena dictate the ever-changing state of Earth's climate

References

Box, J.E., Yang, L., Bromwich, D.H., and Bai, L.-S. 2009. Greenland ice sheet surface air temperature variability: 1840–2007. *Journal of Climate* **22**: 4029–4049.

Bryson, R.A. 1966. Air masses, streamlines, and the boreal forest. *Geographical Review* **8**: 228–269.

Chapman, W. L. and Walsh, J.E. 2007. A synthesis of Antarctic temperatures. *Journal of Climate* **20**: 4096–4117.

Easterling, D.R. and Wehner, M.F. 2009. Is the climate warming or cooling? *Geophysical Research Letters* **36**: 10.1029/2009GL037810.

Hegerl, G.C., Zwiers, F.W., Braconnot, P., Gillett, N.P., Luo, Y., Marengo Orsini, J.A., Nicholls, N., Penner, J.E., and Stott, P.A. 2007. Understanding and attributing climate change. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon, et al.. New York, NY: Cambridge University Press.

Klingbjer, P. and Moberg, A. 2003. A composite monthly temperature record from Tornedalen in northern Sweden, 1802–2002. *International Journal of Climatology* **23**: 1465–1494.

Ladd, M.J. and Gajewski, K. 2010. The North American summer Arctic front during 1948–2007. *International Journal of Climatology* **30**: 874–883.

Manley, G. 1961. Solar variations, climatic change and related geophysical problems. *Nature* **190**: 967–968.

Monaghan, A.J., Bromwich, D.H., Chapman, W., and Comiso, J. C. 2008. Recent variability and trends of Antarctic near-surface temperature. *Journal of Geophysical Research* **113**: doi:1029/2007JD009094.

O'Donnell, R., Lewis, N., McIntyre, S., and Condon, J. 2011. Improved methods for PCA-based reconstructions: case study using the Steig et al. (2009) Antarctic temperature reconstruction. *Journal of Climate* **24**: 2099–2115.

Oliver, J.E. and Fairbridge, R.W., editors. 1987. *The Encyclopedia of Climatology*. New York, NY: Van Nostrand Reinhold.

Perlwitz, J., Hoerling, M., Eischeid, J., Xu, T., and Kumar, A. 2009. A strong bout of natural cooling in 2008. *Geophysical Research Letters* **36**: 10.1029/2009GL041188.

Steig, E.J., Schneider, D.P., Rutherford, . D., Mann, M.E., Comiso, J.C., and Shindell, D.T. 2009. Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year. *Nature* **457**: 459–463.

Vinther, B.M., Anderson, K.K., Jones, P.D., Briffa, K.R., and Cappelen, J. 2006. Extending Greenland temperature records into the late eighteenth century. *Journal of Geophysical Research* **111**: 10.1029/2005JD006810.

Wahlen, E. 1886. Wahre Tagesmittel und Tagliche Variationen der Temperatur an 18 Stationen des Russichen Reiches, Suppl. Rep. Meterol. St. Petersburg, Russia: S. Halbleder.

White, J.W.C., Alley, R.B., Brigham-Grette, J., Fitzpatrick, J.J., Jennings, A.E., Johnsen, S.J., Miller, G.H., Nerem, R.S., and Polyak, L. 2010. Past rates of climate change in the Arctic. *Quaternary Science Reviews* **29**: 1716–1727.

Wood, K.R. and Overland, J.E. 2010. Early 20th century Arctic warming in retrospect. *International Journal of Climatology* **30**: 1269–1279.

Wood, K.R., Overland, J.E., Jonsson, T., and Smoliak, B.V. 2010. Air temperature variations on the Atlantic-Arctic boundary since 1802. *Geophysical Research Letters* **37**: 10.1029/2010GL044176.

3.4 Urban Heat Islands

Population growth and the clustering of people in cities can lead to localized warming from changes in land structure and land use that is both more rapid and much greater (by as much as an order of magnitude) than what the IPCC characterizes as the "unprecedented" warming of the twentieth century.

In the 2009 NIPCC report, Idso and Singer (2009) highlighted scores of studies demonstrating the impact of this phenomenon on temperatures and how population-growth-induced warming—spread across the world—is often incorrectly construed to be CO_2-induced global warming. Here we highlight three additional papers investigating this phenomenon, beginning with a study of the urban heat island along the U.S./Mexico border.

Mexicali City borders the United States at the northern end of Mexico's Baja California. It is an urban settlement that had its beginnings in the first decade of the twentieth century. At that time it had an area of approximately 4 km^2; by 1980 it covered an area in excess of 40 km^2, and by 2005 it covered more than 140 km^2.

Working with daily records of maximum and minimum temperature from six weather stations in Mexicali City and its surroundings covering the period 1950–2000, and with a climatic network of rural and urban weather stations in Mexicali and its valley and the Imperial Valley, California, over the contemporary period (2000–2005), Garcia Cueto et al. (2009) characterized the spatial and temporal development of the city's urban heat island over the latter half of the twentieth century and the first five years of the twenty-first century. They found Mexicali City "changed from being a cold island (1960–1980) to a heat island with a maximum intensity of 2.3°C in the year 2000, when it was compared with rural weather stations of Imperial, California." They note "the replacement of irrigated agricultural land by urban landscapes, anthropogenic activity and population growth, appear to be the major factors responsible for the observed changes." And from the "more updated information (2000–2005)," they learned "the greatest intensity of the urban heat island was in winter with a value of 5.7°C, and the lowest intensity in autumn with 5.0°C."

In another study, Rosenzweig et al. (2009) compared "the possible effectiveness of heat island mitigation strategies to increase urban vegetation, such as planting trees or incorporating vegetation into rooftops, with strategies to increase the albedo of impervious surfaces." With respect to the magnitude of the problem they were seeking to address, they report "surface air temperatures elevated by at least 1°C have been observed in New York City for more than a century (Rosenthal et al., 2003; Gaffin et al., 2008), and the heat island signal, measured as the difference between the urban core and the surrounding rural surface air temperature readings taken at National Weather Service stations, averages ~4°C on summer nights (Kirkpatrick and Shulman, 1987; Gedzelman et al., 2003; Gaffin et al., 2008)," with the greatest temperature differences typically being sustained "between midnight and 0500 Eastern Standard Time (EST; Gaffin et al., 2008)." And on a day that they studied quite intensively (14 August 2002), they report that 0600 EST "the city was several degrees warmer than the suburbs, and up to 8°C warmer than rural areas within 100 km of the city."

With respect to mitigation strategies, the 12 researchers determined "the most effective way to reduce urban air temperature is to maximize the amount of vegetation in the city with a combination of tree planting and green roofs." Based on modeling studies of these approaches, for example, they estimated this strategy could reduce simulated citywide urban air temperature by 0.4°C on average, and 0.7°C at 1500 EST, while reductions of up to 1.1°C at 1500 EST could be expected in some Manhattan and Brooklyn neighborhoods, "primarily because there is more available area in which to plant trees and install vegetated roofs."

These several findings reveal New York City already has experienced an urban-induced warming equivalent to what is predicted to occur by the end of the current century as a result of business-as-usual greenhouse gas emissions, and that planting additional vegetation throughout the city would likely moderate its thermal environment more than all of the greenhouse-gas emissions reductions the world's governments are ever likely to make.

Most urban heat island (UHI) studies have evaluated its magnitude by means of ground-based measurements of near-surface air temperature made at urban and rural weather stations, where the urban-rural air temperature difference is expressed most strongly at night. Imhoff et al. (2010), however, employed satellite-based measurements of surface temperature and found this alternative form of the UHI was most strongly expressed during the day.

Specifically, in a study of 38 of the most populous cities in the continental United States and their rural surroundings, Imhoff et al. obtained land surface temperature (LST) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on NASA's Earth Observing System (EOS) satellites, which they used in a spatial analysis to assess UHI skin temperature amplitude and its relationship to development intensity, size, and ecological setting over three annual cycles (2003–2005), where urban impervious surface area (ISA) was obtained from the Landsat TM-based NLCD 2001 dataset. Their results indicated a city's fractional ISA was a good linear predictor of LST for all cities in the continental United States in all biomes except deserts and xeric shrublands, and that the fraction of ISA explained about 70 percent of the total variance in LST for all cities combined, with the highest correlations (90 percent) in the northeastern United States, where urban areas are often embedded in temperate broadleaf and mixed forests.

They also determined the largest urban-rural LST differences for all biomes occurred during the summer around midday, and the greatest amplitudes were found for urban areas that displaced forests (6.5–9.0°C) followed by temperate grasslands (6.3°C) and tropical grasslands and savannas (5.0°C). Finally, they determined the contrast between urban cores and rural zones was typically "accentuated during the time when the vegetation is physiologically active, especially in forested lands" and "the amplitude of the

UHI is significantly diminished during the winter season when vegetation loses its leaves or is stressed by lower temperatures." Consequently, and based on these findings, Imhoff et al. concluded "the use of ISA as an estimator of the extent and intensity of urbanization is more objective than population density based methods and can be consistently applied across large areas for inter-comparison of impacts on biophysical processes."

Considering each of the three studies described above, plus a host of others discussed in the 2009 NIPCC report, it is difficult to see how the IPCC (2007) can claim to have ferreted out all significant influences of the world's many and diverse urban heat islands from the temperature databases they use to portray the supposedly unprecedented warming of the past few decades.

References

Gaffin, S.R., et al. 2008. Variations in New York City's urban heat island strength over time and space. *Theoretical and Applied Climatology* **94**: 1–11.

Garcia Cueto, O.R., Martinez, A.T., and Morales, G.B. 2009. Urbanization effects upon the air temperature in Mexicali, B.C., Mexico. *Atmosfera* **22**: 349–365.

Gedzelman, S.D., Austin, S., Cermak, R., Stefano, N., Partridge, S., Quesenberry, S., and Robinson, D.A. 2003. Mesoscale aspects of the urban heat island around New York City. *Theoretical and Applied Climatology* **75**: 29–42.

Idso, C.D. and Singer, S.F. 2009. Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC). Chicago, IL: The Heartland Institute.

Imhoff, M.L., Zhang, P., Wolfe, R.E., and Bounoua, L. 2010. Remote sensing of the urban heat island effect across biomes in the continental USA. *Remote Sensing of Environment* **114**: 504–513.

IPCC. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by S. Solomon, et al. Cambridge, UK: Cambridge University Press.

Kirkpatrick, J.S. and Shulman, M.D. 1987. A statistical evaluation of the New York City-northern New Jersey urban heat island effect on summer daily minimum temperature. *National Weather Digest* **12**: 12.

Rosenthal, J., Pena Sastre, M., Rosenzweig, C., Knowlton, K., Goldberg, R., and Kinney, P. 2003. One hundred years of New York City's "urban heat island": Temperature trends and public health impacts. *EOS, Transactions of the American Geophysical Union* **84** (Fall Meeting Supplement), Abstract U32A–0030.

Rosenzweig, C., Solecki, W.D., Parshall, L., Lynn, B., Cox. J., Goldberg, R. Hodges, S., Gaffin, S., Slosberg, R.B., Savio, P., Dunstan, F., and Watson, M. 2009. Mitigating New York City's heat island. *Bulletin of the American Meteorological Society* **90**: 1297–1312.

3.5 El Niño/Southern Oscillation

Computer model simulations have given rise to three claims regarding the influence of global warming on El Niño/Southern Oscillation (ENSO) events: (1) global warming will increase the frequency of ENSO events, (2) global warming will increase the intensity of ENSO events, and (3) weather-related disasters will be exacerbated under El Niño conditions. The 2009 NIPCC report (Idso and Singer, 2009) tested the validity of these assertions and demonstrated they are in conflict with the observational record. In this section we highlight several studies that suggest the virtual world of ENSO, as simulated by state-of-the-art climate models, is at variance with reality, once again drawing upon studies not included in, or published subsequent to, the 2009 NIPCC report.

Examining the subject over the past 3,500 years, Langton et al. (2008) used geochemical data—obtained from a sediment core extracted from the shallow-silled and intermittently dysoxic Kau Bay in Halmahera, Indonesia (1°N, 127.5°E)—to reconstruct century-scale climate variability within the Western Pacific Warm Pool. In doing so, they found "basin stagnation, signaling less El Niño-like conditions, occurred during the time frame of the Medieval Warm Period (MWP), from ca. 1000 to 750 years BP," which was "followed by an increase in El Niño activity that culminated at the beginning of the Little Ice Age ca. 700 years BP." Thereafter, their record suggests "the remainder of the Little Ice Age was characterized by a steady decrease in El Niño activity with warming and freshening of the surface water that continued to the present." And they say "the chronology of flood deposits in Laguna Pallcacocha, Ecuador (Moy et al., 2002; Rodbell et al., 1999), attributed to intense El Niño events, shows similar century-scale periods of increased [and decreased] El Niño frequency."

The nine researchers concluded "the finding of similar century-scale variability in climate archives from two El Niño-sensitive regions on opposite sides of the tropical Pacific strongly suggests that they are dominated by the low-frequency variability of ENSO-related changes in the mean state of the surface ocean in [the] equatorial Pacific." And that "century-scale variability," as they describe it, suggests global warming typically tends to retard El Niño activity, while global cooling tends to promote it.

In a contemporaneous study, Nicholls (2008) prefaced his contribution to the topic by noting there has been a "long-running debate as to how the El Niño-Southern Oscillation (ENSO) might react to global warming," and "the focus in most model studies on ENSO and climate change has been on whether the Pacific will tend to a more permanent El Niño state as the world warms due to an enhanced greenhouse effect." In an attempt to resolve the issue, Nicholls examined "trends in the seasonal and temporal behavior of ENSO, specifically its phase-locking to the annual cycle over the past 50 years," where phase-locking, in his words, "means that El Niño and La Niña events tend to start about April–May and reach a maximum amplitude about December–February," which is why he examined trends in ENSO indices for each month of the year.

The Australian researcher determined "there has been no substantial modulation of the temporal/seasonal behavior of the El Niño-Southern Oscillation"—as measured by the sea surface temperature averaged across the region 5°S–5°N by 120°W–170°W, and the Southern Oscillation Index (the non-standardized difference between sea level pressures at Tahiti and Darwin)—over the past 50 years, during what he describes as "a period of substantial growth in the atmospheric concentrations of greenhouse gases and of global warming." Nicholls' finding that "the temporal/seasonal nature of the El Niño-Southern Oscillation has been remarkably consistent through a period of strong global warming" clearly repudiates the early climate-model-derived inferences of Timmermann et al. (1999), Collins (2000a,b), and Cubasch et al. (2001) that global warming will increase both the frequency and intensity of ENSO events. Those projections (not surprisingly) followed fast on the heels of the powerful 1997–98 El Niño described by some as "the strongest in recorded history" (Jimenez and Cortes, 2003).

Lee and McPhaden (2010) reported "satellite observations suggest that the intensity of El Niño events in the central-equatorial Pacific (CP) has almost doubled in the past three decades," citing the work of Cane et al. (1997) and Cravatte et al. (2009), while noting this phenomenon "appears to be consistent with theoretically predicted change of the background sea surface temperature under global warming scenarios." To test this hypothesis, they used satellite observations of sea surface temperature (SST) over the past three decades "to examine SST in the CP region, distinguishing between the increases in El Niño intensity and changes in background SST."

In conducting their analysis, the two U.S. researchers discovered the SSTs in the CP region during El Niño years were becoming significantly higher while those during La Niña and neutral years were not. Therefore, they reasoned "the increasing intensity of El Niño events in the CP region is not simply the result of the well-documented background warming trend in the western-Pacific warm pool," but "it is the increasing amplitude of El Niño events that causes a net warming trend of SST in the CP region." In light of these findings, they suggest "at least for the past three decades, the warming of the warm pool in the CP region is primarily because of more intense El Niño events in that region." In addition, they report "in contrast to the CP region, the intensity of El Niño events in the EP region does not have a warming trend, and even has a cooling trend (though not significant at the 90% level of confidence) over the three-decade period." Thus, they conclude further investigation is needed "to understand these issues better, given the uncertainty surrounding causal mechanisms and the implications the observed changes have for global climate and societal impacts."

In a contemporaneous study focusing more on the modeling of ENSO behavior, Collins et al. (2010) reviewed the findings of what they describe as "a hierarchy of mathematical models [that] have been used to explain the dynamics, energetics, linear stability and nonlinearity of ENSO," while noting "complex coupled global circulation models have become powerful tools for examining ENSO dynamics and the interactions between global warming and ENSO."

Those powerful tools revealed, among other things, that "the tropical easterly trade winds are expected to weaken; surface ocean temperatures are expected to warm fastest near the equator and more slowly farther away; the equatorial thermocline that marks the transition between the wind-mixed upper ocean and deeper layers is expected to shoal; and the temperature gradients across the thermocline are expected to become steeper." However, they state "it is not yet possible to say whether ENSO activity will be enhanced or damped, or if the frequency of events will change." Nor, it could be added, whether their several expectations will ever come to pass, as Collins et al. conclude "it is not clear at this stage which way ENSO variability will tip," adding, "as far as we know, it could intensify, weaken, or even undergo little change depending on the balance of changes in the underlying processes."

An even more damning assessment of the state of the ENSO modeling enterprise was given by Jin et al. (2008), who investigated the overall skill of ENSO prediction in retrospective forecasts made with ten different state-of-the-art ocean-atmosphere coupled general circulation models (CGCMs)—which they describe as "coupled ocean-land-atmosphere dynamical seasonal prediction systems"—with respect to their ability to "hindcast" real-world observations for the 22 years from 1980 to 2001.

The results indicated, according to the 12 U.S., South Korean, and Japanese researchers, that almost all models have problems simulating the mean equatorial sea surface temperature (SST) and its annual cycle. In fact, they write, "none of the models we examined attain good performance in simulating the mean annual cycle of SST, even with the advantage of starting from realistic initial conditions," while noting "with increasing lead time, this discrepancy gets worse" and "the phase and peak amplitude of westward propagation of the annual cycle in the eastern and central equatorial Pacific are different from those observed." What is more, they find "ENSO-neutral years are far worse predicted than growing warm and cold events" and "the skill of forecasts that start in February or May drops faster than that of forecasts that start in August or November." They and others refer to this behavior as "the spring predictability barrier," which gives an indication of the difficulty of what they are attempting to do.

Given these findings, Jin et al. conclude "accurately predicting the strength and timing of ENSO events continues to be a critical challenge for dynamical models of all levels of complexity," revealing that even the best ocean-atmosphere CGCMs are presently unable to make reasonably accurate predictions of ENSO occurrence and behavior.

References

Cane, M.A., Clement, A.C., Kaplan, A., Kushnir, Y., Pozdnyakov, D., Seager, R., Zebiak, S.E., and Murtugudde, R. 1997. Twentieth-century sea surface temperature trends. *Science* **275**: 957–960.

Collins, M. 2000a. Understanding uncertainties in the response of ENSO to greenhouse warming. *Geophysical Research Letters* **27**: 3509–3513.

Collins, M. 2000b. The El Niño Southern Oscillation in the second Hadley center coupled model and its response to greenhouse warming. *Journal of Climate* **13**: 1299–1312.

Collins, M., An, S.-I., Cai, W., Ganachaud, A., Guilyardi, E., Jin, F.-F., Jochum, M., Lengaigne, M., Power, S., Timmermann, A., Vecchi, G., and Wittenberg, A. 2010. The impact of global warming on the tropical Pacific Ocean and El Niño. *Nature Geoscience* **3**: 391–397.

Cravatte, S., Delcroix, T., Zhang, D., McPhaden, M., and Leloup, J. 2009. Observed freshening and warming of the western Pacific warm pool. *Climate Dynamics* **33**: 565–589.

Cubasch, U., Meehl, G.A., Boer, G.J., Stouffer, R.J., Dix, M., Noda, A., Senior, C.A., Raper, S., and Yap, K.S. 2001. Projections of future climate change. In *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the 3rd Assessment Report of the Intergovernmental Panel on Climate Change,* edited by J.T. Houghton, et al., 525–582. Cambridge, UK Cambridge University Press.

Idso, C.D. and Singer, S.F. 2009. *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

Jimenez, C.E. and Cortes, J. 2003. Coral cover change associated to El Niño, eastern Pacific, Costa Rica, 1992-2001. *Marine Ecology* **24**: 179–192.

Jin, E.K., Kinter III, J.L., Wang, B., Park, C.-K., Kang, I.-S., Kirtman, B.P., Kug, J.-S., Kumar, A., Luo, J.-J., Schemm, J., Shukla, J., and Yamagata, T. 2008. Current status of ENSO prediction skill in coupled ocean-atmosphere models. *Climate Dynamics* **31**: 647–664.

Langton, S.J., Linsley, B.K., Robinson, R.S., Rosenthal, Y., Oppo, D.W., Eglinton, T.I., Howe, S.S., Djajadihardja, Y.S., and Syamsudin, F. 2008. 3500 yr record of centennial-scale climate variability from the Western Pacific Warm Pool. *Geology* **36**: 795–798.

Lee, T. and McPhaden, M.J. 2010. Increasing intensity of El Niño in the central-equatorial Pacific. *Geophysical Research Letters* **37**: 10.1029/2010GL044007.

Moy, C.M., Seltzer, G.O., Rodbell, D.T., and Anderson, D.M. 2002. Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature* **420**: 162–165.

Nicholls, N. 2008. Recent trends in the seasonal and temporal behaviour of the El Niño-Southern Oscillation. *Geophysical Research Letters* **35**: 10.1029/2008GL034499.

Rodbell, D.T., Enfield, D.B., Newman, J.H., Seltzer, G.O., Anderson, D.M., and Abbott, M.B. 1999. An ~15,000-year record of El Niño-driven alluviation in southwestern Ecuador. *Science* **283**: 516–520.

Timmermann, A., Oberhuber, J., Bacher, A., Esch, M., Latif, M., and Roeckner, E. 1999. Increased El Niño frequency in a climate model forced by future future greenhouse warming. *Nature* **398**: 694–696.

4

Observations and Projections: Cryosphere, Ocean Dynamics, and Hydrology

4. Observations and Projections: Cryosphere, Ocean Dynamics, and Hydrology

Introduction

The effects of climate change are visible in the cryosphere (places on Earth so cold that water is usually in solid form as snow or ice), in sea level change and other ocean dynamics, in patterns of precipitation, and in rivers and streamflow. Computer models have been used to project trends in each of these areas, while observations and data are available to test those projections.

According to the Intergovernmental Panel on Climate Change (IPCC), "recent decreases in ice mass are correlated with rising surface air temperatures. This is especially true in the region north of 65°N, where temperatures have increased by about twice the global average from 1965 to 2005" (IPCC 2007, p. 339). The IPCC goes on to report decreased snow cover "in most regions, especially in spring and summer," freeze-up dates in the Northern Hemisphere occurring later, breakup dates occurring earlier, declines in sea ice extent, and similar findings (ibid.).

In their 2009 Nongovernmental International Panel on Climate Change (NIPCC) report, Idso and Singer (2009) contended that many of the IPCC's findings on this subject were incorrect, the result of cherry-picking data or misrepresenting available research. The authors found,

> Glaciers around the world are continuously advancing and retreating, with a general pattern of retreat since the end of the Little Ice Age. There is no evidence of an increased rate of melting overall since CO_2 levels rose above their pre-industrial levels, suggesting CO_2 is not responsible for glaciers melting.
>
> Sea ice area and extent have continued to increase around Antarctica over the past few decades. Evidence shows that much of the reported thinning of Arctic sea ice that occurred in the 1990s was a natural consequences of changes in ice dynamics caused by an atmospheric regime shift, of which there have been several in decades past and will likely be several in the decades to come, totally irrespective of past or future changes in the air's CO_2 content. The Arctic appears to have recovered from its 2007 decline (Idso and Singer 2009, p. 4).

Similar disagreement between IPCC and NIPCC was found on ocean dynamics, with IPCC claiming "there is *high confidence* that the rate of sea level rise has increased between the mid-19th and the mid-20th centuries" (IPCC AR4, p. 387, emphasis in the original) while NIPCC found "the mean rate of global sea level rise has not accelerated over the recent past" (Idso and Singer 2009, p. 4). While the IPCC claimed "it is *likely* that … heavy precipitation events will continue to become more frequent" (IPCC AR4, p. 15), NIPCC said "global studies of precipitation trends show no net increase and no consistent trend with CO_2, contradicting climate model predictions that warming should cause increased precipitation" (Idso and Singer 2009, p. 4).

This chapter reinforces NIPCC's findings of 2009, with new research finding less melting of ice in the Arctic, Antarctic, and mountaintops than previously feared, no sign of acceleration of sea-level rise in recent decades, no trend over the past 50 years in changes to the Atlantic meridional overturning circulation (MOC), and no changes in precipitation patterns or river flows that could be attributed to rising CO_2 levels.

References

Idso, C.D. and Singer, S.F. 2009. *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by S. Solomon, et al. Cambridge, UK: Cambridge University Press.

4.1. The Cryosphere

4.1.1. Antarctica

The study of Antarctica's past, present, and expected future climate has provided valuable insights and spurred contentious debate over issues pertaining to global climate change. Although many individuals concerned about global warming expect Earth's polar regions to manifest the earliest and most severe responses to CO_2-induced climate change, real-world data from Antarctica do not support such expectations. In the 2009 NIPCC report, Idso and Singer (2009) discussed the results of several scientific analyses that demonstrated there is nothing unusual, unprecedented, or unnatural about the climate on this vast continent of ice. In this interim report we highlight the results of several more papers in support of their findings.

Starting with the Antarctic Peninsula, Hall (2009) offered "a summary of existing data concerning Holocene glacial extent and fluctuations within Antarctica and the sub-Antarctic islands." She begins by noting, "in several areas, ice extent was less than at present in mid-Holocene time," which suggests, in her words, "the magnitude of present ice recession and ice-shelf collapse is not unprecedented." She also reports "the first Neoglacial ice advances occurred at ~5.0 ka" and "glaciers in all areas underwent renewed growth in the past millennium." More specifically, Hall states, "the Antarctic Peninsula, along with the adjacent sub-Antarctic islands, yields one of the most complete Holocene glacial records from the southern high latitudes," and most of these locations "show an advance in the past few centuries, broadly coincident with what is known elsewhere as the Little Ice Age." Likewise, she reports "glaciers on most if not all" of the Indian/Pacific sector sub-Antarctic Islands "underwent advance in the last millennium, broadly synchronous with the Little Ice Age." And she notes "glaciers in all areas" have "subsequently undergone recession," but only in "the past 50 years."

In another study, Tedesco and Monaghan (2010) reviewed what has been learned about the melting of snow and ice over all of Antarctica since 1979, when routine measurement of the phenomenon via space-borne passive microwave radiometers first began. Their results revealed that over the course of the past three decades the continent-wide snow and ice melting trend was "negligible." They also observe that during the 2008–2009 austral summer, scientists from the City University of New York and the U.S. National Center for Atmospheric Research observed that snow and ice melt was "a record low for the 30-year period between 1979 and 2009," or as they alternatively describe it, "a new historical minimum." In addition, they note, "December 2008 temperature anomalies were cooler than normal around most of the Antarctic margin, and the overall sea ice extent for the same month was more extensive than usual."

Turning our attention to the West Antarctic Ice Sheet (WAIS), often described as the world's most unstable large ice sheet, it has been postulated that future global warming may cause the WAIS to disappear, resulting in a sea-level rise of several millimeters per year. Yet three groups of researchers have shown in recent papers that the WAIS is likely much more stable than the models predict.

Gomez et al. (2010) state that several studies (Oppenheimer, 1998; Meehl et al., 2007; Vaughan, 2008; Smith et al., 2009) have suggested "climate change could potentially destabilize marine ice sheets, which would affect projections of future sea-level rise." The studies specifically highlight "an instability mechanism (Weertman, 1974; Thomas and Bentley, 1978; Schoof, 2007; Katz and Worster, 2010)" which they say "has been predicted for marine ice sheets such as the West Antarctic ice sheet that rest on reversed bed slopes, whereby ice-sheet thinning or rising sea levels leads to irreversible retreat of the grounding line."

Noting existing analyses of this particular instability mechanism "have not accounted for deformational and gravitational effects that lead to a sea-level fall at the margin of a rapidly shrinking ice sheet," Gomez et al. go on to present "a suite of predictions of gravitationally self-consistent sea-level change following grounding-line migration," in which they "vary the initial ice-sheet size and also consider the contribution to sea-level change from various sub-regions of the simulated ice sheet."

The four researchers report their new results "demonstrate that gravity and deformation-induced sea-level changes local to the grounding line contribute a stabilizing influence on ice sheets grounded on reversed bed slopes," contrary to previously prevailing assumptions based on earlier analyses of the subject. In fact, they conclude, "local sea-level change following rapid grounding-line migration will contribute a stabilizing influence on marine ice sheets, even when grounded on beds of non-negligible reversed slopes."

In a terse statement describing the implications of their work, Gomez et al. write their new and more "accurate" treatment of sea-level change "should be incorporated into analyses of past and future marine-ice-sheet dynamics."

Introducing their study of the WAIS, Naish et al. (2009) write, "an understanding of the behavior of the marine-based West Antarctic ice sheet during the 'warmer-than-present' early-Pliocene epoch (~5-3 Myr ago) is needed to better constrain the possible range of ice-sheet behavior in the context of future global warming," and they thus undertook a project to provide such understanding. Specifically, as they describe it, they derived "a marine glacial record from the upper 600 meters of the AND-1B sediment core recovered from beneath the northwest part of the Ross ice shelf by the ANDRILL program," which demonstrated the "well-dated ~40-kyr cyclic variations in ice-sheet extent linked to cycles in insolation influenced by changes in the earth's axial tilt (obliquity) during the Pliocene." They state their data "provide direct evidence for orbitally induced oscillations in the WAIS, which periodically collapsed, resulting in a switch from grounded ice, or ice shelves, to open waters in the Ross embayment when planetary temperatures were up to ~3°C warmer than today and atmospheric CO_2 concentration was as high as ~400 ppm," the latter number being about 3 percent greater than what it is today.

An important implication of this last observation is that the much greater periodic warmth of the early-Pliocene was clearly not the primary result of periodic changes in the air's CO_2 concentration. The 56 researchers tacitly acknowledge that fact by attributing the variable warmth to periodic changes in the planet's axial tilt that produced 40,000-year cycles of insolation.

How long did it take for such warmth to bring about a total collapse of the WAIS? An answer to this question can be found in the companion paper of Pollard and DeConto (2009), who state projections of future WAIS behavior "have been hampered by limited understanding of past variations and their underlying mechanisms.” With the findings of Naish et al. (2009), however, Pollard and DeConto gained important new knowledge that helped them frame a greatly improved “ice sheet/ice shelf model capable of high-resolution nesting with a new treatment of grounding-line dynamics and ice-shelf buttressing to simulate Antarctic ice sheet variations over the past five million years.”

The two researchers report they modeled WAIS variations ranging “from full glacial extents with grounding lines near the continental shelf break, intermediate states similar to modern, and brief but dramatic retreats, leaving only small, isolated ice caps on West Antarctic islands.” And they say their work suggests “the WAIS will begin to collapse when nearby ocean temperatures warm by roughly 5°C.” In a “News & Views” story on Pollard and DeConto’s findings, Huybrechts (2009) states, “the amount of nearby ocean warming required to generate enough sub-ice-shelf melting to initiate a significant retreat of the West Antarctic ice sheet ... may well take several centuries to develop.” Once started, he concludes, the transition time for a total collapse of the West Antarctic ice sheet would range from “one thousand to several thousand years.” This time period, he notes, “is nowhere near the century timescales for West Antarctic ice-sheet decay based on simple marine ice-sheet models,” such as have been employed in the past.

The specter of sea-level rise being measured in meters can be seen to be receding ever further into the distance of unreality.

References

Gomez, N., Mitrovica, J.X., Huybers, P., and Clark, P.U. 2010. Sea level as a stabilizing factor for marine-ice-sheet grounding lines. *Nature Geoscience* **3**: 850–853.

Hall, B.L. 2009. Holocene glacial history of Antarctica and the sub-Antarctic islands. *Quaternary Science Reviews* **28**: 2213–2230.

Huybrechts, P. 2009. West-side story of Antarctic ice. *Nature* **458**: 295–296.

Idso, C.D. and Singer, S.F. 2009. *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

Katz, R.F. and Worster, M.G. 2010. Stability of ice-sheet grounding lines. *Proceedings of the Royal Society A* 466: 1597–1620.

Meehl, G.A. et al. 2007. In IPCC *Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et. al, 748–845. Cambridge, UK: Cambridge University Press.

Naish, T., Powell, R., Levy, R., Wilson, G., Scherer, R., Talarico, F., Krissek, L., Niessen, F., Pompilio, M., Wilson, T., Carter, L., DeConto, R., Huybers, P., McKay, R., Pollard, D., Ross, J., Winter, D., Barrett, P., Browne, G., Cody, R., Cowan, E., Crampton, J., Dunbar, G., Dunbar, N., Florindo, F., Gebbherdt, C., Graham, I., Hannah, M., Hansaraj, D., Harwood, D., Helling, D., Henrys, S., Hinnov, L., Kuhn, G., Kyle, P., Laufer, A., Maffioli, P., Magens, D., Mandernack, K., McIntosh, W., Millan, C., Morin, R., Ohneiser, C., Paulsen, T., Persico, D., Raine, I., Reed, J., Riesselman, C., Sagnotti, L., Schmitt, D., Sjunneskog, C., Strong, P., Taviani, M., Vogel, S., Wilch, T. and Williams, T. 2009. Obliquity-paced Pliocene West Antarctic ice sheet oscillations. *Nature* **458**: 322–328.

O’Neill, B.C. and Oppenheimer, M. 2002. Dangerous climate impacts and the Kyoto Protocol. *Science* **296**: 1971–1972.

Oppenheimer, M. 1998. Global warming and the stability of the West Antarctic Ice Sheet. *Nature* **393**: 325–332.

Pollard, D. and DeConto, R.M. 2009. Modelling West Antarctic ice sheet growth and collapse through the past five million years. *Nature* **458**: 329–332.

Schoof, C. 2007. Ice sheet grounding line dynamics: Steady states, stability and hysteresis. *Journal of Geophysical Research* **112**: 10.1029/2006JF000664.

Smith, J.B., Schneider, S.H., Oppenheimer, M., Yohe, G.W., Hare, W., Mastrandrea, M.D., Patwardhan, A., Burton, I., Corfee-Morlot, J., Magadza, C.H.D., Fussel, H.-M., Pittock, A.B., Rahman, A., Suarez, A., and van Ypersele, J.-P. 2009. Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC), ‘reasons for concern’. *Proceedings of the National Academy of Sciences, USA* **106**: 4133–4137.

Tedesco, M. and Monaghan, A.J. 2010. Climate and melting variability in Antarctica. *EOS, Transactions, American Geophysical Union* **91**: 1–2.

Thomas, R.H. and Bentley, C.R. 1978. A model for Holocene retreat of the West Antarctic Ice Sheet. *Quaternary Research* **10**: 150–170.

Vaughan, D.G. 2008. West Antarctic Ice Sheet collapse—the fall and rise of a paradigm. *Climatic Change* **91**: 65–79.

Weertman, J. 1974. Stability of the junction of an ice sheet and an ice shelf. *Journal of Glaciology* **13**: 3–11.

4.1.2. Greenland and Eurasian Ice Caps

Murray et al. (2010) report that during the early 2000s, "the Greenland Ice Sheet's annual ice discharge doubled" and its outlet glaciers were dramatically "thinning, accelerating, and retreating." But as the scientists go on to show, the horror turned out to be short-lived. The 11 researchers "describe the oceanographic setting of the southeast Greenland region and then undertook two analyses to explore the relationship between oceanic processes and glacier dynamics," which helped put things in proper perspective.

Murray et al. report that in 2006, after the initial acceleration of ice loss, "two of the largest outlet glaciers in the sector, Helheim and Kangerdlugssuaq, were reported to have slowed down simultaneously (Howat et al., 2007), ceased thinning (Stearns and Hamilton, 2007; Howat et al., 2007), and readvanced (Joughin et al., 2008), and there was some indication that other glaciers in the region followed suit (Howat et al., 2008; Moon and Joughin, 2008)." In addition, their new work revealed, "the slowdown from 2006 was widespread and synchronized throughout southeast Greenland" and except for a minor reactivation at Helheim during 2007, "continued until at least 2008."

As for the mechanics of the oscillatory phenomenon, Murray et al. present evidence suggesting the original ice wastage speedup "was the result of warm ocean waters coming into contact with the glaciers" and that this speedup "was probably terminated in part by increased discharge from the glaciers themselves, which increased ice sheet runoff and iceberg calving," which in turn "introduced additional cold water strengthening the East Greenland Coastal Current." This slowed glacier melting until warmer water again began to dominate the current's waters.

Murray et al. write that their findings are suggestive of "a negative feedback that currently mitigates against continued very fast loss of ice from the ice sheet in a warming climate." They thus conclude "we should expect similar speedup and slowdown events of these glaciers in the future, which will make it difficult to elucidate any underlying trend in mass loss resulting from changes in this sector of the ice sheet."

Another attempt to assess the rapidity of Greenland ice melt was made by Wake et al. (2009). They write that the mass loss from the Greenland ice sheet over the last decade for which they had data (1995-2005) has caused the impression that "the ice sheet has been behaving anomalously" due to the warming of the 1990s and what has followed, the period the IPCC claims to have been the warmest such interval of the last one to two millennia (Mann et al., 1999; Mann and Jones, 2003). But was the ice sheet's mass loss really extraordinary?

The authors reconstructed the 1866-2005 surface mass-balance (SMB) history of the Greenland ice sheet on a 5 x 5 km grid "using a runoff-retention model based on the positive degree-day method," which accounts "for the influence of year-on-year surface elevation changes on SMB estimates" while being "forced with new datasets of temperature and precipitation patterns dating back to 1866." They did this, they state, in order to compare "the response of the ice sheet to a recent period of warming and a similar warm period during the 1920s to examine how exceptional the recent changes are within a longer time context."

The six scientists determined that present-day SMB changes "are not exceptional within the last 140 years." In fact, they found the SMB decline over the decade 1995-2005 was no different from that of the decade 1923-1933. "Based on the simulations of these two periods," Wake et al. observe, "it could as well be stated that the recent changes that have been monitored extensively (Krabill et al., 2004; Luthcke et al., 2006; Thomas et al., 2006) are representative of natural sub-decadal fluctuations in the mass balance of the ice sheet and are not necessarily the result of anthropogenic-related warming."

In another study, Sharp and Wang (2009) turned their attention to Eurasian ice caps east of Greenland. They report, "Enhanced resolution Ku-band scatterometer data from the Quick Scatterometer were used to map the timing of annual melt onset and freeze-up, and the duration of the summer melt season on the large glaciers and ice caps of Svalbard [Norway], Novaya Zemlya [Russia], and Severnaya Zemlya [Russia] for the 2000-04 period." To place the observations of their five-year study period in a longer-term context, they used "regression relationships between melt season duration and annual (June + August) mean 850-hPa air temperature over each region from the NCEP-NCAR Reanalysis to predict the annual melt duration for each year in the 1948-2005 period."

The two researchers report that with respect to all discrete five-year periods (pentads) between 1950 and 2004, "the 2000-04 pentad has the second longest mean predicted melt duration on Novaya Zemlya (after 1950-54), and the third longest on Svalbard (after 1950-54 and 1970-74) and Severnaya Zemlya (after 1950-54 and 1955-59)." These findings clearly reveal the 1950-54 pentad to have experienced the longest melt season of the past 55 years on all three of the large Eurasian Arctic ice caps.

In one final paper of note, Nick et al. (2009) concentrated their attention on the outlet glaciers that occur around the margins of the Greenland ice sheet. They report "the recent marked retreat, thinning and acceleration of most of Greenland's outlet glaciers south of 70°N has increased concerns over Greenland's contribution to future sea level rise," because, as they continue, "these dynamic changes seem to be parallel to the warming trend in Greenland." The authors developed "a numerical ice-flow model that reproduces the observed marked changes in Helheim Glacier," which they describe as "one of Greenland's largest outlet glaciers." They used the model to study the glacier's dynamics and determine what they might imply about the future mass balance of the Greenland Ice Sheet and subsequent global sea levels.

The four researchers report their model simulations show "ice acceleration, thinning and retreat begin at the calving terminus and then propagate upstream through dynamic coupling along the glacier." They find "these changes are unlikely to be caused by basal lubrication through surface melt propagating to the glacier bed," a phenomenon often cited as a cause of great concern with respect to its impact on sea level. The authors observe that "tidewater outlet glaciers adjust extremely rapidly to changing boundary conditions at the calving terminus," and conclude that "the recent rates of mass loss in Greenland's outlet glaciers are transient and should not be extrapolated into the future."

Despite concerns expressed over the past two decades about global warming becoming ever more intense, especially in the Arctic, conditions during the middle of the twentieth century seem to have been in this respect even more extreme than at any subsequent time, especially on these three major ice caps and their associated glaciers.

References

Howat, I.M., Joughin, I.R., and Scambos, T.A. 2007. Rapid changes in ice discharge from Greenland outlet glaciers. *Science* **315**: 1559–1561.

Howat, I.M., Joughin, I., Fahnestock, M., Smith, B.E., and Scambos, T.A. 2008. Synchronous retreat and acceleration of southeast Greenland outlet glaciers 2000–2006: ice dynamics and coupling to climate. *Journal of Glaciology* **54**: 646–660.

Joughin, I., Howat, I., Alley, R.B., Ekstrom, G., Fahnestock, M., Moon, T., Nettles, M., Truffer, M., and Tsai, V.C. 2008. Ice-front variation and tidewater behavior on Helheim and Kangerdlugssuaq glaciers, Greenland. *Journal of Geophysical Research* **113**: 10.1029/2007JF000837.

Krabill, W., Hanna, E., Huybrechts, P., Abdalati, W., Cappelen, J., Csatho, B., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., and Yungel, J. 2004. Greenland Ice Sheet: increased coastal thinning. *Geophysical Research Letters* **31**: 10.1029/2004GL021533.

Luthcke, S.B., Zwally, H.J., Abdalati, W., Rowlands, D.D., Ray, R.D., Nerem, R.S., Lemoine, F.G., McCarthy, J.J., and Chinn, D.S. 2006. Recent Greenland ice mass loss by drainage system from satellite gravity observations. *Science* **314**: 1286–1289.

Mann, M.E., Bradley, R.S. and Hughes, M.K. 1999. Northern Hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.

Mann, M.E. and Jones, P.D. 2003. Global surface temperature over the past two millennia. *Geophysical Research Letters* **30**: 1820–1823.

Moon, T. and Joughin, I. 2008. Changes in ice front position on Greenland's outlet glaciers from 1992 to 2007. *Journal of Geophysical Research* **113**: 10.1029/2007JF000927.

Murray, T., Scharrer, K., James, T.D., Dye, S.R., Hanna, E., Booth, A.D., Selmes, N., Luckman, A., Hughes, A.L.C., Cook, S., and Huybrechts, P. 2010. Ocean regulation hypothesis for glacier dynamics in southeast Greenland and implications for ice sheet mass changes. *Journal of Geophysical Research* **115**: 10.1029/2009JF001522.

Nick, F.M., Vieli, A., Howat, I.M., and Joughin, I. 2009. Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus. *Nature Geoscience* **2**: 10.1038/NGEO394.

Sharp, M. and Wang, L. 2009. A five-year record of summer melt on Eurasian Arctic ice caps. *Journal of Climate* **22**: 133–145.

Stearns, L.A. and Hamilton, G.S. 2007. Rapid volume loss from two East Greenland outlet glaciers quantified using repeat stereo satellite imagery. *Geophysical Research Letters* **34**: 10.1029/2006GL028982.

Thomas, R., Frederick, E., Krabill, W., Manizade, S., and Martin, C. 2006. Progressive increase in ice loss from Greenland. *Geophysical Research Letters* **33**: 10.1029/GL026075.

Wake, L.M., Huybrechts, P., Box, J.E., Hanna, E., Janssens, I., and Milne, G.A. 2009. Surface mass-balance changes of the Greenland ice sheet since 1866. *Annals of Glaciology* **50**: 176–184.

4.1.3. Montane Glaciers

Achieving a proper perspective on the advance and retreat of glaciers located on mountaintops and in mountain valleys requires that data be viewed in the context of the known extent of Holocene (last 10,000 years) glacial advance and older ice limits during the Pleistocene (last 2.5 million years). Using Alaska as their study area, Barclay et al. (2009) provide an extensive and up-to-date review of what is known about Holocene glacial activity there and its relationship to temperature.

Barclay et al. report the “termini of land-based valley glaciers were in retracted positions during the early to middle Holocene” but “neoglaciation was underway in some areas by 4.5-4.0 ka and major advances of land-based termini occurred by 3.0 ka.” Most dramatic, however, were the Little Ice Age (LIA) glacial advances, which culminated in two phases in the 1540s-1710s and in the 1810s-1880s, of which they state, “moraines of these middle and late LIA maxima are invariably the Holocene maxima in coastal southern Alaska,” adding, “LIA advances are also recognized as major expansions in all glacierized mountain ranges in Alaska.” In addition, they state researchers have determined that “Holocene fluctuations of Alaskan land-terminating glaciers have primarily been forced by multi-decadal and longer timescale changes in temperature.”

These several observations suggest changes in glaciation as experienced in Alaska during the twentieth century likely started at the end of the coldest portion of the current interglacial period. It is valuable to note the Earth descended into that wretched state without any help from declining atmospheric CO_2 concentrations.

A second Holocene glacial study was conducted by Rodbell et al. (2009) in South America. These authors updated “the chronology of Andean glaciation during the Lateglacial and the Holocene from the numerous articles and reviews published over the past three decades,” noting the Andes “offer an unparalleled opportunity to elucidate spatial and temporal patterns of glaciation along a continuous 68-degree meridional transect.” Results indicated “all presently glacierized mountain ranges contain multiple moraines deposited during the last 450 years” and “these correlate with the Little Ice Age as defined in the Northern Hemisphere.” In addition, they note most Andean regions “reveal a nearly continuous temporal distribution of moraines during the Little Ice Age.”

The temporal correspondence of the Little Ice Age in essentially all of the glacierized portions of the Northern Hemisphere and the great meridional expanse of most of Andean South America, as well as the similar glacial activity of both parts of the planet during this time period, provide strong support for the proposition that montane glaciation began to retreat when much of the world commenced its return to its current, milder climatic state from what could be called the Holocene’s “thermal basement.”

In a third study of Holocene glacier change, Nesje (2009) compiled, assessed, and evaluated “evidence of Late Glacial and Holocene glacier fluctuations in Scandinavia as deduced from ice-marginal features, marginal moraines, proglacial terrestrial and lacustrine sites, using especially new information that has become available since the review paper published by Karlen (1988).” Nesje reports his data compilation indicates “significant Lateglacial ice-sheet fluctuations, glacial contraction and disappearance during the early and mid-Holocene and subsequent Neoglacial expansion, peaking during the ‘Little Ice Age’.” These observations, in his words, are “in good agreement with other presently glaciated regions in the world,” as he states has been described by Solomina et al. (2008) and “references therein.”

Other authors confirm that the Little Ice Age in Scandinavia, as in most parts of the world where glaciers formed and grew during that period, was a depressing and dangerous time (Luckman, 1994; Villalba, 1994; Smith et al., 1995; Naftz et al., 1996). Alpine glaciers advanced in virtually all mountainous regions of the globe during that period, eroding large areas of land and producing masses of debris. Like an army of tractors and bulldozers, streams of ice flowed down mountain slopes, carving paths through the landscape, moving rocks, and destroying all vegetation in their paths (Smith and Laroque, 1995).

Continental glaciers and sea ice expanded their ranges as well during this period (Grove, 1988; Crowley and North, 1991). Near Iceland and Greenland, in fact, the expansion of sea ice during the Little Ice Age was so great that it isolated the Viking colony established in Greenland during the Medieval Warm Period, leading to its eventual abandonment (Bergthorsson, 1969; Dansgaard et al., 1975; Pringle, 1997).

Two closely associated phenomena that often occurred during the Little Ice Age were glacial landslides and avalanches (Porter and Orombelli, 1981; Innes, 1985). In Norway, an unprecedented number of petitions for tax and land rent relief were granted in the seventeenth and eighteenth centuries because of the considerable damage caused by landslides, rockfalls, avalanches, floods, and ice movement (Grove, 1988). In one example of catastrophic force and destruction, the Italian settlements of Ameiron and Triolet were destroyed by a rockfall of boulders, water, and ice in 1717. The evidence suggests the rockfall had a volume of 16–20 million cubic meters and descended 1,860 meters over a distance of 7 kilometers in but a few minutes, destroying homes, livestock, and vegetation (Porter and Orombelli, 1980). Other data suggest rockslides and avalanches were also frequent hazards in mountainous regions during this period (Porter and Orombelli, 1981; Innes, 1985).

Flooding was another catastrophic hazard of the Little Ice Age, with meltwater streams from glaciers eroding farmland throughout Norway (Blyth, 1982; Grove, 1988). In Iceland, flooding also wreaked havoc on the landscape when, on occasion, subglacial volcanic activity melted large portions of continental glaciers (Thoroddsen, 1905–06; Thórarinsson, 1959). Peak discharge rates during these episodes have been estimated to have been as high as 100,000 cubic meters per second—a value comparable in magnitude to the mean discharge rate of the Amazon River (Thórarinsson, 1957). During one such eruption-flood in 1660, glacial meltwater streams carried enough rock and debris from the land to the sea to create a dry beach where fishing boats had previously operated in 120 feet (36.6 m) of water (Grove, 1988). Flooding from a later eruption carried enough sediment seaward to fill waters 240 feet (73.2 m) deep (Henderson, 1819).

Another Holocene study, this time of European glacial activity by Ivy-Ochs et al. (2009), presented "a summary of the evidence for suggested periods of glacier advance during the final phase of the Alpine Lateglacial and the Holocene," interweaving "data obtained from ^{10}Be surface exposure dating, radiocarbon dating of wood and peat washed out from the presently melting glacier tongues, dendrochronological investigations on wood from the glacierized basins, tree-line studies and archaeological evidence."

Results indicated "the earliest Holocene (between 11.6 and about 10.5 ka) was still strongly affected by the cold climatic conditions of the Younger Dryas and the Preboreal oscillation," but "at or slightly before 10.5 ka rapid shrinkage of glaciers to a size smaller than their late 20th century size reflects markedly warmer and possibly also drier climate." After 3.3 ka, however, "climate conditions became generally colder and warm periods were brief and less frequent." Finally, they indicate "glaciers in the Alps attained their Little Ice Age maximum extents in the 14th, 17th and 19th centuries, with most reaching their greatest Little Ice Age extent in the final 1850/1860 AD advance."

Like their alpine glacier counterparts in Scandinavia described by Nesje (2009), glaciers of the European Alps also reached their maximum Holocene extensions close to the end of the Little Ice Age. This means that at that time there existed the greatest potential for significant warming of the entire Holocene interglacial, for in an oscillatory climatic regime, the point of lowest temperature decline also represents the point of the greatest potential for a significant temperature increase. It should only have been expected, then, that the subsequent temperature recovery of the Earth would likely be quite substantial, as there was much prior cooling to be overcome in order to return the planet to a climatic state more characteristic of the bulk of the Holocene.

Considering glacial change over a shorter timeframe, Vincent et al. (2007) analyzed the impact of climate change over the past 100 years on high-elevation glaciated areas of the Mont Blanc range, including the ice fields that cover the Mont Blanc (4,808 m) and Dôme du Goûter (4,300 m) peaks. Surface ablation is negligible for these high-elevation areas, and the surface mass balance is mainly controlled by snow accumulation.

At Dôme du Goûter, ice fluxes were calculated through two transversal sections by two independent methods in order to assess long-term surface accumulation. A comparison between these results and recent accumulation observations, together with the strong relationship between valley precipitation and snow accumulation, suggests surface accumulation rates did not change significantly over the entire twentieth century.

Vincent et al. state "the most striking features ... are the small thickness changes observed over the twentieth century. For both areas, thickness variations do not exceed ±15 m. The average changes are +2.6 m at Dôme du Goûter and -0.3 m at Mont Blanc. Considering the uncertainty interval, i.e., ±5 m, it can be concluded that no significant thickness change is detectable over most of these areas." These findings show these high-elevation glaciated areas have not been significantly affected by climate change over the last 100 years.

Finally, Kaser et al. (2010) examined the ice fields that top Mt. Kilimanjaro's highest peak, Kibo. Kaser et al. write these features have garnered "particular attention" since Irion (2001) attributed modern changes in them to "increased air temperature in the context of global warming" and Thompson et al. (2002) reported on what they described as the "near extinction of the ice on Kibo," which they characterized as being "unprecedented over the last 11,700 years." Shortly thereafter, however, Kaser et al. (2004) developed an alternative hypothesis, namely that atmospheric moisture primarily controls the modern-time glacier changes on Kibo, as Kaser et al. (2010) indicate is also suggested by the work of Molg and Hardy (2004), Cullen et al. (2006, 2007) and Molg et al. (2003, 2006, 2009a,b). This finding, in their words, "not only rules out rising local air temperature (i.e. on the peak of Kibo) as the main driver of observed changes during the last 120 years, but also puts the currently accepted 11,700 years age in question."

Based on their review of a compilation of all available information on present-day phenomena that control the glaciers on Kilimanjaro, and after what the five researchers describe as "a careful glaciological evaluation," Kaser et al. (2010) conclude "minor changes in thickness have no impact on the changing surface area of the tabular plateau glaciers," while noting "plateau glacier area decrease has been strikingly constant over the twentieth century" and "ablation rates of the ice walls are [also] persistently constant." In addition, their analyses suggest the mountain's plateau ice "may have come and gone repeatedly throughout the Holocene" and the reduction of plateau ice in modern times "is controlled by the absence of sustained regional wet periods rather than changes in local air temperature on the peak of Kilimanjaro."

References

Barclay, D.J., Wiles, G.C., and Calkin, P.E. 2009. Holocene glacier fluctuations in Alaska. *Quaternary Science Reviews* **28**: 2034–2048.

Bergthorsson, P. 1969. An estimate of drift ice and temperature in 1000 years. *Jökull* **19**: 94–101.

Blyth, J.R. 1982. Storofsen i Ottadalen. Unpublished Dissertation, Department of Geography, University of Cambridge, Cambridge, UK.

Cullen, N.J., Molg, T., Hardy, D.R., Steffen, K., and Kaser, G. 2007. Energy-balance model validation on the top of Kilimanjaro, Tanzania, using eddy covariance data. *Annals of Glaciology* **46**: 227–233.

Cullen, N.J., Molg, T., Kaser, G., Hussein, K., Steffen, K., and Hardy, D.R. 2006. Kilimanjaro: Recent areal extent from satellite data and new interpretation of observed 20th century retreat rates. *Geophysical Research Letters* **33**: 10.1029/2006GL0227084.

Dansgaard, W., Johnsen, S.J., Reeh, N., Gundestrup, N., Clausen, H.B., and Hammer, C.U. 1975. Climate changes, Norsemen, and modern man. *Nature* **255**: 24–28.

Grove, J.M. 1988. *The Little Ice Age*. Cambridge, UK: Cambridge University Press.

Henderson, E. 1819. Iceland: or the Journal of a Residence in that Island, During the Years 1814 and 1815. Edinburgh, UK: Wayward Innes.

Innes, J.L. 1985. Lichenometric dating of debris flow deposits on alpine colluvial fans in southwest Norway. *Earth, Surface Processes and Landforms* **10**: 519–524.

Irion, R. 2001. The melting snows of Kilimanjaro. *Science* **291**: 1690–1691.

Ivy-Ochs, S., Kerschner, H., Maisch, M., Christl, M., Kubik, P.W., and Schluchter, C. 2009. Latest Pleistocene and Holocene glacier variations in the European Alps. *Quaternary Science Reviews* **28**: 2137–2149.

Karlen, W. 1988. Scandinavian glacial and climatic fluctuations during the Holocene. *Quaternary Science Reviews* **7**: 199–209.

Kaser, G., Molg, T., Cullen, N.J., Hardy, D.R. and Winkler, M. 2010. Is the decline of ice on Kilimanjaro unprecedented in the Holocene? *The Holocene* **20**: 1079–1091.

Kaser, G., Hardy, D.R., Molg, T., Bradley, R.S., and Hyera, T.M. 2004. Modern glacier retreat on Kilimanjaro as evidence of climate change: Observations and facts. *International Journal of Climatology* **24**: 329–339.

Luckman, B.H. 1994. Evidence for climatic conditions between ca. 900-1300 A.D. in the southern Canadian Rockies. *Climatic Change* **26**: 171–182.

Molg, T., Chiang, J.C.H., Gohm, A., and Cullen, N.J. 2009a. Temporal precipitation variability versus altitude on a tropical high mountain: Observations and mesoscale atmospheric modeling. *Quarterly Journal of the Royal Meteorological Society* **135**: 1439–1455.

Molg, T., Cullen, N.J., Hardy, D.R., Winkler, M., and Kaser, G. 2009b. Quantifying climate change in the tropical mid-troposphere over East Africa from glacier shrinkage on Kilimanjaro. *Journal of Climate* **22**: 4162–4181.

Molg, T. and Hardy, D.R. 2004. Ablation and associated energy balance of a horizontal glacier surface on Kilimanjaro. *Journal of Geophysical Research* **109**: 1–13.

Molg, T., Hardy, D.R., and Kaser, G. 2003. Solar-radiation-maintained glacier recession on Kilimanjaro drawn from combined ice-radiation geometry modeling. *Journal of Geophysical Research* **108**: 10.1029/2003JD003546.

Molg, T., Renold, M., Vuille, M., Cullen, N.J., Stocker, T.F., and Kaser, G. 2006. Indian Ocean zonal mode activity in a multi-century integration of a coupled AOGCM consistent with climate proxy data. *Geophysical Research Letters* **33**: 10.1029/2006GL026384.

Naftz, D.L., Klusman, R.W., Michel, R.L., Schuster, P.F., Reddy, M.M., Taylor, H.E., Yanosky, E.A., and McConnaughey, E.A. 1996. Little Ice Age evidence from a south-central North American ice core, U.S.A. *Arctic and Alpine Research* **28** (1): 35–41.

Nesje, A. 2009. Latest Pleistocene and Holocene alpine glacier fluctuations in Scandinavia. *Quaternary Science Reviews* **28**: 2119–2136.

Porter, S.C. and Orombelli, G. 1980. Catastrophic rockfall of September 12, 1717 on the Italian flank of the Mont Blanc massif. *Zeitschrift für Geomorphologie N.F.* **24**: 200–218.

Porter, S.C. and Orombelli, G. 1981. Alpine rockfall hazards. *American Scientist* **67**: 69–75.

Pringle, H. 1997. Death in Norse Greenland. *Science* **275**: 924–926.

Rodbell, D.T., Smith, J.A., and Mark, B.G. 2009. Glaciation in the Andes during the Lateglacial and Holocene. *Quaternary Science Reviews* **28**: 2165–2212.

Smith, D.J. and Laroque, C.P. 1995. Dendroglaciological dating of a Little Ice Age glacier advance at Moving Glacier, Vancouver Island, British Columbia. *Géographie physique et Quaternaire* **50** (1): 47–55.

Smith, D.J., McCarthy, D.P., and Colenutt, M.E. 1995. Little Ice Age glacial activity in Peter Lougheed and Elk Lakes provincial parks, Canadian Rocky Mountains. *Canadian Journal of Earth Science* **32**: 579–589.

Solomina, O., Haeberli, W., Kull, C., and Wiles, G. 2008. Historical and Holocene glacier-climate variations: general concepts and overview. *Global and Planetary Change* **60**: 1–9.

Thompson, L.G., Mosely-Thompson, E., Davis, M.E., Henderson, K.A., Brecher, H.H., Zagorodnov, V.S., Mashiotta, T.A., Lin, P.-N., Mikhalenko, V.N., Hardy, D.R., and Beer, J. 2002. Kilimanjaro ice core records: Evidence of Holocene climate change in tropical Africa. *Science* **298**: 589–593.

Thoroddsen, T. 1905–1906. *Island. Grundriss der Geographie und Geologie*, Petermanns Geographische Mitteilungen, Ergänzungsband 32, Heft 152/3.

Thórarinsson, S. 1959. Um möguleika á thví ad segja fyrir næsta Kötlugos. *Jökull* **9**: 6–18.

Thórarinsson, S. 1957. The jökulhlaup from the Katla area in 1955 compared with other jökulhlaups in Iceland. *Jökull* **7**: 21–25.

Vincent, C., Le Meur, E., Six, D., Funk, M., Hoelzle, M., and Preunkert, S. 2007. Very high-elevation Mont Blanc glaciated areas not affected by the 20th century climate change. *Journal of Geophysical Research* **112** D09120, doi:10.1029/2006JD007407.

4.1.4. Sea and Lake Ice

Though semi-permanent sea ice exists around the North Pole, fringing sea ice in both the Arctic and Antarctic is an annual, seasonal feature. Fringing sea ice is therefore particularly susceptible to fast advance or retreat depending upon local oceanographic and atmospheric changes. Even quite major sea-ice changes are not necessarily due to climatic change.

This dynamic, rather than climatic, aspect of sea-ice change is well documented in a recent study by Scott and Marshall (2010), two scientists with the British Antarctic Survey. They found “over the last four decades there has been a trend to earlier summer breakup of the sea ice in western Hudson Bay, Canada" and "the trend to earlier sea-ice breakup has been linked to the long-term effect of warming in the region (Stirling et al., 1999; Gagnon and Gough, 2005)." Subsequently, however, they report "the existence of a sufficiently long-term regional warming trend was disputed by Dyck et al. (2007)," and, therefore, they decided to explore the subject in more detail, to see if they could resolve the controversy.

Working with passive microwave data obtained from the Scanning Multichannel Microwave Radiometer onboard the Nimbus 7 satellite, plus three Special Sensor Microwave/Imager instruments onboard Defense Meteorological Satellite Program satellites, as well as Canadian Ice Service sea-ice charts considered to be "more accurate than passive microwave data for estimates of ice concentration, particularly in the presence of surface melt," as described by Agnew and Howell (2002) and Fetterer et al. (2008), Scott and Marshall performed several new analyses on both datasets, "bringing the time series up to date" (to 2007, from a starting date of 1971) while looking at "temperature trends in the area around the time of breakup in more detail than was [done] in previous studies."

With respect to the chief point of controversy, the researchers found "there has clearly not been a continuous trend in the [time of sea-ice breakup] data, and the change is best described by a step to 12 days earlier breakup occurring between 1988 and 1989, with no significant trend before or after this date." In addition, they remark, "an increase in regional southwesterly winds during the first three weeks of June and a corresponding increase in surface temperature are shown to be likely contributing factors to this earlier breakup."

Proponents of the theory of CO_2-induced global warming have long publicized what they characterize as the gradual development, over the past four decades, of an earlier occurrence of the date of yearly sea-ice breakup in Canada's Hudson Bay, claiming it was a manifestation of anthropogenic climate change that was negatively affecting the region's polar bears. The newer findings of Scott and Marshall argue against that conclusion. Nevertheless—and correctly—the two researchers conclude their analysis by stating "it remains to be seen whether these changes in atmospheric circulation [which appear to be the proximate cause of the significant step-change in the date of sea-ice breakup] might be ascribed to human actions or simply to natural climate variability."

Clearly, the science pertaining to this matter is not settled.

Floating ice pack that is responsive to climatic fluctuations forms on large, intra-continental lakes as well as on the ocean, and Wang et al. (2010) provide an analysis of 70 years of such floating ice for the Great Lakes of North America. Their study covers the winters of 1972–73 to 2008–09 and comprises an analysis of time series of annual average ice area and basin winter average surface air temperature (SAT) and floating ice cover (FIC) for the Great Lakes, which they remind us "contain about 95% of the fresh surface water supply for the United States and 20% of the world."

The primary data of interest are depicted in Figure 4.1.1 below, where after an initial four years of relative warmth and lower annual average ice area, SATs declined and FIC area rose. Then, there began a long period of somewhat jagged SAT rise and FIC decline, which both level out from about 1998 to 2006, after which SAT once again slowly declines and FIC slowly rises. Both parameters terminate at about the same value they exhibited initially.

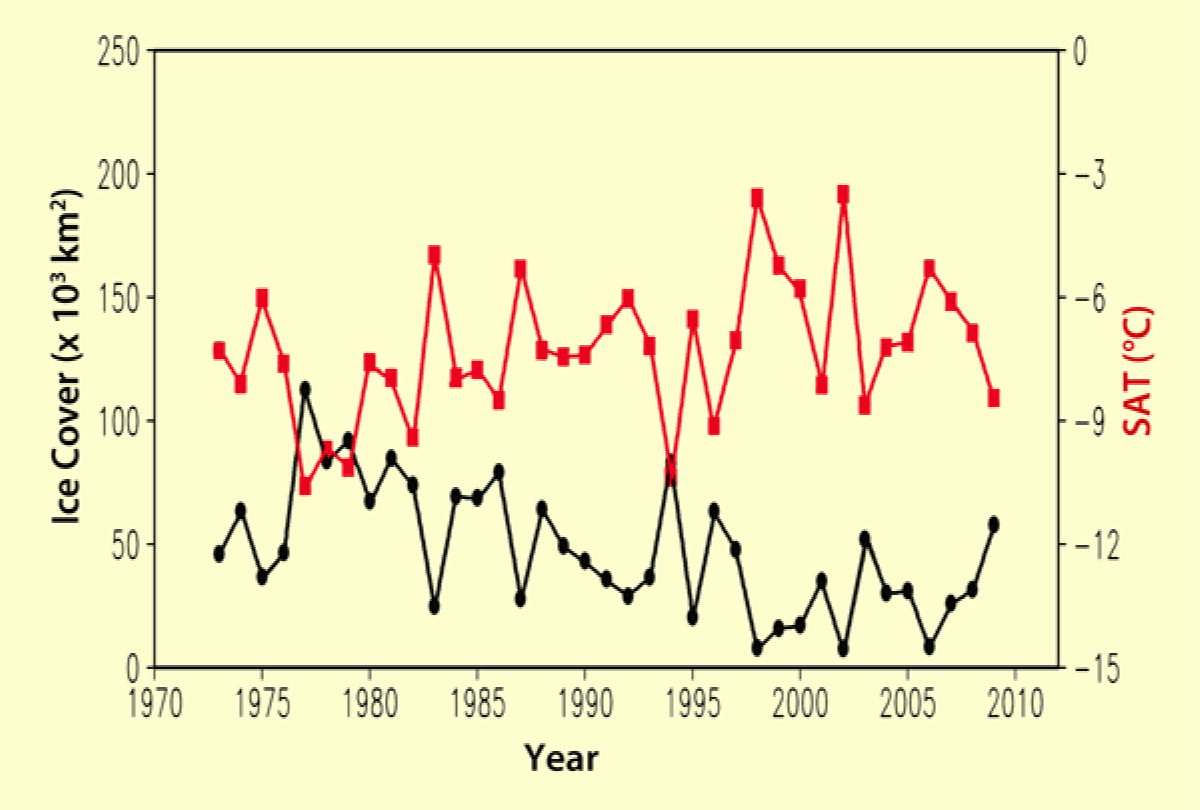


Figure 4.1.1. Annual average ice area of the North American Great Lakes and basin winter average surface air temperature (SAT) vs. time. Adapted from Wang et al. (2010).

Wang et al. conclude from their study that "natural variability dominates Great Lakes ice cover," and that any trend in the data—of which there are some of a few years and one that is lengthier—"is only useful for the period studied." Given this finding, there is no reason to attribute any change in the annual average ice area of the North American Great Lakes to anthropogenic global warming.

References

Agnew, T.A. and Howell, S. 2002. Comparison of digitized Canadian ice charts and passive microwave sea-ice concentrations. *Geoscience and Remote Sensing Symposium, IGARSS 2002* **1**: 231–233.

Dyck, M.G., Soon, W., Baydack, R.K., Legates, D.R., Baliunas, S., Ball, T.F., and Hancock, L.O. 2007. Polar bears of western Hudson Bay and climate change: are warming spring air temperatures the "ultimate" survival control factor? *Ecological Complexity* **4**: 73–84.

Fetterer, F., Knowles, K., Meier, W., and Savoie, M. 2008. Sea ice index. Boulder, Colorado: National Snow and Ice Data Center. http://nsidc.org/data/docs/noaa/g02135_seaiceindex/index.html

Gagnon, A.S. and Gough, W.A. 2005. Trends in the dates of ice freeze-up and breakup over Hudson Bay, Canada. *Arctic* **58**: 370–382.

Scott, J.B.T. and Marshall, G.J. 2010. A step-change in the date of sea-ice breakup in western Hudson Bay. *Arctic* **63**: 155–164.

Stirling, I., Lunn, N.J., and Iacozza, J. 1999. Long-term trends in the population ecology of polar bears in western Hudson Bay in relation to climatic change. *Arctic* **52**: 294–306.

Wang, J., Bai, X., and Leshkevich, G. 2010. Severe ice cover on Great Lakes during winter 2008-2009. *EOS, Transactions, American Geophysical Union* **91**: 41–42.

4.2. Ocean Dynamics

4.2.1. Sea Level Change

In an analysis of the tide gauge record for Brest, a city in north-western France, Woppelmann et al. (2008) examined "the issue of a possible tide gauge datum discontinuity … caused by the bombing of the city in August 1944" via "a detailed analysis of historical levelling information, and comparison of sea level data between adjacent stations."

The Brest tide gauge was found to be "'stable' over the 1889–1996 period." The authors say their work "led to an accurate datum connection between recently rediscovered 18th century sea level data (back to 1711) and those of the present day." In addition, they claim "an interesting by-product" of their work, "the close matching of the Brest and Liverpool [UK] time series over more than 200 years." Both instrumental records "show a roughly coincident increase in the rate of relative sea-level rise around the end of the 19th century," as does the sea-level record of Newlyn in the UK. From 1890 to the ends of the records, which appear to extend to about 2007, all three datasets define similar linear increases with time.

If one splits the period of linear sea-level rise into two equal 57-year parts centered on the middle of the twentieth century—1893 to 1950 and 1950 to 2007—it can be determined from various atmospheric trace gas records that the air's CO_2 concentration rose about 3.8 times faster over the last of these periods than it did over the first period. Since mean sea level rose at a constant rate over the entire 114 years, it is unlikely the historical increase in the atmosphere's CO_2 content was the ultimate cause of the steady mean sea-level rise.

In another study, this time of coastal wetlands in the eastern United States, Langley et al. (2009) discovered, "tidal wetlands experiencing increased rates of sea-level rise (SLR) must increase rates of soil elevation gain to avoid permanent conversion to open water." As for how that might happen, they note "root zone expansion by accumulation of plant material is essential to maintaining a constant surface elevation relative to rising sea level."

In Kirkpatrick Marsh—a microtidal subestuary of Chesapeake Bay, where each of several 200m^2 plots was outfitted with a surface elevation table (SET) to measure soil elevation change—Langley et al. exposed half the plots to an extra 340 ppm of CO_2 for two years, while "data from a greenhouse mesocosm experiment (Cherry et al., 2009) were used to examine how elevated CO_2 might affect elevation response under simulated SLR scenarios."

The five researchers report the extra CO_2 of their marsh experiment increased fine root productivity by an average of 36 percent over the two-year study, and that above-ground biomass production was increased by as much as 30 percent, "consistent with a 20-year record of elevated CO_2 treatment in a previous CO_2 study on the same marsh (Erickson et al., 2007)." In addition, they state the elevated CO_2 caused an increase in root zone thickness of 4.9 mm/year compared with only 0.7 mm/year in the ambient CO_2 treatment, with the result that there was "a slight loss of elevation in ambient CO_2 (-0.9 mm/year) compared with an elevation gain (3.0 mm/year) in the elevated CO_2 treatment." Furthermore, they report the greenhouse mesocosm experiment of Cherry et al. (2009) "revealed that the CO_2 effect was enhanced under salinity and flooding conditions likely to accompany future SLR."

Langley et al. conclude, "by stimulating biogenic contributions to marsh elevation, increases in the greenhouse gas, CO_2, may paradoxically aid some coastal wetlands in counterbalancing rising seas." In this regard, they state their findings "bear particular importance given the threat of accelerating SLR to coastal wetlands worldwide," citing the recent Environmental Protection Agency report of Reed et al. (2008), which suggests "a 2-mm increase in the rate of SLR will threaten or eliminate a large portion of mid-Atlantic marshes." This research suggests the positive growth-promoting effect of atmospheric CO_2 enrichment more than compensates for its hypothetical sea-level-raising effect.

A key issue in understanding eustatic (global) sea-level change is the degree to which glacial meltwater is causing an increase in ocean mass. In a study of Alaskan and nearby Canadian glaciers, Berthier et al. (2010) comment that earlier estimates of mass loss from Alaskan and nearby glaciers "have relied on extrapolating site-specific measurements to the entire region," citing in support the studies of Arendt et al. (2002), Meier and Dyurgerov (2002), and Dyurgerov and Meier (2005).

Berthier et al. Say the "landmark study" of Arendt et al. (2002) used laser altimetry to measure elevation changes on 67 glaciers, but those glaciers represented only 20 percent of the area of the ice field. Therefore, in an attempt to expand the areal coverage and overcome several other methodological deficiencies, Berthier et al. calculated ice elevation changes for nearly three-quarters of the ice-covered areas in the Alaskan glacier range by combining "a comprehensive glacier inventory with elevation changes derived from sequential digital elevation models," the first set having a median date of 1962 and the latter having a date of 2006.

Results indicated "between 1962 and 2006, Alaskan glaciers lost 41.9 ± 8.6 km^3 per year of water, and contributed 0.12 ± 0.02 mm per year to sea-level rise," which they note was 34 percent less than estimated by Arendt et al. (2002) and Meier and Dyurgerov (2002). In discussing this large difference, they say the reasons for their lower values include "the higher spatial resolution of [their] glacier inventory as well as the reduction of ice thinning underneath debris and at the glacier margins, which were not resolved in earlier work." Thus, in addition to significantly revising what was previously believed about the magnitude of ice wastage in Alaska and northwest Canada in recent decades, Berthier et al. say their results suggest "estimates of mass loss from glaciers and ice caps in other mountain regions could be subject to similar revisions." This work calls into serious question claims that Earth's mountain glaciers and ice caps are wasting away rapidly and thereby contributing to global sea level rise.

As glacial melt supplies water that may cause sea-level rise, measurement of that rise may be made by means of its effect on coral reefs, the upper limit of which is closely controlled by mean sea level. "Accepting current IPCC scenarios of eustatic sea-level rise," Webb and Kench (2010) note, "it is widely anticipated that low-lying reef islands will become physically unstable and be unable to support human populations over the coming century." They also write, "it is also widely perceived that island erosion will become so widespread that entire atoll nations will disappear, rendering their inhabitants among the first environmental refugees of climate change."

To draw attention to this perceived threat, members of the Maldives Cabinet donned scuba gear on 17 October 2009 and used hand signals to conduct business at an underwater meeting. During this meeting they signed a document calling on all nations to reduce their carbon emissions. However, Webb and Kench's study of this situation found the theatrics were entirely unnecessary.

Webb and Kench examined the morphological changes of 27 atoll islands located in the central Pacific in four atolls spanning 15 degrees of latitude from Mokil atoll in the north (6°41.01'N) to Funafuti in the south (8°30.59'S). They did this using historical aerial photography and satellite images over periods ranging from 19 to 61 years, during which time interval they say instrumental records indicated a rate of sea-level rise of 2.0 mm per year in the central Pacific.

Based on their analysis, the two researchers—one from Fiji and one from New Zealand—state, "there is no evidence of large-scale reduction in island area despite the upward trend in sea level" and the islands "have predominantly been persistent or expanded in area on atoll rims for the past 20 to 60 years." More specifically, they find 43 percent of the islands "increased in area by more than 3% with the largest increases of 30% on Betio (Tarawa atoll) and 28.3% on Funamanu (Funafuti atoll)." The results of this study, they observe, "contradict widespread perceptions that all reef islands are eroding in response to recent sea level rise." Quite to the contrary, the authors note, "reef islands are geomorphically resilient landforms that thus far have predominantly remained stable or grown in area over the last 20–60 years" and, "given this positive trend, reef islands may not disappear from atoll rims and other coral reefs in the near-future as speculated."

The views of the Maldives cabinet and its supporters notwithstanding, it is evident from first principles that on low-lying shorelines, an incremental increase in sea level will most likely lead to an expansion of reef area.

In a similar study of the Great Barrier Reef (Australia), Dawson and Smithers (2010) note low-lying reef islands are widely perceived to be particularly sensitive to ongoing and projected sea-level increases, but they add "a number of geomorphologists have argued that rising sea levels do not always cause reef islands to erode." They state, "a rise in sea level may promote reef island growth by: i) increasing accommodation space for new sediment; ii) reinvigorating carbonate production on reef flats where further reef growth has been inhibited by a stable sea level; and iii) increasing the efficiency of waves to transport new and stored sediment to an island depocentre (Hopley, 1993; Hopley et al., 2007; Smithers et al., 2007; Woodroffe, 2007)."

Working on Raine Island (11°35'28"S, 144°02'17"E) at the northwest end of a planar reef on the outer edge of Australia's Great Barrier Reef—one of the world's most important nesting sites for marine turtles—Dawson and Smithers employed three historic survey maps and five topographic survey datasets of earlier researchers, supplementing them with digital elevation data collected in 1998, 2006, and 2007, to reconstruct a 40-year (1967–2007) shoreline history of the island. The two Australian researchers report their "detailed quantitative surveys and analyses demonstrate that Raine Island increased in area (~6%) and volume (~4%) between 1967 and 2007," and that "in the 40 years between 1967 and 2007 Raine Island underwent a net accretion of 68,400 ± 6,700 m^3."

In summing up their findings, Dawson and Smithers write, "contrary to perceptions, Raine Island did not erode but instead modestly accreted during the 40-year study period." They therefore conclude, "future management strategies of Raine Island and other islands of the Great Barrier Reef should recognize that perceptions of reef island erosion can arise from large short-term seasonal and storm-derived sediment redistribution from one part of the island to another or to a temporary storage on the adjacent reef flat" but these phenomena do not necessarily lead to "a net permanent loss from the island sediment budget." Considering also the similar findings of Webb and Kench (2010), it can therefore be concluded that the most likely effect of a rising sea level is to add to the area and volume of low-lying reef islands.

Moving on to geophysical studies of sea-level change, Quinn and Ponte (2010) write, "ocean mass, together with steric sea level, are the key components of total observed sea level change" and "monthly observations from the Gravity Recovery and Climate Experiment (GRACE) can provide estimates of the ocean mass component of the sea level budget, but full use of the data requires a detailed understanding of its errors and biases." This belief is true in principle, but the complex operational corrections that often need to be applied to spaceborne geophysical datasets mean "at best, the determination and attribution [in this way] of global-mean sea level change lies at the very edge of knowledge and technology" (Wunsch et al., 2007).

In an effort to provide some of that "detailed understanding" of GRACE's "errors and biases," Quinn and Ponte conduct what they describe as "a detailed analysis of processing and post-processing factors affecting GRACE estimates of ocean mass trends," by "comparing results from different data centers and exploring a range of post-processing filtering and modeling parameters, including the effects of geocenter motion, PGR [postglacial rebound], and atmospheric pressure."

The two researchers report the mean ocean mass trends they calculated "vary quite dramatically depending on which GRACE product is used, which adjustments are applied, and how the data are processed." They state "the PGR adjustment ranges from 1 to 2 mm/year, the geocenter adjustment may have biases on the order of 0.2 mm/year, and the atmospheric mass correction may have errors of up to 0.1 mm/year," while "differences between GRACE data centers are quite large, up to 1 mm/year, and differences due to variations in the processing may be up to 0.5 mm/year."

In light of the fact that Quinn and Ponte indicate "over the last century, the rate of sea level rise has been only 1.7 ± 0.5 mm/year, based on tide gauge reconstructions (Church and White, 2006)," it seems a bit strange that one would question that result on the basis of a GRACE-derived assessment, with its many and potentially very large "errors and biases." In addition, as Ramillien et al. (2006) have noted, "the GRACE data time series is still very short" and results obtained from it "must be considered as preliminary since we cannot exclude that apparent trends [derived from it] only reflect inter-annual fluctuations." And as Quinn and Ponte also note, "non-ocean signals, such as in the Indian Ocean due to the 2004 Sumatran-Andean earthquake, and near Greenland and West Antarctica due to land signal leakage, can also corrupt the ocean trend estimates."

Clearly, the GRACE approach to evaluating ocean mass and sea level trends still has a long way to go—and must develop a long history of data acquisition—before it can be considered a reliable means of providing assessments of ocean mass and sea-level change accurate enough to detect an anthropogenic signal that could be confidently distinguished from natural variability.

Despite the inherent uncertainty of the results, GRACE satellite data nonetheless have been used in several studies to estimate sea-level rise and ice loss due to global warming. A particularly confounding factor in these studies is that continents and ocean basins respond to past and recent mass loss or additions by rising or sinking. Thus the surface of an ice sheet could be rising due to Glacial Isostatic Adjustment (GIA) even though it is currently losing ice mass, or vice versa.

Earlier studies have used an estimated GIA model to adjust for this effect, but these models are not independent of ice accumulation/loss rates. Wu et al. (2010) used the alternative method of simultaneously estimating GIA and present-day surface mass trend (PDMT) for the globe. They use three sources of data: GRACE data, ocean bottom pressure data from the Jet Propulsion Laboratory, and the three-dimensional surface velocities (from GPS data) of a network of 664 globally distributed sites, the goal being to obtain with high accuracy global surface maps of both GIA and PDMT.

The most prominent result of this analysis is a reduction by about a factor of two in the estimate of current rates of ice loss for Greenland and Antarctica compared to previous GRACE estimates based on the *a priori* GIA model, due partly to clear evidence for ice accumulation in the interior of Greenland (accompanied by ice loss around the margins of Greenland). Parts of West Antarctica also show rapid loss and others rapid gain of ice mass, while East Antarctica seems relatively stable. The current (2002–2008) global non-steric (not due to ocean warming and water expansion) sea-level rise attributable to ice mass loss is estimated in the study to be 0.54 mm/yr (about 2 inches per century). This suggests almost none of the ongoing background sea-level rise of about 1.7 mm/yr, as measured by tide gauges worldwide, is due to glacial ice loss.

That sea level has been rising gently for the past 100+ years has been demonstrated by numerous real-world measurements and observations. An important open question, however, is whether the rate of rise has accelerated in recent decades, because an acceleration is implied by greenhouse theory.

Normally, the approach to answering such a question would be to turn to measurements of the phenomenon, but in the case of sea-level rise, there is a major problem in that tide gauge stations rise or fall as the land they sit on rises or falls, thereby confounding the data. In addition, newer satellite measurements do not extend very far back in time. Wenzel and Schroter (2010) adopt a novel technique in order to attempt to overcome these issues: They use neural nets for infilling of missing data at individual stations and for estimating weights for individual gauges.

Using 56 stations with at least 50 years of data each, these authors adjusted the data before use by correcting it for land movement up or down. The training data for the neural net were three sets of altimetry data for recent decades, and all three results were shown. By basin, they indicated no net trend for the South Atlantic and tropical Indian Oceans, and a net decline in sea level for the Southern Indian Ocean. The Pacific Ocean showed an approximate 70-year oscillation in sea level that correlates (with lag) with the Pacific Decadal Oscillation (PDO), while the Atlantic showed cycles of 23 and 65 years. Overall, ocean basin changes showed correlations with the PDO and Southern Annular Mode indices, with lags. Wenzel and Schroter say this work—along with the clear annual cycles in sea level they discern—shows their final result correctly reflects the effects of water temperature on sea level.

For the globe as a whole, the two researchers found a linear upward sea-level trend of 1.56 mm/year, with no sign of acceleration in recent decades. This result is consistent with previous tide gauge estimates, but only about one-half of the value used by the IPCC, and if the rate of rise continued it would produce about one-half foot of sea level rise over the next century. These results agree with those of Hagedoorn et al. (2007) of 1.46 mm/year and Woppelmann et al. (2009) of 1.61 mm/year, as well as several other recent studies that give only slightly higher values around 1.7–1.8 mm/year.

It would appear careful analyses of tide gauge records by multiple teams do not show the acceleration of sea-level rise proposed by the IPCC.

This result notwithstanding, Rahmstorf (2007) has proposed the existence of "a linear relationship between the rate of global mean sea-level rise and the global mean near-surface air temperature deviations," which he claims can be "calibrated with observed data, thus incorporating in a somewhat realistic and condensed manner all known and unknown mechanisms modulating the global sea-level height." The concept sounds reasonable, but does it work? In an intriguing study published in *Ocean Dynamics*, von Storch et al. (2008) find it does not.

One way of addressing Rahmstorf's assertions—which von Storch et al. employ—is "to test the statistical methods in the virtual reality produced in simulations with state-of-the-art climate models." Following that strategy, these authors examined "several hypotheses concerning the relationship between global mean sea level and other thermal surface variables in a long climate simulation of the past millennium with the climate model ECHO-G driven by estimations of past greenhouse gas, volcanic and solar forcing."

The three researchers report the linear link between global mean temperature and the rate of change of global mean sea level proposed by Rahmstorf "turned out to be not reliable over the full time period." They continue, "instead, for some periods, even inverse relationships were found to describe the simulated data best." Likewise, they state the second predictor—the rate of change of temperature—"did not show markedly better results." For both predictors, they report, "there exist periods in the simulation where the prediction errors are very large."

In discussing their own findings, von Storch et al. acknowledge the type of test they performed in the "virtual reality" produced by climate models "cannot prove whether a certain hypothesis, in this case the different statistical relationships, will hold in the real world." However, they continue, "they can be used to falsify a particular hypothesis," noting "if it is not fulfilled in a simple virtual reality, it will probably also fail in a more complex real world."

The IPCC should therefore take note: There is currently no known way to predict with any reasonable and demonstrable degree of confidence what mean global sea level will do over the twenty-first century, even if mean global air temperature begins to rise once again.

Another attempt to assess the global sea-level change "budget" was made by Leuliette and Miller (2009). They assert, "Global mean sea level change results from two major processes that alter the total volume of the ocean." These processes are (1) changes in total heat content and salinity, which produce density or steric changes and (2) the exchange of water between the oceans and other reservoirs (such as glaciers, ice caps, and ice sheets, plus land-based liquid water reservoirs), which result in mass variations. In regard to these several components, they note that although satellite radar altimeters have provided global observations since the early 1990s, only since 2002 have satellite gravity observations allowed for global estimates of mass variations, and not until 2007 did the Argo Project achieve its goal of 3,000 floats measuring truly global steric changes.

Using appropriate data to ascertain whether the sum of global steric and global mass contributions to global sea-level rise were indeed equal to the observed global sea-level rise (within the error bounds of each side of the equation), two prior attempts to close the global sea-level-rise budget were performed by Lombard et al. (2007) and Willis et al. (2008). Both of these attempts were unsuccessful. Consequently, and with a little more data, Leuliette and Miller attempted to obtain closure (and, therefore, greater confidence in the final result) one more time.

The two U.S. researchers state their "new analysis of the sea level rise budget for the period January 2004 to December 2007 used corrected Jason-1 and Envisat altimetry observations of total sea level, improved upper ocean steric sea level [data] from the Argo array, and ocean mass variations inferred from GRACE gravity mission observations." This effort yielded success, as they closed the global sea-level-rise budget by finding that the sum of steric sea level and ocean mass components had a trend of 1.5 ± 1.0 mm/year over the period of their analysis, which they state is "in agreement with the total sea level rise observed by either Jason-1 (2.4 ± 1.1 mm/year) or Envisat (2.7 ± 1.5 mm/year) within a 95% confidence interval."

Of course, there is still the question of which of the three mean results lies closest to the truth, which is of great importance given that the last of the three results is fully 80 percent greater than the first. In this regard, Woppelmann et al. (2009) recently obtained a result of 1.58 ± 0.03 mm/year by analyzing GPS observations from a global network of 227 stations over the period January 1997 to November 2006, and they cite a result of 1.7 mm/year obtained by both Church and White (2006) and Holgate (2007).

We draw attention a second time to the wise caution of Wunsch et al. (2007) that "at best, the determination and attribution of global-mean sea level change lies at the very edge of knowledge and technology." Nonetheless, it would appear researchers are gradually closing in on the truth, which is that we have yet to see any of the catastrophic sea-level rise predicted by the IPCC.

It is, of course, a truism that highly accurate measurements of historic and modern sea-level change have no particular value in their own right but only when they are considered in the proper context of sea-level change over geological time. Knowledge about changes in past (pre-instrumental) sea level comes from measurements of geological proxies and is abundant around the world. Members of the PALeo SEA Level Working Group (PALSEA 2009) recently looked to some of these records of past sea-level change in order to identify the natural contextual limits (both high and low) within which future sea-level rise will occur.

Starting with the IPCC's most recent estimate that global warming of somewhere between 1.1 and 6.3°C will occur in the twenty-first century, the PALSEA group writes, "the last time that a global warming of comparable magnitude occurred was during the termination of the last glacial period," which consisted of "a series of short, sharp steps on millennial to centennial timescales." Hence they looked at what is known about sea-level change during the Bolling-Allerod and post-Younger Dryas/early Holocene periods, noting "the magnitude and rate of warming during these periods are most closely analogous to the magnitude and rate of anthropogenic warming [that is predicted to occur] over the coming centuries." This comparison immediately rules out any type of exponentially increasing sea-level response, pointing more toward an asymptotic response where the sea-level rise is high initially but gradually levels off.

For even greater realism, the PALSEA team next turned to warm periods of the Holocene, since they assert the Earth is now at a much higher "starting" temperature than during the termination of the last great ice age. (This somewhat strange belief conflicts with the gently declining Holocene temperatures recorded in both Greenland and Antarctic ice cores.) Considering what is known about eustatic sea level between 9 and 8.5 ka BP and between 7.6 and 6.8 ka BP (increases of 1.3 and 0.7 m per century, respectively), the PALSEA scientists state, a "rapid demise of ice sheets in a climate similar to today is certainly a possibility," but "an improved understanding of ice sheet dynamics is required before one can conclude that the Greenland or West Antarctic ice sheets will behave in a similar fashion in the future."

Turning finally to previous interglacials, the 32-member research group notes some studies have placed peak sea levels during the last interglacial period somewhere in the range of 3–6 m above modern sea level about 126 ka BP, but only "several thousand years after proxy records of temperature reached interglacial levels."

In considering all of the above lines of argument, the PALSEA scientists conclude, "using palaeo-data and direct observations, it is possible to put loose limits on just how rapidly we might expect sea-level rise to occur over the next century" if the worst-case warming scenario of the IPCC were actually to occur. PALSEA places the projected rise somewhere between the lower limit of twentieth-century sea-level rise (0.12 m per century) and the sea-level rise at the conclusion of the termination of the last glacial period (1 m per century). Interestingly, this range significantly exceeds (at the high end) that reported in the IPCC's Fourth Assessment Report (-0.01 to 0.17 m over the current century); but it is still a far cry from the multiple "meters" suggested by some commentators.

References

Arendt, A.A., Echelmeyer, K.A., Harrison, W.D., Lingle, C.S., and Valentine, V.B. 2002. Rapid wastage of Alaska glaciers and their contribution to rising sea level. *Science* **297**: 382–386.

Berthier, E., Schiefer, E., Clarke, G.K.C., Menounos, B., and Remy, F. 2010. Contribution of Alaskan glaciers to sea-level rise derived from satellite imagery. *Nature Geoscience* **3**: 92–95.

Cherry, J.A., McKee, K., and Grace, J.B. 2009. Elevated CO_2 enhances biological contributions to elevation change in coastal wetlands by offsetting stressors associated with sea-level rise. *Journal of Ecology* **97**: 67–77.

Church, J.A. and White, N.J. 2006. A 20th-century acceleration in global sea-level rise. *Geophysical Research Letters* **33**: 10.1029/2005GL024826.

Dawson, J.L. and Smithers, S.G. 2010. Shoreline and beach volume change between 1967 and 2007 at Raine island, Great Barrier Reef, Australia. *Global and Planetary Change* **72**: 141–154.

Dyurgerov, M.B. and Meier, M.F. 2005. Glaciers and the Changing Earth System: A 2004 Snapshot. Instaar.

Erickson, J.E., Megonigal, J.P., Peresta, G., and Drake, B.G. 2007. Salinity and sea level mediate elevated CO_2 effects on C_3-C_4 plant interactions and tissue nitrogen in a Chesapeake Bay tidal wetland. *Global Change Biology* **13**: 202–215.

Hagedoorn, J.M., Wolf, D., and Martinec, Z. 2007. An estimate of global mean sea-level rise inferred from tide-gauge measurements using glacial-isostatic models consistent with the relative sea-level record. *Pure Applied Geophysics* **164**:791–818.

Holgate, S.J. 2007. On the decadal rates of sea level change during the twentieth century. *Geophysical Research Letters* **34**: 10.1029/2006GL028492.

Hopley, D. 1993. Coral reefs in a period of global sea level rise. In *PACON International: Recent advances in marine science and technology,* edited by N. Saxena, 453–462. Honolulu, HI: PACON.

Hopley, D., Smithers, S.G., and Parnell, K.E. 2007. *The Geomorphology of the Great Barrier Reef: Development, Diversity and Change*. Cambridge, UK: Cambridge University Press.

Langley, J.A., McKee, K.L., Cahoon, D.R., Cherry, J.A., and Megonigal, J.P. 2009. Elevated CO_2 stimulates marsh elevation gain, counterbalancing sea-level rise. *Proceedings of the National Academy of Sciences, USA* **106**: 6182–6186.

Leuliette, E.W. and Miller, L. 2009. Closing the sea level rise budget with altimetry, Argo, and GRACE. *Geophysical Research Letters* **36**: 10.1029/2008GL036010.

Lombard, A., Garcia, D., Ramillien, G., Cazenave, A., Biancale, R., Lemoine, J., Flechtner, F., Schmidt, R., and Ishii, M. 2007. Estimation of steric sea level variations from combined GRACE and Jason-1 data. *Earth and Planetary Science Letters* **254**: 194–202.

Meier, M.F. and Dyurgerov, M.G.B. 2002. Sea level changes: How Alaska affects the world. *Science* **297**: 350–351.

PALSEA (the PALeo SEA level working group: Abe-Ouchi, A., Andersen, M., Antonioli, F., Bamber, J., Bard, E., Clark, J., Clark, P., Deschamps, P., Dutton, A., Elliot, M., Gallup, C., Gomez, N., Gregory, J., Huybers, P., Kawamura, K., Kelly, M., Lambeck, K., Lowell, T., Mitrovica, J., Otto-Bleisner, B., Richards, D., Siddall, M., Stanford, J., Stirling, C., Stocker, T., Thomas, A., Thompson, W., Torbjorn, T., Vazquez Riveiros, N., Waelbroeck, C., Yokoyama, Y., and Yu, S.). 2009. The sea-level conundrum: case studies from palaeo-archives. *Journal of Quaternary Science* **25**: 19–25.

Quinn, K.J. and Ponte, R.M. 2010. Uncertainty in ocean mass trends from GRACE. *Geophysical Journal International* **181**: 762–768.

Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea-level rise. *Science* **315**: 368–370.

Ramillien, G., Lombard, A., Cazenave, A., Ivins, E.R., Llubes, M., Remy, F., and Biancale, R. 2006. Interannual variations of the mass balance of the Antarctica and Greenland ice sheets from GRACE. *Global and Planetary Change* **53**: 198–208.

Reed, D.J., Bishara, D.A., Cahoon, D.R., Donnelly, J., Kearney, M., Kolker, A.S., Leonard, L.L., Orson, R.A., and Stevenson, J.C. 2008. *Site-Specific Scenarios for Wetlands Accretion as Sea Level Rises in the Mid-Atlantic Region. Section 2.1 in: Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1.* Edited by J.G. Titus and E.M. Strange. EPA 430R07004. Washington, DC: U.S. EPA.

Smithers, S.G., Harvey, N., Hopley, D., and Woodroffe, C.D. 2007. Vulnerability of geomorphological features in the Great Barrier Reef to climate change. In *Climate Change and the Great Barrier Reef*, edited by J.E. Johnson and P.A. Marshall, 667–716. Australia: Great Barrier Reef Marine Park Authority and Australian Greenhouse Office.

von Storch, H., Zorita, E. and Gonzalez-Rouco, J.F. 2008. Relationship between global mean sea-level and global mean temperature in a climate simulation of the past millennium. *Ocean Dynamics* **58**: 227–236.

Webb, A.P. and Kench, P.S. 2010. The dynamic response of reef islands to sea-level rise: evidence from multi-decadal analysis of island change in the Central Pacific. *Global and Planetary Change* **72**: 234–246.

Wenzel, M. and Schroter, J. 2010. Reconstruction of regional mean sea level anomalies from tide gauges using neural networks. *Journal of Geophysical Research* **115**: doi:10.1029/2009JC005630.

Willis, J.K., Chambers, D.P., and Nerem, R.S. 2008. Assessing the globally averaged sea level budget on seasonal to interannual timescales. *Journal of Geophysical Research* **113**: 10.1029/2007JC004517.

Woodroffe, C.D. 2007. Reef-island topography and the vulnerability of atolls to sea-level rise. *Global and Planetary Change* **62**: 77–96.

Woppelmann, G., Pouvreau, N., Coulomb, A., Simon, B., and Woodworth, P.L. 2008. Tide gauge datum continuity at Brest since 1711: France's longest sea-level record. *Geophysical Research Letters* **35**: 10.1029/2008GL035783.

Woppelmann, G., Letetrel, C., Sanamaria, A., Bouin, M.N., Collilieux, X., Altamimi, Z., Williams, S.D.P., and Martin Miguez, B. 2009. Rates of sea-level change over the past century in a geocentric reference frame. *Geophysical Research Letters* **36**: 10.1029/2009GL038720.

Wu, Z., Heflin, M.B., Schotman, H., Vermeersen, B.L.A., Dong, D., Gross, R.S., Ivins, E.R., Moore, A.W., and Owen, S.E. 2010. Simultaneous estimation of global present-day water transport and glacial isostatic adjustment. *Nature Geoscience* **3**: 642–646.

Wunsch, C., Ponte, R.M., and Heimback, P. 2007. Decadal trends in sea level patterns: 1993-2004. *Journal of Climate* **20**: 5889–5911.

4.2.2. Ocean Heat

The Earth's climate is not controlled solely by the atmosphere but instead to a large degree by the heat store represented by the ocean, which has a 3,300 times greater heat capacity than the atmosphere. Furthermore, with a global circulation time of roughly

1,000 years, compared with one year for the atmosphere, changes in ocean heat release or uptake operate over the longer multidecadal, centennial, and millennial time scales associated with climate (as opposed to weather) change.

Despite its critical importance for climatic studies, we have a poor record of ocean heat observations, and it is only since the inception in 2004 of the ARGO global network of more than 3,000 drifting and diving ocean probes that we have an adequate estimate of ocean temperatures and heat budget. Though ARGO data are in their infancy and still subject to adjustment for errors, early indications are that the oceans are currently cooling (Loehle, 2009).

In an important paper, Shaviv (2008) has explored some of the key issues relating to change in ocean heat as a driver of climate change, particularly in response to solar variations. As background, Shaviv writes, “climatic variations synchronized with solar variations do exist, whether over the solar cycle or over longer time-scales,” citing numerous references in support of this fact. However, many scientists decline to accept the logical derivative of this fact: that solar variations are driving climate changes. Their prime objection is that measured or reconstructed variations in total solar irradiance seem too small to be capable of producing observed climate change.

One way of resolving this dilemma would be to discover some amplification mechanism, but most attempts to identify one have been fraught with difficulty and met with much criticism. In his 2008 paper, however, Shaviv makes a good case for the existence of such an amplifier, as well as providing a potential mechanism that might fill that role.

Specifically, Shaviv’s study aimed to “use the oceans as a calorimeter to measure the radiative forcing variations associated with the solar cycle” via “the study of three independent records: the net heat flux into the oceans over 5 decades, the sea-level change rate based on tide gauge records over the 20th century, and the sea-surface temperature variations,” each of which can be used “to consistently derive the same oceanic heat flux.”

In pursuing this logic, Shaviv demonstrated “there are large variations in the oceanic heat content together with the 11-year solar cycle.” In addition, he reports the three independent datasets “consistently show that the oceans absorb and emit an order of magnitude more heat than could be expected from just the variations in the total solar irradiance,” thus “implying,” as he describes it, “the necessary existence of an amplification mechanism, although without pointing to which one.”

Finding it difficult to resist pointing, however, Shaviv acknowledges his affinity for the solar-wind modulated cosmic ray flux (CRF) hypothesis, which was suggested by Ney (1959), discussed by Dickinson (1975), and championed by Svensmark (1998). Based on “correlations between CRF variations and cloud cover, correlations between non-solar CRF variations and temperature over geological timescales, as well as experimental results showing that the formation of small condensation nuclei could be bottlenecked by the number density of atmospheric ions,” this concept, according to Shaviv, “predicts the correct radiation imbalance observed in the cloud cover variations” that are needed to produce the magnitude of the net heat flux into the oceans associated with the 11-year solar cycle. Shaviv thus concludes the solar-wind modulated CRF hypothesis is “a favorable candidate” as the primary instigator of many climatic phenomena.

References

Dickinson, R.E. 1975. Solar variability and the lower atmosphere. *Bulletin of the American Meteorological Society* **56**: 1240–1248.

Loehle, C. 2009. Cooling of the global ocean since 2003. *Energy & Environment* **20**: 101–104.

Ney, E.P. 1959. Cosmic radiation and weather. *Nature* **183**: 451.

Shaviv, N.J. 2008. Using the oceans as a calorimeter to quantify the solar radiative forcing. *Journal of Geophysical Research* **113**: 10.1029/2007JA012989.

Svensmark, H. 1998. Influence of cosmic rays on earth’s climate. *Physical Review Letters* **81**: 5027–5030.

4.2.3. Ocean Circulation

The global thermohaline system of circulation of ocean currents, also sometimes called the meridional overturning circulation, provides links for the transfer of heat across, between, and vertically through ocean basins, with complete mixing taking up to 1,000 years and more. Physical forcing of the system is provided by the westerly wind belts of the southern circum-Antarctic Ocean and by the sinking of dense, saline water in the North Atlantic Ocean. Past changes in the flow of this ocean circulation system can be shown to be linked to major climate change; for example, flow speeds of the cold-water Pacific Deep Western Boundary Current increased during past glacial periods (Hall et al., 2001). The IPCC, noting such facts, therefore argues global warming will change the speed of ocean circulation phenomena such as the Gulf Stream in ways that will make the world's climate less hospitable.

In setting out to assess this argument, Baehr et al. (2007) investigated how quickly changes in the North Atlantic meridional overturning circulation (MOC) could be detected by projecting simulated observations onto a time-independent spatial pattern of natural variability, which was derived by regressing the zonal density gradient along 26°N against the strength of the MOC at 26°N within a model-based control climate simulation, which pattern was compared against observed anomalies found between the 1957 and 2004 hydrographic occupations of this latitudinal section.

Looking to the future, this exercise revealed that Atlantic MOC changes could likely be detected with 95 percent reliability after about 30 years, using continuous observations of zonal density gradients that can be obtained from a recently deployed monitoring array. Looking to the past, they report, "for the five hydrographic occupations of the 26°N transect, none of the analyzed depth ranges shows a significant trend between 1957 and 2004, implying that there was no MOC trend over the past 50 years." The finding is significant because to this point in time, over which the IPCC claims the Earth has warmed at a rate and to a level of warmth that is unprecedented over the past two millennia, there has been no observable change in the rate of the North Atlantic MOC, suggesting either the IPCC is significantly in error in its characterization of Earth's current level of warmth or the North Atlantic MOC is not nearly as sensitive to global warming as many climate models employed by the IPCC have suggested it is.

Since Baehr et al. (2007) have used real-world hydrographic transect data to demonstrate "there was no MOC trend over the past 50 years," we will probably have more time to prepare for any undesirable consequences of a drastic decline in the Atlantic MOC than did the unfortunate folks in the non-award-winning film *The Day After Tomorrow*.

In a second paper addressing North Atlantic deep water formation and circulation, Vage et al. (2008) write, "in response to global warming, most climate models predict a decline in the Meridional Overturning Circulation, often due to a reduction of Labrador Sea Water" (which is produced in the Labrador and Irminger Seas of the North Atlantic Ocean), noting further, "since the mid-1990s, convection in the Labrador Sea has been shallow—and at times nearly absent."

This confluence of observations might be interpreted as strengthening claims of an impending climatic disaster. However, Vage et al. document "the return of deep convection to the subpolar gyre in both the Labrador and Irminger seas in the winter of 2007–2008," using "profiling float data from the Argo program to document deep mixing" as well as "a variety of *in situ*, satellite and reanalysis data" to provide context for the phenomenon.

The Canadian, Danish, French, and U.S. scientists observed winter mixing to depths of 1,800 m in the Labrador Sea, 1,000 m in the Irminger Sea, and 1,600 m south of Greenland, whereas base-period (the winters of 2001–2006) mixing depths are less than 1,000 m. They also determined, via analyses of heat flux components, "the main cause of the enhanced heat flux was unusually cold air temperatures during [the 2007–2008] winter."

More specifically, the scientists tell us, "the air temperature recorded at the Prins Christian Sund meteorological station near Cape Farewell was 2.8°C colder in the winter of 2007–2008 than the corresponding mean of the base period." Furthermore, they say the cooling was "not a local phenomenon," noting "the global temperature dropped 0.45°C between the winters of 2006–2007 and 2007–2008" and that across northern North America "the mean winter temperature was more than 3°C colder." In addition, they report "storm tracks, the flux of freshwater to the Labrador Sea and the distribution of pack ice all contributed to an enhanced flux of heat from the sea to the air, making the surface water sufficiently cold and dense to initiate deep convection." This phenomenon was aided by "very strong westerly winds off the Labrador ice edge" that "boosted the advection of cold air towards the region of deep convection," thereby providing a sort of perfect storm situation in which everything came together to create an oceanic overturning the likes of which had not been seen since the late 1980s to early 1990s.

In the words of the nine scientists of the research team, "the return of deep convection to the Labrador and Irminger seas in the winter of 2007–2008 was a surprise." One reason for this reaction, as they describe it, was that "contrary to expectations the transition to a convective state took place abruptly, without going through a phase of preconditioning."

References

Baehr, J., Keller, K. and Marotzke, J. 2008. Detecting potential changes in the meridional overturning circulation at 26°N in the Atlantic. *Climatic Change* **91**: 11–27.

Baehr, J., Haak, H., Alderson, S., Cunningham, S.A., Jungclaus, J.H., and Marotzke, J. 2007. Timely detection of changes in the meridional overturning circulation at 26°N in the Atlantic. *Journal of Climate* **20**: 5827–5841.

Hall, I.R., McCave, I.N., Shackleton, N.J., Weedon, G.P., and Harris, S.E. 2001. Glacial intensification of deep Pacific inflow and ventilation. *Nature*, **412**: 809–811.

Vage, K., Pickart, R.S., Thierry, V., Reverdin, G., Lee, C.M., Petrie, B., Agnew, T.A., Wong, A., and Ribergaard, M.H. 2008. Surprising return of deep convection to the subpolar North Atlantic Ocean in winter 2007-2008. *Nature Geoscience* **2**: 67–72.

4.3. Precipitation

4.3.1. Rainfall

The IPCC contends extreme weather events of all types should become both more frequent and more intense when the world warms. It claims this is particularly true with respect to events having to do with rainfall. Others follow suit. For example, in their popular book *Dire Predictions: Understanding Global Warming*— subtitled "The Illustrated Guide to the Findings of the IPCC"—Mann and Kump (2008) write that as temperatures rise "increases are to be expected in the frequency of very intense rainfall events" and "individual storms will be associated with more severe downpours ... due to the greater amount of water vapor that a warmer atmosphere can hold." But have such things actually been happening in the real world? This is an especially testable proposition in light of the global warming of the last two decades of the twentieth century, which the IPCC describes as having been unprecedented over the past one to two millennia.

Giambelluca et al. (2008) have reported Hawaii warmed recently at a rate of 0.163°C per decade. In a study designed to assess whether this warming caused additional rainfall in Hawaii, Chu et al. (2010) write, "for the first time, five climate change indices for extreme precipitation (four related to wetness and one related to dryness) in Hawaii have been calculated," based on "daily observational records from the 1950s to 2007." These specific indices are (1) the simple daily intensity index, (2) the total number of days with precipitation ≥25.4 mm, (3) the annual maximum consecutive five-day precipitation amount, (4) the fraction of annual total precipitation from events exceeding the 1961–1990 95th percentile, and (5) the number of consecutive dry days.

The three University of Hawaii at Manoa scientists determined that "since the 1980s, there has been a change in the types of precipitation intensity, resulting in more frequent light precipitation and less frequent moderate and heavy precipitation intensity," as well as a "shorter annual number of days with intense precipitation and smaller consecutive 5-day precipitation amounts and smaller fraction of annual precipitation due to events exceeding the 1961–1990 95th percentile in the recent epoch [1980–2007] relative to the first epoch [1950–1979]." They add, "long-term upward trends are observed for consecutive dry days." Thus, Chu et al. show that not only were the excess precipitation predictions of the IPCC not realized throughout the Hawaiian Islands, but in fact just the opposite occurred there.

In a parallel analysis of rainfall patterns in Southern Italy, but over a longer time period, Diodato et al.(2008) studied "Calore River Basin (South Italy) erosive rainfall using data from 425-year-long series of both observations (1922–2004) and proxy-based reconstructions (1580–1921)." The more recent of the two series was based on a scheme that employed the Revised Universal Soil Loss Equation, and documentary descriptions provided the basis for the earlier series.

The authors report the climate history of the Calore River Basin shows pronounced interdecadal variations, with multidecadal erosivity reflecting the mixed population of thermo-convective and cyclonic rainstorms with large anomalies, and they note "the so-called Little Ice Age (16th to mid-19th centuries) was identified as the stormiest period, with mixed rainstorm types and high frequency of floods and erosive rainfall."

In the concluding section of their paper, the three researchers write, “in recent years, climate change (generally assumed as synonymous with global warming) has become a global concern and is widely reported in the media.” One of the chief concerns is that extreme weather phenomena, such as droughts and floods, will become both more frequent and more severe as the planet warms. According to Diodato et al., however, the real world data they studied indicate “climate in the Calore River Basin has been largely characterized by naturally occurring weather anomalies in past centuries (long before industrial CO_2 emissions), not only in recent years.”

In a geomorphological study, Stankoviansky (2003), working in the Myjava Hill Land of Slovakia (in the western part of the country, near the Czech Republic border), employed topographical maps and aerial photographs, field geomorphic investigation, and the study of historical documents from local municipal and church sources to determine the spatial distribution of gully landforms and trace the history of their development.

Stankoviansky’s results indicate “the central part of the area, settled between the second half of the 16th and the beginning of the 19th centuries, was affected by gully formation in two periods, the first between the end of the 16th century and the 1730s and the second roughly between the 1780s and 1840s.” He infers the gullies were formed “during periods of extensive forest clearance and expansion of farmland,” but “the triggering mechanism of gullying was extreme rainfalls during the Little Ice Age.” More specifically, he writes, “the gullies were formed relatively quickly by repeated incision of ephemeral flows concentrated during extreme rainfall events, which were clustered in periods that correspond with known climatic fluctuations during the Little Ice Age.” Subsequently, from the mid-nineteenth century to the present, he reports, “there has been a decrease in gully growth because of the afforestation of gullies and especially climatic improvements since the termination of the Little Ice Age.”

Stankoviansky’s observations suggest extreme and destructive rainfall events were much more common throughout the Myjava Hill Land of Slovakia during the Little Ice Age than in the centuries since. This view, in his words (and in many references he cites), “is often regarded as generally valid for Central Europe.”

The Tibetan Plateau, sometimes termed the “roof of the world,” also has been called the “world’s water tower” because of the strong influence it exerts on northern hemisphere mid-latitude moisture, precipitation, and runoff. In a recent study, Xu et al. (2008) analyzed 50 years (1957–2006) of upper-air Chinese radiosonde observations along with concomitant surface air temperature and precipitation data.

The results indicate that in the summer half of the year, “the Tibetan Plateau acts as a strong ‘dynamic pump’ [that] continuously attracts moist air from the low-latitude oceans.” When reaching the plateau, some of these flows rise along its south side and cause “frequent convections and precipitations,” which feed its mid- and low-latitude glaciers, snowpacks, and lakes, from whence originate many of Asia’s major rivers. This flow system constitutes “the largest river runoff from any single location in the world.” In further analysis of their datasets, the four researchers found “recent warming in the plateau started in the early 1970s, while the water vapor content showed an upward trend in the early 1980s and continues to the present time,” a pattern similar to that found in the annual precipitation data.

Xu et al. write their findings “suggest several possible consequences.” First, they note, “owing to the combined effect of the rapid melting of glaciers and increased precipitation in the Tibetan Plateau due to global warming, the downstream transport of water from the Tibetan water tower would increase in volume,” and “this may cause an increase in severe flooding problems for countries along the major rivers that discharge this water.” Alternatively, “the rapid retreat of glaciers over the plateau’s mountains may pose a serious socio-economical issue for the water resources that feed 40% of the world’s population.” A third scenario, which seems more likely in view of Xu et al.’s results, is that, as these authors describe it, “the increased atmospheric [moisture] supply may alleviate the problem of rapid depletion of water resources arising from the melting of glaciers.” This more optimistic view is perhaps akin to seeing doomsday on the left and doomsday on the right, but salvation in the middle.

Over a longer period, a climate history for the Tibetan Plateau for the past 1,700 years has been developed by Zhao et al. (2009). These authors studied carbonate percentages and ostracode abundances in sediment cores from Hurleg Lake, in the arid Qaidam Basin of the Northeast Tibetan Plateau. They compared their lacustrine history with a contemporaneous history of tree-ring-derived precipitation over nearby mountainous terrain, as well as with changes in solar activity manifest in solar proxy residual $\Delta^{14}C$ data.

Zhao et al. discovered "carbonate percentage and ostracode abundance show a consistent pattern with ~200-year moisture oscillations during the last 1000 years." In addition, the moisture pattern in the Qaidam Basin being "in opposite relation to tree-ring-based monsoon precipitations in the surrounding mountains" suggested "that topography may be important in controlling regional moisture patterns as mediated by rising and subsiding air masses in this topographically-complex region." Cross-spectral analysis between their moisture proxies and the solar activity proxy "shows high coherence at the ~200-year periodicity which is similar to Chinese monsoon intensity records, implying the possible solar forcing of moisture oscillations in the NE Tibetan Plateau."

These findings provide another example of cyclical solar activity controlling parallel precipitation cycles. In the words of the researchers, "higher solar output corresponds to a stronger monsoon, which intensifies the uplift of air mass on the high Tibetan Plateau and strengthens the subsidence of air mass over the Qaidam Basin," while "the reverse is true during the period of lower solar output." They conclude, "high solar activity is correlated with dry climate in the Qaidam Basin and increased precipitation in monsoonal areas." This does not leave a lot of room for CO_2 to control precipitation in this important part of the world.

Lastly, Kim et al. (2009) analyzed a 200-year history of precipitation measured at Seoul, Korea (1807 to 2006). This study is highly relevant to the common allegation that droughts and floods will become more frequent or severe because of global warming. One important way to test this prediction is to study precipitation over the period of time when the planet transited from what was one of the coldest intervals of the current interglacial period (the Little Ice Age) to the end of the twentieth century.

Kim et al. use "progressive methods for assessing drought severity from diverse points of view," starting with (1) the Effective Drought Index (EDI) developed by Byun and Wilhite (1999), which Kim et al. describe as "an intensive measure that considers daily water accumulation with a weighting function for time passage," (2) a Corrected EDI that "considers the rapid runoff of water resources after heavy rainfall" (CEDI), (3) an Accumulated EDI that "considers the drought severity and duration of individual drought events" (AEDI), and finally (4) a year-accumulated negative EDI "representing annual drought severity" (YAEDI).

The researchers' precipitation history and two of their drought severity histories are presented, in that order, in Figures 4.3.1 and 4.3.2.

It is obvious from these results that the only major deviation from long-term normality is the decadal-scale decrease in precipitation and ensuing drought, with both phenomena achieving their most extreme values (low in the case of precipitation, high in the case of drought) around AD 1900. Hence, it is very clear that the significant post-Little Ice Age warming of the planet had essentially no effect on the long-term histories of either precipitation or drought at Seoul, Korea. Similar results are known from around the world.

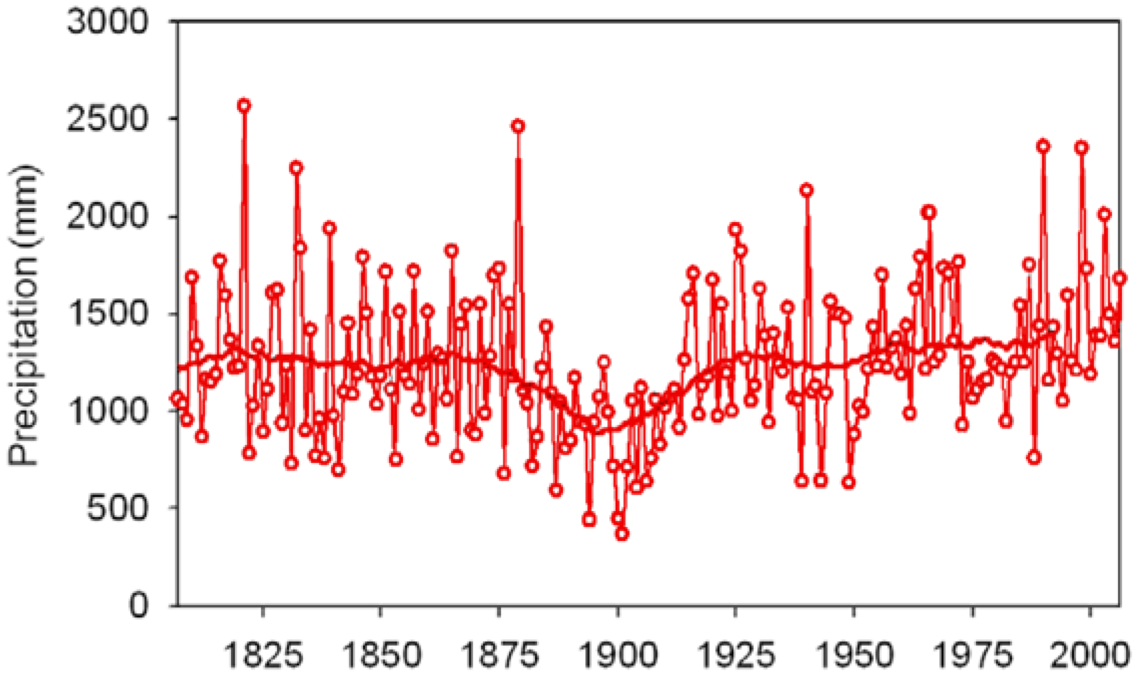


Figure 4.3.1. Annual precipitation history at Seoul, Korea, where the solid line represents a thirty-year moving-average. Adapted from Kim et al. (2009).

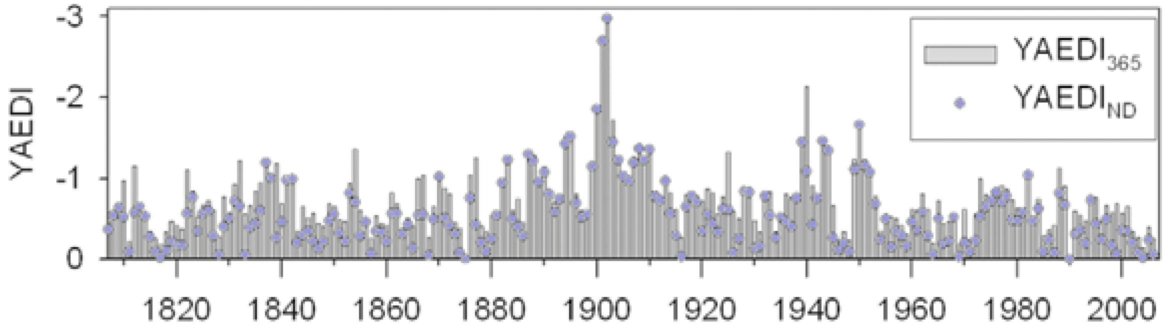


Figure 4.3.2. Annual “dryness” history at Seoul, Korea, represented by YAEDI365 (sum of daily negative EDI values divided by 365, represented by bars) and YAEDIND (sum of daily negative EDI values divided by total days of negative EDI, represented by open circles). Adapted from Kim et al. (2009).

References

Byun, H.R. and Wilhite, D.A. 1999. Objective quantification of drought severity and duration. *Journal of Climate* **12**: 2747–2756.

Chu, P.-S., Chen, Y.R., and Schroeder, T.A. 2010. Changes in precipitation extremes in the Hawaiian Islands in a warming climate. *Journal of Climate* **23**: 4881–4900.

Diodato, N., Ceccarelli, M., and Bellocchi, G. 2008. Decadal and century-long changes in the reconstruction of erosive rainfall anomalies in a Mediterranean fluvial basin. *Earth Surface Processes and Landforms* **33**: 2078–2093.

Giambelluca, T.W., Diaz, H.F., and Luke, M.S.A. 2008. Secular temperature changes in Hawaii. *Geophysical Research Letters* **35**: 10.1029/2008GL034377.

Kim, D.-W., Byun, H.-R., and Choi, K.-S. 2009. Evaluation, modification, and application of the Effective Drought Index to 200-Year drought climatology of Seoul, Korea. *Journal of Hydrology* **378**: 1–12.

Mann, M.E. and Kump, L.R. 2008. Dire Predictions: Understanding Global Warming. The Illustrated Guide to the Findings of the IPCC. London, UK: Dorling Kindersley Limited.

Stankoviansky, M. 2003. Historical evolution of permanent gullies in the Myjava Hill Land, Slovakia. *Catena* **51**: 223–239.

Xu, S., Lu, C., Shi, X., and Gao, S. 2008. World water tower: An atmospheric perspective. *Geophysical Research Letters* **35**: 10.1029/2008GL035867.

Zhao, C., Yu, Z., Zhao, Y., and Ito, E. 2009. Possible orographic and solar controls of Late Holocene centennial-scale moisture oscillations in the northeastern Tibetan Plateau. *Geophysical Research Letters* **36**: 10.1029/2009GL040951.

4.3.2. Snow

In their analysis of the record of snow avalanches from the French Alps, Eckert et al. (2010) comment, "understanding the response of dangerous natural phenomena to variations in corresponding constraining factors can reveal signals of climate change." They add, "since snow avalanches are mainly governed by temperature fluctuations, heavy precipitation and wind regimes, they are likely to be strongly influenced by climatic fluctuations." This reasoning is similar to that used by the IPCC.

Eckert et al. compared several different ways of analyzing snow avalanche data contained in the *Enquete Permanente sur les Avalanches—EPA*, which they say "is a chronicle describing the avalanche events on approximately 5,000 determined paths in the French Alps and the Pyrenees."

The four researchers report finding "no strong modifications in mean avalanche activity or in the number of winters of low or high activity over the last 60 years," and they point out "a similar result was obtained for Switzerland over the second half of the twentieth century by Laternser and Schneebeli (2002) using avalanche indexes and comparison with meteorological data." Eckert et al. also report "Schneebeli et al. (1997) and Bader and Kunz (2000) have seen no change in extreme snowfalls and in the associated number of catastrophic avalanches around Davos, Switzerland during the twentieth century," and "in the Maurienne Valley in France, Jomelli et al. (2007) found no correlation between the fluctuations in avalanche activity between 1978 and 2003 and large-scale atmospheric patterns." And in one final study, which had a slightly different result, they note Jomelli and Pech (2004) "suggest that at low altitudes, avalanche magnitude has declined since 1650 in the Massif des Ecrins in the French Alps."

After considering all they learned from their many analyses and comprehensive review of the work of other scientists, Eckert et al. concluded "climate change has recently had little impact on the avalanching rhythm in this region."

Analyzing a slightly longer record from the Unites States, this time of annual snowfall, and based on the dataset described by Kunkel et al. (2009a), Kunkel et al. (2009b) used 440 long-term, homogeneous snowfall records to examine "temporal variability in the occurrence of the most extreme snowfall years, both those with abundant snowfall amounts and those lacking snowfall" (defined as the highest and lowest tenth percentile winter snow amounts). The analyzed data came from the conterminous United States over the 107-year period from 1900–01 to 2006–07.

Kunkel et al. (2009b) found there were "large decreases in the frequency of low-extreme snowfall years in the west north-central and east north-central United States," but they were "balanced by large increases in the frequency of low-extreme snowfall years in the Northeast, Southeast and Northwest." All in all, therefore, Kunkel et al. determined "the area-weighted conterminous United States results do not show a statistically significant trend in the occurrence of either high or low snowfall years for the 107-year period."

Kilpelainen et al. (2010) report on the degree to which Finnish forests are damaged by snow load on their branches. They write, "within Europe's forests, snow-induced damage"—due to "accumulation of snow load on tree branches"—"has accounted for a mean annual amount of almost one million cubic meters of damaged wood in managed forests over the period 1950–2000." The damage that occurs is primarily to "stem breakage or bending when the soil is frozen," although Kilpelainen et al. also point out "trees can also be uprooted if the soil is not frozen" and damage "by insects or fungal attacks are also common in trees suffering from snow damage."

To calculate risk of snow-induced damage, Kilpelainen et al. employed a snow accumulation model in which cumulative precipitation, air temperature, and wind speed were derived from the A2 scenario of the FINADAPT project (Ruosteenoja et al., 2005), where the air's CO_2 concentration was estimated to rise to 840 ppm by 2100 and mean air temperatures were projected to increase by almost 4°C in summer and more than 6°C in winter. The model was first tested and trained using real-world data obtained by the Finnish Meteorological Institute (Venalainen et al., 2005) for the 30-year baseline period of 1961–1990.

Defining the risk of snow-induced forest damage as proportional to the number of days per year when the accumulated amount of snow exceeds 20 kg m^{-2}, the six scientists calculated the mean annual number of risk days in Finland declined by 11 percent, 23 percent, and 56 percent relative to the 1961–1990 baseline period for the first, second, and third 30-day simulation periods they modeled (1991–2020, 2021–2050, and 2070–2099), respectively. For the most hazardous areas of northwest and northeast Finland they also report "the number of risk days decreased from the baseline period of over 30 days to about 8 days per year at the end of the century," which represents a warming-induced decrease in risk of snow damage to forests on the order of 75 percent.

In another study, from Northern China, Peng et al. (2010) used snow-depth measurements collected at 279 meteorological stations, plus colocated satellite-derived Normalized Difference Vegetation Index (NDVI) data, to investigate spatio-temporal changes in snow depth over the period 1980–2006, and to analyze the effects of those changes on vegetative growth during the following spring and summer.

The five researchers report "over the past three decades, winter snow depth overall increased in northern China, particularly in the most arid and semiarid regions of western China where desert and grassland are mainly distributed." Peng et al. report that in these specific areas, positive correlations existed between mean winter snow depth and spring NDVI data. In addition, they note Piao et al. (2005) determined the net primary productivity of the same desert and grasslands during 1982–1999 "increased by 1.6% per year and 1.1% per year, respectively" and that "desertification has been reversed in some areas of western China since the 1980s," citing Runnstrom (2000), Wu (2001), Zhang et al. (2003), and Piao et al. (2005).

Discussing the implications of their findings, Peng et al. note the "increase in vegetation coverage in arid and semiarid regions of China, possibly driven by winter snow, will likely restore soil and enhance its antiwind-erosion ability, reducing the possibility of released dust and mitigating sand-dust storms." They note, further, that the frequency of sand-dust storms has indeed "declined in China since the early 1980s (Qian et al., 2002; Zhao et al., 2004)."

Thus, as the world has warmed over the past three decades, the concomitant climatic change across China above 40°N latitude has been an increase in winter snow depth that, in turn, promoted increased vegetative growth in desert areas and grasslands and resulted in a reduction in sand-dust storms. These three climate-related changes would be recognized by most rational people as environmentally positive developments.

References

Bader, S. and Kunz, P. 2000. *Climate Risks—The Challenge for Alpine Region—PNR31.* Verlag der Fachvereine Hochschulverlag AG an der ETH Zurich.

Eckert, N., Parent, E., Kies, R., and Baya, H. 2010. A spatio-temporal modelling framework for assessing the fluctuations of avalanche occurrence resulting from climate change: application to 60 years of data in the northern French Alps. *Climatic Change* **101**: 515–553.

Jomelli, V. and Pech, P. 2004. Effects of the little ice age on avalanche boulder tongues in the French Alps (Massif des Ecrins). *Earth Surface Processes and Landforms* **29**: 553–564.

Jomelli, V., Delval, C., Grancher, D., Escande, S., Brunstein, D., Hetu, B., Filion, L., and Pech, P. 2007. Probabilistic analysis of recent snow avalanche activity and climate in the French Alps. *Cold Regions Science and Technology* **47**: 180–192.

Kilpelainen, A., Gregow, H., Strandman, H., Kellomaki, S., Venalainen, A., and Peltola, H. 2010. Impacts of climate change on the risk of snow-induced forest damage in Finland. *Climatic Change* **99**: 193–209.

Kunkel, K.E., Palecki, M.A., Ensor, L., Easterling, D., Hubbard, K.G., Robinson, D., and Redmond, K. 2009a. Trends in twentieth-century U.S. extreme snowfall seasons. *Journal of Climate* **22**: 6204–6216.

Kunkel, K.E., Palecki, M.A., Ensor, L., Hubbard, K.G., Robinson, D.A., Redmond, K.T., and Easterling, D.R. 2009b. Trends in twentieth-century U.S. snowfall using a quality-controlled dataset. *Journal of Atmospheric and Oceanic Technology* **26**: 33–44.

Laternser, M. and Schneebeli, M. 2002. Temporal trend and spatial distribution of avalanche activity during the last 50 years in Switzerland. *Natural Hazards* **27**: 201–230.

Peng, S., Piao, S., Ciais, P., Fang, J., and Wang, X. 2010. Change in winter snow depth and its impacts on vegetation in China. *Global Change Biology* **16**: 3004–3013.

Piao, S.L., Fang, J.Y., Liu, H.Y., and Zhu, B. 2005. NDVI-indicated decline in desertification in China in the past two decades. *Geophysical Research Letters* **32**: 10.1029/2004GL021764.

Qian, Z.A., Song, M.H., and Li, W.Y. 2002. Analysis on distributive variation and forecast of sand-dust storms in recent 50 years in north China. *Journal of Desert Research* **22**: 106–111.

Runnstrom, M.C. 2000. Is northern China winning the battle against desertification? Satellite remote sensing as a tool to study biomass trends on the Ordos plateau in semiarid China. *Ambio* **29**: 468–476.

Ruosteenoja, K., Jylha, K., and Tuomenvirta, H. 2005. Climate scenarios for FINADAPT studies of climate change adaptation. FINADAPT Working Paper 15. Helsinki, Finland: Finnish Environment Institute Mimeographs 345.

Schneebeli, M., Laternser, M., and Ammann, W. 1997. Destructive snow avalanches and climate change in the Swiss Alps. *Eclogae Geologicae Helvetiae* **90**: 457–461.

Venalainen, A., Tuomenvirta, H., and Pirinen, P. et al. 2005. A basic Finnish climate data set 1961–2000—description and illustrations. Finnish Meteorological Institute Reports 2005:5, Helsinki, Finland.

Wu, W. 2001. Study on process of desertification in Mu Us sandy land for last 50 years, China. *Journal of Desert Research* **21**: 164–169.

Zhang, L., Yue, L.P., and Xia, B. 2003. The study of land desertification in transitional zones between the UM US desert and the Loess plateau using RS and GIS—a case study of the Yulin region. *Environmental Geology* **44**: 530–534.

Zhao, C.S., Dabu, X., and Li, Y. 2004. Relationship between climatic factors and dust storm frequency in inner Mongolia of China. *Geophysical Research Letters* **31**: 10.1029/2003GL018351.

4.3.3. Monsoon

Bombardi and Carvalho (2009) evaluated the ability of ten IPCC global coupled climate models (with distinct physics and resolutions) to simulate characteristics of the real-world South American Monsoon System (SAMS). For comparison with model outputs, they used real-world data pertaining to the onset, end, and total rainfall of SAMS, as characterized by precipitation data for the period 1979–2006, which they derived from the Global Precipitation Climatology Project.

Bombardi and Carvalho report that over northern South America the annual precipitation cycle "is poorly represented by most models." More specifically, they found "most models tend to underestimate precipitation during the peak of the rainy season." They attribute the lack of success of their model runs to "the misrepresentation of the Inter-Tropical Convergence Zone and its seasonal cycle," noting also that "poor representation of the total monsoonal precipitation over the Amazon and northeast Brazil is observed in a large majority of the models." Finally, they note, "simulations of the total seasonal precipitation, onset and end of the rainy season diverge among models and are notoriously unrealistic over [the] north and northwest Amazon for most models."

This is another demonstration of the failure of computer-model output to correspond to real-world data, giving little confidence in the models' ability to correctly simulate future climatic trends.

Reference

Bombardi, R.J. and Carvalho, L.M.V. 2009. IPCC global coupled model simulations of the South America monsoon system. *Climate Dynamics* **33**: 893–916.

4.3.4. Evaporation

Climate scientists have a particular interest in the process of evaporation, because evaporation is the primary source of atmospheric water vapor, a powerful greenhouse gas.

Recognizing the importance of near-surface wind speed for evaporation, McVicar et al. (2010) note "the occurrence of widespread declining trends of wind speed measured by terrestrial anemometers at many mid-latitude sites over the last 30-50 years," citing papers by Roderick et al. (2007), McVicar et al. (2008), Pryor et al. (2009), and Jiang et al. (2010) in support.

McVicar et al. assert that this "stilling," as it has come to be called, is "a key factor in reducing atmospheric evaporative demand," which drives actual evapotranspiration when water availability is not limited, as in the case of lakes and rivers. In addition, they note (1) near-surface wind speed (u) nearly always increases as land-surface elevation (z) increases (as demonstrated by McVicar et al., 2007), (2) increasing wind speeds lead to increases in atmospheric evaporative demand, and (3) decreasing wind speeds do the opposite.

All of these changes are significant to people dependent on water resources derived from mountainous headwater catchments. It would therefore be advantageous to learn how this latter phenomenon (the change in near-surface wind speed with ground elevation) might have varied over the last few decades of global warming, because, as the authors point out, "over half the global population live in catchments with rivers originating in mountainous regions (Beniston, 2005), with this water supporting about 25% of the global gross domestic product (Barnett et al., 2005)."

Defining u_z as change in wind speed with change in elevation—$u_z = \Delta u/\Delta z$, where $\Delta u = u_2 - u_1$, $\Delta z = z_2 - z_1$, and $z_2 > z_1$—McVicar et al. calculated monthly averages of u_z, using monthly average u data from low-set (10-meter) anemometers maintained by the Chinese Bureau of Meteorology at 82 sites in central China and by MeteoSwiss at 37 sites in Switzerland from January 1960 through December 2006. Their research constitutes, in their words, "the first time that long-term trends in u_z in mountainous regions have been calculated." The seven scientists determined, "for both regions u_z trend results showed that u has declined more rapidly at higher than lower elevations."

This double-benefit—a general decline in wind speed at many mid-latitude sites and a further decline in wind speed at higher elevations—should act to reduce water loss via evaporation from high-altitude catchments in many of the world's mountainous regions, thus providing more water for people who obtain it from such sources. Finally, McVicar et al. note the "reductions in wind speed will serve to reduce rates of actual evapo-transpiration partially compensating for increases in actual evapo-transpiration due to increasing air temperatures."

References

Barnett, T.P., Adam, J.C., and Lettenmaier, D.P. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **438**: 303–309.

Beniston, M. 2005. Mountain climates and climatic change: An overview of processes focusing on the European Alps. *Pure and Applied Geophysics* **162**: 1587–1606.

Jiang, Y., Luo, Y., Zhao, Z., and Tao, S. 2010. Changes in wind speed over China during 1956–2004. *Theoretical and Applied Climatology* **99**: 421–430.

McVicar, T.R., Van Niel, T.G., Li, L.T., Hutchinson, M.F., Mu, X.-M., and Liu, Z.-H. 2007. Spatially distributing monthly reference evapotranspiration and pan evaporation considering topographic influences. *Journal of Hydrology* **338**: 196–220.

McVicar, T.R., Van Niel, T.G., Li, L.T., Roderick, M.L., Rayner, D.P., Ricciardulli, L., and Donohue, R.G. 2008. Capturing the stilling phenomenon and comparison with near-surface reanalysis output. *Geophysical Research Letters* **35**: 10.1029/2008GL035627.

McVicar, T.R., Van Niel, T.G., Roderick, M.L., Li, L.T., Mo, X.G., Zimmermann, N.E., and Schmatz, D.R. 2010. Observational evidence from two mountainous regions that near-surface wind speeds are declining more rapidly at higher elevations than lower elevations: 1960–2006. *Geophysical Research Letters* **37**: 10.1029/2009GL042255.

Pryor, S.C., Barthelmie, R.J., Young, D.T., Takle, E.S., Arritt, R.W., Flory, D., Gutowski Jr., W.J., Nunes, A., and Roads, J. 2009. Wind speed trends over the contiguous United States. *Journal of Geophysical Research* **114**: 10.1029/2008JD011416.

Roderick, M.L., Rotstayn, L.D., Farquhar, G.D., and Hobbins, M.T. 2007. On the attribution of changing pan evaporation. *Geophysical Research Letters* **34**: 10.1029/2007GL031166.

4.4. Rivers and Streamflow

The IPCC claims that global warming will lead to the occurrence of both more floods and more droughts. As a check on this hypothesis, Zhang et al. (2010) analyzed twentieth century streamflow changes within the Susquehanna River Basin. This basin includes parts of the states of Maryland, New York, and Pennsylvania and is the largest freshwater contributor to Chesapeake Bay in the eastern United States, comprising 43 percent of the bay's drainage area and providing 50 percent of its water.

Zhang et al. studied long-term, continuous, daily streamflow records for eight unregulated streams. The records start at slightly different times, but all end in 2006 with record-lengths ranging from 68 to 93 years and an average length of 82.5 years. These data were subjected to repeated monotonic trend tests, each using different beginning and ending times, to search for trends and to detect changes in annual minimum, median, and maximum daily streamflow.

The four researchers, who are members of the Susquehanna River Basin Commission, report there was "a considerable increase in annual minimum flow for most of the examined watersheds and a noticeable increase in annual median flow for about half of the examined watersheds." However, they found annual maximum streamflow "does not show significant long-term change."

Predicting that global warming will lead to more frequent and/or more intense flooding *and* drought, as the IPCC does, would seem almost to ensure predictive success nearly all the time and nearly everywhere. The Susquehanna River Basin study, however, yields no support for this contention. This is because the increases in minimum streamflow should be accompanied by less severe and/or less frequent drought, whereas the lack of change in annual maximum streamflow shows there has been no significant long-term change at the opposite end of the spectrum, where floods might be expected.

Mauas et al. (2008) conducted a similar study of the Parana River in South America. They write that streamflows "are excellent climatic indicators," especially in the case of rivers "with continental scale basins" that "smooth out local variations" and can thus "be particularly useful to study global forcing mechanisms." The Parana River is the world's fifth-largest in terms of drainage area and fourth-largest with respect to streamflow. Mauas et al. analyzed streamflow data that have been collected continuously on a daily basis since 1904.

The three researchers looked for any trends or periodicities that might be present. They found "the flow of the Parana is larger in the last three decades, with a mean value almost 20% larger than that of the first 70 years of the twentieth century." Even more importantly, they state, "the stream flow during the last 30 years has increased in the months in which the flow is minimum, while the flow remains more or less constant during the months of maximum," noting "the same trend is also found in other rivers of the region."

With respect to periodicities, they report that detrended time series of streamflow data are correlated with detrended times series of both sunspot number and total solar irradiance, with Pearson's correlation coefficients between streamflow and the two solar parameters of 0.78 and 0.69, respectively, at "a significance level higher than 99.99% in both cases."

In a study of United Kingdom rivers, Hannaford and Marsh (2008) write, "recent flood events have led to speculation that climate change is influencing the high-flow regimes of UK catchments, and projections suggest that flooding may increase in [the] future as a result of human-induced warming." Utilizing the UK "benchmark network" of 87 "near-natural catchments" (as identified by Bradford and Marsh, 2003), Hannaford and Marsh conducted "a UK-wide appraisal of trends in high-flow regimes unaffected by human disturbances" to test such speculation.

The two researchers report "significant positive trends were observed in all high-flow indicators ... over the 30–40 years prior to 2003, primarily in the maritime-influenced, upland catchments in the north and west of the UK." However, they write, "there is little compelling evidence for high-flow trends in lowland areas in the south and east." They also note, "in western areas, high-flow indicators are correlated with the North Atlantic Oscillation Index (NAOI)," so "recent trends may therefore reflect an influence of multi-decadal variability related to the NAOI." In addition, they state longer river flow records from five additional catchments they studied "provide little compelling evidence for long-term (>50 year) trends, but do show evidence of pronounced multi-decadal fluctuations." Lastly, they add, "in comparison with other indicators, there were fewer trends in flood magnitude" and "trends in peaks-over-threshold frequency and extended-duration maxima at a gauging station were not necessarily associated with increasing annual maximum instantaneous flow."

Hannaford and Marsh conclude, "considerable caution should be exercised in extrapolating from any future increases in runoff or high-flow frequency to an increasing vulnerability to extreme flood events." This word to the wise is something climate policymakers, especially those residing within the U.K., would do well to consider carefully.

Lloyd (2010) provides another study of historical trends in riverine flow trends, this time from the Breede River, which "is the largest in South Africa's Western Province, and plays a significant part in the province's economy." Modeling studies of the Breede River have predicted that flows into it could be seriously affected by climate change. For example, Steynor et al. (2009) used "a form of neural network" that was "trained on historical climate data" that were "linked to historical flow data at five stations in the Breede River valley," in order to "downscale from a global climate model to the typical area of a catchment" and thereby determine the consequences of predicted future global warming for Breede River flows. The Steynor et al. modeling results indicated Breede River flows will decrease if temperatures rise over the next 60 years in the fashion predicted by climate models.

As a check upon this approach to divining the region's hydrologic future, the Steynor et al. authors—who include a researcher based at the Energy Institute of the Cape Peninsula University of Technology in Cape Town—used flow data for five sites in the Breede Valley to compute historical flow-rate trends over prior periods of warming that ranged from 29 to 43 years in length.

All of the future flow rates calculated by Steynor et al. exhibited double-digit negative percentage changes, averaging -25 percent for one global climate model and -50 percent for another. The mean past trend of four of Lloyd's five stations also was negative (-13 percent); one station had a positive trend (+14.6 percent). But in a vital piece of additional research, by "examination of river flows over the past 43 years in the Breede basin" Lloyd was able to demonstrate that "changes in land use, creation of impoundments, and increasing abstraction have primarily been responsible for changes in the observed flows" of all the negative-trend stations.

Interestingly, Steynor et al. presumed warming would lead to decreased flow rates, as their projections suggested, and they thus assumed their projections were correct. However, Lloyd was able to demonstrate that those results were driven primarily by unaccounted-for land use changes in the five catchments, and that in his newer study the one site that had "a pristine watershed" was the one that had the "14% increase in flow over the study period," which was "contrary to the climate change predictions" and indicative of the fact that "climate change models cannot yet account for local climate change effects."

Lloyd concluded, "predictions of possible adverse local impacts from global climate change should therefore be treated with the greatest caution" and "above all, they must not form the basis for any policy decisions until such time as they can reproduce known climatic effects satisfactorily."

It is apparent from the conclusions of Lloyd's work that a vital aspect of analyzing river flow time series for climatic signals is to normalize the studies for vegetation and groundwater recharge change while remembering that such changes may be of either human or natural origin.

In a study designed to explore that point, Texas A&M researchers Wilcox and Huang (2010) analyzed the long-term (85-year) trends of both baseflow (groundwater-derived) and stormflow (precipitation-derived) streamflow components of four major rivers in the Edwards Plateau region of Texas (USA)—the Nueces, Frio, Guadalupe, and Llano Rivers. Over the period of study, this region experienced a significant increase in the presence of woody plants, indicating that "contrary to widespread perceptions," streamflows in the study region "have not been declining."

In a review of all large free-air carbon-enrichment (FACE) studies conducted over the prior 15 years, Ainsworth and Long (2005) had previously reported the greatest CO_2-induced benefits were accrued by trees, which experienced a mean biomass increase of 42 percent in response to a 300 ppm increase in the atmosphere's CO_2 concentration. In comparison, they found that C_4 sorghum posted a yield increase of only 7 percent and the C_3 crops rice and wheat exhibited yield increases of 16 percent and 22 percent, respectively. Thus, it is natural to presume that as the air's CO_2 content continues to climb higher, Earth's woody plants will gradually encroach upon areas where herbaceous plants previously ruled the landscape. That is typically observed to be the case.

However, as noted by Wilcox and Huang, trees typically use deeper water than grasses, and consequently, they write, the "prevailing belief is that woody plant encroachment leads to declining groundwater recharge and, therefore, to lower groundwater contributions to streams," which typically would be viewed as an undesirable outcome. Noting their findings "run counter to current thinking in both lay and scientific circles," the Texas researchers speculate that "baseflows are higher now than in pre-settlement times, because rooting by trees has facilitated groundwater recharge." In addition, the transpiration-reducing effect of atmospheric CO_2 enrichment may also have played a role in this regard, as has been suggested by several prior studies of river basin hydrology (Idso and Brazel, 1984; Gedney et al., 2006; Betts et al., 2007).

In any event, and whatever the answer or answers may be, it would appear good things have been happening to degraded grasslands throughout the world, as the atmosphere's CO_2 concentration has been gradually rising and woody plants have been extending their ranges and growing where they previously had been unable to survive, thereby helping to make more water available for many other uses by man and nature alike.

Finally, in a riverine geomorphological and archaeological study, Panin and Nefedov (2010) write, a "long-term decrease in seasonal peaks of water levels allows the [human] settling of relatively low geomorphic locations, such as river and lake floodplains, while a rise in flood levels causes settlements to be shifted to higher elevations." They base this assumption on the logic that "ancient settlements could not persist under the impact of regular inundations."

The authors studied regions of the Upper Volga and Zapadnaya Dvina Rivers (Russia) in order to document "the geomorphological and altitudinal positions of [human] occupational layers corresponding to 1224 colonization epochs at 870 archaeological sites in river valleys and lake depressions in southwestern Tver province." In the process they identified "a series of alternating low-water (low levels of seasonal peaks, many-year periods without inundation of flood plains) and high-water (high spring floods, regular inundation of floodplains) intervals of various hierarchial rank" associated with periods of warming and cooling.

The two Russian researchers report "low-water epochs coincide with epochs of relative warming, while high-water epochs [coincide] with cooling epochs," because "during the climate warming epochs, a decrease in duration and severity of winters should have resulted in a drop in snow cover water equivalent by the snowmelt period, a decrease in water discharge and flood stage, and a decrease in seasonal peaks in lake levels." They note, too, that "a model of past warming epochs can be the warming in the late 20th century, still continuing now." They also report, "in the Middle Ages (1.8–0.3 Ky ago), the conditions were favorable for long-time inhabiting [of] river and lake floodplains, which are subject to inundation nowadays." In addition, their results overall indicate that over the total time period studied, the interval AD 1000–1300 hosted the greatest number of floodplain occupations.

One of Panin and Nefedov's main conclusions is that the interval AD 1000–1300 and other "epochs of floodplain occupation by humans in the past can be regarded as hydrological analogues of the situation of the late 20th-early current century," which, they add, "is forming under the effect of directed climate change." This relationship implies that the current level of warmth in the portion of Russia that hosts the Upper Volga and Zapadnaya Dvina Rivers is not yet as great as it was during the AD 1000–1300 portion of the Medieval Warm Period.

References

Ainsworth, E.A. and Long, S.P. 2005. What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. *New Phytologist* **165**: 351–372.

Betts, R.A., Boucher, O., Collins, M., Cox, P.M., Falloon, P.D., Gedney, N., Hemming, D.L., Huntingford, C., Jones, C.D., Sexton, D.M.H., and Webb, M.J. 2007. Projected increase in continental runoff due to plant responses to increasing carbon dioxide. *Nature* **448**: 1037–1041.

Bradford, R.B. and Marsh, T.M. 2003. Defining a network of benchmark catchments for the UK. *Proceedings of the Institution of Civil Engineers, Water and Maritime Engineering* **156**: 109–116.

Gedney, N., Cox, P.M., Betts, R.A., Boucher, O., Huntingford, C., and Stott, P.A. 2006. Detection of a direct carbon dioxide effect in continental river runoff records. *Nature* **439**: 835–838.

Hannaford, J. and Marsh, T.J. 2008. High-flow and flood trends in a network of undisturbed catchments in the UK. *International Journal of Climatology* **28**: 1325–1338.

Idso, S.B. and Brazel, A.J. 1984. Rising atmospheric carbon dioxide concentrations may increase streamflow. *Nature* **312**: 51–53.

Lloyd, P. 2010. Historical trends in the flows of the Breede River. *Water SA* **36**: 329–333.

Mauas, P.J.D., Flamenco, E., and Buccino, A.P. 2008. Solar forcing of the stream flow of a continental scale South American river. *Physical Review Letters* **101**: 168501.

Panin, A.V. and Nefedov, V.S. 2010. Analysis of variations in the regime of rivers and lakes in the Upper Volga and Upper Zapadnaya Dvina based on archaeological-geomorphological data. *Water Resources* **37**: 16–32.

Steynor, A.C., Hewitson, B.C., and Tadross, M.A. 2009. Projected future runoff of the Breede River under climate change. *Water SA* **35**: 433–440.

Wilcox, B.P. and Huang, Y. 2010. Woody plant encroachment paradox: rivers rebound as degraded grasslands convert to woodlands. *Geophysical Research Letters* **37**: 10.1029/2009GL041929.

Zhang, Z., Dehoff, A.D., Pody, R.D., and Balay, J.W. 2010. Detection of streamflow change in the Susquehanna River Basin. *Water Resources Management* **24**: 1947–1964.

5

Observations and Projections: Extreme Weather

5. Observations and Projections: Extreme Weather

Introduction

According to the Intergovernmental Panel on Climate change (IPCC), "based on a range of models, it is *likely* that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical sea surface temperature" (IPCC 2007, p. 15). Since the IPCC contends the Earth already has experienced a warming unprecedented over the past millennium or more, the validity of these claims can be assessed by examining the extent to which the planet's emergence from the global chill of the Little Ice Age affected the frequency and magnitude of these extreme and often-deadly forces of nature.

When the historical record is reviewed, the data reveal there have not been any significant warming-induced increases in extreme weather events. This was the conclusion of the 2009 Nongovernmental International Panel on Climate Change (NIPCC) report (Idso and Singer 2009), and it is supported by the new scientific papers presented in this chapter.

References

Idso, C.D. and Singer, S.F. 2009. *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by S. Solomon et al. Cambridge, UK: Cambridge University Press.

5.1 Precipitation

As noted in the previous chapter (see Section 4.3.1), Chu et al. (2010) found the precipitation predictions of the IPCC had not been realized throughout the part of the Pacific that is home to the Hawaiian Islands, and in fact just the opposite had occurred there: The three scientists determined, "since the 1980s, there has been a change in the types of precipitation intensity, resulting in more frequent light precipitation and less frequent moderate and heavy precipitation intensity," as well as a "shorter annual number of days with intense precipitation and smaller consecutive 5-day precipitation amounts and smaller fraction of annual precipitation due to events exceeding the 1961–1990 95th percentile in the recent epoch [1980–2007] relative to the first epoch [1950–1979]."

Similarly, in that chapter we noted Stankoviansky (2003) found extreme and destructive rainfall events were much more common throughout the Myjava Hill Land of Slovakia during the Little Ice Age than they have been subsequently, and this, in his words (and in harmony with the many references he cites), "is often regarded as generally valid for Central Europe." This conclusion runs counter to that of the IPCC, which equates destructive precipitation events and the flooding they cause with global warming.

In a model-based study of precipitation, Schliep et al. (2010) compared estimates of local extreme precipitation events using six regional climate models (RCMs), which run at a higher spatial resolution than global climate models (GCMs). The six RCMs were forced with a common set of reanalysis data, created by running a climate model that was fed real-world data for a 20-year simulation period. The area analyzed was North America, where winter precipitation was the response variable and the one-hundred-year extremum of daily winter precipitation was the test statistic, extreme values of which were estimated by fitting a tailed distribution to the data, taking into account their spatial aspects.

The six RCMs showed similar general spatial patterns of extremes across North America, with the highest extremes in the Southeast and along the West Coast. However, when comparing absolute levels, which are most relevant to risk forecasts, the models exhibited strong disagreement. The lowest-predicting model was low almost everywhere in North America compared to the mean of the six models and, similarly, the highest-predicting model was above the mean almost everywhere. The difference between the two models was almost 60mm of daily precipitation (for the one-hundred-year extreme event) over much of the United States.

The other four models showed greatly differing spatial patterns of extremes from each other, and those differences were found to be statistically significant by F test. The researchers speculate that when driven by multiple GCMs rather than reanalysis data, the range of extreme outcomes would only increase. As a result, extreme rainfall event predictions may vary considerably among models and extend well beyond the realm of reality. The lesson we take from Schliep et al. is that model-based claims of a CO_2-induced increase in extreme precipitation events should be treated with considerable skepticism.

Another way to approach the question is to consider research on other possible causes of extreme participation events. The larger the effect of other causes, the less likely it is that CO_2 or warmer temperatures are responsible for observed trends. Along these lines, Hossain et al. (2009) review and discuss meteorological effects observed to occur in response to the impounding of water behind large dams.

Hossain et al. begin by noting, "in the United States alone, about 75,000 dams are capable of storing a volume of water equaling almost 1 year's mean runoff of the nation (Graf, 1999)," and "at least 45,000 large dams have been built worldwide since the 1930s." They also report "dam-driven land cover change can trigger changes in extreme precipitation patterns," citing the finding of Avissar and Liu (1996) that land use and land cover [LULC] patchiness "can enhance heavy rainfall." Likewise, they report "through LULC sensitivity studies (Pielke et al., 1997; Pielke and Zeng, 1989; Pielke et al., 2007), irrigated land near multipurpose reservoirs is seen to enhance thunderstorm development more than natural land cover conditions do (meaning before the dam was built)." They add, "Kishtawal et al. (2009) recently showed that increased urbanization downstream of large flood control dams can also trigger heavy rainfall patterns."

With respect to additional findings suggestive of the phenomenon they describe, Hossain et al. (2010) report Hossain et al. (2009) and Hossain (2010) have shown "extreme precipitation (99th percentile) has increased considerably more than increases seen in median precipitation (50th percentile) during the past century" and "this alteration may be more pronounced in arid and semiarid regions after the dam is built." Regarding the latter, they note "large dams in the regions of southern Africa, India, western United States, and Central Asia appeared to induce a greater increase in extreme precipitation than in other regions." Although there is a clear correlation between the building of large dams throughout the world and subsequent increases in extreme precipitation, the three scientists state in a cautionary note, "other factors may be involved, such as global climate change."

References

Avissar, R. and Liu, Y. 1996. Three-dimensional numerical study of shallow convective clouds and precipitation induced by land surface forcing. *Journal of Geophysical Research* **101**: 7499–7518.

Chu, P.-S., Chen, Y.R., and Schroeder, T.A. 2010. Changes in precipitation extremes in the Hawaiian Islands in a warming climate. *Journal of Climate* **23**: 4881–4900.

Graf, W.L. 1999. Dam nation: a geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research* **35**: 1305–1311.

Hossain, F. 2010. On the empirical relationship between the presence of large dams and the alteration in extreme precipitation. *Natural Hazards Review* **11**: 97–101.

Hossain, F., Jeyachandran, I., and Pielke Sr., R. 2009. Have large dams altered extreme precipitation patterns? *EOS, Transactions, American Geophysical Union* **90**: 453–454.

Hossain, F., Jeyachandran, I., and Pielke Sr., R. 2010. Dam safety effects due to human alteration of extreme precipitation. *Water Resources Research* **46**: 10.1029/2009WR007704.

Kishtawal, C.M., Niyogi, D., Tewari, M., Pielke Sr., R.A., and Shepherd, J.M. 2009. Urbanization signature in the observed heavy rainfall climatology over India. *International Journal of Climatology*: 10.1002/joc.2044.

Pielke Sr., R.A., Adegoke, J., Beltran-Przekurat, A., Hiemstra, C.A., Lin, J., Nair, U.S., Niyogi, D., and Nobis, T.E. 2007. An overview of regional land use and land cover impacts on rainfall. *Tellus Series B* **59**: 587–601.

Pielke Sr., R.A., Lee, T.J., Copeland, J.H., Eastman, J.L., Ziegler, C.L., and Finley, C.A. 1997. Use of USGS-provided data to improve weather and climate simulations. *Ecological Applications* **7**: 3–21.

Pielke Sr., R.A. and Zeng, X. 1989. Influence on severe storm development of irrigated land. *National Weather Digest* **14**: 16–17.

Schliep, E.M., Cooley, D., Sain, S.R., and Hoeting, J.A. 2010. A comparison study of extreme precipitation from six different regional climate models via spatial hierarchical modeling. *Extremes* **13**: 219–239.

Stankoviansky, M. 2003. Historical evolution of permanent gullies in the Myjava Hill Land, Slovakia. *Catena* **51**: 223–239.

5.2. Floods

The IPCC claims flooding has become more frequent and severe in response to twentieth century global warming. But it is important to establish whether floods are truly becoming more frequent or severe, and whether other factors might be behind such trends if they in fact exist. In this section we highlight studies addressing both questions.

To test for long-term changes in flood magnitudes and frequencies in the Mississippi River system of the United States, Pinter et al. (2008) "constructed a hydrologic database consisting of data from 26 rated stations (with both stage and discharge measurements) and 40 stage-only stations." Then, to help "quantify changes in flood levels at each station in response to construction of wing dikes, bendway weirs, meander cutoffs, navigational dams, bridges, and other modifications," they put together a geospatial database consisting of "the locations, emplacement dates, and physical characteristics of over 15,000 structural features constructed along the study rivers over the past 100–150 years." As a result of these operations, Pinter et al. write, "significant climate- and/or land use-driven increases in flow were detected," but they indicate "the largest and most pervasive contributors to increased flooding on the Mississippi River system were wing dikes and related navigational structures, followed by progressive levee construction."

In discussing the implications of their findings, Pinter et al. write, "the navigable rivers of the Mississippi system have been intensively engineered, and some of these modifications are associated with large decreases in the rivers' capacity to convey flood flows." Hence, it would appear man has indeed been responsible for the majority of the increased flooding of the rivers of the Mississippi system over the past century or so, but not in the way suggested by the IPCC. The question that needs addressing by the region's inhabitants has nothing to do with CO_2 and everything to do with how to "balance the local benefits of river engineering against the potential for large-scale flood magnification."

In a study designed to determine the environmental origins of extreme flooding events throughout the southwestern United States, Ely (1997) wrote, "paleoflood records from nineteen rivers in Arizona and southern Utah, including over 150 radiocarbon dates and evidence of over 250 flood deposits, were combined to identify regional variations in the frequency of extreme floods," and that information "was then compared with paleoclimatic data to determine how the temporal and spatial patterns in the occurrence of floods reflect the prevailing climate." The results of this comparison indicated "long-term variations in the frequency of extreme floods over the Holocene are related to changes in the climate and prevailing large-scale atmospheric circulation patterns that affect the conditions conducive to extreme flood-generating storms in each region." These changes, in Ely's view, "are very plausibly related to global-scale changes in the climate system."

With respect to the Colorado River watershed, which integrates a large portion of the interior western United States, she writes, "the largest floods tend to be from spring snowmelt after winters of heavy snow accumulation in the mountains of Utah, western Colorado, and northern New Mexico," such as occurred with the "cluster of floods from 5 to 3.6 ka," which occurred in conjunction with "glacial advances in mountain ranges throughout the western United States" during the "cool, wet period immediately following the warm mid-Holocene."

The frequency of extreme floods also increased during the early and middle portions of the first millennium AD, many of which coincided "with glacial advances and cool, moist conditions both in the western U.S. and globally." Then came a "sharp drop in the frequency of large floods in the southwest from AD 1100-1300," which corresponded, in her words, "to the widespread Medieval Warm Period, which was first noted in European historical records." With the advent of the Little Ice Age, however, there was another "substantial jump in the number of floods in the southwestern U.S.," which was "associated with a switch to glacial advances, high lake levels, and cooler, wetter conditions." Distilling her findings down to a single succinct statement and speaking specifically of the southwestern United States, Ely writes, "global warm periods, such as the Medieval Warm Period, are times of dramatic *decreases* in the number of high-magnitude floods in this region" [emphasis added].

Looking at the other side of the continent, Villarini and Smith (2010) "examined the distribution of flood peaks for the eastern United States using annual maximum flood peak records from 572 U.S. Geological Survey stream gaging stations with at least 75 years of observations." This work revealed, "in general, the largest flood magnitudes are concentrated in the mountainous central Appalachians and the smallest flood peaks are concentrated along the low-gradient Coastal Plain and in the northeastern United States." They also found "landfalling tropical cyclones play an important role in the mixture of flood generating mechanisms, with the frequency of tropical cyclone floods exhibiting large spatial heterogeneity over the region." They additionally write, "warm season thunderstorm systems during the peak of the warm season and winter-spring extratropical systems contribute in complex fashion to the spatial mixture of flood frequency over the eastern United States."

Of greater interest to the climate change debate, however, were their more basic findings: (1) "only a small fraction of stations exhibited significant linear trends," (2) "for those stations with trends, there was a split between increasing and decreasing trends," and (3) "no spatial structure was found for stations exhibiting trends." Thus they concluded, (4) "there is little indication that human-induced climate change has resulted in increasing flood magnitudes for the eastern United States."

Much the same was reported for Canada by Cunderlik and Ouarda (2009). They evaluated trends in the timing and magnitude of seasonal maximum flood events across that country, based on pertinent data obtained from 162 stations of the Reference Hydrometric Basin Network established by Environment Canada over the 30-year period 1974 to 2003. In spite of the supposedly unprecedented warming over the period of time they studied, the Canadian researchers report finding "only 10% of the analyzed stations show significant trends in the timing of snowmelt floods during the last three decades (1974–2003)," and they say these results imply "the occurrence of snowmelt floods is shifting towards the earlier times of the year," as would be expected in a warming world. However, they note most of the identified trends "are only weakly or medium significant results," and they add "no significant trends were found in the timing of rainfall-dominated flood events."

With respect to flood magnitudes, the two scientists state the trends they observed "are much more pronounced than the trends in the timing of the floods," but they note most of these trends "had negative signs, suggesting that the magnitude of the annual maximum floods has been decreasing over the last three decades." In addition, they found "the level of significance was also higher in these trends compared to the level of significance of the trends in the timing of annual maximum floods."

In Europe, Schmocker-Fackel and Naef (2010a) explored the relationship between climate and flooding from a paleo-perspective. Specifically, they collected and analyzed historical flood time-series of

14 catchments located in northern Switzerland, datasets for which stretched back a full five centuries. From these data the two Swiss scientists were able to identify four periods of frequent flooding in northern Switzerland, lasting between 30 and 100 years each (1560–1590, 1740–1790, 1820–1940, and since 1970). They report the first three periods of intervening low flood frequency (1500–1560, 1590–1740, and 1790–1810) were found to correspond to periods of low solar activity. However, they report, "after 1810 no relationship between solar activity and flood frequency was found, nor could a relationship be established between reconstructed North Atlantic Oscillation indices or reconstructed Swiss temperatures." In addition, they determined "the current period of increased flood frequencies has not yet exceeded those observed in the past." They also write, "a comparison with the flood patterns of other European rivers suggests that flood frequencies are not in phase over Europe." In light of their several diverse findings, Schmocker-Fackel and Naef (2010a) thus concluded "the current period with more floods in northern Switzerland, which started in the mid 1970s, might continue for some decades," even under conditions of "natural climatic variation."

In a contemporaneous paper on Switzerland floods, also authored by Schmocker-Fackel and Naef (2010b), the two researchers further explored this subject by analyzing "streamflow data from 83 stations with a record length of up to 105 years, complemented with data from historical floods dating back to 1850," in an effort to place the extreme flooding that occurred in their country in 1999, 2005, and 2007 in an historical construct. This expanded analysis indicated "in Switzerland, periods with frequent floods have alternated with quieter periods during the last 150 years" and "since 1900, flood-rich periods in northern Switzerland corresponded to quiet periods in southern Switzerland and vice versa." As for the fact that over the same period of time "three of the four largest large-scale flood events in northern Switzerland have all occurred within the last ten years," they report "a similar accumulation of large floods has already been observed in the second half of the 19th century." In addition, they state, "studies about changes in precipitation frequencies in Switzerland come to similar conclusions," citing the work of Bader and Bantle (2004).

In another paper from Europe, Diodato et al. (2008) conducted a detailed study of erosive rainfall in the Calore River Basin (southern Italy) "using data from 425-year-long series of both observations (1922–2004) and proxy-based reconstructions (1580–1921)." Their results showed pronounced interdecadal variations, "with multi-decadal erosivity reflecting the mixed population of thermo-convective and cyclonic rainstorms with large anomalies," while noting "the so-called Little Ice Age (16th to mid-19th centuries) was identified as the stormiest period, with mixed rainstorm types and high frequency of floods and erosive rainfall."

In the concluding section of their paper, the three researchers write, "in recent years, climate change (generally assumed as synonymous with global warming) has become a global concern and is widely reported in the media." In regard to concern over floods becoming more frequent and more severe as the planet warms, however, Diodato et al. say their study shows "climate in the Calore River Basin has been largely characterized by naturally occurring weather anomalies in past centuries (long before industrial CO_2 emissions), not only in recent years," and there has been a "relevant smoothing" of such events during the modern era.

Working in southeast Spain, Benito et al. (2010) reconstructed flood frequencies of the Upper Guadalentin River using "geomorphological evidence, combined with one-dimensional hydraulic modeling and supported by records from documentary sources at Lorca in the lower Guadalentin catchment." According to these scientists, the combined palaeoflood and documentary records indicated past floods were clustered during particular time periods: AD 950–1200 (10), AD 1648–1672 (10), AD 1769–1802 (9), AD 1830–1840 (6), and AD 1877–1900 (10). The first time interval coincides with the Medieval Warm Period, and the latter four fall within the confines of the Little Ice Age. By calculating mean rates of flood occurrence over each of the five intervals, one obtains a value of 0.40 floods per decade during the Medieval Warm Period and an average value of 4.31 floods per decade over the four parts of the Little Ice Age.

Czymzik et al. (2010) explored the relationship between level of warmth and degree of flooding as it may have been manifested in southern Germany over the past 450 years. In the opening paragraph of their paper, they observe "assumptions about an increase in extreme flood events due to an intensified hydrological cycle caused by global warming are still under discussion and must be better verified," while noting some historical flood records indicate "flood frequencies were higher during colder periods (Knox, 1993; Glaser and Stangl, 2004), challenging the hypothesis of a correlation between the frequency of extreme floods and a warmer climate."

Against this backdrop, Czymzik et al. retrieved two sediment cores from the deepest part of Lake Ammersee in southern Germany (48°00'N, 11°07'E), which they then analyzed via what they describe as "a novel methodological approach that combines microfacies analyses, high-resolution element scanning (µ-XRF), stable isotope data from bulk carbonate samples ($\delta^{13}C_{carb}$, $\delta^{18}O_{carb}$), and X-ray diffraction (XRD) analyses (Brauer et al., 2009)."

The six scientists determined the flood frequency distribution over the entire 450-year time series "is not stationary but reveals maxima for colder periods of the Little Ice Age when solar activity was reduced," while reporting "similar observations have been made in historical flood time series of the River Main, located approximately 200 km north of Ammersee (Glaser and Stangl, 2004), pointing to a wider regional significance of this finding."

Working in the United Kingdom a couple years earlier, Hannaford and Marsh (2008) noted "recent flood events have led to speculation that climate change is influencing the high-flow regimes of UK catchments" and "projections suggest that flooding may increase in [the] future as a result of human-induced warming." Utilizing the U.K. "benchmark network" of 87 "near-natural catchments" identified by Bradford and Marsh (2003), Hannaford and Marsh conducted "a UK-wide appraisal of trends in high-flow regimes unaffected by human disturbances" to test such speculation. They found "significant positive trends were observed in all high-flow indicators ... over the 30–40 years prior to 2003, primarily in the maritime-influenced, upland catchments in the north and west of the UK." However, they state, "there is little compelling evidence for high-flow trends in lowland areas in the south and east." They also note, "in western areas, high-flow indicators are correlated with the North Atlantic Oscillation Index (NAOI)," so "recent trends may therefore reflect an influence of multi-decadal variability related to the NAOI." In addition, they state, longer river flow records from five additional catchments they studied "provide little compelling evidence for long-term (>50 year) trends but show evidence of pronounced multi-decadal fluctuations." Finally, they note, "in comparison with other indicators, there were fewer trends in flood magnitude" and "trends in peaks-over-threshold frequency and extended-duration maxima at a gauging station were not necessarily associated with increasing annual maximum instantaneous flow." In light of their several observations, Hannaford and Marsh conclude, "considerable caution should be exercised in extrapolating from any future increases in runoff or high-flow frequency to an increasing vulnerability to extreme flood events."

In another paper from Europe, Matthews et al. (2009) conducted detailed investigations at three alpine slope-foot mires located in the valley of Leirdalen in an area known as Sletthamn, above the treeline among some of the highest mountains in southern Norway, where they say "exceptionally detailed radiocarbon-dating controlled chronologies of Holocene debris-flow events have been reconstructed." This allowed them to analyze "the frequency and timing of debris flows since c. 8500 cal. BP which, in turn, are related to climatic variability, extreme climatic events and site conditions."

The results of this exercise revealed "no obvious correlation between debris-flow frequency and a relative warm climate." In fact, they write, "debris-flow frequency was lowest post-8000 cal. BP during the Holocene Thermal Maximum" and most of the "century- to millennial-scale phases of enhanced debris-flow activity appear to correlate with Neoglacial events," one of which was the Little Ice Age. In addition, they write, "the Sletthamn record agrees quite closely with a compilation of other debris-flow records from widely distributed sites in east and west Norway." What is more—citing the work of Berrisford and Matthews (1997), Stoffel and Beniston (2006), Pelfini and Santilli (2008), and Stoffel et al. (2008)—they report "there appears to be no consistent upward trend in debris-flow frequencies over recent decades," when one might have expected them to be growing in both number and magnitude if the model-based claims were correct. Given these findings, the Norwegian and U.K. researchers conclude there is little real-world evidence "for the association of higher debris-flow frequencies with an increasingly warm climate." In fact, they state, "the evidence suggests the opposite."

Panin and Nefedov (2010) identified "a series of alternating low-water (low levels of seasonal peaks, many-year periods without inundation of flood plains) and high-water (high spring floods, regular inundation of floodplains) intervals of various hierarchal rank" for the Upper Volga and Zapadnaya Dvina Rivers of

Russia. The two Russian researchers report "low-water epochs coincide with epochs of relative warming, while high-water epochs [coincide] with cooling epochs," because "during the climate warming epochs, a decrease in duration and severity of winters should have resulted in a drop in snow cover water equivalent by the snowmelt period, a decrease in water discharge and flood stage, and a decrease in seasonal peaks in lake levels," noting "a model of past warming epochs can be the warming in the late 20th century, still continuing now." They also report finding, "in the Middle Ages (1.8–0.3 Ky ago), the conditions were favorable for long-time inhabiting [of] river and lake floodplains, which are subject to inundation nowadays." In addition, their results indicate that of this time interval, the period AD 1000–1300 hosted the greatest number of floodplain occupations.

Interestingly, Panin and Nefedov state this last period and other "epochs of floodplain occupation by humans in the past can be regarded as hydrological analogues of the situation of the late 20th-early current century," which they say "is forming under the effect of directed climate change." This relationship clearly implies the current level of warmth in the portion of Russia that hosts the Upper Volga and Zapadnaya Dvina Rivers is not yet as great as it was during the AD 1000–1300 portion of the Medieval Warm Period.

References

Bader, S. and Bantle, H. 2004 . Das schweizer klima im trend, Temperatur—und Niederschlagsentwicklung 1864-2001. Veroffentlichung der MeteoSchweiz Nr. 68, 45 p.

Benito, G., Rico, M., Sanchez-Moya, Y., Sopena, A., Thorndycraft, V.R., and Barriendos, M. 2010. The impact of late Holocene climatic variability and land use change on the flood hydrology of the Guadalentin River, southeast Spain. *Global and Planetary Change* **70**: 53–63.

Berrisford, M.S. and Matthews, J.A. 1997. Phases of enhanced rapid mass movement and climate variation during the Holocene: a synthesis. In Rapid mass movement as a source of climatic evidence for the Holocene. *Palaoklimaforschung* **19**: 409–440, edited by J.A. Matthews, et al.

Bradford, R.B. and Marsh, T.M. 2003. Defining a network of benchmark catchments for the UK. *Proceedings of the Institution of Civil Engineers, Water and Maritime Engineering* **156**: 109–116.

Brauer, A., Dulski, P., Mangili, C., Mingram, J., and Liu, J. 2009. The potential of varves in high-resolution paleolimnological studies. *PAGESnews* **17**: 96–98.

Cunderlik, J.M. and Ouarda, T.B.M.J. 2009. Trends in the timing and magnitude of floods in Canada. *Journal of Hydrology* **375**: 471–480.

Czymzik, M., Dulski, P., Plessen, B., von Grafenstein, U., Naumann, R., and Brauer, A. 2010. A 450 year record of spring-summer flood layers in annually laminated sediments from Lake Ammersee (southern Germany). *Water Resources Research* **46**: 10.1029/2009WR008360.

Diodato, N., Ceccarelli, M., and Bellocchi, G. 2008. Decadal and century-long changes in the reconstruction of erosive rainfall anomalies in a Mediterranean fluvial basin. *Earth Surface Processes and Landforms* **33**: 2078–2093.

Ely, L.L. 1997. Response of extreme floods in the southwestern United States to climatic variations in the late Holocene. *Geomorphology* **19**: 175–201.

Glaser, R. and Stangl, H. 2004. Climate and floods in Central Europe since AD 1000: Data, methods, results and consequences. *Surveys in Geophysics* **25**: 485–510.

Hannaford, J. and Marsh, T.J. 2008. High-flow and flood trends in a network of undisturbed catchments in the UK. *International Journal of Climatology* **28**: 1325–1338.

Knox, J.C. 1993. Large increases in flood magnitude in response to modest changes in climate. *Nature* **361**: 430–432.

Matthews, J.A., Dahl, S.O., Dresser, P.Q., Berrisford, M.S., Lie, O., Nesje, A., and Owen, G. 2009. Radiocarbon chronology of Holocene colluvial (debris-flow) events at Sletthamn, Jotunheimen, southern Norway: a window on the changing frequency of extreme climatic events and their landscape impact. *The Holocene* **19**: 1107–1129.

Panin, A.V. and Nefedov, V.S. 2010. Analysis of variations in the regime of rivers and lakes in the Upper Volga and Upper Zapadnaya Dvina based on archaeological-geomorphological data. *Water Resources* **37**: 16–32.

Pelfini, M. and Santilli, M. 2008. Frequency of debris flows and their relation with precipitation: a case study in the Central Alps, Italy. *Geomorphology* **101**: 721–730.

Pinter, N., Jemberie, A.A., Remo, J.W.F., Heine, R.A., and Ickes, B.S. 2008. Flood trends and river engineering on the Mississippi River system. *Geophysical Research Letters* **35**: 10.1029/2008GL035987.

Schmocker-Fackel, P. and Naef, F. 2010a. Changes in flood frequencies in Switzerland since 1500. *Hydrology and Earth System Sciences* **14**: 1581–1594.

Schmocker-Fackel, P. and Naef, F. 2010b. More frequent flooding? Changes in flood frequency in Switzerland since 1850. *Journal of Hydrology* **381**: 1–8.

Stoffel, M. and Beniston, M. 2006. On the incidence of debris flows from the early Little Ice Age to a future greenhouse climate: a case study from the Swiss Alps. *Geophysical Research Letters* **33**: 10.1029/2006GL026805.

Stoffel, M., Conus, D., Grichting, M.A., Lievre, I., and Maitre, G. 2008. Unraveling the patterns of late Holocene debris-flow activity on a cone in the Swiss Alps: chronology, environment and implications for the future. *Global and Planetary Change* **60**: 222–234.

Villarini, G. and Smith, J.A. 2010. Flood peak distributions for the eastern United States. *Water Resources Research* **46**: 10.1029/2009WR008395.

5.3. Drought

As in the case of floods, the IPCC foresees drought as one of the many dangers of CO_2-induced global warming. An examination of the pertinent scientific literature, however, demonstrates droughts are not becoming more frequent, more severe, or longer-lasting.

Springer et al. (2008) constructed a multidecadal-scale history of east-central North America's hydroclimate over the past 7,000 years, based on Sr/Ca ratios and $\delta^{13}C$ data obtained from a stalagmite in West Virginia, USA. Their results indicated the presence of seven significant mid- to late-Holocene droughts that "correlate with cooling of the Atlantic and Pacific Oceans as part of the North Atlantic Ocean ice-rafted debris [IRD] cycle, which has been linked to the solar irradiance cycle," as demonstrated by Bond et al. (1997, 2001). In addition, they found "the Sr/Ca and $\delta^{13}C$ time series display periodicities of ~200 and ~500 years," and "the ~200-year periodicity is consistent with the de Vries (Suess) solar irradiance cycle," and that the ~500-year periodicity is likely "a harmonic of the IRD oscillations." They also reported "cross-spectral analysis of the Sr/Ca and IRD time series yields statistically significant coherencies at periodicities of 455 and 715 years," noting the latter values "are very similar to the second (725-years) and third (480-years) harmonics of the 1450 ± 500-years IRD periodicity."

The five researchers concluded these findings "corroborate works indicating that millennial-scale solar-forcing is responsible for droughts and ecosystem changes in central and eastern North America (Viau et al., 2002; Willard et al., 2005; Denniston et al., 2007)" and that their high-resolution time series "provide much stronger evidence in favor of solar-forcing of North American drought by yielding unambiguous spectral analysis results."

Writing in the *Journal of Quaternary Science*, Cook et al. (2009) note "IPCC Assessment Report 4 model projections suggest that the subtropical dry zones of the world will both dry and expand poleward in the future due to greenhouse warming" and "the US southwest is particularly vulnerable in this regard and model projections indicate a progressive drying there out to the end of the 21st century." They then note "the USA has been in a state of drought over much of the West for about 10 years now," but "while severe, this turn of the century drought has not yet clearly exceeded the severity of two exceptional droughts in the 20th century." Therefore, they conclude, "while the coincidence between the turn of the century drought and projected drying in the Southwest is cause for concern, it is premature to claim that the model projections are correct."

We begin to understand this fact when we compare the turn-of-the-century-drought with the two "exceptional droughts" that preceded it by a few decades. Based on gridded instrumental Palmer Drought Severity indices for tree-ring reconstruction that extend back to 1900, Cook et al. calculated the turn-of-the-century drought had its greatest Drought Area Index value of 59 percent in the year 2002, whereas the Great Plains/Southwest drought covered 62 percent of the United States in its peak year of 1954 and the Dust Bowl drought covered 77 percent of the United States in 1934.

In terms of drought duration, things are not quite as clear. Stahle et al. (2007) estimated the first two droughts lasted for 12 and 14 years, respectively; Seager et al. (2005) estimated them to have lasted for eight and ten years; and Andreadis et al. (2005) estimated periods of seven and eight years. That yields means of nine and 11 years for the two exceptional droughts, compared to ten or so years for the turn-of-the-century drought. This, too, makes the latter drought not unprecedented compared with those that occurred in the twentieth century.

Real clarity, however, comes when the turn-of-the-century drought is compared to droughts of the prior millennium. Cook et al. write, "perhaps the most famous example is the 'Great Drouth' [sic] of AD 1276–1299 described by A.E. Douglass (1929, 1935)." This 24-year drought was eclipsed by the 38-year drought found by Weakley (1965) to have occurred in Nebraska from AD 1276 to 1313, which Cook et al. say "may have been a more prolonged northerly extension of the 'Great Drouth'." But even these multi-decade droughts pale in comparison with the "two extraordinary droughts discovered by Stine (1994) in California that lasted more than two centuries before AD 1112 and more than 140 years before AD 1350." Each of these megadroughts, as Cook et al. describe them, occurred, in their words, "in the so-called Medieval Warm Period." They add, "all of this happened prior to the strong greenhouse gas warming that began with the Industrial Revolution."

In further ruminating about these facts in the "Conclusions and Recommendations" section of their paper, Cook et al. again state the medieval megadroughts "occurred without any need for enhanced radiative forcing due to anthropogenic greenhouse gas forcing"—because, of course, there was none at that time—and therefore, they say, "there is no guarantee that the response of the climate system to greenhouse gas forcing will result in megadroughts of the kind experienced by North America in the past."

Reinforcing the findings of Cook et al. two years later, Stambaugh et al. (2011) "used a new long tree-ring chronology developed from the central U.S. to reconstruct annual drought and characterize past drought duration, frequency, and cycles in the U.S. Corn Belt during the last millennium." This new record, in their words, "is the first paleoclimate reconstruction achieved with subfossil oak wood in the U.S.," and they indicate it "increases the current dendroclimatic record in the central U.S. agricultural region by over 500 years."

Of great significance among their findings is the fact that the new drought reconstruction indicates "drought conditions over the period of instrumental records (since 1895) do not exhibit the full range of variability, severity, or duration of droughts during the last millennium." As an example, the six scientists compared the 1930s-era Dust Bowl drought with other prior severe events, finding "three years in the last millennium were drier than 1934, a classic Dust-Bowl year and the driest year of the instrumental period," and "three of the top ten most severe droughts occurred within a 25-year period corresponding to the late 16th century." Likewise, they state "the four longest droughts occurred prior to Euro-American settlement of the region (ca. AD 1850)," the longest of which occurred in the middle of the Medieval Warm Period and, as the authors describe it, "lasted approximately 61 years (AD 1148–1208)."

Other studies in North America also point to a large and persistent Medieval drought unequaled in modern times. Working in the Sierra de Manantlan Biosphere Reserve (SMBR) in west-central Mexico, Figueroa-Rangel et al. (2010) constructed a 1,300-year history of cloud forest vegetation dynamics via analyses of fossil pollen, microfossil charcoal, and organic and inorganic sediment data obtained from a 96-cm core of black organic material retrieved from a small forest hollow (19°35'32"N, 104°16'56"W). Their results showed oscillating intervals of humidity, including a major dry period that lasted from approximately AD 800 to 1200 in the SMBR, a dry period that corresponds with those of other locations in the region.

Quoting the four researchers, "results from this study corroborate the existence of a dry period from 1200 to 800 cal years BP in mountain forests of the region (B.L. Figueroa-Rangel, unpublished data); in central Mexico (Metcalfe and Hales, 1994; Metcalfe, 1995; Arnauld et al., 1997; O'Hara and Metcalfe, 1997; Almeida-Lenero et al., 2005; Ludlow-Wiechers et al., 2005; Metcalfe et al., 2007); lowlands of the Yucatan Peninsula (Hodell et al., 1995, 2001, 2005a,b) and the Cariaco Basin in Venezuela (Haug et al., 2003)." In addition, they write, "the causes associated to this phase of climate change have been attributed to solar activity (Hodell et al., 2001; Haug et al., 2003), changes in the latitudinal migration of the Intertropical Convergence Zone (ITCZ, Metcalfe et al., 2000; Hodell et al., 2005a,b; Berrio et al., 2006) and to ENSO variability (Metcalfe, 2006)."

In one final study from Mexico, Escobar et al. (2010) analyzed sediment cores from Lakes Punta Laguna, Chichancanab, and Peten Itza on the Yucatan Peninsula. With respect to drought, they report "relatively dry periods were persistently dry, whereas relatively wet periods were composed of wet and dry times." Their findings also "confirm the interpretations of Hodell et al. (1995, 2007) and Curtis et al. (1996) that there were persistent dry climate episodes associated with the Terminal Classic Maya Period." In fact, they find "the Terminal Classic Period from ca. AD 910 to 990 was not only the driest period in the last 3,000 years, but also a persistently dry period." In further support of this interpretation, they note "the core section encompassing the Classic Maya collapse has the lowest sedimentation rate among all layers and the lowest oxygen isotope variability."

Moving to South America, Marengo (2009) examined the hydrological history of the Amazon Basin in an effort "to explore long-term variability of climate since the late 1920s and the presence of trends and/or cycles in rainfall and river indices in the basin." These analyses were based on northern and southern Amazonian rainfall data originally developed by Marengo (1992) and Marengo and Hastenrath (1993) and subsequently updated by Marengo (2004).

In describing the results of the analysis, the Brazilian researcher reports, "no systematic unidirectional long-term trends towards drier or wetter conditions have been identified since the 1920s." Instead, he found "the rainfall and river series show variability at inter-annual scales." Marengo states the patterns he uncovered are "characteristic of decadal and multi-decadal modes," which he describes as "indicators of natural climate variability" that are linked to the El Niño Southern Oscillation, "rather than any unidirectional trend towards drier conditions (as one would expect, due to increased deforestation or to global warming)."

In Europe, based on data obtained from hundreds of moisture-sensitive Scots pine tree-ring records originating in Finland, and using regional curve standardization (RCS) procedures, Helama et al. (2009) developed what they describe as "the first European dendroclimatic precipitation reconstruction," which "covers the classical climatic periods of the Little Ice Age (LIA), the Medieval Climate Anomaly (MCA), and the Dark Ages Cold Period (DACP)," running from AD 670 to AD 1993.

The authors state their data indicate "the special feature of this period in climate history is the distinct and persistent drought, from the early ninth century AD to the early thirteenth century AD," which "precisely overlaps the period commonly referred to as the MCA, due to its geographically widespread climatic anomalies both in temperature and moisture." In addition, they report, "the reconstruction also agrees well with the general picture of wetter conditions prevailing during the cool periods of the LIA (here, AD 1220–1650) and the DACP (here, AD 720–930)."

The three Finnish scientists note "the global medieval drought that we found occurred in striking temporal synchrony with the multicentennial droughts previously described for North America (Stine, 1994; Cook et al., 2004, 2007), eastern South America (Stine, 1994; Rein et al., 2004), and equatorial East Africa (Verschuren et al., 2000; Russell and Johnson, 2005, 2007; Stager et al., 2005) between AD 900 and 1300." Noting further "the global evidence argues for a common force behind the hydrological component of the MCA," they report "previous studies have associated coeval megadroughts during the MCA in various parts of the globe with either solar forcing (Verschuren et al., 2000; Stager et al., 2005) or the ENSO (Cook et al., 2004, 2007; Rein et al., 2004; Herweijer et al., 2006, 2007; Graham et al., 2007, Seager et al., 2007)." They state, "the evidence so far points to the medieval solar activity maximum (AD 1100–1250), because it is observed in the Δ^{14}C and ^{10}Be series recovered from the chemistry of tree rings and ice cores, respectively (Solanki et al., 2004)."

Moving next to Asia, Sinha et al. (2011) write of "the potential consequences that would be associated with a drought lasting years to decades, or even a century (*megadrought*)."They state such a phenomenon "constitutes one of the greatest threats to human welfare," noting it would be "a particular serious threat for the predominantly agrarian-based societies of monsoon Asia, where the lives of billions of people are tightly intertwined with the annual monsoon cycle."

In exploring this ominous subject in great detail, Sinha et al. review what is known about it as a result of numerous pertinent studies, relying heavily on the work of Sinha et al. (2007) and Berkelhammer et al. (2010), based on the δ^{18}O record of a speleothem from Dandak Cave in central-eastern India, which documents Indian monsoon rainfall variations between AD 600 and 1500.

The eight researchers, from China, Germany, and the United States, report "proxy reconstructions of precipitation from central India, north-central China [Zhang et al., 2008], and southern Vietnam [Buckley et al., 2010] reveal a series of monsoon droughts during the mid 14th–15th centuries that each lasted for several years to decades," and they say "these monsoon *megadroughts* have no analog during the instrumental period." They also note "emerging tree ring-based reconstructions of monsoon variability from SE Asia (Buckley et al., 2007; Sano et al., 2009) and India (Borgaonkar et al., 2010) suggest that the mid 14th–15th century megadroughts were the first in a series of spatially widespread megadroughts that occurred during the Little Ice Age" and that they "appear to have played a major role in shaping significant regional societal changes at that time." Among these upheavals, they make special mention of "famines and significant political reorganization within India (Dando, 1980; Pant et al., 1993; Maharatna, 1996), the collapse of the Yuan dynasty in China (Zhang et al., 2008), Rajarata civilization in Sri Lanka (Indrapala, 1971), and the Khmer civilization of Angkor Wat fame in Cambodia (Buckley et al., 2010)," noting the evidence suggests "monsoon megadroughts may have played a major contributing role in shaping these societal changes."

In light of the fact that there were, in the words of Sinha et al., "at least five episodes of monsoon megadroughts during the Little Ice Age (nominally, AD 1350–1850)," we should be extremely thankful the Earth has emerged from this unique period of global coolness—which is universally recognized as having been the coldest interval of the current interglacial—especially because "the present-day water-resource infrastructure and planning are barely sufficient to meet the welfare of billions of people during a single season of anomalous weak monsoon, let alone a protracted failure," such as what occurred repeatedly during the global chill of the Little Ice Age.

Another paper from Asia, Kim et al. (2009), was previously summarized in Chapter 4. The only major multiyear deviation from long-term normalcy they found were a decadal-scale decrease in precipitation and ensuing drought, both of which achieved their most extreme values (low in the case of precipitation, high in the case of drought) around AD 1900. The warming of the twentieth century had essentially no effect on the long-term histories of either precipitation or drought at Seoul, Korea.

Closing out this section on drought, we highlight a study published in *Science* by Zhao and Running (2010), who raised some concerns that global warming was affecting global net primary production of biomass due to the increased frequency of drought. In introducing their work, the two authors note "previous studies have shown that climate constraints [on global production of biomass] were relaxing with increasing temperature and solar radiation, allowing an upward trend in NPP [net primary production] from 1982–1999," but over the past decade (2000–2009), satellite data "suggest a reduction in the global NPP." Closer examination of this study, however, shows little reason for concern.

Zhao and Running state their work shows "a reduction in the global NPP of 0.55 petagrams of carbon" over the period 2000–2009. But in viewing a graphical representation of their results (see Figure 5.3.1 below), it can be seen that apart from the starting point of the initial year (2000) of their study, there is only one other year (2004) in which the global NPP was greater than what it was at the end of the study (2009). And since global NPP was on the rise from 1982 to 1999, what the more recent data show would more accurately be described as a leveling off from that prior upward trend.

Zhao and Running say the leveling off of global NPP over the past decade was induced by drought, and that "NPP in the tropics explains 93% of variations in the global NPP" and "tropical rainforests explain 61% of global NPP variations." These findings also serve to undermine whatever concerns that selective reporting of their study's results might have raised, since the recent work of Coelho and Goddard (2009) shows climate models forecast fewer tropical droughts in a warming world.

Coelho and Goddard write, "the majority of drought-related hazards and the attendant economic losses and mortality risks reside in the tropics," citing Dilley et al. (2005). They write, "El Niño brings widespread drought (i.e., precipitation deficit) to the tropics," and "stronger or more frequent El Niño events in the future" would "exacerbate drought risk in highly vulnerable tropical areas."

The two researchers evaluated "the patterns, magnitude, and spatial extent of El Niño-induced tropical droughts during a control period in the twentieth century in climate simulations, which have realistic evolution of greenhouse gases," after which they examined "the projected changes in the characteristics of El Niño and in the strength of the identified patterns of El Niño-induced tropical drought in the twenty-first century." That allowed them to examine patterns of mean precipitation changes in order to "assess whether those changes exacerbate or ameliorate the risk of El Niño-induced drought conditions in the twenty-first century."

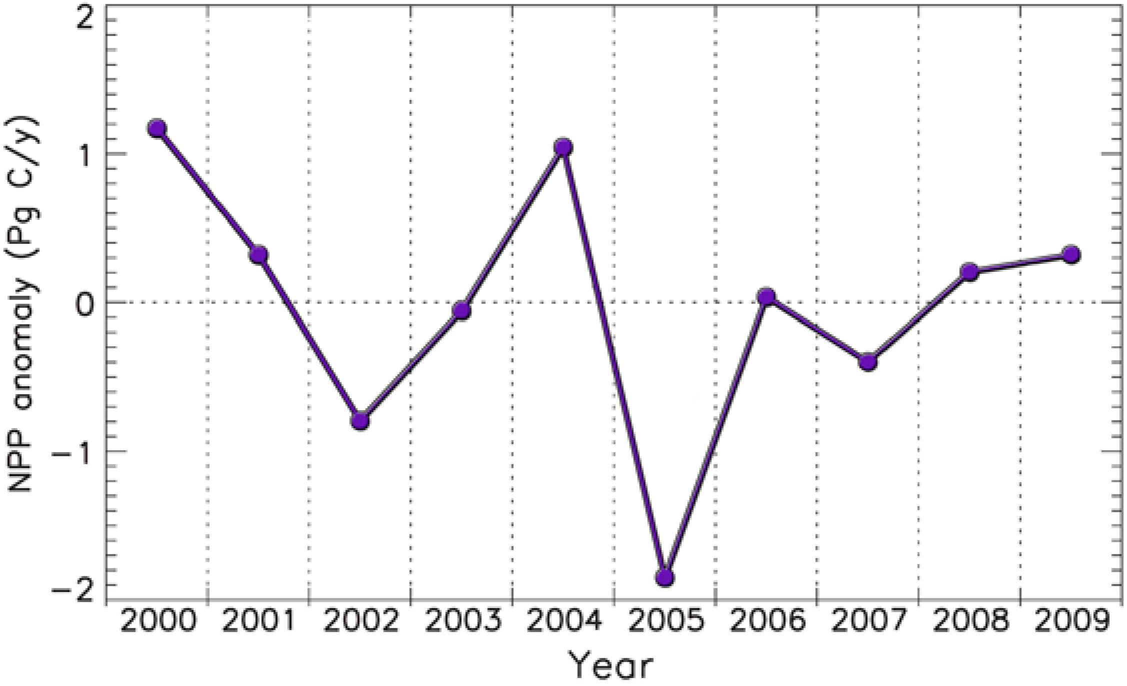


Figure 5.3.1. Interannual variations from the mean of global Net Primary Production (NPP) over the past ten years. Adapted from Zhao and Running (2010).

Coelho and Goddard report "a possible slight reduction in the spatial extent of droughts is indicated over the tropics as a whole," and they report "all model groups investigated show similar changes in mean precipitation for the end of the twenty-first century, with increased precipitation projected between 10°S and 10°N." So it would appear—at least from a climate modeling perspective—that we can probably expect tropical drought to *decrease* throughout the remainder of the twenty-first century, which should enable the historical "greening of the Earth" to continue.

References

Almeida-Lenero, L., Hooghiemstra, H., Cleef, A.M., and van Geel, B. 2005. Holocene climatic and environmental change from pollen records of lakes Zempoala and Quila, central Mexican highlands. *Review of Palaeobotany and Palynology* **136**: 63–92.

Andreadis, K.M., Clark, E.A., Wood, A.W., Hamlet, A.F., and Lettenmaier, D.P. 2005. Twentieth-century drought in the conterminous United States. *Journal of Hydrometeorology* **6**: 985–1001.

Arnauld, C., Metcalfe, S., and Petrequin, P. 1997. Holocene climatic change in the Zacapu Lake Basin, Michoacan: synthesis of results. *Quaternary International* **43/44**: 173–179.

Berkelhammer, M., Sinha, A., Mudelsee, M., and Cannariato, K.G. 2010. Persistent multidecadal power in the Indian summer monsoon. *Earth and Planetary Science Letters* **290**: 166–172.

Berrio, J.C., Hooghiemstra, H., van Geel, B., and Ludlow-Wiechers, B. 2006. Environmental history of the dry forest biome of Guerrero, Mexico, and human impact during the last c. 2700 years. *The Holocene* **16**: 63–80.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G. 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. *Science* **278**: 1257–1266.

Borgaonkar, H.P., Sikdera, A.B., Rama, S., and Panta, G.B. 2010. El Niño and related monsoon drought signals in 523-

year-long ring width records of teak (*Tectona grandis* L.F.) trees from south India. *Palaeogeography, Palaeoclimatology, Palaeoecology* **285**: 74–84.

Buckley, B.M., Anchukaitis, K.J., Penny, D., Fletcher, R., Cook, E.R., Sano, M., Nam, L.C., Wichienkeeo, A., Minh, T.T., and Hong, T.M. 2010. Climate as a contributing factor in the demise of Angkor, Cambodia. *Proceedings of the National Academy of Sciences USA* **107**: 6748–6752.

Buckley, B.M., Palakit, K., Duangsathaporn, K., Sanguantham, P., and Prasomsin, P. 2007. Decadal scale droughts over northwestern Thailand over the past 448 years: links to the tropical Pacific and Indian Ocean sectors. *Climate Dynamics* **29**: 63–71.

Coelho, C.A.S. and Goddard, L. 2009. El Niño-induced tropical droughts in climate change projections. *Journal of Climate* **22**: 6456–6476.

Cook, E.R., Seager, R., Cane, M.A., and Stahle, D.W. 2007. North American droughts: Reconstructions, causes and consequences. *Earth Science Reviews* **81**: 93–134.

Cook, E.R., Seager, R., Heim Jr., R.R., Vose, R.S., Herweijer, C., and Woodhouse, C. 2009. Megadroughts in North America: placing IPCC projections of hydroclimatic change in a long-term palaeoclimate context. *Journal of Quaternary Science* **25**: 48–61.

Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M., and Stahle, D.W. 2004. Long-term aridity changes in the western United States. *Science* **306**: 1015–1018.

Curtis, J.H., Hodell, D.A., and Brenner, M. 1996. Climate variability on the Yucatan Peninsula (Mexico) during the past 3,500 years, and implications for Maya cultural evolution. *Quaternary Research* **46**: 37–47.

Dando, W.A. 1980. *The Geography of Famine*. 209. New York, NY: John Wiley.

Denniston, R.F., DuPree, M., Dorale, J.A., Asmerom, Y., Polyak, V.J., and Carpenter, S.J. 2007. Episodes of late Holocene aridity recorded by stalagmites from Devil's Icebox Cave, central Missouri, USA. *Quaternary Research* **68**: 45–52.

Dilley, M., Chen, R.S., Deichmann, U., Lerner-Lam, A.L., and Arnold, M. 2005. *Natural Disaster Hotspots: A Global Risk Analysis.* World Bank.

Douglass, A.E. 1929. The secret of the Southwest solved with talkative tree rings. *National Geographic* **December**: 736–770.

Douglass, A.E. 1935. Dating Pueblo Bonito and other ruins of the Southwest. National Geographic Society Contributed Technical Papers. *Pueblo Bonito Series* **1**: 1–74.

Escobar, J., Curtis, J.H., Brenner, M., Hodell, D.A., and Holmes, J.A. 2010. Isotope measurements of single ostracod valves and gastropod shells for climate reconstruction: evaluation of within-sample variability and determination of optimum sample size. *Journal of Paleolimnology* **43**: 921–938.

Figueroa-Rangel, B.L., Willis, K.J., and Olvera-Vargas, M. 2010. Cloud forest dynamics in the Mexican neotropics during the last 1300 years. *Global Change Biology* **16**: 1689–1704.

Graham, N., Hughes, M.K., Ammann, C.M., Cobb, K.M., Hoerling, M.P., Kennett, D.J., Kennett, J.P., Rein, B., Stott, L., Wigand, P.E., and Xu, T. 2007. Tropical Pacific-mid-latitude teleconnections in medieval times. *Climatic Change* **83**: 241–285.

Haug, G.H., Gunther, D., Peterson, L.C., Sigman, D.M., Hughen, K.A., and Aeschlimann, B. 2003. Climate and the collapse of Maya civilization. *Science* **299**: 1731–1725.

Helama, S., Merilainen, J., and Tuomenvirta, H. 2009. Multicentennial megadrought in northern Europe coincided with a global El Niño-Southern Oscillation drought pattern during the Medieval Climate Anomaly. *Geology* **37**: 175–178.

Herweijer, C., Seager, R., and Cook, E.R. 2006. North American droughts of the mid to late nineteenth century: History, simulation and implications for Medieval drought. *The Holocene* **16**: 159–171.

Herweijer, C., Seager, R., Cook, E.R., and Emile-Geay, J. 2007. North American droughts of the last millennium from a gridded network of tree-ring data. *Journal of Climate* **20**: 1353–1376.

Hodell, D.A., Brenner, M., and Curtis, J.H. 2005a. Terminal classic drought in the northern Maya lowlands inferred from multiple sediment cores in Lake Chichancanab (Mexico). *Quaternary Science Reviews* **24**: 1413–1427.

Hodell, D.A., Brenner, M., and Curtis, J.H. 2007. Climate and cultural history of the Northeastern Yucatan Peninsula, Quintana Roo, Mexico. *Climatic Change* **83**: 215–240.

Hodell, D.A., Brenner, M., Curtis, J.H., and Guilderson, T. 2001. Solar forcing of drought frequency in the Maya lowlands. *Science* **292**: 1367–1369.

Hodell, D.A., Brenner, M., Curtis, J.H., Medina-Gonzalez, R., Can, E. I.-C., Albornaz-Pat, A., and Guilderson, T.P. 2005b. Climate change on the Yucatan Peninsula during the Little Ice Age. *Quaternary Research* **63**: 109–121.

Hodell, D.A., Curtis, J.H., and Brenner, M. 1995. Possible role of climate in the collapse of classic Maya civilization. *Nature* **375**: 391–394.

Indrapala, K. 1971. The Collapse of the Rajarata Civilization and the Drift to the Southwest. University of Ceylon Press.

Kim, D.-W., Byun, H.-R., and Choi, K.-S. 2009. Evaluation, modification, and application of the Effective Drought Index to 200-year drought climatology of Seoul, Korea. *Journal of Hydrology* **378**: 1–12.

Ludlow-Wiechers, B., Almeida-Lenero, L., and Islebe, G. 2005. Paleoecological and climatic changes of the Upper Lerma Basin, Central Mexico during the Holocene. *Quaternary Research* **64**: 318–332.

Maharatna, A. 1996. *The Demography of Famines: An Indian Historical Perspective*. 317. Delhi, India: Oxford University Press.

Marengo, J.A. 1992. Interannual variability of surface climate in the Amazon basin. *International Journal of Climatology* **12**: 853–863.

Marengo, J.A. 2004. Interdecadal and long term rainfall variability in the Amazon basin. *Theoretical and Applied Climatology* **78**: 79–96.

Marengo, J.A. 2009. Long-term trends and cycles in the hydrometeorology of the Amazon basin since the late 1920s. *Hydrological Processes* **23**: 3236–3244.

Marengo, J. and Hastenrath, S. 1993. Case studies of extreme climatic events in the Amazon basin. *Journal of Climate* **6**: 617–627.

Metcalfe, S.E. 1995. Holocene environmental change in the Zacapu Basin, Mexico: a diatom based record. *The Holocene* **5**: 196–208.

Metcalfe, S.E. 2006. Late Quaternary environments of the northern deserts and central transvolcanic belt of Mexico. *Annals of the Missouri Botanical Garden* **93**: 258–273.

Metcalfe, S.E., Davies, S.J., Braisby, J.D., Leng, M.J., Newton, A.J., Terrett, N.L., and O’Hara, S.L. 2007. Long-term changes in the Patzcuaro Basin, central Mexico. *Palaeogeography, Palaeoclimatology, Palaeoecology* **247**: 272–295.

Metcalfe, S.E. and Hales, P.E. 1994. Holocene diatoms from a Mexican crater lake—La Piscina Yuriria. In *Proceedings of the 11th International Diatom Symposium, San Francisco, USA, 1990* **17**: 155-171. San Francisco, CA: California Academy of Sciences.

Metcalfe, S.E., O’Hara, S.L., Caballero, M., and Davies, S.J. 2000. Records of Late Pleistocene-Holocene climatic change in Mexico—a review. *Quaternary Science Reviews* **19**: 699–721.

O’Hara, S.L. and Metcalfe, S.E. 1997. The climate of Mexico since the Aztec period. *Quaternary International* **43/44**: 25–31.

Pant, G.B., Rupa-Kumar, K.N., Sontakke, A., and Borgaonkar, H.P. 1993. Climate variability over India on century and longer time scales. In *Tropical Meteorology*, edited by R.N. Keshavamurty and P.C. Joshi, 149–158. New Delhi, India: Tata McGraw-Hill.

Rein, B., Luckge, A., and Sirocko, F. 2004. A major Holocene ENSO anomaly during the Medieval period. *Geophysical Research Letters* **31**: 10.1029/2004GL020161.

Russell, J.M. and Johnson, T.C. 2005. A high-resolution geochemical record from Lake Edward, Uganda Congo and the timing and causes of tropical African drought during the late Holocene. *Quaternary Science Reviews* **24**: 1375–1389.

Russell, J.M. and Johnson, T.C. 2007. Little Ice Age drought in equatorial Africa: Intertropical Convergence Zone migrations and El Niño-Southern Oscillation variability. *Geology* **35**: 21–24.

Sano, M., Buckley, B.M., and Sweda, T. 2009. Tree-ring based hydroclimate reconstruction over northern Vietnam from *Fokienia hodginsii*: eighteenth century mega-drought and tropical Pacific influence. *Climate Dynamics* **33**: 331–340.

Seager, R., Graham, N., Herweijer, C., Gordon, A.L., Kushnir, Y., and Cook, E. 2007. Blueprints for Medieval hydroclimate. *Quaternary Science Reviews* **26**: 2322–2336.

Seager, R., Kushnir, Y., Herweijer, C., Naik, N., and Velez, J. 2005. Modeling of tropical forcing of persistent droughts and pluvials over western North America: 1856–2000. *Journal of Climate* **18**: 4068–4091.

Sinha, A., Cannariato, K.G., Stott, L.D., Cheng, H., Edwards, R.L., Yadava, M.G., Ramesh, R., and Singh, I.B. 2007. A 900-year (600 to 1500 A.D.) record of the Indian summer monsoon precipitation from the core monsoon zone of India. *Geophysical Research Letters* **34**: 10.1029/2007GL030431.

Sinha, A., Stott, L., Berkelhammer, M., Cheng, H., Edwards, R.L., Buckley, B., Aldenderfer, M., and Mudelsee, M. 2011. A global context for megadroughts in monsoon Asia during the past millennium. *Quaternary Science Reviews* **30**: 47–62.

Solanki, S.K., Usoskin, I.G., Kromer, B., Schussler, M., and Beer, J. 2004. Unusual activity of the sun during recent decades compared to the previous 11,000 years. *Nature* **431**: 1084–1087.

Springer, G.S., Rowe, H.D., Hardt, B., Edwards, R.L., and Cheng, H. 2008. Solar forcing of Holocene droughts in a stalagmite record from West Virginia in east-central North America. *Geophysical Research Letters* **35**: 10.1029/2008GL034971.

Stahle, D.W., Fye, F.K., Cook, E.R., and Griffin, R.D. 2007. Tree-ring reconstructed megadroughts over North America since AD 1300. *Climatic Change* **83**: 133–149.

Stambaugh, M.C., Guyette, R.P., McMurry, E.R., Cook, E.R., Meko, D.M., and Lupo, A.R. 2011. Drought duration and frequency in the U.S. corn belt during the last millennium (AD 992–2004). *Agricultural and Forest Meteorology* **151**: 154–162.

Stager, J.C., Ryves, D., Cumming, B.F., Meeker, L.D., and Beer, J. 2005. Solar variability and the levels of Lake Victoria, East Africa, during the last millennium. *Journal of Paleolimnology* **33**: 243–251.

Stine, S. 1994. Extreme and persistent drought in California and Patagonia during mediaeval time. *Nature* **369**: 546–549.

Verschuren, D., Laird, K.R., and Cumming, B.F. 2000. Rainfall and drought in equatorial East Africa during the past 1,100 years. *Nature* **403**: 410–414.

Viau, A.E., Gajewski, K., Fines, P., Atkinson, D.E., and Sawada, M.C. 2002. Widespread evidence of 1500 yr climate variability in North America during the past 14,000 yr. *Geology* **30**: 455–458.

Weakly, H.E. 1965. Recurrence of drought in the Great Plains during the last 700 years. *Agricultural Engineering* **46**: 85.

Willard, D.A., Bernhardt, C.E., Korejwo, D.A., and Meyers, S.R. 2005. Impact of millennial-scale Holocene climate variability on eastern North American terrestrial ecosystems: pollen-based climatic reconstruction. *Global and Planetary Change* **47**: 17–35.

Zhang, P.Z., Cheng, H., Edwards, R.L., Chen, F.H., Wang, Y.J., Yang, X.L., Liu, J., Tan, M., Wang, X.F., Liu, J.H., An, C.L., Dai, Z.B., Zhou, J., Zhang, D.Z., Jia, J.H., Jin, L.Y., and Johnson, K.R. 2008. A test of climate, sun, and culture relationships from an 1810-year Chinese cave record. *Science* **322**: 940–942.

Zhao, M. and Running, S.W. 2010. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science* **329**: 940943.

5.4. Storms

Among the highly publicized changes in weather phenomena predicted to accompany the ongoing rise in the air's CO_2 content are increases in the frequency and severity of storms. Many researchers have examined historical and proxy records in an attempt to determine how temperature changes over the recent or more distant past have affected this aspect of Earth's climate. This section reviews the latest findings from this research.

Based on surface pressure data for January 1874 through January 2008, obtained from 11 sites scattered throughout the northeast Atlantic region, Wang et al. (2009) computed, and analyzed trends in, the seasonality and regional differences of storm conditions characterized by the 95th and 99th percentiles of geostrophic wind speeds, which they calculated from sea level pressure data over the period of time when the Earth recovered from the global chill of the Little Ice Age and transited into the Current Warm Period.

Wang et al. determined that storminess conditions in their study region "have undergone substantial decadal or longer time scale fluctuations, with considerable seasonal and regional differences." With respect to annual percentiles of geostrophic wind speeds for the entire study region, however, they state "the Kendall test identifies a downward trend of at least 5% significance in both the 99th and 95th percentile series." The four Canadian researchers state the question of whether there is an anthropogenic contribution to the changes they observed "remains open."

In another paper from the same vicinity, Gascon et al. (2010) write, "autumn and winter storms in the eastern Canadian Arctic are typically characterized by heavy precipitation and strong winds [that] can have major effects on the human population and infrastructures, as well as paralyzing transport," and they state local Inuit "have reported higher occurrences of hazardous weather and unanticipated changes, which increase northern communities' vulnerability and limit their capacity to adapt to environmental change." In a study they describe as "the first to document the climatology of major cold-season precipitation events that affect southern Baffin Island," Gascon et al. examined the characteristics and climatology of the 1955–2006 major cold-season precipitation events that occurred at Iqaluit—the capital of Nunavut, located on the southeastern part of Baffin Island in the northwestern end of Frobisher Bay—based on analyses of hourly surface meteorological data obtained from the public archives of Environment Canada. They corrected the data to account for gauge catchment errors due to wind effects, snow-water equivalence variations, and human error in the manually retrieved precipitation data for the period 1955–1996, while the remainder of the data were used in their uncorrected state.

The three researchers report they detected a non-significant decrease in autumn and winter storm activity over the period of their study, which they say is in line with the results of Curtis et al. (1998), who observed a concomitant decrease in annual precipitation in the western Arctic. And this was the case in spite of the findings of Zhang et al. (2004), who the Canadian scientists say "reported an increase in cyclonic activity over the past fifty years, as well as McCabe et al. (2001), Wang et al. (2004) and Yin (2005)," who reported a northward shift in such activity, but which was apparently not great enough to "translate into major precipitation events, or at least not in Iqaluit," as revealed by the authors' results depicted in Figure 5.4.1.

The results of this data-based analysis would appear to raise questions about the validity of the collective memory of the local Inuit or, perhaps more fairly, of the usefulness of anecdotes about the weather.

Moving on to Europe, "based on an approach combining AMS ^{14}C [radiocarbon] dating, sedimentological and rock magnetic analyses on sediment cores complemented with seismic data collected in the macrotidal Bay of Vilaine [47°20'-47°35'N, 2°50'-2°30'W]," Sorrel et al. (2010) documented "the depositional history of the inner bay coeval to the mid- to late-Holocene transgression in south Brittany."

The results of this study indicated an increase in the contribution of riverine inputs during the Medieval Warm Period at "times of strong fluvial influences in the estuary during ca. 880–1050 AD" and "preservation of medieval estuarine flood deposits implies that sediment remobilization by swells considerably waned at that time, and thus that the influence of winter storminess was minimal," in accordance with the findings of Proctor et al. (2000) and Meeker and Mayewski (2002). They also state the preservation of fine-grained sediments during the Middle Ages has been reported in other coastal settings, citing the studies of Chaumillon et al. (2004) and Billeaud et al. (2005). In fact, the researchers state "all sedimentary records from the French and Spanish Atlantic coasts" suggest "the MWP appears to correspond to a period of marked and recurrent increases in soil erosion with enhanced transport of suspended matter to the shelf as a result of a likely accelerated human land-use development." In addition, they write, "milder climatic conditions during ca. 880–1050 AD may have favored the preservation of estuarine flood deposits in estuarine sediments through a waning of winter storminess, and, thus, reduced coastal hydrodynamics at subtidal depths."

The eight researchers also note the upper

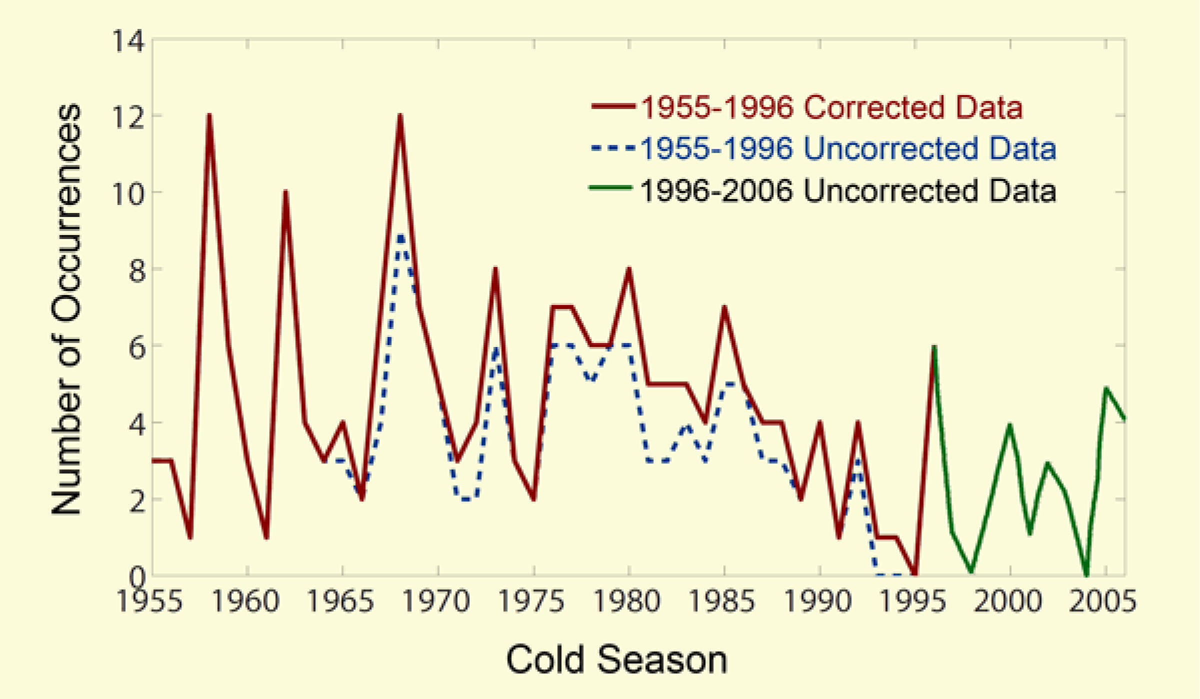


Figure 5.4.1. Cold-season occurrences of major precipitation events at Iqaluit, Nunavut, Canada. Adapted from Gascon et al. (2010).

successions of the sediment cores “mark the return to more energetic conditions in the Bay of Vilaine, with coarse sands and shelly sediments sealing the medieval clay intervals,” adding “this shift most probably documents the transition from the MWP to the Little Ice Age,” which led to the “increased storminess both in the marine and continental ecosystems (Lamb, 1979; Clarke and Rendell, 2009)” that was associated with “the formation of dune systems over a great variety of coastal environments in northern Europe: Denmark (Aagaard et al., 2007; Clemmensen et al., 2007, 2009; Matthews and Briffa, 2005), France (Meurisse et al., 2005), Netherlands (Jelgersma et al., 1995) and Scotland (Dawson et al., 2004).” And in what they call an even “wider perspective,” they note the Medieval Warm Period “is recognized as the warmest period of the last two millennia (Mayewski et al., 2004; Moberg et al., 2005).”

Also in Europe, but three years earlier, Ogrin (2007) presented “an overview of severe storms and a reconstruction of periods with their reiterative occurrence in sub-Mediterranean Slovenia in the warm half of the year during the so-called pre-instrumental period,” based on “data gathered in secondary and tertiary historical sources.”

Speaking of “violent storms” and “the periods in which these phenomena were more frequent and reached, as to the costs of damage caused, the level of natural disasters or even catastrophes,” Ogrin reports “the 17th and 18th centuries were undoubtedly such periods, particularly their first halves, when besides storms also some other weather-caused natural disasters occurred quite often, so that the inhabitants, who mainly depended on the self-subsistent agriculture, could not recover for several years after some consecutive severe rigors of the weather.” In addition, he notes, “the frequency of violent storms in that time was comparable to the incidence towards the end of the 20th century.”

In commenting on these findings, Ogrin, who is in the Department of Geography of the University of Ljubljana, writes that the late twentieth-century increase in violent storms “is supposed to be a human-generated consequence of emitting greenhouse gasses and of the resulting global warming of the atmosphere.” However, he reports “the damage done by severe storms in the past does not differ significantly from the damage in the present.” And this suggests the weather extremes of today may well be caused by something else, for if they have occurred in the past for a different reason (and they have), they can be occurring today for a different reason as well.

Moving to the Southern Hemisphere, Page et al. (2010) extracted sediment cores from Lake Tutira on the eastern North Island of New Zealand in an effort to develop a 7,200-year history of the frequency and magnitude of storm activity, based on analyses of (1) sediment grain size; (2) diatom, pollen, and spore types and concentrations; plus (3) carbon and nitrogen concentrations; together with (4) tephra and radiocarbon dating. Results indicated “the average frequency of all storm layers is one in five years,” but that “for storm layers >= 1.0 cm thick, the average frequency is every 53 years.” And in this regard, they state that over the course of their record, “there are 25 periods with an increased frequency of large storms” and the onset and cessation of these stormy periods “was usually abrupt, occurring on an inter-annual to decadal scale.” They also note the duration of these stormy periods “ranged mainly from several decades to a century,” but “a few were up to several centuries long” and “intervals between stormy periods range from about thirty years to a century.” In addition, they find millennial-scale cooling periods tend to “coincide with periods of increased storminess in the Tutira record, while warmer events match less stormy periods.”

Concluding their analysis, Page et al. note there is growing concern today, driven by climate models, that global warming may cause abrupt changes in various short-term meteorological phenomena, “when either rapid or gradual forces on components of the earth system exceed a threshold or tipping point.” However, as is demonstrated by the results of their work in the real world, the sudden occurrence of a string of years—or even decades—of unusually large storms can happen at almost any time on its own, without being driven by human activities such as the burning of fossil fuels.

Noting “hail is one of the most extreme weather phenomena, causing great loss to agriculture every year in China (Han, 1999),” Xie and Zhang (2010) decided to see whether this particular storm phenomenon had gotten any worse throughout China in recent years.

Xie et al. (2008) had previously found a “significant decreasing trend of hail frequency in most of China from the early 1980s based on 46 years of data during 1960–2005.” Thus Xie and Zhang began with the knowledge that for this vast country one of two types of potential hail extremes (hailstorm frequency) had not complied with the IPCC's predictions. Therefore, the two researchers focused on the other type of extreme (hailstone size), noting "changes in hail size are also an important aspect of hail climatology." They went on to study the long-term trend of hail size in four regions of China over the period 1980–2005, using maximum hail diameter data obtained from the Meteorological Administrations of Xinjiang Uygur Autonomous Region (XUAR), Inner Mongolia Autonomous Region (IMAR), Guizhou Province, and Hebei Province.

The two authors report their work revealed an uptrend in maximum hail diameter in Hebei, a flat trend in XUAR, and a slight downtrend in Guizhou and IMAR, but they add "none of the trends is statistically significant." In light of these findings, it seems clear the global warming of the past few decades has led to no increase in the extremeness of Chinese hail storms.

Examining dust storms in China, Zhu et al. (2008) write, "changes in occurrences of natural disasters, which are possibly associated with global warming, have been receiving ever-increasing attention worldwide" and the "dust storm is one of the severe disastrous weather [phenomena] in China." In this regard, however, and in contrast to the general tenor of most discussions of the issue, they say "a number of studies have shown that the spring dust storm frequency (DSF) bears a negative correlation with the local surface air temperature, and exhibits a downward trend over the past 50 years," citing the studies of Qian et al. (2002a), Zhou and Zhang (2003), Zhai and Li (2003), Zhao et al. (2004), Fan et al. (2006), and Gong et al. (2006, 2007) in support of this statement.

Zhu et al. explored "the long-term variation of Chinese DSF in spring (March to May), and its possible linkage with the global warming and its related circulation changes in the Northern Hemisphere," using data from 258 stations within the region surrounding Lake Baikal (70–130°E, 45–65°N) over the period 1954 to 2007. The results of this effort indicated a "prominent warming" in recent decades, as well as "an anomalous dipole circulation pattern" in the troposphere that "consists of a warm anti-cyclone centered at 55°N and a cold cyclone centered around 30°N," leading to "a weakening of the westerly jet stream and the atmospheric baroclinicity in northern China and Mongolian regions, which suppress the frequency of occurrence and the intensity of the Mongolian cyclones and result in the decreasing DSF in North China."

Peng et al. (2010) used snow-depth measurements collected at 279 meteorological stations scattered across the country, plus collocated satellite-derived Normalized Difference Vegetation Index (NDVI) data, to investigate spatio-temporal changes in snow depth over the period 1980–2006 and the effects of those changes on vegetative growth the following spring and summer. The five researchers report, "over the past three decades, winter snow depth overall increased in northern China, particularly in the most arid and semiarid regions of western China where desert and grassland are mainly distributed," and they state that in those specific areas there were positive correlations between mean winter snow depth and spring NDVI data. In addition, they note Piao et al. (2005) determined the net primary productivity of the same desert and grasslands during 1982–1999 "increased by 1.6% per year and 1.1% per year, respectively," and "desertification has been reversed in some areas of western China since the 1980s," citing the work of Runnstrom (2000), Wu (2001), Zhang et al. (2003), and Piao et al. (2005).

In discussing the implications of their findings, Peng et al. write the "increase in vegetation coverage in arid and semiarid regions of China, possibly driven by winter snow, will likely restore soil and enhance its antiwind-erosion ability, reducing the possibility of released dust and mitigating sand-dust storms," while noting the frequency of sand-dust storms has indeed "declined in China since the early 1980s (Qian et al., 2002b; Zhao et al., 2004)." Thus, as the world has warmed over the past three decades, there has been another concomitant climatic change across China above 40°N latitude (an increase in winter snow depth) that has prompted a biological change (increased vegetative growth in desert areas and grasslands) that has prompted yet another climatic change (a reduction in sand-dust storms), all of which could be considered positive developments.

In examining another storm-related extreme weather event, Diffenbaugh et al. (2008) briefly reviewed what is known about responses of U.S. tornadoes to rising temperatures. On the theoretical side of the issue, Diffenbaugh et al. indicate there are competing ideas about whether tornadoes might become more or less frequent and/or severe as the planet warms. On the observational side, there is also much uncertainty about the matter. They write, for example, "the number of tornadoes reported in the United States per year has been increasing steadily (~14 per year) over the past half century." However, they state, "determining whether this is a robust trend in tornado occurrence is difficult" because "the historical record is both relatively short and non-uniform in space and time." In addition, the increase in yearly tornado numbers runs parallel with the concurrent increase in the country's population, which makes for that much better geographical coverage and more complete (i.e., numerous) observations.

On the other hand, the three researchers report the number of tornadoes classified as the most damaging (F2–F5 on the Fujita scale) may have decreased over the past five decades (1954–2003), as their reported frequency of occurrence runs counter to the trend of the country's population. The graphs they present show yearly F2–F5 tornado numbers in the latter half of the record period dropping to only about half of what they were during its first half, while corresponding data from the U.S. Southern Great Plains show damaging tornado numbers dropping to only about a third of what they were initially. Nevertheless, Diffenbaugh et al. consider the question posed in the title of their paper—"Does global warming influence tornado activity?"—to be unresolved, stating, "determining the actual background occurrence and trend in tornado activity over recent decades will certainly require further development of other analysis approaches."

In another study of the subject published two years later, Timbal et al. (2010) explored the presumed effect of global warming on cool-season tornadoes in southern Australia, where four climate models were employed in their analysis, with the IPCC's highest greenhouse gas emissions scenario (A2) being used for projections. Previously, it had been shown two climate variables were strongly predictive of tornado frequency in this region: (1) an atmospheric instability threshold, and (2) the strength of vertical wind shear. These two variables were tuned to each climate model employed so the predicted tornado frequency for the base-case model run matched actual data in order to accommodate different spatial resolution and bias in the models.

The exercise revealed the future climates projected by the four models over the next 100 years all yielded *lower* probabilities of cool-season tornado occurrence. The authors attributed this decline to increases in the Southern Annular Mode index, which causes increased atmospheric stability in the lower troposphere. This study demonstrates that even climate models, in which we admittedly do not have much confidence, do not always forecast worse weather in a warmer world.

Barredo (2010) writes, "on 18 January 2007, windstorm Kyrill battered Europe with hurricane-force winds killing 47 people and causing 10 billion US$ in damage." In light of model-based predictions that such storms will increase in the future, the author "put Kyrill into an historical context by examining large historical windstorm event losses in Europe for the period 1970–2008 across 29 European countries," asking the question "what economic losses would these historical events cause if they were to recur under 2008 societal conditions?"

According to the researcher—who is employed by the Institute for Environment and Sustainability, European Commission-Joint Research Centre in Ispra, Italy—loss data resulting from numerous prior storms "were sourced from reinsurance firms and augmented with historical reports, peer-reviewed articles and other ancillary sources," and the extracted data were "adjusted for changes in population, wealth, and inflation at the country level and for inter-country price differences using purchasing power parity." The results obtained indicate "no trend in the normalized windstorm losses and confirm increasing disaster losses are driven by society factors and increasing exposure." Barredo thus concludes, "increasing disaster losses are overwhelmingly a consequence of changing societal factors."

Although it is frequently claimed that recent destructive storms of all types are the result of the historical warming of the world over the past several decades, it is incorrect to do so, for Barredo states that what is true of windstorms in Europe also has "been shown to be the case for flood and hurricane losses in the US (Pielke Jr. and Landsea, 1998; Pielke Jr. and Downton, 2000; Pielke Jr. et al., 2008), tornadoes in the U.S. (Brooks and Doswell, 2001), hurricane losses in the Caribbean region (Pielke Jr. et al., 2003), weather extremes in the U.S. (Changnon et al., 2000; Changnon, 2003), flood losses in Europe (Barredo, 2009), tropical cyclones in India (Raghavan and Rajesh, 2003), and weather-driven disasters in Australia (Crompton and McAneney, 2008)." He notes "all of these studies found no significant trends of losses after historical events were normalized to current conditions in order to account for demonstrably changing societal/demographic factors.”

References

Aagaard, T., Orford, J., and Murray, A.S. 2007. Environmental controls on coastal dune formation: Skallingen Spit, Denmark. *Geomorphology* **83**: 29–47.

Barredo, J.I. 2009. Normalized flood losses in Europe: 1970-2006. *Natural Hazards and Earth System Sciences* **9**: 97–104.

Barredo, J.I. 2010. No upward trend in normalized windstorm losses in Europe: 1970–2008. *Natural Hazards and Earth System Sciences* **10**: 97–104.

Brooks, H.E. and Doswell, C.A. 2001. Normalized damage from major tornadoes in the United States: 1890-1999. *Weather and Forecasting* **16**: 168–176.

Billeaud, I., Chaumillon, E., and Weber, N. 2005. Evidence of a major environmental change recorded in a macrotidal bay (Marennes-Oleron Bay, France) by correlation between VHR seismic profiles and cores. *Geo-marine Letters* **25**: 1–10.

Changnon, S.A. 2003. Shifting economic impacts from weather extremes in the United States: a result of societal changes, not global warming. *Natural Hazards* **29**: 273–290.

Changnon, S.A., Pielke, R.A., Changnon, D., Sylves, R.T., and Pulwarty, R. 2000. Human factors explain the increased losses from weather and climate extremes. *Bulletin of the American Meteorological Society* **81**: 437–442.

Chaumillon, E., Tessier, B., Weber, N., Tesson, M., and Bertin, X. 2004. Buried sandbodies within present-day estuaries (Atlantic coast of France) revealed by very high-resolution seismic surveys. *Marine Geology* **211**: 189–214.

Clarke, M.L. and Rendell, H.M. 2009. The impact of North Atlantic storminess on western European coasts: a review. *Quaternary International* **195**: 31–41.

Clemmensen, L.B., Bjornsen, M., Murray, A., and Pedersen, K. 2007. Formation of aeolian dunes on Anholt, Denmark since AD 1560: a record of deforestation and increased storminess. *Sedimentary Geology* **199**: 171–187.

Clemmensen, L.B., Murray, A., Heinemeier, J., and de Jong, R. 2009. The evolution of Holocene coastal dune fields, Jutland, Denmark: a record of climate change over the past 5000 years. *Geomorphology* **105**: 303–313.

Crompton, R.P. and McAneney, K.J. 2008. Normalized Australian insured losses from meteorological hazards: 1967-2006. *Environmental Science and Policy* **11**: 371–378.

Curtis, J., Wendler, G., Stone, R., and Dutton, E. 1998. Precipitation decrease in the western Arctic, with special emphasis on Barrow and Barter Island, Alaska. *International Journal of Climatology* **18**: 1687–1707.

Dawson, S., Smith, D.E., Jordan, J., and Dawson, A.G. 2004. Late Holocene coastal sand movements in the Outer Hebrides, NW Scotland. *Marine Geology* **210**: 281–306.

Diffenbaugh, N.S., Trapp, R.J., and Brooks, H. 2008. Does global warming influence tornado activity? *EOS, Transactions, American Geophysical Union* **89**: 553–554.

Fan, Y.-D., Shi, P.-J., Zhu, A.-J., Gong, M.-X., and Guan, Y. 2006. Analysis of connection between dust storm and climate factors in northern China. *Journal of Natural Disasters* **15**: 12–18.

Gascon, G., Stewart, R.E., and Henson, W. 2010. Major cold-season precipitation events at Iqaluit, Nunavut. *Arctic* **63**: 327–337.

Gong, D.-Y., Mao, R., and Fan, Y.-D. 2006. East Asian dust storm and weather disturbance: possible links to the Arctic Oscillation. *International Journal of Climatology* **26**: 1379–1396.

Gong, D.-Y., Mao, R., Shi, P.-J., and Fan, Y.-D. 2007. Correlation between east Asian dust storm frequency and PNA. *Geophysical Research Letters* **34**: 10.1029/2007GL029944.

Han, G.F. 1999. The analysis on the feathers of hail hazard in Hebei province. *Journal of Catastrophe* **14**: 243–246.

Jelgersma, S., Stive, M.J.F., and van der Walk, L. 1995. Holocene storm surge signatures in the coastal dunes of the western Netherlands. *Marine Geology* **125**: 95–110.

Lamb, H.H. 1979. Climatic variations and changes in the wind and ocean circulation. *Quaternary Research* **11**: 1–20.

Matthews, J.A. and Briffa, K.R. 2005. The ‘Little Ice Age’: re-evaluation of an evolving concept. *Geografiska Annaler* **87A**: 17–36.

Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlen, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G. Rack, F., Staubwasser, M., Schneider, R.R., and Steig, E.J. 2004. Holocene climate variability. *Quaternary Research* **62**: 243–255.

McCabe, G.J., Clark, M.P., and Serreze, M.C. 2001. Trends in Northern Hemisphere surface cyclone frequency and intensity. *Journal of Climate* **14**: 2763–2768.

Meeker, L.D. and Mayewski, P.A. 2002. A 1400-year high-resolution record of atmospheric circulation over the North Atlantic and Asia. *The Holocene* **12**: 257–266.

Meurisse, M., van Vliet-Lanoe, B., Talon, B., and Recourt, P. 2005. Complexes dunaires et tourbeux holocenes du littoral du Nord de la France. *Comptes Rendus Geosciences* **337**: 675–684.

Moberg, A., Sonechkin, K.M., Holmgren, K., Datsenko, N.M., and Karlen, W. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* **433**: 613–617.

Ogrin, D. 2007. Severe storms and their effects in sub-Mediterranean Slovenia from the 14th to the mid-19th century. *Acta Geographica Slovenia* **47**: 7–24.

Page, M.J., Trustrum, N.A., Orpin, A.R., Carter, L., Gomez, B., Cochran, U.A., Mildenhall, D.C., Rogers, K.M., Brackley, H.L., Palmer, A.S., and Northcote, L. 2010. Storm frequency and magnitude in response to Holocene climate variability, Lake Tutira, North-Eastern New Zealand. *Marine Geology* **270**: 30–44.

Peng, S., Piao, S., Ciais, P., Fang, J., and Wang, X. 2010. Change in winter snow depth and its impacts on vegetation in China. *Global Change Biology* **16**: 3004–3013.

Piao, S.L., Fang, J.Y., Liu, H.Y., and Zhu, B. 2005. NDVI-indicated decline in desertification in China in the past two decades. *Geophysical Research Letters* **32**: 10.1029/2004GL021764.

Pielke Jr., R.A. and Downton, M.W. 2000. Precipitation and damaging floods: trends in the United States, 1932-1997. *Journal of Climate* **13**: 3625–3637.

Pielke Jr., R.A., Gratz, J., Landsea, C.W., Collins, D., Saunders, M.A., and Musulin, R. 2008. Normalized hurricane damage in the United States: 1900–2005. *Natural Hazards Review* **31**: 29–42.

Pielke Jr., R.A. and Landsea, C.W. 1998. Normalized hurricane damages in the United States: 1925–95. *Weather and Forecasting* **13**: 621–631.

Pielke Jr., R.A., Rubiera, J., Landsea, C., Fernandez, M.L., and Klein, R. 2003. Hurricane vulnerability in Latin America and the Caribbean: normalized damage and loss potentials. *Natural Hazards Review* **4**: 101–114.

Proctor, C.J., Baker, A., Barnes, W.L., and Gilmour, M.A. 2000. A thousand year speleothem record of North Atlantic climate from Scotland. *Climate Dynamics* **16**: 815–820.

Qian, W.-H., Quan, L.-S., and Shi, S.-Y. 2002a. Variations of the dust storm in China and its climatic control. *Journal of Climate* **15**: 1216–1229.

Qian, Z.A., Song, M.H., and Li, W.Y. 2002b. Analysis on distributive variation and forecast of sand-dust storms in recent 50 years in north China. *Journal of Desert Research* **22**: 106–111.

Raghavan, S. and Rajesh, S. 2003. Trends in tropical cyclone impact: a study in Andhra Pradesh, India. *Bulletin of the American Meteorological Society* **84**: 635–644.

Runnstrom, M.C. 2000. Is northern China winning the battle against desertification? Satellite remote sensing as a tool to study biomass trends on the Ordos plateau in semiarid China. *Ambio* **29**: 468–476.

Sorrel, P., Tessier, B., Demory, F., Baltzer, A., Bouaouina, F., Proust, J.-N., Menier, D., and Traini, C. 2010. Sedimentary archives of the French Atlantic coast (inner Bay of Vilaine, south Brittany): depositional history and late Holocene climatic and environmental signals. *Continental Shelf Research* **30**: 1250–1266.

Timbal, B., Kounkou, R., and Mills, G.A. 2010. Changes in the risk of cool-season tornadoes over southern Australia due to model projections of anthropogenic warming. *Journal of Climate* **23**: 2440–2449.

Wang, X.L., Swail, V.R., and Zwiers, F.W. 2004. Changes in extratropical storm tracks and cyclone activity as derived from two global reanalyses and the Canadian CGCM2 projections of future climate. *Eighth International Workshop on Wave Hindcasting and Forecasting, 14–19 November 2004, Oahu, Hawaii.* Environment Canada, Paper B1.

Wang, X.L., Zwiers, F.W., Swail, V.R., and Feng, Y. 2009. Trends and variability of storminess in the Northeast Atlantic region, 1874–2007. *Climate Dynamics* **33**: 1179–1195.

Wu, W. 2001. Study on process of desertification in Mu Us sandy land for last 50 years, China. *Journal of Desert Research* **21**: 164–169.

Xie, B. and Zhang, Q. 2010. Observed characteristics of hail size in four regions in China during 1980–2005. *Journal of Climate* **23**: 4973–4982.

Xie, B., Zhang, Q., and Wang, Y. 2008. Trends in hail in China during 1960–2005. *Geophysical Research Letters* **35**: 10.1029/2008GL034067.

Yin, J.H. 2005. A consistent poleward shift of the storm tracks in simulations of 21st century climate. *Geophysical Research Letters* **32**: 10.1029/2005GL023684.

Zhai, P.M. and Li, X.Y. 2003. On climate background of dust storms over northern China. *Chinese Journal of Geophysics* **58**: 125–131.

Zhang, L., Yue, L.P., and Xia, B. 2003. The study of land desertification in transitional zones between the UM US desert and the Loess plateau using RS and GIS—a case study of the Yulin region. *Environmental Geology* **44**: 530–534.

Zhang, X., Walsh, J.E., Zhang, J., Bhatt, U.S., and Ikeda, M. 2004. Climatology and interannual variability of Arctic cyclone activity: 1948–2002. *Journal of Climate* **17**: 2300–2317.

Zhao, C.S., Dabu, X., and Li, Y. 2004. Relationship between climatic factors and dust storm frequency in inner Mongolia of China. *Geophysical Research Letters* **31**: 10.1029/2003GL018351.

Zhou, Z.-J. and Zhang, G.-C. 2003. Typical severe dust storms in northern China: 1954–2002. *Chinese Science Bulletin* **48**: 1224–1228.

Zhu, C., Wang, B., and Qian, W. 2008. Why do dust storms decrease in northern China concurrently with the recent global warming? *Geophysical Research Letters* **35**: 10.1029/2008GL034886.

5.5. Hurricanes

In its Fourth Assessment Report, the IPCC states “it is *likely* that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures” (IPCC, 2007). However, as was shown in the 2009 NIPCC report (Idso and Singer, 2009), numerous peer-reviewed studies reveal that will not be the case. In this section we present the results of more recent studies not reviewed in the 2009 NIPCC report.

Fan and Liu (2008) note “the recent increase in typhoon (tropical cyclone) activity has attracted great interest and induced heated debates over whether it is linked to global warming” and “skeptics of the global warming connection think that we are just at an active phase of multi-decadal variations in typhoons.” They present “a brief review and synthesis on the major research advances and findings of paleotempestology,” which they describe as “a young science” that “studies past typhoon activity spanning several centuries to millennia before the instrumental era through the use of geological proxies and historical documentary records.”

The two researchers report “typhoon-proxy data show that there does not exist a simple linear relationship between typhoon frequency and Holocene climate (temperature) change,” noting “case studies based on geological proxy records show that a warmer climate alone during the Holocene Optimum may not have increased the frequency of intense typhoons” and “in the last millennium, the frequency of typhoon activity was not found to fluctuate linearly with climatic change over the centennial timescale.” In fact, and “on the contrary,” as they continue, “typhoon frequency seemed to have increased at least regionally during the coldest phases of the Little Ice Age.” In addition, they report “more typhoons and hurricanes make landfalls in China, Central and North America during La Niña years than El Niño years,” which finding, if anything, is the opposite of what the IPCC contends.

Swinging the pendulum slightly in the opposite direction one year later were Mann et al. (2009), who developed two 1,500-year histories of North Atlantic tropical cyclone (TC) activity. The first of these proxy records, as they describe it, was derived from “a composite of regional sedimentary evidence of landfalling hurricanes,” which included “a site from the Caribbean (Vieques, Puerto Rico), one from the US Gulf Coast, one from the southeastern US coast, three from the mid-Atlantic coast (one from New York and two from New Jersey) and two from southeastern New England (one from Rhode Island and another from Massachusetts).”

The second of the two estimates employed “a previously published statistical model of Atlantic tropical cyclone activity driven by proxy reconstructions of past climate changes,” the three climate factors being “(1) the sea surface temperature over the main development region for tropical Atlantic tropical cyclones, which reflects the favorability of the local thermodynamic environment, (2) the El Niño/Southern Oscillation, which influences the amount of (unfavorable) vertical wind shear, and (3) the North Atlantic Oscillation, which affects the tracking of storms, determining how favorable an environment they encounter.”

The results of this enterprise revealed, in their words, “periods of high [TC] activity (that is, comparable to current levels) during a medieval era of roughly AD 900–1100.” And because they found the level of medieval activity “matches or even exceeds current levels of activity within uncertainties for the statistical model,” it is highly likely the temperatures of the North Atlantic’s main TC development region, as well as the Niño3 region, were equivalent to, or even greater than, those of the recent past.

Even more support for this conclusion is provided by the study of Landsea et al. (2009), who explored the influence of TC duration on observed changes in TC frequency, using the HURDAT Atlantic TC database. Their work revealed “the occurrence of short-lived storms (duration two days or less) in the database has increased dramatically, from less than one per year in the late-19th/early-20th Century to about five per year since about 2000, while moderate to long-lived storms have increased little, if at all." They conclude, "the previously documented increase in total TC frequency since the late 19th Century in the database is primarily due to an increase in very short-lived TCs," which they attribute to "improvements in the quantity and quality of observations, along with enhanced interpretation techniques."

Interestingly, just as in the case of the discredited "hockey stick" temperature history of Mann et al. (1998, 1999) and Mann and Jones (2003), the Atlantic TC history of Mann et al. (2009) consists of reconstructed results ("apples") up until the mid-nineteenth century, after which observational results ("oranges") are employed. And those oranges pile up ever faster over the most recent 150 years of observational data, leaving the prior apples in their dust, just as the results of Landsea et al.'s analysis suggest they should. But when the latter researchers adjust for this artifactual phenomenon, they find "no significant [TC] trend remains using either an 1878 or a 1900 starting point." This development suggests the Medieval Warm Period may have been much warmer than what the Current Warm Period has been to date.

Further tilting the scales in favor of the skeptics, Wallace and Anderson (2010) collected 37 sediment cores along eight transects within Laguna Madre, an elongate water body located behind the narrow low-elevation barrier that is Texas, USA's South Padre Island. Based on the vertical distribution and grain size of storm over-wash sediments contained within four of those cores from two transects that were most ideally positioned, they were able to construct a detailed history of intense hurricane strikes from 5,300 to 900 years before present (BP).

Based on their analyses, Wallace and Anderson report "there has been no notable variation in intense storm impacts across the northwestern Gulf of Mexico coast during this time interval," i.e., 5,300–900 yr BP, "implying no direct link between changing climate conditions and annual hurricane impact probability." In addition, they state, "there have been no significant differences in the landfall probabilities of storms between the eastern and western Gulf of Mexico during the late Holocene, suggesting that storm steering mechanisms have not varied during this time."

In discussing their findings—as well as the similar results obtained by others for Western Lake, Florida, and Lake Shelby, Alabama—the two Rice University (Houston, Texas) researchers say current rates of intense hurricane impacts "do not seem unprecedented when compared to intense strikes over the past 5000 years" and "similar probabilities in high-intensity hurricane strikes for the eastern and western Gulf of Mexico do not show any clear-cut out-of-phase relationship that would enlighten us as to climate controls on storm pathways."

In a study of tropical cyclone trends in the more recent past, Vecchi et al. (2008) write "a key question in the study of near-term climate change is whether there is a causal connection between warming tropical sea surface temperatures (SSTs) and Atlantic hurricane activity." As they explain in more detail, there are two schools of thought on this topic. One posits that the intensity of Atlantic Basin hurricanes is directly related to the absolute SST of the basin's main development region, which would be expected to rise in response to global warming. The other posits that Atlantic hurricane intensity is directly related to the SST of the Atlantic basin's main development region relative to the SSTs of the other tropical ocean basins, a factor that could rise or fall to a modest degree in response to global warming.

In conducting their analysis of the subject, based on pertinent data obtained between 1946 and 2007, Vecchi et al. plotted Atlantic hurricane power dissipation index (PDI) anomalies calculated from both the absolute SST values of the Atlantic Basin and the relative SST values derived from all tropical ocean basins as a function of time, extending them throughout most of the current century based on projections of the two parameters obtained from 24 different climate models. They then compared the results they obtained between1946 and 2007 with the measured PDI anomalies. "Between 1946 and 2007," the researchers found, the relative SST "is as well correlated with Atlantic hurricane activity as the absolute SST." However, they report the "relative SST does not experience a substantial trend in 21st-century projections" and, therefore, they conclude, "a future where relative SST controls Atlantic hurricane activity is a future similar to the recent past, with periods of higher and lower hurricane activity relative to present-day conditions due to natural climate variability, but with little long-term trend."

This result, as Vecchi et al. describe it, "suggests that we are presently at an impasse" and that "many years of data will be required to reject one hypothesis in favor of the other," as the projections derived from the absolute and relative SST parameters "do not diverge completely until the mid-2020s." Consequently, if the absolute SST ultimately proves to be the proper forcing factor, concerns based on this thesis would have some validity. But if the relative SST proves to be the controlling factor, the researchers state, "an attribution of the recent increase in hurricane activity to human activities is not appropriate, because the recent changes in relative SST in the Atlantic are not yet distinct from natural climate variability."

In a contemporaneous study also focused on the Atlantic basin, Chylek and Lesins (2008) write, "on the basis of hurricane thermodynamics it is plausible to expect hurricane strength to increase with increasing sea surface temperature," and they say some recent papers have "claimed detection of such an increase (Emanuel, 2005; Webster et al., 2005; Holland and Webster, 2007) while others reported little or no trend (Solow and Moore, 2002; Landsea, 2005; Pielke, 2005; Klotzbach, 2006; Landsea et al., 2006; Nyberg et al., 2007; Kossin et al., 2007)."

To explore this issue, Chylek and Lesins "apply simple statistical methods to the NOAA HURDAT record of storm activity in the North Atlantic basin between 1851 and 2007 to investigate a possible linear trend, periodicity and other features of interest." Using "a hurricane activity index that integrates over hurricane numbers, durations, and strengths," the two researchers report discovering "a quasi-periodic behavior with a period around 60 years superimposed upon a linearly increasing background." However, they note "the linearly increasing background is significantly reduced or removed when various corrections were applied for hurricane undercounting in the early portion of the record."

Further noting "the last minimum in hurricane activity occurred around 1980," Chylek and Lesins compare the two 28-year periods on either side of this date and find "a modest increase of minor hurricanes, no change in the number of major hurricanes, and a decrease in cases of rapid hurricane intensification." They conclude, "if there is an increase in hurricane activity connected to a greenhouse gas induced global warming, it is currently obscured by the 60-year quasi-periodic cycle."

In another study published the same year, Klotzbach and Gray (2008) employed sea surface temperature (SST) data for the far North Atlantic (50–60°N, 50–10°W) and sea-level pressure (SLP) data for the North Atlantic (0–50°N, 70–10°W) to construct an index of the Atlantic Multidecadal Oscillation (AMO), which they defined as the difference between the standardized SST and SLP anomalies (SST-SLP) for the hurricane season of June–November, and which they evaluated for the period 1878–2006. They then compared their results (to which they applied a 1-2-3-2-1 filter) with several hurricane properties.

Klotzbach and Gray's analysis revealed the existence of three positive and two negative AMO phases over the period of their study, as can be seen in Figure 5.5.1.

In comparing annually averaged results for tropical cyclone (TC) characteristics between the positive and negative AMO phases indicated in the above graph, it can be calculated from the TC data of the authors that the positive AMO phase-to-negative AMO phase ratios of hurricane numbers, hurricane days, major hurricane numbers, and major hurricane days were 1.53, 1.89, 2.00, and 2.46, respectively, over the period studied, while for the 20 most positive and 20 most negative AMO years the same ratios, in the same order, were 1.73, 2.41, 2.80, and 4.94.

Given such findings, it is clear the state of the North Atlantic AMO is tremendously important to hurricane genesis and development, and this striking natural variability makes it impossible to determine whether there is any long-term trend in the TC data that might be due to twentieth-century global warming.

In one final study of the Atlantic basin, Bender et al. (2010) "explored the influence of future global warming on Atlantic hurricanes with a downscaling strategy by using an operational hurricane-prediction model that produces a realistic distribution of intense hurricane activity for present-day conditions." The researchers worked with 18 models from the World Climate Research Program's Coupled Model Intercomparison Project 3 and employed the Intergovernmental Panel on Climate Change's A1B emissions scenario.

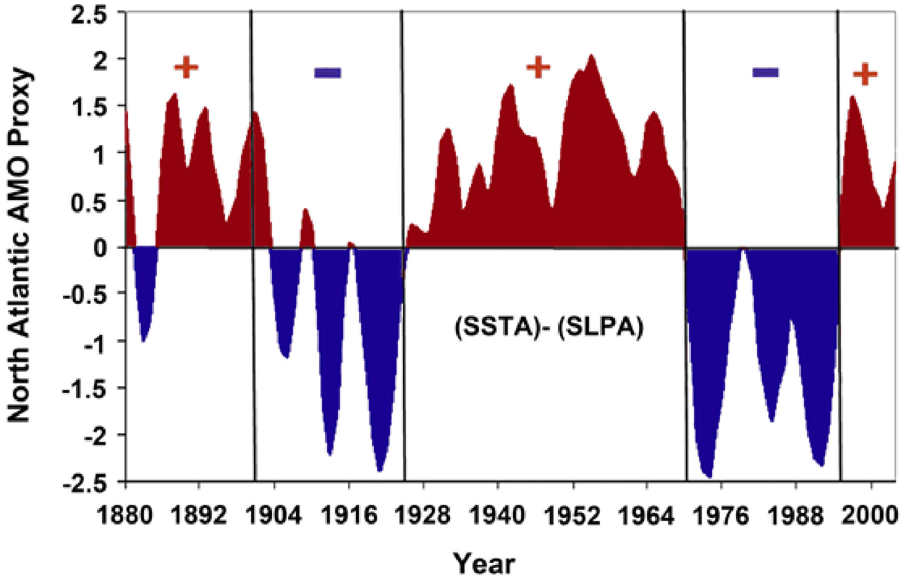


Figure 5.5.1. North Atlantic Multidecadal Oscillation (AMO) Index. Adapted from Klotzbach and Gray (2008).

The result of this exercise was, in their words, "an increase in the number of the most intense storms for the warmer climate compared with the control climate." Bender et al.'s modeling work predicted that for "category 4 and 5 hurricanes with maximum winds greater than 60 m/s, the total number increased sharply from 24 to 46," and "hurricanes with winds greater than 65 m/s increased from 6 to 21." However, they report there were reductions in the total number of hurricanes of all categories, which seems to contradict that finding.

In further discussing their findings, the researchers comment on the wide range of variability in what the various models predicted. They note, for example, that an increase in hurricane-caused "damage potential" of +30% was projected for the 18-model ensemble, while a range of -50% to +70% was found for four models for which they did more detailed work. This extreme range of variability reduces confidence in their mean result.

On another point, Bender et al.'s findings contradict the popular claim of a link between the occurrence of strong hurricanes of the recent past and supposedly unnatural and unprecedented CO_2-induced global warming. Although the new model results suggest "a significant anthropogenic increase in the frequency of very intense Atlantic hurricanes may emerge from the background climate variability," the researchers find this development would likely not occur until "the latter half of the 21st century."

Kerr (2010) reports, in a commentary on Bender et al.'s study, that the researchers "are looking for yet more computer power and higher resolution to boost the realism of simulations." Kerr further writes, "if the models continue to converge as realism increases, the monster storms that seemed to be already upon us would be removed to decades hence."

But who really knows, when one is working with much-less-than-perfect models of a complex planetary climate/weather system? As Kerr reports, even the researchers themselves "caution" that their findings are still "far from the last word" on the subject.

Moving next to the Pacific Ocean, Harper et al. (2008) begin their analysis by noting there is "increasing concern that anthropogenic climate change may be increasing TC [tropical cyclone] intensity." In their contribution to the debate, they analyze several "potential influences on the accuracy of estimating TC intensity over time due to increasing technology, methodology, knowledge and skill" for TCs that occurred off the coast of northwestern Australia, primarily in a band between 5 and 25°S, over the period 1968/69 to 2000/01.

The results of this research show, in the words of the four Australian researchers, that "a bias towards lower intensities likely exists in earlier (mainly pre-1980) TC central pressure deficit estimates of the order of at least 20 per cent in 1970, reducing to around ten per cent by 1980 and to five per cent in 1985," indicating "inferred temporal trends in the estimated intensity from the original data-sets are therefore significantly reduced in the objectively reviewed data-set." They conclude, "there is no prima facie evidence of a potential climate-change induced trend in TC intensity in northwestern Australia over the past 30 years."

Weighing in on the subject two years later were Song et al. (2010), who write, "in recent years, there has been increasing interest in whether global warming is enhancing tropical cyclone (TC) activity," as has been claimed by Emanuel (2005) and Webster et al. (2005). One of the main sources of contention over this matter has been the work of Wu et al. (2006) and Yeung (2006), who examined the best track data from the Regional Specialized Meteorological Center (RSMC), Tokyo, Japan, and of the Hong Kong Observatory of China (HKO). "In contrast to Webster et al. (2005)," as Song et al. describe it, these authors (Wu et al. and Yeung) found "there was no increase in category 4–5 typhoon activity in the western North Pacific [WNP] basin," and that "neither RSMC nor HKO best track data suggest an increase in TC destructiveness." They further state, "other studies also examined the differences in TC data sets from the Joint Typhoon Warning Center (JTWC) of the U.S. Naval Pacific Meteorology Oceanography Center in Hawaii, the RSMC, and the Shanghai Typhoon Institute (STI) of [the] China Meteorological Administration in Shanghai (Lei, 2001; Kamahori et al., 2006; Ott, 2006; Yu et al., 2007)," and they indicate, "so far, the reported trends in TC activity in the WNP basin have been detected mainly in the JTWC best track data set." This anomalous dataset was employed by Emanuel (2005) and Webster et al. (2005) in drawing their anomalous conclusions.

To help resolve the discrepancies exhibited by the JTWC typhoon database, Song et al. analyzed differences of track, intensity, frequency, and the associated long-term trends of those TCs that were simultaneously recorded and included within the best track data sets of the JTWC, the RSMC, and the STI from 1945 to 2007. In the words of the Chinese researchers, "though the differences in TC tracks among these data sets are negligibly small, the JTWC data set tends to classify TCs of category 2–3 as category 4–5, leading to an upward trend in the annual frequency of category 4–5 TCs and the annual accumulated power dissipation index, as reported by Webster et al. (2005) and Emanuel (2005)." They add "this trend and potential destructiveness over the period 1977–2007 are found only with the JTWC data set," and that actual downward trends "are apparent in the RSMC and STI data sets."

In light of the findings of Song et al., plus those of the other scientists they cite, there would appear to be little doubt that the studies of Emanuel (2005) and Webster et al. (2005), which the IPCC has hailed as proof of their claim that global warming leads to more intense tropical cyclones/hurricanes, actually provide no such evidence at all.

Concerns over the possibility of more frequent and more intense tropical cyclones for China were discussed in a contemporaneous study by Fengjin and Ziniu (2010). They note, "in 2006, meteorological disasters in China caused 3485 casualties and 25.2 billion yuan RMB in direct economic losses, of which TCs accounted for 30% of the total economic losses and 43% of the casualties." In an attempt to establish whether the past few decades give any indication of the alarmist expectations occurring any time soon, Fengjin and Ziniu used "data on the time and site of TC generation and landfall, TC tracks, and the intensity and duration of TCs in the Western North Pacific [WNP] and China during 1951–2008," which they obtained from the China Meteorological Administration, to analyze the characteristics of TCs that made landfall in China over that period.

According to the two researchers, the data indicate "a decreasing trend in the generation of TCs in the WNP since the 1980s" and "the number of TCs making landfall has remained constant or shown only a slight decreasing trend." They report "the number of casualties caused by TCs in China appears to show a slight decreasing trend," as would be expected under these less-dangerous circumstances. On the other hand, they find "the value of economic loss is increasing significantly," which they attribute to "the rapid economic development in China, particularly in TC-prone areas."

Working in the northwest Australian (NWAUS) sub-basin of the southeastern Indian Ocean (0–35°S, 105°–135°E), Goebbert and Leslie (2010) examined interannual TC variability over the 39-year time period 1970–2008, using the Woodside Petroleum Ltd. reanalysis TC dataset described by Harper et al. (2008), in order to focus on these two important TC characteristics (frequency and intensity), as well as 11 other TC metrics.

The two researchers found "no significant linear trends in either mean annual TC frequencies or TC days," and there was also "no trend in the number of intense TCs for the NWAUS sub-basin." In fact, they state, "none of the 13 NWAUS TC metrics exhibited statistically significant linear trends." In addition, they note, "known climate indices—such as Niño-3.4, Niño-4, SOI, NOI, PDO, NAO, and others—generally were found not to be significantly correlated to the variability of TC frequency or TC days in the NWAUS region." Once again, theoretical concerns are not supported by real-world data.

Examining hurricane trends in two ocean basins, Wang and Lee (2009) write that in the Western Hemisphere, tropical cyclones (TCs) "can form and develop in both the tropical North Atlantic (NA) and eastern North Pacific (ENP) Oceans, which are separated by the narrow landmass of Central America," and "in comparison with TCs in the NA, TCs in the ENP have received less attention although TC activity is generally greater in the ENP than in the NA (e.g., Maloney and Hartmann, 2000; Romero-Vadillo et al., 2007)." In exploring how the TC activities of the NA and ENP ocean basins might be related to each other over the period 1949–2007, as well as over the shorter period of 1979–2007, Wang and Lee employed several different datasets to calculate the index of accumulated cyclone energy (ACE), which accounts for the number, strength, and duration of all TCs in a given season.

The two U.S. scientists discovered "TC activity in the NA varies out-of-phase with that in the ENP on both *interannual* and *multidecadal* timescales," meaning "when TC activity in the NA increases (decreases), TC activity in the ENP decreases (increases)." They found "the out-of-phase relationship seems to [have] become stronger in the recent decades," as evidenced by interannual and multidecadal correlations between the NA and ENP ACE indices of -0.70 and -0.43, respectively, for the period 1949–2007, but -0.79 and -0.59, respectively, for the period 1979–2007.

Thus, in terms of the combined TC activity over the NA and ENP ocean basins as a whole, there is little variability on either interannual or multidecadal timescales, and real-world empirical data suggest the variability that does exist over the two basins has grown slightly weaker as the Earth has warmed over the past six decades. This, too, contradicts claims that hurricanes or tropical cyclones become more numerous, stronger, and longer-lasting as temperatures rise.

In another multiple-ocean-basin study focusing on five ocean basins—the Atlantic (1960–2007), the Western North Pacific (1960–2007), the Eastern North Pacific (1960–2007), the South Indian Ocean (1981–2007), and the South Pacific (1981–2007)—Chan (2009) examined the relationship between the seasonally averaged maximum potential intensity (MPI, an index of thermodynamic forcing) over each basin where TCs typically form and the seasonal frequency of occurrence of intense TCs.

The results of this work indicated "only in the Atlantic does the MPI have a statistically significant relationship with the number of intense TCs, explaining about 40% of the [observed] variance," whereas "in other ocean basins, there is either no correlation or the correlation is not significant." Moreover, "even in the Atlantic, where a significant correlation between the thermodynamic [temperature-related] factors and the frequency of intense TCs exists," the Chinese researcher states, "it is not clear whether global warming will produce a net increase in such a frequency, because model projections suggest an increase in vertical wind shear associated with an increase in sea surface temperature," and this phenomenon tends to inhibit intense TC development. He concludes, "it remains uncertain whether the frequency of occurrence of intense TCs will increase under a global warming scenario."

Finally, Wang et al. (2010) examined the impact of the rising sea surface temperature (SST) on tropical cyclone activity, noting, "with the observed warming of the tropics of around 0.5°C over the past four to five decades, detecting the observed change in the TC activity may shed light on the impact of the global warming on TC activity."

Wang et al. examined cross-basin spatial-temporal variations of TC storm days for the Western North Pacific (WNP), the Eastern North Pacific (ENP), the North Atlantic (NAT), the North Indian Ocean (NIO), and the Southern Hemisphere Ocean (SHO) over the period 1965–2008, for which time interval pertinent satellite data were obtained from the U.S. Navy's Joint Typhoon Warning Center for the WNP, NIO and SHO, and from the U.S. NASA's National Hurricane Center for the NAT and ENP.

The five researchers report, "over the period of 1965–2008, the global TC activity, as measured by storm days, shows a large amplitude fluctuation regulated by the El Niño-Southern Oscillation and the Pacific Decadal Oscillation, but has no trend, suggesting that the rising temperature so far has not yet [had] an impact on the global total number of storm days." This implies "the spatial variation of SST, rather than the global mean temperature, may be more relevant to understanding the change of the global storm days."

In conclusion, four decades of data and the many studies discussed here conclusively disprove the claim that global warming increases tropical storm activity on a global basis.

References

Bender, M.A., Knutson, T.R., Tuleya, R.E., Sirutis, J.J., Vecchi, G.A., Garner, S.T., and Held, I.M. 2010. Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes. *Science* **327**: 454–458.

Chan, J.C.L. 2009. Thermodynamic control on the climate of intense tropical cyclones. *Proceedings of the Royal Society A* **465**: 3011–3021.

Chylek, P. and Lesins, G. 2008. Multidecadal variability of Atlantic hurricane activity: 1851–2007. *Journal of Geophysical Research* **113**: 10.1029/2008JD010036.

Emanuel, K.E. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* **436**: 686–688.

Fan, D. and Liu, K.-b. 2008. Perspectives on the linkage between typhoon activity and global warming from recent research advances in paleotempestology. *Chinese Science Bulletin* **53**: 2907–2922.

Fengjin, X. and Ziniu, X. 2010. Characteristics of tropical cyclones in China and their impacts analysis. *Natural Hazards* **54**: 827–837.

Goebbert, K.H. and Leslie, L.M. 2010. Interannual variability of Northwest Australian tropical cyclones. *Journal of Climate* **23**: 4538–4555.

Harper, B.A., Stroud, S.A., McCormack, M., and West, S. 2008. A review of historical tropical cyclone intensity in northwestern Australia and implications for climate change trend analysis. *Australian Meteorological Magazine* **57**: 121–141.

Holland, G.J. and Webster, P.J. 2007. Heightened tropical cyclone activity in the North Atlantic: natural variability or climate trend? *Philosophical Transactions of the Royal Society of London, Series A*: 10.1098/rsta.2007.2083.

Idso, C.D. and Singer, S.F. 2009. Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC). Chicago, IL: The Heartland Institute.

IPCC. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by S. Solomon et al. Cambridge, UK: Cambridge University Press.

Kamahori, H., Yamazaki, N., Mannoji, N., and Takahashi, K. 2006. Variability in intense tropical cyclone days in the western North Pacific. *SOLA* **2**: 104–107.

Kerr, R.A. 2010. Models foresee more-intense hurricanes in the greenhouse. *Science* **327**: 399.

Klotzbach, P.J. 2006. Trends in global tropical cyclone activity over the past twenty years (1986–2005). *Geophysical Research Letters* **33**: 10.1029/2006GL025881.

Klotzbach, P.J. and Gray, W.M. 2008. Multidecadal variability in North Atlantic tropical cyclone activity. *Journal of Climate* **21**: 3929–3935.

Kossin, J.P., Knapp, K.R., Vimont, D.J., Murnane, R.J., and Harper, B.A. 2007. A globally consistent reanalysis of hurricane variability and trends. *Geophysical Research Letters* **34**: 10.1029/2006GL028836.

Landsea, C.W. 2005. Hurricanes and global warming. *Nature* **438**: E11–E13.

Landsea, C.W., Harper, B.A., Hoarau, K., and Knaff, J.A. 2006. Can we detect trends in extreme tropical cyclones? *Science* **313**: 252–254.

Landsea, C.W., Vecchi, G.A., Bengtsson, L., and Knutson, T.R. 2009. Impact of duration thresholds on Atlantic tropical cyclone counts. *Journal of Climate* **23**: 2508–2519.

Lei, X. 2001. The precision analysis of the best positioning on WNP TC. *Journal of Tropical Meteorology* **17**: 65–70.

Maloney, E.D. and Hartmann, D.L. 2000. Modulation of eastern North pacific hurricanes by the Madden-Julian Oscillation. *Journal of Climate* **13**: 1451–1460.

Mann, M.E., Bradley, R.S., and Hughes, M.K. 1998. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* **392**: 779–787.

Mann, M.E., Bradley, R.S., and Hughes, M.K. 1999. Northern Hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.

Mann, M.E. and Jones, P.D. 2003. Global surface temperatures over the past two millennia. *Geophysical Research Letters* **30**: 10.1029/2003GL017814.

Mann, M.E., Woodruff, J.D., Donnelly, J.P., and Zhang, Z. 2009. Atlantic hurricanes and climate over the past 1,500 years. *Nature* **460**: 880–883.

Nyberg, J., Malmgren, B.A., Winter, A., Jury, M.R., Kilbourne, K.H., and Quinn, T.M. 2007. Low Atlantic hurricane activity in the 1970s and 1980s compared to the past 270 years. *Nature* **447**: 698–701.

Ott, S. 2006. Extreme winds in the Western North Pacific. *Rep. Rise-R-1544(EN)*, Riso National Laboratory, Technical University of Denmark, Copenhagen.

Pielke, R.A. 2005. Are there trends in hurricane destruction? *Nature* **438**: E11.

Romero-Vadillo, E., Zaytsev, O., and Morales-Perez, R. 2007. Tropical cyclone statistics in the northeastern Pacific. *Atmosfera* **20**: 197–213.

Solow, A.R. and Moore, L.J. 2002. Testing for trend in North Atlantic hurricane activity, 1900–98. *Journal of Climate* **15**: 3111–3114.

Song, J.-J., Wang, Y., and Wu, L. 2010. Trend discrepancies among three best track data sets of western North Pacific tropical cyclones. *Journal of Geophysical Research* **115**: 10.1029/2009JD013058.

Vecchi, G.A., Swanson, K.L., and Soden, B.J. 2008. Whither hurricane activity? *Science* **322**: 687–689.

Wallace, D.J. and Anderson, J.B. 2010. Evidence of similar probability of intense hurricane strikes for the Gulf of Mexico over the late Holocene. *Geology* **38**: 511–514.

Wang, B., Yang, Y., Ding, Q.-H., Murakami, H., and Huang, F. 2010. Climate control of the global tropical storm days (1965–2008). *Geophysical Research Letters* **37**: 10.1029/2010GL042487.

Wang, C. and Lee, S.-K. 2009. Co-variability of tropical cyclones in the North Atlantic and the eastern North Pacific. *Geophysical Research Letters* **36**: 10.1029/2009GL041469.

Webster, P.J., Holland, G.J., Curry, J.A., and Chang, H.-R. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* **309**: 1844–1846.

Wu, M.-C., Yeung, K.-H., and Chang, W.-L. 2006. Trends in western North Pacific tropical cyclone intensity. *EOS, Transactions, American Geophysical Union* **87**: 537–538.

Yeung, K.H. 2006. Issues related to global warming—myths, realities and warnings. Paper presented at the 5th Conference on Catastrophe in Asia, Hong Kong Observatory, Hong Kong, China, 20-21 June.

Yu, H., Hu, C., and Jiang, L. 2007. Comparison of three tropical cyclone intensity datasets. *Acta Meteorologica Sinica* **21**: 121–128.

5.6. Fire

According to model-based predictions, CO_2-induced global warming will cause larger and more intense wildfires. Girardin et al. (2009), for example, write, "in boreal forests, climate change may act upon fuels through increased evapotranspiration not compensated for by increasing precipitation, or increased frequency of extreme drought years due to more persistent and frequent blocking high-pressure systems," both of which phenomena are typically predicted to lead to more and larger wildfires. In addition, they state, "earlier snowmelt and longer summer droughts with climate change [i.e., warming] could also expose forests to higher wildfire risk."

To explore this possibility, Girardin et al. investigated "changes in wildfire risk over the 1901–2002 period with an analysis of broad-scale patterns of drought variability on forested eco-regions of the North American and Eurasian continents." The seven scientists report their analyses "did not reveal widespread patterns of linear increases in dryness through time as a response to rising Northern Hemisphere temperatures." Instead, they "found heterogeneous patterns of drought severity changes that were inherent to the non-uniformly distributed impacts of climate change on dryness." In addition, they note, "despite warming since about 1850 and increased incidence of large forest fires in the 1980s, a number of studies indicated a decrease in boreal fire activity in the last 150 years or so (e.g. Masters, 1990; Johnson and Larsen, 1991; Larsen, 1997; Lehtonen and Kolstrom, 2000; Bergeron et al., 2001, 2004a,b; Mouillot and Field, 2005)." And they state "this holds true for boreal southeastern Canada, British Columbia, northwestern Canada and Russia."

With respect to this long-term "diminishing fire activity," as they describe it, Girardin et al. state, "the spatial extent for these long-term changes is large enough to suggest that climate is likely to have played a key role in their induction." Interestingly, that role would appear to be one of *reducing* fire activity, just the opposite of what the IPCC contends should occur. To emphasize that point and provide still more evidence for it, they state, "the fact that diminishing fire activity has also been detected on lake islands on which fire suppression has never been conducted provides another argument in support of climate control" over the incidence of fires.

Working on a much smaller geographical scale, Turner et al. (2008) analyzed micro-charcoal, pollen, and stable oxygen isotope ($\delta^{18}O$) data from sediment cores extracted from two crater lake basins in central Turkey, from which they reconstructed synchronized fire, vegetation, and climate histories extending back more than 15,000 years. Based on this analysis, the authors determined "climatically-induced variation in biomass availability was the main factor controlling the timing of regional fire activity during the Last Glacial-Interglacial climatic transition, and again during Mid-Holocene times, with fire frequency and magnitude increasing during wetter climatic phases." In addition, spectral analysis of the Holocene part of the record "indicates significant cyclicity with a periodicity of ~1500 years that may be linked with large-scale climate forcing."

Likewise working on a small geographical scale in a drainage basin located in southeastern Arizona (USA) and northeastern Sonora (Mexico), Brunelle et al. (2010) collected sediments during the summers of 2004 and 2005 from the incised channel wall of the Rio de San Bernardino arroyo and the *cienega* (a wet, marshy area where groundwater bubbles to the surface) surface of the San Bernardino National Wildlife Refuge, from which samples were taken, as they describe it, "for charcoal analysis to reconstruct fire history," as well as pollen data to infer something about climate.

The U.S. and Mexican researchers say "preliminary pollen data show taxa that reflect winter-dominated precipitation [which implies summer drought] correspond to times of greater fire activity." The results from the fire reconstruction "show an increase in fire activity coincident with the onset of ENSO, and an increase in fire frequency during the Medieval Climate Anomaly." During this latter period, from approximately AD 900 to 1260, "background charcoal reaches the highest level of the entire record and fire peaks are frequent," after which they state, "the end of the MCA shows a decline in both background charcoal and fire frequency, likely associated with the end of the MCA-related drought in western North America (Cook et al., 2004)."

With respect to the future, Brunelle et al. forecast that if the region of their study warms, "the role of fire in the desert grasslands is likely to change," such that "warming and the continuation of ENSO variability will likely increase fire frequency (similar to the MCA) while extreme warming and the shift to a persistent El Niño climate would likely lead to the absence of fires, similar to >5000 cal yr BP." Consequently, it would appear that the region of their study is not yet as warm as it was during the MCA, and if the region's temperature ever were to significantly eclipse that of the MCA, the frequency of wildfires there could drop to a barely noticeable level.

Moving further west and north, Beaty and Taylor (2009) developed a 14,000-year record of fire frequency based on high-resolution charcoal analysis of a 5.5-m-long sediment core extracted from Lily Pond (39°3'26"N, 120°7'21"W) in the General Creek Watershed on the west shore of Lake Tahoe in the northern Sierra Nevada in California (USA), as well as a 20-cm-long surface core that "preserved the sediment-water interface."

The results of this effort indicated "fire episode frequency was low during the Lateglacial period but increased through the middle Holocene to a maximum frequency around 6500 cal. yr BP," which "corresponded with the Holocene temperature maximum (7000–4000 cal. yr BP)." Thereafter, as the temperature gradually declined, so too did fire frequency decline, except for a multi-century aberration they describe as "a similar peak in fire episode frequency [that] occurred between c. 1000 and 600 cal. yr BP during the 'Medieval Warm Period'." This, they write, was followed by an interval "between c. 500 and 200 cal. yr BP with few charcoal peaks [that] corresponded with the so-called 'Little Ice Age'." Regarding the present, they found the "current fire episode frequency on the west shore of Lake Tahoe is at one of its lowest points in at least the last 14,000 years."

As for the future, the two researchers state, "given the strong relationship between climate and fire episode frequency, warming due to increased levels of greenhouse gases in the atmosphere may increase fire episode frequency to levels experienced during the 'Medieval Warm Period'," which is saying a lot since the part of the planet they studied is currently experiencing one of the lowest levels of fire frequency of the last 14,000 years.

Approaching the subject from a different angle were McAneney et al. (2009), who assembled a much different database for evaluating the global warming/fire relationship in Australia. Their primary source of information for their study was "Risk Frontiers' disaster database of historic building losses—PerilAUS—which provides a reasonably faithful testimony of national building losses from 1900," with additional information being provided by the Insurance Council of Australia's database of significant insured losses. The three researchers noted "the annual aggregate numbers of buildings destroyed by bushfire since 1926 ... is 84," but "most historical losses have taken place in a few extreme fires." They state "the most salient result is that the annual probability of building destruction has remained almost constant over the last century," even in the face of "large demographic and social changes as well as improvements in fire fighting technique and resources."

They find: (1) "the historical evidence shows no obvious trend," (2) "the likelihood of losing homes to bushfire has remained remarkably stable over the last century with some building destruction expected in around 55% of years," (3) "this same stability is also exhibited for the bigger events with an annual probability of losing more than 25 or 100 homes in a single week remaining around 40% and 20% respectively," and (4) "the statistics on home destruction have remained obstinately invariant over time." What is more, McAneney et al. note "Australia's population has increased from around 4 to 20 million over the last century," and therefore we might logically have expected "the likelihood of bushfire losses to have increased with population or at least with the population living immediately adjacent to bushlands." However, their data clearly reveal it "is not so."

Given these findings, McAneney et al. conclude in the final sentence of their paper's abstract, "despite predictions of an increasing likelihood of conditions favoring bushfires under global climate change, we suspect that building losses due to bushfires are unlikely to alter materially in the near future."

Finally, Marlon et al. (2008) examined the subject on a global scale and report, "large, well-documented wildfires have recently generated worldwide attention, and raised concerns about the impacts of humans and climate change on wildfire regimes," noting "climate-change projections indicate that we will be moving quickly out of the range of the natural variability of the past few centuries."

To see what the global wildfire "range of natural variability" actually has been, Marlon et al. used "sedimentary charcoal records spanning six continents to document trends in both natural and anthropogenic biomass burning [over] the past two millennia." The international team of researchers reports "global biomass burning declined from AD 1 to ~1750, before rising sharply between 1750 and 1870," after which it "declined abruptly." In attributing the cause of these variations, the researchers state the initial long-term decline in global biomass burning was due to "a long-term global cooling trend," and they suggest the rise in fires that followed was "linked to increasing human influences." With respect to the final decline in fires after 1870, however, they note it occurred "despite increasing air temperatures and population." As for what may have overpowered the tendency for increased global wildfires that "normally" would have been expected to result from the global warming of the transition from the Little Ice Age to the Current Warm Period, the nine scientists attribute the "reduction in the amount of biomass burned over the past 150 years to the global expansion of intensive grazing, agriculture and fire management."

In conclusion, in spite of evidence from prior centuries that global warming may have had a tendency to promote wildfires on a global basis (since global cooling had a tendency to reduce them), technological developments during the industrial age appear to have overpowered this natural tendency, leading to a decrease in global wildfires over the past century and a half.

References

Beaty, R.M. and Taylor, A.H. 2009. A 14,000-year sedimentary charcoal record of fire from the northern Sierra Nevada, Lake Tahoe Basin, California, USA. *The Holocene* **19**: 347–358.

Bergeron, Y., Flannigan, M., Gauthier, S., Leduc, A., and Lefort, P. 2004a. Past, current and future fire frequency in the Canadian boreal forest: Implications for sustainable forest management. *Ambio* **33**: 356–360.

Bergeron, Y., Gauthier, S., Flannigan, M., and Kafka, V. 2004b. Fire regimes at the transition between mixedwood and coniferous boreal forest in northwestern Quebec. *Ecology* **85**: 1916–1932.

Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P., and Lesieur, D. 2001. Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. *Canadian Journal of Forest Research* **31**: 384–391.

Brunelle, A., Minckley, T.A., Blissett, S., Cobabe, S.K., and Guzman, B.L. 2010. A ~8000 year fire history from an Arizona/Sonora borderland cienega. *Journal of Arid Environments* **24**: 475–481.

Cook, E.R., Woodhouse, C., Eakin, C.M., Meko, D.M., and Stahle, D.W. 2004. Long-term aridity changes in the western United States. *Science* **306**: 1015–1018.

Girardin, M.P., Ali, A.A., Carcaillet, C., Mudelsee, M., Drobyshev, I., Hely, C., and Bergeron, Y. 2009. Heterogeneous response of circumboreal wildfire risk to climate change since the early 1900s. *Global Change Biology* **15**: 2751–2769.

Johnson, E.A. and Larsen, C.P.S. 1991. Climatically induced change in fire frequency in the southern Canadian Rockies. *Ecology* **72**: 194–201.

Larsen, C.P.S. 1997. Spatial and temporal variations in boreal forest fire frequency in northern Alberta. *Journal of Biogeography* **24**: 663–673.

Lehtonen, H. and Kolstrom, T. 2000. Forest fire history in Viena Karelia, Russia. *Scandinavian Journal of Forest Research* **15**: 585–590.

Marlon, J.R., Bartlein, P.J., Carcaillet, C., Gavin, D.G., Harrison, S.P., Higuera, P.E., Joos, F., Power, M.J., and Prentice, I.C. 2008. Climate and human influences on global biomass burning over the past two millennia. *Nature Geoscience* **1**: 697–702.

Masters, A.M. 1990. Changes in forest fire frequency in Kootenay National Park, Canadian Rockies. *Canadian Journal of Botany* **68**: 1763–1767.

McAneney, J., Chen, K. and Pitman, A. 2009. 100-years of Australian bushfire property losses: Is the risk significant and is it increasing? *Journal of Environmental Management* **90**: 2819–2822.

Mouillot, F. and Field, C.B. 2005. Fire history and the global carbon budget: a 1° x 1° fire history reconstruction for the 20th century. *Global Change Biology* **11**: 398–420.

Turner, R., Roberts, N., and Jones, M.D. 2008. Climatic pacing of Mediterranean fire histories from lake sedimentary microcharcoal. *Global and Planetary Change* **63**: 317–324.

5.7. Other Weather-Related Events

In this section we discuss other weather-related events not addressed in earlier sections of this chapter.

5.7.1. Debris Flows

Authors Bollschweiler and Stoffel (2010) note it has been suggested global warming may increase the frequency of extreme precipitation events and, therefore, may increase the occurrence of natural mass-movement processes such as debris flows in mountainous regions. In fact, they state in regard to this particular phenomenon that there is a “widely accepted assumption that climatic changes will univocally lead to an increase in event frequency.”

In a study designed to explore this question, Bollschweiler and Stoffel developed a history of debris-flow frequencies for eight different areas in the Zermatt Valley—a dry inner-alpine valley of the Valais Alps (Switzerland, with central coordinates of 46°10’N, 47°7’E)—based on data obtained from “tree-ring series of affected conifers and complemented, where available, with data from local archives,” which entailed the sampling of 2,467 individual trees that had been affected by debris-flow activity in order to obtain 4,491 pertinent increment cores.

The two Swiss scientists found there were peaks in debris-flow activity “toward the end of the Little Ice Age and in the early twentieth century when warm-wet conditions prevailed during summers in the Swiss Alps,” but they also observed “a considerable decrease in frequency over the past decades which results from a decrease in the frequency of triggering precipitation events.” Most importantly, they report that when longer-term changes were sought, they could not identify “any significant trends in the debris-flow series between 1850 and 2009.”

In discussing their real-world debris-flow results, Bollschweiler and Stoffel say they “contradict the widely accepted assumption that climatic changes will univocally lead to an increase in event frequency.” They then note their findings “are in concert with data from Jomelli et al. (2007), indicating that the most recent past (2000–2009) represents the period with the lowest frequency of debris-flow events since AD 1900,” even though the intervening century presumably experienced what the IPCC calls global warming unprecedented in the past millennium or more.

References

Bollschweiler, M. and Stoffel, M. 2010. Changes and trends in debris-flow frequency since AD 1850: results from the Swiss Alps. *The Holocene* **20**: 907–916.

Jomelli, V., Brunstein, D., Grancher, D.M and Pech, P. 2007. Is the response of hill slope debris flows to recent climate change univocal? A case study in the Massif des Ecrins (French Alps). *Climatic Change* **85**: 119–137.

5.7.2. Financial Losses Due to Extreme Weather Events

If global warming causes more frequent and more extreme bad weather, it also could increase the loss of human life and hardship due to hurricanes, floods, landslides, etc. Monetary losses due to extreme weather events have been trending upwards over the past several decades, a fact that mistakenly has been taken to be proof that global warming has been causing real harms to human well-being. However, several factors make these trends misleading and the conclusion wrong.

As the population and the economy grow, loss of life and property increase even if storm intensity and frequency remain the same. It also has been shown that increased wealth in a country like the United States has led to disproportionately increased development in places most likely to be hit by tropical storms: e.g., the U.S. Southeast coastal zone. Inflation also must be taken into account. The standard approach for dealing with these factors is to correct (normalize) for them by adjusting for inflation and by accounting for increases in population and wealth.

Bouwer (2010) conducted a meta-analysis based on 22 studies from around the world that had previously analyzed losses due to storms, tornados, floods, landslides, and other weather, seeking to determine if (1) proper normalization had been done, (2) how much of the effect was removed by normalization, and (3) whether extraneous factors—such as deforestation causing increased flood risk—could explain any remaining trends. The meta-analysis concluded the following: "All 22 studies show that increases in exposure and wealth are the most important drivers for growing disaster losses. Most studies show that disaster losses have remained constant after normalization, including losses from earthquakes (see Vranes and Pielke 2009). Studies that did find increases after normalization did not fully correct for wealth or population increases, or identified other sources of exposure increases or vulnerability changes, or changing environmental conditions. *No study identified changes in extreme weather due to anthropogenic climate change as the main driver for any remaining trend*" [emphasis added].

Reference

Bouwer, L.M. 2010. Have disaster losses increased due to anthropogenic climate change? *Bulletin of the American Meteorological Society* doi: 10.1175/2010BAMS3092.1.

Vranes, K., and R. A. Pielke Jr. 2009: Normalized earthquake damage and fatalities in the United States: 1900–2005. *Natural Hazards Review* **10,** 84–101.

5.7.3. Heat Waves

Jeong et al. (2010) note modeling studies in the IPCC AR4 suggest future heat waves over Europe will be more severe, longer-lasting, and more frequent than those of the recent past, due largely to an intensification of quasi-stationary anticyclone anomalies accompanying future warming. They cite in support of this statement the publications of Meehl and Tebaldi (2004) and Della-Marta et al. (2007).

In conducting their own analysis of the subject, Jeong et al. investigated "the impact of vegetation-climate feedback on the changes in temperature and the frequency and duration of heat waves in Europe under the condition of doubled atmospheric CO_2 concentration in a series of global climate model experiments." Land surface processes were calculated by the Community Land Model (version 3) described by Oleson et al. (2004), which includes a modified version of the Lund-Potsdam-Jena scheme for computing vegetation establishment and phenology for specified climate variables.

The calculations performed by the six scientists indicated "the projected warming of 4°C over most of Europe with static vegetation has been reduced by 1°C as the dynamic vegetation feedback effects are included" and "examination of the simulated surface energy fluxes suggests that additional greening in the presence of vegetation feedback effects enhances evapotranspiration and precipitation, thereby limiting the warming, particularly in the daily maximum temperature." In addition, they state, "the greening also tends to reduce the frequency and duration of heat waves."

Although Jeong et al.'s findings by no means constitute the final word on the climatic consequences of a doubling of the air's CO_2 content, they indicate just how easily the incorporation of a new suite of knowledge, in even the best climate models of the day, can dramatically alter what the IPCC and some individual scientists purport to be reality.

References

Della-Marta, P.M., Luterbacher, J., von Weissenfluh, H., Xoplaki, E., Brunet, M., and Wanner, H. 2007. Summer heat waves over western Europe 1880–2003, their relationship to large-scale forcings and predictability. *Climate Dynamics* **29**: 251–275.

Jeong, S.-J., Ho, C.-H., Kim, K.-Y., Kim, J., Jeong, J.-H., and Park, T.-W. 2010. Potential impact of vegetation feedback on European heat waves in a 2 x CO_2 climate. *Climatic Change* **99**: 625–635.

Meehl, G.A. and Tebaldi, C. 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. *Science* **305**: 994–997.

Oleson, K.W. et al. 2004. *Technical Description of the Community Land Model (CLM)*. Technical Note NCAR/TN-461+STR, 174p.

6

Terrestrial Animals

6. Terrestrial Animals

Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), “new evidence suggests that climate-driven extinctions and range retractions are already widespread” and the “projected impacts on biodiversity are significant and of key relevance, since global losses in biodiversity are irreversible (very high confidence)” (IPCC-II, 2007, p. 213). The IPCC claims that “globally about 20% to 30% of species (global uncertainty range from 10% to 40%, but varying among regional biota from as low as 1% to as high as 80%) will be at increasingly high risk of extinction, possibly by 2100, as global mean temperatures exceed 2 to 3°C above pre-industrial levels” (ibid.).

The Nongovernmental International Panel on Climate Change (NIPCC) disagreed. According to Idso and Singer (2009), “These claims and predictions are not based on what is known about the phenomenon of extinction or on real-world data about how species have endured the warming of the twentieth century, which the IPCC claims was unprecedented in the past two millennia” (p. 579).

The basis of the IPCC’s forecasts is an assumption that the increase in temperature predicted to result from the ongoing rise in the atmosphere’s CO_2 concentration will be so fast and of such great magnitude that many animal species will not be able to migrate poleward in latitude or upward in elevation rapidly enough to avoid extinction. In this chapter we review new research that contradicts this assumption as well as extensive observational data that contradict the claim of impending species extinctions.

References

Idso, C.D. and Singer, S.F. 2009. *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

IPCC. 2007-II. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.D. Hanson. (Eds.) Cambridge University Press, Cambridge, UK.

6.1. Problems with Model-based Predictions of Extinctions

Thomas et al. (2004) developed projections of future habitat distributions for more than a thousand plant and animal species. Using those projections, they produced estimates of extinction probabilities associated with climate change scenarios for the year 2050 that were promoted by the Intergovernmental Panel on Climate Change (IPCC, 2007). Their ominous projections (the annihilation of more than a million unique species if anthropogenic CO_2 emissions were not quickly and dramatically reduced) were widely disseminated to the popular media even before the research was published, and they were typically portrayed as well-founded scientific predictions of what was bound to occur.

The 19 scientist-authors of the paper began their analysis by determining the "climate envelopes" of 1,103 species. Each of these envelopes represented the current climatic conditions under which a given species was found in nature. Then, after seeing how the habitat area of each of the studied species would be expected to change in response to an increase in temperature, they used an empirical power-law relationship that relates species number to habitat area size to determine extinction probability calculations.

At first blush, this procedure seems reasonable enough, all else being equal. But "all else" is almost always not equal when something changes in the real world. An entirely different analysis of the available data was provided by Stockwell (2004), who noted, for example, that Thomas et al.'s approach to the issue "ignores species that are currently threatened with extinction by non-climatic factors, and which could therefore benefit from an expanded potential habitat and so escape extinction in the new CO_2/climate regime."

As Stockwell described it, "a CO_2- or climate-driven range expansion would clearly help species that are threatened with extinction due to increasing habitat loss attributable to expanding urbanization and agricultural activities; while it may help other species that are threatened with extinction by habitat fragmentation to cross geographical barriers that were previously insurmountable obstacles to them." Consequently, he continued, "by neglecting the many species that fall into these and other like categories, no decrease in extinctions is possible under Thomas et al.'s approach to the problem, even under [a] free dispersal scenario, with the result that a massive increase in extinctions is a foregone conclusion."

Stockwell further noted, "the no dispersal scenario also forces an unrealistic decrease in range with any climatic change that shifts habitat area without reducing it; while 'overfitting' reduces ranges even more, producing systematic errors on the order of 10-20%, particularly with smaller data sets, deficiencies in data sampling and modeling methods, and the inclusion of irrelevant variables (Stockwell and Peterson 2002a, 2002b, 2003)." With respect to the study of Bakkenes et al. (2002), for example, Stockwell wrote, "two independent climate variables adequately explain 93% of the variation in their dependent variable; while the use of more climate variables ends up incorporating more random variation than it does actual signal, leading to a contraction of the climate envelope and a systematic bias towards smaller predicted ranges." It should come as no surprise, therefore, as Stockwell continued, "that in this study and that of Peterson et al. (2002)—which comprise two of the six major studies on which the analysis of Thomas et al. is based—the use of only two climate variables by the two studies yields extinction percentages of 7% and 9%, while the four additional studies upon which Thomas et al. rely (which use from 3 to 36 independent variables) yield extinction percentages ranging from 20% to 34%, consistent with what would be expected from errors associated with statistical over-fitting."

Because ecological models are so unreliable for reasons cited by Stockwell, the common-sense response should be to attempt to verify model-based projects with independent data. However, in the words of Stockwell, "their single attempt to do so with a real-world extinction supposedly caused by global warming (Pounds et al., 1999) has been satisfactorily explained by changes in local weather patterns due to upwind deforestation of adjacent lowlands (Lawton et al., 2001)." Stockwell concluded, "Thomas et al. have a dearth of pertinent hard data to support their contentions; and while the absence of evidence does not necessarily disprove a claim, the lack of any real extinction data to support the results of their analysis certainly suggests that the models they are using are not 'tried and true'."

Stockwell's final thoughts on the matter, therefore, were, "Thomas et al. (2004) seek to create the impression of impending ecological disaster due to CO_2-induced global warming, claiming their results justify mandating reductions of greenhouse gas emissions," but their findings "are forced by the calculations, confounded with statistical bias, lack supporting real-world evidence, and are perforated with speculation." Stockwell concludes "their doctrine of 'massive extinction' is actually a case of 'massive extinction *bias*'."

In another critique of the Thomas et al. paper, Dormann (2007) found it important to "review the main shortcomings of species distribution models and species distribution projections" such as those employed and derived by Thomas et al. In doing so, he carefully analyzed three aspects of what he described as "problems associated with species distribution models."

The first of these aspects is general species distribution model issues, under which Dormann listed four major problems. The second is extrapolation issues, where he found five major problems; and the third is statistical issues, where he listed six major problems. The methods employed and findings claimed by studies such as Thomas et al., Dormann writes, "have been challenged for conceptual and statistical reasons" by many other researchers, including Buckley and Roughgarden, 2004; Harte et al., 2004; Thuiller et al., 2004; Lewis, 2006; and Botkin et al., 2007. Dormann thus concluded, "projections of species distributions are not merely generating hypotheses to be tested by later data" but instead are being presented as "predictions of tomorrow's diversity, and policy makers and the public will interpret them as forecasts, similar to forecasts about tomorrow's weather," which he clearly believes is unwarranted and unwise.

Nogues-Bravo (2009) noted climate envelope models—which are often employed to predict species responses to global warming—"are sensitive to theoretical assumptions, to model classes and to projections in non-analogous climates, among other issues." Against this backdrop, the researcher reviewed the pertinent scientific literature to determine how appropriate existing models were for determining whether a species will be driven to extinction by hypothesized planetary warming.

In the researcher's own words, "the studies reviewed: (1) rarely test the theoretical assumptions behind niche modeling such as the stability of species climatic niches through time and the equilibrium of species with climate; (2) they only use one model class (72% of the studies) and one palaeoclimatic reconstruction (62.5%) to calibrate their models; (3) they do not check for the occurrence of non-analogous climates (97%); and (4) they do not use independent data to validate the models (72%)."

According to Nogues-Bravo, "ignoring the theoretical assumptions behind niche modeling and using inadequate methods for hindcasting" may well produce "a cascade of errors and naïve ecological and evolutionary inferences." He concludes, "there are a wide variety of challenges that [climate envelope models] must overcome in order to improve the reliability of their predictions through time."

In conclusion, it is clear that model-based projections of extinctions are riddled with assumptions and limitations that make them an unreliable guide to the actual impact of climate change on species. As Dormann (2007) concluded, the shortcomings associated with analyses of the impact of climate on distributions of species "are so numerous and fundamental that common ecological sense should caution us against putting much faith in relying on their findings for further extrapolations."

References

Bakkenes, M., Alkemade, J.R.M., Ihle, F., Leemans, R., and Latour, J. B. 2002. Assessing effects of forecasted climate change on the diversity and distribution of European higher plants for 2050. *Global Change Biology* **8**: 390–407.

Botkin, D.B., Saxe, H., Araújo, M.B., Betts, R., Bradshaw, R.H.W., Cedhagen, T., Chesson, P., Dawson, T.P., Etterson, J.R., Faith, D.P., Ferrier, S., Guisan, A., Skjoldborg Hansen, A., Hilbert, D.W., Loehle, C., Margules, C., New, M., Sobel, M.J., and Stockwell, D.R.B. 2007. Forecasting the effects of global warming on biodiversity. *BioScience* **57:** 227–236.

Buckley, L. B. and Roughgarden, J. 2004. Biodiversity conservation: Effects of changes in climate and land use change. *Nature* **430**: 10.1038/nature02717.

Dormann, C.F. 2007. Promising the future? Global change projections of species distributions. *Basic and Applied Ecology* **8**: 387–397.

Harte, J., Ostling, A., Green, J.L., and Kinzig, A. 2004. Biodiversity conservation: Climate change and extinction risk. *Nature* **430**: 10.1038/nature02718.

IPCC, 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Edited by M.L. Parry, et al. Cambridge, UK: Cambridge University Press.

Lawton, R.O., Nair, U.S., Pielke Sr., R.A., and Welch, R.M. 2001. Climatic impact of tropical lowland deforestation on nearby montane cloud forests. *Science* **294**: 584–587.

Lewis, O.T. 2006. Climate change, species-area curves and the extinction crisis. *Philosophical Transactions of the Royal Society B* **361:** 163–171.

Nogues-Bravo, D. 2009. Predicting the past distribution of species climatic niches. *Global Ecology and Biogeography* **18**: 521–531.

Peterson, A.T., Ortega-Heuerta, M.A., Bartley, J., Sánchez-Cordero, V., Soberón, J., Buddemeier, R.H., and Stockwell, D.R.B. 2002. Future projections for Mexican faunas under global climate change scenarios. *Nature* **416**: 626–629.

Pounds, J.A., Fogden, M.P.L., and Campbell, J.H. 1999. Biological response to climate change on a tropical mountain. *Nature* **398**: 611–615.

Stockwell, D.R.B. 2004. *Biased Towards Extinction*. Guest Editorial, *CO_2 Science* **7** (19): http://www.co2science.org/articles/V7/N19/EDIT.php.

Stockwell, D.R.B. and Peterson, A.T. 2002a. Controlling bias during predictive modeling with museum data. In *Predicting Species Occurrences: Issues of Scale and Accuracy*. Edited by J.M. Scott et al. Covello, CA: Island Press.

Stockwell, D.R.B. and Peterson, A.T. 2002b. Effects of sample size on accuracy of species distribution models. *Ecological Modelling* **148**: 1–13.

Stockwell, D.R.B. and Peterson, A.T. 2003. Comparison of resolution of methods for mapping biodiversity patterns from point-occurrence data. *Ecological Indicators* **3**: 213–221.

Thuiller, W., Araújo, M.B., Pearson, R.G., Whittaker, R.J., Brotons, L., and Lavorel, S. 2004. Biodiversity conservation: Uncertainty in predictions of extinction risk. *Nature* **430**: 10.1038/nature02716.

Thomas, C.D., Cameron, A., Green, R.E., Bakkenes, M., Beaumont, L.J., Collingham, Y.C., Erasmus, B.F.N., Ferreira de Siqueira, M., Grainger, A., Hannah, L., Hughes, L., Huntley, B., van Jaarsveld, A.S., Midgley, G.F., Miles, L., Ortega-Huerta, M.A., Peterson A.T., Phillips, O.L., and Williams, S.E. 2004. Extinction risk from climate change. *Nature* **427**: 145–148.

6.2. Comparing Model Projections with Observations

Model-based projections of CO_2 and warming-induced extinctions suffer a major loss of credibility when tested against real-world data. Animal life flourished during past epochs of planetary warmth, and warming of the magnitude experienced during the twentieth and early twenty-first centuries has occurred many times in the past and typically has benefitted terrestrial animals. In the subsections that follow, we highlight studies that focus on seven types of animals, beginning with amphibians.

6.2.1. Amphibians

Still et al. (1999) and Pounds et al. (1999) published a pair of papers in *Nature* dealing with the cause of major decreases in frog and toad populations in the highland forests of Monteverde, Costa Rica. Those diebacks—in which 20 of 50 local species totally went extinct locally, or were extirpated—had occurred over the prior two decades, a period described by the IPCC as having experienced unprecedented warming. Holmes (1999), in a popular science article describing the mystery's putative solution, wrote that the authors of the two reports made "a convincing case blaming global climate change for these ecological events."

Then, however, came the study of Lawton et al. (2001), which presented "an alternative mechanism—upwind deforestation of lowlands—that may increase convective and orographic cloud bases even more than changes in sea surface temperature do."

The four scientists began by noting the trade winds that reach the Monteverde cloud-forest ecosystem flow across approximately 100 km of lowlands in the Rio San Juan basin, and that deforestation proceeded rapidly in the Costa Rican part of the basin over the past century. By 1992, only 18 percent of the original lowland forest remained. They noted this conversion of forest to pasture and farmland altered the properties of the air flowing across the landscape. The reduced evapotranspiration that followed deforestation, for example, decreased the moisture content of the air mass, and regional atmospheric model simulations suggested there should be reduced cloud formation and higher cloud bases over such deforested areas, which would cause there to be fewer and higher-based clouds than otherwise would have been the case when the surface-modified air moved into the higher Monteverde region.

At this point there were two competing theories from which to choose a candidate mechanism for the environmental changes that had altered the

Monteverde cloud-forest ecosystem: one that was global in nature (CO_2-induced warming) and one that was local (upwind lowland deforestation). The matter was resolved by Lawton et al. Noting the lowland forests north of the San Juan River in southeastern Nicaragua had remained largely intact—providing a striking contrast to the mostly deforested lands in neighboring Costa Rica—they used satellite imagery to show "deforested areas of Costa Rica's Caribbean lowlands remain relatively cloud-free when forested regions have well-developed dry season cumulus cloud fields," noting further the prominent zone of reduced cumulus cloudiness in Costa Rica "lies directly upwind of the Monteverde tropical montane cloud forest." Consequently, they demonstrated by direct observation that the effects predicted by the theory they espoused did indeed occur in the real world, alongside a "control" area identical in all respects but for the deforestation that produced the cloud effects.

Two years later, Nair et al. (2003) demonstrated that the reduced evapotranspiration that followed prior and ongoing deforestation upwind of the Monteverde cloud forest decreased the moisture contents of the air masses that ultimately reached the tropical preserve, while regional atmospheric model simulations they conducted indicated there also should have been reduced cloud formation and higher cloud bases over these areas than there were before the deforestation began. Three years after that—in a study that extended the work of Lawton et al. and Nair et al., while exploring in more detail the impact of deforestation in Costa Rican lowland and premontane regions on orographic cloud formation during the dry season month of March—Ray et al. (2006) used the mesoscale numerical model of Colorado State University's Regional Atmospheric Modeling System to derive high-spatial-resolution simulations "constrained by a variety of ground based and remotely sensed observations," in order to "examine the sensitivity of orographic cloud formation in the Monteverde region to three different land use scenarios in the adjacent lowland and premontane regions," namely, "pristine forests, current conditions and future deforestation."

This observation-constrained modeling work revealed, in the researchers' words, that historic "deforestation has decreased the cloud forest area covered with fog in the montane regions by around 5–13% and raised the orographic cloud bases by about 25–75 meters in the afternoon." In addition, they write, their work suggested "further deforestation in the lowland and premontane regions would lead to around [a] 15% decrease in the cloud forest area covered with fog and also raise the orographic cloud base heights by up to 125 meters in the afternoon." These findings clearly relieved anthropogenic CO_2 emissions of blame for the decreases in frog and toad populations that had been experienced in the highland forests of Monteverde, Costa Rica, instead placing that blame squarely on the shoulders of those responsible for the felling of the adjacent lowland forests.

As additional cases of amphibian mass mortality were reported throughout the world, Parmesan (2006) and Pounds et al. (2006) pointed accusing fingers at CO_2, this time claiming global warming was promoting the spread of *Batrachochytrium dendrobatidis* (*Bd*), a non-hyphal zoosporic fungus that was the immediate cause of the amphibian declines and triggering outbreaks of chytridiomycosis via what came to be known as the climate-linked epidemic hypothesis (CLEH).

Investigating this concept within the Penalara Natural Park in the Sierra de Guadarrama of Central Spain, Bosch et al. (2007) looked for relationships between 20 different meteorological variables and the development of chytridiomycosis infection in the area's amphibian populations, focusing on "two time periods according to the lack (1976–1996) or presence (1997–2003) of observed chytrid-related mortalities." This work revealed, as they described it, "a significant association between change in local climatic variables and the occurrence of chytridiomycosis," leading them to conclude, "rising temperature is linked to the occurrence of chytrid-related disease."

Being careful not to be too adamant about what their data implied, however, Bosch et al. noted "associations between climate and disease do not necessarily imply causation." They also stated, "chytrid-related declines are probably the result of a complex web of interaction, and the effects of climate will be conditional on other factors such as host density, amphibian community composition, microbial competitors and zooplankton predators, to name but a few." To disentangle this network and break it down into its key components, they said it would be necessary "to collect seasonal data on amphibian densities, contemporary and historical measurements of the prevalence and intensity of infection, seasonal mortalities, and fine-scale meteorological conditions from a range of sites that represent altitudinal clines," and conduct "molecular epidemiological analyses." Consequently, and in light of the many complexities they listed, it was clear the last word on the subject was yet to be written—and, in fact, several additional studies appeared in print the following year.

Lips et al. (2008) evaluated data pertaining to population declines of frogs of the genus *Atelopus*, as well as similar data from other amphibian species, in Lower Central America and Andean South America, based on their own work and that of others recorded in the scientific literature. They sought to determine whether the documented population declines were more indicative of an emerging infectious disease or a climate-change-driven infectious disease, noting in this regard, "both field studies on amphibians (Briggs et al., 2005; Lips et al., 2006) and on fungal population genetics (Morehouse et al., 2003; Morgan et al., 2007) strongly suggest that *Bd* is a newly introduced invasive pathogen."

In discussing their findings, Lips et al. said they revealed "a classical pattern of disease spread across native populations, at odds with the CLEH proposed by Pounds et al. (2006)." Emphasizing that the latter's "analyses and re-analyses of data related to the CLEH all fail to support that hypothesis," Lips et al. went on to conclude their own analyses supported "a hypothesis that *Bd* is an introduced pathogen that spreads from its point of origin in a pattern typical of many emerging infectious diseases," reemphasizing that "the available data simply do not support the hypothesis that climate change has driven the spread of *Bd* in our study area."

Although the four U.S. scientists made it clear disease dynamics are indeed "affected by micro- and macro-climatic variables," and "such synergistic effects likely act on *Bd* and amphibians," their work clearly showed the simplistic scenario represented by the CLEH—which posits, in their words, that "outbreaks of chytridiomycosis are triggered by a shrinking thermal envelope"—paints an unrealistic picture of the role of global climate change in the much-more-complicated setting of real-world biology, where many additional factors may play even greater roles in determining amphibian well-being.

Laurance (2008) tested the hypothesis, put forward by Pounds et al. (2006), that "the dramatic, fungal pathogen-linked extinctions of numerous harlequin frogs (*Atelopus* spp.) in upland rainforests of South America mostly occurred immediately following exceptionally warm years, implicating global warming as a likely trigger for these extinctions." This he did "using temperature data for eastern Australia, where at least 14 upland-rainforest frog species [had] also experienced extinctions or striking population declines attributed to the same fungal pathogen, and where temperatures [had] also risen significantly in recent decades." This work, in Laurance's words, provided "little direct support for the warm-year hypothesis of Pounds et al." Instead, he "found stronger support for a modified version of the warm-year hypothesis," where frog declines were likely to occur only following three consecutive years of unusually warm weather; and these declines were observed "only at tropical latitudes, where rising minimum temperatures were greatest."

In further discussing his findings, Laurance stated many researchers "remain unconvinced that ongoing disease-linked amphibian declines are being widely instigated by rising global temperatures or associated climatic variables, as proposed by Pounds et al." He noted, for example, "chytrid-linked amphibian declines have been documented on several continents and at varying times" and to date, "no single environmental stressor has been identified that can easily account for these numerous population crashes." He continued, "it stretches plausibility to argue that the chytrid pathogen is simply an opportunistic, endemic microparasite that has suddenly begun causing catastrophic species declines as a consequence of contemporary global warming."

Rohr et al. (2008) provided a rigorous test of the two competing hypotheses by evaluating "(1) whether cloud cover, temperature convergence, and predicted temperature-dependent *Bd* growth are significant positive predictors of amphibian extinctions in the genus *Atelopus* and (2) whether spatial structure in the timing of these extinctions can be detected without making assumptions about the location, timing, or number of *Bd* emergences." After completing their research, the five scientists reported "almost all of our findings are contrary to the predictions of the chytrid-thermal-optimum hypothesis," even noting "not all of the data presented by Pounds et al. (2006) are consistent with the chytrid-thermal-optimum hypothesis." They note, "there was no regional temperature convergence in the 1980s when extinctions were increasing, and that convergence only occurred in the 1990s when *Atelopus spp.* extinctions were decreasing, opposite to the conclusions of Pounds et al. (2006) and the chytrid-thermal-optimum hypothesis." On the other hand, they report, "there is a spatial structure to the timing of *Atelopus spp.* extinctions but that the cause of this structure remains equivocal, emphasizing the need for further molecular characterization of *Bd*."

The next year, Alford et al. (2009)—no longer feeling any need to address the repudiated climate-linked epidemic hypothesis—quantified four movement characteristics of three groups of radio-tracked cane toads (*Bufo marinus*) at three places in Australia: (1) a location where the toads had been established for some 50 years at the time of their sampling, (2) a location where the first toads arrived about six months before sampling began in 1992 and 1993, and (3) a location where sampling occurred for a period of 13 months, starting at the time of the toads' initial arrival in 2005. The results of this exercise revealed that for all of the movement parameters they studied, "toads from the current invasion front differed dramatically from animals in the long-established population, while toads from the earlier invasion front were intermediate between these extremes."

The five researchers report "cane toads are now spreading through tropical Australia about 5-fold faster than in the early years of toad invasion." As for why this is so, they state "the current invasion-front animals achieved these [high invasion speeds] by rarely reusing the same retreat site two days in succession, by travelling further each night when they did move, and by moving along straighter paths." Therefore, as they describe it, the toad invasion front "advances much more rapidly than would occur if the toads retained ancestral behaviors (less frequent relocation, with shorter movements, and fewer toads using straight paths)." And because of the fact that "invasion-front toads in 1992 were more dispersive than origin-population toads in the same year, but that invasion-front toads have continued to evolve heightened dispersal ability and dispersed even more effectively in 2005 than they did in 1992," these observations suggest "as long as toads continue to invade suitable new habitat, dispersal ability will be selected upwards."

In discussing their findings, Alford et al. write that the rapidity and magnitude of the shifts in cane toads "are truly remarkable," having been accomplished in only 50 generations (about 70 years), and they state "such a major shift over such a brief period testifies to the intense selective pressure exerted on frontal populations of range-shifting species." This development, in their words, "not only has implications for our understanding of the rates of invasion by non-native species, but also for the rate of range-shift in native taxa affected by climate change." The implication to which they refer is that the capacity for species to respond to changing environments may be underestimated when it is based on observations of individuals at the core of their range.

In further exploration of the issue, Bustamante et al. (2010) exposed groups of Panamanian golden frogs (*Atelopus zeteki*) to varying dosages of zoospores of *Batrachochytrium dendrobatidis* (*Bd*) as well as to different temperatures and hydric environments, in order to ascertain whether the frogs were susceptible to the pathogen and, if so, how environmental factors might affect the frogs' survival. Results of these several operations indicated (1) "frogs exposed to a dosage of 100 *Bd* zoospores survived significantly longer than those that had been exposed to 10^4 or 10^6 zoospores," (2) "exposed frogs housed at 23°C survived significantly longer than those that were housed at 17°C," and (3) "exposed frogs held in dry conditions survived significantly longer than those in wet conditions."

Since their study was conducted in a laboratory, Bustamante et al. acknowledge their results "do not directly test hypotheses about the relation between climate change and the decline of the frogs in the field," but they note their data nevertheless "do not support the contention that rising global temperatures are necessary to cause the death of amphibians infected with this pathogen, because the pathogen was just as lethal at 17°C as at 23°C, and frogs at the warmer temperature lived significantly longer than those at the cooler one." This result is inconsistent with the climate-linked epidemic hypothesis of Pounds et al. (2006)—and Bustamante was a coauthor of that paper.

The most recent work to be devoted to the struggles of amphibians comes from Anchukaitis and Evans (2010). They write, "widespread amphibian extinctions in the mountains of the American tropics have been blamed on the interaction of anthropogenic climate change and a lethal pathogen." In this regard, they note, "limited meteorological records make it difficult to conclude whether current climate conditions at these sites are actually exceptional in the context of natural variability," questioning once again the original contention that modern global warming was the primary culprit in the demise of the Monteverde golden toad (*Bufo periglenes*).

In an attempt to shed significant new light on the subject, Anchukaitis and Evans developed annual proxy records of hydroclimatic variability over the past century within the Monteverde Cloud Forest of Costa Rica, based on measurements of the stable oxygen isotope ratio ($\delta^{18}O$) made on trees lacking annual rings, as described in the papers of Evans and Schrag (2004) and Anchukaitis et al. (2008). That work revealed, in the words of the two researchers, that "contrary to interpretations of the short instrumental record (Pounds et al., 1999), no long-term trend in dry season hydroclimatology can be inferred from our $\delta^{18}O$ time series at Monteverde (1900–2002)." Instead, they found, "variability at the interannual scale dominates the isotope signal, particularly during the period of increased ENSO variance since the late 1960s," and they add, in this regard, "there is no evidence of a trend associated with global warming." They emphasize "the extinction of the Monteverde golden toad appears to have coincided with an exceptionally dry interval caused by the 1986–1987 El Niño event," which they describe as "one of the longest driest periods in the last 100 years," based on their $\delta^{18}O$ chronology. In addition, they report, there is currently no consensus on how anthropogenic climate change might influence the El Niño Southern Oscillation, while indicating, "ENSO anomalies in the most recent decades are not beyond the range of natural variability during the instrumental period (Rajagopalan et al., 1997)."

In conclusion, Anchukaitis and Evans state their analysis suggests "the cause of the specific and well-documented extinction of the Monteverde golden toad was the combination of the abnormally strong ENSO-forced dryness and the lethality of the introduced chytrid fungus, but was not directly mediated by anthropogenic temperature trends, a finding from paleoclimatology that is in agreement with statistical reanalysis (Rohr et al., 2008; Lips et al., 2008) of the 'climate-linked epidemic hypothesis'." The latter two analyses also had revealed the chytrid-thermal-optimum hypothesis, as it alternatively has been described, to be devoid of merit. Consequently, even in the case of struggling amphibians, there are no real-world data that provide any support for the contention that global warming is, or ever will be, responsible for driving them to extinction. In fact, there are examples of just the opposite occurring.

Writing that "phenotypic plasticity, the capacity of a genotype to produce distinct phenotypes under different environmental conditions, is a common and powerful method of adaptation in nature," Orizaola and Laurila (2009) investigated variations in temperature-induced plasticity in larval life-history traits among populations of an isolated metapopulation of pool frogs (*Rana lessonae*) in Central Sweden. This they did by exposing larvae from three closely located populations to two temperatures (20 and 25°C) in the laboratory and then documenting their growth and development responses at the two different temperatures. According to the two Swedish researchers, the results of their experiment indicated (1) "in general, larvae exposed to warmer temperature experienced higher survival and metamorphosed faster," (2) there "were differences among the populations in both trait mean values and in the plastic responses," and (3) "among-family variation within populations was found in growth rate and time to metamorphosis, as well as in plasticity suggesting that these traits have a capacity to evolve."

Based on these observations, Orizaola and Laurila found "strong population differentiation at a microgeographic scale in life-history characteristics and temperature-induced plasticity in [the] isolated amphibian metapopulation," and that in spite of "the near absence of molecular genetic variation within [the] metapopulation, [their] study detected strong variation in trait means and plastic responses both among and within populations, possibly suggesting that natural selection is shaping life-history traits of the local populations," which phenomenon may be preparing them for still further temperature increases by providing them "ample phenotypic variation" to deal with a potentially warming environment.

In additional studies showing real-world data refute the contention that global warming is driving amphibians to extinction, Berger et al. (2004) found *lower* temperatures enhanced the development of chytridiomycosis in a study of eastern Australian frogs, while Seimon et al. (2007) determined glacial recession in the Peruvian Andes has been creating new amphibian habitats at recently deglaciated sites. McCaffery and Maxell (2010) documented an increase in survival and breeding probability in the Columbia spotted frog of the Bitterroot Mountains of Montana (USA) as the severity of winter decreased, leading them to conclude "a warming climate with less severe winters is likely to promote population viability in this montane frog population."

Woodhams et al. (2010) recently noted "amphibian skin peptides are one important defense against chytridiomycosis," while examining "the population-level variation in this innate immune defense to understand its relationship with disease dynamics." Briggs et al. (2010) have noted some amphibians with chytridiomycosis "develop only minor infections and suffer little or no negative effects." And Zukerman (2010) reports some of the most devastated populations of Australia's barred river frogs (*Mixophyes esiteratus*), tusked-frogs (*Adelotus sp.*), and several tree frog species (*Litoria sp.*), once thought to have been wiped out by the fungus, are now showing strong signs of recovery.

References

Alford, R.A., Brown, G.P., Schwarzkopf, L, Phillips, B.L., and Shine, R. 2009. Comparisons through time and space suggest rapid evolution of dispersal behavior in an invasive species. *Wildlife Research* **36**: 23–28.

Anchukaitis, K.J. and Evans, M.N. 2010. Tropical cloud forest climate variability and the demise of the Monteverde golden toad. *Proceedings of the National Academy of Sciences, USA* **107**: 5036–5040.

Anchukaitis, K.J., Evans, M.N., Wheelwright, N.T., and Schrag, D.P. 2008. Stable isotope chronology and climate signal in neotropical montane cloud forest trees. *Journal of Geophysical Research* **113**: G03030.

Berger, L, Speare, R, Hines, H.B., Marantelli, G., Hyatt, A.D., McDonald, K.R., Skerratt, L.F., Olsen, V., Clarke, J.M., Gillespie, G., Mahony, M., Sheppard, N., Williams, C., and Tyler, M.J. 2004. Effect of season and temperature on mortality in amphibians due to chytridiomycosis. *Australian Veterinary Journal* **82**: 432–439.

Bosch, J., Carrascal, L.M., Duran, L., Walker, S., and Fisher, M.C. 2007. Climate change and outbreaks of amphibian chytridiomycosis in a montane area of Central Spain: Is there a link? *Proceedings of the Royal Society B* **274**: 253–260.

Briggs, C.J., Knapp, R.A., and Vredenburg, V.T. 2010. Enzootic and epizootic dynamics of the chytrid fungal pathogen of amphibians. *Proceedings of the National Academy of Sciences, USA* **107**: 9695–9700.

Briggs, C.J., Vredenburg, V., Knapp, R.A., and Rachowicz, L.J. 2005. Investigating the population-level effects of chytridiomycosis, an emerging infectious disease of amphibians. *Ecology* **86**: 3149–3159.

Bustamante, H.M., Livo, L.J., and Carey, C. 2010. Effects of temperature and hydric environment on survival of the Panamanian Golden Frog infected with a pathogenic chytrid fungus. *Integrative Zoology* **5**: 143–153.

Evans, M.N. and Schrag, D.P. 2004. A stable isotope-based approach to tropical dendroclimatology. *Geochimica et Cosmochimica Acta* **68**: 3295–3305.

Holmes, R. 1999. Heads in the clouds. *New Scientist* (8 May): 32–36.

Laurance, W.F. 2008. Global warming and amphibian extinctions in eastern Australia. *Austral Ecology* **33**: 1–9.

Lawton, R.O., Nair, U.S., Pielke Sr., R.A., and Welch, R.M. 2001. Climatic impact of tropical lowland deforestation on nearby montane cloud forests. *Science* **294**: 584–587.

Lips, K.R., Brem, F., Brenes, R., Reeve, J.D., Alford, R.A., Voyles, J., Carey, C., Livo, L., Pessier, A.P., and Collins, J.P. 2006. Emerging infectious disease and the loss of biodiversity in a Neotropical amphibian community. *Proceedings of the National Academy of Sciences USA* **103**: 3165–3170.

Lips, K.R., Diffendorfer, J., Mendelson III, J.R., and Sears, M.W. 2008. Riding the wave: reconciling the roles of disease and climate change in amphibian declines. *PLoS (Public Library of Science) Biology* **6**(3): e72. doi:10.1371/journal.pbio.0060072.

McCaffery, R.M. and Maxell, B.A. 2010. Decreased winter severity increases viability of a montane frog population. *Proceedings of the National Academy of Sciences, USA* **107**: 8644–8649.

Morehouse, E.A., James, T.Y., Ganley, A.R.D., Vilgalys, R., Berger, L., Murphy, P.J., and Longcore, J.E. 2003. Multilocus sequence typing suggests the chytrid pathogen of amphibians is a recently emerged clone. *Molecular Ecology* **12**: 395–403.

Morgan, J.A.T., Vredenburg, V., Rachowicz, L.J., Knapp, R.A., Stice, M.J., Tunstall, T., Bingham, R.E., Parker, J.M., Longcore, J.E., Moritz, C., Briggs, C.J., and Taylor, J.W. 2007. Enigmatic amphibian declines and emerging infectious disease: population genetics of the frog-killing fungus *Batrachochytrium dendrobatidis*. *Proceedings of the National Academy of Sciences USA* **104**: 13,845–13,850.

Nair, U.S., Lawton, R.O., Welch, R.M., and Pielke Sr., R.A. 2003. Impact of land use on Costa Rican tropical montane cloud forests: sensitivity of cumulus cloud field characteristics to lowland deforestation. *Journal of Geophysical Research* **108**: 10.1029/2001JD001135.

Orizaola, G. and Laurila, A. 2009. Microgeographic variation in temperature-induced plasticity in an isolated amphibian metapopulation. *Evolutionary Ecology* **23**: 979–991.

Parmesan, C. 2006. Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics* **37**: 637–669.

Pounds, J.A., Bustamante, M.R., Coloma, L.A., Consuegra, J.A., Fogden, M.P.L., Foster, P.N., La Marca, E., Masters, K.L., Merino-Viteri, A., Puschendorf, R., Ron, S.R., Sanchez-Azofeifa, G.A., Still, C.J., and Young, B.E. 2006. Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature* **439**: 161–167.

Pounds, J.A., Fogden, M.P.L., and Campbell, J.H. 1999. Biological response to climate change on a tropical mountain. *Nature* **398**: 611–615.

Rajagopalan, B., Lall, U., and Cane, M.A. 1997. Anomalous ENSO occurrences: An alternate view. *Journal of Climate* **10**: 2351–2357.

Ray, D.K., Nair, U.S., Lawton, R.O., Welch, R.M., and Pielke Sr., R.A. 2006. Impact of land use on Costa Rican tropical montane cloud forests: Sensitivity of orographic cloud formation to deforestation in the plains. *Journal of Geophysical Research* **111**: 10.1029/2005JD006096.

Rohr, J.R., Raffel, T.R., Romansic, J.M., McCallum, H., and Hudson, P.J. 2008. Evaluating the links between climate, disease spread, and amphibian declines. *Proceedings of the National Academy of Sciences USA* **105**: 17,436–17,441.

Seimon, T.A., Seimon, A., Daszak, P., Halloy, S.R.P., Schloegel, L.M., Aguilar, C.A., Sowell, P., Hyatt, A.D., Konecky, B., and Simmons, J.E. 2007. Upward range extension of Andean anurans and chytridiomycosis to extreme elevations in response to tropical deglaciation. *Global Change Biology* **13**: 288–299.

Still, C.J., Foster, P.N., and Schneider, S.H. 1999. Simulating the effects of climate change on tropical montane cloud forests. *Nature* **398**: 608–610.

Woodhams, D.C., Kenyon, N., Bell, S.C., Alford, R.A., Chen, S., Billheimer, D., Shyr, Y., and Rollins-Smith, L.A. 2010. Adaptations of skin peptide defenses and possible response to the amphibian chytrid fungus in populations of Australian green-eyed treefrogs, *Litoria genimaculata*. *Diversity and Distributions* **16**: 703–712.

Zukerman, W. 2010. Fungus out! The frog resistance is here. *NewScientist* **2790** (10 December) http://www.newscientist.com/article/mg20827903.500-fungus-out-the-frog-resistance-is-here.html.

6.2.2. Birds

The IPCC characterizes global warming as detrimental for most of the planet's animals, including birds, even suggesting rising temperatures could drive many of them to extinction. When contemplating the special abilities of these winged creatures—such as the ability to fly—one would think highly mobile species such as birds could overcome whatever degree of stress a temperature increase might impose upon them, merely by moving to more-hospitable habitat, of course, or to take advantage of whatever new opportunities global warming might present for them.

In what follows, we review several studies that indicate birds do indeed respond in such a manner. The studies also show birds are able to tolerate much greater heat stress than previously thought.

Thomas and Lennon (1999) helped initiate extinction concerns about birds when they analyzed temporal trends in the spatial distributions of British birds over a 20-year period of global warming, looking for climate-induced changes in their breeding ranges. In doing so, they found the northern margins of southerly species' breeding ranges shifted northward by an average of 19 km from 1970 to 1990, while the southern margins of northerly species' breeding ranges shifted, in the mean, not at all. British birds have expanded their ranges in the face of global warming, clearly a positive response that makes extinction much less a possibility than it was before the warming.

Simultaneously, Brown et al. (1999) had been studying a natural population of individually recognizable, color-banded Mexican jays in the Chiricahua Mountains of Arizona (USA) over the period 1971–1998 for trends in egg-laying dates and monthly minimum air temperatures. Over the 29-year period of their study, they determined the date of first nest construction occurred 10.8 days earlier, while the date of first clutch in the population came 10.1 days earlier. These changes were associated with significant upward trends in monthly minimum temperature in the study area, of which they said that in many bird species "breeding is timed so as to have young in the nest when the principal food of the nestlings is at its peak." With warmer minimum temperatures occurring earlier and earlier over their study period, they suggested this climatic trend could be producing an earlier abundance of such food, which would help explain the increasingly earlier egg-laying date.

The three researchers also identified a second way in which earlier-occurring warmer night temperatures might lead to earlier breeding dates in birds: by alleviating thermal stresses on females on cold nights. Citing several studies that had revealed similar breeding trends in European birds, they suggested the "recognition of similar trends on both continents in very different environments is consistent with the interpretation that some avian populations are already responding to climate changes in the last 29 years or so." And once again, these widespread changes are positive in nature, for not only are bird ranges increasing in size as air temperatures rise, the temporal availability of food needed to sustain important life processes is advancing in synchrony with the timing of egg-laying.

Five years later in Europe, Brommer (2004) categorized birds of Finland as either northerly (34 species) or southerly (116 species) and quantified changes in their range margins and distributions from two atlases of breeding birds, one covering the period 1974–79 and one covering the period 1986–89, in an attempt to determine how the two groups of species responded to what he called "the period of the earth's most rapid climate warming in the last 10,000 years," citing McCarthy et al. (2001). This exercise revealed southern species experienced a mean poleward advancement of their northern range boundaries of 18.8 km over the 12-year period. However, the southern range boundaries of the northern species remained essentially unaltered. Noting similar results had been obtained for birds in the United Kingdom (Thomas and Lennon, 1999) and other species (primarily butterflies) elsewhere (Parmesan, 1996; Parmesan et al., 1999), Brommer concluded "in general, for Northern Hemisphere species, southerly range margins of species are less responsive to climate change than the northerly margins." This demonstrates once again that the ranges of birds (and possibly other animals) in a warming world will likely increase in size, as their northern range boundaries expand poleward and upward while their southern range boundaries remain largely unaltered, which should render them less subject to extinction than they are currently or have been in the past.

Also working in Europe, and using data from the *Breeding Bird Atlas* of Lake Constance, which borders Germany, Switzerland, and Austria, Lemoine et al. (2007) analyzed the impact of land-use and climate changes on the region's abundance of Central European birds between the periods 1980–1981 and 1990–1992, and between 1990–1992 and 2000–2002. This work revealed, in their words, "the total number of [bird] species in the Lake Constance region increased from 141 species in 1980 to 146 species in 1990 and to 154 species in 2000," while "winter temperatures increased by 2.71°C and spring temperatures increased by 2.12°C over the 23 years from the first to the last census." These and other data led them to conclude, "increases in temperature appear to have allowed increases in abundance of species whose range centers were located in southern Europe and that may have been limited by low winter or spring temperature." In addition, they report "the impact of climate change on bird populations increased in importance between 1990 and 2000 and is now more significant than any other tested factor." This is a very important finding because the warming has tremendously benefited European birds and helped to buffer them against extinction.

Contemporaneously, for the portion of the United States east of the Rocky Mountains, Hitch and Leberg (2007) used data from the North American Breeding Bird Survey to evaluate shifts in the northern range boundaries of 26 species of birds with southern distributions and the southern range boundaries of 29 species of birds with northern distributions between the periods 1967–1971 and 1998–2002. They found the northern margins of the southern group of birds showed significant northward shifts that averaged 2.35 km per year for all species studied, which finding they describe as being "consistent with the results of Thomas and Lennon (1999) from Great Britain." Also in agreement with the observations about British birds, they determined "levels of warming do not appear to be so great [that] they are forcing birds to abandon the southernmost portions of their distributions," a finding that is being replicated around the world.

Halupka et al. (2008) documented various breeding parameters of reed warblers (long-lived passerine birds that spend their winters in Africa but breed in the reed beds of marshlands in the Palaearctic, with some of them nesting in fishponds of southwest Poland) during 12 breeding seasons (1970–73, 1980–83, 1994, 2003, and 2005–06) that encompassed the period 1970–2006. They compared trends in what they measured with concomitant trends in mean monthly temperatures. This work revealed that mean breeding season (April–August) temperature increased significantly between 1970 and 2006, as did the mean temperature of each individual month of the breeding season, with the average temperature for the May–July period rising by 2°C. They found that in 2005 and 2006, egg-laying started three weeks earlier than in 1970 (as assessed by the first-egg date of the earliest pair of breeding birds), and the median first-egg date shifted forward in time by 18 days.

The end of egg-laying, however, did not change significantly in either direction, so there was a corresponding increase in the length of the egg-laying period, and with this longer laying period available to them, more birds were able to rear second broods. In the 1970s and 1980s, for example, the Polish researchers report, "only about 0–15% of individuals laid second clutches," but "between 1994 and 2006 up to 35% of birds reared second broods." In addition, they report, "during seasons with warm springs, early nests were better protected by being hidden in newly emerged reeds" and "as a result, these nests suffered fewer losses from predation." They concluded, "the studied population of reed warblers benefits from climate warming."

Another case in point was described by Jensen et al. (2008), who wrote, "global climate change is expected to shift species ranges polewards, with a risk of range contractions and population declines of especially high-Arctic species," citing contentions of the Arctic Climate Impact Assessment (ACIA, 2005). To evaluate this claim, they constructed species distribution models for the Svalbard-nesting pink-footed goose (*Anser brachyrhynchus*), in order to "relate their occurrence to environmental and climatic variables." They then used the most parsimonious of these models to "predict their distribution under a warmer climate scenario," based upon "mean May temperature, the number of frost-free months and the proportion of moist and wet moss-dominated vegetation in the area," the latter of which is "an indicator of suitable feeding conditions."

The results of this exercise indicated, in the words of the six scientists, that global warming "will have a positive effect on the suitability of Svalbard for nesting geese in terms of range expansion into the northern and eastern parts of Svalbard which are currently unsuitable." They also noted this result does not even consider the likelihood that glaciers will decrease in size and expose still more potential nest sites. Thus they concluded their paper by stating increased temperatures could release the population of pink-footed geese from the "present density-dependent regulation during the nesting period," and "elongation of the frost-free season in Svalbard may relax their dependence on the acquisition of body stores before arrival (so-called 'capital' breeding, *sensu* Drent and Daan, 1980), so that geese will have more time to acquire the necessary resources upon arrival and still breed successfully," noting "both factors are likely to have a positive effect on the population growth."

In another relevant study, based on bird-ringing records covering a time span of 41 years (1964–2004), Husek and Adamik (2008) "documented shifts in the timing of breeding and brood size in a long-distance migrant, the red-backed shrike (*Lanius collurio*) from a central European population," after which they compared their results with the climatic history of the region over the same time period. They thus determined temperatures in May significantly increased over the period of their study, and they state, "in line with this increasing May temperature" there was "a 3– to 4–day shift towards earlier breeding." This pattern, in their words, "is consistent with the results of similar studies on other long-distance migrating songbirds (e.g., Dunn, 2004)." In addition, they report, there was "an increase in brood size by approximately 0.3 nestlings since 1964." And of this latter finding they state, "given that early broods are usually larger (Lack, 1968; this study) and that they have a higher nest success (Muller et al., 2005), this may have a positive effect on future population increases as the temperature continues to rise."

About the same time, Seoane and Carrascal (2008) wrote, "it has been hypothesized that species preferring low environmental temperatures, which inhabit cooler habitats or areas, would be negatively affected by global warming as a consequence of the widely accepted increase of temperature during the last two decades," while noting "this effect is assumed to be more intense at higher latitudes and altitudes because these areas seem to be changing more rapidly." They devised a study "to assess whether population changes agree with what could be expected under global warming (a decrease in species typical of cooler environments)," focusing on birds.

Working in the Spanish portion of the Iberian Peninsula in the southwestern part of the Mediterranean Basin, the two researchers determined breeding population changes for 57 species of common passerine birds between 1996 and 2004 in areas without any apparent land-use changes. This work revealed, in their words, that "one-half of the study species showed significant increasing recent trends despite the public concern that bird populations are generally decreasing," while "only one-tenth showed a significant decrease."

In discussing their findings, Seoane and Carrascal state, "the coherent pattern in population trends we found disagrees with the proposed detrimental effect of global warming on bird populations of western Europe." They are not the only ones to have come to this conclusion. They noted, for example, "one-half of terrestrial passerine birds in the United Kingdom exhibited increasing recent trends in a very similar time period (1994–2004)," citing Raven et al. (2005), and they explained "there is also a marked consistency between the observed increasing trends for forest and open woodland species in the Iberian Peninsula and at more northern European latitudes in the same recent years," citing Gregory et al. (2005). Likewise, they indicated "Julliard et al. (2004a), working with 77 common bird species in France, found that species with large ecological breadth showed a tendency to increase their numbers throughout the analyzed period."

Commenting further on their findings, Seoane and Carrascal state that in their study, "bird species that inhabit dense wooded habitats show striking patterns of population increase throughout time." Noting "this is also the case with those bird species mainly distributed across central and northern Europe that reach their southern boundary limits in the north of the Iberian Peninsula," they theorize "these short- to medium-term population increases may be due to concomitant increases in productivity." In support of this notion they cite the thinking of Julliard et al. (2004b) and the empirical observations of Myneni et al. (1997), Tucker et al. (2001), Zhou et al. (2001), Fang et al. (2003), and Slayback et al. (2003), whose work figured prominently in establishing the reality of the late twentieth-century warming- and CO_2-induced greening of the Earth phenomenon, which has produced, in the words of the Spanish scientists, "an increase in plant growth or terrestrial net primary production in middle latitudes of the Northern Hemisphere since the 1980s, particularly in forest environments."

It should be abundantly clear from these several observations that the supposedly unprecedented warmth of the past two decades has not led to what Seoane and Carrascal call "the proposed detrimental effect of global warming on bird populations of western Europe."

After observing two second clutches in a newly established population of tree swallows in the Shenandoah Valley of Virginia (USA), Monroe et al. (2008) monitored all late nests in the following two breeding seasons to see what they could learn about the phenomenon. This surveillance revealed, "among all females nesting in the early breeding rounds of 2006 and 2007, 5% of birds with successful first clutches later laid second clutches." In addition, they report the mean productivity for double-brooded females for 2006–2007 was 4.4 ± 1.3 fledglings from first clutches and 3.4 ± 0.8 from second clutches, so "double-brooded females significantly increased their total annual productivity compared to birds nesting only in the early rounds of breeding." In fact, the productivity of the double-brooded females was approximately 75 percent greater than that of the single-brooded females. And in summarizing their findings in the concluding paragraph of their paper, Monroe et al. write, "in general, late summer and fall nesting among North American birds is underappreciated and may be increasing due to global warming," citing the work of Koenig and Stahl (2007).

Noting "climate envelopes (or the climatic niche concept) are the current methods of choice for prediction of species distributions under climate change," Beale et al. (2008) remind us that "climate envelope methods and assumptions have been criticized as ecologically and statistically naive (Pearson and Dawson, 2003; Hampe, 2004)," and "there are many reasons why species distributions may not match climate, including biotic interactions (Davis et al., 1998), adaptive evolution (Thomas et al., 2001), dispersal limitation (Svenning and Skov, 2007), and historical chance (Cotgreave and Harvey, 1994)." To shed more light on the subject, they evaluated the degree of matchup of species distributions to environment by generating synthetic distributions that retained the spatial structure of observed distributions but were randomly placed with respect to climate. More specifically, "using data on the European distribution of 100 bird species, [they] generated 99 synthetic distribution patterns for each species," and "for each of the 100 species, [they] fitted climate envelope models to both the true distribution and the 99 simulated distributions by using standard climate variables." They then determined the goodness-of-fit of the many distribution patterns, because, as they note, "there has been no attempt to quantify how often high goodness-of-fit scores, and hence ostensibly good matches between distribution and climate, can occur by chance alone."

In a rather surprising result, the three U.K. researchers determined "species-climate associations found by climate envelope methods are no better than chance for 68 of 100 European bird species." And, they write, "because birds are perceived to be equally strongly associated with climate as other species groups and trophic levels (Huntley et al., 2004)," their results "cast doubt on the predictions of climate envelope models for all taxa." They conclude, "many, if not most, published climate envelopes may be no better than expected from chance associations alone, questioning the implications of many published studies." The bottom line with respect to our stewardship of the Earth is thus well described by their conclusion: "scientific studies and climate change adaptation policies based on the indiscriminate use of climate envelope methods irrespective of species sensitivity to climate may be misleading and in need of revision," as is also evident from the results of the many other studies reviewed in this brief analysis of the subject.

Grandgeorge et al. (2008) analyzed population sizes and phylogenetic and spatial structures of British and Irish seabirds based on "(1) presence or absence of the seabird species in the different counties of Britain and Ireland between 1875 to 1900 and 1968 to 1972, (2) seabird breeding censuses of Britain and Ireland from 1969 to 1970, 1985 to 1988 and 1998 to 2002, (3) at-sea abundance and distribution surveys of seabirds in the North Sea from 1980 to 1985 and 1990 to 1995, and (4) a bioenergetics model to estimate energy expenditures for 40 seabird species." This work revealed, in their words, "a marked expansion in the breeding range of seabirds in Britain and Ireland between 1875 and 1972." In addition, they report total seabird numbers "increased at an average rate of 1% per annum between 1969 and 2002, with a related increase of 115% in predicted total seabird predation." What is more, they state, "between 1875 and 1972 no seabird species was lost and there was an overall expansion in breeding range of the seabird population of Britain and Ireland, with the number of counties occupied increasing from 31 to 47."

In light of these findings, the six scientists concluded, "the seabird community of Britain and Ireland has been remarkably resilient to environmental change in the 20th century." In fact, it "prospered during the 20th century," and "significantly raised ocean temperatures in the North Sea (Beaugrand, 2004)" may even have "created more favorable environmental conditions for some seabird species," citing the work of Thompson (2006). These conclusions are of course very different from the "end of the world" scenarios painted by the IPCC.

In much the same vein, Brommer (2008) wrote that a "population-level change expected under a climate-warming scenario is a poleward shift in the distribution of organisms," and he stated it is thus believed by many that birds that "do not shift their range margin consist of species that are declining, and would therefore be of particular management concern." A few years earlier, Brommer (2004) had measured the range sizes and northern range margin locations of 116 bird species with a predominantly southern distribution in Finland, and of those species he noted "the trend slope describing the change in their abundance for the period 1983–2005 was calculated for 53 species by Vaisanen (2006)." This, he noted, resulted in "the largest dataset available of the long-term trends in population numbers of Finnish birds that is comparable across species, because it has both been gathered and analyzed using the same procedures." Therefore, to complete the behavioral picture of the latter 53 species, Brommer (2008) determined the concomitant changes in their northern range margins.

The Finnish bird specialist found "species foraging in wet habitats had experienced strong range margin shifts as compared with other feeding ecologies." But he said he found "no evidence that those feeding ecological groups that showed a relatively small shift in range margin had experienced low population growth or a population decline." Therefore, in discussing "the lack of correlation between the shift in range margin of the different feeding ecologies and the change in their mean abundance," Brommer stated this real-world finding "is contrary to expected under a climate-change scenario, because, all else being equal, a clear range-margin shift should indicate a good capacity to track climatic change, which should result in a more positive trend in abundance if climate change is indeed the main driver of population-level change."

In another revealing study, Maclean et al. (2008) analyzed counts of seven wading bird species—the Eurasian oystercatcher, grey plover, red knot, dunlin, bar-tailed godwit, Eurasian curlew, and common redshank—made at approximately 3,500 different sites in Belgium, Denmark, France, Germany, Ireland, the Netherlands, and the United Kingdom on at least an annual basis since the late 1970s. They did this in order to determine what range adjustments the waders may have made in response to regional warming, calculating the weighted geographical centroids of the bird populations for all sites with complete coverage for every year between 1981 and 2000.

This work revealed, in the words of the seven scientists, that "the weighted geographical centroid of the overwintering population of the majority of species has shifted in a northeasterly direction, perpendicular to winter isotherms," with overall 20-year shifts ranging from 30 to 119 km. In addition, they report, "when the dataset for each species was split into 10 parts, according to the mean temperature of the sites, responses are much stronger at the colder extremities of species ranges." In fact, they found, "at warmer sites, there was no palpable relationship between changes in bird numbers and changes in temperature." They concluded, "range expansions rather than shifts are occurring" as the planet warms.

In discussing the significance of their findings, the members of the international research team state the commonly used climate-envelope approach to predicting warming-induced species migrations "essentially assumes that as climate alters, changes at one margin of a species' range are mirrored by those at the other, such that approximately the same 'climate space' is occupied regardless of actual climate," whereas the evidence suggests "that this may not be the case: climate space can also change."

In further discussing their important finding, Maclean et al. write, "it is actually not surprising that responses to temperature appear only to be occurring at the colder extremities of species ranges," for "it has long been known that it is common for species to be limited by environmental factors at one extremity, but by biological interactions at the other," citing the work of Connell (1983) and Begon et al. (2005). They concluded it is likely "the warmer extremities of the species ranges examined in this study are controlled primarily by biotic interactions, whereas the colder margins are dependent on temperature."

Dyrcz and Halupka (2009) examined long-term responses in the breeding performance of Great Reed Warblers (living on fish ponds near Milicz in southwest Poland) during various years from 1970 to 2007 (1970–1974, 1981–1984, 1997, and 2004–2007), over which period mean temperatures during the egg-laying months of the species (May–July) rose by a remarkable 2.2°C, from 15.3 to 17.5°C. The two researchers found a "significant advancement in both earliest and annual median first-egg-laying dates" that "correlated with temperature increases early in the season." Latest first-egg-laying dates remained unchanged, as did several other breeding statistics, including clutch size, nest losses, and number of young per nest. Consequently—and contrary to a Bavarian population of Great Reed Warblers that also advanced its latest first-egg-laying date—the Polish bird population expanded its breeding season in response to regional warming, whereas the Bavarian birds merely shifted theirs, as documented by Schaefer et al. (2006).

The two researchers thus concluded, "the studied population does not benefit from climate warming (as found in Bavaria), but apparently does not suffer," reiterating "the Great Reed Warbler has adapted well ... by shifting the timing of breeding." The results of their study, they state, "do not confirm the prediction of Bairlein and Winkel (2000) that long-distance migrants would suffer due to climate change." In addition, they write, a comparison of their data with that of the Bavarian population "provides evidence that different populations of the same species can adapt in different ways to climate change," noting "this was also previously found for woodland species," citing the work of Visser et al. (2002) and Sanz (2003).

Moving from Europe to Asia, Qian et al. (2009) compiled a comprehensive dataset of bird species richness in China—based on pertinent scientific literature published over the past three decades—for 207 localities (the vast majority of which were national nature reserves with a mean area of 3270 km^2), which they then analyzed for their relationships to 13 different environmental variables. In the words of the authors, "of all environmental variables examined, normalized difference vegetation index [NDVI], a measure of plant productivity, is the best variable to explain the variance in breeding bird richness." More specifically, they determined that four of the 13 variables they tested explained 45.3 percent of the total species richness variance, with 21.2 percent being accounted for by NDVI, 12.5 percent by elevation range, and 11.6 percent by annual potential evapotranspiration and mean annual temperature together. In addition, they note the two most important predictors of their study (NDVI and elevation range) "have been found to be major predictors for breeding bird richness in other regions and the whole of the globe, indicating that the finding of [their] study at a smaller scale is to a large degree consistent with those of previous studies of breeding birds at larger scales."

These findings make a good deal of sense, for in a major review of plant-animal interactions in 51 terrestrial ecosystems conducted 20 years earlier, McNaughton et al. (1989) found the biomass of plant-eating animals is a strongly increasing function of aboveground primary production, and in a subsequent review of 22 aquatic ecosystems, Cyr and Pace (1993) found the herbivore biomass of watery habitats also increases in response to increases in vegetative productivity. As such, it should be abundantly clear that greater plant productivity—both terrestrial and aquatic—leads to greater populations of plants and the animals that feed upon them, which should therefore lead to greater ecosystem biodiversity, because each species of plant and animal must maintain a certain "critical biomass" to sustain its unique identity and ensure its long-term viability. And that's where atmospheric CO_2 enrichment enters the picture: It increases plant productivity, which supports more animal life, which leads to greater animal biodiversity, which is good for the planet and good for mankind, the stewards and beneficiaries of all life upon it.

Moving on from Asia to Africa, Hockey and Midgley (2009) write, "in the influential fourth assessment report of the Intergovernmental Panel on Climate Change, Rosenzweig et al. (2007) tested several thousand time-series data sets for changes in species behavior and geographic range consistent with climate change, reaching the conclusion that it is very likely that climate change is driving changes in natural biological systems." However, they state "the use of such large data sets in meta-analyses may discourage the close inspection of observations and result in naively misattributing observed shifts to climate when other explanations may be more parsimonious."

To test this hypothesis, Hockey and Midgley "collated information about recent range changes in South African birds, specifically indigenous species that have colonized the Cape Peninsula, at the south-western tip of Africa in the Western Cape province, since the 1940s," where they state there have been "widespread anthropogenic changes of many kinds to the landscape, including urbanization, commercial afforestation and the introduction and spread of invasive alien trees, most of which occurred before climate change accelerated in the 1970s."

The two researchers found the colonization events "concur with a 'climate change' explanation, assuming extrapolation of Northern Hemisphere results and simplistic application of theory," but "on individual inspection, all bar one may be more parsimoniously explained by direct anthropogenic changes to the landscape than by the indirect effects of climate change." Also, "no *a priori* predictions relating to climate change, such as colonizers being small and/or originating in nearby arid shrub-lands, were upheld."

In discussing their findings, the South African scientists state their work suggests "observed climate changes have not yet been sufficient to trigger extensive shifts in the ranges of indigenous birds in this region, or that *a priori* assumptions are incorrect." Either way, they continue, "this study highlights the danger of naive attribution of range changes to climate change, even if those range changes accord with the predictions of climate-change models," because "misattribution could distract conservationists from addressing pressing issues involving other drivers of biodiversity change such as habitat transformation, and obscure important lessons that might be learned from the dynamics that pertain to such changes."

Also in 2009, but farther south in the Southern Hemisphere, Huang et al. (2009) evaluated paleo-evidence for penguin populations at Gardner Island in East Antarctica. According to the five researchers, penguins colonized the site shortly after it became ice-free 8,500 years ago. A pronounced population peak is also evident in the data from about 4,700 to 2,400 BP, which corresponds closely to a substantially warmer period at this site. While this is interesting in and of itself, the authors document four other studies (all of the studies conducted to date) showing a penguin optimum roughly 3,000 to 4,000 years ago and coinciding with notably warm conditions. Together, these five studies encompass East Antarctica, the Ross Sea region, and the West Antarctic Peninsula. Studies of elephant seals (Hall, 2006) show they, too, were found closer to the South Pole during past warmer periods. And since all data currently available point to penguins having been most abundant during the warmest period of the Holocene several thousand years ago, it would seem reasonable to presume that penguins would respond positively, not negatively as the IPCC contends, to any future warming that may occur.

Additional support for this thesis comes from Carey (2009), who notes “organisms living today are descended from ancestors that experienced considerable climate change in the past,” and she thus suggests “species that persist into future climates may be able to do so in part owing to the genetic heritage passed down from ancestors who survived climate changes in the past.” She also states, “if climate change were the only new challenge facing birds, one might imagine that many species could become adapted to new conditions and survive with existing population variability and the genetic information that their ancestors used to survive past climate change.”

In another study exploring bird responses to past periods of climate change, Tyrberg (2010) compared fossil avifaunas of the Last Interglacial (LIG), about 130,000 to 117,000 years ago, from multiple sites around the world to the modern avifaunas found in those locations. During much of this time interval, the globe was about 2°C warmer than it is today, and it was up to 10°C warmer in much of the Arctic. For fossil faunas, however, only species that still exist were included in the comparisons, because during the cold period of the last glacial, which followed the LIG, many species went extinct due to the cold, and climate tolerance can be determined reliably only for living species. Based on the areal distributions of fossil avifaunas in different parts of the world, therefore, regions were delineated in which many of the identified species coexisted, and if it was found the same sets of species share the same common ranges today, it was concluded that the avifauna, as a whole, did not respond to any significant degree to the warmer temperatures of the LIG.

For sites that were about 2°C warmer during the LIG—including four sites in Florida, one in Alaska, two in Germany, and one in New Zealand—species present during the LIG were found to be the same as the species that inhabit those regions today. At a site in Wales, however, where LIG temperatures were a full 4°C warmer than today, the fossil avifauna was similar to the current avifauna of Spain and Portugal, indicating the fossil avifauna had indeed located themselves further northward during the LIG in response to the much greater warmth of that period. And in another exception to the study’s primary findings, the LIG avifauna at a site in North Africa (which is now desert with no birds present) was similar to that of the area south of the desert today, indicating—in light of the fact that during the LIG the Sahara desert received much more rainfall than it does currently—precipitation was the overriding factor determining both the current and fossil avifauna choice of territories.

In light of these and other findings, Tyrberg concludes “as for the effect of the generally warmer climate during the LIG it seems clear that differences on the order of 2°C or less, both on land and in sea-surface temperatures, are barely, if at all, detectable in the avifaunas.”

Another concern about the effects of potential global warming on birds is that various links of certain food chains may not respond in a compatible manner in terms of the temporal development of the different stages of their life cycles, leading to a serious mismatch among the unique needs of different ecosystem trophic levels that could well spell disaster for some species. This concept has been said by Visser and Both (2005) to constitute an “insufficient adjustment” to climate change.

In a study designed to explore this phenomenon for certain elements of an important ecosystem of Central Europe, Bauer et al. (2010) examined the responses to 47 years of warming (1961–2007) of (1) the time of leafing-out of dominant English oak (*Quercus robur*) trees at four different research sites in the Czech Republic that are located in full-grown, multi-aged floodplain forests that had been under no forestry management; (2) the time of appearance of the two most abundant species of caterpillars in the floodplain forests—the winter moth (*Operophtera brumata*) and the tortrix moth (*Tortrix viridana*); and (3) the first and mean laying dates of two of the ecosystem’s most common birds: great tits (*Parus major*) and collared flycatchers (*Ficedula albicollis*).

According to the researchers, “mean annual temperature showed a significant increase of 0.27–0.33°C per decade, with approximately the same magnitude of change during spring at all sites.” They also found, “on average (all four sites), the bud burst date for English Oak has advanced by 7.9 days and full foliage by 8.9 days, with approximately the same shifts being recorded for the peak of the beginning and end of frass for herbivorous caterpillars,” which was the observational variable they used to characterize the caterpillars’ presence. Last, they determined “the first laying date of Great Tits has advanced by between 6.2 to 8.0 days,” while “the mean laying date has advanced by 6.4 to 8.0 days.” Likewise, they found the “Collared Flycatcher first laying date has advanced by 8.5 to 9.2 days over the past 47 years, and the mean laying date by 7.7 to 9.6 days."

With respect to the importance of their findings, Bauer et al. state that because "trends in the timing of reproduction processes of both bird species are coherent with the trends in development of English Oak and with peak herbivorous caterpillar activity," it is readily apparent that in this specific food chain the common shifting of the different organisms' phenological stages toward the beginning of the year "does not appear to have led to mistiming in the trophic food chain." Hence, there is reason to believe other food chains also may not be as seriously disrupted by global warming as many have postulated they could be. Of course, much more work of this nature is needed before any generalities are warranted.

In a contemporaneous study, Van Buskirk et al. (2010) write, "recent climate change has caused comparatively rapid shifts in the phenology and geographic distributions of many plants and animals," but "there is debate over the degree to which populations can meet the challenges of climate change with evolutionary or phenotypic responses in life history and morphology," which for a warming climate includes a reduction in body size. They devised an experimental strategy to further explore the issue. Specifically, they studied the body sizes of birds captured in mist-nets and traps between June 1961 and November 2006 at the Powdermill Nature Reserve—a field station operated by the Carnegie Museum of Natural History in Pennsylvania (USA) at a location that is broadly representative of bird communities in the Appalachian region of eastern North America. At this location, (1) 35 mist nets were operated five to six days per week during spring and autumn migrations, (2) a reduced number of nets was used during summer, and (3) birds for winter banding were caught in wire traps when the temperature was below freezing.

The three researchers report migrating birds captured at the banding station "have steadily decreasing fat-free mass and wing chord since 1961, consistent with a response to a warmer climate" and confirming that "phenotypic responses to climate change are currently underway in entire avian assemblages," where "size was negatively correlated with temperature in the previous year, and long-term trends were associated with the direction of natural selection acting on size over the winter." In addition, they note "species undergoing the strongest selection favoring small wing chord showed the most rapid long-term declines in wing [size]," which suggests, as they describe it, that "phenotypic changes are therefore in line with the prevailing selection regime." Noting "in summer, 51 of 65 breeding species had negative slopes of mass against year, 20 of 26 wintering species had negative slopes, 60 of 83 spring migrants had negative slopes, and 66 of 75 autumn migrants had negative slopes," Van Buskirk et al. state their results "offer compelling evidence that climate change has already produced observable adaptive shifts in morphology, behavior, and phenology of a great many species," which suggests these birds have evolved a capacity for rapid phenotypic shifts to optimum body mass in response to climate fluctuations.

Popy et al. (2010) employed data from two bird atlas surveys performed on a 1 km by 1 km grid (the first in 1992–94 and the second in 2003–05) in an alpine valley in the Italian Piedmont to see if there was any evidence for an upward shift in the ranges of 75 bird species (68 of which were detected in both surveys) over this period, during which time the region's mean air temperature rose by 1.0°C. Their results indicated "the number of species whose mean elevation increased (n = 42) was higher than the number whose mean elevation decreased (n = 19), but the overall upward shift [29 m] was not significantly different from zero." In addition, they state even the 29 m increase was "smaller than would be expected from 'climatic envelope' models," as the "1.0°C increase in temperature would be equivalent to *c.* 200 m in elevation, based on an average gradient of -0.5°C per 100 m." In addition, they indicate, "at the European scale, no overall expansion or contraction of the distributions of the studied species was detected." In light of their findings, as well as those of others they cite, Popy et al. thus conclude, "until a better understanding of the underlying mechanisms is achieved, predictions based only on 'climate envelope' models should be either validated or considered cautiously."

In one final study to be considered here, Thomas et al. (2010) write, "the timing of annual breeding is a crucial determinant of reproductive success, individual fitness, and population performance, particularly in insectivorous passerine birds," because "by synchronizing hatching with the narrow time window of maximal food abundance, parents can enhance their reproductive success through an increase in offspring growth rate and body condition, survival to fledging, and subsequent recruitment into the breeding population." Many people worry, in this regard, that global warming may upset such biological synchronizations, leading to downward trends in the populations of many species of birds and other animals.

Thomas et al. studied this situation using "confirmatory path analysis and data on laying date" for two populations of blue tits in northern Corsica (Muro and Pirio) in order to determine "how laying date is related to spring temperatures and vegetation phenology"—as these two factors figure highly in determining the peak period of blue tit food abundance (in this case caterpillars)—in order to provide "critical information on how passerine birds may adjust breeding in the face of directional climate change [such as regional warming] by identifying the causal paths that link laying date and environmental cues." The French and Canadian researchers discovered, in their words, "Blue Tits use a cue system that is context specific to fine-tune laying dates to match local conditions both on a spatial (habitat) scale and on a temporal (interannual) scale," and their "reliance on both temperature and phenology when breeding late in the season, as occurs in most populations where tits have been intensively studied north of the Mediterranean region, satisfactorily explains how these populations can advance breeding in response to rising spring temperatures while maintaining a relatively large variation in the onset of breeding on a local spatial scale."

In discussing their findings, Thomas et al. acknowledge that "if a single environmental feature [such as temperature] were responsible for the timing of breeding, climate change could cause a severe decline in breeding success, with negative demographic consequences." However, they state they "have not detected any consistent mismatch between Blue Tit breeding dates and caterpillar peak [abundance] dates over the 14 and 21 years for which they have data for Muro and Pirio, respectively." Their findings, they conclude, "offer some hope that breeding populations will respond well to global warming."

References

ACIA. 2005. *Arctic Climate Impact Assessment*. New York, NY: Cambridge University Press.

Bairlein, F. and Winkel, W. 2000. Birds and climate change. In *Climate of the 21st Century: Changes and Risks*, edited by J.L. Lozan, H. Grassl, and P. Hupfer. 278–282. Hamburg, Germany: Wissenschaftliche Auswertungen.

Bauer, Z., Trnka, M., Bauerova, J., Mozny, M., Stepanek, P., Bartosova, L., and Zalud, Z. 2010. Changing climate and the phenological response of great tit and collared flycatcher populations in floodplain forest ecosystems in Central Europe. *International Journal of Biometeorology* **54**: 99–111.

Beale, C.M., Lennon, J.J., and Gimona, A. 2008. Opening the climate envelope reveals no macroscale associations with climate in European birds. *Proceedings of the National Academy of Sciences USA* **105**: 14,908–14,912.

Beaugrand, G. 2004. The North Sea regime shift: evidence, mechanisms and consequences. *Progress in Oceanography* **60**: 245–262.

Begon, M., Townsend, C., and Harper, J. 2005. *Ecology: From Individuals to Ecosystems*. Oxford, UK: Blackwell.

Brommer, J.E. 2004. The range margins of northern birds shift polewards. *Annales Zoologici Fennici* **41**: 391–397.

Brommer, J.E. 2008. Extent of recent polewards range margin shifts in Finnish birds depends on their body mass and feeding ecology. *Ornis Fennica* **85**: 109–117.

Brown, J.L, Shou-Hsien, L., and Bhagabati, N. 1999. Long-term trend toward earlier breeding in an American bird: a response to global warming? *Proceedings of the National Academy of Science, U.S.A.* **96**: 5565–5569.

Carey, C. 2009. The impacts of climate change on the annual cycles of birds. *Philosophical Transactions of the Royal Society B* **364**: 3321–3330.

Connell, J.H. 1983. On the prevalence and relative importance of interspecific competition: evidence from field experiments. *The American Naturalist* **122**: 661–696.

Cotgreave, P. and Harvey, P.H. 1994. Associations among biogeography, phylogeny and bird species diversity. *Biodiversity Letters* **2**: 46–55.

Cyr, H. and Pace, M.L. 1993. Magnitude and patterns of herbivory in aquatic and terrestrial ecosystems. *Nature* **361**: 148–150.

Davis, A.J., Jenkinson, I.S., Lawton, J.H., Shorrocks, B., and Wood, S. 1998. Making mistakes when predicting shifts in species range in response to global warming. *Nature* **391**: 783–786.

Drent, R.H. and Daan, S. 1980. The prudent parent: energetic adjustment in avian breeding. *Ardea* **68**: 225–252.

Dunn, P. 2004. Breeding dates and reproductive performance. *Advances in Ecological Research* **35**: 69–87.

Dyrcz, A. and Halupka, L. 2009. The response of the Great Reed Warbler *Acrocephalus arundinaceus* to climate change. *Journal of Ornithology* **150**: 39–44.

Fang, J., Piao, S., Field, C.B., Pan, Y., Guo, Q., Zhou, L., Peng, C., and Tao, S. 2003. Increasing net primary production in China from 1982 to 1999. *Frontiers in Ecology and the Environment* **1**: 293–297.

Grandgeorge, M., Wanless, S., Dunn, T.E., Maumy, M., Beaugrand, G., and Gremillet, D. 2008. Resilience of the British and Irish seabird community in the twentieth century. *Aquatic Biology* **4**: 187–199.

Gregory, R.D., van Strien, A.J., Vorisek, P., Gmelig Meyling, A.W., Noble, D.G., Foppen, R.P.B., and Gibbons, D.W. 2005. Developing indicators for European birds. *Philosophical Transactions of the Royal Society B: Biological Sciences* **360**: 269.

Hall, B.L., Hoelzel, A.R., Baroni, C., Denton, G.H., Le Boeuf, B.J., Overturf, B., and Topf, A.L. 2006. Holocene elephant seal distribution implies warmer-than-present climate in the Ross Sea. *Proceedings of the National Academy of Sciences, USA* **103**: 10,213–10,217.

Halupka, L., Dyrcz, A., and Borowiec, M. 2008. Climate change affects breeding of reed warblers *Acrocephalus scirpaceus*. *Journal of Avian Biology* **39**: 95–100.

Hampe, A. 2004. Bioclimate envelope models: what they detect and what they hide. *Global Ecology and Biogeography* **13**: 469–471.

Hitch, A.T. and Leberg, P.L. 2007. Breeding distributions of North American bird species moving north as a result of climate change. *Conservation Biology* **21**: 534–539.

Hockey, P.A.R. and Midgley, G.F. 2009. Avian range changes and climate change: a cautionary tale from the Cape Peninsula. *Ostrich* **80**: 29–34.

Huang, T., Sun, L, Wang, Y., Liu, X., and Zhu, R. 2009. Penguin population dynamics for the past 8500 years at Gardner Island, Vestfold Hills. *Antarctic Science* **21**:571–578.

Huntley, B., Green, R.E., Collingham, Y.C., Hill, J.K., Willis, S.G., Bartlein, P.J., Cramer, W., Hagemeijer, W.J.M., and Thomas, C.J. 2004. The performance of models relating species geographical distributions to climate is independent of trophic level. *Ecology Letters* **7**: 417–426.

Husek, J. and Adamik, P. 2008. Long-term trends in the timing of breeding and brood size in the Red-Backed Shrike *Lanius collurio* in the Czech Republic, 1964–2004. *Journal of Ornithology* **149**: 97–103.

Jensen, R.A., Madsen, J., O'Connell, M., Wisz, M.S., Tommervik, H., and Mehlum, F. 2008. Prediction of the distribution of Arctic-nesting pink-footed geese under a warmer climate scenario. *Global Change Biology* **14**: 1–10.

Julliard, R., Jiguet, F., and Couvet, D. 2004a. Common birds facing global changes: what makes a species at risk? *Global Change Biology* **10**: 148–154.

Julliard, R., Jiguet, F., and Couvet, D. 2004b. Evidence for the impact of global warming on the long-term population dynamics of common birds. *Proceedings of the Royal Society B: Biological Sciences* **271**: S490–S492.

Koenig, W.D. and Stahl, J.T. 2007. Late summer and fall nesting in the Acorn Woodpecker and other North American terrestrial birds. *The Condor* **109**: 334–350.

Lack, D. 1968. *Ecological Adaptations for Breeding in Birds*. London, UK: Methuen.

Lemoine, N., Bauer, H.-G., Peintinger, M., and Bohning-Gaese, K. 2007. Effects of climate and land-use change on species abundance in a central European bird community. *Conservation Biology* **21**: 495–503.

Maclean, I.M.D., Austin, G.E., Rehfisch, M.M., Blew, J., Crowe, O., Delany, S., Devos, K., Deceuninck, B., Gunther, K., Laursen, K., van Roomen, M., and Wahl, J. 2008. Climate change causes rapid changes in the distribution and site abundance of birds in winter. *Global Change Biology* **14**: 2489–2500.

McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., and White, K.S., Eds. 2001. *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. Cambridge, UK: Cambridge University Press.

McNaughton, S.J., Oesterheld, M., Frank, D.A., and Williams, K.J. 1989. Ecosystem-level patterns of primary productivity and herbivory in terrestrial habitats. *Nature* **341**: 142–144.

Monroe, A.P., Hallinger, K.K., Brasso, R.L., and Cristol, D.A. 2008. Occurrence and implications of double brooding in a southern population of tree swallows. *The Condor* **110**: 382–386.

Muller, M., Pasinelli, G., Schiegg, K., Spaar, R., and Jenni, L. 2005. Ecological and social effects on reproduction and local recruitment in the red-backed shrike. *Oecologia* **143**: 37–50.

Myneni, R.C., Keeling, C.D., Tucker, C.J., Asrar, G., and Nemani, R.R. 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* **386**: 698–702.

Parmesan, C. 1996. Climate and species' range. *Nature* **382**: 765–766.

Parmesan, C., Ryrholm, N., Stefanescu, C., Hill, J.K., Thomas, C.D., Descimon, H., Huntley, B., Kaila, L., Kullberg, J., Tammaru, T., Tennent, W.J., Thomas, J.A., and Warren, M. 1999. Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature* **399**: 579–583.

Pearson, R.G. and Dawson, T.P. 2003. Predicting the impacts of climate change on the distribution of species: Are bioclimate envelope models useful? *Global Ecology and Biogeography* **12**: 361–371.

Popy, S., Bordignon, L., and Prodon, R. 2010. A weak upward elevational shift in the distributions of breeding birds in the Italian Alps. *Journal of Biogeography* **37**: 57–67.

Qian, H., Wang, S., Li, Y., and Wang, X. 2009. Breeding bird diversity in relation to environmental gradients in China. *Acta Oecologica* **35**: 819–823.

Raven, M.J., Noble, D.G., and Baillie, S.R. 2005. *The Breeding Bird Survey 2004*. Thetford, UK: British Trust for Ornithology.

Rosenzweig, C., Casassa, G., Karoly, D.J., Imeson, A., Liu, C., Menzel, A., Rawlins, S., Root, T.L., Seguin, B., and Tryjanowski, P. 2007. Assessment of observed changes and responses in natural and managed systems. In *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Working Group II Contribution to the 4th Assessment Report of the Intergovernmental Panel on Climate Change, edited by M. Parry, et al. 79–131. Cambridge, UK: Cambridge University Press.

Sanz, J.J. 2003. Large-scale effect of climate change on breeding parameters of pied flycatchers in Western Europe. *Ecography* **26**: 45–50.

Schaefer, T., Lebedur, G., Beier, J., and Leisler, B. 2006. Reproductive responses of two related coexisting songbird species to environmental changes: global warming, competition, and population sizes. *Journal of Ornithology* **147**: 47–56.

Seoane, J. and Carrascal, L.M. 2008. Interspecific differences in population trends of Spanish birds are related to habitat and climatic preferences. *Global Ecology and Biogeography* **17**: 111–121.

Slayback, D., Pinzon, J., and Tucker, C. 2003. Northern hemisphere photosynthetic trends 1982–1999. *Global Change Biology* **9**: 1–15.

Svenning, J.C. and Skov, F. 2007. Could the tree diversity pattern in Europe be generated by postglacial dispersal limitation? *Ecology Letters* **10**: 453–460.

Thomas, C.D., Bodsworth, E.J., Wilson, R.J., Simmons, A.D., Davies, Z.G., Musche, M., and Conradt, L. 2001. Ecological and evolutionary processes at expanding range margins. *Nature* **411**: 577–581.

Thomas, C.D. and Lennon, J.J. 1999. Birds extend their ranges northwards. *Nature* **399**: 213.

Thomas, D.W., Bourgault, P., Shipley, B., Perret, P., and Blondel, J. 2010. Context-dependent changes in the weighting of environmental cues that initiate breeding in a temperate passerine, the Corsican Blue Tit (*Cyanistes caeruleus*). *The Auk* **127**: 129–139.

Thompson, P.M. 2006. Identifying drivers of change: did fisheries play a role in the spread of North Atlantic fulmars? In *Management of Marine Ecosystems: Monitoring Change in Upper Trophic Levels*, edited by I.A. Boyd, S. Wanless, and C.J. Camphuysen. Cambridge, UK: Cambridge University Press.

Tucker, C.J., Slayback, D.A., Pinzon, J.E., Los, S.O., Myneni, R.B., and Taylor, M.G. 2001. Higher northern latitude NDVI and growing season trends from 1982 to 1999. *International Journal of Biometeorology* **45**: 184–190.

Tyrberg, T. 2010. Avifaunal responses to warm climate: the message from last interglacial faunas. *Records of the Australian Museum* **62**: 193–205.

Vaisanen, R.A. 2006. Maalinnuston kannanvaihtelut Etela-ja Pohjois-Suomessa 1983-2005. *Linnut-vuosikirja* **2005**: 83–98.

Van Buskirk, J., Mulvihill, R.S., and Leberman, R.C. 2010. Declining body sizes in North American birds associated with climate change. *Oikos* **119**: 1047–1055.

Visser, M.E. and Both, C. 2005. Shifts in phenology due to global climate change: the need for yardstick. *Proceedings of the Royal Society B* **272**: 2561–2569.

Visser, M.E., Silverin, B., Lambrechts, M.M. and Tinbergen, J.M. 2002. No evidence for tree phenology as a cue for the timing of reproduction in tits *Parus* spp. *Avian Science* **2**: 1–10.

Zhou, L., Tucker, C.J., Kaufmann, R.K., Slayback, D., Shabanov, N.V., and Myneni, R.B. 2001. Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. *Journal of Geophysical Research* **106**: 20.069–20,083.

6.2.3. Butterflies

The butterfly is another animal species the IPCC claims to be at risk of extinction due to global warming. In this section, we analyze how butterflies respond to rising air temperatures and CO_2 concentrations.

Over the prior century of global warming, Parmesan et al. (1999) examined the distributional changes of non-migratory butterfly species whose northern boundaries were in northern Europe (52 species) and whose southern boundaries were in southern Europe or northern Africa (40 species). This work revealed the northern boundaries shifted northward for 65 percent of of the first group, remained stable for 34 percent, and shifted southward for 2 percent. The southern boundaries shifted northward for 22 percent of of the second group , remained stable for 72 percent, and shifted southward for 5 percent. Thus "nearly all northward shifts," according to Parmesan et al., "involved extensions at the northern boundary with the southern boundary remaining stable."

This behavior is precisely what we would expect to see if the butterflies were responding to shifts in the ranges of the plants upon which they depend for their sustenance, because increases in atmospheric CO_2 concentration tend to ameliorate the effects of heat stress in plants and induce an upward shift in the temperature at which they function optimally. These phenomena tend to cancel the impetus for poleward migration at the warm edge of a plant's territorial range, yet they continue to provide the opportunity for poleward expansion at the cold edge of its range. Hence it is possible the observed changes in butterfly ranges over the past century of warming and rising atmospheric CO_2 concentration are related to matching changes in the ranges of the plants upon which they feed. Alternatively, this similarity could be a result of some more complex phenomenon, possibly even some direct physiological effect of temperature and atmospheric CO_2 concentration on the butterflies themselves. In any event, and in the face of the 0.8°C of warming that occurred in Europe over the twentieth century, the consequences for European butterflies were primarily beneficial.

Across the Atlantic in the United States, Fleishman et al. (2001) used comprehensive data on butterfly distributions from six mountain ranges in the U.S. Great Basin to study how butterfly populations of that region may respond to IPCC-projected climate change. Their work revealed "few if any species of montane butterflies are likely to be extirpated from the entire Great Basin (i.e., lost from the region as a whole)." In discussing their results, the three researchers noted "during the Middle Holocene, approximately 8000–5000 years ago, temperatures in the Great Basin were several degrees warmer than today." They note "we might expect that most of the montane species—including butterflies—that currently inhabit the Great Basin would be able to tolerate the magnitude of climatic warming forecast over the next several centuries."

Thomas et al. (2001) documented an unusually rapid expansion of the ranges of two butterfly species (the silver-spotted skipper and the brown argus) along with two cricket species (the long-winged cone-head and Roesel's bush cricket). They observed the warming-induced "increased habitat breadth and dispersal tendencies have resulted in about 3- to 15-fold increases in expansion rates." In commenting on these findings, Pimm (2001) remarked that the geographical ranges of these insects were "expanding faster than expected" and the synergies involved in the many intricacies of the range expansion processes were "unexpected."

Three years later, Crozier (2004) noted "*Atalopedes campestris*, the sachem skipper butterfly, expanded its range from northern California into western Oregon in 1967, and into southwestern Washington in 1990," where she reports temperatures rose by 2–4°C over the prior half-century. Thus intrigued, and in an attempt to assess the importance of this regional warming for the persistence of *A. campestris* in the recently colonized areas, Crozier "compared population dynamics at two locations (the butterfly's current range edge and just inside the range) that differ by 2–3°C." Then, to determine the role of over-winter larval survivorship, she "transplanted larvae over winter to both sites."

This work revealed, in Crozier's words, "combined results from population and larval transplant analyses indicate that winter temperatures directly affect the persistence of *A. campestris* at its northern range edge, and that winter warming was a prerequisite for this butterfly's range expansion." Noting "populations are more likely to go extinct in colder climates," Crozier indicated "the good news about rapid climate change [of the warming type] is that new areas may be available for the introduction of endangered species." The species she studied responded to regional warming by extending its northern range boundary, thereby expanding its range, which should enable it to move further back from the "brink of extinction" that some advocates associate with rapid global warming.

Davies et al. (2006) introduced their study of the silver-spotted skipper butterfly (*Hesperia comma*) by noting that during the twentieth century it "became increasingly rare in Britain [as] a result of the widespread reduction of sparse, short-turfed calcareous grassland containing the species' sole larval host plant, sheep's fescue grass," while describing the "refuge" colonies of 1982 as but a "remnant" of what once had been. But that was not the end of the matter, for then came the warming claimed by some to have been unprecedented over the past two millennia, which could ultimately drive the already decimated species to extinction.

The four researchers analyzed population density data, estimates of the percent of bare ground, and the percent of sheep's fescue available to the butterflies, based on surveys conducted in Surrey in the chalk hills of the North Downs, south of London, in 1982 (Thomas et al., 1986), 1991 (Thomas and Jones, 1993), 2000 (Thomas et al., 2001; Davies et al., 2005), and 2001 (R.J. Wilson, unpublished data). They also assessed egg-laying rates in different microhabitats, as well as the effects of ambient and oviposition site temperatures on egg-laying, and the effects of sward composition on egg location. This multifaceted work of Davies et al. (2006) revealed, in their words, that "in 1982, 45 habitat patches were occupied by *H. comma*," but "in the subsequent 18-year period, the species expanded and, by 2000, a further 29 patches were colonized within the habitat network." In addition, they found "the mean egg-laying rate of *H. comma* females increased with rising ambient temperatures" and "a wider range of conditions have become available for egg-laying."

In discussing their findings, Davies et al. write, "climate warming has been an important driving force in the recovery of *H. comma* in Britain [as] the rise in ambient temperature experienced by the butterfly will have aided the metapopulation re-expansion in a number of ways." First, they suggest "greater temperatures should increase the potential fecundity of *H. comma* females," and "if this results in larger populations, for which there is some evidence (e.g. 32 of the 45 habitat patches occupied in the Surrey network experienced site-level increases in population density between 1982 and 2000), they will be less prone to extinction," with "larger numbers of dispersing migrant individuals being available to colonize unoccupied habitat patches and establish new populations." Second, they state "the wider range of thermal and physical microhabitats used for egg-laying increased the potential resource density within each grassland habitat fragment," and "this may increase local population sizes." Third, they argue "colonization rates are likely to be greater as a result of the broadening of the species realized niche, [because] as a larger proportion of the calcareous grassland within the species' distribution becomes thermally suitable, the relative size and connectivity of habitat patches within the landscape increases." Fourth, they note "higher temperatures may directly increase flight (dispersal) capacity, and the greater fecundity of immigrants may improve the likelihood of successful population establishment." Consequently, Davies et al. conclude "the warmer summers predicted as a consequence of climate warming are likely to be beneficial to *H. comma* within Britain," and they suggest "warmer winter temperatures could also allow survival in a wider range of microhabitats."

In a concurrent study, Menendez et al. (2006) provided what they called "the first assessment, at a geographical scale, of how species richness has changed in response to climate change," concentrating on British butterflies. They tested "whether average species richness of resident British butterfly species has increased in recent decades, whether these changes are as great as would be expected given the amount of warming that has taken place, and whether the composition of butterfly communities is changing towards a dominance by generalist species." By these means they determined "average species richness of the British butterfly fauna at 20 x 20 km grid resolution has increased since 1970–82, during a period when climate warming would lead us to expect increases." They also found, as expected, "southerly habitat generalists increased more than specialists," which require a specific type of habitat that is sometimes difficult for them to find, especially in the modern world where habitat destruction is commonplace. In addition, they were able to determine that observed species richness increases lagged behind those expected on the basis of climate change.

These results "confirm," according to the nine U.K. researchers, "that the average species richness of British butterflies has increased since 1970–82." Some of the range shifts responsible for the increase in species richness take more time to occur than those of other species, and the researchers state their results imply "it may be decades or centuries before the species richness and composition of biological communities adjusts to the current climate."

Also working in Britain, Hughes et al. (2007) examined evolutionary changes in adult flight morphology in six populations of the speckled wood butterfly—*Pararge aegeria*—along a transect from its distribution core to its warming-induced northward-expanding range margin. The results of this exercise were then compared with the output of an individual-based spatially explicit model developed "to investigate impacts of habitat availability on the evolution of dispersal in expanding populations." This work indicated the empirical data the researchers gathered "were in agreement with model output" and "showed increased dispersal ability with increasing distance from the distribution core." This included favorable changes in thorax shape, abdomen mass, and wing aspect ratio for both males and females, as well as thorax mass and wing loading for females. In addition, the researchers indicate "increased dispersal ability was evident in populations from areas colonized >30 years previously."

In discussing their findings, Hughes et al. suggest "evolutionary increases in dispersal ability in expanding populations may help species track future climate changes and counteract impacts of habitat fragmentation by promoting colonization." However, they report that in the specific situation they investigated, "at the highest levels of habitat loss, increased dispersal was less evident during expansion and reduced dispersal was observed at equilibrium, indicating that for many species, continued habitat fragmentation is likely to outweigh any benefits from dispersal." Put another way, it would appear global warming is proving not to be an insurmountable problem for the speckled wood butterfly, which is evolving physical characteristics that allow it to keep up with the poleward migration of its current environmental niche, whereas direct destructive assaults of humanity upon its natural habitat could still end up driving it to extinction.

Analyzing data pertaining to the general abundance of Lepidoptera in Britain over the period 1864–1952, based on information assembled by Beirne (1955) via his examination of "several thousand papers in entomological journals describing annual abundances of moths and butterflies," Dennis and Sparks (2007) reported, "abundances of British Lepidoptera were significantly positively correlated with Central England temperatures in the current year for each month from May to September and November" and "increased overall abundance in Lepidoptera coincided significantly with increased numbers of migrants," having derived the latter data from the work of Williams (1965). In addition, they report Pollard (1988) subsequently found much the same thing for 31 butterfly species over the period 1976–1986, and Roy et al. (2001) extended the latter investigation to 1997 and found "strong associations between weather and population fluctuations and trends in 28 of 31 species which confirmed Pollard's (1988) findings." All of these observations indicate the warming-driven increase in Lepidopteran species and numbers in Britain has been an ongoing phenomenon since the end of the Little Ice Age.

In another analysis from Britain, Gonzalez-Megias et al. (2008) investigated species turnover in 51 butterfly assemblages by examining regional extinction and colonization events that occurred between the two periods 1976–1982 and 1995-2002. The five researchers found regional colonizations exceeded extinctions: "over twice as many sites gained species as lost species," such that "the average species richness of communities has increased." They also found species abundances following colonization likewise increased, due to "climate-related increases in the [land's] carrying capacity."

In comparing their results with those of a broader range of animal studies, Gonzalez-Megias et al. found "analyses of distribution changes for a wide range of other groups of animals in Britain suggest that southern representatives of most taxa are moving northwards at a rate similar to—and in some cases faster than—butterflies (Hickling et al., 2006)," and they report, "as with butterflies, most of these taxonomic groups have fewer northern than southern representatives, so climate-driven colonisations are likely to exceed extinctions." They suggest "most of these taxa will also be experiencing slight community-level increases in species richness."

White and Kerr (2006) "report butterfly species' range shifts across Canada between 1900 and 1990 and develop spatially explicit tests of the degree to which observed shifts result from climate or human population density," describing the latter factor as "a reasonable proxy for land use change." In this category they included such elements as "habitat loss, pesticide use, and habitat fragmentation," all of which anthropogenic-driven factors have been tied to declines of various butterfly species. In addition, they state that to their knowledge, "this is the broadest scale, longest term dataset yet assembled to quantify global change impacts on patterns of species richness."

The two researchers discovered butterfly species richness "generally increased over the study period, a result of range expansion among the study species." They further found this increase "from the early to late part of the 20th century was positively correlated with temperature change," which had to have been the cause of the increase, for they also found species richness was "negatively correlated with human population density change."

In another study conducted in Canada, Westwood and Blair (2010) measured the responses of 19 common butterfly species of the boreal forests of Manitoba to temperature changes experienced there during 1971–2004, focusing on each species' date of first appearance, week of peak abundance, and length of flight period. Autumn temperatures were found to have warmed significantly, and the two Canadian researchers observed "13 of 19 species showed a significant increase in flight period extending longer into the autumn," when "flight period extensions increased by 31.5 ± 13.9 days over the study period." They note "two species, *Junonia coenia* and *Euphydryas phaeton*, increased their northerly ranges by ~150 and 70 km, respectively."

Westwood and Blair state, "warmer autumns and winters may be providing opportunities for range extensions of more southerly butterfly species held at bay by past climatic conditions." In addition, they cite other investigators who have obtained similar results, stating "northward expansions in butterfly species range correlating with northward shifts in isotherms have been documented in both Europe and North America (Karl et al., 1996; Parmesan, 1996; Parmesan et al., 1999; Hill et al., 1999; Hickling et al., 2006)," while indicating "in Canada, the Gorgone checkerspot (*Chlosyne gorgone*, Hubner) and the Delaware skipper (*Anatryone logan*, W.H. Edwards) have recently expanded their northern ranges significantly (Kerr, 2001)." These results confirm the observations of White and Kerr and contradict the negative prognostications about climate impacts from warming.

One additional means by which butterflies can cope with high temperatures is through the production of heat-shock proteins (HSPs). According to Karl et al. (2008), HSPs "are thought to play an important ecological and evolutionary role in thermal adaptation," where "the up-regulation of stress-inducible HSPs may help organisms to cope with stress thus enhancing survival (Sorensen et al., 2003; Dahlhoff, 2004; Dahlhoff and Rank, 2007)."

Working with *Lycaena tityrus,* a widespread temperate-zone butterfly that ranges from western Europe to central Asia, Karl et al. tested this hypothesis by comparing expression patterns of stress-inducible HSPs across replicated populations originating from different altitudes and across different ambient temperatures. Their observations revealed "a significant interaction between altitude and rearing temperature [that] indicates that low-altitude animals showed a strongly increased HSP70 expression at the higher compared with at the lower rearing temperature." This is exactly where one would expect to see such a response in light of its obvious utility in warmer conditions.

In discussing their findings, Karl et al. state their observation that "HSP70 expression increased substantially at the higher rearing temperature in low-altitude butterflies ... might represent an adaptation to occasionally occurring heat spells," which further suggests this response should serve these organisms well in the days and years to come, especially if the dramatic warming and increase in heat spells predicted by the IPCC should come to pass.

Most recently, Forister et al. (2010) analyzed 35 years of butterfly presence-absence data collected by a single observer at ten sites approximately every two weeks along an elevation gradient stretching from sea level to an altitude of 2,775 meters in the Sierra Nevada Mountains of Northern California (USA). During the data-collection period (1) both maximum and minimum temperatures rose, (2) low-altitude habitat was negatively affected by encroaching land development, and (3) there was no systematic variation in precipitation. This effort revealed, in the words of the eight researchers, that over this period, species richness "declined at half of the sites, with the most severe reductions at the lowest elevations," where "habitat destruction [was] greatest." At intermediate elevations, they report, there were "clear upward shifts in the elevational ranges of species, consistent with the influence of global warming." And at the highest site, they found species richness actually increased, and "in addition to an increase in richness, abundance has also generally increased at the highest-elevation site."

References

Beirne, B.P. 1955. Natural fluctuations in abundance of British Lepidoptera. *Entomologist's Gazette* **6**: 21–52.

Crozier, L. 2004. Warmer winters drive butterfly range expansion by increasing survivorship. *Ecology* **85**: 231–241.

Dahlhoff, E.P. 2004. Biochemical indicators of stress and metabolism: applications for marine ecological studies. *Annual Review of Physiology* **66**: 183–207.

Dahlhoff, E.P. and Rank, N.E. 2007. The role of stress proteins in responses of a montane willow leaf beetle to environmental temperature variation. *Journal of Biosciences* **32**: 477–488.

Davies, Z.G., Wilson, R.J., Brereton, T.M., and Thomas, C.D. 2005. The re-expansion and improving status of the silver-spotted skipper butterfly (*Hesperia comma*) in Britain: a metapopulation success story. *Biological Conservation* **124**: 189–198.

Davies, Z.G., Wilson, R.J., Coles, S., and Thomas, C.D. 2006. Changing habitat associations of a thermally constrained species, the silver-spotted skipper butterfly, in response to climate warming. *Journal of Animal Ecology* **75**: 247–256.

Dennis, R.L.H. and Sparks, T.H. 2007. Climate signals are reflected in an 89 year series of British Lepidoptera records. *European Journal of Entomology* **104**: 763–767.

Fleishman, E., Austin, G.T., and Murphy, D.D. 2001. Biogeography of Great Basin butterflies: revisiting patterns, paradigms, and climate change scenarios. *Biological Journal of the Linnean Society* **74**: 501–515.

Forister, M.L., McCall, A.C., Sanders, N.J., Fordyce, J.A., Thorne, J.H., O'Brien, J., Waetjen, D.P., and Shapiro, A.M. 2010. Compounded effects of climate change and habitat alteration shift patterns of butterfly diversity. *Proceedings of the National Academy of Sciences USA* **107**: 2088–2092.

Gonzalez-Megias, A., Menendez, R., Roy, D., Brereton, T., and Thomas, C.D. 2008. Changes in the composition of British butterfly assemblages over two decades. *Global Change Biology* **14**: 1464–1474.

Hickling, R., Roy, D.B., Hill, J.K., Fox, R., and Thomas, C.D. 2006. The distributions of a wide range of taxonomic groups are expanding polewards. *Global Change Biology* **12**: 450–455.

Hill, J.K., Thomas, C.D., and Huntley, B. 1999. Climate and habitat availability determine 20th century changes in a butterfly's range margin. *Proceedings of the Royal Society of London, Series B* **266**: 1197–1206.

Hughes, C.L., Dytham, C., and Hill, J.K. 2007. Modelling and analyzing evolution of dispersal in populations at expanding range boundaries. *Ecological Entomology* **32**: 437–445.

Karl, I., Sorensen, J.G., Loeschcke, V., and Fischer, K. 2008. HSP70 expression in the Copper butterfly *Lycaena tityrus* across altitudes and temperatures. *Journal of Evolutionary Biology* **22**: 172–178.

Karl, T.R., Knight, R.W., Easterling, D.R., and Quayle, R.G. 1996. Indices of climate change for the United States. *Bulletin of the American Meteorological Society* **77**: 279–292.

Kerr, J.K. 2001. Butterfly species richness patterns in Canada: energy, heterogeniety, and the potential consequences of climate change. *Conservation Ecology* **5**: 10.

Menendez, R., Gonzalez-Megias, A., Hill, J.K., Braschler, B., Willis, S.G., Collingham, Y., Fox, R., Roy, D.B., and Thomas, C.D. 2006. Species richness changes lag behind climate change. *Proceedings of the Royal Society B* **273**: 1465–1470.

Parmesan, C. 1996. Climate and species' range. *Nature* **382**: 765–766.

Parmesan, C., Ryrholm, N., Stefanescu, C., Hill, J.K., Thomas, C.D., Descimon, H., Huntley, B., Kaila, L., Kullberg, J., Tammaru, T., Tennent, W.J., Thomas, J.A., and Warren, M. 1999. Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature* **399**: 579–583.

Pimm, S.L. 2001. Entrepreneurial insects. *Nature* **411**: 531–532.

Pollard, E. 1988. Temperature, rainfall and butterfly numbers. *Journal of Applied Ecology* **25**: 819–828.

Roy, D.B., Rothery, P., Moss, D., Pollard, E., and Thomas, J.A. 2001. Butterfly numbers and weather: predicting historical trends in abundance and the future effects of climate change. *Journal of Animal Ecology* **70**: 201–217.

Sorensen, J.G., Kristensen, T.N., and Loeschcke, V. 2003. The evolutionary and ecological role of heat shock proteins. *Ecology Letters* **6**: 1025–1037.

Thomas, C.D., Bodsworth, E.J., Wilson, R.J., Simmons, A.D., Davies, Z.G., Musche, M., and Conradt, L. 2001. Ecological and evolutionary processes at expanding range margins. *Nature* **411**: 577–581.

Thomas, C.D. and Jones, T.M. 1993. Partial recovery of a skipper butterfly (*Hesperia comma*) from population refuges: lessons for conservation in a fragmented landscape. *Journal of Animal Ecology* **62**: 472–481.

Thomas, J.A., Thomas, C.D., Simcox, D.J., and Clarke, R.T. 1986. Ecology and declining status of the silver-spotted skipper butterfly (*Hesperia comma*) in Britain. *Journal of Applied Ecology* **23**: 365–380.

Westwood, A.B. and Blair, D. 2010. Effect of regional climate warming on the phenology of butterflies in boreal forests in Manitoba, Canada. *Environmental Entomology* **39**: 1122–1133.

White, P. and Kerr, J.T. 2006. Contrasting spatial and temporal global change impacts on butterfly species richness during the 20th century. *Ecography* **29**: 908–918.

Williams, C.B. 1965. *Insect Migration*. London, UK: Collins.

6.2.4. Other Insects

Hickling et al. (2005) analyzed changes in the northern and southern range boundaries of 37 non-migratory British Odonata (dragonfly and damselfly) species—four of which have northern ranges, 24 of which have southern ranges, and nine of which are ubiquitous—between the two ten-year periods 1960–70 and 1985–95. Their work revealed all but two of the 37 species increased their ranges between the two ten-year periods. They report their "findings that species are shifting northwards faster at their northern range margin than at their southern range margin, are consistent with the results of Parmesan et al. (1999)," adding "this could suggest that species at their southern range margins are less constrained by climate than by other factors."

In prefacing their study of the subject, Nyamukondiwa and Terblanche (2010) write, "acclimation, acclimatization or hardening responses all describe different forms of phenotypic plasticity (i.e. the ability of an organism to respond to environmental stimuli with a change in phenotype)," as described by West-Eberhard (2003) and Whitman (2009). In addition, they state, "phenotypic plasticity may alter the performance of an organism through compensatory modifications of physiological function and tolerance as a result of changes in environmental conditions," suggesting this multifaceted phenomenon will likely play a major role in determining future geographic distributions of insects in a warming world.

Against this backdrop the two South African scientists explored the phenomenon as it operates in two species of fruit fly (*Ceratitis rosa* and *C. capitata*). Using a full-factorial design, as they describe it, one-week-long acclimation responses of each species' critical minimum and maximum temperature ($CT_{\mathbf{min}}$ and $CT_{\mathbf{max}}$) to exposure to temperatures of 20, 25, and 30°C were investigated, as well as their interactions with short-term sub-lethal temperature exposures to the same conditions as arrived at via different rates of warming.

In discussing their findings, the two authors report, "generally, increasing the acclimation temperature significantly increased $CT_{\mathbf{max}}$, whereas decreasing the acclimation temperature significantly lowered $CT_{\mathbf{min}}$." In addition, they found "slower ramping rates significantly increase $CT_{\mathbf{max}}$ in both *C. rosa* and *C. capitata*." This suggests "more time during heating (i.e. a slower heating rate) provides the flies with an opportunity to develop some heat protection, and therefore suggests that *C. capitata*, and possibly also *C. rosa*, might have short-term phenotypic plasticity of high temperature tolerance." They describe this as being "similar to the rapid heat hardening or the heat shock responses in *Drosophila* (Loeschcke and Hoffmann, 2006; Johnson et al., 2009) and other insect species (Huang et al., 2007)."

In light of their observations, Nyamukondiwa and Terblanche conclude fruit flies "are capable of adjusting their thermal tolerance within a single generation at both weekly and hourly time scales," noting "high temperature acclimation improves high temperature tolerance, in keeping with much of the literature on thermal acclimation (Whitman, 2009)." They also state "both *C. rosa* and *C. capitata* have the capacity to adjust their thermal tolerance over short timescales in the wild," further stating this phenomenon will "probably allow both species to track changes in ambient temperature and survive sudden extremes of temperature that might otherwise be potentially lethal," additionally citing Chown and Nicolson (2004) in this regard.

This phenomenon is not restricted to flies. The two researchers indicate, for example, that in several insect species "survival of lethal temperatures or critical thermal limits to activity can be significantly improved by prior exposure to sub-lethal temperatures," citing the work of Lee et al. (1987), Kelty and Lee (2001), Shreve et al. (2004), and Powell and Bale (2006), while further indicating this phenomenon is a major mechanism used by insects to cope with temperature variation at both daily (Kelty and Lee, 2001; Kelty, 2007; Overgaard and Sorensen, 2008) and seasonal (Powell and Bale, 2006; Hoffmann et al., 2005; Terblanche et al., 2006) time scales.

Hillstrom et al. (2010) write, "natural forest systems constitute a major portion of the world's land area, and are subject to the potentially negative effects of both global climate change and invasion by exotic insects." They report, in this regard, "a suite of invasive weevils has become established in the northern hardwood forests of North America," noting that how these insects will respond to continued increases in the air's CO_2 content is "unknown."

Hillstrom et al. collected 200 mating pairs of *Polydrusus sericeus* weevils—which they describe as "the second most abundant invasive weevil species in northern hardwood forests"—from birch trees growing on the perimeter of the Aspen Face facility in Oneida County, Wisconsin (USA). They fed them leaves taken from the birch, aspen, and maple trees growing within either the facility's ambient-air rings or its CO_2-enriched rings (maintained at a target concentration of 560 ppm) under controlled laboratory conditions throughout the summer of 2007, while closely monitoring parameters affecting weevil longevity and fecundity.

According to the five researchers, all from the University of Wisconsin's Department of Entomology, the results indicate feeding the weevils with foliage produced on trees in the CO_2-enriched plots had no effect on male longevity, but it reduced female longevity by 19 percent. They also note "*Polydrusus sericeus* egg production rate declined by 23% and total egg production declined by 29% for females fed foliage produced under elevated CO_2 compared with ambient CO_2."

In light of their findings and the continued upward trend in the air's CO_2 content, Hillstrom et al. conclude, "concentrations of elevated CO_2 above 500 ppm have the potential to decrease *P. sericeus* populations by reducing female longevity and fecundity," which should be particularly beneficial for the northern hardwood forests of North America that are currently growing under atmospheric CO_2 concentrations of 390 ppm and rising.

In one final study focusing on the future effects of rising atmospheric CO_2, as opposed to temperature, Rao et al. (2009) determined what foliage-mediated effects atmospheric CO_2 enrichment might have on another pernicious insect pest. As background for their study, they explain that castor "is an important non-edible oilseed crop grown in many parts of the arid and semi-arid regions of India," and the castor semilooper (*Achaea janata*) and tobacco caterpillar (*Spodoptera litura*) "occur during early and late stages of growth of castor, respectively," during which periods castor oil yields can be reduced "by 30-50% by the semilooper alone," and the tobacco caterpillar "can cause yield losses of 25-40%."

In conducting their study, Rao et al. allowed larvae of both species to feed on castor foliage grown in present-day air (presumed to contain 350 ppm CO_2) and in air enriched with CO_2 to concentrations of 550 and 700 ppm. Their results indicated, "compared to the larvae fed on ambient CO_2 foliage, the larvae fed on 700 and 550 ppm CO_2 foliage exhibited greater consumption." However, the efficiency of conversion of both ingested and digested food into larval biomass "decreased in the case of larvae grown on 700 and 550 ppm CO_2 foliage," so they "grew slower and took longer time (two days more than ambient) to pupation," which would allow significantly more time (~13 percent) for them to be preyed upon by higher orders of creatures, many of which are considered to be much less of a threat to crop production than are insect larvae.

In the case of castor beans, then, it would appear that in addition to the productivity enhancement likely to be provided by the stimulation of photosynthesis driven by atmospheric CO_2 enrichment—an approximate 34 percent increase in response to a 300 ppm increase in the air's CO_2 content (Grimmer and Komor, 1999; Grimmer et al., 1999)—a substantial increase in atmospheric CO_2 likely also would curtail yield losses currently caused by the castor semilooper and tobacco caterpillar.

References

Chown, S.L. and Nicolson, S.W. 2004. *Insect Physiological Ecology: Mechanisms and Patterns*. Oxford, UK: Oxford University Press.

Grimmer, C. and Komor, E. 1999. Assimilate export by leaves of *Ricinus communis* L. growing under normal and elevated carbon dioxide concentrations: the same rate during the day, a different rate at night. *Planta* **209**: 275–281.

Grimmer, C., Bachfischer, T., and Komor, E. 1999. Carbohydrate partitioning into starch in leaves of *Ricinus communis* L. grown under elevated CO_2 is controlled by sucrose. *Plant, Cell and Environment* **22**: 1275–1280.

Hickling, R., Roy, D.B., Hill, J.K., and Thomas, C.D. 2005. A northward shift of range margins in British Odonata. *Global Change Biology* **11**: 502–506.

Hillstrom, M.L., Vigue, L.M., Coyle, D.R., Raffa, K.F., and Lindroth, R.L. 2010. Performance of the invasive weevil *Polydrusus sericeus* is influenced by atmospheric CO_2 and host species. *Agricultural and Forest Entomology* **12**: 285–292.

Hoffmann, A.A., Shirriffs, J., and Scott, M. 2005. Relative importance of plastic versus genetic factors in adaptive differentiation: geographic variation for stress resistance in

Drosophila melanogaster from eastern Australia. *Functional Ecology* **19**: 222–227.

Huang, L.H., Chen, B., and Kang, L. 2007. Impacts of mild temperature hardening on thermo tolerance, fecundity and Hsp gene expression in *Liriomyza huidobrensis*. *Journal of Insect Physiology* **53**: 1199–1205.

Johnson, T.K., Cockerell, F.E., Carrington, L.B., Rako, L., Hoffmann, A.A., and McKechnie, S.W. 2009. The capacity of *Drosophila* to heat harden associates with low rates of heat-shocked protein synthesis. *Journal of Thermal Biology* **34**: 327–331.

Kelty, J.D. 2007. Rapid cold-hardening of *Drosophila melanogaster* in a field setting. *Physiological Entomology* **32**: 343–350.

Kelty, J.D. and Lee Jr., R.E. 2001. Rapid cold-hardening of *Drosophila melanogaster* (Diptera: Drosophilidae) during ecologically based thermoperiodic cycles. *Journal of Experimental Biology* **204**: 1659–1666.

Lee, R.E., Chen, C.P., and Denlinger, D.L. 1987. A rapid cold-hardening process in insects. *Science* **238**: 1415–1417.

Loeschcke, V. and Hoffmann, A.A. 2006. Consequences of heat hardening on a field fitness component in *Drosophila* depend on environmental temperature. *American Naturalist* **169**: 175–183.

Nyamukondiwa, C. and Terblanche, J.S. 2010. Within-generation variation of critical thermal limits in adult Mediterranean and Natal fruit flies *Ceratitis capitata* and *Ceratitis rosa*: thermal history affects short-term responses to temperature. *Physiological Entomology* **35**: 255–264.

Overgaard, J. and Sorensen, J.G. 2008. Rapid thermal adaptation during field temperature variations in *Drosophila melanogaster*. *Cryobiology* **56**: 159–162.

Parmesan, C., Ryrholm, N., Stefanescu, C., Hill, J.K., Thomas, C.D., Descimon, H., Huntley, B., Kaila, L., Kullberg, J., Tammaru, T., Tennent, W.J., Thomas, J.A., and Warren, M. 1999. Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature* **399**: 579–583.

Powell, S.J. and Bale, J.S. 2006. Effect of long-term and rapid cold hardening on the cold torpor temperature of an aphid. *Physiological Entomology* **31**: 348–352.

Rao, M.S., Srinivas, K., Vanaja, M., Rao, G.G.S.N., Venkateswarlu, B., and Ramakrishna, Y.S. 2009. Host plant (*Ricinus communis* Linn.) mediated effects of elevated CO_2 on growth performance of two insect folivores. *Current Science* **97**: 1047–1054.

Shreve, S.M., Kelty, J.D., and Lee, R.E. 2004. Preservation of reproductive behaviors during modest cooling: rapid cold-hardening fine-tunes organismal response. *Journal of Experimental Biology* **207**: 1797–1802.

Terblanche, J.S., Klok, C.J., Krafsur, E.S., and Chown, S.L. 2006. Phenotypic plasticity and geographic variations in thermal tolerance and water loss of tsetse *Glossina pallidipes* (Diptera: Glossinidae): implications for distribution modeling. *American Journal of Tropical Medicine and Hygiene* **74**: 786–794.

West-Eberhard, M.J. 2003. *Developmental Plasticity and Evolution*. New York, NY: Oxford University Press.

Whitman, D.W. 2009. Acclimation. In *Phenotypic Plasticity of Insects. Mechanisms and Consequences*, edited by D.W. Whitman and T.N. Ananthakrishnan, 675–739. Enfield, NH: Science Publishers.

6.2.5. Lizards

Chamaille-Jammes et al. (2006) studied four discontinuous subpopulations of the common lizard (*Lacerta vivipara*), a small live-bearing lacertid that lives in peat bogs and heath lands scattered across Europe and Asia, concentrating on a small region near the top of Mont Lozere in southeast France, at the southern limit of the species' range. More specifically, from 1984 to 2001 they monitored several life-history traits of the subpopulations, including body size, reproduction characteristics, and survival rates, while local air temperatures rose by approximately 2.2°C. They found individual body size increased dramatically in all four lizard populations over the 18-year study period, with snout-vent length expanding by roughly 28 percent. This increase in body size occurred in all age classes and, as they describe it, "appeared related to a concomitant increase in temperature experienced during the first month of life (August)." As a result, they found "adult female body size increased markedly, and, as fecundity is strongly dependent on female body size, clutch size and total reproductive output also increased." In addition, for a population where capture-recapture data were available, they learned "adult survival was positively related to May temperature."

Since all fitness components investigated responded positively to the increase in temperature, the French researchers stated, "it might be concluded that the common lizard has been advantaged by the shift in temperature." This finding, in their words, stands in stark contrast to the "habitat-based prediction that these populations located close to mountain tops on the southern margin of the species range should be unable to cope with the alteration of their habitat." They concluded, "to achieve a better prediction of a species persistence, one will probably need to combine both habitat and individual-based approaches.” Furthermore, they note individual responses, such as those documented in their study (which were all positive), represent “the ultimate driver of a species response to climate change.”

In providing some background for their study of montane rainforest lizards, Bell et al. (2010) note tropical species long have been considered to be “especially sensitive to climatic fluctuations because their narrow thermal tolerances and elevational ranges can restrict their ability to persist in, or disperse across, alternate habitats.” NASA’s James Hansen expressed this concept much more bluntly on 21 November 2006—when accepting the World Wildlife Fund’s Duke of Edinburgh Conservation Medal at St. James Palace in London—by declaring, “species living on the biologically diverse slopes leading to mountains will be pushed off the planet” as the planet warms, opining—as we have already noted he also did before the U.S. House of Representatives—that there will simply be no place else for them to go.

In an empirical test of this idea, Bell et al. compared “responses to historical climate fluctuation in a montane specialist skink, *Lampropholis robertsi*, and its more broadly distributed congener, *L. coggeri*, both endemic to rainforests of northeast Australia,” by combining “spatial modeling of potential distributions under representative palaeoclimates, multi-locus phylogeography and analyses of phenotypic variation.” This work revealed, in the words of the seven scientists, that “both species exhibit pronounced phylogeographic structuring for mitochondrial and nuclear genes, attesting to low dispersal and high persistence across multiple isolated regions.” Referring specifically to *L. robertsi*, the researchers state their evidence demonstrates “persistence and isolation” of most populations of the montane species “throughout the strong climate oscillations of the late Pleistocene, and likely extending back to the Pliocene.”

Noting many of the isolated refugia they studied “are particularly rich in narrowly endemic species,” Bell et al. state this characteristic has been attributed to “their relative stability during recent episodes of climate change (Williams and Pearson, 1997; Yeates et al., 2002; Graham et al., 2006; VanDerWal et al., 2009).” Furthermore, they indicate these observations “support the general hypothesis that isolated tropical montane regions harbor high levels of narrow-range taxa because of their resilience to past climate change,” citing Fjeldsa and Lovett (1997) and Jetz et al. (2004). Thus, they write, “at first sight, species such as *L. robertsi* would seem especially prone to local extinction and loss of considerable genetic diversity with any further warming; yet, these populations and those of other high-montane endemic species (*Cophixalus* frogs; Hoskin, 2004) have evidently persisted through past warming events.”

References

Bell, R.C., Parra, J.L., Tonione, M., Hoskin, C.J., Mackenzie, J.B., Williams, S.E., and Moritz, C. 2010. Patterns of persistence and isolation indicate resilience to climate change in montane rainforest lizards. *Molecular Ecology* **19**: 2531–2544.

Chamaille-Jammes, S., Massot, M., Aragon, P., and Clobert, J. 2006. Global warming and positive fitness response in mountain populations of common lizards *Lacerta vivipara*. *Global Change Biology* **12:** 392–402.

Fjeldsa, J. and Lovett, J.C. 1997. Biodiversity and environmental stability. *Biodiversity and Conservation* **6**: 315–323.

Graham, C.H., Moritz, C., and Williams, S.E. 2006. Habitat history improves prediction of biodiversity in rainforest fauna. *Proceedings of the National Academy of Sciences, USA* **103**: 632–636.

Hoskin, C.J. 2004. Australian microhylid frogs (*Cophixalus and Austrochaperina*): phylogeny, taxonomy, calls, distributions and breeding biology. *Australian Journal of Zoology* **52**: 237–269.

Jetz, W., Rahbek, C., and Colwell, R.K. 2004. The coincidence of rarity and richness and the potential signature of history in centers of endemism. *Ecology Letters* **7**: 1180–1191.

VanDerWal, J., Shoo, L.P., and Williams, S.E. 2009. New approaches to understanding late Quaternary climate fluctuations and refugial dynamics in Australian wet tropical rain forests. *Journal of Biogeography* **36**: 291–301.

Williams, S.E. and Pearson, R.G. 1997. Historical rainforest contractions, localized extinctions and patterns of vertebrate endemism in the rainforests of Australia’s wet tropics. *Proceedings of the Royal Society of London Series B - Biological Sciences* **264**: 709–716.

Yeates, D.K., Bouchard, P., and Monteith, G.B. 2002. Patterns and levels of endemism in the Australian wet tropics rainforest: evidence from flightless insects. *Invertebrate Systematics* **16**: 605–661.

6.2.6. Mammals

Norment et al. (1999) summarized and compared the results of many surveys of mammal populations observed along the Thelon River and its tributaries in the Canadian Northwest Territories from the 1920s through much of the 1990s. Over this time period, red squirrel, moose, porcupine, river otter, and beaver were found to have established themselves in the area, significantly increasing its biodiversity. The three researchers stated these primarily northward range expansions could be explained by "a recent warming trend at the northern treeline during the 1970s and 1980s." Alternatively, they noted the influx of new species may have been due to "increasing populations in more southerly areas." But in either case, we have a situation where several types of mammals appear to have fared quite well in the face of increasing temperatures in this forest-tundra landscape.

Millar and Westfall (2010) studied American pikas, small generalist herbivores that are relatives of rabbits and hares, inhabit patchily distributed rocky slopes of western North American mountains, and are good at tolerating cold. Given the latter characteristic, it is not surprising that pikas are widely believed to have a physiological sensitivity to warming, which when "coupled with the geometry of decreasing area at increasing elevation on mountain peaks," in the words of the two scientists, "has raised concern for the future persistence of pikas in the face of climate change." In fact, they note, the species "has been petitioned under California [USA] state and federal laws for endangered species listing."

In a study designed to investigate the validity of the basis for that classification, Millar and Westfall developed a rapid assessment method for determining pika occurrence and used it "to assess geomorphic affinities of pika habitat, analyze climatic relationships of sites, and evaluate refugium environments for pikas under warming climates." The researchers gathered data over the course of two field seasons in the Sierra Nevada Mountains of California, the southwestern Great Basin of California and Nevada, and the central Great Basin of Nevada, as well as a small area in the central Oregon Cascades.

In reporting their findings, the two U.S. Forest Service researchers state, "whereas concern exists for diminishing range of pikas relative to early surveys, the distribution and extent in our study, pertinent to four subspecies and the Pacific southwest lineage of pikas, resemble the diversity range conditions described in early 20th-century pika records (e.g., Grinnell and Storer, 1924)." The lowest site at which they detected the current presence of pikas, at an elevation of 1827 meters, "is below the historic lowest elevation of 2350 m recorded for the subspecies by Grinnell and Storer (1924) in Yosemite National Park; below the low elevation range limit for the White Mountains populations given by Howell (1924) at 2440 m; and below the lowest elevation described for the southern Sierra Nevada populations of 2134 m (Sumner and Dixon, 1953)." In addition, they write, "a similar situation occurred for another lagomorph of concern, pygmy rabbit (*Brachylagus idahoensis*), where a rapid assessment method revealed much wider distribution than had been implied from historic population databases or resurvey efforts (Himes and Drohan, 2007)."

Millar and Westfall thus conclude "pika populations in the Sierra Nevada and southwestern Great Basin are thriving, persist in a wide range of thermal environments, and show little evidence of extirpation or decline." Moreover, the documentation of a similar phenomenon operating among pygmy rabbits suggests still other animals may also be better able to cope with various aspects of climate change than we have been led to believe possible.

In a study of moose, Lowe et al. (2010) write, "intuitively, we would expect that a large northern ungulate with low tolerance for high temperatures would gradually be pushed out of the southern reaches of its range as the climate continues to warm and temperature conditions become increasingly unfavorable," the logic being that "persistent temperatures above the upper critical limit will suppress foraging time and consequently cause mass loss during the summer, and that this reduced condition could affect overwinter survival and productivity," citing the work of Schwartz and Renecker (1998).

The authors thus "tested the hypothesis that climate limits the southern distribution of moose (*Alces alces*) by documenting space use and behavior of 36 females at the margin of the species' range in Ontario, Canada." They did this in 2006, 2007, and 2008 through the use of "global positioning system (GPS) telemetry to study their habitat use and movement," in an attempt "to document behavioral mechanisms indicative of adaptive responses to warm temperatures." This work was conducted during periods of the year when ambient temperatures frequently exceeded known critical thresholds (-5°C in winter and 14°C in summer) that had been demonstrated by Dussault et al. (2004) to induce heat stress in moose.

Lowe et al. state they "detected no differences in habitat use relative to thermoregulation thresholds," which they deemed to be particularly important during the summer, when they report the temperatures of all habitat classes greatly exceeded—by an average of 6°C, and by as much as 19°C in the first week of August 2006—the 14°C threshold for a large extent of the day and partially during the night. As a result, the three Canadian researchers conclude "moose in their southern range either ameliorate heat stress at a finer resolution than we measured or are more resilient to temperature than previously thought."

In a contemporaneous study, Garroway et al. (2010) write, "many species have responded to contemporary climate change through shifts in their geographic ranges," and they state "this could lead to increased sympatry [i.e., partially overlapping ranges] between recently diverged species, likely increasing the potential for hybridization." They further note this phenomenon "can be positive if it increases genetic variability and creates new gene combinations that increase the potential to adapt."

To test this hypothesis, between 2002 and 2004, Garroway et al. conducted more than 1,600 successful live-trappings of southern (*Glaucomys volans*) and northern (*Glaucomys sabrinus*) flying squirrels throughout portions of Ontario, Canada, and Pennsylvania, USA. From the hairs of these squirrels they extracted nuclear and mitochondrial DNA, which they analyzed in ways that allowed them to obtain the following results.

It already had been determined by Bowman et al. (2005) that *G. volans* had expanded its range from the south beginning in the mid-1990s in concert with a series of warm winters; and now the nine Canadian and U.S. researchers' new findings indicate "the expansion of *G. volans* north into the *G. sabrinus* range in Ontario has resulted in the formation of a new hybrid zone." In addition, their analyses suggest "the hybridization was recent, coinciding with the recent increase in sympatry." Thus, they go on to state that, to their knowledge, "this is the first report of hybrid zone formation following a range expansion induced by contemporary climate change." These unique findings indicate yet another way in which living organisms can both physically (by shifting their ranges) and genetically (by hybridization) successfully confront the challenges that may be presented to them by global warming.

Pockley (2001) reported the results of a survey of the plants and animals on Australia's Heard Island, a small island located 4,000 kilometers southwest of Perth. Over the prior 50 years, this sub-Antarctic island had experienced a local warming of approximately 1°C that had resulted in a modest (12 percent) retreat of its glaciers. For the first time in a decade, scientists were attempting to document what this warming and melting had done to the ecology of the island.

Pockley began by stating the scientists' work had unearthed "dramatic evidence of global warming's ecological impact," which obviously consisted of "rapid increases in flora and fauna." He quoted Dana Bergstrom, an ecologist at the University of Queensland in Brisbane, as stating that areas once poorly vegetated had become "lush with large expanses of plants." And he added that populations of birds, fur seals, and insects also had expanded rapidly. One of the real winners in this regard was the king penguin, which, according to Pockley, had "exploded from only three breeding pairs in 1947 to 25,000."

Eric Woehler of Australia's environment department was listed as a source of other equally remarkable information, such as the Heard Island cormorant's comeback from "vulnerable" status to a substantial 1,200 pairs, and fur seals' emergence from "near extinction" to a population of 28,000 adults and 1,000 pups. Given such findings, it can be concluded the regional warming experienced at Heard Island actually rescued these threatened animal populations from the jaws of extinction.

References

Bowman, J., Holloway, G.L., Malcolm, J.R., Middel, K.R., and Wilson, P.J. 2005. Northern range boundary dynamics of southern flying squirrels: evidence of an energetic bottleneck. *Canadian Journal of Zoology* **83**: 1486–1494.

Dussault, C., Ouellet, J.-P., Courtois, R., Huot, J., Breton L., and Larochelle, J. 2004. Behavioural responses of moose to thermal conditions in the boreal forest. *Ecoscience* **11**: 321–328.

Garroway, C.J., Bowman, J., Cascaden, T.J., Holloway, G.L., Mahan, C.G., Malcolm, J.R., Steele, M.A., Turner, G., and Wilson, P.J. 2010. Climate change induced hybridization in flying squirrels. *Global Change Biology* **16**: 113–121.

Grinnell, J. and Storer, T.I. 1924. *Animal Life in the Yosemite.* Berkeley, CA: University of California Press.

Himes, J.G. and Drohan, P.J. 2007. Distribution and habitat selection of the pygmy rabbit, *Brachylagus idahoensis*, in Nevada (USA). *Journal of Arid Environments* **68**: 371–382.

Howell, A.H. 1924. *Revision of the American Pikas.* North American Fauna No. 47. Washington, DC: USDA Bureau of Biological Survey.

Lowe, S.J., Patterson, B.R., and Schaefer, J.A. 2010. Lack of behavioral responses of moose (*Alces alces*) to high ambient temperatures near the southern Periphery of their range. *Canadian Journal of Zoology* **88**: 1032–1041.

Millar, C.I. and Westfall, R.D. 2010. Distribution and climatic relationships of the American Pika (*Ochotona princeps*) in the Sierra Nevada and Western Great Basin, U.S.A.: periglacial landforms as refugia in warming climates. *Arctic, Antarctic, and Alpine Research* **42**: 76–88.

Norment, C.J., Hall, A., and Hendricks, P. 1999. Important bird and mammal records in the Thelon River Valley, Northwest Territories: range expansions and possible causes. *The Canadian Field-Naturalist* **113**: 375–385.

Pockely, P. 2001. Climate change transforms island ecosystem. *Nature* **410**: 616.

Schwartz, C.C. and Renecker, L.A. 1998. Nutrition and energetics. In *Ecology and Management of the North American Moose*, edited by A.W. Franzmann and C.C. Schwartz, C.C., 441–478. Washington, DC: Smithsonian Institution.

Sumner, L. and Dixon, J.S. 1953. *Birds and Mammals of the Sierra Nevada.* Berkeley, Ca: University of California Press.

6.2.7. Worms

Small oligochaete worms known as enchytraeids, according to Maraldo et al. (2010), "are widely distributed from the Arctic to tropical areas, and typically inhabit the organic horizon in soils," where they "contribute to the decomposition processes and nutrient mineralization." These activities have been shown to lead to increased nutrient availability and uptake by plants (Laakso and Setala, 1999; Cragg and Bardgett, 2001). Enchytraeids provide these benefits directly, as these authors describe it, "by consuming large amounts of organic matter," and indirectly "by their feeding activity and modifications of soil structure." And they note, in this regard, "the presence of enchytraeids is especially important in nutrient poor ecosystems" such as "temperate heathland and northern coniferous forests, where their biomass dominates the soil faunal community," citing the work of Cragg (1961) and Swift et al. (1998).

Working on a hilly nutrient-poor sandy soil with a dry heath/grassland cover at Brandbjerg, Denmark, the seven scientists conducted an experiment beginning October 2005 and extending through 2007. They studied the individual and combined effects of (1) soil warming: a mean daily temperature increase of 0.3°C in winter and 0.7°C in summer at a depth of 5 cm, provided by a scaffolding that carried a curtain—which reflected the outgoing infrared radiation from the soil/plant surface back toward the ground—that was automatically pulled over the vegetation at sunset and retracted at sunrise; (2) drought: peak soil water content reductions of 11 percent and 13 percent compared to control plots in 2006 and 2007, provided by waterproof curtains that were automatically pulled over the vegetation during rain events; and (3) atmospheric CO_2 enrichment: a CO_2 concentration increase from 382 to 481 ppm, provided by a free-air CO_2 enrichment (FACE) system.

Maraldo et al. report their experimentally imposed warming had no significant impact on enchytraeid biomass production, but their drought treatment decreased it by 40 percent. On the other hand, the extra 99 ppm of CO_2 stimulated enchytraeid biomass by 40 percent. They remark that at certain times this latter phenomenon was "especially positive," as in the summer of 2007, when they state "the total enchytraeid biomass in the CO_2 plots was increased by 108% compared to ambient plots." They found no interactions among the three factors, so "the positive effect of increased CO_2 [+40%] and the negative effect of drought [-40%] were cancelled out when applied in combination."

References

Cragg, J.B. 1961. Some aspects of the ecology of moorland animals. *Journal of Ecology* **49**: 477.

Cragg, R.G. and Bardgett, R.D. 2001. How changes in soil faunal diversity and composition within a trophic group influence decomposition processes. *Soil Biology and Biochemistry* **33**: 2073–2081.

Laakso, J. and Setala, H. 1999. Sensitivity of primary production to changes in the architecture of belowground food webs. *Oikos* **87**: 58–64.

Maraldo, K., Krogh, P.H., van der Linden, L., Christensen, B., Mikkelsen, T.N., Beier, C., and Holmstrup, M. 2010.

The counteracting effects of atmospheric CO_2 concentrations and drought episodes: studies of enchytraeid communities in a dry heathland. *Soil Biology & Biochemistry* **42**: 1958–1966.

Swift, M.J., Andren, O., Brussaard, L., Briones, M., Couteaux, M.M., Ekschmitt, K., Kjoller, A., Loiseau, P., and Smith, P. 1998. Global change, soil biodiversity, and nitrogen cycling in terrestrial ecosystems—three case studies. *Global Change Biology* **4**: 729–743.

6.2.8. Other Studies

Results of other studies also suggest the model-based species extinction hypothesis is unlikely to occur. In a review paper published in *Current Biology*, for example, Erwin (2009) explored past epochs and the myriad nooks and crannies of contemporary Earth, all in a search for the primary trigger of speciation. His conclusion? Warmth is the fire that fuels the process by which species originate, whereas cold tends to destroy what warmth produced.

Headquartered in the Department of Paleobiology at the National Museum of Natural History in Washington, DC (USA), Erwin writes, “some of the best evidence for a link between biodiversity and climate comes from latitudinal gradients in diversity, which provide an avenue to explore the more general relationship between climate and evolution.” In reviewing that evidence, he indicates “among the wide range of biotic hypotheses, those with the greatest empirical support indicate that warmer climates [1] have provided the energetic foundation for increased biodiversity by fostering greater population size and thus increased extinction resistance, [2] have increased metabolic scope, [3] have allowed more species to exploit specialized niches as a result of greater available energy, and [4] have generated faster speciation and/or lower extinction rates.” He states “in combination with geologic evidence for carbon dioxide levels and changing areas of tropical seas, these observations provide the basis for a simple, first-order model of the relationship between climate through the Phanerozoic and evolutionary patterns and diversity,” and he adds “such a model suggests that we should expect greatest marine diversity during globally warm intervals,” as is typically also found to be the case for terrestrial diversity.

Erwin notes “the three best-studied mass extinction events are associated with sharp changes in climate and support the contention that rapid shifts in climate can reduce global diversity,” which sounds much like the mantra of the IPCC with respect to global warming. However, the climate shifts Erwin cites consist mostly of cooling, and it is not only the shift to cooling but stagnating in a cool state that bodes badly for Earth’s biodiversity. As Erwin describes it, “the long interval of stagnant evolution during the Permo-Carboniferous glaciation is consistent with studies of modern-day latitudinal diversity that [indicate] rates of evolutionary innovation and diversification are higher in high-energy climates than in low-energy climates.”

In further explanation of this conceptual framework, Erwin notes “contemporary studies suggest a positive relationship between high-energy climates and [1] increased diversification rates, [2] increased number of niches because of increased metabolic scope, and [3] more specialized niches, and possibly because of [4] niche construction.” Indeed, he states “studies showing that the tropics are a cradle of diversity, pumping clade representatives into higher latitudes, as well as evidence of increased ordinal level originations in the tropics, and of the sudden appearance of several mammalian groups during the Paleocene-Eocene Thermal Maximum suggest an asymmetric pattern of innovations associated with high-energy climate regimes.”

Erwin’s parting comment in this regard is his statement, “there is an intriguing possibility that diversity does not track climate, but rather builds up during warm intervals but without falling by proportional amounts when climates turn cooler,” with the result that “warmer climates may serve as an evolutionary diversification pump with higher diversity persisting [throughout following cooler periods], at least for a time.”

Whatever the details may be, two generalizations clearly can be made: warmth typically begets speciation, whereas cold tends to lead to species extinctions.

Independent support for this thesis was provided in two papers by Jaramillo et al. (2010) and Willis et al. (2010). Jaramillo et al. (2010) examined the Paleocene-Eocene Thermal Maximum (PETM), which occurred some 56.3 million years ago, at sites in Venezuela and Columbia. The PETM provides an interesting analog to the Current Warm Period, and it is postulated that at that time, carbon dioxide rose rapidly over a period of 10,000 to 20,000 years and global temperatures were elevated approximately 5 °C for 100,000 to 200,000 years.

The PETM was clearly identifiable in terms of temperature, where it was between 31 and 34 °C during the peak of global warmth. Using pollen and other organic materials, the authors were also able to identify various plant species that existed during this period. In spite of the high temperatures and possibly less-moist conditions, it was found the number of drought-tolerant plants did not increase, nor were moisture-requiring plants shown to decrease during the PETM. These facts led the authors to speculate that either rainfall or water use efficiency increased because of higher levels of atmospheric carbon dioxide, which would have compensated for the higher temperatures.

It was also noted the PETM brought a radical increase in diversity, measured in both absolute terms (number of species/taxa) and in terms of evenness (relatively more even species percentages). This was achieved by addition of new taxa. The origination rate for new taxa during the PETM was two to six times higher than during the periods before and after, but extinction rates were not unusual. The species/taxa that originated, and the overall diversity, continued after the PETM. Thus the gains in plant species richness during the PETM were relatively persistent rather than transient.

It is believed that tropical forests of today are currently growing in climates near the maximum temperature the plants can tolerate (~27.5 °C), and that future global warming in tropical zones may stress plants and cause a reduction in forest growth, perhaps leading some species to extinction. However, as shown by Jaramillo et al., temperatures of 31 to 34 °C seem not only to have been tolerated but to have caused a burst of speciation in the PETM, including major taxa that persist today. The high temperatures of the PETM were not detrimental to the tropical moist forests examined in this study.

In the study by Willis et al. (2010), past historical periods were identified in which climate was similar to that projected by global climate models for the next century or so, or in which the rate of temperature change was unusually rapid. These real-world periods were examined to see if any real-world climate-related extinctions had occurred.

The first period they examined was the Eocene Climatic Optimum (53–51 million years ago), when the atmosphere's CO_2 concentration exceeded 1,200 ppm and tropical temperatures were 5–10°C warmer than current values. Far from causing extinctions of the tropical flora (where the data are best), the four researchers report, "all the evidence from low-latitude records indicates that, at least in the plant fossil record, this was one of the most biodiverse intervals of time in the Neotropics." They also note "ancestors of many of our modern tropical and temperate plants evolved ... when global temperatures and CO_2 were much higher than present, ... indicating that they have much wider ecological tolerances than are predicted based on present-day climates alone."

The second period they examined consisted of two rapid-change climatic events in the Holocene—one at 14,700 years ago and one at 11,600 years ago—when temperatures increased in the mid- to high-latitudes of the Northern Hemisphere by up to 10°C over periods of less than 60 years. There is evidence from many sites for rapid plant responses to rapid warming during these events. The authors note, "at no site yet studied, anywhere in the world, is there evidence in the fossil record for large-scale climate-driven extinction during these intervals of rapid warming." On the other hand, they report extinctions did occur due to the cold temperatures of the glacial epoch, when subtropical species in southern Europe were driven out of their ecological tolerance zone.

The study by Willis et al. also makes use of recent historical data, as in the case of the 3°C rise in temperature at Yosemite Park over the past 100 years. Comparing surveys of mammal fauna conducted near the beginning and end of this period, they detected some changes, but no local extinctions. Thus they determined for all of the periods they studied, with either very warm temperatures or very rapid warming, there were no detectable extinctions.

Taking a slightly different approach to the subject were D'Odorico et al. (2008), who write, "recent climate change predictions indicate that, in addition to trends in the mean values of climate variables, an increase in interannual variability is expected to occur in the near future." Also noting "environmental fluctuations are usually believed to play a 'destructive role' in ecosystem dynamics," they explore the validity of this latter assumption in the context of current climate model predictions, asking, "Can environmental variability have only 'negative' effects on ecosystem dynamics?"

After lengthy mathematical analysis, D'Odorico et al. determined "opportunities for species existence/coexistence are found to increase with 'moderate' values of the variance of environmental fluctuations, while they decrease when these fluctuations are relatively strong." This outcome constitutes what has come to be known as the "intermediate disturbance hypothesis," which grew out of the work of Connell (1978)—who, in the words of D'Odorico et al., suggested "coral reefs and rain forests maintain high levels of diversity only in a non-equilibrium state"—and Huston (1979), who noted "most communities have relatively high levels of diversity because environmental variability maintains them in a non-equilibrium state."

Noting numerous real-world indications (Chapin et al., 1997; Steneck et al., 2002; Bengtsson et al., 2003; Elmqvist et al., 2003; Bellwood et al., 2004; Folke et al., 2004) that "biodiversity may enhance ecosystem resilience," the four researchers provide a theoretical basis for this phenomenon, demonstrating the validity of the ecological equivalent of the common dictum of physical exercise gurus: no pain, no gain. In light of this exercise, it would appear what the IPCC looks upon as unfavorable may be just what is needed to (1) increase the diversity and resilience of myriads of terrestrial and aquatic ecosystems and (2) propel them to higher levels of activity in the brave new world of our CO_2-enriched future.

Finally, in an overview of a symposium titled "Molecules to Migration: Pressures of Life"— held in Africa on the Maasai Mara National Reserve of Kenya—Fuller et al. (2010) write the theoretical approach most commonly used to predict future species distributions in a CO_2-enriched and warmer world (the "climate envelope" approach) assumes "animals and plants can persist only in areas with an environment similar to the one they currently inhabit." This approach "typically ignores the potential physiological capacity of animals to respond to climate change," and they go on to explain how "behavioral, autonomic, and morphological modifications such as nocturnal activity, selective brain cooling, and body color may potentially serve as buffers to the consequences of climate change."

The six scientists begin by noting all organisms "have the capacity to adapt to changing environmental conditions both by phenotypic plasticity within a life span and by microevolution over a few life spans." In the latter instance, they note, "there is evidence that microevolution—that is, heritable shifts in allele frequencies in a population (without speciation)—has occurred in response to climate warming," citing Bradshaw and Holzapfel (2006, 2008). And in the first case, they state phenotypic plasticity "is likely to represent the first response of individual organisms," and they report "adaptive changes in phenotype induced by climate change have been documented, for example, in the morphology and phenology of birds (Charmantier et al., 2008) and mammals (Reale et al., 2003; Linnen et al., 2009; Maloney et al., 2009; Ozgul et al., 2009)."

Fuller et al. cite the work of Pincebourde et al. (2009), who "showed that intertidal sea stars can behaviorally regulate their thermal inertia by increasing their rate of water uptake during high tide on hot days," which is "a response that affords protection against extreme aerial temperatures during subsequent low tides." Next they note "exposure of humans to hot conditions on successive days induces an increase in sweat capacity (Nielsen et al., 1993)." And they state "other adaptations also ensue, including plasma volume expansion and decreased electrolyte content of sweat," such that "a typical unacclimatized male, who can produce about 600 ml of sweat per hour, can double that output with heat acclimatization (Henane and Valatx, 1973)," which "phenotypic adaptation (in this case, heat acclimatization) can alter physiological tolerance (the risk of heat illness)."

The Australian, South African, and U.S. scientists also cite several studies—Zervanos and Hadley (1973), Belovsky and Jordan (1978), Grenot (1992), Hayes and Krausman (1993), Berger et al. (1999), Dussault et al. (2004), Maloney et al. (2005), and Hetem et al. (2010)—of large herbivores that "increase nocturnal activity in the face of high diurnal heat loads." And they state "another adaptation that may enhance plasticity in response to aridity that is available to oryx and other artiodactyls, as well as members of the cat family (Mitchell et al., 1987), is selective brain cooling," whereby cooling the hypothalamus and the temperature sensors that drive evaporative heat loss "inhibits evaporative heat loss and conserves body water (Kuhnen, 1997; Fuller et al., 2007)," which "is likely to be particularly valuable to animals under concurrent heat stress and dehydration." Finally, they suggest maintaining genetic diversity for a trait such as fur or feather color that adapts various organisms to different thermal environments "may provide important plasticity for future climate change," citing Millien et al. (2006), and they add "there is already evidence that, over the past 30 years as the climate has warmed, the proportion of dark-colored to light-colored Soay sheep has decreased on islands in the outer Hebrides," citing Maloney et al. (2009).

Clearly, much of Earth's animal life is well-endowed with inherent abilities to cope, either through behavior or otherwise, with climate changes over a period of a few generations, a single generation, or even in real time.

References

Bellwood, D.R., Houghes, T.P., Folke, C., and Nystrom, M. 2004. Confronting the coral reef crisis. *Nature* **429**: 827–833.

Belovsky, G.E. and Jordan, P.A. 1978. The time-energy budget of a moose. *Theoretical Population Biology* **14**: 76–104.

Bengtsson, J., Angelstam, P., Elmqvist, T., Emanuelsson, U., Folke, C., Ihse, M., Moberg, F., and Nystrom, M. 2003. Reserves, resilience and dynamic landscapes. *Ambio* **32**: 389–396.

Berger, A., Scheibe, K.-M., Eichhorn, K., Scheibe, A., and Streich, J. 1999. Diurnal and ultradian rhythms of behavior in a mare group of Przewalski horse (*Equus ferus przewalskii*), measured through one year under semi-reserve conditions. *Applied Animal Behavior Science* **64**: 1–17.

Bradshaw, W.E. and Holzapfel, C.M. 2006. Climate change: evolutionary response to rapid climate change. *Science* **312**: 1477–1478.

Bradshaw, W.E. and Holzapfel, C.M. 2008. Genetic response to rapid climate change: it's seasonal timing that matters. *Molecular Ecology* **17**: 157–166.

Chapin III, F.S., Walker, B.H., Hobbs, R.J., Hooper, D.U., Lawton, J.H., Sala, O.E., and Tilman, D. 1997. Biotic controls of the functioning of ecosystems. *Science* **277**: 500–504.

Charmantier, A., McCleery, R.H., Cole, L.R., Perrins, C., Kruuk, L.E.B., and Sheldon, B.C. 2008. Adaptive phenotypic plasticity in response to climate change in a wild bird population. *Science* **320**: 800–803.

Connell, J.H. 1978. Diversity in tropical rain forests and coral reefs: high diversity of trees and corals is maintained only in a non-equilibrium state. *Science* **199**: 1302–1310.

D'Odorico, P., Laio, F., Ridolfi, L., and Lerdau, M.T. 2008. Biodiversity enhancement induced by environmental noise. *Journal of Theoretical Biology* **255**: 332–337.

Dussault, C., Ouellet, J.P., Courtois, R., Huot, J., Breton, L., and Larochelle, J. 2004. Behavioral responses of moose to thermal conditions in the boreal forest. *Ecoscience* **11**: 321–328.

Elmqvist, T., Folke, C., Nystrom, M., Peterson, G., Bengtsson, L., Walker, B., and Norberg, J. 2003. Response diversity and ecosystem resilience. *Frontiers in Ecology and Environment* **1**: 488–494.

Erwin, D.H. 2009. Climate as a driver of evolutionary change. *Current Biology* **19**: R575–R583.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., and Holling, C.S. 2004. Regime shifts, resilience and biodiversity in ecosystem management. *Annual Review of Ecology and Evolution Systems* **35**: 557–581.

Fuller, A., Dawson, T., Helmuth, B., Hetem, R.S., Mitchell, D., and Maloney, S.K. 2010. Physiological mechanisms in coping with climate change. *Physiological and Biochemical Zoology* **83**: 713–720.

Fuller, A., Meyer, L.C.R., Mitchell, D., and Maloney, S.K. 2007. Dehydration increases the magnitude of selective brain cooling independently of core temperature in sheep. *American Journal of Physiology* **293**: R438–R446.

Grenot, C.J. 1992. Ecophysiological characteristics of large herbivorous mammals in arid Africa and the Middle East. *Journal of Arid Environments* **23**: 125–155.

Hayes, C.L. and Krausman, P.R. 1993. Nocturnal activity of female desert mule deer. *Journal of Wildlife Management* **57**: 897–904.

Henane, R. and Valatx, J.L. 1973. Thermoregulatory changes induced during heat acclimatization by controlled hyperthermia in man. *Journal of Physiology* **230**: 255–271.

Hetem, R.S., Strauss, W.M., Fick, L.G., Maloney, S.K., Meyer, L.C., Shobrak, M., Fuller, A., and Mitchell, D. 2010. Variation in the daily rhythm of body temperature of free-living Arabian oryx (*Oryx leucoryx*): does water limitation drive heterothermy? *Journal of Comparative Physiology B* **180**: 10.1007/s00360-010-0480-z.

Huston, M. 1979. A general hypothesis of species diversity. *American Naturalist* **113**: 81–101.

Jaramillo, C., Ochoa, D., Contreras, L., Pagani, M., Carvajal-Ortiz, H., Pratt, L.M., Krishnan, S., Cardona, A., Romero, M., Quiroz, L., Rodriguez, G., Rueda, M.J., de la Parra, F., Morón, S., Green, W., Bayona, G., Montes, C., Quintero, O., Ramirez, R., Mora, G., Schouten, S., Bermudez, H., Navarrete, R., Parra, F., Alvarán, M., Osorno, J., Crowley, J.L., Valencia, V., and Vervoort, J. 2010. Effects of rapid global warming at the Paleocene-Eocene boundary on neotropical vegetation. *Science* **330**: 957–961

Kuhnen, G. 1997. Selective brain cooling reduces respiratory water loss during heat stress. *Comparative Biochemistry and Physiology A* **118**: 891–895.

Linnen, C.R., Kingsley, E.P., Jensen, J.D., and Hoekstra, H.E. 2009. On the origin and spread of an adaptive allele in deer mice. *Science* **325**: 1095–1098.

Maloney, S.K., Fuller, A., and Mitchell, D. 2009. Climate change: is the dark Soay sheep endangered? *Biological Letters* **5**: 826–829.

Maloney, S.K., Moss, G., Cartmell, T., and Mitchell, D. 2005. Alteration in diel activity patterns as a thermoregulatory strategy in black wildebeest (*Connochaetes gnou*). *Journal of Comparative Physiology A* **191**: 1055–1064.

Millien, V., Lyons, S.K., Olson, L., Smith, F.A., Wilson, A.B., and Yom-Tov, Y. 2006. Ecotypic variation in the context of global climate change: revisiting the rules. *Ecology Letters* **9**: 853–869.

Mitchell, D., Laburn, H.P., Nijland, M.J.M., and Zurovsky, Y. 1987. Selective brain cooling and survival. *South African Journal of Science* **83**: 598–604.

Nielsen, B., Hales, J.R.S., Strange, S., Christensen, N.J., Warberg, J., and Saltin, B. 1993. Human circulatory and thermoregulatory adaptations with heat acclimation and exercise in a hot, dry environment. *Journal of Physiology* **46**: 467–485.

Ozgul, A., Tuljapurkar, S., Benton, T.G., Pemberton, J.M., Clutton-Brock, T.H., and Coulson, T. 2009. The dynamics of phenotypic change and the shrinking sheep of St. Kilda. *Science* **325**: 464–467.

Pincebourde, S., Sanford, E., and Helmuth, B. 2009. An intertidal sea star adjusts thermal inertia to avoid extreme body temperatures. *American Naturalist* **174**: 890–897.

Reale, D., McAdam, A.G., Boutin, S., and Berteaux, D. 2003. Genetic and plastic responses of a northern mammal to climate change. *Proceedings of the Royal Society B* **270**: 591–596.

Steneck, R.S., Graham, M.H., Bourque, B.J., Corbett, D., Erlandson, J.M., Estes, J.A., and Tegner, M.J. 2002. Kelp forest ecosystems: biodiversity, stability, resilience and future. *Environmental Conservation* **29**: 436–459.

Willis, K.J., Bennett, K.D., Bhagwat, S.A., and Birks, H.J.B. 2010. Perspective: 4 deg C and beyond: what did this mean for biodiversity in the past? *Systematics and Biodiversity* **8**: 3–9.

Zervanos, S.M. and Hadley, N.F. 1973. Adaptational biology and energy relationships of the collared peccary (*Tayassu tajacu*). *Ecology* **54**: 759–774.

6.3. Diseases

Another animal-related concern with respect to global warming is that rising temperatures will increase the prevalence of parasitic and vector-borne diseases, resulting in increasing mortality rates. To date, very little research has been published on this concern. Here, however, we cite two papers that have provided some understanding of the subject.

Writing in *Trends in Parasitology*, Morgan and Wall (2009) state “global climate change predictions suggest that far-ranging effects might occur in population dynamics and distributions of livestock parasites, provoking fears of widespread increases in disease incidence and production loss.” However, they indicate, “just as development rates of many parasites of veterinary importance increase with temperature, so [too] do their mortality rates [increase].” They further note “temperature will also affect mortality indirectly through the action of predators, parasitoids, pathogens and competitors, whose development and abundance are also potentially temperature sensitive,” so that, in the end, “the net effect of climate change could be complex and far from easily predicted.”

In perusing the subject in greater detail, as they elucidate some of the many complexities involved, the two U.K. researchers indicate “several biological mechanisms (including increased parasite mortality and more rapid acquisition of immunity), in tandem with changes in husbandry practices (including reproduction, housing, nutrition, breed selection, grazing patterns and other management interventions), might act to mitigate increased parasite development rates, preventing dramatic rises in overall levels of diseases.” However, because “optimum mitigation strategies will be highly system specific and depend on detailed understanding of interactions between climate, parasite abundance, host availability and the cues for and economics of farmer intervention,” as they characterize the situation, they conclude “there is a need for research that considers likely effects of climate change and mitigation strategies in terms of the whole host-parasite system, including anthropogenic responses, and not just in terms of parasite population dynamics.” It likely will be some time before the temperature-related parasitic disease relationship for animals is resolved.

Turning to a well-known vector-borne disease, Conte et al. (2009) note “the midge *Culicoides imicola* is the principal vector of bluetongue virus (BTV) that causes an infectious disease of domestic and wild ruminants," and "over the last ten years, BTV has invaded Mediterranean countries and much of Northern Europe," inducing several scientists and others to contend the BTV vector had expanded its range northward "because of rising temperatures," as suggested by the work of Mellor (2004), Purse et al. (2005), and Mellor et al. (2008). However, a careful examination of *Culicoides* population data in Italy prior to 2000 was made by Goffredo et al. (2003). They determined "trapping conditions of previous collections would have had very little chance of catching *C. imicola*," or detecting its presence, suggesting there was insufficient evidence to make the case for a warming-induced northward expansion of the BTV vector, because it may already have been present there but undetected.

In response to even earlier fears of a potential BTV invasion, a national surveillance program for *C. imicola* had been established in Italy in the year 2000, where 70,000 light-trap collections were made at about 3,800 different sites. Using the first year of data obtained from this program, Conte et al. defined the spatial distributions of three different *C. imicola* infection zones: zone I (endemicity), zone II (transition), and zone III (absence). Then, using data from 2002–2007, they quantified how *C. imicola* populations evolved through time in these three zones, working under the logical assumption that "a species that is undergoing geographical range expansion should have a population that remains stable over time in zone I and increases in zones II and III."

The three researchers state their results indicated "no detectable range expansion of *C. imicola* population in Italy over the past six years." In fact, they report "a weak, but significant reduction was observed in the transition zone." Conte et al. therefore conclude their data "support the hypothesis that the spread of BTV in Italy is not because of the geographical expansion of its main vector, but due to a modification of the interaction between the virus, the vector and the environment, as may also have been the case in northern Europe." As for the future, they write, their results indicate "precautions should be taken when inferring range progression for species requiring highly targeted forms of sampling and for which a constant probability of detection over time should be established." This demonstrates once again that it is easy to blame global warming for the poleward expansion of a vector-spread disease, but it is quite another thing to prove the case.

References

Conte, A., Gilbert, M., and Goffredo, M. 2009. Eight years of entomological surveillance in Italy show no evidence of *Culicoides imicola* geographical range expansion. *Journal of Applied Ecology* **46**: 1332–1339.

Goffredo, M., Conte, A., Cocciolito, R., and Meiswinkel, R. 2003. Distribution and abundance of *Culicoides imicola* in Italy. *Veterinaria Italiana* **47**: 22–32.

Mellor, P.S. 2004. Infection of the vectors and bluetongue epidemiology in Europe. *Veterinaria Italiana* **40**: 167–174.

Mellor, P.S., Carpenter, S., Harrup, L, Baylis, M., and Mertens, P.P.C. 2008. Bluetongue in Europe and the Mediterranean Basin: History of occurrence prior to 2006. *Preventive Veterinary Medicine* **87**: 4–20.

Morgan, E.R. and Wall, R. 2009. Climate change and parasitic disease: farmer mitigation? *Trends in Parasitology* **25**: 308–313.

Purse, B.V., Mellor, P.S., Rogers, D.J., Samuel, A.R., Mertens, P.P.C., and Baylis, M. 2005. Climate change and the recent emergence of bluetongue in Europe. *Nature Reviews Microbiology* **3**: 171–181.

7

Terrestrial Plants and Soils

7. Terrestrial Plants and Soils

Introduction

In its 2007 report, the Intergovernmental Panel on Climate Change (IPCC) hardly mentions the beneficial effects of rising atmospheric carbon dioxide (CO_2) concentration on terrestrial plants. In a chapter titled "Changes in Atmospheric Constituents and in Radiative Forcing," the authors write:

> Increased CO_2 concentrations can also "fertilize" plants by stimulating photosynthesis, which models suggest has contributed to increased vegetation cover and leaf area over the 20th century (Cramer *et al.,* 2001). Increases in the Normalized Difference Vegetation Index, a remote sensing product indicative of leaf area, biomass and potential photosynthesis, have been observed (Zhou *et al.*, 2001), although other causes including climate change itself are also likely to have contributed. Increased vegetative cover and leaf area would decrease surface albedo, which would act to oppose the increase in albedo due to deforestation. The RF due to this process has not been evaluated and there is a very low scientific understanding of these effects the following (IPCC 2007, p. 186).

Later in that report, in a chapter titled "Couplings Between Changes in the Climate System and Biogeochemistry," a single paragraph is devoted to the "effects of elevated carbon dioxide" on plants. The paragraph concludes, "it is not yet clear how strong the CO_2 fertilization effect actually is" (p. 527).

The Nongovernmental International Panel on Climate Change (NIPCC) strongly dissented. In a chapter spanning more than 200 pages and citing more than 1,300 peer-reviewed articles, Idso and Singer (2009) contend "the IPCC's failure to report the beneficial effects of rising CO_2 concentrations is surprising when literally thousands of peer-reviewed journal articles exist on the subject. It is also a major defect of the IPCC report and one reason why it is not a reliable summary of the science of climate change."

This chapter begins with a survey of the latest scientific literature on the productivity responses of plants to higher CO_2 concentrations, and then reviews research on other plant responses, responses of plants under stress, effect on biodiversity, carbon sequestion, plant and animal extinction, evolution, food production, the greening of the Earth, and the nitrogen cycle. Like the 2009 report, this survey of the literature confirms what the IPCC so carefully avoids admitting, that atmospheric CO_2 enrichment benefits plant life in many ways.

References

Idso, C.D. and Singer, S.F. 2009. *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller. (Eds.) Cambridge University Press, Cambridge, UK.

7.1. Plant Growth Responses to Atmospheric CO_2 Enrichment

7.1.1. C_3 Plants

We begin our review of atmospheric CO_2 enrichment effects on Earth's vegetation with a consideration of C_3 plants—those in which the enzyme RuBisCO is involved in the uptake of CO_2 and the subsequent photosynthetic process, which results in its incorporation into a 3-carbon compound—starting with the study of Norikane et al. (2010). They focused on the genus *Cymbidium*, which comprises about 50 species distributed throughout tropical and subtropical Asia and Oceania.

The four researchers worked with shoots of Music Hour 'Maria,' a type of orchid, possessing two to three leaves, which they obtained from a mass of protocorm-like bodies they derived from shoot-tip culture. They grew them *in vitro* on a modified Vacin and Went medium in air augmented with either 0, 3,000, or 10,000 ppm CO_2 under two photosynthetic photon flux densities (either 45 or 75 µmol m^{-1} s^{-1}) provided by cold cathode fluorescent lamps for a period of 90 days. They then transferred the plants to *ex vitro* culture for 30 more days. Relative to plants grown *in vitro* in ambient air, the percent increases in shoot and root dry weight due to enriching the air in which the plants grew by 3,000 ppm CO_2 were, respectively, 216 percent and 1,956 percent under the low-light regime and 249 percent and 1,591 percent under the high-light regime, while corresponding increases for the plants grown in air enriched with an extra 10,000 ppm CO_2 were 244 percent and 2,578 percent under the low-light regime and 310 percent and 1,879 percent under the high-light regime. Similarly, in the *ex vitro* experiment, the percent increases in shoot and root dry weight due to enriching the air in which the plants grew by 3,000 ppm CO_2 were 223 percent and 436 percent under the low-light regime and 279 percent and 469 percent under the high-light regime, while corresponding increases for the plants grown in air enriched with an extra 10,000 ppm CO_2 were 271 percent and 537 percent under the low-light regime and 332 percent and 631 percent under the high-light regime. Consequently, the Japanese scientists concluded, "super-elevated CO_2 enrichment of in vitro-cultured *Cymbidium* could positively affect the efficiency and quality of commercial production of clonal orchid plantlets."

Turning from ornamental plants to food crops, Vanaja et al. (2010) note grain legumes "provide much needed nutritional security in the form of proteins to the predominant vegetarian populations of India and also the world." They further state that legumes—of which pigeon peas are an important example—"have the potential to maximize the benefit of elevated CO_2 by matching stimulated photosynthesis with increased N_2 fixation," citing Rogers et al. (2009). Therefore, they grew pigeon peas (*Cajanus cajan* L. Millsp.) from seed to maturity outdoors at Hyderabad, India within open-top chambers maintained at atmospheric CO_2 concentrations of either 370 or 700 ppm. They then harvested the plants and measured pertinent productivity parameters.

This work revealed, according to the team of nine Indian scientists, that in the higher of the two CO_2 concentrations, "total biomass recorded an improvement of 91.3%, grain yield 150.1% and fodder yield 67.1%." They also found "the major contributing components for improved grain yield under elevated CO_2 were number of pods, number of seeds and test weight," with these items exhibiting increases of 97.9 percent, 119.5 percent, and 7.2 percent, respectively. In addition, they found there was "a significant positive increase of harvest index at elevated CO_2 with an increment of 30.7% over ambient values," which they say was due to the crop's "improved pod set and seed yield under enhanced CO_2 concentration." These multiple positive findings, according to the scientists from India's Central Research Institute for Dryland Agriculture, illustrate the importance of pigeon peas for "sustained food with nutritional security under a climate change scenario."

In much the same vein, Yang et al. (2009) declared, "rice is unequivocally one of the most important food crops that feed the largest proportion of the world's population," that "the demand for rice production will continue to increase in the coming decades, especially in the major rice-consuming countries of Asia, Africa and Latin America," and that "accurate predictions of rice yield and of the ability of rice crops to adapt to high CO_2 environments are therefore crucial for understanding the impact of climate change on the future food supply." In fact, they forcefully state—and rightly—that "there is a pressing need to identify genotypes which could optimize harvestable yield as atmospheric CO_2 increases."

They set out to do that in a standard paddy culture free-air CO_2 enrichment (FACE) experiment conducted at Yangzhou, Jiangsu, China over the period 2004–2006. The team of eight researchers grew a two-line inter-subspecific hybrid rice variety (Liangyoupeijiu) at ambient and elevated atmospheric CO_2 concentrations of 376 and 568 ppm, respectively, at two levels of field nitrogen (N) application: low N (12.5 g N m^{-2}) and high N (25 g N m^{-2}), measuring numerous aspects of crop growth, development, and final yield production in the process. The Chinese scientists found the 51 percent increase in atmospheric CO_2 concentration employed in their study increased the final grain yield of the low N rice crop by 28 percent and that of the high N rice crop by 32 percent. As a result, and "compared with the two prior rice FACE experiments (Kim et al., 2003; Yang et al., 2006)," they state, "hybrid rice appears to profit much more from CO_2 enrichment than inbred rice cultivars (c. +13 percent)." Yang et al. describe Liangyoupeijiu as "one of the most popular 'super' hybrid rice varieties in China (Peng et al., 2004)," and it appears it will become increasingly "super" as the air's CO_2 content continues to rise, helping China to lead the way in future food production.

References

Kim, H.Y., Lieffering, M., Kobayashi, K., Okada, M., Mitchell, M.W., and Gumpertz, M. 2003. Effects of free-air CO_2 enrichment and nitrogen supply on the yield of temperate paddy rice crops. *Field Crops Research* **83**: 261–270.

Norikane, A., Takamura, T., Morokuma, M., and Tanaka, M. 2010. In vitro growth and single-leaf photosynthetic response of *Cymbidium* plantlets to super-elevated CO_2 under cold cathode fluorescent lamps. *Plant Cell Reports* **29**: 273–282.

Peng, S., Laza, R.C., Visperas, R.M., Khush, G.S., Virk, P., and Zhu, D. 2004. Rice: progress in breaking the yield ceiling. In *New Directions for a Diverse Planet: Proceedings of the Fourth International Crop Science Congress*, 26 Sep-1 Oct 2004, Brisbane, Australia. Gosford, Australia: Regional Institute Ltd.

Rogers, A., Ainsworth, E.A., and Leakey, A.D.B. 2009. Will elevated carbon dioxide concentration amplify the benefits of nitrogen fixation in legumes? *Plant Physiology* **151**: 1009–1016.

Vanaja, M., Reddy, P.R.R., Lakshmi, N.J., Razak, S.K.A., Vagheera, P., Archana, G., Yadav, S.K., Maheswari, M., and Venkateswarlu, B. 2010. Response of seed yield and its components of red gram (*Cajanus cajan* L. Millsp.) to elevated CO_2. *Plant, Soil and Environment* **56**: 458–462.

Yang, L., Liu, H., Wang, Y., Zhu, J., Huang, J., Liu, G., Dong, G., and Wang, Y. 2009. Yield formation of CO_2-enriched inter-subspecific hybrid rice cultivar Liangyoupeijiu under fully open-air condition in a warm sub-tropical climate. *Agriculture, Ecosystems and Environment* **129**: 193–200.

Yang, L.X., Huang, J.Y., Yang, H.J., Zhu, J.G., Liu, H.J., Dong, G.C., Liu, G., Han, Y., and Wang, Y.L. 2006. The impact of free-air CO_2 enrichment (FACE) and N supply on yield formation of rice crops with large panicle. *Field Crops Research* **98**: 141–150.

7.1.2. C_4 Plants

Moving on to C_4 plants—where the enzyme PEP carboxylase allows CO_2 to be taken in very quickly and delivered directly to RuBisCO for photosynthetic incorporation into a 4-carbon compound—Vu and Allen (2009) note such vegetation represents "fewer than 4% of all angiosperm species," yet "their ecological and economic significance is substantial." On a global basis, for example, they write, "up to one-third of terrestrial productivity is provided by C_4 plants," citing Cerling et al. (1997), Ghannoum et al. (1997), and Brown et al. (2005), and they note "in many tropical regions, the food source is primarily based on C_4 crops, among [which] maize, millet, sorghum and sugarcane are the most agriculturally important monocots in terms of production (Brown, 1999)," with "up to 75% of the world sugar production provided by sugarcane (De Souza et al., 2008)." In addition, they indicate the emerging "use of sugarcane as a source for biofuel production has been highly recognized," citing Goldenberg (2007).

So what will happen to the productivity of this important crop as the air's CO_2 content continues its upward climb, especially if global air temperatures rise along with it?

Historically, C_4 crops have been thought to be relatively unresponsive to atmospheric CO_2 enrichment, as they possess a CO_2-concentrating mechanism that allows them to achieve a greater photosynthetic capacity than C_3 plants at the current atmospheric CO_2 concentration, particularly at high growth temperatures (Matsuoka et al., 2001). Thus, simple reasoning might suggest C_4 plants may be little benefited, if at all, in a CO_2-enriched and warmer world of the future. However, in the case of sugarcane, as the research of Vu and Allen demonstrates, simple reasoning would be incorrect, especially with respect to the most important measure of sugarcane's economic value: stem juice production.

The two researchers with the USDA's Agricultural Research Service, who hold joint appointments in the Agronomy Department of the University of Florida (USA), grew two cultivars of sugarcane (*Saccharum officinarum*) for a period of three months in paired-companion, temperature-gradient, sunlit greenhouses under daytime CO_2 concentrations of 360 and 720 ppm and air temperatures of 1.5°C (near ambient) and 6.0°C higher than outside ambient temperature, after which they measured several different plant properties.

"On a main stem basis," Vu and Allen write, "leaf area, leaf dry weight, stem dry weight and stem juice volume were increased by growth at doubled CO_2 [as well as at] high temperature," and they state these increases were even greater under the combination of doubled CO_2 and high temperature, with plants grown under these conditions averaging "50%, 26%, 84% and 124% greater leaf area, leaf dry weight, stem dry weight and stem juice volume, respectively, compared with plants grown at [the] ambient CO_2/near-ambient temperature combination." In addition, they write, "plants grown at [the] doubled CO_2/high temperature combination were 2- to 3-fold higher in stem soluble solids than those at [the] ambient CO_2/near-ambient temperature combination."

Consequently, as Vu and Allen conclude, "sugarcane grown under predicted rising atmospheric CO_2 and temperature in the future may use less water, utilize water more efficiently, and would perform better in sucrose production." This bodes well for tropical-region agriculture, especially, as they note, "with the worldwide continued increase in demand for sugarcane as a source of food and biofuel."

Last, they add that significant "improvements in stem sucrose and biomass through classical breeding and/or new biotechnology" may also be achieved; and, hence, they state, "studies to identify the cultivars with high efficiency in water use and stem sucrose production under future changes in CO_2 and climate are of great importance and should be initiated and explored." Working hand-in-hand with the benefits provided by the ongoing rise in the air's CO_2 content, therefore, as well as those provided by the possibility of still higher air temperatures to come, we may yet be able to meet the increasing food needs of our expanding numbers without taking vast amounts of land and freshwater resources from Earth's natural ecosystems.

Also studying sugarcane, Gouvea et al. (2009) used the agrometeorological model of Doorenbos and Kassam (1994) "to estimate sugarcane yield in tropical southern Brazil, based on future A1B climatic scenarios presented in the fourth Intergovernmental Panel on Climate Change report." They first calculated potential productivity, which considers "the possible impacts caused by changes in temperature, precipitation, sunshine hours and CO_2 concentration in the atmosphere, as well as technological advances," and then actual productivity, which additionally accounts for the yield-reducing effects of water stress.

Based on their calculations, Gouvea et al. determined "potential productivity will increase by 15% in relation to the present condition in 2020, by 33% in 2050 and by 47% in 2080," and "actual productivity will increase by 12% in relation to the present condition in 2020, by 32% in 2050 and by 47% in 2080." They further indicate expected technological advances, including the development of new varieties and best-management practices, will account for 35 percent of the yield gains in 2020, 51 percent in 2050, and 61 percent in 2080. Consequently, and in spite of the gloomy prognostications of the IPCC and its followers, this modeling exercise suggests there will be, in the words of the four researchers, "a beneficial effect of forecasted climate changes on sugarcane productivity, due to the expected increases in temperature and CO_2 concentration."

Finally, in a study of aquatic C_4 vegetation, Mateos-Naranjo et al. (2010) focused their attention on *Spartina maritima*, a cordgrass they say is "an important pioneer and ecosystem engineer in salt marshes on the Atlantic coast of southern Europe," citing Castellanos et al. (1994), noting this particular halophyte "produces extensive stands in a range of marsh environments," citing Castellanos et al. (1998). Working with 15-cm-diameter clumps of the plant obtained from a low-marsh site along the southwest coast of Spain in April 2007, they transplanted them into individual plastic pots filled with pearlite that rested on shallow trays filled with Hoagland's solution of three different salinities (0, 170, or 510 mM NaCl), which they maintained in controlled environment chambers having atmospheric CO_2 concentrations of either 380 ppm or 700 ppm for periods of 30 days, during which time they measured several plant properties and processes.

The four researchers discovered the 84 percent increase in the atmosphere's CO_2 concentration stimulated the growth of *S. maritima* by about 65 percent in all three salinity treatments, while their graphical representation of the halophyte's water use efficiency indicates this important plant property was enhanced by approximately 10 percent, 100 percent, and 160 percent in the 0, 170, and 510 mM salinity treatments, respectively, because, as they describe it, "increasing CO_2 concentration has a positive effect on the photochemical apparatus, helping to counteract salt stress experienced by plants at current CO_2 concentrations." Thus, the U.K. and Spanish scientists concluded the productivity of *S. maritima* "might increase in a future scenario of rising atmospheric CO_2 concentration in environments with salinities as high as that of seawater." That is extremely good news regarding what they describe as "an important pioneer and ecosystem engineer in salt marshes."

References

Brown, R.H. 1999. Agronomic implications of C_4 photosynthesis. In *C_4 Plant Biology*, edited by R.F. Sage and R.K. Monson, 473–507. San Diego, CA: Academic Press.

Brown, N.J., Parsley, K., and Hibberd, J.M. 2005. The future of C_4 research - maize, *Flaveria* or *Cleome*? *Trends in Plant Science* **10**: 215–221.

Castellanos, E.M., Figueroa, M.E., and Davy, A.J. 1994. Nucleation and facilitation in saltmarsh succession: interactions between *Spartina maritima* and *Arthrocnemum perenne*. *Journal of Ecology* **82**: 239–248.

Castellanos, E.M., Heredia, C., Figueroa, M.E., and Davy, A.J. 1998. Tiller dynamics of *Spartina maritima* in successional and non-successional Mediterranean salt marsh. *Plant Ecology* **137**: 213–225.

Cerling, T.E., Harris, J.M., MacFadden, B.J., Leakey, M.G., Quade, J., Eisenmann, V., and Ehleringer, J.R. 1997. Global vegetation change through the Miocene/Pliocene boundary. *Nature* **389**: 153–158.

De Souza, A.P., Gaspar, M., Da Silva, E.A., Ulian, U.C., Waclawovsky, A.J., Nishiyama Jr., M.Y., Dos Santos, R.V., Teixeira, M.M., Souza, G.M., and Buckeridge, M.S. 2008. Elevated CO_2 increases photosynthesis, biomass and productivity, and modifies gene expression in sugarcane. *Plant, Cell and Environment* **31**: 1116–1127.

Doorenbos, J. and Kassam, A.H. 1994. Efeito da agua no rendimento das culturas. Campina Grande: UFPB. Estudos FAO Irrigacao e Drenagem.

Ghannoum, O., von Caemmerer, S., Barlow, E.W.R., and Conroy, J.P. 1997. The effect of CO_2 enrichment and irradiance on the growth, morphology and gas exchange of a C_3 (*Panicum laxum*) and a C_4 (*Panicum antodotale*) grass. *Australian Journal of Plant Physiology* **24**: 227–237.

Goldenberg, J. 2007. Ethanol for a sustainable energy future. *Science* **315**: 808–810.

Gouvea, J.R.F., Sentelhas, P.C., Gazzola, S.T., and Santos, M.C. 2009. Climate changes and technological advances: impacts on sugarcane productivity in tropical southern Brazil. *Scientia Agricola* **66**: 593–605.

Mateos-Naranjo, E., Redondo-Gomez, S. Andrades-Moreno, L., and Davy, A.J. 2010. Growth and photosynthetic responses of the cordgrass *Spartina maritima* to CO_2 enrichment and salinity. *Chemosphere* **81**: 725–731.

Matsuoka, M., Furbank, R.T., Fukayama, H., and Miyao, M. 2001. Molecular engineering of C_4 photosynthesis. *Annual Review of Plant Physiology and Plant Molecular Biology* **52**: 297–314.

Vu, J.C.V. and Allen Jr., L.H. 2009. Stem juice production of the C_4 sugarcane (*Saccharum officinarum*) is enhanced by growth at double-ambient CO_2 and high temperature. *Journal of Plant Physiology* **166**: 1141–1151.

7.1.3. CAM Plants

Concluding this brief review of plant productivity responses to atmospheric CO_2 enrichment, we consider the impact of this phenomenon on Crassulacean Acid Metabolism or CAM plants, where CO_2 enters the plants through their stomata at night and is stored in the form of an acid that is broken down the next day, when its CO_2 is released to RuBisCO for the purpose of participating in the process of photosynthesis.

The first study of this type that we consider deals with the process of micropropagation, which, to quote Yoon et al. (2009), "is an established technique for [the] rapid propagation of uniform plants," although they note leaves formed during *in vitro* growth "may never attain photosynthetic competence." Consequently, to maintain a positive carbon balance over the *in vitro* to *ex vitro* transition, they write, "sugar is supplemented as the source of carbon." They go on to state, however, that "addition of sugar to the culture media [has been] negatively correlated with growth, photosynthesis and expression of enzymes of the carbon assimilation pathway," so the standard cure for the problem is partially self-defeating. Thus, the question arises: Can CO_2 do anything to help?

In investigating this possibility, Yoon et al. grew plantlets of *Phalaenopsis* "Amaglade"—a monopodial epiphytic CAM orchid with succulent leaves—derived from flower stalk cultures and multiplied on a hyponex medium either with or without the addition of 30 g sugar per liter of medium, in air of either 400 or 1,000 ppm CO_2, for a period of 90 days *in vitro* followed by 40 days *ex vitro*, "to identify the more suitable treatments *in vitro* for the best acclimatization of *Phalaenopsis* plantlets to *ex vitro* conditions," which they did by monitoring several plant morphological traits, photosynthetic attributes, and intrinsic elements of the CAM pathway.

The results of these operations indicated the extra CO_2 eliminated the need for any sugar to be supplied to the plantlets, with shoot dry weight in the CO_2-enriched air exceeding that in the ambient air by 120 percent in the nonsweetened treatment at the end of the *in vitro* period, and with root dry weight in the CO_2-enriched air exceeding that in the ambient air by 350 percent. Likewise, at the end of the *ex vitro* period, the CO_2-induced shoot and root dry weight increases in the nonsweetened treatment were 55 percent and 86 percent, respectively. Thus, the four Korean researchers concluded, "plantlets grown under CO_2 enrichment"—and without the help of any applied sugar—"developed completely viable photosynthetic apparatus ready to be efficiently transferred to *ex vitro* conditions," which they state has "far-reaching implications" for the micropropagation of *Phalaenopsis* and possibly other plants as well.

In another pertinent paper, Weiss et al. (2010) introduce their newest work on the subject by noting the CAM cacti *Hylocereus undatus* (red pitaya) and *Selenicereus megalanthus* (yellow pitaya) "are cultivated in a dozen countries around the world and were introduced into and developed in Israel as export fruit crops (Mizrahi et al., 1997)." They write, "both species consist of elongated, three-ribbed stems that cling to trees and rocks in their natural habitat, which, for *S. megalanthus*, is characterized by humid tropical forests (Colombia, Ecuador, Peru and the Amazon Basin." *H. undatus*, on the other hand, grows naturally in the dry forests of Mexico, indicating it is better adapted to semi-arid conditions.

Working in the northern Negev Desert of Israel, the three researchers grew rooted shoot cuttings of the two vine-cactus fruit-crop species in pots filled with volcanic gravel for a period of one full year (August 2006 to August 2007). This was done within vented chambers maintained at either ambient or elevated atmospheric CO_2 concentrations (380 or 1,000 ppm, respectively) in a cooled greenhouse, where the plants were "fertigated" twice weekly with 0.5-strength Hoagland's solution, and where the researchers measured net photosynthesis on four days in mid-April and made final biomass determinations at the conclusion of the study. In addition, they conducted a second one-year study of more-mature, eight-year-old plants in order to investigate their fruit development responses to atmospheric CO_2 enrichment. This work was done in open-top chambers maintained within the same greenhouse.

As Weiss et al. describe it, their results indicated "*H. undatus* plants enriched with CO_2 demonstrated 52%, 22%, 18% and 175% increases, relative to plants measured in ambient CO_2, in total daily net CO_2 uptake, shoot elongation, shoot dry mass, and number of reproductive buds, respectively," while corresponding responses for *S. megalanthus* were 129 percent, 73 percent, 68 percent, and 233 percent. In addition, they found a slight (7 percent) increase in the fruit fresh mass of *H. undatus* and a much greater, 63 percent, increase in the fruit fresh mass of *S. megalanthus*, resulting from the extra 620 ppm of CO_2 enrichment of the air in which the plants had been grown. The three researchers write that, to the best of their knowledge, "this is the first study of the reproductive responses of CAM plants to CO_2 enrichment," and they conclude their experiments demonstrate "the vast potential of possible increases in the yields of CAM crops under CO_2 enrichment."

References

Mizrahi, Y., Nerd, A., and Nobel, P.S. 1997. Cacti as crops. *Horticultural Reviews* **18**: 321–346.

Weiss, I., Mizrahi, Y., and Raveh, E. 2010. Effect of elevated CO_2 on vegetative and reproductive growth characteristics of the CAM plants *Hylocereus undatus* and *Selenicereus megalanthus*. *Scientia Horticulturae* **123**: 531–536.

Yoon, Y.-J., Mobin, M., Hahn, E.-J., and Paek, K.-Y. 2009. Impact of *in vitro* CO_2 enrichment and sugar deprivation on acclamatory responses of *Phalaenopsis* plantlets to *ex vitro* conditions. *Environmental and Experimental Botany* **65**: 183–188.

7.1.4. Ecosystems: Forests

Moving up from individual species and small groups of plants to the ecosystem scale, we consider the case of natural and plantation-type forests, beginning with studies of the latter type, where the air around groups of trees has been experimentally enriched with CO_2, starting with the study of McCarthy et al. (2010). Conducted at the Duke Forest Free-Air CO_2-Enrichment (FACE) facility, this study is a long-term experiment designed to investigate the effects of an extra 200 ppm of atmospheric CO_2 on the growth and development of a plantation of loblolly pine (*Pinus taeda*) trees with an understory of various broadleaf species, including *Liriodendron tulipifera, Liquidambar styraciflua, Acer rubrum, Ulmus alata*, and *Cornus florida*, plus various other trees, shrubs, and vines. All of these were grown on a soil that Finzi and Schlesinger (2003) describe as being in "a state of acute nutrient deficiency that can only be reversed with fertilization." Many researchers had long thought such fertility deficiency would stifle the ability of the extra aerial supply of CO_2 to significantly stimulate the forest's growth on a continuing basis.

Working with data for the years 1996–2004, the team of nine researchers writes, "net primary productivity [NPP] for pines, hardwoods and the entire stand was calculated as the sum of the production of coarse wood (stems, branches, coarse roots), leaf litter (lagged for pines), fine roots and reproductive structures." The results of this protocol indicated "elevated CO_2 increased pine biomass production, starting in 1997 and continuing every year thereafter," and "the CO_2-induced enhancement remained fairly consistent as the stand developed." In addition, they found "elevated CO_2 increased stand (pine plus all other species) biomass production every year from 1997 onwards with no trend over time," while the average yearly increase in NPP caused by the approximate 54 percent increase in the air's CO_2 content was 28 percent. Thus, and in spite of the original belief of many scientists that low levels of soil nitrogen—especially an acute deficiency—would preclude any initial growth stimulation provided by atmospheric CO_2 enrichment from long persisting, the suite of trees, bushes, and shrubs that constitute the Duke Forest has continued to maintain the extra CO_2-enabled vitality it exhibited right from the start of the study, with no sign of it even beginning to taper off.

Further extending the results of the Duke Forest FACE study were Jackson et al. (2009), who describe new belowground data they obtained there, after which they present a synthesis of these and other results obtained from 1996 through 2008, seeking to determine "which, if any, variables show evidence for a decrease in their response to atmospheric CO_2 during that time frame."

Among many other things, Jackson et al. report "on average, in elevated CO_2, fine-root biomass in the top 15 cm of soil increased by 24%," and in recent years the fine-root biomass increase "grew stronger, averaging ~30% at high CO_2." Regarding coarse roots having diameters greater than 2 mm and extending to a soil depth of 32 cm, they report, "biomass sampled in 2008 was twice as great in elevated CO_2." We calculate from the graphical representation of their results that the coarse-root biomass was fully 130 percent greater, which is astounding, particularly given that the extra 200 ppm of CO_2 supplied to the air surrounding the CO_2-enriched trees represented only about a 55 percent increase over ambient conditions. In the concluding sentence of their paper's abstract, Jackson et al. state, "overall, the effect of elevated CO_2 belowground shows no sign of diminishing."

In expanding on this statement, the four researchers note "if progressive nitrogen limitation were occurring in this system, we would expect differences in productivity to diminish for trees in the elevated vs. ambient CO_2 plots," but they state, "in fact there is little evidence from estimates of aboveground or total net primary productivity in the replicated Duke experiment that progressive nitrogen limitation is occurring there or at other forest FACE experiments," even "after more than a decade of manipulation" of the air's CO_2 content, citing in this regard—with respect to the latter portion of their statement—the report of Finzi et al. (2007). Consequently, there is very good reason to believe the "aerial fertilization effect" of atmospheric CO_2 enrichment will continue to benefit Earth's forests significantly as long as the atmosphere's CO_2 concentration continues to rise.

Also studying this important subject were Darbah et al. (2010), who worked with photosynthesis data they and others collected over 11 years at the Aspen

FACE site near Rhinelander, Wisconsin (USA). They too evaluated the progressive nitrogen limitation hypothesis, working with two different quaking aspen (*Populus tremuloides* Michx.) clones (42E and 271), which were exposed to all combinations of ambient and elevated (560 ppm) CO_2 and ambient and elevated (1.5 times ambient) ozone (O_3). As an added bonus, they investigated whether the same principle might apply to leaf stomatal conductance.

In a crisp and clear report of what they learned, the eight researchers state their results "suggest no long-term photosynthetic and stomatal acclimation to elevated CO_2, O_3 or CO_2 + O_3 in aspen trees exposed to elevated CO_2 and/or O_3 gases for 11 years," and that the aspen trees "have sustained their maximum instantaneous photosynthesis stimulation for over a decade." In commenting on their findings, Darbah et al. state they support the observations of (1) Liberloo et al. (2007), who measured a 49 percent increase in net photosynthetic rate in poplar trees after six years of exposure to elevated CO_2, (2) the findings of Sholtis et al. (2004), who reported a 44 percent stimulation of net photosynthesis in sweetgum trees after three years of exposure to elevated CO_2, (3) Crous and Ellsworth (2004), who found a photosynthetic enhancement of 51–69 percent in *Pinus taeda* trees after six years of exposure to elevated CO_2, and (4) Davey et al. (2006) and (5) Paoletti et al. (2007), of whose work Darbah et al. state, "there was no photosynthetic acclimation (down-regulation) occurring in *Quercus ilex* under long-term CO_2 enrichment." In addition, they remark that (6) even in white clover (*Trifolium repens*), Ainsworth et al. (2003) found photosynthetic stimulation "remained after nine years of exposure to elevated CO_2."

Additional support for this upbeat view of the matter is provided by Bader et al. (2010), who, while working at the Swiss Canopy Crane facility in a species-rich deciduous forest 15 km south of Basel, Switzerland, where the 100-year-old stand reaches canopy heights of 30 to 35 meters, measured light-saturated rates of net photosynthesis between 8:30 am and 12:20 pm at ambient (380 ppm) and elevated (550 ppm) atmospheric CO_2 concentrations, the latter of which were maintained throughout all daylight periods over the course of the eighth growing season of their long-term study—just as they had been similarly maintained over the prior seven years—in three *Quercus petraea* trees, three *Carpinus betulus* trees, one *Tilia platyphyllos* tree, and one *Acer campestre* tree.They then compared the results of their measurements with those obtained in earlier years of the experiment.

Bader et al. report the mean net photosynthetic rate of the upper-canopy foliage was 48 percent greater in the CO_2-enriched foliage than in the ambient-treatment foliage in July and 42 percent greater in September, yielding an average increase of 45 percent in response to the 45 percent increase in the air's CO_2 content. They go on to observe, "in the same stand, Zotz et al. (2005) found 36 and 49% photosynthetic enhancement in the mid and late growing season, respectively." This represents a mean response of 42.5 percent, slightly less than what Bader et al. observed most recently.

As for the significance of their findings, the three Swiss scientists write, "the lack of photosynthetic down-regulation is consistent with the findings for mature and understory sweetgum trees growing at the ORNL- and Duke-FACE sites, respectively, and three poplar species growing at short-rotation coppice at the POP-FACE site, as well as for aspen and birch at the ASPEN-FACE stands (Herrick and Thomas, 2001; Sholtis et al., 2004; Liberloo et al., 2007; Uddling et al., 2009)." And in their final comment about their own study, they state their findings suggest "the enhancement of photosynthesis may persist in these mature deciduous trees under high future atmospheric CO_2 concentrations," while adding in the abstract of their paper that they will likely do so "without reductions in photosynthetic capacity."

Kets et al. (2010) also explored the phenomenon of acclimation by investigating diurnal changes in the rate of light-saturated net photosynthesis (Pn) under both ambient and elevated CO_2 and/or ozone (O_3) concentrations over wide ranges of leaf stomatal conductance, leaf water potential, intercellular CO_2 concentration, leaf temperature, and vapor pressure difference between leaf and air in two clones (271 and 42E) of quaking aspen (*Populus tremuloides* Michx.) trees that differed in their sensitivity to ozone and had been growing at the Aspen FACE site for seven to eight years. In describing their findings, they state Pn was typically enhanced by 33–46 percent in the CO_2-enriched treatments over the course of their study, and there was a small increase in leaf chlorophyll concentration as well.

Consequently, and noting that "previous Aspen FACE studies have reported 25–36% increases in Pn (Noormets et al., 2001; Takeuchi et al., 2001; Sharma et al., 2003; Ellsworth et al., 2004)," the six scientists emphasize that the aerial fertilization effect of atmospheric CO_2 enrichment on Pn observed in their study "has rather been increasing in time than decreasing," stating this phenomenon may be caused by the "slight but significant increase in leaf chlorophyll content per leaf area, which is rather positive acclimation in photosynthetic apparatus than negative acclimation." In support of this conclusion they also cite the studies of Centritto and Jarvis (1999) and Eichelmann et al. (2004). Hence, their experiment demonstrated that some of the benefits of elevated atmospheric CO_2 concentrations may actually increase with the passage of time.

Taking the study of this important subject a major step forward, via a totally different approach, Phillips et al. (2008) begin by noting there is "a long held view," as they describe it, that "old trees exhibit little potential for growth." Hence, they write, "it may seem reasonable to conclude that old trees are not responsive to increased CO_2," as some researchers do indeed claim. They go on, however, to demonstrate this view is far from the truth.

The three researchers begin their analysis of the subject by stating, "hydraulic constraints in tall trees," such as those of great age, "constitute a fundamental form of water limitation; indeed, one that is indistinguishable from soil water limitations," citing Koch et al. (2004) and Woodruff et al. (2004). They also report "recent research indicates that tree size and its hydraulic correlates, rather than age per se, controls carbon gain in old trees," as indicated by the study of Mencuccini et al. (2005). These findings imply, in their words, that "factors that alleviate internal or external resource constraints on old trees could improve physiological function and ultimately growth," which is something elevated CO_2 does quite well by increasing plant water use efficiency. They list several phenomena that suggest "a fundamental potential for old growth trees to show greater photosynthesis and growth under industrial age increases in CO_2 than they would under constant, pre-industrial CO_2 levels."

Drawing from their own work, Phillips et al. find "500- and 20-year-old Douglas-fir trees both show high sensitivity of photosynthesis to atmospheric CO_2," presenting data that clearly demonstrate, as they phrase it, "under optimal conditions there exists the potential for an approximately 30% increase in photosynthetic rate with an increase in CO_2 from pre-industrial to current levels [i.e., from 280 to 385 ppm] in old trees." And they go on to note "the phenomenon of twentieth-century ring-width increase," which could thus be expected to accompany the twentieth-century increase in the air's CO_2 content, has in fact been detected in several other studies, including those of LaMarche et al., (1984), Jacoby (1986), Graybill (1987), Kienast and Luxmoore (1988), Graumlich (1991), Knapp et al. (2001), Bunn et al. (2005), and Soule and Knapp (2006), to which could be added the study of Graybill and Idso (1993).

Further commenting on the significance of the findings of these studies, the three researchers write that the results of LaMarche et al. (1984) "could not be explained by temperature or precipitation variation over this time period, but were consistent with, and attributed to, the rise in atmospheric CO_2," which also was the case with the results of Graybill and Idso (1993). Although these data, in their words, "appear to represent compelling circumstantial evidence for carbon fertilization of old growth trees," they note "this possibility has been discounted and climate change has instead been implicated for the observed responses in subsequent research." That invalid discounting is likely based on the erroneous claim that twentieth-century global warming was unprecedented over the past one to two millennia. Instead, it is quite probable that a good portion of the twentieth-century increase in tree growth was a consequence of the growth-promoting and water-use-efficiency-enhancing increase in the air's CO_2 content.

In summation, the analysis of Phillips et al. (2008) provides substantial support for the two-part thesis that (1) old-growth forests can continue to sequester carbon for multiple centuries in the face of ever-increasing atmospheric CO_2 concentrations, and (2) the global temperature history employed by the Intergovernmental Panel on Climate Change depicts an unrealistically large temperature increase over the course of the twentieth century.

Additional evidence for this thesis has recently come from Pan et al. (2010). They examined "how changes in atmospheric composition (CO_2, O_3 and N deposition), climate and land-use affected carbon dynamics and sequestration in Mid-Atlantic temperate forests during the 20th century," by modifying and applying "a well established process-based ecosystem model with a strong foundation of ecosystem knowledge from experimental studies," which they validated "using the U.S. Forest Inventory and Analysis data."

For previously harvested and currently regrowing forests, the calibrated model produced the following percentage changes in net ecosystem productivity (NEP) due to observed changes in N deposition (+32 percent), CO_2 (+90 percent), O_3 (-40 percent), CO_2 + O_3 (+60 percent), CO_2 + N deposition (+184 percent), and CO_2 + N deposition + O_3 (+138 percent), while corresponding changes in NEP for undisturbed forests were +18 percent, +180 percent, -75 percent, +78 percent, +290 percent, and +208 percent. In addition, the results of Pan et al. revealed "the 'fertilization' effect of N deposition mainly stimulates carbon allocation to short-lived tissues such as foliage and fine roots," but "the 'fertilization' effect by elevated CO_2 likely enhances more sustainable carbon storage such as woody biomass (including coarse roots)."

The four USDA Forest Service scientists conclude the evidence indicates "the change in atmospheric composition, particularly elevated CO_2, will gradually account for more of the carbon sink of temperate forests in the Mid-Atlantic region," and they state, "such a significant 'fertilization effect' on the forest carbon sequestration could eventually result in a 'greener world' after a long period of chronic change in atmospheric composition and cumulative impact."

Real-world evidence for this phenomenon is provided by Cole et al. (2010). They begin by noting that quaking aspen (*Populus tremuloides* Michx.) is a dominant forest type in north-temperate, montane, and boreal regions of North America," stating that it is, in fact, "the most widely distributed tree species on the continent," while further noting that aspen—and related poplars—are "quintessential foundation species (Ellison et al., 2005), shaping the structure and function of the communities and ecosystems in which they occur (Whitham et al., 2006; Schweitzer et al., 2008; Madritch et al., 2009)." This being the case, they considered it important to determine how this keystone species may have responded to the increase in atmospheric CO_2 concentration that has occurred over the past several decades, especially within the context of the climatic changes that occurred concurrently.

The four researchers collected branches from 919 trees after their leaves had dropped in the fall, obtaining samples that represented 189 genets or clones (five trees per clone) at 11 sites distributed throughout three regions of Wisconsin (USA). The sampled trees ranged from five to 76 years of age and came from second-growth unmanaged forests south of the areas defoliated by forest tent caterpillars in 1980–1982, 1989–1990, and 2001–2002. In addition, they recorded trunk diameter at breast height for each sampled tree. This parameter, they write, "is very highly correlated with total biomass in aspen," citing Bond-Lamberty et al. (2002).

The Minnesota and Wisconsin scientists learned that "age-specific ring width increased over time" and "the greatest increase occurred for relatively young trees, so that young trees grew faster in recent years than did young trees several decades ago." During the past half-century, for example, they found the growth of trees 11–20 years old rose by 60 percent. In addition, they observed "rising CO_2 causes ring width to increase at all moisture levels, apparently resulting from improved water use efficiency," so that "the overall increase results from historical increases in both CO_2 and water availability." And when they separated out the impacts of the two factors, they found "the effect of rising CO_2 had been to increase ring width by about 53%," as a result of the "19.2% increase in ambient CO_2 levels during the growing season, from 315.8 ppm in 1958 (when CO_2 records began) to 376.4 ppm in 2003."

Cole et al. comment, "the magnitude of the growth increase uncovered by this analysis raises the question of how much other major forest species have responded to the joint effects of long-term changes in CO_2 and precipitation." In this regard, we note many additional tree species may indeed have experienced similar growth stimulation, particularly in light of the analysis of Tans (2009), who demonstrated that Earth's land surfaces were a net source of CO_2 to the atmosphere until about 1940—primarily due to the felling of forests and the plowing of grasslands to make way for expanded agricultural activities—but from 1940 onward the terrestrial biosphere had become, in the mean, an increasingly greater sink for CO_2, and that it has done so even in the face of massive global deforestation, for which it apparently more than compensated. The combined findings of the studies of Tans and Cole et al. clearly testify to the phenomenal ability of the ongoing rise in the air's CO_2 content to transform the face of the Earth.

Other studies complement these findings. For example, Martinez-Vilalta et al.(2008) used tree-ring data from the Catalan Ecological and Forest Inventory "to study the temporal variability of Scots pine stem radial growth (period 1901–1997) across a relatively large region (Catalonia, NE Spain) situated close to the southern limit of the distribution of the species."

This inventory, as they describe it, "included a total of 10,664 plots randomly distributed throughout the forested area of Catalonia," where Scots pine was present in 30.2 percent of the plots and was the dominant tree species in 18.4 percent of them.

The five researchers' work revealed, in their words, "an overall increase of 84% in Scots pine BAI [basal area increment] during the 20th century, consistent with most previous studies for temperate forests" and in harmony with the greening of the Earth that has accompanied the historical increase in the air's CO_2 content. They make a point of stating "this trend was associated with increased atmospheric CO_2 concentration," which they interpret to be "a fertilization effect," while observing "there was also a marked increase in temperature across the study region (0.19°C per decade on average)."

Some people, however, worry rising temperatures will lead to greater respiration rates in the world's forests. Bronson and Gower (2010), for example, write, "the boreal forest historically has been considered a carbon sink," but "autotrophic respiration is more sensitive than photosynthesis to increases in temperature," and therefore, in response to global warming "most models predict autotrophic respiration will increase at a greater rate than photosynthesis, which infers decreased carbon use efficiency and net primary production." This in turn implies "a substantial increase in temperature could turn the boreal forest into a carbon source," and this positive feedback phenomenon could lead to an intensification of the warming of the globe.

So the argument goes, but the study found otherwise. Working about 20 km south of Thompson, Manitoba, Canada (55°53'N, 98°20'W), within large enclosed greenhouse chambers containing black spruce trees (*Picea mariana* (Mill.) B.S.P.) and the majority of their fine roots, along with soil-heating cables that were used to warm air and soil temperatures about 5°C over ambient control temperatures, Bronson and Gower measured light-saturated net photosynthesis, foliage respiration, and stem respiration in heated and control forest plots during the 2005, 2006, and 2007 growing seasons. Throughout the study, "both the older foliage, which developed before the experiment, and the new foliage, developed during the experiment, had similar rates of light-saturated net photosynthesis, foliage respiration and stem respiration across all treatments." This they write, "underscores the ability of black spruce to maintain homeostasis in a 5°C warmer environment." In addition, while noting many global change models predict a doubling of respiration for every 10°C increase in temperature, Bronson and Gower state in the concluding sentence of their paper—and in no uncertain terms—that "the results from this and other whole-ecosystem warming experiments do not support this model assumption."

In another study utilizing real-world measurements, Lewis et al. (2009) evaluated tropical forest inventory data, plant physiology experiments, ecosystem flux observations, earth observations, atmospheric measurements, and dynamic global vegetation models, which, "taken together," in their words, "provide new opportunities to cross-validate results."

According to the five researchers, both theory and experimental findings suggest that over the past several decades "plant photosynthesis should have increased in response to increasing CO_2 concentrations, causing increased plant growth and forest biomass." In this regard they find "long-term plot data collectively indicate an increase in carbon storage, as well as significant increases in tree growth, mortality, recruitment, and forest dynamism." They also report that satellite measurements "indicate increases in productivity and forest dynamism" and that "five Dynamic Global Vegetation Models, incorporating plant physiology, competition, and dynamics, all predict increasing gross primary productivity, net primary productivity, and carbon storage when forced using late-twentieth century climate and atmospheric CO_2 concentration data." In addition, they state "the predicted increases in carbon storage via the differing methods are all of similar magnitude (0.2% to 0.5% per year)."

"Collectively," Lewis et al. write, "these results point toward a widespread shift in the ecology of tropical forests, characterized by increased tree growth and accelerating forest dynamism, with forests, on average, getting bigger (increasing biomass and carbon storage)." These findings are just the opposite of what some researchers claim will result from the "twin evils" of rising air temperatures and CO_2 concentrations. Instead of being the bane of Earth's tropical forests, twentieth-century increases in air temperature and atmospheric CO_2 concentrations have been a great boon to the trees of the tropics.

Also studying the effects of rising air temperature and CO_2 concentration on tropical rainforests were Jaramillo et al. (2010), within a much different context: that of the Paleocene-Eocene Thermal

Maximum (PETM) of some 56 million years ago, which they state was "one of the most abrupt global warming events of the past 65 million years (Kennett and Stott, 1991; Zachos et al., 2003; Westerhold et al., 2009)." It was driven, they remark, by "a massive release of ^{13}C-depleted carbon (Pagani et al., 2006; Zeebe et al., 2009)" which led to "an approximate 5°C increase in mean global temperature in about 10,000 to 20,000 years (Zachos et al., 2003)." They note many people argue that during this warm period the Earth's tropical ecosystems "suffered extensively because mean temperatures are surmised to have exceeded the ecosystems' heat tolerance (Huber, 2008)."

To find out whether the ancient warming of the world truly constituted a major problem for the planet's rainforests, the 29 researchers, hailing from eight countries, analyzed pollen and spore contents and the stable carbon isotopic composition of organic materials obtained from three tropical terrestrial PETM sites in eastern Colombia and western Venezuela. Contrary to the prevailing wisdom of the recent past, this work revealed that the onset of the PETM was "concomitant with an increase in diversity produced by the addition of many taxa (with some representing new families) to the stock of preexisting Paleocene taxa." They further determined that this increase in biodiversity "was permanent and not transient."

In discussing their findings, Jaramillo et al. write, "today, most tropical rainforests are found at mean annual temperatures below 27.5°C," and they state several scientists have argued "higher temperatures could be deleterious to the health of tropical ecosystems." In fact, they report that tropical warming during the PETM is believed to have produced intolerable conditions for tropical ecosystems, citing the writings of Huber (2008, 2009). Nevertheless, they reiterate that at the sites they studied, "tropical forests were maintained during the warmth of the PETM (~31° to 34°C)," and they state "it is possible that higher Paleocene CO_2 levels (Royer, 2010) contributed to their success." Such would indeed appear to be the case, in light of the well-established fact that most plants, including trees, tend to exhibit their greatest photosynthetic rates at ever-warmer temperatures as the air's CO_2 content continues to rise (Bjorkman et al., 1978; Nilsen et al., 1983; Jurik et al., 1984; Seeman et al., 1984; Harley et al., 1986; Stuhlfauth and Fock, 1990; McMurtrie et al., 1992; Sage et al., 1995; Ziska and Bunce, 1997; Cowling and Sage, 1998; Lewis et al., 2001; Roberntz, 2001; Borjigidai et al., 2006; Ghannoum et al., 2010).

In light of Jaramillo et al.'s findings, it is becoming increasingly clear that greater warmth and atmospheric CO_2 concentrations are not "twin evils." Quite to the contrary, they are just what the Earth's ecosystems need in order to make them both more stable and more productive, characteristics essential for sustaining the still-expanding human population of the globe while preserving wildlife habitat.

Two other recent studies look beyond the present and contemplate still other factors of potential significance. Doherty et al. (2010) modeled future changes in land biogeochemistry and biogeography in the region bounded by 12.5°N, 12.5°S, 25°E, and 42.5°E, representing the whole of East Africa (Kenya, Tanzania, Uganda, Rwanda, Burundi, Ethiopia, and Somalia), plus portions of Central Africa (the Democratic Republic of Congo and Southern Sudan). They used 18 climate projections derived from nine general circulation models that figured prominently in the IPCC's Fourth Assessment Report, employing the projections as input to the Lund-Potsdam-Jena dynamic global vegetation model that simulates changes in vegetation and ecosystem carbon cycling under future climate conditions, based on what they describe as "a coupled photosynthesis-hydrological scheme [that] computes gross primary productivity, plant respiration, and evapotranspiration on a daily time step based on the current climate, atmospheric CO_2 concentration, vegetation structure and phenological state, and soil water content."

Doherty et al. report "all simulations showed future increases in tropical woody vegetation over the region," noting "regional increases in net primary productivity (18–36%) and total carbon storage (3–13 percent) by 2080–2099 compared with the present-day were common to all simulations," and "seven out of nine simulations continued to show an annual net land carbon sink in the final decades of the 21st century because vegetation biomass continued to increase." The researchers conclude, "overall, our model results suggest that East Africa, a populous and economically poor region, is likely to experience some ecosystem service benefits through increased precipitation, river runoff and fresh water availability," and they state, "resulting enhancements in net primary productivity may lead to improved crop yields in some areas." They specifically state their results "stand in partial contradiction of other studies that suggest possible negative consequences for agriculture, biodiversity and other ecosystem services caused by temperature increases."

Hillstrom et al. (2010) note, "natural forest systems constitute a major portion of the world's land area, and are subject to the potentially negative effects of both global climate change and invasion by exotic insects." In this regard, they report "a suite of invasive weevils has become established in the northern hardwood forests of North America," noting that how these insects will respond to continued increases in the air's CO_2 content is currently "unknown." To examine this subject, they collected 200 mating pairs of *Polydrusus sericeus* weevils—which they describe as "the second most abundant invasive weevil species in northern hardwood forests"—from birch trees growing on the perimeter of the Aspen FACE facility, after which they fed them leaves taken from the birch, aspen, and maple trees growing within either the facility's ambient-air rings or its CO_2-enriched rings (maintained at a target concentration of 560 ppm) under controlled laboratory conditions throughout the summer of 2007, closely monitoring parameters related to weevil longevity and fecundity.

The five researchers, all from the University of Wisconsin's Department of Entomology, report that feeding the weevils with foliage produced on trees in the CO_2-enriched FACE plots had no effect on male longevity but reduced female longevity by 19 percent. Also, "*Polydrusus sericeus* egg production rate declined by 23% and total egg production declined by 29% for females fed foliage produced under elevated CO_2 compared with ambient CO_2." Hillstrom et al. conclude, "concentrations of elevated CO_2 above 500 ppm have the potential to decrease *P. sericeus* populations by reducing female longevity and fecundity," which should benefit the northern hardwood forests of North America.

References

Ainsworth, A.E., Rogers, A., Blum, H., Nosberger, J., and Long, S.P. 2003. Variation in acclimation of photosynthesis in *Trifolium repens* after eight years of exposure to free air CO_2 enrichment (FACE). *Journal of Experimental Botany* **54**: 2769–2774.

Bader, M.K.-F., Siegwolf, R., and Korner, C. 2010. Sustained enhancement of photosynthesis in mature deciduous forest trees after 8 years of free air CO_2 enrichment. *Planta* **232**: 1115–1125.

Bjorkman, O., Badger, M., and Armond, P.A. 1978. Thermal acclimation of photosynthesis: effect of growth temperature on photosynthetic characteristics and components of the photosynthetic apparatus in *Nerium oleander*. *Carnegie Institution of Washington Yearbook* **77**: 262–276.

Bond-Lamberty, B., Wang, C., and Gower, S.T. 2002. Aboveground and belowground biomass and sapwood area allometric equations for six boreal tree species of northern Manitoba. *Canadian Journal of Forest Research* **32**: 1441–1450.

Borjigidai, A., Hikosaka, K., Hirose, T., Hasegawa, T., Okada, M., and Kobayashi, K. 2006. Seasonal changes in temperature dependence of photosynthetic rate in rice under a free-air CO_2 enrichment. *Annals of Botany* **97**: 549–557.

Bronson, D.R. and Gower, S.T. 2010. Ecosystem warming does not affect photosynthesis or aboveground autotrophic respiration for boreal black spruce. *Tree Physiology* **30**: 441–449.

Bunn, A.G., Graumlich, L.J., and Urban, D.L. 2005. Trends in twentieth-century tree growth at high elevations in the Sierra Nevada and White Mountains, USA. *The Holocene* **15**: 481–488.

Centritto, M. and Jarvis, P.G. 1999. Long-term effects of elevated carbon dioxide concentration and provenance on four clones of Sitka spruce (*Picea sitchensis*). II. Photosynthetic capacity and nitrogen use efficiency. *Tree Physiology* **19**: 807–814.

Cole, C.T., Anderson, J.E., Lindroth, R.L., and Waller, D.M. 2010. Rising concentrations of atmospheric CO_2 have increased growth in natural stands of quaking aspen (*Populus tremuloides*). *Global Change Biology* **16**: 2186–2197.

Cowling, S.A. and Sage, R.F. 1998. Interactive effects of low atmospheric CO_2 and elevated temperature on growth, photosynthesis and respiration in *Phaseolus vulgaris*. *Plant, Cell and Environment* **21**: 427–435.

Crous, K.Y. and Ellsworth, D.S. 2004. Canopy position affects photosynthetic adjustments to long-term elevated CO_2 concentration (FACE) in aging needles in a mature *Pinus taeda* forest. *Tree Physiology* **24**: 961–970.

Darbah, J.N.T., Kubiske, M.E., Nelson, N., Kets, K., Riikonen, J., Sober, A., Rouse, L., and Karnosky, D.F. 2010. Will photosynthetic capacity of aspen trees acclimate after long-term exposure to elevated CO_2 and O_3? *Environmental Pollution* **158**: 983–991.

Davey, P.A., Olcer, H., Zakhleniuk, O., Bernacchi, C.J., Calfapietra, C., Long, S.P., and Raines, C.A. 2006. Can fast growing plantation trees escape biochemical down-regulation of photosynthesis when growing throughout their complete production cycle in the open air under elevated carbon dioxide? *Plant, Cell and Environment* **29**: 1235–1244.

Doherty, R.M., Sitch, S., Smith, B., Lewis, S.L., and Thornton, P.K. 2010. Implications of future climate and atmospheric CO_2 content for regional biogeochemistry, biogeography and ecosystem services across East Africa. *Global Change Biology* **16**: 617–640.

Eichelmann, H., Oja, V., Rasulov, B., Padu, E., Bichele, I., Pettai, H., Mols, T., Kasparova, I., Vapaavuori, E., and Laisk, A. 2004. Photosynthetic parameters of birch (*Betula pendula* Roth) leaves growing in normal and in CO_2- and O_3-enriched atmospheres. *Plant, Cell and Environment* **27**: 479–495.

Ellison, A.M., Bank, M.S., Clinton, B.D., Colburn, E.A., Elliott, K., Ford, C.R., Foster, D.R., Kloeppel, B.D., Knoepp, J.D., Lovett, G.M., Mohan, J., Orwig, D.A., Rodenhouse, N.L., Sobczak, W.V., Stinson, K.A., Stone, J.K., Swan, C.M., Thompson, J., Holle, B.V., and Webster, J.R. 2005. Loss of foundation species: consequences for the structure and dynamics of forested ecosystems. *Frontiers in Ecology and the Environment* **3**: 479–486.

Ellsworth, D.S., Reich, P.B., Naumburg, E.S., Koch, G.W., Kubiske, M.E., and Smith, S.D. 2004. Photosynthesis, carboxylation and leaf nitrogen responses of 16 species to elevated pCO_2 across four free-air CO_2 enrichment experiments in forest, grassland and desert. *Global Change Biology* **10**: 2121–2138.

Finzi, A.C., Norby, R.J., Calfapietra, C., Gallet-Budynek, A., Gielen, B., Holmes, W.E., Hoosbeek, M.R., Iversen, C.M., Jackson, R.B., Kubiske, M.E., Ledford, J., Liberloo, M., Oren, R., Polle, A., Pritchard, S., Zak, D.R., Schlesinger, W.H., and Ceulemans, R. 2007. Increases in nitrogen uptake rather than nitrogen-use efficiency support higher rates of temperate forest productivity under elevated CO_2. *Proceedings of the National Academy of Sciences, USA* **104**: 14,014–14,019.

Finzi, A.C. and Schlesinger, W.H. 2003. Soil-nitrogen cycling in a pine forest exposed to 5 years of elevated carbon dioxide. *Ecosystems* **6**: 444–456.

Ghannoum, O., Phillips, N.G., Sears, M.A., Logan, B.A., Lewis, J.D., Conroy, J.P., and Tissue, D.T. 2010. Photosynthetic responses of two eucalypts to industrial-age changes in atmospheric [CO_2] and temperature. *Plant, Cell and Environment* **33**: 1671–1681.

Graumlich, L.J. 1991. Subalpine tree growth, climate, and increasing CO_2: an assessment of recent growth trends. *Ecology* **72**: 1–11.

Graybill, D.A. 1987. A network of high elevation conifers in the western US for detection of tree-ring growth response to increasing atmospheric carbon dioxide. In *Proceedings of the International Symposium on Ecological Aspects of Tree-Ring Analysis*, edited by G.C. Jacoby and J.W. Hornbeck, 463–474. Washington, DC: U.S. Department of Energy Conference Report DOE/CONF8608144.

Graybill, D.A. and Idso, S.B. 1993. Detecting the aerial fertilization effect of atmospheric CO_2 enrichment in tree-ring chronologies. *Global Biogeochemical Cycles* **7**: 81–95.

Harley, P.C., Tenhunen, J.D., and Lange, O.L. 1986. Use of an analytical model to study the limitations on net photosynthesis in *Arbutus unedo* under field conditions. *Oecologia* **70**: 393–401.

Herrick, J.D. and Thomas, R.B. 2001. No photosynthetic down-regulation in sweetgum trees (*Liquidambar styraciflua* L.) after three years of CO_2 enrichment at the Duke forest FACE experiment. *Plant, Cell, and Environment* **24**: 5364.

Hillstrom, M.L., Vigue, L.M., Coyle, D.R., Raffa, K.F., and Lindroth, R.L. 2010. Performance of the invasive weevil *Polydrusus sericeus* is influenced by atmospheric CO_2 and host species. *Agricultural and Forest Entomology* **12**: 285–292.

Huber, M. 2008. A hotter greenhouse? *Science* **321**: 353–354.

Huber, M. 2009. Snakes tell a torrid tale. *Nature* **457**: 669–670.

Jackson, R.B., Cook, C.W., Pippen, J.S., and Palmer, S.M. 2009. Increased belowground biomass and soil CO_2 fluxes after a decade of carbon dioxide enrichment in a warm-temperate forest. *Ecology* **90**: 3352–3366.

Jacoby G.C. 1986. Long-term temperature trends and a positive departure from the climate-growth response since the 1950s in high elevation lodgepole pine from California. In *Proceedings of the NASA Conference on Climate-Vegetation Interactions*, edited by C. Rosenzweig and R. Dickinson, 81–83. Boulder, CO: Office for Interdisciplinary Earth Studies (OIES), University Corporation for Atmospheric Research (UCAR).

Jaramillo, C., Ochoa, D., Conteras, L., Pagani, M., Carvajal-Ortiz, H., Pratt, L.M., Krishnan, S., Cardona, A., Romero, M., Quiroz, L., Rodriguez, G., Rueda, M.J., de la Parra, F., Moron, S., Green, W., Bayona, G., Montes, C., Quintero, O., Ramirez, R., Mora, G., Schouten, S., Bermudez, H., Navarrete, R., Parra, F., Alvaran, M., Osorno, J., Crowley, J.L., Valencia, V., and Vervoort, J. 2010. Effects of rapid global warming at the Paleocene-Eocene boundary on neotropical vegetation. *Science* **330**: 957–961.

Jurik, T.W., Weber, J.A., and Gates, D.M. 1984. Short-term effects of CO_2 on gas exchange of leaves of bigtooth aspen (*Populus grandidentata*) in the field. *Plant Physiology* **75**: 1022–1026.

Kennett, J.P. and Stott, L.D. 1991. Abrupt deep-sea warming, palaeoceanographic changes and benthic extinctions at the end of the Palaeocene. *Nature* **353**: 225–229.

Kets, K., Darbah, J.N.T., Sober, A., Riikonen, J., Sober, J., and Karnosky, D.F. 2010. Diurnal changes in photosynthetic parameters of *Populus tremuloides*, modulated by elevated concentrations of CO_2 and/or O_3 and daily climatic variation. *Environmental Pollution* **158**: 1000–1007.

Kienast, F. and Luxmoore, R.J. 1988. Tree-ring analysis and conifer growth responses to increased atmospheric CO_2 levels. *Oecologia* **76**: 487–495.

Knapp, P.A., Soule, P.T., and Grissino-Mayer, H.D. 2001. Detecting potential regional effects of increased atmospheric CO_2 on growth rates of western juniper. *Global Change Biology* **7**: 903–917.

Koch, G.W., Sillett, S.C., Jennings, G.M., and Davis, S.D. 2004. The limits to tree height. *Nature* **428**: 851–854.

LaMarche Jr., V.C., Graybill, D.A., Fritts, H.C., and Rose, M.R. 1984. Increasing atmospheric carbon dioxide: tree ring evidence for growth enhancement in natural vegetation. *Science* **225**: 1019–1021.

Lewis, S.L., Lloyd, J., Sitch, S., Mitchard, E.T.A., and Laurance, W.F. 2009. Changing ecology of tropical forests: evidence and drivers. *Annual Review of Ecology, Evolution, and Systematics* **40**: 529–549.

Lewis, J.D., Lucash, M., Olszyk, D., and Tingey, D.T. 2001. Seasonal patterns of photosynthesis in Douglas fir seedlings during the third and fourth year of exposure to elevated CO_2 and temperature. *Plant, Cell and Environment* **24**: 539–548.

Liberloo, M., Tulva, I., Raim, O., Kull, O., and Ceulemans, R. 2007. Photosynthetic stimulation under long-term CO_2 enrichment and fertilization is sustained across a closed *Populus* canopy profile (EUROFACE). *New Phytologist* **173**: 537–549.

Madritch, M.D., Greene, S.G., and Lindroth, R.L. 2009. Genetic mosaics of ecosystem functioning across aspen-dominated landscapes. *Oecologia* **160**: 119–127.

Martinez-Vilalta, J., Lopez, B.C., Adell, N., Badiella, L., and Ninyerola, M. 2008. Twentieth century increase of Scots pine radial growth in NE Spain shows strong climate interactions. *Global Change Biology* **14**: 2868–2881.

McCarthy, H.R., Oren, R., Johnsen, K.H., Gallet-Budynek, A., Pritchard, S.G., Cook, C.W., LaDeau, S.L., Jackson, R.B., and Finzi, A.C. 2010. Re-assessment of plant carbon dynamics at the Duke free-air CO_2 enrichment site: interactions of atmospheric [CO_2] with nitrogen and water availability over stand development. *New Phytologist* **185**: 514–528.

McMurtrie, R.E., Comins, H.N., Kirschbaum, M.U.F., and Wang, Y.-P. 1992. Modifying existing forest growth models to take account of effects of elevated CO_2. *Australian Journal of Botany* **40**: 657–677.

Mencuccini, M., Martinez-Vilalta, J., Vanderklein, D., Hamid, H.A., Korakaki, E., Lee, S., and Michiels, B. 2005. Size-mediated ageing reduces vigour in trees. *Ecology Letters* **8**: 1183–1190.

Nilsen, S., Hovland, K., Dons, C., and Sletten, S.P. 1983. Effect of CO_2 enrichment on photosynthesis, growth and yield of tomato. *Scientia Horticulturae* **20**: 1–14.

Noormets, A., Sober, A., Pell, E.J., Dickson, R.E., Podila, G.K., Sober, J., Isebrands, J.G., and Karnosky, D.F. 2001. Stomatal and non-stomatal limitation to photosynthesis in two trembling aspen (*Populus tremuloides* Michx.) clones exposed to elevated CO_2 and O_3. *Plant, Cell and Environment* **24**: 327–336.

Pagani, M., Caldeira, K., Archer, D., and Zachos, J.C. 2006. An ancient carbon mystery. *Science* **314**: 1556–1557.

Pan, Y., Birdsey, R., Hom, J., and McCullough, K. 2010. Separating effects of changes in atmospheric composition, climate and land-use on carbon sequestration of U.S. Mid-Atlantic temperate forests. *Forest Ecology and Management* **259**: 151–164.

Paoletti, E., Seufert, G., Della Rocca, G., and Thomsen, H. 2007. Photosynthetic response to elevated CO_2 and O_3 in *Quercus ilex* leaves at a natural CO_2 spring. *Environmental Pollution* **147**: 516–524.

Phillips, N.G., Buckley, T.N., and Tissue, D.T. 2008. Capacity of old trees to respond to environmental change. *Journal of Integrative Plant Biology* **50**: 1355–1364.

Roberntz, P. 2001. Atmospheric carbon dioxide concentration, nitrogen availability, temperature and the photosynthetic capacity of current-year Norway spruce shoots. *Tree Physiology* **21**: 931–940.

Royer, D.L. 2010. Fossil soils constrain ancient climate sensitivity. *Proceedings of the National Academy of Sciences, USA* **107**: 517–518.

Sage, R.F., Santrucek, J., and Grise, D.J. 1995. Temperature effects on the photosynthetic response of C_3 plants to long-term CO_2 enrichment. *Vegetatio* **121**: 67–77.

Schweitzer, J.A., Madritch, M.D., Bailey, J.K., LeRoy, C.J., Fischer, D.G., Rehill, B.J., Lindroth, R.L., Hagerman, A.E., Wooley, S.C., Hart, S.C., and Whitham, T.G. 2008. The genetic basis of condensed tannins and their role in nutrient regulation in a *Populus* model system. *Ecosystems* **11**: 1005–1020.

Seemann, J.R., Berry J.A., and Downton, J.S. 1984. Photosynthetic response and adaptation to high temperature in desert plants. A comparison of gas exchange and fluorescence methods for studies of thermal tolerance. *Plant Physiology* **75**: 364–368.

Sharma, P., Sober, A., Sober, J., Podila, G.K., Kubiske, M.E., Mattson, W.J., Isebrands, J.G., and Karnosky, D.F. 2003. Moderation of CO_2-induced gas exchange responses by elevated tropospheric O_3 in trembling aspen and sugar maple. *Ekologia* **22** (S1): 304–317.

Sholtis, J.D., Gunderson, C.A., Norby, R.J., and Tissue, D.T. 2004. Persistent stimulation of photosynthesis by elevated CO_2 in a sweetgum (*Liquidambar styraciflua*) forest stand. *New Phytologist* **162**: 343–354.

Soule, P.T. and Knapp, P.A. 2006. Radial growth rate increases in naturally occurring ponderosa pine trees: a late-20th century CO_2 fertilization effect? *New Phytologist* **171**: 379–390.

Stuhlfauth, T. and Fock, H.P. 1990. Effect of whole season CO_2 enrichment on the cultivation of a medicinal plant, *Digitalis lanata*. *Journal of Agronomy and Crop Science* **164**: 168–173.

Takeuchi, Y., Kubiske, M.E., Isebrands, J.G., Pregitzer, K.S., Hendrey, G., and Karnosky, D.F. 2001. Photosynthesis, light and nitrogen relationships in a young deciduous forest canopy under open-air CO_2 enrichment. *Plant, Cell and Environment* **24**: 1257–1268.

Tans, P. 2009. An accounting of the observed increase in oceanic and atmospheric CO_2 and an outlook for the future. *Oceanography* **22**: 26–35.

Uddling, J., Teclaw, R.M., Pregitzer, K.S., and Ellsworth, D.S. 2009. Leaf and canopy conductance in aspen and aspen-birch forests under free-air enrichment of carbon dioxide and ozone. *Tree Physiology* **29**: 1367–1380.

Westerhold, T., Rohl, U., McCarren, H.K., and Zachos, J.C. 2009. Latest on the absolute age of the Paleocene-Eocene Thermal Maximum (PETM): new insights from exact stratigraphic position of key ash layers + 19 and - 17. *Earth and Planetary Science Letters* **287**: 412–419.

Whitham, T.G., Bailey, J.K., and Schweitzer, J.A. 2006. A framework for community and ecosystem genetics from genes to ecosystems. *Nature Reviews Genetics* **7**: 510–523.

Woodruff, D.R., Bond, J.B., and Meinzer, F.C. 2004. Does turgor limit growth in tall trees? *Plant, Cell and Environment* **27**: 229–236.

Zachos, J.C., Wara, M.W., Bohaty, S., Delaney, M.L., Petrizzo, M.R., Brill, A., Bralower, T.J., and Premoli-Silva, I. 2003. A transient rise in tropical sea surface temperature during the Paleocene-Eocene Thermal Maximum. *Science* **302**: 1551–1554.

Zeebe, R.E., Zachos, J.C., and Dickens, G.R. 2009. Carbon dioxide forcing alone insufficient to explain Palaeocene-Eocene Thermal Maximum warming. *Nature Geoscience* **2**: 576–580.

Ziska, L.H. and Bunce, J.A. 1997. The role of temperature in determining the stimulation of CO_2 assimilation at elevated carbon dioxide concentration in soybean seedlings. *Physiologia Plantarum* **100**: 126–132.

Zotz, G., Pepin, S., and Korner, C. 2005. No down-regulation of leaf photosynthesis in mature forest trees after three years of exposure to elevated CO_2. *Plant Biology* **7**: 369–374.

7.1.5. Ecosystems: Other

Shifting from forests to other ecosystems, we turn to the study of Tian et al. (2010), who like others before them note terrestrial ecosystems provide food, fiber, and various amenities for man and nature alike, and who once again state climate change is typically forecast to negatively affect ecosystem productivity, with potentially disruptive consequences.

Not convinced of the validity of these dire forecasts, Tian et al. used a mechanistic ecosystem model—employing historical (real-world) data for land use, atmospheric CO_2 concentration, nitrogen deposition, fertilization, ozone, and climate—to simulate plant growth responses for multiple biome types (grasslands, forests, wetlands, and agriculture) of the Southern United States at an 8x8-km grid resolution from 1895 to 2007. They found that from Texas through Virginia, net primary productivity rose by 27 percent over the study period (most of it occurring after 1950), with increases in grassland and shrubland (mainly in Texas) and with large increases in cropland. These gains came in spite of increased tropospheric ozone damage.The ten researchers note all biomes showed increases in water use efficiency, contradicting assertions that negative effects of climate change are not only sure to occur but are already apparent.

Contemporaneously, Anderson et al. (2010) studied various root responses of a C_3-C_4 grassland community at Temple, Texas over a CO_2 concentration gradient stretching from 230 to 550 ppm, which they created in two CO_2-gradient above-ground "tunnels" of clear polyethylene film. One of the 60-meter-long and 1.5-meter-wide chambers had ambient air pumped into one end of it, and by the time the air exited the chamber at its other end, its CO_2 concentration was reduced by the photosynthetic activity of the plants within the chamber to a value of approximately 230 ppm. At the same time, the other chamber had air enriched to a CO_2 concentration of 550 ppm pumped into one end of it, and as this air exited the other end of the chamber, its CO_2 concentration was reduced to a value approximately equivalent to that of the ambient air (~380 ppm). Community in-growth root biomass was assessed along the lengths of the tunnels every two to four months from May 1997 through November 1999, with the help of two in-growth cores in each five-meter chamber section, and root biomass response was calculated as the ratio of each measurement date's result to that prevailing at the start of the experiment in May 1997.

Anderson et al. report that based on the linear relationship they derived from all 20 of the in-growth biomass assessments they conducted, there was a 40 percent increase in the in-growth root biomass ratio going from 380 to 480 ppm CO_2, and a 36 percent increase going from 280 to 380 ppm. However, excluding one extremely variable data point and using a power function they fit to the data, the researchers found "the contrast is even greater: a 50% increase from 380 to 480 ppm vs. a 41% increase from 280 to 380 ppm." And in going from the linear relationship to the power function, the r^2 value of the relationship jumped from 0.10 to 0.50, and P dropped from 0.095 to less than 0.001.

Thus the six scientists state their data "suggest that root biomass in grasslands may have changed markedly as atmospheric CO_2 increased since the last glacial period, but more substantial changes are ahead if the air's CO_2 content doubles by the end of this century as predicted."

Moving upward in scale and in latitude, Qian et al. (2010) note it has been hypothesized that if or when the frozen soils of Earth's Northern High Latitudes (NHLs, poleward of 60°N) begin to thaw in response to any new global warming that might occur, the metabolism of soil microbes will be enhanced and the decomposition of soil organic matter will accelerate, and that this, in turn, will lead to an increase in soil organic carbon release to the atmosphere that will amplify global warming. Satellite and phenology studies, however, have shown that during the past several decades the planet's boreal forests have experienced greening and an increase in photosynthetic activity, which extracts carbon (in the form of CO_2) from the atmosphere.

Consequently, and in order to get some indication as to which of these two outcomes might likely predominate over the course of the twenty-first century, Qian et al. explored the potential magnitudes of the two sets of competing processes by analyzing the outputs of ten different models that took part in the Coupled Carbon Cycle Climate Model Intercomparison Project (C4MIP) of the International Geosphere-Biosphere Program and the World Climate Research Program. All of the models, in their words, "used the same anthropogenic fossil fuel emissions from Marland et al. (2005) from the beginning of the industrial period until 2000 and the IPCC SRES A2 scenario for the 2000-2100 period."

According to the three scientists, the ten models predicted a mean warming of 5.6°C from 1901 to 2100 in the NHLs, and they state "the NHLs will be a carbon sink of 0.3 ± 0.3 $PgCyr^{-1}$ by 2100." They also state "the cumulative land organic carbon storage is modeled to increase by 38 ± 20 PgC over 1901 levels, of which 17 ± 8 PgC comes from vegetation [a 43 percent increase] and 21 ± 16 PgC from the soil [an 8 percent increase]," noting "both CO_2 fertilization and warming enhance vegetation growth in the NHLs." Thus over the course of the current century, even the severe warming predicted by current climate models would likely not be a detriment to plant growth and productivity in the NHLs. In fact, it would likely prove a benefit, enhancing plant growth and soil organic carbon storage, which in addition to their own intrinsic virtues would provide a significant negative feedback to global warming.

In a similar study, Friend (2010) calculated the percentage changes in terrestrial plant production that would occur throughout the world in response to (1) projected climate changes alone and (2) projected concurrent changes in climate and atmospheric CO_2 concentration. Friend worked with the *Hybrid6.5* model of terrestrial primary production, which "simulates the carbon, nitrogen, phosphorus, water, and energy fluxes and structural changes in terrestrial ecosystems at hourly to decadal timescales, and at spatial scales ranging from the individual plant to the whole earth," while employing "the climate change anomalies predicted by the GISS-AOM GCM under the A1B emissions scenario for the 2090s [relative] to observed modern climate, and with atmospheric CO_2 increased from 375.7 ppm to 720 ppm."

In response to projected climate changes between 2001–2010 and 2091–2100, the net primary production (NPP) of the planet as a whole was found to be reduced by 2.5 percent, with the largest negative impacts occurring over southern Africa, central Australia, northern Mexico, and the Mediterranean region, where reductions of more than 20 percent were common. At the other extreme, climatic impacts were modestly positive throughout most of the world's boreal forests, as might be expected when these colder regions receive an influx of heat. When both climate and atmospheric CO_2 concentration were changed concurrently, however, the story was vastly different, with a mean *increase* in global NPP of 37.3 percent, driven by mean increases of 43.9–52.9 percent among C_3 plants and 5.9 percent among C_4 species. And in this case of concurrent increases in the globe's air temperature and CO_2 concentration, the largest increases occurred in tropical rainforests and C_3 grass and croplands.

In conclusion, it would appear—at least from climate models—that we can probably expect the historical "greening of the earth" phenomenon to continue.

References

Anderson, L.J., Derner, J.D., Polley, H.W., Gordon, W.S., Eissenstat, D.M., and Jackson, R.B. 2010. Root responses along a subambient to elevated CO_2 gradient in a C_3-C_4 grassland. *Global Change Biology* **16**: 454–468.

Dilley, M., Chen, R.S., Deichmann, U., Lerner-Lam, A.L., and Arnold, M. 2005. *Natural Disaster Hotspots: A Global Risk Analysis.* Washington, DC: The World Bank and Columbia University.

Friend, A.D. 2010. Terrestrial plant production and climate change. *Journal of Experimental Botany* **61**: 1293–1309.

Marland, G., Boden, T.A., and Andres, R.J. 2005. Global, regional, and national CO_2 emissions. In *Trends: A Compendium of Data on Global Change.* Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy. Available at http://cdiac.ornl.gov/trends/emis/overview.html.

Qian, H., Joseph, R., and Zeng, N. 2010. Enhanced terrestrial carbon uptake in the Northern High Latitudes in the 21st century from the Coupled Carbon Cycle Climate Model Intercomparison Project model projections. *Global Change Biology* **16**: 641–656.

Tian, H., Chen, G., Liu, M., Zhang, C., Sun, G., Lu, C., Xu, X., Ren, W., Pan, S., and Chappelka, A. 2010. Model estimates of net primary productivity, evapotranspiration, and water use efficiency in the terrestrial ecosystems of the southern United States during 1895–2007. *Forest Ecology and Management* **259**: 1311–1327.

7.2. Belowground Biotic Responses to Atmospheric CO_2 Enrichment

7.2.1. Soil Fungi

Andrew and Lilleskov (2009) studied sporocarps (the reproductive structures of fungi), which can be significant carbon sinks for the ectomycorrhizal fungi that develop symbiotic relationships with plants by forming sheaths around their root tips, where they are the last sinks for carbon in the long and winding pathway that begins at the source of carbon assimilation in plant leaves. The researchers note "it is critical to understand how ectomycorrhizal fungal sporocarps are affected by elevated CO_2 and ozone," because, they continue, "sporocarps facilitate genetic recombination, permit long-distance dispersal and contribute to food webs," and we need to know how these important processes will be affected by continued increases in the concentrations of these two trace constituents of the atmosphere.

Accordingly, the two researchers evaluated sporocarp biomass for a period of four years at the Aspen free-air CO_2 enrichment (FACE) site near Rhinelander, Wisconsin, which provided, in their words, a "unique opportunity to examine the effects of both elevated CO_2 and O_3 on a forested ecosystem." The examination was conducted during years four through seven of the aspen and aspen-birch forests' exposures to ambient and enriched concentrations of the two gases: CO_2 (350 and 550 ppm) and O_3 (33–67 and 50-–00 ppb). The scientists found total mean sporocarp biomass "was generally lowest under elevated O_3 with ambient CO_2," and it "was greatest under elevated CO_2, regardless of O_3 concentration." They also found "a complete elimination of O_3 effects on sporocarp production when [extra] CO_2 was added." And they state they "expect that the responses seen in the present study were conservative compared to those expected under regional to global changes in CO_2 and O_3." Consequently, by itself or in combination with rising ozone concentrations, the ongoing rise in the atmosphere's CO_2 content appears destined to enhance the genetic recombination and long-distance dispersal of the ectomycorrhizal fungi that form symbiotic relationships with the roots of aspen and birch trees, thereby positively contributing to various food webs that will be found within aspen and aspen-birch forests of the future.

In another study dealing with soil fungi, Alberton et al. (2010) write, "roots of a very large number of plant species are regularly colonized by a group of ascomycete fungi with usually dark-pigmented (melanized) septate hyphae (Mandyam and Jumpponen, 2005; Sieber and Grunig, 2006)" that are referred to as "dark septate root endophytic (DSE) fungi," with "most species belonging to the Leotiomycetes (Kernaghan et al., 2003; Wang et al., 2006)." To study these fungi, the three researchers grew Scots pine (*Pinus sylvestris*) plants from seed for 125 days in Petri dishes—both with and without inoculation with one of seven different species/strains of DSE fungi—within controlled environment chambers maintained at atmospheric CO_2 concentrations of either 350 or 700 ppm, destructively harvesting some of the seedlings at the 98-day point of the experiment and the rest of them at the experiment's conclusion. They found "across all plants (DSE-inoculated and control plants) under elevated CO_2, shoot and root biomass increased significantly by 21% and 19%, respectively, relative to ambient," with "higher values over the final four weeks (increases of 40% and 30% for shoots and roots, respectively)." In addition, they indicate "on average, shoot nitrogen concentration was 57% lower under elevated CO_2," and "elevated CO_2 decreased root nitrogen concentration on average by 16%."

Alberton et al. thus acknowledge their study "did not suggest a role for DSE fungi in increased nutrient uptake." In fact, they emphasize that "under elevated CO_2, DSE fungi even reduced nitrogen content of the pine seedlings." But they also emphasize that "surprisingly, even under reduced nitrogen availability, elevated CO_2 led to increases in both above-ground and below-ground plant biomass."

To explain how that happened, the Brazilian and Dutch scientists write, "a potential mechanism for the increase of plant biomass even when plant nutrient uptake decreases is the production of phytohormones by DSE fungi." They observe that "earlier authors noted that DSE fungi enhance plant growth by producing phytohormones or inducing host hormone production without any apparent facilitation of host nutrient uptake or stimulation of host nutrient metabolism (Addy et al., 2005; Schulz and Boyle, 2005)," further demonstrating that low levels of soil nitrogen availability need not be an insurmountable impediment to significant CO_2-induced increases in plant growth and development.

In another study of note, Compant et al. (2010) write, "virtually all land plant taxa investigated have well-established symbioses with a large variety of microorganisms (Nicolson, 1967; Brundrett, 2009)," some of which "are known to support plant growth and to increase plant tolerance to biotic and abiotic stresses (Bent, 2006)." Many of these microorganisms colonize the rhizosphere (Lugtenberg and Kamilova, 2009), while others "enter the root system of their hosts and enhance their beneficial effects with an endophytic lifestyle (Stone et al., 2000)." This is the case, as they put it, "for plant growth-promoting fungi such as arbuscular mycorrhizae, ectomycorrhizae and other endophytic fungi," as well as for plant growth-promoting bacteria and the more specialized plant growth-promoting rhizobacteria. Many members of the first two categories, they note, "are applied as biocontrol agents, biofertilizers and/or phytostimulators in agriculture (Vessey, 2003; Welbaum et al., 2004) or as degrading microorganisms in phytoremediation applications (Denton, 2007)."

Consequently, and in order to determine how beneficial plant growth-promoting microorganisms might be affected by continued increases in the air's CO_2 content and by possible concomitant changes in climate, Compant et al. reviewed the results of 135 studies that investigated the effects of CO_2 and changes in various climatic factors on "beneficial microorganisms and their interactions with host plants." They found "the majority of studies showed that elevated CO_2 had a positive influence on the abundance of arbuscular and ectomycorrhizal fungi," which, in their words, "is generally in agreement with meta-analyses performed by Treseder (2004) and by Alberton et al. (2005)." But they also found "the effects on plant growth-promoting bacteria and endophytic fungi were more variable." Nevertheless, they state, "in most cases, plant-associated microorganisms had a beneficial effect on plants under elevated CO_2." In addition, they report "numerous studies indicated that plant growth-promoting microorganisms (both bacteria and fungi) positively affected plants subjected to drought stress." Temperature effects, on the other hand, were more of a wash, as Compant et al. state "the effects of increased temperature on beneficial plant-associated microorganisms were more variable, positive and neutral," and "negative effects were equally common and varied considerably with the study system and the temperature range investigated."

In concluding, Compant et al. note the stress of drought is disadvantageous for nearly all terrestrial vegetation, but plant growth-promoting microorganisms should help land plants overcome this potentially negative aspect of future climate change, as long as the air's CO_2 content continues to rise. Temperature effects, on the other hand, would appear to be no more negative than they are positive in a warming world, and when they might be negative, continued atmospheric CO_2 enrichment should prove to be a huge benefit to plants by directly enhancing their growth rates and water use efficiencies. And under the best of climatic conditions, atmospheric CO_2 enrichment should bring out the best of Earth's plants, plus the best of the great majority of plant growth-promoting microorganisms that benefit them biochemically.

References

Addy, H.D., Piercey, M.M., and Currah, R.S. 2005. Microfungal endophytes in roots. *Canadian Journal of Botany* **83**: 1–13.

Andrew, C. and Lilleskov, E.A. 2009. Productivity and community structure of ectomycorrhizal fungal sporocarps under increased atmospheric CO_2 and O_3. *Ecology Letters* **12**: 813–822.

Alberton, O., Kuyper, T.W., and Gorissen, A. 2005. Taking mycocentrism seriously: mycorrhizal fungal and plant responses to elevated CO_2. *New Phytologist* **167**: 859–868.

Alberton, O., Kuyper, T.W., and Summerbell, R.C. 2010. Dark septate root endophytic fungi increase growth of Scots pine seedlings under elevated CO_2 through enhanced nitrogen use efficiency. *Plant and Soil* **328**: 459–470.

Bent, E. 2006. Induced systemic resistance mediated by plant growth-promoting rhizobacteria (PGPR) and fungi (PGPF). In *Multigenic and Induced Systemic Resistance in Plants*, edited by S. Tuzun and E. Bent, 225–258. Berlin, Germany: Springer.

Brundrett, M.C. 2009. Mycorrhizal associations and other means of nutrition of vascular plants: understanding the global diversity of host plants by resolving conflicting information and developing reliable means of diagnosis. *Plant and Soil* **320**: 37–77.

Compant, S., van der Heijden, M.G.A., and Sessitsch, A. 2010. Climate change effects on beneficial plant-microorganism interactions. *FEMS Microbiology Ecology* **73**: 197–214.

Denton, B.D. 2007. Advances in phytoremediation of heavy metals using plant growth promoting bacteria and fungi. *Microbiology and Molecular Genetics* **3**: 1–5.

Kernaghan, G., Sigler, L., and Khasa, D. 2003. Mycorrhizal and root endophytic fungi of containerized *Picea glauca* seedlings assessed by rDNA sequence analysis. *Microbial Ecology* **45**: 128–136.

Lugtenberg, B. and Kamilova, F. 2009. Plant-growth-promoting rhizobacteria. *Annual Review of Microbiology* **63**: 541–556.

Mandyam, K. and Jumpponen, A. 2005. Seeking the elusive function of the root-colonizing dark septate endophytic fungi. *Studies in Mycology* **53**: 173–189.

Nicolson, T.H. 1967. Vesicular-arbuscular mycorrhiza—a universal plant symbiosis. *Science Progress* **55**: 561–581.

Schulz, B. and Boyle, C. 2005. The endophytic continuum. *Mycological Research* **109**: 661–686.

Sieber, T.N. and Grunig, C.R. 2006. Biodiversity of fungal root-endophyte communities and populations, in particular of the dark septate endophyte *Phialocephala fortinii* s.1.In *Microbial Root Endophytes* [of series], edited by B. Schulz, C. Boyle, and T.N. Sieber. *Soil Biology* **9**: 107–132.

Stone, J.K., Bacon, C.W., and White, J.F. 2000. An overview of endophytic microbes: endophytism defined. In *Microbial Endophytes*, edited by C.W. Bacon and J.F. White, 3–29. New York, NY: Marcel Dekker Inc.

Treseder, K.K. 2004. A meta-analysis of mycorrhizal responses to nitrogen, phosphorus and atmospheric CO_2 in field studies. *New Phytologist* **164**: 347–355.

Vessey, J.K. 2003. Plant growth promoting rhizobacteria as biofertilizers. *Plant and Soil* **255**: 571–586.

Wang, Z., Johnston, P.R., Takamatsu, S., Spatafora, J.W., and Hibbett, D.S. 2006. Toward a phylogenetic classification of the Leotiomycetes based on rDNA data. *Mycologia* **98**: 1065–1075.

Welbaum, G., Sturz, A.V., Dong, Z., and Nowak, J. 2004. Fertilizing soil microorganisms to improve productivity of agroecosystems. *Critical Reviews in Plant Sciences* **23**: 175–193.

7.2.2. Plant Roots

Concentrating on plant roots, Wang and Taub (2010) conducted a series of meta-analyses that reveal how differences in the availability of soil fertility and water, as well as the stress of ozone pollution, affect biomass allocation in plants—as expressed by the change in the fraction of root mass to total biomass (root mass fraction, or RMF)—that occurs when plants are exposed to air enriched with CO_2 to levels ranging anywhere from 500 to 1,000 ppm. They used data extracted from 541 peer-reviewed scientific journal articles, which yielded a total of 1,349 RMF observations.

Their analysis determined that lower soil fertility increased RMF, and the magnitude of the increase "was similar for ambient and elevated CO_2-grown plants." They also found that lower soil water content increased RMF, but it did so "to a greater extent at elevated than at ambient CO_2." Finally, they discovered "CO_2 enrichment had little effect on the magnitude of O_3-caused reduction in RMF in herbaceous species," but "it alleviated the adverse effect of higher O_3 on root production in woody species."

Given these findings, the two researchers concluded, "under abiotic stresses, e.g., drought and higher O_3, elevated CO_2-grown plants will likely increase biomass allocation below-ground," where it can be used to construct more roots that can be used to acquire more water and nutrients. However, "because of the non-uniform changes in drought and O_3 projected for different parts of the world," they conclude "elevated CO_2 will have regional, but not global, effects on biomass allocation under various global change scenarios." These responses should make plants—some regionally and some globally—better able to acquire more of the nutrients and water they will need to sustain the increased growth that can be expected in a high-CO_2 world of the future, even in the face of significant ozone pollution.

In another interesting study, Colleen Iversen of the Oak Ridge National Laboratory in Oak Ridge, Tennessee (USA) conducted a review of the pertinent scientific literature "to examine the potential mechanisms for, and consequences of, deeper rooting distributions under elevated CO_2 as they relate to ecosystem carbon and nitrogen cycling," focusing primarily on forests (Iversen, 2010). Iverson found "experimental evidence from a diverse set of forested ecosystems indicates that fine roots of trees exposed to elevated CO_2 are distributed more deeply in the soil profile relative to trees grown under ambient CO_2." As a revealing example, she reports, "in a FACE experiment in a sweetgum (*Liquidambar styraciflua*) plantation, Iversen et al. (2008) found that, over nine years, there was a 220% stimulation in cumulative carbon inputs from fine roots under elevated CO_2 at 45–60 cm soil depth, compared with a 30% stimulation of root carbon inputs at 0–15 cm depth." She also notes "Pritchard et al. (2008a) found a similar response in a CO_2-enriched loblolly pine (*Pinus taeda*) plantation." In fact, she found "of those experiments that examined rooting depth responses to elevated CO_2, 73% found deeper rooting distributions." In addition, she notes, "increased proliferation at depth in the soil has not been limited to fine roots: increased production of mycorrhizas (Pritchard et al., 2008b) and coarse roots (Liberloo et al., 2006) also occurred deeper in the soil under CO_2 enrichment."

Turning to what many have called the progressive nitrogen limitation hypothesis, Iversen notes "a disconnect between observed root dynamics and modeled nutrient availability has confounded projections of forest responses to elevated CO_2," and "while models predict that soil nitrogen availability will limit forest responses to elevated CO_2 (Thornton et al., 2007), many of the forested FACE experiments found a sustained increase in nitrogen uptake from the soil in response to CO_2 enrichment (Finzi et al., 2007)." She then observes, "there has been much speculation on the source of this 'extra' nitrogen (Johnson, 2006), and a greater cumulative amount of nitrogen available at depth in the soil may be the answer (i.e. a 'bigger box' of nitrogen when deeper soil depths are considered)."

In another experiment with implications for the progressive nitrogen limitation hypothesis, McCormack et al. (2010) grew 12 identical mini-ecosystems—each consisting of three longleaf pine (*Pinus palustris*) seedlings, three wiregrass (*Aristida stricta*) C_4 grass plants, two sand post oak (*Quercus margaretta*) seedlings, one rattlebox (*Croatalaria rotundifolia*) C_3 perennial herbaceous legume, and one butterfly weed (*Asclepias tuberose*) herbaceous C_3 dicotyledonous perennial—for three years under natural meteorological conditions in an outdoor soil bin at the National Soil Dynamics Laboratory in Auburn, Alabama (USA) within 12 open-top chambers, half of which were maintained for three years at 365 ppm CO_2 and half of which were maintained at 720 ppm CO_2 for the same period. Throughout this period, the "standing crops" of fine-root length, rhizomorph length, and number of mycorrhizal root tips were assessed in the upper (0–17 cm) and lower (17–34 cm) halves of the plants' root zones at four-week intervals via microvideo cameras installed within each of two mini-rhizotron tubes located within each of the 12 plots into which the soil bin was divided.

The greatest impacts of the 97 percent increase in the air's CO_2 content were generally observed in the lower halves of the ecosystems' root zones, where the standing crops of fine roots, rhizomorphs, and mycorrhizal root tips were increased by 59 percent, 66 percent, and 64 percent, respectively, although the mean standing crop of rhizomorphs in the upper halves of the ecosystems' root zones was increased by 114 percent.

Given these findings, McCormack et al. state that as the atmosphere's CO_2 content continues to rise, "greater biomass production in deeper soils in the coming decades has the potential to contribute to greater carbon storage in forest soils" because "carbon in deeper soil turns over (decomposes) more slowly than litter nearer the soil surface," citing Trumbore (2000) and Schoning and Kogel-Knabner (2006). In addition, they "fungal tissues consist largely of chitin, a potentially recalcitrant compound that may build up soil organic matter and persist for long periods of time relative to more labile carbon," citing Langley and Hungate (2003). Thus they suggest, "regenerating longleaf pine-wiregrass systems may act as a carbon sink as atmospheric CO_2 rises in the coming decades through increased biomass production and potentially through directed allocation of carbon to deeper soils." This, they note, is "consistent with the recent assertion that greater allocation of forest carbon to deeper soil is a general response to atmospheric CO_2-enrichment," citing Iversen (2010). And, very importantly, they state, "significant increases in mycorrhizae and rhizomorphs," as they found in their study, "may explain why the magnitude of the increase in forest net primary productivity caused by elevated CO_2, in several long-term demonstrably nitrogen-limited FACE experiments, has not decreased after nearly a decade (Finzi et al., 2007)." That helps explain why the progressive nitrogen limitation hypothesis has been shown repeatedly to be wrong.

Finally, in a recent review article, Herder et al. (2010) write that humanity "is facing the major challenge of providing food security for an ever growing world population," citing Godfray et al. (2010), while further noting the planet's agricultural area is shrinking, due, in their words, "to erosion of hill-sides, soil degradation, landslides and the increasing demand for biofuels." They indicate the magnitude of the problem is such that currently applied technology and available crop plants "will not be sufficient to feed the rapidly growing world population."

Reviewing potential remedies, the four researchers state, "in the past, improvement of crops and agricultural techniques has mainly focused on increasing shoot biomass and seed yield," but "the relevance of the root system for food production has often been overlooked." This myopic view was unfortunate, for many aspects of root system development are essential for enabling optimal plant growth in the face of numerous belowground environmental stresses such as drought, salinity, and soil-borne pathogenic attacks. They state that achieving improvements in this "hidden half" of a crop's environment represents "an underestimated and not fully exploited area for strategies to enhance yield."

Herder et al.'s analysis indicates crop plants of the future will need "an increased and more efficient root system" that includes "more lateral branches and/or higher number of root hairs," in order to "take up water and nutrients, to fix fertile soil and to prevent soil degradation." These are things that enriching the air with CO_2 helps to bring about. The scientists also note "80% of land plants obtain important mineral nutrition through the ancient arbuscular endomycorrhizal symbiosis with *Glomeromycota* fungi species," which, according to Parniske (2008), are ubiquitous in soils. This, too, is something elevated CO_2 helps to promote. In addition, they note the need for sufficient nitrogen availability to plants, which is provided to legumes by nitrogen-fixing soil bacteria located within nodules on their roots. This need is also met by increasing atmospheric CO_2 concentrations.

References

Finzi, A.C., Norby, R.J., Calfapietra, C., Gallet-Budynek, A., Gielen, B., Holmes, W.E., Hoosbeek, M.R., Iversen, C.M., Jackson, R.B., Kubiske, M.E., Ledford, J., Liberloo, M., Oren, R., Polle, A., Pritchard, S., Zak, D.R., Schlesinger, W.H., and Ceulemans, R. 2007. Increases in nitrogen uptake rather than nitrogen-use efficiency support higher rates of temperate forest productivity under elevated CO_2. *Proceedings of the National Academy of Sciences, USA* **104**: 14,014–14,019.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., and Toulmin, C. 2010. Food security: the challenge of feeding 9 billion people. *Science* **327**: 812–818.

Herder, G.D., Van Isterdael, G., Beeckman, T., and De Smet, I. 2010. The roots of a new green revolution. *Trends in Plant Science* **15**: 600–607.

Iversen, C.M. 2010. Digging deeper: fine-root responses to rising atmospheric CO_2 concentration in forested ecosystems. *New Phytologist* **186**: 346–357.

Iversen, C.M., Ledford, J., and Norby, R.J. 2008. CO_2 enrichment increases carbon and nitrogen input from fine roots in a deciduous forest. *New Phytologist* **179**: 837–847.

Johnson, D.W. 2006. Progressive N limitation in forests: review and implications for long-term responses to elevated CO_2. *Ecology* **87**: 64–75.

Langley, J.A. and Hungate, B.A. 2003. Mycorrhizal controls on belowground litter quality. *Journal of Ecology* **84**: 2302–2312.

Liberloo, M., Calfapietra, C., Lukac, M., Godbold, D., Luo, Z.-B., Polle, A., Hoosbeek, M.R., Kull, O., Marek, M., Raines, C., Rubino, M., Taylor, G., Scarascia-Mugnozza, G., and Ceulemans, R. 2006. Woody biomass production during the second rotation of a bio-energy *Populus* plantation increases in a future high CO_2 world. *Global Change Biology* **12**: 1094–1106.

McCormack, M.L., Pritchard, S.G., Breland, S., Davis, M.A., Prior, S.A., Runion, G.B., Mitchell, R.J., and Rogers, H.H. 2010. Soil fungi respond more strongly than fine roots to elevated CO_2 in a model regenerating longleaf pine-wiregrass ecosystem. *Ecosystems* **13**: 901–916.

Parniske, M. 2008. Arbuscular mycorrhiza: the mother of plant root endosymbioses. *Nature Reviews Microbiology* **6**: 763–775.

Pritchard, S.G., Strand, A.E., McCormack, M.L., Davis, M.A., Finzi, A.C., Jackson, R.B., Matamala, R., Rogers, H.H., and Oren, R. 2008a. Fine root dynamics in a loblolly pine forest are influenced by free-air-CO_2-enrichment: a six-year-minirhizotron study. *Global Change Biology* **14**: 588–602.

Pritchard, S.G., Strand, A.E., McCormack, M.L., Davis, M.A., and Oren, R. 2008b. Mycorrhizal and rhizomorph dynamics in a loblolly pine forest during 5 years of free-air-CO_2-enrichment. *Global Change Biology* **14**: 1–13.

Schoning, I. and Kogel-Knabner, I. 2006. Chemical composition of young and old carbon pools throughout Camisol and Luvisol profiles under forests. *Soil Biology and Biochemistry* **38**: 2411–2424.

Thornton, P.E., Lamarque, J.F., Rosenbloom, N.A., and Mahowald, N.M. 2007. Influence of carbon-nitrogen cycle coupling on land model response to CO_2 fertilization and climate variability. *Global Biogeochemical Cycles* **21**: 10.1029/2006GB002868.

Trumbore, S. 2000. Age of soil organic matter and soil respiration: radiocarbon constraints on belowground C dynamics. *Ecological Applications* **10**: 399–411.

Wang, X. and Taub, D.R. 2010. Interactive effects of elevated carbon dioxide and environmental stresses on root mass fraction in plants: a meta-analytical synthesis using pairwise techniques. *Oecologia* **163**: 1–11.

7.3. Other Plant Responses to Atmospheric CO_2 Enrichment

7.3.1. Transpiration and Water Use Efficiency

In a study of marsh plants, Li et al. (2010) write, “wetlands evapotranspire more water than other ecosystems, including agricultural, forest and grassland ecosystems,” but the “effects of elevated atmospheric carbon dioxide concentration on wetland evapotranspiration (ET) are largely unknown.” In an effort to help fill this knowledge void, they present the results of “twelve years of measurements of ET, net ecosystem CO_2 exchange (NEE), and ecosystem water use efficiency (EWUE, i.e., NEE/ET) at 13:00–15:00 hours in July and August for a *Scirpus olneyi* (C_3 sedge) community and a *Spartina patens* (C_4 grass) community exposed to ambient and elevated (ambient + 340 ppm) CO_2 in a Chesapeake Bay wetland.”

The results of their study indicate “although a decrease in stomatal conductance at elevated CO_2 in the *S. olneyi* community was counteracted by an increase in leaf area index (LAI) to some extent, ET was still reduced by 19% on average over 12 years,” while “in the *S. patens* community, LAI was not affected by elevated CO_2 and the reduction of ET was 34%.” They found NEE “was stimulated about 36% at elevated CO_2 in the *S. olneyi* community but was not significantly affected by elevated CO_2 in the *S. patens* community.” Merging the ET and NEE responses of the two species, they determined “EWUE was increased about 83% by elevated CO_2 in both the *S. olneyi* and *S. patens* communities.”

Li et al. conclude rising concentrations of atmospheric CO_2 “could have significant impacts on the hydrologic cycles of coastal wetlands,” noting “reduced ET could increase carbon uptake by mitigating the effects of drought on carbon uptake (Rasse et al., 2005),” and it “could also facilitate ground water recharge to counteract salinity intrusion in coastal areas caused by rising sea levels from global warming.” They state salinity intrusion has been identified as "a serious problem in the United States" based on the work of Stevenson et al. (1988) and Day et al. (2000).

Mateos-Naranjo et al. (2010) also worked with a marsh plant—*S. maritima*, which they obtained from a low-marsh site along the southwest coast of Spain. They watered clumps of the plant with Hoagland's solution of three different salinities (0, 170, or 510 mM NaCl), conducting an experiment with the plants in controlled environment chambers maintained at atmospheric CO_2 concentrations of either 380 or 700 ppm for periods of 30 days, during which time they measured several plant properties and processes. They found the 84 percent increase in the atmosphere's CO_2 concentration stimulated the growth of *S. maritima* by about 65 percent in all three salinity treatments, while the halophyte's water use efficiency was increased by about 10 percent, 100 percent, and 160 percent in the 0, 170, and 510 mM salinity treatments, respectively. They conclude, "increasing CO_2 concentration has a positive effect on the photochemical apparatus, helping to counteract salt stress experienced by plants at current CO_2 concentrations."

In another recent study, Shimono et al. (2010) write, "by 2050, the world's population will have increased by about 37%, from the current level of 6.7 billion to an estimated 9.2 billion (UN, 2009), with a corresponding increase in global food demand." They also state "about 0.6 billion Mg of rice is produced annually from an area of 1.5 million km^2, making rice one of the most important crops for supporting human life." As noted by Pritchard and Amthor (2005), rice supplies the planet's human population with an estimated 20 percent of its energy needs (on a caloric basis) and 14 percent of its protein requirements (on a weight basis).

The six scientists further note "rice production depends heavily on water availability," as "irrigated lowlands account for 55% of the total area of harvested rice and typically produce two to three times the crop yield of rice grown under non-irrigated conditions (IRRI, 2002)." And because the demand for ever-greater quantities of water will continue to rise due to the need to feed growing numbers of people, "efficient use of water will thus be essential for future rice production."

In an attempt to determine how agriculture may be affected by the ongoing rise in the air's CO_2 content, the Japanese researchers conducted a two-year free-air CO_2 enrichment (FACE) study in fields at Shizukuishi, Iwate (Japan) to learn how elevated CO_2 may reduce crop water use via its impact on the leaf stomatal conductance (g_s) of three varieties of rice (*Oryza sativa* L.): early-maturing Kirara397, intermediate-maturing Akitakomachi, and latest-maturing Hitomebore.

In response to the 53 percent increase in daytime atmospheric CO_2 concentration employed in their experiments, Shimono et al. report, "the reduction in g_s due to elevated CO_2 was similar across measurements, averaging around 20% in the morning, 24% around noon and 23% in the afternoon across all growth stages." They add "there was no significant CO_2 x cultivar interaction." Consequently, with the concomitant increase in grain yield that also results from atmospheric CO_2 enrichment, it should be apparent that the ongoing rise in the air's CO_2 content will play a major role in enabling a growing world population to meet its food needs.

Moving on from crops to grasslands, we consider Barbosa et al. (2010), who studied an alpine grassland in Switzerland. Citing the principle expressed by DeNiro and Epstein (1978), who coined the phrase "you are what you eat isotopically," they decided to use the horns of numerous deceased alpine ibex (*Capra ibex*) because they are composed of yearly growth layers that possess a temporal archive of the $\delta^{13}C$ values of the alpine grassland plants the animals ate while they were alive. The researchers were given access by the Natural History Museum of Bern to the horns of 24 males that had lived in the grassland they were studying. These horns covered the period from 1938 to 2006 and provided a total of 233 yearly $\delta^{13}C$ data points.

From information obtained from the ibex horns, Barbosa et al. determined the intrinsic water-use efficiency (iWUE) of the alpine grassland plants had increased by approximately 18 percent over the 69-year period from 1938 to 2006, when the atmosphere's CO_2 concentration rose by about 23 percent. Between 1955 and 2006, however, meteorological data indicate the vapor pressure deficit (or evaporative demand) of the air in their study area had risen by about 0.1 kPa, just enough to offset the iWUE benefit provided by the rise in the air's CO_2 content. Thus, although the net effect of the increase in the air's CO_2 content (which tended to reduce plant water loss) and the increase in the air's dryness (which tended to enhance plant water loss) resulted in no net change in plant iWUE, it can be appreciated that had the air's CO_2 content not risen over the period in question, the alpine plants would have fared far worse than they did in reality.

Moving on to trees, we begin with Silva et al. (2009), who studied *Araucaria angustifolia*, which they describe as “an indigenous conifer tree restricted to the southern region of South America that plays a key role in the dynamics of regional ecosystems where forest expansion over grasslands has been observed.” Working with various types of tree-ring data obtained from trees growing in both forest and grassland sites in southern Brazil, they compared changes in intrinsic water use efficiency (iWUE)—which they defined as the ratio of the rate of CO_2 assimilation by the trees’ needles to their stomatal conductance—with historical changes in temperature, precipitation, and atmospheric CO_2 concentration that occurred in the region over the past century.

The four researchers report that during the past several decades, “iWUE increased over 30% in both habitats,” and “this increase was highly correlated with increasing levels of CO_2 in the atmosphere.” Over this latter period, however, tree growth remained rather stable, due to lower-than-normal precipitation and higher-than-normal temperatures, which would normally tend to depress the growth of this species: Katinas and Crisci (2008) describe *A. angustifolia* as being “intolerant of dry seasons and requiring cool temperatures.” Therefore, Silva et al. conclude the “climatic fluctuations during the past few decades,” which would normally be expected to have been deleterious to the growth of *A. angustifolia*, appear to have had their growth-retarding effects “compensated by increases in atmospheric CO_2 and changes [i.e., increases] in iWUE.”

Regarding global water scarcity, Kummu et al. (2010) write, “due to the rapidly increasing population and water use per capita in many areas of the world, around one third of the world’s population currently lives under physical water scarcity (e.g. Vorosmarty et al., 2000; Alcamo et al., 2003; Oki and Kanae, 2006).” They note that despite the large number of water scarcity studies conducted over the years, “no global assessment is available of how this trend has evolved over the past several centuries to millennia.” To fill this void, Kummu et al. conducted a study of AD 0 to 2005. This analysis was carried out for ten different time slices, defined as those times at which the human population of the globe was approximately double the population of the previous time slice. Global population data for these analyses were derived from the 5’ latitude x 5’ longitude-resolution global HYDE dataset of Klein Goldewijk (2005) and Klein Goldewijk et al. (2010), and evaluation of water resources availability over the same period was based on monthly temperature and precipitation output from the climate model ECBilt-CLIO-VECODE, as calculated by Renssen et al. (2005).

These operations indicated “moderate water shortage first appeared around 1800, but it commenced in earnest from about 1900, when 9% of the world population experienced water shortage, of which 2% was under chronic water shortage (<1000 m^3/capita/year).” Thereafter, from 1960 onwards, “water shortage increased extremely rapidly, with the proportion of global population living under chronic water shortage increasing from 9% (280 million people) in 1960 to 35% (2,300 million) in 2005.” Currently, they note, “the most widespread water shortage is in South Asia, where 91% of the population experiences some form of water shortage,” while “the most severe shortage is in North Africa and the Middle East, where 77% and 52% of the total population lives under extreme water shortage (<500 m^3/capita/year), respectively.”

To alleviate these freshwater shortages, Kummu et al. note measures generally have been taken to increase water availability, such as building dams and extracting groundwater. However, they state, “there are already several regions in which such measures are no longer sufficient, as there is simply not enough water available in some regions.” They also note “this problem is expected to increase in the future due to increasing population pressure (e.g. United Nations, 2009), higher welfare (e.g. Grubler et al., 2007), [and] production of water intensive biofuels (e.g. Varis, 2007; Berndes, 2008).” Hence, they conclude there will be an increasing need for many nonstructural measures to be implemented, the first and foremost of which they indicate to be “increasing the efficiency of water use,” a property of plants almost universally promoted by atmospheric CO_2 enrichment.

References

Alcamo, J., Doll, P., Henrichs, T., Kaspar, F., Lehner, B., Rosch, T., and Siebert, S. 2003. Global estimates of water withdrawals and availability under current and future ‘business-as-usual’ conditions. *Hydrological Sciences Journal* **48**: 339–348.

Barbosa, I.C.R., Kohler, I.H., Auerswald, K., Lups, P., and Schnyder, H. 2010. Last-century changes of alpine grassland water-use efficiency: a reconstruction through carbon isotope analysis of a time-series of *Capra ibex* horns. *Global Change Biology* **16**: 1171–1180.

Berndes, G. 2008. Future biomass energy supply: the consumptive water use perspective. *International Journal of Water Resources Development* **24**: 235–245.

Day, J., Shaffer, G., Britsch, L., Reed, D., Hawes, S., and Cahoon, D. 2000. Pattern and processes of land loss in the Mississippi Delta: a spatial and temporal analysis of wetland habitat change. *Estuaries* **23**: 425–438.

DeNiro, M. J. and Epstein, S. 1978. Influence of diet on the distribution of carbon isotopes in animals. *Geochimica et Cosmochimica Acta* **42**: 495–506.

Grubler, A., O'Neill, B., Riahi, K., Chirkov, V., Goujon, A., Kolp, P., Prommer, I., Scherbov, S., and Slentoe, E. 2007. Regional, national, and spatially explicit scenarios of demographic and economic change based on SRES. *Technological Forecasting and Social Change* **74**: 980–1021.

IRRI (International Rice Research Institute). 2002. *Rice Almanac: Source Book for the Most Important Economic Activity on Earth.* Oxfordshire, UK: CABI Publishing.

Katinas, L. and Crisci, J.V. 2008. Reconstructing the biogeographical history of two plant genera with different dispersion capabilities. *Journal of Biogeography* **35**: 1374–1384.

Klein Goldewijk, K. 2005. Three centuries of global population growth: a spatial referenced population (density) database for 1700-2000. *Population and Environment* **26**: 343–367.

Klein Goldewijk, K., Beusen, A., and Janssen, P. 2010. Long-term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1. *The Holocene* **20**: 565–573.

Kummu, M., Ward, P.J., de Moel, H., and Varis, O. 2010. Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia. *Environmental Research Letters* **5**: 10.1088/1748-9326/5/3/034006.

Li, J.H., Erickson, J.E., Peresta, G., and Drake, B.G. 2010. Evapotranspiration and water use efficiency in a Chesapeake Bay wetland under carbon dioxide enrichment. *Global Change Biology* **16**: 234–245.

Mateos-Naranjo, E., Redondo-Gomez, S., Andrades-Moreno, L., and Davy, A.J. 2010. Growth and photosynthetic responses of the cordgrass *Spartina maritima* to CO_2 enrichment and salinity. *Chemosphere* **81**: 725–731.

Oki, T. and Kanae, S. 2006. Global hydrological cycles and world water resources. *Science* **313**: 1068–1072.

Pritchard, S.G. and Amthor, J.S. 2005. *Crops and Environmental Change.* New York, NY: Food Production Press.

Rasse, D.P., Peresta, G., Saunders, C.J., and Drake, B.G. 2005. Seventeen years of elevated CO_2 exposure in a Chesapeake Bay Wetland: sustained but contrasting responses of plant growth and CO_2 uptake. *Global Change Biology* **11**: 369–377.

Renssen, H., Goosse, H., Fichefet, T., Brovkin, V., Driesschaert, E., and Wolk, F. 2005. Simulating the Holocene climate evolution at northern high latitudes using a coupled atmosphere-sea-ice-ocean-vegetation model. *Climate Dynamics* **24**: 23–43.

Shimono, H., Okada, M., Inoue, M., Nakamura, H., Kobayashi, K., and Hasegawa, T. 2010. Diurnal and seasonal variations in stomatal conductance of rice at elevated atmospheric CO_2 under fully open-air conditions. *Plant, Cell and Environment* **33**: 322–331.

Silva, L.C.R., Anand, M., Oliveira, J.M., and Pillar, V.D. 2009. Past century changes in *Araucaria angustifolia* (Bertol.) Kuntze water use efficiency and growth in forest and grassland ecosystems of southern Brazil: implications for forest expansion. *Global Change Biology* **15**: 2387–2396.

Stevenson, J., Kearney, M., and Pendleton, E. 1988. Sedimentation and erosion in a Chesapeake Bay brackish marsh system. *Marine Geology* **67**: 213–235.

United Nations. 2009. *The 2006 World Population Prospects. The 2008 Revision Population Database.* New York, NY: United Nations. Available at http://esa.un.org/unpp/.

Varis, O. 2007. Water demands for bioenergy production. *International Journal of Water Resources Development* **23**: 519–535.

Vorosmarty, C.J., Green, P., Salisbury, J., and Lammers, R.B. 2000. Global water resources: vulnerability from climate change and population growth. *Science* **289**: 284–288.

7.3.2. Flowers, Leaves, and Seeds

Focusing on flowers, Johnston and Reekie (2008) state "there have been marked changes in plant phenology over the past century," and they indicate these changes "have been interpreted as a consequence of the increase in temperature that has been observed over this time." However, they add a new twist to the phenomenon, speculating that "the concentration of atmospheric CO_2 may also directly affect time of flowering, even in the absence of temperature change."

In exploring this possibility, the two researchers examined the effects of elevated atmospheric CO_2 concentration by itself (ambient and ambient + 330 ppm), as well as the combined effect of elevated CO_2 and elevated air temperature (ambient + 1.5°C), on the flowering phenology of 22 species of plants in the family Asteraceae, which were grown under natural seasonally varying temperature and daylength in separate compartments of a glasshouse in Wolfville, Nova Scotia, Canada. This work revealed, as they describe it, that "on average, elevated CO_2 by itself advanced flowering by four days," while "increasing temperature as well as CO_2 advanced flowering by an additional three days." They also found "CO_2 was more likely to hasten phenology in long- than in short-day species," and "early- and late-flowering species did not differ in response to elevated CO_2, but the combined effect of elevated CO_2 and temperature hastened flowering more in early- than late-flowering species." In light of their several findings, they concluded that with respect to time of flowering in Asteraceae species, "the direct effect of CO_2 on phenology may be as important as its indirect effect through climate change."

Concentrating on leaves, McGrath et al. (2010) note "early spring leaf-out is critical to the growth and survival of competing trees in deciduous forests (Augspurger, 2008)," and "individuals or genotypes that more quickly reach high LAI [leaf area index] will more successfully compete with neighbors for light energy and space." Therefore, working at the Aspen FACE facility, where aspen clones had been grown since 1997 in conditions simulating CO_2 and O_3 concentrations predicted for the mid-twenty-first century (560 ppm CO_2 and 1.5 times current-ambient O_3), the three researchers documented the history of leaf area development and leaf photosynthetic operating efficiency over the first month of spring leaf-out 11 years later in 2008. They found the trees in the elevated CO_2 plots showed a 36 percent stimulation of leaf area index, whereas the trees in the elevated O_3 plots showed a 20 percent reduction in LAI. In addition, they report the photosynthetic operating efficiency of the CO_2-enriched aspen leaves was enhanced by 51 percent.

Studying seeds at the Duke Forest FACE facility in the Piedmont region of North Carolina, which was established in an unmanaged plantation of 13-year-old loblolly pine (*Pinus taeda* L.) trees, Way et al. (2010) collected in ground traps the seeds released by the trees, counted the number of seeds collected, and analyzed various properties of the seeds over the 12-year period 1997–2008, during which time the trees were growing in either ambient air or air enriched with an extra 200 ppm of CO_2. At the conclusion of their experiment, they determined "the number of mature, viable seeds doubled per unit basal area in high-CO_2 plots from 1997 to 2008 ($P<0.001$)," but "there was no CO_2 effect on mean seed mass, viability, or nutrient content," which they state "is consistent with observations from the few other studies examining reproductive responses to elevated CO_2 in trees," citing the earlier work of LaDeau and Clark (2001, 2006), Stiling et al. (2004), and Kimball et al. (2007). In addition, they report, "the mass of male catkins collected in ground traps was more than doubled over two years in elevated CO_2 plots compared with ambient plots." Based on their and others' findings, the seven scientists concluded, "increased production of high-quality seeds by woody species in response to rising CO_2 would give them a reproductive advantage over herbaceous species that produce more seeds but cannot maintain seed quality," and they suggest this phenomenon "may facilitate woody encroachment into herbaceous communities, a wide-spread phenomenon that has already been linked to rising CO_2 (Bond and Midgley, 2000; Davis et al., 2007)."

In another study, De Frenne et al. (2010) collected seeds of *Anemone nemorosa* L.—a model species for slow-colonizing herbaceous forest plants—found in populations growing along a 2400-km latitudinal gradient stretching from northern France to northern Sweden during three separate growing seasons (2005, 2006, and 2008). They then conducted sowing trials in incubators, a greenhouse, and under field conditions in a forest, where they measured effects of different temperature treatments (growing degree hours, or GDH) on seed and seedling traits. Based on their analyses, they report, "seed mass, germination percentage, germinable seed output and seedling mass all showed a positive response to increased GDH experienced by the parent plant." Seed and seedling mass increased by 9.7 percent and 10.4 percent, respectively, for every 1,000 °C-hours increase in GDH, which they state is equivalent to a 1°C increase in temperature over a 42-day period. As a result, the 19 researchers—from Belgium, Estonia, France, Germany, and Sweden—concluded, "if climate warms, this will have a pronounced positive impact on the reproduction of *A. nemorosa*, especially in terms of seed mass, germination percentage and seedling mass," because "if more seeds germinate and resulting seedlings show higher fitness, more individuals may be recruited to the adult stage." In addition, they write, since "rhizome growth also is likely to benefit from higher winter temperatures (Philipp and Petersen, 2007), it can be hypothesized that the migration potential of *A. nemorosa* may increase as the climate in NW-Europe becomes warmer in the coming decades." And increasing migration potential implies decreasing extinction potential.

In a third seed study, with the help of real-world micrometeorological data measured during the vegetative growth period (May–September) of ten consecutive years (1998–2007) in a boreal forest of southern Finland, Kuparinen et al. (2009) investigated the effects of a warming-induced increase in local convective turbulence (due to a postulated 3°C increase in local temperature) on the long-distance dispersal (LDD) of seeds and pollen based on mechanistic models of wind dispersal (Kuparinen et al., 2007) and population spread (Clark et al., 2001). For light-seeded herbs, they found spread rates increased by 35–42 m/yr (6.--9.2 percent), while for heavy-seeded herbs the increase was 0.01–0.06 m/yr (1.9–6.7 percent). Similarly, light-seeded trees increased their spread rates by 27–39 m/yr (3.5–6.2 percent), while for heavy-seeded trees the increase was 0.2–0.5 m/yr (4.0–8.5 percent). In addition, they discovered "climate change driven advancements of flowering and fruiting phenology can increase spread rates of plant populations because wind conditions in spring tend to produce higher spread rates than wind conditions later in the year."

The four researchers (from France, Germany, Israel, and the United States), write that, in addition to the obvious benefits of greater LLD (being better able to move towards a more hospitable part of the planet), the increased wind dispersal of seeds and pollen may "promote geneflow between populations, thus increasing their genetic diversity and decreasing the risk of inbreeding depression," citing Ellstrand (1992) and Aguilar et al. (2008). They further note "increased gene flow between neighboring populations can accelerate adaptation to environmental change," citing Davis and Shaw (2001) and Savolainen et al. (2007). These phenomena are all very positive developments. In fact, they report the "dispersal and spread of populations are widely viewed as a means by which species can buffer negative effects of climate change."

References

Aguilar, R., Quesada, M., Ashworth, L., Herrerias-Diego, Y., and Lobo, J. 2008. Genetic consequences of habitat fragmentation in plant populations: susceptible signals in plant traits and methodological approaches. *Molecular Ecology* **17**: 5177–5188.

Augspurger, C.K. 2008. Early spring leaf out enhances growth and survival of saplings in a temperate deciduous forest. *Oecologia* **156**: 281–286.

Bond, W.J. and Midgley, G.F. 2000. A proposed CO_2-controlled mechanism of woody plant invasion in grasslands and savannas. *Global Change Biology* **6**: 865f–869.

Clark, J.S., Lewis, M., and Hovarth, L. 2001. Invasion by extremes; population spread with variation in dispersal and reproduction. *American Naturalist* **157**: 537–544.

Davis, M.A., Reich, P.B., Knoll, M.J.B., Dooley, L., Hundtoft, M., and Attleson, I. 2007. Elevated atmospheric CO_2: a nurse plant substitute for oak seedlings establishing in old fields. *Global Change Biology* **13**: 2308–2316.

Davis, M.B. and Shaw, R.G. 2001. Range shifts and adaptive responses to quaternary climate change. *Science* **292**: 673–679.

De Frenne, P., Graae, J.J., Kolb, A., Brunet, J., Chabrerie, O., Cousins, S.A.O., Decocq, G., Dhondt, R., Diekmann, M., Eriksson, O., Heinken, T., Hermy, M., Jogar, U., Saguez, R., Shevtsova, A., Stanton, S., Zindel, R., Zobel, M., and Verheyen, K. 2010. Significant effects of temperature on the reproductive output of the forest herb *Anemone nemorosa* L. *Forest Ecology and Management* **259**: 809–817.

Ellstrand, N.C. 1992. Gene flow by pollen: implications for plant conservation genetics. *Oikos* **63**: 77–86.

Johnston, A. and Reekie, E. 2008. Regardless of whether rising atmospheric carbon dioxide levels increase air temperature, flowering phenology will be affected. *International Journal of Plant Science* **169**: 1210–1218.

Kimball, B.A., Idso, S.B., Johnson, S., and Rillig, M.C. 2007. Seventeen years of carbon dioxide enrichment of sour orange trees: final results. *Global Change Biology* **13**: 2171–2183.

Kuparinen, A., Katul, G., Nathan, R., and Schurr, F.M. 2009. Increases in air temperature can promote wind-driven dispersal and spread of plants. *Proceedings of the Royal Society B* **276**: 3081–3087.

Kuparinen, A., Markkanen, T., Riikonen, H., and Vesala, T. 2007. Modeling air-mediated dispersal of spores, pollen and seeds in forested areas. *Ecological Modelling* **208**: 177–188.

LaDeau, S.L. and Clark, J.S. 2001. Rising CO_2 levels and the fecundity of forest trees. *Science* **292**: 95–98.

LaDeau, S.L. and Clark, J.S. 2006. Elevated CO_2 and tree fecundity: the role of tree size, inter-annual variability and population heterogeneity. *Global Change Biology* **32**: 822–833.

McGrath, J.M., Karnosky, D.F., and Ainsworth, E.A. 2010. Spring leaf flush in aspen (*Populus tremuloides*) clones is altered by long-term growth at elevated carbon dioxide and elevated ozone concentration. *Environmental Pollution* **158**: 1023–1028.

Philipp, M. and Petersen, P.M. 2007. Long-term study of dry matter allocation and rhizome growth in *Anemone nemorosa*. *Plant Species Biology* **22**: 23–31.

Savolainen, O., Pyhajarvi, T., and Knurr, T. 2007. Gene flow and local adaptation in trees. *Annual Review of Ecology, Evolution and Systematics* **38**: 595–619.

Stiling, P., Moon, D., Hymus, G., and Drake, B. 2004. Differential effects of elevated CO_2 on acorn density, weight, germination, and predation among three oak species in a scrub-oak forest. *Global Change Biology* **10**: 228–232.

Way, D.A., LaDeau, S.L., McCarthy, H.R., Clark, J.S., Oren, R., Finzi, A.C., and Jackson, R.B. 2010. Greater seed production in elevated CO_2 is not accompanied by reduced seed quality in *Pinus taeda* L. *Global Change Biology* **16**: 1046–1056.

7.3.3. Secondary Carbon Compounds

Condensed tannins are one example of naturally occurring secondary carbon compounds produced in the leaves of several different plants that often deter herbivorous insects. In New Zealand, the Legume Lotus is a good source of these substances. Scientists with the country's AgResearch Grasslands institute have additionally determined that sheep and cattle feeding on forage that contains this plant may see their methane emissions significantly reduced.

In a study designed to further explore this phenomenon, for a period of four years (2000–2003), Kelly et al. (2010) grew twice-weekly-watered six-year-old quaking aspen (*Populus tremuloides*) clones, two-year-old white willow (*Salix alba*) clones, and two-year-old sugar maple (*Acer saccharum*) siblings outdoors at the University of Michigan Biological Station in northern Michigan (USA) in open-bottom root boxes enclosed within clear-plastic-wall open-top chambers continuously supplied throughout the growing season (from May until leaf senescence in November) with either ambient-CO_2-level air (360 ppm) or elevated-CO_2-air (720 ppm). At the conclusion of the four-year period, the fallen leaves were collected, dried, and analyzed for simple phenolic and condensed tannin concentrations.

From Kelly et al.'s tabular results, it can be calculated that the 360-ppm CO_2 increase employed in their study boosted the simple phenolics concentrations of the aspen, maple, and willow leaves by 16, 30, and 22 percent, respectively, while it boosted their condensed tannin concentrations by 60, 85, and 26 percent, respectively. Because both foliar phenolics and condensed tannins often enhance plant resistance to herbivore and pathogen attack, plus the fact that ruminants browsing on foliage containing condensed tannins may have a tendency to expel less methane (an important greenhouse gas) to the atmosphere, the increased concentrations of these substances in the leaves of trees grown in CO_2-enriched air bodes well for the health of the trees and for people concerned about CO_2- and methane-induced global warming.

In another study dealing with tannins, Huttunen et al. (2009) grew, from seed, well-watered silver birch (*Betula pendula*) plants in small containers filled with peat that were supplied with nitrogen (N) at low, moderate, and high rates equivalent to 0, 150, or 500 kg N per hectare per year, respectively, and maintained within climate-controlled closed-top chambers located outdoors at the University of Joensuu in Finland at either ambient or elevated air temperature (T or T + 2°C), at either ambient or elevated air CO_2 concentrations (360 or 720 ppm), from mid-June 1999 to the end of the 2000 growing season. The researchers then harvested the trees' leaves and determined their insoluble condensed tannin concentrations. As best as can be estimated from the graphical presentations of their results, the doubling of the atmospheric CO_2 concentration they imposed on the tree seedlings led to the following increases in insoluble condensed tannin concentrations: 52 percent (low N), 17 percent (moderate N), and 99 percent (high N) under the ambient air temperature regime, and 61 percent (low N), 67 percent (moderate N), and 20 percent (high N) under the elevated air temperature regime. With all air temperature and soil nitrogen treatments showing

CO_2-induced increases in insoluble condensed tannin concentrations in silver birch leaves, it can be expected that this phenomenon would help to protect the trees' foliage from predation by voracious insect herbivores and reduce methane emissions from ruminants that might eat birch-tree foliage produced in CO_2-enriched air.

Another important group of secondary carbon compounds is that composed of reactive oxygen species (ROS), which can cause severe oxidative damage in plants. To ascertain whether atmospheric CO_2 enrichment could alleviate the harm done by higher plant ROS concentrations caused by the stress of soil salinity, Perez-Lopez et al. (2009) grew two barley (*Hordeum vulgare* L.) cultivars, Alpha and Iranis, within controlled-environment growth chambers at either ambient (350 ppm) or elevated (700 ppm) atmospheric CO_2 concentrations in a 3:1 perlite:vermiculite mixture watered with Hoagland's solution every two days (until the first leaf was completely expanded at 14 days), after which a salinity treatment was administered by adding 0, 80, 160, or 240 m*M* NaCl to the Hoagland's solution every two days for 14 more days. After a total of 28 days, the primary leaf of each barley plant was harvested and assessed for several biochemical properties.

The seven scientists report that in the various ambient-air salinity treatments, the deleterious effects of reactive oxygen species (ROS) on barley leaves were made apparent through ion leakage and increases in thiobarbituric acid reactive substances (TBARS), which rose ever-higher as salt concentrations increased. "On the other hand," they continue, "when [the] salinity treatment was imposed under elevated CO_2 conditions, lower solute leakage and TBARS levels were observed, suggesting that the oxidative stress caused by salinity was lower." In interpreting their findings, Perez-Lopez et al. conclude, "elevated CO_2 protects barley cultivars from oxidative stress," noting "the relief of oxidative stress damage observed in our barley leaves grown under [a] CO_2 enriched atmosphere has also been observed in alfalfa (Sgherri et al., 1998), pine (Vu et al., 1999) and oak (Schwanz and Polle, 2001)." Hence, it would appear the ongoing rise in the air's CO_2 content may help a wide variety of plants cope with the many serious problems caused by high soil salinity, and perhaps additional stresses as well.

Still other secondary carbon compounds comprise what are known as biogenic volatile organic compounds or BVOCs. Plants re-emit a substantial portion of their assimilated CO_2 back to the atmosphere as BVOCs, and these substances affect both the chemical and physical properties of the air, where they generate large quantities of organic aerosols that can affect the planet's climate by forming cloud condensation nuclei that may lead to increased cooling during the day by reflecting a greater portion of the incoming solar radiation back to space. In addition, many BVOCs protect plants from a host of insect pests. But not all BVOCs are so helpful.

Isoprene, for example, is a highly reactive non-methane hydrocarbon (NMHC) emitted in copious quantities by vegetation and responsible for the production of vast amounts of tropospheric ozone, which is a debilitating scourge of plant and animal life alike. It has been calculated by Poisson et al. (2000), for example, that current levels of NMHC emissions may increase surface ozone concentrations by up to 40 percent in the marine boundary-layer and by 50–60 percent over land, and that the current tropospheric ozone content extends the atmospheric lifetime of methane—one of the world's most powerful greenhouse gases—by approximately 14 percent. Thus, it is readily understood that anything that reduces isoprene emissions from vegetation is something to be desired.

In a recent paper on the subject, Lathiere et al. (2010) (1) describe the development and analysis of a new model based on the Model of Emissions of Gases and Aerosols from Nature (MEGAN) developed by Guenther et al. (2006) for estimating isoprene emissions from terrestrial vegetation, (2) validate the new model with compilations of published field-based canopy-scale observations, and (3) use the new model to calculate changes in isoprene emissions from the terrestrial biosphere in response to climate change, atmospheric CO_2 increase, and land use change throughout the twentieth century.

The scientists found that between 1901 and 2002, climate change at the global scale "was responsible for a 7% increase in isoprene emissions," but "rising atmospheric CO_2 caused a 21% reduction," and "by the end of the 20th century, anthropogenic cropland expansion had the largest impact, reducing isoprene emissions by 15%," so that "overall, these factors combined to cause a 24% decrease in global isoprene emissions during the 20th century."

These findings represent good news, as the factors identified should reduce the undesirable consequences of increases in tropospheric ozone and methane concentrations. The three scientists warn, however, that "the possible rapid expansion of biofuel production with high isoprene-emitting plant species (e.g., oil palm, willow and poplar) may reverse the trend by which conversion of land to food crops leads to lower isoprene emissions." This provides yet another reason not to force use of biofuels as replacements for fossil fuels.

Finally, the reader is referred to the discussion in Chapter 2, Section 2.1, of papers by Kiendler-Scharr et al., Kiemann, and Ziemann that appeared in *Nature* in 2009. Those authors warned that if vegetative isoprene emissions were to increase, driven directly by rising temperatures and/or indirectly by warming-induced changes in the species composition of boreal forests, the resulting decrease in cloud condensation nuclei "could lead to increased global-warming trends." However, and as almost an afterthought, Ziemann mentions "the potential suppression of terpene emissions by elevated carbon dioxide concentrations." In fact, that suppression is more than sufficient to offset any increase in isoprene emissions from plants, as shown by the literature review of Young et al. (2009), also summarized in Chapter 2.

References

Guenther, A., Karl, T., Harley, P., Wiedinmyer, C., Palmer, P.I., and Geron, C. 2006. Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature). *Atmospheric Chemistry and Physics* **6**: 3181–3210.

Huttunen, L., Aphalo, P.J., Lehto, T., Niemela, P., Kuokkanen, K., and Kellomaki, S. 2009. Effects of elevated temperature, elevated CO_2 and fertilization on quality and subsequent decomposition of silver birch leaf litter. *Soil Biology & Biochemistry* **41**: 2414–2421.

Kelly, J.J., Bansal, A., Winkelman, J., Janus, L.R., Hell, S., Wencel, M., Belt, P., Kuehn, K.A., Rier, S.T., and Tuchman, N.C. 2010. Alteration of microbial communities colonizing leaf litter in a temperate woodland stream by growth of trees under conditions of elevated atmospheric CO_2. *Applied and Environmental Microbiology* **76**: 4950–4959.

Kiendler-Scharr, A., Wildt, J., Dal Maso, M., Hohaus, T., Kleist, E., Mentel, T.F., Tillmann, R., Uerlings, R., Schurr, U., and Wahner, A. 2009. New particle formation in forests inhibited by isoprene emissions. *Nature* **461**: 381–384.

Lathiere, J., Hewitt, C.N., and Beerling, D.J. 2010. Sensitivity of isoprene emissions from the terrestrial biosphere to 20th century changes in atmospheric CO_2 concentration, climate, and land use. *Global Biogeochemical Cycles* **24**: 10.1029/2009GB003548.

Perez-Lopez, U., Robredo, A., Lacuestra, M., Sgherri, C., Munoz-Rueda, A., Navari-Izzo, F., and Mena-Petite, A. 2009. The oxidative stress caused by salinity in two barley cultivars is mitigated by elevated CO_2. *Physiologia Plantarum* **135**: 29–42.

Poisson, N., Kanakidou, M., and Crutzen, P.J. 2000. Impact of non-methane hydrocarbons on tropospheric chemistry and the oxidizing power of the global troposphere: 3-dimensional modeling results. *Journal of Atmospheric Chemistry* **36**: 157–230.

Schwanz, P. and Polle, A. 2001. Differential stress responses of antioxidative systems to drought in pendunculate oak (*Quercus robur*) and maritime pine (*Pinus pinaster*) grown under high CO_2 concentrations. *Journal of Experimental Botany* **52**: 133–143.

Sgherri, C., Quartacci, M., Menconi, M., Raschi, A., and Navari-Izzo, F. 1998. Interactions between drought and elevated CO_2 on alfalfa plants. *Journal of Plant Physiology* **152**: 118–124.

Vu, J.C., Gesch, R., Allen, L.H., Boote, K., and Bowes, G. 1999. CO_2 enrichment delays a rapid, drought induced decrease in Rubisco small subunit transcript abundance. *Journal of Plant Physiology* **155**: 139–142.

Young, P.J., Arneth, A., Schurgers, G., Zeng, G., and Pyle, J.A. 2009. The CO_2 inhibition of terrestrial isoprene emission significantly affects future ozone projections. *Atmospheric Chemistry and Physics* **9**: 2793–2803.

Ziemann, P.J. 2009. Thwarting the seeds of clouds. *Nature* **461**: 353–354.

7.4. Ecosystem Responses to Elevated Temperature

7.4.1. Respiration

In a recent News & Views item published in *Nature Geoscience*, Agren (2010) states "it is often assumed that warming will stimulate carbon dioxide release from soils," but he notes "soil-warming experiments suggest that warming-induced increases in soil carbon dioxide release are transitory, and that emissions return to pre-warming levels after a period of five to ten years," citing Kirschbaum (2004) and Eliasson et al. (2005). In much the same vein, Bradford et al. (2010) write that in actual field studies "elevated soil respiration rates under experimental warming are relatively short-lived," citing Jarvis and Linder (2000), Oechel et al. (2000), Luo et al. (2001), Rustad et al. (2001), and Melillo et al. (2002).

Similarly, Bronson and Gower (2010) state "the boreal forest historically has been considered a carbon sink," but "autotrophic respiration is [supposedly] more sensitive than photosynthesis to increases in temperature (Ryan, 1991; Amthor, 1994)," and therefore, in response to global warming, "most models predict autotrophic respiration will increase at a greater rate than photosynthesis, which infers decreased carbon use efficiency and net primary production (Ryan, 1995; VEMAP Members, 1995; Ryan et al., 1996)," which implies "a substantial increase in temperature could turn the boreal forest into a carbon source (Goulden et al., 1998)." That positive feedback phenomenon could lead to an intensification of the warming of the globe—if the assumptions are correct, which was tested by the next study.

Working about 20 km south of Thompson, Manitoba, Canada (55°53'N, 98°20'W), within large enclosed greenhouse chambers containing black spruce trees (*Picea mariana* (Mill.) B.S.P.) and the majority of their fine roots, along with soil-heating cables used to warm air and soil temperatures about 5°C over ambient control temperatures, Bronson and Gower (2010) measured light-saturated net photosynthesis, foliage respiration, and stem respiration in heated and control forest plots during the 2005, 2006, and 2007 growing seasons. Throughout the entire study, "both the older foliage, which developed before the experiment, and the new foliage, developed during the experiment, had similar rates of light-saturated net photosynthesis, foliage respiration and stem respiration across all treatments." This, Bronson and Gover write, "underscores the ability of black spruce to maintain homeostasis in a 5°C warmer environment." In addition, while noting many climate change models predict a doubling of respiration for every 10°C increase in temperature, Bronson and Gower state in the concluding sentence of their paper, and in no uncertain terms, that "the results from this and other whole-ecosystem warming experiments do not support this model assumption."

In another study, Mahecha et al. (2010) write, "the respiratory release of carbon dioxide from the land surface is a major flux in the global carbon cycle," and "understanding the sensitivity of respiratory processes to temperature is central for quantifying the climate-carbon cycle feedback." They set out to do that via a complex set of operations that "approximated the sensitivity of terrestrial ecosystem respiration to air temperature (Q_{10}) across 60 FLUXNET sites with the use of a methodology that circumvents confounding effects." The international team of 14 researchers—from Belgium, Canada, Germany, Italy, Norway, Portugal, Switzerland, and the United States—reports their results "may partly explain recent findings indicating a less pronounced climate-carbon cycle sensitivity (Frank et al., 2010) than assumed by current climate-carbon cycle model parameterizations." In fact, "contrary to previous findings," they state their results "suggest that Q_{10} is independent of mean annual temperature, does not differ among biomes, and is confined to values around 1.4 ± 0.1"

Perhaps the most significant consequence of this new assessment was articulated by Reich (2010) in a Perspective article in *Science* that discusses the Mahecha et al. findings; he writes that their new work "reduces fears that respiration fluxes may increase strongly with temperature, accelerating climate change." This concern longer appears to have much support within the community of global-change researchers.

Two years earlier, Burton et al. (2008) also had cited the theory that "increases in terrestrial ecosystem respiration as temperatures warm could create a positive feedback that causes atmospheric CO_2 concentration, and subsequently global temperature, to increase more rapidly," but they suggested "if plant tissue respiration acclimates to temperature over time, this feedback loop will be weakened, reducing the potential temperature increase." And when Burton et al. demonstrated that plant tissue respiration does indeed so acclimate, Bradford et al. (2008) explored the same subject as it pertains to soil microbial respiration, acquiring pertinent data obtained as late as 15 years after the start of a soil-warming experiment established in 1991 on an even-aged mixed-deciduous tract of trees in the Harvard Forest (Massachusetts, USA), where heating cables were used to elevate soil temperatures to 5°C above ambient temperatures measured in non-heated control plots. They discovered—as has been found by many others in long-term field experiments—that "elevated respiration rates under soil warming return to pre-warming values within a few years," citing the corroborative findings of Jarvis and Linder (2000), Oechel et al. (2000), Luo et al.

(2001), Rustad et al. (2001), Melillo et al. (2002), and Eliasson et al. (2005).

In light of this wealth of empirical observations, the nine researchers state, in the concluding sentence of the abstract of their paper, “stimulatory effects of global temperature rise on soil respiration rates may be lower than currently predicted,” and in the final sentence of the body of their paper they reiterate, in slightly different language, “the changes in the biomass and physiology of soil microbial communities that we observed may decrease the expected strength of climate warming on soil respiration rates,” a state of affairs that ends up “reducing the potential temperature increase.”

In a temperate steppe grassland located in Duolun County, Inner Mongolia, China (42°02’N, 116°17’E, 1,324 meters above sea level), Wan et al. (2009) suspended infrared radiators 2.25 meters above the ground over 24 plots divided into four temperature treatments: (1) control, (2) day (06:00–18:00, local time) warming, (3) night (18:00–06:00) warming, and (4) diurnal (24–hour) warming,. They then measured diurnal cycles of net ecosystem gas exchange and daytime ecosystem respiration twice a month over the growing seasons (May–October) of 2006, 2007, and 2008.

The researchers found “nocturnal warming increased leaf respiration of two dominant grass species by 36.3%, enhanced consumption [drawdown] of carbohydrates in the leaves (72.2% and 60.5% for sugar and starch, respectively), and consequently stimulated plant photosynthesis by 19.8% in the subsequent days.” In addition, they state “the enhancement of plant photosynthesis overcompensated the increased carbon loss via plant respiration under nocturnal warming and shifted the steppe ecosystem from a minor carbon source (1.87 g C/m^2/year) to a carbon sink (21.72 g C/m^2/year) across the three growing seasons.” In addition, the four Chinese researchers note the local climate in their study area “experienced asymmetrical diurnal warming (0.57, 0.45 and 0.30°C increases in daily minimum, mean and maximum temperatures per decade, respectively) over the past half century (1953–2005),” and “similar diurnal scenarios of climate warming have been widely reported at the regional and global scales,” citing the studies of Karl et al. (1991), Easterling et al. (1997), Stone and Weaver (2002), Vose et al. (2005), Lobell et al. (2007), and Zhou et al. (2007). Consequently, and in light of the many well-documented “greater increases in daily minimum than maximum temperature” that have been observed throughout the world, Wan et al. conclude, “plant photosynthetic overcompensation may partially serve as a negative feedback mechanism for [the] terrestrial biosphere to climate warming,” where “the photosynthetic overcompensation induced by nocturnal warming can ... regulate terrestrial carbon sequestration and negatively feed back to climate change.”

References

Agren, G.I. 2010. Microbial mitigation. *Nature Geoscience* **3**: 303–304.

Amthor, J.S. 1994. Scaling CO_2 photosynthesis relationships from the leaf to the canopy. *Photosynthesis Research* **39**: 321–350.

Bradford, M.A., Davies, C.A., Frey, S.D., Maddox, T.R., Melillo, J.M., Mohan, J.E., Reynolds, J.F., Treseder, K.K., and Wallenstein, M.D. 2008. Thermal adaptation of soil microbial respiration to elevated temperature. *Ecology Letters* **11**: 1316–1327.

Bradford, M.A., Watts, B.W., and Davies, C.A. 2010. Thermal adaptation of heterotrophic soil respiration in laboratory microcosms. *Global Change Biology* **16**: 1576–1588.

Bronson, D.R. and Gower, S.T. 2010. Ecosystem warming does not affect photosynthesis or aboveground autotrophic respiration for boreal black spruce. *Tree Physiology* **30**: 441–449.

Burton, A.J., Melillo, J.M., and Frey, S.D. 2008. Adjustment of forest ecosystem root respiration as temperature warms. *Journal of Integrative Plant Biology* **50**: 1467–1483.

Easterling, D.R., Horton, B., Jones, P.D., Peterson, T.C., Karl, T.R., Parker, D.E., Salinger, M.J., Razuvayev, V., Plummer, N., Jamason, P., and Folland, C.K. 1997. Maximum and minimum temperature trends for the globe. *Science* **277**: 364–367.

Eliasson, P.E., McMurtrie, R.E., Pepper, D.A., Stromgren, M., Linder, S., and Agren, G.I. 2005. The response of heterotrophic CO_2 flux to soil warming. *Global Change Biology* **11**: 167–181.

Frank, D.C., Esper, J., Raible, C.C., Büntgen, U., Trouet, V., Stocker, B., and Joos, F. 2010. Ensemble reconstruction constraints on the global carbon cycle sensitivity to climate. *Nature* **463**: 527–530.

Goulden, M.L., Wofsy, S.C., and Harden, J.W. 1998. Sensitivity of boreal forest carbon balance to soil thaw. *Science* **279**: 214–217.

Jarvis, P. and Linder, S. 2000. Constraints to growth of boreal forests. *Nature* **405**: 904–905.

Karl, T.R., Kukla, G., Razuvayev, N., Changery, M.J., Quayle, R.G., Heim, R.R., Easterling, D.R., and Fu, C.B. 1991. Global warming—evidence for asymmetric diurnal temperature-change. *Geophysical Research Letters* **18**: 2253–2256.

Kirschbaum, M.U.F. 2004. Soil respiration under prolonged soil warming: are rate reductions caused by acclimation or substrate loss? *Global Change Biology* **10**: 1870–1877.

Lobell, D.B., Bonfils, C., and Duffy, P.B. 2007. Climate change uncertainty for daily minimum and maximum temperatures: a model inter-comparison. *Geophysical Research Letters* **34**: 10.1029/2006GL028726.

Luo, Y.Q., Wan, S.Q., Hui, D.F., and Wallace, L.L. 2001. Acclimation of soil respiration to warming in a tall grass prairie. *Nature* **413**: 622–625.

Mahecha, M.D., Reichstein, M., Varvalhais, N., Lasslop, G., Lange, H., Seneviratne, S.I., Vargas, R., Ammann, C., Arain, M.A., Cescatti, A., Janssens, I.A., Migliavacca, M., Montagnani, L., and Richardson, A.D. 2010. Global convergence in the temperature sensitivity of respiration at ecosystem level. *Science* **329**: 838–840.

Melillo, J.M., Steudler, P.A., Aber, J.D., Newkirk, K., Lux, H., Bowles, F.P., Catricala, C., Magill, A., Ahrens, T., and Morrisseau, S. 2002. Soil warming and carbon-cycle feedbacks to the climate system. *Science* **298**: 2173–2176.

Oechel, W.C., Vourlitis, G.L., Hastings, S.J., Zulueta, R.C., Hinzman, L., and Kane, D. 2000. Acclimation of ecosystem CO_2 exchange in the Alaskan Arctic in response to decadal climate warming. *Nature* **406**: 978–981.

Reich, P.B. 2010. The carbon dioxide exchange. *Science* **329**: 77–-775.

Rustad, L., Campbell, J.L., Marion, G.M., Norby, R.J., Mitchell, M.J., Hartley, A.E., Cornelissen, J.H.C., and Gurevitch, J. 2001. A meta-analysis of the response of soil respiration, net nitrogen mineralization, and above-ground plant growth to experimental ecosystem warming. *Oecologia* **126**: 543–562.

Ryan, M.G. 1991. Effects of climate change on plant respiration. *Ecological Applications* **1**: 157–167.

Ryan, M.G. 1995. Foliar maintenance respiration of sub-alpine and boreal trees and shrubs in relation to nitrogen-content. *Plant, Cell and Environment* **18**: 765‑772.

Ryan, M.G., Hunt, E.R., McMurtrie, R.E., Agren, G.I., Aber, J.D., Friend, A.D., Rastetter, E.B., Pulliam, W.M., Raison, R.J., and Linder, S. 1996. Comparing models of ecosystem function for temperate conifer forests. In *Global Change: Effects on Coniferous Forests and Grasslands*, edited by A.I. Greymeyer, D.O. Hall, G.I. Agren, and J.M. Melillo, 313–361. New York, NY: John Wiley.

Stone, D.A. and Weaver, A.J. 2002. Daily maximum and minimum temperature trends in a climate model. *Geophysical Research Letters* **29**: 10.1029/2001GL014556.

VEMAP Members. 1995. Vegetation Ecosystem Modeling and Analysis Project: comparing biogeography and biogeochemistry models in a continental-scale of terrestrial ecosystem response to climate change and CO_2 doubling. *Global Biogeochemical Cycles* **9**: 407–437.

Vose, R.S., Easterling, D.R., and Gleason, B. 2005. Maximum and minimum temperature trends for the globe: an update through 2004. *Geophysical Research Letters* **32**: 10.1029/2005GL024379.

Wan, S., Xia, J., Liu, W., and Niu, S. 2009. Photosynthetic overcompensation under nocturnal warming enhances grassland carbon sequestration. *Ecology* **90**: 2700–2710.

Zhou, L., Dickinson, R.E., Tian, Y., Vose, R.S., and Dai, Y. 2007. Impact of vegetation removal and soil aridation on diurnal temperature range in a semiarid region: application to the Sahel. *Proceedings of the National Academy of Sciences USA* **104**: 17,937–17,942.

7.4.2. Agricultural Crops

In a controversial study published in the *Proceedings of the National Academy of Sciences* (USA), Schlenker and Roberts (2009) compared U.S. county-level yields of corn, soybeans, and cotton for the years 1950–2005 with fine-scale weather datasets that incorporated the entire distribution of temperatures that occurred within each day and across all days of the crops' growing seasons, in order to determine yield responses to the range of temperatures experienced by the crops. They then used the yield vs. temperature relationships they had thereby derived to estimate yield changes expected throughout the remainder of the twenty-first century, based on temperatures predicted to occur by the Hadley III climate model.

The first stage of the scientists' research indicated yields had historically increased as temperatures rose to an optimum value of 29°C for corn, 30°C for soybeans, and 32°C for cotton. At temperatures above these optimum values, crop yields declined, and they did so with slopes that were significantly steeper than the upward slopes that had preceded them. Then, in the second stage of their research, Schlenker and Roberts found, "holding current growing regions fixed, area-weighted average yields are predicted to decrease by 30–46% before the end of the century under the slowest warming scenario and decrease by 63–82% under the most rapid warming scenario under the Hadley III model."

This was not good news, but on the upside, it was much too bad to be true. About six weeks later, the *Proceedings* published a letter by Meerburg et al. (2009) that provided a new perspective on the issue.

The seven Dutch scientists began their critique of Schlenker and Roberts' study by noting that yields of the crops in question will continue to increase in years to come, because of "the development and adoption of new technologies and improved farm management," citing Ewert et al. (2005), who found that continuing advances in technology historically have been the most important driver of productivity change, outweighing the negative effects of detrimental climate change. And in further illustration of this phenomenon, Meerburg et al. report that between 1961 and 2007, "average US corn yields increased by 240%, from 3.9 tons per hectare per year to 9.4 tons per hectare per year (FAO, 2009)," while noting some researchers have predicted "advances in agronomics, breeding, and biotechnology will lead to an average corn yield in the US of just over 20 tons per hectare per year in 2030," citing Duvick (2005).

Meerburg et al. also make note of the fact that farmers in Brazil successfully increased the productivity of soybeans, maize, and cotton during the past decade even though the cumulative number of days of exposure to temperatures above the three crops' optimum values "is far greater than in the US." In the Brazilian state of Mato Grosso, for example, "maximum average day temperature exceeds 35°C for 118 days per year, of which 75 days are in the average soybean-growing season." Nevertheless, they report, in 2008 average production of soybeans was about 3.1 tons per hectare per year in Mexico, while the average yield in the US was 2.8 tons per hectare per year. Similarly, they note the mean cotton yield in Brazil in 2006/2007 was 1.4 tons per hectare per year, while in the U.S. it was only 0.9 tons per hectare per year.

The seven scientists thus conclude "temperatures higher than currently experienced in the US do not necessarily need to coincide with lower crop yields and that already existing technology and future advances (new varieties, optimized farm management, biotechnology, etc.) can overrule the negative effect of increasing temperatures on yield," as has in fact been observed in the historical crop yield data of the United States.

A final flaw in the analysis of Schlenker and Roberts (2009) is their acknowledged "inability to account for CO_2 concentrations," the increasing levels of which, in their own words, "might spur plant growth and yields," such that "yield declines stemming from warmer temperatures therefore may be offset by CO_2 fertilization." This has been found to be the case by many different studies, as we recount in Section 5.5 of this report.

In light of Schlenker and Roberts' stated admissions, therefore, as well as the facts cited by Meerburg et al.—which should have been known by the two U.S. researchers as well as the communicator of their paper to the *Proceedings of the National Academy of Sciences* and the editorial staff of the journal—it is clear their paper never should have been published, especially with a title that proclaims as fact that "nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change."

References

Duvick, D.N. 2005. The contribution of breeding to yield advances in maize (*Zea mays* L.). *Advances in Agronomy* **86**: 83–145.

Ewert, F., Rounsevell, M.D.A., Reginster, I., Metzger, M.J., and Leemans, R. 2005. Future scenarios of European agricultural land use: I. Estimating changes in crop productivity. *Agriculture, Ecosystems and Environment* **107**: 101–116.

FAO (Food and Agriculture Organization). 2009. FAOSTAT Database. United Nations Food and Agriculture Organization. Available at www.fao.org. Accessed 8 September 2009.

Meerburg, B.G., Verhagen, A., Jongschaap, R.E.E., Franke, A.C., Schaap, B.F., Dueck, T.A., and van der Werf, A. 2009. Do nonlinear temperature effects indicate severe damages to US crop yields under climate change? *Proceedings of the National Academy of Sciences USA* **106**: 10.1073 pnas.0910618106.

Schlenker, W. and Roberts, M.J. 2009. Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences USA* **106**: 15,594–15,598.

7.5. Responses of Plants Under Stress to Atmospheric CO_2 Enrichment

7.5.1. The Stress of Disease

Eastburn et al. (2010) note, “globally, soybean is the most widely planted dicot crop and has economic significance due to its wide variety of uses, ranging from food and health products to printing inks and biodiesal,” but “little to no work has evaluated the influence of future atmospheric conditions on soybean diseases.” This is particularly surprising given that “worldwide yield losses to all soybean diseases combined are about 11% (Wrather et al., 1997), which is equivalent to more than 24 million metric tons based on current production.” In an attempt to begin to fill this knowledge void, Eastburn et al. evaluated the individual and combined effects of elevated carbon dioxide (CO_2, 550 ppm) and ozone (O_3, 1.2 times ambient) on three economically important soybean diseases—downy mildew, *Septoria* brown spot, and sudden death syndrome (SDS)—over the three-year period 2005–2007 under natural field conditions at the soybean free-air CO_2-enrichment (SoyFACE) facility on the campus of the University of Illinois (USA).

The five researchers found “elevated CO_2 alone or in combination with O_3 significantly reduced downy mildew disease severity by 39–66% across the three years of the study.” On the other hand, they state “elevated CO_2 alone or in combination with O_3 significantly increased brown spot severity in all three years,” but “the increase was small in magnitude.” Finally, they state “the atmospheric treatments had no effect on the incidence of SDS.” Taken in their entirety, these findings thus suggest, on balance, that elevated CO_2 should provide a net benefit to soybean productivity throughout the world, as its concentration continues to rise in the years and decades to come.

In the introduction to another soybean study, Kretzschmar et al. (2009) write, “isoflavonoids constitute a group of natural products derived from the phenylpropanoid pathway, which is abundant in soybeans,” and they state “the inducible accumulation of low molecular weight antimicrobial pterocarpan phytoalexins, the glyceollins, is one of the major defense mechanisms implicated in soybean resistance.” Thus, in their study, as they describe it, they “evaluated the effect of an elevated CO_2 atmosphere on the production of soybean defensive secondary chemicals induced by nitric oxide and a fungal elicitor.” They did this in a glasshouse where they grew soybeans from seed for a period of nine days in large, well-watered pots placed within open-top chambers that were maintained at atmospheric CO_2 concentrations of either 380 or 760 ppm, while they examined changes in the production of phytoalexins and some of their precursors.

This work revealed that elevated CO_2 “resulted in an increase of intermediates and diverted end products (daidzein by 127%, coumestrol by 93%, genistein by 93%, luteolin by 89% and apigenin by 238%) with a concomitant increase of 1.5–3.0 times in the activity of enzymes related to their biosynthetic routes.” The Brazilian researchers state these findings “indicate changes in the pool of defense-related flavonoids in soybeans due to increased carbon availability, which may differentially alter the responsiveness of soybean plants to pathogens in CO_2 atmospheric concentrations such as those predicted for future decades.” Or to put it more simply, the ongoing rise in the air’s CO_2 content will likely increase the ability of soybeans to withstand the attacks of various plant diseases in the years and decades to come.

In a very different type of study, AL-Kayssi (2009) investigated soil solarization, “a method of heating the soil by using polyethylene sheets as mulching over moistened soil, to retain solar radiation during the hot season,” so that “soil-borne pathogens may be killed by lethal heat (>40°C) and weakened by sub-lethal heat (<38-40°C) to the extent that they are unable to cause damage to plants or they are more susceptible to chemical toxicants.” This technique, the Iraqi researcher writes, “has been successfully used to control soil-borne pathogens and weeds,” as observed in the studies of Katan et al. (1976), Mahrer (1979), Grinstein et al. (1979), Katan (1981), Mahrer et al. (1984), Avissar et al. (1986), AL-Karaghouli et al. (1990), and AL-Kayssi and AL-Karaghouli (1991).

Against this background, AL-Kayssi conducted a laboratory experiment where “clay soil samples infested with *Verticillium dahliae* were exposed to different CO_2 concentrations (350, 700, 1050, 1400, 1750 ppm air) and incubated in hot water baths at 35, 40, 45, 50 and 55°C,” while “field plots were exposed to the same CO_2 levels during soil solarization in three periods (1st of July to 30th of September, 1st of August to 30th of September, and 1st to 30th of September).” He found that higher than normal CO_2 contents in the soil increased maximum soil temperatures while reducing the length of time required to kill 90 percent of the propagules of *V. dahliae* in natural field soil with moisture content at field capacity. As an example, he notes this killing time parameter in soil heated to 35°C was reduced from 24 days at the normal ambient CO_2 concentration to 15 days at 1,750 ppm CO_2, and he states sub-lethal soil temperatures were raised to lethal levels as the soil's CO_2 content was raised. In a high-CO_2 world of the future, therefore, soil solarization could become an even more viable method of controlling soil-borne pathogens and weeds than it is today.

We next consider leaf spot disease, which is characterized by chlorotic to necrotic localized leaf lesions caused by the *Cercospora* (a large genus of ascomycete fungi) that affect, in the words of McElrone et al. (2010), "numerous economically important plant species around the world, including grapes, cereals, soybeans, peanuts, orchids, coffee, alfalfa and potatoes (Sinclair et al., 1987)," as well as redbud (*Cercis canadensis*) and sweetgum (*Liquidambar styraciflua*) trees, such as those growing at the Duke Forest FACE Facility in Orange County, North Carolina (USA), where McElrone et al. studied the disease throughout the growing seasons of five different years (2000, 2001, 2002, 2003, 2005). The six scientists assessed how elevated CO_2 (to 200 ppm above the ambient air's CO_2 concentration) and natural interannual climatic variability affected the incidence and severity of leaf spot disease among the sweetgum and redbud trees growing in the several FACE rings. In order "to determine how photosynthetic capacity surrounding pathogen damage was affected by CO_2 exposure, the spatial pattern of photosystem II operating efficiency was quantified on *C. canadensis* leaves still attached to plants with an imaging chlorophyll fluorometer."

By these means, McElrone et al. found "disease incidence and severity for both species were greater in years with above average rainfall," while "in years with above average temperatures, disease incidence for *Liquidambar styraciflua* was decreased significantly." On the other hand, they found elevated CO_2 increased disease incidence and severity "in some years." However, they state the "chlorophyll fluorescence imaging of leaves revealed that any visible increase in disease severity induced by elevated CO_2 was mitigated by higher photosynthetic efficiency in the remaining undamaged leaf tissue and in a halo surrounding lesions." Consequently, even in a situation where atmospheric CO_2 enrichment was observed to increase the incidence and severity of leaf spot disease, the photosynthesis-enhancing effect of the extra CO_2 was found to compensate for the photosynthetic productivity lost to the disease by enhancing productivity in healthy portions of diseased leaves and in leaves without lesions, for no net ill effect.

As for what has been observed in other studies of this nature, McElrone et al. report that disease incidence or severity also has been observed to be enhanced by elevated CO_2 in four other "pathosystems" (Thompson and Drake, 1994; Mitchell et al., 2003; Kobayashi et al., 2006; Eastburn et al., 2010), that disease incidence or severity has been observed to be unaffected by elevated CO_2 in another four pathosystems (Hibberd et al., 1996; Tiedemann and Firsching, 2000; Percy et al., 2002; Eastburn et al., 2010), and that the two disease parameters have been reduced by elevated CO_2 in another seven pathosystems (Thompson et al., 1993; Thompson and Drake, 1994; Chakraborty et al., 2000b; Jwa and Walling, 2001; Pangga et al., 2004; McElrone et al., 2005; Eastburn et al., 2010). Among the numerous pertinent studies conducted to date, elevated CO_2 has been found, generally speaking to lead to (1) no net loss in the productivity of disease-infected plants in 31 percent of the studies, (2) a moderate increase in the productivity of disease-infected plants in 25 percent of the studies, and (3) a large increase in productivity in 44 percent of the studies, while the study of McElrone et al. (2010) suggests concomitant warming may further enhance the productivity of infected plants.

As a prelude to another analysis of CO_2 effects on diseased plants, Runion et al. (2010) note obligate pathogens "have a more intimate relationship with their host and must have the host to survive," whereas facultative pathogens "live saprophytically and generally result in disease (or tend to be more severe) under conditions of plant stress such as low nutrition or water." In their experiment, well-watered and -fertilized seedlings of loblolly pine (*Pinus taeda*) and northern red oak (*Quercus rubra*) were grown outdoors in open-top chambers constructed within large soil bins located at the USDA-ARS National Soil Dynamics Laboratory in Auburn, Alabama (USA), where they were exposed to atmospheric CO_2 concentrations of either 360 or 720 ppm with or without being infected by the fusiform rust fungus (the obligate pathogen *Cronartium quercuum* f.sp. *fusiforme*), and where the pines were also grown with or without being infected by the pitch canker fungus (the facultative pathogen *Fusarium circinatum*) for various lengths of time that ranged from weeks to a full year, with each of the three experiments being conducted twice.

Regarding the pine *Fusarium* rust study, Runion et al. report "percent infection was not significantly affected by CO_2 concentration," but in spite of this fact "the percentage of loblolly pine seedlings which died as a result of rust infection was generally significantly lower under elevated CO_2 in both runs of the experiment." In the oak *Fusarium* rust study, they state "the percent of oak seedlings with uredia was consistently lower for seedlings exposed to elevated CO_2 in both runs," and "the percent of oak seedlings with telia was significantly lower for seedlings exposed to elevated CO_2 at the 16 and 19 days evaluations in both runs of the experiment." In the pine pitch canker study, the four researchers indicate "the percent of loblolly pine seedlings which developed cankers following inoculation with the pitch canker fungus was consistently lower for seedlings grown under elevated CO_2 in both runs of the experiment ... with infection in elevated CO_2-grown seedlings remaining about half that of ambient-grown seedlings." In light of these results, Runion et al. state "disease incidence—regardless of pathogen type—may be reduced as atmospheric CO_2 concentration continues to rise," a phenomenon that should significantly benefit the two species of trees they studied in the high-CO_2 world of the future.

Rounding out our review of diseased-plant responses to atmospheric CO_2 enrichment, we focus on the *Phytophthora citricola* pathogen, which can infect the roots and trunks of European Beech (*Fagus sylvatica* L.) trees. Introducing their study of the subject, Fleischmann et al. (2010) state that several reviews of the effects of elevated atmospheric CO_2 on plant parasite interactions—including those of Manning and Tiedemann (1995), Chakraborty et al. (2000b), and Garrett et al. (2006)—conclude "it is uncertain whether elevated CO_2 favors or suppresses pathogens in herbaceous or woody plants."

Therefore, in an attempt to obtain additional pertinent data, Fleischmann et al. grew well-watered *Fagus sylvatica* plants from seed in several 40-cm by 60-cm containers—which were 30 cm deep and filled with natural forest soil—for four years within growth chambers maintained at either 400 or 700 ppm CO_2 within a greenhouse. During this period, the trees received an adequate supply of all essential nutrients, but in the case of nitrogen (N), there were low-N and high-N treatments, with the high-N treatment receiving twice as much nitrogen as the low-N treatment. Finally, half of the seedlings were infected with *P. citricola* in the early summer of the third year of the study, and half of the trees in each treatment were harvested at the ends of the third and fourth years of the experiment.

The three German researchers found "chronic elevation of atmospheric CO_2 increased the susceptibility of beech seedlings towards the root pathogen *P. citricola*, while additional nitrogen supply reduced susceptibility." In fact, they found 27 percent of the infected plants in the low-N high-CO_2 treatment were killed by the pathogen by the end of their study, whereas only 9 percent of the infected plants in the high-N high-CO_2 treatment died. In terms of the bigger picture, they found surviving beech seedlings of the low-N high-CO_2 treatment "managed to tolerate the root infection by (a) increasing their carbon gain, (b) improving their fine root functionality and (c) changing their allometric relation between below-ground and above-ground biomass." Thus, Fleischmann et al. concluded infected beech seedlings in the low-N high-CO_2 treatment rose to the challenge presented by the pernicious pathogen and "enhanced [their] primary production rates in the second year of the experiment and increased above-ground biomass significantly as compared to control trees."

References

AL-Karaghouli, A.A., AL-Kayssi, A.W., and Hasson, A.M. 1990. The photometric properties of different colored plastic mulches used for soil solarization. *Solar and Wind Technology* **7**: 119–123.

AL-Kayssi, A.W. 2009. Impact of elevated CO_2 concentrations in the soil on soil solarization efficiency. *Applied Soil Ecology* **43**: 150–158.

AL-Kayssi, A.W. and AL-Karaghouli, A.A. 1991. Influence of different colored plastic mulches used for soil solarization on the effectiveness of soil heating. *Soil Solarization* **109**: 297–308.

Avissar, R., Mahrer, Y., Margulies, L., and Katan, J. 1986. Field aging of transparent polyethylene mulch: I. Photometric properties. *Soil Science Society of America Journal* **50**: 202–205.

Chakraborty, S., Pangga, I.B., Lupton, J., Hart, L., Room, P.M., and Yates, D. 2000a. Production and dispersal of

Colletotrichum gloeosporiodies spores on *Stylosanthes scabra* under elevated CO_2. *Environmental Pollution* **108**: 381–387.

Chakraborty, S., Tiedeman, A.V., and Teng, P.S. 2000b. Climate change: potential impact on plant diseases. *Environmental Pollution* **108**: 317–326.

Eastburn, D.M., Degennaro, M.M., DeLucia, E.H., Dermody, O., and McElrone, A.J. 2010. Elevated atmospheric carbon dioxide and ozone alter soybean diseases at SoyFACE. *Global Change Biology* **16**: 320–330.

Fleischmann, F., Raidl, S., and Osswald, W.F. 2010. Changes in susceptibility of beech (*Fagus sylvatica*) seedlings towards *Phytophthora citricola* under the influence of elevated atmospheric CO_2 and nitrogen fertilization. *Environmental Pollution* **158**: 1051–1060.

Garrett, K.A., Dendy, S.P., Frank, E.E., Rouse, M.N., and Travers, S.E. 2006. Climate change effects on plant disease: genomes to ecosystems. *Annual Review of Phytopathology* **44**: 489–509.

Grinstein, A., Orion, D., Greenberger, A., and Katan, J. 1979. Solar heating of the soil for the control of *Verticillium dahliae* and *Pratylenchus thornei* in potatoes. In *Soilborne Plant Pathogens*, edited by B. Shippers and W. Gams, 431–438. London, UK: Academic Press.

Hibberd, J.M., Whitbread, R., and Farrar, J.F. 1996. Effect of elevated concentrations of CO_2 on infection of barley by *Erysiphe graminis*. *Physiological and Molecular Plant Pathology* **48**: 37–53.

Jwa, N.S. and Walling, L.L. 2001. Influence of elevated CO_2 concentration on disease development in tomato. *New Phytologist* **149**: 509–518.

Katan, J. 1981. Solar heating (solarization) of soil for control of soilborne pests. *Annual Review of Phytopathology* **19**: 211–236.

Katan, J., Greenberger, A., Alon, H., and Grinstein, A. 1976. Solar heating by polyethylene mulching for the control of diseases caused by soilborne pathogens. *Phytopathology* **66**: 683–688.

Kobayashi, T., Ishiguro, K., Nakajima, T., Kim, H.Y., Okada, M., and Kobayashi, K. 2006. Effects of elevated atmospheric CO_2 concentration on the infection of rice blast and sheath blight. *Phytopathology* **96**: 425–431.

Kretzschmar, F. d S., Aidar, M.P.M., Salgado, I., and Braga, M.R. 2009. Elevated CO_2 atmosphere enhances production of defense-related flavonoids in soybean elicited by NO and a fungal elicitor. *Environmental and Experimental Botany* **65**: 319–329.

Mahrer, Y. 1979. Prediction of soil temperatures of a soil mulched with transparent polyethylene. *Journal of Applied Meteorology* **18**: 1263–1267.

Mahrer, Y., Naot, O., Rawitz, E., and Katan, J. 1984. Temperature and moisture regimes in soils mulched with transparent polyethylene. *Soil Science Society of America Journal* **48**: 362–367.

Manning, W.J. and Tiedemann, A. 1995. Climate change: potential effects of increased atmospheric carbon dioxide (CO_2), ozone (O_3), and ultraviolet-B (UV-B) radiation on plant diseases. *Environmental Pollution* **88**: 219–245.

McElrone, A.J., Hamilton, J.G., Krafnick, A.J., Aldea, M., Knepp, R.G., and DeLucia, E.H. 2010. Combined effects of elevated CO_2 and natural climatic variation on leaf spot diseases of redbud and sweetgum trees. *Environmental Pollution* **158**: 108–114.

McElrone, A.J., Reid, C.D., Hoye, K.A., Hart, E., and Jackson, R.B. 2005. Elevated CO_2 reduces disease incidence and severity of a red maple fungal pathogen via changes in host physiology and leaf chemistry. *Global Change Biology* **11**: 1828–1836.

Mitchell, C.E., Reich, P.B., Tilman, D., and Groth, J.V. 2003. Effects of elevated CO_2, nitrogen deposition, and decreased species diversity on foliar fungal plant disease. *Global Change Biology* **9**: 438–451.

Pangga, I.B., Chakraborty, S., and Yates, D. 2004. Canopy size and induced resistance in *Stylosanthes scabra* determine anthracnose severity at high CO_2. *Phytopathology* **94**: 221–227.

Percy, K.E., Awmack, C.S., Lindroth, R.L., Kopper, B.J., Isebrands, J.G., Pregitzer, K.S., Hendrey, G.R., Dickson, R.E., Zak, D.R., Oksanen, E., Sober, J., Harrington, R., and Karnosky, D.F. 2002. Altered performance of forest pests under atmospheres enriched by CO_2 and O_3. *Nature* **420**: 403–407.

Runion, G.B., Prior, S.A., Rogers, H.H., and Mitchell, R.J. 2010. Effects of elevated atmospheric CO_2 on two southern forest diseases. *New Forests* **39**: 275–285.

Sinclair, W.A., Lyon, H.H., and Johnson, W.T. 1987. *Diseases of Trees and Shrubs.* Ithaca, NY: Cornell University Press.

Thompson, G.B., Brown, J.K.M., and Woodward, F.I. 1993. The effects of host carbon dioxide, nitrogen and water supply on the infection of wheat by powdery mildew and aphids. *Plant, Cell and Environment* **16**: 687–694.

Thompson, G.B. and Drake, B.G. 1994. Insects and fungi on a C_3 sedge and a C_4 grass exposed to elevated atmospheric CO_2 concentrations in open-top chambers in the field. *Plant, Cell and Environment* **17**: 1161–1167.

Tiedemann, A.V. and Firsching, K.H. 2000. Interactive effects of elevated ozone and carbon dioxide on growth and yield of leaf rust-infected versus non-infected wheat. *Environmental Pollution* **108**: 357–363.

Wrather, J.A., Anderson, T.R., Arsyad, D.M., Gai, J., Ploper, L.D., Porta-Puglia, A., Ram, H.H., and Yourinori, J.T. 1997. Soybean disease loss estimates for the top 10 soybean producing countries in 1994. *Plant Disease* **81**: 107–110.

7.5.2. Nitrogen Insufficiency

Since nitrogen is one of the plant world's most important nutrients, a lack of sufficient nitrogen for maximum growth can be thought of as a significant environmental stress. This is especially important in the case of rice. As Feng et al. (2009) write, rice fields "represent the most important agricultural ecosystems in Asia since rice and wheat are the main source for food supply, and more than 90% of rice fields around the world are located in Asia." In this context, they note "purple phototrophic bacteria (PPB) are thought to be crucial in the nutrient cycling of rice fields." The Chinese researchers state PPB "thrive in the anaerobic portions of all kinds of aquatic environments, and have long been recognized as one of the key players in global carbon and nitrogen cycles."

Against this backdrop, in a FACE study conducted within a rice/wheat rotation system at the Nianyu Experimental Station in Jiangsu Province, China, Feng et al. grew rice (*Oryza sativa* L.) plants under standard paddy culture at two levels of soil nitrogen (N) fertility—low (150 kg N/hectare) and high (250 kg N/hectare)—at ambient and ambient plus 200 ppm CO_2 concentrations, throughout which period they measured several characteristics of PPB within the rhizosphere and bulk soils of the two CO_2 treatments. The seven scientists found (1) "based on denaturant gradient gel electrophoresis (DGGE) analysis of *pufM* gene encoding the M subunit of anoxygenic PPB light reaction center, elevated CO_2 appeared to enhance the biodiversity of PPB in flooded paddy soils," (2) "this was further supported by canonical correspondence analysis (CCA) of DGGE fingerprinting pattern of *pufM* genes in paddy soils as well as Shannon diversity indices," (3) "real-time quantitative PCR analysis of *pufM* gene further indicated that PPB abundance was stimulated by elevated CO_2 in bulk soil," and (4) "N fertilization enhanced the biodiversity of PPB under elevated atmospheric CO_2."

The significance of Feng et al.'s findings—especially the positive synergism of atmospheric CO_2 enrichment and N fertilization working together—is brought into perspective by their noting it has been found that "PPB inoculation into the flood water [in rice paddy culture] could lead to grain yield increase by 29% (Elbadry et al., 1999; Harada et al., 2005)." Therefore, the ongoing rise in the air's CO_2 content in the presence of adequate N availability—which can itself be improved by atmospheric CO_2 enrichment, as Feng et al. state "PPB are thought to be capable of fixing nitrogen"—can help provide the boost in food production that will be needed to feed the planet's still-expanding human population in the decades ahead.

Finally, Churkina et al. (2009) state "to investigate feedbacks between climate, atmospheric CO_2, atmospheric nitrogen deposition and carbon uptake of the land over almost two centuries [1860–2030]," they coupled "an earth system model of intermediate complexity" with "a biogeochemical process model" used with a "carbon and nitrogen allocation routine" that was "parameterized for seven vegetation types" including "deciduous broadleaf forest, evergreen needleleaf forest, evergreen broadleaf forest, evergreen deciduous forest, shrubland, C_4 and C_3 grasslands." They initialized the system by running the model "to a steady state to obtain the size of the ecosystem's carbon and nitrogen pools" under the assumption the ecosystem was "in equilibrium with the long-term climate," utilizing "daily climate data from NCEP Reanalysis for 1968–1977, constant preindustrial atmospheric nitrogen deposition, and CO_2 concentration."

The scientists first determined their global- and continental-scale estimates of land carbon uptake in the 1990s were "consistent with previously reported data." This comparison with the real world gave them confidence in the results their modeling exercise projected for the future, namely that "increasing nitrogen deposition and the physiological effect of elevated atmospheric CO_2 on plants have the potential to increase the land carbon sink, to offset the rise of CO_2 concentration in the atmosphere, and to reduce global warming." Specifically, they found that predicted changes in climate, CO_2, and nitrogen deposition for the year 2030 were sufficient to offset atmospheric CO_2 by a sizable 41 ppm. And if likely land use changes were included in the calculations, the offset rose to 76 ppm. The six scientists who conducted the work conclude their study suggests "reforestation and sensible ecosystem management in industrialized regions may have larger potential for climate change mitigation than anticipated."

References

Churkina, G., Brovkin, V., von Bloh, W., Trusilova, K., Jung, M., and Dentener, F. 2009. Synergy of rising nitrogen depositions and atmospheric CO_2 on land carbon uptake moderately offsets global warming. *Global Biogeochemical Cycles* **23**: 10.1029/2008GB003291.

Elbadry, M., Gamal-Eldin, H., and Elbanna, K. 1999. Effects of *Rhodobacter capsulatus* inoculation in combination with graded levels of nitrogen fertilizer on growth and yield of rice in pots and lysimeter experiments. *World Journal of Microbiology and Biotechnology* **15**: 393–395.

Feng, Y., Lin, X., Wang, Y., Zhang, J., Mao, T., Yin, R., and Zhu, J. 2009. Free-air CO_2 enrichment (FACE) enhances the biodiversity of purple phototrophic bacteria in flooded paddy soil. *Plant and Soil* **324**: 317–328.

Harada, N., Nishiyama, M., Otsuka, S., and Matsumoto, S. 2005. Effects of inoculation of phototrophic bacteria on grain yield of rice and nitrogenase activity of paddy soil in a pot experiment. *Soil Science and Plant Nutrition* **51**: 361–367.

7.5.3. Ozone Pollution

Logan et al. (2010) describe and discuss what was revealed at a "Tropospheric Ozone Changes Workshop" held in Boulder, Colorado (USA) on 14–16 October 2009: "long-term ozone records from regionally representative surface and mountain sites, ozonesondes, and aircraft were reviewed by region." In brief, they report, "in the Southern Hemisphere, surface measurements from South Africa and Tasmania and sonde data from New Zealand show a significant increase over the past 25 years." North of the equator, on the other hand, the story is different. In western Europe, for example, they write, "several time series of ~15-40 years ... show a rise in ozone into the middle to late 1990s and a leveling off, or in some cases declines, in the 2000s, in general agreement with precursor emission changes." Similarly, they state "surface measurements within North America show a pattern of mostly unchanged or declining ozone over the past two decades that [also] seems broadly consistent with decreases in precursor emissions," while noting "the Japanese sonde record suggests rising ozone into the 1980s and small changes thereafter."

The spatial and temporal distributions of these observations would seem to suggest that, whereas increasing industrialization initially tends to increase the emissions of precursor substances that lead to the creation of greater tropospheric ozone pollution, subsequent technological advances tend to ameliorate that phenomenon, as they appear gradually to lead to (1) a leveling off of the magnitude of precursor emissions and (2) an ultimately decreasing trend in tropospheric ozone pollution. In light of these observations, it can be appreciated that when atmospheric ozone and CO_2 concentrations both rise together, the plant-growth-enhancing effect of atmospheric CO_2 enrichment is significantly muted by the plant-growth-retarding effect of contemporaneous increases in ozone pollution, but as the troposphere's ozone concentration gradually levels off and then declines—as it appears to be doing with the development of new and better antipollution technology in the economically advanced countries—we should begin to see faster-than-usual increases in the planet's vegetative productivity, which should promote a further acceleration of the greening of the earth phenomenon.

Exploring this relationship, Tu et al. (2009) examined what happens when agricultural crops exposed to various degrees of ozone pollution are grown in CO_2-enriched air. The researchers grew peanut (*Arachis hypogaea* L.) plants from seed to maturity outdoors near Raleigh, North Carolina (USA) in open-top chambers under adequately watered and fertilized conditions, while exposing the plants to (1) charcoal-filtered air, which was thus ozone-free, (2) ambient air of unaltered ozone (O_3) concentration, and (3) air containing 1.6 times the ambient O_3 concentration. All of the O_3 treatments were exposed to air of 376, 550, and 730 ppm CO_2. Throughout the study period, the researchers made many different plant physiological measurements, and at the end of the period they harvested the crop and measured its final stem, leaf, and pod biomass.

Tu et al. state, "elevated CO_2 generally increased biomass production while O_3 suppressed it, and CO_2 ameliorated the O_3 effect." In terms of the season-long mean of midday net photosynthesis, for example, the 94 percent increase in the atmosphere's CO_2 concentration experienced in going from the lowest to the highest CO_2 treatment resulted in a 25 percent increase in net photosynthesis in the charcoal-filtered air, a 50 percent increase in the nonfiltered air, and a 104 percent increase in the ozone-polluted air. For the final aboveground biomass produced, the corresponding CO_2-induced increases were 10 percent, 41 percent, and 105 percent.

On the other hand, the four researchers found "at mid-vegetative growth, elevated CO_2 significantly reduced leaf nitrogen concentrations by up to 44%," but "plant nitrogen concentrations only differed by 8% among CO_2 treatments at harvest while N_2 fixation was increased," and they state data from their experiment suggest "symbiotic N_2 fixation is important for maintaining seed N concentrations and that CO_2 enhancement of symbiotic N_2 fixation may compensate for low soil N availability."

Tu et al. additionally note several experiments, like theirs, "have shown that elevated CO_2 can offset the adverse effects of O_3 on crop biomass production and yield," citing Olszyk et al. (2000), Fuhrer (2003), and Fiscus et al. (2005). In addition, they note "the protective effect of elevated CO_2 against O_3 injury has been observed in several C_3 plant species, including cotton, peanut, rice, soybean, and wheat, due in large part to a reduction in O_3 uptake from reduced stomatal conductance and possibly from increases in photoassimilation rates and antioxidant metabolism," citing McKee et al. (2000), Booker and Fiscus (2005), Fiscus et al. (2005), and Booker et al. (2007).

Clearly, therefore, and contrary to the contention of the U.S. Environmental Protection Agency, CO_2 is *not* a pollutant. On the contrary, it is a pollution *fighter* that reduces the negative effects of true pollutants (such as ozone) on important agricultural crops and replaces them with positive effects of great worth to mankind.

In a study of what atmospheric CO_2 enrichment can do for trees growing in ozone-polluted air, Vapaavuori et al. (2009) grew 20 initially-seven-year-old trees of each of two different silver birch (*Betula pendula* Roth) clones—4 and 80 (V5952 and K1659, respectively, in the Finnish forest genetic register)—outdoors at the Suonenjoki Research Unit site of the Finnish Forest Research Institute for three years (1999–2001) within individual open-top chambers maintained at all combinations of (1) ambient CO_2 and ambient O_3, (2) ambient CO_2 and double O_3, (3) double CO_2 and ambient O_3, and (4) double CO_2 and double O_3. CO_2 treatments were imposed 24 hours per day, and O_3 treatments were imposed for 12, 12, and 14 hours per day in 1999, 2000, and 2001, respectively. Throughout the course of the experiment they measured a variety of plant physiological responses to the four different treatments, including net photosynthesis, leaf stomatal conductance, leaf soluble proteins, leaf phenolic compounds, leaf nutrient concentrations, trunk and branch growth, physiology of the foliage and root systems, crown structure, wood properties, and interactions with folivorous insects. The many results they thus obtained indicated, in general, that the negative effects of elevated O_3 on the various growth parameters and properties of the trees "were mainly found in ambient CO_2," and elevated CO_2 typically "reversed or diminished the effects of elevated O_3.".

In a similar study conducted at the Aspen FACE facility, where aspen clones had been grown since 1997 in conditions simulating atmospheric CO_2 and O_3 concentrations predicted for the mid-twenty-first century (560 ppm CO_2 and 1.5 times the current ambient O_3 concentration), McGrath et al. (2010) documented the history of leaf area index (LAI) development and leaf photosynthetic operating efficiency over the first month of spring leaf-out 11 years later in 2008, at a time when the yearly growth-season CO_2 fumigation had begun but before O_3 fumigation was started. The trees in the elevated CO_2 plots showed a 36 percent stimulation of leaf area index, while the trees in the elevated O_3 plots showed a 20 percent reduction in LAI. In addition, the photosynthetic operating efficiency of the CO_2-enriched aspen leaves was enhanced by 51 percent. Given these findings, atmospheric CO_2 enrichment would appear to be capable of providing young aspen trees with a great head start on the growing season, even in the debilitating presence of elevated ozone concentrations.

In studying others' experimental work, Wang and Taub (2010) conducted a series of meta-analyses that reveal how differences in the availability of soil fertility and water, as well as the stress of ozone (O_3) pollution, affect the biomass allocation in plants—as expressed by the change in the fraction of root mass to total biomass (i.e., *root mass fraction* or RMF)—that occurs when plants are exposed to air enriched with CO_2 to levels ranging anywhere from 500 to 1,000 ppm. Using data extracted from 541 peer-reviewed scientific journal articles, which yielded a total of 1,349 RMF observations, the researchers discovered that lower soil fertility increased RMF, and the magnitude of the increase "was similar for ambient and elevated CO_2-grown plants." They also discovered that lower soil water content also increased RMF, but in this case they report it did so "to a greater extent at elevated than at ambient CO_2." Finally, they discovered "CO_2 enrichment had little effect on the magnitude of O_3-caused reduction in RMF in herbaceous species," but "it alleviated the adverse effect of higher O_3 on root production in woody species."

Given these findings, the two researchers conclude, "under abiotic stresses, e.g., drought and higher O_3, elevated CO_2-grown plants will likely increase biomass allocation below-ground," where it can be used to construct more roots that can be used to acquire more water and nutrients. However, "because of the non-uniform changes in drought and O_3 projected for different parts of the world," they state "elevated CO_2 will have regional, but not global, effects on biomass allocation under various global change scenarios."

In one final CO_2 vs. O_3 study, Andrew and Lilleskov (2009) note sporocarps (the reproductive structures of fungi) can be significant carbon sinks for the ectomycorrhizal fungi that develop symbiotic relationships with plants by forming sheaths around their root tips, where they are the last sinks for carbon in the long and winding pathway that begins at the source of carbon assimilation in plant leaves. They also note "it is critical to understand how ectomycorrhizal fungal sporocarps are affected by elevated CO_2 and O_3" because, as they continue, "sporocarps facilitate genetic recombination, permit long-distance dispersal and contribute to food webs," and we need to know how these important processes will be affected by continued increases in the concentrations of these two trace constituents of the atmosphere.

In an effort to find some answers, the authors sampled aboveground sporocarps for four years at the Aspen FACE site, which provided, in their words, a "unique opportunity to examine the effects of both elevated CO_2 and O_3 on a forested ecosystem." The examination was conducted during years four through seven of the aspen and aspen-birch forests' exposures to ambient and enriched concentrations of the two gases: CO_2 (350 and 550 ppm) and O_3 (33–67 and 50–100 ppb).

The two researchers found total mean sporocarp biomass "was generally lowest under elevated O_3 with ambient CO_2," and it "was greatest under elevated CO_2, regardless of O_3 concentration." They also state there was "a complete elimination of O_3 effects on sporocarp production when [extra] CO_2 was added." Finally, they say they "expect that the responses seen in the present study were conservative compared to those expected under regional to global changes in CO_2 and O_3."

Consequently, by itself or in combination with rising ozone concentrations, the ongoing rise in the air's CO_2 content can be expected to enhance the genetic recombination and long-distance dispersal of the ectomycorrhizal fungi that form symbiotic relationships with the roots of aspen and birch trees, thereby positively contributing to various food webs found within aspen and aspen-birch forests.

References

Andrew, C. and Lilleskov, E.A. 2009. Productivity and community structure of ectomycorrhizal fungal sporocarps under increased atmospheric CO_2 and O_3. *Ecology Letters* **12**: 813–822.

Booker, F.L., Burkey, K.O., Pursley, W.A., and Heagle, A.S. 2007. Elevated carbon dioxide and ozone effects on peanut: I. Gas-exchange, biomass, and leaf chemistry. *Crop Science* **47**: 1475–1487.

Booker, F.L. and Fiscus, E.L. 2005. The role of ozone flux and antioxidants in the suppression of ozone injury by elevated CO_2 in soybean. *Journal of Experimental Botany* **56**: 2139–2151.

Fiscus, E.L., Booker, F.L., and Burkey, K.O. 2005. Crop responses to ozone: uptake, modes of action, carbon assimilation and partitioning. *Plant, Cell and Environment* **28**: 997–1011.

Fuhrer, J. 2003. Agroecosystem responses to combinations of elevated CO_2, ozone, and global climate change. *Agriculture, Ecosystems and Environment* **97**: 1–20.

Logan, J., Schultz, M., and Oltmans, S. 2010. Observing and understanding tropospheric ozone changes. *EOS, Transactions, American Geophysical Union* **91**: 119.

McGrath, J.M., Karnosky, D.F., and Ainsworth, E.A. 2010. Spring leaf flush in aspen (*Populus tremuloides*) clones is altered by long-term growth at elevated carbon dioxide and elevated ozone concentration. *Environmental Pollution* **158**: 1023–1028.

McKee, I.F., Mulholland, B.J., Craigon, J., Black, C.R., and Long, S.P. 2000. Elevated concentrations of atmospheric CO_2 protect against and compensate for O_3 damage to photosynthetic tissues of field-grown wheat. *New Phytologist* **146**: 427–435.

Olszyk, D.M., Tingey, D.T., Watrud, L., Seidler, R., and Andersen, C. 2000. Interactive effects of O_3 and CO_2:

implications for terrestrial ecosystems. In *Trace Gas Emissions and Plants*, edited by S.N. Singh, 97–136. Dordrecht: Netherlands.

Tu, C., Booker, F.L., Burkey, K.O., and Hu, S. 2009. Elevated atmospheric carbon dioxide and O_3 differentially alter nitrogen acquisition in peanut. *Crop Science* **49**: 1827–1836.

Vapaavuori, E., Holopainen, J.K., Holopainen, T., Julkunen-Titto, R., Kaakinen, S., Kasurien, A., Kontunen-Soppela, S., Kostiainen, K., Oksanen, E., Peltonen, P., Riikonen, J., and Tulva, I. 2009. Rising atmospheric CO_2 concentration partially masks the negative effects of elevated O_3 in silver birch (*Betula pendula* Roth). *Ambio* **38**: 418–424.

Wang, X. and Taub, D.R. 2010. Interactive effects of elevated carbon dioxide and environmental stresses on root mass fraction in plants: a meta-analytical synthesis using pairwise techniques. *Oecologia* **163**: 1–11.

7.5.4. Phosphorus Insufficiency

With respect to the CO_2-induced increase in the growth of plants generally observed in atmospheric CO_2 enrichment experiments, Khan et al. (2010) write, “if faster and more vigorous plant growth is to be sustained,” such as in the case of trees that may live for many decades or even centuries, “a sufficient nutrient supply must be available” to sustain that growth. This concept underlies the well-known but long-discredited progressive nitrogen limitation hypothesis. And since the researchers note “phosphorus is one of the key elements often considered to limit productivity in terrestrial ecosystems,” they state its gradual depletion in the soil may also “act as a negative feedback to increased growth.”

In a test of this hypothesis regarding phosphorus, Khan et al. grew three species of poplar trees (*Populus alba*, *P. nigra* and *P. x euramericana*) at ambient and elevated (550 ppm) CO_2 concentrations at the EuroFACE facility in Viterbo (Central Italy) in a low-nitrogen soil for a period of five years. Started as stem cuttings in 1999, the trees experienced a significant CO_2-induced stimulation of biomass production over the first three years of the study, at which point they were coppiced and allowed to grow for two more years. During that period, they continued to exhibit a significant CO_2-induced enhancement of growth. Afterward, numerous soil samples were taken to a depth of 60 cm under each species and analyzed for phosphorus (P) availability. This work revealed that rather than decreasing under elevated CO_2, and contrary to their own initial hypothesis, “the plant available, the weatherable mineral P pool and degradable organic P pools increased under FACE.” This, they state, suggests “the availability of P can actually increase in elevated CO_2, forming a positive feedback with increased biomass production on P limited soils.”

In the last paragraph of their paper, Khan et al. conclude their study “shows that increased tree growth under elevated CO_2 has not resulted in depletion of P pools in soils, but rather in replenishment and increased storage of P in the rooting zone.” Therefore, and contrary to even their own expectations before beginning their experiment, they conclude “phosphorus limitation may therefore not reduce tree growth in a high CO_2 world.”

Reference

Khan, F.N., Lukac, M., Miglietta, F., Khalid, M., and Godbold, D.L. 2010. Tree exposure to elevated CO_2 increases availability of soil phosphorus. *Pakistan Journal of Botany* **42**: 907–916.

7.5.5. Salinity Stress

Soil salinity stress, according to Perez-Lopez et al. (2010), results from a buildup of salt in soils, which “can inhibit the growth of valuable crops such as barley” because the “osmotic stress caused by low water potential in salinized soils reduces the availability of water for uptake by plants.” This stress, however, may be mitigated by plants actively decreasing their osmotic potential via a phenomenon known as osmotic adjustment, but the processes involved in this adjustment require extra energy that often leads to a reduction in plant growth. This penalty, or tax, is sometimes referred to as “the cost of salt tolerance.”

To further investigate this penalty, Perez-Lopez et al. (2009) grew two barley (*Hordeum vulgare* L.) cultivars, Alpha and Iranis, within controlled-environment growth chambers at either ambient (350 ppm) or elevated (700 ppm) atmospheric CO_2 concentrations in a 3:1 perlite:vermiculite mixture watered with Hoagland’s solution every two days (until the first leaf was completely expanded at 14 days), after which a salinity treatment was administered by adding 0, 80, 160, or 240 m*M* NaCl to the Hoagland’s solution every two days for 14 more days. Then, after a total of 28 days, the primary leaf of each barley plant was harvested and assessed for several biochemical properties.

The seven scientists determined that in the various ambient-air salinity treatments, the deleterious effects of reactive oxygen species (ROS) on barley leaves were made apparent through ion leakage and increases in thiobarbituric acid reactive substances (TBARS), which rose ever-higher as salt concentrations increased. "On the other hand," they continue, "when [the] salinity treatment was imposed under elevated CO_2 conditions, lower solute leakage and TBARS levels were observed, suggesting that the oxidative stress caused by salinity was lower." In discussing their findings, Perez-Lopez et al. write, "elevated CO_2 protects barley cultivars from oxidative stress," and they note "the relief of oxidative stress damage observed in our barley leaves grown under [a] CO_2 enriched atmosphere has also been observed in alfalfa (Sgherri et al., 1998), pine (Vu et al., 1999) and oak (Schwanz and Polle, 2001)." Hence, it would appear the ongoing rise in the air's CO_2 content may help a wide variety of Earth's plants cope with the serious problems caused by high soil salinity.

One year later, Perez-Lopez et al. (2010) once again grew two barley cultivars under well-watered and -fertilized conditions in pots placed within controlled-environment chambers they maintained at atmospheric CO_2 concentrations of either 350 or 700 ppm for a period of 28 days. During this time, midday leaf water potential, osmotic potential, osmotic potential at full turgor, dehydration, and osmotic adjustment were routinely measured, after which the primary leaf of each plant was harvested and assessed for the concentrations of various minerals and organic compounds it contained. The scientists found "elevated CO_2 permitted plant metabolism to be maintained at a better status under salt stress than did ambient CO_2," noting "growth was reduced more at ambient than at elevated CO_2." In addition, they determined "elevated CO_2 widens the range of salt concentrations at which osmotic adjustment continues to be efficient by providing the greater supply of carbon and ATP [Adenosine-5'-triphosphate]," which is a multifunctional nucleotide that transports chemical energy within cells for metabolism and is, in their words, "needed to perform the energetically expensive salt tolerance mechanisms." Given these findings, the Spanish scientists state their data suggest "under future environmental conditions, barley species will be able to succeed in salinized areas in which growth is not currently possible."

Turning our attention to halophytes, Geissler et al. (2009) note they are "naturally salt tolerant plants which are able to complete their life cycle on a substrate rich in NaCl," and that cash-crop halophytes "can be used for various economical and ecological purposes, e.g. for food, fodder, for obtaining timber, fibers, reeds or chemicals, as ornamental plants, for coastal protection, land reclamation or greenification of deserts." They note that *Aster tripolium*, in particular, "can be used for food (the leaves have a high nutritional value and can be eaten as salad or vegetable), for fodder and as an ornamental plant."

In their study of this plant, Geissler et al. grew adequately fertilized two-month-old seedlings for an additional month within open-top chambers maintained at atmospheric CO_2 concentrations of either 370 or 520 ppm inside a controlled-environment greenhouse, where they were irrigated with water having a salt (NaCl) content equivalent to 0, 50, or 100 percent sea water salinity (SWS), while monitoring several plant properties and processes. This work revealed, first, that the 40 percent increase in the air's CO_2 content increased the light-saturated rate of net photosynthesis by 56 percent, 82 percent, and 71 percent, respectively, in the plants irrigated with water of 0, 50, and 100 percent SWS, while it increased their water use efficiencies by 14, 26, and 61 percent at the same respective SWS percentages. Other positive impacts of the CO_2-enriched air were "an enhanced synthesis of proline, carbohydrates and proteins." The three researchers state "these mechanisms led to a higher survival rate under saline conditions, i.e. to an improved salt tolerance." Geissler et al. conclude their paper by stating, "*A. tripolium* is a promising cash crop halophyte which will probably benefit from rising atmospheric CO_2 concentrations in the future," and "its sustainable use can help feeding the growing world population and counteracting the greenhouse effect."

In another study of a halophyte, Mateos-Naranjo et al. (2010) note the cordgrass *Spartina maritima* "is an important pioneer and ecosystem engineer in salt marshes on the Atlantic coast of southern Europe," citing Castellanos et al. (1994). They state that "using the C_4 pathway," this halophyte "produces extensive stands in a range of marsh environments," citing Castellanos et al. (1998). Working with 15-cm-diameter clumps of *S. maritima* they obtained from a low-marsh site along the southwest coast of Spain in

April 2007, which they transplanted into individual plastic pots filled with pearlite that rested on shallow trays filled with Hoagland's solution of three different salinities (0, 170, or 510 mM NaCl), Mateos-Naranjo et al. conducted an experiment in which they maintained the plants in controlled environment chambers having atmospheric CO_2 concentrations of either 380 ppm or 700 ppm (an increase of 84 percent) for 30 days, during which time they measured several plant properties and processes.

The 84 percent increase in the atmosphere's CO_2 concentration stimulated the growth of *S. maritima* by about 65 percent in all three salinity treatments, while the halophyte's water use efficiency was enhanced by approximately 10 percent, 100 percent, and 160 percent in the 0, 170, and 510 mM salinity treatments, respectively, because "increasing CO_2 concentration has a positive effect on the photochemical apparatus, helping to counteract salt stress experienced by plants at current CO_2 concentrations." Therefore, the U.K. and Spanish scientists state their results suggest the productivity of *S. maritima* "might increase in a future scenario of rising atmospheric CO_2 concentration in environments with salinities as high as that of seawater," which is good news, indeed, about what they describe as "an important pioneer and ecosystem engineer in salt marshes."

References

Castellanos, E.M., Figueroa, M.E., and Davy, A.J. 1994. Nucleation and facilitation in saltmarsh succession: interactions between *Spartina maritima* and *Arthrocnemum perenne*. *Journal of Ecology* **82**: 239–248.

Castellanos, E.M., Heredia, C., Figueroa, M.E., and Davy, A.J. 1998. Tiller dynamics of *Spartina maritima* in successional and non-successional Mediterranean salt marsh. *Plant Ecology* **137**: 213–225.

Geissler, N., Hussin, S. and Koyro, H.-W. 2009. Interactive effects of NaCl salinity and elevated atmospheric CO_2 concentration on growth, photosynthesis, water relations and chemical composition of the potential cash crop halophyte *Aster tripolium* L. *Environmental and Experimental Botany* **65**: 220-231.

Mateos-Naranjo, E., Redondo-Gomez, S., Andrades-Moreno, L., and Davy, A.J. 2010. Growth and photosynthetic responses of the cordgrass *Spartina maritima* to CO_2 enrichment and salinity. *Chemosphere* **81**: 725–731.

Perez-Lopez, U., Robredo, A., Lacuesta, M., Munoz-Rueda, A., and Mena-Petite, A. 2010. Atmospheric CO_2 concentration influences the contributions of osmolyte accumulation and cell wall elasticity to salt tolerance in barley cultivars. *Journal of Plant Physiology* **167**: 15–22.

Perez-Lopez, U., Robredo, A., Lacuestra, M., Sgherri, C., Munoz-Rueda, A., Navari-Izzo, F., and Mena-Petite, A. 2009. The oxidative stress caused by salinity in two barley cultivars is mitigated by elevated CO_2. *Physiologia Plantarum* **135**: 29–42.

Schwanz, P. and Polle, A. 2001. Differential stress responses of antioxidative systems to drought in pendunc.ulate oak (*Quercus robur*) and maritime pine (*Pinus pinaster*) grown under high CO_2 concentrations. *Journal of Experimental Botany* **52**: 133–143.

Sgherri, C., Quartacci, M., Menconi, M., Raschi, A., and Navari-Izzo, F. 1998. Interactions between drought and elevated CO_2 on alfalfa plants. *Journal of Plant Physiology* **152**: 118–124.

Vu, J.C., Gesch, R., Allen, L.H., Boote, K., and Bowes, G. 1999. CO_2 enrichment delays a rapid, drought induced decrease in Rubisco small subunit transcript abundance. *Journal of Plant Physiology* **155**: 139–142.

7.5.6. Temperature Stress

Focusing on an agricultural crop, Xiong et al. (2009) write, "rice is an essential component of the diet in more than half the world's population, and it is the most socially and economically important crop in China," where they indicate it "contributes 43.7% of total national grain production," citing Yao et al. (2007). In light of this importance, Xiong et al. assess "the effect of greenhouse gas-induced climate change, as well as the direct fertilization effect of CO_2, on rice yields and production in China," by coupling "the regional climate model PRECIS (Providing Regional Climates for Impacts Studies) with the CERES (Crop Environment Resources Synthesis) rice crop model to simulate current (1961–1990) and future (2011–2100) rice yields and production under [the] A2 and B2 climate change scenarios" of the Intergovernmental Panel on Climate Change, which include significant global warming.

The four researchers report that with anticipated climate changes, "single rice cropping may expand further north in China, and double rice cropping may move to the northern portion of the Yangtze River basin." In addition, they write, "the national mean rice production is estimated to increase by 2.7 to 19.2% considering the combined effects of climate change,

CO_2 and shifting rice-producing areas.” Therefore, even considering the inflated temperature increases predicted by the IPCC, the estimated net effect of global warming and concomitant growth in anthropogenic CO_2 emissions ends up producing an increase in rice production in the world’s most populous country, where it is the people’s single most important food source. This is a benefit of the ongoing rise in the air’s CO_2 content that simply cannot be ignored.

Noting “responses to elevated CO_2 may differ at different temperature levels and that a potential reduction in yield due to high temperatures” is “very relevant,” Yoon et al. (2009) grew well-watered and -fertilized cotton (*Gossypium hirsutum* L.) plants from seed to maturity—one plant to each container of washed sand, with spacing between plants similar to the plant spacing found in typical cotton fields—within the University of Georgia’s Envirotron, where they were placed within chambers maintained at all combinations of two day/night air temperature regimes (25/15°C and 35/25°C) and three atmospheric CO_2 concentrations (400, 600, and 800 ppm), during which time, as well as at the end of the study, various plant properties were measured.

Describing the final yield obtained, Yoon et al. report that at the lower of the two air temperature regimes, “final boll weight at harvest was 1.59 times (at 600 ppm) and 6.3 times (at 800 ppm) higher compared to ambient CO_2,” and “increasing the temperature increased this difference, as the final boll weight was 34.1 times (at 600 ppm) and 23.3 times (at 800 ppm) higher compared to ambient CO_2.” In addition, they state “the response of final lint yield to CO_2 was more or less similar to the response of boll weight.”

Clearly, both higher air temperatures and higher atmospheric CO_2 concentrations—individually and in combination—were a great boon to cotton productivity in this well-controlled study, indicating that in this experiment not only were the twin evils of the radical environmentalist movement not detrimental to cotton growth and development, they were incredibly beneficial, demonstrating the enormous disconnect between forecasts of biospheric doom and experimental studies of how various species of both plants and animals actual to respond to changes in climate.

The study of Wertin et al. (2010) demonstrates that disconnect in the case of loblolly pine. The commercial forestry industry in the Southeast United States depends heavily on loblolly pine, and this part of the country is forecast to become warmer and perhaps slightly drier over time as the air’s CO_2 content continues to increase. Any climate-induced damage to this tree would thus have a huge negative impact on the region’s economy. Therefore, the three researchers set out to evaluate the effects of elevated CO_2, elevated temperature, and moisture stress on loblolly pine trees in a full-factorial experiment replicated at three sites spanning most of the north-south range of Georgia. Few studies have evaluated all three factors in this way, but Wertin et al. were able to do so using controlled-environment chambers that could not only keep the air’s CO_2 concentration continuously elevated at 700 ppm but could also keep its temperature a constant 2°C above ambient.

The study revealed there was essentially no effect of temperature on net assimilation rate (A_{net}), which the researchers attribute to the very broad temperature optimum of loblolly pine, which extends from about 20 to 35°C. Thus, there is no realistically possible global warming scenario under which a direct warming-induced negative effect would be detectable on this important commercial tree species.

The CO_2 effect, on the other hand, was substantial. A_{net} in the CO_2-enriched trees was 43 percent higher than in the ambient-air trees in June in the high-water treatment and 79 percent higher in the low-water treatment. The critical interaction between water stress and CO_2 also showed the low-water with high-CO_2 treatment had equal or higher A_{net} than the high-water with ambient-CO_2 treatment at all sites and during all seasons, indicating even a substantial decrease in moisture in this region would be compensated for by the positive A_{net} response to increased atmospheric CO_2 under future warmer conditions. Even under the worst-case predicted scenario, the dominant tree species in the Southeastern United States—loblolly pine—will grow as well as, or even better than, it does at present. And if the increases in precipitation forecast by some climate models come to pass, these climate conditions would lead to even greater growth enhancements.

In another illuminating study, Darbah et al. (2010) report that an unusual heat wave and drought occurred in northern Wisconsin (USA) during the summer of 2006, leading to maximum leaf temperatures that varied between 30 and 38°C and drought-exacerbated heat stress on the leaves of most trees. The scientists measured leaf gas exchange characteristics and several other plant physiological properties of the leaves of paper birch trees (*Betula papyrifera*) and two clones (271 and 42E) of quaking aspen trees (*Populus tremuloides* Michx) exposed to either ambient or elevated (ambient + 200 ppm) atmospheric CO_2 concentrations at the Aspen FACE facility before, during, and after the highest air temperatures recorded during that period of extreme heat. The four researchers discovered, "elevated CO_2 protected photosynthesis of both species against moderate heat stress" by increasing "carboxylation capacity, photosynthetic electron transport capacity and triose phosphate use." In addition, they "observed significant increases in transpiration rates in both aspen clones and the birch trees under elevated CO_2," the cooling effect of which decreased the leaf temperatures of the aspen trees by 1.9°C in clone 42E and by 2.7°C in clone 171, while the leaf temperatures of the birch trees were decreased by 3.1°C.

As for how this cooling could have occurred, Darbah et al. note under normal, less-stressful conditions, atmospheric CO_2 enrichment typically does just the opposite: It reduces transpiration and increases leaf temperature. This behavior earlier in the growing season in the elevated CO_2 treatment may have left more water in the soil, enabling the trees to transpire at a greater rate and thereby cool their leaves when it was most needed (during the subsequent heat wave and drought). They describe this phenomenon as "one part of the increased thermotolerance of the plants under high CO_2."

As a result of these various stress-relieving phenomena, Darbah et al.'s CO_2 gas exchange data indicated that whereas the CO_2-induced stimulation of net photosynthesis in aspen clone 42E was about 31 percent over the leaf temperature range 32–35°C, it was approximately 218 percent over the temperature range 36–39°C, while for aspen clone 171 the corresponding CO_2-induced net photosynthesis enhancements were 38 and 199 percent, and for the birch trees they were 95 and 297 percent.

In discussing their findings, Darbah et al. state they agree with those of Veteli et al. (2007), who "reported that elevated CO_2 ameliorated the negative effects of high temperature in three deciduous tree species," as well as those of Wayne et al. (1998), who "reported that elevated CO_2 ameliorated high temperature stress in yellow birch trees," and that all of these observations are "in agreement with Idso and Kimball (1992), who reported that elevated CO_2 (ambient + 300 ppm) increased net photosynthetic rate in sour orange tree leaves exposed to full sunlight by 75, 100 and 200% compared to those in ambient CO_2 concentration at temperatures of 31, 35 and 42°C, respectively, suggesting that elevated CO_2 ameliorates heat stress in tree leaves." Hence, they conclude, "in the face of rising atmospheric CO_2 and temperature (global warming), trees will benefit from elevated CO_2 through increased thermotolerance."

References

Darbah, J.N.T., Sharkey, T.D., Calfapietra, C., and Karnosky, D.F. 2010. Differential response of aspen and birch trees to heat stress under elevated carbon dioxide. *Environmental Pollution* **158**: 1008–1014.

Idso, S.B. and Kimball, B.A. 1992. Effects of atmospheric CO_2 enrichment on photosynthesis, respiration and growth of sour orange trees. *Plant Physiology* **99**: 341–343.

Veteli, T.O., Mattson, W.J., Niemela, P., Julkunen-Tiitto, R., Kellomaki, S., Kuokkanen, K., and Lavola, A. 2007. Do elevated temperature and CO_2 generally have counteracting effects on phenolic phytochemistry of boreal trees? *Journal of Chemical Ecology* **33**: 287–296.

Wayne, P.M., Reekie, E.G., and Bazzaz, F.A. 1998. Elevated CO_2 ameliorates birch response to high temperature and frost stress: implications for modeling climate-induced geographic range shifts. *Oecologia* **114**: 335–342.

Wertin, T.M., McGuire, M.A., and Teskey, R.O. 2010. The influence of elevated temperature, elevated atmospheric CO_2 concentration and water stress on net photosynthesis of loblolly pine (*Pinus taeda* L.) at northern, central and southern sites in its native range. *Global Change Biology* **16**: 2089–2103.

Xiong, W., Conway, D., Lin, E., and Holman, I. 2009. Potential impacts of climate change and climate variabiity on China's rice yield and production. *Climate Research* **40**: 23–35.

Yao, F.M., Xu, Y.L., Lin, E.D., Yokozawa, M., and Zhang, J.H. 2007. Assessing the impacts of climate change on rice yields in the main rice areas of China. *Climatic Change* **80**: 395–409.

Yoon, S.T., Hoogenboom, G., Flitcroft, I., and Bannayan, M. 2009. Growth and development of cotton (*Gossypium hirsutum* L.) in response to CO_2 enrichment under two different temperature regimes. *Environmental and Experimental Botany* **67**: 178–187.

7.5.7. Water Insufficiency and Over-Sufficiency

In a study of the more common type of extreme water availability (insufficiency), Wertin et al. (2010) used controlled-environment chambers that maintained the air's CO_2 concentration at either normal or elevated (700 ppm) values and its temperature either normal or elevated (2°C above ambient), while they studied the photosynthetic responses of loblolly pine trees growing in both high-water and low-water conditions in a full-factorial experiment replicated at three sites spanning most of the north-south range of Georgia (USA). This work revealed the net assimilation rate ($A_{\mathbf{net}}$) in the CO_2-enriched trees was 43 percent higher than in the ambient-air trees in June in the high-water treatment, but 79 percent higher in the low-water treatment, and that the low-water with high-CO_2 treatment had equal or higher $A_{\mathbf{net}}$ than the high-water with ambient-CO_2 treatment at all sites and during all seasons, indicating even a substantial decrease in moisture in this region would be compensated for by the positive $A_{\mathbf{net}}$ response to increased atmospheric CO_2 under future warmer conditions.

In a pertinent contemporaneous study, Wyckoff and Bowers (2010) write, "with continued increases in global greenhouse gas emissions, climate models predict that, by the end of the 21st century, Minnesota [USA] summer temperature will increase by 4–9°C and summer precipitation will slightly decrease," citing in this regard Kling et al. (2003) and Christensen et al. (2007); and they state certain "forest models and extrapolations from the paleoecological record suggest that, in response to increased temperature and/or drought, forests may retreat to the extreme north-eastern parts of the state," citing Pastor and Post (1998), Hamilton and Johnson (2002), and Galatowitsch et al. (2009).

Working with bur oak trees (*Quercus macrocarpa*), Wyckoff and Bowers evaluated the drought effect by: "(i) using tree rings to establish the relationship between drought and *Q. macrocarpa* growth for three sites along Minnesota's prairie-forest border, (ii) calculating the current relationship between growth and mortality for adult *Q. macrocarpa* and (iii) using the distributions of current growth rates for *Q. macracarpa* to predict the susceptibility of current populations to droughts of varying strength." In addition, they looked for "temporal trends in the correlation between *Q. macrocarpa* growth and climate, hypothesizing that increases in CO_2 may lead to weaker relationships between drought and tree growth over time," because atmospheric CO_2 enrichment typically leads to increases in plant water use efficiency, which generally makes them less susceptible to the deleterious impact of drought on growth.

The two University of Minnesota researchers discovered "the sensitivity of annual growth rates to drought has steadily declined over time as evidenced by increasing growth residuals and higher growth rates for a given PDSI [Palmer Drought Severity Index] value after 1950 [when the atmosphere's CO_2 concentration rose by 57 ppm from 1950 to 2000] compared with the first half of the century [when the CO_2 increase was only 10 ppm]." In addition, Wyckoff and Bowers write, "for *Q. macrocarpa*, declining sensitivity of growth to drought translates into lower predicted mortality rates at all sites" and "at one site, declining moisture sensitivity yields a 49% lower predicted mortality from a severe drought (PDSI = -8, on a par with the worst 1930s 'American Dust Bowl' droughts)." Hence, they conclude "the decreasing drought sensitivity of established trees may act as a buffer and delay the movement of the prairie-forest ecotone for many decades even in the face of climate change."

At the other end of the moisture spectrum, we confront the problem of an over-sufficiency of water, which we equate with complete submergence in water. This phenomenon was recently studied by Pedersen et al. (2010), who write, with respect to terrestrial plants in general, that complete submergence in water "impedes exchange of O_2 and CO_2 with shoots (Voesenek et al., 2006)," and that underwater photosynthesis "is limited by CO_2 availability owing to slow diffusion in water, and stomatal closure (Mommer and Visser, 2005)." These submergence-induced phenomena—if long sustained—typically lead to plant death.

To learn how the wetland plant *Hordeum marinum* Huds. would respond when fully submerged in water, Pedersen et al. grew several 28-day-old plants consisting of three Nordic Gene Bank accessions (H21, H90, and H546) for seven additional days while exposing them to four different treatments: "aerated root zone controls with shoots in air; stagnant root zone with shoots in air; stagnant root zone with shoots also completely submerged with 18 µM CO_2 (air equilibrium); stagnant root zone with shoots also completely submerged with 200 µM CO_2 (simulating CO_2 enrichment in many natural flood waters)," while measuring numerous plant responses.

This revealed, as they describe it, that "plants submerged for 7 days in water at air equilibrium (18 µM CO_2) suffered loss of biomass, whereas those with 200 µM CO_2 continued to grow." In addition, "higher underwater net photosynthesis at 200 µM CO_2 increased by 2.7- to 3.2-fold sugar concentrations in roots of submerged plants, compared with at air equilibrium CO_2." They state this phenomenon "is likely to have contributed to the greater root growth in submerged plants with the higher CO_2 supply." Finally, they note the latter CO_2-enriched plants "tillered similarly to plants with shoots in air."

Pedersen et al. further report that CO_2 enrichment of submerging water to ~290 µM enhanced by twofold the growth of two cultivars of rice, compared to plants submerged with water in equilibrium with normal ambient air (Setter et al., 1989), and they state such elevated CO_2 concentrations "have been reported at various field sites," citing Setter et al. (1987) and Ram et al. (1999). Thus, they indicate plants experiencing total submergence during floods typically lose mass and die under normal conditions, but when the water is supersaturated with CO_2, they can not only survive, they actually continue to grow.

References

Christensen, J.H., et al.. 2007. Regional climate projections. In Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon, et al., 847–940. Cambridge, UK: Cambridge University Press.

Galatowitsch, S., Frelich, L., and Phillips-Mao, L. 2009. Regional climate change adaptation strategies for biodiversity conservation in a mid-continental region of North America. *Biological Conservation* **142**: 2012–2022.

Hamilton, J.D. and Johnson, S. 2002. *Playing with Fire: Climate Change in Minnesota.* St. Paul, MN: Minnesotans for an Energy-Efficient Economy.

Kling, G.W., et al. 2003. *Confronting Climate Change in the Great Lakes Region: Impacts on our Communities and Ecosystems.* Washington, DC: Union of Concerned Scientists and Ecological Society of America.

Mommer, L. and Visser, E.J.W. 2005. Underwater photosynthesis in flooded terrestrial plants: a matter of leaf plasticity. *Annals of Botany* **96**: 581–589.

Pastor, J. and Post, W.M. 1988. Response of northern forests to CO_2-induced climate change. *Nature* **334**: 55–58.

Pedersen, O., Malik, A., and Colmer, T.D. 2010. Submergence tolerance in *Hordeum marinum*: dissolved CO_2 determines underwater photosynthesis and growth. *Functional Plant Biology* **37**: 524–531.

Ram, P.C., Singh, A.K., Singh, B.B., Singh, V.K., Singh, H.P., Setter, T.L., Singh, V.P., and Singh, R.K. 1999. Environmental characterization of floodwater in Eastern India: relevance to submergence tolerance of lowland rice. *Experimental Agriculture* **35**: 141–152.

Setter, T.L., Kupkanchanakul, T., Kupkanchankul, K., Bhekasut, P., Wiengweera, A., and Greenway, H. 1987. Concentrations of CO_2 and O_2 in floodwater and in internodal lacunae of floating rice growing at 1–2 meter water depths. *Plant, Cell and Environment* **10**: 767–776.

Setter, T.L., Waters, I., Wallace, I., Bhekasut, P., and Greenway, H. 1989. Submergence of rice. I. Growth and photosynthetic response to CO_2 enrichment of floodwater. *Australian Journal of Plant Physiology* **16**: 251–263.

Voesenek, L.A.C.J., Colmer, T.D., Pierik, R., Millenaar, F.F., and Peeters, A.J.M. 2006. How plants cope with complete submergence. *New Phytologist* **170**: 213–226.

Wertin, T.M., McGuire, M.A., and Teskey, R.O. 2010. The influence of elevated temperature, elevated atmospheric CO_2 concentration and water stress on net photosynthesis of loblolly pine (*Pinus taeda* L.) at northern, central and southern sites in its native range. *Global Change Biology* **16**: 2089–2103.

Wyckoff, P.H. and Bowers, R. 2010. Response of the prairie-forest border to climate change: impacts of increasing drought may be mitigated by increasing CO_2. *Journal of Ecology* **98**: 197–208.

7.6. Ecosystem Biodiversity

How will the biodiversity of Earth's ecosystems respond to predicted changes in the planet's climate? This question is among the top concerns about potential CO_2-induced global warming, and it has been addressed in several different ways.

Studying the direct effects of elevated CO_2 itself, Lau et al. (2010) grew thale cress (*Arabidopsis thaliana*) either alone or together with the C_3 grass *Bromus inermis* or the C_4 grass *Andropogon gerardii* in small pots placed within open-field FACE arrays at the Cedar Creek Ecosystem Science Reserve, Minnesota (USA). These were maintained at atmospheric CO_2 concentrations of either 368 or 560 ppm from the time of emergence to the time of plant senescence. At the time of harvest, the CO_2-induced stimulation of *A. thaliana* biomass was approximately 42 percent when it was grown alone, but 46 percent when it was grown together with *A. gerardii* and 50 percent when grown together with *B. inermis,* while corresponding stimulation values were 1 percent, 3 percent, and 4 percent for leaf number; 15 percent, 17 percent, and 21 percent for plant height; 11 percent, 21 percent, and 20 percent for stem number; and 25 percent, 43 percent, and 39 percent for fruit number. All of this indicates greater CO_2-induced benefits for *A. thaliana* when grown in competitive mixtures with other species. Lau et al. conclude, "elevated CO_2 reduces the effects of competition on mean fitness ... and minimizes the strength of competition as a selective agent." Therefore, it may logically be expected (all else being equal) that ecosystem species richness or biodiversity should at least remain stable, or possibly even increase, in response to continued increases in the air's CO_2 content.

In a related study, Peter B. Reich of the University of Minnesota (2009) wrote, "levels of N [nitrogen] deposition and CO_2 have risen in recent decades and are expected to increase further," and in the case of natural ecosystems, he writes, "the suppression of diversity by increasing N availability is almost ubiquitous," while stating "evidence of CO_2 effects on species richness is scarce and shows mixed results, with positive, neutral, and negative responses seen in the few published reports."

In what Collins (2009) appropriately describes as "a rare gem in long-term ecological research," Reich presided over the ten-year-long BioCON study conducted at the Cedar Creek Long-Term Ecological Research site, where, as Reich describes it, "species richness was measured in 48 experimental grassland plots (each 2 m by 2 m) planted in 1997 with 16 perennial species [four species from each of four functional groups (C_4 grasses, C_3 grasses, legumes and non-legume forbs)] and treated since 1998 with all combinations of ambient and elevated atmospheric CO_2 (ambient and +180 ppm delivered by means of a free-air CO_2 enrichment technique) and ambient and enriched N (ambient and +4 g N m^{-2} $year^{-1}$ delivered as ammonium nitrate in three equal doses each year)," while several plant physiological processes and properties were measured throughout each growing season.

Reich found that at the ambient soil N concentration, elevated CO_2 had minimal impact on observed species richness (-2 percent), while at the ambient atmospheric CO_2 concentration, elevated N decreased species richness by fully 15 percent over the last seven years of the ten-year-long study. But when the elevated soil N concentration was combined with the elevated atmospheric CO_2 concentration, species richness declined by only 5 percent, leading Reich to conclude, "elevated CO_2 reduces losses of plant diversity caused by nitrogen deposition." This was such an important finding that he made it the title of his paper. With levels of nitrogen deposition "expected to increase further," as Reich notes, the Earth's natural ecosystems will benefit from the fact that the atmosphere's CO_2 concentration is rising in tandem with the increasing level of N deposition that is being experienced throughout the world.

Regarding possible indirect effects of rising CO_2 concentrations, some researchers contend that CO_2-induced global warming will be so fast and furious that many species of plants will not be able to migrate poleward in latitude or upward in altitude at rates required to keep them within the geographically shifting temperature regimes to which they have been adapted. Thus, they claim, many species will be driven to extinction, and the species richness of various ecosystems will be greatly reduced.

As some examples of these contentions, Dyer (1995) wrote, "the magnitude of the projected warming is considerable" and "the rate at which it is predicted to occur is unprecedented," and consequently, "there is genuine reason for concern that the extent of range shifts will exceed the dispersal abilities of many plant species." Malcolm and Markham (2000) similarly wrote, "rapid rates of global warming are likely to increase rates of habitat loss and species extinction," and "many species may be unable to shift their ranges fast enough to keep up with global warming." Malcolm et al. (2002) added, "migration rates required by the warming are unprecedented by historical standards, raising the possibility of extensive, and in many cases, catastrophic, species loss." In his 26 April 2007 testimony to the Select Committee of Energy Independence and Global Warming of the United States House of Representatives, NASA's James Hansen echoed these fears, saying "greenhouse gas emissions threaten many ecosystems," contending "very little additional forcing is needed ... to cause the extermination of a large fraction of plant and animal species," claiming "polar species can be pushed off the planet, as they have no place else to go," and stating "life in alpine regions ... is similarly in danger of being pushed off the planet."

An enlightening reality check on these doomsday scenarios was provided by Le Roux and McGeoch (2008), who examined patterns of altitudinal range changes in the totality of the native vascular flora of sub-Antarctic Marion Island (46°54'S, 37°45'E) in the southern Indian Ocean, which warmed by 1.2°C between 1965 and 2003. These South African researchers found that between 1966 and 2006, there was "a rapid expansion in altitudinal range," with species expanding their upper elevational boundaries by an average of 70 meters. And because, as they describe it, "the observed upslope expansion was not matched by a similar change in lower range boundaries," they emphasize "the flora of Marion Island has undergone range expansion rather than a range shift," noting "the expansion of species distributions along their cooler boundaries in response to rising temperatures appears to be a consistent biological consequence of recent climate warming," citing references to several other studies that have observed the same type of response.

An important consequence of the stability of lower-range boundaries of species together with expanding upper-range boundaries is a greater overlapping of ranges, which results in greater local species richness or biodiversity everywhere up and down various altitudinal transects. As a further consequence, le Roux and McGeoch indicate "the present species composition of communities at higher altitudes is not an analogue of past community composition at lower altitudes, but rather constitutes a historically unique combination of species," a new world significantly richer in species in a greater number of locations than in the recent past.

Working on the outskirts of Jena, Germany, Steinbeiss et al. (2008) sowed 20-m by 20-m plots of soil with seeds of either one, two, four, eight, 16, or 60 species of either one, two, three, or four plant functional groups (grasses, small herbs, tall herbs, and legumes), creating 16 replicate plots per species level except for the 16-species level plots (14 replicates) and the 60-species level plots (four replicates) in April 2002, just before soil carbon content sampling was performed, and after which similar sampling was repeated in April 2004 and April 2006.

During the first two years of their study, soil carbon storage was limited to the top 5 cm of soil, while below 10 cm depth, carbon was actually lost. After four years, however, carbon stocks had increased significantly within the top 20 cm of the soil. However, and "more importantly," in the words of Steinbeiss et al., "carbon storage significantly increased with sown species richness in all depth segments and even carbon losses were significantly smaller with higher species richness." Consequently, they concluded, "plant species richness ... accelerate[d] the build-up of new carbon pools within four years," and "higher plant diversity mitigated soil carbon losses in deeper horizons."

The researchers state their findings suggest "higher biodiversity might lead to higher soil carbon sequestration in the long-term," and, therefore, "the conservation of biodiversity might play a role in greenhouse gas mitigation." It also should be added that this phenomenon represents a previously unrecognized negative feedback, since studies such as that of Le Roux and McGeoch have demonstrated global warming typically leads to higher local and regional biodiversity wherever the process has been studied throughout the world.

The study of Odland et al. (2010) provides what can be seen as the icing on the cake when it comes to refuting James Hansen's wild contention of mountaintop species being "pushed off the planet" by global warming. Based on their documentation of plant species diversity on 13 mountain summits in southern Norway—in a reenactment of what Lye (1973) had done more than three decades earlier—and their assessment of regional warming over the intervening years, the three scientists sought to ascertain how plant species richness may have changed in response to what turned out to have been a significant increase in local temperatures. They found average summer temperatures had risen by approximately 1.3°C between the times of the two studies, and over that period plant taxa richness had risen by an average of 90 percent, with two of the summits experiencing increases of fully 200 percent.

Odland et al. state the average rise they identifed "is in accordance with similar studies in both Scandinavia and southern Europe (Kullman, 2007a,b; Parmesan, 2005; Pauli et al., 2007)," but the 200 percent increase in taxa richness they documented on two of the summits "is exceptional." And because the latter result is also true, it can validly be called an exceptional truth. And giving credit where credit is due, the three Norse researchers conclude "the present increase in species richness is mainly a result of recent climatic change."

Not all ecosystems, however, respond so dramatically to warming, though still positively, as evidenced by the study of Hudson and Henry (2010). They employed open-top chambers to passively warm an evergreen-shrub heath, which was dominated by several shrub species and bryophytes, by 1.0–1.3°C over a period of 15 years (when there was also a significant background warming) in the vicinity of Alexandra Fiord, Nunavut, Canada (79°N). In what they describe as "the longest-running passive warming experiment in the Canadian Arctic," the two University of British Columbia researchers found "experimental warming did not strongly affect vascular plant cover, canopy height or species diversity, but it did increase bryophyte cover by 6.3% and decrease lichen cover by 3.5%," although they note "temporal changes in plant cover were more frequent and of greater magnitude than changes due to experimental warming." These findings thus prompted them to state, "this evergreen-shrub heath continues to exhibit community-level resistance to long-term experimental warming."

In about the only logical conclusion that could be reached on the basis of their observations, Hudson and Henry state their findings "support the view that only substantial climatic changes will alter unproductive ecosystems," such as the one they studied. In further support of this statement they note other plant communities also have "exhibited strong resistance to simulated climate change manipulations (e.g. Grime et al., 2008), where resistance is defined as the ability of a community to maintain its composition and structure in the face of environmental change." They amplify this conclusion by stating, "at other Arctic sites, lichen, bryophyte and evergreen-shrub dominated heaths were [also] less responsive to experimental warming than other plant communities," citing the studies of Hollister et al. (2005), Jonsdottir et al. (2005), and Wahren et al. (2005).

In the first of two studies of an agricultural crop that looks at the phenomenon in question from a very different point of view, Yang et al. (2009) write, "rice (*Oryza sativa* L.) is unequivocally one of the most important food crops that feed the largest proportion of the world's population," and they note "the demand for rice production will continue to increase in the coming decades, especially in the major rice-consuming countries of Asia, Africa and Latin America, due to the population explosion and cropland reduction." Hence, they state "as sufficient intraspecific variation in yield response [of rice] exists under field conditions, there is a pressing need to identify genotypes which would produce maximum grain yield under projected future CO_2 levels." In other words, they are looking to go beyond nature in determining what will grow where, in order to take best advantage of what Earth's changing environment has to offer.

Working with that same goal in mind at the National Institute for Agro-Environmental Sciences in Tsukuba, Japan, Lou et al. (2008) grew plants of four different rice cultivars—Dular (a traditional indica variety), IR72 (an improved indica variety), Koshihikari (a temperate japonica variety), and IR65598 (a new variety not yet released to farmers)—within growth chambers in submerged pots filled with a fertilized soil collected from the plough layer of a paddy field in Chiba Prefecture, Japan, at two atmospheric CO_2 concentrations: ambient (~370 ppm) and elevated (~570 ppm). This protocol revealed the extra 200 ppm of CO_2 reduced the ultimate grain yield of Dular (by 0.7 percent), while it increased the final grain yield of IR72 by 8.0 percent, that of Koshihikari by 13.4 percent, and that of IR65598 by 17.7 percent.

Shortly thereafter—working at the FACE facility at Yangzhou City, Jiangsu Province, China—Yang et al. (2009) focused on a single two-line inter-subspecific hybrid rice variety (Liangyoupeijiu), produced as part of "a nationwide mega project" to develop what they call "super" hybrid cultivars that would "further break the yield ceiling." In their three-year CO_2-enrichment study, which employed the same CO_2 levels as the study of Lou et al., they found a much greater grain yield stimulation: a 28.4 percent CO_2-induced increase under a low nitrogen fertility treatment of 12.5 g N m^{-2} and a 31.7 percent CO_2-induced increase under a high nitrogen fertility treatment of 25 g N m^{-2}.

In discussing their findings, Yang et al. state their hybrid cultivar "appears to profit much more from elevated CO_2 than inbred japonica cultivars," which does indeed seem to be the case, as both Japanese and Chinese FACE studies of inbred japonica cultivars have found CO_2-induced grain yield enhancements only on the order of 13 percent for a 200 ppm increase in the air's CO_2 concentration. Therefore, noting "there is a pressing need to identify genotypes which could optimize harvestable yield as atmospheric CO_2 increases," Yang et al. conclude, "on the basis of available FACE data on rice," the hybrid rice cultivar Liangyoupeijiu "appears to be particularly promising."

References

Collins, S.L. 2009. Biodiversity under global change. *Science* **326**: 1353–1354.

Dyer, J.M. 1995. Assessment of climatic warming using a model of forest species migration. *Ecological Modelling* **79**: 199–219.

Grime, J.P., Fridley, J.D., Askew, A.P., Thompson, K., Hodgson, J.G. and Bennett, C.R. 2008. Long-term resistance to simulated climate change in an infertile grassland. *Proceedings of the National Academy of Sciences of the United States ofAmerica* **105**: 10028–10032.

Grime, J.P., Brown, V.K., Thompson, K., Masters, G.J., Hillier, S.H., Clarke, I.P., Askew, A.P., Corker, D., and Kielty, J.P. 2000. The response of two contrasting limestone grasslands to simulated climate change. *Science* **289**: 762–765.

Hollister, R.D., Webber, P.J., and Tweedie, C.E. 2005. The response of Alaskan arctic tundra to experimental warming: differences between short- and long-term responses. *Global Change Biology* **11**: 525–536.

Hudson, J.M.G. and Henry, G.H.R. 2010. High Arctic plant community resists 15 years of experimental warming. *Journal of Ecology* **98**: 1035–1041.

Jonsdottir, I.S., Magnusson, B., Gudmundsson, J., Elmarsdottir, A., and Hjartarson, H. 2005. Variable sensitivity of plant communities in Iceland to experimental warming. *Global Change Biology* **11**: 553–563.

Kullman, L. 2007a. Long-term geobotanical observations of climate change impacts in the Scandes of West-Central Sweden. *Nordic Journal of Botany* **24**: 445–467.

Kullman, L. 2007b. Modern climate change and shifting ecological sates of the subalpine/alpine landscape in the Swedish Scandes. *Geooko* **28**: 187–221.

Lau, J.A., Shaw, R.G., Reich, P.B., and Tiffin, P. 2010. Species interactions in a changing environment: elevated CO_2 alters the ecological and potential evolutionary consequences of competition. *Evolutionary Ecology Research* **12**: 435–455.

Le Roux, P.C. and McGeoch, M.A. 2008. Rapid range expansion and community reorganization in response to warming. *Global Change Biology* **14**: 2950–2962.

Lou, Y., Inubushi, K., Mizuno, T., Hasegawa, T., Lin, Y., Sakai, H., Cheng, W., and Kobayashi, K. 2008. CH_4 emission with differences in atmospheric CO_2 enrichment and rice cultivars in a Japanese paddy soil. *Global Change Biology* **14**: 2678–2687.

Lye, K.A. 1973. The vascular plants on alpine peaks at Filefjell, south Norway. *Norwegian Journal of Botany* **20**: 51–55.

Malcolm, J.R., Liu, C., Miller, L.B., Allnutt, T., and Hansen, L. 2002. *Habitats at Risk: Global Warming and Species Loss in Globally Significant Terrestrial Ecosystems.* Gland, Switzerland: World Wide Fund for Nature.

Malcolm, J.R. and Markham, A. 2000. *Global Warming and Terrestrial Biodiversity Decline.* Gland, Switzerland: World Wide Fund for Nature.

Odland, A., Hoitomt, T., and Olsen, S.L. 2010. Increasing vascular plant richness on 13 high mountain summits in southern Norway since the early 1970s. *Arctic, Antarctic, and Alpine Research* **42**: 458–470.

Parmesan, C. 2005. Biotic response: range and abundance changes. In *Climate Change and Biodiversity*, edited by T.E. Lovejoy and H. Lee, H. 41–55. New Haven, CT and London, UK: Yale University Press.

Pauli, H., Gottfried, M., Reiter, K., and Grabherr, G. 2007. Signals of range expansions and contractions of vascular plants in the high Alps: observations 1994–2004 at the GLORIA master site Schrankogel, Tyrol, Austria. *Global Change Biology* **13**: 147–156.

Reich, P.B. 2009. Elevated CO_2 reduces losses of plant diversity caused by nitrogen deposition. *Science* **326**: 1399–1402.

Steinbeiss, S., Bessler, H., Engels, C., Temperton, V.M., Buchmann, N., Roscher, C., Kreutziger, Y., Baade, J., Habekost, M., and Gleixner, G. 2008. Plant diversity positively affects short-term soil carbon storage in experimental grasslands. *Global Change Biology* **14**: 2937–2949.

Wahren, C.H.A., Walker, M.D., and Bret-Harte, M.S. 2005. Vegetation responses in Alaskan arctic tundra after 8 years of a summer warming and winter snow manipulation experiment. *Global Change Biology* **11**: 537–552.

Yang, L., Liu, H., Wang, Y., Zhu, J., Huang, J., Liu, G., Dong, G., and Wang, Y. 2009. Yield formation of CO_2-enriched inter-subspecific hybrid rice cultivar Liangyoupeijiu under fully open-air condition in a warm sub-tropical climate. *Agriculture, Ecosystems and Environment* **129**: 193–200.

7.7. Soil Carbon Sequestration

7.7.1. Agricultural Crops

According to Martens et al. (2009), "the generally higher above and belowground productivity of C_3 plants under elevated CO_2 leads to the conclusion that more rhizodepositions (roots and exudates) are transferred into soils, potentially increasing soil carbon content," but they note most free-air CO_2-enrichment (FACE) and outdoor chamber studies have failed to detect significant changes in soil organic carbon (SOC) due to the typically large amount and spatially heterogeneous nature of pre-existing SOC. In an attempt to overcome these difficulties, they cultivated well-watered and -fertilized spring wheat (cv. Minaret) within stainless steel cylinders forced into the soil of control and free-air CO_2-enriched (to 180 ppm above ambient) FACE plots at the experimental farm of the Federal Research Institute in Braunschweig, Germany. Between stem elongation and beginning of ripening the plants were repeatedly pulse-labelled with $^{14}CO_2$ and thereafter monitored daily for soil-borne total CO_2 and $^{14}CO_2$ until harvest, after which the distribution of ^{14}C was analyzed in all plant parts, soil, soil mineral fractions, and soil microbial biomass.

The researchers found, "in comparison to ambient conditions, 28% more $^{14}CO_2$ and 12% more total CO_2 was evolved from soil under elevated CO_2," and "in the root-free soil 27% more residual ^{14}C was found in the free-air CO_2-enriched soil than in the soil from the ambient treatment." In addition, in soil samples from both treatments about 80 percent of residual ^{14}C was "integrated into the stable, clay bound soil organic matter pool," which suggests, in the researchers' words, that "under FACE conditions a considerable contribution was made to the long-term storage of soil carbon in this soil." By these means, Martens et al. state they were able to "show for the first time," as they describe it, "that a crop plant grown under FACE conditions deposited significantly more carbon to soil than those grown under ambient CO_2 in the field," and "the additional carbon input under elevated CO_2 did not induce an accelerated degradation of pre-existing soil organic matter (no positive priming effect)," thereby indicating "wheat plants grown under elevated CO_2 can contribute to an additional net carbon gain in soils."

Reference

Martens, R., Heiduk, K., Pacholski, A., and Weigel, H.-J. 2009. Repeated $^{14}CO_2$ pulse-labelling reveals an additional net gain of soil carbon during growth of spring wheat under free air carbon dioxide enrichment (FACE). *Soil Biology & Biochemistry* **41**: 2422–2429.

7.7.2. Grasslands

Shifting from agricultural fields to grasslands, Adair et al. (2009) employed mass balance calculations to quantify the effects of biodiversity, atmospheric CO_2 concentration, and soil nitrogen content on the total amount of carbon (C) allocated belowground by plants (total belowground C allocation or TBCA), as well as ecosystem C storage, in an eight-year experiment that was part of the BioCON study of a periodically burned Minnesota grassland. They found annual TBCA increased in response to all three treatment variables—"elevated CO_2, enriched N, and increasing diversity"—and it also was "positively related to standing root biomass." Upon removing the influence of root biomass, however, they found the effects of N and diversity became neutral or even negative (depending on the year), but "the effect of elevated CO_2 remained positive." In the case of years with fire, they found "greater litter production in high diversity, elevated CO_2, and enhanced nitrogen treatments increased annual ecosystem C loss." Given these findings, it would appear that under normal, non-fire conditions, increasing CO_2 concentrations, nitrogen deposition, and increasing biodiversity generally tend to increase ecosystem carbon gain; but if grasslands are frequently burned, they could remain neutral in this regard.

Halfway around the world, in a temperate steppe grassland located in Duolun County, Inner Mongolia, China, Wan et al. (2009) suspended infrared radiators 2.25 meters above the ground over 24 plots divided into four temperature treatments—(1) control, (2) day (06:00–18:00, local time) warming, (3) night (18:00–06:00) warming, and (4) diurnal (24-hour) warming—after which they measured diurnal cycles of net ecosystem gas exchange and daytime ecosystem respiration twice a month over the growing seasons (May–October) of 2006, 2007, and 2008. They found "nocturnal warming increased leaf respiration of two dominant grass species by 36.3%, enhanced consumption [drawdown] of carbohydrates in the leaves (72.2% and 60.5% for sugar and starch, respectively), and consequently stimulated plant photosynthesis by 19.8% in the subsequent days." In addition, they write, "the enhancement of plant photosynthesis overcompensated the increased carbon loss via plant respiration under nocturnal warming and shifted the steppe ecosystem from a minor carbon source (1.87 g C/m^2/year) to a carbon sink (21.72 g C/m^2/year) across the three growing seasons."

In addition, the four researchers report the local climate in their study area "experienced asymmetrical diurnal warming (0.57, 0.45 and 0.30°C increases in daily minimum, mean and maximum temperatures per decade, respectively) over the past half century (1953–2005)," and "similar diurnal scenarios of climate warming have been widely reported at the regional and global scales," citing the studies of Karl et al. (1991), Easterling et al. (1997), Stone and Weaver (2002), Vose et al. (2005), Lobell et al. (2007), and Zhou et al. (2007). Consequently, and in light of the many well-documented cases of "greater increases in daily minimum than maximum temperature" that they say have been observed throughout the world, Wan et al. conclude, "plant photosynthetic overcompensation may partially serve as a negative feedback mechanism for [the] terrestrial biosphere to climate warming," where "the photosynthetic overcompensation induced by nocturnal warming can ... regulate terrestrial carbon sequestration and negatively feed back to climate change."

Also working in China, Yang et al. (2010) conducted five consecutive regional soil surveys of that country's grasslands during 2001–2005 and sampled 981 soil profiles from 327 sites across the northern part of the country. They then compared their results with data of 275 soil profiles derived from China's National Soil Inventory during the 1980s. This work indicated the organic carbon stock in the upper 30 cm of soil in northern China's grasslands "did not show significant association with mean annual temperature, but was positively correlated with mean annual precipitation," reaching a plateau when soil moisture was above 30 percent. And in perhaps their most important observation, they found "grassland soil organic carbon stock did not change significantly over the past two decades, with a change of 0.08 kg carbon per m^2, ranging from -0.30 to +0.46 kg carbon per m^2 at 95% confidence interval."

In discussing their findings, Yang et al. write, "it has been often asserted that soil will act as a carbon source because of its sensitivity to global environmental change (e.g., Melillo et al., 2002; Bellamy et al., 2005; Schipper et al., 2007)," but "in contrast to these previous reports, our results indicate that soil organic carbon stock in northern China's grasslands has not experienced significant changes during the past two decades, despite measureable climate change," i.e., global warming. Hence, there is very good reason (i.e., real-world data) not to believe "climate warming is likely to accelerate the decomposition of soil organic carbon which could lead to increased carbon release from soils, providing a positive feedback to climate change," as some have suggested based primarily on theoretical considerations.

In one final study of carbon sequestration in the soils of grasslands, Belay-Tedla et al. (2009) write, "the stability of carbon (C) and nitrogen (N) in soil organic matter (SOM) to perturbations such as global warming is critically important," because "on a global scale, the soil contains 1500 Pg (1 Pg = 10^{15} g) of organic carbon and 300 Pg of total nitrogen" in its uppermost meter, so that "relatively small changes in the amounts of soil C and N may therefore bring about substantial effects on atmospheric concentrations," which in the case of the carbon contained in CO_2 may feed back either positively or negatively to enhance or reduce the original warming of the air.

In an experiment designed to explore these interactions within a specific biome, Belay-Tedla et al. "used sulfuric acid hydrolysis to quantify changes in labile and recalcitrant C and N fractions of soil in a tallgrass prairie ecosystem that had been continuously warmed with or without clipping for about 2.5 years," conducting their work in "an old-field tallgrass prairie abandoned from agriculture 30 years ago and without grazing during the past 20 years" at a location within the Great Plains Apiaries of McClain County, Oklahoma, USA, where infrared heaters suspended 1.5 m above the ground warmed half of the plots 24 hours a day, 365 days a year, for the 2.5-year period, increasing the daily mean air temperature at 25 cm above the ground by 1.1°C and soil temperature at 2.5 cm depth by 2.0°C.

The work of the five researchers revealed, as they describe it, "significant increases in both labile C and N (including microbial biomass) pools in response to experimental warming," which "largely resulted from increased above- and below-ground biomass." They also observed "a possible shift to a fungi-dominated microbial community," noting "such a shift could favor soil C storage" as well. In addition, they found evidence suggesting "warming increased the percentage of total N for microbial biomass N," and they state this enhanced N use efficiency "may be conducive for a continued supply of organic inputs." As a result, Belay-Tedla et al. conclude their combined findings favor "long-term N retention and C accumulation in soils, leading to negative feedbacks of terrestrial ecosystems to climate warming."

References

Adair, E.C., Reich, P.B., Hobbie, S.E., and Knops, J.M.H. 2009. Interactive effects of time, CO_2, N, and diversity on total belowground carbon allocation and ecosystem carbon storage in a grassland community. *Ecosystems* **12**: 1037–1052.

Belay-Tedla, A., Zhou, X., Su, B., Wan, S., and Luo, Y. 2009. Labile, recalcitrant, and microbial carbon and nitrogen pools of a tallgrass prairie soil in the US Great Plains subjected to experimental warming and clipping. *Soil Biology & Biochemistry* **41**: 110–116.

Bellamy, P.H., Loveland, P.J., Bradley, R.I., Lark, R.M., and Kirk, G.J.D. 2005. Carbon losses from all soils across England and Wales 1978-2003. *Nature* **437**: 245–248.

Easterling, D.R., Horton, B., Jones, P.D., Peterson, T.C., Karl, T.R., Parker, D.E., Salinger, M.J., Razuvayev, V., Plummer, N., Jamason, P., and Folland, C.K. 1997. Maximum and minimum temperature trends for the globe. *Science* **277**: 364–367.

Karl, T.R., Kukla, G., Razuvayev, N., Changery, M.J., Quayle, R.G., Heim, R.R., Easterling, D.R., and Fu, C.B. 1991. Global warming—evidence for asymmetric diurnal temperature-change. *Geophysical Research Letters* **18**: 2253–2256.

Lobell, D.B., Bonfils, C., and Duffy, P.B. 2007. Climate change uncertainty for daily minimum and maximum temperatures: a model inter-comparison. *Geophysical Research Letters* **34**: 10.1029/2006GL02872.

Melillo, J.M., Steudler, P.A., Aber, J.D., Newkirk, K., Lux, H., Bowles, F.P., Catricala, C., Magill, A., Ahrens, T., and Morrisseau, S. 2002. Soil warming and carbon-cycle feedbacks to the climate system. *Science* **298**: 2173–2176.

Schipper, L.A., Baisden, T., Parfitt, R.L., Ross, C., and Claydon, J.J. 2007. Large losses of soil C and N from soil profiles under pasture in New Zealand during the past 20 years. *Global Change Biology* **13**: 1138–1144.

Stone, D.A. and Weaver, A.J. 2002. Daily maximum and minimum temperature trends in a climate model. *Geophysical Research Letters* **29**: 10.1029/2001GL014556.

Vose, R.S., Easterling, D.R., and Gleason, B. 2005. Maximum and minimum temperature trends for the globe: an update through 2004. *Geophysical Research Letters* **32**: 10.1029/2005GL024379.

Wan, S., Xia, J., Liu, W., and Niu, S. 2009. Photosynthetic overcompensation under nocturnal warming enhances grassland carbon sequestration. *Ecology* **90**: 2700–2710.

Yang, Y., Fang, J., Ma, W., Smith, P., Mohammat, A., Wang, S., and Wang, W. 2010. Soil carbon stock and its changes in northern China's grasslands from 1980s to 2000s. *Global Change Biology* **16**: 3036–3047.

Zhou, L., Dickinson, R.E., Tian, Y., Vose, R.S., and Dai, Y. 2007. Impact of vegetation removal and soil aridation on diurnal temperature range in a semiarid region: application to the Sahel. *Proceedings of the National Academy of Sciences USA* **104**: 17,937–17,942.

7.7.3. Forests

Moving up from grasslands to forests—literally—Hoosbeek and Scarascia-Mugnozza (2009) report the final soil carbon sequestration results of the POP-EuroFACE experiment conducted on a poplar plantation established in early 1999 on former agricultural fields near Biterbo, Italy, where three control plots and three CO_2-enriched plots (to a target atmospheric concentration of 560 ppm) were each planted with equal-area sections of three *Populus* genotypes: *P. x euramericana* Dode (Guinier) genotype I-214, *P. nigra* L. (Jean Pourtet), and *P. alba* L. (genotype 2AS11). Their final analysis indicated over the course of the six-year study there was an additional mean carbon (C) sink of 32 g C m^{-2} $year^{-1}$ in the forest floor litter layer. In the case of the soil itself, they found over the first half of the experiment the increase in soil carbon was suppressed under FACE, but over the second half of the study they measured an additional mean sink of 54 g C m^{-2} $year^{-1}$ in the top 10 cm of the FACE treatment's mineral soil. This expanded sink was not statistically significant, however, because of a combination of high soil spatial variability and the low number of treatment replicates. Nevertheless, it suggested that if the experiment had been allowed to continue for a longer period of time, the difference likely would have become significant. Last, they report the amount of stabilized soil organic matter increased significantly under FACE. Thus, the two researchers conclude the forest floor as a whole "will serve as an additional carbon sink under future increased atmospheric CO_2 concentrations in poplar stands," which should help to mitigate further increases in the air's CO_2 content and whatever increase in global temperature might possibly cause to occur.

One year later, in the United States, Thomas et al. (2010) wrote, "human activities have greatly accelerated emissions of both carbon dioxide and biologically reactive nitrogen to the atmosphere," and "as nitrogen availability often limits forest productivity, it has long been expected that anthropogenic nitrogen deposition could stimulate carbon sequestration in forests." However, they noted spatially extensive evidence for this phenomenon "has been lacking," and they proceeded to provide some, using "spatially extensive forest inventory data to discern the effect of nitrogen deposition on the growth and survival of the 24 most common tree species of the northeastern and north-central US, as well as the effect of nitrogen deposition on carbon sequestration in trees across the breadth of the northeastern US."

They found "nitrogen deposition (which ranged from 3 to 11 kg ha^{-1} yr^{-1}) enhanced the growth of 11 species and decreased the growth of three species," while it "enhanced growth of all tree species with arbuscular mycorrhizal fungi associations," leading to "a 40% enhancement over pre-industrial conditions." This response "includes the direct effects of nitrogen deposition on tree growth through soil fertilization, foliar nitrogen uptake and other potential interactions between nitrogen deposition and other environmental changes, including CO_2 fertilization." To give some idea of the magnitude of this response, they state it "exceeds the 23% enhancement of net primary production anticipated for the year 2050 from a doubling of atmospheric CO_2 over preindustrial levels, as estimated using free-air CO_2 enrichment studies," citing in this regard Norby et al. (2005).

Thomas et al. thus conclude "nitrogen deposition is an important mechanism contributing to carbon sequestration within these temperate forests," but this phenomenon is still "unlikely to explain all of the observed terrestrial carbon sink." Nevertheless, it does go a long way toward doing so, and it demonstrates the major benefits of the concomitant increases in (1) the air's CO_2 content and (2) the air's temperature, with which (3) the increase in nitrogen deposition interacted over the course of the Industrial Revolution and its aftermath. Therefore, whereas the IPCC considers the increases in the air's CO_2 content and temperature to be two of the worst things ever to have happened to the biosphere, they clearly were not. And neither was the increase in anthropogenic nitrogen deposition, for all three of these phenomena interacted with each other in such a way as to greatly increase the productivity of the Earth's forests.

Finally, in a study of a process that is changing the face of much of the planet, Springsteen et al. (2010) write, "woody plant expansion within grassland ecosystems is a worldwide phenomenon, and dramatic vegetation shifts from grassland to savanna/woodlands have occurred over the past 50–100 years in North America." They note one of the chief factors that has contributed to this phenomenon is believed by many to have been the historical increase in the air's carbon dioxide concentration, as suggested by the studies of Archer et al. (1995), Polley (1997), Bond and Midgley (2000), and Bond et al. (2003). They also indicate that once shrublands are established, they tend to persist for several possible reasons, one of which is a type of feedback phenomenon referred to as islands of fertility, which "occurs when resources accumulate in soils beneath woody plants due to litterfall, interception of wet and dry deposition, nitrogen fixation, and animal droppings," as described by Schlesinger et al. (1990), Archer et al. (1995), Reynolds et al. (1999), and Lopez-Pintor et al. (2006). Springsteen et al. report in this regard, "changes in soil attributes under woody vegetation have been documented in the arid grasslands of the southern Great Plains, including increases in soil carbon and nitrogen," citing Reynolds et al. (1999), Hibbard et al. (2001, 2003), McCulley et al. (2004), Schade and Hobbie (2005), and Liao et al. (2006).

Considering these findings, while working at the USDA-ARS Northern Great Plains Research Laboratory near Mandan, North Dakota (USA), Springsteen et al. examined near-surface (upper 15 cm) soil biogeochemistry along a 42-year (1963–2005) chronosequence, which encompassed grassland, woodland, and grassland-woodland transition zones in a northern Great Plains grassland, to determine the influence of woody plant expansion on soil carbon and nitrogen contents. They report total soil carbon content rose by 26 percent across the chronosequence from grassland to woodland within the 0–15 cm soil depth, while total soil nitrogen content rose by 31 percent. And they observe the rate of woody shrub expansion from 1963 to 1988 (25 years) was ~1,800 m^2 per year at their study site, whereas from 1988 to 2005 (17 years) it was ~3,800 m^2 per year, just a little more than double the rate of the earlier period.

Therefore, as more experiments of this nature are conducted at more sites around the world, it is becoming increasingly evident that soil carbon sequestration driven by woody-plant invasions of grasslands (driven to a significant degree by the ongoing rise in the air's CO_2 content), as well as the increases in soil nitrogen content required to sustain them, are growing with the passage of time as the greening of the Earth continues.

References

Archer, S., Schimel, D.S., and Holland, E.A. 1995. Mechanisms of shrubland expansion: land use, climate or CO_2? *Climatic Change* **29**: 91–99.

Bond, W.J. and Midgley, G.F. 2000. A proposed CO_2-controlled mechanism of woody plant invasion in grasslands and savannas. *Global Change Biology* **6**: 865–869.

Bond, W.J., Midgley, G.F., and Woodward, F.I. 2003. The importance of low atmospheric CO_2 and fire in promoting the spread of grasslands and savannas. *Global Change Biology* **9**: 973–982.

Hibbard, K.A., Archer, S., Schimel, D.S., and Valentine, D.W. 2001. Biogeochemical changes accompanying woody plant encroachment in a subtropical savanna. *Ecology* **82**: 1999–2011.

Hibbard, K.A., Schimel, D.S., Archer, S., Ojima, D.S., and Parton, W. 2003. Grassland to woodland transitions: integrating changes in landscape structure and biogeochemistry. *Ecological Applications* **13**: 911–926.

Hoosbeek, M.R. and Scarascia-Mugnozza, G.E. 2009. Increased litter build up and soil organic matter stabilization in a poplar plantation after 6 years of atmospheric CO_2 enrichment (FACE): final results of POP-EuroFACE compared to other forest FACE experiments. *Ecosystems* **12**: 220–239.

Liao, J.D., Boutton, T.W., and Jastrow, J.D. 2006. Storage and dynamics of carbon and nitrogen in soil physical fractions following woody plant invasion of grassland. *Soil Biology and Biochemistry* **38**: 3184–3196.

Lopez-Pintor, A., Sal, A.G., and Benayas, J.M. R. 2006. Shrubs as a source of spatial heterogeneity—the case of *Retama sphaerocarpa* in Mediterranean pastures of central Spain. *Acta Oecologia* **29**: 247–255.

McCulley, R.L., Archer, S.R., Boutton, T.W., Hons, F.M., and Zuberer, D.A. 2004. Soil respiration and nutrient cycling in wooded communities developing in grassland. *Ecology* **85**: 2804–2817.

Norby, R.J., DeLucia, E.H., Gielen, B., Calfapietra, C., Giardina, C.P., King, S.J., Ledford, J., McCarthy, H.R., Moore, D.J.P., Ceulemans, R., De Angelis, P., Finzi, A.C., Karnosky, D.F., Kubiske, M.E., Lukac, M., Pregitzer, K.S., Scarasci-Mugnozza, G.E., Schlesinger, W.H., and Oren, R. 2005. Forest response to elevated CO_2 is conserved across a broad range of productivity. *Proceedings of the National Academy of Sciences* **102**: 18,052–18,056.

Polley, H.W. 1997. Implications of rising atmospheric carbon dioxide concentration for rangelands. *Journal of Range Management* **50**: 561–577.

Reynolds, J.F., Virginia, R.A., Kemp, P.R., de Soyza, A.G., and Tremmel, D.C. 1999. Impact of drought on desert shrubs: effects of seasonality and degree of resource island development. *Ecological Monographs* **69**: 69–106.

Schade, J.D. and Hobbie, S.E. 2005. Spatial and temporal variation in islands of fertility in the Sonoran Desert. *Biogeochemistry* **73**: 541–553.

Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jarrell, W.M., Ross, V.A., and Whitford, W.G. 1990. Biological feedbacks in global desertification. *Science* **247**: 1043–1048.

Springsteen, A., Loya, W., Liebig, M., and Hendrickson, J. 2010. Soil carbon and nitrogen across a chronosequence of woody plant expansion in North Dakota. *Plant and Soil* **328**: 369–379.

Thomas, R.Q., Canham, C.D., Weathers, K.C., and Goodale, C.L. 2010. Increased tree carbon storage in response to nitrogen deposition in the US. *Nature Geoscience* **3**: 13–17.

7.7.4. Tundra

It has been hypothesized that if—or when—the frozen soils of Earth's Northern High Latitudes (NHLs, land poleward of 60°N) begin to thaw in response to any new global warming that might occur, the metabolism of soil microbes will be accelerated and the decomposition of soil organic matter will speed up; and it has been further postulated that this, in turn, will lead to an increase in soil organic carbon release to the atmosphere that will amplify global warming.

On the other hand, satellite and phenology studies have shown that during the past several decades the planet's boreal forests have experienced greening and an increase in photosynthetic activity, which extracts carbon (in the form of CO_2) from the atmosphere.

To find some indication as to which of these two outcomes might likely predominate over the course of the twenty-first century, Qian et al. (2010) explored the potential magnitudes of the two competing sets of processes by analyzing the outputs of ten models that took part in the Coupled Carbon Cycle Climate Model Intercomparison Project (C4MIP) of the International Geosphere-Biosphere Program and the World Climate Research Program, all of which, in their words, "used the same anthropogenic fossil fuel emissions from Marland et al. (2005) from the beginning of the industrial period until 2000 and the IPCC SRES A2 scenario for the 2000–2100 period."

According to the three researchers, the ten C4MIP models predicted a mean warming of 5.6°C from 1901 to 2100 in the NHLs, and they state "the NHLs will be a carbon sink of 0.3 ± 0.3 $PgCyr^{-1}$ by 2100." They also state "the cumulative land organic carbon storage is modeled to increase by 38 ± 20 PgC over 1901 levels, of which 17 ± 8 PgC comes from vegetation [a 43 percent increase] and 21 ± 16 PgC from the soil [an 8 percent increase]," noting "both CO_2 fertilization and warming enhance vegetation growth in the NHLs." Consequently, over the course of the current century even the severe warming predicted by current climate models would likely not be a detriment to plant growth and productivity in the NHLs. In fact, it would likely be a benefit, enhancing plant growth and soil organic carbon storage, which (in addition to their own virtues) would provide a significant negative feedback to global warming.

As background for their study of the subject, Bao et al. (2010) write that peatland ecosystems "play a key role in the global carbon cycle and are influenced by global climate change," within which context the some researchers say the ongoing warming of the planet will lead to great releases of previously sequestered carbon to the atmosphere in the form of CO_2 and methane. This, they argue, will greatly exacerbate global warming, as was declared quite prominently and publicly to be a confirmed fact by former U.S. Vice President Al Gore in his 21 March 2007 testimony before the U.S. Senate's Environment and Public Works Committee. But, of course, he was wrong, as is clear from the work cited above and will be clear from the work cited below.

Working in the Changbai mountain region that runs along the boundary between China and North Korea, Bao et al. extracted eight peat cores they analyzed for numerous parameters, among which were those required to calculate the recent rate of carbon accumulation (RERCA) in the peatlands of that region over the past two centuries. The four researchers report "obvious increasing trends in RERCA were observed in all peat cores," as "organic carbon content declined from the top to the substrate." What is more, they state the temporal increase in RERCA in the upper regions of the cores—which likely corresponded to the warmest segment of their two-century study period—"changed to a much greater extent in recent decades than in the earlier period of peat formation."

Consequently, this study indicates that researchers who raise concerns over warming peatlands have got things 180 degrees out of phase with reality. Earth's peatlands provide a *negative* feedback to global warming, whereby when they warm, they extract more—not less—CO_2 from the atmosphere, applying a brake on rising temperatures.

Blok et al. (2010) likewise note there are "fears" that if Earth's permafrost thaws, "much of the carbon stored will be released to the atmosphere," as will great quantities of the greenhouse gas methane, further exacerbating warming, as has been claimed is already happening—and at an accelerating rate—by Michael Mann and Lee Kump (2008) in their *Dire Predictions* book. Quite to the contrary, however, Blok et al. state "it has been demonstrated that increases in air temperature sometimes lead to vegetation changes that offset the effect of air warming on soil temperature," citing the research of Walker et al. (2003) and Yi et al. (2007) as specific examples of this phenomenon.

Exploring the subject in real-world experimentation, Blok et al. conducted a study within the Kytalyk nature reserve in the Indigirka lowlands of northeastern Siberia (Russia), where they measured the thaw depth or active layer thickness (ALT) of the soil, the ground heat flux, and the net radiation in ten-meter-diameter plots either possessing or not possessing a natural cover of bog birch (*Betula nana*) shrubs, the latter of which set of plots had all *B. nana* shrubs removed from their native tundra vegetation in 2007.

The Dutch, Swiss, and Russian researchers state the "experimental *B. nana* removal had increased ALT significantly by an average of 9% at the end of the 2008 growing season, compared with the control plots," which implies reduced warming in the more shrub-dominated plots, and "in the undisturbed control plots with varying natural *B. nana* cover, ALT decreased with increasing *B. nana* cover," also "showing a negative correlation between *B. nana* cover and ALT," which again implies reduced warming in the more shrub-dominated plots.

Blok et al. state their results suggest "the expected expansion of deciduous shrubs in the Arctic region, triggered by climate warming, may reduce summer permafrost thaw," and the "increased shrub growth may thus partially offset further permafrost degradation by future temperature increases." In further support of their conclusion, the six scientists note (1) permafrost temperature records "do not show a general warming trend during the last decade (Brown and Romanovsky, 2008), despite large increases in surface air temperature," (2) during the decade before that, "data from several Siberian Arctic permafrost stations do not show a discernible trend between 1991 and 2000 (IPCC, 2007)," and (3) "a recent discovery of ancient permafrost that survived several warm geological periods suggests that vegetation cover may help protect permafrost from climate warming (Froese et al., 2008)." And finally, they note this phenomenon "could feedback negatively to global warming, because the lower soil temperatures in summer would slow down soil decomposition and thus the amount of carbon released to the atmosphere."

Zhuang et al. (2010) used a process-based biogeochemistry model—the Terrestrial Ecosystem Model or TEM, which also employed a soil thermal model—to examine permafrost dynamics and their effects on the carbon dynamics of the Tibetan Plateau over the past century. This was done by "parameterizing and verifying" the TEM using existing real-world data for soil temperature, permafrost distribution, and carbon and nitrogen distributions throughout the region, and then extrapolating the model and its parameters to the whole of the plateau. The six scientists found "during the 20th century, the Tibetan Plateau changed from a small carbon source or neutral in the early part of the century to a sink later," such that "net primary production and soil respiration increased by 0.52 and 0.22 Tg C/year, respectively, resulting in a regional carbon sink increase of 0.3 Tg C/year." Thus, "by the end of the century, the regional carbon sink reached 36 Tg C/year," and carbon storage in vegetation and soils was 32 and 16 Pg C, respectively.

In explaining their findings, Zhuang et al. state the "increasing soil temperature and deepening active layer depth enhanced soil respiration, increasing the net nitrogen mineralization rate," and "together with the [positive] effects of warming air temperature and rising CO_2 concentrations on photosynthesis, the stronger plant nitrogen uptake due to the enhanced available nitrogen stimulate[d] plant carbon uptake, thereby strengthening the regional carbon sink as the rate of increase in net primary production was faster than that of soil respiration." Thus, they state their study implies "future warming will increase thawing of the permafrost, increase soil temperature and dry up soil moisture," and "these physical dynamics may enhance [the] future strength of the regional carbon sink, since the rate of increase of net primary production is higher than that of soil respiration on the Tibetan Plateau."

References

Bao, K., Yu, X., Jia, L., and Wang, G. 2010. Recent carbon accumulation in Changbai Mountain peatlands, northeast China. *Mountain Research and Development* **30**: 33–41.

Blok, D., Heijmans, M.M.P.D., Schaepman-Strub, G., Kononov, A.V., Maximov, T.C., and Berendse, F. 2010. Shrub expansion may reduce summer permafrost thaw in Siberian tundra. *Global Change Biology* **16**: 1296–1305.

Brown, J. and Romanovsky, V.E. 2008. Report from the International Permafrost Association: state of permafrost in the first decade of the 21st century. *Permafrost and Periglacial Processes* **19**: 255–260.

Froese, D.G., Westgate, J.A., Reyes, A.V., Enkin, R.J., and Preece, S.J. 2008. Ancient permafrost and a future, warmer Arctic. *Science* **321**: 1648.

IPCC. 2007. In *Intergovernmental Panel on Climate Change. Fourth Assessment Report: Working Group I Report "The Physical Science Basis,"* edited by S. Solomon, et al. Cambridge, UK: Cambridge University Press.

Mann, M.E. and Kump, L.R. 2008. *Dire Predictions: Understand Global Warming.* New York, NY: DK Publishing Inc.

Marland, G., Boden, T.A., and Andres, R.J. 2005. Global, regional, and national CO_2 emissions. In *Trends: A Compendium of Data on Global Change.* Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy. Available at http://cdiac.ornl.gov/trends/emis/overview.html.

Qian, H., Joseph, R., and Zeng, N. 2010. Enhanced terrestrial carbon uptake in the Northern High Latitudes in the 21st century from the Coupled Carbon Cycle Climate Model Intercomparison Project model projections. *Global Change Biology* **16**: 641–656.

Walker, D.A., Jia, G.J., Epstein, H.E., Raynolds, M.K., Chapin III, F.S., Copass, C., Hinzman, L.D., Knudson, J.A., Maier, H.A., Michaelson, G.J., Nelson, F., Ping, C.L., Romanovsky, V.E., and Shiklomanov, N. 2003. Vegetation-soil-thaw-depth relationships along a low-arctic bioclimate gradient, Alaska: synthesis of information from the ATLAS studies. *Permafrost and Periglacial Processes* **14**: 103–123.

Yi, S., Woo, M., and Arain, M.A. 2007. Impacts of peat and vegetation on permafrost degradation under climate warming. *Geophysical Research Letters* **34**: 10.1029/2007GL030550.

Zhuang, Q., He, J., Lu, Y., Ji, L., Xiao, J., and Luo, T. 2010. Carbon dynamics of terrestrial ecosystems on the Tibetan Plateau during the twentieth century: an analysis with a process-based biogeochemical model. *Global Ecology and Biogeography* **19**: 649–662.

7.7.5. Urban Areas

Working in Europe, Trusilova and Churkina (2008) analyzed carbon sink dynamics driven by urbanization-induced changes in land use, climate, atmospheric CO_2 concentration, and nitrogen deposition. They used the BIOME-BGC terrestrial ecosystem model to calculate responses of the local biosphere to these several "urban changes" applied individually and together. Some examples of the four classes of urban-induced environmental changes considered in this approach are (1) for land use, pristine soils and their associated vegetation being replaced by buildings, roads, parking lots, etc.; (2) for climate, increases in temperature due to the urban heat island phenomenon, together with associated changes in local precipitation; (3) for atmospheric CO_2 concentration, increases in the air's CO_2 content from vehicle exhaust and other combustion processes that produce the urban CO_2 dome phenomenon; and (4) for nitrogen deposition, many of the same processes that simultaneously release nitrogen to the air.

Trusilova and Churkina found "fertilization effects from the elevated CO_2 and atmospheric nitrogen deposition made the strongest positive contributions to the carbon uptake (0.023 PgC per year and 0.039 PgC per year, respectively), whereas the impervious urban land and local urban meteorological conditions resulted in a reduction of carbon uptake (-0.005 PgC per year and -0.007 PgC per year, respectively)." The synergetic effect of the four urbanization-induced changes, however, "was an increase of the carbon sequestration in Europe of 0.058 PgC per year," a result greater than the algebraic sum of the four individual components of the carbon sequestration equation. This amplification of the two positive responses (which manifests itself when the two phenomena occur in unison) happens because "atmospheric CO_2 and soil nitrogen availability co-limit [the] productivity of land ecosystems," as the two researchers describe it, so that if more nitrogen becomes available to plants, the aerial fertilization effect of the elevated CO_2 concentration is generally magnified. Another reason for the dominance of the CO_2- and nitrogen-induced phenomena is that "the land use and urban climate changes affect rather small land areas while the urban CO_2 and nitrogen pollution spread over larger areas."

When all is said and done, therefore, it is clear—although perhaps not intuitively so—that the urbanization process actually leads to an amplification of carbon sequestration in the vegetation and soils of urban ecosystems, which in the words of Trusilova and Churkina has "led to a net increase of [the] carbon sink in Europe."

Reference

Trusilova, K. and Churkina, G. 2008. The response of the terrestrial biosphere to urbanization: land cover conversion, climate, and urban pollution. *Biogeosciences* **5**: 1505–1515.

7.7.6. Entire Earth

Gloor et al. (2010) note the ratio of CO_2 accumulating in the atmosphere to the CO_2 flux into the atmosphere due to human activities—which is known as the airborne fraction (AF)—is central to predicting changes in Earth's surface temperature due to greenhouse gas-induced warming, and they note this ratio has remained remarkably constant over the past five decades. However, they report Canadell et al. (2007) and Raupach et al. (2008) claim to have detected a long-term increasing trend in the airborne fraction, which they interpret as being indicative of "a decreasing trend in the efficiency of the ocean and land carbon sinks."

Gloor et al. note Knorr (2009) already had challenged Canadell et al. and Raupach et al. over their detection of a positive AF trend, "arguing that given the noise in the data, the trend is not detectable." Thus, they challenged the second claim of Canadell et al. and Raupach et al., that a positive AF trend is indicative of a decreasing planetary carbon sink efficiency, by investigating "the question of what controls trends and decadal scale variations in CO_2 airborne fraction using simple linear models describing the evolution of an atmospheric perturbation in CO_2."

The three researchers determined, first of all, that there is no one-to-one association between positive trends in CO_2 flux to the atmosphere (due to fossil fuel emissions and changes in land use) and negative trends in Earth's carbon sink efficiency. Second, they found that in order to detect trends in sink efficiencies from the time course of fossil fuel-derived CO_2 emissions and temporal changes in land use, "it is necessary to disentangle the spin-up time and fossil fuel growth rate variation signatures in the airborne fraction from signatures due to other causes."

And when they make the pertinent calculations for fossil-fuel and land-use changes, they state they "do indeed find a positive trend in the residuals," but they argue this trend "is not statistically significant after correcting for known events such as the temporal distribution of the extrinsic forcings and likely omissions in the emissions (particularly from land-use change)." They further note their analysis suggests "trends in airborne fraction are not a very good diagnostic to detect changes in carbon sink efficiency because variations in the signal are complex and the signal-to-noise ratio is small."

Thus Gloor et al. conclude "atmospheric data, if analyzed adequately, do not yet reveal a statistically significant signal," which suggests it's too soon to say whether the carbon sink efficiency of the Earth is increasing, decreasing, or remaining relatively constant.

References

Canadell, J.G., Le Quere, C., Raupach, M.R., Field, C.B., Buitenhuis, E.T., Ciais, P., Conway, T.J., Gillett, N.P., Houghton, R., and Marland, G. 2007. Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the National Academy of Sciences USA* **104**: 18,866–18,870.

Gloor, M., Sarmiento, J.L. and Gruber, N. 2010. What can be learned about carbon cycle climate feedbacks from the CO_2 airborne fraction? *Atmospheric Chemistry and Physics* **10**: 7739-7751.

Knorr, W. 2009. Is the airborne fraction of anthropogenic CO_2 emissions increasing? *Geophysical Research Letters* **36**: 10.1029/2009GL040613.

Raupach, M.R., Canadell, J.G. and Le Quere, C. 2008. Anthropogenic and biophysical contributions to increasing atmospheric CO_2 growth rate and airborne fraction. *Biogeosciences* **5**: 1601-1613.

7.8. Extinction

Scherrer and Korner (2010) write, "climate warming scenarios predict higher than average warming in most alpine areas," and therefore, they state, "alpine regions are often considered as particularly threatened." In testimony presented to the Select Committee on Energy Independence and Global Warming of the United States House of Representatives on 26 April 2007, NASA's James Hansen declared life in alpine regions is in danger of being "pushed off the planet" as the Earth warms, since it has "no place else to go."

In a study designed to test this contention, Scherrer and Korner employed thermal imagery and microloggers to assess the fine-scale detail of both surface and root zone temperatures in three temperate-alpine and subarctic-alpine regions: one in the Swiss Alps, one in Northern Sweden, and one in Northern Norway. All of these sites were located on steep mountain slopes above the climatic tree line that exhibited a rich microtopography but no significant change in macroexposure. The two Swiss scientists report observing, "microclimatic variation on clear sky days was strong within all slopes, with 8.4 ± 2.5°C (mean ± SD) surface temperature differences persisting over several hours per day along horizontal (i.e., equal elevation) transects." These differences, as they describe them, "are larger than the temperature change predicted by the IPCC."

These findings, in the words of Scherrer and Korner, are "important in the context of climate change" because they show "species do not necessarily need to climb several hundred meters in elevation to escape the warmth." Quite often, in fact, a "few meters of horizontal shift will do," so that for plants "unable or too slow to adapt to a warmer climate, thermal microhabitat mosaics offer both refuge habitats as well as stepping stones as atmospheric temperatures rise." Discussing the greater implications of their results, the Swiss scientists state their data "challenge the stereotype of particularly sensitive and vulnerable alpine biota with respect to climatic warming," noting "high elevation terrain may in fact be more suitable to protect biodiversity under changing climatic conditions than most other, lower elevation types of landscapes." Thus, in what would appear to be a bit of good advice to all—and James Hansen in particular—the two researchers state they "advocate a more cautious treatment of this matter."

In another report on the status of alpine communities, this one in the Swedish Scandes, Kullman (2010) writes, "alpine plant life is proliferating, biodiversity is on the rise, and the mountain world appears more productive and inviting than ever," which is about as far from being "pushed off the planet" as one could imagine. The professor of physical geography at Sweden's Umea University states this particular course of biotic landscape evolution "has reached historical dimensions and broken a multi-millennial trend of plant cover retrogression, alpine tundra expansion, floristic and faunal impoverishment, all imposed by progressive and deterministic neoglacial climate cooling." And he concludes "continued modest warming over the present century will likely be beneficial to alpine biodiversity, geoecological stability, resilience, sustainable reindeer husbandry and aesthetic landscape qualities." He came to these conclusions, he writes, via "an integrative review of results from long-term monitoring of subalpine/alpine vegetation."

Enlarging on some of these positive warming-induced impacts, Kullman writes, "plant species diversity will further increase, both in remaining treeless alpine areas and emerging forest outliers on the former alpine tundra," and this "new alpine landscape may come to support a previously unseen mosaic of richly flowering and luxuriant plant communities of early Holocene character," citing the works of Smith (1920), Iversen (1973), and Birks (2008). In describing what already has been documented, he states, "in contrast to model predictions, no single alpine plant species has become extinct, neither in Scandinavia nor in any other part of the world, in response to climate warming over the past century," citing the studies of Pauli et al. (2001, 2007), Theurillat and Guisan (2001), and Birks (2008).

Tracing the evidence to the source of all these warming-induced ecological benefits, Kullman writes, "many alpine species are extremely tolerant of high temperatures per se," citing Dahl (1998) and Birks (2008), as indicated "by their prospering and spread along roadsides far below the treeline, where emerging trees and shrubs are regularly mechanically exterminated (Kullman, 2006; Westerstrom, 2008)." He notes "another argument against the much-discussed option of pending mass-extinction of alpine species in a warmer future is that some alpine and arctic plant species contain a variety of ecotypes, pre-adapted to quite variable microclimatic and edaphic conditions, which could buffer against extinction in a possibly warmer future (Crawford, 2008)." In addition, he writes, this view is supported "by the fact that in the early Holocene, alpine plants survived, reproduced and spread in accordance with higher and more rapidly rising temperatures than those projected for the future by climate models (Oldfield, 2005; Birks, 2008)."

Kullman observes the "extended ranges of many flowering species and increasing plant species richness and habitat diversity imply a highly variable and aesthetically appealing mountain landscape, which should be positive from a nature conservation point of view (Jurasinski and Kreyling, 2007)." In fact, he states "such a course of landscape evolution adds to physical and ecological stability, functional efficiency, resilience and assures against 'system failure'," citing McCann (2000), Korner (2002), and McLaren (2006). Therefore, as Kullman concludes, "continued warming throughout the present century would be potentially and predominantly advantageous for alpine flora and vegetation."

In a very different type of study, Willis et al. (2010) identified past historical periods in which climate was either similar to that projected by global climate models for the next century or so, or in which the rate of temperature change was unusually rapid. They examined these real-world periods to see if any real-world climate-related extinctions occurred.

The first period they examined was the Eocene Climatic Optimum (53–51 million years ago), when the atmosphere's CO_2 concentration exceeded 1,200 ppm and tropical temperatures were 5–10°C warmer than modern values. Yet far from causing extinctions of the tropical flora (where the data are best), the four researchers report "all the evidence from low-latitude records indicates that, at least in the plant fossil record, this was one of the most biodiverse intervals of time in the Neotropics." They also note "ancestors of many of our modern tropical and temperate plants evolved ...when global temperatures and CO_2 were much higher than present ... indicating that they have much wider ecological tolerances than are predicted based on present-day climates alone."

The second period they examined included two rapid-change climatic events in the Holocene—one at 14,700 years ago and one at 11,600 years ago—when temperatures increased in the mid- to high-latitudes of the Northern Hemisphere by up to 10°C over periods of less than 60 years. There is evidence from many sites for rapid plant responses to rapid warming during these events. The researchers note "at no site yet studied, anywhere in the world, is there evidence in the fossil record for large-scale climate-driven extinction during these intervals of rapid warming." On the other hand, they report extinctions did occur due to the cold temperatures of the glacial epoch, when subtropical species in southern Europe were driven out of their comfort zone.

The Willis et al. study also makes use of recent historical data, as in the case of the 3°C rise in temperature at Yosemite Park over the past 100 years. In comparing surveys of mammal fauna conducted near the beginning and end of this period, they detected some changes but no local extinctions. Thus they determined that for all of the periods they studied, with either very warm temperatures or very rapid warming, there were no detectable species extinctions.

In a study that may help explain how some researchers could have gotten things so wrong in predicting massive extinctions of both plants and animals in response to projected future warming, Nogues-Bravo (2009) explains the climate envelope models (CEMs)—often employed to predict species responses to global warming (and whether or not a species will be able to survive projected temperature increases)—"are sensitive to theoretical assumptions, to model classes and to projections in non-analogous climates, among other issues." To determine how appropriate these models are for determining whether a particular species will be driven to extinction by hypothesized planetary warming, Nogues-Bravo reviewed the scientific literature pertaining to the subject and found several flaws. Nogues-Bravo writes, "the studies reviewed: (1) rarely test the theoretical assumptions behind niche modeling such as the stability of species climatic niches through time and the equilibrium of species with climate; (2) they only use one model class (72% of the studies) and one palaeoclimatic reconstruction (62.5%) to calibrate their models; (3) they do not check for the occurrence of non-analogous climates (97%); and (4) they do not use independent data to validate the models (72%)." Nogues-Bravo writes, "ignoring the theoretical assumptions behind niche modeling and using inadequate methods for hindcasting" can produce "a cascade of errors and naïve ecological and evolutionary inferences." Hence, he concludes, "there are a wide variety of challenges that CEMs must overcome in order to improve the reliability of their predictions through time." Until these challenges are met, contentions of impending species extinctions must be considered little more than guesswork (see also Chapman, 2010).

Employing yet another way of assessing the potential for plants to avoid extinction in a warming world, De Frenne et al. (2010) collected seeds of *Anemone nemorosa* L.—a model species for slow-colonizing herbaceous forest plants—found in populations growing along a 2,400-km latitudinal gradient stretching from northern France to northern Sweden during three separate growing seasons (2005, 2006, and 2008). They then conducted sowing trials in incubators, in a greenhouse, and under field conditions in a forest, where they measured the effects of different temperature treatments (growing degree hours or GDHs) on various seed and seedling traits.

The 19 researchers—from Belgium, Estonia, France, Germany, and Sweden—determined "seed mass, germination percentage, germinable seed output and seedling mass all showed a positive response to increased GDHs experienced by the parent plant," noting seed and seedling mass increased by 9.7 percent and 10.4 percent, respectively, for every 1,000 °C-hours increase in GDHs, which they say is equivalent to a 1°C increase in temperature over a 42-day period. Therefore, they conclude, "if climate warms, this will have a pronounced positive impact on the reproduction of *A. nemorosa*, especially in terms of seed mass, germination percentage and seedling mass," because "if more seeds germinate and resulting seedlings show higher fitness, more individuals may be recruited to the adult stage." In addition, since "rhizome growth also is likely to benefit from higher winter temperatures (Philipp and Petersen, 2007), it can be hypothesized that the migration potential of *A. nemorosa* may increase as the climate in NW-Europe becomes warmer in the coming decades."

And, we would add, increasing migration potential implies a decreasing chance of extinction.

References

Birks, H.H. 2008. The late-quaternary history of arctic and alpine plants. *Plant Ecology and Diversity* **1**: 135–146.

Chapman, D.S. 2010. Weak climatic associations among British plant distributions. *Global Ecology and Biogeography* **19**: 831–841.

Crawford, R.M.M. 2008. Cold climate plants in a warmer world. *Plant Ecology and Diversity* **1**: 285–297.

Dahl, E. 1998. *The Phytogeography of Northern Europe.* Cambirdge, UK: Cambridge University Press.

De Frenne, P., Graae, J.J., Kolb, A., Brunet, J., Chabrerie, O., Cousins, S.A.O., Decocq, G., Dhondt, R., Diekmann, M., Eriksson, O., Heinken, T., Hermy, M., Jogar, U., Saguez, R., Shevtsova, A., Stanton, S., Zindel, R., Zobel, M.. and Verheyen, K. 2010. Significant effects of temperature on the reproductive output of the forest herb *Anemone nemorosa* L. *Forest Ecology and Management* **259**: 809–817.

Iversen, J. 1973. The development of Denmark's nature since the last glacial. *Danmarks Geologiske Undersogelse Series V. Raeeke* **7-C**: 1–126.

Jurasinski, G. and Kreyling, J. 2007. Upward shift of alpine plants increases floristic similarity of mountain summits. *Journal of Vegetation Science* **18**: 711–718.

Korner, C. 2002. Mountain biodiversity, its causes and function: an overview. In *Mountain Biodiversity, a Global Assessment*, edited by C. Korner and E.M. Spehn, 3–20. Boca Raton, FL: The Parthenon Publishing Group.

Kullman, L. 2006. Transformation of alpine and subalpine vegetation in a potentially warmer future, the Anthropocene era. Tentative projections based on a long-term observations and paleovegetation records. *Current Trends in Ecology* **1**: 1–16.

Kullman, L. 2010. A richer, greener and smaller alpine world: review and projection of warming-induced plant cover change in the Swedish Scandes. *Ambio* **39**: 159–169.

McCann, K.S. 2000. The diversity-stability debate. *Nature* **405**: 228–233.

McLaren, J.R. 2006. Effects of plant functional groups on vegetation dynamics and ecosystems properties. *Arctic* **59**: 449–452.

Nogues-Bravo, D. 2009. Predicting the past distribution of species climatic niches. *Global Ecology and Biogeography* **18**: 521–531.

Oldfield, F. 2005. Environmental Change. Key Issues and Alternative Perspectives. Cambridge , UK: Cambridge University Press.

Pauli, H., Gottfried, M., and Grabherr, G. 2001. High summits of the Alps in a changing climate. In *Fingerprints of Climate Change*, edited by G.-R. Walther, C.A. Burga, and P.J. Edwards, 139–149. New York, NY: Kluwer.

Pauli, H., Gottfried, M., Reiter, K., Klettner, C., and Grabherr, G. 2007. Signals of range expansions and contractions of vascular plants in the high Alps: observations (1994–2004) at the GLORIA master site Schrankogel, Tyrol, Austria. *Global Change Biology* **13**: 147–156.

Philipp, M. and Petersen, P.M. 2007. Long-term study of dry matter allocation and rhizome growth in *Anemone nemorosa*. *Plant Species Biology* **22**: 23–31.

Scherrer, D. and Korner, C. 2010. Infra-red thermometry of alpine landscapes challenges climatic warming projections. *Global Change Biology* **16**: 2602–2613.

Smith, H. 1920. *Vegetationen och dess Utvecklingshistoria i det Centralsvenska Hogfjallsomradet*. Uppsala, Sweden: Almqvist och Wiksell.

Theurillat, J.-P. and Guisan, A. 2001. Potential impacts of climate change on vegetation in the European Alps: a review. *Climatic Change* **50**: 77–109.

Westerstrom, G. 2008. Floran i tre socknar i nordvastra Angermanland. *Svensk Botanisk Tidskrift* **102**: 225–261.

Willis, K.J., Bennett, K.D., Bhagwat, S.A., and Birks, H.J.B. 2010. Perspective: 4 deg C and beyond: what did this mean for biodiversity in the past? *Systematics and Biodiversity* **8**: 3–9.

7.9. Evolution

One of the most powerful means plant and animal species have for avoiding extinction during climate change is the ability to evolve in ways that enable them to deal with the change. Several studies have demonstrated the abilities of numerous plants and animals to do just that.

Working in the Swiss Alps, Stocklin et al. (2009) studied the consequences of the highly structured alpine landscape for evolutionary processes in four different plants (*Epilobium fleischeri*, *Geum reptans*, *Campanula thyrsoides*, and *Poa alpina*), testing for whether genetic diversity within their populations was related to altitude and land use, while seeking to determine whether genetic differentiation among populations was related more to different land use or to geographic distances. In pursuit of these goals, the three Swiss scientists determined that within-population genetic diversity of the four species was high and mostly not related to altitude and population size, while genetic differentiation among populations was pronounced and strongly increased with distance, implying "considerable genetic drift among populations of alpine plants."

Based on these findings and the observations of others, Stocklin et al. write, "phenotypic plasticity is particularly pronounced in alpine plants," and "because of the high heterogeneity of the alpine landscape, the pronounced capacity of a single genotype to exhibit variable phenotypes is a clear advantage for the persistence and survival of alpine plants." Hence they conclude, "the evolutionary potential to respond to global change is mostly intact in alpine plants, even at high altitude." This result makes it much easier to understand why—even in the face of significant twentieth-century global warming—no species of plants have been observed to have been "pushed off the planet" in alpine regions. This has been shown to be the case in several pertinent studies, including Walther et al. (2005), Kullman (2007), Holzinger et al. (2008), Randin et al. (2009), and Erschbamer et al. (2009).

Describing another approach to the subject, Franks and Weis (2009) note a "rigorous way to determine if evolution has occurred in a natural population is to collect propagules before and after an environmental change and raise them under common conditions." They state "this approach was used previously to show that *Brassica rapa* [a self-incompatible weedy winter annual] evolved drought escape through earlier flowering following a series of recent dry years in Southern California, and that early flowering results in higher fitness under drought conditions (Franks et al., 2007)." They also note "a related study showed that multiple phenological traits and their interactions evolved in response to the drought (Franks and Weis, 2008)."

Working with the same pre- and post-drought collection lines from their earlier experiment (Franks et al., 2007), the two researchers estimated the amount of assortative mating within, and the degree of phenological isolation between, two *B. rapa* populations. Their results indicated "climate change can alter plant phenology, which can change patterns of assortative mating within populations," and "this assortative mating can directly change genotype frequencies and can also increase the rate of evolution by interacting with selection." In addition, they demonstrated "climatically driven changes in phenology can potentially influence gene flow among populations due to changes in overlap in flowering schedules," and "these changes in gene flow can also influence both the rate and pattern of evolutionary change."

Given these findings, the two scientists conclude "the high degree of interdependence of flowering time, assortative mating, selection and gene flow make predicting evolutionary responses to changes in climate particularly complex and challenging." This great degree of complexity suggests that among the multiplicity of outcomes, there is a good chance one or more will be just what the plants need to respond successfully to the climate change that elicited the outcomes.

Finally, Kuparinen et al. (2010) note "climate change is predicted to increase average air surface temperatures by several degrees in this century," and "species exposed to changes in the environmental conditions may first show plastic phenotypic responses (e.g. Rehfeldt et al., 2002); but, in the long term, rapid climate change raises the question how quickly species can evolutionarily adapt to future climates in their habitats." Against this backdrop, therefore, the authors investigated "the adaptation of Scots pine (*Pinus sylvestris*) and Silver birch (*Betula pendula*) to climate change induced prolongation of the thermal growing season," using "quantitative genetic individual-based simulations to disentangle the relative roles of mortality, dispersal ability and maturation age for the speed of adaptation."

The three scientists state their simulations predict "after 100 years of climate change, the genotypic growth period length of both species will lag more than 50% behind the climatically determined optimum," but "this lag is reduced by increased mortality of established trees," in conformity with the prior suggestion of Savolainen et al. (2004) and Kramer et al. (2008) that "the persistence of maladapted old trees preventing the establishment of seedlings better adapted to a changed environment" is not helpful to their long-term survival.

In addition, and in light of the fact that Kuparinen et al.'s findings suggest, as they put it, "adaptation might be sped up if mortality factors such as storms, fires, or insect outbreaks get more common in the future," it could actually turn out to be a positive thing—in this particular instance, at least, and for these specific species—if some of the envisioned negative consequences of global warming were ever to become a reality.

References

Erschbamer, B., Kiebacher, T., Mallaun, M., and Unterluggauer, P. 2009. Short-term signals of climate change along an altitudinal gradient in the South Alps. *Plant Ecology* **202**: 79–89.

Franks, S.J., Sim, S., and Weis, A.E. 2007. Rapid evolution of flowering time by an annual plant in response to a climate fluctuation. *Proceedings of the National Academy of Sciences USA* **104**: 1278–1282.

Franks, S.J. and Weis, A.E. 2008. A change in climate causes rapid evolution of multiple life-history traits and their interactions in an annual plant. *Journal of Evolutionary Biology* **21**: 1321–1334.

Franks, S.J. and Weis, A.E. 2009. Climate change alters reproductive isolation and potential gene flow in an annual plant. *Evolutionary Applications* **2**: 481–488.

Holzinger, B., Hulber, K., Camenisch, M., and Grabherr, G. 2008. Changes in plant species richness over the last century in the eastern Swiss Alps: elevational gradient, bedrock effects and migration rates. *Plant Ecology* **195**: 179–196.

Kramer, K., Bulteveld, J., Forstreuter, M., Geburek, T., Leonardi, S., Menozzi, P., Povillon, F., Scherlhaas, M.J., Teissier du Cros, E., Vendramin, G.G., and van der Werf, D.C. 2008. Bridging the gap between ecophysiological and genetic knowledge to assess the adaptive potential of European beech. *Ecological Modelling* **216**: 333–353.

Kullman, L. 2007. Long-term geobotanical observations of climate change impacts in the Scandes of West-Central Sweden. *Nordic Journal of Botany* **24**: 445–467.

Kuparinen, A., Savolainen, O., and Schurr, F.M. 2010. Increased mortality can promote evolutionary adaptation of forest trees to climate change. *Forest Ecology and Management* **259**: 1003–1008.

Randin, C.F., Engler, R., Normand, S., Zappa, M., Zimmermann, N.E., Pearman, P.B., Vittoz, P., Thuiller, W., and Guisan, A. 2009. Climate change and plant distribution: local models predict high-elevation persistence. *Global Change Biology* **15**: 1557–1569.

Rehfeldt, G.R., Tchebakova, N.M., Parfenova, Y.I., Wykoff, W.R., Kuzmina, N.A., and Milyutin, L.I. 2002. Intraspecific responses to climate change in *Pinus sylvestris*. *Global Change Biology* **8**: 912–929.

Savolainen, O., Bokma, F., Garcia-Gil, R., Komulainen, P., and Repo, T. 2004. Genetic variation in cessation of growth and frost hardiness and consequences for adaptation of *Pinus sylvestris* to climatic changes. *Forest Ecology and Management* **197**: 79–89.

Stocklin, J., Kuss, P., and Pluess, A.R. 2009. Genetic diversity, phenotypic variation and local adaptation in the alpine landscape: case studies with alpine plant species. *Botanica Helvetica* **119**: 125–133.

Walther, G.-R., Beissner, S., and Burga, C.A. 2005. Trends in the upward shift of alpine plants. *Journal of Vegetation Science* **16**: 541–548.

7.10. Food Production

7.10.1. Meeting Global Food and Water Needs

Several years ago, Waggoner (1995) rhetorically asked: How much land can ten billion people spare for nature? That was the title of an essay he wrote to illuminate the dynamic tension between the need for land to support the agricultural enterprises that sustain mankind and the need for land to support the natural ecosystems that sustain all other creatures. As noted by Huang et al. (2002), human populations "have encroached on almost all of the world's frontiers, leaving little new land that is cultivatable." And in consequence of humanity's ongoing usurpation of this most basic of natural resources, Raven (2002) has noted "species-area relationships, taken worldwide in relation to habitat destruction, lead to projections of the loss of fully two-thirds of all species on earth by the end of this century." In addition, Wallace (2000) has calculated we will need to divert essentially all usable non-saline water on the face of the Earth to the agricultural enterprises that will be required to meet the food and fiber needs of humanity's growing numbers well before that.

So what parts of the world are likely to be hit hardest by the great land-grabbing and water-consuming machine of humanity? Tilman et al. (2001) report developed countries are expected to withdraw large areas of land from farming between now and the middle of the century (2050), leaving developing countries to shoulder essentially all of the growing burden of feeding our expanding population. In addition, they calculate the loss of these countries' natural ecosystems to crops and pasture represent about half of all potentially suitable remaining land, which "could lead to the loss of about a third of remaining tropical and temperate forests, savannas, and grasslands," along with the many unique species they support.

If one were to pick the most significant problem currently facing the biosphere, this would probably be it: a single species of life, *Homo sapiens*, is on course to annihilate two-thirds of the ten million or so other species with which we share the planet within the next several decades, simply by taking their land and water. Global warming, by comparison, pales in significance, as its impact is nowhere near as severe and in fact may be neutral or even positive. In addition, its chief cause is highly debated, and actions to thwart it are much more difficult, if not impossible, to define and implement. Furthermore, what many people believe to be the main cause of global warming—anthropogenic CO_2 emissions—may actually be a powerful force for preserving land and water for nature.

In an analysis of the problem of human land-use expansion, Tilman et al. (2002) introduced a few more facts before suggesting some solutions. They noted, for example, that by 2050 the human population of the globe is projected to be 50 percent larger than it was in 2000, and that global grain demand could double because of expected increases in per-capita real income and dietary shifts toward a higher proportion of meat. Hence, they stated the obvious when they concluded, "raising yields on existing farmland is essential for 'saving land for nature'."

So how is it to be done? Tilman et al. (2002) suggested a strategy built around three essential tasks: (1) increasing crop yield per unit land area, (2) increasing crop yield per unit of nutrients applied, and (3) increasing crop yield per unit of water used.

Regarding the first of these requirements, Tilman et al. note that in many parts of the world the historical rate of increase in crop yields is declining, as the genetic ceiling for maximal yield potential is being approached. This observation, in their words, "highlights the need for efforts to steadily increase the yield potential ceiling." With respect to the second requirement, they indicate, "without the use of synthetic fertilizers, world food production could not have increased at the rate it did [in the past] and more natural ecosystems would have been converted to agriculture." Hence, they state the solution "will require significant increases in nutrient use efficiency, that is, in cereal production per unit of added nitrogen, phosphorus," and so forth. Finally, as to the third requirement, Tilman et al. remind us "water is regionally scarce," and "many countries in a band from China through India and Pakistan, and the Middle East to North Africa either currently or will soon fail to have adequate water to maintain per capita food production from irrigated land." Increasing crop water use efficiency, therefore, is also a must.

Although the impending biological crisis and several important elements of its potential solution are thus well defined, Tilman et al. (2001) noted "even the best available technologies, fully deployed, cannot prevent many of the forecasted problems." This was also the conclusion of Idso and Idso (2000), who stated that although "expected advances in agricultural technology and expertise will significantly increase the food production potential of many countries and regions," these advances "will not increase production fast enough to meet the demands of the even faster-growing human population of the planet."

Fortunately, we have a powerful ally in the ongoing rise in the air's CO_2 content that can provide what we can't. Since atmospheric CO_2 is the basic "food" of essentially all plants, the more of it there is in the air, the bigger and better they grow. For a nominal doubling of the air's CO_2 concentration, for example, the productivity of Earth's herbaceous plants rises by 30 to 50 percent (Kimball, 1983; Idso and Idso, 1994), and the productivity of its woody plants rises by 50 to 80 percent or more (Saxe et al. 1998; Idso and Kimball, 2001). Hence, as the air's CO_2 content continues to rise, the land use efficiency of the planet will rise right along with it. In addition, atmospheric CO_2 enrichment typically increases plant nutrient use efficiency and plant water use efficiency. Thus, with respect to all three of the major needs identified by Tilman et al. (2002), increases in the air's CO_2 content pay huge dividends, helping to increase agricultural output without the taking of new land and water from nature.

Many other researchers have broached this subject. In a paper recently published in the *Annual Review of Plant Biology*, three scientists associated with the Institute of Genomic Biology at the University of Illinois at Urbana-Champaign (USA) write that meeting the global increase in agricultural demand during this century "is predicted to require a doubling of global production," but "the world has limited capacity to sustainably expand cropland," and this capacity is actually "shrinking in many developed countries." Thus, Zhu et al. (2010) state, "meeting future increases in demand will have to come from a near doubling of productivity on a land area basis," and they conclude "a large contribution will have to come from improved photosynthetic conversion efficiency," estimating "at least a 50% improvement will be required to double global production."

The researchers' reason for focusing on photosynthetic conversion efficiency derives from the experimentally observed facts that increases in the atmosphere's CO_2 concentration increase the photosynthetic rates of nearly all plants, and those rate increases generally lead to equivalent—or only slightly smaller—increases in plant productivity on a land area basis. That provides a solid foundation for their enthusiasm in this regard. In their review of the matter, however, they examine the prospects for boosting photosynthetic conversion efficiency in an entirely different way: genetically, without increasing the air's CO_2 content.

"Improving photosynthetic conversion efficiency will require," the three scientists state, "a full suite of tools including breeding, gene transfer, and synthetic biology in bringing about the designed alteration to photosynthesis." For some of these "near-term" endeavors, they indicate "implementation is limited by technical issues that can be overcome by sufficient investment," meaning they can "be bought." But several "mid-term" goals could take 20 years or more to achieve; and they state "even when these improvements are achieved, it may take an additional 10–20 years to bring such innovations to farms in commercial cultivars at adequate scale." And if that is not bad enough, they say of still longer-term goals that "too little of the science has been undertaken to identify what needs to be altered to effect an increase in yield," while in some cases they acknowledge that what they envision may not even be possible, as in developing a form of RuBisCO that exhibits a significant decrease in oxygenation activity, or in designing C_3 crops to utilize the C_4 form of photosynthetic metabolism.

Clearly, we do not have the time to gamble on our ability to accomplish what needs to be done in order to forestall massive human starvation of global dimensions within the current century. Therefore—in addition to trying what Zhu et al. suggest—we must rely on the "tested and true": the CO_2-induced stimulation of plant photosynthesis and crop yield production. And all we need to do in this regard is to refrain from interfering with the natural evolution of the Industrial Revolution, which is destined to be carried for some time yet on the backs of fossil-fuel-driven enterprises that can provide the atmosphere with the extra carbon dioxide that will be needed to provide the extra increase in crop growth that may mean the difference between global food sufficiency and human starvation on a massive scale a mere few decades from now.

Another take on the matter has been provided by Hanjra and Qureshi (2010). They begin their treatment of the subject by quoting Benjamin Franklin's well-known homily, "When the well is dry, we know the worth of water," and they write we "must not lose sight of surging water scarcity." Noting "population and income growth will increase the demand for food and water," they contend "irrigation will be the first sector to lose water, as water competition by non-agricultural uses increases and water scarcity intensifies." As "increasing water scarcity will have implications for food security, hunger, poverty, and ecosystem health and services," they report "feeding the 2050 population will require some 12,400 km^3 of water, up from 6800 km^3 used today." This huge increase, they continue, "will leave a water gap of about 3300 km^3 even after improving efficiency in irrigated agriculture, improving water management, and upgrading of rainfed agriculture," as per the findings of de Fraiture et al. (2007), Molden (2007), and Molden et al. (2010).

This water deficiency, according to Hanjra and Qureshi, "will lead to a food gap unless concerted actions are taken today." Some of the measures they propose are to conserve water and energy resources, develop and adopt climate-resilient crop varieties, modernize irrigation, shore up domestic food supplies, reengage in agriculture for further development, and reform the global food and trade markets. To achieve these goals, they write, "unprecedented global cooperation is required," which by the looks of today's world is an exceedingly remote possibility.

What, then, can we do to defuse the ticking time-bomb of this looming food and water crisis? One option is to do nothing: don't mess with the normal, unforced evolution of civilization's means of acquiring energy. This is because on top of everything else we may try to do to conserve both land and freshwater resources, we will still fall short of what is needed to be achieved unless the air's CO_2 content rises significantly and thereby boosts the water use efficiency of Earth's crop plants and that of the plants that provide food and habitat for what could be called "wild nature," enabling both sets of plants to produce more biomass per unit of water used.

To ensure this happens, we will need all of the CO_2 that will be produced by the burning of fossil fuels, until other forms of energy truly become more cost-efficient than coal, gas, and oil. In fact, these other energy sources will have to become much more cost-efficient before fossil fuels are phased out, because the positive externality of the CO_2-induced increase in plant water use efficiency provided by the steady rise in the atmosphere's CO_2 concentration due to the burning of fossil fuels will be providing a most important service in helping us feed and sustain our own species without totally decimating what yet remains of wild nature.

In yet another paper to address this important issue—this one published in the *Journal of Proteome Research*—Sarkar et al. (2010) write, "increasing population and unsustainable exploitation of nature and natural resources have made 'food security' a burning issue in the 21st century," echoing the sentiments expressed by Farrell (2009), who noted "the alarming increase in biofuel production, the projected demand for livestock products, and the estimated food to feed the additional 700 million people who will arrive here by 2016, will have unprecedented consequences," among which are likely to be that "arable land, the environment, water supply and sustainability of the agricultural system will all be affected," and not in a positive way. Furthermore, when the human population of the globe reaches 8.7–11.3 billion by the year 2050 (Bengtsson et al., 2006), the situation will become truly intolerable, unless something is done, far in advance of that date, to mitigate the situation dramatically. Thus, as Sarkar et al. suggest, "a normal approach for any nation/region is to strengthen its agricultural production for meeting future demands and provide food security." But a major difficulty, which could spoil mankind's ability to do so, is the ongoing rise in the atmosphere's ozone concentration. This is the subject of Sarkar et al.'s new paper.

In a study designed to elucidate the many ways in which ozone (O_3) is harmful to plants, the eight researchers grew two high-yielding cultivars (Sonalika and HUW 510) of wheat (*Triticum aestivum* L.) outdoors at the Agriculture Research Farm of India's Banaras Hindu University. This was done within open-top chambers maintained at the ambient O_3 concentration and at elevated O_3 concentrations of 25 percent and 50 percent above ambient during the peak O_3 period of the day (10:00 to 15:00 hours local time) for a total of 50 days, during which time they measured numerous responses of the plants to the two levels of ozone enrichment.

Sarkar et al. determined, among several other things, that the moderate increases in the air's O_3 concentration resulted in higher foliar injury, a reduction in photosynthetic efficiency, induced inhibition in photochemical efficacy of photosystem II, lowered concentrations of photosynthetic pigments and proteins, and what they describe as "drastic reductions" in RuBisCO large and small subunits, while noting major leaf photosynthetic proteins and important energy metabolism proteins were also "drastically reduced."

Discussing the results, the scientists from India, Japan, and Nepal remark that anthropogenic activities have made ozone a "major environmental pollutant of our time," while noting some are predicting it to be an even "greater problem for the future." Adding this dilemma to the problem of feeding the world over the next few decades and beyond makes humanity's future look incredibly bleak. Thus, Sarkar et al. suggest we focus on "engineering crops for future high O_3," concentrating on maintaining "effective stomatal conductance of plants which can avoid O_3 entry but not hamper their productivity." We agree.

But not knowing to what extent we will be successful in this endeavor, we also need to do something we know will work: allowing the air's CO_2 content to rise, unimpeded by the misguided efforts of those who would curtail anthropogenic CO_2 emissions in the guise of fighting what they claim is anthropogenic-induced global warming. This contention is largely theoretical and wholly unproven, but we know, as a result of literally hundreds, if not thousands, of real-world experiments, that atmospheric CO_2 enrichment increases both the productivity and water-use efficiency of nearly all plants, and that it often more than compensates for the negative effects of O_3 pollution.

Introducing another review of food security studies pertinent to the challenge of feeding 9 billion people just four decades from now, Godfray et al. (2010) note "more than one in seven people today still do not have access to sufficient protein and energy from their diet and even more suffer some form of micronutrient malnourishment," citing the FAO (2009). Although "increases in production will have an important part to play" in correcting this problem and keeping it from worsening in the future, mankind "will be constrained by the finite resources provided by the earth's lands, oceans and atmosphere," This set of difficulties they describe at the end of their review as constituting a "perfect storm."

In considering ways to mitigate these problems, the first question they ask is: "How can more food be produced sustainably?" They state the primary solution to food shortages of the past was "to bring more land into agriculture and to exploit new fish stocks," but they note there is precious little remaining of either of these pristine resources. Thus, they conclude "the most likely scenario is that more food will need to be produced from the same or less land." As they suggest, "we must avoid the temptation to sacrifice further the earth's already hugely depleted biodiversity for easy gains in food production, not only because biodiversity provides many of the public goods upon which mankind relies, but also because we do not have the right to deprive future generations of its economic and cultural benefits." And, we might add, because we should be enlightened enough to realize we have a moral responsibility to drive no more species to extinction than we already have sent to that sorry state.

So how can these diverse requirements all be met simultaneously? A clue comes from Godfray et al.'s statement that "greater water and nutrient use efficiency, as well as tolerance of abiotic stress, are likely to become of increasing importance." And what is there that can bring about these changes in mankind's crops? You guessed it: carbon dioxide.

Rising concentrations of atmospheric CO_2 increase the photosynthetic prowess of essentially all of the Earth's plants, while generally reducing the rate at which they transfer water from the soil to the air. In addition, more CO_2 in the air tends to enhance the efficiency with which plants utilize nutrients in constructing their tissues and producing the edible portions that we and all of Earth's animals depend upon for our very existence.

Focusing on the water scarcity aspect of the food shortage problem, Kummu et al. (2010) write, "due to the rapidly increasing population and water use per capita in many areas of the world, around one third of the world's population currently lives under physical water scarcity (e.g. Vorosmarty et al., 2000; Alcamo et al., 2003; Oki and Kanae, 2006)." But despite the large number of water scarcity studies conducted over the years, "no global assessment is available of how this trend has evolved over the past several centuries to millennia." Thus they conducted a study covering AD 0 to 2005. This analysis was carried out for ten different time slices, defined as those times at which the human population of the globe was approximately double the population of the previous time slice. Global population data for these analyses were derived from the 5' latitude x 5' longitude-resolution global HYDE dataset of Klein Goldewijk (2005) and Klein Goldewijk et al. (2010), while evaluation of water resources availability over the same period was based on monthly temperature and precipitation output from the climate model ECBilt-CLIO-VECODE, as calculated by Renssen et al. (2005).

After completing these assessments, the four researchers found "moderate water shortage first appeared around 1800, but it commenced in earnest from about 1900, when 9% of the world population experienced water shortage, of which 2% was under chronic water shortage (<1000 m^3/capita/year)." Thereafter, from 1960 onwards, they write, "water shortage increased extremely rapidly, with the proportion of global population living under chronic water shortage increasing from 9% (280 million people) in 1960 to 35% (2300 million) in 2005." And currently, they continue, "the most widespread water shortage is in South Asia, where 91% of the population experiences some form of water shortage," while "the most severe shortage is in North Africa and the Middle East, where 77% and 52% of the total population lives under extreme water shortage (<500 m^3/capita/year), respectively."

To alleviate these freshwater shortages, Kummu et al. state measures generally have been taken to increase water availability, such as building dams and extracting groundwater. But they note "there are already several regions in which such measures are no longer sufficient, as there is simply not enough water available in some regions." In addition, they observe, "this problem is expected to increase in the future due to increasing population pressure (e.g. United Nations, 2009), higher welfare (e.g. Grubler et al., 2007) [and] production of water intensive biofuels (e.g. Varis, 2007, Berndes, 2008)." Hence, they conclude there will be an increasing need for many nonstructural measures, the first and foremost of which they indicate to be "increasing the efficiency of water use." This characteristic of nearly all of Earth's plants is almost universally promoted by atmospheric CO_2 enrichment.

References

Alcamo, J., Doll, P., Henrichs, T., Kaspar, F., Lehner, B., Rosch, T., and Siebert, S. 2003. Global estimates of water withdrawals and availability under current and future 'business-as-usual' conditions. *Hydrological Sciences Journal* **48**: 339–348.

Bengtsson, M., Shen, Y., and Oki, T. 2006. A SRES-based gridded global population dataset for 1990-2100. *Population & Environment* **28**: 113–131.

Berndes, G. 2008. Future biomass energy supply: the consumptive water use perspective. *International Journal of Water Resources Development* **24**: 235–245.

de Fraiture, C., Wichelns, D., Rockstrom, J., Kemp-Benedict, E., Eriyagama, N., Gordon, L.J., Hanjra, M.A., Hoogeveen, J., Huber-Lee, A., and Karlberg, L. 2007. Looking ahead to 2050: scenarios of alternative investment approaches. In *Comprehensive Assessment of Water Management in Agriculture. Water for Food, Water for Life: A Comprehensive Assessment of Water Management*, edited by D. Molden, 91–145. London, UK: Earthscan and Colombo, Sri Lanka: International Water Management Institute.

FAO (Food and Agriculture Organization). 2009. *State of Food Insecurity in the World 2009.* Rome, Italy: Food and Agriculture Organization.

Farrell, D. 2009. Feeding the future. *Livestock Research for Rural Development* **21**: 219. http://www.lrrd.org/lrrd21/12/farr21219.htm.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., and Toulmin, C. 2010. Food security: the challenge of feeding 9 billion people. *Science* **327**: 812–818.

Grubler, A., O'Neill, B., Riahi, K., Chirkov, V., Goujon, A., Kolp, P., Prommer, I., Scherbov, S., and Slentoe, E. 2007. Regional., national, and spatially explicit scenarios of demographic and economic change based on SRES. *Technological Forecasting and Social Change* **74**: 980–1021.

Hanjra, M.A. and Qureshi, M.E. 2010. Global water crisis and future food security in an era of climate change. *Food Policy* **35**: 365–377.

Huang, J., Pray, C., and Rozelle, S. 2002. Enhancing the crops to feed the poor. *Nature* **418**: 678–684.

Idso, C.D. and Idso, K.E. 2000. Forecasting world food supplies: the impact of the rising atmospheric CO_2 concentration. *Technology* **7S**: 33–55.

Idso, K.E. and Idso, S.B. 1994. Plant responses to atmospheric CO_2 enrichment in the face of environmental constraints: a review of the past 10 years' research. *Agricultural and Forest Meteorology* **69**: 153–203.

Idso, S.B. and Kimball, B.A. 2001. CO_2 enrichment of sour orange trees: 13 years and counting. *Environmental and Experimental Botany* **46**: 147–153.

Kimball, B.A. 1983. Carbon dioxide and agricultural yield: an assemblage and analysis of 430 prior observations. *Agronomy Journal* **75**: 779–788.

Klein Goldewijk, K. 2005. Three centuries of global population growth: a spatial referenced population (density) database for 1700-2000. *Population and Environment* **26**: 343–367.

Klein Goldewijk, K., Beusen, A., and Janssen, P. 2010. Long-term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1. *The Holocene* **20**: 565–573.

Kummu, M., Ward, P.J., de Moel, H., and Varis, O. 2010. Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia. *Environmental Research Letters* **5**: 10.1088/1748-9326/5/3/034006.

Molden, D. 2007. Water responses to urbanization. *Paddy and Water Environment* **5**: 207–209.

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., and Kijne, J. 2010. Improving agricultural water productivity: between optimism and caution. *Agricultural Water Management* **97**: 528–535.

Oki, T. and Kanae, S. 2006. Global hydrological cycles and world water resources. *Science* **313**: 1068–1072.

Raven, P.H. 2002. Science, sustainability, and the human prospect. *Science* **297**: 954–959.

Renssen, H., Goosse, H., Fichefet, T., Brovkin, V., Driesschaert, E., and Wolk, F. 2005. Simulating the Holocene climate evolution at northern high latitudes using a coupled atmosphere-sea-ice-ocean-vegetation model. *Climate Dynamics* **24**: 23–43.

Sarkar, A., Rakwal, R., Agrawal, S.B., Shibato, J., Ogawa, Y., Yoshida, Y., Agrawal, G.K., and Agrawal, M. 2010. Investigating the impact of elevated levels of ozone on tropical wheat using integrated phenotypical, physiological, biochemical, and proteomics approaches. *Journal of Proteome Research* **9**: 4565–4584.

Saxe, H., Ellsworth, D.S., and Heath, J. 1998. Tree and forest functioning in an enriched CO_2 atmosphere. *New Phytologist* **139**: 395–436.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., and Polasky, S. 2002. Agricultural sustainability and intensive production practices. *Nature* **418**: 671–677.

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D., and Swackhamer, D. 2001. Forecasting agriculturally driven global environmental change. *Science* **292**: 281–284.

United Nations. 2009. *World Population Prospects: The 2008 Revision.* Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat. http://esa.un.org/unpp.

Varis, O. 2007. Water demands for bioenergy production. *International Journal of Water Resources Development* **23**: 519–535.

Vorosmarty, C.J., Green, P., Salisbury, J., and Lammers, R.B. 2000. Global water resources: vulnerability from climate change and population growth. *Science* **289**: 284–288.

Waggoner, P.E. 1995. How much land can ten billion people spare for nature? Does technology make a difference? *Technology in Society* **17**: 17–34.

Wallace, J.S. 2000. Increasing agricultural water use efficiency to meet future food production. *Agriculture, Ecosystems & Environment* **82**: 105–119.

Zhu, X.-G., Long, S.P., and Ort, D.R. 2010. Improving photosynthetic efficiency for greater yield. *Annual Review of Plant Biology* **61**: 235–261.

7.10.2. Prospects for Rice

Shimono et al. (2010) write, "by 2050, the world's population will have increased by about 37%, from the current level of 6.7 billion to an estimated 9.2 billion (United Nations, 2009), with a corresponding increase in global food demand." They note "about 0.6 billion Mg of rice is produced annually from an area of 1.5 million km^2, making rice one of the most important crops for supporting human life"; as noted by Pritchard and Amthor (2005), it supplies the planet's human population with an estimated 20 percent of its energy needs (on a caloric basis) and 14 percent of its protein requirements (on a weight basis).

The six scientists further note "rice production depends heavily on water availability," stating "irrigated lowlands account for 55% of the total area of harvested rice and typically produce two to three times the crop yield of rice grown under non-irrigated conditions (IRRI, 2002)." With the demand for water continuing to rise in order to feed our growing numbers, they conclude, "efficient use of water will thus be essential for future rice production."

To determine how agricultural productivity may be impacted by the ongoing rise in the air's CO_2 content, the Japanese researchers conducted a two-year free-air CO_2 enrichment (FACE) study in fields at Shizukuishi, Iwate (Japan) to learn how elevated CO_2 might reduce crop water use via its impact on the leaf stomatal conductance (g_s) of three varieties of rice (*Oryza sativa* L.): early maturing Kirara397, intermediate-maturing Akitakomachi, and latest-maturing Hitomebore.

In response to the 53 percent increase in daytime atmospheric CO_2 concentration employed in their experiments, Shimono et al. found "the reduction in g_s due to elevated CO_2 was similar across measurements, averaging around 20% in the morning, 24% around noon and 23% in the afternoon across all growth stages." They also note "there was no significant CO_2 x cultivar interaction."

Also focusing on rice were Xiong et al. (2009), who began their study by noting "rice is an essential component of the diet in more than half the world's population, and it is the most socially and economically important crop in China," where they say it "contributes 43.7% of total national grain production," citing Yao et al. (2007). Xiong et al. "assessed the effect of greenhouse gas-induced climate change, as well as the direct fertilization effect of CO_2, on rice yields and production in China," by coupling "the regional climate model PRECIS (Providing Regional Climates for Impacts Studies) with the CERES (Crop Environment Resources Synthesis) rice crop model to simulate current (1961–1990) and future (2011–2100) rice yields and production under [the] A2 and B2 climate change scenarios" of the Intergovernmental Panel on Climate Change.

The four researchers report that with anticipated climate changes, "single rice cropping may expand further north in China, and double rice cropping may move to the northern portion of the Yangtze River basin." In addition, they state "the national mean rice production is estimated to increase by 2.7 to 19.2% considering the combined effects of climate change, CO_2 and shifting rice-producing areas." Thus, even considering the inflated temperature increases predicted by the IPCC, the estimated net effect of global warming and concomitant growth in anthropogenic CO_2 emissions ends up producing an increase in rice production in the world's most populous country, where it is the people's single most important food source.

In another study of rice's role in world food security, Yang et al. (2009) begin by noting (1) "rice is unequivocally one of the most important food crops that feed the largest proportion of the world's population," (2) "the demand for rice production will continue to increase in the coming decades, especially in the major rice-consuming countries of Asia, Africa and Latin America," and (3) "accurate predictions of rice yield and of the ability of rice crops to adapt to high CO_2 environments are therefore crucial for understanding the impact of climate change on the future food supply." They forcefully declare, "there is a pressing need to identify genotypes which could optimize harvestable yield as atmospheric CO_2 increases."

They set out to do so in a standard paddy culture FACE experiment conducted at Yangzhou, Jiangsu, China, in 2004–2006. Yang et al. grew a two-line inter-subspecific hybrid rice variety (Liangyoupeijiu) at ambient and elevated atmospheric CO_2 concentrations of 376 and 568 ppm, respectively, at two levels of field nitrogen (N) application: low N (12.5 g N m^{-2}) and high N (25 g N m^{-2}), measuring numerous aspects of crop growth, development, and final yield production in the process. Their "bottom-line" finding was that the 51 percent increase in atmospheric CO_2 concentration increased the final grain yield of the low N rice crop by 28 percent and that of the high N rice crop by 32 percent. As a result, and "compared with the two prior rice FACE experiments (Kim et al., 2003; Yang et al., 2006)," they report "hybrid rice appears to profit much more from CO_2 enrichment than inbred rice cultivars (c. +13%)." Little wonder, then, that Yang et al. describe Liangyoupeijiu as "one of the most popular 'super' hybrid rice varieties in China (Peng et al., 2004)."

Highlighting an especially important aspect of the role of atmospheric CO_2 enrichment in promoting rice production, Feng et al. (2009) write, "purple phototrophic bacteria (PPB) are thought to be crucial in the nutrient cycling of rice fields." The Chinese researchers note PPB "thrive in the anaerobic portions of all kinds of aquatic environments, and have long been recognized as one of the key players in global carbon and nitrogen cycles." Against this backdrop, therefore, in a FACE study conducted within a rice/wheat rotation system at the Nianyu Experimental Station in Jiangsu Province, China, they grew rice (*Oryza sativa* L.) plants under standard paddy culture at two levels of soil nitrogen (N) fertility—low (150 kg N/hectare) and high (250 kg N/hectare)—at ambient and ambient plus 200 ppm CO_2 concentrations, while measuring several characteristics of PPB within the rhizosphere and bulk soils of the two CO_2 treatments.

The seven scientists found "elevated CO_2 appeared to enhance the biodiversity of PPB in flooded paddy soils"; "PPB abundance was stimulated by elevated CO_2 in bulk soil"; and "N fertilization enhanced the biodiversity of PPB under elevated atmospheric CO_2." Feng et al. highlight the significance of these findings by noting "PPB inoculation into the flood water [in rice paddy culture] could lead to grain yield increase by 29% (Elbadry et al., 1999; Harada et al., 2005)," and "PPB are thought to be capable of fixing nitrogen." Thus these two phenomena—enhanced by the ongoing rise in the air's CO_2 content—can help provide the boost in food production that will be needed to feed the planet's still-growing human population in the years and decades ahead.

Turning to the effect of warming on cultivation, Dong et al. (2009) state "the annual mean surface air temperature in China has increased 1.1°C over the past 50 years," adding that "striking warming has occurred since the mid-1980s, particularly in northern China." Noting annual accumulated temperatures greater than 10°C (AAT10) represent "an important indicator of thermal conditions in crop ecology (Qiu and Lu, 1980; Bai et al., 2008)," which "affects the choice of crop varieties, the crop calendar, cropping systems and crop patterns (Zheng et al., 2008)," the five Chinese scientists decided to "assess the relationship between accumulated temperature change and cultivated land use in China from the late 1980s to 2000," in order to determine the impact of the dramatic warming on the nation's agriculture.

They found "since the late 1980s, AAT10 has noticeably risen in most of China." More specifically, Dong et al. indicate 1.22 x 10^{15} km^2 of land moved from the potato accumulated temperature zone (ATZ) to the spring wheat ATZ, that 3.16 x 10^{15} km^2 of land moved from the spring wheat ATZ to the winter wheat ATZ, and that 1.64 x 10^{15} km^2 of land moved from the winter wheat ATZ to the rice ATZ. In addition, they determined "because of improved thermal conditions since the late 1980s," farmers changed from a single crop per year to three crops in two years in many regions, while "the growth boundary of winter wheat moved northward."

With respect to the cropping index, which they define as the number of crops grown per year on a given area of land, the researchers from the Chinese Academy of Sciences state, "as a result of climate warming on a national scale, it is feasible for the cropping index to improve." They report that, indeed, "cropping indices have improved in many regions since the 1980s," citing the studies of Yan et al. (2005) and Li et al. (2008). Hence, they indicate "to acquire higher yields of food and income, people have improved the cropping index in regions that had previously been difficult to crop and also in some areas where the index was low."

The past century's increasing temperature and atmospheric CO_2 concentration have not in any way hurt the people of China. Quite to the contrary, they have improved the country's capacity to provide the quantities of food needed to support its population.

Much the same can be said of Canada. Working with a homogenized temperature dataset consisting of daily maximum and minimum air temperatures for the period 1895–2007 obtained from 210 meteorological stations distributed across the country, plus an adjusted precipitation dataset developed at the Climate Research Division of Environment Canada, Qian et al. (2010) derived a set of agroclimatic indices that are sure to prove useful for agricultural production planning purposes for many years to come. They report, for example, that their results indicate "a significant lengthening of the growing season due to a significantly earlier start and a significantly later end of the growing season," and they state "significant positive trends are also observed for effective growing degree-days and crop heat units at most locations across the country." They also report "the occurrence of extremely low temperatures has become less frequent during the non-growing season, implying a more favorable climate for overwinter survival," and "the total numbers of cool days, frost days, and killing-frost days within a growing season have a decreasing trend," so "crops may also be less vulnerable to cold stress and injury during the growing season." They also found "extreme daily precipitation amounts and 10-day precipitation totals during the growing season have been increasing," and "significant trends associated with increased availability of water during the growing season are identified."

These desirable results clearly indicate the global warming that brought an end to the debilitating cold of the Little Ice Age and ushered the planet into the Current Warm Period is proving to be a real boon to Canada, as well as to the rest of the world, which may have to depend upon North America's northernmost country to supply a significant portion of the food that will be required to support Earth's burgeoning human population in the decades to come.

References

Bai, Q.F., Huo, Z., Li, S., Du, H., He, N., and Jiang, Y. 2008. Comparison of accumulated temperature above 10°C before and after the year 1978 in China. *Chinese Journal of Applied Ecology* **19**: 1810–1816.

Dong, J., Liu, J., Tao, F., Xu, X., and Wang, J. 2009. Spatio-temporal changes in annual accumulated temperature in China and the effects on cropping systems, 1980s to 2000. *Climate Research* **40**: 37–48.

Elbadry, M., Gamal-Eldin, H., and Elbanna, K. 1999. Effects of *Rhodobacter capsulatus* inoculation in combination with graded levels of nitrogen fertilizer on growth and yield of rice in pots and lysimeter experiments. *World Journal of Microbiology and Biotechnology* **15**: 393–395.

Feng, Y., Lin, X., Wang, Y., Zhang, J., Mao, T., Yin, R., and Zhu, J. 2009. Free-air CO_2 enrichment (FACE) enhances the biodiversity of purple phototrophic bacteria in flooded paddy soil. *Plant and Soil* **324**: 317–328.

Harada, N., Nishiyama, M., Otsuka, S., and Matsumoto, S. 2005. Effects of inoculation of phototrophic bacteria on grain yield of rice and nitrogenase activity of paddy soil in a pot experiment. *Soil Science and Plant Nutrition* **51**: 361–367.

IRRI (International Rice Research Institute). 2002. *Rice Almanac: Source Book for the Most Important Economic Activity on Earth.* Oxfordshire, UK: CABI Publishing.

Kim, H.Y., Lieffering, M., Kobayashi, K., Okada, M., Mitchell, M.W., and Gumpertz, M. 2003. Effects of free-air CO_2 enrichment and nitrogen supply on the yield of temperate paddy rice crops. *Field Crops Research* **83**: 261-270.

Li, J., Gao, P., Chen, Y.C., Chen, H., and Yang, T.M. 2008. Relationships between farming system and effective accumulated temperature in East China. *Chinese Journal of Ecology* **27**: 361–368.

Peng, S., Laza, R.C., Visperas, R.M., Khush, G.S., Virk, P., and Zhu, D. 2004. Rice: progress in breaking the yield ceiling. In *New Directions for a Diverse Planet: Proceedings of the Fourth International Crop Science Congress*, 26 Sep-1 Oct 2004, Brisbane, Australia. Gosford, Australia: Regional Institute Ltd.

Pritchard, S.G. and Amthor, J.S. 2005. *Crops and Environmental Change.* New York, NY: Food Production Press.

Qian, B., Zhang, X., Chen, K., Feng, Y., and O'Brien, T. 2010. Observed long-term trends for agroclimatic conditions in Canada. *Journal of Applied Meteorology and Climatology* **49**: 604–618.

Qiu, B. and Lu, Q. 1980. A tentative regionalization of agroclimate of China. *Acta Geographica Sinica* **35**: 116–125.

Shimono, H., Okada, M., Inoue, M., Nakamura, H., Kobayashi, K., and Hasegawa, T. 2010. Diurnal and seasonal variations in stomatal conductance of rice at elevated atmospheric CO_2 under fully open-air conditions. *Plant, Cell and Environment* **33**: 322–331.

United Nations. 2009. *The 2006 World Population Prospects. The 2008 Revision Population Database.* New York, NY: United Nations. Available at http://esa.un.org/unpp/.

Xiong, W., Conway, D., Lin, E., and Holman, I. 2009. Potential impacts of climate change and climate variabiity on China's rice yield and production. *Climate Research* **40**: 23–35.

Yan, H., Liu, J., and Cao, M. 2005. Remotely sensed multiple cropping index variations in China during 1981–2000. *Acta Geographica Sinica* **60**: 559–566.

Yang, L., Liu,. H., Wang, Y., Zhu, J., Huang, J., Liu, G., Dong, G., and Wang, Y. 2009. Yield formation of CO_2-enriched inter-subspecific hybrid rice cultivar Liangyoupeijiu under fully open-air condition in a warm sub-tropical climate. *Agriculture, Ecosystems and Environment* **129**: 193–200.

Yang, L.X., Huang, J.Y., Yang, H.J., Zhu, J.G., Liu, H.J., Dong, G.C., Liu, G., Han, Y., and Wang, Y.L. 2006. The impact of free-air CO_2 enrichment (FACE) and N supply on yield formation of rice crops with large panicle. *Field Crops Research* **98**: 141–150.

Yao, F.M., Xu, Y.L., Lin, E.D., Yokozawa, M., and Zhang, J.H. 2007. Assessing the impacts of climate change on rice yields in the main rice areas of China. *Climatic Change* **80**: 395–409.

Zheng, D., Ou, Y., and Zhou, C.H. 2008. Understanding of and thinking over geographical regionalization methodology. *Acta Geographica Sinica* **63**: 563–573.

7.10.3. Pigeon Peas

Citing Sinha et al. (1998), Vanaja et al. (2010) write, "food grain requirements of India (both human and cattle) are estimated at 300 Mt in 2020," and they note "grain legumes are one of the mainstays of the drylands, as these crops provide much needed nutritional security in the form of proteins to the predominant vegetarian populations of India and also the world." They state that legumes, of which pigeon peas are an important example, "have the potential to maximize the benefit of elevated CO_2 by matching stimulated photosynthesis with increased N_2 fixation," citing Rogers et al. (2009).

With this in mind, Vanaja et al. grew pigeon peas (*Cajanus cajan* L. Millsp.) from seed to maturity outdoors at Hyderabad (India) within open-top chambers maintained at atmospheric CO_2 concentrations of either 370 or 700 ppm (ambient or enriched, respectively). They then harvested them and measured several pertinent productivity parameters. The team of nine Indian scientists from their country's Central Research Institute for Dryland Agriculture determined "total biomass recorded an improvement of 91.3%, grain yield 150.1% and fodder yield 67.1%." They also state "the major contributing components for improved grain yield under elevated CO_2 were number of pods, number of seeds and test weight," which exhibited increases of 97.9 percent, 119.5 percent, and 7.2 percent, respectively. In addition, they found there was "a significant positive increase of harvest index at elevated CO_2 with an increment of 30.7% over ambient values," which they say was due to the crop's "improved pod set and seed yield under enhanced CO_2 concentration." These very positive findings, in the words of Vanaja et al., illustrate the importance of pigeon peas for "sustained food with nutritional security under a climate change scenario."

References

Rogers, A., Ainsworth, E.A., and Leakey A.D.B. 2009. Will elevated carbon dioxide concentration amplify the benefits of nitrogen fixation in legumes? *Plant Physiology* **151**: 1009–1016.

Sinha, S.K., Kulshreshtha, S.M., Purohit, A.N., and Singh, A.K. 1998. Base Paper. *Climate Change and Perspective for Agriculture*, 20. New Delhi, India: National Academy of Agricultural Sciences.

Vanaja, M., Reddy, P.R.R., Lakshmi, N.J., Razak, S.K.A., Vagheera, P., Archana, G., Yadav, S.K., Maheswari, M., and Venkateswarlu, B. 2010. Response of seed yield and its components of red gram (*Cajanus cajan* L. Millsp.) to elevated CO_2. *Plant, Soil and Environment* **56**: 458–462.

7.10.4. CO_2 Enrichment for Crops

Noting the CO_2 concentrations in greenhouses may range from 100 to 250 ppm during the day due to their being tightly sealed (concentrations that are suboptimal for growth), Jin et al. (2009) proposed "a new strategy of CO_2 enrichment," wherein they compost crop residues and animal manure (CRAM) "directly in the greenhouse." The composting units they designed to demonstrate this low-tech approach to enriching greenhouse air with CO_2 were made of wood and had a height of 1.2 meters and diameter of 0.6 meter. The unit's bottom was constructed of 6-cm-wide wood bars with a 2-cm-wide interval between them that ensured sufficient aeration. The composting material consisted of 25 kg of crop residue (rice straw, in their case) and 8 kg of moist manure, to which mixture 90 liters of water were added initially, after which the mixture was kept at a moisture content of approximately 70 percent. Then the CRAM mixture was inoculated with three different species of fungi (*Panusconclmtw* zj3, *Trichoderma viride* zj2, and *Aspergillas niger* zj1), to increase CO_2 production via accelerated fermentation. And "to prevent NH_3 emission from the compost into the greenhouse," as they describe it, "a sponge layer permeated with 2 M H_2SO_4 was placed on top of the composting mixture to trap volatizing NH_3."

The six scientists tested their technique in three pairs of greenhouses placed over a uniform soil surface, in which they planted celery (*Apium graveolens* L.), leaf lettuce (*Lactuca virosa* L.), stem lettuce (*Lactuca saiva* L.), oily sowthistle (*Sonchus oleraceus* L.), and Chinese cabbage (*Brassica chinensis* L.). One of each of these greenhouse pairs acted as a control, while the other housed one of their low-tech CO_2 generators, which they emptied every 21 days onto an adjacent field to provide it with an organic fertilizer over the course of their 63-day growing season. As best as can be determined from Jin et al.'s graphs of the hourly CO_2 measurements they made on specific days, as well as every-day or every-other-day measurements of CO_2 made at one specific time of day, mean daylight CO_2 concentrations in the CO_2-enriched greenhouses were just a little over twice as great as those measured in the control greenhouses. As for the effects of this slightly more than doubling of the air's CO_2 content, they report, "the average percentage of yield increases of all three sites were 270%, 257%, 87%, 140% and 227% for celery, leaf lettuce, stem lettuce, oily sowthistle, and Chinese cabbage, respectively." In addition, they state the extra CO_2 from the composting units increased the concentration of vitamin C in all five species: "by 13%, 39%, 25%, 72% and 37% for celery, leaf lettuce, stem lettuce, oily sowthistle, and Chinese cabbage, respectively."

The five Chinese researchers and their Australian collaborator conclude their CRAM procedure "is an efficient way to elevate CO_2 concentrations," that it "represents a simple, cheap and adoptable management tool for use in greenhouse vegetable production," and that its "use of crop residues and animal manures decreases the possible environmental problems caused by burning and [other less-than-desirable] practices of disposal of these agricultural by-products." Considering these environmental benefits, the increased crop yields, and the increased nutritive value of the edible produce they harvested, Jin et al.'s low-tech approach to enriching greenhouse air with CO_2 would appear to be a winning proposition, especially where it may not feasible to employ more sophisticated techniques.

Reference

Jin, C., Du, S., Wang, Y., Condon, J., Lin, X., and Zhang, Y. 2009. Carbon dioxide enrichment by composting in greenhouses and its effect on vegetable production. *Journal of Plant Nutrition and Soil Science* **172**: 418–424.

7.11. Greening of the Earth

In light of what we know about the aerial fertilization and anti-transpirant effects of atmospheric CO_2 enrichment, we would expect Earth's terrestrial plant life to become increasingly productive as the air's CO_2 content continues to rise, even in the face of rising air temperatures. The following sections highlight real-world evidence about plant productivity as CO_2 increases.

7.11.1. Africa

Ciais et al. (2009) modeled the terrestrial carbon balance of Africa over the past century (1901–2002) using a spatially resolved, process-based vegetation model (ORCHIDEE), which is forced by changing climate, human-induced changes in land use, and a parameterization of natural fires. They found "the African net terrestrial carbon (C) balance increased from a net CO_2 source to the atmosphere of 0.14 Pg C per year in the 1980s to a net sink of 0.15 Pg C per year in the 1990s.” In addition, they state the land use flux due to deforestation was “a source of 0.13 Pg C per year,” and “this implies that climatic trends (mainly increasing precipitation) and CO_2 increase (the fertilization effect), are causing a sink of 0.28 Pg C per year which offsets the land-use source.”

The five researchers also indicate “the trend of gross primary production is closely matching the trend in satellite observed NDVI,” or Normalized Difference Vegetation Index, and they note their simulated trend in gross primary production “is also consistent with an increased vegetation activity over [the] Sahel reported by Eklundh and Olsson (2003) and Olsson et al. (2005),” while at the continental scale the gross primary production trend can be largely (70 percent) explained by the CO_2 fertilization effect. Primarily in response to the ongoing rise in the air’s CO_2 content, therefore, it would appear from the results of this study that the African continent is significantly “greening up,” and that it has been doing so recently at a significantly enhanced rate.

Examining what might be next for Africa, Doherty et al. (2010) modeled future changes in land biogeochemistry and biogeography in the region bounded by 12.5°N, 12.5°S, 25°E, and 42.5°E, representing most of East Africa (Kenya, Tanzania, Uganda, Rwanda, Burundi, Ethiopia, and Somalia), and portions of Central Africa (the Democratic Republic of Congo and Southern Sudan). They did this using 18 future climate projections derived from nine general circulation models that figured prominently in the IPCC’s Fourth Assessment Report, employing the projections as input to the Lund-Potsdam-Jena dynamic global vegetation model that simulates changes in vegetation and ecosystem carbon cycling under future climate conditions, based on what they describe as “a coupled photosynthesis-hydrological scheme [that] computes gross primary productivity, plant respiration, and evapotranspiration on a daily time step based on the current climate, atmospheric CO_2 concentration, vegetation structure and phenological state, and soil water content.”

Doherty et al. report “all simulations showed future increases in tropical woody vegetation over the region at the expense of grasslands,” noting “regional increases in net primary productivity (18–36%) and total carbon storage (3–13%) by 2080–2099 compared with the present-day were common to all simulations,” and “seven out of nine simulations continued to show an annual net land carbon sink in the final decades of the 21st century because vegetation biomass continued to increase.” The researchers conclude “overall, our model results suggest that East Africa, a populous and economically poor region, is likely to experience some ecosystem service benefits through increased precipitation, river runoff and fresh water availability,” and they state “resulting enhancements in net primary productivity may lead to improved crop yields in some areas.” They specifically state their results “stand in partial contradiction of other studies that suggest possible negative consequences for agriculture, biodiversity and other ecosystem services caused by temperature increases.”

Regarding the continent as a whole, Scheiter and Higgins (2009) write, “recent IPCC projections suggest that Africa will be subject to particularly severe changes in atmospheric conditions” in the decades ahead, and these changes could have severe repercussions for its flora and fauna. However, they say that how the continent’s “grassland-savanna-forest complex will respond to these changes has rarely been investigated,” and “most studies on global carbon cycles use vegetation models that do not adequately account for the complexity of the interactions that shape the distribution of tropical grasslands, savannas and forests.”

In an attempt to overcome these shortcomings, the two scientists developed a new vegetation model—the adaptive dynamic global vegetation model (aDGVM)—that employs established sub-models for photosynthesis, respiration, canopy scaling, competition for water, competition for light, reproduction, and mortality, and which additionally contains the novel elements of dynamic carbon allocation and phenology functions. They also employed a fire model that estimates fire intensity as a function of fuel biomass, fuel moisture, and wind speed and simulates topkill (stem mortality) as a function of individual tree size and fire intensity. All of these phenomena are related to the individual plant’s physiological state and the environmental conditions surrounding it.

Forward simulations to the year 2100 with this model suggest, in the words of the two researchers, that “grasslands will spread into the Sahara and into the horn of Africa, such that the total area covered by deserts or bare soil decreases by 5.7%.” In addition, they write, “it is predicted that 34.6% of today’s grasslands are transformed into savannas” and “45.3% of today’s savannas are transformed into deciduous woodlands." Hence, "the total biomass stored in each of the biomes increases, with high relative changes in grasslands and savannas (by 256% and 241%, respectively)" and a 102 percent increase in tree biomass.

In conclusiuon, the CO_2- and warming-induced greening of the Earth, which has been manifest throughout the world over the past few decades, seems destined to continue through the twenty-first century in Africa with positive results for plant and animal life.

References

Ciais, P., Piao, S.-L., Cadule, P., Friedlingstein, P., and Chedin, A. 2009. Variability and recent trends in the African terrestrial carbon balance. *Biogeosciences* **6**: 1935–1948.

Doherty, R.M., Sitch, S., Smith, B., Lewis, S.L., and Thornton, P.K. 2010. Implications of future climate and atmospheric CO_2 content for regional biogeochemistry, biogeography and ecosystem services across East Africa. *Global Change Biology* **16**: 617–640.

Eklundh, L. and Olsson, L. 2003. Vegetation index trends for the African Sahel 1982–1999. *Geophysical Research Letters* **30**: 10.1029/2002GL016772.

Olsson, L., Eklundh, L., and Ardo, J. 2005. A recent greening of the Sahel, trends, patterns and potential causes. *Journal of Arid Environments* **63**: 556–566.

Scheiter, S. and Higgins, S.I. 2009. Impacts of climate change on the vegetation of Africa: an adaptive dynamic vegetation modeling approach. *Global Change Biology* **15**: 2224–2246.

7.11.2. Forests

McMahon et al. (2010) note "there are indications that forest biomass accumulation may be accelerating where nutrients and water are not limiting," citing Myneni et al. (1997), Lewis et al. (2004), Lewis et al. (2009a), Boisvenue and Running (2006), Delpierre et al. (2009), Salzer et al. (2009), and Chave et al. (2008). They further investigate the subject because of the great significance such a phenomenon would hold for the planet's carbon balance and the future course of potential CO_2-induced global warming. Using unique datasets of tree biomass collected over the past 22 years from 55 temperate forest plots with known land-use histories and stand ages ranging from five to 250 years—which were derived from knowledge of when the stands had begun to regrow following major disturbances such as significant logging, various natural disasters that had decimated large patches of trees, or the clearing of trees to make room for agriculture that was ultimately abandoned—McMahon et al. "estimated biomass change, while controlling for stand regeneration." They did this within various parts of a temperate deciduous forest in the vicinity of the Smithsonian Environmental Research Center, Edgewater, Maryland (USA) by comparing recent (last 22 years or less) rates of biomass accumulation of the various stands with rates predicted for those age intervals by the overall growth function derived from the combined data of all of the stands. Finally, they compared their findings with "over 100 years of local weather measurements and 17 years of on-site atmospheric CO_2 measurements."

The three researchers report "recent biomass accumulation greatly exceeded the expected growth caused by natural recovery," noting that in stands younger than 50 years the observed increase was generally at least one-third of total growth, and in older stands it typically was "the majority of growth," even though past experience and the ensemble relationship of growth vs. age derived from the totality of their data suggest "old forests should grow very little as they approach equilibrium." As for what could have caused the tremendous recent increases in forest plot growth rates detected by the Smithsonian scientists, they state "increases in temperature, growing season [which is largely driven by temperature], and atmospheric CO_2 have documented influences on tree physiology, metabolism, and growth," and they state these global-change factors—the magnitudes of which rose significantly over the course of their study—may have been "critical to changing the rate of stand growth observed across stands." Such findings and this explanation provide additional important evidence for the greening of the Earth phenomenon that is transforming the face of the planet as the air's CO_2 content continues to rise.

Further north, satellite studies based on Normalized Difference Vegetation Index (NDVI) data have produced conflicting trend estimates, ranging from greening to browning, for the boreal forest zone of Canada. In an attempt to resolve this disagreement, Alcaraz-Segura et al. (2010) argue that a significant factor not considered in past studies is fire history. If points in time are compared before and after a fire, for example, NDVI will be seen to have decreased, but not for the reason for which the data were sought.

Similarly, trends that begin right after a fire will show increasing NDVI that is unrelated to climate factors, as the vegetation recovers from fire. Hence, they use this latter phenomenon of vegetation recovery after fire as a ground-truth test for two satellite datasets.

Working with GIMMS satellite data that represent 64-km^2 cells and newly available CCRS data that represent 1-km^2 cells, the five researchers used an algorithm shown to detect recent fires to correctly classify pixels as burned or not-burned, comparing the performance of the two datasets for detecting trends. They found the GIMMS data were unable to properly detect increases in NDVI over time in burned areas compared to the CCRS data, and that GIMMS data are thus a poor choice for this type of study. The CCRS data, on the other hand, detected strong greening in burned areas (as expected) and a weaker but consistent greening in unburned forest areas over 1996 to 2006. As a result, Alcaraz-Segura et al. suggest (1) the widely-used GIMMS data may have produced false results in other studies and should be used with caution, (2) satellite data need to be better calibrated with ground data before use, and (3) the greening of the Canadian boreal forest is probably real for the most recent decades.

Although many high-latitude regions may indeed be experiencing greening due to increases in the air's CO_2 content, as well as concomitant warming that allows crops and forests to grow where it has previously been too cold for them to survive, some researchers worry about Earth's tropical regions, where they claim just a little extra warming may spell disaster for local forests. Consequently, in a thorough review of the scientific literature on this important subject, Lewis et al. (2009b) evaluated tropical forest inventory data, plant physiology experiments, ecosystem flux observations, Earth observations, atmospheric measurements, and dynamic global vegetation models, which "taken together," in their words, "provide new opportunities to cross-validate results."

The five researchers note both theory and experiments suggest over the past several decades "plant photosynthesis should have increased in response to increasing CO_2 concentrations, causing increased plant growth and forest biomass." And they did indeed find "long-term plot data collectively indicate an increase in carbon storage, as well as significant increases in tree growth, mortality, recruitment, and forest dynamism." They also state satellite measurements "indicate increases in productivity and forest dynamism," and five Dynamic Global Vegetation Models, incorporating plant physiology, competition, and dynamics, all predict increasing gross primary productivity, net primary productivity, and carbon storage when forced using late-twentieth century climate and atmospheric CO_2 concentration data. In addition, they state "the predicted increases in carbon storage via the differing methods are all of similar magnitude (0.2% to 0.5% per year)."

"Collectively," they conclude, "these results point toward a widespread shift in the ecology of tropical forests, characterized by increased tree growth and accelerating forest dynamism, with forests, on average, getting bigger (increasing biomass and carbon storage)." Far from being the bane of the Earth's tropical forests, twentieth-century increases in air temperature and atmospheric CO_2 concentration—which have returned these meteorological parameters to more normal post-Little Ice Age values—have been a great boon to the trees of the tropics.

Commenting on this state of affairs, Gloor et al. (2009) reiterated that "large-scale changes in forest dynamics are currently occurring in Amazonia (Phillips and Gentry, 1994; Phillips et al., 2004), and that an increase in aboveground biomass has occurred, with increases in mortality tending to lag increases in growth (Phillips et al., 1998; Baker et al., 2004a,b; Lewis et al., 2004)." However, they state this conclusion has been challenged recently by an overzealous application of the "Slow in, Rapid out" dictum, which recognizes that forest growth is a slow process, whereas mortality can be dramatic and singular in time, such that sampling over relatively short observation periods may miss these more severe events, leading to positively biased estimates of aboveground biomass trends, when either no trend or negative trends actually exist.

To test this claim, Gloor et al. statistically characterized "the disturbance process in Amazon old-growth forests as recorded in 135 forest plots of the RAINFOR network up to 2006, and other independent research programs, and explore the consequences of sampling artifacts using a data-based stochastic simulator." They found "over the observed range of annual aboveground biomass losses, standard statistical tests show that the distribution of biomass losses through mortality follow an exponential or near-identical Weibull probability distribution and not a power law as assumed by others." In addition, they state "the simulator was parameterized using both an exponential disturbance probability distribution as well as a mixed exponential-power law distribution to account for potential large-scale blow-down events," and they report "in both cases, sampling biases turn out to be too small to explain the gains detected by the extended RAINFOR plot network."

Gloor et al. therefore conclude their results lend "further support to the notion that currently observed biomass gains for intact forests across the Amazon are actually occurring over large scales at the current time, presumably as a response to climate change," which in many of their earlier papers is explicitly stated to include the aerial fertilization effect of the historical increase in the air's CO_2 content.

In another of several contemporaneous studies, Silva et al. (2009) describe *Araucaria angustifolia* as "an indigenous conifer tree restricted to the southern region of South America that plays a key role in the dynamics of regional ecosystems where forest expansion over grasslands has been observed." Working with various types of tree-ring data obtained from such trees growing in both forest and grassland sites in southern Brazil, they compared changes in intrinsic water use efficiency—iWUE, defined as the ratio of the rate of CO_2 assimilation by the trees' needles to their stomatal conductance—with concomitant historical changes in temperature, precipitation, and atmospheric CO_2 concentration over the past century.

They found "iWUE increased over 30% in both habitats" over the past several decades, and "this increase was highly correlated with increasing levels of CO_2 in the atmosphere." Tree growth, however, remained rather stable, due to lower-than-normal precipitation and higher-than-normal temperatures, which would normally tend to depress the growth of this species—Katinas and Crisci (2008) describe *A. angustifolia* as being "intolerant of dry seasons and requiring cool temperatures." Therefore, Silva et al. conclude the "climatic fluctuations during the past few decades," which would have been expected to have been deleterious to the growth of *A. angustifolia*, seem to have had their growth-retarding effects "compensated by increases in atmospheric CO_2 and changes [i.e., increases] in iWUE."

Also dealing with the expansion of forests onto grasslands were Springsteen et al. (2010), who write, "woody plant expansion within grassland ecosystems is a worldwide phenomenon, and dramatic vegetation shifts from grassland to savanna/woodlands have occurred over the past 50–100 years in North America," while noting one of the chief factors that has contributed to this phenomenon is believed by many to have been the increase in the air's CO_2 content, as suggested by Archer et al. (1995), Polley (1997), Bond and Midgley (2000), and Bond et al. (2003). They also note once shrublands are established, they tend to persist for several different reasons, one of which is a type of feedback phenomenon referred to as islands of fertility, which "occurs when resources accumulate in soils beneath woody plants due to litterfall, interception of wet and dry deposition, nitrogen fixation, and animal droppings," as described by Schlesinger et al. (1990), Archer et al. (1995), Reynolds et al. (1999), and Lopez-Pintor et al. (2006). They report "changes in soil attributes under woody vegetation have been documented in the arid grasslands of the southern Great Plains, including increases in soil carbon and nitrogen," citing Reynolds et al. (1999), Hibbard et al. (2001, 2003), McCulley et al. (2004), Schade and Hobbie (2005), and Liao et al. (2006).

For their part of this massive undertaking—while working at the USDA-ARS Northern Great Plains Research Laboratory near Mandan, North Dakota (USA)—Springsteen et al. examined near-surface (upper 15 cm) soil biogeochemistry along a 42-year (1963–2005) chronosequence that encompassed grassland, woodland, and grassland-woodland transition zones in a northern Great Plains grassland, in order to determine the influence of woody plant expansion on soil carbon and nitrogen contents. They found total soil carbon content rose by 26 percent across the chronosequence from grassland to woodland within the 0–15 cm soil depth, and total soil nitrogen content rose by 31 percent. The rate of woody shrub expansion from 1963 to 1988 (25 years) was ~1,800 m^2 per year at their study site, whereas from 1988 to 2005 (17 years) it was ~3,800 m^2 per year, or a little more than double the initial rate, as the greening of the Earth accelerated to keep pace with the accelerating increase of the air's CO_2 content.

In the U.S. mid-Atlantic region, Pan et al. (2010) examined "how changes in atmospheric composition (CO_2, O_3 and N deposition), climate and land-use affected carbon dynamics and sequestration in Mid-Atlantic temperate forests during the 20th century." They modified and applied "a well established process-based ecosystem model with a strong foundation of ecosystem knowledge from experimental studies," which they validated "using the U.S. Forest Inventory and Analysis (FIA) data."

For previously harvested and currently regrowing forests, the calibrated model produced the following percentage changes in net ecosystem productivity (NEP) due to observed changes in N deposition (+32 percent), CO_2 (+90 percent), O_3 (-40 percent), CO_2 + O_3 (+60 percent), CO_2 + N deposition (+184 percent), and CO_2 + N deposition + O_3 (+138 percent), while corresponding changes in NEP for undisturbed forests were +18 percent, +180 percent, -75 percent, +78 percent, +290 percent, and +208 percent. The model results also revealed "the 'fertilization' effect of N deposition mainly stimulates carbon allocation to short-lived tissues such as foliage and fine roots," but "the 'fertilization' effect by elevated CO_2 likely enhances more sustainable carbon storage such as woody biomass (including coarse roots)." The four USDA Forest Service scientists state their findings indicate "the change in atmospheric composition, particularly elevated CO_2, will gradually account for more of the carbon sink of temperate forests in the Mid-Atlantic region," and they conclude "such a significant 'fertilization effect' on the forest carbon sequestration could eventually result in a 'greener world' after a long period of chronic change in atmospheric composition and cumulative impact."

Martinez-Vilalta et al. (2008) used tree-ring data from the Catalan Ecological and Forest Inventory "to study the temporal variability of Scots pine stem radial growth (period 1901–1997) across a relatively large region (Catalonia, NE Spain) situated close to the southern limit of the distribution of the species." This inventory "included a total of 10,664 plots randomly distributed throughout the forested area of Catalonia," where Scots pine was present in 30.2 percent of the plots and was the dominant tree species in 18.4 percent of the plots. The inventory "showed an overall increase of 84% in Scots pine BAI [basal area increment] during the twentieth century, consistent with most previous studies for temperate forests." The scientists state "this trend was associated with increased atmospheric CO_2 concentration," which they interpret as "a fertilization effect." In addition, over the same time period, the five researchers note "there was also a marked increase in temperature across the study region (0.19°C per decade on average)," and they report "this warming had a negative impact on radial growth, particularly at the drier sites," but "its magnitude was not enough to counteract the fertilization effect."

Cole et al. (2010) introduce their study of the subject by noting that quaking aspen (*Populus tremuloides* Michx.) is a dominant forest type in north-temperate, montane and boreal regions of North America," stating it is, in fact, "the most widely distributed tree species on the continent." They also note that aspen—and related poplars—are "quintessential foundation species (Ellison et al., 2005), shaping the structure and function of the communities and ecosystems in which they occur (Whitham et al., 2006; Schweitzer et al., 2008; Madritch et al., 2009)." This being the case, they attempted to determine how this keystone species may have responded to the twentieth-century increase in atmospheric CO_2 concentration.

The four researchers collected branches from 919 trees after their leaves had dropped in the fall, obtaining samples that represented 189 genets or clones (five trees per clone) at 11 sites distributed throughout three regions of Wisconsin (USA). The sampled trees ranged from five to 76 years of age and came from second-growth unmanaged forests south of the areas defoliated by forest tent caterpillars in 1980–1982, 1989–1990, and 2001–2002. In addition, they recorded trunk diameter at breast height for each sampled tree, which parameter, in their words, "is very highly correlated with total biomass in aspen," citing Bond-Lamberty et al. (2002).

The Minnesota and Wisconsin scientists determined "age-specific ring width increased over time," and "the greatest increase occurred for relatively young trees, so that young trees grew faster in recent years than did young trees several decades ago." They found, for example, that during the past half-century the growth of trees 11–20 years old rose by 60 percent. In addition, they observed "rising CO_2 causes ring width to increase at all moisture levels, apparently resulting from improved water use efficiency," so "the overall increase results from historical increases in both CO_2 and water availability." And when they separated the impacts of the two factors, they found "the effect of rising CO_2 had been to increase ring width by about 53%," as a result of "a 19.2% increase in ambient CO_2 levels during the growing season, from 315.8 ppm in 1958 (when CO_2 records began) to 376.4 ppm in 2003."

Cole et al. state "the magnitude of the growth increase uncovered by this analysis raises the question of how much other major forest species have responded to the joint effects of long-term changes in CO_2 and precipitation." Indeed, there is reason to believe many other tree species may have experienced similar large growth stimulation, particularly in light of the analysis of Tans (2009), who demonstrated the Earth's land surfaces were a net source of CO_2 to the atmosphere until about 1940—primarily due to the felling of forests and the plowing of grasslands to make way for expanded agricultural activities—but from 1940 onward the terrestrial biosphere had become, in the mean, an increasingly greater sink for CO_2 and had done so even in the face of massive global deforestation, for which it apparently more than compensated.

References

Alcaraz-Segura, D., Chuvieco, E., Epstein, H.E., Kasischke, E.S., and Trishchenko, A. 2010. Debating the greening vs. browning of the North American boreal forest: differences between the satellite datasets. *Global Change Biology* **16**: 760–770.

Archer, S., Schimel, D.S., and Holland, E.A. 1995. Mechanisms of shrubland expansion: land use, climate or CO_2? *Climatic Change* **29**: 91–99.

Baker, T.R., Phillips, O.L., Malhi, Y., Almeida, S., Arroyo, L., Di Fiore, A., Erwin, T., Higuchi, N., Killeen, T.J., Laurance, S.G., Laurance, W.F., Lewis, S.L., Monteagudo, A., Neill, D.A., Núñez Vargas, P., Pitman, N.C.A., Silva, J.N.M., and Vásquez Martinez, R. 2004a. Increasing biomass in Amazonian forest plots. *Philosophical Transactions of the Royal Society of London Series B - Biological Sciences* **359**: 353–365.

Baker, T.R., Phillips, O.L., Malhi, Y., Almeida, S., Arroyo, L., Di Fiore, A., Erwin, T., Killeen, T.J., Laurance, S.G., Laurance, W.F., Lewis, S.L., Lloyd, J., Monteagudo, A., Neil, D.A., Patiño, S., Pitman, N.C.A., Silva, N.M., and Vásquez Martinez, R. 2004b. Variation in wood density determines spatial patterns in Amazonian forest biomass. *Global Change Biology* **10**: 545–562.

Boisvenue, C. and Running, S. 2006. Impacts of climate change on natural forest productivity—evidence since the middle of the 20th century. *Global Change Biology* **12**: 862–882.

Bond, W.J. and Midgley, G.F. 2000. A proposed CO_2-controlled mechanism of woody plant invasion in grasslands and savannas. *Global Change Biology* **6**: 865–869.

Bond, W.J., Midgley, G.F., and Woodward, F.I. 2003. The importance of low atmospheric CO_2 and fire in promoting the spread of grasslands and savannas. *Global Change Biology* **9**: 973–982.

Bond-Lamberty, B., Wang, C., and Gower, S.T. 2002. Aboveground and belowground biomass and sapwood area allometric equations for six boreal tree species of northern Manitoba. *Canadian Journal of Forest Research* **32**: 1441–1450.

Chave, J., Condit, R., Muller-Landau, H.C., Thomas, S.C., Ashton, P.S., Bunyavejchewin, S., Co, L.L., Dattaraja, H.S., Davies, S.J., Esufali, S., Ewango, C.E.N., Feeley, K.J., Foster, R.B., Gunatilleke, N., Gunatilleke, S., Hall, P., Hart, T.B., Hernández, C., Hubbell, S.P., Itoh, A., Kiratiprayoon, S., LaFrankie, J.V., de Lao, S.L., Makana, J.-R., Noor, Md.N.S., Kassim, A.R., Samper, C., Sukumar, R., Suresh, H.S., Tan, S., Thompson, J., Tongco, Ma.D.C., Valencia, R., Vallejo, M., Villa, G., Yamakura, T., Zimmerman, J.K., and Losos, E.C. 2008. Assessing evidence for a pervasive alteration in tropical tree communities. *PLoS Biology* **6**: 10.1371/journal.pbio.0060045.

Cole, C.T., Anderson, J.E., Lindroth, R.L., and Waller, D.M. 2010. Rising concentrations of atmospheric CO_2 have increased growth in natural stands of quaking aspen (*Populus tremuloides*). *Global Change Biology* **16**: 2186–2197.

Delpierre, N., Soudani, K., Francois, C., Kostner, B., Pontailler, J.-Y., Nikinmaa, E., Misson, L., Aubinet, M., Bernhofer, C., Granier, A., Grunwald, T., Heinesch, B., Longdoz, B., Ourcival, J.-M., Rambal, S., Vesala, T., and Dufrene, E. 2009. Exceptional carbon uptake in European forests during the warm spring of 2007: A data-model analysis. *Global Change Biology* **15**: 1455–1474.

Ellison, A.M., Bank, M.S., Clinton, B.D., Colburn, E.A., Elliott, K., Ford, C.R., Foster, D.R., Kloeppel, B.D., Knoepp, J.D., Lovett, G.M., Mohan, J., Orwig, D.A., Rodenhouse, N.L., Sobczak, W.V., Stinson, K.A., Stone, J.K., Swan, C.M., Thompson, J., Holle, B.V., and Webster, J.R. 2005. Loss of foundation species: consequences for the structure and dynamics of forested ecosystems. *Frontiers in Ecology and the Environment* **3**: 479–486.

Gloor, M., Phillips, O.L., Lloyd, J.J., Lewis, S.L., Malhi, Y., Baker, T.R., Lopez-Gonzalez, G., Peacock, J., Almeida, S., Alves de Oliveira, A.C., Alvarez, E., Amaral, I., Arroyo, L., Aymard, G., Banki, O., Blanc, L., Bonal, D., Brando, P., Chao, K.-J., Chave, J., Davila, N., Erwin, T., Silva, J., DiFiore, A., Feldpausch, T.R., Freitzs, A., Herrera, R., Higuchi, N., Honorio, E., Jimenez, E., Killeen, T., Laurance, W., Mendoza, C., Monteagudo, A., Andrade, A. Neill, D., Nepstad, D., Nunez Vargas, P., Penuela, M.C., Pena Cruz, A., Prieto, A., Pitman, N., Quesada, C., Salomao, R., Silveira, M., Schwarz, M., Stropp, J., Ramirez, F., Ramirez, H., Rudas, A., ter Steege, H., Silva, N., Torres, A., Terborgh, J., Vasquez, R., and van der Heijden, G. 2009. Does the disturbance hypothesis explain the biomass increase in basin-wide Amazon forest plot data? *Global Change Biology* **15**: 2418–2430.

Hibbard, K.A., Archer, S., Schimel, D.S., and Valentine, D.W. 2001. Biogeochemical changes accompanying woody plant encroachment in a subtropical savanna. *Ecology* **82**: 1999–2011.

Hibbard, K.A., Schimel, D.S., Archer, S., Ojima, D.S., and Parton, W. 2003. Grassland to woodland transitions: integrating changes in landscape structure and biogeochemistry. *Ecological Applications* **13**: 911–926.

Katinas, L. and Crisci, J.V. 2008. Reconstructing the biogeographical history of two plant genera with different dispersion capabilities. *Journal of Biogeography* **35**: 1374–1384.

Lewis, S.L., Lloyd, J., Sitch, S., Mitchard, E.T.A., and Laurance, W.F. 2009b. Changing ecology of tropical forests: Evidence and drivers. *Annual Review of Ecology, Evolution, and Systematics* **40**: 529–549.

Lewis, S.L., Lopez-Gonzalez, G., Sonke, B., Affum-Baffoe, K., Baker, T.R., Ojo, L.O., Phillips, O.L., Reitsma, J.M., White, L., Comiskey, J.A., Djuikouo Kamden, M.-N., Ewango, C.E.N., Feldpausch, T.R., Hamilton, A.C., Gloor, M., Hart, T., Hladik, A., Lloyd, J., Lovett, J.C., Makana, J.-R., Malhi, Y., Mbago, F.M., Ndangalasi, H.J., Peacock, J., Peh, K. S.-H., Sheil, D., Sunderland, T., Swaine, M.D., Taplin, J., Taylor, D., Thomas, S.C., Votere, R., and Woll, H. 2009a. Increasing carbon storage in intact African tropical forests. *Nature* **457**: 1003–1006.

Lewis, S.L., Phillips, O.L., Baker, T.R., Lloyd, J., Malhi, Y., Almeida, S., Higuchi, N., Laurance, W.F., Neill, D.A., Silva, J.N.M., Terborgh, J., Lezama, A.T., Vasquez Martinez, R., Brown, S., Chave, J., Kuebler, C., Núñez Vargas, P., and Vinceti, B. 2004. Concerted changes in tropical forest structure and dynamics: evidence from 50 South American long-term plots. *Philosophical Transactions of the Royal Society of London Series B - Biological Sciences* **359**: 421–436.

Liao, J.D., Boutton, T.W., and Jastrow, J.D. 2006. Storage and dynamics of carbon and nitrogen in soil physical fractions following woody plant invasion of grassland. *Soil Biology and Biochemistry* **38**: 3184–3196.

Lopez-Pintor, A., Sal, A.G., and Benayas, J.M. R. 2006. Shrubs as a source of spatial heterogeneity—the case of *Retama sphaerocarpa* in Mediterranean pastures of central Spain. *Acta Oecologia* **29**: 247–255.

Madritch, M.D., Greene, S.G., and Lindroth, R.L. 2009. Genetic mosaics of ecosystem functioning across aspen-dominated landscapes. *Oecologia* **160**: 119–127.

Martinez-Vilalta, J., Lopez, B.C., Adell, N., Badiella, L., and Ninyerola, M. 2008. Twentieth century increase of Scots pine radial growth in NE Spain shows strong climate interactions. *Global Change Biology* **14**: 2868–2881.

McCulley, R.L., Archer, S.R., Boutton, T.W., Hons, F.M., and Zuberer, D.A. 2004. Soil respiration and nutrient cycling in wooded communities developing in grassland. *Ecology* **85**: 2804–2817.

McMahon, S.M., Parker, G.G., and Miller, D.R. 2010. Evidence for a recent increase in forest growth. *Proceedings of the National Academy of Sciences USA* **107**: 3611–3615.

Myneni, R., Keeling, C., Tucker, C., Asrar, G., and Nemani, R. 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* **386**: 698–702.

Pan, Y., Birdsey, R., Hom, J., and McCullough, K. 2010. Separating effects of changes in atmospheric composition, climate and land-use on carbon sequestration of U.S. Mid-Atlantic temperate forests. *Forest Ecology and Management* **259**: 151–164.

Phillips, O.L., Baker, T.R., Arroyo, L., Higuchi, N., Killeen, T.J., Laurance, W.F., Lewis, S.L., Lloyd, J., Malhi, Y., Monteagudo, A., Neill, D.A., Núñez Vargas, P., Silva, J.N.M., Terborgh, J., Vásquez Martinez, R., Alexiades, M., Almeida, S., Brown, S., Chave, J., Comiskey, J.A., Czimczik, C.I., Di Fiore, A., Erwin, T., Kuebler, C., Laurance, S.G., Nascimento, H.E.M., Olivier, J., Palacios, W., Patiño, S., Pitman, N.C.A., Quesada, C.A., Saldias, M., Torres Lezama, A.B., and Vinceti, B. 2004. Pattern and process in Amazon tree turnover: 1976–2001. *Philosophical Transactions of the Royal Society of London Series B - Biological Sciences* **359**: 381–407.

Phillips, O.L. and Gentry, A.H. 1994. Increasing turnover through time in tropical forests. *Science* **263**: 954–958.

Phillips, O.L., Malhi, Y., Higuchi, N., Laurance, W.F., Nunez, P.V., Vasquez, R.M., Laurance, S.G., Ferreira, L.V., Stern, M., Brown, S., and Grace, J. 1998. Changes in the carbon balance of tropical forests: evidence from long-term plots. *Science* **282**: 439–442.

Polley, H.W. 1997. Implications of rising atmospheric carbon dioxide concentration for rangelands. *Journal of Range Management* **50**: 561–577.

Reynolds, J.F., Virginia, R.A., Kemp, P.R., de Soyza, A.G., and Tremmel, D.C. 1999. Impact of drought on desert shrubs: effects of seasonality and degree of resource island development. *Ecological Monographs* **69**: 69–106.

Salzer, M., Hughes, M., Bunn, A., and Kipfmueller, K. 2009. Recent unprecedented tree-ring growth in bristlecone pine at the highest elevations and possible causes. *Proceedings of the National Academies of Science USA* **106**: 20,346–20,353.

Schade, J.D. and Hobbie, S.E. 2005. Spatial and temporal variation in islands of fertility in the Sonoran Desert. *Biogeochemistry* **73**: 541–553.

Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jarrell, W.M., Ross, V.A., and Whitford, W.G. 1990. Biological feedbacks in global desertification. *Science* **247**: 1043–1048.

Schweitzer, J.A., Madritch, M.D., Bailey, J.K., LeRoy, C.J., Fischer, D.G., Rehill, B.J., Lindroth, R.L., Hagerman, A.E., Wooley, S.C., Hart, S.C., and Whitham, T.G. 2008. The genetic basis of condensed tannins and their role in nutrient regulation in a *Populus* model system. *Ecosystems* **11**: 1005–1020.

Silva, L.C.R., Anand, M., Oliveira, J.M., and Pillar, V.D. 2009. Past century changes in *Araucaria angustifolia* (Bertol.) Kuntze water use efficiency and growth in forest and grassland ecosystems of southern Brazil: implications for forest expansion. *Global Change Biology* **15**: 2387–2396.

Springsteen, A., Loya, W., Liebig, M., and Hendrickson, J. 2010. Soil carbon and nitrogen across a chronosequence of woody plant expansion in North Dakota. *Plant and Soil* **328**: 369–379.

Tans, P. 2009. An accounting of the observed increase in oceanic and atmospheric CO_2 and an outlook for the future. *Oceanography* **22**: 26–35.

Whitham, T.G., Bailey, J.K., and Schweitzer, J.A. 2006. A framework for community and ecosystem genetics from genes to ecosystems. *Nature Reviews Genetics* **7**: 510–523.

7.11.3. High Latitudes

In the introduction to their report on the response of High Arctic tundra vegetation to the warming experienced in that part of the world over the past quarter-century, Hudson and Henry (2009) note the Arctic warmed by about 1.6°C over the past four decades, citing McBean et al. (2005). They state this temperature increase “led the Arctic Climate Impact Assessment (ACIA) and Intergovernmental Panel on Climate Change (IPCC) to predict that tundra ecosystems will be particularly threatened by climate change [i.e., warming] over the next century.” To test this prediction, the authors set out to find if plants of the High Arctic tundra have been growing more or less vigorously or abundantly during the recent warming period.

At an 8-km^2 coastal lowland adjacent to Alexandra Fiord on the east-central coast of Ellesmere Island, Nunavut, Canada, Hudson and Henry measured biomass and composition changes in a heath community dominated by several vascular plants and bryophytes. They did this over a period of 13 years (1995–2007), using a point-intercept method in permanent plots, and over a period of 27 years (1981–2008) using a biomass harvest comparison. “Results from both methods,” in the words of the Canadian scientists, “indicate that the community became more productive over time.” The note “bryophyte and evergreen shrub abundances increased,” while “deciduous shrub, forb, graminoid, and lichen cover did not change,” so that “species diversity also remained unchanged.” All of these changes—and non-changes—are a far cry from the “particularly threatened” view of the ACIA and IPCC.

In further support of their findings, Hudson and Henry report “satellite-based remote sensing models, such as green trends derived from the normalized difference vegetation index (NDVI; e.g., Myneni et al., 1997; Zhou et al., 2001; Stow et al., 2004; Verbyla, 2008), and global vegetation and ecosystem process simulations of the terrestrial carbon cycle (e.g., Kimball et al., 2006; Zhang et al., 2008), indicate increasing trends in vegetation photosynthetic activity and net primary production in the Arctic over the past several decades.” As for what drove this welcome transformation of the tundra, Hudson and Henry say “it is likely that warming directly increased plant growth and reproduction and indirectly increased resource supply,” while “increased temperatures also lengthened the growing season, increased soil temperature, deepened the active [soil] layer, and consequently may have influenced nutrient uptake in the plant community.”

Nevertheless, some people continue to claim anthropogenic global warming will have widespread adverse effects on ecosystems, and one of the regions they claim to be most vulnerable is the Arctic. Jia et al. (2009) utilized 25 years of satellite data covering the period of most rapid recent warming (1982 to 1996) to evaluate this contention via NDVI data obtained from the GIMMS dataset, which consists of 64-km^2 cells minus those cells with too much open water or bare ground within them that are known to inject significant bias into NDVI data analyses. This study showed tundra ecosystems exhibited an average increase in greenness of 5.6 percent per decade over 96 percent of the pixels evaluated, which was proportional to the rate of summer warming as measured by growing degree days. The three researchers state the decadal increases of vegetation greenness over the tundra biome in summer “reflect increasing vegetation productivity during the growing season.”

Working at a site just three kilometers from the Abisko Scientific Research Station (68°21'N, 18°49'E) in the Northern Swedish Scandes, Hallinger et al. (2010) studied male plants of the medium-sized *Juniperus nana* shrub, collecting the main stems of five to eight shrubs every hundred meters of elevation until the shrub zone ended. They then performed ring-width measurements on these stems, "to measure radial and vertical growth, to track growth changes over time, to age the shrub individuals and to correlate annual shrub growth with climate." Data for the latter factor were derived from records of the nearby Abisko Station. By these means the three researchers identified "a distinct increase in radial and vertical growth rates of *J. nana* shrubs during recent decades in the subalpine zone of North Sweden," and they state "the age structure of shrubs along the elevational gradient provides evidence that an upslope advance of the altitudinal shrubline is underway." In addition, they state they observed "significant, strong and stable correlations between annual ring width and summer temperatures (June, July, August)," and "the acceleration of radial and vertical growth since 1970 also coincides with the recent three decades of rising arctic air temperatures and the warming trend of 0.2°C per decade for the average temperature since 1956 at Abisko." Thus, the German scientists' study adds to what they call the "mounting evidence that shrubs are expanding into alpine and arctic areas because of climate warming," and they note "this expansion occurs in both evergreen and deciduous shrub types," citing Forbes et al. (2010).

Other remote-sensing data suggest tundra vegetation in North America may be responding to recent warming via increased photosynthetic activity (Goetz et al., 2005; Verbyla , 2008). Forbes et al. (2010) write, "at a circumpolar scale, the highest photosynthetic activity and strongest growth trends are reported in locations characterized by erect shrub tundra (Reynolds et al., 2006)," noting "live leaf phytomass from deciduous shrubs, shown to have increased in northern Alaska during the second half of the last century (Sturm et al., 2001; Tape et al., 2006), is believed to be a key driver of the observed trends (Jia et al., 2003; Goetz et al., 2005; Verbyla, 2008)." Therefore, working with *Salix lanata* L. (*sensu latu*)—an abundant deciduous dioecious willow with nearly circumpolar geographic distribution from the northern boreal forest to the northern limits of the Low Arctic—Forbes et al. analyzed annual ring growth for 168 stem slices of 2- to 3-cm thickness collected from 40 discrete individuals spread across 15 sample sites within an area of approximately 3 x 2.3 km, located at about 68°40'N, 58°30'E, to further examine this phenomenon.

The three scientists state they detected "a clear relationship with photosynthetic activity for upland vegetation at a regional scale for the period 1981–2005, confirming a parallel 'greening' trend reported for similarly warming North American portions of the tundra biome," and they state "the standardized growth curve suggests a significant increase in shrub willow growth over the last six decades." Additionally noting "the quality of the chronology as a climate proxy is exceptional," Forbes et al. go on to state their findings "are in line with field and remote sensing studies that have assigned a strong shrub component to the reported greening signal since the early 1980s," adding the growth trend agrees with the qualitative observations of nomadic reindeer herders, which suggest there have been "recent increases in willow size in the region." They state their analysis "provides the best proxy assessment to date that deciduous shrub phytomass has increased significantly in response to an ongoing summer warming trend."

Contemporaneously, Zhuang et al. (2010) used a process-based biogeochemistry model—the Terrestrial Ecosystem Model or TEM, which also employed a soil thermal model—to examine permafrost dynamics and their effects on the carbon dynamics of the Tibetan Plateau over the past century. This was done by "parameterizing and verifying" the TEM using existing real-world data for soil temperature, permafrost distribution, and carbon and nitrogen distributions throughout the region, and then extrapolating the model and its parameters to the whole of the plateau. The six scientists found, "during the 20th century, the Tibetan Plateau changed from a small carbon source or neutral in the early part of the century to a sink later." They note "net primary production and soil respiration increased by 0.52 and 0.22 Tg C/year, respectively, resulting in a regional carbon sink increase of 0.3 Tg C/year," so that "by the end of the century, the regional carbon sink reached 36Tg C/year and carbon storage in vegetation and soils is 32 and 16 Pg C, respectively."

Zhuang et al. state the "increasing soil temperature and deepening active layer depth enhanced soil respiration, increasing the net nitrogen mineralization rate," and "together with the [positive] effects of warming air temperature and rising CO_2

concentrations on photosynthesis, the stronger plant nitrogen uptake due to the enhanced available nitrogen stimulated plant carbon uptake, thereby strengthening the regional carbon sink as the rate of increase in net primary production was faster than that of soil respiration.” Thus, they conclude “future warming will increase thawing of the permafrost, increase soil temperature and dry up soil moisture,” and “these physical dynamics may enhance [the] future strength of the regional carbon sink, since the rate of increase of net primary production is higher than that of soil respiration on the Tibetan Plateau.”

References

Forbes, B.C., Fauria, M., and Zetterberg, P. 2010. Russian Arctic warming and ‘greening’ are closely tracked by tundra shrub willows. *Global Change Biology* **16**: 1542–1554.

Goetz, S.J., Bunn, A.G., Fiske, G.J., and Houghton, R.A. 2005. Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance. *Proceedings of the National Academy of Sciences USA* **102**: 13,521–13,525.

Hallinger, M., Manthey, M., and Wilmking, M. 2010. Establishing a missing link: warm summers and winter snow cover promote shrub expansion into alpine tundra in Scandinavia. *New Phytologist* **186**: 890–899.

Hudson, J.M.G. and Henry, G.H.R. 2009. Increased plant biomass in a High Arctic heath community from 1981 to 2008. *Ecology* **90**: 2657–2663.

Jia, G.J., Epstein, H.E., and Walker, D.A. 2003. Greening of arctic Alaska, 1981–2001. *Geophysical Research Letters* **30**: 31–33.

Jia, G.J., Epstein, H.E., and Walker, D.A. 2009. Vegetation greening in the Canadian Arctic related to decadal warming. *Journal of Environmental Monitoring* **11**: 2231–2238.

Kimball, J.S., Zhao, M., Mcguire, A.D., Heinsch, F.A., Clein, J., Calef, M.P., Jolly, W.M., Kang, S., Euskirchen, S.E., McDonald, K.C., and Running, S.W. 2006. Recent climate-driven increases in vegetation productivity for the Western Arctic: evidence for an acceleration of the northern terrestrial carbon cycle. *Earth Interactions* **11**: 1–23.

McBean, G., Alekseev, G., Chen, D., Forland, E., Fyfe, J., Groisman, P.Y., King, R., Melling, H., Vose, R., and Whitfield, P.H. 2005. Arctic climate: past and present. In *Arctic Climate Impact Assessment: Scientific Report*, 21–60. Cambridge, UK: Cambridge University Press.

Myneni, R.B., Keeling, C.D., Tucker, C.J., Asrar, G., and Nemani, R.R. 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* **386**: 698–702.

Reynolds, M.K., Walker, D.A., and Maier, H.A. 2006. NDVI patterns and phytomass distribution in the circumpolar Arctic. *Remote Sensing of Environment* **102**: 271–281.

Stow, D.A., Hope, A., McGuire, D., Verbyla, D., Gamon, J., Huemmrich, F., Houston, S., Racine, C., Sturm, M., Tape, K., Hinzman, L., Yoshikawa, K., Tweedie, C., Noyle, B., Silapaswan, C., Douglas, D., Griffith, B., Jia, G., Epstein, H., Walker, D., Daeschner, S., Petersen, A., Liming, Z., and Myneni, R. 2004. Remote sensing of vegetation and land-cover change in Arctic tundra ecosystems. *Remote Sensing of Environment* **89**: 281–308.

Sturm, M., Racine, C., and Tape, K. 2001. Increasing shrub abundance in the Arctic. *Nature* **411**: 546–547.

Tape, K., Sturm, M., and Racine, C.H. 2006. The evidence for shrub expansion in northern Alaska and the Pan-Arctic. *Global Change Biology* **32**: 686–702.

Verbyla, D. 2008. The greening and browning of Alaska based on 1982–2003 satellite data. *Global Ecology and Biogeography* **17**: 547–555.

Zhang, K., Kimball, J.S., Hogg, E.H., Zhao, M.S., Oechel, W.C., Cassano, J.J., and Running, S.W. 2008. Satellite-based model detection of recent climate-driven changes in northern high-latitude vegetation productivity. *Journal of Geophysical Research-Biogeosciences* **113**: G03033.

Zhou, L.M., Tucker, C.J., Kaufmann, R.K., Slayback, D., Shabanov, N.V., and Myneni, R.B. 2001. Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. *Journal of Geophysical Research* **106**: 20,069–20,083.

Zhuang, Q., He, J., Lu, Y., Ji, L., Xiao, J., and Luo, T. 2010. Carbon dynamics of terrestrial ecosystems on the Tibetan Plateau during the 20th century: an analysis with a process-based biogeochemical model. *Global Ecology and Biogeography* **19**: 649–662.

7.11.4. The Globe

Periodically, even in some of the world’s most prestigious scientific journals, it is said the natural sinks of Earth’s carbon cycle are becoming decreasingly effective in removing from the atmosphere the CO_2 released to it as a result of humanity’s energy-intensive activities (Canadell et al., 2007; LeQuere et al., 2007). This myth, however, has been put to rest once and for all by a new analysis of real-world data.

In a study published in the December 2009 issue of *Oceanography* that considered several related topics, Pieter Tans of the National Oceanic and Atmospheric Administration (NOAA) employed measurements of atmospheric and oceanic carbon contents, along with reasonably constrained estimates of global anthropogenic CO_2 emissions, to calculate the residual fluxes of carbon (in the form of CO_2) from the terrestrial biosphere to the atmosphere (+) or from the atmosphere to the terrestrial biosphere (-), obtaining the results depicted in Figure 7.11.1.

As the figure illustrates, Earth's land surfaces were a net source of CO_2-carbon to the atmosphere until about 1940, primarily due to the felling of forests and the plowing of grasslands to make way for expanded agricultural activities. From 1940 onward, however, the terrestrial biosphere has become, in the mean, an increasingly greater sink for CO_2-carbon, and it has done so even in the face of massive global deforestation, for which it has more than compensated. These findings do "not depend on models" but "only on the observed atmospheric increase and estimates of fossil fuel emissions," Tans notes.

Tans concludes, "suggestions that the carbon cycle is becoming less effective in removing CO_2 from the atmosphere (e.g., LeQuere et al., 2007; Canadell et al., 2007) can perhaps be true locally, but they do not apply globally, not over the 50-year atmospheric record, and not in recent years." In fact, he adds, "to the contrary" and "despite global fossil fuel emissions increasing from 6.57 GtC in 1999 to 8.23 in 2006, the five-year smoothed global atmospheric growth rate has not increased during that time, which requires more effective uptake [of CO_2] either by the ocean or by the terrestrial biosphere, or both, to satisfy atmospheric observations." Tans' results, depicted in Figure 6.11.1, clearly indicate this "more effective uptake" of CO_2-carbon has occurred primarily over land.

This observation-based analysis of real-world data provides strong evidence for both the reality and the tremendous strength of the CO_2-induced greening of the Earth phenomenon, which has been observed in numerous independent studies conducted throughout the world. In addition, it refutes the unfounded arguments that various environmental stresses and resource limitations will not allow the full potential of the aerial fertilization effect of atmospheric CO_2 enrichment to be manifest in nature. This phenomenon is itself a "force of nature" that can be neither hindered nor halted.

Most recently, Lin et al. (2010) noted "most models predict that climate warming will increase the

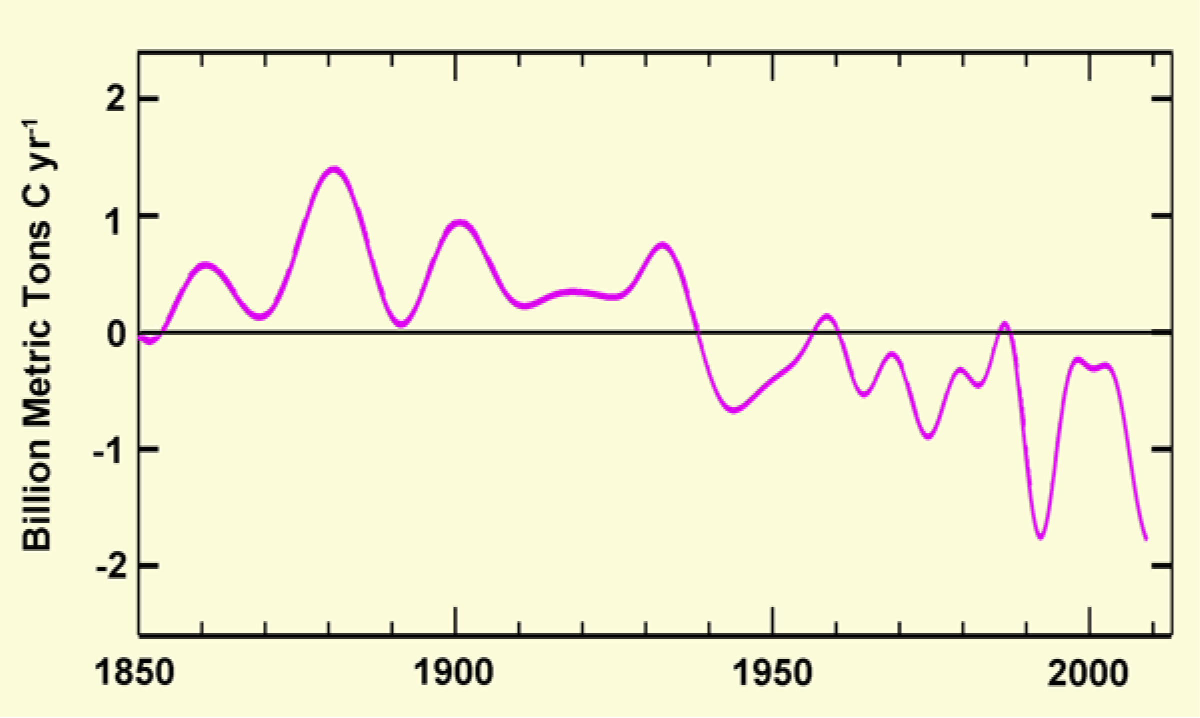


Figure 7.11.1. Five-year smoothed rates of global carbon transfer from land to air (+) or from air to land (-) vs. time. Adapted from Tans (2009).

release of carbon dioxide from the terrestrial biosphere into the atmosphere, thus triggering positive climate-terrestrial carbon feedback which leads to a warmer climate." However, they state the "stimulation of biomass accumulation and net primary productivity of terrestrial ecosystems under rising temperature (Rustad et al., 2001; Melillo et al., 2002; Luo et al., 2009) may enhance carbon sequestration and attenuate the positive feedback between climate warming and the terrestrial biosphere."

In an effort to find out which view is correct, Lin et al. conducted a meta-analysis of pertinent data from 127 individual studies published before June 2009, in order to ascertain whether the overall impact of a substantial increase in the air's CO_2 concentration on terrestrial biomass production would likely be positive or negative. The three scientists determined that for the totality of terrestrial plants included in their analysis, "warming significantly increased biomass by 12.3%," and there was a "significantly greater stimulation of woody (+26.7%) than herbaceous species (+5.2%)." They also found the warming effects on plant biomass production "did not change with mean annual precipitation or experimental duration," and "other treatments, including CO_2 enrichment, nitrogen addition, drought and water addition, did not alter warming responses of plant biomass."

The Chinese researchers thus conclude "results in this and previous meta-analyses (Arft et al., 1999; Rustad et al., 2001; Dormann and Woodin, 2002; Walker et al., 2006) have revealed that warming generally increases terrestrial plant biomass, indicating enhanced terrestrial carbon uptake via plant growth and net primary productivity." Thus, we can logically expect that the ongoing rise in the air's CO_2 content will soften its tendency to increase global temperatures while causing greater growth rates and biomass production of terrestrial vegetation.

References

Arft, A.M., Walker, M.D., Gurevitch, J., Alatalo, J.M., Bret-Harte, M.S., Dale, M., Diemer, M., Gugerli, F., Henry, G.H.R., Jones, M.H., Hollister, R.D., Jonsdottir, I.S., Laine, K., Levesque, E., Marion, G.M., Molau, U., Molgaard, P., Nordenhall, U., Raszhivin, V., Robinson, C.H., Starr, G., Stenstrom, A., Stenstrom, M., Totland, O., Turner, P.L., Walker, L.J., Webber, P.J., Welker, J.M., and Wookey, P.A. 1999. Responses of tundra plants to experimental warming: meta-analysis of the international tundra experiment. *Ecological Monographs* **69**: 491–511.

Canadell, J.G., LeQuere, C., Raupach, M.R., Field, C.B., Buitenhuis, E.T,., Ciais, P., Conway, T.J., Gillett, N.P., Houghton, R.A., and Marland, G. 2007. Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the National Academy of Sciences of the United States of America* **104**: 18,866–18,870.

Dormann, C.F. and Woodin, S.J. 2002. Climate change in the arctic: using plant functional types in a meta-analysis of field experiments. *Functional Ecology* **16**: 4–17.

LeQuere, C., Rodenbeck, C., Buitenhuis, E.T., Conway, T.J., Langenfelds, R., Gomez, A., Labuschagne, C., Ramonet, M., Nakazawa, T., Metzl, N., Gillett, N., and Heimann, M. 2007. Saturation of the Southern Ocean CO_2 sink due to recent climate change. *Science* **316**: 1735–1738.

Lin, D., Xia, J., and Wan, S. 2010. Climate warming and biomass accumulation of terrestrial plants: a meta-analysis. *New Phytologist* **188**: 187–198.

Luo, Y.Q., Sherry, R., Zhou, X.H., and Wan, S.Q. 2009. Terrestrial carbon-cycle feedback to climate warming: experimental evidence on plant regulation and impacts of biofuel feedstock harvest. *Global Change Biology Bioenergy* **1**: 62–74.

Melillo, J.M., Steudler, P.A., Aber, J.D., Newkirk, K., Lux, H., Bowles, F.P., Catricala, C., Magill, A., Ahrens, T., and Morrisseau, S. 2002. Soil warming and carbon-cycle feedbacks to the climate system. *Science* **298**: 2173–2176.

Rustad, L.E., Campbell, J.L., Marion, G.M., Norby, R.J., Mitchell, M.J., Hartley, A.E., Cornelissen, J.H.C., Gurevitch, J., and GCTE-NEWS. 2001. A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. *Oecologia* **126**: 543–562.

Tans, P. 2009. An accounting of the observed increase in oceanic and atmospheric CO_2 and an outlook for the future. *Oceanography* **22**: 26–35.

Walker, M.D., Wahren, C.H., Hollister, R.D., Henry, G.H.R., Ahlquist, L.E., Alatalo, J.M., Bret-Harte, M.S., Calef, M.P., Callaghan, T.V., Carroll, A.B., Epstein, H.E., Jonsdottir, I.S., Klein, J.A., Magnusson, B., Molaug, U., Oberbauer, S.F., Rewan, S.P., Robinson, C.H., Shaver, G.R., Suding, K.N., Thompson, C.C., Tolvanen, A., Totland, O., Turner, P.L., Tweedie, C.E., Webber, P.J., and Wookey, P.A. 2006. Plant community responses to experimental warming across the tundra biome. *Proceedings of the National Academy of Sciences USA* **103**: 1342–1346.

7.11.5. Miscellaneous

Logan et al. (2010) describe and discuss what was revealed at a Tropospheric Ozone Changes Workshop in Boulder, Colorado (USA) on 14–16 October 2009, where "long-term ozone records from regionally representative surface and mountain sites, ozonesondes, and aircraft were reviewed by region." They report, "in the Southern Hemisphere, surface measurements from South Africa and Tasmania and sonde data from New Zealand show a significant increase over the past 25 years." North of the equator, on the other hand, the story is somewhat different. In western Europe, for example, "several time series of ~15-40 years ... show a rise in ozone into the middle to late 1990s and a leveling off, or in some cases declines, in the 2000s, in general agreement with precursor emission changes." Similarly, they state "surface measurements within North America show a pattern of mostly unchanged or declining ozone over the past two decades that seems broadly consistent with decreases in precursor emissions," while noting "the Japanese sonde record suggests rising ozone into the 1980s and small changes thereafter."

The spatial and temporal distributions of these observations would seem to suggest: Whereas increasing industrialization originally tends to increase the emissions of precursor substances that lead to the creation of greater tropospheric ozone pollution, subsequent technological advances tend to ameliorate that phenomenon as they gradually lead to (1) a leveling off of the magnitude of precursor emissions and (2) an ultimately decreasing trend in tropospheric ozone pollution. This suggests that when atmospheric ozone and CO_2 concentrations both rise together, the plant-growth-enhancing effect of atmospheric CO_2 enrichment is significantly muted by the plant-growth-retarding effect of contemporaneous increases in ozone pollution, but as the troposphere's ozone concentration gradually levels off and declines—as it appears to be doing with the development of new and better anti-pollution technology in the planet's more economically advanced countries—we should begin to see more-rapid-than-usual increases in Earth's vegetative productivity, which should promote an acceleration of the greening of the Earth.

Contemporaneously, Lazzarotto et al. (2010) note "white clover (*Trifolium repens* L.) is the most important pasture legume grown in temperate climates in association with a variety of grasses, notably perennial ryegrass (*Lolium perenne* L.)." They explain "white clover improves the nutritional quality and digestibility of the herbage" and "contributes substantially to the nitrogen status of the sward through biological nitrogen fixation." They state, however, that there is some concern future drought predicted to occur in tandem with CO_2-induced global warming will hurt clover more than the grass with which it is intermingled, thereby degrading the nutritional quality and digestibility of pasture swards.

To test this mix of facts and presumptions, Lazzarotto et al. planned and conducted a study in which "mechanisms controlling transient responses to elevated CO_2 concentration and climate change in an unfertilized grassland on the Swiss Plateau were examined in light of simulations with PROGRASS," a process-based model of grass-clover interactions developed by Lazzarotto et al. (2009) in which "daily weather for a series of transient climate scenarios spanning the 21st century were developed for the study site with the help of the LARS-WG weather generator," which is described by Semenov and Barrow (1997) and Semenov et al. (1998). In addition, "changes in the length of dry and wet spells, temperature, precipitation and solar radiation defining the scenarios were obtained from regional climate simulations carried out in the framework of the PRUDENCE project," which is described by Christensen and Christensen (2007).

"Compared to 1961–1990," the Swiss and UK scientists write, the climate scenarios they developed for a CO_2 increase from 370 to 860 ppm "indicated that for 2071–2100 there would be a noticeable increase in temperature (roughly 3°C in winter and 5°C in summer), a significant drop in summer precipitation (of the order of -30%), and a nearly 2-fold increase in the length of dry spells." The four researchers report these significant climate changes had no projected negative effect on the grass-clover swards: "clover abundance did not decline even in the absence of CO_2 stimulation." And when the atmospheric CO_2 concentration was programmed to gradually rise from an initial value of 370 ppm to a final value of 860 ppm, they found "clover development benefited from the overall positive effects of CO_2 on nitrogen acquisition," which they report was also "the reason for increasing productivity of the [entire] sward."

For Swiss grass-clover swards, therefore, the rather large predicted increases in temperature and decreases in precipitation predicted for the remainder of the twenty-first century will not have much of an effect, but the concomitant increase in the air's CO_2 content will be of considerable benefit. In addition, Lazzarotto et al. state it is likely "technical progress in the management of grasslands and pastures," which will surely occur, will help such pastures even more.

In a similar type of study, Friend (2010) used an advanced mechanistic physiological model (Hybrid6.5) of leaf and whole-plant canopy response to climate for basically the same purposes as Lazzarotto et al. This model considers light extinction within the leaf and through the canopy, the gradient of nitrogen content through the canopy, and other factors. It also distinguishes between C_3 and C_4 plants, broadleaf and conifer trees, and other life forms; and it has been verified by close matches to local, regional, and global net primary production (NPP) data. The model was run with current global vegetation distributions and the GISS-AOM climate model using the IPCC A1B scenario, with CO_2 rising to 720 ppm by AD 2100. When it was run with only climate change (CO_2 fixed at current levels), it showed a 2.5 percent reduction in global NPP, but when CO_2 change was added to the model, global NPP increased 37.3 percent to 80.7 Pg C/year.

This rise was most evident in absolute terms in tropical rainforests. In percentage terms, temperate and boreal forests and tundra showed the largest increases, along with C_3 grasslands and agricultural lands. C_4 grasses and crops showed only a 5.9 percent increase in NPP, because of the less-responsive photosynthetic pathway in C_4 plants. Only very small areas of the globe showed any decrease in NPP with this model. The results therefore suggest elevated CO_2 will help plants cope with the modest changes in climate that might otherwise be slightly harmful to their growth. The study also confirms past work showing that as models of plant growth become more realistic and mechanistic, they tend to predict positive responses to CO_2 and climate changes over the next 100 years in most regions and ecosystems.

References

Christensen, J.H. and Christensen, O.B. 2007. A summary of the PRUDENCE model projections of changes in European climate by the end of this century. *Climatic Change* **81**: 7–30.

Friend, A.D. 2010. Terrestrial plant production and climate change. *Journal of Experimental Botany* **61**: 10.1093/jxb/erq019.

Lazzarotto, P., Calanca, P., and Fuhrer, J. 2009. Dynamics of grass-clover mixtures—an analysis of the response to management with the PROductive GRASsland Simulator (PROGRASS). *Ecological Modelling* **220**: 703–724.

Lazzarotto, P., Calanca, P., Semenov, M., and Fuhrer, J. 2010. Transient responses to increasing CO_2 and climate change in an unfertilized grass-clover sward. *Climate Research* **41**: 221–232.

Logan, J., Schultz, M., and Oltmans, S. 2010. Observing and understanding tropospheric ozone changes. *EOS, Transactions, American Geophysical Union* **91**: 119.

Semenov, M.A. and Barrow, E.M. 1997. Use of a stochastic weather generator in the development of climate change scenarios. *Climatic Change* **35**: 397–414.

Semenov, M.A., Books, R.J., Barrow, E.M., and Richardson, C.W. 1998. Comparison of the WGEN and LARS-WG stochastic weather generators for diverse climates. *Climate Research* **10**: 95–107.

7.12. Nitrogen

7.12.1. Nitrogen Cycling

Jin and Evans (2010) write, "resource limitations, such as the availability of soil nitrogen (N), are expected to constrain continued increases in plant productivity under elevated atmospheric carbon dioxide." This is a common belief. Providing a glimmer of hope, however, they state, "one potential but under-studied N source for supporting increased plant growth under elevated CO_2 is soil organic N." They report, "in arid ecosystems, there have been no studies examining plant organic N uptake to date."

To help remedy this situation, Jin and Evans grew seedlings of the desert shrub *Larrea tridentata* in environmentally controlled chambers in ambient or CO_2-enriched air (380 or 600 ppm) in pots filled with Mojave Desert (Nevada, USA) soils injected with isotopically labeled ^{15}N obtained from one of three different organic and inorganic sources—(1) organic ^{15}N glycine, (2) inorganic $^{15}NH_4^+$, or (3) inorganic $^{15}NO_3^-$. They then destructively harvested the plants following zero, two, ten, 24, and 49 additional days of growth and determined the amounts of soil N they had taken up from each of the three N sources. The scientists found "elevated CO_2 positively affected root uptake of N derived from all three N forms by day 10, with NO_3^--derived N taken up at the highest rates," and "added glycine was taken up as intact amino acid within one hour of treatment application, indicating that *L. tridentata* can directly utilize soil organic sources." They note, "to date, this study is the first to report organic N uptake by a plant species from a hot, arid ecosystem."

In further discussing their findings, Jin and Evans state "there is increasing consensus that organic N uptake could be a major plant N acquisition pathway (Lipson and Nasholm, 2001; Schimel and Bennett, 2004), with 10–90% of the total annual plant N requirement potentially met by the uptake of external soil organic N (Chapin et al., 1993; Kielland, 1994; Jones and Darrah, 1994)." In addition, they note "long-term exposure to elevated CO_2 has altered the quality and quantity of plant-derived carbon inputs into Mojave Desert soils, leading to higher extracellular enzyme activities indicative of a greater or more active soil fungal component (Jin and Evans, 2007)," such that "increased soil fungi may lead to the greater release of monomeric organic N under elevated CO_2, enhancing substrate availability for soil microbes as well as for plant uptake." Hence, they found several encouraging indications that the ongoing rise in the air's CO_2 content will significantly increase the vitality of arid-land ecosystems, just as it does for other ecosystems.

In a related study, Brantly and Young (2010) note woody plant encroachment in herbaceous ecosystems "represents a key shift in community structure that has [the] potential to alter regional and global C and N cycling." However, they write, "there is considerable uncertainty regarding the effects of woody [plant] encroachment on global terrestrial C storage," due to the possibility that "increases in C sequestration in woody biomass may be offset by associated increases in soil CO_2 efflux (i.e., combined heterotrophic respiration and root respiration) resulting from increased litterfall, increased soil moisture, and associated increases in microbial activity that often accompany woody [plant] encroachment."

To further investigate this situation by determining "if young, sandy soils on a barrier island became a sink for C after encroachment of the nitrogen-fixing shrub *Morella cerifera*, or if associated stimulation of soil CO_2 efflux mitigated increased litterfall," Brantley and Young "monitored variations in litterfall in shrub thickets across a chronosequence of shrub expansion and compared those data to previous measurements of ANPP [annual net primary production] in adjacent grasslands," after which they "quantified standing litter C and N pools in shrub thickets and soil organic matter (SOM) , soil organic carbon (SOC), soil total nitrogen (TN) and soil CO_2 efflux in shrub thickets and adjacent grasslands," This field work was conducted on the north end of Hog Island (37°27'N, 75°40'W), a barrier island just east of the Virginia portion of the DelMarVa peninsula, USA.

The two researchers discovered that although soil CO_2 efflux was indeed stimulated by shrub encroachment in the younger soils, "soil CO_2 efflux did not vary between shrub thickets and grasslands in the oldest soils, and increases in CO_2 efflux in shrub thickets did not offset contributions of increased litterfall to SOC." In fact, they found "SOC was 3.6–9.8 times higher beneath shrub thickets than in grassland soils, and soil TN was 2.5–7.7 times higher under shrub thickets." These facts led them to conclude the expansion of shrubs on barrier islands—which often have low levels of soil carbon but a high potential for ANPP—can "significantly increase ecosystem C sequestration." In addition, "stimulation of N storage beneath shrub thickets will also favor future growth of species with lower nutrient use efficiencies than native grasses, including climax maritime forest species that could sequester additional C in biomass," citing Ehrenfeld (1990) and Vitousek et al. (2002). The phenomena presaged by their work bode well for barrier islands and the planet's less-productive grasslands.

References

Brantley, S.T. and Young, D.R. 2010. Shrub expansion stimulates soil C and N storage along a coastal soil chronosequence. *Global Change Biology* **16**: 2052–2061.

Chapin III, F.S., Moilanen, L., and Kielland, K. 1993. Preferential use of organic nitrogen for growth by a non-mycorrhizal arctic sedge. *Nature* **361**: 150–153.

Ehrenfeld, J.G. 1990. Dynamics and processes of barrier island vegetation. *Reviews in Aquatic Sciences* **2**: 437–480.

Jin, V.L. and Evans, R.D. 2007. Elevated CO_2 increases microbial carbon substrate use and N cycling in Mojave Desert soils. *Global Change Biology* **13**: 452–465.

Jin, V.L. and Evans, R.D. 2010. Elevated CO_2 increases plant uptake of organic and inorganic N in the desert shrub *Larrea tridentata*. *Oecologia* **163**: 257–266.

Jones, D.L. and Darrah, P.R. 1994. Amino-acid influx at the soil-root interface of *Zea mays* L. and its implications in the rhizosphere. *Plant and Soil* **163**: 1–12.

Kielland, K. 1994. Amino acid absorption by arctic plants: implications for plant nutrition and nitrogen cycling. *Ecology* **75**: 2373–2383.

Lipson, D.A. and Nasholm, T. 2001. The unexpected versatility of plants: organic nitrogen use and availability in terrestrial ecosystems. *Oecologia* **128**: 305–316.

Schimel, J.A. and Bennett, J. 2004. Nitrogen mineralization: challenges of a changing paradigm. *Ecology* **85**: 591–602.

Vitousek, P.M., Cassman, K., Cleveland, C., Crews, T., Field, C.B., Grimm, N.B., Howarth, R.W., Marino R., Martinelli, L., Rastetter, E.B., and Sprent, J.I. 2002. Towards an ecological understanding of biological N fixation. *Biogeochemistry* **57**: 1–45.

7.12.2. Nitrogen Deposition

Noting "human activities have greatly accelerated emissions of both carbon dioxide and biologically reactive nitrogen to the atmosphere," Thomas et al. (2010) report, "as nitrogen availability often limits forest productivity, it has long been expected that anthropogenic nitrogen deposition could stimulate carbon sequestration in forests." However, they note geographically extensive evidence for this phenomenon "has been lacking," and, therefore, they proceeded to provide some, using "spatially extensive forest inventory data to discern the effect of nitrogen deposition on the growth and survival of the 24 most common tree species of the northeastern and north-central US, as well as the effect of nitrogen deposition on carbon sequestration in trees across the breadth of the northeastern US."

They determined that "nitrogen deposition (which ranged from 3 to 11 kg ha^{-1} yr^{-1}) enhanced the growth of eleven species and decreased the growth of three species," while it "enhanced growth of all tree species with arbuscular mycorrhizal fungi associations," leading to "a 40% enhancement over pre-industrial conditions," This response "includes the direct effects of nitrogen deposition on tree growth through soil fertilization, foliar nitrogen uptake and other potential interactions between nitrogen deposition and other environmental changes, including CO_2 fertilization." To provide a sense of the significance of this response, they note it "exceeds the 23% enhancement of net primary production anticipated for the year 2050 from a doubling of atmospheric CO_2 over preindustrial levels, as estimated using free-air CO_2 enrichment studies," citing Norby et al. (2005).

Thomas et al. thus conclude "nitrogen deposition is an important mechanism contributing to carbon sequestration within these temperate forests," though this phenomenon is still "unlikely to explain all of the observed terrestrial carbon sink."

In a study described previously in Section 7.6, Reich (2009) states, "levels of nitrogen deposition and CO_2 have risen in recent decades and are expected to increase further." He notes that in the case of natural ecosystems, the subsequent suppression of diversity by increasing N availability "is almost ubiquitous," while "evidence of CO_2 effects on species richness is scarce and shows mixed results, with positive, neutral, and negative responses seen in the few published reports." So Reich explored what is most likely to happen when the two phenomena occur together using the ten-year-long BioCON study conducted at the Cedar Creek Long-Term Ecological Research site.

According to Reich, at the ambient soil nitrogen concentration, elevated CO_2 had reduced observed species richness by 2 percent while at the ambient atmospheric CO_2 concentration elevated nitrogen decreased species richness by 15 percent over the last seven years of the ten-year-long study. When the elevated soil N concentration was combined with the elevated atmospheric CO_2 concentration, however, species richness declined by only 5 percent, leading Reich to conclude, "elevated CO_2 reduces losses of plant diversity caused by nitrogen deposition." With nitrogen deposition "expected to increase further," as Reich notes, Earth's many natural ecosystems will be protected by the rise in the air's CO_2 content that is expected to accompany it.

References

Norby, R.J., DeLucia, E.H., Gielen, B., Calfapietra, C., Giardina, C.P., King, S.J., Ledford, J., McCarthy, H.R., Moore, D.J.P., Ceulemans, R., De Angelis, P., Finzi, A.C., Karnosky, D.F., Kubiske, M.E., Lukac, M., Pregitzer, K.S., Scarasci-Mugnozza, G.E., Schlesinger, W.H., and Oren, R. 2005. Forest response to elevated CO_2 is conserved across a broad range of productivity. *Proceedings of the National Academy of Sciences* **102**: 18,052–18,056.

Reich, P.B. 2009. Elevated CO_2 reduces losses of plant diversity caused by nitrogen deposition. *Science* **326**: 1399–1402.

Thomas, R.Q., Canham, C.D., Weathers, K.C., and Goodale, C.L. 2010. Increased tree carbon storage in response to nitrogen deposition in the US. *Nature Geoscience* **3**: 13–17.

7.12.3. Nitrogen Fixation

Tu et al. (2009) grew peanut (*Arachis hypogaea* L.) plants from seed to maturity outdoors near Raleigh, North Carolina (USA) in open-top chambers under adequately watered and fertilized conditions, while exposing the plants to (1) charcoal-filtered air, which was thus ozone-free, (2) ambient air of unaltered ozone (O_3) concentration, and (3) air containing 1.6 times the ambient O_3 concentration. All of these O_3 treatments were exposed to air of 376, 550, and 730 ppm CO_2, while the researchers made many plant physiological measurements. At the end of the period they harvested the crop and measured its final steam, leaf, and pod biomass. The four researchers found "at mid-vegetative growth, elevated CO_2 significantly reduced leaf nitrogen concentrations by up to 44%," but "plant nitrogen concentrations only differed by 8% among CO_2 treatments at harvest while N_2 fixation was increased." They state their findings suggest "symbiotic N_2 fixation is important for maintaining seed N concentrations and that CO_2 enhancement of symbiotic N_2 fixation may compensate for low soil N availability."

One year later, Prevost et al. (2010) grew soybean (*Glycine max* [L.] Merr. cv. *Lotus*) plants from seed in 24-cm-deep pots filled with a sandy loam soil that was watered and fertilized according to standard agricultural procedures for a period of six weeks within controlled-environment chambers maintained at atmospheric CO_2 concentrations of either 400 or 800 ppm, after inoculating either the soil or the seeds with either a reference strain (532c) of the nitrogen-fixing bacteria *Bradyrhizobium japonicum*, which is widely used in commercial operations in Canada, or with one of two strains of *B. japonicum* that are indigenous to the soils of Quebec (5Sc2 or 12NS14). They found "elevated CO_2 increased mass (+63%) and number (+50%) of soybean nodules, particularly medium and large, allowed a deeper nodule development, and increased shoot dry weight (+30%), shoot carbon uptake (+33%) and shoot nitrogen uptake (+78%), compared to ambient CO_2."

The four Canadian scientists state their results "constitute the first report showing that elevated CO_2 affects nodule size by allowing a greater production of large nodules, and influences nodule localization by favoring deeper nodule development on roots." Regarding the significance of these findings, they write, "medium and/or large nodules may confer advantages to legumes," since "they have been shown to improve drought tolerance of soybean (King and Purcell, 2001) and to exhibit higher nitrogenase activity in peanut (Tajima et al., 2007)." Also, they say their finding that "both shoot nitrogen and carbon uptakes are stimulated by elevated CO_2 agrees with Rogers et al. (2009), who stated that photosynthetic activity in legumes under elevated CO_2 does not acclimate [decrease with time] under optimal growing conditions, since the additional photosynthates produced are allocated to root nodules for N_2 fixation." And they note similar increases in nodule mass and number have been observed "with other legume species (Schortemeyer et al., 2002; Cabrerizo et al., 2001; Haase et al., 2007)," as well as "with soybean under drought (Serraj et al., 1998)." These findings bode well for legume farmers of the future and for the people and livestock that will consume their produce.

References

Cabrerizo, P.M., Gonzalez, E.M., Aparico-Tejo, P.M., and Aresse-Igor, C. 2001. Continuous CO_2 enrichment leads to increased nodule biomass, carbon availability to nodules and activity of carbon-metabolizing enzymes but does not enhance specific nitrogen fixation in pea. *Physiologia Plantarum* **113**: 33–40.

Haase, S., Neumann, G., Kania, A., Kuzyakov, Y., Romheld, V., and Kandeler, E. 2007.

Elevation of atmospheric CO_2 and N-nutritional status modify nodulation, nodule-carbon supply, and root exudation of *Phaseolus vulgaris* L. *Soil Biology & Biochemistry* **39**: 2208–2221.

King, C.A. and Purcell, L.C. 2001. Soybean nodule size and relationship to nitrogen fixation response to water deficit. *Crop Science* **41**: 1099–1107.

Prevost, D., Bertrand, A., Juge, C., and Chalifour, F.P. 2010. Elevated CO_2 induces differences in nodulation of soybean depending on bradyrhizobial strain and method of inoculation. *Plant and Soil* **331**: 115–127.

Rogers, A., Ainsworth, E.A., and Leakey, A.D.B. 2009. Will elevated carbon dioxide concentration amplify the benefits of nitrogen fixation in legumes? *Plant Physiology* **151**: 1009–1016.

Shortemeyer, M., Atkin, O.K., McFarlane, N., and Evans, J.R. 2002. N_2 fixation by *Acacia* species increases under elevated atmospheric CO_2. *Plant, Cell and Environment* **25**: 567–579.

Serraj, R., Sinclair, T.R., and Allen, L.H. 1998. Soybean nodulation and N_2 fixation response to drought under carbon dioxide enrichment. *Plant, Cell and Environment* **21**: 491–500.

Tajima, R., Lee, O.N., Abe, J., Lux, A., and Morita, S. 2007. Nitrogen-fixing activity of root nodules in relation to their size in peanut (*Arachis hypogaea* L.). *Plant Production Science* **10**: 423–429.

Tu, C., Booker, F.L., Burkey, K.O., and Hu, S. 2009. Elevated atmospheric carbon dioxide and O_3 differentially alter nitrogen acquisition in peanut. *Crop Science* **49**: 1827–1836.

7.12.4. The Progressive Nitrogen Limitation Hypothesis (Part 1)

In an article published in the *Los Angeles Times* on May 14, 2010, headlined “Plant Study Dims Silver Lining to Global Warming,” Amina Khan wrote “some biologists had theorized earlier that rising greenhouse gas levels would encourage plant growth over the long term because of the increased amount of carbon dioxide in the atmosphere,” but she went on to say “plant physiologists from UC Davis may have dashed those hopes.” She quoted the principal investigator of the research project that prompted her article as stating, “we thought rising carbon dioxide levels might actually have some benefit, but it proves to be wrong. ... Over a period of time, be it weeks or years, that stimulation [of photosynthetic and growth rates] disappears.”

In the scientific paper describing the research, published the same day as the Khan article, Bloom et al. (2010) claimed to have used “five independent methods with wheat and *Arabidopsis* to show that atmospheric carbon dioxide enrichment inhibited the assimilation of nitrate into organic nitrogen compounds,” and “this inhibition may be largely responsible for carbon dioxide acclimation, the decrease in photosynthesis and growth of plants conducting C_3 carbon fixation after long exposures (days to years) to carbon dioxide enrichment.”

Interestingly, this concept had a nearly identical incarnation eight years earlier in the *Proceedings of the National Academy of Sciences, USA*, wherein Bloom and three other collaborators (Bloom et al., 2002) made essentially the same claims as Bloom and his second set of associates in 2010. And what was wrong then remains wrong now.

In the earlier study, Bloom et al. (2002) analyzed the ability of two-week-old seedlings of hydroponically grown wheat to respond to a near-doubling of the air’s CO_2 content when their roots were bathed in a non-nitrogen-limiting solution of either ammonium (NH_4^+) or nitrate (NO_3^-). The results of that experiment demonstrated that the 94 percent increase in the air’s CO_2 content enhanced the biomass of the young wheat plants by 44 percent when the seedlings received their nitrogen in the form of NO_3^-. This result was a significant positive response. Nevertheless, the study’s findings were widely portrayed by various organizations, Web sites, and publications as presaging significant negative consequences in the years and decades to come for almost all of Earth’s vegetation, including both agricultural crops and natural ecosystems.

One reason for the negativism may have been that the positive result obtained for the plants whose roots were bathed in the NH_4^+ solution was even more impressive. Instead of “just” a 44 percent increase in plant biomass, these plants exhibited a 78 percent increase. And thus it was that on February 4, 2002—one day before the Bloom et al. (2002) paper appeared in print—that NASA’s Earth Observatory News posted an article on its Web site titled “High CO_2 Levels Hamper Nitrate Incorporation by Plants,” in which it was claimed “nitrate fertilizer is not nearly as efficient as ammonium fertilizer when atmospheric carbon dioxide levels are unusually high.” This is quite an expansive conclusion to draw from a study that lasted only two weeks, dealt with only one species, and utilized only seedlings growing only in nutrient solution.

This report was followed by several similar stories of much the same negative bent. *Scientific American* introduced its take on the Bloom et al. (2002) paper with an equally expansive title, stating “Rising CO_2 Levels Could Force Shift in Fertilizer Use,” which was reproduced the same day by the Climate Ark organization. Simultaneously, AmeriScan displayed an article titled “Rising CO_2 Hampers Fertilizers,” which began with the declaration that “as carbon dioxide levels rise, plant life around the globe may lose the ability to incorporate certain forms of nitrogen, like those found in most fertilizers.” It ended by stating, “as atmospheric CO_2 levels continue to rise, nitrate-sensitive plant and tree species in the wild could be at a competitive disadvantage," and "this could change the distribution of plants in natural ecosystems."

Eerily, several press reports also said that "for many years, scientists believed ... rising levels of carbon dioxide would actually benefit plants," as if to suggest that was no longer the case. They also matter-of-factly stated that the initial positive growth response to atmospheric CO_2 enrichment observed in most experiments "wasn't sustained," dropping back to just a few percent above normal "within a few days or weeks," but which Bloom et al. (2010) have now extended to "days to years."

It was also interesting—but not unexpected—that the environmental press highly hyped so many of the presumed negative ramifications of the Bloom et al. (2002) experiment for both agricultural and natural ecosystems, when the experiment upon which those presumptions were based lasted only 14 days and had been performed under sterile laboratory conditions that included no soil, no competing plants, and a totally unnatural mix of antibiotics in the water surrounding the seedlings' roots. These antibiotics were introduced to suppress naturally occurring nitrogen-transforming processes that Bloom et al. (2002) admitted are "rapid in nonsterile cultures (Padgett and Leonard, 1993) and sensitive to atmospheric CO_2 (Smart et al., 1997)," which made the experimental conditions very different from the real world of nature.

It should not surprise us, then, that longer experiments conducted under more realistic conditions have refuted the claims made by the press. We first consider the three-part claim—which, to be fair to the press, was actually made by Bloom et al. (2002)—that (1) "a doubling of CO_2 level initially accelerates carbon fixation in C_3 plants by about 30%," (2) this growth stimulation "after days to weeks" dramatically declines, and (3) the CO_2-induced growth enhancement thereafter "stabilizes at a rate that averages 12% above ambient controls."

All three parts of this contention are inadequate generalizations of what is called acclimation to CO_2 enrichment. In the first instance, a doubling of the air's CO_2 content often will accelerate biomass production in young C_3 plants in the early stages of CO_2 enrichment by much more than 30 percent. Even in their own experiment, Bloom et al. (2002) found that slightly less than a doubling of the air's CO_2 content increased the biomass of their NO_3^--treated plants by fully 44 percent, and it increased the biomass of their NH_4^+-treated plants by 78 percent. In addition, the mini-review of Idso (1999) cites at least 20 experiments where the initial growth stimulation exceeded 100 percent.

With respect to the decline in growth stimulation claimed by Bloom et al. to follow hard on the heels of the initial CO_2-induced growth enhancement, we note it in some cases it never occurs (Gunderson et al., 1993; Fernandez et al., 1998; Garcia et al., 1998). In other instances, the reverse occurs: The CO_2-induced growth stimulation increases over time (Arp and Drake, 1991; Vogel and Curtis, 1995; Jacob et al., 1995). And in those cases where there is a decline in the strength of the CO_2 aerial fertilization effect, it sometimes does not begin until one or more years after the initiation of the experiment. In the long-term sour orange tree study of Idso and Kimball (2001), for example, a decline in the CO_2-induced growth stimulation did not begin until the 2.5-year point of the experiment.

Finally, the degree of CO_2-induced growth stimulation at which the aerial fertilization effect of atmospheric CO_2 enrichment eventually stabilizes is often significantly larger than the 12 percent value suggested by Bloom et al. (2002) for a doubling of the air's CO_2 content. In their summary report of the Phoenix, Arizona sour orange tree study, for example, Kimball et al. (2007) write that rather than "a continual acclimation" or neverending long-term decline in the strength of the CO_2-induced aerial fertilization effect, there was a "sustained enhancement," a near-constant 70 percent increase in total yearly biomass production over the entire last decade of the 17-year study in response to the 75 percent increase in the air's CO_2 content employed throughout the experiment, which for a doubling of the air's CO_2 content implies there would have been a CO_2-induced productivity enhancement on the order of 93 percent, nearly eight times greater than what Bloom et al. (2002) declared to be typical.

Having thus clarified the record with respect to the erroneously summarized aspects of the CO_2 acclimation phenomenon presented in the Bloom et al. (2002) article, there is a need to address their contention that plants respond better to atmospheric CO_2 enrichment when they obtain their nitrogen in the ammonium form as opposed to the nitrate form. For in spite of their claim that theirs may have been "the first study to examine CO_2 responses under controlled levels of NH_4^+ vs. NO_3^- as sole N sources," there have in fact been many other studies, some of which are briefly highlighted below, that provide important—and vastly different—information about this topic.

Bauer and Berntson (2001) grew seedlings of *Betula alleghanienis* and *Pinus strobus* for 15 weeks—as opposed to the abbreviated two weeks of the Bloom et al. (2002) experiment—in growth chambers maintained at atmospheric CO_2 concentrations of 400 and 800 ppm, while the seedlings' roots were suspended in nutrient solutions whose sole sources of N were, as in the study of Bloom et al. (2002), either NO_3^- or NH_4^+. In this experiment, the extra CO_2 did not have any effect on the growth of the *Pinus* species in either solution, but it increased total seedling dry weight in the *Betula* species by 61 percent in the nitrate treatment and by 79 percent in the ammonium treatment. Although this result is qualitatively the same as that obtained by Bloom et al., the ammonium/nitrate (A/N) response ratio, i.e., 79%/61% = 1.30, was much lower than the A/N response ratio of the Bloom et al. (2002) experiment, i.e., 78%/44% = 1.77, suggesting perhaps the A/N response ratio could be undergoing a type of acclimation as experimental duration lengthens. That suggests the possibility that for still longer (and more realistic) periods of differential CO_2 exposure, there may be little or no plant preference for a particular N source.

Van der Merwe and Cramer (2000) grew tomato seedlings for two weeks—bringing them to the same age as the wheat plants studied by Bloom et al. (2002)—in air of 360 ppm CO_2, while the roots of the seedlings were enclosed in sealed vessels containing either NO_3^- or NH_4^+ solutions, after which the solutions were equilibrated with air as high in CO_2 concentration as 20,000 ppm. This rhizospheric CO_2 enrichment had no effect on the uptake of NH_4^+ by the tomato seedlings, but it resulted in an enhanced uptake of NO_3^-, with the maximum effect occurring at a rhizospheric CO_2 concentration of 5,000 ppm, which is to be compared to a normal root-zone CO_2 concentration of something less than 5,000 ppm but more than 1,000 ppm, as is typical of soil airspace in most outdoor environments. Although we cannot be confident about all the possible implications of this observation, it does indicate a preferential plant uptake of nitrate N at higher-than-normal rhizospheric CO_2 concentrations, which is difficult to understand if plants are supposed to prefer ammonium N at high CO_2 concentrations, as suggested by Bloom et al. (2002).

It can be additionally noted, at this point, that attempting to discern and characterize a possible CO_2-mediated plant preference for a particular form of nitrogen must involve considerably more complex investigations than simple laboratory experiments with individual plants whose roots never have been exposed to anything other than sterile nutrient solutions. Actual nonsterile soils are required to host the plants if one is ever going to learn how plants operate in the world of nature. Hence, this aspect of our investigation begins with a brief review of an intermediate sort of study conducted by Constable et al. (2001). Although not using totally natural soil, they at least got beyond the hydroponic stage of investigation for the major portion of their experiment, and they also dealt with the added complexity supplied by the presence of two types of fungal symbionts, which often live in close association with the roots of plants in their normal habitats and serve as a living link between them and the soil environment.

Constable et al. studied mycorrhizal- and non-mycorrhizal-infected seedlings of both sweetgum and loblolly pine seedlings rooted in pots filled with fine sand above a layer of mycorrhizal inoculum, or clay lacking such inoculum, and grown for six months outdoors in open-top chambers maintained at atmospheric CO_2 concentrations of either 350 or 700 ppm. They then brought the seedlings into the laboratory, washed the sand from their roots and from the fungal hyphae associated with the roots of half of the plants, and placed the roots and root/hyphae systems in hydroponic solutions of NO_3^- and NH_4^+ for N uptake evaluations conducted within controlled environment chambers maintained at the same atmospheric CO_2 concentrations to which the seedlings had been exposed while growing outside.

In this part of the experiment, both tree species exhibited a greater preference for NH_4^+ than for NO_3^-, regardless of mycorrhizal treatment, as is commonly reported for trees exposed to normal atmospheric CO_2 concentrations (Gessler et al., 1998; Wallenda and Read, 1999). Nevertheless, the presence of mycorrhizae clearly improved nitrogen acquisition in both species at both CO_2 concentrations; and, as the researchers reported, "this increase in uptake capacity was preferentially for NO_3^- as opposed to NH_4^+." Furthermore, they noted "in loblolly pine, the relative enhancement of NO_3^- uptake capacity by ectomycorrhizal fungi was significantly higher at elevated CO_2 compared with ambient CO_2," in direct opposition to what would be expected on the basis of the Bloom et al. (2002) experiment. In sweetgum, however, the reverse was true. Thus the authors urged caution in concluding too much from observations derived from too few species of both plants and mycorrhizae—a caution, we might add, that seems not to have occurred to either Bloom et al. (2002) or the members of the press who wrote so confidently about the global applicability of the results of their highly artificial wheat experiment.

In a still more realistic set of experiments, BassiriRad et al. (1999) grew two tree species—red maple and sugar maple—for close to 1.5 years outdoors in open-top chambers (OTCs) maintained at atmospheric CO_2 concentrations of ambient and ambient plus 300 ppm, as well as two crop species—soybean and sorghum—studied for one full growing season in OTCs maintained at atmospheric CO_2 concentrations of ambient and ambient plus 360 ppm. The trees were planted directly into the natural soil upon which the OTCs of their experiment were constructed, while the crops were planted in natural soil that filled a 2-meter-deep bin, measuring 6 meters wide and 76 meters long, upon which the OTCs of their experiment were constructed.

In both sets of experiments, small groups of fine roots were carefully exposed, cleaned, and inserted into tubes containing known volumes of 25, 50, 75, 100, 150, and 200 µM solutions of NH_4NO_3, after which the roots were allowed to take up whatever amounts of each form of N they preferred over periods of 30 to 60 minutes. The roots were then removed from the tubes and the portions that had been immersed in the nutrient solution excised, dried, and weighed. The volume of the remaining solution in each tube was stored for later assessment of the amounts of NH4+ and NO3- that had not been removed by the roots.

All four species exhibited a distinct preference for NH_4^+ uptake over NO_3^- uptake when grown in air of normal atmospheric CO_2 concentration, but this preference was only to be expected, because the energy requirements associated with the uptake and assimilation of NO_3^- are considerably greater than those associated with the uptake and assimilation of NH_4^+, as demonstrated by Haynes and Goh (1978), Blacquiere (1987), and Glass and Siddiqi (1995). BassiriRad et al. also noted "the greater preference for NH_4^+ vs. NO_3^- is almost a universal root characteristic in tree species and is often associated with an adaptation to forest soils that are relatively low in NO_3^-."

So what happened with the plants in the CO_2-enriched chambers? Red maple exhibited a slight increase of its ambient-air preference for NH_4^+. The other three species showed no change in N preference at the higher CO_2 concentration. Hence, one of the four species studied provided weak support for the hypothesis of the Bloom et al. (2002) study, and the other three species provided no support.

Where does all of this discussion lead? For one thing, the body of literature discussed above suggests different species may behave differently with respect to the effects of atmospheric CO_2 enrichment on their N uptake kinetics. BassiriRad et al. additionally note, for example, that "using potted seedlings we have shown elsewhere (BassiriRad et al., 1997a, b) that high CO_2 increased, decreased or had no significant effect on NO_3^- uptake kinetics depending upon species tested." They also note that in a hydroponic experiment using soybean and sunflower, they found "root N uptake kinetics response to CO_2 enrichment was highly dependent on the stages of development and root age." Hence, they state "a 'one point in time' determination"—such as that which comprised the study of Bloom et al. (2002)—"is not adequate," and "more measurements of root N uptake kinetics are necessary to draw valid conclusions about possible effects of CO_2."

Clearly, the Bloom et al. (2002) experiment in no way supports any of the monumental biospheric problems that they and many in the press have attempted to convince us will occur on the basis of their severely restricted study. The newer study of Bloom et al. (2010) likewise provides no support for their equally wild speculations about the future of Earth's biosphere. In all five of their newest experiments, for example, the plants they studied were grown (1) hydroponically in (2) isolation under (3) sterile laboratory conditions for (4) only a few weeks, while measurements of the key processes they made were generally conducted over (5) only a matter of hours.

That is not the way to ascertain what might happen over the long haul in the real world. The way to find out what really happens in the real world is to conduct long-term studies in as natural a setting as possible. For many people this means working outdoors in open-top chambers with plants rooted directly in the ground, which is how the 17-year Phoenix, Arizona sour orange tree study was conducted. For others it likewise means working outside but doing so within the context of free-air CO_2 enrichment experiments.

Summarizing nine years of such work at the Duke Forest FACE facility in North Carolina (USA), where portions of an aggrading loblolly pine plantation had been continuously exposed to an extra 200 ppm of CO_2 since 1996, Lichter et al. (2008) reported the CO_2-induced increase in productivity there had amounted to about 30 percent annually—which roughly equates to a 45 percent increase for a 300 ppm increase in CO_2, and even more for a true doubling of the air's CO_2 content. The scientists add there is "little evidence to indicate a diminished response through time," citing, in this regard, Finzi et al. (2007), who found the same to be true at three other long-term forest FACE studies conducted at Rhinelander, Wisconsin (USA), Oak Ridge National Laboratory (USA), and Tuscania (Italy).

As but one example, after working at the EuroFACE facility in Central Italy for a period of several years, Davey et al. (2006) published their observations in a paper titled "Can fast-growing plantation trees escape biochemical down-regulation of photosynthesis when grown throughout their complete production cycle in the open air under elevated carbon dioxide?" They report that poplar trees exposed to a 50 percent increase in atmospheric CO_2 concentration over four growing seasons "showed a sustained increase in photosynthesis of between 35 and 60 percent prior to coppicing," and "this increase in daily photosynthesis [was] maintained during the re-growth," such that "no long-term photosynthetic acclimation to CO_2 occurred in these plants." They note "poplar trees are able to 'escape' from long-term, acclamatory down-regulation of photosynthesis" and "the acclamatory loss of the initial increase in photosynthetic rate under elevated CO_2 is not inevitable." In their report of another study conducted on the same trees, Calfapietra et al. (2005) write, "photosynthetic acclimation of poplar plantations is unlikely to occur in an atmosphere enriched in CO_2 and thereby will not influence the response of poplar plantations to increasing atmospheric CO_2 concentrations either over the long term or under conditions of nitrogen deposition."

But perhaps the most amazing example of avoiding long-term photosynthetic acclimation in the real world comes from Paoletti et al. (2007). They measured rates of net photosynthesis during a two-week period in June 2002 "at the end of the spring rains" when midday air temperatures rose above 40°C in upper sunlit leaves of mature holm oak trees growing close to (5 m) and further away from (130 m) a natural CO_2-emitting spring near Laiatico (Pisa, Italy), where the trees had experienced lifetime exposure to atmospheric CO_2 concentrations of approximately 1,500 and 400 ppm, respectively. They found the net photosynthetic rates of the leaves on the trees growing closest to the CO_2 spring were approximately 250 percent greater than those of the leaves on the trees growing 125 meters further away, where the atmospheric CO_2 concentration was 1,100 ppm lower than it was in the vicinity of the trees nearest the spring. The four Italian researchers thus concluded, "the considerable photosynthetic stimulation at the very high CO_2 site suggests no photosynthetic down-regulation over long-term CO_2 enrichment." This real-world finding demonstrates the truly amazing potential for very large increases in the air's CO_2 content to greatly stimulate photosynthesis and significantly enhance the growth and development of plants over the very long term.

Contrary to the claims of Bloom et al. (2002) and Bloom et al. (2010), trees—including those thought to have access to less-than-adequate soil nitrogen supplies—are entirely capable of maintaining the sizable increases in their growth rates that are made possible by elevated concentrations of atmospheric CO_2. In the case of North Carolina's Duke Forest, for example, "even after nine years of experimental CO_2 fertilization," as Lichter et al. (2008) state, "attenuation of the CO_2-induced productivity enhancement has not been observed." This also has been noted to be the case by Finzi et al. (2006). This finding at this particular location is significant because the growth of pine-hardwood forests in the southeastern United States often removes so much nitrogen from the soils in which they grow that they induce what Finzi and Schlesinger (2003) have described as "a state of acute nutrient deficiency that can only be reversed with fertilization." This operation, however, has not been employed in the Duke Forest FACE study, which makes it about as challenging a situation as there could be for the long-term persistence of the growth-promoting aerial fertilization effect of atmospheric CO_2 enrichment. Yet the phenomenon does precisely that: It persists.

References

Arp, W.J. and Drake, B.G. 1991. Increased photosynthetic capacity of Scirpus olneyi after 4 years of exposure to elevated CO_2. *Plant, Cell and Environment* **14**: 1003–1006.

BassiriRad, H., Griffin, K.L., Reynolds, J.F., and Strain, B.R. 1997a. Changes in root NH_4^+ and NO_3^- absorption rates of loblolly and ponderosa pine in response to CO_2 enrichment. *Plant and Soil* **190**: 1–9.

BassiriRad, H., Prior, S.A., Norby, R.J., and Rogers, H.H. 1999. A field method of determining NH_4^+ and NO_3^- uptake kinetics in intact roots: Effects of CO_2 enrichment on trees and crop species. *Plant and Soil* **217**: 195–204.

BassiriRad, H., Reynolds, J.F., Virginia, R.A., and Brunelle, M.H. 1997b. Growth and root NO_3^- and PO_3^- uptake capacity of three desert species in response to atmospheric CO_2 enrichment. *Australian Journal of Plant Physiology* **24**: 353–358.

Bauer, G.A. and Berntson, G.M. 2001. Ammonium and nitrate acquisition by plants in response to elevated CO_2 concentration: the roles of root physiology and architecture. *Tree Physiology* **21**: 137–144.

Blacquiere, T. 1987. Ammonium and nitrate nutrition in Plantago lanceolata and P. major ssp. major. II. Efficiency of root respiration and growth. Comparison of measured and theoretical values of growth respiration. *Plant Physiology and Biochemistry* **25**: 1775–1785.

Bloom, A.J., Burger, M., Asensio, J.S.R., and Cousins, A.B. 2010. Carbon dioxide enrichment inhibits nitrate assimilation in wheat and Arabidopsis. *Science* **328**: 899–903.

Bloom, A.J., Smart, D.R., Nguyen, D.T., and Searles, P.S. 2002. Nitrogen assimilation and growth of wheat under elevated carbon dioxide. *Proceedings of the National Academy of Sciences, USA* **99**: 1730–1735.

Calfapietra, C., Tulva, I., Eensalu, E., Perez, M., De Angelis, P., Scarascia-Mugnozza, G., and Kull, O. 2005. Canopy profiles of photosynthetic parameters under elevated CO_2 and N fertilization in a poplar plantation. *Environmental Pollution* **137**: 525–535.

Constable, J.V.H., BassiriRad, H., Lussenhop, J., and Zerihun, A. 2001. Influence of elevated CO_2 and mycorrhizae on nitrogen acquisition: contrasting responses in Pinus taeda and Liquidambar styraciflua. *Tree Physiology* **21**: 83–91.

Davey, P.A., Olcer, H., Zakhleniuk, O., Bernacchi, C.J., Calfapietra, C., Long, S.P., and Raines, C.A. 2006. Can fast-growing plantation trees escape biochemical down-regulation of photosynthesis when grown throughout their complete production cycle in the open air under elevated carbon dioxide? *Plant, Cell and Environment* **29**: 1235–1244.

Finzi, A.C., Moore, D.J.P., DeLucia, E.H., Lichter, J., Hofmockel, K.S., Jackson, R.B., Kim, H.-S., Matamala, R., McCarthy, H.R., Oren, R., Pippen, J.S., and Schlesinger, W.H. 2006. Progressive nitrogen limitation of ecosystem processes under elevated CO_2 in a warm-temperate forest. *Ecology* **87**: 15–25.

Finzi, A.C., Norby, R.J., Calfapietra, C., Gallet-Budynek, A., Gielen, B., Holmes, W.E., Hoosbeek, M.R., Iversen, C.M., Jackson, R.B., Kubiske, M.E., Ledford, J., Liberloo, M., Oren, R., Polle, A., Pritchard, S., Zak, D.R., Schlesinger, W.H., and Ceulemans, R. 2007. Increases in nitrogen uptake rather than nitrogen-use efficiency support higher rates of temperate forest productivity under elevated CO_2. *Proceedings of the National Academy of Sciences, USA* **104**: 14,014–14,019.

Finzi, A.C. and Schlesinger, W.H. 2003. Soil-nitrogen cycling in a pine forest exposed to 5 years of elevated carbon dioxide. *Ecosystems* **6**: 444–456.

Fernandez, M.D., Pieters, A., Donoso, C., Tezara, W., Azuke, M., Herrera, C., Fengifo, E., and Herrera, A. 1998. Effects of a natural source of very high CO_2 concentration on the leaf gas exchange, xylem water potential and stomatal characteristics of plants of Spatiphylum cannifolium and Bauhinia multinervia. *New Phytologist* **138**: 689–697.

Garcia, R.L., Long, S.P., Wall, G.W., Osborne, C.P., Kimball, B.A., Nie, G.Y., Pinter Jr., P.J., LaMorte, R.L., and Wechsung, F. 1998. Photosynthesis and conductance of spring-wheat leaves: field response to continuous free-air atmospheric CO_2 enrichment. *Plant, Cell and Environment* **21**: 659–669.

Gessler, A., Schneider, S., Von Sengbusch, D., Weber, P., Hanemann, W., Huber, C., Rothe, A., Kreutzer, K., and Rennenberg, H. 1998. Field and laboratory experiments on net uptake of nitrate and ammonium by the roots of spruce (Picea abies) and beech (Fagus sylvatica) trees. *New Phytologist* **138**: 275–285.

Glass, A.D.M. and Siddiqi, M.Y. 1995. Nitrogen absorption by plant roots. In *Nitrogen Nutrition in Higher Plants*, edited by H.S. Srivastava and R.P. Singh, 21–56. New Delhi, India: Associated Publishing Co.

Gunderson, C.A., Norby, R.J., and Wullschleger, S.D. 1993. Foliar gas exchange responses of two deciduous hardwoods during three years of growth in elevated CO_2: no loss of photosynthetic enhancement. *Plant, Cell and Environment* **16**: 797–807.

Haynes, R.J. and Goh, K.M. 1978. Ammonium and nitrate nutrition of plants. *Biological Reviews* **53**: 465–510.

Idso, S.B. 1999. The long-term response of trees to atmospheric CO_2 enrichment. *Global Change Biology* **5**: 493–495.

Idso, S.B. and Kimball, B.A. 2001. CO_2 enrichment of sour orange trees: 13 years and counting. *Environmental and Experimental Botany* **46**: 147–153.

Jacob, J., Greitner, C., and Drake, B.G. 1995. Acclimation of photosynthesis in relation to Rubisco and non-structural carbohydrate contents and in situ carboxylase activity in Scirpus olneyi grown at elevated CO_2 in the field. *Plant, Cell and Environment* **18**: 875–884.

Kimball, B.A., Idso, S.B., Johnson, S., and Rillig, M.C. 2007. Seventeen years of carbon dioxide enrichment of sour orange trees: final results. *Global Change Biology* **13**: 2171–2183.

Lichter, J., Billings, S.A., Ziegler, S.E., Gaindh, D., Ryals, R., Finzi, A.C., Jackson, R.B., Stemmler, E.A., and Schlesinger, W.H. 2008. Soil carbon sequestration in a pine forest after 9 years of atmospheric CO_2 enrichment. *Global Change Biology* **14**: 2910–2922.

Padgett, P.E. and Leonard, R.T. 1993. Contamination of ammonium-based nutrient solutions by nitrifying organisms and the conversion of ammonium to nitrate. *Plant Physiology* **101**: 141–146.

Paoletti, E., Seufert, G., Della Rocca, G., and Thomsen, H. 2007. Photosynthetic responses to elevated CO_2 and O3 in Quercus ilex leaves at a natural CO_2 spring. *Environmental Pollution* **147**: 516–524.

Smart, D.R., Ritchie, K., Stark, J.M., and Bugbee, B. 1997. Evidence that elevated CO_2 levels can indirectly increase rhizosphere denitrifier activity. *Applied and Environmental Microbiology* **63**: 4621–4624.

Van der Merwe, C.A and Cramer, M.D. 2000. Effect of enriched rhizosphere carbon dioxide on nitrate and ammonium uptake in hydroponically grown tomato plants. *Plant and Soil* **221**: 5–11.

Vogel, C.S. and Curtis, P.S. 1995. Leaf gas exchange and nitrogen dynamics of N2-fixing, field-grown Alnus glutinosa under elevated atmospheric CO_2. *Global Change Biology* **1**: 55–61.

Wallenda, T. and Read, D.J. 1999. Kinetics of amino acid uptake by ectomycorrhizal roots. *Plant, Cell and Environment* **22**: 179–187.

7.12.5. The Progressive Nitrogen Limitation Hypothesis (Part 2)

Land plants grow best when supplied with optimum levels of soil nitrogen. When this reactive nitrogen (Nr) is present in soils in concentrations that are less than optimal, terrestrial vegetation grows less vigorously and removes less CO_2 from the atmosphere. As a result, there have been claims that less-than-optimal soil nitrogen concentrations will eventually cause a significant reduction in the strength of the growth stimulation provided by the aerial fertilization effect of the ongoing rise in the air's CO_2 content because the limited amount of Nr in the soil simply cannot supply enough of this essential nutrient to maintain the increase in growth stimulated by the rising CO_2. This string of suppositions has come to be called the progressive nitrogen limitation hypothesis (Hungate et al., 2003; Luo et al., 2004).

Expressing the opposite concern about Nr are scientists such as Fujimaki et al. (2009), who contend "anthropogenic addition of reactive nitrogen to the biosphere"—"through production of fertilizers, cultivation of N-fixing plants, and utilization of fossil fuels"—"is increasing globally and some terrestrial ecosystems are suffering from a state of excess Nr." They contend "excess Nr has a harmful impact on vegetation cover and species diversity," as a result of "increasing competitive abilities for a small number of nitrophilic species, increase of herbivory, decreases in mutualistic fungi, increases in pathogenic fungi, and enhanced invasibility by exotic species that are highly competitive under conditions of high soil nitrate." Both sides of this debate feel strongly about their positions, and both foresee undesirable consequences in the fairly near future if certain aspects of the way modern societies operate are not radically changed.

What neither side seems to consider, however, is that the two extreme phenomena might work together to produce a harmonious outcome. Instead of suppressing economic activity (to reduce CO_2 emissions) and agricultural production (to reduce addition of nitrogen to the soil), we could simply let each phenomenon proceed unimpaired by overt human intervention. Thus the addition of nitrogen to the soil should provide what is needed (more reactive nitrogen) to enable the world's terrestrial vegetation to capture and sequester more of the carbon supplied to the air by anthropogenic CO_2 emissions. This will be needed to increase the productivity of the world's cropped and naturally vegetated land in order to feed the still-growing human population.

Evidence that such a laissez-faire approach to the two concerns is indeed reasonable is provided by the fact that even Fujimaki et al. admit "ecosystem net primary production seems to be under N limitation," and "in global trends to date, plant growth itself tends to be stimulated with increase of N deposition." This observation leads them to conclude, "if N deposition continues at the present rates in the next few decades, ecosystem net primary production would be released from the limitation of N availability." Better yet, there is evidence that vegetation growing in CO_2-enriched air can find the nitrogen it needs even when it seems not to be there.

Consider the Duke Forest free-air CO_2-enrichment (FACE) study: a long-term experiment designed to investigate the effects of an extra 200 ppm of atmospheric CO_2 on the growth and development of a plantation of loblolly pine (*Pinus taeda*) trees with an understory of various broadleaf species (*Liriodendron tulipifera, Liquidambar styraciflua*, *Acer rubrum*, *Ulmus alata*, and *Cornus florida*), plus various other trees, shrubs, and vines, all growing on a soil that Finzi and Schlesinger (2003) have described as being in "a state of acute nutrient deficiency that can only be reversed with fertilization." Many people had long thought this fertility deficiency would stifle the ability of the extra aerial supply of CO_2 to significantly stimulate the forest's productivity on a continuing basis. Based on data for the years 1996–2004, however, McCarthy et al. (2010) calculated the net primary productivity (NPP) for the pines, the hardwoods, and the entire stand as the sum of the production of coarse wood (stems, branches, and coarse roots), leaf litter (lagged for pines), fine roots, and reproductive structures. They found "elevated CO_2 increased pine biomass production, starting in 1997 and continuing every year thereafter," and "the CO_2-induced enhancement remained fairly consistent as the stand developed."

They also found "elevated CO_2 increased stand (pine plus all other species) biomass production every year from 1997 onwards with no trend over time," such that the average yearly increase in NPP caused by the approximate 54 percent increase in the air's CO_2 content was a solid 28 percent. Thus, and in spite of the original belief of many scientists that low levels of soil nitrogen—especially an acute deficiency—would preclude the persistence of any growth stimulation provided by atmospheric CO_2 enrichment, the suite of trees, bushes, and shrubs that constitute the Duke Forest has continued to maintain the extra CO_2-enabled vitality exhibited right from the start of the study, with no sign of it even beginning to taper off.

Also working at the Duke Forest FACE facility, Jackson et al. (2009) described belowground data they obtained there, after which they presented a synthesis of these and other results they obtained between 1996 and 2008, seeking to determine "which, if any, variables show evidence for a decrease in their response to atmospheric CO_2 during that time frame."

Among many other things, Jackson et al. report "on average, in elevated CO_2, fine-root biomass in the top 15 cm of soil increased by 24%," and in recent years the fine-root biomass increase "grew stronger, averaging ~30% at high CO_2." Regarding coarse roots having diameters greater than 2 mm and extending to a soil depth of 32 cm, they report "biomass sampled in 2008 was twice as great in elevated CO_2." We calculate from the graphical representation of their results that the coarse-root biomass was fully 130 percent greater, while the extra 200 ppm of CO_2 supplied to the air surrounding the CO_2-enriched trees represented an enhancement of only about 55 percent above ambient conditions. In the concluding sentence of their paper's abstract, they state, "overall, the effect of elevated CO_2 belowground shows no sign of diminishing."

The four researchers thus conclude, "if progressive nitrogen limitation were occurring in this system, we would expect differences in productivity to diminish for trees in the elevated vs. ambient CO_2 plots," but "there is little evidence from estimates of aboveground or total net primary productivity in the replicated Duke experiment that progressive nitrogen limitation is occurring there or at other forest FACE experiments," even "after more than a decade of manipulation" of the air's CO_2 content, citing, with respect to the latter portion of their statement, Finzi et al. (2007). Consequently, there is good reason to believe the "aerial fertilization effect" of atmospheric CO_2 enrichment will continue to significantly benefit Earth's forests as long as the atmosphere's CO_2 concentration continues to rise.

Working with photosynthesis data they and others collected over 11 years at the Aspen FACE site near Rhinelander, Wisconsin (USA), Darbah et al. (2010) evaluated the merits of the progressive nitrogen limitation hypothesis for two different quaking aspen (*Populus tremuloides* Michx.) clones (42E and 271) exposed to all combinations of ambient and elevated (560 ppm) CO_2 and ambient and elevated (1.5 times ambient) ozone (O_3). They also investigated whether the same hypothesis applied to leaf stomatal conductance.

The eight researchers say their results “suggest no long-term photosynthetic and stomatal acclimation to elevated CO_2, O_3 or $CO_2 + O_3$ in aspen trees exposed to elevated CO_2 and/or O_3 gases for 11 years,” adding the aspen trees “have sustained their maximum instantaneous photosynthesis stimulation for over a decade.” Commenting further, they say their findings support the observations of (1) Liberloo et al. (2007), who measured a 49 percent increase in net photosynthetic rate in poplar trees after six years of exposure to elevated CO_2, (2) Sholtis et al. (2004), who reported a 44 percent stimulation of net photosynthesis in sweetgum trees after three years of exposure to elevated CO_2, (3) Crous and Ellsworth (2004), who found a photosynthetic enhancement of 51–69 percent in *Pinus taeda* trees after six years of exposure to elevated CO_2, as well as (4) Davey et al. (2006) and (5) Paoletti et al. (2007), of whose work Darbah et al. state “there was no photosynthetic acclimation (down-regulation) occurring in *Quercus ilex* under long-term CO_2 enrichment.” In addition, Darbah et al. remark that (6) even in white clover (*Trifolium repens*), Ainsworth et al. (2003) found photosynthetic stimulation “remained after nine years of exposure to elevated CO_2.”

Focusing her efforts belowground, Colleen Iversen of the Oak Ridge National Laboratory in Oak Ridge, Tennessee (USA) reviewed the pertinent scientific literature “to examine the potential mechanisms for, and consequences of, deeper rooting distributions under elevated CO_2 as they relate to ecosystem carbon and nitrogen cycling,” focusing primarily on forests (Iversen, 2010). She found “experimental evidence from a diverse set of forested ecosystems indicates that fine roots of trees exposed to elevated CO_2 are distributed more deeply in the soil profile relative to trees grown under ambient CO_2.” As an example, she reports, “in a FACE experiment in a sweetgum (*Liquidambar styraciflua*) plantation, Iversen et al. (2008) found that, over nine years, there was a 220% stimulation in cumulative carbon inputs from fine roots under elevated CO_2 at 45-60 cm soil depth, compared with a 30% stimulation of root carbon inputs at 0-15 cm depth,” and she notes “Pritchard et al. (2008a) found a similar response in a CO_2-enriched loblolly pine (*Pinus taeda*) plantation.” In fact, she found, “of those experiments that examined rooting depth responses to elevated CO_2, 73% found deeper rooting distributions.” In addition, she notes “increased proliferation at depth in the soil has not been limited to fine roots: increased production of mycorrhizas (Pritchard et al., 2008b) and coarse roots (Liberloo et al., 2006) also occurred deeper in the soil under CO_2 enrichment.”

Regarding the progressive nitrogen limitation hypothesis, therefore, Iversen writes, “a disconnect between observed root dynamics and modeled nutrient availability has confounded projections of forest responses to elevated CO_2.” She notes “while models predict that soil nitrogen availability will limit forest responses to elevated CO_2 (Thornton et al., 2007), many of the forested FACE experiments found a sustained increase in nitrogen uptake from the soil in response to CO_2 enrichment (Finzi et al., 2007).” She goes on to state “there has been much speculation on the source of this ‘extra’ nitrogen (Johnson, 2006), and a greater cumulative amount of nitrogen available at depth in the soil may be the answer (i.e. a ‘bigger box’ of nitrogen when deeper soil depths are considered).”

Shifting from forests to grasslands, Dijkstra et al. (2008) used open-top chambers to examine the effects of elevated atmospheric CO_2 concentration (720 vs. 368 ppm) on nitrogen dynamics in a semi-arid grassland ecosystem in northeastern Colorado (USA), where they studied the impacts of elevated CO_2 on nitrogen mineralization and plant N uptake by tracking initially applied ^{15}N and total N in both plants and soil over a period of five years. This work revealed an increase in aboveground biomass on the order of 40 percent in response to their specific degree of elevated CO_2; and they state it “did not lead to a progressive decline in soil N availability.” On the contrary, the six scientists write, “soil N availability remained higher after 5 years of elevated than ambient CO_2,” likely due to “a greater mineralization rate under elevated CO_2.” As for why this was so, they speculate the “elevated CO_2 increased soil moisture due to decreased plant transpiration at [their] site (Nelson et al., 2004), which could have stimulated microbial activity and N mineralization.”

In another illuminating experiment, McCormack et al. (2010) constructed 12 identical mini-ecosystems—each consisting of three longleaf pine (*Pinus palustris*) seedlings, three wiregrass (*Aristida stricta*) C_4 grass plants, two sand post oak (*Quercus margaretta*) seedlings, one rattlebox (*Croatalaria rotundifolia*) C_3 perennial herbaceous legume, and one butterfly weed (*Asclepias tuberose*) herbaceous C_3 dicotyledonous perennial—which they allowed to grow for three years in an outdoor soil bin at the National Soil Dynamics Laboratory in Auburn, Alabama (USA), within 12 open-top chambers (half of which were maintained for three years at 365 ppm CO_2 and half of which were maintained at 720 ppm CO_2 for the same period). During this time the "standing crops" of fine-root length, rhizomorph length, and number of mycorrhizal root tips were assessed in the upper (0–17 cm) and lower (17–34 cm) halves of the plants' root zones at four-week intervals via microvideo cameras installed within each of two mini-rhizotron tubes located within each of the 12 plots into which the soil bin was divided.

They found the greatest impacts of the 97 percent increase in the air's CO_2 content were generally observed in the lower halves of the ecosystems' root zones, where the standing crops of fine roots, rhizomorphs, and mycorrhizal root tips were increased, respectively, by 59 percent, 66 percent, and 64 percent, although the mean standing crop of rhizomorphs in the upper halves of the ecosystems' root zones was increased by 114 percent.

Based on these findings, McCormack et al. state that as the atmosphere's CO_2 concentration continues to rise, "greater biomass production in deeper soils in the coming decades has the potential to contribute to greater carbon storage in forest soils," because "carbon in deeper soil turns over (decomposes) more slowly than litter nearer the soil surface," citing Trumbore (2000) and Schoning and Kogel-Knabner (2006). In addition, they note "fungal tissues consist largely of chitin, a potentially recalcitrant compound that may build up soil organic matter and persist for long periods of time relative to more labile carbon," citing Langley and Hungate (2003). Thus they suggest "regenerating longleaf pine-wiregrass systems may act as a carbon sink as atmospheric CO_2 rises in the coming decades through increased biomass production and potentially through directed allocation of carbon to deeper soils," This, they note, is "consistent with the recent assertion that greater allocation of forest carbon to deeper soil is a general response to atmospheric CO_2-enrichment," citing Iversen (2010). And, very importantly, they state "significant increases in mycorrhizae and rhizomorphs," as they found in their study, "may explain why the magnitude of the increase in forest net primary productivity caused by elevated CO_2, in several long-term demonstrably nitrogen-limited FACE experiments, has not decreased after nearly a decade (Finzi et al., 2007)." This observation helps explain why the progressive nitrogen limitation hypothesis repeatedly has been shown to be wrong.

Also studying roots were Alberton et al. (2010), who write, "roots of a very large number of plant species are regularly colonized by a group of ascomycete fungi with usually dark-pigmented (melanized) septate hyphae (Mandyam and Jumpponen, 2005; Sieber and Grunig, 2006)" that are referred to as "dark septate root endophytic (DSE) fungi," with "most species belonging to the Leotiomycetes (Kernaghan et al., 2003; Hambleton and Sigler, 2005; Wang et al., 2006)." To study these fungi further, the authors grew Scots pine (*Pinus sylvestris*) plants from seed for 125 days in Petri dishes—both with and without inoculation with one of seven different species/strains of DSE fungi—within controlled environment chambers maintained at atmospheric CO_2 concentrations of either 350 or 700 ppm, destructively harvesting some of the seedlings at the 98-day point of the study and the rest at the end of the experiment.

At the conclusion of their study, the three researchers found, "across all plants (DSE-inoculated and control plants) under elevated CO_2, shoot and root biomass increased significantly by 21% and 19%, respectively, relative to ambient," with "higher values over the final four weeks (increases of 40% and 30% for shoots and roots, respectively)." In addition, they state "on average, shoot nitrogen concentration was 57% lower under elevated CO_2," and "elevated CO_2 decreased root nitrogen concentration on average by 16%." Nevertheless, they emphasize that "surprisingly, even under reduced nitrogen availability, elevated CO_2 led to increases in both above-ground and below-ground plant biomass."

In explaining how this happened, the Brazilian and Dutch researchers write, "a potential mechanism for the increase of plant biomass even when plant nutrient uptake decreases is the production of phytohormones by DSE fungi." They report "earlier authors noted that DSE fungi enhance plant growth by producing phytohormones or inducing host hormone production without any apparent facilitation of host nutrient uptake or stimulation of host nutrient metabolism (Addy et al., 2005; Schulz and Boyle, 2005)," further demonstrating that low levels of nitrogen availability need not impede significant CO_2-induced increases in plant growth and development.

In another pertinent study, Langley et al. (2009) once again state "it has been suggested that stimulation of productivity with elevated CO_2 ties up nitrogen in plant litter, which, if not offset by increases in N-use efficiency or N supply, will limit the ecosystem CO_2 response (Reich et al., 2006).” To test this hypothesis, they used “an acid-hydrolysis-incubation method and a net nitrogen-mineralization assay to assess stability of soil carbon pools and short-term nitrogen dynamics in a Florida scrub-oak ecosystem after six years of exposure to elevated CO_2,” This work was conducted at a multiple open-top-chamber facility on a barrier island located at NASA’s Kennedy Space Center on the east coast of central Florida, USA.

The researchers found elevated atmospheric CO_2 (to 350 ppm above ambient concentrations) tended to increase net N mineralization in the top 10 cm of the soil, but it also decreased total soil organic carbon content there by 21 percent. However, that loss of carbon mass was equivalent only to “roughly one-third of the increase in plant biomass that occurred in the same experiment.” In addition, they state the strongest increases in net N mineralization were observed in the 10–30 cm depth increment, and “release of N from this depth may have allowed the sustained CO_2 effect on productivity in this scrub-oak forest,” which over the four years leading up to their study “increased litterfall by 19–59%,” citing Hungate et al. (2006) for the latter figures. This is yet another experimental demonstration that plants are generally able to find the extra nitrogen they need to take full advantage of the aerial fertilization effect of elevated atmospheric CO_2 concentrations, which increases total ecosystem carbon content and thus results in a negative feedback to anthropogenic CO_2 emissions.

We conclude our review of the progressive nitrogen limitation hypothesis with a brief analysis of the paper of Thornton et al. (2009), who provided powerful political fodder for the claim that there will be even greater global warming in the future than the amount that already has been predicted by climate models, due to the supposedly smaller amount of CO_2 being removed from the air by the supposedly less-vigorously growing vegetation, due to the imagined gradual weakening of CO_2’s aerial fertilization effect on plants growing in nitrogen-limited soils.

As for why we should believe this model-based projection, the ten authors of the study state their conclusion “is supported by previous studies,” including “stand-alone ecosystem models (McGuire et al., 2001), [an] offline land component of a coupled climate model (Thornton et al., 2007), [a] coupled model of intermediate complexity (Sokolov et al., 2008), and now here for the case of a fully-coupled climate system model.” In addition, they state, “each of these studies is based on either the TEM or the CLM-CN model.”

You may get the impression that Thornton et al.’s work depends just a little too heavily on models, as compared to real-world experimental data. That is indeed the case, as numerous experimental studies provide no evidence for the progressive nitrogen limitation hypothesis, even in plants growing in soils of extremely low nitrogen content, where evidence for it surely would be expected to be found if the hypothesis were correct.

Historically, far too many falsehoods have been foisted on the world by mere hypotheses and models to justify accepting the outcome of Thornton et al.’s study, especially when the numerous results of the many real-world experiments reviewed here clearly indicate the study’s conclusion is false. As ever-more long-term experiments are conducted on long-lived plants growing outdoors and rooted in the earth, where their roots are not artificially confined to a limited volume of soil, it is becoming abundantly clear that plants generally do not experience any significant decline in the initial photosynthetic stimulation provided them by the extra CO_2 to which they are exposed in CO_2 enrichment studies.

References

Addy, H.D., Piercey, M.M., and Currah, R.S. 2005. Microfungal endophytes in roots. *Canadian Journal of Botany* **83**: 1–13.

Ainsworth, A.E., Rogers, A., Blum, H., Nosberger, J., and Long, S.P. 2003. Variation in acclimation of photosynthesis in *Trifolium repens* after eight years of exposure to free air CO_2 enrichment (FACE). *Journal of Experimental Botany* **54**: 2769–2774.

Alberton, O., Kuyper, T.W., and Summerbell, R.C. 2010. Dark septate root endophytic fungi increase growth of Scots pine seedlings under elevated CO_2 through enhanced nitrogen use efficiency. *Plant and Soil* **328**: 459–470.

Crous, K.Y. and Ellsworth, D.S. 2004. Canopy position affects photosynthetic adjustments to long-term elevated CO_2 concentration (FACE) in aging needles in a mature *Pinus taeda* forest. *Tree Physiology* **24**: 961–970.

Darbah, J.N.T., Kubiske, M.E., Nelson, N., Kets, K., Riikonen, J., Sober, A., Rouse, L., and Karnosky, D.F. 2010. Will photosynthetic capacity of aspen trees acclimate after long-term exposure to elevated CO_2 and O_3? *Environmental Pollution* **158**: 983–991.

Davey, P.A., Olcer, H., Zakhleniuk, O., Bernacchi, C.J., Calfapietra, C., Long, S.P., and Raines, C.A. 2006. Can fast growing plantation trees escape biochemical down-regulation of photosynthesis when growing throughout their complete production cycle in the open air under elevated carbon dioxide? *Plant, Cell and Environment* **29**: 1235–1244.

Dijkstra, F.A., Pendall, E., Mosier, A.R., King, J.Y., Milchunas, D.G., and Morgan, J.A. 2008. Long-term enhancement of N availability and plant growth under elevated CO_2 in a semi-arid grassland. *Functional Ecology* **22**: 975–982.

Finzi, A.C., Norby, R.J., Calfapietra, C., Gallet-Budynek, A., Gielen, B., Holmes, W.E., Hoosbeek, M.R., Iversen, C.M., Jackson, R.B., Kubiske, M.E., Ledford, J., Liberloo, M., Oren, R., Polle, A., Pritchard, S., Zak, D.R., Schlesinger, W.H., and Ceulemans, R. 2007. Increases in nitrogen uptake rather than nitrogen-use efficiency support higher rates of temperate forest productivity under elevated CO_2. *Proceedings of the National Academy of Sciences, USA* **104**: 14,014–14,019.

Finzi, A.C. and Schlesinger, W.H. 2003. Soil-nitrogen cycling in a pine forest exposed to 5 years of elevated carbon dioxide. *Ecosystems* **6**: 444–456.

Fujimaki, R., Sakai, A., and Kanedo, N. 2009. Ecological risks in anthropogenic disturbance of nitrogen cycles in natural terrestrial ecosystems. *Ecological Research* **24**: 955–964.

Hambleton, S. and Sigler, L. 2005. *Meliniomyces*, a new anamorph genus for root-associated fungi with phylogenetic affinities to *Rhizoscyphus ericae* (= *Hymenoscyphus ericae*), *Leotiomycetes*. *Studies in Mycology* **53**: 1–27

Hungate, B.A., Dukes, J.S., Shaw, M.R., Luo, Y., and Field, C.B. 2003. Nitrogen and climate change. *Science* **302**: 1512–1513.

Hungate, B.A., Johnson, D.W., Dijkstra, P., Hymus, G., Stiling, P., Megonigal, J.P., Pagel, A.L., Moan, J.L., Day, F., Li, J., Hinkle, C.R., and Drake, B.G. 2006. Nitrogen cycling during seven years of atmospheric CO_2 enrichment in a scrub oak woodland. *Ecology* **87**: 26–40.

Iversen, C.M. 2010. Digging deeper: fine-root responses to rising atmospheric CO_2 concentration in forested ecosystems. *New Phytologist* **186**: 346–357.

Iversen, C.M., Ledford, J., and Norby, R.J. 2008. CO_2 enrichment increases carbon and nitrogen input from fine roots in a deciduous forest. *New Phytologist* **179**: 837–847.

Jackson, R.B., Cook, C.W., Pippen, J.S., and Palmer, S.M. 2009. Increased belowground biomass and soil CO_2 fluxes after a decade of carbon dioxide enrichment in a warm-temperate forest. *Ecology* **90**: 3352–3366.

Johnson, D.W. 2006. Progressive N limitation in forests: review and implications for long-term responses to elevated CO_2. *Ecology* **87**: 64–75.

Kernaghan, G., Sigler, L., and Khasa, D. 2003. Mycorrhizal and root endophytic fungi of containerized *Picea glauca* seedlings assessed by rDNA sequence analysis. *Microbial Ecology* **45**: 128–136.

Langley, J.A. and Hungate, B.A. 2003. Mycorrhizal controls on belowground litter quality. *Journal of Ecology* **84**: 2302–2312.

Langley, J.A., McKinley, D.C., Wolf, A.A., Hungate, B.A., Drake, B.G., and Megonigal, J.P. 2009. Priming depletes soil carbon and releases nitrogen in a scrub-oak ecosystem exposed to elevated CO_2. *Soil Biology & Biochemistry* **41**: 54–60.

Liberloo, M., Calfapietra, C., Lukac, M., Godbold, D., Luo, Z.-B., Polle, A., Hoosbeek, M.R., Kull, O., Marek, M., Raines, C., Rubino, M., Taylor, G., Scarascia-Mugnozza, G., and Ceulemans, R. 2006. Woody biomass production during the second rotation of a bio-energy *Populus* plantation increases in a future high CO_2 world. *Global Change Biology* **12**: 1094–1106.

Liberloo, M., Tulva, I., Raim, O., Kull, O., and Ceulemans, R. 2007. Photosynthetic stimulation under long-term CO_2 enrichment and fertilization is sustained across a closed *Populus* canopy profile (EUROFACE). *New Phytologist* **173**: 537–549.

Luo, Y., Su, B., Currie, W.S., Dukes, J.S., Finzi, A., Hartwig, U., Hungate, B., McMurtrie, R.E., Oren, R., Parton, W.J., Pataki, D.E., Shaw, M.R., Zak, D.R., and Field, C.B. 2004. Progressive nitrogen limitation of ecosystem responses to rising atmospheric carbon dioxide. *BioScience* **54**: 731–739.

Mandyam, K. and Jumpponen, A. 2005. Seeking the elusive function of the root-colonizing dark septate endophytic fungi. *Studies in Mycology* **53**: 173–189.

McCarthy, H.R., Oren, R., Johnsen, K.H., Gallet-Budynek, A., Pritchard, S.G., Cook, C.W., LaDeau, S.L., Jackson, R.B., and Finzi, A.C. 2010. Re-assessment of plant carbon dynamics at the Duke free-air CO_2 enrichment site: interactions of atmospheric [CO_2] with nitrogen and water availability over stand development. *New Phytologist* **185**: 514–528.

McCormack, M.L., Pritchard, S.G., Breland, S., Davis, M.A., Prior, S.A., Runion, G.B., Mitchell, R.J., and Rogers, H.H. 2010. Soil fungi respond more strongly than fine roots to elevated CO_2 in a model regenerating longleaf pine-wiregrass ecosystem. *Ecosystems* **13**: 901–916.

McGuire, A.D., Sitch, S., Clein, J.S., Dargaville, R., Esser, G., Foley, J., Heimann, M., Joos, F., Kaplan, J., Kicklighter, D.W., Meier, R.A., Melillo, J.M., Moore III, B., Prentice, I.C., Ramankutty, N., Reichenau, T., Schloss, A., Tian, H., Williams, L.J., and Wittenberg, U. 2001. Carbon balance of the terrestrial biosphere in the twentieth century: analyses of CO_2, climate and land use effects with four process-based ecosystem models. *Global Biogeochemical Cycles* **15**: 183–206.

Nelson, J.A., Morgan, J.A., LeCain, D.R., Mosier, A., Milchunas, D.G., and Parton, B.A. 2004. Elevated CO_2 increases soil moisture and enhances plant water relations in a long-term field study in semi-arid shortgrass steppe of Colorado. *Plant and Soil* **259**: 169–179.

Paoletti, E., Seufert, G., Della Rocca, G., and Thomsen, H. 2007. Photosynthetic response to elevated CO_2 and O_3 in *Quercus ilex* leaves at a natural CO_2 spring. *Environmental Pollution* **147**: 516–524.

Pritchard, S.G., Strand, A.E., McCormack, M.L., Davis, M.A., Finzi, A.C., Jackson, R.B., Matamala, R., Rogers, H.H., and Oren, R. 2008a. Fine root dynamics in a loblolly pine forest are influenced by free-air-CO_2-enrichment: a six-year-minirhizotron study. *Global Change Biology* **14**: 588–602.

Pritchard, S.G., Strand, A.E., McCormack, M.L., Davis, M.A., and Oren, R. 2008b. Mycorrhizal and rhizomorph dynamics in a loblolly pine forest during 5 years of free-air-CO_2-enrichment. *Global Change Biology* **14**: 1–13.

Reich, P.B., Hungate, B.A., and Luo, Y. 2006. Carbon-nitrogen interactions in terrestrial ecosystems in response to rising atmospheric carbon dioxide. *Annual Review of Ecology, Evolution and Systematics* **37**: 611–636.

Schoning, I. and Kogel-Knabner, I. 2006. Chemical composition of young and old carbon pools throughout Camisol and Luvisol profiles under forests. *Soil Biology and Biochemistry* **38**: 2411–2424.

Schulz, B. and Boyle, C. 2005. The endophytic continuum. *Mycological Research* **109**: 661–686.

Sholtis, J.D., Gunderson, C.A., Norby, R.J., and Tissue, D.T. 2004. Persistent stimulation of photosynthesis by elevated CO_2 in a sweetgum (*Liquidambar styraciflua*) forest stand. *New Phytologist* **162**: 343–354.

Sieber, T.N. and Grunig, C.R. 2006. Biodiversity of fungal root-endophyte communities and populations, in particular of the dark septate endophyte *Phialocephala fortinii* s.1.In *Microbial Root Endophytes* [of series], edited by B. Schulz, C. Boyle, and T.N. Sieber. *Soil Biology* **9**: 107–132.

Sokolov, A.P., Kicklighter, D.W., Melillo, J.M., Felzer, B.S., Schlosser, C.A., and Cronin, T.W. 2008. Consequences of considering carbon-nitrogen interactions on the feedbacks between climate and the terrestrial carbon cycle. *Journal of Climate* **21**: 3776–3796.

Thornton, P.E., Doney, S.C., Lindsay, K., Moore, J.K., Mahowald, N., Randerson, J.T., Fung, I., Lamarque, J.-F., Feddema, J.J., and Lee, Y.-H. 2009. Carbon-nitrogen interactions regulate climate-carbon cycle feedbacks: results from an atmosphere-ocean general circulation model. *Biogeosciences* **6**: 2120–2120.

Thornton, P.E., Lamarque, J.F., Rosenbloom, N.A., and Mahowald, N.M. 2007. Influence of carbon-nitrogen cycle coupling on land model response to CO_2 fertilization and climate variability. *Global Biogeochemical Cycles* **21**: 10.1029/2006GB002868.

Trumbore, S. 2000. Age of soil organic matter and soil respiration: radiocarbon constraints on belowground C dynamics. *Ecological Applications* **10**: 399–411.

Wang, Z., Johnston, P.R., Takamatsu, S., Spatafora, J.W., and Hibbett, D.S. 2006. Toward a phylogenetic classification of the Leotiomycetes based on rDNA data. *Mycologia* **98**: 1065–1075.

7.13. Phenology

The progressively earlier arrival of spring with each succeeding year is widely viewed as an indicator of global warming. Scheifinger et al. (2002) and Schaber and Badeck (2005) claim to have detected earlier spring arrival in Europe over the course of the twentieth century.

A difficulty with such studies, however, is the lack of a commonly agreed-upon metric for the arrival of spring. Therefore, White et al. (2009) compared ten algorithms for processing satellite Normalized Difference Vegetaton Index (NDVI) data for this purpose, based on the expectation that satellite data, with their continental coverage, should allow such trends to be more easily detected. A question that remains, however, is whether the various methods employed measure the same things or correspond to on-the-ground measurements.

White et al.'s study covered the period of most rapid global warming (1982–2006), and a unique aspect of it was their use of 16,000 ground-based phenological measurements from across North America, as well as data on snow melt and hydrology. They found the ten methods of extracting a start-of-spring (SOS) signal from the satellite data differed widely, yielding a range of 60 days around the ten-model mean estimate. The methods also tended to be biased toward detecting SOS earlier than ground-based phenology data indicated, and to have weak correlations with the ground data, perhaps because there were difficulties classifying pixels in some cases, particularly for desert, semi-tropical, and Mediterranean (California) zones in which the arrival of "spring" is not a well-defined phenomenon.

In the end, therefore, the 21 researchers say they "found no evidence for time trends in spring arrival from ground- or model-based data," and "using an ensemble estimate from two methods that were more closely related to ground observations than other methods, SOS trends could be detected for only 12% of North America," with 7 percent of them showing a trend to earlier spring and 5 percent exhibiting a trend toward later spring. Thus, the possibility arises that the wide range of results obtained by most past and current methods of detecting the start of spring may have led to premature claims of spring's increasingly earlier annual occurrence over the latter part of the twentieth century. That finding, in turn, raises significant concerns about the validity of near-surface air temperature measurements that suggest that North America has warmed significantly over the past several decades.

In the introduction to their study of the subject, however, Johnston and Reekie (2008) write there have indeed "been marked changes in plant phenology over the past century," and they say these changes "have been interpreted as a consequence of the increase in temperature that has been observed over this time." But in an added twist to the subject, they speculate "the concentration of atmospheric CO_2 may also directly affect time of flowering, even in the absence of temperature change."

In exploring these possibilities, the two researchers examined the effect of elevated atmospheric CO_2 concentration by itself (ambient and ambient + 330 ppm), as well as the combined effect of elevated CO_2 and elevated air temperature (ambient + 1.5°C), on the flowering phenology of 22 species of plants in the Asteraceae family. These were grown under natural, seasonally varying temperature and daylength in separate compartments of a glasshouse in Wolfville, Nova Scotia, Canada. The researchers found, "on average, elevated CO_2 by itself advanced flowering by four days," while "increasing temperature as well as CO_2 advanced flowering by an additional three days." They also found "CO_2 was more likely to hasten phenology in long- than in short-day species," and "early- and late-flowering species did not differ in response to elevated CO_2, but the combined effect of elevated CO_2 and temperature hastened flowering more in early- than late-flowering species." As a result of these findings, they conclude, with respect to time of flowering in Asteraceae species, "the direct effect of CO_2 on phenology may be as important as its indirect effect through climate change," further complicating the interpretation of a progressively earlier start of spring as an indication of regional or global warming.

Another concern about global warming possibly hastening various types of biological activity associated with the arrival of spring is that various links of certain food chains may not respond in a compatible manner in terms of the temporal development of the different stages of their life cycles, leading to a serious mismatch among the unique needs of different ecosystem trophic levels that could spell disaster for some species. This concept has been said by Visser and Both (2005) to constitute an "insufficient adjustment" to climate change.

In a study designed to discover whether this phenomenon actually occurs in the real-world of nature for certain elements of an important ecosystem of Central Europe, Bauer et al. (2010) studied the effect of 47 years of warming (1961–2007) on (1) the time of leafing-out of dominant English Oak (*Quercus robur*) trees at four different research sites in the Czech Republic located in full-grown, multi-aged floodplain forests that had been under no forestry management, (2) the time of appearance of the two most abundant species of caterpillars in the floodplain forests, the Winter Moth (*Operophtera brumata*) and the Tortrix Moth (*Tortrix viridana*), and (3) the first and mean laying dates of two of the ecosystem's most common birds: Great Tits (*Parus major*) and Collared Flycatchers (*Ficedula albicollis*).

According to the seven scientists, "mean annual temperature showed a significant increase of 0.27–0.33°C per decade, with approximately the same magnitude of change during spring at all sites." They also found "on average (all four sites), the bud burst date for English Oak has advanced by 7.9 days and full foliage by 8.9 days, with approximately the same shifts being recorded for the peak of the beginning and end of frass for herbivorous caterpillars." This was the observational variable they used to characterize the caterpillars' presence. Last, they determined "the first laying date of Great Tits has advanced by between 6.2 to 8.0 days," while "the mean laying date has advanced by 6.4 to 8.0 days." Likewise, they found the "Collared Flycatcher first laying date has advanced by 8.5 to 9.2 days over the past 47 years, and the mean laying date by 7.7 to 9.6 days."

As to the importance of their findings, Bauer et al. state that because "trends in the timing of reproduction processes of both bird species are coherent with the trends in development of English Oak and with peak herbivorous caterpillar activity," it is apparent that in this specific food chain the common temporal shifting of the different organisms' phenological stages toward the beginning of the year "does not appear to have led to mistiming in the trophic food chain." Hence, there is reason to believe other food chains also may not be as seriously disrupted by global warming as many have postulated they could be. Of course, more work of this nature is needed before any generalizations are warranted.

References

Bauer, Z., Trnka, M., Bauerova, J., Mozny, M., Stepanek, P., Bartosova, L., and Zalud, Z. 2010. Changing climate and the phenological response of great tit and collared flycatcher populations in floodplain forest ecosystems in Central Europe. *International Journal of Biometeorology* **54**: 99–111.

Johnston, A. and Reekie, E. 2008. Regardless of whether rising atmospheric carbon dioxide levels increase air temperature, flowering phenology will be affected. *International Journal of Plant Science* **169**: 1210–1218.

Schaber, J. and Badeck, F. 2005. Plant phenology in Germany over the 20th Century. *Regional Environmental Change* **5**: 37–46.

Scheifinger, H., Menzel, A., Koch, E., Peter, C., and Ahas, R. 2002. Atmospheric mechanisms governing the spatial and temporal variability of phenological phases in central Europe. *International Journal of Climatology* **22**: 1739–1755.

Visser, M.E. and Both, C. 2005. Shifts in phenology due to global climate change: the need for yardstick. *Proceedings of the Royal Society B* **272**: 2561–2569.

White, Michael A., de Beurs, K.M., Kidan, K., Inouye, D.W., Richardson, A.D., Jensen, O.P., O'Keefe, J., Zhang, G., Nemani, R.R., van Leeuwen, W.J.D., Brown, J.F., de Wit, A., Schaepman, M., Lin, X., Dettinger, M., Bailey, A.S., Kimball, J., Schwartz, M.D., Baldocchi, D.D., Lee, J.T., and Lauenroth, W.K. 2009. Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote sensing for 1982–2006. *Global Change Biology* **15**: 2335–2359.

7.14. Range Expansion

When the air's CO_2 content is experimentally increased, the vast majority of Earth's plants lose less water to the atmosphere via transpiration while producing more biomass. The latter phenomenon is generally more strongly expressed in woody perennial species than in annual herbaceous plants. Consequently, and in concert with future increases in the atmosphere's CO_2 concentration, Earth's bushes, shrubs, and trees will likely grow better than non-woody species will. In addition, the increase in the air's CO_2 content will make many plants of all types actually prefer warmer temperatures, as reported by Idso and Idso (1994), which suggests that if air temperatures continue to rise, global warming will cause both woody and non-woody plants to grow more vigorously and expand their ranges, but with woody plants doing so in much more dramatic fashion.

In this summary, we review some of the more recent evidence for this phenomenon as it has operated among a wide variety of plants, beginning with trees.

Citing Bowman et al. (2001), Banfai and Bowman (2006), Bowman and Dingle (2006), and Brook and Bowman (2006), Bowman et al. (2010) write, "a large research program in the Australian monsoon tropics has concluded that monsoon rainforests have expanded within the savanna matrix" since "the middle of the last century," while noting a similar trend "has been emulated throughout the tropics worldwide," citing Schwartz et al. (1996), Guillet et al. (2001), Puyravaud et al. (2003), and Wigley et al. (2009). They say this phenomenon has been "suggested to be linked to a long-term trend towards wetter climates, atmospheric CO_2 enrichment, and changed fire regimes," although they remark that the observed forest expansion in Australia "is remarkable, being contrary to the widely accepted view that fire limits the extent of rainforests."

Following this introduction to the subject, Bowman et al. (2010) further discuss this suite of findings, paying particular attention to their "analytical and evidentiary basis and plausibility." And at the conclusion of their review, they note they "consider it most likely that the expansion of rainforest patches is related to global climate change via increased rainfall and/or the CO_2 'fertilizer effect'," since the expansion of Australia's monsoon rainforests occurred "despite hostile fire regimes." And they note this conclusion "is consistent with the recent finding from South Africa that strongly contrasting localized land management practices had little effect on the dramatic expansion of forest patches into the surrounding savanna in the latter half of the 20th century, strongly implicating global environmental change." This study confirms evidence that atmospheric CO_2 enrichment is the cause of the range expansion of woody plants that has been occurring around the world.

In a contemporary paper published in *Austral Ecology*, Kgope et al. (2010) similarly write, "over the last century, there has been a trend of increasing woody biomass in many savanna regions (Polley et al., 2002; Ward, 2005)," which is "generally attributed to changes in land use practice, particularly grazing and fire use, and to episodes of high or low rainfall." But they state "the phenomenon may also have been influenced by increasing atmospheric CO_2," citing the papers of Idso (1992), Polley (1997), and Polley et al. (1999). Consequently, in an investigation into the strength of the latter hypothesis, the three South African researchers conducted an experiment where they monitored "photosynthetic, growth and carbon allocation responses of African savanna trees (*Acacia karroo* and *Acacia nilotica*) and a C_4 grass, *Themeda triandra*, exposed to a gradient of CO_2 concentrations from 180 (typical of the Last Glacial Maximum) to 1000 ppm in open-top chambers in a glasshouse," as well as intermediate concentrations of 280, 370 (representing the present), 550, and 700 ppm.

The well-watered and -fertilized nitrogen-fixing *Acacia* trees they studied were started from seed and grown under the above-described conditions from the age of one week for a period of two years, at the midpoint of which time interval they were cut back and allowed to regrow for a second season, while the *T. triandra* plants they evaluated—which constitute "the dominant grass species in many frequently burnt grasslands and savannas in South Africa," as they describe them—were established from tillers obtained from a C_4 grassland in southern Kwa-Zulu-Natal, South Africa.

As a result of their efforts, Kgope et al. determined "photosynthesis, total stem length, total stem diameter, shoot dry weight and root dry weight of the acacias increased significantly across the CO_2 gradient, saturating at higher CO_2 concentrations." And they say "after clipping to simulate fire, plants showed an even greater response in total stem length, total stem diameter and shoot dry weight, signaling the importance of re-sprouting following disturbances such as fire or herbivory in savanna systems." However, and "in contrast to the strong response of tree seedlings to the CO_2 gradient," the three researchers found "grass productivity showed little variation."

Kgope et al. report, "at the end of the first growing season, SDW [shoot dry weight] had increased by 529% in *A. karroo* and 110% on average in *A. nilotica* under ambient relative to sub-ambient CO_2 treatments," and "a further increase in CO_2 from ambient to elevated CO_2 significantly increased SDW of *A. nilotica* by 86%." As for the second-season results, they found the SDW of re-sprouted *A. karoo* shoot material increased by 366 percent from sub-ambient to ambient CO_2, while that of *A. nilotica* increased by 133 percent on average. The South African scientists state, "changes in CO_2 from pre-industrial times to the present have effectively produced acacia 'super seedlings' in relation to their growth potential over the past several million years."

In light of these findings, Kgope et al. conclude, "where fires once killed seedlings, they are unlikely to do so today, resulting in much higher seedling recruitment rates," and they write "the rate of sapling release to adult height classes will also be greatly enhanced because they are able to grow out of the fire trap more rapidly." In addition, they state the trees "should also be better defended against mammal browsers and insect herbivores." And citing yet-to-be-published results, they state "both structural (spines) and chemical (tannins) defenses showed significant increases with increasing CO_2."

As for the implications of these several observations, the three researchers write they "provide experimental support for suggestions and simulation studies predicting that reductions in CO_2 alone could have led to loss of tree cover in grassy environments in the last glacial (Bond et al., 2003; Harrison and Prentice, 2003)," and they state "the large increases in CO_2 from industrial emissions over the last century would now favor trees at the expense of grasses." This conclusion is supported by palaeo-records that indicate "trees disappeared from current savanna sites in South Africa during the Last Glacial Maximum (Scott, 1999), re-appeared in the Holocene, and have rapidly increased over the last half century."

Addressing the same subject, Springsteen et al. (2010) write, "woody plant expansion within grassland ecosystems is a worldwide phenomenon, and dramatic vegetation shifts from grassland to savanna/woodlands have occurred over the past 50–100 years in North America," while noting one of the chief factors that has contributed to this phenomenon is believed by many to have been the concomitant historical increase in the air's carbon dioxide concentration, as suggested by the studies of Archer et al. (1995), Polley (1997), Bond and Midgley (2000), and Bond et al. (2003). They also indicate once shrublands are established, they tend to persist for several different reasons, one of which is a type of feedback phenomenon that "occurs when resources accumulate in soils beneath woody plants due to litterfall, interception of wet and dry deposition, nitrogen fixation, and animal droppings," as described by Schlesinger et al. (1990), Archer et al. (1995), Reynolds et al. (1999), and Lopez-Pintor et al. (2006). And they report in this regard that "changes in soil attributes under woody vegetation have been documented in the arid grasslands of the southern Great Plains, including increases in soil carbon and nitrogen," citing Reynolds et al. (1999), Hibbard et al. (2001, 2003), McCulley et al. (2004), Schade and Hobbie (2005), and Liao et al. (2006).

While working at the USDA-ARS Northern Great Plains Research Laboratory near Mandan, North Dakota (USA), Springsteen et al. examined near-surface (upper 15 cm) soil biogeochemistry along a 42-year (1963–2005) chronosequence, which encompassed grassland, woodland, and grassland-woodland transition zones in a northern Great Plains grassland, in order to determine the influence of woody plant expansion on soil carbon and nitrogen contents. The four researchers found total soil carbon content rose by 26 percent across the chronosequence from grassland to woodland within the 0–15 cm soil depth, while total soil nitrogen content rose by 31 percent. They add the rate of woody shrub expansion from 1963 to 1988 was ~1,800 m^2 per year, while from 1988 to 2005 it was ~3,800 m^2 per year, or a little more than double the rate of what it was in the first period.

In another pertinent paper, Souza et al. (2010) describe "how elevated CO_2 affects aboveground biomass within the understory community of a temperate deciduous forest at the Oak Ridge National Laboratory sweetgum (*Liquidambar styraciflua*) free-air carbon dioxide enrichment (FACE) facility in eastern Tennessee, USA," where growing-season (April to November) CO_2 treatments—ambient (aCO_2) and enriched (eCO_2)—were initiated in 1998. For the years 2001–2003 and 2008, when total understory aboveground biomass was assessed, the dominant sweetgum trees were approximately 16 meters tall during the first period and 18 meters tall in the second; and for these four years the daytime aCO_2 and eCO_2 concentrations in the forest understory averaged 474 and 577 ppm, respectively, for an eCO_2-aCO_2 difference (103 ppm) that was considerably less than that experienced in the sweetgum canopy above (161 ppm).

Under these conditions, Souza et al. report, "across years, aboveground biomass of the understory community was on average 25% greater in eCO_2 than in aCO_2 plots." In addition, they found "in 2001–03, little of the understory biomass was in woody species." In fact, they report "herbaceous species made up 94% of the total understory biomass across CO_2 treatments." In 2008, however, they discovered the contribution of herbaceous species to total understory biomass had dropped to 61 percent in the aCO_2 plots and had declined all the way to 33 percent in the eCO_2 plots.

In considering these results, the growth stimulation provided to the understory plants in the sweetgum plantation was truly outstanding: a 25 percent increase for a mere 103 ppm increase in the CO_2 concentration of the air to which they were exposed. Likewise, the rapid shift from a predominantly herbaceous understory to one that was fully two-thirds woody in the eCO_2 plots a mere five years later was also rather amazing, indicating, in the words of the five researchers, a "more rapid development of the tree regeneration layer and faster successional development of the stand," which they state could "influence long-term forest dynamics." In addition, the researchers' findings provide support for the theory that atmospheric CO_2 enrichment is enabling woody plants to expand their ranges into areas that previously had supported primarily herbaceous plants.

Still more recently, Keenan et al. (2011) note climate models "consistently project significant increases in temperature and decreases in precipitation in the Mediterranean basin," and they state these changes may have a large impact on current Mediterranean forests and the related ecosystem services they provide. In addition, they note niche-based models—also known as bioclimatic envelope models or habitat models—are by far the most commonly used method for predicting potential species distribution responses to future climatic changes. These models typically predict significant negative consequences for terrestrial plants in the face of continued increases in atmospheric CO_2 concentrations.

Keenan et al., however, prefer process-based models, which describe eco-physiological processes ranging from purely empirical relationships to mechanistic descriptions based on physical laws. They note these models—supported by experiments and growth and yield surveys—"suggest that global warming will have a positive impact on forest productivity (van der Meer et al., 2002; Nigh et al., 2004; Norby and Luo, 2004; Briceño-Elizondo et al., 2006; Gaucharel et al., 2008), due to the direct fertilization effect of increased CO_2 and indirect effects such as lengthening of the growing period."

To elucidate the difference in results obtained when employing these two approaches to forecasting the future, the five researchers assessed and compared the projections of each of them when applied to stands of three forest species (*Quercus ilex, Pinus halepensis,* and *Pinus sylvestris*) with widely contrasting distributions in continental Spain. They found "CO_2 fertilization through projected increased atmospheric CO_2 concentrations is shown to increase forest productivity in the mechanistic process-based model (despite increased drought stress) by up to three times that of the non-CO_2 fertilization scenario by the period 2050–2080, which is in stark contrast to projections of reduced habitat suitability from the niche-based models."

Given these findings, the Spanish and U.S. scientists say their results show "previous reports of species decline in continental Spain (e.g. Benito-Garzon et al., 2008) may be overestimated due to two reasons: the use of only one predictive niche-based model, and the failure to account for possible effects of CO_2 fertilization." They add "similar studies in other regions, which do not consider these two aspects, are also potentially overestimating species decline due to climate change." Furthermore, they suggest "niche-based model results also likely overestimate the decline in [habitat] suitability," and they therefore conclude "an organism's niche must be modeled mechanistically if we are to fully explain distribution limits," additionally citing Kearney (2006) in this regard.

In another intriguing study, a review of all large FACE studies conducted over the prior 15 years, Ainsworth and Long (2005) reported the greatest CO_2-induced benefits were accrued by trees, which experienced a mean biomass increase of 42 percent in response to a 300 ppm increase in the atmosphere's CO_2 concentration. In comparison, they found C_4 sorghum posted a yield increase of only 7 percent, while the C_3 crops rice and wheat exhibited yield increases of 16 percent and 22 percent, respectively. Thus, it is only natural to presume that as the air's CO_2 content continues to climb ever-higher, Earth's woody plants gradually will encroach upon areas where herbaceous plants previously ruled the landscape. Such is typically observed to be the case throughout the entire world. However, as noted by Wilcox and Huang (2010), trees typically use deeper water than grasses, and consequently they say the "prevailing belief is that woody plant encroachment leads to declining groundwater recharge and, therefore, to lower groundwater contributions to streams."

That typically would be an undesirable outcome, and in a study they designed to explore whether the declining-groundwater hypothesis is correct, the Texas A & M University researchers analyzed the long-term (85-year) trends of both baseflow (groundwater-derived) and stormflow (precipitation-derived) streamflow components of four major rivers in the Edwards Plateau region of Texas (USA)—the Nueces, Frio, Guadalupe, and Llano Rivers—over which time period the region experienced a significant increase in the presence of woody plants. The results of their analysis indicated "contrary to widespread perceptions," streamflows in their study region "have not been declining." In fact, they write, "the contribution of baseflow has doubled—even though woody cover has expanded and rainfall amounts have remained constant."

Noting their findings "run counter to current thinking in both lay and scientific circles," the Texas researchers speculate that "baseflows are higher now than in pre-settlement times, because rooting by trees has facilitated groundwater recharge." In addition, the transpiration-reducing effect of atmospheric CO_2 enrichment also may have played a role in this regard, as has been suggested by several prior studies of river basin hydrology (Idso and Brazel, 1984; Gedney et al., 2006; Betts et al., 2007). Whatever the answer or answers may be, it would appear good things have been happening to degraded grasslands throughout the world as the atmosphere's CO_2 concentration has been rising and woody plants have been extending their ranges and growing where they previously had been unable to survive, thus helping to make more water available for many other uses by man and nature alike.

Shifting from trees to shrubs, Brantly and Young (2010) note woody plant encroachment in herbaceous ecosystems "represents a key shift in community structure that has [the] potential to alter regional and global carbon and nitrogen cycling." However, they state "there is considerable uncertainty regarding the effects of woody [plant] encroachment on global terrestrial C storage," because of the possibility that "increases in C sequestration in woody biomass may be offset by associated increases in soil CO_2 efflux (i.e., combined heterotrophic respiration and root respiration) resulting from increased litterfall, increased soil moisture, and associated increases in microbial activity that often accompany woody [plant] encroachment."

In an attempt to determine "if young, sandy soils on a barrier island became a sink for C after encroachment of the nitrogen-fixing shrub *Morella cerifera*, or if associated stimulation of soil CO_2 efflux mitigated increased litterfall," the two researchers "monitored variations in litterfall in shrub thickets across a chronosequence of shrub expansion and compared those data to previous measurements of ANPP [annual net primary production] in adjacent grasslands." They then "quantified standing litter C and N pools in shrub thickets and soil organic matter (SOM), soil organic carbon (SOC), soil total nitrogen (TN) and soil CO_2 efflux in shrub thickets and adjacent grasslands." They conducted this field work on the north end of a barrier island just east of the Virginia portion of the DelMarVa peninsula, USA.

The two researchers report that although soil CO_2 efflux was indeed stimulated by shrub encroachment in the younger soils, "soil CO_2 efflux did not vary between shrub thickets and grasslands in the oldest soils, and increases in CO_2 efflux in shrub thickets did not offset contributions of increased litterfall to SOC." In fact, they found "SOC was 3.6–9.8 times higher beneath shrub thickets than in grassland soils, and soil TN was 2.5–7.7 times higher under shrub thickets." Thus Brantly and Young determined the expansion of shrubs on barrier islands has the ability "to significantly increase ecosystem C sequestration." What is more, they write, "stimulation of N storage beneath shrub thickets will also favor future growth of species with lower nutrient use efficiencies than native grasses, including climax maritime forest species that could sequester additional C in biomass," citing Ehrenfeld (1990) and Vitousek et al. (2002). All of these phenomena presaged by their work bode well for Earth's barrier islands and the woody plants they have the potential to support.

Continuing in much the same vein, and in light of the planet's significant warming over the last few decades of the twentieth century, it is only natural to presume many plants have concurrently expanded their ranges in a northward direction, providing for more overlapping of individual ranges and concomitant increases in local species diversity. One way of documenting this northward expansion of vegetation is what Hallinger et al. (2010) call "the long tradition of tree-line research." Now, however, they augment that older approach with an analogous study of the range expansion of shrubs.

Working at a site just three kilometers from the Abisko Scientific Research Station (68°21'N, 18°49'E) in the Northern Swedish Scandes, Hallinger et al. studied male plants of the medium-sized *Juniperus nana* shrub, collecting the main stems of five to eight shrubs every hundred meters of elevation until the shrub zone ended. Ring-width measurements on these stems were then performed, as they describe it, "to measure radial and vertical growth, to track growth changes over time, to age the shrub individuals and to correlate annual shrub growth with climate." The climate data were derived from records of the nearby Abisko Station.

The three researchers report they "documented a distinct increase in radial and vertical growth rates of *J. nana* shrubs during recent decades in the subalpine zone of North Sweden," and they state "the age structure of shrubs along the elevational gradient provides evidence that an upslope advance of the altitudinal shrubline is underway." In addition, they "observed significant, strong and stable correlations between annual ring width and summer temperatures (June, July, August)," and "the acceleration of radial and vertical growth since 1970 also coincides with the recent three decades of rising arctic air temperatures and the warming trend of 0.2°C per decade for the average temperature since 1956 at Abisko." Thus, the fruits of the German scientists' work add to what they call the "mounting evidence that shrubs are expanding into alpine and arctic areas because of climate warming," and they note "this expansion occurs in both evergreen and deciduous shrub types," citing the additional findings of Forbes et al. (2010).

Examining what happens even further north, Prach et al. (2010) studied a site in the High Arctic located at 78°38'N, 16°45'E, near Brucebyen at the

Adolfbukta Bay in central Spitsbergen (Svalbard), where the vegetation had been carefully surveyed, identified, and mapped in the 1930s and the results published by Acock (1940). In the summer of 2008, Prach et al. repeated the vegetation mapping and identification of species "on the same strip of land 2,042 x 521 meters in size, as surveyed by Acock in 1936–1937 and using the same methods." According to the four researchers, all from the Czech Republic, their work "did not reveal any changes in vegetation, since [the] previous study in 1936–1937, that could be attributed to climate change." Therefore, they "endorse the opinion that the vegetation on Svalbard is still resistant to climate fluctuations, in line with a statement of Jonsdottir (2005): 'Svalbard ecosystems are adapted to extreme fluctuations in climate on different temporal scales and can thus be regarded as rather robust'." Then, quoting Parmesan (2006), who had said "nearly every Arctic ecosystem shows marked shifts due to climate change," they concluded their paper by writing, "based on the results presented here, we wanted to note that some Arctic ecosystems still show no evident change." This lack of change may simply be because it may not have warmed as much in this High Arctic land as some researchers would have us believe, which also is suggested by Prach et al.

Also concerned about the future of Earth's biosphere, and especially the Arctic, Geml et al. (2010) note "the ability to migrate is of particular importance, because climate warming is expected to cause a northward shift in the distribution of many Arctic species, and the long-distance dispersal capability of individual species will greatly influence the composition of future Arctic communities." To assess the ability of two Arctic-alpine lichens to cope with such an eventuality, they examined the genetic structure and long-distance gene flow in two lichenized ascomycetes—*Flavocetraria cucullata* and *F. nivalis*—which are widespread in Arctic and alpine tundra. They did this via DNA sequencing of 49 specimens of *F. cucullata* and 41 of *F. nivalis* collected from various locations throughout Europe, Asia, and North America, employing "phylogenetic, nonparametric permutation methods and coalescent analyses" to assess "population divergence and to estimate the extent and direction of migration among continents."

The four researchers discovered both *F. cucullata* and *F. nivalis* had "high and moderately high intraspecific genetic diversity, respectively," and "clades within each species contained specimens from both North America and Eurasia." Thus, they concluded "at least some Arctic lichens have strong potential to adapt to the changing Arctic by tracking their ecological niche and to maintain high genetic diversity through intercontinental dispersal and sexual reproduction." As a result, whatever nature—or man—ultimately may send their way in terms of global warming, Arctic-alpine lichens should be good to go, wherever it is they need to go.

Another enlightening look at how plants have been responding to recent warming was provided by Le Roux and McGeoch (2008), who examined patterns of altitudinal range changes in the totality of the native vascular flora of sub-Antarctic Marion Island (46°54'S, 37°45'E) in the southern Indian Ocean, which warmed by 1.2°C between 1965 and 2003. The work of these South African researchers revealed between 1966 and 2006 there was "a rapid expansion in altitudinal range," with species expanding their upper elevational boundaries by an average of 70 meters. And because, as they describe it, "the observed upslope expansion was not matched by a similar change in lower range boundaries," they emphasize "the flora of Marion Island has undergone range expansion rather than a range shift." And an important consequence of the stability of lower-range boundaries together with expanding upper-range boundaries is that there is now a greater overlapping of ranges, resulting in greater local species richness or biodiversity everywhere up and down various altitudinal transects of the island. As a further consequence of this fact, Le Roux and McGeoch indicate "the present species composition of communities at higher altitudes is not an analogue of past community composition at lower altitudes, but rather constitutes a historically unique combination of species," or what we could truly call a "brave new world" significantly richer in variety than that of the recent past.

Finally, based on their documentation of plant species diversity on 13 mountain summits in southern Norway (61°06'–61°14'N, 7°52'–8°15'E)—in a reenactment of what Lye (1973) had done more than three decades earlier—as well as their assessment of regional warming over the intervening years, Odland et al. (2010) sought to see how plant species richness may have changed in response to what turned out to have been a significant increase in local temperature between the times of the two studies. Average summer temperatures, for example, increased by approximately 1.3°C over the time interval between the two studies. Over the same time period, they found plant taxa richness rose by an average of 90 percent, with two of the summits experiencing increases of fully 200 percent.

Of these results, Odland et al. state the average "is in accordance with similar studies in both Scandinavia and southern Europe (Kullman, 2007a,b; Parmesan, 2005; Pauli et al., 2007)," but they state the 200 percent increase in taxa richness they documented on two of the summits "is exceptional." And to make their view of the issue perfectly clear, the three Norse researchers conclude, "the present increase in species richness is mainly a result of recent climatic change."

References

Acock, A.M. 1940. Vegetation of a calcareous inner fjord region in Spitsbergen. *Journal of Ecology* **28**: 81–106.

Ainsworth, E.A. and Long, S.P. 2005. What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. *New Phytologist* **165**: 351–372.

Archer, S., Schimel, D.S., and Holland, E.A. 1995. Mechanisms of shrubland expansion: land use, climate or CO_2? *Climatic Change* **29**: 91–99.

Banfai, D.S. and Bowman, D.M.J.S. 2006. Forty years of lowland monsoon rainforest expansion in Kakadu National Park, northern Australia. *Biological Conservation* **131**: 553–565.

Benito-Garzon, M., Sanchez de Dios, R., and Sainz Ollero, H. 2008. Effects of climate change on the distribution of Iberian tree species. *Applied Vegetation Science* **11**: 169–178.

Betts, R.A., Boucher, O., Collins, M., Cox, P.M., Falloon, P.D., Gedney, N., Hemming, D.L., Huntingford, C., Jones, C.D., Sexton, D.M.H., and Webb, M.J. 2007. Projected increase in continental runoff due to plant responses to increasing carbon dioxide. *Nature* **448**: 1037–1041.

Bond, W.J. and Midgley, G.F. 2000. A proposed CO_2-controlled mechanism of woody plant invasion in grasslands and savannas. *Global Change Biology* **6**: 865–869.

Bond, W.J., Midgley, G.F., and Woodward, F.I. 2003. The importance of low atmospheric CO_2 and fire in promoting the spread of grasslands and savannas. *Global Change Biology* **9**: 973–982.

Bowman, D.M.J.S. and Dingle, J.K. 2006. Late 20th century landscape-wide expansion of *Allosyncarpia ternata* (Myrtaceae) forests in Kakadu National Park, northern Australia. *Australian Journal of Botany* **54**: 707–715.

Bowman, D.M.J.S., Murphy, B.P., and Banfai, D.S. 2010. Has global environmental change caused monsoon rainforests to expand in the Australian monsoon tropics? *Landscape Ecology* **25**: 1247–1260.

Bowman, D.M.J.S., Walsh, A., and Milne, D.J. 2001. Forest expansion and grassland contraction within a *Eucalyptus savanna* matrix between 1941 and 1994 at Litchfield National Park in the Australian monsoon tropics. *Global Ecology and Biogeography* **10**: 535–548.

Brantley, S.T. and Young, D.R. 2010. Shrub expansion stimulates soil C and N storage along a coastal soil chronosequence. *Global Change Biology* **16**: 2052–2061.

Briceño-Elizondo, R., Garcia-Gonzalo, J., Peltola, H., Matala, J., and Kellomaki, S. 2006. Sensitivity of growth of Scots pine, Norway spruce and silver birch to climate change and forest management in boreal conditions. *Forest Ecology and Management* **232**: 152–167.

Brook, B.W. and Bowman, D.M.J.S. 2006. Postcards from the past: charting the landscape-scale conversion of tropical Australian savanna to closed forest during the 20th century. *Landscape Ecology* **21**: 1253–1266.

Ehrenfeld, J.G. 1990. Dynamics and processes of barrier island vegetation. *Reviews in Aquatic Sciences* **2**: 437–480.

Forbes, B.C., Fauria, M., and Zetterberg, P. 2010. Russian Arctic warming and 'greening' are closely tracked by tundra shrub willows. *Global Change Biology* **16**: 1542–1554.

Gaucharel, C., Guiot, J., and Misson, L. 2008. Changes of the potential distribution area of French Mediterranean forests under global warming. *Biogeosciences* **5**: 1493–1503.

Gedney, N., Cox, P.M., Betts, R.A., Boucher, O., Huntingford, C., and Stott, P.A. 2006. Detection of a direct carbon dioxide effect in continental river runoff records. *Nature* **439**: 835–838.

Geml, J., Kauff, F., Brochmann, C., and Taylor, D.L. 2010. Surviving climate changes: high genetic diversity and transoceanic gene flow in two arctic-alpine lichens, *Flavocetraria cucullata* and *F. nivalis* (Parmeliaceae, Ascomycota). *Journal of Biogeography* **37**: 1529–1542.

Guillet, B., Achoundong, G., Happi, J.Y., Beyala, V.K.K., Bonvallot, J., Riera, B., Mariotti, A., and Schwartz, D. 2001. Agreement between floristic and soil organic carbon isotope ($^{13}C/^{12}C$, ^{14}C) indicators of forest invasion of savannas during the last century in Cameroon. *Journal of Tropical Ecology* **17**: 809–832.

Hallinger, M., Manthey, M., and Wilmking, M. 2010. Establishing a missing link: warm summers and winter snow cover promote shrub expansion into alpine tundra in Scandinavia. *New Phytologist* **186**: 890–899.

Harrison, S.P. and Prentice, I.C. 2003. Climate and CO_2 controls on global vegetation distribution at the last glacial maximum: analysis based on paleovegetation data, biome modeling and paleoclimate simulations. *Global Change Biology* **9**: 983–1004.

Hibbard, K.A., Archer, S., Schimel, D.S., and Valentine, D.W. 2001. Biogeochemical changes accompanying woody plant encroachment in a subtropical savanna. *Ecology* **82**: 1999–2011.

Hibbard, K.A., Schimel, D.S., Archer, S., Ojima, D.S., and Parton, W. 2003. Grassland to woodland transitions: integrating changes in landscape structure and biogeochemistry. *Ecological Applications* **13**: 911–926.

Idso, K.E. and Idso, S.B. 1994. Plant responses to atmospheric CO_2 enrichment in the face of environmental constraints: a review of the past 10 years' research. *Agricultural and Forest Meteorology* **69**: 153–203.

Idso, S.B. 1992. Shrubland expansion in the American southwest. *Climatic Change* **22**: 85–86.

Idso, S.B. and Brazel, A.J. 1984. Rising atmospheric carbon dioxide concentrations may increase streamflow. *Nature* **312**: 51–53.

Jonsdottir, I.S. 2005. Terrestrial ecosystems on Svalbard: heterogeneity, complexity and fragility from an Arctic island perspective. *Biology and Environment: Proceedings of the Royal Irish Academy* **105B**: 155–165.

Kearney, M. 2006. Habitat, environment and niche: what are we modeling? *Oikos* **115**: 186–191.

Keenan, T., Serra, J.M., Lloret, F., Ninyerola, M., and Sabate, S. 2011. Predicting the future of forests in the Mediterranean under climate change, with niche- and process-based models: CO_2 matters! *Global Change Biology* **17**: 565–579.

Kgope, B.S., Bond, W.J., and Midgley, G.F. 2010. Growth responses of African savanna trees implicate atmospheric [CO_2] as a driver of past and current changes in savanna tree cover. *Austral Ecology* **35**: 451–463.

Kullman, L. 2007a. Long-term geobotanical observations of climate change impacts in the Scandes of West-Central Sweden. *Nordic Journal of Botany* **24**: 445–467.

Kullman, L. 2007b. Modern climate change and shifting ecological sates of the subalpine/alpine landscape in the Swedish Scandes. *Geooko* **28**: 187–221.

Le Roux, P.C. and McGeoch, M.A. 2008. Rapid range expansion and community reorganization in response to warming. *Global Change Biology* **14**: 2950–2962.

Liao, J.D., Boutton, T.W., and Jastrow, J.D. 2006. Storage and dynamics of carbon and nitrogen in soil physical fractions following woody plant invasion of grassland. *Soil Biology and Biochemistry* **38**: 3184–3196.

Lopez-Pintor, A., Sal, A.G., and Benayas, J.M. R. 2006. Shrubs as a source of spatial heterogeneity—the case of *Retama sphaerocarpa* in Mediterranean pastures of central Spain. *Acta Oecologia* **29**: 247–255.

Lye, K.A. 1973. The vascular plants on alpine peaks at Filefjell, south Norway. *Norwegian Journal of Botany* **20**: 51–55.

McCulley, R.L., Archer, S.R., Boutton, T.W., Hons, F.M., and Zuberer, D.A. 2004. Soil respiration and nutrient cycling in wooded communities developing in grassland. *Ecology* **85**: 2804–2817.

Nigh, G.D., Ying, C.C., and Qian, H. 2004. Climate and productivity of major conifer species in the interior of British Columbia, Canada. *Forest Science* **50**: 659–671.

Norby, R.J. and Luo, Y. 2004. Evaluating ecosystem responses to rising atmospheric CO_2 and global warming in a multi-factor world. *New Phytologist* **162**: 281–293.

Odland, A., Hoitomt, T., and Olsen, S.L. 2010. Increasing vascular plant richness on 13 high mountain summits in southern Norway since the early 1970s. *Arctic, Antarctic, and Alpine Research* **42**: 458–470.

Parmesan, C. 2005. Biotic response: range and abundance changes. In *Climate Change and Biodiversity*, edited by T.E. Lovejoy and H. Lee, 41–55. New Haven, CT and London, UK: Yale University Press.

Parmesan, C. 2006. Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution and Systematics* **37**: 637–669.

Pauli, H., Gottfried, M., Reiter, K., and Grabherr, G. 2007. Signals of range expansions and contractions of vascular plants in the high Alps: observations 1994–2004 at the GLORIA master site Schrankogel, Tyrol, Austria. *Global Change Biology* **13**: 147–156.

Polley, H.W. 1997. Implications of rising atmospheric carbon dioxide concentration for rangelands. *Journal of Range Management* **50**: 562–577.

Polley, H.W., Tischler, C.R., Johnson, H.B., and Derner, J.D. 2002. Growth rate and survivorship of drought: CO_2 effects on the presumed tradeoff in seedlings of five woody legumes. *Tree Physiology* **22**: 383–391.

Polley, H.W., Tischler, C.R., Johnson, H.B., and Pennington, R.E. 1999. Growth, water relations, and survival of drought-exposed seedlings from six maternal families of honey mesquite (*Prosopis glandulosa*): responses to CO_2 enrichment. *Tree Physiology* **19**: 359–366.

Prach, K., Kosnar, J., Klimesova, J., and Hais, M. 2010. High Arctic vegetation after 70 years: a repeated analysis from Svalbard. *Polar Biology* **33**: 635–639.

Puyravaud, J.-P., Dufour, C., and Aravajy, S. 2003. Rainforest expansion mediated by successional processes in vegetation thickets in the Western Ghats of India. *Journal of Biogeography* **30**: 1067–1080.

Reynolds, J.F., Virginia, R.A., Kemp, P.R., de Soyza, A.G., and Tremmel, D.C. 1999. Impact of drought on desert shrubs: effects of seasonality and degree of resource island development. *Ecological Monographs* **69**: 69–106.

Schade, J.D. and Hobbie, S.E. 2005. Spatial and temporal variation in islands of fertility in the Sonoran Desert. *Biogeochemistry* **73**: 541–553.

Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jarrell, W.M., Ross, V.A., and Whitford, W.G. 1990. Biological feedbacks in global desertification. *Science* **247**: 1043–1048.

Schwartz, D., de Foresta, H., Mariotti, A., Balesdent, J., Massimba, J.P., and Girardin, C. 1996. Present dynamics of the savanna-forest boundary in the Congolese Mayombe: a pedological, botanical and isotopic (^{13}C/ and ^{14}C) study. *Oecologia* **106**: 516–524.

Scott, L. 1999. Vegetation history and climate in the Savanna biome of South Africa since 190,000 ka: a comparison of pollen data from the Tswaing Crater (the Pretoria Saltpan) and Wonderkrater. *Quaternary International* **57/58**: 517–544.

Souza, L., Belote, R.T., Kardol, P., Weltzin, J.F., and Norby, R.J. 2010. CO_2 enrichment accelerates successional development of an understory plant community. *Journal of Plant Ecology* **3**: 33–39.

Springsteen, A., Loya, W., Liebig, M., and Hendrickson, J. 2010. Soil carbon and nitrogen across a chronosequence of woody plant expansion in North Dakota. *Plant and Soil* **328**: 369–379.

van der Meer, P.J., Jorritsma, I.T.M., and Kramer, J.K. 2002. Assessing climate change effects on long-term forest development: adjusting growth, phenology and seed production in a gap model. *Forest Ecology and Management* **162**: 39–52.

Vitousek, P.M., Cassman, K., Cleveland, C., Crews, T., Field, C.B., Grimm, N.B., Howarth, R.W., Marino R., Martinelli, L., Rastetter, E.B., and Sprent, J.I. 2002. Towards an ecological understanding of biological N fixation. *Biogeochemistry* **57**: 1–45.

Ward, D. 2005. Do we understand the causes of bush encroachment in African savannas? *African Journal of Range and Forage Science* **22**: 101–105

Wigley, B.J., Bond, W.J., and Hoffmann, M.T. 2009. Thicket expansion in a South African savanna under divergent land use: local vs. global drivers? *Global Change Biology* **16**: 964–976.

Wilcox, B.P. and Huang, Y. 2010. Woody plant encroachment paradox: rivers rebound as degraded grasslands convert to woodlands. *Geophysical Research Letters* **37**: 10.1029/2009GL041929.

8

Aquatic Life

8. Aquatic Life

Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), CO_2-induced global warming is increasing the temperatures of Earth's oceans and seas and lowering their pH values, a process called acidification. Both processes, according to the IPCC, are likely to harm aquatic life. "Many studies incontrovertibly link coral bleaching to warmer sea surface temperature … and mass bleaching and coral mortality often results beyond key temperature thresholds" (IPCC 2007-II, p. 235). "Modelling," the IPCC goes on to say, "predicts a phase switch to algal dominance on the Great Barrier Reef and Caribbean reefs in 2030 to 2050." The IPCC further claims that "coral reefs will also be affected by rising atmospheric CO_2 concentrations … resulting in declining calcification" (ibid.).

The Nongovernmental Panel on Climate Change (NIPCC) disagreed with the IPCC in 2009, presenting a review of the extensive literature on coral reefs showing, inter alia, that there was no simple linkage between high temperatures and coral bleaching, that coral reefs have persisted through geologic time when temperatures were as much as 10° – 15°C warmer than at present and when CO_2 concentrations were two to seven times higher than they are currently, and that coral readily adapts to rising sea levels (Idso and Singer, 2009).

In the following pages we review new scientific research on coral reefs, finding new support for Idso and Singer's positions, and expand the analysis to include research on the effects of rising temperature and acidification on other marine plants, marine animals, and marine ecosystems.

References

Idso, C.D. and Singer, S.F. 2009. *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC).* Chicago, IL: The Heartland Institute.

IPCC, 2007-II. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Chan*ge. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson. (Eds.) Cambridge University Press, Cambridge, UK.

8.1. Temperature-Induced Stress

8.1.1. Effects on Corals

Coral bleaching is the process whereby the corals in Earth's seas expel the algal symbionts, or *zooxanthellae*, living within their tissues, upon which they depend for their sustenance, when subjected to various environmental stresses, one of the most discussed of which is rising water temperatures. Calls for reductions in anthropogenic CO_2 emissions are often justified as necessary in order to prevent species of corals from being driven to extinction. But the science underlying this popular trope points in quite different directions.

Carricart-Ganivet and Gonzalez-Diaz (2009) measured yearly coral extension rates and densities of the dominant Caribbean reef-building coral *Montastraea annularis* for the period 1991 to 2003 at two reef sites on the northwest coast of Cuba—one in the Guanahacabibes Gulf just off the Pinar del Rio Province and the other north of Havana Bay, from which data they calculated annual coral calcification rates. Plotting the calcification data against mean annual sea surface temperature (SST, obtained from the U.K.'s Hadley Centre), Carricart-Ganivet and Gonzalez-Diaz compared their results with those of Carricart-Ganivet (2004), who had identified a similar relationship between coral calcification rate and annual average SST based on data collected from colonies of the same coral species at several localities in the Gulf of Mexico and the Caribbean Sea.

The results of the two investigations are presented in Figure 8.1.1. Coral calcification, or growth, increases linearly with temperature at a rate of approximately 0.5 g cm^{-2} $year^{-1}$ for each 1°C increase in annual average SST. Thus the dominant reef-building corals of the tropical Atlantic Ocean seem not only to do fine, but actually to do better, when the waters within which they grow periodically warm. In addition, it is noteworthy that when Carricart-Ganivet (2004) had earlier pooled his calcification data with those of *M. annularis* and *M. faveolata* growing at Carrie Bow Cay, Belize, those from reefs at St. Croix in the U.S. Virgin Islands, and those of *M. faveolata* at Curacao, Antilles, he also obtained a mean increase in calcification rate of ~0.5 g cm^{-2} $year^{-1}$ for each 1°C increase in annual average SST, which finding is similar to other studies from distant locations around the world, as reported by Idso and Singer (2009).

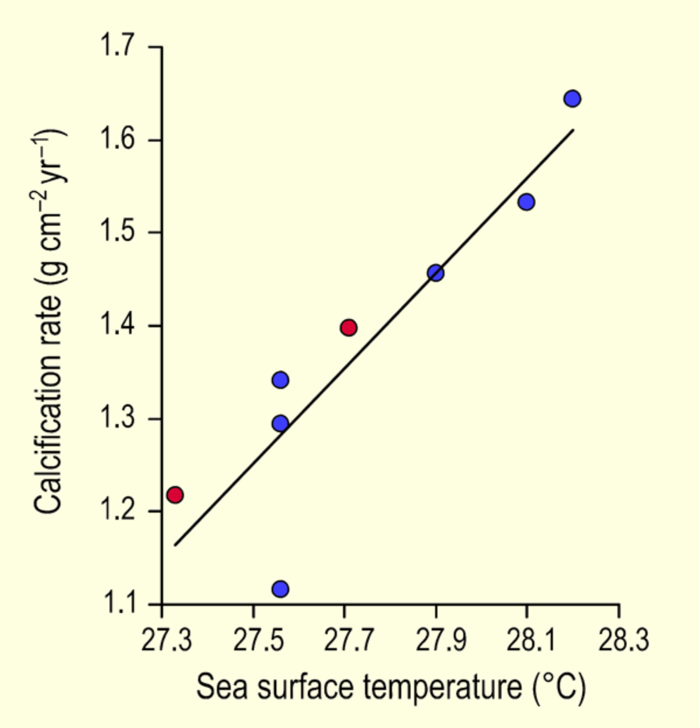


Figure 8.1.1. Mean yearly calcification rate of *Montastraea annularis* vs. mean annual sea surface temperature for the several sites studied by Carricart-Ganivet (2004) (blue circles) and the two sites studied by Carricart-Ganivet and Gonzalez-Diaz (2009) (red circles). The line that has been fit to the data is described by: Calcification Rate = 0.51 SST - 12.85 ($r^2 = 0.82$, $p < 0.002$). Adapted from Carricart-Ganivet and Gonzalez-Diaz (2009).

So why do some corals exhibit a propensity to bleach and die as temperatures rise, when the data of Carricart-Ganivet and Gonzalez-Diaz and others suggest their growth should increase? To answer this question, we turn to an article published in the journal *Coral Reefs*, where Maynard et al. (2008a) questioned the wisdom of "popularizing predictions based on essentially untested assumptions," among which they list the commonly heard claims that (1) "all corals live close to their thermal limits" and (2) "corals cannot adapt/acclimatize to rapid rates of change."

In discussing the first of these "untested assumptions," the three Australian researchers note "predictions that reefs will disappear as a result of global warming are based, at least in part, on the assumption that corals are living close to their maximum thermal limits." However, they observe "the severity of bleaching responses varies dramatically within and among taxa," citing McClanahan et al. (2009a), and "such variable bleaching susceptibility implies that there is a considerable variation in the extent to which coral species are adapted to local environmental conditions."

The three scientists further report little is known about the sensitivity of coral population response to climate-induced changes in vital rates, but they note a large body of evidence "supports temperature tolerance varying among species, populations, communities, and reef regions (Marshall and Baird, 2000; Coles and Brown, 2003)." They conclude, "even in the absence of an adaptive response, a change in the relative abundance of species is a far more likely outcome of climate change than the disappearance of reef corals," citing Loya et al. (2001), McClanahan et al. (2002), and Hughes et al. (2003).

As to whether there is indeed "an adaptive response" in contradiction of the second untested assumption Maynard et al. (2008a) discuss, the three researchers clearly believe there is. They state, "a number of studies suggest that bleaching mortality rates have declined and thermal tolerance has increased in some regions." As one example, they report "mortality rates in the Eastern Pacific were significantly lower in 1998 when compared with 1982 and 1983 (Glynn et al., 2001)," and as another example they note "Maynard et al. (2008b) found thermal tolerance of three common coral genera on the Great Barrier Reef to be greater in 2002 than that expected from the relationship between temperature stress and bleaching severity observed in 1998."

As to how this adaptation is accomplished, the Australian scientists state there is "circumstantial evidence for ongoing evolution of temperature tolerance between both species and reefs," citing the review of Coles and Brown (2003). In addition, they suggest "symbiont shuffling from less to more stress-resistant clades is another mechanism by which corals may increase the thermal tolerance of the holobiont." And they observe "there is growing evidence that such shuffling can increase thermal tolerance, at least in the short term," citing Berkelmans and van Oppen (2006). Maynard et al. (2008a) conclude "it is premature to suggest that widespread reef collapse is a certain consequence of ongoing bleaching, or that this will inevitably lead to fisheries collapses."

Other studies further demonstrate the resilience and adaptive nature of corals to warmer ocean temperatures. Grimsditch et al. (2010) write, "it has been shown that it is possible for [coral] colonies to acclimatize to increased temperatures and high irradiance levels so that they are able to resist bleaching events when they occur." They note, in this regard, "threshold temperatures that induce coral bleaching-related mortality vary worldwide—from 27°C in Easter Island (Wellington et al., 2001) to 36°C in the Arabian Gulf (Riegl, 1999)—according to the maximum water temperatures that are normal in the area, implying a capacity of corals and/or zooxanthellae to acclimatize to high temperatures depending on their environment."

In further exploration of this phenomenon, Grimsditch et al. examined "bleaching responses of corals at four sites (Nyali, Mombasa Marine Park, Kanamai and Vipingo) representing two distinct lagoon habitats on the Kenyan coast (deeper and shallower lagoons)." This was done for the coral community as a whole, while zooxanthellae densities and chlorophyll levels were monitored for three target species (*Pocillopora damicornis*, *Porites lutea*, and *Porites cylindrica*) during a non-bleaching year (2006) and a mild bleaching year (2007).

According to the four researchers, results indicated "during the 2007 bleaching season, corals in the shallow lagoons of Kanamai and Vipingo were more resistant to bleaching stress than corals in the deeper lagoons of Mombasa Marine Park and Nyali," which suggests, in their words, "corals in the shallower lagoons have acclimatized and/or adapted to the fluctuating environmental conditions they endure on a daily basis and have become more resistant to bleaching stress." Such results suggest corals have the ability to evolve in such a way as to successfully adjust to changing environmental conditions that when first encountered may prove deadly to a significant percentage of their populations. Those individuals genetically blessed to better withstand various stresses weather the storm, so to speak, to grow and widely proliferate another day.

In another study, Stuart-Smith et al. (2010) write, “despite increasing scientific and public concerns [about] the potential impacts of global ocean warming on marine biodiversity, very few empirical data on community-level responses to rising water temperatures are available.” To help fill this important data void, they undertook, as they describe it, “a study of sub-tidal reef communities over a decadal time scale, comparing data on fishes, macroinvertebrates and macroalgae collected at 136 sites, spanning hundreds of kilometers around the island of Tasmania (southeastern Australia) in the early to mid 1990s, with data from the same sites in 2006/2007.” This region, in their words, “has experienced relatively rapid warming during the last century as a consequence of a strengthening of the warm East Australian Current (Ridgway, 2007),” such that there has been “an increase in sea surface temperature of 2.28 ± 0.35°C per century for the period 1944–2002 (Ridgway, 2007), which is considerably more rapid than the global mean of 0.6 ± 0.2°C per century estimated by Smith and Reynolds (2003), and a mean increase in surface air temperature of 0.6–0.8°C (Salinger, 2005; Hansen et al., 2006).” The warming around this part of Tasmania has been more than three times greater than that of the global mean.

Contrary to what they had expected to find, the four researchers discovered “Tasmanian shallow rocky reef communities have been relatively stable over the past decade,” in spite of the “substantial rise in sea surface temperature over this period” and the “continuation of a considerable warming trend in oceanographic conditions over the last 50 years.” They report “the northeast and southeast bioregions, which are most influenced by the East Australian Current and hence have experienced the greatest warming over the past century, appeared to have changed very little.” In addition, “not only were Tasmanian reef communities remarkably similar between 1994 and 2006 in a multivariate sense, but univariate community characteristics such as species richness and total fish abundance were also consistent.” Thus, contrary to many people’s expectations and the researchers’ own initial thoughts on the subject, the Australian scientists found very little evidence to support the “doomsday” scenarios of the IPCC, who foresee continued global warming decimating Earth’s costal marine ecosystems.

In another study, Mydlarz et al. (2008) set out to learn what resources corals may possess that could help them cope with possible future global warming and various diseases that may accompany and/or be facilitated by rising temperatures. Specifically, they documented the responses of Caribbean sea fan corals (Anthozoa, Alcyonacea; Gorgoniidae) and their cell-based immune defenses (granular acidophilic amoebocytes, which are known to be involved in wound repair and histocompatibility) to both (1) naturally occurring infections and (2) experimental inoculations with the fungal pathogen *Aspergillus sydowii*, as well as to (3) experimentally induced increases in water temperature under laboratory conditions and (4) warming associated with the 2005 Caribbean Bleaching Event, which they describe as a “once-in-hundred-year climate event.”

Their results indicated “an increase of amoebocytes was observed in sea fan corals naturally temperature stressed during the 2005 Caribbean-wide bleaching event, as well as experimentally temperature stressed sea fans in the lab,” and “with both naturally occurring infections and experimental inoculations with the fungal pathogen *Aspergillus sydowii*, an inflammatory response, characterized by a massive increase of amoebocytes, was evident near infections.” In addition, they note “the sea fan has been shown to produce lipid-based anti-fungal metabolites which can halt growth of *A. sydowii* in culture (Kim et al., 2000),” and they note Ward et al. (2007) observed “higher anti-fungal activity of sea fans during experimental heat stress and detected a dramatic (176%) increase in potency of anti-fungal metabolites extracted from the sea fans kept at 31.5°C (2.5°C above summer ambient) and exposed to fungus, relative to controls.”

What all of this reveals about the likely future of these corals, according to Mydlarz et al., is this: “taken together, these studies suggest an unexpected degree of resilience under adverse environmental conditions.” Indeed, they state, “it is clear from the data presented in this paper that the sea fan aggressively combats infection in the gorgonian-*Aspergillus* pathosystem and exhibits the capability for resilience against multiple challenges,” including warming of the surrounding waters.

In another study of corals, Meyer et al. (2009) write, “whether corals can adapt to increasing temperatures over the course of generations will depend in part on heritable variation in thermal physiology and dispersal potential, which may serve as the raw material for natural selection.” In an effort to determine such potential, Meyer et al. “performed controlled crosses between three genetically distinct colonies of the branching coral *Acropora millepora*," after which they "compared the families of larvae (which in this species naturally lack symbionts) for several physiological traits." This work was conducted at the standard culturing temperature of 28°C, an elevated temperature of 32°C, and an even higher temperature of 34°C that was maintained for two days.

The U.S., Canadian, and Australian researchers confirmed the existence of phenotypic variance for several pertinent thermal and dispersive factors among the families of coral they studied. This finding, in their words, "suggests the existence of considerable heritable variation in natural coral populations," which in turn supports "the possibility of effective adaptive responses to climate change." In addition, they report other analyses of the species they studied have found "high levels of genetic diversity both within and between reefs (Smith-Keune and van Oppen, 2006)," and "studies in other coral species have also uncovered substantial genetic diversity within populations (Ayre and Hughes, 2000; Underwood, 2009; Wang et al., 2009)."

Based on these findings, Myer et al. conclude, "additive genetic variance exists within coral populations for several traits that might reasonably be expected to have fitness consequences during global climate change," which "supports the possibility of effective adaptive responses to climate change."

Such effective adaptive responses might well be illustrated in another 2009 study by Scopelitis et al. (2009), who constructed a history of changes in a coral community on Saint-Leu Reef on la Reunion (a mountainous volcanic island of the Mascarene Archipelago in the South West Indian Ocean) over a period of 35 years (1973–2007). During this time the reef was subjected to a series of major devastating events, including a category 5 cyclone (Firinga, of 29 January 1989) that "caused 99% coral cover loss (Naim et al., 1997)," a severe coral bleaching event in March 2002 that followed on the heels of cyclone Dina of January 2002, plus other bleaching episodes in 1983, March–April 1987, and February 2003. Yet "despite the multiple disturbance events," in the words of the six scientists, "the coral community distribution and composition in 2006 on Saint-Leu Reef did not display major differences compared to 1973." This pattern of recurrent recovery is truly remarkable in light of the fact that "in the wake of cyclone Firinga, Saint-Leu Reef phase-shifted and became algae-dominated for a period of five years." Remarkably, following an unnamed cyclone of 27 January 1948, *no* corals survived.

In light of these findings, the Australian and French researchers state their results suggest "a high degree of coral resilience at the site, led by rapid recovery of compact branching corals," which demonstrates the ability of corals to cope with bleaching and other devastating effects.

These studies suggest this may be the way all corals behave when not burdened by a host of local assaults on their environment through impacts of mankind. Destructive cyclones and high temperature excursions always have been a part of the coral reef environment, but the intensive activities of modern human societies have not. It is these newer activities that likely constitute the greatest threat to the health of Earth's corals. Mitigate them significantly, and coral reefs likely would cope successfully with the vagaries of nature.

In illustrating this latter point, it has been hypothesized that any increases in coral bleaching that may have occurred in response to periods of elevated water temperature over the past two decades have occurred because of a long-term weakening of coral resistance to thermal stress caused by the gradual intensification of a multitude of local anthropogenic assaults upon the environments in which corals live (Idso et al., 2000). These include, among a large number of other things, chemical insults to reef environments, such as the rising levels of nutrients and toxins in coastal waters caused by runoff from agricultural activities on land and associated increases in sediment delivery. Nearly a decade later, scientists are providing significant evidence for the validity of that contention.

Carilli et al. (2009) collected 92 cores from *Montastraea faveolata* corals growing at four different sites on the Mesoamerican Reef off the coast of Belize in the Caribbean Sea that had been exposed to either relatively high (Sapodilla Cayes, Utila) or low (Turneffe Atoll, Cayos Cochinos) chronic local stress levels induced by "(1) sedimentation, (2) nutrient input, (3) local human population size adjacent to [the] sites, and (4) a relative measure of fishing pressure based on fish abundance surveys." Then, based on measurements made on these cores, they determined yearly coral extension rates from 1955 to 2006, from which they assessed the degree of rapidity with which the corals at each site recovered from the huge growth-retarding bleaching event of 1998.

Following the 1998 bleaching event, the researchers found, "coral growth rates at sites with higher local anthropogenic stressors remained suppressed for at least eight years, while coral growth rates at sites with lower stress recovered in two to three years." Thus the authors state "it is clear that coral colonies experiencing higher local stress before 1998 were more severely affected by bleaching and recovered more slowly than those exposed to lower chronic stress," and "local stressors such as increased sedimentation may depress a coral's energy reserves (Rogers, 1990), making it less likely to survive or recover from a bleaching event (Rodrigues and Grottoli, 2007)." Therefore, they confidently conclude "local conservation efforts that reduce stress, such as reducing runoff by replanting mangroves at the coast or protecting an area from overfishing, could have significant impacts on the ability of corals to withstand the effects of climate change," or as they state more succinctly in the final sentence of their abstract, "reducing chronic stress through local coral reef management efforts may increase coral resilience to global climate change."

In another paper illustrating the significance of local threats to coral health, authors Hoeksema and Koh (2009) note Singapore "is one of the busiest ports of the world and land area is very limited," so "space needed for industrial activities depending on maritime resources [has been] created at the coast or in the sea, which has caused suspended matter to decrease light penetration in coastal waters." In addition, they note, "besides the creation of landfills and dredging activities for port extensions, the seawater may also become sediment-enriched by logging and subsequent terrigenous run-off along the nearby coastline." And they state "all these activities may cause damage to coral growth and survival," citing the work of Dodge et al. (1974), Dodge and Vaisnys (1977), Rogers (1990), and McClanahan and Obura (1997).

Against this backdrop, Hoeksema and Koh studied the characteristics of mushroom corals (Scleractinia: Fungiidae) that had been collected from the coastal waters of Singapore or photographed in place, based on historical records and specimen collections maintained at Singapore's Raffles Museum of Biodiversity Research, which were provided by researchers in the 1860s, 1890s, 1970, 1986–1991, and 2006, with the goal of identifying all the species present at each of the times of observation.

All of the records together yielded a total of 19 species, but "four species represented in collections made before 2006 were not observed during the 2006 survey." In addition, the researchers state, three of the four species "are usually absent on reefs close to river outlets and most abundant on offshore reefs (Hoeksema and Moka, 1989; Hoeksema, 1990,1993)." This suggests, in their words, that these species "are less capable to withstand sedimentation" and, therefore, that the "increase in sediment load at Singapore is a likely cause for their disappearance."

Focusing more on the topic at hand, Hoeksema and Koh state, "although Singapore's reefs suffered severe coral bleaching in 1998, some species (including *Fungia* spp.) were also known to have recovered quite soon," citing Chou (2001). Likewise, they state, "coral populations in the offshore Thousand Islands off Jakarta showed recovery after the 1983 bleaching event (Brown and Suharsono, 1990; Hoeksema, 1991)," and "during a coral reef survey in 2005 species richness of mushroom corals in the same area showed no visible decrease in species numbers." Therefore, they continue, "coral bleaching is not a likely cause for a decrease in fungiid species richness in Singapore."

Hoeksema and Koh concluded: "The observed loss in mushroom coral species in Singapore is most likely linked to an increased sediment load of the water and the reefs as a result of land reclamation projects in the harbor of Singapore (Hilton and Chou, 1999) and deforestation of Singapore's hinterland (Brook et al., 2003)."

In examining local threats from another angle, Mumby and Harborne (2010) note that while the efficacy of no-take marine reserves in promoting biodiversity and fish biomass by reducing local-scale stressors, such as fishing, has been widely documented, there remains a need to determine "whether reserves can also build coral resilience and offset the effects of global climate change that elevate coral mortality and constrain coral calcification."

To explore this question, Mumby and Harborne "studied coral population dynamics at 10 sites throughout the Exuma Cays (Bahamas) over a 2.5-year period (2004–2007) in order to contrast the trajectories of coral populations both inside and outside reserves [that were] severely disturbed by the 1998 coral bleaching event, and later by hurricane Frances in the summer of 2004." This approach was taken based on the oft-observed fact that "protecting large herbivorous fishes from fishing can generate a trophic cascade that reduces the cover of macroalgae," which are major competitors of corals.

The two researchers determined "the proportional increase in coral cover after 2.5 years was fairly high at reserve sites (mean of 19% per site) and significantly greater than that in non-reserve sites which, on average, exhibited no net recovery." This differential response was attributed by them to the reduced density of competing macroalgae in the marine reserves that were "depleted by more abundant communities of grazers that benefit[ed] from reduced fishing pressure." Mumby and Harborne conclude marine reserves can indeed "build coral resilience and offset the effects of global climate change." They also suggest that were it not for the site-specific deleterious effects of humanity on reef environments, this resilience likely would be the case nearly everywhere. This, in turn, suggests the local environmental impacts of human activities are what are harming Earth's corals, not the more speculative global impacts the IPCC typically blames on anthropogenic CO_2 emissions.

In a contemporaneous study, Sandin et al. (2010) note "ecological baselines of the structure and functioning of ecosystems in the absence of human impacts can provide fundamental insights for conservation and restoration," which is especially important in understanding likely responses of coral reefs to possible future global warming. Thus, Sandin et al. "surveyed coral reefs on uninhabited atolls in the northern Line Islands to provide a baseline of reef community structure, and on increasingly populated atolls to document changes associated with human activities."

On the uninhabited atolls, the 19 researchers observed fish biomass and the proportion of apex predators "greater than previously described from any coral reef ecosystem," and "high cover of reef-building corals and crustose coralline algae, abundant coral recruits, and low levels of coral disease." They also note "uninhabited reefs appear to retain greater capacity to survive or recover from major episodes of coral disease or bleaching," whereas reefs with highly altered food webs "do not." Consequently, they state the uninhabited atolls of the Line Islands "have remained remarkably intact in comparison to the global norm."

In light of their results, Sandin et al. conclude "protection from overfishing and pollution appears to increase the resilience of reef ecosystems to the effects of global warming," which is essentially the aforementioned position espoused by Idso et al. (2000), who concluded more than ten years ago that "increases in coral bleaching that may have occurred in response to periods of elevated water temperature over the past two decades have only occurred because of a long-term weakening of coral resistance to thermal stress caused by the gradual intensification of a multitude of local anthropogenic assaults upon the watery environments in which corals live."

In another view of the subject, McClanahan et al. (2009b) note many people are so convinced about the postulated negative impact of global warming on coral reefs that they automatically assume "climate overrides and undermines local resource use and management" and there is thus a "need for management of the atmosphere at the global scale."

In a study designed to evaluate that assumption, McClanahan et al. conducted surveys of coral reefs in northern Tanzania "in 2004/5 with the aim of comparing them over an ~8-year period during a time of increased efforts at fisheries management and the 1998 El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole coral mortality event that caused 45% mortality in northern Tanzania and much of the Indian Ocean."

According to the Kenyan, Swedish, Tanzanian, and U.S. researchers, their repeated surveys "indicate general stability of these reefs over time," and "in the context of the high bleaching and mortality of western Indian Ocean reefs after 1998 (Goreau et al., 2000; McClanahan et al., 2007), the general stability and improvement of these reefs six to seven years after the largest ENSO in recent history (McPhaden, 1999) indicates reefs with considerable resilience to climate change."

Given that "all reefs exhibited some resilience and ecological stability and even improvements during this time of climate and management change," as they describe it, McClanahan et al. concluded this observation "creates considerably more optimism for poor countries, such as Tanzania, to effectively manage their reefs in an environment of climate change." Consequently, they state, "Tanzanian and possibly many other reefs that exhibit similar environmental conditions have the ability to recover from large-scale climatic and human disturbances."

Finally, we highlight the work of Woodroffe et al. (2010), who noted "coral reefs track sea level and are particularly sensitive to changes in climate" and wondered whether “warmer sea surface temperatures might enable reef expansion into mid latitudes.” To explore this possibility, Woodroffe et al. employed sonar mapping of the seabed topography around Lord Howe Island (31°30’S)—which is fringed by the southernmost reef in the Pacific Ocean—supplemented with single-beam echosounder and Laser Airborne Depth Sounder (LADS) data, while bottom sediments were examined using an acoustic sub-bottom profiler and a grab sampler aided by radiocarbon and uranium-series dating. This work enabled the nine researchers to discover an extensive relict coral reef around Lord Howe Island in water depths of 25–50 meters, which flourished in early Holocene times, about 9,000 to 7,000 years ago. They describe this reef as “immense,” as it was “more than twenty times the area” of the modern reef at that site.

Woodroffe et al. state this finding “demonstrates that reefs were much more extensive 9000 years ago than they are at present at this latitudinal limit to reef growth,” and they conclude the “relict reef, with localized re-establishment of corals in the past three millennia, could become a substrate for reef expansion in response to warmer temperatures, anticipated later this century and beyond.” Indicating this situation is not unique, they report “shelf-edge reefs are common throughout the Caribbean (Hubbard et al., 2008), and backstepped to modern reef locations 7000–6500 years ago,” while noting “complex early Holocene shelf reefs flourished 9000–7000 years ago in southeast Florida, at the northern latitudinal limit to reef growth, ceasing growth before 6000 calendar years before present (Toscano and Lundberg, 1998; Banks et al., 2008).” They opine that these and similar sites “may represent important refugia from increases in sea surface temperature,” citing additionally in this regard the work of Riegl and Piller (2003).

References

Ayre, D.J. and Hughes, T.P. 2000. Genotypic diversity and gene flow in brooding and spawning corals along the Great Barrier Reef, Australia. *Evolution* **54**: 1590–1605.

Banks, K.W., Riegl, B.M., Richards, V.P., Walker, B.K., Helme, K.P., Jordan, L.K.B., Phipps, M., Shivji, M.S., Speiler, R.E., and Dodge, R.E. 2008. The reef tract of continental southeast Florida (Miami-Dade, Broward, and Palm Beach counties, USA). In *Coral Reefs of the USA*, edited by B.M. Riegl and R.E. Dodge, 175–220. Dordrecht, Netherlands: Springer.

Berkelmans, R. and van Oppen, M. 2006. The role of zooxanthellae in the thermal tolerance of corals: a ‘nugget of hope’ for coral reefs in an era of climate change. *Proceedings of the Royal Society of London B* **273**: 2305–2312.

Brook, B.W., Sodhi, N.S., and Ng, P.K.L. 2003. Catastrophic extinctions follow deforestation in Singapore. *Nature* **424**: 420–423.

Brown, B.E. and Suharsono. 1990. Damage and recovery of coral reefs affected by El Niño related seawater warming in the Thousand Islands, Indonesia. *Coral Reefs* **8**: 163–170.

Carilli, J.E., Norris, R.D., Black, B.A., Walsh, S.M., and McField, M. 2009. Local stressors reduce coral resilience to bleaching. *PLoS ONE* **4**: 10.1371/journal.pone.0006324.

Carricart-Ganivet, J.P. 2004. Sea surface temperature and the growth of the West Atlantic reef-building coral *Montastraea annularis*. *Journal of Experimental Marine Biology and Ecology* **302**: 249–260.

Carricart-Ganivet, J.P. and Gonzalez-Diaz, P. 2009. Growth characteristics of skeletons of *Montastraea annularis* (Cnidaria: Scleractinia) from the northwest coast of Cuba. *Ciencias Marinas* **35**: 237–243.

Chou, I.M. 2001. Country report: Singapore. Report of the International Coral Reef Initiative.

Coles, S.L. and Brown, B.E. 2003. Coral bleaching—capacity for acclimatization and adaptation. *Advances in Marine Biology* **46**: 183–223.

Dodge, R.E., Aller, R.C., and Thomson, J. 1974. Coral growth related to resuspension of bottom sediments. *Nature* **247**: 574–577.

Dodge, R.E. and Vaisnys, J.R. 1977. Coral populations and growth patterns: responses to sedimentation and turbidity associated with dredging. *Journal of Marine Research* **35**: 715–730.

Glynn, P.W., Mate, J.L., Baker, A.C., and Calderon, M.O. 2001. Coral bleaching and mortality in Panama and Ecuador during the 1997–1998 El Nino-Southern Oscillation event: spatial/temporal patterns and comparisons with the 1982–1983 event. *Bulletin of Marine Science* **69**: 79–109.

Goreau, T., McClanahan, T., Hayes, R., and Strong, A. 2000. Conservation of coral reefs after the 1998 global bleaching event. *Conservation Biology* **14**: 5–15.

Grimsditch, G., Mwaura, J.M., Kilonzo, J., and Amiyo, N. 2010. The effects of habitat on coral bleaching responses in Kenya. *Ambio* **39**: 295–304.

Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D.W., and Medina-Elizade, M. 2006. Global temperature change.

Proceedings of the National Academy of Sciences USA **103**: 14,288–14,293.

Hilton, M.J. and Chou, L.M. 1999. Sediment facies of a low-energy, meso-tidal fringing reef, Singapore. *Singapore Journal of Tropical Geography* **20**: 111–130.

Hoeksema, B.W. 1990. *Systematics and Ecology of Mushroom Corals (Scleractinia: Fungiidae)*. Ph.D. thesis. Leiden, Netherlands: University of Leiden.

Hoeksema, B.W. 1991. Control of bleaching in mushroom coral populations (Scleractinia: Fungiidae) in the Java Sea: stress tolerance and interference by life history strategy. *Marine Ecology Progress Series* **74**: 225–237.

Hoeksema, B.W. 1993. Mushroom corals (Scleractinia: Fungiidae) of Madang Lagoon, northern Papua New Guinea: an annotated check-list with the description of *Cantherellus jebbi* spec. nov. *Zoologische Mededelingen, Leiden* **67**: 1–19.

Hoeksema, B.W. and Koh, E.G.L. 2009. Depauperation of the mushroom coral fauna (Fungiidae) of Singapore (1860s–2006) in changing reef conditions. *The Raffles Bulletin of Zoology* (Supplement **22**): 91–101.

Hoeksema, B.W. and Moka, W. 1989. Species assemblages and phenotypes of mushroom corals (Fungiidae) related to coral reef habitats in the Flores Sea. *Netherlands Journal of Sea Research* **23**: 149–160.

Hubbard, D.K., Burke, R.B., Gill, I.P., Ramirez, W.R., and Sherman, C. 2008. Coral-reef geology: Puerto Rico and the US Virgin Islands. In *Coral Reefs of the USA*, edited by B.M. Riegl and R.E. Dodge, 263–302. Dordrecht, Netherlands: Springer.

Hughes, T.P., Baird, A.H., Bellwood, D.R., Card, M., Connolly, S.R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J.B.C., Kleypas, J., Lough, J.M., Marshall, P., Nystrom, M., Palumbi, S.R., Pandolfi, J.M., Rosen, B., and Roughgarden, J. 2003. Climate change, human impacts, and the resilience of coral reefs. *Science* **301**: 929–933.

Idso, C.D. and Singer, S.F. 2009. *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

Idso, S.B., Idso, C.D., and Idso, K.E. 2000. CO_2, global warming and coral reefs: Prospects for the future. *Technology* **75S**: 71–93.

Kim, K., Harvell, C.D., Kim, P.D., Smith, G.W., and Merkel, S.M. 2000. Fungal disease resistance of sea fan corals (Gorgonia spp.). *Marine Biology* **136**: 259–267.

Loya, Y., Sakai, K., Yamazato, K., Nakano, Y., Sambali, H., and van Woesik, R. 2001. Coral bleaching: the winners and the losers. *Ecology Letters* **4**: 122–131.

Marshall, P.A. and Baird, A.H. 2000. Bleaching of corals on the Great Barrier Reef: differential susceptibilities among taxa. *Coral Reefs* **19**: 155–163.

Maynard, J.A., Anthony, K.R.N., Marshall, P.A., and Masiri, I. 2008b. Major bleaching events can lead to increased thermal tolerance in corals. *Marine Biology* **155**: 173–182.

Maynard, J.A., Baird, A.H., and Pratchett, M.S. 2008a. Revisiting the Cassandra syndrome; the changing climate of coral reef research. *Coral Reefs* **27**: 745–749.

McClanahan, T., Maina, J., and Pet-Soede, L. 2002. Effects of the 1998 coral mortality event on Kenyan coral reefs and fisheries. *Ambio* **31**: 543–550.

McClanahan, T., Weil, E., Cortes, J., Baird, A.H., and Ateweberhan, M. 2009a. Consequences of coral bleaching for sessile reef organisms. In *Ecological Studies: Coral Bleaching: Patterns, Processes, Causes and Consequences*, edited by M.J.H. van Oppen and J.M. Lough. Berlin, Germany: Springer-Verlag.

McClanahan, T.R., Ateweberhan, M., Sebastian, C.R., Graham, N.A.J., Wilson, S.K., Bruggemann, H., and Guillaume, M. 2007. Western Indian Ocean coral communities, bleaching responses, and susceptibility to extinction. *Marine Ecology Progress Series* **337**: 1–13.

McClanahan, T.R., Muthiga, N.A., Maina, J., Kamukuru, A.T., and Yahya, S.A.S. 2009b. Changes in northern Tanzania coral reefs during a period of increased fisheries management and climatic disturbance. *Aquatic Conservation: Marine and Freshwater Ecosystems* **19**: 758–771.

McClanahan, T.R. and Obura, D. 1997. Sedimentation effects on shallow coral communities in Kenya. *Journal of Experimental Marine Biology and Ecology* **209**: 103–122.

McPhaden, M.J. 1999. Genesis and evolution of the 1997-98 El Niño. *Science* **283**: 950–954.

Meyer, E., Davies, S., Wang, S., Willis, B.L., Abrego, D., Juenger, T.E., and Matz, M.V. 2009. Genetic variation in responses to a settlement cue and elevated temperature in the reef-building coral *Acropora millepora*. *Marine Ecology Progress Series* **392**: 81–92.

Mumby, P.J. and Harborne, A.R. 2010. Marine reserves enhance the recovery of corals on Caribbean reefs. *PLoS ONE* **5**: 10.1371/journal.pone.0008657.

Mydlarz, L.D., Holthouse, S.F., Peters, E.C., and Harvell, C.D. 2008. Cellular responses in sea fan corals: granular amoebocytes react to pathogen and climate stressors. *PLoS ONE* **3**: 10.1371/journal.pone.0001811.

Naim, O., Cuet, P., and Letourneur, Y. 1997. Experimental shift in benthic community structure. In *Final Proceedings of the 8th International Coral Reef Symposium*, 1873–1878. Panama City, Panama: University of Panama and Smithsonian Tropical Research Institute.

Ridgway, K.R. 2007. Long-term trend and decadal variability of the southward penetration of the East Australian current. *Geophysical Research Letters* **34**: 10.1029/2007GL030393.

Riegl, B. 1999. Corals in a non-reef setting in the southern Arabian Gulf (Dubai, UAE): fauna and community structure in response to recurring mass mortality. *Coral Reefs* **18**: 63–73.

Riegl, B. and Piller, W.E. 2003. Possible refugia for reefs in times of environmental stress. *International Journal of Earth Sciences* **92**: 520–531.

Rogers, C. 1990. Responses of coral reefs and reef organisms to sedimentation. *Marine Ecology Progress Series* **62**: 185–202.

Rodrigues, I. and Grottoli, A.G. 2007. Energy reserves and metabolism as indicators of coral recovery from bleaching. *Limnology and Oceanography* **52**: 1874–1882.

Salinger, M. 2005. Climate variability and change: past, present and future—an overview. *Climatic Change* **70**: 9–29.

Sandin, S.A., Smith, J.E., DeMartini, E.E., Dinsdale, E.A., Donner, S.D., Friedlander, A.M., Konotchick, T., Malay, M., Maragos, J.E., Obura, D., Pantos, O., Paulay, G., Richie, M., Rohwer, F., Schroeder, R.E., Walsh, S., Jackson, J.B.C., Knowlton, N., and Sala, E. 2010. Baselines and degradation of coral reefs in the northern Line Islands. *PLoS ONE* **3**: 10.1371/journal.pone.0001548.

Scopelitis, J., Andrefouet, S., Phinn, S., Chabanet, P., Naim, O., Tourrand, C., and Done, T. 2009. Changes of coral communities over 35 years: integrating *in situ* and remote-sensing data on Saint-Leu Reef (la Reunion, Indian Ocean). *Estuarine, Coastal and Shelf Science* **84**: 342–352.

Smith, T.M. and Reynolds, R.W. 2003. Extended reconstruction of global sea surface temperatures based on COADS data (1854–1997). *Journal of Climate* **16**: 1495–1510.

Smith-Keune, C. and van Oppen, M. 2006. Genetic structure of a reef-building coral from thermally distinct environments on the Great Barrier Reef. *Coral Reefs* **25**: 493–502.

Stuart-Smith, R.D., Barrett, N.S., Stevenson, D.G., and Edgar, G.J. 2010. Stability in temperate reef communities over a decadal time scale despite concurrent ocean warming. *Global Change Biology* **16**: 122–134.

Toscano, M.A. and Lundberg, J. 1998. Early Holocene sea-level record from submerged fossil reefs on the southeast Florida margin. *Geology* **26**: 255–258.

Underwood, J.N. 2009. Genetic diversity and divergence among coastal and offshore reefs in a hard coral depend on geographic discontinuity and oceanic currents. *Evolutionary Applications* **2**: 222–233.

Wang, S., Zhang, L., and Matz, M. 2009. Microsatellite characterization and marker development from public EST and WGS databases in the reef-building coral *Acropora millepora* (Cnidaria, Anthozoa, Scleractinia). *Journal of Heredity* **100**: 329–337.

Ward, J.R., Kim, K., and Harvell, C.D. 2007. Temperature drives coral disease resistance and pathogen virulence. *Marine Ecology Progress Series* **329**: 115–121.

Wellington, G.M., Glynn, P.W., Strong, A.E., Nauarrete, S.A., Wieters, E., and Hubbard, D. 2001. Crisis on coral reefs linked to climate change. *EOS, Transactions, American Geophysical Union* **82**: 1,7.

Woodroffe, C.D., Brooke, B.P., Linklater, M., Kennedy, D.M., Jones, B.G., Buchanan, C., Mleczko, R., Hua, Q., and Zhao, J.-X. 2010. Response of coral reefs to climate change: expansion and demise of the southernmost Pacific coral reef. *Geophysical Research Letters* **37**: 10.1029/2010GL044067.

8.1.2. Effects on Other Marine Plants and Animals

Since the 2009 NIPCC report (Idso and Singer, 2009), several new studies have investigated the effects of rising temperatures on aquatic species other than corals. In this section we highlight several of them, beginning with a study examining marine phytoplankton.

Renaudie et al. (2010) conducted a quantitative micropalaeontological analysis of siliceous phytoplankton remains found in a sediment core extracted from the seabed at an ocean depth of 2,549 meters at ODP Site 1260 (~9.2°N, 54.65°W) on the Demerara Rise, which is a continental shelf located off the coast of Surinam, focusing on a 200,000-year period of warmth during the Eocene between approximately 40.0 and 40.2 million years ago. According to the five French scientists, their results indicated “the pre-warming flora, dominated by cosmopolitan species of the diatom genus *Triceratium*, was replaced during the warming interval by a new and more diverse assemblage, dominated by *Paralia sulcata* (an indicator of high productivity) and two endemic tropical species of the genus *Hemiaulus*." In addition, they state "the critical warming interval was characterized by a steady increase in tropical species of the genus *Hemiaulus*." They also state "the microflora preserved above the critical interval was once again of low diversity and dominated by various species of the diatom genus *Hemiaulus*."

Renaudie et al.'s findings establish that warmer is better, a maxim exemplified in the current case by (1) the greater productivity of the tropical ocean during the warmer period and (2) the ocean's continuous upward trend in the diversity of phytoplanktonic species throughout the period of warming.

Simultaneously, while noting "temperature is a dominant environmental factor that mediates the behavior, physiology, growth, survival, distribution, and recruitment of ectothermic animals living in temperate and high latitudes," Stoner et al. (2010) explored how the growth and survival of the red king crab (RKC: *Paralithodes camtschaticus*) "may be affected by warming trends expected in Alaska," since the RKC was once that state's "most economically valuable crustacean fishery." Specifically, Stoner et al. reared RKC "using four temperature treatments ranging from 1.5 to 12°C for a period of 60 days, both individually and in low-density populations," and at the end of that period they measured various physiological processes and properties of the RKC.

Among other things, the three researchers report finding "temperature had no significant effect on survival of RKC," while noting "there was no consistent difference in survival between individually cultured crabs and those in populations." As for growth, they found it "was very slow at 1.5°C, and increased rapidly with temperature with both a contracted inter-molt period and small increase in growth increment." In addition, they state "20% of the crabs held at 1.5°C never molted, while more than 90% of the crabs in 12°C reached juvenile state 4 or higher." Overall, therefore, "growth increased as an exponential function of temperature, with slightly higher growth rates observed in populations than for isolated individuals." Also of great importance, they found "no evidence that culturing RKC juveniles at elevated temperatures led to a decrease in condition or nutritional status."

In addition to the benefits listed above, which bode well for the RKC in a possibly warmer future world, Stoner et al. conclude the "accelerated growth" they observed in the RKC raised at the highest temperature might yet have a "positive, indirect effect on survival," in that "larger size associated with high temperature could provide for earlier refuge in size from the typical fish and invertebrate predators on RKC."

In a study that investigated a freshwater fish species, Rypel (2009) applied tree-ring techniques to incremental growth patterns in largemouth bass (*Micropterus salmoides* Lacepede) otoliths—the aragonite ($CaCO_3$) structures in fish that are used for acoustic perception and balance—in order to explore potential relationships between annual bass growth and various climate metrics in the southeastern United States, as manifest in six rivers and seven reservoirs distributed across Alabama, Georgia, and Mississippi sampled during the summers and autumns of 2005–2008, and from which 397 largemouth bass were collected and analyzed.

Rypel reports, "results from multiple regressions suggested that on average roughly 50% of the annual variability in largemouth bass growth was attributable to climatic variations," with annual growth indices typically being found to be "above-average during the warmest, driest years, and below-average during the coldest, wettest years," because "annual bass growth was significantly negatively correlated with annual precipitation metrics, and significantly positively correlated with annual temperature metrics."

Considering these findings, the warming the IPCC contends will occur in many places would appear to be good news for largemouth bass and the people who love to catch them—and for many other types of fish as well, because an increase in temperature generally "stimulates metabolism, and enhances growth rates of fishes," according to Rypel, citing the studies of Beitinger and Fitzpatrick (1979) and Brander (1995).

In one final study with a different twist on ocean warming, Peck et al. (2010) note the loss of glaciers and ice shelves is often thought of as something that "will predominantly increase warming of the earth because of changes in albedo and heat uptake by newly uncovered ground and ocean." However, they state an important opposing effect of this phenomenon "is the opening up of new areas for biological productivity."

Working with the database of Cook et al. (2005) that contains a detailed centennial history of changes in all coastal ice fronts associated with the Antarctic

Peninsula—compiled from historical accounts, aerial photographs, and satellite imagery—Peck et al. developed a time series of changes in the surface ice/water boundary surrounding the Antarctic Peninsula since the early twentieth century. Complementing this information with a ten-year time series of chlorophyll depth profiles (1997–2007) obtained from a near-shore site in northern Marguerite Bay developed by Clarke et al. (2008), they reconstructed the magnitude of new oceanic production that developed around the Antarctic Peninsula as sea ice progressively gave way to evermore open water.

The five researchers with the British Antarctic Survey report that as the ice cover along the Antarctic Peninsula has retreated over the past 50 years, "more than 0.5 Mtonnes of carbon has been incorporated into biological standing stock that was not there previously, 3.5 Mtonnes is fixed by phytoplankton blooms and 0.7 Mtonnes deposited to the seabed." Regarding likely future trends, they state that if only 15 percent of the remaining ice-covered areas act in the same way, "over 50 Mtonnes of new carbon would be fixed annually and around 10 Mtonnes of this deposited to the seabed in coastal or adjacent areas," while "over 9 Mtonnes of carbon would be locked up in biological communities in the water column or on the sea bed." And they suggest that over a period of tens, hundreds, or thousands of years, "this process may act as a climate control mechanism."

References

Beitinger, T.L. and Fitzpatrick, L.C. 1979. Physiological and ecological correlates of preferred temperature in fish. *Integrative and Comparative Biology* **19**: 319–329.

Brander, K. 1995. The effect of temperature on growth of Atlantic cod (*Gadus morhua* L.). *ICES Journal of Marine Science* **52**: 1–10.

Clarke, A., Meredith, M.P., Wallace, M.I., Brandon, M.A., and Thomas, D.N. 2008. Seasonal and interannual variability in temperature, chlorophyll and macronutrients in northern Maguerite Bay, Antarctica. *Deep Sea Research Part II* **55**: 1988–2006.

Cook, A.J., Fox, A.J., Vaughan, D.G., and Ferrigno, J.G. 2005. Retreating glacier fronts on the Antarctic Peninsula over the past half-century. *Science* **308**: 541–544.

Idso, C.D. and Singer, S.F. 2009. *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

Peck, L.S., Barnes, D.K.A., Cook, A.J., Fleming, A.H., and Clarke, A. 2010. Negative feedback in the cold: ice retreat produces new carbon sinks in Antarctica. *Global Change Biology* **16**: 2614–2623.

Renaudie, J., Danelian, T. Saint Martin, S., Le Callonnec, L., and Tribovillard, N. 2010. Siliceous phytoplankton response to a Middle Eocene warming event recorded in the tropical Atlantic (Demerara Rise, ODP Site 1260A). *Palaeogeography, Palaeoclimatology, Palaeoecology* **286**: 121–134.

Rypel, A.L. 2009. Climate-growth relationships for largemouth bass (*Micropterus salmoides*) across three southeastern USA states. *Ecology of Freshwater Fish* **18**: 620–628.

Stoner, A.W., Ottmar, M.L., and Copeman, L.A. 2010. Temperature effects on the molting, growth, and lipid composition of newly-settled red king crab. *Journal of Experimental Marine Biology and Ecology* **393**: 138–147.

8.1.3. Effects on Biodiversity

Closely tied to the prior two sections, but deserving its own treatment, is the potential effect of CO_2-induced global warming on aquatic biodiversity. Some experts claim rising temperatures will suppress or reduce ecosystem species richness. We examine this hypothesis as it pertains to both freshwater and saltwater ecosystems.

Working in Switzerland along an elevation gradient stretching from 210 to 2,760 meters above sea level, Rosset et al. (2010) identified 55 colline ponds with an overlying mean annual air temperature of more than 8°C, 27 montane ponds with mean annual air temperatures of 5–8°C, 15 subalpine ponds in the 2.5–5°C temperature range, and 16 alpine ponds with temperatures less than 2.5°C. For all of these ponds, they evaluated species richness in five taxonomic groups: aquatic vascular plants, aquatic gastropoda, aquatic coleoptera (larvae and adults), odonata adults, and amphibia. Then, utilizing 15 environmental variables—including mean annual air temperature, which they found to be "the best climatic variable to characterize pond thermal conditions"—they developed generalized additive models of species richness and used them to predict richness for the end of the next century (2090–2100) based on the temperature increase predicted to occur in conjunction with the A2 emission scenario of the IPCC.

The paper's authors found "temperature rise could significantly increase pond species richness," while noting "for the five taxonomic groups pooled, species richness would potentially increase from 41 to 75 (+83%) in lowland ponds," and "in presently species-poor high altitude ponds, the potential increase would be particularly marked, with a proportional increase (+150%; from 14–35 species) almost double that in lowland areas."

Prior to the Rosset et al. study, the effects of global warming on the biodiversity of small ecosystems had been given little attention. At the regional scale, species richness had "been shown to increase under the influence of climate warming in Europe and North America (e.g. Iverson and Prasad, 2001; Daufresne and Boet, 2007; Buisson et al., 2008)." And Rosset et al. write "it is also well-known and well-described in almost every ecology textbook, that terrestrial and freshwater species richness tends to be lower in colder areas, i.e., at higher altitude or latitude (e.g. Gaston and Spicer, 2004; Nagy and Grabherr, 2009)." They note "this trend has also been well-described at the local scale for plants, invertebrates, and vertebrates (reviewed in Rahbek, 1995)," while noting still further "among the few existing studies, Henderson (2007) and Hiddink and ter Hofstede (2008), using time series, report an increase in fish species richness in marine ecosystems in response to climate warming," and "long-term monitoring of vegetation plots in terrestrial environments indicates an increase in local species richness (Pauli et al., 2007; Vittoz et al., 2009)." Clearly, the findings of Rosset et al. harmonize well with a vast body of other research conducted at many scales and across many different environments, all of which demonstrate warming tends to increase ecosystem species richness.

Investigating another way in which temperatures have been hypothesized to harm aquatic ecosystem biodiversity, D'Odorico et al. (2008) write, "recent climate change predictions indicate that, in addition to trends in the mean values of climate variables, an increase in interannual variability is expected to occur in the near future." Adding that "environmental fluctuations are usually believed to play a 'destructive role' in ecosystem dynamics," they go on to explore the validity of this assumption within the context of current climate model predictions, asking the question, "Can environmental variability have only 'negative' effects on ecosystem dynamics?"

After lengthy mathematical analysis, D'Odorico et al. ultimately determined "opportunities for species existence/coexistence are found to increase with 'moderate' values of the variance of environmental fluctuations, while they decrease when these fluctuations are relatively strong." This outcome constitutes the "intermediate disturbance hypothesis," which grew out of the work of Connell (1978)—who in the words of D'Odorico et al. suggested "coral reefs and rain forests maintain high levels of diversity only in a non-equilibrium state"—and Huston (1979), who noted "most communities have relatively high levels of diversity because environmental variability maintains them in a non-equilibrium state." Furthermore, citing a number (Chapin et al., 1997; Steneck et al., 2002; Bengtsson et al., 2003; Elmqvist et al., 2003; Bellwood et al., 2004; Folke et al., 2004)of real-world indications that "biodiversity may enhance ecosystem resilience," the four researchers provide a theoretical basis for this phenomenon. As noted in Chapter 6, CO_2-enriched conditions that the IPCC assumes to be unfavorable may actually be just what is needed to increase the diversity and resilience of terrestrial and aquatic ecosystems.

Exploring this from another angle, Brown et al. (2010) state "climate change is altering the rate and distribution of primary production in the world's oceans," which in turn "plays a fundamental role in structuring marine food webs (Hunt and McKinnell, 2006; Shurin et al., 2006)," which are "critical to maintaining biodiversity and supporting fishery catches." They examine what the future might hold in this regard, noting "effects of climate-driven production change on marine ecosystems and fisheries can be explored using food web models that incorporate ecological interactions such as predation and competition," citing the work of Cury et al. (2008), which is what they set out to do.

Specifically, Brown et al. first used the output of an ocean general circulation model driven by a "plausible" greenhouse gas emissions scenario (IPCC 2007 scenario A2) to calculate changes in climate over a 50-year time horizon. The results were then fed into a suite of models for calculating primary production of lower trophic levels (phytoplankton, macroalgae, seagrass, and benthic microalgae), after which the results of the latter set of calculations were used as input to "twelve existing Ecopath with Ecosim (EwE) dynamic marine food web models to describe different Australian marine ecosystems." This protocol ultimately predicted "changes in fishery catch, fishery value, biomass of animals of conservation interest, and indicators of community composition."

The 17 scientists state that under the IPCC's "plausible climate change scenario, primary production will increase around Australia" with "overall positive linear responses of functional groups to primary production change," and "generally this benefits fisheries catch and value and leads to increased biomass of threatened marine animals such as turtles and sharks." In addition, the calculated responses "are robust to the ecosystem type and the complexity of the model used." Given these findings, Brown et al. state the primary production increases suggested by their work to result from future IPCC-envisioned greenhouse gas emissions and their calculated impacts on climate "will provide opportunities to recover overfished fisheries, increase profitability of fisheries and conserve threatened biodiversity." That set of consequences is obviously different from the unmitigated catastrophe the IPCC forecasts.

Returning to real-world observations, working in lagoons on the north shore of Moorea (French Polynesia) throughout 2002–2003, Holbrook et al. (2008) used a combination of reef surveys and field experimentation to (1) estimate the functional forms of the local relationships between variation in coral cover and three attributes of the associated fish assemblage (species richness, total abundance, and species composition), and (2) isolate the influence of variation in the cover of living coral tissue from that due merely to the physical presence of the coral, be it living or dead. The latter objective was achieved through the use of 25 experimental patch reefs, which they constructed on a sand plain in the Maharepa lagoon by transplanting different proportions of live and dead colonies of the branching coral *Pocillopora eydouxi*, while the first objective was achieved by scuba divers who identified and counted all reef-associated fish and mapped the corals in each of 19 50x10-m survey plots located midway between the shore and barrier reef in the Vaipahu and Maharepa lagoons.

The results indicated "all measured attributes of the fish community were insensitive to changes in live coral cover over a wide range before falling sharply as live coral cover approached zero," and the researchers determined "there was qualitative agreement in the pattern of abundance response of fish with variation in cover of live coral between the experiment and field surveys." Holbrook et al. state "the apparent tipping point for these attributes of the fish community occurred when cover of live coral fell below 5%."

In discussing their findings, Holbrook et al. state their results suggest "that local fish assemblages could be resistant to variation in abundance of live coral, changing significantly only as coral becomes rare, while recovery may occur with only modest increases in live coral." Put another way, the three researchers state that after a major disturbance such as a temperature-induced coral bleaching episode, "the observed functional relationships in [their] study suggest that biodiversity, trophic structure, and overall abundance of fishes could essentially recover to their pre-disturbance states after only a modest return in the cover of living coral."

Similar findings have been reported by Cheal et al. (2008), who examined several responses of reef fish communities to varied levels of coral decline—caused by a combination of crown-of-thorns starfish outbreaks, coral bleaching, and cyclones—derived from annual surveys conducted over the 11-year period 1995–2005 of 22 individual reefs located between 14 and 24°S latitude that comprised parts of Australia's Great Barrier Reef system.

Based on seven different measures of species diversity, Cheal et al. found "fish diversity rarely decreased due to coral declines, even on seven reefs that suffered massive coral losses," where living coral cover declined by more than 75 percent in these "worst-case scenarios." What generally did happen was that there were often "increases in abundance of large herbivores and decreases in abundance of both coral-dependent fishes and species with no obvious dependence on coral."

The five researchers write their findings are "encouraging," in that "maintenance of fish diversity should assist recovery of fish species whose abundances declined with coral cover," and "maintenance of a wide taxonomic range of species should also confer greater stability on a community during major perturbations through functional redundancy." They speculate, however, that "widespread abundance decreases might lead to loss of ecosystem function," yet they add "the significance of the functional roles of many fish taxa to coral reef resilience is not known, nor is it clear what abundances of fishes are necessary to retain ecosystem services." Consequently, their "compelling" finding that "reef fish diversity was maintained despite large coral declines" must indeed be considered to be "encouraging," as they described it.

In another coral reef-related study, Stuart-Smith et al. (2010) write, "despite increasing scientific and public concerns [about] the potential impacts of global ocean warming on marine biodiversity, very few empirical data on community-level responses to rising water temperatures are available." In an effort designed to help fill this important data void, the authors undertook what they describe as "a study of sub-tidal reef communities over a decadal time scale, comparing data on fishes, macroinvertebrates and macroalgae collected at 136 sites, spanning hundreds of kilometers around the island of Tasmania (southeastern Australia) in the early to mid 1990s, with data from the same sites in 2006/2007." This region, in their words, "has experienced relatively rapid warming during the last century as a consequence of a strengthening of the warm East Australian Current (Ridgway, 2007)," such that there has been "an increase in sea surface temperature of 2.28 ± 0.35°C per century for the period 1944–2002 (Ridgway, 2007), which is considerably more rapid than the global mean of 0.6 ± 0.2°C per century estimated by Smith and Reynolds (2003), and a mean increase in surface air temperature of 0.6–0.8°C (Salinger, 2005; Hansen et al., 2006)." In fact, the warming around this part of Tasmania has been more than three times greater than that of the global mean.

Contrary to what they had expected to find, the four researchers discovered "Tasmanian shallow rocky reef communities have been relative stable over the past decade," in spite of the "substantial rise in sea surface temperature over this period" and the "continuation of a considerable warming trend in oceanographic conditions over the last 50 years." Indeed, they report "the northeast and southeast bioregions, which are most influenced by the East Australian Current and hence have experienced the greatest warming over the last century, appeared to have actually changed very little," adding "not only were Tasmanian reef communities remarkably similar between 1994 and 2006 in a multivariate sense, but univariate community characteristics such as species richness and total fish abundance were also consistent." Thus, contrary to many people's expectations as well as their own initial thoughts on the subject, the Australian scientists found very little evidence to support the IPCC's doomsday scenarios in which continued global warming decimates Earth's highly productive costal marine ecosystems.

In one final study based on real-world observations, Rombouts et al. (2009) developed the first global description of geographical variation in the diversity of marine copepods, which are small crustaceans that are found throughout the world's oceans and form a key trophic link between phytoplankton and fish, some of which are planktonic and drift in sea water, and some of which are benthic and live on the ocean floor. The results of their work indicated "ocean temperature was the most important explanatory factor among all environmental variables tested, accounting for 54 percent of the variation in diversity." Hence it was not surprising that "diversity peaked at subtropical latitudes in the Northern Hemisphere and showed a plateau in the Southern Hemisphere where diversity remained high from the equator to the beginning of the temperate regions." This pattern, in their words, "is consistent with latitudinal variations found for some other marine taxa, e.g. foraminifera (Rutherford et al., 1999), tintinnids (Dolan et al., 2006) and fish (Worm et al., 2005; Boyce et al., 2008), and also in the terrestrial environment, e.g. aphids, sawflies and birds (Gaston and Blackburn, 2000)."

"Given the strong positive correlation between diversity and temperature," the six scientists write, "local copepod diversity, especially in extra-tropical regions, is likely to increase with climate change as their large-scale distributions respond to climate warming." This state of affairs is much the same as what has typically been found on land for birds, butterflies, and several other terrestrial life-forms as their ranges expand and overlap in response to global warming. And with more territory available to them, their "foothold" on the planet becomes ever stronger, fortifying them against forces (many of them human-induced) that might otherwise lead to their extinction.

In considering all of the results presented above, it is difficult not to conclude that global warming—be it natural or anthropogenic—will likely enhance the biodiversity of aquatic ecosystems.

References

Bellwood, D.R., Houghes, T.P., Folke, C., and Nystrom, M. 2004. Confronting the coral reef crisis. *Nature* **429**: 827–833.

Bengtsson, J., Angelstam, P., Elmqvist, T., Emanuelsson, U., Folke, C., Ihse, M., Moberg, F., and Nystrom, M. 2003. Reserves, resilience and dynamic landscapes. *Ambio* **32**: 389–396.

Boyce, D.G., Tittensor, D.P., and Worm, B. 2008. Effects of temperature on global patterns of tuna and billfish richness. *Marine Ecology Progress Series* **355**: 267–276.

Brown, C.J., Fulton, E.A., Hobday, A.J., Matear, R.J., Possingham, H.P., Bulman, C., Christensen, V., Forrest, R.E., Gehrke, P.C., Gribble, N.A., Griffiths, S.P., Lozano-Montes, H., Martin, J.M., Metcalf, S., Okey, T.A., Watson, R., and Richardson, A.J. 2010. Effects of climate-driven primary production change on marine food webs: implications for fisheries and conservation. *Global Change Biology* **16**: 1194–1212.

Buisson, L., Thuiller, W., Lek, S., Lim, P., and Grenouillet, G. 2008. Climate change hastens the turnover of stream fish assemblages. *Global Change Biology* **14**: 2232–2248.

Chapin III, F.S., Walker, B.H., Hobbs, R.J., Hooper, D.U., Lawton, J.H., Sala, O.E., and Tilman, D. 1997. Biotic controls of the functioning of ecosystems. *Science* **277**: 500–504.

Cheal, A.J., Wilson, S.K., Emslie, M.J., Dolman, A.M., and Sweatman, H. 2008. Responses of reef fish communities to coral declines on the Great Barrier Reef. *Marine Ecology Progress Series* **372**: 211–223.

Connell, J.H. 1978. Diversity in tropical rain forests and coral reefs: high diversity of trees and corals is maintained only in a non-equilibrium state. *Science* **199**: 1302–1310.

Cury, P.M., Shin, Y.J., Planque, B., Durant, J.M., Fromentin, J.-M., Kramer-Schadt, S., Stenseth, N.C., Travers, M., and Grimm, V. 2008. Ecosystem oceanography for global change in fisheries. *Trends in Ecology and Evolution* **23**: 338–346.

D’Odorico, P., Laio, F., Ridolfi, L., and Lerdau, M.T. 2008. Biodiversity enhancement induced by environmental noise. *Journal of Theoretical Biology* **255**: 332–337.

Daufresne, M. and Boet, P. 2007. Climate change impacts on structure and diversity of fish communities in rivers. *Global Change Biology* **13**: 2467–2478.

Dolan, J.R., Lemee, R., Gasparini, S., Mousseau, L., and Heyndrickx, C. 2006. Probing diversity in the plankton: using patterns in Tintinnids (planktonic marine ciliates) to identify mechanisms. *Hydrobiologia* **555**: 143–157.

Elmqvist, T., Folke, C., Nystrom, M., Peterson, G., Bengtsson, L., Walker, B., and Norberg, J. 2003. Response diversity and ecosystem resilience. *Frontiers in Ecology and Environment* **1**: 488–494.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., and Holling, C.S. 2004. Regime shifts, resilience and biodiversity in ecosystem management. *Annual Review of Ecology and Evolution Systems* **35**: 557–581.

Gaston, K.J. and Blackburn, T.M. 2000. *Pattern and Process in Macroecology*. Oxford, UK: Blackwell Science Ltd.

Gaston, K.J. and Spicer, J.I. 2004. *Biodiversity. An Introduction.* Oxford, UK: Blackwell Science Ltd.

Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D.W., and Medina-Elizade, M. 2006. Global temperature change. *Proceedings of the National Academy of Sciences USA* **103**: 14,288–14,293.

Henderson, P.A. 2007. Discrete and continuous change in the fish community of the Bristol Channel in response to climate change. *Journal of the Marine Biological Association of the United Kingdom* **87**: 589–598.

Hiddink, J.G. and ter Hofstede, R. 2008. Climate induced increases in species richness of marine fishes. *Global Change Biology* **14**: 453–460.

Holbrook, S.J., Schmitt, R.J., and Brooks, A.J. 2008. Resistance and resilience of a coral reef fish community to changes in coral cover. *Marine Ecology Progress Series* **371**: 263–271.

Hunt, G.L. and McKinnell, S. 2006. Interplay between top-down, bottom-up, and wasp-waist control in marine ecosystems. *Progress in Oceanography* **68**: 115–124.

Huston, M. 1979. A general hypothesis of species diversity. *American Naturalist* **113**: 81–101.

Iverson, L.R. and Prasad, A.M. 2001. Potential changes in tree species richness and forest community types following climate change. *Ecosystems* **4**: 186–199.

Nagy, L. and Grabherr, G. 2009. *The Biology of Alpine Habitats.* Oxford, UK: Oxford University Press.

Pauli, H., Gottfried, M., Reier, K., Klettner, C., and Grabherr, G. 2007. Signals of range expansions and contractions of vascular plants in the high Alps: observations (1994–2000) at the GLORIA master site Schrankogel, Tyrol, Austria. *Global Change Biology* **13**: 147–156.

Rahbek, C. 1995. The elevational gradient of species richness—a uniform pattern. *Ecography* **18**: 200–205.

Ridgway, K.R. 2007. Long-term trend and decadal variability of the southward penetration of the East Australian current. *Geophysical Research Letters* **34**: 10.1029/2007GL030393.

Rombouts, I., Beaugrand, G., Ibanez, F., Gasparini, S., Chiba, S., and Legendre, L. 2009. Global latitudinal variations in marine copepod diversity and environmental factors. *Proceedings of the Royal Society B* **276**: 3053–3062.

Rosset, V., Lehmann, A., and Oertli, B. 2010. Warmer and richer? Predicting the impact of climate warming on species richness in small temperate waterbodies. *Global Change Biology* **16**: 2376–2387.

Rutherford, S., D'Hondt, S., and Prell, W. 1999. Environmental controls on the geographic distribution of zooplankton diversity. *Nature* **400**: 749–753.

Salinger, M. 2005. Climate variability and change: past, present and future—an overview. *Climatic Change* **70**: 9–29.

Shurin, J.B., Gruner, D.S., and Hillebrand, H. 2006. All wet or dried up? Real differences between aquatic and terrestrial food webs. *Proceedings of the Royal Society B—Biological Sciences* **273**: 1–9.

Smith, T.M. and Reynolds, R.W. 2003. Extended reconstruction of global sea surface temperatures based on COADS data (1854-1997). *Journal of Climate* **16**: 1495–1510.

Steneck, R.S., Graham, M.H., Bourque, B.J., Corbett, D., Erlandson, J.M., Estes, J.A., and Tegner, M.J. 2002. Kelp forest ecosystems: biodiversity, stability, resilience and future. *Environmental Conservation* **29**: 436–459.

Stuart-Smith, R.D., Barrett, N.S., Stevenson, D.G., and Edgar, G.J. 2010. Stability in temperate reef communities over a decadal time scale despite concurrent ocean warming. *Global Change Biology* **16**: 122–134.

Vittoz, P., Dussex, N., Wassef, J., and Guisan, A. 2009. Diaspore traits discriminate good from weak colonizers on high-elevation summits. *Basic and Applied Ecology* **10**: 508–515.

Worm, B., Oschlies, A., Lotze, H.K., and Myers, R.A. 2005. Global patterns of predator diversity in the open oceans. *Science* **309**: 1365–1369.

8.2. Marine and Freshwater Acidification

The global increase in the atmosphere's CO_2 content has been hypothesized to possess the potential to harm corals and other aquatic life by inducing changes in water chemistry that can lead to reductions in the calcium carbonate saturation state of the water in which the organisms live, producing negative responses in various growth and developmental parameters, and in some cases even death.

Concerns about the viability of Earth's corals and other calcifying organisms were brought to light in the debate over rising anthropogenic CO_2 emissions with the publication of the papers of Kleypas et al. (1999) and Langdon et al. (2000), which claimed the ongoing rise in the air's CO_2 content was slowly but surely lowering oceanic pH, making it increasingly difficult for calcifying organisms to produce their calcium carbonate skeletons and possibly leading to their extinction. In summarizing the anxiety expressed by the IPCC on this issue, Feely et al. (2009) reviewed what is supposedly known about the current pH status of the world's oceans, as well as what they state it is likely to be by the end of the century.

The three researchers write in the abstract of their paper, "estimates based on the Intergovernmental Panel on Climate Change business-as-usual emission scenarios suggest that atmospheric CO_2 levels could approach 800 ppm near the end of the century," and "corresponding biogeochemical models for the ocean indicate that surface water pH will drop from a pre-industrial value of about 8.2 to about 7.8 in the IPCC A2 scenario by the end of this century." As a result, they state, "skeletal growth rates of calcium-secreting organisms will be reduced," ending with the warning that "if anthropogenic CO_2 emissions are not dramatically reduced in the coming decades, there is the potential for direct and profound impacts on our living marine ecosystems."

Expressing similar sentiments on the subject of ocean acidification, Pelejero et al. (2010) write, "the surface waters of the oceans have already acidified by an average of 0.1 pH unit from pre-industrial levels," and "by the end of the twenty-first century, projections based on different scenarios indicate that ocean pH will have decreased by 0.3 to 0.4 pH unit." This "steady acidification of the oceans (nicknamed the 'evil twin' of global warming)," as they describe it, is said by them to be yet another "insidious consequence of rising levels of atmospheric CO_2," and "evidence gathered over the last years suggests that ocean acidification could represent an equal (or perhaps even greater) threat to the biology of our planet."

In assessing these claims, we should first consider the absolute pH values pertinent to them. The preindustrial-to-present 0.1-pH-unit drop reported to have occurred by Pelejero et al. represents a decline from a mean value of about 8.16 to a value of 8.06, as best as can be discerned from their graphical representation of the decline. However, another of their graphs depicts interannual pH variations in the North Atlantic Ocean near Bermuda ranging from a high of approximately 8.18 to a low of about 8.03 at various times over the period 1984 to 2007 (Bates, 2007), which demonstrates that even larger pH variations are occurring in some ocean basins as a result of seasonal seawater pH variability.

Even greater natural pH variability is evident on both shorter and longer time scales in still other of Pelejero et al.'s graphs. Over a mere two days in July 2001 on a Molokai (Hawaii) Reef flat, for example, seawater pH ranged from a high of 8.29 to a low of 7.79 (Yates and Halley, 2006); and over a period of about a decade in the mid-twentieth century, the pH at Arlington Reef in Australia's Great Barrier Reef system ranged from a high of approximately 8.25 to a low of about 7.71 (Wei et al., 2009). Both of these natural and recurring pH declines (0.50 and 0.54) are greater than the 0.3 to 0.4 projected decline that Pelejero et al. expect to occur between now and the end of the century. What is more, the calcifying organisms in these regions have fared just fine, as they have faced and successfully adapted to each of these worse-than-"evil" pH declines.

Moving more closely to the substance of the analysis of Pelejero et al., Tans (2009) found the pH decline expected by Pelejero et al. between now and the end of the century is fully twice as great as what is likely to occur in reality, and that by AD 2500 the spatial and vertical pH distributions within the world's oceans will likely have returned to almost the same sets of values that are characteristic of today.

Tans begins his analysis by indicating the effect of CO_2 on climate—and on its own concentration in the atmosphere—"depends primarily on the total amount emitted, not on the rate of emissions," and that "unfortunately, the IPCC reports have not helped public understanding of this fact by choosing, somewhat arbitrarily, a rather short time horizon (100 years is most commonly used) for climate forcing by CO_2." Thus, "instead of adopting the common economic point of view, which, through its emphasis on perpetual growth, implicitly assumes infinite earth resources," Tans notes the cumulative extraction of fossil-fuel carbon currently stands at about 345 GtC, and that there appears to be another 640 or so GtC of proven reserves, yielding a total original reserve of about 1,000 GtC, from which he proceeds with his analysis.

Figure 8.2.1 shows much of the past and projected history of fossil-fuel carbon utilization, together with historical and projected atmospheric CO_2 concentrations out to the year 2500, as calculated by Tans. As can be seen there, his analysis indicates the air's CO_2 concentration peaks well before 2100 and at only 500 ppm, as compared to the 800 ppm projected by the IPCC. In addition, by the year 2500 the air's CO_2 concentration will have fallen to about what it is today.

Based on his more modest projections of future atmospheric CO_2 concentrations, Tans also finds the projected pH reduction of ocean waters in the year 2100 (as compared to preindustrial times) to be only one-half of the 0.4 value calculated by Feely et al. (2009) and Pelejero et al. (2010), with a recovery to a

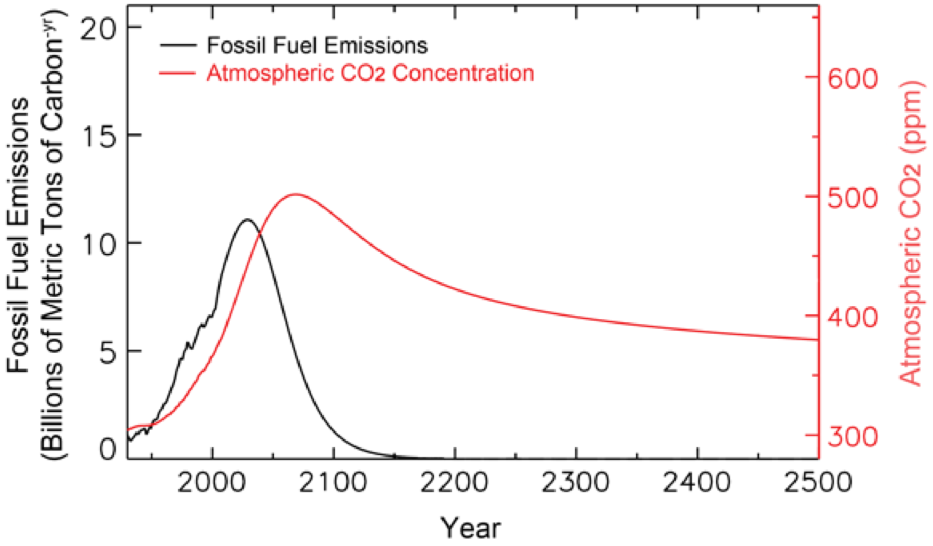


Figure 8.2.1. Past and projected trends of fossil-fuel carbon utilization and atmosphereic CO_2 concentration. Adapted from Tans (2009).

reduction of just over 0.1 pH unit by 2500, which is less than the range of pH values typical of today's oceans (8.231 in the Arctic Ocean minus 8.068 in the North Indian Ocean equals 0.163, according to Feely et al.).

Another reason to doubt Pelejero et al.'s forecast of falling pH levels is that high rates of aquatic photosynthesis by marine micro- and macro-algae, which have been shown to be stimulated and maintained by high levels of atmospheric CO_2—see, for example, Wu et al. (2008), Fu et al. (2008), and Egge et al. (2009)—can dramatically increase the pH of marine bays, lagoons, and tidal pools (Gnaiger et al., 1978; Santhanam et al., 1994; Macedo et al., 2001; Hansen, 2002; Middelboe and Hansen, 2007) and significantly increase the surface-water pH of areas as large as the North Sea (Brussaard et al., 1996). Thus it is logical to presume anything else that enhances marine photosynthesis, such as nutrient delivery to the waters of the world's coastal zones (i.e., eutrophication), may increase pH as well.

Thinking along these lines, Borges and Gypens (2010) employed an idealized biogeochemical model of a river system (Billen et al., 2001) and a complex biogeochemical model describing carbon and nutrient cycles in the marine domain (Gypens et al., 2004) "to investigate the decadal changes of seawater carbonate chemistry variables related to the increase of atmospheric CO_2 and of nutrient delivery in the highly eutrophied Belgian coastal zone over the period 1951–1998."

The findings of the two researchers indicate, as they describe it, that "the increase of primary production due to eutrophication could counter the effects of ocean acidification on surface water carbonate chemistry in coastal environments," and "changes in river nutrient delivery due to management regulation policies can lead to stronger changes in carbonate chemistry than ocean acidification," as well as changes that are "faster than those related solely to ocean acidification." And to make these facts perfectly clear, they add, "the response of carbonate chemistry to changes of nutrient delivery to the coastal zone is stronger than ocean acidification."

As more and more pertinent studies have been conducted, the extreme view of ocean acidification has been greatly tempered. In a review of the subject by Doney et al. (2008), for example, it was reported many calcifying species "exhibit reduced calcification and growth rates in laboratory experiments under high-CO_2 conditions," but they also report "some photosynthetic organisms (both calcifying and non-calcifying) have higher carbon fixation rates under high CO_2." And as Idso et al. (2000) have noted in the case of corals, the "photosynthetic activity of zooxanthellae is the chief source of energy for the energetically-expensive process of calcification," and much evidence suggests, in their words, that "long-term reef calcification rates generally rise in direct proportion to increases in rates of reef primary production."

In light of these divergent observations, plus the fact that most of what we know about the topic "stems largely from short-term laboratory and mesocosm experiments," as Doney et al. describe them, the latter conclude the ultimate long-term response of "individual organisms, populations, and communities to more realistic gradual changes [in atmospheric CO_2 concentration] is largely unknown." Additionally acknowledging, therefore, that "the broader implications for ocean ecosystems are not well known," they state "the impact of rising CO_2 on marine biota will be more varied than previously thought." Instead of one grand catastrophe for Earth's calcifying marine life, there may well be both "winners and losers," as they put it, with the vast bulk of species likely sandwiched somewhere in between these two extremes. In fact, when real-world evidence for rapid adaptation and evolution is considered, the future actually looks quite bright for Earth's aquatic (and terrestrial) life (Idso, 2009; Idso and Idso, 2009).

In the ensuing subsections we review the results of numerous ocean acidification experiments that have been performed on various types of marine organisms, results that further demonstrate ocean acidification is not as bad as the IPCC makes it out to be.

References

Bates, N.R. 2007. Interannual variability of the oceanic CO_2 sink in the subtropical gyre of the North Atlantic Ocean over the last 2 decades. *Journal of Geophysical Research* **112**: 10.1029/2006JC003759.

Billen, G., Garnier, J., Ficht, A., and Cun, C. 2001. Modeling the response of water quality in the Seine river estuary to human activity in its watershed over the last 50 years. *Estuaries* **24**: 977–993.

Borges, A.V. and Gypens, N. 2010. Carbonate chemistry in the coastal zone responds more strongly to eutrophication than to ocean acidification. *Limnology and Oceanography* **55**: 346–353.

Brussaard, C.P.D., Gast, G.J., van Duyl, F.C., and Riegman, R. 1996. Impact of phytoplankton bloom magnitude on a pelagic microbial food web. *Marine Ecology Progress Series* **144**: 211–221.

Doney, S.C., Fabry, V.J., Feely, R.A., and Kleypas, J.A. 2008. Ocean acidification: the other CO_2 problem. *Annual Review of Marine Science* **1**: 169–192.

Egge, J.K, Thingstad, T.F., Larsen, A., Engel, A., Wohlers, J., Bellerby, R.G.J., and Riebesell, U. 2009. Primary production during nutrient-induced blooms at elevated CO_2 concentrations. *Biogeosciences* **6**: 877–885.

Feely, R.A., Doney, S.C., and Cooley, S.R. 2009. Ocean acidification: pPresent conditions and future changes in a high-CO_2 world. *Oceanography* **22**: 36–47.

Fu, F.-X., Mulholland, M.R., Garcia, N.S., Beck, A., Bernhardt, P.W., Warner, M.E., Sanudo-Wilhelmy, S.A., and Hutchins, D.A. 2008. Interactions between changing pCO_2, N_2 fixation, and Fe limitation in the marine unicellular cyanobacterium *Crocosphaera*. *Limnology and Oceanography* **53**: 2472–2484.

Gnaiger, E., Gluth, G., and Weiser, W. 1978. pH fluctuations in an intertidal beach in Bermuda. *Limnology and Oceanography* **23**: 851–857.

Gypens, N., Lancelot, C., and Borges, A.V. 2004. Carbon dynamics and CO_2 air-sea exchanges in the eutrophied coastal waters of the Southern Bight of the North Sea: A modelling study. *Biogeosciences* **1**: 147–157.

Hansen, P.J. 2002. The effect of high pH on the growth and survival of marine phytoplankton: implications for species succession. *Aquatic Microbiology and Ecology* **28**: 279–288.

Idso, C.D. 2009. *CO_2, Global Warming and Coral Reefs: Prospects for the Future*. Pueblo West, CO: Vales Lake Publishing, LLC.

Idso, C.D. and Idso, S.B. 2009. *CO_2, Global Warming, and Species Extinctions: Prospects for the Future*. Pueblo West, CO: Vales Lake Publishing, LLC.

Idso, S.B., Idso, C.D., and Idso, K.E. 2000. CO_2, global warming and coral reefs: Prospects for the future. *Technology* **7S**: 71–94.

Kleypas, J.A., Buddemeier, R.W., Archer, D., Gattuso, J-P., Langdon, C., and Opdyke, B.N. 1999. Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. *Science* **284**: 118–120.

Langdon, C., Takahashi, T., Sweeney, C., Chipman, D., Goddard, J., Marubini, F., Aceves, H., Barnett, H., and Atkinson, M.J. 2000. Effect of calcium carbonate saturation state on the calcification rate of an experimental coral reef. *Global Biogeochemical Cycles* **14**: 639–654.

Macedo, M.F., Duarte, P., Mendes, P., and Ferreira, G. 2001. Annual variation of environmental variables, phytoplankton species composition and photosynthetic parameters in a coastal lagoon. *Journal of Plankton Research* **23**: 719–732.

Middelboe, A.L. and Hansen, P.J. 2007. High pH in shallow-water macroalgal habitats. *Marine Ecology Progress Series* **338**: 107–117.

Pelejero, C., Calvo, E., and Hoegh-Guldberg, O. 2010. Paleo-perspectives on ocean acidification. *Trends in Ecology and Evolution* **25**: 332–344.

Santhanam, R., Srinivasan, A., Ramadhas, V., and Devaraj, M. 1994. Impact of *Trichodesmium* bloom on the plankton and productivity in the Tuticorin bay, southeast coast of India. *Indian Journal of Marine Science* **23**: 27–30.

Tans, P. 2009. An accounting of the observed increase in oceanic and atmospheric CO_2 and an outlook for the future. *Oceanography* **22**: 26–35.

Wei, G., McCulloch, M. T., Mortimer, G., Deng, W., and Xie, L. 2009. Evidence for ocean acidification in the Great Barrier Reef of Australia. *Geochimica et Cosmochimica Acta* **73**: 2332–2346.

Wu, H.-Y., Zou, D.-H., and Gao, K.-S. 2008. Impacts of increased atmospheric CO_2 concentration on photosynthesis and growth of micro- and macro-algae. *Science in China Series C: Life Sciences* **51**: 1144–1150.

Yates, K.K. and Halley, R.B. 2006. $CO3^{-2}$ concentration and pCO_2 thresholds for calcification and dissolution on the Molokai reef flat, Hawaii. *Biogeosciences* **3**: 357–369.

8.2.1. Effects on Marine Plants

8.2.1.1.Phytoplankton

Writing in the Journal Club section of *Nature*, Stoll (2009) restates the IPCC's mantra that "ocean acidification in response to excess carbon dioxide in the atmosphere could become a problem for marine organisms, especially those that make skeletons or shells out of calcium carbonate," including "the coccolithophorids—microscopic algae that are, by volume, the most important shell producers." She has a much more optimistic view of the subject, however, thanks in large part to the research of Langer et al. (2009).

The latter scientists—hailing from France, Germany, Spain, and the Netherlands—grew four different strains of the coccolithophore *Emiliania* *huxleyi* in dilute batch cultures of seawater with carbonate chemistries characteristic of those expected to prevail beneath an atmosphere of four different CO_2 concentrations ranging from approximately 200 to 1200 ppm, while they measured particulate organic carbon content, particulate inorganic carbon content, and organic and inorganic carbon production. In doing so, they found the four strains "did not show a uniform response to carbonate chemistry changes in any of the analyzed parameters and none of the four strains displayed a response pattern previously described for this species."

In light of these findings—plus other aspects of their earlier studies (Langer et al., 2006, 2007) and the diverse findings of others who had studied still other strains of the species—the five scientists concluded "the sensitivity of different strains of *E. huxleyi* to acidification differs substantially and that this likely has a genetic basis." Stoll agrees with this assessment, stating that Langer et al. "argue convincingly" in this regard, and she adds that the work of those who foresee disastrous consequences typically "precludes the kind of natural selection and adaptation that might occur over decades and centuries in the ocean."

In further discussing the subject, Langer et al. (2009) write, "shifts in dominance between species and/or between clones within a species might therefore be expected," as the air's CO_2 content continues to rise; but they state that too often "the possibility of adaptation is not taken into account." This should not be assumed away, for the great genetic diversity that exists both among and within species, in the words of Stoll, "is good insurance in a changing ocean." Indeed, this could be interpreted as evidence that Earth's coccolithophorids are well prepared for whatever the future may thrust at them in this regard, for as Langer et al. (2006) have more boldly and explicitly stated, "genetic diversity, both between and within species, may allow calcifying organisms to prevail in a high CO_2 ocean."

Support for that notion was, in fact, provided one year earlier. Based on data obtained from a sediment core extracted from the subpolar North Atlantic Ocean, Iglesias-Rodriguez et al. (2008) determined there had been a 40 percent increase in oceanic coccolith mass over the past 220 years, during which time the atmosphere's CO_2 concentration rose by approximately 90 ppm. They further found this response to be consistent with the results of several batch incubations of the far-ranging coccolithophore species *Emiliania hyxleyi*, conducted while bubbling air of several different atmospheric CO_2 concentrations through the culture medium they employed for that purpose.

Working with materials derived from the same sediment core, Halloran et al. (2008) analyzed the size distribution of $CaCO_3$ particles in the less-than-10-µm sediment fraction over the past quarter-century. This analysis revealed "a changing particle volume since the late 20th century consistent with an increase in the mass of coccoliths produced by the larger coccolithophore species," which included *Oolithotus fragilis, Calcidicus leptoporus, Coccolithus pelagicus* var. *pelagicus,* and *Helicosphaera carteri*.

Commenting on their findings, Halloran et al. state their data suggest "in the real ocean the larger coccolithophore species increase their calcification in response to anthropogenic CO_2 release," and "such a calcification response could be attributed to an alleviation of CO_2 limitation in species that partly rely on the diffusive supply of dissolved carbon dioxide for photosynthesis, as demonstrated by a rise in photosynthetic efficiency with increasing carbon dioxide in cultures of *E. huxleyi* (Rost et al., 2003)."

Examining other phytoplankton, Lombard et al. (2010) studied the effects of ocean acidification on two planktonic foraminifera, which in the words of the authors, "are widespread calcifying protozoa, responsible for 32–80% of the global deep-ocean calcite fluxes (Schiebel, 2002)." Working with specimens of *Orbulina universa* collected by scuba divers off the coast of Catalina Island, California, and *Globigerinoides sacculifer* obtained near Puerto Rico, USA, Lombard et al. cultured them under high and low irradiances in filtered sea water whose pH and carbonate ion concentration—$[CO_3^{2-}]$—were manipulated by adding NaOH or HCl. Among other things, the data they collected in these experiments included "measurements of the initial and final size (µm), the survival time (days from collection to gametogenesis), and final weight of the shell (µg)," but only for "individuals that underwent gametogenesis and grew at least one chamber."

The four researchers report "under the IS92a 'business as usual' scenario as defined by the Intergovernmental Panel on Climate Change and projected for the year 2100," their results suggest "in 2100, the rate of calcification of *G. sacculife*r and *O. universa* could decline by 6–13% compared to recent rates." In addition, they state "the future increase in temperature [predicted by the IPCC] could increase the production of calcite by foraminifera, counteracting the negative impact of ocean acidification." In addition, the results of the analysis of Tans (2009), illustrated in Figure 8.2.2, suggest (1) the true decline in oceanic pH by the year 2100 is more likely to be only about half of that projected by the IPCC and (2) this drop will begin to be ameliorated after 2100, gradually returning oceanic pH to present-day values after 2500.

In another experiment on foraminifers, Kuroyanagi et al. (2009) cultured asexually produced individuals of *Marginopora kudakajimensis*—a calcifying microorganism that contributes to both organic and inorganic carbon production in coral reefs—under carefully controlled laboratory conditions for a period of 71 days in glass jars containing approximately 110 ml of filtered natural seawater (control pH of about 8.2) and two less-basic pH conditions of about 7.9 and 7.7, created by additions of 0.1 N HCl.

In declining from the control pH of 8.2 to a pH of 7.9, the mean maximum shell diameter of the large foraminifer actually rose by 8.6 percent, while its mean shell weight rose by a much smaller and insignificant 0.7 percent. As the seawater's pH declined to 7.7, however, the organism's mean maximum shell diameter fell by 12.1 percent, and its mean shell weight fell by 49.3 percent.

Based on these results, Kuroyanagi et al. conclude that if oceanic pH remains within the range of 8.2 to 7.9, the "large foraminifers should be able to maintain present calcification rates," but they note any further drop in pH could lead to reduced rates of calcification. That said, although the IPCC's A2 scenario predicts a maximum pH decline of approximately 0.5 pH units by about AD 2270, the more recent analysis of Tans (2009) suggests a maximum pH drop of only about 0.14 unit at about AD 2090, after which pH begins to rise to asymptotically return to its current value after several hundred years. This latter projection suggests oceanic pH will not come close to creating a major decline in the calcification rate of *M. kudakajimensis*.

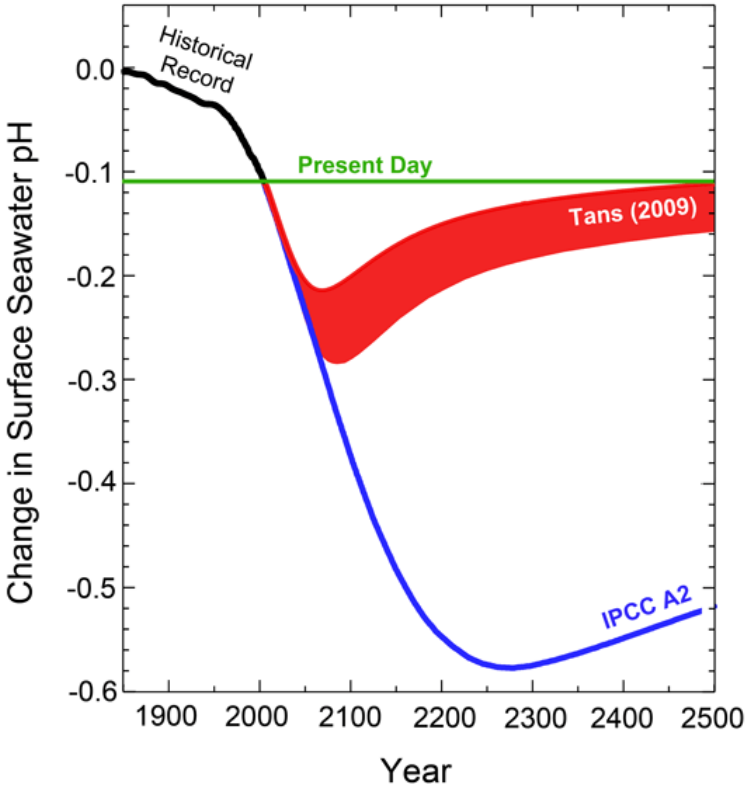


Figure 8.2.2. Change in surface seawater pH vs. time as observed for the prior century and a half and as calculated by the IPCC and Tans (2009) for the next five centuries.

We next report the results of two ocean acidification studies on phytoplankton communities. In prefacing their work, Wyatt et al. (2010) state "the assimilation of inorganic nutrients fuels phytoplankton growth," and, therefore, "any alteration in the bioavailability of these nutrients is likely to impact productivity and, by extension, climate regulation through the uptake of CO_2 by marine algae." They note "the reduction of surface ocean pH anticipated for the next century will alter the equilibrium coefficient between dissolved ammonia (NH_3(aq)) and ammonium (NH_4^+) shifting the equilibrium towards NH_4^+ (Zeebe and Wolf-Gladrow, 2001; Bell et al., 2007, 2008)," such that the future decease in ocean pH due to the ongoing rise in the air's CO_2 content could result in the transfer of more gaseous NH_3 from the overlying atmosphere to the ocean, as has been noted by Jacobson (2005).

To further explore this scenario, Wyatt et al. collected surface seawater samples from a coastal monitoring site in the western English Channel (WEC) from 17 March to 21 July 2008, which included two distinct phases of the annual spring phytoplankton bloom (a pre-bloom period of five weeks and the bloom proper of 11 weeks). In addition, they measured ambient pH for carbonate system estimates and dissolved inorganic nutrients, and they equilibrated the samples with CO_2-in-air mixtures that resulted in CO_2 concentrations of 380, 500, 760, and 1,000 ppm that led to pH values of 8.05, 8.01, 7.87, and 7.76, respectively, which are to be compared with the mean ambient value of 8.18.

The six scientists report their results indicated the phytoplankton community "was predominantly limited by the availability of inorganic nitrogen," and "during early and mid-summer, NH_X became the primary source of inorganic nitrogen." Interestingly, they also report "an overall increase in NH_X concentrations by 20% was observed between the present day CO_2 treatment (380 ppm) and 1000 ppm."

Given these findings, Wyatt et al. write, "as excess CO_2 dissociates in the oceans, the increased hydrogen ion concentration ionizes NH_3(aq) and decreases the ratio of NH_3(aq):NH_4^+," and this reduction in NH_3(aq) "would lead to an imbalance in the equilibrium between NH_3(aq) in the surface water and gaseous NH_3 in the overlying atmosphere resulting in the drawdown of atmospheric NH_3 to the surface ocean." Based on this finding, they further calculate that whereas the surface waters of the WEC "are a net source of 150 μmol/m^2/year of NH_3 to the atmosphere at present (2009)," it is likely "the WEC will become a net sink of 300 μmol/m^2/year for atmospheric NH_3 as atmospheric CO_2 rises to 717 ppm and the surface pH decreases to 7.83," due to the increase in phytoplanktonic productivity driven by the increased transfer of gaseous NH_3 from the air to the surface waters of the WEC. This phenomenon would (1) boost the productivity of higher oceanic trophic levels, (2) help sequester more carbon at the bottom of the sea, and thereby (3) reduce the rate of increase in radiative forcing that is speculated to fuel global warming.

In a contemporaneous study of a phytoplankton community, Breitbarth et al. (2010) write as background for their report, "studies of artificial and natural iron input have demonstrated iron control of phytoplankton productivity and CO_2 drawdown over vast oceanic regions (Boyd et al., 2007; Blain et al., 2007; Pollard et al., 2009) and in coastal upwelling regions (Bruland et al., 2001; Hutchins and Bruland, 1998)," and they state "temporal control of iron on phytoplankton productivity was also observed in a Norwegian fjord system (Ozturk et al., 2002)."

Following the development of natural phytoplanktonic blooms in the Pelagic Ecosystem CO_2 Enrichment (PeECE III) study—where the blooms were monitored in mesocosms consisting of two-meter-diameter polyethylene bags submerged to a depth of ten meters in an adjacent fjord, where they were maintained in equilibrium with air possessing CO_2 concentrations of either 350, 700, or 1,050 ppm via aeration of the water column and the overlying atmosphere with air of the three CO_2 concentrations (Schulz et al., 2008), Breitbarth et al. measured dissolved iron (dFe) concentrations as well as levels and oxidation rates of Fe(II)—a necessary trace element (the ferrous species of iron) used by almost all living organisms—over the course of the study to determine whether ocean acidification may affect iron speciation in seawater.

The eight researchers report CO_2 perturbation and phytoplanktonic bloom development resulted in pH value ranges of 7.67–7.97, 7.82–8.06, and 8.13–8.26 at 1,050, 700, and 350 ppm CO_2, respectively. They state their measurements revealed significantly higher dFe concentrations in the high CO_2 treatment compared to the mid and low CO_2 treatments, and that the high-CO_2 mesocosms showed higher values of FE(II) compared to the lower CO_2 treatments.

Breitbarth et al. thus conclude "ocean acidification may lead to enhanced Fe-bioavailability due to an increased fraction of dFe and elevated Fe(II) concentrations in coastal systems ... due to pH induced changes in organic iron complexation and Fe(II) oxidation rates," noting these phenomena "will result in increased turnover of Fe in surface seawater, potentially maintaining iron bioavailability given a sufficient supply of total Fe, since equilibrium partitioning eventually restores the biolabile Fe pools that have been depleted by biological uptake." They suggest "these processes may further fuel increased phytoplankton carbon acquisition and export at future atmospheric CO_2 levels," citing the work of Riebesell et al. (2007). They thus reach their final conclusion that "changes in iron speciation and the resulting potential negative feedback mechanism of phytoplankton productivity on atmospheric CO_2"—i.e., the drawdown of atmospheric CO_2 due to enhanced phytoplanktonic growth and transferal of the carbon thus removed from the atmosphere to the ocean depths—"need to be considered when assessing the ecological effects of ocean acidification."

References

Bell, T.G., Johnson, M.T., Jickells, T.D., and Liss, P.S. 2007. Ammonia/ammonium dissociation coefficient in seawater: a significant numerical correction. *Environmental Chemistry* **4**: 183–186.

Bell, T.G., Johnson, M.T., Jickells, T.D., and Liss, P.S. 2008. Ammonia/ammonium dissociation coefficient in seawater: a significant numerical correction (vol. 4 pg 183, 2007). *Environmental Chemistry* **5**: 258 U8.

Blain, S., Queguiner, B., Armand, L., Belviso, S., Bombled, B., Bopp, L., Bowie, A., Brunet, C., Brussaard, C., Carlotti, F., Christaki, U., Corbiere, A., Durand, I., Ebersbach, F., Fuda, J.-L., Garcia, N., Gerringa, L., Griffiths, B., Guigue, C., Guillerm, C., Jacquet, S., Jeandel, C., Laan, P., Lefevere, D., Lo Monaco, C., Malits, A., Mosseri, J., Obermosterer, I., Park, Y.-H., Picheral, M., Pondaven, P., Remenyi, T., Sandroni, V., Sarthou, G., Savoye, N., Scouarnec, L., Souhaut, M., Thuiller, D., Timmermans, K., Trull, T., Uitz, J., van Beek, P., Veldhuis, M., Vincent, D., Viollier, E., Vong, L., and Wagener, T. 2007. Effect of natural iron fertilization on carbon sequestration in the Southern Ocean. *Nature* **446**: 1070–1074.

Boyd, P.W., Jickells, T., Law, C.S., Blain, S., Boyle, E.A., Buesseler, K.O., Coale, K.H., Cullen, J.J., de Baar, H.J.W., Follows, M., Harvey, M., Lancelot, C., Levasseur, M., Owens, N.P.J., Pollard, R., Rivkin, R.B., Sarmiento, J., Schoemann, V., Smetacek, V., Takeda, S., Tsuda, A., Turner, S., and Watson, A.J. 2007. Mesoscale iron enrichment experiments 1993–2005: synthesis and future directions. *Science* **315**: 612–617.

Breitbarth, E., Bellerby, R.J., Neill, C.C., Ardelan, M.V., Meyerhofer, M., Zollner, E., Croot, P.L., and Riebesell, U. 2010. Ocean acidification affects iron speciation during a coastal seawater mesocosm experiment. *Biogeosciences* **7**: 1065–1073.

Bruland, K.W., Rue, E.L., and Smith, G.J. 2001. Iron and macronutrients in California coastal upwelling regimes: implications for diatom blooms. *Limnology and Oceanography* **46**: 1661–1674.

Halloran, P.R., Hall, I.R., Colmenero-Hidalgo, E., and Rickaby, R.E.M. 2008. Evidence for a multi-species coccolith volume change over the past two centuries: understanding a potential ocean acidification response. *Biogeosciences* **5**: 1651–1655.

Hutchins, D.A. and Bruland, K.W. 1998. Iron-limited diatom growth and Si:N uptake ratios in a coastal upwelling regime. *Nature* **393**: 561–564.

Iglesias-Rodriguez, M.D., Halloran, P.R., Rickaby, R.E.M., Hall, I.R., Colmenero-Hidalgo, E., Gittins, J.R., Green, D.R.H., Tyrrell, T., Gibbs, S.J., von Dassow, P., Rehm, E., Armbrust, E.V., and Boessenkool, K.P. 2008. Phytoplankton calcification in a high-CO_2 world. *Science* **320**: 336–340.

Jacobson, M.Z. 2005. Studying ocean acidification with conservative, stable numerical schemes for non-equilibrium air-ocean exchange and ocean equilibrium chemistry. *Journal of Geophysical Research* **110**: 10.1029/2004JD005220.

Kuroyanagi, A., Kawahata, H., Suzuki, A., Fujita, K., and Irie, T. 2009. Impacts of ocean acidification on large benthic foraminifers: Results from laboratory experiments. *Marine Micropaleontology* **73**: 190–195.

Langer, G., Geisen, M., Baumann, K.-H., Klas, J. , Riebesell, U., Thoms, S., and Young, J.R. 2006. Species-specific responses of calcifying algae to changing seawater carbonate chemistry. *Geochemistry, Geophysics, Geosystems* **7**: 10.1029/2005GC001227.

Langer, G., Gussone, N., Nehrke, G., Riebesell, U., Eisenhauer, A., and Thoms, S. 2007. Calcium isotope fractionation during coccolith formation in *Emiliania huxleyi*: Independence of growth and calcification rate. *Geochemistry, Geophysics, Geosystems* **8**: 10.1029/2006GC001422.

Langer, G., Nehrke, G., Probert, I., Ly, J., and Ziveri, P. 2009. Strain-specific responses of *Emiliania huxleyi* to changing seawater carbonate chemistry. *Biogeosciences Discussions* **6**: 4361–4383.

Lombard, F., da Rocha, R.E., Bijma, J., and Gattuso, J.-P. 2010. Effect of carbonate ion concentration and irradiance on calcification in planktonic foraminifera. *Biogeosciences* **7**: 247–255.

Ozturk, M., Steinnes, E., and Sakshaug, E. 2002. Iron speciation in the Trondheim Fjord from the perspective of iron limitation for phytoplankton. *Estuarine, Coastal and Shelf Science* **55**: 197–212.

Pollard, R.T., Salter, I., Sanders, R.J., Lucas, M.I., Moore, C.M., Mills, R.A., Statham, P.J., Allen, J.T., Baker, A.R., Bakker, D.C.E., Charette, M.A., Fielding, S., Fones, G.R., French, M., Hickman, A.E., Holland, R.J., Hughes, J.A., Jickells, T.D., Lampitt, R.S., Morris, P.J., Nedelec, F.H., Nielsdottir, M., Planquette, H., Popova, E.E., Poulton, A.J., Read, J.F., Seeyave, S., Smith, T., Stinchcombe, M., Taylor, S., Thomalla, S., Venables, H.J., Williamson, R., and Zubkov, M.V. 2009. Southern Ocean deep-water carbon export enhanced by natural iron fertilization. *Nature* **457**: 577–580.

Riebesell, U., Schulz, K., Bellerby, R., Botros, M., Fritsche, P., Meyerhofer, M., Neill, C., Nondal, G., Oschlies, A., Wohlers, J., and Zollner, E. 2007. Enhanced biological carbon consumption in a high CO_2 ocean. *Nature* **450**: 545–548.

Rost, B., Riebesell, U., Burkhart, S., and Sultemeyer, D. 2003. Carbon acquisition of bloom-forming marine phytoplankton. *Limnology and Oceanography* **48**: 55–67.

Schiebel, R. 2002. Planktic foraminiferal sedimentation and the marine calcite budget. *Global Biogeochemical Cycles* **16**: 1010.1029/2001GB001459.

Schulz, K.G., Riebesell, U., Bellerby, R.G.J., Biswas, H., Meyerhofer, M., Muller, M.N., Egge, J.K., Nejstgaard, J.C., Neill, C., Wohlers, J., and Zollner, E. 2008. Build-up and decline of organic matter during PeECE III. *Biogeosciences* **5**: 707–718.

Stoll, H. 2009. A biogeochemist sees the value of diversity in a changing ocean. *Nature* **460**: 935.

Tans, P. 2009. An accounting of the observed increase in oceanic and atmospheric CO_2 and an outlook for the future. *Oceanography* **22**: 26–35.

Wyatt, N.J., Kitidis, V., Woodward, E.M.S., Rees, A.P., Widdicombe, S., and Lohan, M. 2010. Effects of high CO_2 on the fixed nitrogen inventory of the Western English Channel. *Journal of Plankton Research* **32**: 631–641.

Zeebe, R.E. and Wolf-Gladrow, D.A. 2001. *CO_2 in Seawater: Equilibrium, Kinetics, Isotopes.* Amsterdam, Netherlands: Elsevier Oceanographic Book Series.

8.2.1.2. Macroalgae

Writing as background for their study, Jiang et al. (2010) note “seagrasses are flowering plants that thrive in shallow oceanic and estuarine waters around the world, and are ranked as one of the most ecologically and economically valuable biological systems on earth,” citing the work of Beer et al. (2006). They state *Thalassia hemprichii* “is among the most widely-distributed seagrass species in an Indo-Pacific flora, dominating in many mixed meadows,” citing the work of Short et al. (2007).

In conducting their analysis, the authors collected intact vegetative plants of *T. hemprichii* from Xincun Bay of Hainan Island, Southern China, which they transported to the laboratory and cultured in flow-through seawater aquaria bubbled with four different concentrations of CO_2 representative of (1) the present global ocean, with a pH of 8.10, (2) the projected ocean for 2100, with a pH of 7.75, (3) the projected ocean for 2200, with a pH of 7.50, and (4) the ocean characteristic of “an extreme beyond the current predictions” (a hundredfold increase in free CO_2, with a pH of 6.2).

The three researchers report the “leaf growth rate of CO_2-enriched plants was significantly higher than that in the unenriched treatment,” that “nonstructural carbohydrates (NSC) of *T. hemprichii*, especially in belowground tissues, increased strongly with elevated CO_2,” and “belowground tissues showed a similar response with NSC.”

The Chinese scientists identify several implications of their findings that “CO_2 enrichment enhances photosynthetic rate, growth rate and NSC concentrations of *T. hemprichii*.” With higher atmospheric CO_2 concentrations, they note, “colonization beyond current seagrass depth limits is possible”; the extra stored NSC “can be used to meet the carbon demands of plants during periods of low photosynthetic carbon fixation caused by severe environmental disturbance such as underwater light reduction”; it can enhance “rhizome growth, flowering shoot production and vegetative proliferation”; and it “may buffer the negative effects of transplant shock by increasing rhizome reserve capacity.” They also write, “the globally increasing CO_2 may enhance seagrass survival in eutrophic coastal waters, where populations have been devastated by algal proliferation and reduced column light transparency,” and “ocean acidification will stimulate seagrass biomass and productivity, leading to more favorable habitat and conditions for associated invertebrate and fish species."

Also researching the potential effects of ocean acidification on macroalgae were Xu et al. (2010), who write, "*Gracilaria lemaneiformis* (Bory) Weber-van Bosse is an economically important red seaweed that is cultivated on a large scale in China due to the quantity and quality of agar in its cell walls." In addition, they state "much attention has been paid to the biofiltration capacity of the species (Yang et al., 2005, 2006; Zhou et al., 2006)," and that it has thus been suggested to be "an excellent species for alleviating coastal eutrophication in China (Fei, 2004)." Considering these important characteristics of this seaweed, the authors set out to examine how this aquatic plant might respond to elevated CO_2.

In conducting their experiment, plants were grown from thalli—collected at 0.5 m depth from a farm located in Shen'ao Bay, Nanao Island, Shantou (China)—for 16 days in 3-L flasks of natural seawater maintained at either natural (0.5 µM) or high (30 µM) dissolved inorganic phosphorus (Pi) concentrations in contact with air of either 370 or 720 ppm CO_2, while their photosynthetic rates, biomass production, and uptake of nitrate and phosphate were examined.

As best as can be determined from Xu et al.'s graphical representations of their results, algal photosynthetic rates in the natural Pi treatment were increased only by a non-significant 5 percent as a result of the 95 percent increase in the air's CO_2 concentration, and in the high Pi treatment they were increased by approximately 41 percent. In the case of growth rate or biomass production, on the other hand, the elevated CO_2 treatment exhibited a 48 percent increase in the natural Pi treatment, whereas in the high Pi treatment there was no CO_2-induced increase in growth, because the addition of the extra 29.5 µM Pi boosted the biomass production of the low-CO_2 natural-Pi treatment by approximately 83 percent, and additional CO_2 did not increase growth rates beyond that point.

The three Chinese researchers state "elevated levels of CO_2 in seawater increase the growth rate of many seaweed species despite the variety of ways in which carbon is utilized in these algae," noting "some species, such as *Porphyra yezoensis* Ueda (Gao et al., 1991) and *Hizikia fusiforme* (Harv.) Okamura (Zou, 2005) are capable of using HCO_3^-, but are limited by the current ambient carbon concentration in seawater," and "enrichment of CO_2 relieves this limitation and enhances growth." Regarding the results they obtained with *Gracilaria lemaneiformis*, on the other hand—which they state "efficiently uses HCO_3^- and whose photosynthesis is saturated at the current inorganic carbon concentration of natural seawater (Zou et al., 2004)"—they write, "the enhancement of growth could be due to the increased nitrogen uptake rates at elevated CO_2 levels," which in their experiment were 40 percent in the natural Pi treatment, because "high CO_2 may enhance the activity of nitrate reductase (Mercado et al., 1999; Gordillo et al., 2001; Zou, 2005) and stimulate the accumulation of nitrogen, which could contribute to growth." Whatever strategy might be employed, these several marine macroalgae appear to be capable of benefiting greatly from increased atmospheric CO_2 concentrations.

References

Beer, S., Mtolera, M., Lyimo, T., and Bjork, M. 2006. The photosynthetic performance of the tropical seagrass *Halophila ovalis* in the upper intertidal. *Aquatic Botany* **84**: 367–371.

Fei, X.G. 2004. Solving the coastal eutrophication problem by large scale seaweed cultivation. *Hydrobiologia* **512**: 145–151.

Gao, K., Aruga, Y., Asada, K., Ishihara, T., Akano, T., and Kiyohara, M. 1991. Enhanced growth of the red alga *Porphyra yezoensis* Ueda in high CO_2 concentrations. *Journal of Applied Phycology* **3**: 356–362.

Gordillo, F.J.L., Niell, F.X., and Figueroa, F.L. 2001. Non-photosynthetic enhancement of growth by high CO_2 level in the nitrophilic seaweed *Ulva rigida* C. Agardh (Chlorophyta). *Planta* **213**: 64–70.

Jiang, Z.J., Huang, X.-P., and Zhang, J.-P. 2010. Effects of CO_2 enrichment on photosynthesis, growth, and biochemical composition of seagrass *Thalassia hemprichii* (Ehrenb.) Aschers. *Journal of Integrative Plant Biology* **52**: 904–913.

Mercado, J.M., Javier, F., Gordillo, L., Niell, F.X., and Figueroa, F.L. 1999. Effects of different levels of CO_2 on photosynthesis and cell components of the red alga *Porphyra leucosticia*. *Journal of Applied Phycology* **11**: 455–461.

Short, F.T., Carruthers, T.J., Dennison, W.C., and Waycott, M. 2007. Global seagrass distribution and diversity: a bioregional model. *Journal of Experimental Marine Biology and Ecology* **350**: 3–20.

Xu, Z., Zou, D., and Gao, K. 2010. Effects of elevated CO_2 and phosphorus supply on growth, photosynthesis and nutrient uptake in the marine macroalga *Gracilaria lemaneiformis* (Rhodophyta). *Botanica Marina* **53**: 123–129.

Yang, H., Zhou, Y., Mao, Y., Li, X., Liu, Y., and Zhang, F. 2005. Growth characters and photosynthetic capacity of *Gracilaria lemaneiformis* as a biofilter in a shellfish farming area in Sanggou Bay, China. *Journal of Applied Phycology* **17**: 199–206.

Yang, Y.F., Fei, X.G., Song, J.M., Hu, H.Y., Wang, G.C., and Chung, I.K. 2006. Growth of *Gracilaria lemaneiformis* under different cultivation conditions and its effects on nutrient removal in Chinese coastal waters. *Aquaculture* **254**: 248–255.

Zhou, Y., Yang, H., Hu, H., Liu, Y., Mao, Y., Zhou, H., Xu, X., and Zhang, F. 2006. Bioremediation potential of the macroalga *Gracilaria lemaneiformis* (Rhodophyta) integrated into fed fish culture in coastal waters of north China. *Aquaculture* **252**: 264–276.

Zou, D. 2005. Effects of elevated atmospheric CO_2 on growth, photosynthesis and nitrogen metabolism in the economic brown seaweed, *Hizikia fusiforme* (Sargassaceae, Phaeophyta). *Aquaculture* **250**: 726–735.

Zou, D., Xia, J., and Yang, Y. 2004. Photosynthetic use of exogenous inorganic carbon in the agarophyte *Gracilaria lemaneiformis* (Rhodophyta). *Aquaculture* **237**: 421–431.

8.2.2. Effects on Marine Animals

8.2.2.1. Bivalves

In the introductory material to their paper on potential effects of predicted near-future increases in CO_2-driven ocean acidification on shell-producing calcification in a species of oyster, Watson et al. (2009) report over the past two centuries CO_2 emissions from deforestation and the burning of fossil fuels have increased atmospheric CO_2 concentrations from 280 to 380 ppm, citing NOAA/ESRL records produced and maintained by Pieter Tans. They additionally state the portion of this extra CO_2 that has been taken up by the planet's oceans has caused a 0.1 unit drop in the pH of their surface waters, which would appear to be correct. However, they predict there will be a further reduction in ocean pH of 0.3 to 0.5 units by 2100, citing the work of Haugan and Drange (1996), Orr et al. (2005), and Caldeira and Wickett (2005), while noting these predicted changes in ocean pH "are not only greater but far more rapid than any experienced in the last 24 million years," citing Blackford and Gilbert (2007), or "possibly the last 300 million years," citing Caldeira and Wickett (2003). But how likely are such predictions?

Consider the findings of Tans himself, who Watson et al. approvingly cite in regard to the CO_2 history they mention. In a paper published in *Oceanography*, Tans (2009) concluded the future trajectory of oceanic pH will likely be significantly different from that suggested by the scientists cited by Watson et al., while at the same time bravely criticizing the IPCC reports that also have accepted the highly inflated acidification predictions of those scientists. Indeed, whereas Watson et al. and the IPCC accept the claims of those who project a decline in pH somewhere in the range of 0.3 to 0.5 between now and the end of the century, Tans' projections yield a pH decline somewhere in the range of 0.09 to 0.17, which would be expected to have significantly reduced biological impacts compared to those suggested by the experimental work of Watson et al.

Based on the results of their experiments and the maximum decline in ocean-water pH they accept, Watson et al. predict a significant decline of 72 percent in Sydney rock oyster (*Saccostrea glomerata*) larval survival by the year 2100. However, utilizing Watson et al.'s data but with the maximum ocean-water pH decline calculated by Tans, one obtains a non-significant larval survival decline of only 14 percent, based on interpolation of the graphical results portrayed in Watson et al.'s paper. Similar assessments of changes in antero-posterior measurement yield a significant decline of 8.7 percent using Watson et al.'s assumptions about ocean pH, but a non-significant decline of only 1.8 percent according to Tans' pH calculations. Corresponding results for dorso-ventral measurement were a significant decline of 7.5 percent with Watson et al.'s pH values, but a non-significant decline of only 1.5 percent with Tans' values, and for larval dry mass there was a decline of 50 percent in Watson et al.'s analysis, but an actual increase (albeit non-significant) of 6 percent using Tans' pH analysis. Last, for empty shells remaining there was a significant decline of 90 percent in the Watson et al. study, but a non-significant decline of only 6 percent when Tans' pH projections were used.

Based on their experimental data and the ocean pH projections for the end of the century that are promoted by them and the IPCC, Watson et al. find what they characterize as "a dramatic negative effect on the survival, growth, and shell formation of the early larval stages of the Sydney rock oyster." On the other hand, employing the pH values projected by Tans, there are no statistically significant reductions in any of the five biological parameters measured and evaluated by Watson et al.

In a separate effort designed to project potential CO_2-induced changes in estuarine calcification in the years ahead, larvae of two oyster species—the Eastern oyster (*Crassostrea virginica*) and the Suminoe oyster (*Crassostrea ariakensis*)—were grown by Miller et al. (2009) for up to 28 days in estuarine water in equilibrium with air of four different CO_2 concentrations (280, 380, 560, and 800 ppm), which were chosen to represent atmospheric conditions in the preindustrial era, the present day, and the years 2050 and 2100, respectively, as projected by the IS92a business-as-usual scenario of the IPCC, which were maintained by periodically aerating the different aquaria employed in the study with air containing 1 percent CO_2. Larval growth was assessed via image analysis, and calcification was determined by means of chemical analyses of calcium in the shells of the oyster larvae.

When the larvae of both species were cultured continuously from 96 hours post fertilization for 26 to 28 days while exposed to elevated CO_2 concentrations, the authors state they "appeared to grow, calcify and develop normally with no obvious morphological deformities, despite conditions of significant aragonite undersaturation." They write these findings "run counter to expectations that aragonite shelled larvae should be especially prone to dissolution at high pCO_2." More specifically, the authors state "both oyster species generated larval shells that were of similar mean thickness, regardless of pCO_2, $O_{\mathbf{arag}}$ [aragonite compensation point] or shell area," remarking they "interpret the pattern of similar shell thickness as further evidence of normal larval shell development." And because these two calcifying organisms appeared not to have suffered deleterious consequences, the four researchers concluded "biological responses to acidification, especially [in] calcifying biota, will be species specific and therefore much more variable and complex than reported previously."

In another study examining "the very earliest, and critical, process of fertilization," Havenhand and Schlegel (2009) collected specimens of the oyster *Crassostrea gigas*—which they obtained from a mixed mussel/oyster bed on the coast of western Sweden and kept within flow-through tanks of filtered sea water that they maintained at either (1) the normal ambient pH level or (2) a level reduced by about 0.35 units that was created by bubbling CO_2 through the water—and observed and measured the species' sperm-swimming behavior and fertilization kinetics. Their results indicated that in water of pH 8.15, mean sperm-swimming speeds were 92.1 ± 4.8μm/s, but in water of pH 7.8 they were slightly higher, at 94.3 ± 5.5μm/s, although the difference was not statistically significant. Mean fertilization success in water of pH 8.15 was 63.4 percent, whereas in water of pH 7.8 it was also slightly higher at 64.1 percent, although this difference, too, was not statistically significant.

Based on these findings, the Swedish scientists state "the absence of significant overall effects of pH on sperm swimming behavior and fertilization success is remarkable," and they emphasize the power analyses they conducted "showed clearly that these results were not due to inadequate statistical power." Moreover, they write, "the absence of significant effect is likely a true reflection of the responses of *Crassostrea gigas* gametes and zygotes from the Swedish west coast to levels of CO_2-induced acidification expected by the end of this century," a very encouraging finding.

References

Blackford, J.C. and Gilbert, F.J. 2007. pH variability and CO_2 induced acidification in the North Sea. *Journal of Marine Systems* **64**: 229–241.

Caldeira, K. and Wickett, M.E. 2003. Anthropogenic carbon and ocean pH. *Nature* **425**: 365.

Caldeira, K. and Wickett, M.E. 2005. Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean. *Journal of Geophysical Research* **110**: 10.1029/2004JC002671.

Haugan, P.M. and Drange, H. 1996. Effects of CO_2 on the ocean environment. *Energy Conversion and Management* **37**: 1019–1022.

Havenhand, J.N. and Schlegel, P. 2009. Near-future levels of ocean acidification do not affect sperm motility and fertilization kinetics in the oyster *Crassostrea gigas*. *Biogeosciences* **6**: 3009–3015.

Miller, A.W., Reynolds, A.C., Sobrino, C., and Riedel, G.F. 2009. Shellfish face uncertain future in high CO_2 world: influence of acidification on oyster larvae calcification and growth in estuaries. *PLoS ONE* **4**: 10.1371/journal.pone.0005661.

Orr, J.C., Fabry, V.J., Aumont, O., Bopp, L., Doney, S.C., Feely, R.A., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., Key, R.M., Lindsay, K., Maier-Reimer, E., Matear, R., Monfray, P., Mouchet, A., Najjar, R.G., Plattner, G.-K., Rodgers, K.B., Sabine, C.L., Sarmiento, J.L., Schlitzer, R., Slater, R.D., Totterdell, I.J., Weirig, M.-F., Yamanaka, Y., and Yool, A. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature* **437**: 681–686.

Tans, P. 2009. An accounting of the observed increase in oceanic and atmospheric CO_2 and an outlook for the future. *Oceanography* **22**: 26–35.

Watson, S.-A., Southgate, P.C., Tyler, P.A., and Peck, L.S. 2009. Early larval development of the Sydney rock oyster *Saccostrea glomerata* under near-future predictions of CO_2-driven ocean acidification. *Journal of Shellfish Research* **28**: 431–437.

8.2.2.2. Cephalopods

In studying the common cuttlefish, *Sepia officinalis*, Gutowska et al. (2008) found it "is capable of not only maintaining calcification, but also growth rates and metabolism when exposed to elevated partial pressures of carbon dioxide." Over a six-week test period, they found "juvenile *S. officinalis* maintained calcification under ~4000 and ~6000 ppm CO_2, and grew at the same rate with the same gross growth efficiency as did control animals," gaining approximately 4 percent body mass daily and increasing the mass of their calcified cuttlebone by more than 500 percent. These findings led them to conclude specifically that "active cephalopods possess a certain level of pre-adaptation to long-term increments in carbon dioxide levels," and to conclude generally that our "understanding of the mechanistic processes that limit calcification must improve before we can begin to predict what effects future ocean acidification will have on calcifying marine invertebrates."

In another study examining the common cuttlefish (*Sepia officinalis*) and published one year later, Lacoue-Labarthe et al. (2009) monitored fertilized eggs of this species throughout their full development time at controlled temperature (16 or 19°C) and pH (8.1, 7.85, or 7.6) conditions. The latter values were maintained within ± 0.05 of a pH unit by periodically bubbling pure CO_2 into the bottles (which were continuously aerated with CO_2-free air), resulting in mean CO_2 concentrations of the air in contact with the surface of the water of either 400, 900, or 1,400 ppm.

This group of authors found "decreasing pH resulted in higher egg weight at the end of development at both temperatures ($p < 0.05$), with maximal values at pH 7.85 (1.60 ± 0.21 g and 1.83 ± 0.12 g at 16°C and 19°C, respectively)." In addition, they found "hatchlings were smaller when they developed at 16°C than at 19°C ($p < 0.05$)." They also observed zinc (Zn) accumulation "was higher at pH 7.85 during the full developmental period," when "high embryonic requirements for Zn are not fully covered by the maternal pool," so the higher accumulation of Zn "was associated with a greater rate of growth of both egg and embryo." Concurrently, there was also a greater accumulation of potentially detrimental silver in the tissues of the hatchlings; but any deleterious effects of the extra silver were apparently more than overcome by the positive effects of lowered pH on beneficial zinc accumulation, while toxic cadmium accumulation was actually reduced in the lower pH (or higher CO_2) treatments.

The seven scientists conclude their paper by noting "decreasing pH until 7.85," such as could be expected to occur in air enriched with carbon dioxide to a concentration of 900 ppm, "should lead to some possibly beneficial effects, such as a larger egg and presumably hatchling size and a better incorporation of the essential element[s] such as Zn in the embryonic tissue." These phenomena, in their words, "may improve the survival [of] the newly hatched juveniles."

Given the findings of both papers presented above, it would appear the ongoing rise in the air's CO_2 content would benefit cuttlefish.

References

Gutowska, M.A., Portner, H.O., and Melzner, F. 2008. Growth and calcification in the cephalopod *Sepia officinalis* under elevated seawater pCO_2. *Marine Ecology Progress Series* **373**: 303–309.

Lacoue-Labarthe, T., Martin, S., Oberhansli, F., Teyssie, J.-L., Markich, S., Ross, J., and Bustamante, P. 2009. Effects of increased pCO_2 and temperature on trace element (Ag, Cd and Zn) bioaccumulation in the eggs of the common cuttlefish, *Sepia officinalis*. *Biogeosciences* **6**: 2561–2573.

8.2.2.3. Miscellaneous

In a Brevia item published in *Science*, Checkley et al. (2009) "grew eggs and pre-feeding larvae of white sea bass (*Atractoscion nobilis*) under a range of CO_2 concentrations [380, 993, and 2,558 ppm] and measured the size of their sagittal otoliths," which, in the words of the authors, "are bony structures used by fish to sense orientation and acceleration and consist of aragonite-protein bilayers," or as the dictionary states, they are "small vibrating calcareous particles in ... the ears of some animals, especially of fishes." Noting atmospheric CO_2 enrichment has been calculated, on a purely chemical basis, to decrease the saturation state of carbonate minerals such as aragonite in the world's oceans, the six scientists "hypothesized that otoliths in eggs and larvae reared in seawater with elevated CO_2 would grow more slowly than they do in seawater with normal CO_2." To test this hypothesis they conducted their experiment.

"Contrary to expectations," in the words of Checkley et al., "the otoliths of fish grown in seawater with high CO_2, and hence lower pH and aragonite saturation, were significantly larger than those of fish grown under simulations of present-day conditions." More specifically, the researchers found "for 7- to 8-day-old fish grown under 993 and 2558 ppm CO_2, the areas of the otoliths were 7 to 9% and 15 to17% larger, respectively, than those of control fish grown under 380 ppm CO_2."

As for why the otoliths were larger at a lower pH, the marine researchers went on to state young fish are "able to control the concentration of ions (H^+ and Ca^{2+}) ... in the endolymph surrounding the otolith," where "with constant pH, elevated CO_2 increases CO_3^{2-} concentration and thus the aragonite saturation state, accelerating formation of otolith aragonite."

Dupont et al. (2010) state, "echinoderms are among the most abundant and ecologically successful groups of marine animals (Micael et al., 2009), and are one of the key marine groups most likely to be impacted by predicted climate change events," presumably because "the larvae and/or adults of many species from this phylum form skeletal rods, plates, test, teeth, and spines from an amorphous calcite crystal precursor, magnesium calcite, which is 30 times more soluble than normal calcite (Politi et al., 2004)." This fact would normally be thought to make it much more difficult for them (relative to most other calcifying organisms) to produce calcification-dependent body parts.

Working with naturally fertilized eggs of the common sea star *Crossaster papposus*, which they collected and transferred to five-liter culture aquariums filled with filtered seawater (a third of which was replaced every four days), Dupont et al. tested this hypothesis by regulating the pH of the tanks to values of either 8.1 or 7.7 by adjusting environmental CO_2 levels to either 372 ppm or 930 ppm. During the testing period they documented (1) settlement success as the percentage of initially free-swimming larvae that affixed themselves to the aquarium walls, (2) larval length at various time intervals, and (3) degree of calcification.

The three researchers report just the opposite of what is often predicted actually happened, as the echinoderm larvae and juveniles were "positively impacted by ocean acidification." More specifically, they found "larvae and juveniles raised at low pH grow and develop faster, with no negative effect on survival or skeletogenesis within the time frame of the experiment (38 days)." In fact, they state the sea stars' growth rates were "two times higher" in the acidified seawater; and they remark, "*C. papposus* seem to be not only more than simply resistant to ocean acidification, but are also performing better."

Given these findings, the Swedish scientists concluded, "in the future ocean, the direct impact of ocean acidification on growth and development potentially will produce an increase in *C. papposus* reproductive success" and "a decrease in developmental time will be associated with a shorter pelagic period with a higher proportion of eggs reaching settlement," causing the sea stars to become "better competitors in an unpredictable environment." Not bad for a creature that makes its skeletal rods, plates, test, teeth, and spines from a substance that is 30 times more soluble than normal calcite.

Lastly, Rodolfo-Metalpa et al. (2010) worked with bryozoans or "moss animals"—a geologically important group of small animals that resemble corals and are major calcifiers, found on rocky shores in cool-water areas of the planet, where they comprise a significant component of the carbonate sediments in shallow sublittoral habitats, and where they form long-lived, three-dimensional structures that provide attachment sites for numerous epifauna and trap sediment and food for a variety of infauna—in what they describe as "the first coastal transplant experiment designed to investigate the effects of naturally acidified seawater on the rates of net calcification and dissolution of the branched calcitic bryozoan *Myriapora truncata*." They did this by transplanting colonies of the species to normal (pH 8.1), high (pH 7.66), and extremely high (pH 7.43) CO_2 conditions at gas vents located just off Italy's Ischia Island in the Tyrrhenian Sea, where they calculated the net calcification rates of live colonies and the dissolution rates of dead colonies by weighing them before and after 45 days of *in situ* residence in May–June (when seawater temperatures ranged from 19 to 24°C) and after 128 days of *in situ* residence in July–October (when seawater temperatures ranged from 25–28°C).

Throughout the first and cooler observation period, "dead *M. truncata* colonies dissolved at high CO_2 levels (pH 7.66), whereas live specimens maintained the same net calcification rate as those growing at normal pH," the researchers write. At the extremely high CO_2 level, however, the net calcification rate of the live specimens was reduced to only about 20 percent of what it was at normal pH, but life continued. Throughout the second and warmer observation period, on the other hand, calcification ceased in both the normal and high CO_2 treatments,and in the extremely high CO_2 treatment, the transplants died.

Based on these findings the five scientists concluded, "at moderate temperatures," such as those to which they are currently adapted, "adult *M. truncata* are able to up-regulate their calcification rates and survive in areas with higher levels of pCO_2 than are predicted to occur due to anthropogenic ocean acidification, although this ability broke down below mean pH 7.4." This latter level, however, is below what even the IPCC predicts will occur in response to continued burning of fossil fuels, and far below what the more realistic analysis of Tans (2009) suggests.

References

Checkley Jr., D.M., Dickson, A.G., Takahashi, M., Radich, J.A., Eisenkolb, N., and Asch, R. 2009. Elevated CO_2 enhances otolith growth in young fish. *Science* **324**: 1683.

Dupont, S., Lundve, B., and Thorndyke, M. 2010. Near future ocean acidification increases growth rate of the lecithotrophic larvae and juveniles of the sea star *Crossaster papposus*. *Journal of Experimental Zoology (Molecular and Developmental Evolution)* **314B**: 382–389.

Micael, J., Alves, M.J., Costa, A.C., and Jones, M.B. 2009. Exploitation and conservation of echinoderms. *Oceanography and Marine Biology* **47**: 191–208.

Politi, Y., Arod, T., Klein, E., Weiner, S., and Addadi, L. 2004. Sea urchin spine calcite forms via a transient amorphous calcite carbonate phase. *Science* **306**: 1161–1164.

Rodolfo-Metalpa, R., Lombardi, C., Cocito, S., Hall-Spencer, J.M., and Gambi, M.C. 2010. Effects of ocean acidification and high temperatures on the bryozoan *Myriapora truncata* at natural CO_2 vents. *Marine Ecology* **31**: 447–456.

Tans, P. 2009. An accounting of the observed increase in oceanic and atmospheric CO_2 and an outlook for the future. *Oceanography* **22**: 26–35.

8.2.3. Effects on Marine Ecosystems

8.2.3.1 Coral Reefs

Several studies have investigated the response of corals to a decline in oceanic pH, and like the studies cited above, their results indicate the model-projected decline is highly exaggerated.

Suwa et al. (2010) employed controlled infusions of pure CO_2 to create mean pH values of 8.0, 7.6, and 7.3 in filtered seawater that flowed continuously through three sets of multiple tanks into which they had introduced the gametes of two *Acropora* coral species (A. *digitifera* and A. *tenuis*) they had collected during a natural spawning event. Seven days later they determined the percent that survived; after ten additional days, they documented the size of the developing polyps; and after 14 days they documented the percentage of polyps that had acquired zooxanthellae that the researchers had collected from the giant clam *T. crocea* and released into the several treatment tanks.

Results indicated "*A. digitifera* larval survival rate did not differ significantly among pH treatments," and the graphs of their data indicate survivorship in *A. tenuis* was about 18.5 percent greater in the lowest pH (highest CO_2) treatment than in the ambient seawater treatment. At the end of the subsequent ten-day study, however, polyp size was reduced in the lowest pH treatment, but by only about 14 percent, not too bad for an atmospheric CO_2 concentration of more than 2,000 ppm. And in the *A. tenuis* coral, this reduction in individual size was more than compensated by the even greater percentage increase in survivorship. In addition, after only four days of being exposed to the zooxanthellae derived from giant clams, all polyps in all treatments had acquired a full complement of the symbiotic zooxanthella.

In discussing their findings, the seven scientists state "the survival of coral larvae may not be strongly affected by pH change," or "in other words," they continue, "coral larvae may be able to tolerate ambient pH decreases of at least 0.7 pH units." That, in fact, is something that will likely never occur, as it implies atmospheric CO_2 concentrations of more than 2,000 ppm. And in the unlikely event that such high concentrations ever were to happen, they would be a long, long time in coming, giving corals more than sufficient time to acclimate—and even evolve (Idso and Idso, 2009)—to cope with the slowly developing situation.

In another study, zooxanthellate colonies of the scleractinian coral *Astrangia poculata* were grown by Holcomb et al. (2010) in controlled laboratory conditions under all four combinations of ambient and elevated (5 µM NO_3^-, 0.3 µM PO_4^{-3}, and 2 nM Fe^{+2}) nutrients and ambient and elevated (~780 ppm) $p\mathrm{CO}_2$ for a period of six months. Coral calcification rates were measured via two different techniques—both one month after the start of the experiment and again five months later—and the carbonate chemistry and saturation state of the seawater of each treatment were calculated from measured values of alkalinity, salinity, phosphate, and pCO_2.

The results of these operations indicated mean calcification rates of the studied corals were 2.1, 0.7, 1.4, and 1.3 g/m^2/day for the ambient, CO_2-treated, nutrient-treated, and CO_2-plus-nutrient-treated corals, respectively, so that relative to ambient conditions, calcification rates were reduced by the CO_2 treatment to approximately 33 percent of the ambient rate, but with the addition of nutrients bounced partway back to 62 percent of the ambient rate.

In light of their findings, Holcomb et al. conclude "nutritionally replete corals should be able to compensate for reduced saturation state under elevated pCO_2 conditions." As $p\mathrm{CO}_2$ increases and seawater saturation state declines, for example, they write, the "availability of DIC [dissolved inorganic carbon] to the zooxanthellae will increase, potentially allowing increased photosynthesis which provides both alkalinity and energy to help drive calcification." Thus, if corals are experiencing carbon limitation, "elevated pCO_2 could even positively impact calcification."

It becomes clear, therefore, as the three researchers continue, that "saturation state alone is not an effective predictor of coral calcification." They note "the interaction between nutritional status of the coral, DIC availability, and saturation state may help to explain the wide range of calcification responses seen in published acidification and nutrient enrichment studies."

Two earlier studies reported similar findings. Atkinson et al. (1995) showed "nutritionally replete zooxanthellate corals in naturally low [aragonite] saturation-state seawaters are capable of accreting skeletons at rates comparable to those achieved by conspecifics in high-saturation-state seawaters." And Cohen and Holcomb (2009) reported "today, several reefs, including Galapagos, areas of Pacific Panama, and Jarvis (southern Line Islands), experience levels of aragonite saturation equivalent to that predicted for the open ocean under two times and three times pre-industrial CO_2 levels (Manzello et al., 2008; Kathryn Shamberger [PMEL/NOAA] and colleagues, *pers. comm.*, August 2009)," and "available data on coral colony growth rates on these reefs, albeit limited, suggest that they are equivalent to and sometimes even rival those of conspecifics in areas where aragonite saturation states are naturally high, such as the western Pacific warm pool."

Probably the most important deduction to flow from these observations is the fact, in the words of Cohen and Holcomb, that "naturally elevated levels of inorganic nutrients and, consequently, high levels of primary and secondary production, may already be facilitating high coral calcification rates in regions with naturally high dissolved CO_2 levels."

In another study, Kreif et al. (2010) collected two colonies of massive *Porites* corals (which form large multi-century-old colonies and calcify relatively slowly) and four colonies of the branching *Stylophora pistillata* coral (which is short-lived and deposits its skeleton rather rapidly) from a reef at the northern tip of the Red Sea. They grew fragments of these corals in 1,000-liter tanks through which they pumped Gulf of Eilat seawater adjusted to be in equilibrium with air of three different CO_2 concentrations (385, 1,904, and 3,970 ppm), which led to corresponding pH values of 8.09, 7.49, and 7.19 and corresponding aragonite saturation state ($\Omega_{\mathbf{arag}}$) values of 3.99, 1.25, and 0.65. After an incubation period of six months for *S. pistillata* and seven months for the *Porites* corals, several fragments were sampled and analyzed for a number of different coral properties. Then, 14 months from the start of the experiment, fragments of each coral species from each CO_2 treatment were analyzed for zooxanthellae cell density, chlorophyll *a* concentration, and host protein concentration.

In the words of the seven scientists who conducted the study, "following 14 months incubation under reduced pH conditions, all coral fragments survived and added new skeletal calcium carbonate, despite $\Omega_{\mathbf{arag}}$ values as low as 1.25 and 0.65." This was done, however, at a reduced rate of calcification compared to fragments growing in the normal pH treatment with a $\Omega_{\mathbf{arag}}$ value of 3.99. Yet in spite of this reduction in skeletal growth, they report, "tissue biomass (measured by protein concentration) was found to be higher in both species after 14 months of growth under increased CO_2." And they further note the same phenomenon had been seen by Fine and Tchernov (2007), who, as they describe it, "reported a dramatic increase (orders of magnitude larger than the present study) in protein concentration following incubation of scleractinian Mediterranean corals (*Oculina patagonica* and *Madracis pharencis*) under reduced pH," stating "these findings imply tissue thickening in response to exposure to high CO_2." Also, in a somewhat analogous situation, Krief et al. report "a decrease in zooxanthellae cell density with decreasing pH was recorded in both species," but they state "this trend was accompanied by an increase in chlorophyll concentration per cell at the highest CO_2 level."

In discussing their findings, the Israeli, French, and U.K. researchers write, "the inverse response of skeleton deposition and tissue biomass to changing CO_2 conditions is consistent with the hypothesis that calcification stimulates zooxanthellae photosynthesis by enhancing CO_2 concentration within the coelenteron (McConnaughey and Whelan, 1997)," and they write, "since calcification is an energy-consuming process . . a coral polyp that spends less energy on skeletal growth can instead allocate the energy to tissue biomass," citing Anthony et al. (2002) and Houlbreque et al. (2004). Thus, they suggest "while reduced calcification rates have traditionally been investigated as a proxy of coral response to environmental stresses, tissue thickness and protein concentrations are a more sensitive indicator of the health of a colony," citing Houlbreque et al. (2004) in this regard as well.

In concluding their paper, Krief et al. state "the long acclimation time of this study allowed the coral colonies to reach a steady state in terms of their physiological responses to elevated CO_2," and "the deposition of skeleton in seawater with $\Omega_{\mathbf{arag}} < 1$ demonstrates the ability of both species to calcify by modifying internal pH toward more alkaline conditions." As a result, they further state "the physiological response to higher CO_2/lower pH conditions was significant, but less extreme than reported in previous experiments," suggesting "scleractinian coral species will be able to acclimate to a high CO_2 ocean even if changes in seawater pH are faster and more dramatic than predicted."

In further examining the complexities of this issue, Jury et al. (2010) write as background for their analysis, "physiological data and models of coral calcification indicate that corals utilize a combination of seawater bicarbonate and (mainly) respiratory CO_2 for calcification, not seawater carbonate," but "a number of investigators are attributing observed negative effects of experimental seawater acidification by CO_2 or hydrochloric acid additions to a reduction in seawater carbonate ion concentration and thus aragonite saturation state." Thus, they state there is "a discrepancy between the physiological and geochemical views of coral biomineralization." In addition, they report "not all calcifying organisms respond negatively to decreased pH or saturation state," and they state, "together, these discrepancies suggest that other physiological mechanisms, such as a direct effect of reduced pH on calcium or bicarbonate ion transport and/or variable ability to regulate internal pH, are responsible for the variability in reported experimental effects of acidification on calcification."

In an effort to shed more light on this conundrum, Jury et al. performed incubations with the coral *Madracis auretenra* (= *Madracis mirabilis sensu* Wells, 1973) in modified seawater chemistries, where, as they describe it, "carbonate parameters were manipulated to isolate the effects of each parameter more effectively than in previous studies, with a total of six different chemistries." Their results indicated among-treatment differences "were highly significant," and "the corals responded strongly to variation in bicarbonate concentration, but not consistently to carbonate concentration, aragonite saturation state or pH." They found, for example, that "corals calcified at normal or elevated rates under low pH (7.6–7.8) when the sea water bicarbonate concentrations were above 1800 µM," and, conversely, "corals incubated at normal pH had low calcification rates if the bicarbonate concentration was lowered."

Jury et al. conclude, "coral responses to ocean acidification are more diverse than currently thought," and they question "the reliability of using carbonate concentration or aragonite saturation state as the sole predictor of the effects of ocean acidification on coral calcification." They state, "if we truly wish to decipher the response of coral calcification to ocean acidification, a firmer grasp of the biological component of biomineralization is paramount."

Lastly, Ries et al. (2010) investigated the impact of CO_2-induced ocean acidification on "the temperate scleractinian coral *Oculina arbuscula* by rearing colonies for 60 days in experimental seawaters bubbled with air-CO_2 gas mixtures of 409, 606, 903 and 2,856 ppm CO_2, yielding average aragonite saturation states (Ω_A) of 2.6, 2.3, 1.6 and 0.8." These operations indicated that "following the initial acclimation phase, survivorship in each experimental treatment was 100 percent," and, in regard to the corals' rates of calcification and linear extension, "no significant difference was detected relative to the control treatment ($\Omega_A = 2.6$) for corals reared under Ω_A of 2.3 and 1.6." The latter values correspond to pH reductions from current conditions of 0.08 and 0.26, respectively. It is enlightening to note the 0.26 pH reduction is approximately twice the maximum reduction derived from the analysis of Tans (2009) that would likely result from the burning of all fossil fuels in the crust of the Earth.

Given the above findings, the three researchers, in their words, "propose that the apparent insensitivity of calcification and linear extension within *O. arbuscula* to reductions in Ω_A from 2.6 to 1.6 reflects the corals' ability to manipulate the carbonate chemistry at their site of calcification." And it would further appear that ability should serve the corals well as the pH of the ocean declines in the future.

References

Anthony, K.R., Connolly, S.R., and Willis, B.L. 2002. Comparative analysis of energy allocation to tissue and skeletal growth in corals. *Limnology and Oceanography* **47**: 1417–1429.

Atkinson, M.J., Carlson, B., and Crowe, J.B. 1995. Coral growth in high-nutrient, low pH seawater: a case study in coral growth at the Waikiki aquarium. *Coral Reefs* **14**: 215–233.

Cohen, A.L. and Holcomb, M. 2009. Why corals care about ocean acidification: uncovering the mechanism. *Oceanography* **22**: 118–127.

Fine, M. and Tchernov, D. 2007. Scleractinian coral species survive and recover from decalcification. *Science* **315**: 10.1126/science.1137094.

Holcomb, M., McCorkle, D.C., and Cohen, A.L. 2010. Long-term effects of nutrient and CO_2 enrichment on the temperate coral *Astrangia poculata* (Ellis and Solander, 1786). *Journal of Experimental Marine Biology and Ecology* **386**: 27–33.

Houlbreque, F., Tambutte, E., Allemand, D., and Ferrier-Pages, C. 2004. Interactions between zooplankton feeding, photosynthesis and skeletal growth in the scleractinian coral *Stylophora pistillata*. *Journal of Experimental Biology* **207**: 1461–1469.

Idso, C.D. and Idso, S.B. 2009. *CO_2, Global Warming and Species Extinctions: Prospects for the Future.* Pueblo West, CO: Vales Lake Publishing, LLC.

Jury, C.P., Whitehead, R.F., and Szmant, A.M. 2010. Effects of variations in carbonate chemistry on the calcification rates of *Madracis auretenra* (= *Madracis mirabilis sensu* Wells, 1973): bicarbonate concentrations best predict calcification rates. *Global Change Biology* **16**: 1632–1644.

Krief, S., Hendy, E.J., Fine, M., Yam, R., Meibom, A., Foster, G.L., and Shemesh, A. 2010. Physiological and isotopic responses of scleractinian corals to ocean acidification. *Geochimica et Cosmochimica Acta* **74**: 4988–5001.

Manzello, D.P., Kleypas, J.A., Budd, D., Eakin, C.M., Glynn, P.W., and Langdon, C. 2008. Poorly cemented coral reefs of the eastern Tropical Pacific: Possible insights into reef development in a high-CO_2 world. *Proceedings of the National Academy of Sciences USA* **105**: 10.1073/pnas.0712167105.

McConnaughey, T. and Whelan, J.F. 1997. Calcification generates protons for nutrient and bicarbonate uptake. *Earth Science Reviews* **42**: 95–117.

Ries, J.B., Cohen, A.L., and McCorkle, D.C. 2010. A nonlinear calcification response to CO_2-induced ocean acidification by the coral *Oculina arbuscula*. *Coral Reefs* **29**: 661–674.

Suwa, R., Nakamura, M., Morita, M., Shimada, K., Iguchi, A., Sakai, K., and Suzuki, A. 2010. Effects of acidified seawater on early life stages of scleractinian corals (Genus *Acropora*). *Fisheries Science* **76**: 93–99.

Tans, P. 2009. An accounting of the observed increase in oceanic and atmospheric CO_2 and an outlook for the future. *Oceanography* **22**: 26–35.

8.2.4. Multiple Species

Two additional papers have examined the potential effects of ocean acidification and furthered our understanding of this phenomenon. The first, by Ries et al. (2009), explored the effects of lowering seawater pH on 18 oceanic species. The second study, by Hendriks et al. (2010), presented an ocean acidification meta-analysis in which the researchers calculated such effects on dozens of marine species.

Acknowledging “there is mounting concern over the impact that future CO_2-induced reductions in the $CaCO_3$ saturation state of seawater will have on marine organisms that construct their shells and skeletons from this mineral,” Ries et al. (2009) set out to conduct an experiment in which they “reared 18 calcifying species for 60 days in isothermal (25°C) experimental seawaters equilibrated with average [atmospheric] CO_2 values of 409, 606, 903 and 2856 ppm, corresponding to modern CO_2, and ~2, 3 and 10 times pre-industrial levels (~280 ppm), respectively, and yielding average seawater saturation states of 2.5, 2.0, 1.5 and 0.7 with respect to aragonite.” Then, “the organisms’ net rates of calcification (total calcification minus total dissolution) under the various CO_2 treatments were estimated from changes in their buoyant weight and verified with dry weight measurements after harvesting.”

According to the three Woods Hole Oceanographic Institution (USA) researchers, their study showed “in ten of the 18 species (temperate corals, pencil urchins, hard clams, conchs, serpulid worms, periwinkles, bay scallops, oysters, whelks, soft clams), net calcification decreased with increasing CO_2,” and “in six of the ten negatively impacted species (pencil urchins, hard clams, conchs, periwinkles, whelks, soft clams) [they] observed net dissolution of the shell in the highest CO_2 treatment.” However, as they continue, “in four of the 18 species (limpets, purple urchins, coralline red algae, calcareous green algae), net calcification increased relative to the control under intermediate CO_2 levels (605 and 903 ppm), and then declined at the highest CO_2 level (2856 ppm).” Last, they state “in three species (crabs, lobsters, and shrimps), net calcification was greatest under the highest level of CO_2 (2856 ppm),” and “one species, the blue mussel, exhibited no response to elevated CO_2.”

In light of their many, diverse findings, Ries et al. concluded “the impact of elevated atmospheric CO_2 on marine calcification is more varied than previously thought,” and so it is, with the reported responses ranging from negative to neutral to positive.

In another multiple-species study, Hendriks et al. (2010) assembled a database of 372 experimentally evaluated responses of 44 different marine species to ocean acidification that was induced by equilibrating seawater with CO_2-enriched air. At the time, this study represented the most comprehensive analysis ever conducted on this issue.

Of the 372 published reports they scrutinized, 154 assessed the significance of responses relative to controls; and of those reports, 47 reported no significant response, so “only a minority of studies,” in their words, demonstrated “significant responses to acidification.” And when the results of that minority group of studies were pooled, there was no significant mean effect. Nevertheless, the three researchers found some types of organisms and certain functional processes did exhibit significant responses to seawater acidification. However, since their analyses to this point had included some acidification treatments that were extremely high, they repeated their analyses for only those acidification conditions induced by atmospheric CO_2 concentrations of 2,000 ppm or less, the latter limiting concentration having been predicted to occur around the year 2300 by Caldeira and Wickett (2003).

In this second analysis, Hendriks et al. once again found the overall response, including all biological processes and functional groups, was not significantly different from that of the various control treatments, although calcification was reduced by 33 ± 4.5 percent and fertility by 11 ± 3.5 percent across groups, while survival and growth showed no significant overall responses. And when the upper limiting CO_2 concentrations were in the range of 731–759 ppm, or just below the value predicted by the IPCC (2007) for the end of the twenty-first century (790 ppm)—calcification rate reductions of only 25 percent were observed. What is more, the three researchers state this decline “is likely to be an upper limit, considering that all experiments involve the abrupt exposure of organisms to elevated pCO_2 values, while the gradual increase in pCO_2 that is occurring in nature may allow adaptive and selective processes to operate,” citing the work of Widdicombe et al. (2008) and noting “these gradual changes take place on the scale of decades, permitting adaptation of organisms even including genetic selection.”

Indeed, there is a large and accumulating volume of research that demonstrates rapid microevolutionary processes operate in almost all of Earth's life forms, and these phenomena enable them to successfully cope with significant environmental changes at rates that correspond to those environmental changes (Balanya et al., 2006; Jump et al., 2006; Franks et al., 2007; Rae et al., 2007; Skelly et al., 2007; Van Doorslaer et al., 2007; Franks and Weis, 2008; Jump et al., 2008; Purcell et al., 2008; Alford et al., 2009; Bell and Gonzalez, 2009; Onoda et al., 2009; Van Doorslaer et al., 2009). Thus, species that respond negatively to dramatic step increases in the air's CO_2 content employed in many of the experiments analyzed by Hendriks et al. will likely be able to gradually adjust to, and successfully cope with, the restrained and slower rate at which the atmospheric CO_2 concentration of the real world will rise in the future.

Yet even this mitigating factor is not the end of the good news, for Hendriks et al. write "most experiments assessed organisms in isolation, rather than [within] whole communities," and they state the responses of other entities and processes within the community may well buffer the negative impacts of CO_2-indced acidification on Earth's corals. As an example, they note "sea-grass photosynthetic rates may increase by 50 percent with increased CO_2, which may deplete the CO_2 pool, maintaining an elevated pH that may protect associated calcifying organisms from the impacts of ocean acidification."

In describing another phenomenon that benefits corals, the researchers write, "seasonal changes in pCO_2 are in the range of 236–517 ppm in the waters of the northern East China Sea (Shim et al., 2007)," and "metabolically-active coastal ecosystems experience broad diel changes in pH, such as the diel changes of >0.5 pH units reported for sea grass ecosystems (Invers et al., 1997)," which they say represent "a broader range than that expected to result from ocean acidification expected during the 21st century." They remark these fluctuations also "offer opportunities for adaptation to the organisms involved."

Hendriks et al. additionally state the models upon which the ocean acidification threat is based "focus on bulk water chemistry and fall short of addressing conditions actually experienced by [marine] organisms," which are "separated from the bulk water phase by a diffusive boundary layer." They also note "photosynthetic activity"—such as that of the zooxanthellae that are hosted by corals—"depletes pCO_2 and raises pH (Kuhl et al., 1995) so the pH actually experienced by organisms may differ greatly from that in the bulk water phase (Sand-Jensen et al., 1985)."

The insightful scientists then note "calcification is an active process where biota can regulate intracellular calcium concentrations," so that "marine organisms, like calcifying coccolithophores (Brownlee and Taylor, 2004), actively expel Ca^{2+} through the ATPase pump to maintain low intracellular calcium concentrations (Corstjens et al., 2001; Yates and Robbins, 1999)." And they state, "as one Ca^{2+} is pumped out of the cell in exchange for $2H^+$ pumped into the cell, the resulting pH and Ca^{2+} concentrations increase the $CaCO_3$ saturation state near extracellular membranes and appear to enhance calcification (Pomar and Hallock, 2008)," so much so, in fact, that they indicate "there is evidence that calcification could even increase in acidified seawater, contradicting the traditional belief that calcification is a critical process impacted by ocean acidification (Findlay et al., 2009)."

Hendriks et al. conclude the world's marine biota are "more resistant to ocean acidification than suggested by pessimistic predictions identifying ocean acidification as a major threat to marine biodiversity," noting this phenomenon "may not be the widespread problem conjured into the 21st century" by the IPCC. And in one final parting blow to the theory, Hendriks et al. state, "biological processes can provide homeostasis against changes in pH in bulk waters of the range predicted during the 21st century."

References

Alford, R.A., Brown, G.P., Schwarzkopf, L, Phillips, B.L., and Shine, R. 2009. Comparisons through time and space suggest rapid evolution of dispersal behaviour in an invasive species. *Wildlife Research* **36**: 23–28.

Balanya, J., Oller, J.M., Huey, R.B., Gilchrist, G.W., and Serra, L. 2006. Global genetic change tracks global climate warming in *Drosophila subobscura*. *Science* **313**: 1773–1775.

Bell, G. and Gonzalez, A. 2009. Evolutionary rescue can prevent extinction following environmental change. *Ecology Letters* **12**: 942–948.

Brownlee, C. and Taylor, A. 2004. Calcification in coccolithophores: a cellular perspective. In *Coccolithophores*, edited by H.R. Thierstein and J.R. Young, 31–49. Berlin, Germany: Springer.

Caldeira, K. and Wickett, M.E. 2003. Anthropogenic carbon and ocean pH. *Nature* **425**: 365.

Corstjens, P.L.A.M., Araki, Y., and Gonzalez, E.L. 2001. A coccolithophorid calcifying vesicle with a vacuolar-type ATPase proton pump: cloning and immunolocalization of the V0 subunit *c*. *Journal of Phycology* **37**: 71–78.

Findlay, H.S., Wood, H.L., Kendall, M.A., Spicer, J.I., Twitchett, R.J., and Widdicombe, S. 2009. Calcification, a physiological process to be considered in the context of the whole organism. *Biogeosciences Discussions* **6**: 2267–2284.

Franks, S.J., Sim, S., and Weis, A.E. 2007. Rapid evolution of flowering time by an annual plant in response to a climate fluctuation. *Proceedings of the National Academy of Sciences USA* **104**: 1278–1282.

Franks, S.J. and Weis, A.E. 2008. A change in climate causes rapid evolution of multiple life-history traits and their interactions in an annual plant. *Journal of Evolutionary Biology* **21**: 1321–1334.

Hendriks, I.E., Duarte, C.M., and Alvarez, M. 2010. Vulnerability of marine biodiversity to ocean acidification: A meta-analysis. *Estuarine, Coastal and Shelf Science* **86**: 157–164.

Invers, O., Romero, J., and Perez, M. 1997. Effects of pH on seagrass photosynthesis: a laboratory and field assessment. *Aquatic Botany* **59**: 185–194.

IPCC. 2007. Climate Change 2007: Synthesis Report.

Jump, A.S., Hunt, J.M., Martinez-Izquierdo, J.A., and Penuelas, J. 2006. Natural selection and climate change: temperature-linked spatial and temporal trends in gene frequency in *Fagus sylvatica*. *Molecular Ecology* **15**: 3469–3480.

Jump, A.S., Penuelas, J., Rico, L., Ramallo, E., Estiarte, M., Martinez-Izquierdo, J.A., and Lloret, F. 2008. Simulated climate change provokes rapid genetic change in the Mediterranean shrub *Fumana thymifolia*. *Global Change Biology* **14**: 637–643.

Kuhl, M., Cohen, Y., Dalsgaard, T., and Jorgensen, B.B. 1995. Microenvironment and photosynthesis of zooxanthellae in scleractinian corals studied with microsensors for O_2, pH and light. *Marine Ecology Progress Series* **117**: 159–172.

Onoda, Y., Hirose, T., and Hikosaka, K. 2009. Does leaf photosynthesis adapt to CO_2-enriched environments? An experiment on plants originating from three natural CO_2 springs. *New Phytologist* **182**: 698–709.

Pomar, L. and Hallock, P. 2008. Carbonate factories: a conundrum in sedimentary geology. *Earth-Science Reviews* **87**: 134–169.

Purcell, K.M., Hitch, A.T., Klerks, P.L., and Leberg, P.L. 2008. Adaptation as a potential response to sea-level rise: a genetic basis for salinity tolerance in populations of a coastal marsh fish. *Evolutionary Applications* **1**: 155–160.

Rae, A.M., Tricker, P.J., Bunn, S.M., and Taylor, G. 2007. Adaptation of tree growth to elevated CO_2: quantitative trait loci for biomass in *Populus*. *New Phytologist* **175**: 59–69.

Ries, J.B., Cohen, A.L., and McCorkle, D.C. 2009. Marine calcifiers exhibit mixed responses to CO_2-induced ocean acidification. *Geology* **37**: 1131–1134.

Sand-Jensen, K., Revsbech, N.P., and Barker Jorgensen, B.B. 1985. Microprofiles of oxygen in epiphyte communities on submerged macrophytes. *Marine Biology* **89**: 55–62.

Shim, J.H., Kim, D., Kang, Y.C., Lee, J.H., Jang, S.T., and Kim, C.H. 2007. Seasonal variations in pCO_2 and its controlling factors in surface seawater of the northern East China Sea. *Continental Shelf Research* **27**: 2623–2636.

Skelly, D.K., Joseph, L.N., Possingham, H.P., Freidenburg, L.K., Farrugia, T.J., Kinnison, M.T., and Hendry, A.P. 2007. Evolutionary responses to climate change. *Conservation Biology* **21**: 1353–1355.

Van Doorslaer, W., Stoks, R., Duvivier, C., Bednarska, A., and De Meester, L. 2009. Population dynamics determine genetic adaptation to temperature in *Daphnia*. *Evolution* **63**: 1867–1878.

Van Doorslaer, W., Stoks, R., Jeppesen, E., and De Meester, L. 2007. Adaptive microevolutionary responses to simulated global warming in *Simocephalus vetulus*: a mesocosm study. *Global Change Biology* **13**: 878–886.

Widdicombe, S., Dupont, S., and Thorndyke, M. 2008. Laboratory Experiments and Benthic Mesocosm Studies. Guide for Best Practices in Ocean Acidification Research and Data Reporting. Nice, France: European Project on Ocean Acidification (EPOCA).

Yates, K.K. and Robbins, L.L. 1999. Radioisotope tracer studies of inorganic carbon and Ca in microbially derived $CaCO_3$. *Geochimica et Cosmochimica Acta* **63**: 129–136.

8.2.5. Freshwater Acidification

Although many studies have examined the possible effects of declining ocean water pH, few have examined such effects for fresh water bodies. In one exception, Hargrave et al. (2009) “used free air CO_2 enrichment to compare effects of *e*CO_2 (i.e., double ambient ~720 ppm) relative to ambient CO_2 (*a*CO_2 ~360 ppm) on several ecosystem properties and functions in large, outdoor, experimental mesocosms that mimicked shallow sand-bottom prairie streams." The results of this experiment indicated "*e*CO_2 decreased water-column pH," as the IPCC projects it also does in the world's oceans, thereby leading to acidification.

However, the three U.S. scientists discovered the all-important primary productivity of benthic algae "was about 1.6, 1.9, 2.5 and 1.3 times greater in the *e*CO_2 treatment on days 30, 45, 60 and 75, respectively." They also determined the carbon/phosphorus (C/P) ratio of the algae was on average 2 and 1.5 times greater in the *e*CO_2 treatment than in the *a*CO_2 treatment on days 45 and 90, respectively; and this result implies a reduced availability of phosphorus, which would supposedly make the algae less nutritious and, therefore, less beneficial for the ecosystem's consumers.

However, and quite to the contrary of this hypothesis, Hargrave et al. observed *e*CO_2 "had positive effects on benthic invertebrates, significantly increasing chironomid density, biomass, and average size." They note "chironomid density was about 3, 5 and 2.5 times greater in the *e*CO_2 treatment than in the *a*CO_2 treatment on days 30, 60 and 90, respectively"; "biomass was about 4, 3 and 3 times greater in the *e*CO_2 treatment than in the *a*CO_2 treatment on days 30, 60 and 90, respectively"; and "individual mass was about two times greater on days 30 and 60." Thus, "contrary to the dominating hypotheses in the literature," in the words of Hargrave et al., "*e*CO_2 might have positive, bottom-up effects on secondary production in some stream food webs."

Consequently, they conclude their experimental findings and "the large literature from terrestrial and marine ecosystems suggests that future [i.e., higher] atmospheric CO_2 concentrations are likely to have broad reaching effects on autotrophs and consumers across terrestrial and aquatic biomes," which effects could be positive, as were those observed in their study. Nevertheless, more research in freshwater ecosystems would be welcomed to explore these possibilities further.

Reference

Hargrave, C.W., Gary, K.P., and Rosado, S.K. 2009. Potential effects of elevated atmospheric carbon dioxide on benthic autotrophs and consumers in stream ecosystems: a test using experimental stream mesocosms. *Global Change Biology* **15**: 2779–2790.

8.3 Simultaneous Aquatic Acidification and Warming

In the previous two sections of this chapter we examined the potential indirect (rising water temperatures) and direct (marine and freshwater acidification) threats claimed by the IPCC to result from Earth's rising atmospheric CO_2 concentration. In this section, we review studies that combine these two potential stressors to examine possible impacts of simultaneous aquatic acidification and warming.

We begin with the study of Grelaud et al. (2009), who note "coccolithophores are unicellular pelagic algae that represent a large part of the world ocean's nannophytoplankton and play a significant role in the carbon cycle as major producers of biogenic calcium carbonate," and "the inorganic fossil remains of coccolithophores consist of <20μm calcareous plates called coccoliths," the small size and large abundance of which "make it possible to sample marine sediment cores at mm to sub-mm intervals with ultra-high resolution." Against this backdrop and "in the context of modern global warming and ocean acidification due to anthropogenic CO_2 release," Grelaud et al. "investigated the morphometry (size, weight) of selected species of the order Isochrysidales (i.e., *E. huxleyi*, *G. muellerae* and *G. oceanica*) to understand how coccolithophores' carbonate mass is influenced by recent oceanographic global changes." They did this for sediment cores taken from "the deep center of the Santa Barbara Basin (SBB) on the North American Pacific margin in the interval from AD 1917 to 2004."

Based on their analysis, the three researchers report "morphometric parameters measured on *E. Huxleyi*, *G. muellerae* and *G. oceanica* indicate increasing coccolithophore shell carbonate mass from ~1917 until 2004 concomitant with rising *p*CO_2 and sea surface temperature in the region of the SBB." More specifically, they state "a >33% increase in mean coccolith weight was determined for the order Isochrysidales over 87 years from ~1917 until 2004." Given these findings, Grelaud et al. write, "the last century has witnessed an increasing net influx of atmospheric carbon dioxide into the world's oceans, a rising of *p*CO_2 of surface waters, and under-saturation with respect to aragonite, especially along the North American Pacific margin," which was the site of their study. These conditions, as they describe them, have been predicted by the IPCC "to result in reduced coccolithophore carbonate mass and a concomitant decrease in size and weight of coccoliths." As indicated by Grelaud et al.'s study, however, just the opposite appears to be the case in the real world, even in places where the predicted calcification reductions are expected to be greatest. This also has been demonstrated to be the case by the work of Iglesias-Rodriguez et al. (2008), who observed—in the words of Grelaud et al.—"a 40% increase in average coccolith weight across the last 220 years, as recorded in a box core from the subpoloar North Atlantic," and as has been further confirmed by the complimentary work of Halloran et al. (2008).

In a study of jellyfish, authors Winans and Purcell (2010) write, "scyphozoans have two main stages in their life cycles, the benthic polyps and pelagic jellyfish." The polyps reproduce asexually by budding polyps and through the process of strobilation, in which ephyrae (juvenile jellyfish) are produced by transverse fission. And, as they continue, "like many other marine invertebrates, jellyfish have statocysts, balance organs that enable them to sense gravity," and they state "inside these statocysts are numerous statoliths of trigonal crystals of calcium sulfate hemihydrate that are formed during strobilation."

Against this backdrop, the two researchers carried out an experiment designed to test the ability of jellyfish to respond to changes in water temperature and pH during their early life stages. Polyps produced by medusae collected from the moon jellyfish (*Aurelia labiata*) in Dyes Inlet, Washington (USA) were arbitrarily assigned (18 each) to one of six treatments constituting all combinations of two water temperatures (9 and 15°C) and three pH levels (7.2, 7.5, and 7.9), where they were allowed to develop under controlled conditions for 122 days.

The results of this undertaking indicated "polyp survival was 100% after 122 days in seawater in all six temperature and pH combinations." And because few polyps strobilated at 9°C and "temperature effects on budding were consistent with published results," the researchers state they "did not analyze data from those three treatments further." At 15°C, there were also no significant effects of pH on the numbers of ephyrae or buds produced per polyp or on the numbers of statoliths per statocyst. However, they state "statolith size was significantly smaller in ephyrae released from polyps reared at low pH."

Given the findings presented above, Winans and Purcell conclude "*A. labiata* polyps are quite tolerant of low pH, surviving and reproducing asexually even at the lowest tested pH," which degree of "acidification" is not expected to occur (even by the IPCC) until about AD 2300. But to avoid coming up empty-handed with respect to potential bad news, they note "the effects of small statoliths on ephyra fitness are unknown," which means the phenomenon *could* bode poorly for Earth's jellyfish. On the other hand, they acknowledge many organisms "may be able to acclimate or adapt to slowly changing pH conditions." And in this context they report that in Puget Sound "pH fluctuates from 7.2 to 9.6 in 2.4-meter deep water over the span of a couple of days," stating "with such large pH fluctuations due to plant photosynthesis during the day and respiration at night, many organisms may be exposed to low pH conditions routinely."

In a contemporaneous study, Byrne et al. (2010a) examined the interactive effects of near-future (ca. AD 2070–2100) ocean warming (temperature increases of 2–6°C) and ocean acidification (pH reductions of 0.2–0.6) on fertilization in four intertidal and shallow subtidal echinoids (*Heliocidaris erythrogramma, Heliocidaris Tuberculata, Tripneustes gratilla, Centrostephanus rodgersii*), an asteroid (*Patiriella regularis*), and an abalone (*Haliotis coccoradiata*). They worked with batches of eggs collected from multiple females fertilized by sperm obtained from multiple males, all of which were maintained and employed in all combinations of three temperature and three pH treatments.

Their results indicated, in the words of the eight researchers, "there was no significant effect of warming and acidification on the percentage of fertilization." In light of their comprehensive findings, Byrne et al. state their results indicate "fertilization in these species is robust to temperature and pH/P_{CO2} fluctuation," while opining that their findings "may reflect adaptation to the marked fluctuation in temperature and pH that characterizes their shallow water coastal habitats." This interpretation further suggests other marine fauna in still other circumstances may likewise be capable of adapting to any warming and acidification that might possibly develop throughout the world's oceans during the remaining decades of the twenty-first century.

Also in 2010, and in another paper in which Byrne served as the lead author (Byrne et al. (2010b)), it was noted changes in seawater chemistry—such as a decline in pH—have the potential to negatively impact fertilization kinetics in free-spawning marine invertebrates, but that ocean warming could do the opposite and "may enhance fertilization due to positive effects on sperm swimming speeds and heightened sperm-egg collisions," such that the net effect of both phenomena acting in unison could be negligible.

To explore the degree of likelihood of this scenario occurring in the real world, Byrne et al. (2010b) investigated the effects of projected near-future oceanic warming and acidification for conditions that have been predicted for southeast Australia within the timeframe of 2070–2100: an increase in sea surface temperature of 2 to 4°C and a decline in pH of 0.2 to 0.4. This they did in a fertilization study of the sea urchin *Heliocidaris erythrogramma* via multi-factorial experiments that incorporated a titration of sperm density (10–10^3 sperm per ml) across a range of sperm-to-egg ratios (10:1–1500:1).

The five Australian researchers found "across all treatments there was a highly significant effect of sperm density, but no significant effect of temperature or interaction between factors." In fact, they state, "low pH did not reduce the percentage of fertilization even at the lowest sperm densities used, and increased temperature did not enhance fertilization at any sperm density." In addition, they remark, "a number of ecotoxicology and climate change studies, where pH was manipulated with CO_2 gas, show that sea urchin fertilization is robust to a broad pH range with impairment only at extreme levels well below projections for ocean acidification by 2100 (pH 7.1–7.4, 2,000–10,000 ppm CO_2)," citing the work of Bay et al. (1993), Carr et al. (2006), and Kurihara and Shirayama (2004).

Interestingly, neither seawater warming nor seawater acidification (caused by contact with CO_2-enriched air) had either a positive or a negative effect on sea urchin fertilization, suggesting, as the five scientists concluded, that "sea urchin fertilization is robust to climate change stressors."

Also studying sea urchins that year were Brennand et al. (2010), who reared embryos of *Tripneustes gratilla* in flow-through chambers filled with filtered seawater maintained at all combinations of three different temperatures (24, 27, and 30°C) and three different pH values (8.15, 7.8, and 7.6), where the 24°C/pH 8.15 combination represented normal control conditions. After five days of such exposure, the growth and development of the larvae were assessed.

Brennand et al. report "larvae reared at pH 7.6 and pH 7.8 had smaller post oral arms when compared with those reared at control pH." However, they report "a +3°C warming diminished the negative effects of low pH/high CO_2," as was "seen in the similar post oral arm length of larvae treated at 27°C/pH 7.6 and 27°C/pH 7.8 and those reared in control temperature and pH." In addition, they state, "as total length of calcite rods is largely comprised of the post oral arms, this measure [of calcification] followed a similar pattern."

The results of this study suggest the negative effects of a 0.35 to 0.55 CO_2-induced decline in seawater pH on the growth and calcification of the sea urchin *Tripneustes gratilla* can be largely overcome by a 3°C increase in water temperature. And since the analysis of Tans (2009) suggests the maximum decline in seawater pH that will likely ever be produced by the burning of fossil fuels will be somewhere in the range of only 0.1 to 0.18 in the vicinity of AD 2100 (after which pH begins to rebound), there would seem to be little reason for concern about any negative impact of rising atmospheric CO_2 concentrations on this particular species of sea urchin, which is widely distributed throughout the Indo-Pacific region and is well-suited for production by aquaculture (Lawrence and Agatsuma, 2007; Juinio-Menez et al., 1998; Dworjanyn et al. 2007).

Shifting to a study of simultaneous aquatic acidification and warming on corals, Rodolfo-Metalpa et al. (2010) collected three live colonies of *Cladocora caespitosa* in the Bay of Villefranche (Ligurian Sea, France) at about 25 meters depth in July 2006 and three other colonies in February 2007. They divided the colonies into fragments and carefully removed single polyps that they attached to PVC plates and randomly assigned to aquariums that were continuously supplied with unfiltered seawater and maintained at ambient or elevated water temperature (T or T + 3°C) in equilibrium with air of ambient or elevated CO_2 concentration (400 or 700 ppm), subjecting them to "(1) mid-term perturbations (1 month) in summer and winter conditions of irradiance and temperature, and (2) a long-term perturbation (1 year), mimicking the seasonal changes in temperature and irradiance."

The results of their experimentation indicated that for the Mediterranean zooxanthellate coral, "an increase in CO_2, in the range predicted for 2100, does not reduce its calcification rate," and "an increase in CO_2, alone or in combination with elevated temperature, had no significant effect on photosynthesis, photosynthetic efficiency and calcification." In addition, they report a 3°C rise in temperature in winter resulted in a 72 percent increase in gross photosynthesis and a significant increase in daytime calcification rate.

In light of their several significant findings, Rodolfo-Metalpa et al. conclude, "the conventional belief that calcification rates will be affected by ocean acidification may not be widespread in temperate corals." They note, for example, that Ries et al. (2009) reported the calcification rate of the temperate coral *Oculina arbuscula* is also unaffected by an increase in atmospheric CO_2 concentration of up to 840 ppm, and that a large decrease in calcification was found only at a CO_2 concentration in excess of 2,200 ppm. In addition, they write, "some marine invertebrates may be able to calcify in the face of ocean acidification or, contrary to what is generally expected, may increase their calcification rates as reported on the ophiourid brittlestar *Amphiura filiformis* (Wood et al., 2008), the seastar *Pisaster ochraceus* (Gooding et al., 2009) exposed to lower pH (7.8–7.3), the Caribbean coral *Madracis mirabilis* at pH 7.6 (Jury et al., 2010), and shown for coralline red algae, calcareous green algae, temperate urchins, limpets, crabs, lobsters and shrimp (Ries et al., 2009)." In addition, they write there are many cases where "rates of photosynthesis are either not affected (e.g. Langdon et al., 2003; Reynaud et al., 2003; Schneider and Erez, 2006; Marubini et al., 2008) or slightly increased (e.g. Langdon and Atkinson, 2005) at the level of CO_2 expected in 2100."

Also studying corals, Kiessling (2009)—who hails from the Museum fur Naturkunde of the Leibniz Institute for Research on Evolution and Biodiversity at Berlin's Humboldt University—reviewed the then-current state of knowledge of the long-term effects of changes in oceanic temperature and the atmosphere's CO_2 concentration on the vigor of the planet's coral reefs. He reports, "on geologic timescales, there is little evidence for climate change affecting reefs in a linear fashion" and "changes in mean global temperature as reconstructed from stable oxygen isotopes and the distribution of non-reef climate-sensitive sediments do not correspond to changes in reef abundance or latitudinal distribution," citing some of his own analyses of the subject (Kiessling, 2001a, 2002). And he states "reports linking reef expansions and declines to climate change fail to explain why other changes in temperature did not lead to a similar response in reefs and why the reported (fairly modest) temperature changes would have such a dramatic effect."

With respect to ocean acidification, the German researcher states "just like temperature," it is currently receiving much attention as "a control of reef development," but "the boom and bust pattern of reefs and hyper-calcifiers is difficult to explain with inferred long-term changes in the saturation state of ocean water, at least if the major trigger is atmospheric pCO_2," because "previous analyses failed to find any significant cross-correlation between changes in pCO_2 and changes in reef attributes," citing Kiessling (2001b, 2002).

As a result of these and many other observations, Kiessling concludes "neither climate nor sea-level nor chemical changes in the oceans can elucidate the waxing and waning of reefs" throughout their history on Earth, and their "boom and bust pattern" is "impossible to explain by linear responses to physicochemical changes." Furthermore, Kiessling states, "ecologically complex reef systems have been around for hundreds of millions if not billions of years," and "geologic models of CO_2 concentrations in the atmosphere suggest that these were much greater during most of Earth's history than today," which further suggests something other than CO_2-induced global warming and ocean acidification must have been responsible for their prior "boom and bust" pattern of behavior.

Another example of these complexities is seen in the paper of De'ath et al. (2009), who detected a 14 percent drop in *Porites* calcification rate on the Great Barrier Reef from 1990 to 2005 (actually from 1970 to 2005, if one goes by their graph of the phenomenon, reproduced below) and declared that decline to be "unprecedented in at least the past 400 years," which is indeed what their data show. But if one follows their calcification history back in time a mere 33 more years, from 1605 to 1572, when the air's CO_2 concentration was more than 100 ppm less than what it is today and, therefore, was supposedly much healthier for corals (if one assumes the IPCC's claim to be correct)—the coral calcification rate at that earlier time is seen to have been approximately 23 percent lower than what it was at its twentieth-century peak.

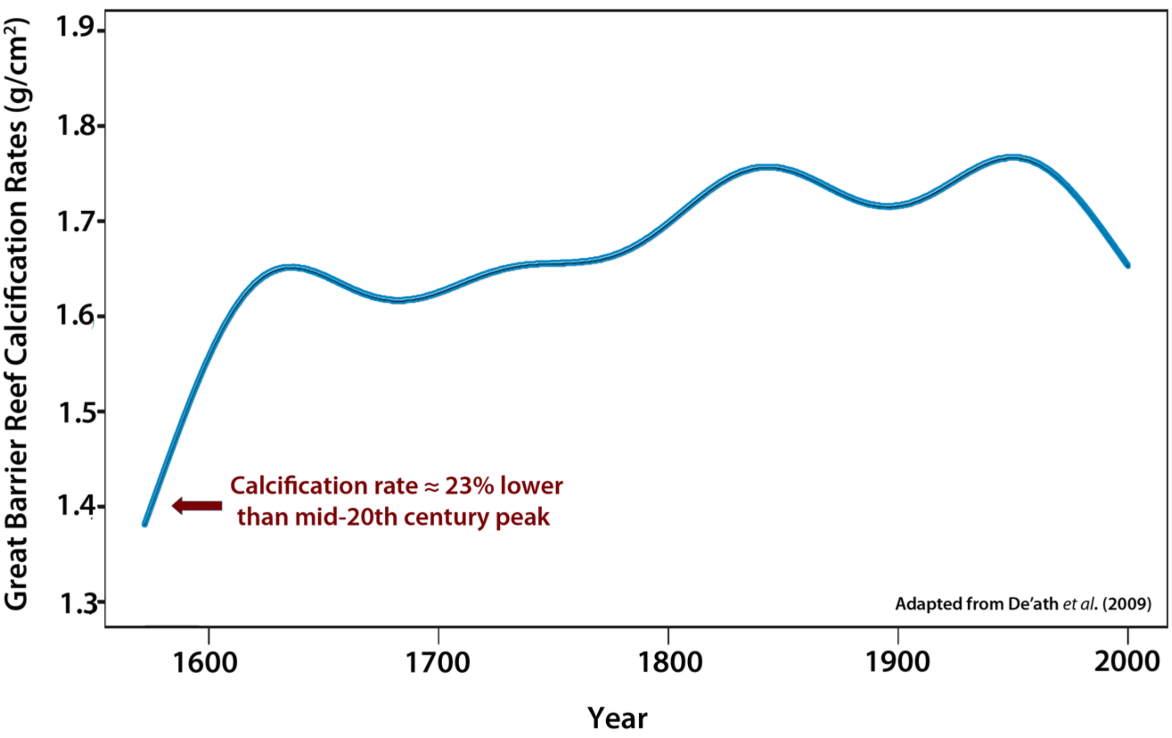


Figure 8.3.1. Calcification rates of *Porites* corals from the Great Barrier Reef over the period 1572-2001. Adapted from De'ath et al. (2009).

Another way of looking at De'ath et al.'s data is to realize that from 1572 to 1970 *Porites* calcification rates on the Great Barrier Reef rose, by about 27 percent, as atmospheric CO_2 concentration and air temperature rose concurrently, after which calcification rates declined, but by a much smaller 14 percent, as these same air temperature and CO_2 trends continued, further obfuscating the issue and presumably causing the researchers from the Australian Institute of Marine Science to state "the causes for the Great Barrier Reef-wide decline in coral calcification of massive *Porites* remain unknown."

Clearly, the effects of simultaneous ocean acidification and warming are more complex than the IPCC seems to believe.

References

Bay, S., Burgess, R., and Nacci, D. 1993. Status and applications of echinoid (Phylum Echinodermata) toxicity test methods. In *Environmental Toxicology and Risk Assessment*, edited by W.G. Landis, J.S. Hughes, and M.A. Lewis, 281–302. Philadelphia, PA: American Society for Testing and Materials.

Brennand, H.S., Soars, N., Dworjanyn, S.A., Davis, A.R., and Byrne, M. 2010. Impact of ocean warming and ocean acidification on larval development and calcification in the sea urchin *Tripneustes gratilla*. *PLoS ONE* **5**: 10.1371/journal.pone.0011372.

Byrne, M., Soars, N.A., Ho, M.A., Wong, E., McElroy, D., Selvakumaraswamy, P., Dworjanyn, S.A., and Davis A.R. 2010a. Fertilization in a suite of coastal marine invertebrates from SE Australia is robust to near-future ocean warming and acidification. *Marine Biology* **157**: 2061–2069.

Byrne, M., Soars, N., Selvakumaraswamy, P., Dworjanyn, S.A., and Davis, A.R. 2010b. Sea urchin fertilization in a warm, acidified and high pCO_2 ocean across a range of sperm densities. *Marine Environmental Research* **69**: 234–239.

Carr, R.S., Biedenbach, J.M., and Nipper, M. 2006. Influence of potentially confounding factors on sea urchn porewaer toxicity tests. *Archives of Environmental Contamination and Toxicology* **51**: 573–579.

De'ath, G., Lough, J.M., and Fabricius, K.E. 2009. Declining coral calcification on the Great Barrier Reef. *Science* **323**: 116–119.

Dworjanyn, S.A., Pirozzi, I., and Liu, W. 2007. The effect of the addition of algae feeding stimulants to artificial diets for the sea urchin *Tripneustes gratilla*. *Aquaculture* **273**: 624–633.

Gooding, R.A., Harley, C.D.G., and Tang, E. 2009. Elevated water temperature and carbon dioxide concentration increase the growth of a keystone echinoderm. *Proceedings of the National Academy of Sciences USA* **106**: 9316–9321.

Grelaud, M., Schimmelmann, A., and Beaufort, L. 2009. Coccolithophore response to climate and surface hydrography in Santa Barbara Basin, California, AD 1917–2004. *Biogeosciences* **6**: 2025–2039.

Halloran, P.R., Hall, I.R., Colmenero-Hidalgo, E., and Rickaby, R.E.M. 2008. Evidence for a multi-species coccolith volume change over the past two centuries: understanding a potential ocean acidification response. *Biogeosciences* **5**: 1651–1655.

Iglesias-Rodriguez, M.D., Halloran, P.R., Rickaby, R.E.M., Hall, I.R., Colmenero-Hidalgo, E., Gittins, J.R., Green, D.R.H., Tyrrell, T., Gibbs, S.J., von Dassow, P., Rehm, E., Armbrust, E.V., and Boessenkool, K.P. 2008. Phytoplankton calcification in a high-CO_2 world. *Science* **320**: 336–340.

Juinio-Menez, M.A., Macawaris, N., and Bangi, H. 1998. Community-based sea urchin (*Tripnuestes gratilla*) grow-out culture as a resource management tool. *Canadian Special Publication of Fisheries and Aquatic Science* **125**: 393–399.

Jury, C.P., Whitehead, R.F., and Szmant, A.M. 2010. Effects of variations in carbonate chemistry on the calcification rates of *Madracis auretenra* (= *Madracis mirabilis sensu* Wells, 1973): bicarbonate concentrations best predict calcification rates. *Global Change Biology* **16**: 1632–1644.

Kiessling, W. 2001a. Paleoclimatic significance of Phanerozoic reefs. *Geology* **29**: 751–754.

Kiessling, W. 2001b. Phanerozoic reef trends based on the Paleoreefs database. In *The History and Sedimentology of Ancient Reef Systems*, edited by G.D. Stanley, 41–88. New York, NY: Plenum Press.

Kiessling, W. 2002. Secular variations in the Phanerozoic reef ecosystem. In *Phanerozoid Reef Patterns, Volume 22*, edited by W. Kiessling, E. Flugel, and J. Golonka, 625–690. Tulsa, OK: Society of Economic and Paleontological Mineralogy.

Kiessling, W. 2009. Geologic and biologic controls on the evolution of reefs. *Annual Review of Ecological and Evolutionary Systems* **40**: 173–192.

Kurihara, H. and Shirayama, Y. 2004. Effects of increased atmospheric CO_2 on sea urchin early development. *Marine Ecology Progress Series* **274**: 161–169.

Langdon, C. and Atkinson, M.J. 2005. Effect of elevated pCO_2 on photosynthesis and calcification of corals and interactions with seasonal change in temperature, irradiance and nutrient enrichment. *Journal of Geophysical Research* **110**: 1–54.

Langdon, C., Broecker, W.S., Hammond, D.E., Glenn, E., Fitzsimmons, K., Nelson, S.G., Peng, T.-S., Hajdas, I., and Bonani, G. 2003. Effect of elevated CO_2 on the community metabolism of an experimental coral reef. *Global Biogeochemical Cycles* **17**: 10.1029/2002GB001941.

Lawrence, J.M. and Agatsuma, Y. 2007. Ecology of *Tripneustes*. In *The Biology and Ecology of Edible Urchins*, edited by J.M. Lawrence, 499–520. Amsterdam, Netherlands: Elsevier Science.

Marubini, F., Ferrier-Pages, C., Furla, P., and Allemand, D. 2008. Coral calcification responds to seawater acidification: a working hypothesis towards a physiological mechanism. *Coral Reefs* **27**: 491–499.

Reynaud, S., Leclercq, N., Romaine-Lioud, S., Ferrier-Pages, C., Jaubert, J., and Gattuso, J.-P. 2003. Interacting effects of CO_2 partial pressure and temperature on photosynthesis and calcification in a scleractinian coral. *Global Change Biology* **9**: 1660–1668.

Ries J., Cohen A., and McCorkle, D. 2009. Marine calcifiers exhibit mixed responses to CO_2-induced ocean acidification. *Geology* **37**: 1131–1134.

Rodolfo-Metalpa, R., Martin, S., Ferrier-Pages, C., and Gattuso, J.-P. 2010. Response of the temperate coral *Cladocora caespitosa* to mid- and long-term exposure to pCO_2 and temperature levels projected for the year 2100 AD. *Biogeosciences* **7**: 289–300.

Schneider, K. and Erez, J. 2006. The effect of carbonate chemistry on calcification and photosynthesis in the hermatypic coral *Acropora eurystoma*. *Limnology and Oceanography* **51**: 1284–1293.

Tans, P. 2009. An accounting of the observed increase in oceanic and atmospheric CO_2 and an outlook for the future. *Oceanography* **22**: 26–35.

Winans, A.K. and Purcell, J.E. 2010. Effects of pH on asexual reproduction and statolith formation of the scyphozoan, *Aurelia labiata*. *Hydrobiologia* **645**: 39–52.

Wood, H.L., Spicer, J.I., and Widdicombe, S. 2008. Ocean acidification may increase calcification rates, but at a cost. *Proceedings of the Royal Society B* **275**: 1767–1773.

9

Human Health Effects

9. Human Health Effects

Introduction

The authors of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) claimed to have "*very high* confidence" that "climate change currently contributes to the global burden of disease and premature deaths" (IPCC, 2007-II, p. 393, emphasis in the original). They also claim climate change will "increase malnutrition and consequent disorders … increase the number of people suffering from death, disease and injury from heatwaves, floods, storms, fires and droughts … continue to change the range of some infectious disease vectors … increase the burden of diarrhoeal diseases … increase cardio-respiratory morbidity and mortality associated with ground-level ozone … [and] increase the number of people at risk of dengue." The IPCC admits warming weather would "bring some benefits to health, including fewer deaths from cold," but says those benefits "will be outweighed by the negative effects of rising temperatures worldwide, especially in developing countries" (ibid.).

The 2009 report of the Nongovernmental International Panel on Climate Change (NIPCC) debunked many of those claims, starting with the simple fact that the modest warming that occurred in the twentieth century did not cause more "heatwaves, floods, storms, fires and droughts," and consequently these imagined phenomena could not have harmed human health or well-being. Readers of the current report are referred to Chapter 5, where they will find more, and more recent, evidence to that effect.

Idso and Singer (2009) went on to examine research on the relationships between temperature and CO_2 and diseases, heat-related mortality, nutrition, and human longevity, finding global warming is likely to improve rather than harm human health.

In the following pages we review new scientific research on these same matters, finding it supports the same conclusion. That analysis is followed by a brief discussion of viral and vector-borne diseases, after which we review papers that document CO_2-induced changes in certain of the medicinal and nutritional properties of plants, which should bode well for future human health gains.

References

Idso, C.D. and Singer, S.F. 2009. *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

IPCC. 2007-II. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Cambridge, UK: Cambridge University Press.

9.1. Temperature-Related Human Mortality

Christidis et al. (2010) report, "the IPCC AR4 states with very high confidence that climate change contributes to the global burden of disease and to increased mortality," citing the contribution of Confalonieri et al. (2007) to that document. Idso and Singer (2009), however, reported that rising temperatures lead to a greater reduction in winter deaths than the increase they cause in summer deaths, resulting in a large net decrease in human mortality, based on findings described in the peer-reviewed scientific literature through 2007. In this interim report we review studies of the subject published after that time.

Christidis et al. extracted the numbers of daily deaths from all causes reported on death registration data supplied by the U.K. Office of National Statistics for men and women 50 years of age or older in England and Wales for the period 1976–2005, which they divided by daily population estimates they obtained by fitting a fifth-order polynomial to midyear population data, yielding deaths per million people. They compared the results with surface air temperature data that showed a warming trend during the three-decade period of 0.47°C per decade. In addition, they employed a technique called optimal detection, which can be used to estimate the role of human adaptation in the temperature-related changes in mortality they observed.

As expected, during the hottest months of the year, warming led to increases in death rates, while during the coldest months of the year warming led to decreases in death rates. The three scientists reported, for example, that if no adaptation had taken place, there would have been 1.6 additional deaths per million people per year due to warming in the hottest part of the year over the period 1976–2005, but there would have been 47 fewer deaths per million people per year due to warming in the coldest part of the year, for a lives-saved to life-lost ratio of 29.4. That, of course, represents a substantial net benefit from the warming experienced in England and Wales during the three-decade period. When adaptation was included in the analysis, they found there was an increase of only 0.7 deaths per million people per year due to warming in the hottest part of the year, but a decrease of fully 85 deaths per million people per year due to warming in the coldest part of the year, for a lives-saved to life-lost ratio of 121.4.

Working in the Castile-Leon region of Spain—a plateau in the northwestern part of the country which includes nine provinces with a low population density that can be considered as aging—Fernandez-Raga et al. (2010) obtained (from the country's National Meteorological Institute) meteorological data from weather stations situated in eight of the provincial capitals for 1980–1998, and they obtained contemporary mortality data from the country's National Institute for Statistics for deaths associated with cardiovascular, respiratory, and digestive-system diseases.

Various analyses of the monthly averaged data revealed a number of interesting results. First, for all three of the disease types studied, the three researchers found "the death rate is about 15% higher on a winter's day than on a summer's day," which they describe as "a result often found in previous studies," citing the work of Fleming et al. (2000), Verlato et al. (2002), Grech et al. (2002), Law et al. (2002), and Eccles (2002). Second, in a finding that helps to explain the first finding, the three researchers discovered that when monthly averaged human death rates were plotted against monthly averages of daily mean, maximum, and minimum air temperature, the results nearly always took the form of a U-shaped concave parabola, as shown in Figure 9.1.1.

For all three disease types, Fernandez-Raga et al. found all three temperatures (daily mean, maximum, and minimum) at which minimum death rates occurred—which they refer to as *ideal* or *comfort* temperatures—were all within about 1°–7°C of the maximum values typically reached by those three types of temperature, whereas they were anywhere from 14° to 24°C away from their minimum values. Consequently, the ideal or comfort temperatures were always very close to (and sometimes nearly identical to) the maximum values reached by the mean, maximum, and minimum temperatures experienced in the region, and they were much more removed from the minimum values of those three temperature parameters, as illustrated in the figure.

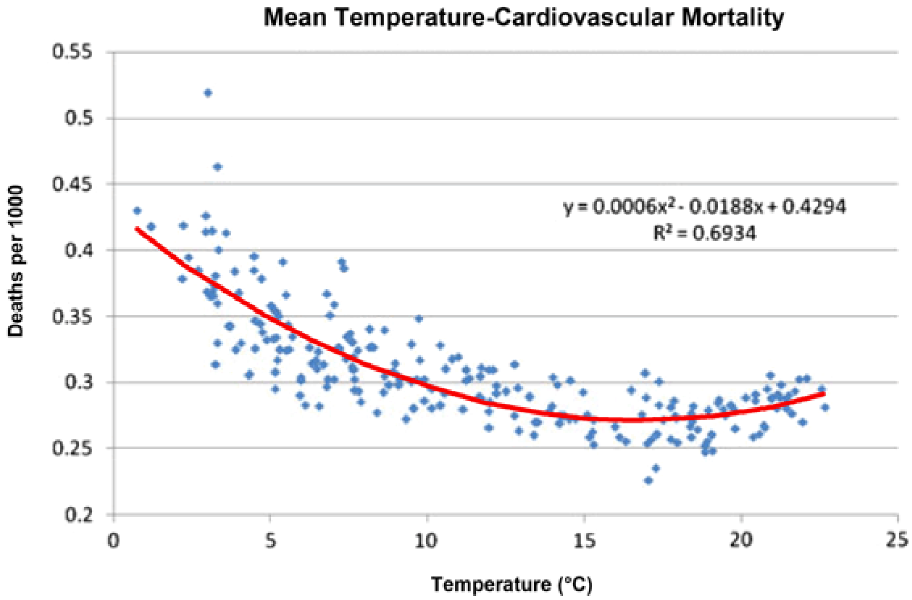


Figure 9.1.1. Monthly deaths in the Castile-Leon region of Spain attributable to cardiovascular disease vs. mean daily air temperature. Adapted from Fernandez-Raga et al. (2010).

The data clearly demonstrate the people of the Castile-Leon region of Spain are much more likely to die from a cardiovascular disease in the extreme cold of winter than in the extreme heat of summer. The same was found to hold true with respect to respiratory and digestive system diseases. Cold has been found to be a much greater killer of people than heat almost everywhere in the world, and in conjunction with almost any type of illness.

In a more broad-based study, Analitis et al. (2008) wrote, "in recent years, the effects of meteorologic factors on health have attracted renewed interest because of the observed and predicted climate change, which is expected to result in a general rise in temperature." This development, in their words, has led to a "recent focus on heat-wave episodes," which may have fostered the perception that cold-related mortality is not as important a public health concern as is heat-related mortality.

To rectify this situation, the 14 researchers analyzed short-term effects of cold weather on mortality in 15 European cities (Athens, Greece; Barcelona, Spain; Budapest, Hungary; Dublin, Ireland; Helsinki, Finland; Ljubljana, Slovenia; London, United Kingdom; Milan, Italy; Paris, France; Prague, Czech Republic; Rome, Italy; Stockholm, Sweden; Turin, Italy; Valencia, Spain; and Zurich, Switzerland). Specifically, they assessed the effects of minimum apparent temperature on cause- and age-specific daily mortality over the cold half of the year (October–March), using data from 1990–2000 analyzed via "Poisson regression and distributed lag models, controlling for potential confounders."

The international team of scientists—from Finland, Greece, Ireland, Italy, Slovenia, Spain, and Sweden—found "a 1°C decrease in temperature was associated with a 1.35% increase in the daily number of total natural deaths and a 1.72%, 3.30%, and 1.25% increase in cardiovascular, respiratory, and cerebrovascular deaths, respectively." In addition, they reported "the increase was greater for the older age groups," and the cold effect "persisted up to 23 days, with no evidence of mortality displacement." The latter finding is extremely important because in the case of heat-related deaths there is such a displacement, and its impact is substantial.

In Germany, for example, Laschewski and Jendritzky (2002) analyzed daily mortality rates in Baden-Wurttemberg (10.5 million inhabitants) over the 30-year period 1958–97 to determine the sensitivity of the population of this moderate climatic zone to long- and short-term episodes of heat and cold. Their research indicated mortality showed "a marked seasonal pattern with a minimum in summer and a maximum in winter.” With respect to short-term exposure to heat and cold, however, they found “cold spells lead to excess mortality to a relatively small degree, which lasts for weeks,” and “the mortality increase during heat waves is more pronounced, but is followed by lower than average values in subsequent weeks.” Thissuggests, in their words, that people who died from short-term exposure to heat “would have died in the short term anyway.”

With respect to this short-term mortality displacement that occurs in conjunction with heat-related deaths, Laschewski and Jendritzky’s data demonstrate it is precisely that: merely a displacement of deaths and not an overall increase. They found, for example, that the mean duration of above-normal mortality for the 51 heat episodes that occurred from 1968 to 1997 was ten days, with a mean increase in mortality of 3.9 percent, after which there was a mean decrease in mortality of 2.3 percent for 19 days. The net effect of the two perturbations was an overall decrease in mortality of 0.2 percent over the full 29-day period. Analitis et al. concluded their paper by stating their results “add evidence that cold-related mortality is an important public health problem across Europe and should not be overlooked by public health authorities because of the recent focus on heat-wave episodes.”

In providing some background for another recent study of the subject, Young and Kakinen (2010) write, “Arctic populations, especially indigenous people, could be considered as ‘vulnerable,’ because their health status generally shows disparities when compared to the national or more southern populations,” and they state “it is not known if the harsh climate, and especially cold temperatures, could be a contributing or causative factor of the observed health inequalities.” To seek answers to this, the two researchers determined mean January and July temperatures for 27 Arctic regions, based on weather station data for the period 1961–1990, and their association with a variety of health outcomes assessed by correlation and multiple linear regression analyses.

The two researchers found mean January temperature correlated negatively with several health outcomes, including infant mortality rate, age-standardized mortality rates (all causes), perinatal mortality rate, and tuberculosis incidence rate, but it correlated positively with life expectancy. That is to say, as mean January temperature rose, the desirable metric of life expectancy at birth rose right along with it, while all of the undesirable health metrics (such as mortality and disease incidence) declined. For example, they report “for every 10°C increase in mean January temperature, the life expectancy at birth among males increased by about six years” and “infant mortality rate decreased by about four deaths per thousand live births.”

Young and Kakinen concluded the cold climate of the Arctic is “significantly associated with higher mortality” and “should be recognized in public health planning,” noting that “within a generally cold environment, colder climate results in worse health.” For people living in these regions, therefore, a little global warming could go a long way toward improving their quality of life, as well as the length of time they have to enjoy it.

In another impressive study, Deschenes and Moretti (2009) analyzed the relationship between weather and mortality, based on data that included the universe of deaths in the United States over the period 1972–1988, wherein they matched each death to weather conditions on the day of death and in the county of occurrence. These high-frequency data and the fine geographical detail allowed them to estimate with precision the effect of cold and hot temperature shocks on mortality, as well as the dynamics of such effects—most notably, the existence or absence of a “harvesting effect” whereby the temperature-induced deaths either are or are not subsequently followed by a drop in the normal death rate that could either partially or fully compensate for the prior extreme temperature-induced deaths.

The two researchers state their results “point to widely different impacts of cold and hot temperatures on mortality.” In the latter case, they discovered “hot temperature shocks are indeed associated with a large and immediate spike in mortality in the days of the heat wave,” but “almost all of this excess mortality is explained by near-term displacement,” so that “in the weeks that follow a heat wave, we find a marked decline in mortality hazard, which completely offsets the increase during the days of the heat wave,” such that “there is virtually no lasting impact of heat waves on mortality.”

In the case of cold temperature days, they also found “an immediate spike in mortality in the days of the cold wave,” but “there is no offsetting decline in the weeks that follow,” so “the cumulative effect of one day of extreme cold temperature during a thirty-day window is an increase in daily mortality by as much as 10%.” In addition, they write, “this impact of cold weather on mortality is significantly larger for females than for males," but "for both genders, the effect is mostly attributable to increased mortality due to cardiovascular and respiratory diseases."

In further discussing their findings, Deschenes and Moretti state, "the aggregate magnitude of the impact of extreme cold on mortality in the United States is large," noting it "roughly corresponds to 0.8% of average annual deaths in the United States during the sample period." They estimate "the average person who died because of cold temperature exposure lost in excess of ten years of potential life," whereas the average person who died because of hot temperature exposure likely lost no more than a few days or weeks of life.

Interestingly, the two scientists additionally report many people in the United States have taken advantage of these obvious facts by moving "from cold northeastern states to warm southwestern states." Based on their findings, they calculate "each year 4,600 deaths are delayed by the changing exposure to cold temperature due to mobility," and "3% to 7% of the gains in longevity experienced by the U.S. population over the past three decades are due to the secular movement toward warmer states in the West and the South, away from the colder states in the North."

Working in the Southern Hemisphere, Bi et al. (2008) used correlation and autoregressive integrated moving average regression analyses to derive relationships between various aspects of weather and mortality in the general population and elderly (65 years of age and older) of Brisbane, Australia—which they describe as having a subtropical climate—over the period 1986–1995. In doing so, they determined "death rates were around 50–80 per 100,000 in June, July, and August [winter], while they were around 30–50 per 100,000 in the rest of the year, including the summer." They state "this finding applied both to the general population and to the elderly population, and to deaths from various causes."

In discussing the fact that "more deaths occurred in the winter than during other seasons of the year, although winter in Brisbane is very mild," the researchers noted "it is understandable that more deaths would occur in winters in cold or temperate regions, but even in a subtropical region, as indicated in this study, a decrease in temperatures (in winters) may increase human mortality." Consequently, the evidence continues to grow that extremes of cold lead to the deaths of many more people than extremes of heat in both cold and warm climates.

In a study with a slightly different take on the subject, Tam et al. (2009) studied daily mortality data from 1997 to 2002, which they obtained from the Hong Kong Census and Statistics Department, examining the association between diurnal temperature range (DTR = daily maximum temperature minus daily minimum temperature), while focusing on cardiovascular disease among the elderly (people aged 65 and older). They discovered "a 1.7% increase in mortality for an increase of 1°C in DTR at lag days 0–3," and they describe these results as being "similar to those reported in Shanghai."

In discussing their findings, the four Hong Kong researchers stated, "a large fluctuation in the daily temperature—even in a tropical city like Hong Kong—has a significant impact on cardiovascular mortality among the elderly population." In addition, we note it has long been known that the DTR has declined significantly over many parts of the world as mean global temperature has risen over the past several decades (Easterling et al., 1997), which is perhaps another reason why colder temperatures are a much greater risk to human life than are warmer temperatures: As the planet warms, local DTRs tend to decline, which leads to a corresponding decline in human death rates.

Turning to the Shanghai study mentioned by Tam et al., we find that Cao et al. (2009)—working within the nine urban districts of Shanghai, China—used time-series and case-crossover approaches to assess the relationship between DTR and coronary heart disease (CHD) deaths between 1 January 2001 and 31 December 2004, based on mortality data for elderly people (66 years of age or older), obtained from the Shanghai Municipal Center of Disease Control and Prevention, plus temperature data they obtained from a fixed-site station in the Xuhui District of Shanghai, which they adjusted to account for the mortality impacts of long-term and seasonal trends in CHD mortality, day of week, temperature, relative humidity, and concomitant atmospheric concentrations of PM_{10}, SO_2, NO_2, and O_3, which they obtained from the Shanghai Environmental Monitoring Center.

This work revealed, in Cao et al.'s words, that "a 1°C increase in DTR (lag = 2) corresponded to a 2.46% increase in CHD mortality on time-series analysis, a 3.21% increase on unidirectional case-crossover analysis, and a 2.13% increase on bidirectional case-crossover analysis," and "the estimated effects of DTR on CHD mortality were similar in the warm and cool seasons." Thus, the seven scientists concluded their data suggested even "a small increase in DTR is associated with a substantial increase in deaths due to CHD." And since the DTR has declined significantly over most of the world as mean global air temperature has risen over the past several decades, it can be appreciated that the global warming with which this DTR decrease is associated (which is driven by the fact that global warming is predominantly caused by an increase in daily minimum temperature) has likely helped to significantly reduce the CHD-induced mortality of elderly people worldwide.

In one final study dealing with the heart and employing a generalized additive statistical model that blends the properties of generalized linear models with additive models, Bayentin et al. (2010) analyzed the standardized daily hospitalization rates for ischemic heart disease (IHD) and their relationship with climatic conditions up to two weeks prior to the day of admission—controlling for time trends, day of the season, and gender—in order to determine the short-term effects of climate conditions on the incidence of IHD over the 1989–2006 time period for 18 different regions of Quebec. Perhaps the most interesting and important finding of this study was, as they describe it, that "a decline in the effects of meteorological variables on IHD daily admission rates was observed over the period of 1989–2006." This response, in their words, "can partly be explained by the changes in surface air temperature," which they describe as warming "over the last few decades," as is further described by Bonsal et al. (2001) and Zhang et al. (2000) for the twentieth-century portion of the study's duration. In addition, they note "winters have been steadily warmer," while "summers have yet to become hotter for most regions." This is another beneficial characteristic of the warming that was experienced over most of the planet throughout the latter part of the twentieth century: a gradual reduction in DTR, as confirmed by the work of Easterling et al. (1997).

In summation, the material presented in this chapter represents overwhelming evidence for a positive effect of global warming on human health.

References

Analitis, A., Katsouyanni, K., Biggeri, A., Baccini, M., Forsberg, B., Bisanti, L., Kirchmayer, U., Ballester, F., Cadum, E., Goodman, P.G., Hojs, A., Sunyer, J., Tiittanen, P., and Michelozzi, P. 2008. Effects of cold weather on mortality: Results from 15 European cities within the PHEWE project. *American Journal of Epidemiology* **168**: 1397–1408.

Bayentin, L., El Adlouni, S., Ouarda, T.B.M.J., Gosselin, P., Doyon, B., and Chebana, F. 2010. Spatial variability of climate effects on ischemic heart disease hospitalization rates for the period 1989-2006 in Quebec, Canada. *International Journal of Health Geographics* **9**:10.1186/1476-072X-9-5.

Bi, P., Parton, K.A., Wang, J., and Donald, K. 2008. Temperature and direct effects on population health in Brisbane, 1986–1995. *Journal of Environmental Health* **70** (8): 48–53.

Bonsal, B.R., Zhang, X., Vincent, L.A., and Hogg, W.D. 2001. Characteristics of daily and extreme temperatures over Canada. *Journal of Climate* **14**: 1959–1976.

Cao, J., Cheng, Y., Zhao, N., Song, W., Jiang, C., Chen, R., and Kan, H. 2009. Diurnal temperature range is a risk factor for coronary heart disease death. *Journal of Epidemiology* **19**: 328–332.

Christidis, N., Donaldson, G.C., and Stott, P.A. 2010. Causes for the recent changes in cold- and heat-related mortality in England and Wales. *Climatic Change* **102**: 539–553.

Confalonieri, U., Menne, B., Akhtar, R., Ebi, K.L., Hauengue, M., Kovats, R.S., Revich, B., and Woodward, A. 2007. Human health. In *Climate Change 2007: Impacts, Adaptation and Vulnerability*, edited by M.L. Parry, et al. Cambridge, UK: Cambridge University Press.

Deschenes, O. and Moretti, E. 2009. Extreme weather events, mortality, and migration. *The Review of Economics and Statistics* **91**:659–681.

Easterling, D.R., Horton, B., Jones, P.D., Peterson, T.C., Karl, T.R., Parker, D.E., Salinger, M.J., Razuvayev, V., Plummer, N., Jamason, P., and Folland, C.K. 1997. Maximum and minimum temperature trends for the globe. *Science* **277**: 364–367.

Eccles, R. 2002. An explanation for the seasonality of acute upper respiratory tract viral infections. *Acta Oto-Laryngologica* **122**: 183–191.

Fernandez-Raga, M., Tomas, C., and Fraile, R. 2010. Human mortality seasonality in Castile-Leon, Spain, between 1980 and 1998: the influence of temperature, pressure and humidity. *International Journal of Biometeorology* **54**: 379–392.

Fleming, D.M., Cross, K.W., Sunderland, R., and Ross, A.M. 2000. Comparison of the seasonal patterns of asthma identified in general practitioner episodes, hospital admissions, and deaths. *Thorax* **55**: 662–665.

Grech, V., Balzan, M., Asciak, R.P., and Buhagiar, A. 2002. Seasonal variations in hospital admissions for asthma in Malta. *Journal of Asthma* **39**: 263–268.

Idso, C.D. and Singer, S.F. 2009. Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC). Chicago, IL: The Heartland Institute.

Laschewski, G. and Jendritzky, G. 2002. Effects of the thermal environment on human health: an investigation of 30 years of daily mortality data from SW Germany. *Climate Research* **21**: 91–103.

Law, B.J., Carbonell-Estrany, X., and Simoes, E.A.F. 2002. An update on respiratory syncytial virus epidemiology: a developed country perspective. *Respiratory Medicine Supplement B* **96**: S1–S2.

Tam, W.W.S., Wong, T.W., Chair, S.Y., and Wong, A.H.S. 2009. Diurnal temperature range and daily cardiovascular mortalities among the elderly in Hong Kong. *Archives of Environmental and Occupational Health* **64**: 202–206.

Verlato, G., Calabrese, R., and De Marco, R. 2002. Correlation between asthma and climate in the European Community Respiratory Health Survey. *Archives of Environmental Health* **57**: 48–52.

Young, T.K. and Kakinen, T.M. 2010. The health of Arctic populations: Does cold matter? *American Journal of Human Biology* **22**: 129–133.

Zhang, X.B., Vincent, L.A., Hogg, W.D., and Niitsoo, A. 2000. Temperature and precipitation trends in Canada during the 20th century. *Atmosphere-Ocean* **38**: 395–429.

9.2 Viral and Vector-borne Diseases

With respect to viral and vector-borne diseases, in a review of the pertinent literature that describes “those mechanisms that have led to an increase of virus activity in recent years,” Zell et al. (2008) state “it is assumed that global warming is forced by the anthropogenic release of ‘greenhouse gases’,” and that a further “consistent assumption” has been a consequent “increased exposure of humans to tropical pathogens and their vectors.” However, they note “there is dissent about this hypothesis (Taubes, 1997; Reiter, 2001; Hay et al., 2002; Reiter et al., 2003; Randolph, 2004; Zell, 2004; Halstead, 2008),” and they thus go on to explore the subject in more detail, ultimately concluding “only very few examples point toward global warming as a cause of excess viral activity.” Instead, they find, “coupled ocean/atmosphere circulations and continuous anthropogenic disturbances (increased populations of humans and domestic animals, socioeconomic instability, armed conflicts, displaced populations, unbalanced ecosystems, dispersal of resistant pathogens etc.) appear to be the major drivers of disease variability,” and global warming “at best” merely “contributes.”

Similar sentiments were expressed that year by Wilder-Smith and Gubler (2008), who focused on the occurrence of dengue infections, reporting “climate has rarely been the principal determinant of [their] prevalence or range,” and “human activities and their impact on local ecology have generally been much more significant.” In this regard, they cite as contributing factors “urbanization, deforestation, new dams and irrigation systems, poor housing, sewage and waste management systems, and lack of reliable water systems that make it necessary to collect and store water.” They further note “disruption of vector control programs, be it for reasons of political and social unrest or scientific reservations about the safety of DDT, has contributed to the resurgence of dengue around the world.” In addition, they write, “large populations in which viruses circulate may also allow more co-infection of mosquitoes and humans with more than one serotype of virus,” which would appear to be borne out by the fact that “the number of dengue lineages has been increasing roughly in parallel with the size of the human population over the last two centuries.” Most important of all, perhaps, is “the impact of international travel.” Wilder-Smith and Gubler note “humans, whether troops, migrant workers, tourists, business travelers, refugees, or others, carry the virus into new geographic areas.” These movements, in their words, “can lead to epidemic waves.” Given such findings, the two researchers conclude “population dynamics and viral evolution offer the most parsimonious explanation for the observed epidemic cycles of the disease, far more than climatic factors.”

Also exploring this issue were Gage et al. (2008), who reviewed what was then known about it. The four researchers—all from the U.S. Centers for Disease Control’s National Center for Zoonotic, Vector-Borne, and Enteric Diseases—concluded “the precise impacts” of the various climatic changes that are typically claimed to occur in response to rising atmospheric CO_2 concentrations “are difficult to predict.” Indeed, they write, “in some areas, climate change could increase outbreaks and the spread of some vector-borne diseases while having quite the opposite effect on other vector-borne diseases.”

In further discussing this complex situation, they note “the mere establishment of suitable vectors for a particular agent does not necessarily mean that spread to humans will commonly occur, as indicated by the limited transmission of dengue and malaria in the southern U.S.,” because, as they continue, “local transmission has been limited by factors unrelated to the climatic suitability of the areas for the relevant vector species.” In addition, they write, “in instances where a vector-borne disease is also zoonotic, the situation is even more complex, because not only must the vector and pathogen be present, but a competent vertebrate reservoir host other than humans must also be present.”

So what are some of the non-climatic factors that affect the spread of vector-borne diseases among humans? Gage et al. list “many other global changes concurrently transforming the world, including increased economic globalization, the high speed of international travel and transport of commercial goods, increased population growth, urbanization, civil unrest, displaced refugee populations, water availability and management, and deforestation and other land-use changes,” to which could be added the many different ways in which these phenomena are dealt with by different societies.

Kyle and Harris (2008) noted “dengue is a spectrum of disease caused by four serotypes of the most prevalent arthropod-borne virus affecting humans today,” and “its incidence has increased dramatically in the past 50 years,” such that “tens of millions of cases of dengue fever are estimated to occur annually, including up to 500,000 cases of the life-threatening dengue hemorrhagic fever/dengue shock syndrome.” The researchers conducted a review of the pertinent scientific literature, exploring “the human, mosquito, and viral factors that contribute to the global spread and persistence of dengue, as well as the interaction between the three spheres, in the context of ecological and climate change.”

The two researchers note “there has been a great deal of debate on the implications of global warming for human health,” but “at the moment, there is no consensus.” In the case of dengue, they write, “it is important to note that even if global warming does not cause the mosquito vectors to expand their geographic range, there could still be a significant impact on transmission in endemic regions,” as they report that “a 2°C increase in temperature would simultaneously lengthen the lifespan of the mosquito and shorten the extrinsic incubation period of the dengue virus, resulting in more infected mosquitoes for a longer period of time.” Nevertheless, they note there are “infrastructure and socioeconomic differences that exist today and already prevent the transmission of vector-borne diseases, including dengue, even in the continued presence of their vectors.” Consequently, it would appear that whatever advantages rising temperatures might confer upon the dengue virus vector, they can be overcome by proper implementation of modern vector-control techniques.

One year later, Russell (2009)—a professor in the Department of Medicine of the University of Sydney and founding director of its Department of Medical Entomology—reported, “during the past 10 years, there has been increasing concern for health impacts of global warming in Australia, and continuing projections and predictions for increasing mosquito-borne disease as a result of climate change.” However, he wrote, these claims “are relatively simplistic, and do not take adequate account of the current or historic situations of the vectors and pathogens, and the complex ecologies that might be involved.” He then went on to review the consequences of these several inadequacies for malaria, dengue fever, the arboviral arthritides (Ross River and Barmah Forest viruses) and the arboviral encephalitides (Murray Valley encephalitis and Kunjin viruses). He did this within the context of predictions of projected climate changes as proposed and modeled by Australia’s Commonwealth Scientific and Industrial Research Organization and the Intergovernmental Panel on Climate Change. He concluded “there might be some increases in mosquito-borne disease in Australia with a warming climate, but with which mosquitoes and which pathogens, and where and when, cannot be easily discerned.” The strongest statement he could make was that “of itself, climate change as currently projected, is not likely to provide great cause for public health concern with mosquito-borne disease in Australia.”

In another paper, Russell et al. (2009) wrote, “dengue has emerged as a leading cause of morbidity in many parts of the tropics,” noting “Australia has had dengue outbreaks in northern Queensland.” In addition, they reported, “substantial increases in distribution and incidence of the disease in Australia are projected with climate change,” or, more specifically, “with increasing temperatures.” They explored the soundness of these projections by reviewing pertinent facts about the history of dengue in Australia, determining that the dengue vector (the *Aedes aegypti* mosquito) "was previously common in parts of Queensland, the Northern Territory, Western Australia and New South Wales," that it had "in the past, covered most of the climatic range theoretically available to it," and that "the distribution of local dengue transmission has [historically] nearly matched the geographic limits of the vector."

This being the case, the six scientists concluded the vector's current absence from much of Australia, as Russell et al. described it, "is not because of a lack of a favorable climate." Thus, they reasoned that "a temperature rise of a few degrees is not alone likely to be responsible for substantial increases in the southern distribution of *A. aegypti* or dengue, as has been recently proposed." Instead, they reminded everyone that "dengue activity is increasing in many parts of the tropical and subtropical world as a result of rapid urbanization in developing countries and increased international travel, which distributes the viruses between countries." Rather than attempts to limit dengue transmission by controlling the world's climate, therefore, the medical researchers recommend that "well resourced and functioning surveillance programs, and effective public health intervention capabilities, are essential to counter threats from dengue and other mosquito-borne diseases."

Studying dengue simultaneously in three other parts of the world, Johansson et al. (2009) wrote, "mosquito-borne dengue viruses are a major public health problem throughout the tropical and subtropical regions of the world," and "changes in temperature and precipitation have well-defined roles in the transmission cycle and may thus play a role in changing incidence levels." Therefore, as they continued, since "the El Niño Southern Oscillation (ENSO) is a multiyear climate driver of local temperature and precipitation world wide," and since "previous studies have reported varying degrees of association between ENSO and dengue incidence," as they describe it, they decided to analyze "the relationship between ENSO, local weather, and dengue incidence in Puerto Rico, Mexico, and Thailand." They did so by searching for relationships between ENSO, local weather, and dengue incidence in Puerto Rico (1986–2006), Mexico (1985–2006), and Thailand (1983–2006), using wavelet analysis as a tool to identify time- and frequency-specific associations.

The three researchers reported they "did not find evidence of a strong, consistent relationship in any of the study areas," and Rohani (2009), who wrote a Perspective piece on their study, stated they found "no systematic association between multi-annual dengue outbreaks and El Niño Southern Oscillation." Thus, as included in the Editors' Summary of Johansson et al.'s paper, their findings provided "little evidence for any relationship between ENSO, climate, and dengue incidence."

In another review paper dealing with the possible impacts of climate change on the spread of infectious diseases, Randolph (2009) noted it is generally tacitly assumed—and even explicitly stated—that climate change will result only in a worsening of the situation, with the expansion of vector-borne diseases into higher latitudes and an increased disease incidence. In fact, she states that implicit in almost all of the literature on this subject—both popular and scientific—"is an assumption that environmental change is more likely to strengthen the transmission potential and expand the range, rather than to disrupt the delicate balance between pathogen, vector and host upon which these systems depend."

The zoologist from the U.K.'s University of Oxford thus explores the evidence via an analysis of what the bulk of the accurately informed scientific literature on the subject seems to suggest. In doing so, she finds "the mercurial epidemiology of each vector-borne disease is the system-specific product of complex, commonly nonlinear, interactions between many disparate environmental factors." These include "not only climate but also other abiotic conditions (e.g., land cover) and the physical structure of the environment (e.g., water sources), and further biotic factors such as host abundance and diversity." She also indicates that a number of socioeconomic factors drive human living conditions and behaviors that determine the degree of exposure to the risk posed to them, and that nutritional status and concomitant immunity also determine the degree of resistance to infection.

In some interesting examples from the past, Randolph notes the upsurge of tick-borne diseases within preexisting endemic regions in central and Eastern Europe "appears to be an unforeseen consequence of the fall of the iron curtain and the end of the cold war," which she describes as "a sort of political global warming." Also noted is the fact that "the introduction of the mosquito *Aedes aegypti* to the Americas within water containers on board slave ships from Africa was repeated four centuries later by the dispersal of the Asian tiger mosquito, *A. albopictus*, from Japan to the United States within water trapped in used car tires (Hawley et al., 1987; Reiter and Sprenger, 1987)."

This phenomenon, according to Randolph, continues today, augmented by trade in other water-carrying goods such as Asian Luck Bamboo plants. Such activities have allowed this mosquito species "to establish itself in almost all New World countries, a dozen European countries, parts of West Africa, and the Middle East." All of these disease expansions, in her words, have "nothing to do with climate change," which also holds true for such chance events as "the introduction of West Nile virus into New York in 1999, most probably by air from Israel (Lanciotti et al., 1999)," and the introduction "of the BTV-8 strain of bluetongue virus into the Netherlands in 2006 from South Africa (Saegerman et al., 2008)."

Contemporaneously, Harvell et al. (2009) stated that "in temperate climates, we might expect the range and activity of mosquitoes and the pathogens they vector, such as malaria and dengue, to increase with warmer temperatures." However, "from a later vantage point in 2009," they indicated that "surprisingly, insect-vectored diseases resoundingly do not show a net expansion in range or increase in prevalence." As for why this is so, the five scientists gave three explanations attributed to Lafferty (2009a): "(1) anthropogenic activities directly influence the distributions of vectors and infectious disease in ways unrelated to climate, (2) vectors and pathogens are limited by thermal maxima, so that temperature changes lead to shifts rather than expansions in distribution, and (3) other factors such as host acquired immunity and vector or parasite life history traits are linked to habitat suitability in addition to climate." In addition, they noted the important role that may be played by "evolutionary changes in properties of the host or pathogen," and in concluding their paper they therefore wrote, "ecologists need to consider how host biology, including movement behavior and acquired immunity, can mediate the impacts of global change on parasite/pathogen dynamics and disease severity," because, as they concluded, "at present, many of these mechanisms are poorly known."

Turning directly to the Lafferty (2009a) paper, we again read the projection that "global climate change will result in an expansion of tropical diseases, particularly vector-transmitted diseases, throughout temperate areas," examples of which include "schistosomiasis (bilharzia or snail fever), onchocerciasis (river blindness), dengue fever, lymphatic filariasis (elephantiasis), African trypanosomiasis (sleeping sickness), leishmaniasis, American trypanosomiasis (Chagas disease), yellow fever, and many less common mosquito and tick-transmitted diseases of humans," as well as many diseases of "nonhuman hosts." In a critique of this point of view, based on his review of the scientific literature, he concludes, "while climate has affected and will continue to affect habitat suitability for infectious diseases, climate change seems more likely to shift than to expand the geographic ranges of infectious diseases," and "many other factors affect the distribution of infectious disease, dampening the proposed role of climate." In fact, he concludes, "shifts in climate suitability might actually reduce the geographic distribution of some infectious diseases." And of perhaps even greater importance (because it is a real-world observation), he reports, "although the globe is significantly warmer than it was a century ago, there is little evidence that climate change has already favored infectious diseases."

In a companion paper (Lafferty, 2009b), the U.S. researcher lists several ways in which ecologists "can contribute substantially to the general theory of climate and infectious disease," some of the most important of which have to deal with "[1] multiple hosts and parasite species (Dobson, 2009), [2] nonhuman hosts (Harvell et al., 2009), [3] accounting for the effects of immunity (Dobson, 2009; Harvell et al., 2009; Ostfeld, 2009; Pascual and Bouma, 2009), [4] quality and details of [4a] climatic data and [4b] appropriate measures of disease response (Ostfeld, 2009; Pascual and Bouma, 2009; Randolph, 2009), [5] complex analyses to account for multiple, interdependent covariates (Dobson, 2009; Ostfeld, 2009; Pascual and Bouma, 2009; Randolph, 2009), [6] host movement in response to climate change (Harvell et al., 2009), and [7] geographic tools to account for distinctions between fundamental and realized niches (Ostfeld, 2009; Randolph, 2009)." These many and varied challenges confronting the scientific community in this emerging field of study show there is much unfinished business that must be conducted in researching the several potential relationships that may or may not exist between climatic change and the spread of infectious diseases.

In one additional study from 2009, Nabi and Qader (2009) analyze both sides of the global warming/malaria incidence debate, considering the climatic conditions that affect the spread of the disease (temperature, rainfall, and humidity), as well as the host of pertinent non-climatic factors that play important roles in its epidemiology (the presence or absence of mosquito control programs, the availability or non-availability of malaria-fighting drugs, changing resistances to drugs, the quality of vector control, changes in land use, the availability of good health services, human population growth, human migrations, international travel, and standard of living).

According to the two researchers, their results indicate "global warming alone will not be of a great significance in the upsurge of malaria unless it is accompanied by a deterioration in other parameters like public health facilities, resistance to anti-malarial drugs, decreased mosquito control measures," etc. They write, "no accurate prediction about malaria can truly be made," because "it is very difficult to estimate what the other factors will be like in the future." The researchers do note, however, that mosquito-borne diseases were a major public health problem in the United States from the 1600s to the mid-1900s, "with occasional epidemics." By the middle of the twentieth century, however, "malaria disappeared from the country along with the other mosquito borne diseases like Dengue and Yellow fever," and "this decline was attributed to overall improvements in living conditions and better public health measures." The continuance of both of these has kept these diseases at bay throughout the latter half of the twentieth century as well, even though that period experienced what some have characterized as "unprecedented global warming."

In light of these several observations, plus many others from all around the world—which clearly establish the overriding importance of a country's standard of living and concomitant level of health-promoting services—Nabi and Qader conclude, "as public health workers, it would be more justifiable for us to exert our efforts on these other [non-climatic] parameters for the eradication and control of malaria."

Reiter (2010) notes the appearance of the West Nile virus in New York (USA) in 1999, plus the unprecedented panzootic that followed, "have stimulated a major research effort in the Western Hemisphere and a new interest in the presence of this virus in the Old World." These developments have been driven in part by the fact that "a great deal of attention has been paid to the potential impact of climate change on the prevalence and incidence of mosquito-borne disease."

Reiter reviews what researchers have learned about the subject and reports the worldwide implications for public health, summing things up in his final paragraph, where he states: "one point is clear: the importation and establishment of vector-borne pathogens that have a relatively low profile in their current habitat is a serious danger to Europe and throughout the world." This state of affairs, in his view, "is a direct result of the revolution of transport technologies and increasing global trade that has taken place in the past three decades," modern examples of which include "the global circulation of dengue virus serotypes (Gubler, 1998), the intercontinental dissemination of *Aedes albopictus* and other mosquitoes in used tires (Hawley et al., 1987; Reiter, 1998), the epidemic of chikungunya virus in Italy (Angelini et al., 2007), and the importation of bluetongue virus and trypanosomiasis into Europe (Meroc et al., 2008; Moretti, 1969)." In light of what his review reveals, he writes, "globalization is potentially a far greater challenge to public health in Europe than any future changes in climate (Tatem et al., 2006)."

In a study demonstrating the influence of globalization, Shang et al. (2010) used logistic and Poisson regression models to analyze bi-weekly, laboratory-confirmed dengue cases in Taiwan at their onset dates of illness from 1998 to 2007, in order to "identify correlations between indigenous dengue and imported dengue cases (in the context of local meteorological factors) across different time lags." They found "the occurrence of indigenous dengue was significantly correlated with temporally-lagged cases of imported dengue (2–14 weeks), higher temperatures (6–14 weeks), and lower relative humidity (6–20 weeks)," and that "imported and indigenous dengue cases had a significant quantitative relationship in the onset of local epidemics." Given these findings, the six Taiwanese researchers concluded, "imported dengue cases are able to initiate indigenous epidemics when appropriate weather conditions are present," or as they stated in another place, "imported dengue are able to serve as an initial facilitator, or spark, for domestic epidemics." Therefore, they suggest "early detection and case management of imported cases through timely surveillance and rapid laboratory-diagnosis may avert large scale epidemics of dengue/dengue hemorrhagic fever," while noting "meteorology alone does not initiate an epidemic" and "an increase in viremic international travelers has caused global dengue hemorrhagic fever case numbers to surge in the past several decades." This surge is often erroneously claimed to be due to global warming.

Gething et al. (2010) note that based on "model predictions," it is "reported widely in global climate policy debates that climate change is adding to the present-day burden of malaria and will increase both the future range and intensity of the disease," citing the IPCC (2007) and the U.S. Environmental Protection Agency (2010). Noting "it has long been known that the range of malaria has contracted through a century of economic development and disease control (Hay et al., 2009)," when "global temperature increases have been unequivocal," they go on to explore this apparent incongruity "for the first time" in another data-based study by comparing "an evidence-based map of contemporary malaria endemicity (Hay et al., 209)" with "the most reliable equivalent for the pre-intervention era, around 1900 (Lysenko et al., 1968)," when malaria was "at its assumed historical peak." This provides a comparison of "the magnitude of observed changes in range and endemicity to those proposed to occur in response to climate change."

The six scientists—from the Spatial Ecology and Epidemiology Group, the Malaria Public Health and Epidemiology Group, and the Centre for Tropical Medicine of the U.K.'s University of Oxford, plus the Departments of Biology and Geography and the Emerging Pathogens Institute of the University of Florida (USA)—report "comparison of the historical and contemporary maps revealed that endemic/stable malaria is likely to have covered 58% of the world's land surface around 1900 but only 30% by 2007," and "even more marked has been the decrease in prevalence within this greatly reduced range, with endemicity falling by one or more classes in over two-thirds of the current range of stable transmission." They state, "widespread claims that rising mean temperatures have already led to increases in worldwide malaria morbidity and mortality are largely at odds with observed decreasing global trends in both its endemicity and geographic extent." In fact, they report, "the combined natural and anthropogenic forces acting on the disease throughout the twentieth century have resulted in the great majority of locations undergoing a net reduction in transmission between one and three orders of magnitude larger than the maximum future increases proposed under temperature-based climate change scenarios."

Given such findings, Gething et al. conclude there has been "a decoupling of the geographical climate-malaria relationship over the twentieth century, indicating that non-climatic factors have profoundly confounded this relationship over time." They state "non-climatic factors, primarily direct disease control and the indirect effects of a century of urbanization and economic development, although spatially and temporally variable, have exerted a substantially greater influence on the geographic extent and intensity of malaria worldwide during the twentieth century than have climatic factors." As for the future, they write climate-induced effects "can be offset by moderate increases in coverage levels of currently available interventions."

Writing that "pathogens cause roughly one in five human deaths, are responsible for 51% of years of life lost globally, and have long affected human demographics," Dunn et al. (2010) note pathogens "have also been identified as drivers of human behavior, the politics and political stability of countries, human fertility, global economies, and more generally the course and dynamics of human history." And, somewhat ominously, they report "researchers have linked the presence and prevalence of some pathogens to climate, as has been highlighted in recent discussions of climate change and disease." They specifically mention malaria, plague, and dengue as examples. Thus, they conducted, as they describe it, "a global analysis of the relative influence of climate, alternative host diversity and spending on disease prevention on modern patterns in the richness and prevalence of human pathogens."

The U.S., Canadian, and New Zealand researchers found that "pathogen richness (number of kinds) is largely explained by the number of birds and mammal species in a region," and "the most diverse countries with respect to birds and mammals are also the most diverse with respect to pathogens." Noting "we are unlikely to be able to change patterns of pathogen richness dramatically," they observe that "pathogen richness, even when high, does not guarantee high prevalence, because of the potential impact of disease control effort." In fact, they found "pathogen prevalence is much more sensitive to variation in health spending among regions," and "importantly, for human health, the prevalence of key human pathogens is strongly influenced by disease control efforts." Dunn et al. conclude, "even where disease richness is high, we might still control prevalence, particularly if we spend money in those regions where current spending is low, prevalence is high and populations are large."

Finally, in a brief review of the roles played by various factors that may influence the spread of tick-borne diseases, Sarah Randolph (2010) of the University of Oxford's Department of Zoology in the United Kingdom begins by noting many vector-borne diseases "have shown marked increases in both distribution and incidence during the past few decades, just as human-induced climate change is thought to have exceeded random fluctuations." She writes, "this coincidence has led to the general perception that climate change has driven disease emergence." However, after describing some of the outbreaks of tick-borne disease in Europe over the past couple of decades, Randolph states, "the inescapable conclusion is that the observed climate change alone cannot explain the full heterogeneity in the epidemiological change, either within the Baltic States or amongst Central and Eastern European countries," citing the work of Sumilo et al. (2007). Instead, she writes, "a nexus of interrelated causal factors—abiotic, biotic and human—has been identified," and "each factor appears to operate synergistically, but with differential force in space and time, which would inevitably generate the observed epidemiological heterogeneity."

Many of these factors, she continues, "were the unintended consequences of the fall of Soviet rule and the subsequent socio-economic transition (Sumilo et al., 2008b)." among these factors she cites "agricultural reforms resulting in changed land cover and land use, and an increased reliance on subsistence farming; reduction in the use of pesticides, and also in the emission of atmospheric pollution as industries collapsed; increased unemployment and poverty, but also wealth and leisure time in other sectors of the population as market forces took hold." In concluding, Randolph writes, "there is increasing evidence from detailed analyses that rapid changes in the incidence of tick-borne diseases are driven as much, if not more, by human behavior that determines exposure to infected ticks than by tick population biology that determines the abundance of infected ticks," as per the findings of Sumilo et al. (2008a) and Randolph et al. (2008). She ends her brief analysis by stating, "while nobody would deny the sensitivity of ticks and tick-borne disease systems to climatic factors that largely determine their geographical distributions, the evidence is that climate change has not been the most significant factor driving the recent temporal patterns in the epidemiology of tick-borne diseases."

The studies discussed above, coupled with numerous others referenced in the 2009 report of the Nongovernmental International Panel on Climate Change (Idso and Singer, 2009), suggest there is little of substance in the peer-reviewed scientific literature to support the contention that CO_2-induced global warming will elevate human mortality due to an enhanced spreading of vector-borne diseases. In fact, the great bulk of that research tends to refute those claims.

References

Angelini, R., Finarelli, A.C., Angelini, P., Po, C., Petropulacos, K., Macini, P., Fiorentini, C., Fortuna, C., Venturi, G., Romi, R., Majori, G., Nicoletti, L., Rezza, G., and Cassone, A. 2007. An outbreak of chikungunya fever in the province of Ravenna, Italy. *Eurosurveillance* **12**: eurosurveillance.org/ViewArticle.aspx?Articleid=3260.

Dobson, A.P. 2009. Climate variability, global change, immunity, and the dynamics of infectious diseases. *Ecology* **90**: 920–927.

Dunn, R.R., Davies, T.J., Harris, N.C., and Gavin, M.C. 2010. Global drivers of human pathogen richness and prevalence. *Proceedings of the Royal Society B* **277**: 2587–2595.

Gage, K.L., Burkot, T.R., Eisen, R.J., and Hayes, E.B. 2008. Climate and vector borne diseases. *American Journal of Preventive Medicine* **35**: 436–450.

Gething, P.W., Smith, D.L., Patil, A.P., Tatem, A.J., Snow, R.W., and Hay, S.I. 2010. Climate change and the global malaria recession. *Nature* **465**: 342–345.

Gubler, D.J. 1998. The global pandemic of dengue/dengue hemorrhagic fever: current status and prospects for the future. *Annals, Academy of Medicine, Singapore* **27**: 227–234.

Halstead, S.B. 2008. Dengue virus-mosquito interactions. *Annual Review of Entomology* **53**: 273–291.

Harvell, D., Altizer, S., Cattadori, I.M., Harrington, L., and Weil, E. 2009. Climate change and wildlife diseases: when does the host matter the most? *Ecology* **90**: 912–920.

Hawley, W.A., Reiter, P., Copeland, R.S., Pumpuni, C.B., and Craig Jr., G.B. 1987. *Aedes albopictus* in North

America: Probable introduction in used tires from northern Asia. *Science* **236**: 1114–1116.

Hay, S.I., Rogers, D.J., Randolph, S.E., Stern, D.I., Cox, J., Shanks, G.D., and Snow, R.W. 2002. Hot topic or hot air? Climate change and malaria resurgence in East African highlands. *Trends in Parasitology* **18**: 530–534.

Idso, C.D. and Singer, S.F. 2009. *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by M.L. Parry, et al. Cambridge, UK: Cambridge University Press.

Johansson, M.A., Cummings, D.A.T., and Glass, G.E. 2009. Multiyear climate variability and dengue-El Niño Southern Oscillation, weather and dengue incidence in Puerto Rico, Mexico, and Thailand: a longitudinal data analysis. *PLoS Medicine* **6**: e1000168.

Kyle, J.L. and Harris, E. 2008. Global spread and persistence of dengue. *Annual Review of Microbiology* **62**: 71–92.

Lafferty, K.D. 2009a. The ecology of climate change and infectious diseases. *Ecology* **90**: 888–900.

Lafferty, K.D. 2009b. Calling for an ecological approach to studying climate change and infectious diseases. *Ecology* **90**: 932–933.

Lanciotti, R.S., Roehrig, J.T., Deubel, V., Smith, J., Parker, M., Steele, K., Crise, B., Volpe, K.E., Crabtree, M.B., Scherret, J.H., Hall, R.A., MacKenzie, J.S., Cropp, C.B., Panigrahy, B., Ostlund, E., Schmitt, B., Malkinson, M., Banet, C., Weissman, J., Komar, N., Savage, H.M., Stone, W., McNamara, T., and Gubler, D.J. 1999. Origin of the West Nile virus responsible for an outbreak of encephalitis in the northeastern United States. *Science* **286**: 2333–2337.

Lysenko, A.J. and Semashko, I.N. 1968. In *Itogi Nauki: Medicinskaja Geografija*, edited by A.W. Lebedew, 25–126. Moscow, Russia: Academy of Sciences.

Meroc, E., Faes, C., Herr, C., Staubach, C., Verheyden, B., Vanbinst, T., Vandenbussche, F., Hooyberghs, J., Aerts, M., De Clercq, K., and Mintiens, K. 2008. Establishing the spread of bluetongue virus at the end of the 2006 epidemic in Belgium. *Veterinary Microbiology* **131**: 133–144.

Moretti, G. 1969. African trypanosomiasis detected in France: difficulties of diagnosis. *Presse Medicale* **77**(41):1404.

Nabi, S.A. and Qader, S.S. 2009. Is global warming likely to cause an increased incidence of malaria? *Libyan Journal of Medicine* **4**: 18–22.

Ostfeld, R.S. 2009. Climate change and the distribution and intensity of infectious diseases. *Ecology* **90**: 903–905.

Pascual, M. and Bouma, M.J. 2009. Do rising temperatures matter? *Ecology* **90**: 906–931.

Randolph, S.E. 2004. Evidence that climate change has caused ‘emergence’ of tick-borne diseases in Europe? *International Journal of Medical Microbiology* **293**, Suppl. **37**: 5–15.

Randolph, S.E. 2009. Perspectives on climate change impacts on infectious diseases. *Ecology* **90**: 927–931.

Randolph, S.E. 2010. To what extent has climate change contributed to the recent epidemiology of tick-borne diseases? *Veterinary Parasitology* **167**: 92–94.

Randolph, S.E., Asokliene, L., Avsic-Zupanc, T., Bormane, A., Burri, C., Golovljova, I., Hubalek, Z., Knap, N., Kondrusik, M., Kupca, A., Pejcoch, M., Vasilenko, V., and Zygutiene, M. 2008. Variable spikes in TBE incidence in 2006 independent of variable tick abundance but related to weather. *Parasites and Vectors* **1**: e44.

Reiter, P. 1998. *Aedes albopictus* and the world trade in used tires, 1988–1995: The shape of things to come? *Journal of the American Mosquito Control Association* **14**: 83–94.

Reiter, P. 2001. Climate change and mosquito-borne disease. *Environmental Health Perspectives* **109**: 141–161.

Reiter, P. 2010. West Nile virus in Europe: understanding the present to gauge the future. *Eurosurveillance* **15**: eurosurveillance.org/ViewArticle.aspx?Articleid=19508.

Reiter, P., Lathrop, S., Bunning, M., Biggerstaff, B., Singer, D., Tiwari, T., Baber, L., Amador, M., Thirion, J., Hayes, J., Seca, C., Mendez, J., Ramirez, B., Robinson, J., Rawlings, J., Vorndam, V., Waterman, S., Gubler, D., Clark, G., and Hayes, E. 2003. Texas lifestyle limits transmission of dengue virus. *Emerging Infectious Diseases* **9**: 86–89.

Reiter, P. and Sprenger, D. 1987. The used tire trade: a mechanism for the worldwide dispersal of container breeding mosquitoes. *Journal of the American Mosquito Control Association* **3**: 494–501.

Rohani, P. 2009. The link between dengue incidence and El Niño Southern Oscillation. *PLoS Medicine* **6**: e1000185.

Russell, R.C. 2009. Mosquito-borne disease and climate change in Australia: time for a reality check. *Australian Journal of Entomology* **48**: 1–7.

Russell, R.C., Currie, B.J., Lindsay, M.D., Mackenzie, J.S., Ritchie, S.A., and Whelan, P.I. 2009. Dengue and climate change in Australia: predictions for the future should incorporate knowledge from the past. *Medical Journal of Australia* **190**: 265–268.

Saegerman, C., Berkvens, D., and Mellor, P.S. 2008. Bluetongue epidemiology in the European Union. *Emerging Infectious Diseases* **14**: 539–544.

Shang, C.-S., Fang, C.-T., Liu, C.-M., Wen, T.-H., Tsai, K.-H., and King, C.-C. 2010. The role of imported cases and favorable meteorological conditions in the onset of dengue epidemics. *PLoS* **4**: e775.

Sumilo, D., Asokliene, L., Avsic-Zupanc, T., Bormane, A., Vasilenko, V., Lucenko, I., Golovljova, I., and Randolph, S.E. 2008a. Behavioral responses to perceived risk of tick-borne encephalitis: vaccination and avoidance in the Baltics and Slovenia. *Vaccine* **26**: 2580–2588.

Sumilo, D., Asokliene, L., Bormane, A., Vasilenko, V., Golovljova, I., and Randolph, S.E. 2007. Climate change cannot explain the upsurge of tick-borne encephalitis in the Baltics. *PLos ONE* **2**: e500.

Sumilo, D., Bormane, A., Asokliene, L., Vasilenko, V., Golovljova, I., Avsic-Zupanc, T., Hubalek, Z., and Randolph, S.E. 2008b. Socio-economic factors in the differential upsurge of tick-borne encephalitis in Central and Eastern Europe. *Reviews in Medical Virology* **18**: 81–95.

Tatem, A.J., Hay, S.I., and Rogers, D.J. 2006. Global traffic and disease vector dispersal. *Proceedings of the National Academy of Sciences, USA* **103**: 6242–6247.

Taubes, G. 1997. Global warming: apocalypse not. *Science* **278**: 1004–1006.

U.S. Environmental Protection Agency. 2010. Endangerment and Cause or Contribute Findings for Greenhouse Gases Under Section 202(a) of the Clean air Act (Technical Support Document). Washington, DC: U.S. Environmental Protection Agency.

Wilder-Smith, A. and Gubler, D.J. 2008. Geographic expansion of Dengue: the impact of international travel. *Medical Clinics of North America* **92**: 1377–1390.

Zell, R. 2004. Global climate change and the emergence/re-emergence of infectious diseases. *International Journal of Medical Microbiology* **293**, Suppl. **37**: 16–26.

Zell, R., Krumbholz, A., and Wutzler, P. 2008. Impact of global warming on viral diseases: what is the evidence? *Current Opinion in Biotechnology* **19**: 652–660.

9.3. Plant Nutrient and Medicinal Properties

In this section, we survey the peer-reviewed scientific literature pertaining to the effects of higher atmospheric CO_2 concentrations on plant nutrient content and on specific plant compounds of direct medicinal value, such as antioxidants that inhibit oxidation, some of which (vitamins E, C, and beta carotene) are found in the human body and are thought to protect its cells from the damaging effects of oxidation.

Reactive oxygen species (ROS) generated during cellular metabolism or peroxidation of lipids and proteins play a causative role in the pathogenesis of cancer and coronary heart disease (CHD), as demonstrated by Slaga et al. (1987), Frenkel (1992), Marnett (2000), and Zhao et al. (2000). However, Yu et al. (2004) have noted "antioxidant treatments may terminate ROS attacks and reduce the risks of CHD and cancer, as well as other ROS-related diseases such as Parkinson's disease (Neff, 1997; Chung et al., 1999; Wong et al., 1999; Espin et al., 2000; Merken and Beecher, 2000)," and they therefore state, "developing functional foods rich in natural antioxidants may improve human nutrition and reduce the risks of ROS-associated health problems."

Spurred on by these findings and thoughts, Levine et al. (2008) grew well-watered and -fertilized wheat plants (*Triticum aestivum*, cv Yocoro roho) from seed in custom-designed root modules—"consisting of a porous tube embedded in Turface (1-2 mm particle size) substrate containing 5 g Osmocote time release fertilizer per liter"—which were housed in Plexiglas chambers kept at atmospheric CO_2 concentrations of 400, 1,500, or 10,000 ppm for periods of 14, 21, and 28 days, while measurements were made of a number of plant metabolic properties, including the leaf concentrations of several flavonoids capable of scavenging ROS.

According to the 13 researchers, their results indicated "elevated CO_2 promoted the accumulation of secondary metabolites (flavonoids) progressively to a greater extent as plants became mature." And as best as can be determined from the bar graphs of their results, the percentage increase in total wheat leaf flavonoid concentration in going from an atmospheric CO_2 concentration of 400 to 1,500 ppm was 22 percent, 38 percent, and 27 percent (the one exception to this general rule) at 14, 21, and 28 days after planting, respectively, and in going from a CO_2

concentration of 400 to 10,000 ppm, the percentage increase in total flavonoid concentration was 38 percent, 56 percent, and 86 percent, respectively, at 14, 21, and 28 days after planting. In addition, they found "both elevated CO_2 levels resulted in an overall 25% increase in biomass over the control plants."

In addition to the potential for the types of benefits described at the beginning of this section, the U.S., Japanese, and German scientists write, "the increased accumulation of secondary metabolites in plants grown under elevated CO_2 may have implications regarding plant-herbivore interactions, decomposition rates for inedible biomass, and potential beneficial effects on plant tolerance to water stress (Idso, 1988) and cold stress (Solecka and Kacperska, 2003) due to their potentials for the scavenging of reactive oxygen species (ROS)."

In another study published in 2008, Stutte et al. (2008) wrote, as background for their plant CO_2-enrichment experiment, that "many *Scutellaria* species are rich in physiologically active flavonoids that have a wide spectrum of pharmacological activity." They note leaf extracts of *Scutellaria barbata* "have been used in traditional Chinese medicine to treat liver and digestive disorders and cancers (Molony and Molony, 1998)," and "recent research has shown extracts of *S. barbata* to be limiting to the growth of cell lines associated with lung, liver, prostate and brain tumors (Yin et al., 2004)."

Stutte et al. grew *S. barbata* and *S. lateriflora* plants from seed in large, walk-in, controlled environment chambers—which were maintained at atmospheric CO_2 concentrations of either 400, 1,200, or 3,000 ppm—to the time of flowering (35 days after planting) and to the time of seed drop (49 days after planting). The plants were then harvested, their fresh and dry weights were determined, and the concentrations of a host of plant flavonoids within their tissues were measured.

The results of this project indicated that at 49 days after planting, the shoot dry weight of *S. barbata* increased by 54 percent at 1,200 ppm CO_2 and by 57 percent at 3,000 ppm CO_2, and that of *S. lateriflora* increased by 44 percent and 70 percent, respectively, under the same CO_2 concentrations. In addition, the average concentration of the six flavonoids the researchers measured was increased by 48 percent at 1,200 ppm CO_2 and by 81 percent at 3,000 ppm CO_2 in the vegetative tissues of *S. barbata*, and it was increased by more than 2.4-fold at 1,200 and 4.9-fold at 3,000 ppm CO_2 in *S. lateriflora*. Stutte et al. reported that in the case of *S. lateriflora*, "there was a 4.2-fold increase in total flavonoid content when enriching from 400 to 1200 ppm CO_2, and a 13.7-fold increase at 3000 ppm." They state "these results are generally consistent with those of B. Schmidt, W.D. Clark and S.B. Idso (unpublished data) who grew *S. baicalensis* at 700 ppm CO_2" and found "total dry biomass was increased significantly" and "the overall antioxidant capacity, based on the ferric reducing antioxidant power assay, was increased."

The three researchers concluded their results "clearly demonstrate the potential to use controlled environments to increase the production and quality of *Scutellaria* species ... because the practice has the potential to increase the value of the product by reducing the time to harvest, increasing yield per unit area, and increasing bioactivity per gram of dry matter." Likewise, their extremely positive results hint at the likelihood that the active ingredients of many other medicinal plants may also be similarly enhanced by atmospheric CO_2 enrichment and that the historical rise in the air's CO_2 content may have already done much the same thing for many of the plants that people include in their everyday diets.

La et al. (2009) took up the challenge to explore the subject further, writing by way of background, "epidemiological studies show that there is a negative relationship between vegetable intake and the risk of a number of cancers (Wattenberg, 1993; Kohlmeier and Su, 1997; Price et al., 1998)," and "it has been widely recognized that some of the cancer-chemoprotective activities in these vegetables are attributable to their contents of glucosinolates (GSs) (Zhao et al., 1992; Wattenberg, 1993; Tawfiq et al., 1995; Fahey et al., 1997; Rosa et al., 1997; Holst and Williamson, 2004)." They decided to see what effect the ongoing rise in the air's CO_2 content might have on the production of these important cancer-fighting agents.

The five scientists placed seedlings of Chinese broccoli (*Brassica alboglabra* L. var. *Sijicutiao*), in pairs in 1.8-L pots within growth chambers maintained at either 350 or 800 ppm CO_2, where the plant's roots were immersed in culture solutions treated with either low, medium, or high nitrogen and allowed to grow for 35 days, after which the plants were separated into their primary morphological parts and weighed, while their bolting stems were ground into powder for glucosinolate (GS) analyses.

"Regardless of N concentration," state the researchers in describing their findings, the elevated CO_2 treatment "significantly increased plant height [15.64 percent], stem thickness [11.79 percent], dry weights of the total aerial parts [11.91 percent], bolting stems [15.03 percent], and roots [16.34 percent]." In addition, they report the elevated CO_2 increased the total GS concentrations of the bolting stems in the low and medium N treatments by 15.59 percent and 18.01 percent, respectively, compared with those at ambient CO_2, although there was no such effect in the high N treatment. Thus, in terms of the total amount of GS production within the bolting stems of Chinese broccoli, these results suggest increases of 33 to 36 percent may be obtained for plants growing in low to medium N conditions in response to a 450 ppm increase in the air's CO_2 concentration. Such results bode well for people who eat broccoli—and, in all likelihood, other cruciferous vegetables as well—especially for those who will live in the CO_2-enriched world of the future.

Jin et al. (2009) grew well-watered and fertilized spinach (*Spinacia oleracea* cv. Huangjia) plants from seed for approximately three weeks in controlled-environment chambers containing ambient air of 350 ppm CO_2 or enriched air of 800 ppm CO_2, after which they harvested the plants, weighed them, and measured the concentrations of several of the nutritive or health-promoting substances contained in their leaves. As best as can be determined from Jin et al.'s graphs of their results, the extra 450 ppm of CO_2 increased the fresh weight of the spinach shoots by about 67 percent and their dry weight by approximately 57 percent. In addition, it boosted the soluble sugar concentrations of their leaves by approximately 29 percent and their soluble protein concentrations by about 52 percent. As an added bonus, the extra CO_2 also increased spinach leaf concentrations of ascorbate, glutathione, and total flavonoids by 21 percent, 16 percent, and 3 percent, respectively, suggesting that as time progresses and the air's CO_2 content continues its upward climb, spinach should become more nutritious.

Turning our attention to fruit, Bindi et al. (2001), working near Rapolano, Siena (Italy), conducted a two-year free-air CO_2 enrichment (FACE) study of 21-year-old grapevines (*Vitis vinifera* L., cv Sangiovese), where they enriched the air around the plants to 550 and 700 ppm CO_2 while measuring numerous plant parameters, including—after the fermentation process was completed—"the principal chemical compounds that determine the basic red wine quality."

Their results indicated "elevated atmospheric CO_2 levels had a significant effect on biomass components (total and fruit dry weight) with increases that ranged from 40 to 45% in the 550 ppm treatment and from 45 to 50% in the 700 ppm treatment." In addition, they report "acid and sugar contents were also stimulated by rising CO_2 levels up to a maximum increase in the middle of the ripening season (8–14%)," but as the grapes reached the maturity stage, the CO_2 effect on these parameters gradually disappeared. In terms of the primary pigments contained in the wine itself, however, it can be calculated from the bar graphs of their results that in response to the ~50 percent increase in atmospheric CO_2 concentration experienced in going from ambient to 550 ppm CO_2, the concentrations of total polyphenols, total flavonoids, total anthocyanins and non-anthocyanin flavonoids in the wine rose by approximately 19 percent, 33 percent, 31 percent, and 38 percent, respectively. Given these findings, Bindi et al. concluded, "the expected rise in CO_2 concentrations may strongly stimulate grapevine production without causing negative repercussions on quality of grapes and wine."

Similar results have been reported by Goncalves et al. (2009). Working with a native grape variety (Touriga Franca, *Vitis vinifera* L.) in the Demarcated Region of Douro, northern Portugal, the six Portuguese researchers investigated "the impact of elevated carbon dioxide concentration on the quality of berries, must, and red wine (with special reference to volatile composition, phenolic content, and antioxidant activity)" in an experiment in which grapevines were grown in open-top chambers maintained at either 365 or 550 ppm CO_2. As they describe their findings, "in general, the increase of CO_2 did not affect berry characteristics" and "did not significantly change the total antioxidant capacity of the red wines." In fact, "thirty-five volatile compounds belonging to seven chemical groups were identified," and "generally, the same volatile compounds were present in all of the wines." Although some of these compounds were "slightly affected," they state "the red wine quality remained almost unaffected."

In considering these findings, Goncalves et al. state their study showed "the predicted rise in CO_2 might strongly stimulate grapevine photosynthesis and yield (data not shown) without causing negative impacts on the quality of grapes and red wine." Putting their personal stamp of approval on their findings, they add that "the informal sensorial analysis carried out by the researchers" also showed "wine quality remained almost unaffected."

Vurro et al. (2009) examined the effect of atmospheric CO_2 enrichment on thyme (*Thymus vulgaris* L.), noting thyme has "a considerable economic value in the nutraceutical and pharmaceutical industry (Vardar-Uenlue et al., 2003; Konyalioglu et al., 2006)," and "thyme essential oil possesses per se considerable antioxidant capacity (Economou et al., 1991), and may therefore contribute towards the control of antioxidant status in the leaves."

Against this backdrop, Vurro et al. grew well-watered one-year-old thyme plants for three additional months out-of-doors within a mini-FACE system at Ravenna, Italy, where the air's CO_2 concentration was maintained at approximately 500 ppm (during daylight hours only), and where control plants were continuously exposed to air of approximately 370 ppm CO_2, and they measured several plant parameters at the end of each of the three months of the study.

In analyzing their results, the four researchers report "none of the plants grown under high levels of CO_2 for 90 days presented either significant differences in fresh weight and dry weight compared with controls, or macroscopic alteration of morphogenesis (number and length of nodes/internodes, branching, leaf area and chlorosis, etc.), at any of the sampling times." However, they did find that "in plants grown under elevated CO_2, a relative increase in oil yield of 32, 34 and 32 percent was, respectively, recorded in the first, second and third sampling-time (July, August and September)," and they observed a "general depression of the oxidative stress under elevated CO^2" that led to a "down-regulation of leaf reactive oxygen species-scavenging enzymes under elevated CO_2." Such findings, in the words of the Italian scientists, point to "a 'low cost' life strategy for growth under elevated CO_2, not requiring synthesis/activation of energy-intensive and expensive metabolic processes," which thus allows the plants to invest more energy in the production of essential plant oils of nutritional and pharmaceutical value.

In another study conducted with pharmaceutical considerations in mind, Ziska et al. (2008) evaluated "the growth and production of opiates for a broad range of recent and projected atmospheric carbon dioxide concentrations using wild poppy (*P. setigerum*) as a surrogate for *P. somniferum*," noting that "among medicinal plants, the therapeutic uses of opiate alkaloids from poppy (*Papaver* spp.) have long been recognized."

Specifically, Ziska et al. grew well-watered and fertilized plants from seed within growth chambers maintained at four different atmospheric CO_2 concentrations—300, 400, 500, and 600 ppm—for 90 to 100 days, while quantifying plant growth and the production of secondary compounds including the alkaloids morphine, codeine, papaverine, and noscapine, which were derived from latex obtained from capsules produced by the plants.

The three researchers' data indicate that relative to the plants grown at 300 ppm CO_2, those grown at 400, 500, and 600 ppm produced approximately 200, 275, and 390 percent more aboveground biomass, respectively, as best as can be determined from their bar graphs. In addition, they report, "reproductively, increasing CO_2 from 300 to 600 ppm increased the number of capsules, capsule weight and latex production by 3.6, 3.0 and 3.7 times, respectively, on a per plant basis," with the ultimate result that "all alkaloids increased significantly on a per plant basis." Based on these findings, Ziska et al. conclude, "as atmospheric CO_2 continues to increase, significant effects on the production of secondary plant compounds of pharmacological interest (i.e. opiates) could be expected." These effects, in their words, "are commonly accepted as having both negative (e.g. heroin) and positive (e.g. codeine) interactions with respect to public health."

In one final study, we report the work of Oliveira et al. (2010). Writing as background for their investigation, the five Brazilian researchers state, "presently, there is a growing interest in the use of inulin as a health food ingredient, as an alternative for low-calorie sweeteners, and as a dietary fiber and fat substitute (Ritsema and Smeekens, 2003)." In addition, they note "it is suggested" that a daily intake of low amounts of inulin or its derivatives generate certain bifidogenic effects that promote the growth of beneficial bacteria in the intestinal tract, as well as anti-tumor effects, citing the writings of Roberfroid (2005). They explain that their experimental subject, *Vernonia herbacea* (Vell.) Rusby, is an Asteraceae from the Brazilian Cerrado that accumulates inulin-type fructans in certain underground organs called rhizophores.

In conducting their experiment, Oliveira et al. grew well-watered and fertilized *V. herbacea* plants in open-top chambers within a glasshouse for 120 days at atmospheric CO_2 concentrations of either 380 or 760 ppm, during which period they measured plant net photosynthetic rates, water use efficiencies, and fructan concentrations after 15, 30, 60, 90, and 120 days of treatment, as well as above- and below-ground biomass at the end of the experiment. Results indicated that "plants under elevated CO_2 presented increases in height (40%), photosynthesis (63%) and biomass of aerial (32%) and underground (47%) organs when compared with control plants." In addition, they state, "water use efficiency was significantly higher in treated plants, presenting a 177% increase at day 60." Finally, they report that although fructan concentration remained unchanged, the significant CO_2-induced increase in underground organ biomass caused "a 24% increase in total fructan yield."

Because of the significant enhancement of inulin-type fructan production by *V. herbacea* under conditions of atmospheric CO_2 enrichment, the positive health effects of those compounds, and the great increase in water-use efficiency displayed by the plants while producing them, a CO_2-enriched future would appear to bode well for their commercial production throughout much of the central fifth—the Cerrado—of Brazil.

References

Bindi, M., Fibbi, L., and Miglietta, F. 2001. Free Air CO_2 Enrichment (FACE) of grapevine (*Vitis vinifera* L.): growth and quality of grape and wine in response to elevated CO_2 concentrations. *European Journal of Agronomy* **14**: 145–155.

Chung, H.S., Chang, L.C., Lee, S.K., Shamon, L.A., Breemen, R.B.V., Mehta, R.G., Farnsworth, N.R., Pezzuto, J.M., and Kinghorn, A.D. 1999. Flavonoid constituents of chorizanthe diffusa with potential cancer chemopreventive activity. *Journal of Agricultural and Food Chemistry* **47**: 36–41.

Economou, K.D., Oreopoulou, V., and Thomopoulos, C.D. 1991. Antioxidant activity of some plant extracts of the family Labiatae. *Journal of the American Oil Chemists' Society* **68**: 109–113.

Espin, J.C., Soler-Rivas, C., and Wichers, H.J. 2000. Characterization of the total free radical scavenger capacity of vegetable oils and oil fractions using 2,2-diphenyl-1-picryhydrazyl radical. *Journal of Agricultural and Food Chemistry* **48**: 648–656.

Fahey, J.W., Zhang, Y., and Talalay, P. 1997. Broccoli sprouts: an exceptionally rich source of inducers of enzymes that protect against chemical carcinogens. *Proceedings of the National Academy of Sciences, USA* **94**: 10,367–10,372.

Frenkel, K. 1992. Carcinogen-mediated oxidant formation and oxidative DNA damage. *Pharmacology and Therapeutics* **53**: 127–166.

Goncalves, B., Falco, V., Moutinho-Pereira, J., Bacelar, E., Peixoto, F., and Correia, C. 2009. Effects of elevated CO_2 on grapevine (*Vitis vinifera* L.): Volatile composition, phenolic content, and *in vitro* antioxidant activity of red wine. *Journal of Agricultural and Food Chemistry* **57**: 265–273.

Holst, B. and Williamson, G. 2004. A critical review of the bioavailability of glucosinolates and related compounds. *Natural Product Reports* **21**: 425–447.

Idso, S.B. 1988. Three phases of plant response to atmospheric CO_2 enrichment. *Plant Physiology* **87**: 5–7.

Jin, C.W., Du, S.T., Zhang, Y.S., Tang, C., and Lin, X.Y. 2009. Atmospheric nitric oxide stimulates plant growth and improves the quality of spinach (*Spinacia oleracea*). *Annals of Applied Biology* **155**: 113–120.

Kohlmeier L. and Su, L. 1997. Cruciferous vegetable consumption and colorectal cancer risk: meta-analysis of the epidemiological evidence. *FASEB Journal* **11**: 2141.

Konyalioglu, S., Ozturk, B., and Meral, G.E. 2006. Comparison of chemical compositions and antioxidant activities of the essential oils of two *Ziziphora* taxa from Anatolia. *Pharmaceutical Biology* **44**: 121–126.

La, G.-X, Fang, P., Teng, Y.-B, Li, Y.-J, and Lin, X.-Y. 2009. Effect of CO_2 enrichment on the glucosinolate contents under different nitrogen levels in bolting stem of Chinese kale (*Brassica alboglabra* L.). *Journal of Zhejiang University Science B* **10**: 454–464.

Levine, L.H., Kasahara, H., Kopka, J., Erban, A., Fehrl, I., Kaplan, F., Zhao, W., Littell, R.C., Guy, C., Wheeler, R., Sager, J., Mills, A., and Levine, H.G. 2008. Physiologic and metabolic responses of wheat seedlings to elevated and super-elevated carbon dioxide. *Advances in Space Research* **42**: 1917–1928.

Marnett, L.J. 2000. Oxyradicals and DNA damage. *Carcinogenesis* **21**: 361–370.

Merken, H.M. and Beecher, G.R. 2000. Measurement of food flavonoids by high-performance liquid chromatography: a review. *Journal of Agricultural and Food Chemistry* **48**: 577–599.

Molony, D. and Molony, M.M.P. 1998. The American Association of Oriental Medicines Complete Guide to Chinese Herbal Medicine. New York, NY: Berkley Publishing Group.

Neff, J. 1997. Big companies take nutraceuticals to heart. *Food Processing* **58**(10): 37–42.

Oliveira, V.F., Zaidan, L.B.P., Braga, M.R., Aidar, M.P.M., and Carvalho, M.A.M. 2010. Elevated CO_2 atmosphere promotes plant growth and inulin production in the cerrado species *Vernonia herbacea*. *Functional Plant Biology* **37**: 223–231.

Price, K.R., Casuscelli, F., Colquhoun, I.J., and Rhodes, M.J.C. 1998. Composition and content of flavonol glycosides in broccoli florets (*Brassica oleracea*) and their fate during cooking. *Journal of the Science of Food and Agriculture* **77**: 468–472.

Ritsema, T. and Smeekens, S. 2003. Fructans: beneficial for plants and humans. *Current Opinion in Plant Biology* **6**: 223–230.

Roberfroid, M.B. 2005. Introducing inulin-type fructans. *British Journal of Nutrition* **93**: S13–S25.

Rosa, E., Heaney, R.K., Fenwick, G.R., and Portas, C.A.M. 1997. Glucosinolates in crop plants. *Horticultural Reviews* **19**: 99–215.

Slaga, T.J., O’Connell, J., Rotstein, J., Patskan, G., Morris, R., Aldaz, M., and Conti, C. 1987. Critical genetic determinants and molecular events in multistage skin carcinogenesis. *Symposium on Fundamental Cancer Research* **39**: 31–34.

Solecka, D. and Kacperska, A. 2003. Phenylpropanoid deficiency affects the course of plant acclimation to cold. *Physiologia Plantarum* **119**: 253–262.

Stutte, G.W., Eraso, I., and Rimando, A.M. 2008. Carbon dioxide enrichment enhances growth and flavonoid content of two *Scutellaria* species. *Journal of the American Society for Horticultural Science* **133**: 631–638.

Tawfiq, N., Heaney, R.K., Pulumb, J.A., Fenwick, G.R., Musk, S.R., and Williamson, G. 1995. Dietary glucosinolates as blocking agents against carcinogenesis: glucosinolate breakdown products assessed by induction of quinine reductase activity in murine hepa1c1c7 cells. *Carcinogenesis* **16**: 1191–1194.

Vardar-Uenlue, G., Candan, F., Soekmen, A., Daferera, D., Polissiou, M., Soekmen, M., Doenmez, E., and Tepe, B. 2003. Antimicrobial and antioxidant activity of the essential oil and methanol extracts of *Thymus pectinatus* Fisch. et Mey var. pectinatus (Lamiaceae). *Journal of Agricultural and Food Chemistry* **51**: 63–67.

Vurro, E, Bruni, R., Bianchi, A., and di Toppi, L.S. 2009. Elevated atmospheric CO_2 decreases oxidative stress and increases essential oil yield in leaves of *Thymus vulgaris* grown in a mini-FACE system. *Environmental and Experimental Botany* **65**: 99–106.

Wattenberg, L.W. 1993. *Food and Cancer Prevention: Chemical and Biological Aspects.* London, UK: Royal Society of Chemistry.

Wong, S.S., Li, R.H.Y., and Stadlin, A. 1999. Oxidative stress induced by MPTP and MPP+: selective vulnerability of cultured mouse astocytes. *Brain Research* **836**: 237–244.

Yin, X., Zhou, J., Jie, C., Xing, D., and Zhang, Y. 2004. Anticancer activity and mechanism of *Scutellaria barbata* extract on human lung cancer cell line A549. *Life Sciences* **75**: 2233–2244.

Yu, L., Haley, S., Perret, J., and Harris, M. 2004. Comparison of wheat flours grown at different locations for their antioxidant properties. *Food Chemistry* **86**: 11–16.

Zhao, F., Evans, E.J., Bilsborrow, P.E., Schnug, E., and Syers, J.K. 1992. Correction for protein content in the determination of the glucosinolate content of rapeseed by the XRF method. *Journal of the Science of Food and Agriculture* **58**: 431–433.

Zhao, J., Lahiri-Chatterjee, M., Sharma, Y., and Agarwal, R. 2000. Inhibitory effect of a flavonoid antioxidant silymarin on benzoyl peroxide-induced tumor promotion, oxidative stress and inflammatory responses in SENCAR mouse skin. *Carcinogenesis* **21**: 811–816.

Ziska, L.H., Panicker, S., and Wojno, H.L. 2008. Recent and projected increases in atmospheric carbon dioxide and the potential impacts on growth and alkaloid production in wild poppy (*Papaver setigerum* DC.). *Climatic Change* **91**: 395–403.

10

Economic and Other Policy Implications

10. Economic and Other Policy Implications

Introduction

The Intergovernmental Panel on Climate Change (IPCC) claims CO_2-induced global warming is already occurring and “climate change currently contributes to the global burden of disease and premature deaths” (IPCC, 2007-II, p. 393). While the IPCC recognizes climate change could “bring some benefits to health, including fewer deaths from cold,” it says those benefits must be weighed against “the negative effects of rising temperatures worldwide, especially in developing countries” (ibid.). Policy proposals aimed at mitigating climate change have been justified by the claim that the net costs of action for present and future populations would exceed that of inaction.

According to the IPCC narrative, the well-being of the vast majority of humanity should have deteriorated due to anthropogenic climate change. But in fact, human well-being has in aggregate never been better than it is currently. This is partly because the IPCC’s projections of future impacts severely underestimate the ability of humans to cope with and adapt to climate change, a topic we also addressed in Chapter 9.

For the 2009 report of the Nongovernmental International Panel on Climate Change (NIPCC), Idso and Singer (2009) addressed some of these issues in sections 9.4 and 9.5 of the report’s final chapter on “human health effects.” Section 9.4 of that report explained how “the aerial fertilization effect of the increase in the air’s CO_2 content that is expected to occur by the year 2050 would boost crop yields by the amounts required to prevent mass starvation in many parts of the globe, without a large-scale encroachment on the natural world” (p. 698). Section 9.5 described the unintended consequences of increased use of biofuels – ethanol, biodiesel, and methanol – which the IPCC encouraged as a way to reduce greenhouse gas emissions. “Biofuels may have some advantages over gasoline and diesel fuels, but they are more expensive to produce and can supply only a small part of the world’s total transportation energy needs. Because they compete with food crops and nature for land and nutrients, expanding the use of biofuels could negatively affect human health and natural ecosystems” (p. 701).

This chapter significantly expands Idso and Singer’s earlier work. It shows how real-world data on human well-being (e.g., hunger, disease, poverty, and deaths from droughts, floods, and other extreme weather events) contradict claims about the impacts of warming in the twentieth century. It present results from impact assessments cited by IPCC (2007-II) and co-written by several of its contributors that reveal climate change should be a minor player among the factors that determine human well-being worldwide through the foreseeable future. New research on the economics and ecology of biofuels is presented, as well as some research and commentary on the role climate change might play in matters of war and social unrest.

References

Idso, C.D. and Singer, S.F. 2009. *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

IPCC. 2007-II. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson. Cambridge, UK: Cambridge University Press.

10.1. Climate and Economy

One of the fundamental rationales behind the desire to control greenhouse gas emissions is the frequent claim that CO_2-induced global warming will negatively affect livelihoods and reduce well-being in the developing world. However, as shown in the material below, decades-long empirical trends of climate-sensitive measures of human well-being reveal improvement, notwithstanding the historic increase in atmospheric CO_2 concentrations or any climate change.

10.1.1. Hunger

Proponents of greenhouse gas controls frequently claim global warming will reduce crop productivity in the developing world, thereby exacerbating hunger and famine (e.g., Freeman and Guzman, 2009). Idso and Singer (2009) rebutted this claim, citing a series of studies showing that important food crops benefit from higher CO_2 concentrations (pp. 696–697). This, coupled with technological advances, has increased crop productivity and production dramatically during the latter half of the twentieth century in least developed countries (LDCs) as well as globally, as is shown in Figure 10.1.1.

Because of the increase in agricultural

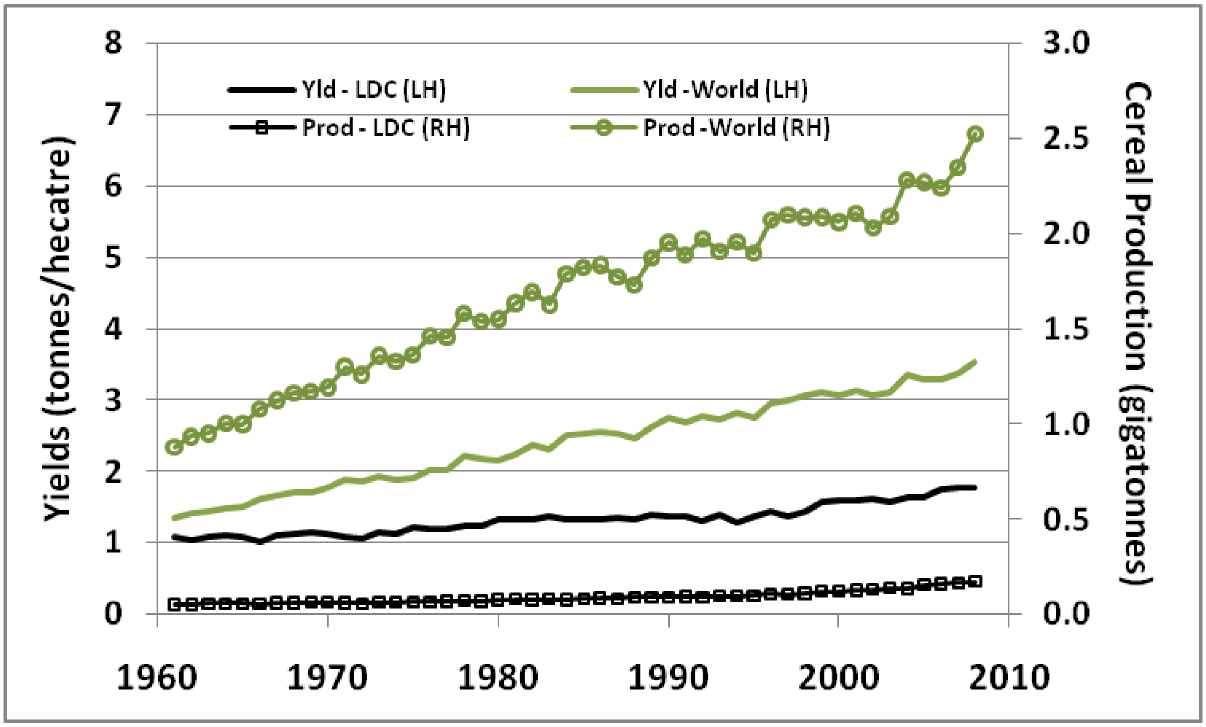


Figure 10.1.1. Cereal yield and production, 1961-2008, for Least Developed Countries (LDCs) and globally. Source: Food and Agricultural Organization (2010a).

productivity and trade in agricultural and food inputs and outputs, the portion of the developing world's population suffering from chronic hunger has been declining for decades. From 1969–1971 to 2003–2005, it declined from 33 percent to 16 percent (FAO, 2009a). However, it has started to rise once again, at least temporarily (see Figure 10.1.2; FAO, 2009a). It increased to about 17 percent in 2008 and 19 percent in 2009 before being projected to decline to 16 percent once again in 2010. But as shown in Figure 10.1.1 (which goes only through 2008), neither productivity nor production has declined. Therefore, the recent increase in hunger cannot be a result of any loss of productivity or production due to global warming.

The Food and Agricultural Organization (FAO) ascribes the increase in hunger to a surge in food prices, the global economic slowdown, insufficient investment in agriculture, and biofuel production that has diverted crops from food to fuel production (FAO, 2009a; 2009b). Ironically, concern over global warming is responsible for the mandates and subsidies that drive biofuel production. In addition, as spending on global warming has increased, investments in agriculture have dropped.

10.1.2. Life Expectancy and Diseases

While the IPCC claims death and disease have increased due to the modest global warming of the twentieth century driven by economic development and energy use, actual data on life expectancy and the incidence of diseases tell a different story. Average life expectancies around the world have increased from 31 years in 1900 to 47 years in the early 1950s and 69 years today (Goklany, 2007; World Bank, 2010a). For developing countries, life expectancies increased from twenty-five to thirty years in 1900 to forty-one years in the early 1950s and sixty-nine years at present (Goklany, 2009a; World Bank, 2010a).

For Sub-Saharan Africa, life expectancy increased from 40.9 years in 1960 to 52.1 years in 2008. In virtually every country, health-adjusted life expectancies currently exceed unadjusted life expectancies from just a few decades ago (Goklany 2007). [“Health-adjusted” life expectancy is the life expectancy adjusted downward to partially discount the numbers of years of life an average person would spend in a disabled or diseased condition.] In other words, people in developing countries are not only living longer, they are also healthier.

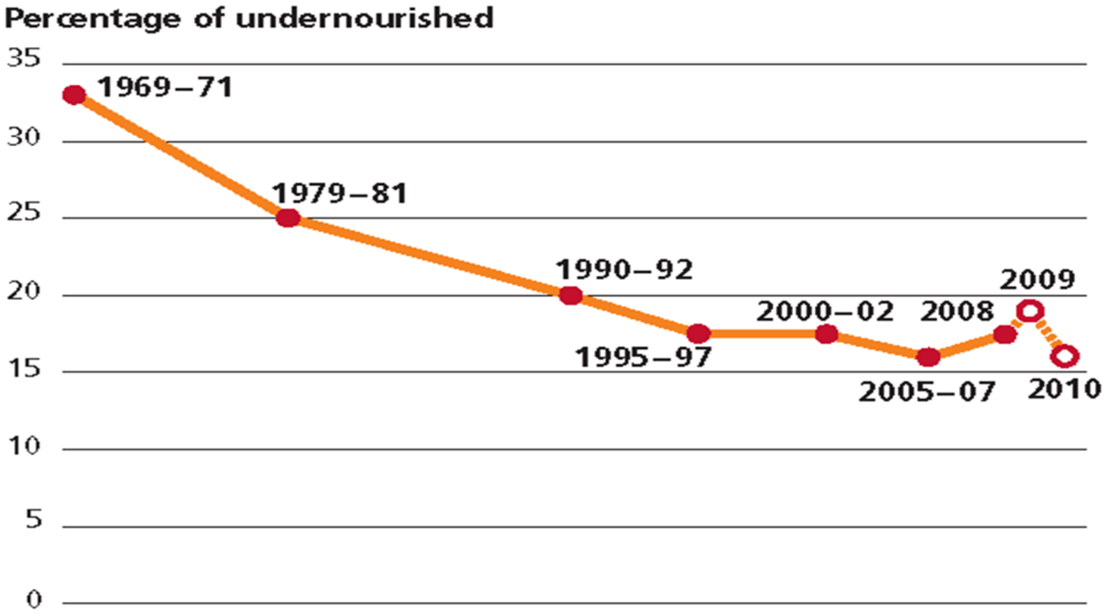


Figure 10.1.2. Percent of developing world population suffering from chronic hunger, 1969/71-2010. Source: Food and Agricultural Organization (2010b).

Meanwhile, the ranges of the most critical climate-sensitive infectious diseases have shrunk. Malaria accounts for about 75 percent of the global burden of disease from vector-borne diseases and therefore serves as a good surrogate for the latter (IPCC, 2001). As indicated in Figure 10.1.3, the area in which malaria due to *Plasmodium falciparum* – the deadliest of the four protozoan parasites that cause malaria – is endemic has been reduced substantially since 1900 (Gething et al., 2010).

Endemic/stable malaria is estimated to have covered 58 percent of the world's land surface around 1900 but only 30 percent by 2007. *P. falciparum* malaria is today restricted largely to developing countries in the tropics. Equally important, its endemicity has fallen by one or more classes in more than two-thirds of the current range of stable transmission. See Figure 10.1.3c.

Gething et al. (2010) note:

> [O]f the 66 million km^2 of the Earth's surface thought to have sustained stable/endemic malaria in 1900, 12%, 18% and 57% had exhibited proportional decreases in the reproductive number of up to one, between one and two, and greater than two orders of magnitude, respectively; 11% had shown no evidence of change; and 2% had shown evidence of an increase in the reproductive number by 2007.

Figure 10.1.3 does not show the rebound in malaria in many developing areas that occurred in the 1980s and 1990s because of a combination of poor policies (such as cessation of indoor spraying of DDT in many countries partly due to a reluctance of developed countries' aid programs to support DDT use), development of resistance to drugs and insecticides, and a deterioration of public health infrastructure in many African countries coincident with a period in which their economies deteriorated and AIDS was ascendant (Goklany, 2007). Since then, however, matters have improved substantially. According to the World Health Organization's *World Malaria Report 2010*, estimated deaths from malaria in Africa declined from 900,000 in 2000 to 709,000 in 2009 (WHO 2010, 61). Globally, the number of malaria deaths over the same period fell from 985,000 to 781,000.

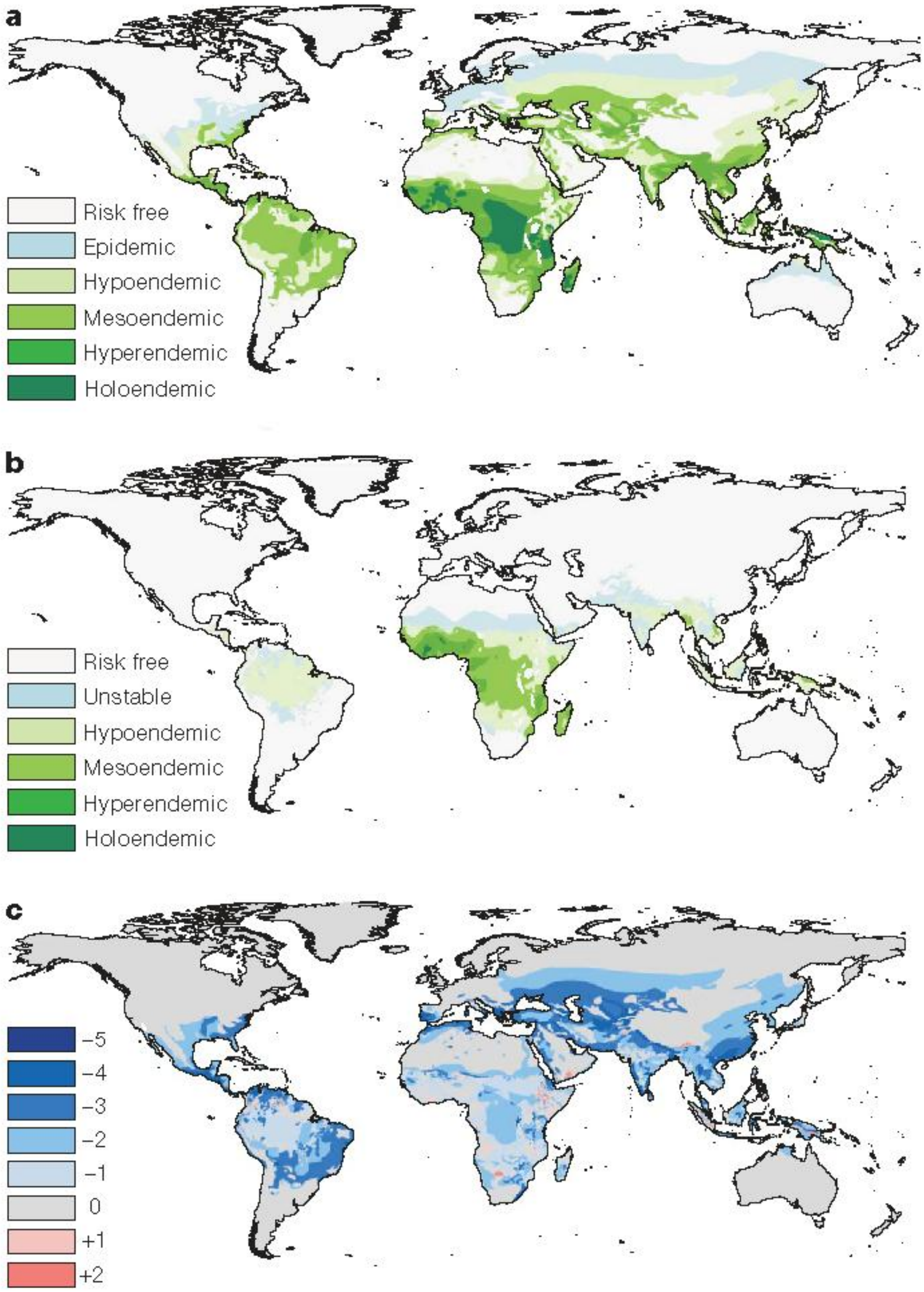


Figure 10.1.3. Changing global malaria endemicity since 1900. (a) Pre-intervention endemicity (approximately 1900). (b) Contemporary endemicity for 2007. (c) Change in endemicity class between 1900 and 2007. Negative values denote a reduction in endemicity, positive values an increase. Source: Gething et al. (2010).

10.1.3. Poverty

Did CO_2-induced global warming during the second half of the twentieth century cause rising levels of poverty in developing countries? If the IPCC's catastrophic claims (IPCC, 2007-II, 835) were true, one would expect to see some evidence of this in economic statistics. But the data, in fact, show just the opposite trend.

The proportion of the developing world's population living in extreme poverty (defined as less than $1.25 per day in 2005 dollars) was halved from 52 percent in 1981 to 25 percent in 2005 (World Bank, 2010b). The number of people living in extreme poverty declined from 1.9 billion to 1.374 billion even as world population grew from 3.7 billion to 5.5 billion. See Figure 10.1.4.

The most spectacular improvements in personal income were in East Asia and the Pacific, where the headcount of those in poverty dropped from 1.071 billion to 316 million. More people escaped poverty at a faster rate in these countries than at any other time in human history. It is no accident that the fastest reductions in poverty occurred in areas that experienced the greatest increases in both economic development and greenhouse gas emissions.

10.1.4. Extreme Weather Events

The IPCC claims death, disease, and property damage from extreme weather events will increase if man-made greenhouse gases were not restricted. While property damage indeed has increased over time, this seems to be due to an increase in both population and wealth, which increases the property at risk (Bouwer, 2010; Neumayer and Barthel, 2011), losses of life due to extreme weather events have fallen.

Data for 1900 to 2008 indicate that since the 1920s, cumulative annual deaths from all extreme weather events – droughts, floods, extreme temperatures (both extreme heat and extreme cold), wet mass movement (slides, waves, and surges), wildfires, and storms (hurricanes, cyclones, tornados, typhoons, etc.) – declined globally by 93 percent on average while the annual death rate dropped by 98 percent (Goklany, 2009b). See Figure 10.1.5.

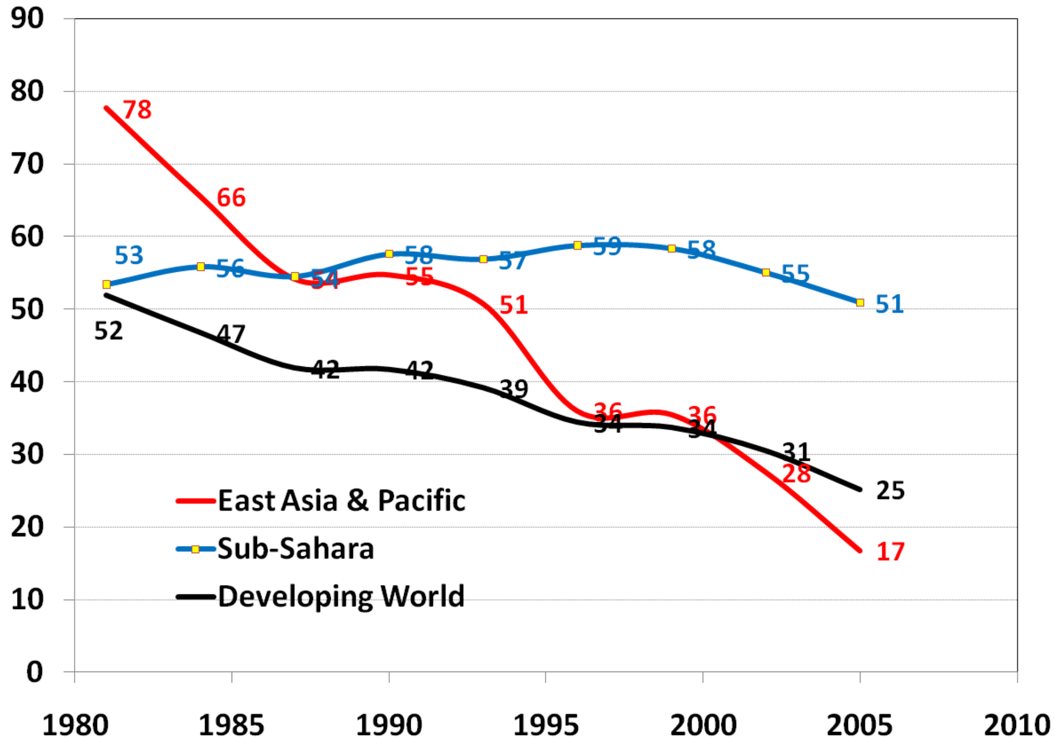


Figure 10.1.4. Poverty rates in the developing world, 1981-2005. Source: PovCalNet, World Bank (2010b).

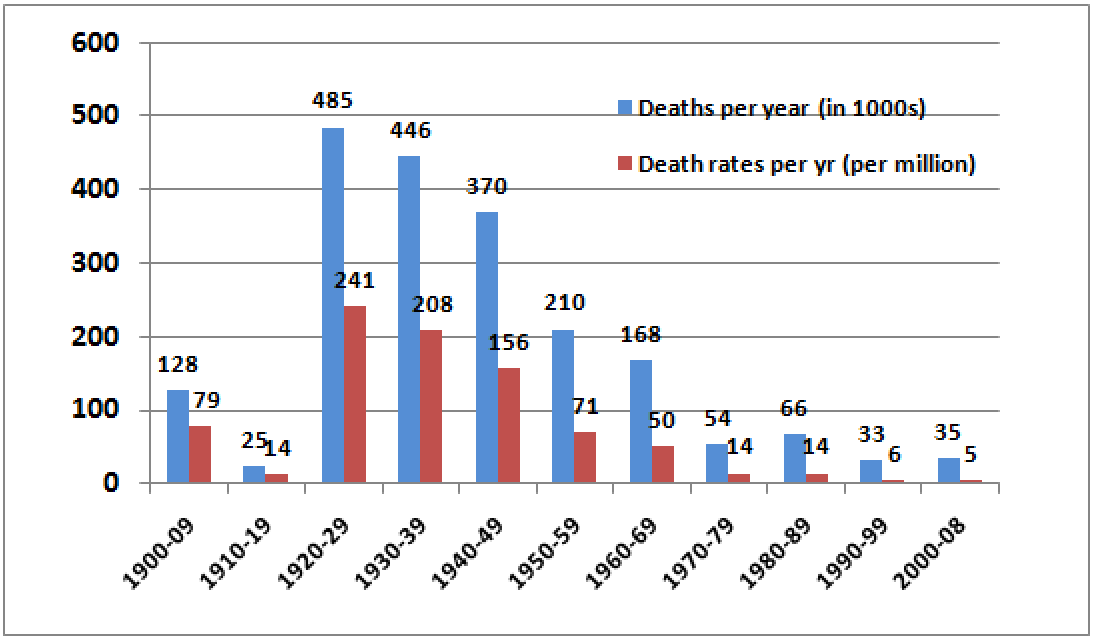


Figure 10.1.5. Global deaths per year and death rates due to extreme weather events, 1900-2008. Extreme events include the following: droughts, floods, extreme temperatures (both extreme heat and extreme cold), wet mass movement (slides, waves, and surges), wildfires, and storms (hurricanes, cyclones, tornados, typhoons, etc.). Data for the last period are averaged over nine years. Source: Goklany (2009b), using data from EM-DAT (2009).

Between 1900 and 2008, droughts were responsible for most (58 percent) of the global fatalities due to extreme weather events. Global deaths and death rates from droughts peaked in the 1920s and have since fallen by 99.97 percent and 99.99 percent, respectively (Goklany, 2009b). The death toll that inevitably used to follow in the wake of drought has been reduced almost to the vanishing point.

In 2000–2009, according to the EM-DAT, the International Disaster Database, an average of only 116 people died annually due to drought (EM-DAT, 2010), compared to 472,000 deaths annually in 1920–29. To place these numbers in context, currently more than 58 million people die each year due to all causes worldwide (WHO, 2008).

With respect to floods, the second most deadly form of extreme weather event, deaths and death rates crested in the 1930s. By 2000–2008 they were down by 98.7 percent and 99.6 percent, respectively (Goklany, 2009b).

Extreme weather events today contribute only 0.06 percent of the global (and U.S.) mortality burdens in an average year. They have declined even as all-cause mortality has increased (Goklany, 2009b). This indicates that the world, including the developing world, is coping better with risks of death from extreme weather events than it is with other, larger health risks. It also suggests that it might pay greater dividends to society if more resources were expended on the latter than on reducing man-made greenhouse gas emissions.

10.1.5. Water Shortages

The possibility of water shortages leading to droughts and hunger are recurring themes in the climate change literature (e.g., Freeman and Guzman, 2009; IPCC, 2007-II). Droughts, which are a manifestation of severe water shortages, have plagued humanity from time immemorial, and deaths from droughts are probably the best indicator of the socioeconomic impact of such water shortages. As noted above, deaths and death rates from droughts have declined by 99.97 percent and 99.99 percent since the 1920s. This decline occurred despite a more-than-tripling of the global population.

There is also a concern that the combination of population growth and global warming might reduce access to safe water. Yet between 1990 and 2008, although global population increased 27 percent, the percentage of global population with access to safe water increased from 76.8 percent to 86.8 percent. An additional 1.8 billion people gained access to safer water over this period (World Bank, 2010a; WRI, 2010). At the same time, 1.3 billion more people gained access to improved sanitation..

Even Sub-Saharan Africa, historically a slow-development region, has seen improvements. Despite a 60 percent increase in population, the proportion with access to improved water sources increased from 48.9 percent in 1990 to 59.7 percent in 2008, as 240 million more people in that region gained such access (World Bank, 2010a; WRI, 2010).

Clearly, long-term trends for hunger, disease, and deaths from droughts, floods, and other extreme weather events are not consistent with the IPCC's narrative regarding the impacts of global warming. Perhaps global warming is not happening after all, or if it is, its effect are relatively small and/or overwhelmed by improvements in human adaptive capacity or other factors. Or perhaps the global warming narrative is simply based on false expectations, that warming's real impacts are more positive than negative. Whichever explanation (or combination of explanations) is correct, the salient fact is that real-world data do not support claims that global warming is reducing human well-being.

References

Bouwer, L.M. 2010. Have disaster losses increased due to anthropogenic climate change? *Bulletin of the American Meteorological Society* doi: 10.1175/2010BAMS3092.1.

EM-DAT. 2009. The OFDA/CRED International Disaster Database. Brussels, Belgium: Université Catholique de Louvain. Available at http://www.em-dat.net. Data downloaded 24 August 2009.

EM-DAT. 2010. The OFDA/CRED International Disaster Database. Brussels, Belgium: Université Catholique de Louvain. Available at http://www.em-dat.net. Data downloaded 22 May 2010.

Food and Agricultural Organization (FAO). 2009a. *State of Food Insecurity 2009*. Rome, Italy: FAO.

Food and Agricultural Organization (FAO). 2009b. *The State of Food Insecurity in the World: Economic crisis: impacts and lessons learned*. Available at http://www.fao.org/economic/es-policybriefs/multimedia0/presentation-the-state-of-food-insecurity/en/.

Food and Agricultural Organization (FAO). 2010a. *FAOSTAT*. Available at http://faostat.fao.org/default.aspx, visited 9 May 2010.

Food and Agricultural Organization (FAO). 2010b. *State of Food Insecurity 2010*. Rome, Italy: FAO.

Freeman, J. and Guzman, A. 2009. Climate change & U.S. interests. *Columbia Law Review* **100**: 101–171.

Gething, P.W., Smith, D.L., Patil, A.P., Tatem, A.J., Snow, R.W., and Hay, S.I. 2010. Climate change and the global malaria recession. *Nature* **465**: 342–345.

Goklany, I.M. 1998. Saving habitat and conserving biodiversity on a crowded planet. *BioScience* **48**: 941–953.

Goklany, I.M. 2007. *The Improving State of the World*. Washington, DC: Cato Institute.

Goklany, I.M. 2009a. Have increases in population, affluence and technology worsened human and environmental well-being? *Electronic Journal of Sustainable Development* **1**(3). Available at http://www.ejsd.org/docs/HAVE_INCREASES_IN_POPULATION_AFFLUENCE_AND_TECHNOLOGY_WORSENED_HUMAN_AND_ENVIRONMENTAL_WELL-BEING.pdf.

Goklany, I.M. 2009b. Deaths and death rates from extreme weather events: 1900–2008. *Journal of American Physicians and Surgeons* **14**: 102–09.

IPCC (Intergovernmental Panel on Climate Change). 2001. *Climate Change 2001. Impacts, adaptation, and vulnerability*. New York, NY: Cambridge University Press.

IPCC. 2007-II. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Chan*ge. Edited by M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson. Cambrridge, UK: Cambridge University Press.

Neumayer, E., and Barthel, F. 2011. Normalizing economic loss from natural disasters: A global analysis. Global Environmental Change 21: 13-24.

World Health Organization (WHO). 2008. *Global Burden of Disease and Risk Factors: 2004 Update*. Geneva, Switzerland: WHO.

World Health Organization (WHO). 2010. *World Malaria Report 2010*. Geneva, Switzerland: WHO.

World Bank. 2010a. *World Development Indicators*, available at http://ddp-ext.worldbank.org/ext/DDPQQ/member.do?method=getMembers&userid=1&queryId=135

World Bank. 2010b. *PovCalNet.* Available at http://iresearch.worldbank.org/PovcalNet/povDuplic.html, visited 28 May 2010.

World Resources Institute (WRI). 2010. *EarthTrends*. Available at http://earthtrends.wri.org/.

10.2. Projected Impacts and Damages from Global Warming

The basic premise for policy proposals aimed at mitigating climate change is that without them the net impacts of climate change would be severely negative and future populations would be worse off than humans are today. The magnitude of these impacts and their associated damages depends on society's adaptability (adaptive capacity), which is determined by, among other things, the wealth and human resources society can access in order to obtain, install, operate, and maintain technologies necessary to cope with or take advantage of climate change impacts (IPCC 2001; IPCC 2007-II, p. 138; Goklany 2007a). Thus, estimates of the impacts of global warming must necessarily consider the adaptive capacity of the societies that experience it.

The IPCC recognizes this principle. Its "standard" impacts assessment methodology incorporates consideration of autonomous adaptation (IPCC 2007-II, p. 136, footnote 2). However, many of the studies that it draws upon fail to recognize that these autonomous adaptations should be based on society's adaptive capacity *at the time for which impacts are to be estimated.* That is, if impacts are to be estimated for 2100, the adaptive capacity used to develop those estimates also should be projected for 2100. Equally importantly, projections for adaptive capacity must be consistent with the assumptions about economic growth and technological change used to drive the emission scenario that is used to estimate climate change.

As will be shown below, for the most part impact assessments account only partially for changes in adaptive capacity between the baseline year and the projection year. As a result, negative impacts are overestimated and positive impacts are underestimated. Together, these errors inflate the forecasts of net damage from projected climate change.

The following discussion examines the dependence of adaptive capacity on economic and technological development; whether economic growth assumptions used in the IPCC scenarios should reflect a significantly different adaptive capacity relative to the baseline level; and the extent to which such changes were incorporated in state-of-the-art global impact assessments used in the IPCC's 2007 report, and the implications for future per-capita incomes and human well-being.

10.2.1. Determining Adaptive Capacity

Among the determinants of adaptive capacity are economic development, availability of and access to technology, and human capital. Many of the indicators of human well-being – education level, health status, availability of food supplies, malnutrition level, access to safe water and sanitation, health expenditures, and research and development expenditures – enhance these determinants and, in turn, are enhanced by them (Goklany, 2007a). In effect, these indicators of human well-being also serve as determinants of adaptive capacity.

For any specific level of economic development, these indicators and determinants improve with time. Time is a surrogate for technology, where technology is defined broadly as including hardware (such as tractors, dams, carbon adsorption systems) and software technologies (e.g., policies and institutions that govern or modulate human actions and behavior, trade, and other forms of exchange; culture, management techniques; computer programs to track or model environmental quality; and emissions trading) (Ausubel, 1991; Goklany, 1995).

Cross-country data show that at any point in time, each of these indicators of well-being generally advances with the level of gross domestic product (GDP) per capita, a measure of economic development or per-capita income. The five figures that follow show the close correlation between per-capita GDP and cereal yields (a surrogate for agricultural productivity), available daily food supplies per capita, the prevalence of malnutrition (which is a consequence of hunger and a determinant of health), infant mortality, and life expectancy. The latter two – infant mortality and life expectancy – capture the aggregate effect on human well-being of many of the indicators noted previously, such as education, health status, availability of food supplies, prevention of malnutrition, access to safe water and sanitation, and health research and development expenditures (Goklany, 2007a, 2007b)[1]. That is, they capture the total effect of societies' abilities to cope with death and disease from *all* causes.

Figure 10.2.1 shows cereal yields measured in thousands of kilograms per hectare increased linearly with per-capita GDP in both 1975 and 2003. The upward displacement of the cereal yield curve from 1975 to 2003 indicates that, in general, yield increased at any given level of income with the passage of time. This upward displacement can be attributed to secular technological change which, under the definition employed here, includes increases in fertilizer and pesticide usage, improvements in yields due to greater knowledge, improved management techniques, exchange of ideas, and more reliable weather forecasts.

Higher yields should result in greater food supplies, and Figure 10.2.2 shows available food supplies per capita per day (FS) increases with per-capita income. However, the relationship between food supplies and income is log-linear, not linear as it is for yield, probably because wealthier countries can buy food (via trade) on the world market and even a small amount of additional income goes a long way toward meeting food requirements. Increasing income from $100 to $1,000 (or from $1,000 to $10,000) increases average daily FS by 816 kcal per capita per day, while secular technological change raised food supply by 166 kcal per capita per day from 1975 to 2002, regardless of income level (Goklany 2007b).

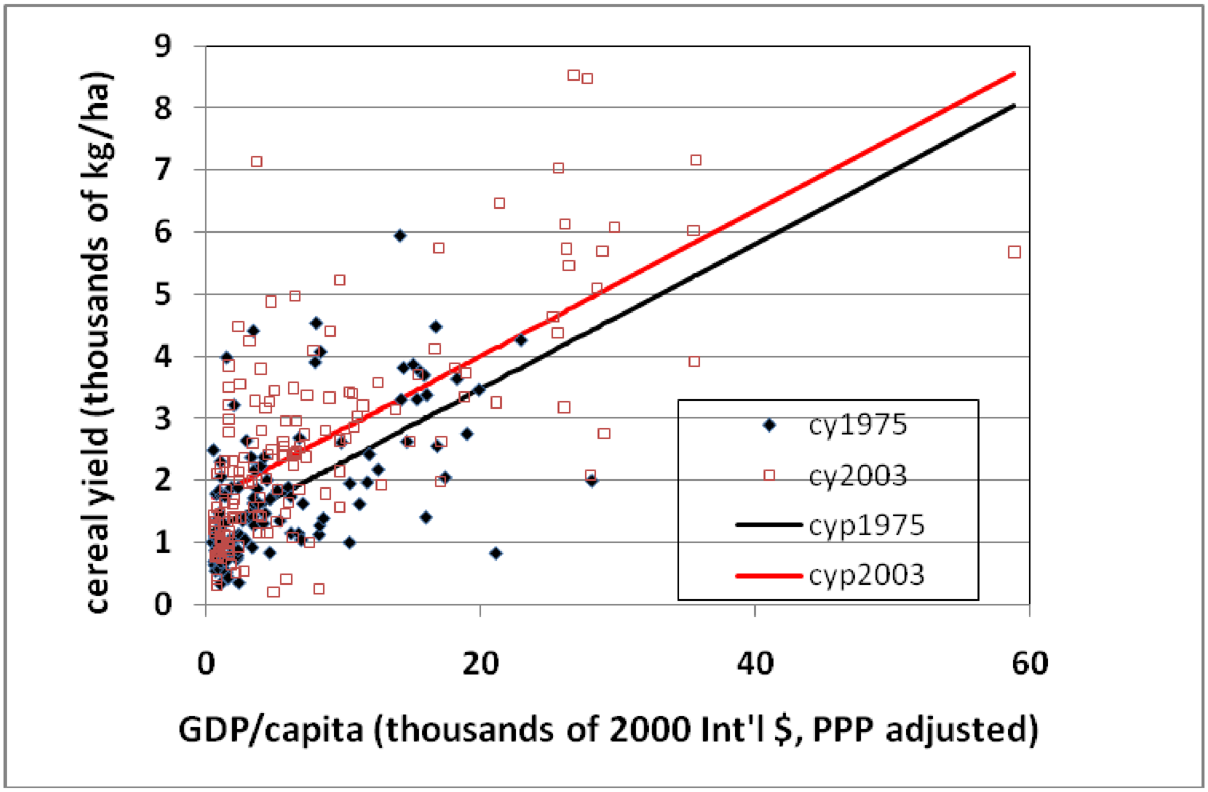


Figure 10.2.1. Cereal yields vs. per-capita GDP across countries, 1975–2003. Source: Goklany (2007b).

---

[1] Figures 10.2.1 through 10.2.5 are taken from Goklany (2007b), which uses the same methodology as in Goklany (2007a), except the former used per-capita GDP adjusted for purchasing power, whereas the latter uses per-capita GDP based on market exchange rates.

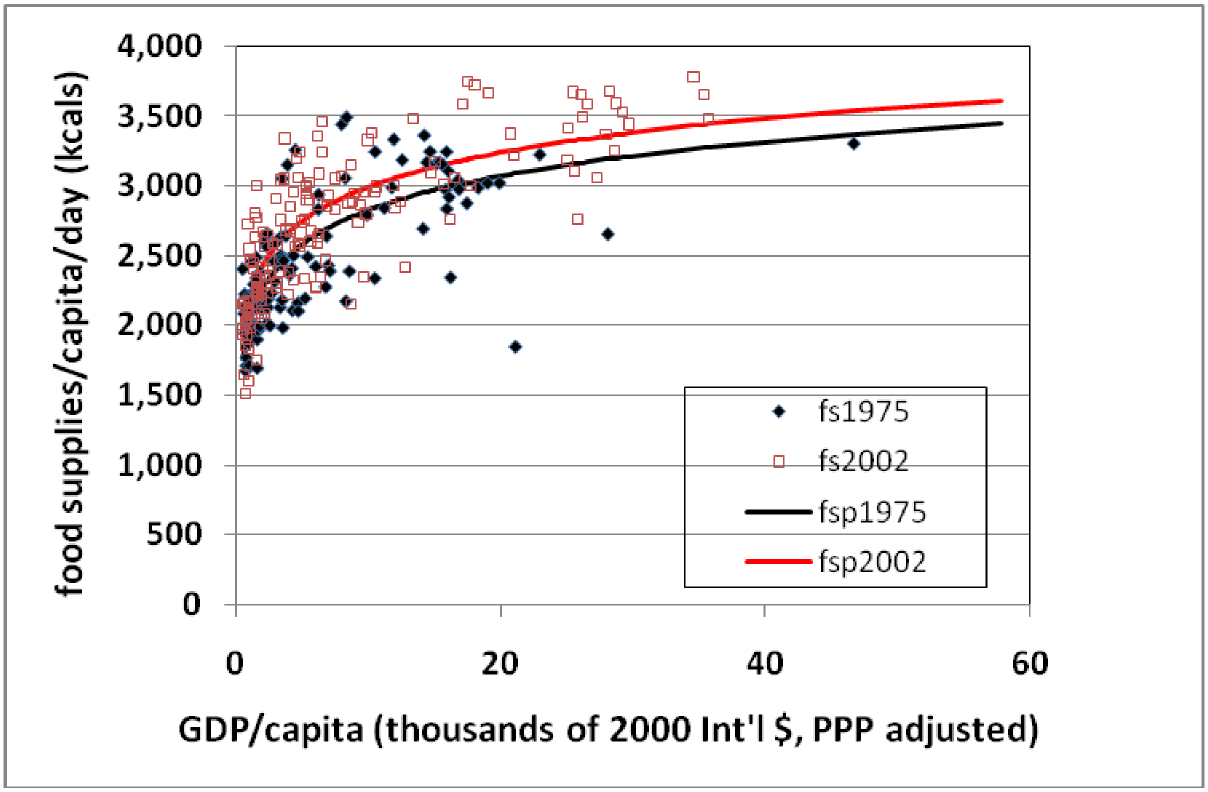


Figure 10.2.2. Available food supplies per capita per day (FS) vs. per-capita GDP across countries, 1975–2002. Source: Goklany (2007b).

Higher food supplies should lower malnutrition rates, and Figure 10.2.3 indicates malnutrition as percent of population declines as GDP per capita rises. Because of technological change, even if a country's average income were frozen at a dollar a day (in 2000 international dollars, adjusted for purchasing power), malnutrition would drop from 79.5 percent in 1987 to 58.6 percent of population in 2000. If average income were doubled in 2000, malnutrition would drop further to 35.2 percent (Goklany 2007b).

Malnutrition declines more rapidly as per-capita income rises than food supplies increase at the lowest levels of income. This is because although food supplies are critical to reducing malnourishment, other income-sensitive factors, such as public health services and infrastructure to transport food and medicine, reinforce the resulting reductions in malnutrition. Lower malnutrition (better nutrition) also reduces susceptibility to disease, and thus the amount of food needed to maintain healthy weight is lowered; better health helps reduce malnutrition even if food supplies are fixed.

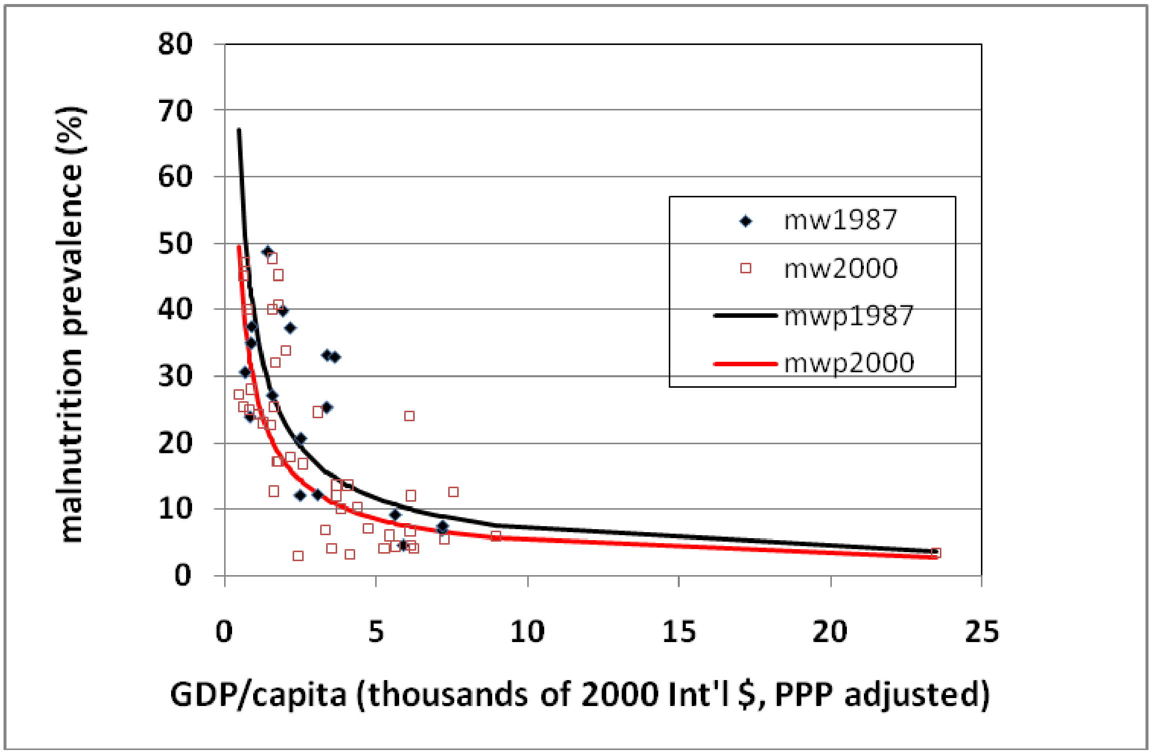


Figure 10.2.3. Prevalence of malnutrition (as percent of population) vs. per-capita GDP across countries, 1987–2000. Source: Goklany (2007b).

Lower malnutrition should also translate into lower mortality rates. As shown in Figure 10.2.4, infant mortality improves with income and technological change (time). If a country doubled its average income from $1 to $2 a day, infant mortality would decline from 355 per 1,000 live births to 199 in 1980, and from 207 to 116 in 2000. The combination of the two – a doubling of income and technological change – would, therefore, reduce infant mortality from 355 per 1,000 live births in 1980 to 116 in 2000.

If infant mortality rates decline, life expectancies should increase. Figure 10.2.5 confirms life expectancy improves with economic development and time. Had per-capita income doubled from $1 a day to $2 a day, life expectancy would have increased from 40.7 years to 46.2 years in 1977, and from 44.6 to 50.2 years in 2003 (Goklany 2007b).

These figures illustrate that both economic development and time (a surrogate for technology), meaning secular technological change, independently and together increase society's ability to adapt to and cope with whatever problems it faces. Many other indicators of well-being, such as access to safe water and sanitation and educational levels, also improve with income and technological change (Goklany (2007a; 2007b).

These figures also indicate the compounded effect of economic development and technological change (time) can result in quite dramatic improvements even over the relatively short period over which these figures were developed. Figure 10.2.5, for instance, covered 26 years. By contrast, climate change impacts analyses frequently look 50 to 100 years into the future. Over such long periods, the compounded effect of economic development and technological change could be spectacular.

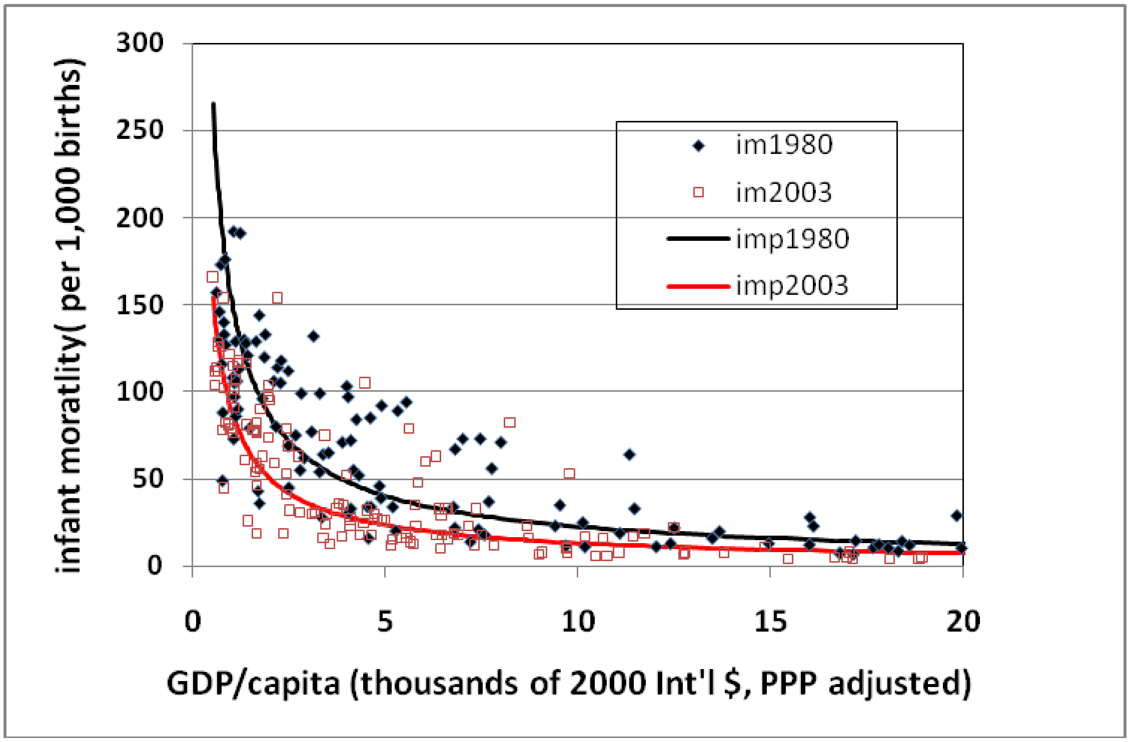


Figure 10.2.4. Infant mortality vs. per-capita GDP across countries, 1987–2000. Source: Goklany (2007b).

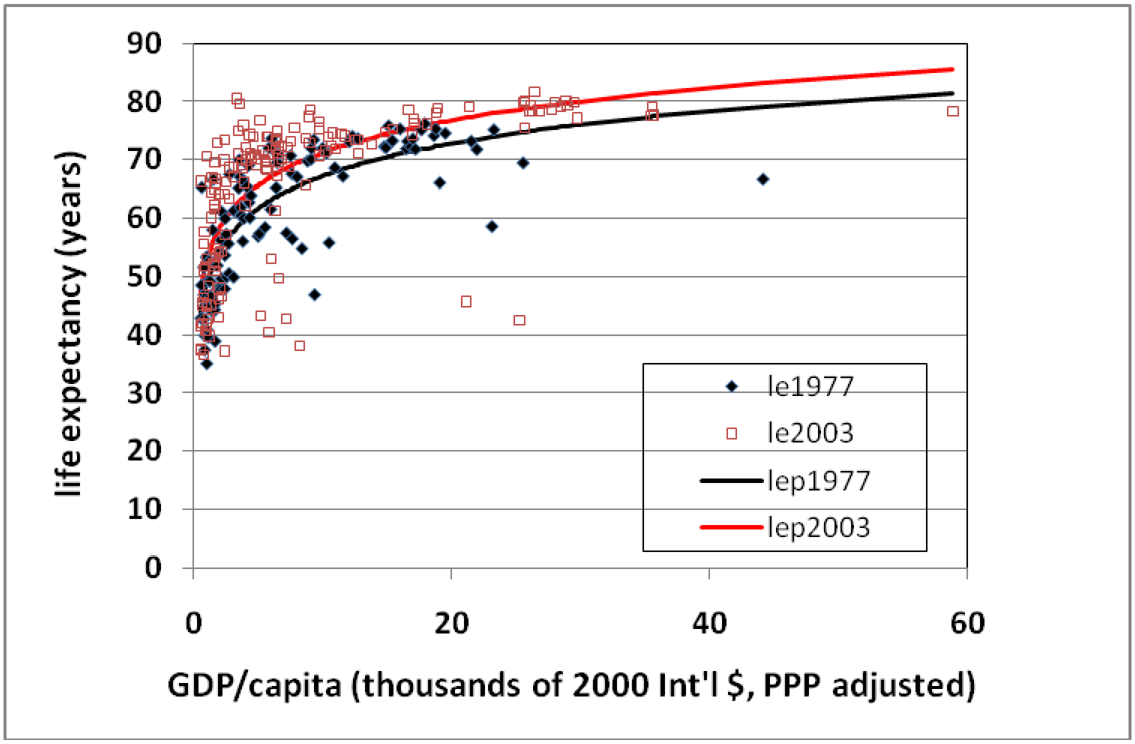


Figure 10.2.5. Life expectancy vs. per-capita GDP across countries, 1977–2003. Source: Goklany (2007b).

Longer-term analyses of climate-sensitive indicators of human well-being show the combination of economic growth and technological change can, over decades, reduce negative impacts on human beings by an order of magnitude – that is, a factor of ten – or more. In some instances, this combination has virtually eliminated such negative impacts. For instance, during the twentieth century, deaths from various climate-sensitive waterborne diseases were all but eliminated in the United States. From 1900 to 1970, U.S. per-capita GDP nearly quadrupled, while deaths from malaria were eliminated and death rates for gastrointestinal disease fell by 99.8 percent (Maddison 2010; Goklany 2009a). From 1900 to 1997 per-capita GDP rose sevenfold while deaths from typhoid and paratyphoid were eliminated, and from 1900 to 1998 the death rate for dysentery fell by 99.6 percent (Goklany 2009a). Similarly, since the 1920s global per-capita GDP has risen fivefold while aggregate global death rates from all extreme weather events were reduced by 98 percent and death rates from droughts have fallen by 99.99 percent.

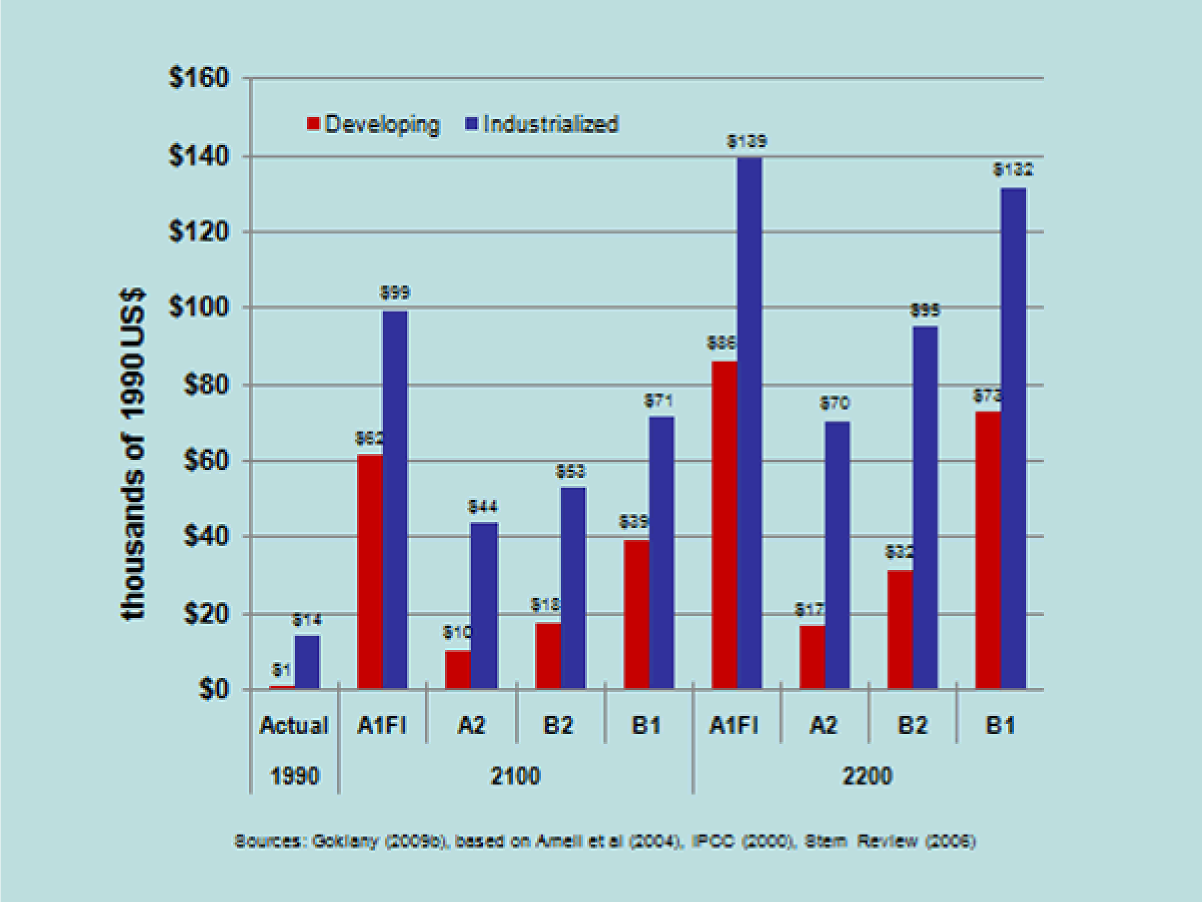
These trends suggest global warming impact analyses that extend more than two or three decades into the future should account for the *compounded* increases in adaptive capacity from increasing per-capita income and secular technological change. Higher adaptive capacity enables a society to adapt, overcome, and even thrive in the presence of climate changes that, in their absence, might be expected to cause hardships. The models used by the IPCC and other voices in the debate over global warming incorporate this economic growth in their emission and climate change scenarios, but fail to take it into account when projecting society's response to whatever climate change those emissions might generate. As a result, these models almost invariably tend to overestimate the net future damages from climate change.

10.2.2. Future Income and Human Well-being in a Warmer World

Virtually all impact assessments undertaken since 2000 have relied on the IPCC (2000) temperature and emissions scenarios, all of which assume substantial economic growth in both developing and industrialized countries (Arnell et al. 2002). Using the insights gained from the previous section, what can we say about the future adaptive capacities and human well-being under these scenarios?

One way to answer the question is to accept the economic assumptions built into the various IPCC scenarios and the resulting estimates of per-capita income for developing and industrialized countries in the absence of any future climate change relative to the base year. Then we can adjust these estimates downward to account for the highest estimates of the losses due to climate change based on the same IPCC scenarios. For the latter, we rely on the highest damage estimates from Stern et al. (2006), a report that anchors the alarmist end of studies of the potential impact of climate change. Figure 10.2.6 shows the results of that highest exercise.

Figure 10.2.6 provides per-capita GDP for 1990, the base year used by the IPCC's emissions scenarios, and estimates of future per-capita GDP in 2100, using four IPCC reference scenarios for areas that comprise today's developing and industrialized countries. It also provides estimates for 2200, as detailed below. As indicated, the net per-capita GDP is calculated by subtracting the equivalent costs per capita of global warming, as reported by Stern et al., from per-capita GDP in the absence of any warming (unadjusted per-capita GDP) as forecast by the IPCC.



Sources: Goklany (2009b), based on Arnell et al (2004), IPCC (2000), Stern Review (2006)

Figure 10.2.6. Net per-capita GDP, 1990–2200, after accounting for losses due to global warming for four major IPCC emission and climate scenarios. See text for definitions. Source: Goklany (2009c).

For 2100 and 2200, the scenarios are arranged from the warmest (A1FI) on the left to the coolest (B1) on the right. The average global temperature increases from 1990 to 2085 for the scenarios are as follows: 4°C for A1FI, 3.3°C for A2, 2.4°C for B2, and 2.1°C for B1.

Unlike most other studies, Stern et al. account for losses due not only to market impacts of global warming but also to nonmarket (i.e., environmental and public health) impacts, plus the risk of catastrophe (see, e.g., Freeman and Guzman 2009, 127). Thus, the net per-capita income shown in Figure 10.2.6 is a good surrogate for human well-being.

For context, in 2006, per-capita GDP for industrialized countries was $19,300; for the United States, $30,100; and for developing countries, $1,500.

Also, the figure uses the Stern Review's 95th percentile (upper bound) estimate of the losses in GDP due to global warming. Per the Stern Review, these costs amount to 7.5 percent of global GDP in 2100 and 35.2 percent in 2200. These losses are adjusted downward for the cooler scenarios per Goklany (2007c, 2009c). Many economists believe even the central estimates of the Stern Report overstate losses due to global warming. Tol (2008), for example, observes, "[The Stern Review's] impact estimates are pessimistic even when compared to other studies in the gray literature and other estimates that use low discount rates" (p. 9).

For 2200, the unadjusted per-capita GDP is assumed to be double that in 2100, which is equivalent to a compounded annual growth rate of 0.7 percent, which is less than the Stern Review assumption of 1.3 percent. Thus, we substantially understate the unadjusted per-capita GDP and, therefore, also the net per-capita GDP, in 2200.

The answer to our question, as shown in Figure 10.2.6, is that future societies – whether developing or industrialized – will be much wealthier in 2100 and 2200 despite any global warming and despite the various assumptions designed to overstate losses from global warming and understate the unadjusted per-capita GDP in the absence of any warming. And their well-being will be correspondingly higher. In fact, under the IPCC's warmest scenario, which would increase globally averaged temperature by 4°C from 1990 to 2085, net per-capita GDP in developing countries in 2100 will be *double* the 2006 level of the United States, and *triple* that level in 2200. Thus, even developing countries' future ability to cope with climate change and, more importantly, their levels of well-being would be much better than that of the United States today.

Additional implications of the above exercise are:

- For populations living in countries currently classified as "developing," net per-capita GDP (after subtracting the cost of global warming) will be at least 11–65 times higher in 2100 than it was in the base year. It will be even higher (at least 18–95 times) in 2200.
- Industrialized countries will have net per-capita GDP three to seven times higher in 2100 than in 1990. In 2200 it will be five to ten times higher.
- Net per-capita GDP in today's developing countries will be higher in 2200 than it was in industrialized countries in the base year (1990) under all scenarios, despite global warming. That is, regardless of any global warming, populations living in today's developing countries will be better off in the future than people currently inhabiting those nations. This is also true for 2100 for all but the "poorest" (A2) scenario.
- Under the warmest scenario (A1FI), the one that prompts many of the apocalyptic warnings about global warming, net per-capita GDP of inhabitants of developing countries in 2100 ($61,500) will be double that of the United States in 2006 ($30,100), and almost triple in 2200 ($86,200 versus $30,100). [All dollar estimates are in 1990 US dollars.]

In other words, everywhere – even in developing countries – people will be wealthy by today's standards, and their adaptive capacity and well-being should be correspondingly higher. Therefore, even if one assumes that there would be no secular technological change – no new or improved technologies, nor would the price of technology drop between the 1990s – and 2100 – developing countries' adaptive capacity would on average far exceed that of the United States today. Therefore, although claims that developing countries will be unable to cope with climate change (UNEP 1993) might have been true for the world of 1990 (the base year), they simply would not hold for the world of 2100 under the assumptions built into the IPCC scenarios and the Stern Review's own (exaggerated) analysis.

The problems of poverty that warming supposedly would exacerbate (such as low agricultural productivity, hunger, malnutrition, malaria, and other vector-borne diseases) would be reduced if not eliminated by 2100, even if one ignores (contrary to the lessons of history captured in Figures 10.2.1 through 10.2.5) any secular technological change that ought to occur in the interim. Tol and Dowlatabadi (2001), for example, show malaria has been functionally eliminated in a society whose annual per-capita income reaches $3,100. Therefore, even under the poorest scenario (A2), the average developing country should be free of malaria well before 2100, even assuming no technological change in the interim.

Similarly, if the lower bound of the average net per-capita GDP in 2100 for developing countries is $10,000–$62,000, then their farmers would be able to afford technologies that are unaffordable today (such as precision agriculture) as well as new technologies that should come on line by then (such as drought-resistant seeds formulated for specific locations).

It may be argued that the high levels of economic development depicted in Figure 10.2.6 are unlikely. But these are the estimates built into the IPCC emission scenarios. If they are overestimates, then so are the estimates of emissions, temperature increases, and impacts and damages of global warming projected by the IPCC.

10.2.3. Systematic Overestimation of Negative Impacts Cited by the IPCC

It is possible to obtain an idea of whether and to what extent the impact assessments used in the IPCC's latest assessment report account for changes in adaptive capacity over time. Consider the so-called Fast Track Assessments (FTAs) of the global impacts of climate change. These British government-sponsored FTAs, which were state-of-the-art at the time of the writing of the IPCC's Fourth Assessment Report (AR4WG2), have an impeccable provenance from the point of view of proponents of greenhouse gas controls. Many of the FTA authors were major contributors to the IPCC's Third and Fourth Assessments (IPCC, 2001; 2007). For instance, the lead author of the FTA's hunger assessments (Parry et al., 1999; 2004), Professor Martin Parry, was co-chair of IPCC Working Group 2 during its latest (2007) assessment. Similarly, the authors of the FTA's water resources and coastal flooding studies also were lead authors of corresponding chapters in the same IPCC Fourth Assessment Report.

An evaluation of the FTA methodologies shows the following shortcomings:

- The water resources study (Arnell 2004) completely ignores adaptation even though many adaptations to water-related problems – such as building dams, reservoirs, and canals – are already-existing technologies and, in fact, are among mankind's oldest adaptations (Goklany 2007c, pp. 1034–35).
- The study of agricultural productivity and hunger (Parry et al. 2004) allows for increases in crop yield with economic growth due to greater usage of fertilizer and irrigation in richer countries, decreases in hunger due to economic growth, some secular (time-dependent) increase in agricultural productivity, and some farm level adaptations to deal with climate change. But these adaptations are based on 1990s technologies instead of technologies that would be available at the time for which impacts are estimated (i.e., 2025, 2055, and 2085 in the FTA). Nor do Parry et al. account for any technologies developed specifically to cope with the negative impacts of global warming or take advantage of any positive outcomes (Parry et al., 2004, 57; Goklany 2007c, pp. 1032–33). The potential for future technologies to cope with climate change is large, especially bioengineered crops and precision agriculture (Goklany, 2007b; 2007c).
- The Nicholls (2004) study on coastal flooding from sea level rise makes an effort to incorporate improvements in adaptive capacity resulting from increasing wealth, but it includes several questionable assumptions. First, it assumes societies will implement measures to reduce the risk of coastal flooding in response to 1990 surge conditions, but not to subsequent sea level rise (p. 74). This defies logic. One should expect that any measures implemented would consider the latest available data and information on the surge situation at the time the measures are initiated. That is, if the measure is initiated in, say, 2050, the measure's design would at least consider sea level and sea level trends as of 2050, rather than the 1990 level. By that time, we should know the rate of sea level rise with much greater confidence. Second, Nicholls assumes a constant lag time between initiating protection and sea level rise. But one should expect that if sea level continues to rise, the time lag between upgrading protection standards and higher per-capita GDP will be reduced over time, and might even turn negative. That is, the further we go into the future, if sea level rise accelerates (as indicated by some models), then it is more likely adaptations would be anticipatory rather than reactive, particularly as societies become more affluent (as the IPCC scenarios assume they will) (see Figure 20.2.6). Third, Nicholls does not allow for any deceleration in the preferential migration of the population to coastal areas, as is likely if coastal storms and flooding become more frequent and costly (Goklany 2007b, pp. 1036–37).
- The analysis for malaria undertaken by van Lieshout et al. (2004) incorporates adaptive capacity as it existed in 1990 (the base year) but does not adjust it to account for any subsequent advances in economic and technological development. There is simply no justification for such an assumption. If the IPCC's assumptions about future economic development are even half right, it is, as already noted, likely that malaria will have been eliminated by 2100.

Consideration of both economic development and technological change would make a large difference in the estimated impact of global warming on humanity. If impacts were to be estimated for five or so years into the future, ignoring changes in adaptive capacity between now and then probably would not be fatal, because neither economic development nor technological change likely would advance substantially during such a brief period. However, the time horizon of climate change impact assessments is often 35 to 100 years or more beyond the base year. The Fast Track Assessments, for example, use a base year of 1990 to estimate impacts for 2025, 2055, and 2085. The Stern Review's time horizon extends to 2100–2200 and beyond. Over such periods one ought to expect substantial advances in adaptive capacity due to increases in economic development, technological change, and human capital.

The assumption that few or no improved or new technologies would become available between 1990 and 2100 (or 2200) is clearly unfounded. From 1990 to 2005, for example, the portion of the developing world's population living in absolute poverty declined from 42 percent to 25 percent (World Bank 2009, 47). In Sub-Saharan Africa, the proportion of Internet users increased from 0 to 74 million from 1990 to 2009, and the proportion of cellular phone users went from 0 per 100 to 37 per 100 (World Bank 2011).

Some of the newer impact assessments have begun to account for changes in adaptive capacity. For example, Yohe et al. (2006), in an exercise exploring the vulnerability to climate change under various climate change scenarios, allowed adaptive capacity to increase between the present and 2050 and 2100. However, the researchers arbitrarily limited any increase in adaptive capacity to "either the current global mean or to a value that is 25 percent higher than the current value – whichever is higher" (Yohe et al., 2006, p. 4). There is no rationale for such an assumption: Such a limitation would have missed, for example, most of the increase in U.S. adaptive capacity during the twentieth century that virtually eliminated death and disease from climate-sensitive water-borne vector diseases.

More recently, Tol et al. (2007) analyzed the sensitivity of deaths from malaria, diarrhea, schistosomiasis, and dengue to warming, economic development, and other determinants of adaptive capacity through the year 2100. Their results indicate, unsurprisingly, that consideration of economic development alone could reduce mortality substantially. For malaria, for instance, deaths would be eliminated before 2100 in several of the more affluent Sub Saharan countries (Tol et al., 2007, p. 702). This is a much more realistic assessment of the impact of global warming on malaria in a wealthier (if not more technologically advanced) world than the corresponding FTA study. It is also more consistent with long-term trends in the extent of malaria, which indicate that the extent of *P. falciparum* malaria – the most deadly kind – declined from 58 percent of the world's land surface around 1900 to 30 percent by 2007 (Gething et al. 2010). Finally, it should be noted that it is precisely the failure to account for the combination of economic and technological development that caused high-profile prognostications such as Malthus's original conjecture about running out of cropland, *The Limits to Growth*, and Paul Ehrlich's over-population warning, *The Population Bomb*, to turn out to be so wrong. (Goklany 2007b; 2009a). And there is no reason to believe that the IPCC impact projections will not be just as wrong, unless economic and technological development is stymied.

References

Arnell, N.W. 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global Environmental Change* **14** (1): 31–52.

Arnell, N.W., Cannell, M.G.R., Hulme, M., Kovats, R.S., Mitchell, J.F.B., Nicholls, R.J., Parry, M.L., Livermore, M.T.J., and White, A. 2002. The consequences of CO_2 stabilization for the impacts of climate change. *Climatic Change* **53**: 413–446.

Ausubel, J.H. 1991. Does climate still matter? *Nature* **350**: 649–652.

Freeman, J. and Guzman, A. 2009. Climate change and U.S. interests. *Columbia Law Review* **100**: 101–171 (Version 3.1, dated 09/13/2009).

Gething, P.W., Smith, D.L., Patil, A.P., Tatem, A.J., Snow, R.W., and Hay, S.I. 2010. Climate change and the global malaria recession. *Nature* **465**: 342–345.

Goklany, I.M. 1995. Strategies to enhance adaptability: technological change, economic growth and free trade. *Climatic Change* **30**: 427–449.

Goklany, I.M. 2007a. Integrated strategies to reduce vulnerability and advance adaptation, mitigation, and sustainable development. *Mitigation and Adaption Strategies for Global Change* DOI 10.1007/s11027-007-9098-1.

Goklany, I.M. 2007b. *The Improving State of the World*. Washington, DC: Cato Institute.

Goklany, I.M. 2007c. Is a richer-but-warmer world better than poorer-but-cooler worlds? *Energy & Environment* **18** (7 and 8): 1023–1048.

Goklany, I.M. 2009a. Have increases in population, affluence and technology worsened human and environmental well-being? *Electronic Journal of Sustainable Development* **1**(3). Available at http://www.ejsd.org/docs/HAVE_INCREASES_IN_POPULATION_AFFLUENCE_AND_TECHNOLOGY_WORSENED_HUMAN_AND_ENVIRONMENTAL_WELL-BEING.pdf.

Goklany, I.M. 2009b. Deaths and death rates from extreme weather events: 1900–2008, *Journal of American Physicians and Surgeons* **14** (4): 102–09.

Goklany, I.M. 2009c. Discounting the future. *Regulation* **32** (Spring): 36–40.

Goklany, I.M. 2009d. Is climate change the "defining challenge of our age"? *Energy & Environment* **20**(3): 279–302.

Intergovernmental Panel on Climate Change (IPCC). 2000. *Special Report on Emissions Scenarios*. New York, NY: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate change 2001. Impacts, adaptation, and vulnerability*. New York, NY: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate change 2007. Impacts, adaptation, and vulnerability*. New York, NY: Cambridge University Press.

Maddison, A. 2010. *Statistics on World Population, GDP and Per Capita GDP, 1-2008 AD*. Available at http://www.ggdc.net/maddison/Historical_Statistics/horizontal-file_02-2010.xls. Visited 15 August 2010.

Morris, J., editor. 2000. *Rethinking Risk and the Precautionary Principle.* Oxford, UK: Butterworth-Heinemann.

Nicholls, R.J. 2004. Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios. *Global Environmental Change* **14** (1): 69–86.

Parry, M., Rosenzweig, C., Iglesias, A., Fischer, G., and Livermore, M. 1999. Climate change and world food security: a new assessment. *Global Environmental Change* **9**: S51–S67.

Parry, M.L., editor. 2004. Special issue: an assessment of the global effects of climate change under SRES emissions and socio-economic scenarios. *Global Environmental Change* **14**: 1–99.

Parry, M.L., Rosenzweig, C., Iglesias, I., Livermore, M., and Fischer, G. 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change* **14** (1): 53–67.

Ridley, M. 2010. *The Rational Optimist: How Prosperity Evolves*. London, UK: Fourth Estate.

Stern, N. et al. 2006. *The Economics of Climate Change*. London, UK: Her Majesty's Treasury.

Tol, R.S.J. and Dowlatabadi, H. 2001. Vector borne diseases, development & climate change. *Integrated Assessment* **2**: 173–181.

Tol, R.S.J., Ebi, K.L., and Yohe, G.W. 2007. Infectious disease, development, and climate change: a scenario analysis. *Environment and Development Economics* **12**: 687–706.

Tol, R,S.J. 2008. The social cost of carbon: trends, outliers and catastrophes. *Economics: The Open-Access, Open-Assessment E-Journal* **2**: 2008–25. Available at http://www.economics-ejournal.org/economics/journalarticles/2008-25.

United Nations Environment Programme (UNEP). 1993. *Climate change and North-South relations*. Climate change fact sheet 109. UNEP, May 1. Available at http://unfccc.int/resource/ccsites/senegal/fact/fs109.htm. Visited 12 May 2003.

Van Lieshout, M., Kovats, R.S., Livermore, M.T.J., and Marten, P. 2004. Climate change and malaria: analysis of the SRES climate and socio-economic scenarios. *Global Environmental Change* **14** (1): 87–99.

World Bank 2009. *Global Economic Prospects 2009*. Available at http://siteresources.worldbank.org/INTGEP2009/Resources/10363_WebPDF-w47.pdf. Visited 19 August 2010.

World Bank. 2011. World Bank Data Search, available http://databank.worldbank.org/ddp/home.do?Step=3&id=4. Visited 13 June 2011.

World Health Organization (WHO). 2009. *Global Health Risks: Mortality and Burden of Disease Attributable to Selected Major Risks*. Geneva, Switzerland: WHO. Available at http://www.who.int/healthinfo/global_burden_disease/global_health_risks/en/index.html.

Yohe, G., Malone, E., Brenkert, A., Schlesinger, M., Meij, H. Xing, X., and Lee, D. 2006. A Synthetic Assessment of the Global Distribution of Vulnerability to Climate Change from the IPCC Perspective that Reflects Exposure and Adaptive Capacity. Palisades, NY: CIESIN (Center for International Earth Science Information Network), Columbia University. Available at http://sedac.ciesin.columbia.edu/mva/ccv/.

10.3. Biofuels

Biofuels are fuels made from organic matter. They include liquid fuels such as ethanol, biodiesel, and methanol; gaseous fuels such as methane and carbon monoxide; and solid fuels such as biochar and the more traditional charcoal. Biofuels may have some environmental advantages over gasoline and diesel fuels, but they are more expensive to produce and cannot supply more than a small part of the world's total transportation energy needs. And because they compete with food crops and nature for land, water, and nutrients, expanding the use of biofuels could negatively affect human health and natural ecosystems.

The 2009 NIPCC report (Idso and Singer, 2009) addressed the likely adverse consequences of expanding the use of biofuels as reported by several scientists in the peer-reviewed literature. Here we document additional studies that raise similar concerns but were published after those discussed in the 2009 report.

We begin with the study of Delucchi (2010), who is associated with the Institute of Transportation Studies at the University of California, Davis (USA). Delucchi writes, "governments worldwide are promoting the development of biofuels, such as ethanol from corn, biodiesel from soybeans, and ethanol from wood or grass, in order to reduce dependency on oil imported from politically unstable regions of the world, spur agricultural development, and reduce the climate impact of fossil fuel combustion." In light of the magnitude of this endeavor, Delucchi reviews what has been learned by many other students of the subject, after which he discusses "the impacts of biofuels on climate change, water use, and land use."

Delucchi's analysis leads him to state, "it is likely that biofuels produced from crops using conventional agricultural practices will *not* mitigate the impacts of climate change." They will instead "exacerbate stresses on water supplies, water quality, and land use, compared with petroleum fuels." He quotes Phalan (2009) as stating, "if risks and uncertainties are inadequately assessed and managed, even the best biofuels have the potential to damage the poor, the climate and biodiversity."

"To avoid these problems," in Delucchi's words, "biofuel feedstocks will have to be grown on land that has no alternative commercial use and no potential alternative ecological benefits, in areas with ample rainfall or groundwater, and with little or no inputs of fertilizers, chemicals, and fossil fuels." He adds, "it is not clear that it can be done economically and sustainably at large scales."

In a paper focusing on economics, Bryan et al. (2010) "assessed the potential benefits, costs, and trade-offs associated with biofuels agriculture to inform bioenergy policy." Specifically, they "assessed different climate change and carbon subsidy scenarios in an 11.9 million hectare region in southern Australia," where they "modeled the spatial distribution of agricultural production, full life-cycle net greenhouse gas (GHG) emissions and net energy, and economic profitability for both food agriculture (wheat, legumes, sheep rotation) and biofuels agriculture (wheat, canola rotation for ethanol/biodiesel production)."

Results indicated "biofuels agriculture was more profitable over an extensive area of the most productive arable land," producing "large quantities of biofuels" that "substantially increased economic profit." The end result, however, was "only a modest net GHG abatement" that had "a negligible effect on net energy production." In addition, they indicate the economic profit was largely due to "farm subsidies for GHG mitigation" and that whatever benefits were accrued came "at the cost of substantially reduced food and fiber production."

Examining the issue from a different angle, Erisman et al. (2010) state, "there is much discussion on the availability of different biomass sources for bioenergy application and on the reduction of greenhouse gas emissions compared to [emissions from] conventional fossil fuels," but "there is much less discussion on the other effects of biomass, such as the acceleration of the nitrogen cycle through increased fertilizer use resulting in losses to the environment and additional emissions of oxidized nitrogen." Erisman et al. thus provide "an overview of the state of knowledge on nitrogen and biofuels," particularly as pertaining to several sustainability issues.

According to the five researchers, "the contribution of N_2O emissions from fertilizer production and application make the greenhouse gas balance for certain biofuels small positive or even negative for some crops compared to fossil fuels" because "N_2O is a 300 times more effective greenhouse gas than CO_2" and N_2O emissions in the course of biofuel production "might be a factor 2–3 [times] higher than estimated up until now from many field trials." In addition, they mention several other nitrogen-related environmental impacts of biofuel production, including modification of land for the growing of biofuels, wastes associated with biomass processing, and the "pollution entailed in constructing and maintaining equipment, transportation and storage facilities," as well as "the higher levels of eutrophication, acidification and ozone depletion" associated with biofuels due to the nitrogenous compounds released to the atmosphere during their agricultural production.

In a contemporaneous article published in *Ecological Applications*, Bouwman et al. (2010) assessed the global consequences of implementing first- and second-generation bioenergy production in the coming five decades. They focused on the nitrogen cycle and used "a climate mitigation scenario from the Organization for Economic Cooperation and Development's (OECD's) Environmental Outlook, in which a carbon tax is introduced to stimulate production of biofuels from energy crops." They calculated "the area of energy crops will increase from 8 Mha in the year 2000 to 270 Mha (14% of total cropland), producing 5.6 Pg dry matter per year (12% of energy use) in 2050." They also found "this production requires an additional annual 19 Tg of N fertilizer in 2050 (15% of total), and this causes a global emission of 0.7 Tg of N_2O-N (8% of agricultural emissions), 0.2 Tg NO-N (6%), and 2.2 Tg of NH_3--N (5%)." In addition, they observed, "2.6 Tg of NO_3--N will leach from fields under energy crops."

What might be some of the unfavorable impacts of these consequences of carbon-tax-supported biofuel production? For starters, the three employees of the Netherlands Environmental Assessment Agency note the greenhouse gas emissions that are supposed to be reduced by using biofuels instead of fossil fuels "are offset by 20% in 2030 and 15% in 2050 if N_2O emission from the cultivation of energy crops is accounted for." And even this blowback is but a fraction – 30–60 percent for maize and sugar cane, according to Bouwman et al. – "of total emissions from the cultivation, processing, and transportation of biofuels." In addition, they write, "on a regional scale, increased N leaching, groundwater pollution, eutrophication of aquatic and terrestrial ecosystems, N_2O and NH_3 emissions from energy crop production, and NO_X emissions from combustion of biofuels may cause relevant loss of human and ecosystem health." With respect to the availability of land for the growing of biofuels, Bouwman et al. write, "the OECD-GC scenario shows a rapid expansion of agricultural land, mainly in Africa and the former Soviet Union," and "this expansion will lead to a further loss of biodiversity." The authors conclude by saying "bioenergy is economically feasible," but only "because of the climate change policies" that are "implemented through carbon taxes."

In an article published in the *Journal of Plant Nutrition and Soil Science*, Rattan Lal (Lal, 2010) of the Carbon Management and Sequestration Center of Ohio State University (USA) introduces the subject of his concern by writing, "the world is faced with the trilemma of climate change, food insecurity, and energy demand." He states, (1) "there still are more than one billion food-insecure people in the world (FAO, 2009a,b)," (2) "the world food supply will have to be doubled between 2005 and 2050 (Borlaug, 2009) because of the increase in population and change in dietary preferences," and (3) "the world energy demand is also increasing rapidly and is projected to increase by 84% by 2050 compared with 2005." What makes the problem even worse, he observes, is that in an attempt to meet the anticipated increase in the global demand for energy, "the emphasis on biofuels is strongly impacting the availability of grains for food and soil resources for grain production."

In response to this latter problem, Lal notes, crop residues are being "widely considered as a source of lignocellulosic biomass." However, he states that removal of crop residues for this purpose "is not an option (Lal, 2007) because of the negative impacts of removal on soil quality, and increase in soil erosion (Lal, 1995)" and the loss of the residue's "positive impacts" on "numerous ecosystem services." Therefore, observing yet another shift in tactics, Lal reports that degraded soils are being considered as possible sites for establishing energy plantations. However, Lal (2010) notes, the extremely low capacity for biomass production from these soils means the amount of biofuel produced on globally abandoned agricultural land cannot even meet 10 percent of the energy needs of North America, Europe, and Asia, citing the work of Campbell et al. (2009) in this regard. Yet even these considerations are only half the problem.

In addition to the need for a considerable amount of land, the "successful establishment of energy plantations also needs plant nutrients" and an "adequate supply of water," Lal notes. An adequate supply of water is on the order of 1,000 to 3,500 liters per liter of biofuel produced, which is, as Lal puts it, "an important factor." And he notes this strategy also will "increase competition for limited land and water resources thereby increasing food crop and livestock prices (Wise et al., 2009)."

In closing, Lal writes society should not take its precious resource base for granted, stating, "if soils are not restored, crops will fail even if rains do not; hunger will perpetuate even with emphasis on biotechnology and genetically modified crops; civil strife and political instability will plague the developing world even with sermons on human rights and democratic ideals; and humanity will suffer even with great scientific strides."

Additional concerns over the use of biofuels have been expressed by other authors. In a paper published in the *Journal of Agricultural and Environmental Ethics*, Gomiero et al. (2010) examine the wisdom of appropriating much of the planet's land and water resources to support large-scale production of biofuels as replacements for fossil fuels. They come to several damning conclusions about the enterprise.

They report there is not enough readily available land to produce much fuel from biomass without causing a severe impact on global food production, while adding, "even allocating the entire USA cropland and grassland to biofuels production, the energy supply will account for only a few percentage points of the USA energy consumption," which suggests "there is no hope for biomass covering an important share of USA energy demand." Noting "the same is true for the European Union," the researchers go on to observe that "biofuel production cannot, in any significant degree, improve the energy security of developed countries," for to do so "would require so vast an allocation of land that it would be impossible for a multitude of reasons."

Another problem Gomiero et al. observe is that biofuel production, including cellulosic ethanol from crop residues and grasslands, "does not appear to be energetically very efficient." In fact, they note, fierce debates have arisen over whether the energy output/input ratio of various biofuel production enterprises is 0.2 of a unit above or below 1.0, which seems rather small in light of another item they report, that "our industrial society is fueled by fossil fuels that have an output/input ratio 15–20 times higher." Indeed, they write that recent assessments demonstrate extensive biofuels production may actually tend to "exacerbate greenhouse gas emissions and in turn global warming." They also state biofuels "may greatly accelerate" the destruction of natural ecosystems and their biodiversity by "the appropriation of far too large a fraction of net primary production," thus resulting in a threat to their "health, soil fertility, and those key services needed by human society."

In concluding, Gomiero et al. warn "biofuels cannot be either our energy panacea, nor supply even a minimal share of energy supply for our society without causing major social and environmental problems." Therefore, they suggest we use our "hard earned money," as they put it, to "help farmers, both in developed and developing countries, to adopt energy saving-environmentally friendly agricultural practices, that can really help to cut greenhouse gas emissions, prevent soil erosion, reduce water consumption, relieve the environment from toxic pollutants, preserve wild and domesticated biodiversity and supply many other services." And as the three scientists advise in their concluding sentence, "we should be careful not to let our 'energetic despair' (or vested interest) lead us to worsen the very same environmental and social problems we wish and need to solve."

Introducing their contribution to the subject, Gelfand et al. (2010) write, "recently, the prospect of biofuel production on a large scale has focused attention on energy efficiencies associated with different agricultural systems and production goals," but "few empirical studies comparing whole-system multiyear energy balances are available." In fact, they state that as far as they are aware, "there are no studies that directly compare food vs. fuel production efficiencies in long-term, well-equilibrated cropping systems with detailed descriptions of fossil energy use."

To begin filling this data void, Gelfand et al., as they describe it, "used 17 years of detailed data on agricultural practices and yields to calculate an energy balance for different cropping systems under both food and fuel scenarios." They examined one forage and four grain systems in the U.S. Midwest that included "corn-soybean-wheat rotations managed with (1) conventional tillage, (2) no till, (3) low chemical input, and (4) biologically based (organic) practices, and (5) continuous alfalfa," and "compared energy balances under two scenarios: all harvestable biomass used for food versus all harvestable biomass used for biofuel production."

The three researchers report "energy efficiencies ranged from output:input ratios of 10 to 16 for conventional and no-till food production and from 7 to 11 for conventional and no-till fuel production, respectively." Such a result, Gelfand et al. write, "points to a more energetically efficient use of cropland for food than for fuel production," and the large differences in efficiencies attributable to the different management techniques they evaluated suggest there are "multiple opportunities for improvement."

Exploring a different aspect of the debate, Witt (2010) notes "several studies in the last five years have warned against the potential impact of promoting biofuel crops that are known to be invasive or to have potentially invasive characteristics," citing the studies of Raghu et al. (2006), Barney and DiTomaso (2008), Howard and Ziller (2008), and Buddenhagen et al. (2009). Witt notes "a large number of proposed biofuel crops share the same traits as known invasive plant species," and many of them "are already present in Africa." In light of these observations, Witt assesses the impacts of several species of the invasive *Prosopis* genus in Kenya and South Africa, where the spiny trees and shrubs have invaded more than four million hectares of crop and pasture land.

Witt writes, "communities in Kenya and elsewhere are becoming increasingly concerned about the displacement of other species important for local livelihoods, especially fodder species for livestock." They are also concerned, he continues, about the invasive species' encroachment onto "paths, dwellings, water sources, farms and pastureland" and their "negative impacts on animal and human health with injuries due to thorns resulting in some human fatalities," citing Mwangi and Swallow (2005) and Maundu et al. (2009). In addition, he notes the plants' tendency to invade riparian zones, dry river beds, and lowlands, where they "tap into underground water sources," means they "interfere with drainage, blocking watercourses and exacerbating the effects of flooding." Witt states the displacement of native plants by *Prosopis* species is especially serious, noting "the World Health Organization estimates that up to 80% of the world's rural populations depend on [native] plants for their primary health care."

Witt concludes that nonnative species that are known to be invasive elsewhere and have been deemed to be a high-risk species "should not be introduced and cultivated," because "the costs associated with invasive species, even those that are deemed to be beneficial, in most cases, outweigh the benefits that accrue from their use." He ends with the warning that "no widespread invasive plant species has been controlled through utilization alone in any part of the world."

Lastly, in a paper published in *AMBIO: A Journal of the Human Environment*, Mulder et al. (2010) assess the connection between water and energy production by conducting a comparative analysis for estimating the energy return on water invested (EROWI) for several renewable and nonrenewable energy technologies using various life cycle analyses. This approach mirrors the energy return on energy investment (EROEI) technique used to determine the desirability of different forms of alternative energy, with the technique's most recent application being adjusted to consider also the global warming potentials of the different forms of non-fossil-fuel energy and the greenhouse gases emitted to the atmosphere in the process of producing and bringing them to the marketplace.

The reason for bringing water into the equation derives from the facts, as noted by Mulder et al., that (1) "water withdrawals are ubiquitous in most energy production technologies," (2) "several assessments suggest that up to two-thirds of the global population could experience water scarcity by 2050 (Vorosmarty et al., 2000; Rijsberman, 2006)," (3) "human demand for water will greatly outstrip any climate-induced quantity gains in freshwater availability (Vorosmarty et al., 2000; Alcamo et al., 2005)," and (4) the increased need for more fresh water "will be driven by the agricultural demand for water which is currently responsible for 90% of global freshwater consumption (Renault and Wallender, 2006)."

The three U.S. researchers state their results suggest "the most water-efficient, fossil-based technologies have an EROWI one to two orders of magnitude greater than the most water-efficient biomass technologies, implying that the development of biomass energy technologies in scale sufficient to be a significant source of energy may produce or exacerbate water shortages around the globe and be limited by the availability of fresh water."

In considering the policy ramifications, these findings will not be welcomed by those who promote biofuel production as a means of combating what they call "the threats posed by 'climate refugees' and 'climate conflict' to international security," as discussed by Hartmann (2010) in the *Journal of*

International Development, where she identifies some of the principals in the spreading of what she calls this "alarmist rhetoric" to various United Nations agencies, NGOs, national governments, security pundits, the popular media, and, specifically, the Norwegian Nobel Committee of 2007, which, as she describes it, "warned that climate-induced migration and resource scarcity could cause violent conflict and war within and between states when it awarded the Nobel Peace Prize to Al Gore, Jr. and the Intergovernmental Panel on Climate Change."

Hartmann goes on to suggest "this beating of the climate conflict drums has to be viewed in the context of larger orchestrations in U.S. national security policy." And in this regard it is clear that the promotion of biofuels to help resolve these concerns will only exacerbate them in one of the worst ways imaginable, providing a "cure" that is worse than the disease.

Hartmann notes, "in the United States, members of Congress eager to pass climate legislation" – which will likely *mandate* the use of more biofuels – "have resorted to the security threat argument as a way to win support on Capitol Hill." She answers this by remarking that "according to the *New York Times* (2009), 'many politicians will do anything for the Pentagon.'"

Clearly, there are various motives involved in the debate over possible CO_2-induced climate change and what to do about it. Yet, it is equally clear that there simply is not enough land or fresh water on the face of the Earth to make the production of biofuels a viable and significant alternative to the mining and usage of fossil fuels.

References

Alcamo, J., van Vuuren, D., Ringler, C., Cramer, W., Masui, T., Alder, J., and Schulze, K. 2005. Changes in nature's balance sheet: model based estimates of future worldwide ecosystem services. *Ecology and Society* **10**: http://www.ecologyandsociety.org/vol10/iss2/art19/.

Barney, J.N. and DiTomaso, J.M. 2008. Nonnative species and bioenergy: are we cultivating the next invader? *BioScience* **58**: 64–70.

Borlaug, N.E. 2009. Foreword. *Food Security* **1**: 1.

Bouwman, A.F., van Grinsven, J.J.M., and Eickhout, B. 2010. Consequences of the cultivation of energy crops for the global nitrogen cycle. *Ecological Applications* **20**: 101–109.

Bryan, B.A., King, D., and Wang, E. 2010. Biofuels agriculture: landscape-scale trade-offs between fuel, economics, carbon, energy, food, and fiber. *Global Change Biology Bioenergy* **2**: 330–345.

Buddenhagen, C.E., Chimera, C., and Clifford, P. 2009. Assessing biofuel crop invasiveness: a case study. *PLoS One* **4**: 1–6.

Campbell, J.E., Lobell, D.B., and Field, C.B. 2009. Greater transportation energy and GHG offsets from bioelectricity than ethanol. *Science* **324**: 1055–1057.

Delucchi, M.A. 2010. Impacts of biofuels on climate change, water use, and land use. *Annals of the New York Academy of Sciences* **1195**: 28–45.

Erisman, J.W., van Grinsven, H., Leip, A., Mosier, A., and Bleeker, A. 2010. Nitrogen and biofuels: an overview of the current state of knowledge. *Nutrient Cycling in Agroecosystems* **86**: 211–223.

Food and Agriculture Organization (FAO). 2009a. 1.02 billion people hungry. FAO Newsroom, http://www.fao.org/news/story/on/item/20568/icode/.

Food and Agriculture Organization (FAO). 2009b. FAO Statistics Database. Rome, Italy: FAO.

Gelfand, I., Snapp, S.S., and Robertson, G.P. 2010. Energy efficiency of conventional, organic and alternative cropping systems for food and fuel at a site in the U.S. Midwest. *Environmental Science and Technology* **44**: 4006–4011.

Gomiero, T., Paoletti, M.G., and Pimentel, D. 2010. Biofuels: efficiency, ethics, and limits to human appropriation of ecosystem services. *Journal of Agricultural and Environmental Ethics* **23**: 403–434.

Hartmann, B. 2010. Rethinking climate refugees and climate conflict: rhetoric, reality and the politics of policy discourse. *Journal of International Development* **22**: 233–246.

Howard, G. and Ziller, S. 2008. Alien alert – plants for biofuel may be invasive. *Bioenergy Business* **July/August**: 14–16.

Idso, C.D. and Singer, S.F. 2009. *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

Lal, R. 1995. Erosion-crop productivity relationships for soils of Africa. *Soil Science Society of America Journal* **59**: 661–667.

Lal, R. 2007. There is no such thing as a free biofuel from crop residues. *CSA News* **52**: 12–13.

Lal, R. 2010. Managing soils for a warming earth in a food-insecure and energy-starved world. *Journal of Plant Nutrition and Soil Science* **173**: 4–15.

Maundu, P., Kibet, S., Morimoto, Y., Imbumi, M., and Adeka, R. 2009. Impact of *Prosopis juliflora* on Kenya's semi-arid and arid ecosystems and local livelihoods. *Biodiversity* **10**: 33–50.

Mwangi, E. and Swallow, B. 2005. *Invasion of Prosopis juliflora and Local Livelihoods: Case Study from the Lake Baringo Area of Kenya*. ICRAF Working Paper No. 3. Nairobi, Kenya: World Agroforestry Center.

Mulder, K., Hagens, N., and Fisher, B. 2010. Burning water: A comparative analysis of the energy return on water invested. *Ambio* **39**: 30–39.

New York Times. 2009. The climate and national security. Editorial, 17 August. Available at http://www.nytimes.com/2009/08/18/opinion/18tue1.html?_r=1&adxnnl=1&adxnnlx=1254075176-6uv9m0Js29a+HJeDEXZSFg.

Phalan, P. 2009. The social and environmental impacts of biofuels in Asia: an overview. *Applied Energy* **86**: S21–S29.

Raghu, S., Anderson, R.C., Daehler, C.C., Davis, A.S., Wiedenmann, R.N., Simberloff, D., and Mack, R.N. 2006. Adding biofuels to the invasive species fire? *Science* **313**: 1742.

Renault, D. and Wallender, W. 2006. Nutritional water productivity and diets. *Agricultural Water Management* **45**: 275–296.

Rijsberman, F.R. 2006. Water scarcity: fact or fiction. *Agricultural Water Management* **80**: 5–22.

Vorosmarty, C.J., Green, P., Salisbury, J., and Lammers, R.B. 2000. Global water resources: vulnerability from climate change and population growth. *Science* **289**: 284–288.

Wise, M., Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R., Smith, S.J., Janetos, A., and Edmonds, J. 2009. Implications of limiting CO_2 concentrations for land use and energy. *Science* **324**: 1183–1186.

Witt, A.B.R. 2010. Biofuels and invasive species from an African perspective – a review. *Global Change Biology Bioenergy* **2**: 321–329.

10.4. War and Social Unrest

Many political and opinion leaders say it is important to enact legislation to limit carbon dioxide emissions out of concern that global warming is detrimental to society. High among their list of anxieties is the fear that CO_2-induced global warming will lead to social unrest and perhaps even war, given postulated reductions in agricultural output followed by population turmoil due to lack of food.

An emerging body of research suggests those concerns are not only unfounded, but even backwards – that it is global cooling from which society stands the most to lose. Global warming, by contrast, tends to promote social stability, as evidenced in the peer-reviewed papers discussed below.

China is a good test case for the relationship between global warming and social stability because it has been a well-populated, primarily agricultural country for millennia, and it has a relatively well-recorded history over this period. Accordingly, several researchers have conducted analyses of factors influencing social stability in China. Zhang et al. (2005) note historians typically identify political, economic, cultural, and ethnic unrest as the chief causes of war and civil strife there. However, the five Chinese scientists contend climate plays a key role as well, and to examine their thesis they compared proxy climate records with historical data on wars, social unrest, and dynastic transitions in China from the late Tang to Qing Dynasties (mid-ninth century to early twentieth century).

Their research revealed that war frequencies, peak war clusters, nationwide periods of social unrest, and dynastic transitions were all significantly associated with cold, not warm, phases of China's oscillating climate. Specifically, all three distinctive peak war clusters (defined as more than 50 wars in a ten-year period) occurred during cold climate phases, as did all seven periods of nationwide social unrest and nearly 90 percent of all dynastic changes that decimated this largely agrarian society. They conclude climate change was "one of the most important factors in determining the dynastic cycle and alternation of war and peace in ancient China," with warmer climates having been immensely more effective than cooler climates in terms of helping "keep the peace."

In a similar study, Lee and Zhang (2010) examined data on Chinese history, including temperature, wars and rebellions, epidemics, famines, and population for the past millennium. Over the study interval of 911 years, it was found that nomad migrations, rebellions, wars, epidemics, floods, and droughts were all higher during cold periods. All of these factors tended to disrupt population growth or increase mortality. Overall, five of six population contractions, constituting losses of 11.4 to 49.4 percent of peak population, were associated with a cooling climate. The sixth cool period evinced a great reduction in population growth rate during a cool phase, but not a collapse. None of the population contractions was associated with a warming climate.

As background for another study, Zhang et al. (2010) state, "climatic fluctuation may be a significant factor interacting with social structures in affecting the rise and fall of cultures and dynasties," citing Cowie (1998) and Hsu (1998). When the climate worsens beyond what the available technology and economic system can accommodate – that is, beyond the society's adaptive capacity – they state, "people are forced to move or starve."

In this regard, they note, "climate cooling has had a huge impact on the production of crops and herds in pre-industrial Europe and China (Hinsch, 1998; Atwell, 2002; Zhang et al., 2007a), even triggering mass southward migration of northern nomadic societies (Fang and Liu, 1992; Wang, 1996; Hsu, 1998)," and "this ecological and agricultural stress is likely to result in wars and social unrest, often followed by dynastic transitions (Zhang et al., 2005)." In fact, they write, "recent studies have demonstrated that wars and social unrests in the past often were associated with cold climate phases (Zhang et al., 2005, 2007a,b)," and "climate cooling may have increased locust plagues through temperature-driven droughts or floods in ancient China (Stige et al., 2007; Zhang et al., 2009)."

In a study designed to explore the subject further, Zhang et al. (2010) employed "historical data on war frequency, drought frequency and flood frequency" compiled by Chen (1939), and "a multi-proxy temperature reconstruction for the whole of China reported by Yang et al. (2002), air temperature data for the Northern Hemisphere (Mann and Jones, 2003), proxy temperature data for Beijing (Tan et al., 2003), and a historical locust dataset reported by Stige et al. (2007)," plus "historical data of rice price variations reported by Peng (2007)."

In analyzing the linkages among these different factors, the international (Chinese, French, German, and Norwegian) team of researchers concluded "food production during the last two millennia has been more unstable during cooler periods, resulting in more social conflicts." They specifically note "cooling shows direct positive association with the frequency of external aggression war to the Chinese dynasties mostly from the northern pastoral nomadic societies, and indirect positive association with the frequency of internal war within the Chinese dynasties through drought and locust plagues," which have typically been more pronounced during cooler as opposed to warmer times.

Given these findings, Zhang et al. conclude "it is very probable that cool temperature may be the driving force in causing high frequencies of meteorological, agricultural disasters and then man-made disasters (wars) in ancient China," noting "cool temperature could not only reduce agricultural and livestock production directly, but also reduce agricultural production by producing more droughts, floods and locust plagues." They also observe the subsequent "collapses of agricultural and livestock production would cause wars within or among different societies." Consequently, although "it is generally believed that global warming is a threat to human societies in many ways (IPCC, 2007)," Zhang et al. come to a somewhat different conclusion, stating some countries or regions might actually "benefit from increasing temperatures," citing the work of Nemani et al. (2003), Stige et al. (2007), and Zhang et al. (2009), while restating the fact that "during the last two millennia, food production in ancient China was more stable during warm periods owing to fewer agricultural disasters, resulting in fewer social conflicts."

Following in the footsteps of Zhang et al. (2005, 2006), Tol and Wagner (2010) essentially proceeded to do for Europe what Zhang et al. had done earlier for China. In introducing their study the authors state that in "gloomier scenarios of climate change, violent conflict plays a key part," noting in such visions of the future, "war would break out over declining water resources, and millions of refugees would cause mayhem." The two researchers note "the Nobel Peace Prize of 2007 was partly awarded to the IPCC and Al Gore for their contribution to slowing climate change and thus preventing war." However, they observe "scenarios of climate-change-induced violence can be painted with abandon," citing the example of Schwartz and Randall (2003), because "there is "little research to either support or refute such claims." Consequently, and partly to fill this gaping research void, Tol and Wagner conducted their own analysis of the subject for Europe. And as with their colleagues who studied China, their results indicate that "periods with lower temperatures in the pre-industrial era are accompanied by violent conflicts." However, they determined "this effect is much weaker in the modern world than it was in pre-industrial times," which implies, in their words, "that future global warming is not likely to lead to (civil) war between (within) European countries." Therefore, they conclude, "should anyone ever seriously have believed that, this paper does put that idea to rest."

In a contemporaneous study, Field and Lape (2010) note it has been repeatedly suggested that in many parts of the world climate change has "encouraged conflict and territorialism," as this response, in their words, "serves as an immediate means of gaining resources and alleviating shortfalls," such as those that occur when the climate change is detrimental to agriculture and the production of food. To investigate this hypothesis, the authors compared "periods of cooling and warming related to hemispheric-level transitions (namely the Medieval Warm Period and the Little Ice Age) in sub-regions of the Pacific with the occurrence of fortifications at the century-level." Their study revealed "the comparison of fortification chronologies with paleoclimatic data indicate that fortification construction was significantly correlated with periods of cooling, which in the tropical Pacific is also associated with drying." In addition, "the correlation was most significant in the Indo-Pacific Warm Pool, the Southwestern Pacific and New Zealand," where "people constructed more fortifications during periods that match the chronology for the Little Ice Age (AD 1450–1850)," as opposed to the Medieval Warm Period (AD 800–1300) when the Indo-Pacific Warm Pool was both warm and saline "with temperatures approximating current conditions (Newton et al., 2006)." Thus, Field and Lape's study provides more evidence that periods of greater warmth have generally led to more peaceful times throughout the world, whereas periods of lesser warmth have typically led to greater warfare.

Considering North America, Cleaveland et al. (2003) developed a history of winter–spring (November–March) precipitation for the period 1386–1993 for the area around Durango, Mexico, based on earlywood width chronologies of Douglas-fir tree rings collected at two sites in the Sierra Madre Occidental. This reconstruction, in their words, "shows droughts of greater magnitude and longer duration than the worst historical drought," and none of them occurred during a period of unusual warmth, as some researchers claim they should; instead, they occurred during the Little Ice Age. They also note, "Florescano et al. (1995) make a connection between drought, food scarcity, social upheaval and political instability, especially in the revolutions of 1810 and 1910," and they note the great megadrought that lasted from 1540 to 1579 "may be related to the Chicimeca war (Stahle et al., 2000), the most protracted and bitterly fought of the many conflicts of natives with the Spanish settlers." If these concurrent events were indeed related, they too suggest that warmer is far better than cooler for maintaining social stability.

An analogous relationship was found to prevail in East Africa by Nicholson and Yin (2001), who analyzed climatic and hydrologic conditions from the late 1700s to close to the present, based on (1) histories of the levels of ten major African lakes and (2) a water balance model they used to infer changes in rainfall associated with the different conditions, concentrating most heavily on Lake Victoria. The results they obtained were indicative of "two starkly contrasting climatic episodes." The first, which began sometime prior to 1800 during the Little Ice Age, was one of "drought and desiccation throughout Africa." This arid episode, which was most intense during the 1820s and '30s, was accompanied by extremely low lake levels. As the two researchers describe it, "Lake Naivash was reduced to a puddle. ... Lake Chad was desiccated. ... Lake Malawi was so low that local inhabitants traversed dry land where a deep lake now resides. ... Lake Rukwa [was] completely desiccated. ... Lake Chilwa, at its southern end, was very low and nearby Lake Chiuta almost dried up."

Nicholson and Yin state that throughout this period "intense droughts were ubiquitous." Some, in fact, were "long and severe enough to force the migration of peoples and create warfare among various tribes." As the Little Ice Age's grip on the world began to loosen in the middle to latter part of the 1800s, however, things began to change for the better. The two researchers report, "semi-arid regions of Mauritania and Mali experienced agricultural prosperity and abundant harvests; floods of the Niger and Senegal Rivers were continually high; and wheat was grown in and exported from the Niger Bend region." Then, as the nineteenth century came to an end and the twentieth began, there was a slight lowering of lake levels, but nothing like what had occurred a century earlier; and in the latter half of the twentieth century, things once again improved, with the levels of some lakes rivaling high-stands characteristic of the years of transition to the Modern Warm Period.

These findings all clearly suggest warmer temperatures favor social stability and peace.

References

Atwell, W.S. 2002. Time, money and the weather: Ming China and the great depression of the mid-fifteenth century. *Journal of Asian Studies* **61**: 83–113.

Chen, G.Y. 1939. *China Successive Natural and Manmade Disasters Table.* Guangzhou, China: Jinan University Book Series.

Cleaveland, M.K., Stahle, D.W., Therrell, M.D., Villanueva-Diaz, J., and Burns, B.T. 2003. Tree-ring reconstructed winter precipitation and tropical teleconnections in Durango, Mexico. *Climatic Change* **59**: 369–388.

Cowie, J. 1998. *Climate and Human Change: Disaster or Opportunity?* New York, NY: Parthenon Publishing Group.

Fang, J. and Liu, G. 1992. Relationship between climatic change and the nomadic southward migrations in eastern Asia during historical times. *Climatic Change* **22**: 151–168.

Field, J.S. and Lape, P.V. 2010. Paleoclimates and the emergence of fortifications in the tropical Pacific islands. *Journal of Anthropological Archaeology* **29**: 113–124.

Florescano, E., Swan, S., Menegus, M., and Galindo, I. 1995. *Breve Historia de la Sequia en Mexico*. Veracruz, Mexico: Universidad Veracruzana.

Hinsch, B. 1998. Climate change and history in China. *Journal of Asian History* **22**: 131–159.

Hsu, K.J. 19998. Sun, climate, hunger and mass migration. *Science in China Series D – Earth Sciences* **41**: 449–472.

Intergovernmental Panel on Climat Change (IPCC). 2007. *Fourth Assessment Report on Climate Change 2007: Synthesis Report.* Geneva, Switzerland: Intergovernmental Panel on Climate Change.

Lee, H.F. and Zhang, D.D. 2010. Changes in climate and secular population cycles in China, 1000 CE to 1911. *Climate Research* **42**: 235–246.

Mann, M.E. and Jones, P.D. 2003. Global surface temperatures over the past two millennia. *Geophysical Research Letters* **30**: 10.1029/2003GL017814.

Nemani, R.R., Keeling, C.D., Hashimoto, H., Jolly, W.M., Piper, S.C., Tucker, C.J., Myneni, R.B., and Running, S.W. 2003. Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science* **300**: 1560–1563.

Newton, A., Thunnell, R., and Stott, L. 2006. Climate and hydrographic variability in the Indo-Pacific warm pool during the last millennium. *Geophysical Research Letters* **33**: 10.1029/2006GL027234.

Nicholson, S.E. and Yin, X. 2001. Rainfall conditions in equatorial East Africa during the nineteenth century as inferred from the record of Lake Victoria. *Climatic Change* **48**: 387–398.

Peng, X.W. 2007. *History of Chinese Currency.* Shanghai, China: Shanghai People's Press.

Schwartz, P. and Randall, D. 2003. An abrupt climate change scenario and its implications for United States national security. San Francisco, CA: Global Business Network. Available at http://www.edf.org/documents/3566_AbruptClimateChange.pdf.

Stahle, D.W., Cook, E.R., Cleaveland, M.K., Therrell, M.D., Meko, D.M., Grissino-Mayer, H.D., Watson, E., and Luckman, B.H. 2000. Tree-ring data document 16th century megadrought over North America. *EOS, American Geophysical Union, Transactions* **81**: 121, 125.

Stige, L.C., Chan, K.S., Zhang, Z.B., Frank, D., and Stenseth, N.C. 2007. Thousand-year-long Chinese time series reveals climatic forcing of decadal locust dynamics. *Proceedings of the National Academy of Sciences USA* **104**: 16,188–16,193.

Tan, M., Liu, T., Hou, J., Qin, X., Zhang, H., and Li, T. 2003. Cyclic rapid warming on centennial scale revealed by a 2650-year stalagmite record of warm season temperature. *Geophysical Research Letters* **30**: 10.1029/2003GL017352.

Tol, R.S.J. and Wagner, S. 2010. Climate change and violent conflict in Europe over the last millennium. *Climatic Change* **99**: 65–79.

Wang, H.C. 1996. The relationship between the southern migrations of north nomadic tribes and climate change in China. *Scientia Geographica Sinica* **16**: 274–279.

Yang, B., Braeuning, A., Johnson, K.R., and Shi, Y.F. 2002. General characteristics of temperature variation in China during the last two millennia. *Geophysical Research Letters* **29**: 38–42.

Zhang, D., Jim, C.Y., Lin, C.S., He, Y.Q., and Lee, F. 2005. Climate change, social unrest and dynastic transition in ancient China. *Chinese Science Bulletin* **50**: 137–144.

Zhang, D.D., Brecke, P., Lee, H.F., He, Y.Q., and Zhang, J. 2007a. Global climate change, war, and population decline in recent human history. *Proceedings of the National Academy of Sciences USA* **104**: 19,214–19,219.

Zhang, D.D., Jim, C.Y., Lin, G.C.-S., He, Y.-Q., Wang, J.J., and Lee, H.F. 2006. Climatic change, wars and dynastic cycles in China over the last millennium. *Climatic Change* **76**: 459–477.

Zhang, D.D., Zhang, J., Lee, H.F., and He, Y. 2007b. Climate change and war frequency in eastern China over the last millennium. *Human Ecology* **35**: 403–414.

Zhang, Z., Tian, H., Cazelles, B., Kausrud, K.L., Brauning, A., Guo, F., and Stenseth, N.C. 2010. Periodic climate cooling enhanced natural disasters and wars in China during AD 10–1900. *Proceedings of the Royal Society B* **277**: 10.1098/rspb.2010.0890.

Zhang, Z.B., Cazelles, B., Tian, H.D., Stige, L.C., Brauning, A., and Stenseth, N.C. 2009. Periodic temperature-associated drought/flood drives locust plagues in China. *Proceedings of the Royal Society B* **276**: 823–831.

Appendix 1

Acronyms

ACA	Arid Central Asia
ACIA	Arctic Climate Impact Assessment
AEDI	Accumulated Effective Drought Index
AF	airborne fraction
ALT	active layer thickness
AMO	Atlantic Multidecadal Oscillation
AMSR	Advanced Microwave Scanning Radiometer
A/N	ammonium/nitrate
AOGCM	Atmosphere-Ocean General Circulation Model
AOT	aerosol optical thickness
ASI	aeolian sand influx
ATLAS	Airborne Thermal and Land Applications Sensor
ATZ	accumulated temperature zone
AVHRR	Advanced Very High Resolution Radiometer
Ba	barium
BAI	basal area increment
BioCON	Biodiversity, Carbon Dioxide, and Nitrogen Effects on Ecosystem Functioning
BP	before present
BTV	bluetongue virus
BVOC	biogenic volatile organic compound
C4MIP	Coupled Carbon Cycle Climate Model Intercomparison Project
Ca	calcium
CAM	Crassulacean Acid Metabolism
CAM3.1	Community Atmosphere Model version 3
CCA	canonical correspondence analysis
CCN	Cloud condensation nuclei
CEDI	Corrected Effective Drought Index
CEMs	climate envelope models
CERES	Clouds and the Earth’s Radiant Energy System
CEVSA	Carbon Exchanges in the Vegetation-Soil-Atmosphere System
CFC	chlorofluorocarbons
CGCM	Coupled General Circulation Models
$\mathbf{CH_2CII}$	iodocarbon chloroiodomethane
$\mathbf{CH_3C_1}$	methyl chloride
$\mathbf{CH_4}$	methane
$\mathbf{CH_2I_2}$	diiodomethane
CHD	coronary heart disease
CLEH	climate-linked epidemic hypothesis
CMIP3	Coupled Model Intercomparison Project Phase 3
$\mathbf{CO_2}$	carbon dioxide
C/P	carbon/phosphorus
CRF	cosmic ray flux
$\mathbf{CS_2}$	carbon disulfide
CSRM	cloud system-resolving models
CVD	cardiovascular disease
DACP	Dark Ages cold period

DGGE	denaturing gradient gel electrophoresis
DIC	dissolved inorganic carbon
DOC	dissolved organic carbon
DSE	dark septate root endophytic
DSF	dust storm frequency
DTR	diurnal temperature range
EDI	Effective Drought Index
EESC	effective stratospheric chlorine concentrations
ENP	eastern North Pacific
ENSO	El Nino-Southern Oscillation
EOS	Earth Observing System
EROWI	energy return on water invested
ET	evapotranspiration
ETCW	early twentieth-century warming
EWUE	ecosystem water use efficiency
FACE	Free-air CO_2 Enrichment
FAO	Food and Agricultural Organization
FTA	Fast Track Assessment
GCE	Goddard Cumulus Ensemble
GCM	General Circulation Models
GCR	galactic cosmic rays
GCTE	Global Change and Terrestrial Ecosystems
GDH	growing degree hours
GDP	Gross Domestic Product
GHG	green house gas(es)
GIA	Glacial Isostatic Adjustment
GIMMS	Global Inventory Modeling and Mapping Studies
GISS-AOM	Goddard Institute of Space Studies-Atmosphere Ocean Model
gr	gram(s)
GRACE	Gravity Recovery and Climate Experiment
GS	glucosinolate
GTTA	Global Tropospheric Temperature Anomalies
HKO	Hong Kong Observatory of China
HSP	heat-shock protein
IHD	ischemic heart disease
IMAR	Inner Mongolia Autonomous Region
IMP	Internal Multidecadal Pattern
IPCC	Intergovernmental Panel on Climate Change
IPCC 2007-I	Intergovernmental Panel on Climate Change — Group 1 Contribution
IPCC 2007-II	Intergovernmental Panel on Climate Change — Group II Contribution
IPCC 2007-II	Intergovernmental Panel on Climate Change — Group III Contribution
IPCC-FAR	Intergovernmental Panel on Climate Change — First Assessment Report
IPCC-SAR	Intergovernmental Panel on Climate Change — Second Assessment Report
IPCC-TAR	Intergovernmental Panel on Climate Change — Third Assessment Report
IPCC-AR4	Intergovernmental Panel on Climate Change — Fourth Assessment Report
IRD	ice rafted debris
ISA	impervious surface area
ITCZ	Intertropical Convergence Zone
iWUE	intrinsic water-use efficiency
JTWC	Joint Typhoon Warning Center
LADS	Laser Airborne Depth Sounder
LAI	leaf area index
LDC	lease developed countries
LDD	long-distance dispersal
LIA	Little Ice Age
LIG	Last Interglacial
LST	land surface temperature
LT	lower-troposphereic
LTM	long-term mean standardization
LULC	land use and land cover
m	meter
MCA	Medieval Climate Anomaly

MISR	multi-angle imaging spectroradiometer
MJO	Madden-Julian Oscillation
MOC	meridional overturning circulation
MODIS	moderate-resolution imaging spectroradiometer
MPI	maximum potential intensity
MSU	Microwave Sounding Unit
MWP	Medieval Warm Period
MXD	maximum latewood density

N_2O	nitrous oxide
NAO	North Atlantic Oscillation
NAOI	North Atlantic Oscillation Index
NAS	National Academy of Sciences
NC	neutron count
NCEP	National Center for Environmental Prediction
NDVI	Normalized Difference Vegetation Index
NEE	net ecosystem CO_2 exchange
NHL	Northern High Latitude
NIO	North Indian Ocean
NIPCC	Nongovernmental International Panel on Climate Change
NMHC	non-methane hydrocarbon
NPP	net primary production
Nr	reactive nitrogen
NSC	nonstructural carbohydrates
nss-SO_4^{2-}	non-sea-salt sulfate
NWAUS	northwest Australia

O_3	ozone
OECD	Organization for Economic Cooperation and Development
OTC	open-top chambers

P	precipitation
PALSEA	Paleo Sea Level Working Group
PDI	power dissipation index
PDMT	present-day surface mass trend
PDSI	Palmer Drought Severity Index
PeECE	Pelagic Ecosystem CO_2 Enrichment
PETM	Paleocene-Eocene Thermal Maximum
ppb	parts per billion
PPB	purple phototrophic bacteria
ppm	parts per million
PR	Precipitation Radar
Ps	solid precipitation

RATPAC	Radiosonde Atmospheric Temperature Products for Assessing Climate
RCM	regional climate model
RCS	regional curve standardization
RERCA	recent rate of carbon accumulation
Rg	solar irradiance
RKC	red king crab (*Paralithodes camtschaticus*)
RMF	root mass fraction
RMSE	root mean square of errors
ROS	reactive oxygen species
RSMC	Regional Specialized Meteorological Center

SAM	Southern Hemisphere Annular Mode
SAMS	South American Monsoon System
SAT	surface air temperature
SCM	single-column models
SCSMEX	South China Sea Monsoon Experiment
SDS	sudden death syndrome
SET	surface elevation table
SLP	sea-level pressure
SLR	sea-level rise
SMB	surface mass balance
SMBR	Sierra de Manantlan Biosphere Reserve
SN	sunspot number
SO	Southern Ocean
SOC	soil organic carbon
SOI	Southern Oscillation Index
SOM	soil organic matter
SoyFACE	soybean free-air CO_2-enrichment
SR	Scaling Ratio
SN/SSN	sunspot number
SST	sea surface temperatures

STI	Shanghai Typhoon Institute
STD	standardization
SWS	sea water salinity
TBAR	thiobarbituric acid reactive substances
TC	tropical cyclones
TEM	Terrestrial Ecosystem Model
Tmax	maximum temperature
Tmin	minimum temperature
TMI	Tropical Rainfall Measuring Mission Microwave Imager
TN	total nitrogen
TOA	top of the atmosphere
TRMM	Tropical Rainfall Measuring Mission
TWE	Thermal Wind Equation
UHI	urban heat island
UNEP	United Nations Environment Program
UV	ultraviolet
WAIS	West Antarctic Ice Sheet
WCRP	World Clime Research Program
WEG	western English Channel
WG	Wendell Gyre
WNP	Western North Pacific
XUAR	Xinjiang Uygur Autonomous Region
XRD	X-ray diffraction
YAEDI	Year-Accumulated Effective Drought Index

Appendix 2

Contributors to the NIPCC 2011 Interim Report

Lead Authors

Craig D. Idso, Ph.D. is founder and chairman of the Center for the Study of Carbon Dioxide and Global Change. Since 1998, he has been editor and chief contributor to the online magazine *CO2 Science*. He is the author of several books, including *The Many Benefits of Atmospheric CO2 Enrichment* (2011) and *CO2, Global Warming and Coral Reefs* (2009). His writing, which has appeared in peer-reviewed journals, books, and independent reports, has addressed the benefits of atmospheric CO_2 enrichment on plant and animal life, ocean acidification, world food supplies, plant and animal extinctions, the seasonal cycle of atmospheric CO_2, and urban CO_2 concentrations. He has lectured in Meteorology at Arizona State University (ASU), and was a faculty researcher in the Office of Climatology at ASU.

Robert M. Carter, Ph.D. is a stratigrapher and marine geologist with degrees from the University of Otago (New Zealand) and the University of Cambridge (England). His research publications include papers on taxonomic palaeontology, palaeoecology, New Zealand and Pacific geology, stratigraphic classification, sequence stratigraphy, sedimentology, the Great Barrier Reef, Quaternary geology, and sea-level and climate change. He is the author of *Climate: The Counter Consensus* (2010). Carter's professional service includes terms as chairman of the Earth Sciences Panel of the Australian Research Council, chairman of the national Marine Science and Technologies Committee, and director of the Australian Office of the Ocean Drilling Program. He is currently an adjunct research fellow at James Cook University (Townsville) and an emeritus fellow of the Institute of Public Affairs (Melbourne).

S. Fred Singer, Ph.D. is one of the most distinguished atmospheric physicists in the U.S. He established and served as the first director of the U.S. Weather Satellite Service, now part of the National Oceanographic and Atmospheric Administration (NOAA), and earned a U.S. Department of Commerce Gold Medal Award for his technical leadership. He later served as vice chairman of the National Advisory Committee for Oceans and Atmosphere. He is coauthor, with Dennis T. Avery, of *Unstoppable Global Warming Every 1,500 Years* (2007, second ed. 2008). Since retiring from the University of Virginia and from his last federal position as chief scientist of the Department of Transportation, Singer founded and directs the nonprofit Science and Environmental Policy Project.

Contributors

Affiliations are listed for identification purposes only. The work in this document represents the work and views of the individual contributors, not the associated institutions.

Susan Crockford, Ph.D.
Department of Anthropology
University Of Victoria
(Canada)

Joseph D'Aleo
Executive Director, ICECAP
Co-Chief Meteorologist, WeatherBell Analytics
Fellow, American Meteorological Society
(USA)

Indur Goklany, Ph.D.
Independent Scholar
Founder and co-editor, *Electronic Journal of Sustainable Development*
(USA)

Sherwood Idso, Ph.D.
Research Physicist, U.S. Water Conservation Laboratory
Agricultural Research Service, U.S. Department of Agriculture (retired)
(USA)

Madhav Khandekar, Ph.D.
Research Scientist, Environment Canada (retired)
Editorial Board Member (since 2000), *Natural Hazards* (Kluwer Netherlands)
Expert Reviewer IPCC AR4 (2007) Climate Change assessment

Anthony Lupo, Ph.D.
Department of Soil, Environmental, and Atmospheric Sciences
University of Missouri-Columbia
(USA)

Willie Soon, Ph.D.
Independent Scientist
Salem, Massachusetts
(USA)

Mitch Taylor, Ph.D.
Department of Geography
Lakehead University, Ontario
(Canada)

THE NONGOVERNMENTAL INTERNATIONAL PANEL ON CLIMATE CHANGE

The Nongovernmental International Panel on Climate Change (NIPCC) is an international network of scientists first convened in 2003 to examine the same climate data used by the United Nations-sponsored Intergovernmental Panel on Climate Change (IPCC). Unlike the IPCC, the NIPCC is not a government agency and does not receive government funding. Whereas the mission of the IPCC is to justify control of greenhouse gas emissions, the NIPCC has no agenda other than discovering the truth about climate change.

CLIMATE CHANGE RECONSIDERED

Climate Change Reconsidered: 2009 Report of the Nongovernmental Panel on Climate Change (NIPCC) was originally published by The Heartland Institute in 2009. It was, and remains today, the only comprehensive and authoritative reply to the Working Group I Contribution to the Fourth Assessment report of the IPCC. It consists of the largest-ever survey of scientific research on the likely causes and consequences of global warming, and the strengths and weaknesses of the computer models used to help us understand climate processes. Coauthors Craig D. Idso and S. Fred Singer report and interpret the work of thousands of scientists published in peer-previewed journals.

2011 INTERIM REPORT

The current report, *Climate Change Reconsidered: 2011 Interim Report,* is a compilation of new scientific research released since publication of the 2009 report. For this new report , Idso and Singer are joined by Australian scientist Robert (Bob) Carter and eight distinguished contributors. This report, as its title suggests, is not meant to be a complete or comprehensive report, but rather a supplement to the original 2009 report. Work is already underway on a 2012 *Interim Report,* and then a complete new edition of *Climate Change Reconsidered* is planned for 2013, to coincide with release of the IPCC's Fifth Assessment Report.

ABOUT THE COAUTHORS

Dr. Craig D. Idso is the founder and chairman of the Center for the Study of Carbon Dioxide and Global Change. Since 1998, he has been the editor and chief contributor to the online magazine *CO2 Science.* He is the author of several books, including *The Many Benefits of Atmospheric CO_2 Enrichment* (2011) and *CO_2, Global Warming and Coral Reefs* (2009). His writing, which has appeared in peer-reviewed journals, books, and independent reports, has addressed the benefits of atmospheric CO_2 enrichment on plant and animal life, ocean acidification, world food supplies, plant and animal extinctions, and the seasonal cycle of atmospheric CO_2. He has lectured in Meteorology at Arizona State University (ASU), and was a faculty researcher in the Office of Climatology at ASU.

Dr. Robert M. Carter is a stratigrapher and marine geologist with degrees from the University of Otago (New Zealand) and the University of Cambridge (England). His research publications include papers on taxonomic palaeontology, palaeoecology, New Zealand and Pacific geology, stratigraphic classification, sequence stratigraphy, sedimentology, the Great Barrier Reef, Quaternary geology, and sea level and climate change. He is the author of *Climate: The Counter Consensus* (2010). Carter's professional service includes terms as chairman of the Earth Sciences Panel of the Australian Research Council, chairman of the national Marine Science and Technologies Committee, and director of the Australian Office of the Ocean Drilling Program. He is currently an adjunct research fellow at James Cook University (Townsville) and an emeritus fellow of the Institute of Public Affairs (Melbourne).

Dr. S. Fred Singer is one of the most distinguished atmospheric physicists in the U.S. He established and served as the first director of the U.S. Weather Satellite Service, now part of the National Oceanographic and Atmospheric Administration (NOAA), and earned a U.S. Department of Commerce Gold Medal Award for his technical leadership. He later served as vice chairman of the National Advisory Committee for Oceans and Atmosphere. He is coauthor, with Dennis T. Avery, of *Unstoppable Global Warming Every 1,500 Years* (2007, second ed. 2008). Since retiring from the University of Virginia and from his last federal position as chief scientist of the Department of Transportation, Singer founded and directs the nonprofit Science and Environmental Policy Project.

ISBN 978-1-934791-28-8
15400
9 781934 791288

THE HEARTLAND INSTITUTE
19 SOUTH LASALLE STREET #903
CHICAGO, ILLINOIS 60603
WWW.HEARTLAND.ORG