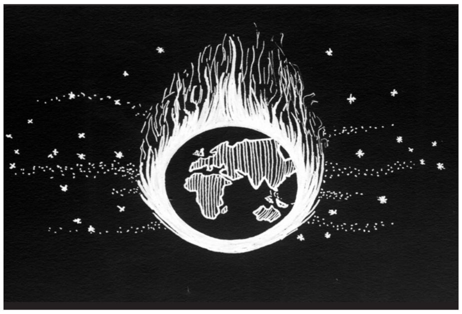
# ARTICLE



# The Science of Climate Change

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## SUMMARY

Central to the findings of the Intergovernmental Panel on Climate Change (IPCC) third assessment report, released in Shanghai in January 2001, was the statement:

> "There is now new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."

This represents a significant strengthening of the analogous statement issued by the IPCC in 1996:

> "The balance of evidence suggests a discernible human influence on global climate"

In this article the scientific evidence leading up to these IPCC statements is reviewed. A historical perspective of the Earth's climate over the last 400,000 years is presented, as is the science of global warming over the last 200 years. The range of projections of climate change over the next century is also summarized giving particular emphasis to projections concerning Canada. The issue of uncertainty in climate change projections is tackled and the public confusion arising from the media portrayal of the science and its entry into the political arena discussed. Finally, The Kyoto Protocol and how it fits within the framework of necessary actions required to reduce greenhouse gas emissions is reviewed.

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Point focal des découvertes décrites dans le troisième rapport du Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC), publié à Shangaï en janvier 2001, on retrouve cette déclaration essentielle : « Il existe maintenant des indications nouvelles et plus convaincantes que la plupart des indices de réchauffement ayant fait l'objet d'observations au cours des derniers 50 ans sont attribuables aux activités humaines ».

Cela constitue un renforcement significatif d'une déclaration similaire publiée en 1996 par le GIEC : « Le bilan des preuves considérées porte à penser que le climat planétaire serait influencé par des causes d'origine humaine ».

Le présent article porte sur l'ensemble des éléments de preuve scientifique sous-jacent aux déclarations de ces deux déclarations du GIEC. Dans une perspective historique, on y présente les fluctuations climatiques de la planète au cours des derniers 400 000 ans, ainsi que les principales étapes du développement de la science du réchauffement au cours des derniers 200 ans. On passe en revue la gamme des projections des changements climatiques pour le prochain siècle, particulièrement en ce qui concerne le Canada. On discute du problème de l'incertitude des projections de changements climatiques, de la confusion du public dans le contexte de l'image de la science dépeint par les médias ainsi que de l'émergence du sujet dans l'arène politique. Finalement, le protocole de Kyoto est revu, surtout en ce qui a trait aux actions requises pour réduire l'émission de gaz à effet de serre.

## INTRODUCTION

Canadians are obsessed with weather, its variability and its affect on everything we do. We are also greatly concerned with our climate, although the difference between weather and climate is often not well understood by the public. By definition, climate is the statistics of weather including, for example, its mean and variance. A torrential downpour is an individual weather event, whereas the likelihood of its occurrence in any given year is an aspect of our climate that is derived from long term averages of many individual weather events.

When we discuss climate change, we are discussing the change in the statistics of weather. The term *Global Warming* has been used to specifically refer to the increase in the Earth's global mean temperature as a consequence of the increased atmospheric loading of greenhouse gases arising from fossil fuel combustion. The basic physics of global warming is not complicated and is long established in the scientific literature. The interesting science questions concern how climate change will influence the regional statistics of weather, and so-called feedback mechanisms that may affect the magnitude of these changes.

Conveying the significance of climate change to the public is a difficult task for scientists. In the summer of 2002, for example, much media attention was given to the torrential rainfalls and flooding in Europe and India. At the same time, the Canadian prairie farmers were suffering one of the worst droughts on record. The dilemma is that when asked: “Are these events caused by global warming”, the scientist must respond with a long discussion of weather, climate and the relationship between the statistics of weather and climate. The media simply want a yes or no answer. We will never be able to say that a particular weather event is caused by climate change. Rather, what science can offer is a quantification of the change in the likelihood of such an event. For example, an expected 20-year return precipitation event in the present climate may become a 10-year return event and, after a few more decades, a 5-year return event under climate change.

Similarly, during February 2003, a cold spell in eastern Canada likely caused some to ponder what this talk about global warming was really all about; at the same time some in British Columbia and Alaska were likely convinced that the warm February was more proof of global warming. Few would examine the typical atmospheric planetary wave teleconnection patterns associated with El Niño conditions in the tropical Pacific.

Nevertheless, it is clear that climate change is upon us. The reality is that even if we dramatically cut fossil fuel emissions today, we have warming in store for centuries due to the slow response time of the climate system. The relevant policy question becomes: What do we as a collective society deem to be an acceptable level of climate change?

It is clear that future projections of climate change share common themes. There will be amplified warming at high latitudes relative to the tropical latitudes, in the northern relative to southern hemisphere, in the winter relative to summer, over land relative to ocean and at night relative to day. There will be an increase in mid- and high-latitude precipitation, especially in the winter and spring, although with warmer temperatures and hence later winter freezes and earlier spring thaws, one might expect a larger component of this to be in the form of rain rather than snow. There will be an increase in extreme precipitation events over large parts of mid to high latitudes. Despite this, there will be an increased likelihood of summer drought. There will be a large-scale retreat of most of the world’s glaciers with less short-term impact on the Greenland and Antarctic ice sheets. Sea ice in the Arctic will melt back significantly in the summer.

Throughout the history of humans, weather and its climate have influenced the rise and fall of civilizations and the livelihood and economic well being of their people (Diamond, 1997). So what is different between then and now? Technology and population increase. In the past, humans did not have the economic or technological wherewithal to rapidly adapt to the challenges posed by changes in the statistics of weather. Today large-scale irrigation, fertilization and land management techniques have substantially improved the adaptive strategies of developed nations to weather and climate fluctuations. The 2002 prairie drought may be one of the worst in our meteorological record, but it certainly pales in comparison to the dust bowl years earlier last century in terms of its affect on Canadian society.

Unfortunately, the popular perception of what constitutes a ‘normal’ climate often relies on an individual’s memory of climate conditions. This in turn depends on where one lives and on one’s ability to accurately remember conditions from decades earlier. To the people living in early 19th century England, a normal climate would be one in which the Thames River would freeze over allowing for festivities at the annual Frost Fair (Fig. 1). If the Thames were to freeze over today, it would be considered a freak event.

In January 2001, the United Nations Intergovernmental Panel on Climate Change (IPCC) released a report emphasizing that there is now new and stronger evidence that most of the climate warming observed over the last 50 years is attributable to human activities. This strong statement, by the world’s leading climate scientists, sent a signal to governments that informed policy is urgently needed to determine a course of action for the future. To set this target, researchers must attempt to reduce uncertainty in climate projections and quantify the socio-economic impacts of climate change. They must also develop the policies and mitigation technologies that will most effectively achieve appropriate levels of net greenhouse gas emissions, and develop the adaptation strategies that will respond to the consequences

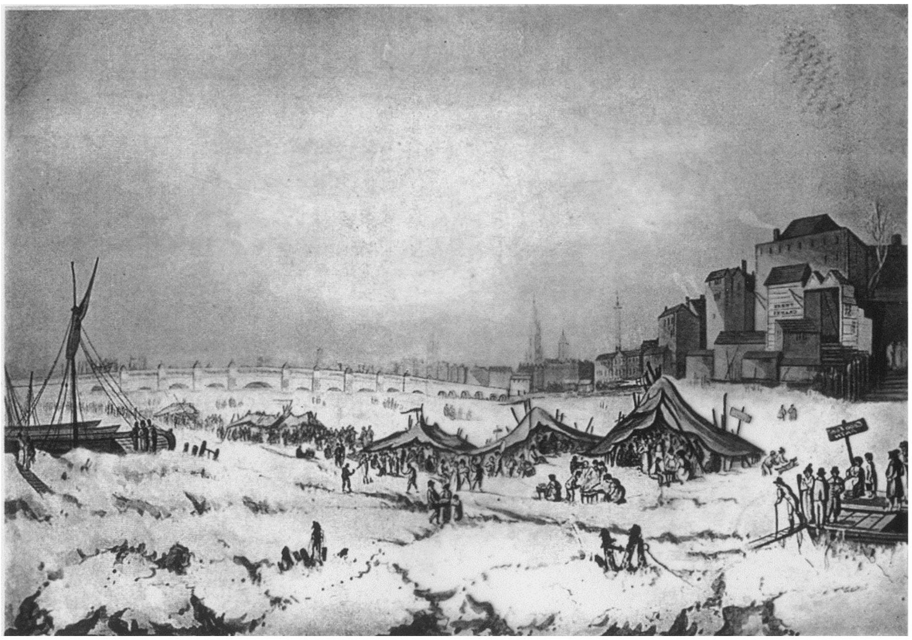

**Figure 1** The last Frost Fair on the Thames River, January 31–February 5, 1814 (from Manley, 1952).
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resulting from those choices. Perhaps most important is the need for a move towards the development of new energy technologies, which will require a re-emergence of new and safer nuclear power technologies and the greatly expanded use of sustainable energy sources (e.g., wind, solar, geothermal) combined with a move to widespread use of hydrogen-based energy storage systems.

In this review, the science of climate change will be examined, starting with a discussion of the 200 year history of the science and leading up to our present-day understanding of the issue of global warming. Since much of the observational evidence and future projections of climate change are derived from the IPCC Third Assessment Report, a brief review of the history behind the formation of the IPCC is given. Climate change detection and attribution, whereby an anthropogenic (human-induced) warming signature is searched for above a background of natural variability is also covered. This is followed by a summary and concluding remarks.

## HISTORY OF THE SCIENCE OF GLOBAL WARMING

A common misconception is that the link between increasing levels of atmospheric carbon dioxide ($CO_2$) and global warming has only recently been realized. In fact, Dr. James Hansen of NASA's Goddard Institute for Space Studies is often credited in the media as being the "father of climate change theory" (e.g., Global warming: The clouds thicken, by Peter Foster, *National Post*, Aug. 19, 2000; Global warming fears cool off. Why impose questionable constraints on economic growth? by Peter Holle, *Winnipeg Free Press*, Jan. 27, 2001). This labeling has apparently occurred in response to Hansen being called before the U.S. Senate Committee on Energy and Natural Resources to testify on June 23, 1988. At that time he argued that he was 99% confident that the greenhouse effect had been detected and that it was changing our climate.

This now famous testimony occurred nearly 100 years after the link was drawn between carbon dioxide and the Earth's temperature (see Christianson, 1999 for a historical review). Nevertheless, it was one of the first times the issue directly entered the U.S. political arena and so received a high profile in the media.

In fact in 1824, Jean-Baptiste-Joseph Fourier (a well-known French mathematician) introduced the hypothesis that the atmosphere blocks outgoing radiation from the Earth and re-radiates a portion of it back, thereby warming the planet (Fourier, 1824). Swedish Nobel Laureate Svante Arrhenius drew upon the work of Fourier, as well as that of American astronomer Samuel Langley and Irish scientist John Tyndall, to develop in 1896 the first theoretical model of how atmospheric $CO_2$ affects the Earth's temperature (Arrhenius, 1896). In 1938, the British coal engineer George Callendar argued that since 1880 the Earth had warmed by about 1°F, and he predicted that this would double in the next half century.

In a seminal paper by Revelle and Suess (1957), it was argued that the oceans could not absorb anthropogenic emissions of $CO_2$ as fast as they were being produced. They further noted that this would leave the $CO_2$ released as a result of human activity in the atmosphere for centuries and stated: "Human beings are now carrying out a large-scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future". They further argued that "we are returning to the atmosphere and oceans the concentrated organic carbon stored in the sedimentary rocks over hundreds of millions of years."

The first sophisticated atmospheric modelling studies aimed at investigating the climatic consequences of increasing atmospheric $CO_2$ were conducted at the NOAA Geophysical Fluid Dynamics Laboratory, now in Princeton, New Jersey. Imbedded within the abstract of a paper written by Manabe and Weatherald (1967) was the conclusion "According to our estimate, a doubling of the $CO_2$ content in the atmosphere has the effect of raising the temperature of the atmosphere (whose relative humidity is fixed) by about 2°C." This early work yielded a projection consistent with the 1996 United Nations IPCC 'best guess' estimate of 2°C warming by 2100 (where atmospheric $CO_2$ is projected to double, relative to preindustrial levels, by year 2070).

By the early 1980s, the issue of climate change began to move from the scientific to policy agendas. Several scientific assessments of the relationship between $CO_2$ and climate began to appear (e.g. NRC, 1979, 1983). On the international scene, it is apparent that a series of conferences and reports organized by the United Nations Environment Programme (UNEP), International Council of Scientific Unions (ICSU), and the World Meteorological Organization (WMO), were especially influential. The Second Joint UNEP/ICSU/WMO International Assessment of the role of Carbon Dioxide and other Greenhouse Gases in Climate Variations and Associated Impact, which took place in October 1985 in Villach, Austria, was particularly important in this regard.

In summary, the theory of global warming is based on elementary principles of physics — principles that were discovered more than a century ago: warm climates can't be maintained unless there is an excess of greenhouse gases to block outgoing radiation; cold climates can't be maintained unless there is a depletion of greenhouse gases (see Fig. 2). If one perturbs these gases, one provides a radiative forcing (see next section) to which the Earth system must respond. Global warming is not a new issue that appeared in 1988 when James Hansen gave testimony to the U.S. Senate, but rather, it is an issue deeply rooted in two centuries of science. National and international assessments have been conducted on the topic since the early 1980s. Most recently, this task has been charged to the United Nations IPCC.

## THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

The Intergovernmental Panel on Climate Change was established in 1988 by the World Meteorological Organization and the United Nations Environment Programme as a means to assess the potential problem of global

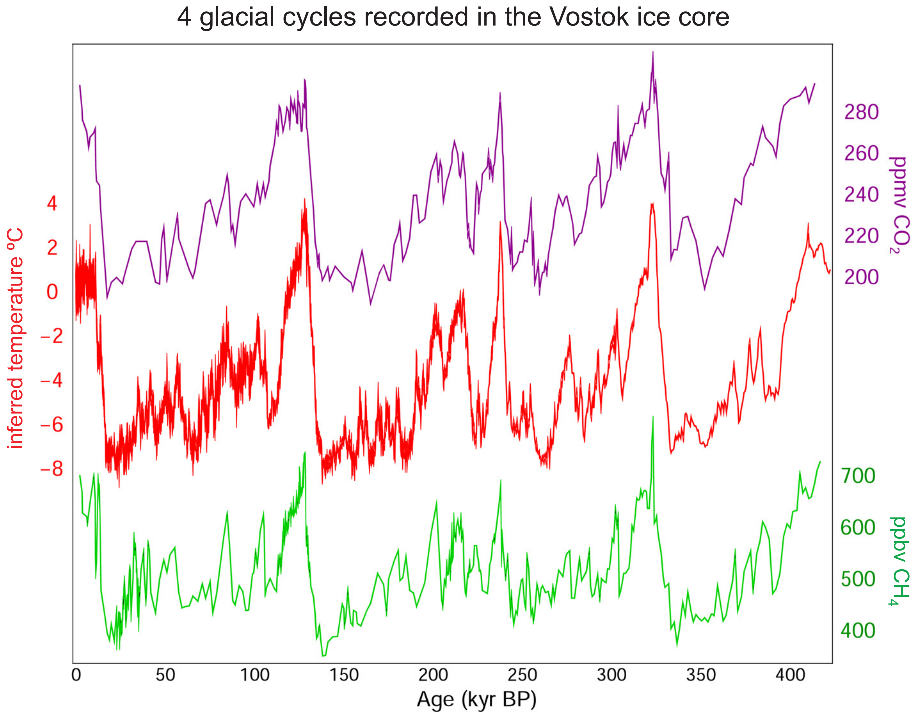


**Figure 2** Variations in local Antarctic atmospheric temperature, as derived from oxygen isotope data, as well as concentrations of atmospheric carbon dioxide and methane from Vostok, Antarctica ice core records. The fact that cold climates aren't maintained without a depletion of greenhouse gases, and that warm climates aren't maintained without an excess of these greenhouse gases is evident. Notice also that the current level of atmospheric $CO_2$ (370 ppm) is >20% larger than at anytime during the last 400,000 years. Similarly, current levels of atmospheric methane $CH_4$ (1750 ppb) are more than double the maximum value found in the 400,000 year record. Notice also that the increase in $CO_2$ from 280 ppm to 370 ppm over the last 150 years, primarily due to fossil fuel burning, is about the same as the increase from the depths of the last ice age (21,000 years ago) to 1750 (190 ppm to 280 ppm) (from Petit et al., 1999).

climate change. It is a United Nations organization governed by United Nations regulations, with a mandate, most recently reaffirmed in Vienna in October 1998: "The role of the IPCC is to assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation. IPCC reports should be neutral with respect to policy, although they may need to deal objectively with scientific, technical and socio-economic factors relevant to the application of particular policies" (http://www.ipcc.ch/about/princ.pdf).

To address this mandate, the IPCC oversees three Working Groups (WGI, WGII, WGIII) aimed at assessing the science, socio-economic impacts and adaptation, and mitigation aspects of climate. In the Third Assessment Report, the mandates of these working groups were:
WGI: assesses the scientific aspects of the climate system and climate change.
WGII: addresses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change, and options for adapting to it.
WGIII: assesses options for limiting greenhouse gas emissions and otherwise mitigating climate change.

A common public misconception is that the IPCC working groups undertake their own independent research. This is not the case — they provide an assessment of the peer-reviewed literature, although they make reference to published technical reports. IPCC does not consider web sites or newspaper opinion pieces and editorials to have passed the standards set by the peer-review system, and so will not include these in their assessments.

There have now been three formal IPCC Assessments of Climate Change. The first, in 1990, led to the setting up of the Intergovernmental Negotiating Committee for a UN Framework Convention on Climate Change by the UN General Assembly. The second assessment, in 1996, was formally used in the negotiations leading up to the adoption of the Kyoto Protocol to the UN Framework Convention on Climate Change at the Third Conference of Parties in 1997. The Kyoto Protocol requires Canadian greenhouse gas emissions to be 6% below 1990 levels in the period spanning 2008–2012. The third IPCC assessment was completed in 2001 and the process has now begun to set the stage for the fourth IPCC Assessment Report.

While the assessments provided by the IPCC ultimately enter the political arena, as noted above, the actual writing of the main body of the assessment is free from political interference, although governments may make suggestions as to potential authors. In the third assessment, for example, 120 of the world's leading climate scientists wrote the WG1 document, with contributions from over 500 other climate scientists. The content of each chapter was chosen exclusively by the Lead Authors of that chapter, in consultation with the Lead Authors of other chapters (to ensure there was no duplication). The final report underwent review three times by more than 300 experts in the field. This review process included an informal review by all Lead Authors, a review by experts in the field, an additional expert review and a government review. The 3rd draft of the document was put together after the IPCC meeting in Victoria, British Columbia (July 24–26, 2000) and was sent to United Nations member states for approval in Shanghai in January 2001. Final changes were made to the Summary for Policy Makers in Shanghai as a consequence of feedback from UN member states. It is at this final UN approval phase of the Summary for Policy Makers that political interference and vested interests can become a problem (see for example Climate Change Detection and Attribution on p. 105).

As noted above, the formal charge of WGI is the assessment of available research on the science of climate change, and its association with human activities. More specifically: "In performing its assessments WGI is concerned with: developments in the scientific understanding of past and present climate, of climate variability, of climate predictability and of climate change including feedbacks from climate impacts; progress in the modelling and projection of global and regional climate and sea level change; observations of climate, including past climates, and assessment of trends and anomalies; gaps and uncertainties in current knowledge" (http://www.meto.gov.uk/sec5/CR_div/ipcc/wg1/).

What follows draws heavily from the assessment that arose from this IPCC WGI process. In particular, some of the key findings of Chapter 2 (*Observed climate variability and change*) are focussed on in the next section, and some of the most important aspects of Chapter 9 (*Projections of future climate change*) and Chapter 12 (*Detection of climate change and attribution of causes*) are highlighted.

## OBSERVATIONAL EVIDENCE OF CLIMATE CHANGE

### Radiative Forcing of Climate

The Earth is said to be in a global radiative equilibrium if the total amount of energy received from the sun equals the total amount of energy emitted by the earth to space. A change in the average net (incoming minus outgoing) radiation at the top of the atmosphere is defined as a *radiative forcing*. Under this terminology, a positive radiative forcing acts to warm the earth's surface, while a negative radiative forcing acts to cool it. That is, a radiative forcing perturbs the balance between incoming and outgoing radiation and over time, the climate system (Fig. 3) responds to try and reestablish global radiative equilibrium.

Carbon dioxide ($CO_2$), Methane ($CH_4$), and Nitrous Oxide ($N_2O$) are examples of greenhouse gases whose increase over the last 150 years has provided a positive radiative forcing (Fig. 4). Aerosols, which are tiny liquid or solid particles in the atmosphere, are most often considered to provide a negative radiative forcing (e.g. sulphate aerosols released in the combustion of coal, for example). These, and other aerosols, affect the radiation balance of the Earth by both directly scattering incoming radiation back to space and indirectly affecting the formation, lifetime and properties of clouds.

Of course, there are significant differences in the atmospheric residence time of individual greenhouse gases and aerosols as a result of natural removal mechanisms. Tropospheric aerosols, for example, stay in the atmosphere only a few days as they are effectively scavenged by precipitation. Stratospheric aerosols, such as those released during volcanic eruptions, have a residence time of up to a few years since they must first descend, through gravity, into the troposphere before they can be scavenged by precipitation. The average carbon dioxide molecule has a residence time in the atmosphere of between 50 and 200 years, methane about 12 years, nitrous oxide about 120 years, CFC-11 about 50 years, and a perfluorocarbon (another greenhouse gas) about 50,000 years.

Finally, it is important to note that the Earth system does not instantly reach radiative equilibrium once a radiative forcing is applied. The slow time scales inherent in the system, such as those associated with the ocean, lead to a lag of several centuries before quasi-equilibrium can be reached. As a specific example, Wigley (1998) considered the climatic effects of the ratification of the Kyoto Protocol. He showed that if all countries followed their baseline changes after 2010 (i.e., all countries met their Kyoto targets but did no more for the rest of this century), the resulting 'best guess' warming of 2.08°C (relative to 2000) by 2100 would only be reduced to 2.0°C. Similarly, the 'best guess' sea level rise of about 50 cm (relative to 2000) would only reduce to 48.5 cm. In fact, if Kyoto targets were met by all and a further 1%/year reduction in emissions occurred after 2010, the warming at 2100 would only drop to 1.80°C and sea level rise to 45.5 cm.

Unlike the case for glacial to interglacial changes which occurred on the timescales of millennia (Fig. 2), thereby allowing the Earth System time to equilibrate with changes in the radiative forcing, the current rate of change in radiative forcing is very rapid. As such, there is inevitable

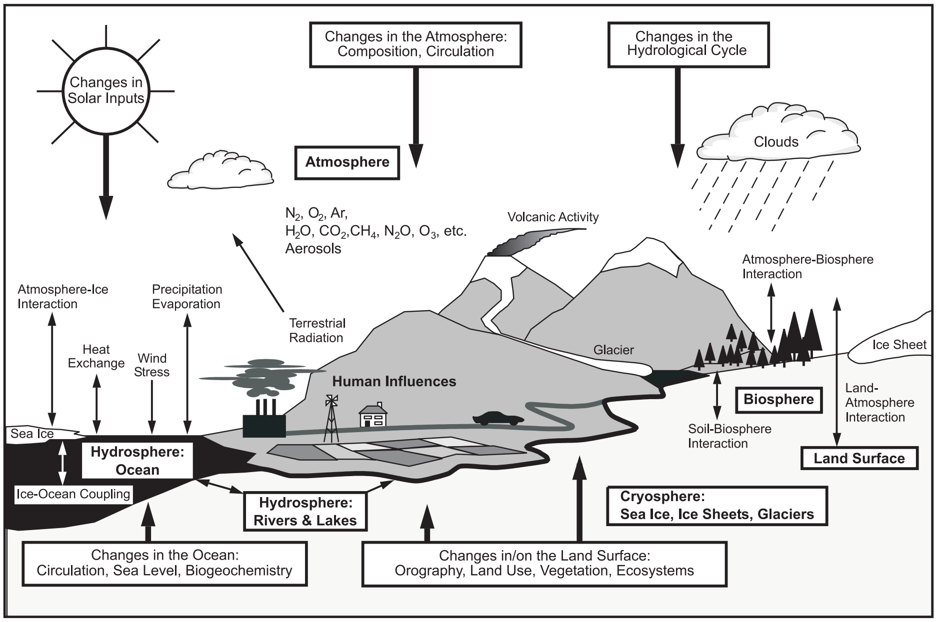


**Figure 3** Schematic representation of the climate system (from IPCC, 2001).

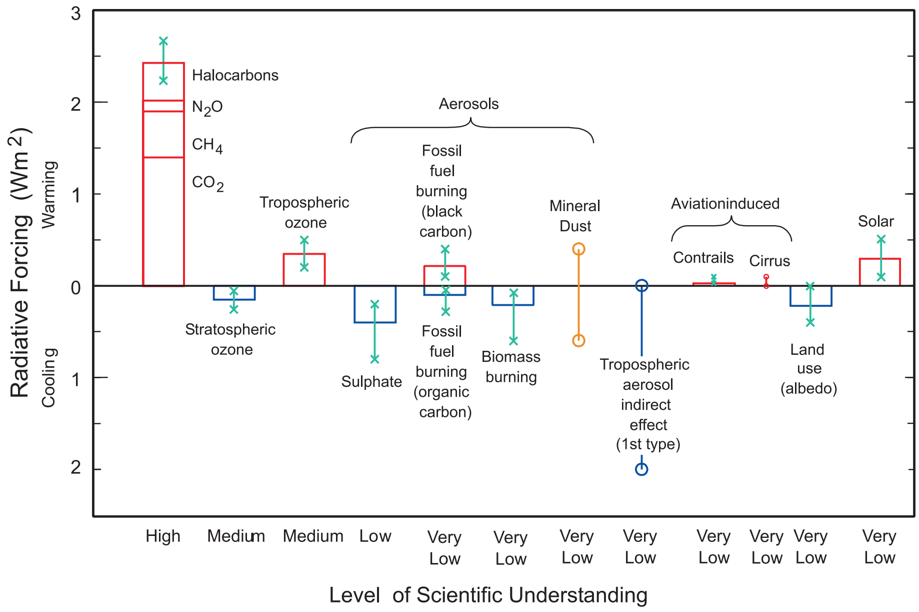


**Figure 4** Global and annual-mean radiative forcing (W/m$^2$) for various agents from pre-industrial (1750) to the present (late 1990s). The height of the rectangular bar denotes a best estimate value, while its absence denotes no best estimate is possible. The vertical line about the rectangular bar with "x" delimiters indicates an estimate of the uncertainty range, for the most part guided by the spread in the published values of the forcing. A vertical line without a rectangular bar and with "o" delimiters denotes a forcing for which no central estimate can be given owing to large uncertainties. A "level of scientific understanding" index is accorded to each forcing, with high, medium, low and very low levels, respectively. This represents the subjective judgment about the reliability of the forcing estimate. The well-mixed greenhouse gases are grouped together into a single rectangular bar. The sign of the effects due to mineral dust is itself an uncertainty and the indirect forcing due to tropospheric aerosols as well as the forcing due to aviation via their effects on contrails and cirrus clouds is poorly understood. The forcing associated with stratospheric aerosols from volcanic eruptions is highly variable over the period and is not considered for this plot. It is emphasized that the positive and negative global-mean forcings cannot be added up and viewed a priori as providing offsets in terms of the complete global climate impact (from IPCC, 2001).

warming in store as the earth system attempts to equilibrate with the higher levels of greenhouse gases. In terms of climate change, therefore, the real policy question that needs to be addressed is: what do we as a society consider to be an acceptable level of future warming?

## Observed Changes in Surface Air Temperature

Several researchers around the world have independently put together global data sets of surface air temperatures from the instrumental record. All of these researchers have either used only non-urban locations or corrected the urban data for what is known as the urban heat island effect, whereby cities naturally warm as they grow.

The globally averaged surface air temperature has increased by about 0.6 ± 0.2°C over the 20th century. Most of this warming has occurred during two periods: 1910–1945 and 1976–2000 (Fig. 5, 6). Very recently, proxy data from, for example, boreholes, corals and tree rings have allowed for the reconstruction of northern hemisphere temperatures back as far as AD 1000. Several such reconstructions are shown in Figure 7 (bottom). Of particular importance is that reconstructed and instrumental records generally agree over their common period. In the last 1,000 years the 20th century is the warmest century, the 1990s the warmest decade. Furthermore, the top 10 warmest years since 1880 in descending order are: 1998; 2002; 2001; 1997; 1995; 1990; 1999; 2000; 1991; 1987 (Fig. 5).

A common misconception is that global warming implies warming everywhere by about the same amount. This is not the case and there are, in fact, regions where the earth has cooled over the 20th century (Fig. 6a). Warming on the global scale is either amplified or reduced through local feedbacks. In general, the warming is much larger over land compared to oceans (see for example Fig. 5 and 6d) as the oceans have a higher heat capacity, and can sequester heat to great depths. Warming is also generally larger at high latitudes than at low latitudes, because of the existence of a powerful positive feedback involving the albedo of snow and ice (the albedo of a surface is defined as the percentage of incoming solar radiation hitting the surface that is reflected back to space). That is, as snow and ice cover retreat, as has been observed over the 20th century, especially since 1979, the land surface darkens and so does not reflect as much radiation back to space. In the case of sea ice, the observed reduction in areal extent also exposes more of the ocean to the atmosphere, thereby allowing the warming of the atmosphere through heat loss from the ocean.

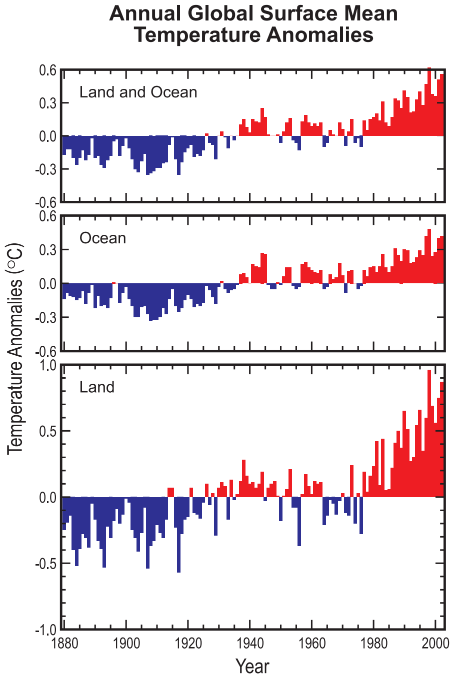


**Figure 5** (top) Annual mean global surface air temperature anomalies (from the US NOAA) over: land + ocean (top panel); ocean only (middle panel); land only (bottom panel).

The warming is also amplified in the winter, and to a lesser extent spring, over land (Fig. 8) since the snow albedo effect is largest at this time of year. In addition, the warming trend over land since 1950, on average, has been about twice as fast at night compared to the day (Fig. 9). That is, night-time low temperatures have increased twice as fast as day-time high temperatures (0.2°C per decade versus 0.1°C per decade). It is currently thought that this decrease in diurnal temperature range is associated with the observed increase in cloud coverage since 1950. This follows since clouds act to dampen diurnal temperature variations by back reflecting incoming solar radiation in the day and absorbing and re-radiating outgoing longwave radiation from the earth at night. Similarly, the direct effect of tropospheric aerosols only acts in the day (when there is incoming solar radiation to backscatter) while greenhouse gases are effective both day and night. As with the warming trends, there are some regions where in fact the diurnal temperature range has increased since 1950, although most regions show a reduction.

## Other Observed Changes

It is not possible to provide an exhaustive discussion of all the observed changes in climate since the start of the 20th century so the reader is referred to Figure 10. This figure captures the essence of most of the major 20th century observed changes. It is important to note that the observed changes are internally consistent with each other, as well as with physical intuition, without needing to appeal to complicated coupled atmosphere-ocean models. Increasing greenhouse gases provide a positive radiative forcing that warms the surface of the Earth and melts glaciers, snow and sea ice. Change is much smaller over the oceans, and hence around Antarctica relative to the Arctic, because of the high heat capacity of the ocean. A warmer atmosphere holds more moisture so that cloud coverage should be expected to increase, leading to a reduction in the diurnal temperature range. The hydrological cycle should also intensify leading to enhanced

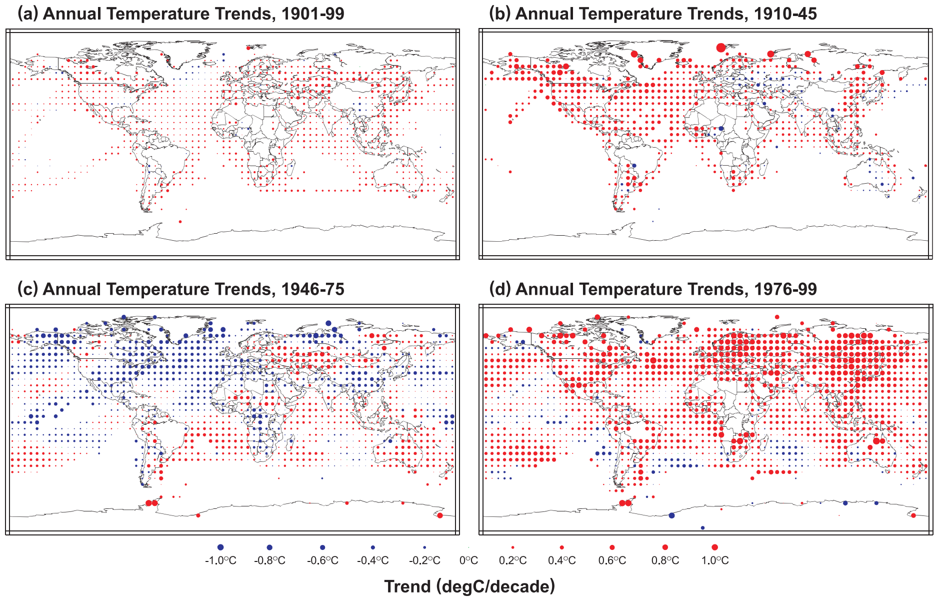


**Figure 6** Annual mean temperature trends (°C/decade) for the periods a) 1901–1999; b) 1910–1945; c) 1946–1975; d) 1976–1999. The magnitude of the trend is given by the area of the circle and the sign of the trend is positive (warming) if the circle is red, and negative (cooling) if the circle is blue (from Chapter 2 of IPCC, 2001).

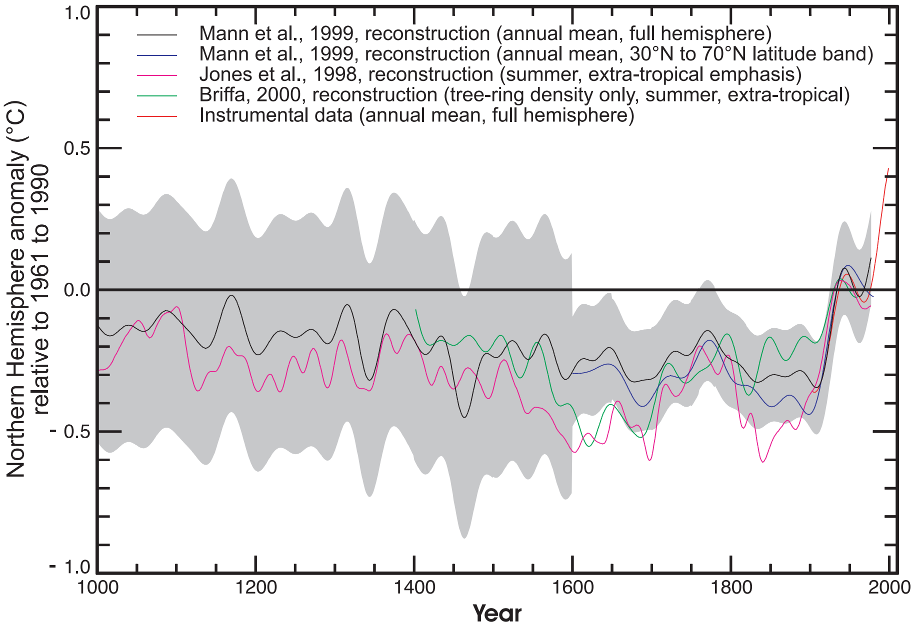


**Figure 7** Northern hemisphere surface air temperature reconstructions since AD 1000: (pink) summer, northern hemisphere, multi-proxy-based (Jones et al., 1998); (black) annual mean, northern hemisphere, multi-proxy-based (Mann et al., 1999); (green) summer, extratropical, tree-ring-based (Briffa, 2000); (blue) annual mean, 30°N-70°N averaged, multi-proxy-based (Mann et al., 1999); (orange) annual mean, northern hemisphere, instrumental record. As noted in IPCC (2001), all curves were smoothed with a 40-year Hamming-weights lowpass filter, with boundary constraints imposed by padding the series with its mean values during the first and last 25 years. Two standard error limits are shown by gray shading. The horizontal zero black line denotes the 1961-1990 reference period mean temperature (from Chapter 2 of IPCC, 2001).

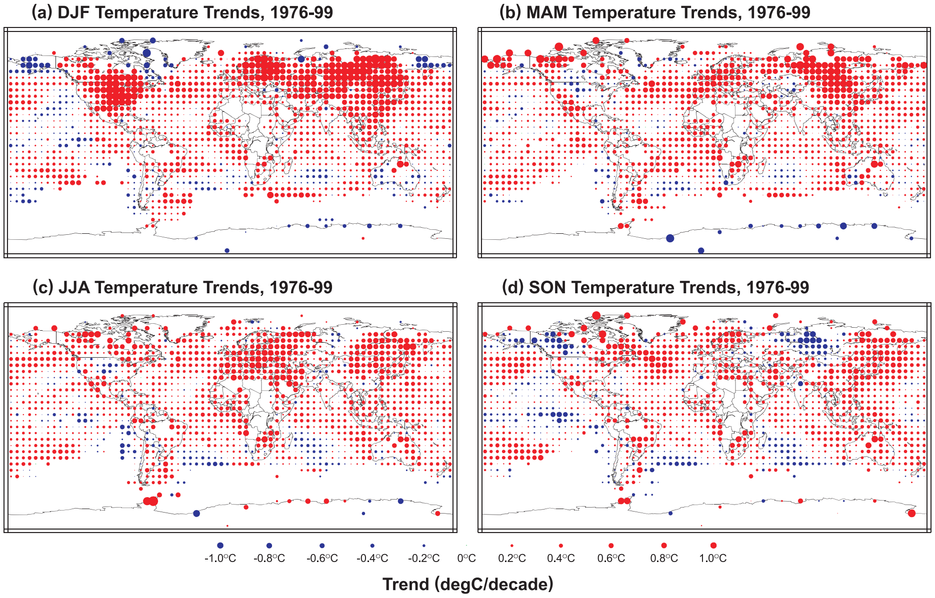


**Figure 8** Seasonal mean temperature trends (°C/decade) for the period 1976–1999. a) Winter: December, January, February; b) Spring: March, April, May; c) Summer: June, July, August; d) Autumn — September, October, November. The magnitude of the trend is given by the area of the circle and the sign of the trend is positive (warming) if the circle is red and negative (cooling) if the circle is blue (from Chapter 2 of IPCC, 2001).

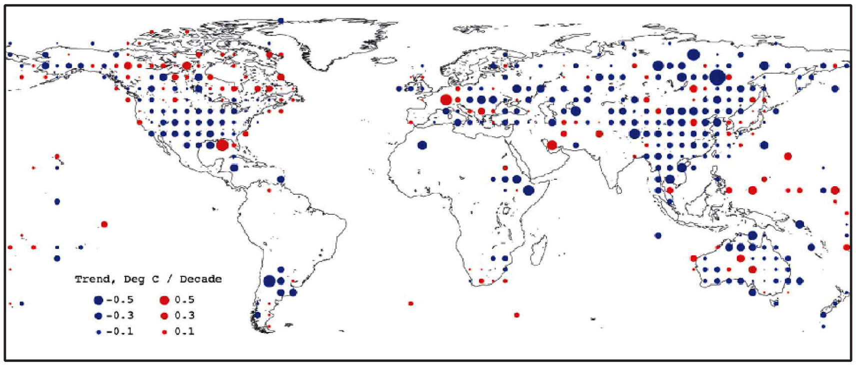


**Figure 9** Trend in annual mean diurnal temperature range (°C/decade). The magnitude of the trend is given by the area of the circle and the sign of the trend is positive (warming) if the circle is red and negative (cooling) if the circle is blue. Data are from the period 1950–1993 and from non-urban stations only (from Chapter 2 of IPCC, 2001).

precipitation at mid- to high-latitudes, with more extreme precipitation events, along with enhanced evaporation at low latitudes.

Figure 10 is particularly useful for comparison with a similar figure that will be reproduced in the next section (Fig. 17). This latter figure will summarize what a variety of coupled atmosphere-ocean general circulation models (GCMs) project for a future climate warmed through increasing greenhouse gases. It will be evident that what has already occurred is consistent with what models suggest should have occurred, and also what these same models project will occur more noticeably in the future.

## PROJECTIONS OF CLIMATE CHANGE WITH APPLICATIONS TO CANADA

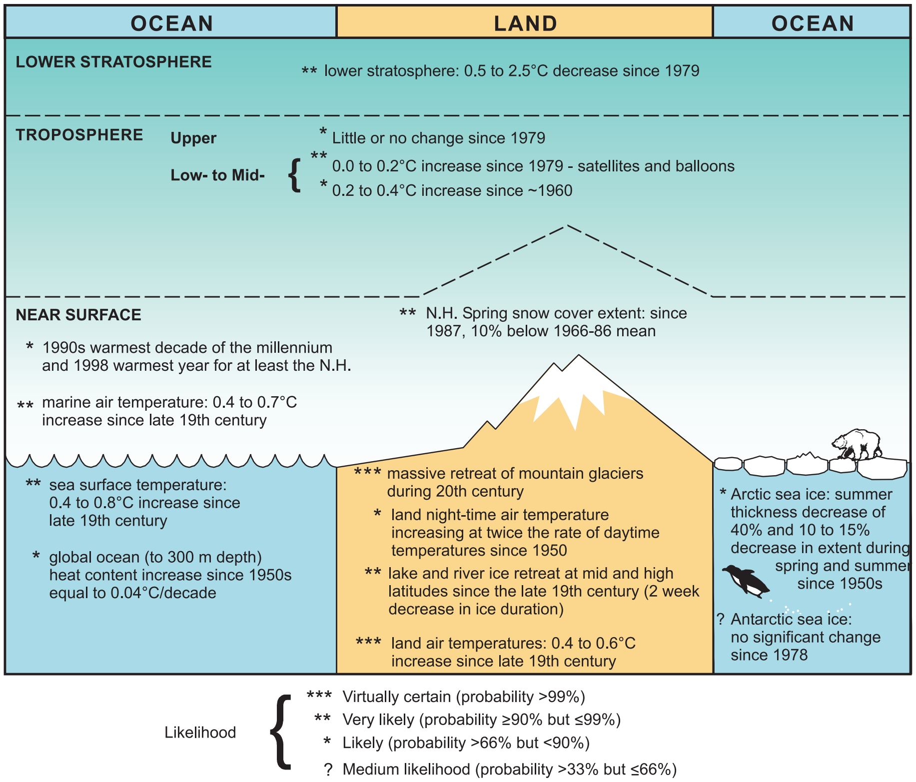
Coupled atmosphere-ocean General Circulation Models (GCMs) have evolved considerably over the years and are continually being improved, both in terms of resolution and through the inclusion of new, sophisticated, physical parametrisations. They consist of an atmospheric component, developed through decades of research in numerical weather prediction around the world, coupled to interactive ocean and sea ice models. All GCMs include a land surface scheme and some now allow predictions of how terrestrial vegetation will respond to a changing climate. Climate models are not used to predict weather, but rather the slow mean change of average weather and its statistics. They are built on the physical principles that we believe govern the various components of the climate system. Before a climate model is deemed useful for future climate projections, it must be satisfactorily tested against the present-day and transient 20th century climate. GCM simulations of past climates (e.g. 6,000 and 21,000 years ago) are also compared with paleo-reconstructions to evaluate the model's performance. Model deficiencies found through this evaluation process are documented, and attempts are then made to reduce or eliminate them.

### Scenarios of Future Emissions

Any projection of future climate change fundamentally requires assumptions to be made as to what future emissions of greenhouse gases and aerosols will be. These in turn are determined by making assumptions on future economic and population growth, technological change, energy use, etc. Clearly it is difficult if not impossible to make accurate projections of these socioeconomic factors over 100 years. As such, the IPCC put forth a number of scenarios of future emissions under a wide range of possible 'story lines' of socioeconomic and technological change in the future. In its second scientific assessment, six such scenarios were developed (IS92a–f). In the third IPCC assessment, 40 different scenarios were put forward (see IPCC, 2000).

Several of the possible scenarios lead to projected reductions of greenhouse gas emissions over the 21st century (see for example the green curve in Fig. 11). Several other scenarios lead to continued growth in emissions, and others suggest that emissions continue to increase in the short term but eventually start to decrease. Six sample profiles are shown in Figure 11 together

(a) Temperature indicators



(b) Hydrological and storm related indicators

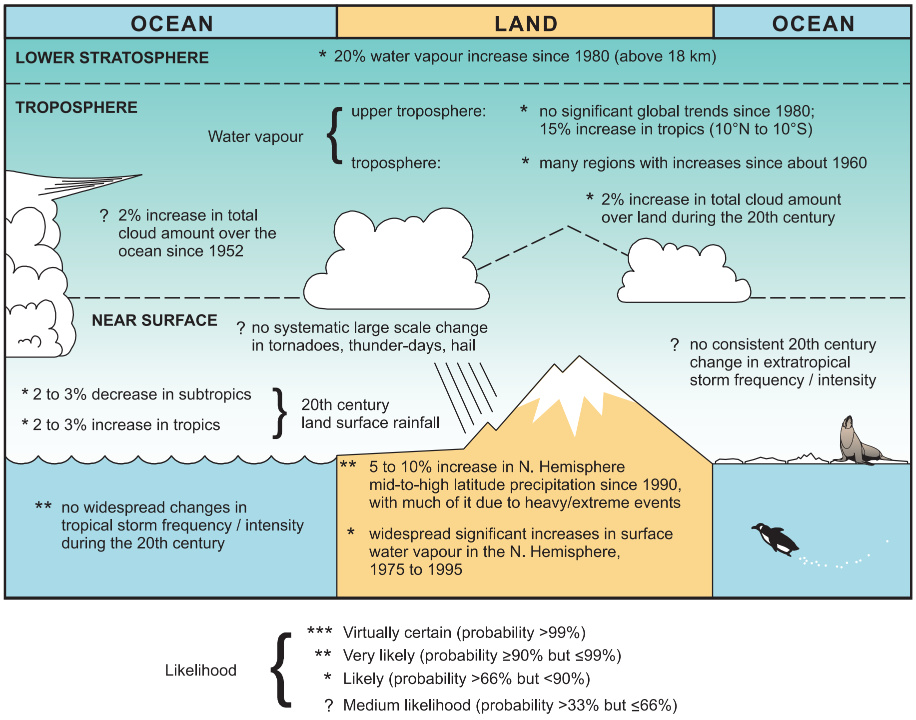


**Figure 10** Schematic diagram of observed variations in a) temperature; b) hydrological and storm-related indicators (from the Technical Summary of IPCC, 2001).

with the IS92a or 'best guess' profile used in the second scientific assessment. None of the individual scenarios can be termed 'correct', since each is as equally plausible or implausible as the other. In order to produce a range of possible climate outcomes, it is therefore advisable to integrate coupled models under as many of the scenarios as possible.

It has, however, not yet been possible for comprehensive GCMs to run century-long integrations using all scenarios solely due to the lack of available computing time. Nevertheless, several groups around the world have run their GCMs under a select number of these scenarios. The climate sensitivity of a particular GCM is defined as the equilibrium warming for a doubling of atmospheric $CO_2$. Together with the oceanic heat uptake obtained from these same GCMs, the GCM climate sensitivities can be used in simpler models to span the full range of scenarios to get estimates of first-order quantities like global sea-level rise and surface air temperature changes over the next century. These simple models, however, do not allow one to make projections of regional changes in climate.

## Projections of Future Temperature Change from Simple Models

Figure 12, derived from a simple climate model that uses climate sensitivity and oceanic heat uptake from more complex climate models, provides an initial illustration of the projected global mean surface temperature change over the 21st century. Using the range of climate sensitivities from coupled GCMs and all emissions scenarios, one arrives at a range of projected 2100 warming, relative to 1990, of 1.4–5.8°C. This range, reported in the IPCC Third Assessment Report (IPCC, 2001), is higher than the 1.0–3.5°C range reported in the Second Assessment Report (IPCC, 1996) simply because a greater range of scenarios are now being used, and not because of any increase in model uncertainty. That is, in the 1996 report, only six scenarios were used, whereas now 40 scenarios are used. Generally, the newer scenarios yield lower sulphur dioxide emissions (bottom panel of Fig. 11) and hence less cooling from the resulting direct and indirect effects of the aerosols.

The international media picked up on the differences between the range of IPCC 1996 and 2001 projections. In articles that appeared in the United Kingdom's Daily Telegraph (*Pace of global warming 'could double'*, by Charles Clover, January 25, 2001) as well as the National Post (*Hot, hot is the range,* by Margaret Munro, January 23, 2001), it was stated: "Global warming could happen twice as quickly as previously forecast over the next 100 years, the most authoritative report yet produced on the science of climate change said".

There were other similar articles that appeared in international, national and local newspapers that left the public with the distinct impression that scientists had now determined that the pace of global warming would double. On the other hand, an article in the Toronto Star (*Top scientists call U.N. report on climate change misleading*, by Peter Calamai, January 23, 2001) quoted me correctly as saying: "Based on the science you can't say it is going to warm faster." The quote was correct, and the content of the article was also accurate, but its headline left the impression that as one of the Lead Authors in IPCC (2001), I was in apparent disagreement with the findings of the Third Assessment Report. In fact, the Toronto Star reporter conveyed to me in an email: "Of course, I disavow any responsibility for the headline". Ironically, the headline led to my ceremoniously being added to several

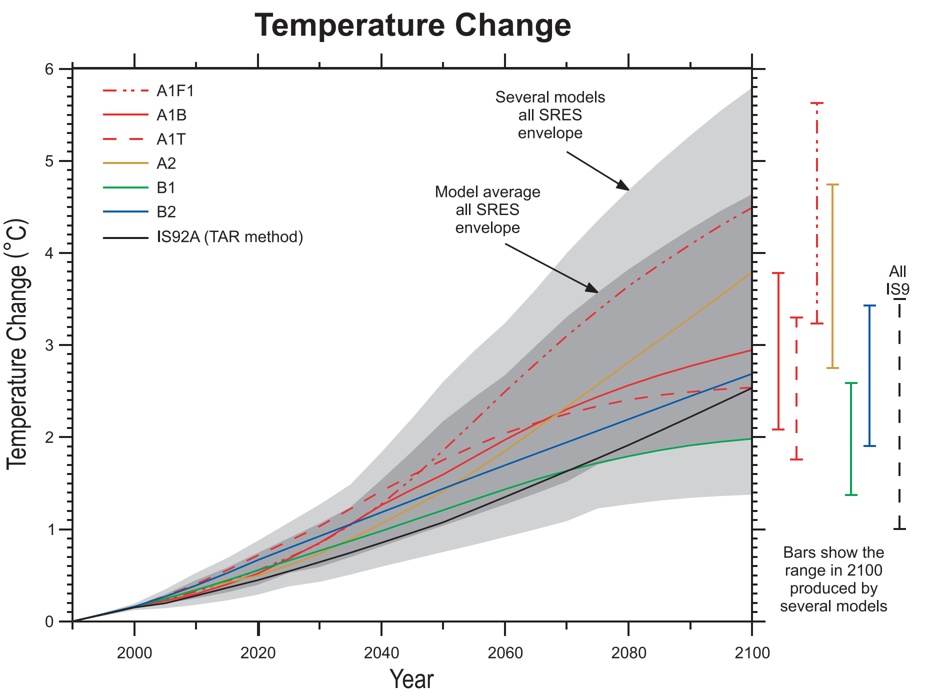


**Figure 12** Simple model projected global and annual mean temperature change relative to 1990 under a wide range of scenarios. The dark shading gives the range using all scenarios and the average model climate sensitivity. The light shading extends this range by calculating the spread for each GCM climate sensitivity independently. Note that in all cases, warming is projected even though in B1, emissions of $CO_2$ and $CH_4$ are assumed to drop substantially below 1990 levels (Fig. 11) (from the Summary for Policy Makers of IPCC, 2001).

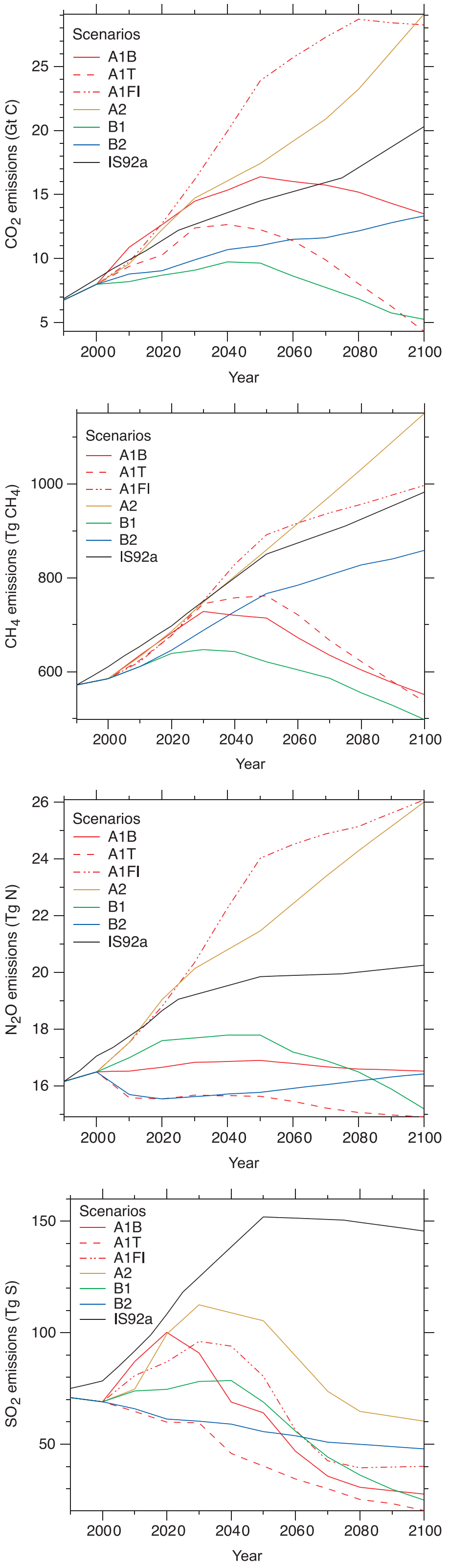


**Figure 11** Projected anthropogenic emissions of carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$) and sulphur dioxide ($SO_2$) for six illustrative scenarios. The six scenarios differ in their assumptions of future population growth, technology paths, economic growth, etc. (see IPCC, 2000). For example, A1F1 represents a world characterized by rapid economic growth although global population peaks in the middle of this century and drops after that. A fossil-fuel intensive path of technological change is assumed as is a reduction in regional differences in per capita income (IPCC, 2000) (from the Technical Summary of IPCC, 2001).

climate change skeptic sites and my being re-quoted in several anti-Kyoto articles internationally. I added this example to highlight the confusion that often arises in the media when the climate change science is reported.

With regards to the IPCC (2001) increased projection of 2100 warming of 1.4–5.8°C, relative to the 1.0–3.5°C range reported in (IPCC, 1996), I attended a presentation by an analyst involved in negotiating Kyoto commitments. The speaker confidently stated that the greater range arose because the climate models had become more uncertain. The reality, of course, is that in the 2001 IPCC report, a wider range of scenarios was used in order to capture a more diverse range of possible socio-economic assumptions, leading to a more diverse range of future emissions. Global warming was not suddenly expected to double (a confusion which arose because the upper bound was raised from 3.5 to 5.8°C); climate models had not become more uncertain (a confusion which arose because the spread between maximum and minimum projected warming had increased from 2.5 to 4.4°C). Very simply, for a more diverse range of emission scenarios, the climate models projected a more diverse range of possible future climates.

## Uncertainty in Climate Change Projections

There are two types of uncertainties involved in climate change projections (NRC, in press): those that are essentially random (aleatoric uncertainty); and those which arise from an incomplete understanding of a particular process (epistemic uncertainty). By its very definition, the aleatoric uncertainty is impossible to reduce (i.e., the odds of getting ‘heads’ when flipping a coin once is never more or less than 50%). In the climate context, the estimation of aleatoric uncertainty is often accomplished by using one model to create an ensemble of climate model integrations. The range spanned by the different integrations, which differ only in their initial condition, then represents an estimate of uncertainty associated with random processes and natural climate variability. The mean of the ensemble represents a best estimate.

An estimation of epistemic uncertainty can be obtained by using different models with different parametrisations of unresolved processes and integrating each of these with the same radiative forcing. As such, the intermodel variation gives an estimate of model uncertainty and the intramodel variation gives an estimate of uncertainty associated with natural variability.

The epistemic uncertainty in climate change projections can further be broken down into two components: one involving uncertainty in climate feedbacks, and one involving uncertainty in the emissions scenario used to drive the climate model. In terms of overall uncertainty, each contributes about 50%, the latter being dependent on poorly constrained assumptions of future population growth, social behaviour, economic growth, energy use and technology change. Compounding the problem of uncertainty is the potential existence of ‘unknown unknowns’ whose importance only becomes apparent once they are discovered.

Nevertheless, extensive research has been conducted over the last several years in an attempt to quantify uncertainty in climate change projections. Stott and Kettleborough (2002) found that in the absence of policies to mitigate climate change, climate change projections over the next 40 years are insensitive to the particular emission scenario used (see also Zwiers, 2002). Knutti et al. (2002) further found that there is a 40% chance that actual warming at 2100 will exceed the upper bound of the range (1.4–5.8°C) estimated in the IPCC Third Assessment Report. They found only a 5% chance that it will be less than the lower bound.

While science is likely to reduce the epistemic uncertainty of the known unknowns over the next decade, it is also likely to discover new unknowns. In terms of projections of climate change over the next 40 years, it is unlikely that science will change the global estimate and range of warming. Nevertheless, where science is likely to make substantial reduction in uncertainty is with regards to the development of better schemes for regional downscaling of climate projections. This will allow for the development of local adaptation strategies while the necessary international negotiations to move towards significantly reduced global emissions takes place.

## Projections of Future Temperature Change from Coupled Atmosphere-Ocean GCMs

As noted earlier, the enormous computational requirements needed to integrate coupled atmosphere-ocean general circulation models under the full 40 scenarios of future emissions meant that only a few illustrative scenarios could be examined for the third IPCC assessment. Figure 13 shows the multi-model ensemble mean projected warming averaged over 2071–2100 relative to 1961–1990 for the A2 and B2 scenarios, whose emissions are shown in Figure 11. To obtain a multi-model ensemble mean, the first step is to collect an ensemble of integrations obtained from one GCM under a particular scenario but with slightly different initial conditions. The second step is to average the results of this model ensemble with analogous ensembles obtained from several different GCMs.

While it is not meaningful to pick a particular place on the Earth’s surface and say unequivocally that it will warm by a certain amount over the next century, a number of key conclusions can be drawn. First, land areas warm more than ocean areas because of the greater heat capacity of the ocean. Second, the interior of the continents warm more than the coasts as they are farther away from the ocean. Third, the west coast at northern midlatitudes tends to warm less than the east coast as the former is more influenced by the ocean since the prevailing winds are from west to east. Fourth, the high latitudes warm more than the lower latitudes as a result of powerful albedo feedbacks associated with retreating snow and sea ice. As noted earlier, an additional positive feedback arising

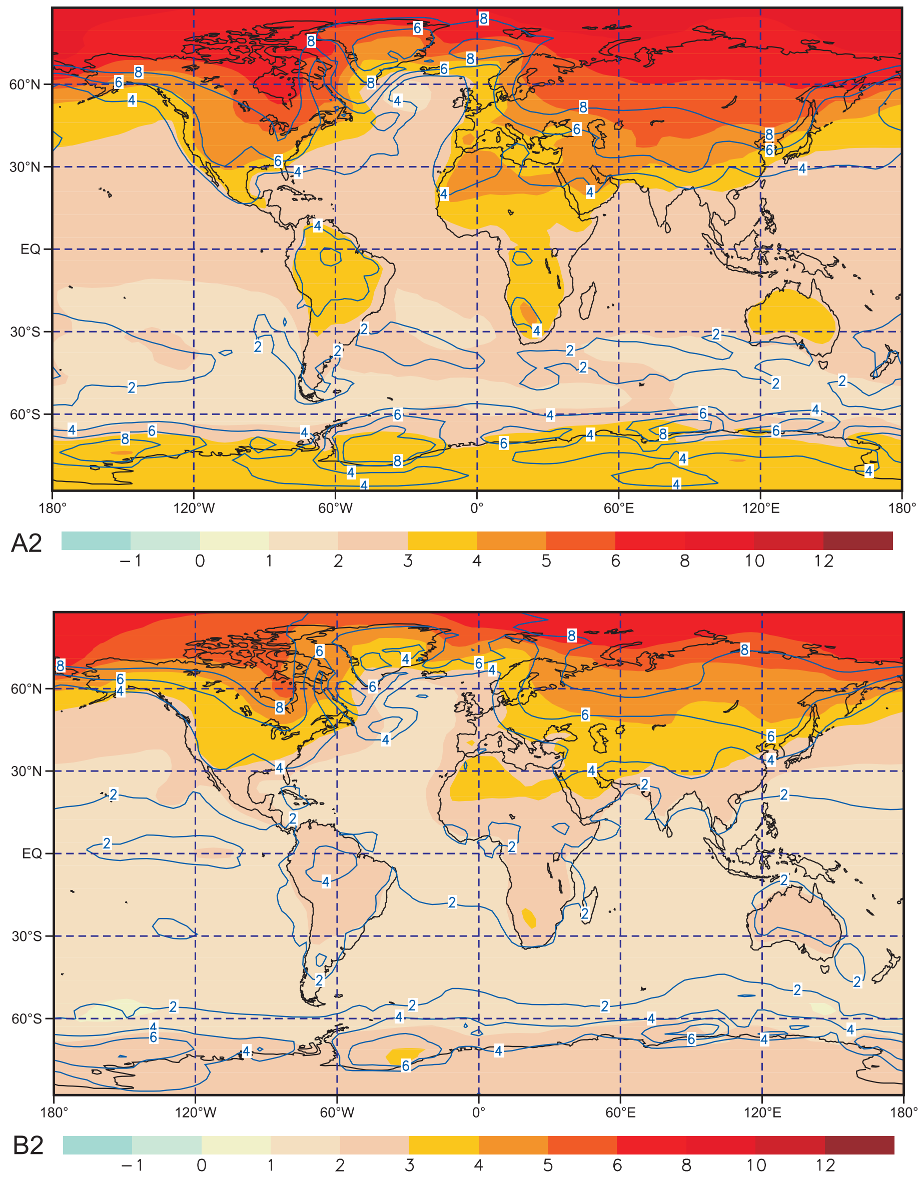


**Figure 13** The annual mean temperature change (coloured shading) and intermodel range (contour lines) between the year 2071–2100 and 1961–1990 average climates. Coupled atmosphere-ocean GCMs were driven by either Scenario A2 (top); or scenario B2 (bottom). All units are in °C (from the Technical Summary of IPCC, 2001).

from retreating sea ice is that the ocean is no longer insulated from the atmosphere and so can warm it from below. Fifth, the northern hemisphere warms more than the southern hemisphere as there is more land there.

Enhanced warming is also projected in the winter months relative to the summer months as indicated in Figure 14 for the Canadian Centre for Climate Modelling and Analysis model integrated under the IS92a scenario. This particular simulation also reveals local cooling around the North Atlantic due to a weakening of the North Atlantic conveyor and subsequent reduction in northward ocean heat transport there. Figure 14 also shows other regions of little warming, or even slight cooling, around India and southeast Asia due to concentrated industrial activity and the local cooling effects associated with anthropogenic tropospheric aerosols.

## EXTREME EVENTS AND THE POSSIBILITY OF SURPRISES

### Extreme Events

Extreme weather events are important from a policy perspective as they cause the most stress on adaptation strategies for climate change. Adaptation strategies aimed exclusively at dealing with a slow mean change in climate could be ineffective if they do not also account for projected changes in climate and weather statistics associated with the projected mean climate change. In its Third Assessment Report, the IPCC (IPCC 2001) undertook a systematic analysis of observed changes in extreme weather and climate events over the 20th century and their projected change over the 21st century (summarized in Table 1, reproduced from IPCC, 2001, below).

### Abrupt Climate Change

Rapid transitions between fundamentally different climate regimes have commonly occurred over the last 400,000 years (Fig. 2; see Clark et al., 2002 for a review). On the other hand, the last 10,000 years (the Holocene) has had a remarkably stable climate, leading to the rise of agriculture and modern society. The potential disruptive impact of an abrupt climate change event has led scientists to try and grapple with its possible likelihood of future occurrence. Two specific climate change surprises have been given special attention. The first involves trying to determine the probability of a collapse of the West Antarctic Ice sheet — an event that would lead to a 6 m global sea level rise over a relatively short period of time. The second involves assessing the likelihood of a complete shutdown of the North Atlantic conveyor — if this were to occur, the global oceanic deep circulation would be reorganized and the amount of heat transported northward in the North Atlantic by the ocean would be substantially reduced; this would tend to affect the climate over land downwind of the ocean (i.e., Europe). In its Third Assessment Report, the IPCC (IPCC 2001) concluded that the former was very unlikely (1-10% chance) to occur over the 21st century and noted that it was too early to determine whether an

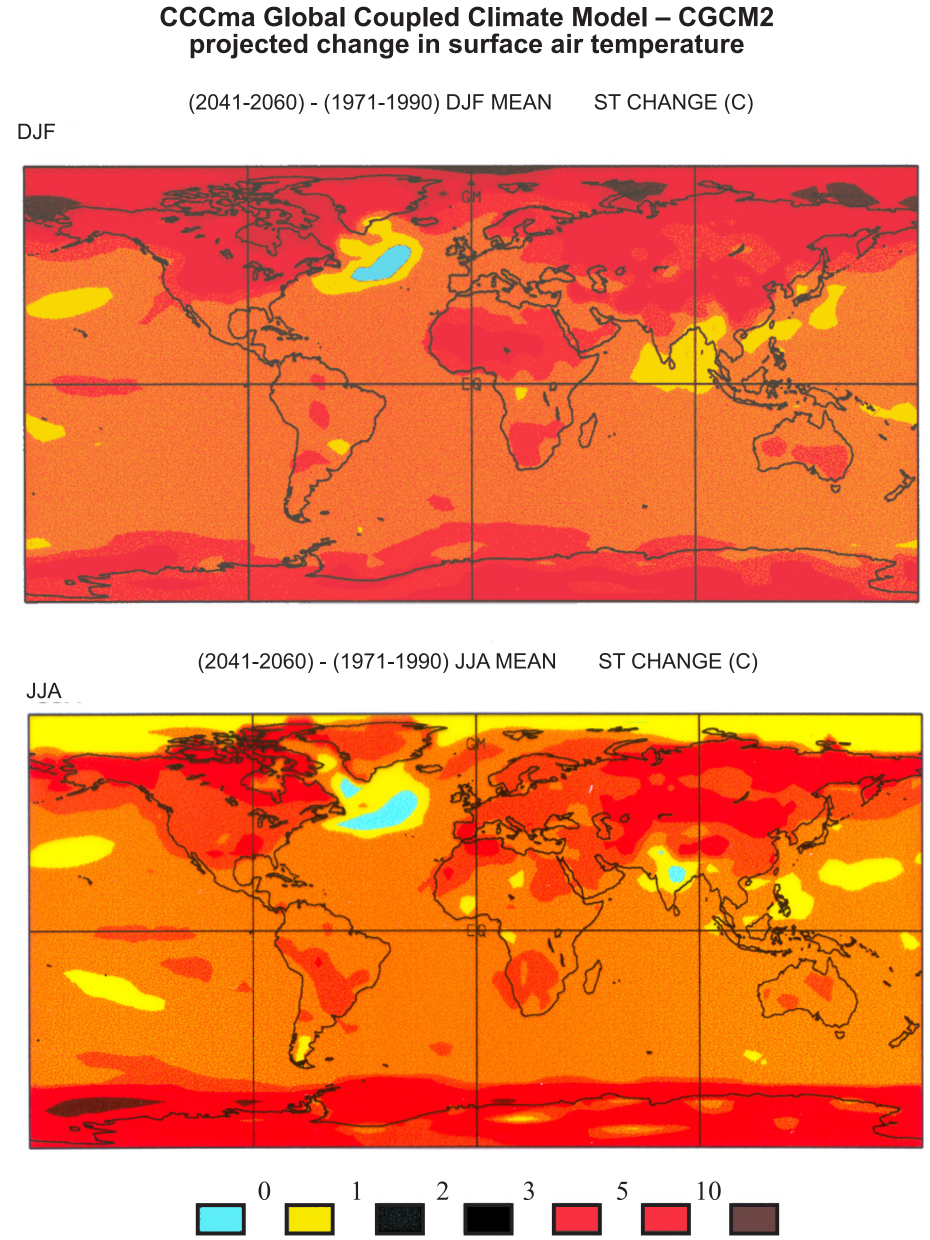


Figure 14 The mean temperature change between the average seasonal climate in 2041–2060 and 1971–1990 under an IS92 scenario. Top) Winter — December, January, February; Bottom) Summer — June, July, August. All units are in °C. This figure was obtained from Dr. G. Flato of the Canadian Centre for Climate Modelling and Analysis in Victoria, British Columbia.

irreversible change in the conveyor is likely or not over this same period.

Most, but not all, coupled model projections of the 21st century climate show a reduction in the strength of the conveyor in the North Atlantic with increasing concentrations of greenhouse gases (IPCC, 2001). Nevertheless, all coupled model simulations show that Europe continues to warm even in those simulations where the conveyor shuts down. In those simulations where the conveyor reduces in the short term, the ocean acts as a negative feedback to high-latitude warming. A reducing conveyor reduces high-latitude ocean heat transport and hence sea surface temperatures. This affects atmospheric surface temperatures both directly and indirectly, through feedbacks on ice areal extent. Over the longer term, most climate models find a reestablishment of the conveyor to present-day levels so that during this reestablishment phase, the ocean conveyor would act as a positive feedback to warming in and around the North Atlantic. What is even less known, and still an outstanding question, is how the stability of the conveyor will change in a future climate warmed through anthropogenic greenhouse gases.

## Projected Climate Change and Canada

Chapter 10 of the IPCC Third Assessment was charged with assessing Regional Climate Information both in terms of the evaluation of regional climates and the projection of regional climate change. This chapter formally showed that the warming found in several coupled atmosphere-ocean GCMs driven by two illustrative scenarios (A2 and B2; see Fig. 11 and 13), was 40% above the global average in the winter months at high northern latitudes (see Fig. 15). The ENA, CNA and WNA regions, which include most of southern Canada, showed greater than average warming, in both summer and winter, for both the A2 and B2 scenarios. The GRL region, which includes some of northern Canada, is projected to have greater than average warming in the summer and much greater than average warming in the winter months. As such, the 1.4–5.8°C globally-averaged warming projections by 2100 should be considered to be amplified over most of Canada (see Fig. 13 and 14).

Similarly, there is intermodel agreement that the GRL and ALA regions, which include much of northern Canada and all of the Canadian Arctic, will receive at least a 5–20% increase in precipitation in summer and winter by the years 2071–2100 (Fig. 16). Under the A2 scenario (Fig. 11 and 13) greater than 20% increases are projected for these regions. Both the WNA and ENA regions are projected to have increases of 5–20% in precipitation by 2071–2100 in the winter, although in the summary as well as in the CAN region, intermodel differences are of inconsistent sign.

**Table 1** Estimates of confidence in observed and projected changes in extreme weather and climate events. Virtually certain (>99% chance that a result is true); Very Likely (90-99% chance); Likely (66-90% chance); Medium Likelihood (33-66% chance); Unlikely (10-33% chance); Very Unlikely (1-10% chance); Exceptionally Unlikely (<1% chance)(from IPCC, 2001).

| Confidence in observed changes (latter half of the 20th century) | Changes in Phenomenon | Confidence in projected changes (during the 21st century) |
|---|---|---|
| Likely | Higher maximum temperatures and more hot days over nearly all land areas | Very Likely |
| Very Likely | Higher minimum temperatures, fewer cold days and frost days over nearly all land areas | Very Likely |
| Very Likely | Reduced diurnal temperature range over most land areas | Very Likely |
| Likely, over many areas | Increase of heat index (a measure of human discomfort) over land areas | Very Likely, over most areas |
| Likely, over many northern hemisphere mid- to high latitude land areas | More intense precipitation events | Very Likely, over many areas |
| Likely, in a few areas | Increased summer continental drying and associated risk of drought | Likely, over most midlatitude continental interiors (lack of consistent projections in other areas) |
| Not observed in the few analyses available | Increase in tropical cyclone peak wind intensities | Likely, over some areas |
| Insufficient data for assessment | Increase in tropical cyclone mean and peak precipitation intensities | Likely, over some areas |

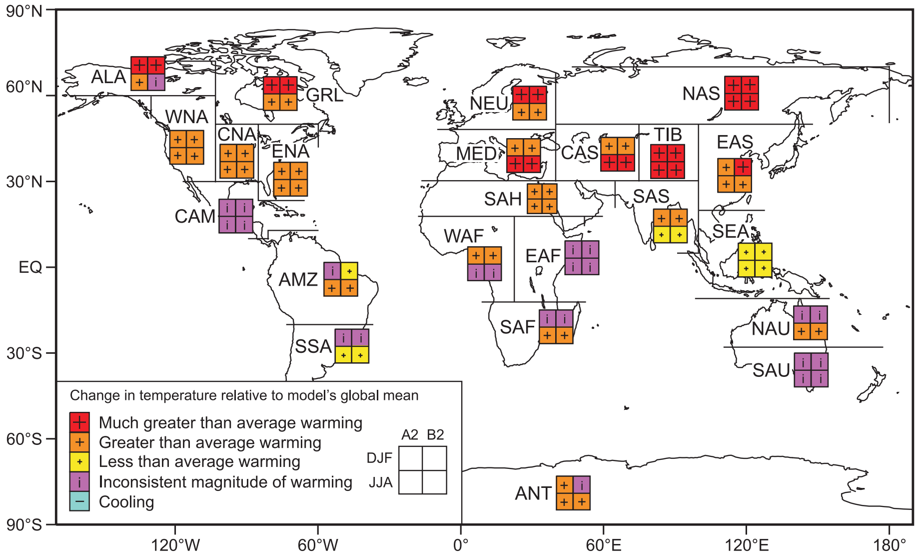


**Figure 15** Analysis of inter-model consistency in regional relative warming (relative to each model's global-average warming). Regions are classified as showing either agreement on warming in excess of 40% above the global average ('Much greater than average warming'); greater than the global average ('Greater than average warming'); less than the global average ('Less than average warming'); or disagreement amongst models on the magnitude of regional relative warming ('Inconsistent magnitude of warming'). There is also a category that never occurs for agreement on cooling. A consistent result from at least seven of the nine models is deemed necessary for agreement. The global annual average warming of the models used span 1.2 to 4.5°C for A2 and 0.9 to 3.4°C for B2, and therefore a regional 40% amplification represents warming ranges of 1.7 to 6.3°C for A2 and 1.3 to 4.7°C for B2 (from the Technical Summary of IPCC, 2001).

## SUMMARY

As is the case for the previous section, there are simply too many projected changes from too many coupled atmosphere GCMs to provide a comprehensive description of all aspects of future projected change. Figure 17, from the IPCC (2001), summarizes the projected changes for the end of the 21st century with an assigned level of confidence (virtually certain: >99% probability; very likely: 90-99% probability; likely: 66-90% probability; medium likelihood: 33-66% probability). The comparison of Figure 17 with Figure 10 suggests that what has already occurred in the climate record is consistent with what models suggest should have occurred, and also what these same models project will occur more noticeably in the future.

There are certain phenomena listed in Figure 10 that are not listed in Figure 17 as they are either not resolved, or there is a disagreement between models as to what might occur. Tornadoes, thunder days, hail, lake and river ice melt, for example, are not resolved in coarse resolution climate

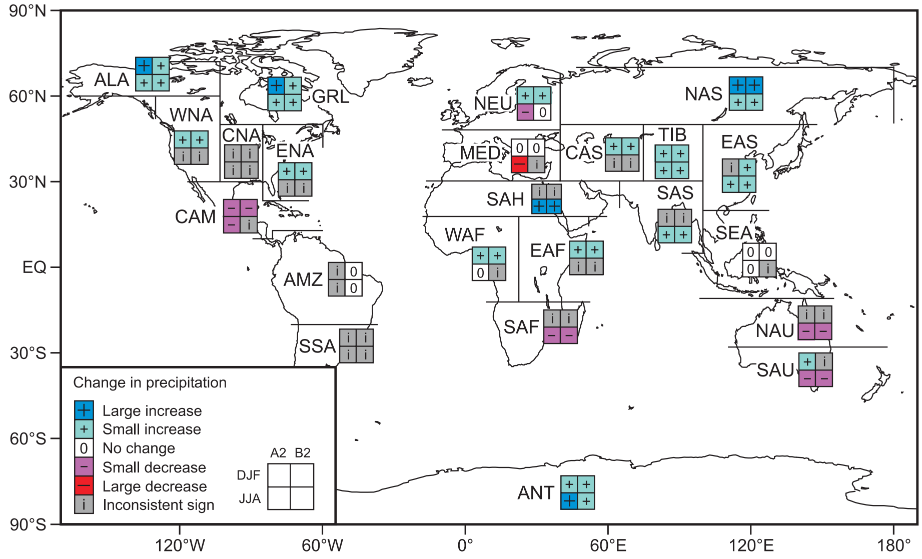


**Figure 16** As in Figure 15 but for precipitation. Regions are classified as showing either agreement on increase with an average change of greater than 20% ('Large increase'); between 5 and 20% ('Increase'); between –5 and +5% ('No change'); agreement on decrease with an average change between –5 and –20% ('Decrease'); less than –20% ('Large decrease'); or disagreement ('Inconsistent sign'). Increases or decreases are for the 2071-2100 mean relative to the 1961–1990 mean. A consistent result from at least seven of the nine models is deemed necessary for agreement (from the Technical Summary of IPCC, 2001).

models so no assessment can yet be made as to their future changes. Climate models all have cloud parametrisations that differ from model to model and the resulting changes in amount and type of clouds varies between models.

## Climate Change Detection and Attribution

The climate system changes on a variety of timescales both through *natural*, internal processes as well as in response to variations in *external* forcing (e.g., solar changes, volcanic emissions, greenhouse gases). As such, the detection of climate change involves looking, in a statistically significant sense, for the emergence of a signal above the background of *natural* climate variability. Attribution involves specifically assigning a cause for the detected signal to human activities, variations in other external forcing, or a combination of both.

In 1996, the IPCC second scientific assessment included the statement:

> "The balance of evidence suggests a discernible human influence on global climate."

despite, as reported in Gelbspan (1997): "…deliberate attempts to obfuscate and undermine the documents by the OPEC nations, principally Saudi Arabia and Kuwait…" This cautious statement represented the consensus view of those scientists working in WGI. It was based on the results of only a few detection and attribution studies available at the time. Since 1996, there have been many more published works firming up the science behind this statement. As a result, in the third WGI IPCC assessment released in January 2001, a much stronger statement was used: "There is now new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."

In fact, there does not appear to be any detection and attribution study that has been able to explain the warming in the second half of the century through any known natural cause.

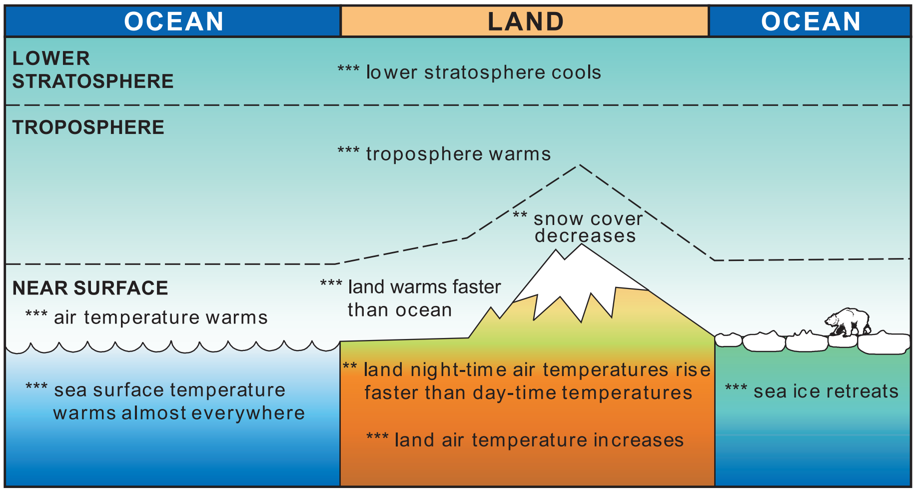
As noted earlier, global mean surface air temperatures have increased by 0.6 ± 0.2 °C since 1860, although this warming has not occurred in a constant fashion. In fact most of the warming has occurred during two distinct periods: from 1910-1945 and since 1976, with a very gradual cooling during the intervening period. Global warming critics have been quick to point out that most models which have simulated the climate of the 20th century have failed to capture this feature.

Researchers at the Hadley Centre in the United Kingdom, among others, have recently reported upon the most comprehensive simulations to date of the climate of the 20th century (Stott et al., 2000). They found that natural forcing agents (solar forcing and volcanic emissions), while necessary to simulate the early century warming, could not account for the warming in recent decades. Similarly, anthropogenic forcing alone (greenhouse gases and sulphate aerosols) was insufficient to explain the 1910–1945 warming but was necessary to simulate the warming since 1976 (see Fig. 18). Very similar results were also obtained using a completely different and independent model (the UVic Earth System model of intermediate complexity — Weaver et al., 2001; Matthews et al., 2003), with very different parametrisations and representations of the individual components of the climate system (Fig. 19).

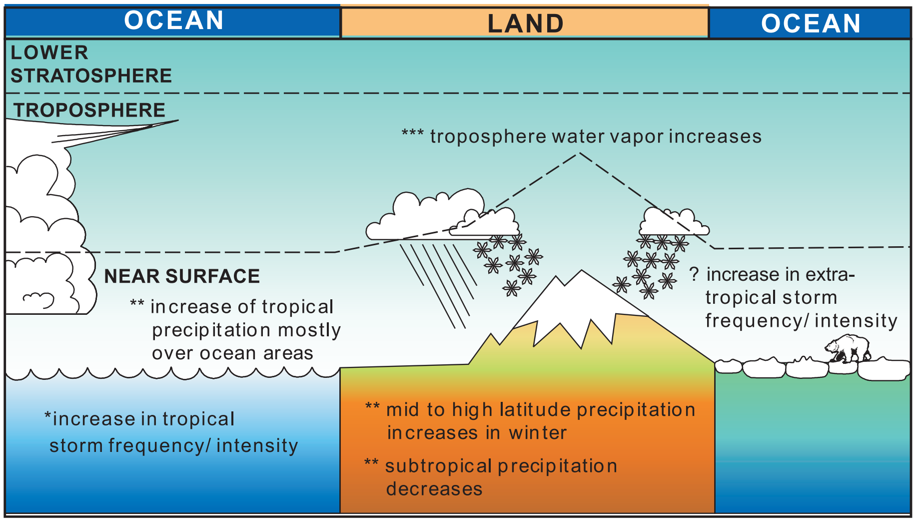
By regressing the large-scale signals from their simulations on decadal mean observations, Stott et al. (2000) demonstrated that natural forcing alone is not a plausible explanation for the observed changes in the 20th century, and that natural and anthropogenic forcing both make significant contributions to the observed change. They showed that when combined, these signals explain approximately 80% of the observed interdecadal variance of global mean temperature.

The experiments performed by Stott and colleagues took into account estimated historical variations in the main anthropogenic and natural external forcing agents that are believed to have affected the climate of the past century. These included heat-trapping greenhouse gases and change in ozone abundance (also a greenhouse gas), and the formation of sulphate aerosols from the industrial emission of sulphur

(a) Temperature indicators



(b) Hydrological and storm related indicators



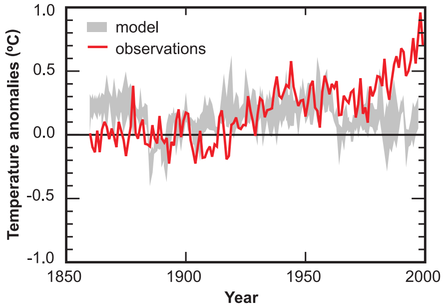
| | |
|---|---|
| *** | virtually certain (many models analysed and all show it) |
| ** | very likely (a number of models analysed show it, or change is physically plausible and could readily be shown for other models) |
| * | likely (some models analysed show it, or change is physically plausible and could be shown for other models) |
| ? | medium likelihood (a few models show it, or results mixed) |

**Figure 17** Schematic diagram of variations in a) temperature; b) hydrological and storm-related indicators from projections of future climate change with coupled atmosphere-ocean GCMs (from Chapter 9 of IPCC, 2001).

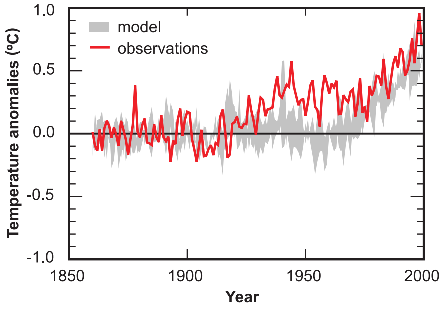
dioxide. Their approach was far from a diagnostic curve-fitting exercise. Rather, a model built on physical principles was used to simulate the climate's response to independent estimates of historical climate forcing. The striking level of agreement obtained between observed and simulated decadal-scale temperature variations strongly supports the contention that radiative forcing from anthropogenic activities, moderated by variations in solar and volcanic forcing, has been the main driver of climate during the past century.

Simulated annual global mean surface temperatures

(a) Natural



(b) Anthropogenic



(c) All forcings

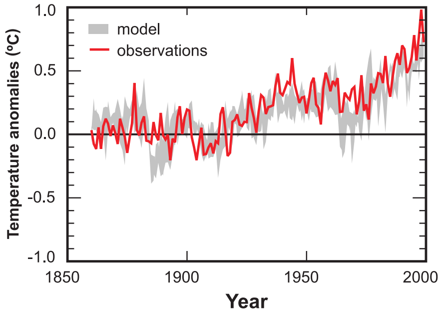


**Figure 18** Annual and global mean temperature anomaly (relative to the 1880–1920 average) from a suite of climate simulation experiments with both natural and anthropogenic forcing agents. The gray shading indicates the range spanned by four independent simulations; the red line indicates observations: a) The natural forcing (solar + volcanic emissions) experiments produce a gradual warming to about 1960 followed by a return to late 19th century temperatures, consistent with the gradual change in solar forcing throughout the 20th century and a resumption of volcanic activity during the past few decades. b) The anthropogenic (greenhouse gas + aerosols) runs reproduce the warming of the last three decades, but underestimate the early century warming and do not adequately capture the slight cooling that occurred between the two periods of rapid warming. c) The combined forcing runs, on the other hand, are able to reproduce much of the observed decadal scale variation in global mean temperature and are also able to capture with some fidelity the large-scale spatial structure of the observed changes (from the Summary for Policy Makers of IPCC, 2001).

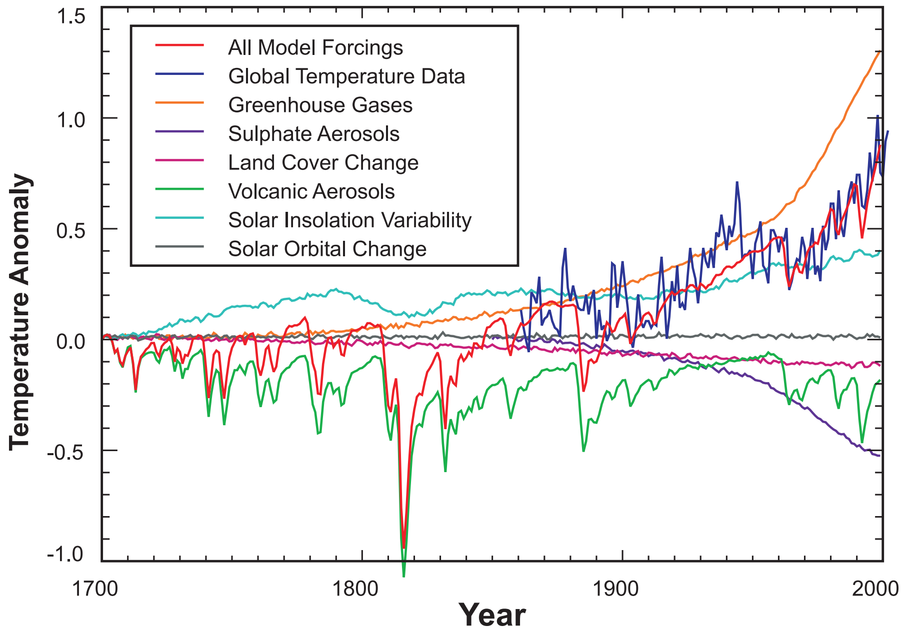


**Figure 19** Global mean surface air temperature anomaly (relative to a year 1700 equilibrium) obtained from simulations using the UVic Earth System Model of intermediate complexity. All model integrations started at year 1700. The observed temperature record is given in blue, while the model simulated change including all natural and anthropogenic forcings is given in red. These are plotted in relation to each other according to their 1961–1990 averages. The 20th century surface air temperature response of the UVic model, driven by changes in individual forcings (either natural or anthropogenic), is also shown: greenhouse gases (orange); sulphate aerosols (purple); land-use change (pink); volcanic activity (green); solar intensity (light blue); solar orbital (Milankovitch) forcing (black).

## SCIENCE AND POLICY

### Summary

In this paper the 200 year history and science of global warming has been outlined. In particular, it has been pointed out that the science is deeply rooted in the peer-reviewed literature. Unfortunately, the media tend to sensationalize the science, often leaving the general public confused. An example of this comes from the Victoria Times Colonist which, on January 14, 2001, published a 'Top Story' on page A3 headlined "*Study deflates global warming*." On January 23, 2001, only nine days later, the lead story on the front page was headlined "*Global warming severity grows*." The average person reading these pieces would think that scientific understanding is swinging like a pendulum from one extreme to the other. They would be entirely confused, and may even dismiss the whole issue, since they would not have the benefit of reading the peer-reviewed literature from which the stories arose. Scientists are of course debating climate change in peer-reviewed, international journals. Yet this debate is not about *if* human-caused climate change is happening — but rather how quickly, to what magnitude, and with what regional implications.

This discussion has appealed to the findings of the latest IPCC report. The observed warming trend and its seasonal and large scale-geographical distribution is consistent with what coupled models have suggested should have occurred, and also what these same models project will occur more noticeably in the future.

With respect to Canada, Figure 6d shows that there has been a strong warming trend in annual mean temperatures, especially during winter (Fig. 8a). Projections of future climate change all consistently show that warming will continue in the region, under all scenarios of future emissions that have been used to drive the coupled models. Most of Canada is projected to have greater-than-average warming in the summer and winter, for both the A2 and B2 scenarios. Northern Canada is projected to have greater-than-average warming in the summer and much greater-than-average warming in the winter months, with precipitation increases occurring in both seasons. As such, the 1.4–5.8°C globally averaged warming projections by 2100 should be considered to be amplified over Canada.

### Future directions of climate modelling

In the IPCC Third Assessment Report, none of the international groups contributing projections of future climate had incorporated interactive terrestrial and oceanic carbon cycle models into their coupled models. Several international groups have subsequently made significant advances in this regard and the first projections including interactive carbon cycle and dynamic terrestrial vegetation are beginning to appear. A major thrust of international coupled modelling efforts over the next few years will be the development of a terrestrial and oceanic carbon cycle modelling capability for use in climate change projections on which policy will be based.

In the IPCC fourth assessment, likely to occur in 2007, the leading climate models will include interactive terrestrial and ocean carbon cycles in which anthropogenic greenhouse gas and aerosol emissions, rather than concentration scenarios, will be specified. In addition, it is likely that these same models will allow both vegetation type and function to vary with the changing climate, thereby allowing important biological feedbacks within the climate system. The state of the art climate models will also incorporate interactive atmospheric sulphur and ozone (tropospheric and stratospheric) cycles, which will allow for a more complete treatment of natural and anthropodenic radiative forcing of the climate system.

In the IPCC fifth assessment, probably in ten years time, one can envision that rather than specifying future emissions of atmospheric aerosols and greenhouse gases, the state-of-the-art models will calculate these emissions internally through the interaction of coupled climate/socio-economic models. That is, emissions will be calculated internally under specified policy, technological, population growth and other socio-economic options.

## SCIENTIFIC CHALLENGES

Some degree of climate change is inevitable as the Earth system moves towards a new global radiative equilibrium under increased levels of greenhouse gases. While the Kyoto Protocol represents a small step towards addressing the issue of climate change, it is only a start. In fact, if we wish to stabilize atmospheric $CO_2$ levels at 3–4 times preindustrial values, global anthropogenic emissions must be reduced by less than half of what they were in 1990 (IPCC, 2001). Meeting the required global reductions in fossil fuel emissions presents numerous scientific challenges, yet at the same time presents an enormous economic opportunity. Our ability to reach and maintain a yet-to-be defined acceptable level of climate change will require the spawning of new energy technologies. The market for these technologies is global, the field is wide open, and every single individual on this planet is a potential customer.

In addition to cutting $CO_2$ emissions at their source, both through slight changes in lifestyle as well as the development of new technologies, enhancing the natural carbon sinks may prove to be a viable and cost-effective, if only short term, approach to mitigation. At the same time, regional adaptation strategies need to be developed for the change that is already in the pipeline. The science behind the projections of regional climate change is still in its infancy. There are large uncertainties in both downscaling global climate change projections onto sub-continental scales, as well as in the basic physics of processes (such as clouds and precipitation) that operate on these regional scales.

## CONCLUDING REMARKS

Over the course of the 20th century the globe has warmed by 0.6 ± 0.2°C as a consequence of natural and anthropogenic changes in radiative forcing. If greenhouse gas emissions were to be curtailed immediately, such that the atmospheric concentration of $CO_2$ remained fixed at 1999 levels (368 ppm), the Earth would still warm a further ~0.5°C over the next several centuries (Weaver et al., 2001) as it tries to equilibrate to the increased radiative forcing. This follows from the slow response time of the ocean component of the climate system to perturbations in radiative forcing. With this said, if emissions were to be stopped, natural carbon sinks, especially in the ocean, could potentially draw down and store a significant portion of past emissions.

In a recent study, Ewen et al. (in press) found that the ocean had the capacity to eventually take up an additional 65–75% of the atmospheric $CO_2$ increase when anthropogenic forcing was stopped. This reduced by about 5% for each 50 year period that anthropogenic emissions were maintained at a stabilized and elevated atmospheric greenhouse $CO_2$ level. The results of this work clearly has encouraging policy implications with respect to future fossil fuel emissions. If we are able to reduce emissions in the near future, there is hope that the ocean can draw down a substantial portion of the atmospheric $CO_2$ solely through the solubility pump (the dissolution of $CO_2$ in water). In particular, 65–70% of all past emissions can be drawn down into the ocean. The longer it takes to reduce emissions, the less the ocean solubility pump is able to draw down. Nevertheless, uncertainties in natural carbon cycle feedbacks are large and are only just beginning to be examined by the scientific community.

Much as the Kyoto Protocol requires countries to consider the implications of their greenhouse gas emissions beyond their immediate national borders, reducing the uncertainties in climate change science requires scientists to transcend traditional disciplinary boundaries. Meeting these challenges will create new scientific opportunities, and from these opportunities we will determine what is an acceptable level of future change.

There is a very real danger that Canadians will believe that the Kyoto Protocol, aimed at curbing global emissions of greenhouse gases, is the answer to climate change. I believe that Kyoto is only a small, yet important, first step on our road to a sustainable future no longer dependent on fossil fuels. Even if all countries meet their Kyoto targets, climate will be negligibly affected over the rest of this century.

Canada, as a wealthy nation, has the economic wherewithal to adapt to a changing climate. If we can adapt to climate change why should we worry? The answer is simple. There are large parts of the world which have neither the technological nor the economic ability to adapt to a changing climate. Couple this with the fact that the problem was caused by industrialized nations and you have sown the seeds of discontent. These seeds could grow to resentment and hostility or, if we take appropriate international steps to both mitigate climate change and assist non-industrialized nations in adapting to its effects, they could blossom into a mechanism for creating global stability. In short, dealing with climate change is about dealing with domestic and global security.

The climate change we are in store for over the next few centuries will be larger and will occur faster than at any time in the last 10,000 years. While our pace of technological advance has historically been fast, it must remain faster than the pace at which climate will change in the future. Kyoto, and the required post-Kyoto agreements, might be the necessary incentives to ensure that these technological targets are met. Along with such steps by governments, individuals need to examine the hard choices that will lessen the impact of climate change on future generations.

The path to decarbonization of our global energy system has been in the works for centuries. With the discovery of coal, wood was replaced as the primary fuel of choice. Throughout the 20th century, the energy market share of coal declined as the share of other hydrocarbons picked up; first oil and then natural gas. Throughout this hydrocarbon age, the evolution from coal to oil to propane to methane was accompanied by a decline in the ratio of carbon to hydrogen (C/H) on a per molecule basis: C/H=2 (Coal) to C/H=1 (Oil) to C/H=0.375 (Propane) to C/H= 0.25 (Methane — $CH_4$).

We currently categorize the evolution of civilization in terms of the history of technology use, moving us from the Stone Age, through the Bronze Age and into the Iron Age. Today, in this Hydrocarbon Age, technology advance and hence the advance of civilization is entirely dependent on energy availability. The natural evolution of the trend in decarbonization of our global energy system is an eventual C/H ratio of zero — pure hydrogen ($H_2$). This transition will mark the beginning of a new era in the history of civilization: The Hydrogen Age.

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