The T3 Tax as a Policy Strategy for Global Warming

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Abstract

Global warming policy has been stuck in a stalemate for well over a decade, leading to considerable frustration on all sides. The stalemate arises in part because people hold widely divergent views on the causes and consequences of global warming, which leads to equally divergent views on the appropriate policy agenda; and in part because reducing carbon emissions by enough to affect the atmospheric concentration will be extremely expensive. I propose a policy mechanism that I think could break the stalemate. I call it the 'T3 Tax', where T3 stands for the Tropical Tropospheric Temperature. Global climate models predict that, if greenhouse gases are responsible for global warming, there will be a distinct spatial pattern to it, dominated by a rapid warming trend in the tropical troposphere, the region from about 1 to 15 km above the surface, between 20 degrees north and south of the equator. Observed warming trends at the surface are hard to interpret, in part due to data quality problems. But high quality measurements of tropospheric climate change are available from weather satellites and weather balloons, and according to models, this is where the most pronounced 'leading indicator' of global warming will be found. I suggest that we calibrate a revenue-neutral tax on carbon emissions to the mean tropical tropospheric temperature, starting it at a low level. That way, if global warming projections are right, the tax will start rising steadily over the coming decades. If the models are exaggerating the problem, the tax won't rise; and under the circumstances we would not want it to. Also, the existence of the tax would create a strong incentive for the private sector to get involved in climate forecasting, improving the basis for policy planning. I also discuss how the T3 tax compares to more formally-derived 'optimal' carbon taxes.

The T3 Tax as a Policy Strategy for Global Warming[*]

1   Introduction

Global warming policy has been stuck in a stalemate for well over a decade, leading to considerable frustration on all sides. The stalemate arises in part because people hold widely divergent views on the causes and consequences of global warming, which leads to equally divergent views on the appropriate policy agenda. It also arises because of the scale of the problem. The climatically-relevant measure is not local emissions but the global average atmospheric carbon dioxide (CO_2) concentration. Local and even national emission cuts have such minuscule global effects as to be largely pointless when viewed in isolation. To actually reduce the global concentration would require a coordinated global reduction in fossil fuel consumption approaching fifty percent, and the costs of doing so effectively rule out serious commitments to such a plan.

In this essay I will propose a policy mechanism for dealing with global warming that might bridge the gap. Stated briefly, the idea is, for those countries wanting to take action, to put a tax on fossil fuels in proportion to their carbon content (a 'carbon tax'), then calibrate the implied carbon price to track a particular measure of atmospheric change, the mean temperature of the troposphere (the region from two to about 16 km up) over the tropics, spanning 20 degrees North and South of the equator. I call it the 'T3' tax, for Tropical Troposphere Temperature. The reason for choosing this climate metric is explained in this first section. The reason for using a tax instrument is explained in Section 2. In the third section I discuss some details of how the policy would work.

My proposal is conceived such that it ought to be equally appealing to people regardless of the views (if any) they hold on the likelihood or severity of human-induced climate change. It is important, however, in order to motivate the T3 tax proposal, to explain why there is legitimate uncertainty over whether and to what extent GHG emissions affect the climate, and why finding a way to measure such effects is not simple. For this reason I will begin by going into more detail about some of the underlying issues in the relevant physical sciences (especially measurement) than is customary in an essay primarily dedicated to policy analysis, drawing in part on my own publications as well as others which directly bear on the questions.

1.1   Greenhouse gases and the climate

The Earth's surface glows with a light that is too red for our eyes to see, called infrared (IR) radiation. All the IR energy coming off the surface of the Earth must escape to space in order to balance the atmospheric energy budget: at the top of the atmosphere, the amount of outgoing IR energy offsets the incoming solar energy. 'Greenhouse gases' (GHGs) is the term applied to water vapour, carbon dioxide (CO_2), methane, nitrous oxide and other gases that absorb outgoing infrared radiation (IR). By absorbing in the IR spectrum, the GHGs make the atmosphere slightly opaque to outgoing energy. Water vapour is by far the most effective greenhouse gas, absorbing across the whole IR spectrum. CO_2 and the others are weak IR absorbers by comparison. Overall, the absorption of IR energy leads to warming of the air near the surface; this explains the steady drop in temperature as one gains altitude, e.g. by climbing a mountain.

The popular presentation of global warming is often illustrated with graphics of the Earth blanketed by so-called "heat-trapping" gases, with a narrative along the following lines.[1]

- Without atmospheric GHGs, IR energy off the surface would escape directly to space and our atmosphere would be about 33 degrees C cooler than it is now.
- All materials absorb and re-emit radiation. The higher a body's temperature, the more intense the radiation emanating from it.
- By adding CO_2 to the atmosphere we are making the atmosphere more opaque in the IR, in effect "making the greenhouse glass thicker."
- All else being equal, the atmosphere must warm up to re-establish the energy balance at the top of the atmosphere. This is called 'global warming.'
- Doubling the CO_2 content of the atmosphere will increase the global temperature at the Earth's surface by somewhere between 2 and 5 degrees C.

Apart from the last bullet point, everything above is non-controversial. The last point is plausible, but it requires conclusions about feedbacks that are controversial.[2] The problem, however, is that the above picture is an argument from a misplaced metaphor. If the above story were complete, the science would be simple. But there are a number of complicating issues that prevent the science from being simple.[3]

- In the above story the atmosphere is a solid, not a fluid. Fluids heated from below undergo convection, which in atmosphere involves hot air rising from the surface, while cooler air descends

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[1] See, for example, http://zfacts.com/p/820.html; Arrow, K.J. (2007) "Global Climate Change: A Challenge to Policy," *The Economists' Voice*: Vol. 4 : Iss. 3, Article 2. Available at: http://www.bepress.com/ev/vol4/iss3/art2.

[2] For a review see Held, I. and B. J. Soden (2000) "Water Vapor Feedback and Global Warming" *Annual Review of Energy and Environment* 25:441—75.

[3] These topics are discussed at greater length in Essex, C. and R. McKitrick (2002) *Taken By Storm: The Troubled Science, Policy and Politics of Global Warming*. Toronto: Key Porter Books.

from above. This removes significant amounts of energy from the Earth's surface, providing a natural "air conditioning" effect. If radiative transfer was the only mechanism draining energy from the surface, the daytime temperature at the Earth's surface would have to be about 30 degrees higher. Likewise, the moon has no atmosphere and no GHG's, yet its daytime surface temperature is much higher than the Earth's—going over 100 degrees C.[4]

- In other words, the presence of a fluid atmosphere induces both a warming effect at the surface (due to IR absorption) and a cooling effect (due to convection). Each process is equally important for energy transfer.

- Accumulation of GHGs in the atmosphere attenuates the radiation drain off the surface, but the total response of the atmosphere involves planetary-scale changes in convection and related processes, including evaporation and condensation of water, cloud formation, and so forth.

- Long-term prediction of the behaviour of the fluid atmosphere is not possible. Fluids in motion display a behaviour called turbulence. Many atmospheric processes involve turbulence, at all scales, from the planetary down to molecular levels. While there are mathematical equations (Navier-Stokes) that are believed to explain the behaviour of turbulent fluids, the underlying theory has never been proven. Nor can the Navier-Stokes equations themselves be solved into a general form for the purpose of numerical computation. Consequently it is not possible to predict, from first principles, how the temperature field at the Earth's surface will change in response to increased IR opacity in the lower atmosphere. There is a standing offer of a $1 million prize from the Clay Mathematics Institute for progress on the Navier-Stokes problem.[5]

- The simple picture also assumes the Earth is in thermodynamic equilibrium, where it makes sense to talk about one 'global temperature.' But the Earth is not in thermodynamic equilibrium, so there is no 'global temperature.' There is, instead, a continuous temperature field spanning well over 120 C, and there is no theoretical basis for projecting the field onto a scalar (i.e. "taking an average") for the purpose of measuring whether the system has 'warmed' up or not by small amounts (on the order of 0.1 C).[6] There are over 100 different averaging formulas in current use for the purpose of defining the climate, but there is no theoretical basis for any of them.

- Since the change in the 'the global temperature' in response to additional GHGs cannot be predicted from first principles, climate scientists use empirical approximations, or parameterizations, of basic atmospheric processes in climate models, and construct ad hoc statistics from observed data to compare to model variables that are defined on different bases.[7] This introduces an irreducible uncertainty and potential circular reasoning, since the modelers construct the parameterizations on the basis of a prior expectation of what a 'reasonable' model should do.

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[4] http://www.solarviews.com/eng/moon.htm; http://www.astronomy.com/asy/default.aspx?c=a&id=1219.

[5] http://www.claymath.org/millennium/Navier-Stokes_Equations.

[6] See Essex, C., B. Andresen and R. McKitrick. "Does a Global Temperature Exist?" *Journal of Nonequilibrium Thermodynamics*, Vol 32 No. 1 pp. 1—28.

[7] For example, in a simple one-dimensional Energy Balance Model there can be a single temperature ("T") for the planet's surface. Checking the model predictions about T against recent changes in a global average of temperature data ("τ") is, at best, a mismatch, since τ does not exist in the model and T does not exist on Earth, and there is no theoretical basis to assert their equivalence.

Moreover, the accumulation of CO_2 is not, itself, a major perturbation of the atmosphere. CO_2 has only a narrow absorption band in the IR spectrum. Much of the effect is hypothesized to arise due to increased water vapour levels in the atmosphere, resulting from indirect feedback processes. Without the water vapour feedback effect, CO_2 on its own would have a very small climatic effect. Using a highly simplified but conventional schematic, Held and Soden (2000)[8] give a value for CO_2 doubling of ~1 degree C if nothing changes except the atmospheric CO_2 content.[9] The bulk of the projected global warming arises due to the internal feedbacks resulting from changed convection processes, water vapour levels, cloud cover and so forth. Many of these processes occur on spatial scales that are too small to be treated formally in global models, so they must be parameterized as well.[10]

The above discussion could be extended, but this should suffice to establish for the reader why the study of climate change is not trivial and why predictions about the effects on weather patterns of adding CO_2 to the atmosphere are contentious. It is a strange paradox that a physical phenomenon involving so many of the most difficult and intractable problems in all of science is so often described in terms of such categorical, dogmatic certainty. One often hears words like *consensus*, *unequivocal*, *unanimous*, *settled*, etc.; and phrases like *there is no debate*, *there is no uncertainty*, etc., to describe the situation. These phrases were introduced by the early 1990s for rhetorical purposes, to create a sense of urgency and imperative about reducing GHG emissions. But the reality is that the science is not nearly as simple or settled.

1.2   Surface and atmospheric climate measurement

There are many topics involved in understanding global warming, and any one of them could be the basis for discussing policy-relevant uncertainty. I will look at two that have direct bearing on the structure of the T3 tax: the difficulty of measuring temperatures at the Earth's surface, and the difficulty of reconciling satellite observations to surface observations and climate model forecasts.

1.2.1 Surface weather data
Weather data is collected around the world using a variety of instruments. Over the oceans, which comprise 70% of the Earth's surface, data has been gathered by commercial and naval vessels using a variety of methods, such as measuring the temperature of water drawn for cooling ship engines. Over land, air temperature data has been collected in white boxes mounted on stands. The older method used a

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[8] Held, I. and B.J. Soden (2000) *op. cit.*

[9] The pre-industrial CO_2 content of the atmosphere (circa 1850) is estimated to be about 280 ppm. The current level is almost 380 ppm (see Keeling, C.D. and T.P. Whorf. 2005. "Atmospheric CO_2 records from sites in the SIO air sampling network." In *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. http://cdiac.esd.ornl.gov/trends/co2/sio-mlo.htm.) Hence we have experienced a 35% increase in CO_2 levels. Adding in CO_2 –equivalence of other infrared-absorbing gases implies a somewhat higher CO_2 level. Depending on emission trends, the concentration may reach 560 ppm by 2080-2100, implying a CO_2 doubling.

[10] See Held and Soden (2000) *op. cit.*; also Kerr, R. (2007) "Another Global Warming Icon Comes Under Attack" *Science* 6 July 2007 Vol 317 pp. 28—29.

wooden box with louvered sides. A mercury-in-glass thermometer in the box must be read at least once a day, or preferably twice, at precisely the same time. Over time, in many countries, the equipment has been converted to electronic sensors, which are remotely monitored, but which must be connected to a power source.

While Europe and the continental USA have been heavily sampled over the 20th century, large regions of Asia, South America and Africa do not have sufficient data to establish long term trends. Moreover, the situation has been getting worse since the 1970s, not better. The number of useable weather stations around the world peaked in the early 1970s and has since fallen by about two-thirds. The global sample fell by about half in a three-year interval from 1990 to 1993.[11] Many stations were lost in the former Soviet Union during the collapse of communism. Even those stations that remained open suddenly started losing a lot of data, so the number of months without records soared (see Figure 1).
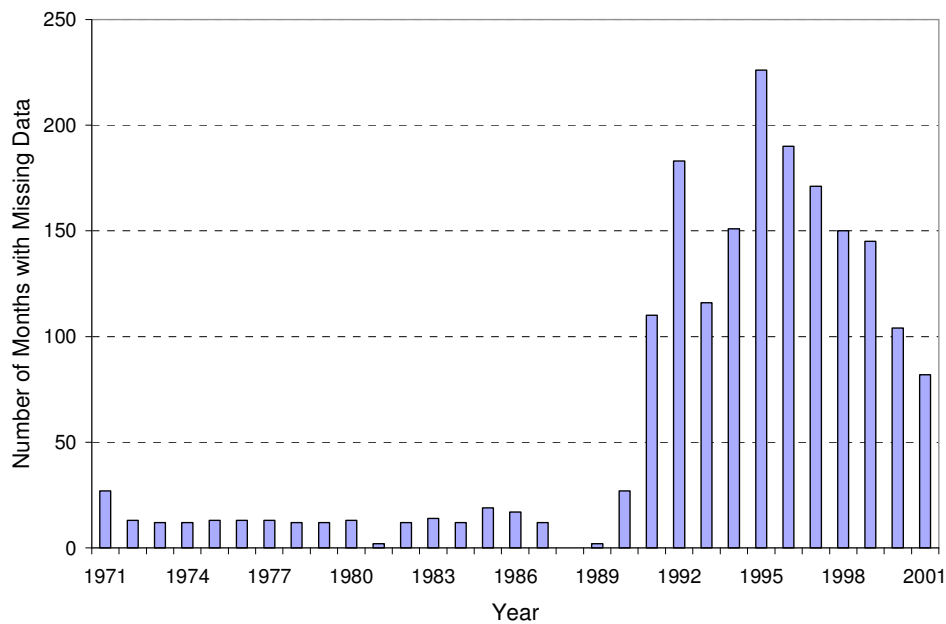

FIGURE 1: For the 110 Russian weather stations reporting weather data continuously from 1971 to 2001, the total number of missing monthly observations each year. Source: McKitrick and Michaels (2004).

Note that after 1990, world climate monitoring groups began to report a string of record-setting global temperature levels, though the differences were very small, measured in tenths and hundredths of a degree. In other words, a discontinuity in the mean seemed to occur at 1990, simultaneous with a

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[11] Peterson T.C. and R.S. Vose (1997) "An Overview of the Global Historical Climatology Network Temperature Database." *Bulletin of the American Meteorological Society* 78:2837—2849.

discontinuity of the sampling methods. The raw station count and raw temperature average are shown in Figure 2. Researchers who compile global average temperatures are of course aware of the loss of sampling locations, and attempt to weight the sample year-by-year to compensate. But the change we are looking for is very small: less than one-tenth of the change in the mean between 1989 and 1990, and researchers had already found that an earlier interval of station closures had added a permanent upward bias to the global average.[12] The dropout is shown in a visually striking animation available from the University of Delaware at[13]
http://climate.geog.udel.edu/~climate/html_pages/Ghcn2_images/air_loc.mpg.
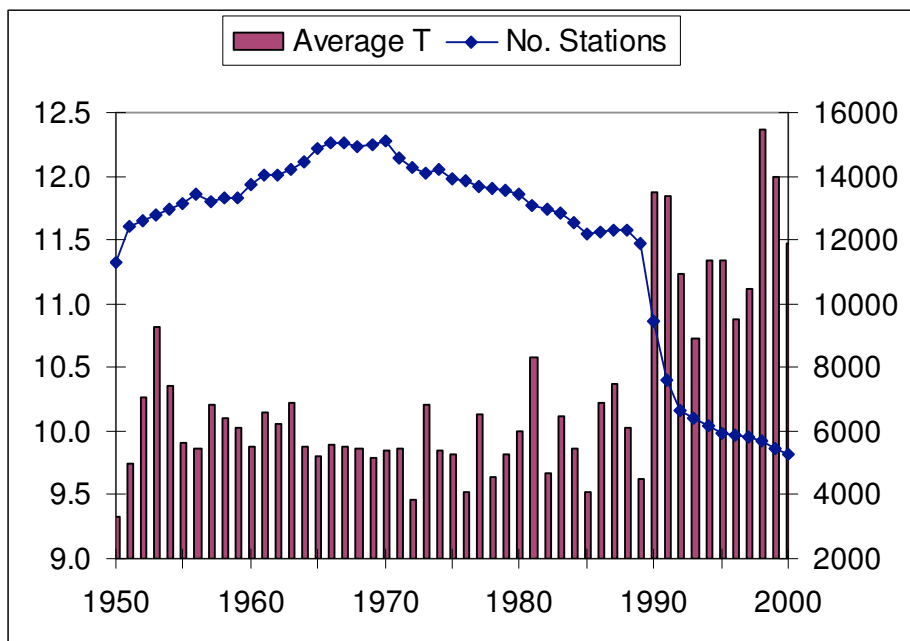

FIGURE 2: All data from US National Oceanographic and Atmospheric Administration (http://www.ncdc.noaa.gov). Right axis (line): total number of individual weather stations with records in Global Historical Climate Network. Left axis (bars): raw annual average temperature from those stations. For details on construction see http://www.uoguelph.ca/~rmckitri/research/nvst.html.

It may be that the data are properly adjusted to account for the sampling disruption, and to remove other non-climatic, contaminating influences, and that the apparent jump in the mean temperature of the climate is due to a climate change that happened around 1990. Or it may be that nothing much happened

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[12] Willmott, C. J., S. M. Robeson and J. J. Feddema, 1991. Influence of Spatially Variable Instrument Networks on Climatic Averages. *Geophysical Research Letters*, 18(12), 2249-2251.

[13] Note: if the web page does not open, start here: http://climate.geog.udel.edu/~climate/index.shtml, click on Available Climate Data and register to access the data. The animation should then be accessible.

to the climate but the data shifted due to the sudden, large change in the number, locations and quality of samples. Or both may be true.

If we confine attention only to places where reasonably good data seem to be collected, such as the US, there is much less evidence of an upward trend in average temperatures over the 20th century.[14] However, even in the US, where money and expertise are available for high quality climate data collection, there are serious flaws in the way weather stations are sited and maintained. The web site *surfacestations.org* was created this year to provide photographic documentation of US weather stations. There is a surprising fraction of sites—possibly a majority—where elementary scientific standards are not met, such as weather stations being located in parking lots, near air conditioning vents, on rooftops, etc., rather than out in open fields well away from structures, which is where they are supposed to be. Also, technical data for weather stations is often lacking, making it difficult to know when stations have been moved. Stations attached to new buildings, for instance, could not have been there for the entire duration of the weather record associated with that site, yet documentation of where the station was previously is often incomplete.

Even when collected over a long interval, weather data is not directly useful for climatic monitoring. Changes to local landscapes, such as the construction of roads, buildings and other structures; converting forests to fields, etc., are known to change the ambient air temperature. Also, if the time of day at which temperature is measured changes, a shift in the daily mean can occur (think, for instance, what would happen if the reading time is changed from 6AM to 7AM). Many temperature monitoring stations are at suburban airports, which have been gradually encircled by expanding cities over the past four decades.

Climate data series are produced from such data using models that are supposed to remove all influences due to urbanization, gaps in data, changes to the time of observation, etc.[15] A climate data series for an urban location—e.g. Vancouver—is supposed to tell us, not what the observed air temperature actually was, but what it would have been had the city never been built, the forests never cleared, the land never farmed, etc.

A few years ago, meteorologist Patrick Michaels and I implemented what was, to our knowledge, the first statistical test of how effective these adjustments are.[16] We sampled post-1979 temperature data from 218 weather stations around the world, and obtained the linear trends from each one. Then we regressed the vector of trends on a group of variables measuring the spatial pattern of local economic activity: total Gross Domestic Product (GDP), average income, local coal consumption, local literacy (to measure the availability of a labour force qualified to collect scientific data), etc. As expected, we found very strong correlations, indicating that the temperature data are not independent of the socioeconomic conditions in

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[14] See, e.g., http://data.giss.nasa.gov/gistemp/graphs/Fig.D_lrg.gif.

[15] The adjustment steps for the US Historical Climatology Network data are described at http://www.ncdc.noaa.gov/oa/climate/research/ushcn/ushcn.html#QUAL. See also Peterson, T.C. (2003). "Assessment of Urban Versus Rural *in situ* Surface Temperatures in the Contiguous United States: No Difference Found." *Journal of Climate* 16(18) 2941—2959 for a description of the general problem and suggested algorithms.

[16] McKitrick, R and P. J. Michaels (2004). "A Test of Corrections for Extraneous Signals in Gridded Surface Temperature Data" *Climate Research* 26(2) pp. 159-173. "Erratum," *Climate Research* 27(3) 265—268.

which they are collected. We then took the "climate" data as published by the Climatic Research Unit at the University of East Anglia for the same locations. This is the data used by the Intergovernmental Panel on Climate Change (IPCC) for measuring global warming. The IPCC claims that the data have been fully corrected and are free of contamination due to urbanization and other socioeconomic influences. But we found the same correlations existed in the post-adjustment climatic data, attenuated in size somewhat, but still quite significant. Using the regression coefficients to quantify the locational biases we concluded that they add up to a net warming effect that overstates the post-1979 global warming trend over land by a factor of about two. In a follow-up study, forthcoming in the *Journal of Geophysical Research-Atmospheres*, we have used a larger sample and more detailed socioeconomic indicators and again found the same global pattern of data contamination with the overstatement of land-based warming amounting to a factor of around two.

At the same time as our first study appeared, a pair of Dutch meteorologists[17] published similar results using a different approach on a different climatic data set. Attributing the pattern of warming over land to the spread of industrial activity did a better job of explaining the data than attributing it to GHG emissions to the atmosphere. Since climate models usually do not treat land-surface modifications as explanatory factors for climate change (see for example, Figure 9.1 in the IPCC Fourth Assessment Report, discussed in connection with Figure 5 below) these studies[18] pointed to a deficiency in the IPCC view that GHG emissions are to blame for global warming since 1980.

When I was asked to serve as an expert reviewer for the first draft of the new IPCC report, in the fall of 2005, I found that they glossed over this important topic, omitting any mention of my work with Michaels or the de Laat and Maurellis findings, instead merely repeating their assertion that their climatic data have been adjusted to remove biases due to land use change, loss of monitoring sites, etc. The text included a disputatious review of the paper by Kalnay and Cai (2003) mentioned in footnote 10, but otherwise focused on three papers—one published back in 1990—that had failed to find evidence of an urbanization bias in some locations, as support for their position. The best of these studies was based on the observation that urban temperature data showed similar trends on calm versus windy nights, but the literature questioning the role of wind speed in attenuating urban heating effects was not reviewed. In my review comments I drew their attention to these studies, but the text was not amended in the second draft. I repeated my criticisms in the second draft comments, but again nothing was changed in the final version.

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[17] De Laat, A.T.J., and A.N. Maurellis (2004). "Industrial CO_2 Emissions as a Proxy for Anthropogenic Influence on Lower Tropospheric Temperature Trends." *Geophysical Research Letters* Vol. 31, L05204, doi:10.1029/2003GL019024. De Laat, A.T.J., and A.N. Maurellis (2006). "Evidence for Influence of Anthropogenic Surface Processes on Lower Tropospheric and Surface Temperature Trends." International Journal of Climatology 26:897—913.

[18] Others since then have found similar conclusions: Kalnay E and M. Cai (2003). "Impacts of Urbanization and Land Use Change on Climate." *Nature*. 423:528-531; Pielke R.A. Sr., G. Marland, R.A. Betts, T.N. Chase, J.L. Eastman, J.O. Niles, D.D.S. Niyogi and S.W. Running. (2002) "The Influence of Land-use Change and Landscape Dynamics on the Climate System: Relevance to Climate-Change Policy Beyond the Radiative Effect of Greenhouse Gases." *Philosophical Transactions of the Royal Society of London*. A360:1705-1719.

The IPCC review comments and replies are now on-line (http://ipcc-wg1.ucar.edu/wg1/Comments/wg1-commentFrameset.html). It is interesting to see how few people are actually involved in writing up any one topic, especially since some people picture a room with 2,500 "top scientists" poring over the data and haggling over every paragraph. In the case of this topic, despite the fundamental importance of ascertaining whether basic global warming data are contaminated, there were only two or three contributing authors and a small number—perhaps half a dozen—reviewers, of which I was one. The authors serve as their own editors, and critical review comments were frequently dismissed either with no adjustment to the text or, at best, grudging and peripheral acknowledgments of the issues.[19] In the end the IPCC refused to acknowledge the evidence of data contamination. At the risk of self-indulgence (or axe-grinding), let me document the reasoning given for ignoring the findings of my *Climate Research* paper. Another reviewer's request for a discussion of my paper with Michaels was rejected on the grounds that it is "full of errors", with no examples or explanation given. In another place the IPCC authors cited the only published comment on our paper as a reason for ignoring it,[20] with no reference to our rebuttal or discussion of the rather minor point at issue in the exchange. But the main reason given for dismissing our findings was as follows:

> The locations of socioeconomic development happen to have coincided with maximum warming, not for the reason given by McKitrick and Mihaels [sic] (2004) but because of the strengthening of the Arctic Oscillation and the greater sensitivity of land than ocean to greenhouse forcing owing to the smaller thermal capacity of land.
> (First Order Draft Comments, Chapter 3, line 3-453)

In effect they acknowledge that the warming pattern coincides with the pattern of socioeconomic development, but they have a novel, and unpublished, theory to explain it away. The comparison between land and ocean patterns is irrelevant in this context because our sample was entirely land-based—we are unaware of any socioeconomic development over the ocean. The Arctic Oscillation (AO) Index refers to a periodic fluctuation in a low-pressure zone over the North Pole, encircled by winds that ring the Arctic Ocean which, among other things, block cold air from spilling south over Europe and North America. When the AO Index is positive (intense), less cold air escapes south from the pole, leading to milder Northern Hemispheric winter conditions. When the AO Index is negative (weak) the cold air more easily escapes south, leading to colder conditions as far down as the US. The regions sampled for constructing the index are the polar ocean, the North Atlantic and the North Pacific.[21] According to the US National Weather Service, the Arctic Oscillation has indeed strengthened in recent decades,[22] primarily due to a discrete step-like increment around 1988; there has been no trend since then.

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[19] There are 'Review Editors' assigned to each chapter, but in examining the comments, replies and the textual changes across drafts it is clear they simply deferred to the authors. A further example is presented in Section 3.2 below.

[20] Benestad, R. (2002) *Climate Research* 27(2) pp. 172-174. Our Reply is in the same issue, pp. 175—176.

[21] See map at http://www.cpc.noaa.gov/products/precip/CWlink/daily_ao_index/ao.loading.shtml

[22] See http://www.cpc.noaa.gov/products/precip/CWlink/daily_ao_index/month_ao_index.shtml and http://ao.atmos.colostate.edu//Figures/AO_1900_Present_JFM_WEB.html.

The AO helps explain winter weather patterns in the Northern Hemisphere, primarily over the ocean near the North Pole, and helps explain the tendency for relatively milder northern winters since the late 1980s. However, no one has ever suggested that it generates a spatial pattern of warming trends around the world that happens to coincide with the spatial pattern of socioeconomic development, all the way down to the southern tips of Africa and South America.

The point to take away is that the choice of a measure for the climate state has to take into account the problems with data collected at the Earth's surface. Well-documented biases in the temperature record at the Earth's surface tend to overstate recent warming trends. The IPCC's consideration of this problem was dismissive and inadequate. Apart from the general policy relevance of the problem that basic global warming data are likely overstating the issue, the immediate point for the purpose of this essay is that selection of a climate metric for calibrating a tax needs to be done carefully.

1.2.2 Weather satellite data

An alternative to surface data became available in 1990, when John Christy and Roy Spencer published a new climatic data series based on an analysis of data retrieved from the Tiros-N weather satellites launched by the US National Oceanographic and Atmospheric Administration (NOAA) in 1979.[23] The satellites carry microwave sounding units (MSU) that measure radiation emerging from oxygen molecules at different layers of the atmosphere, taking a near-complete sample of the entire troposphere and stratosphere each day. Each reading can be interpreted as a proxy for the bulk average of the air temperature. By calibrating the MSU data against atmospheric temperature measurements from a global network of radiosondes,[24] Spencer and Christy were able to publish the first global mean temperature series based on a consistent sampling method that covered the entire atmosphere, especially the all-important tropospheric region.

The troposphere is of particular importance in models of global warming. As mentioned above, energy transfer from the Earth's surface is primarily due to convection and radiation. The proportion due to convection declines with altitude, and at a certain height (depending on latitude) radiation takes over and accounts for all outbound energy transfer.[25] Although radiation occurs at all levels of the atmosphere, this height can be viewed as the "effective altitude" for all IR emission, since at that level, the inflow of solar energy and the outflow of IR radiation are, on average, balanced. Addition of CO_2 to the atmosphere makes it more opaque (i.e., if you look down from space in the IR spectrum, you cannot see as far down), raising the altitude of the effective emissions level. In simple linear models, the increase in altitude from CO_2 doubling is about 150 meters.[26] However, temperature declines with altitude, so the amount of radiation at the new effective emissions altitude is insufficient to maintain energy balance. An adjustment is required, involving an increase in temperature at the effective emissions altitude. This warming is propagated down to the surface, yielding global warming, but it originates in the mid-troposphere.

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[23] Spencer, R.W. and J.C. Christy (1990) "Precise Monitoring of Global Temperature Trends from Satellites." *Science* 247: 1558—1562.

[24] Radiosondes are thermometers mounted on weather balloons that transmit temperature readings by altitude to monitors on the ground. A global sample is obtained from a network of meteorological stations.

[25] Houghton, J. (1997) *Global Warming: The Complete Briefing 2nd Ed.* Cambridge: CUP. p 15.

[26] Held, I. and B. J. Soden (2000) *op. cit.* p. 447.

The Christy and Spencer data soon became the center of a controversy, since climate models predicted the strongest warming pattern would be in the troposphere, yet as of the mid-1990s the global mean tropospheric temperature series from the MSU data showed no upward trend, whereas the surface average was showing a strong upward trend. Figure 3 shows the two series together. The data are expressed as "anomalies"—a local average is subtracted from each local temperature reading, and these residuals are averaged to yield a global average anomaly. Though the two series overlapped for the earliest portion, as of the early 1980s the surface series had embarked on an upward trend while the MSU series had not. The divergence between the two series (Figure 4) has remained to the present, though seems to have stopped growing since both series leveled off by the late 1990s.
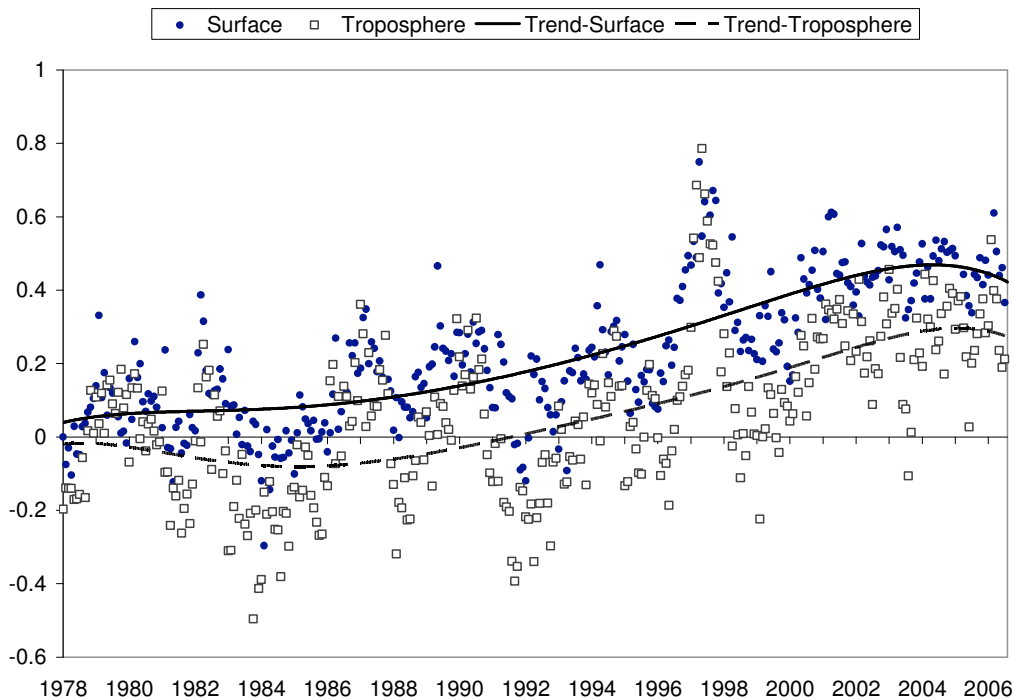

FIGURE 3: Comparison of two global climate metrics, December 1978—June 2007. Dots: Global mean surface temperature anomaly (departure from local average) from UK Hadley Centre http://hadobs.metoffice.com/hadcrut3/diagnostics/global/nh+sh/monthly. Open squares: Global mean tropospheric temperature anomaly from Spencer-Christy MSU data http://vortex.nsstc.uah.edu/public/msu/t2lt/tltglhmam_5.2. Trend lines are 6th-order polynomial smoothers each constrained to start at 0.
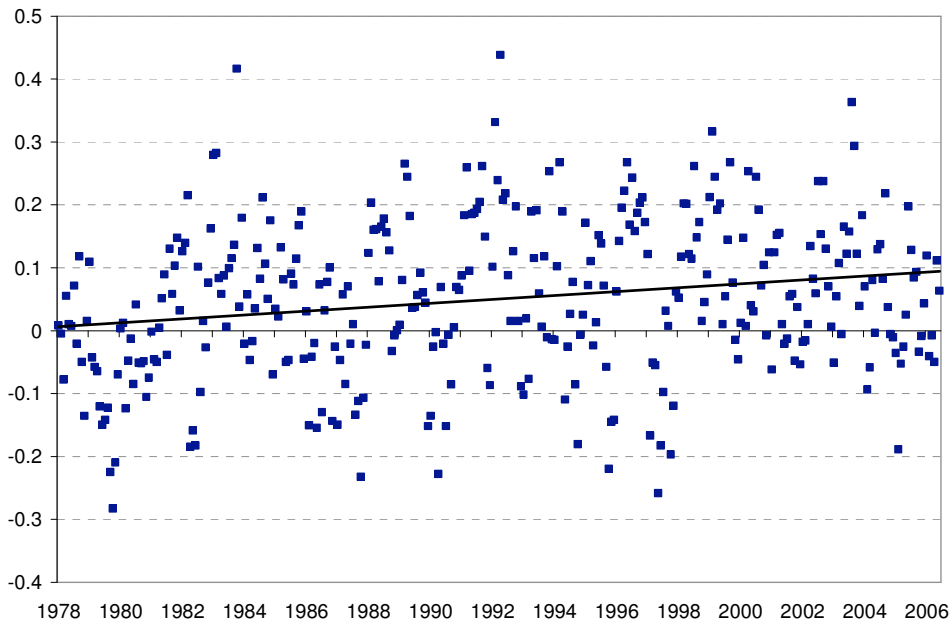
FIGURE 4: Divergence between surface and MSU data, as plotted in Figure 3, adjusted so that mean divergence equals zero in first 12 months of series.

The fact that the MSU data (as well as weather balloon data) showed no observed warming in the troposphere clearly put into question the whole model. Especially puzzling was the lack of warming in the tropics. The general circulation of the atmosphere begins with powerful solar heating near the equator.[27] This causes ascension of hot, moist air, which cools and transfers polewards about 30 degrees latitude in each direction, at which point it descends and joins a return flow towards the equator near the surface. Some of the descending air bifurcates and joins a poleward flow, with separate loops ending at the poles. Global atmospheric models must represent these processes on a rotating sphere with appropriate distributions of moisture, momentum and energy. In experiments using these models, it has consistently turned out that the strongest and earliest warming due to greenhouse gas accumulation is in the tropical troposphere. Held and Soden (2000, *op. cit*. p. 464) report that models assign about 60 percent of the global atmospheric water vapour feedback in the upper troposphere over the tropics from 30 N to 30 S, while only about 40 percent occurs at all other latitudes.[28]

Figure 5 shows the situation in stylized form. The horizontal axis shows latitude, from (left to right) the south pole to the north pole. The vertical axis shows the height through the atmosphere, from the surface

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[27] A simple schematic description of the general circulation is in Lockwood, John G. (1979) *Causes of Climate*, New York: John Wiley, Ch. 4.

[28] These proportions refer to the 'free atmosphere' or troposphere above the boundary layer (the lowest 1—2km). Ten percent of the global effect occurs in the boundary layer, so the total tropospheric proportions are 55% tropics and 35% extra-tropics.

up to the top of the troposphere (the stratosphere continues above that). The grey circles are the locations of expected amplified warming: the poles at the surface and the upper troposphere over the tropics.
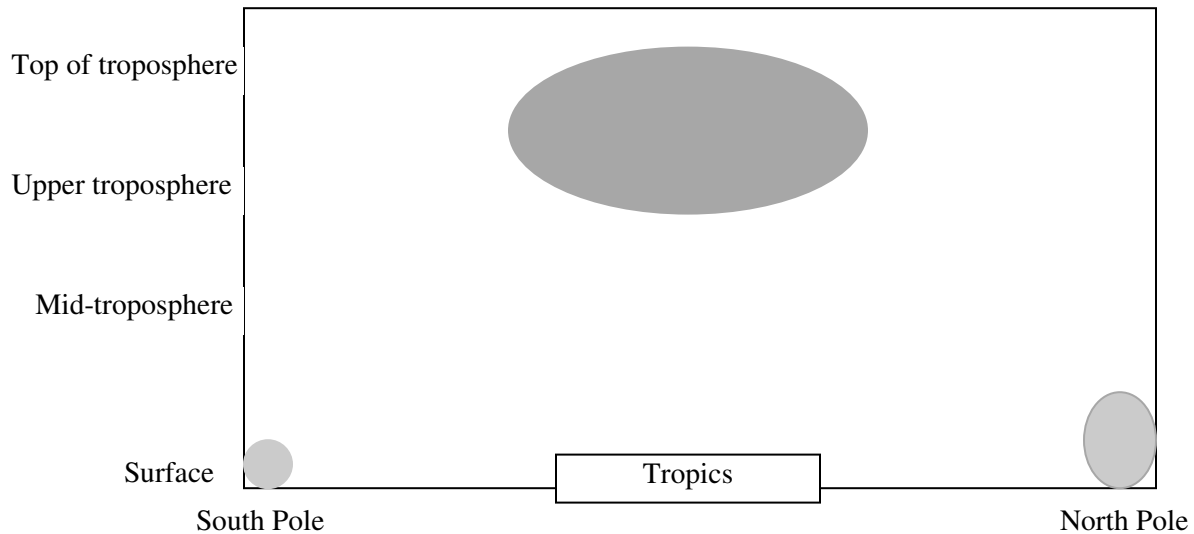

FIGURE 5: Stylized picture of global warming pattern associated with greenhouse warming. Grey circles show locations of expected amplified warming. Horizontal axis: latitude. Vertical axis: altitude. For references to actual model outputs on-line see text.

Figure 5 is obviously a caricature. For comparison to actual model outputs, see the following.

- Twelve IPCC climate model forecasts for the Fourth Assessment Report are shown at: http://ipcc-wg1.ucar.edu/wg1/Report/suppl/Ch10/Ch10_indiv-maps.html: see the column for Figure 10.7. These model experiments follows the 'A1B' emissions scenario, a medium-range emissions trajectory out to 2100. The global average surface warming as of the end of the century for the GISS model is about 2.3 C.[29] The tropospheric average is twice that, reaching 5 C, and the focal pattern emerges at the beginning of the forecast period. The visual pattern shown in Figure 5 is found in all 12 climate model simulations done for the recent IPCC report.

- In the Fourth Assessment Report Figure 9.1 (see http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Pub_Ch09.pdf, page 675) a 'hindcast' is presented examining model-generated climate patterns for the interval 1890 to 1999. The Figure 5 pattern shows up in the greenhouse-only run (panel c) and, because the greenhouse forcing dominates the experiment, in the summed changes (panel f). The clear implication of this graph is that a strong warming trend

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[29] IPCC Fourth Assessment Report (Working Group I) Chapter 10 Fig. 10.5.

in the tropical troposphere ought to be underway already and should be the dominant pattern of change in comparison with all other forcings.

- The Figure 5 pattern is also shown in a model-generated 'hindcast' that simulates climatic changes from 1958 to 1999 under the assumption of strong GHG-warming, which was done for the US Climate Change Science Program Report, Figure 1.3 Panels A and F, page 25, available at http://www.climatescience.gov/Library/sap/sap1-1/finalreport/default.htm. Again, the bright disc in the tropical troposphere is the dominant feature of the diagram.

Taken together the models are unanimous in implying that a pattern of strong tropical tropospheric warming should already be observed, if GHG warming is the dominant long-term effect on our climate, and will dominate the future changes to the climate. The models are unanimous that the upper troposphere warming will be stronger in the tropics than the rest of the whole troposphere, and stronger aloft than at the surface. The models are not consistent in their treatment of the poles. The hindcast experiments (e.g. Figure 9.1 in the Fourth Assessment Report) suggest amplification over the south pole, but the forecasts in IPCC Figure 10.7 show no amplification, and in some cases (such as the Goddard Institute model) a cooling. This will be discussed further in Section 3.1 below.

However, the tropical tropospheric pattern is not observed in the data. The trend in the mean tropical troposphere temperature does not exceed that at the surface, or the globe as a whole, instead it is actually *less* than both. The post-1958 weather balloon series for the tropics is graphed at http://cdiac.esd.ornl.gov/trends/temp/sterin/graphics/tropics.gif. In the tropospheric series there is a step-change around 1978, with no trend afterwards. The post-1979 Spencer-Christy MSU data are on-line at http://vortex.nsstc.uah.edu/data/msu/t2lt/uahncdc.lt. The trend in the tropospheric average (+0.084 C per decade from December 1978 to May 2007) is just over half that for the global average (+0.144 C per decade; see Figure 6 below), and just under half that at the tropical surface (+0.171 C per decade[30]), counter to the pattern predicted by models.

The Spencer-Christy weather satellite data were discussed only obliquely in the IPCC's Third Assessment Report. As of 2000, when the report was being prepared, there was clearly no tropospheric trend to report, opposite to model predictions at the time. As mentioned, the weather balloon data extends back to 1958, and exhibits a step-like change in 1977, with no trend prior and no trend after.[31] If a naïve linear trend is fitted through the entire series, it slopes upwards. So the 2001 IPCC Report Summary[32] referred to a trend in the balloon data and stated: "the overall global temperature increases in the lowest 8 kilometres of the atmosphere and in surface temperature have been similar at 0.1°C per decade." While this carefully dodged the topic, in the next paragraph they acknowledged that the surface and satellite

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[30] Source: Goddard Institute for Space Studies http://data.giss.nasa.gov/gistemp/tabledata/ZonAnn.Ts.txt; using 24N to 24S zone, 1979 to 2006 annual averages.

[31] For a detailed analysis see Seidel DJ, Lanzante JR. 2004. An assessment of three alternatives to linear trends for characterizing global atmospheric temperature changes. *Journal of Geophysical Research* **109**: D14108 DOI:10.1029/2003JD004414.

[32] IPCC Third Assessment Report Summary for Policy Makers http://www.ipcc.ch/pub/spm22-01.pdf page 4.

series have been divergent since 1979, with the largest discrepancy in the tropics. However they attributed the difference to transitory phenomena.
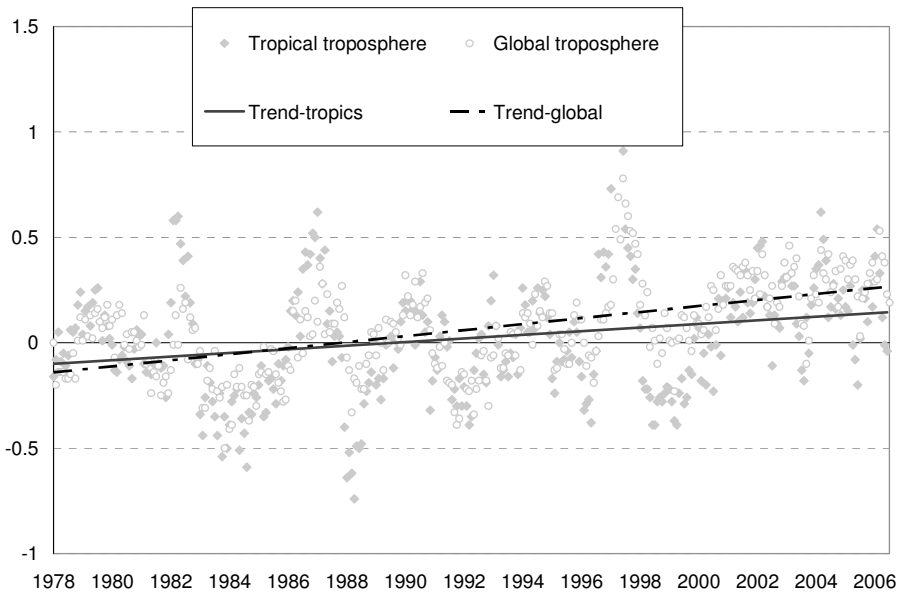

FIGURE 6: Comparison of global and tropical (20S to 20N) trends. Global trend: +0.144 per decade. Tropical trend: +0.084 per decade. Data source: http://vortex.nsstc.uah.edu/data/msu/t2lt/uahncdc.lt

After the 2001 IPCC report, several other teams began studying the MSU data and proposing alternate averaging schemes. Small differences in trends resulted from differing assumptions about how to interpret the data. A group at Remote Sensing Systems (RSS) in California published a new MSU series showing a global warming trend much closer to that at the surface, and a tropical tropospheric mean trend of 0.18 C/decade, slightly exceeding the surface rate.[33] Christy and Spencer accepted and have incorporated a correction to their method proposed by RSS, but disagree with other aspects of the reanalysis.[34] The two series are nonetheless highly correlated. They diverged slightly in the 1990s, but the differences are stable and seem to be declining since 2000; neither one finds amplified warming over the tropics.

The United States Climate Change Science Program (USCCSP) undertook a detailed examination of the tropospheric data question, resulting in a report[35] in 2006 called "Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences." The USCCSP, somewhat

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[33] Mears, C. A., M. Schabel and F.J. Wentz. "A reanalysis of the MSU Channel 2 Tropospheric Temperature Record" *Journal of Climate*, Volume 16, pg. 3650-3664, November, 2003.

[34] The RSS data are described at http://www.remss.com/msu/msu_data_description.html. A review article by Roy Spencer is "Some convergence of global warming estimates." *TechCentralStation.com* August 11, 2005.

[35] On-line at http://www.climatescience.gov/Library/sap/sap1-1/finalreport/default.htm.

remarkably, did not propose any examination of problems the surface data, nor did it question the parameterization of climate models, instead it attributed the discrepancy to problems in the satellite and weather balloon data. The USCCSP compiled 4 different MSU and balloon versions for comparison against 2 surface data sets. The USCCSP Report got a lot of media attention at the time of its release since it claimed that the weather satellite data no longer contradicted climate models outputs. The heavily-quoted opening lines in its Executive Summary read:

> Previously reported discrepancies between the amount of warming near the surface and higher in the atmosphere have been used to challenge the reliability of climate models and the reality of human-induced global warming. Specifically, surface data showed substantial global-average warming, while early versions of satellite and radiosonde data showed little or no warming above the surface. This significant discrepancy no longer exists because errors in the satellite and radiosonde data have been identified and corrected.

And yet, the subsequent Report chapters actually reveal that the mismatch between data and models is still present. The models predict a vertical pattern for the tropical troposphere that runs opposite to what was found in 7 out of the 8 comparisons examined by the USCCSP[36] (the 8th was inconclusive); moreover none of the available tropospheric data series showed a statistically significant warming of the troposphere. With reference to the key equatorial region from 20 N to 20 S, page 2 of the Executive Summary states the following:

> Although the majority of observational data sets show more warming at the surface than in the troposphere, some observational data sets show the opposite behavior. Almost all model simulations show more warming in the troposphere than at the surface. This difference between models and observations may arise from errors that are common to all models, from errors in the observational data sets, or from a combination of these factors. The second explanation is favored, but the issue is still open.

The new IPCC report summary[37] also glosses over the issue, as follows:

> New analyses of balloon-borne and satellite measurements of lower- and mid-tropospheric temperature show warming rates that are similar to those of the surface temperature record and are consistent within their respective uncertainties, largely reconciling a discrepancy noted in the TAR.

It is striking that the wording is chosen so as not to be technically false, yet without conveying the magnitude of the underlying problem: most of the available data sets contradict one of the key climate model predictions. Researchers working on these things are perfectly aware of the issues, however, and are under no illusions about the unresolved complexities they point to.

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[36] See report page 111, Figure 5.4 panel G.
[37] Summary for Policy Makers Page 5, http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Pub_SPM-v2.pdf.

To summarize, climate models unanimously predict that the main effect of GHG's in the atmosphere will be a strong warming in the tropical troposphere, powered by an accumulation of water vapour. Temperatures in this region of the atmosphere are monitored by weather satellites and weather balloons, using algorithms that were subject to detailed review by the US Climate Change Science Program. Consequently, the tropical troposphere provides an appropriate metric for the pace of GHG-induced climate change.

Having looked at some issues in the measurement of global warming, we can now turn to a discussion of the economics. The next section explains the concept of a tax on the carbon content of fuel as a means of controlling carbon emissions. The two topics surveyed in this section will turn out to be particularly relevant to the tax policy proposal I develop in the following section. Much of this material is familiar to economists but is included in part to explain why an emissions tax, instead of regulations or tradable permits, is favoured for CO_2 control.

2   The economics of CO_2 control

2.1   Carbon taxes

The concept of a 'Pigovian' tax (named after the economist Arthur Pigou) has become relatively familiar. If a certain type of pollution is harmful, an economically-elegant way to reduce it would be to apply a tax to each unit of emissions, sort of the way a tax is applied to cigarettes to reduce consumption. In the case of CO_2, putting a tax in place would be relatively easy. Each type of fuel has a measurable carbon content. Upon combustion, all the carbon must be liberated. Some will be released as carbon monoxide, some as hydrocarbons, etc. But these gases undergo further reactions until the carbon reaches its most stable molecular form, which is CO_2. Knowing the carbon content of the fuel therefore permits a nearly-precise prediction of the amount of CO_2 that will be released by its combustion. (This also explains why large reductions in CO_2 emissions must involve large reductions in fossil energy consumption.)

This is not the case for other types of air emissions. Sulphur in fuels also oxidizes and forms SO_2 in the air. But sulphur proportions in fuel are not constant: for instance coal from eastern North America has a higher sulphur content than coal from western North America. By contrast, within classes of coal, the carbon content is the same (i.e. there is no such thing as 'low carbon coal'). Also, sulphur can be scrubbed from the smokestack, so two different firms using the same amount of coal may release very different amounts of sulphur. But there is no scrubber for CO_2, so the two firms release the same amount of carbon if they use the same quantity and type of coal. (This is a major reason why CO_2 emissions are so much more costly to control than conventional air contaminants, exacerbating the stalemate mentioned in the Introduction.) Finally, sulphur in fuel may end up as SO_2, but also may form sulphate aerosols (SO_4) that disperse widely before being scavenged from the air by rain and falling to the ground. So the final SO_2 load is subject to uncertainty arising from the atmospheric chemistry, weather conditions etc. at the time of release.

Thus, since CO_2 release can be accurately predicted based on fuel consumption, it is uniquely suited to a pricing instrument like carbon taxes. There are four particular benefits of using taxes, rather than regulation, to control CO_2.

The first is that an emissions tax[38] achieves the emissions cuts at the lowest-feasible cost to society. Emitters are confronted with a uniform price for their emissions, but they have differing costs of reducing (or abating) their emissions. In principle, we want the most emissions abatement to be undertaken by the people and firms who can do it cheapest, so that we attain our policy goal at the cost of the fewest resources. If one firm has an abatement option that costs $10 per tonne and another can only abate at $30 per tonne, on economic efficiency grounds we would prefer the abatement be undertaken by the first firm. Regulations typically require every firm to abate, thereby artificially raising the cost of achieving the target. But if a tax per tonne of emissions is $20, the first firm will cut emissions but the second firm won't, which is as it ought to be. In addition, every individual and firm will have an incentive to look at its operations and identify the cheapest ways to cut emissions. Anything that costs less per tonne than the tax will be implemented. In this way, over the whole economy, millions of decision-makers will go about finding the cheapest abatement options, in the end achieving the emissions reduction at the lowest possible cost.

The second benefit is that it raises revenue for the government, which can be used to reduce other taxes, thereby minimizing the macroeconomic costs of the policy. Taxes typically cost more to the economy than the amount of money they raise for the government. Adding one dollar to the government's revenue costs the economy more than one dollar in real wealth, for example it might cost $1.30. In that case the difference—thirty cents—would be called the 'excess burden' or deadweight loss of the tax. The concept of deadweight loss is explained in any elementary economic textbook.[39]

The deadweight loss associated with one tax can be exacerbated when another tax is introduced elsewhere in the economy. Because of the link between fossil fuel and energy consumption, this turns out to be a serious problem with taxes on CO_2 emissions.[40] But it is not eliminated by using regulation instead of taxation to control the emissions, instead it is made worse. The suppression of economic activity that occurs when emissions are reduced through regulation gives rise to the same deadweight loss as would have happened under an emissions tax. But regulation generates no new revenue for the government. Emission taxes yield revenue that can be used to reduce other taxes, thereby netting out some of the deadweight losses elsewhere in the economy. Generally speaking, the offsetting reductions in deadweight loss from using carbon taxes to finance reductions in other tax rates would not be sufficient to fully eliminate the net deadweight losses, but it is better than the regulatory alternative.

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[38] The tax is applied to the carbon content of the fuel, but the externality is associated with carbon dioxide. I refer to 'carbon' when talking about the target of the tax, but 'carbon dioxide' when referring to the emissions of concern.

[39] For example, Hal R. Varian (2006) *Intermediate Microeconomics Seventh Edition* Sct. 16.8.

[40] See Bovenberg, A. Lans and Lawrence H. Goulder (1996). "Optimal Environmental Taxation in the Presence of Other Taxes: General-Equilibrium Analyses." *American Economic Review* 86(4) 985—1000; Parry, Ian, Roberton C. Williams III and Lawrence H. Goulder (1999). "When Can Carbon Abatement Policies Increase Welfare? The Fundamental Role of Distorted Factor Markets." *Journal of Environmental Economics and Management* 37: 52—84.

The third advantage is that an emissions tax creates a clear price signal that can be tied to a measure of the actual damages of the emissions. Politicians sometimes note that a certain type of emissions may be harmful, and proceed to enact any policy that might, directly or indirectly, reduce the emissions, regardless of cost. But different policies can carry very different levels of cost. For example, under a goal of reducing US gasoline consumption by 5 percent, tighter Corporate Average Fuel Economy (CAFÉ) standards have been estimated to cost between two and six times as much as raising the gasoline tax.[41] Using an emissions charge, policymakers present a clear price signal as to the implied social benefit of reducing emissions. If policymakers believe the social damages due to CO_2 emissions are not above \$20 per tonne of carbon, then setting an emissions tax at or below that level ensures that abatement will not be pursued if it costs more than \$20 per tonne. But when policymakers implement boutique regulations, such as bans on incandescent light bulbs, tighter vehicle fuel standards, ethanol mandates, closure of coal-fired power plants and so forth, since these sorts of indirect regulatory controls can easily involve costs that work out to thousands of dollars per tonne, they end up imposing abatement strategies with costs that are much higher than the likely social value of the emission reductions. Emission taxes avoid this when the tax rate is set at the estimated marginal social damages of the emissions.

The fourth advantage is low administrative costs. Implementing micro-regulations to control carbon emissions could easily necessitate a massive and costly expansion of the government bureaucracy. But excise taxes already exist, so the staff is already in place to manage them. A carbon tax is simply an adjustment to the existing rates. In principle the current government staff could manage it, and there would be no need for the extensive bureaucracy dedicated to managing the proliferation of greenhouse gas reduction policies.

A carbon tax would be applied 'upstream', where the fuel enters the market for the purpose of combustion. It would not be necessary to apply it at the point of final purchase, since the price effect would be transferred through intermediate market transactions to the final purchaser regardless of where it is first applied. For a carbon-proportional excise tax on fuels to be considered an emissions tax, there would have to be a few adjustments. If fuels are purchased for petrochemical use that does not involve combustion/release, then they would be exempted. Also, in the rare cases where emissions are sequestered (captured and pumped underground) an exemption would be applied.

2.2   Taxes versus tradable permits

An emission charge is not the only way to put a price on pollution. Tradable permits can also be used. In this case, firms acquire, or are issued, a number of permits that allow the emission of a specified volume of CO_2. Firms that have more emissions than permits have to buy the remainder on a market from firms that are able to sell excess permits.

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[41] West, S. E. and R. C. Williams III (2005) "The Cost of Reducing Gasoline Consumption." *American Economic Review* 95(2) 294—299.

In the case of CO_2, tradable permits have three disadvantages. First, it is more cumbersome to administer a tradable permits system, since the regulator has to arrange an initial allocation (via auction, grandfathering or some other method) and must audit the markets that emerge for trades. Second, in practice, governments have typically given permits away free of charge rather than auctioning them. This happened in the case of the US sulfur dioxide allowance market and the new EU carbon permits market. Since this does not raise revenues for the government, offsetting tax cuts cannot be implemented, pushing the macroeconomic costs substantially higher, as discussed above. Empirical work for the US has emphasized that resorting to non-auctioned quotas for CO_2 emissions control severely increases the cost of the policy.[42] The quotas create cartel rents for the recipients, much like agricultural marketing boards and taxi medallion schemes in cities. As such they are regressive, in addition to being inefficient.[43]

The third, and most significant, issue concerns uncertainty. A policymaker can choose a 'quantity', i.e. a targeted level of emissions, and leave it up to the market to work out the cost per unit of achieving that target. Or a policymaker can choose a 'price', i.e. the cost per unit that emitters have to pay, and leave it up to the market to determine the resulting level of emissions. The price mechanism implicitly puts a cap on the amount that firms will pay to reduce emissions. Policymakers often want to ensure that emission targets will not impose unlimited cost burdens on firms: they like to ensure a 'safety valve' is in place so that if the cost per tonne of emissions abatement goes above a certain level, firms are relieved of further emission control requirements. What they cannot do, though, is guarantee both the safety valve price and the total cut in emissions: they have to pick one or the other. Since policy must be based on guesses about both the social costs of the emissions and the private costs of emission controls, it is likely that an error will be made, and the optimal target will not be identified, at least at first. That being the case, is it better to guess at the right quantity or the right price?

This question has been extensively studied by economists, beginning with a classic treatment by Martin Weitzman.[44] The analysis shows that in cases where there are clear hazard points, i.e. where the damages jump substantially over short increments of emissions, a quantity control is preferred. But if damages increase by constant increments over the relevant range of emissions, a price control is preferred. This conclusion is reinforced if there is also a likelihood of sharply increasing marginal abatement costs as the emissions cap gets tighter. Both these conditions appear to be true for CO_2 emission controls. Since carbon dioxide mixes slowly in the global atmosphere, and does not have localized effects, the damage of a tonne of CO_2 emissions is independent of current emission levels. Consequently the damages associated with the first tonne of emissions is approximately the same as that associated with the last tonne. However, since there are so few viable methods for reducing CO_2 emissions, besides cutting energy consumption, the marginal cost of emission reductions likely rises quickly once the easiest methods have been exploited. Consequently, economists who have studied the question pretty much unanimously

[42] In addition to the other references, see Parry, I.W.H. (2003) "Fiscal Interactions and the Case for Carbon Taxes over Grandfathered Carbon Permits." Resources for the Future Discussion Paper 03-46.

[43] Parry, I.W.H. (2004) "Are Emission Permits Regressive?" *Journal of Environmental Economics and Management* 47 (2004) 364–387.

[44] Weitzman, M.L. (1974). "Prices vs. Quantities." *Review of Economic Studies* XLI, 477–491. For a recent review see Jacoby, H. D. and A. D. Ellerman (2004) "The safety valve and climate policy." *Energy Policy* 32 (2004) 481–491.

recommend that policymakers should aim for an optimal *price* for carbon emissions, rather than trying to set a quantity target.[45]

2.3   Damage estimates

Just how costly to society is the release of a tonne of CO_2? For reasons spelled out in Section 1 above, it should be obvious that this question is not at all easy to answer. But if we confine attention to studies that take it for granted that CO_2 has a significant climatic effect, the damage estimates do show some similarity. Tol (2005)[46] canvassed over 100 estimates of the marginal damages of carbon dioxide emissions. While there was variability regarding the methodologies and assumptions, the studies had in common that they took climate forecasts more or less at face value and attached dollar values to the global consequences of emissions. They differed in how they valued those effects, but the overall results were nevertheless surprisingly clustered. Figure 7, reproduced from Tol's paper, shows the overall distribution. There is a huge modal concentration between $0 and $10 (US) per tonne of carbon. Tol's diagram had to cut off the spike in the middle, so I have re-drawn it in Figure 7.

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[45] See Pizer, William A. (1997). "Prices vs. Quantities Revisited: The Case of Climate Change." Resources for the Future Discussion Paper 98-02; also Ekins, P. and T. Barker, (2001) "Carbon Taxes and Carbon Emissions Trading." *Journal of Economic Surveys* 15(3) 325—376.

[46] Tol, Richard S.J. (2005) "The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties." *Energy Policy* 33 (2005) 2064–2074.
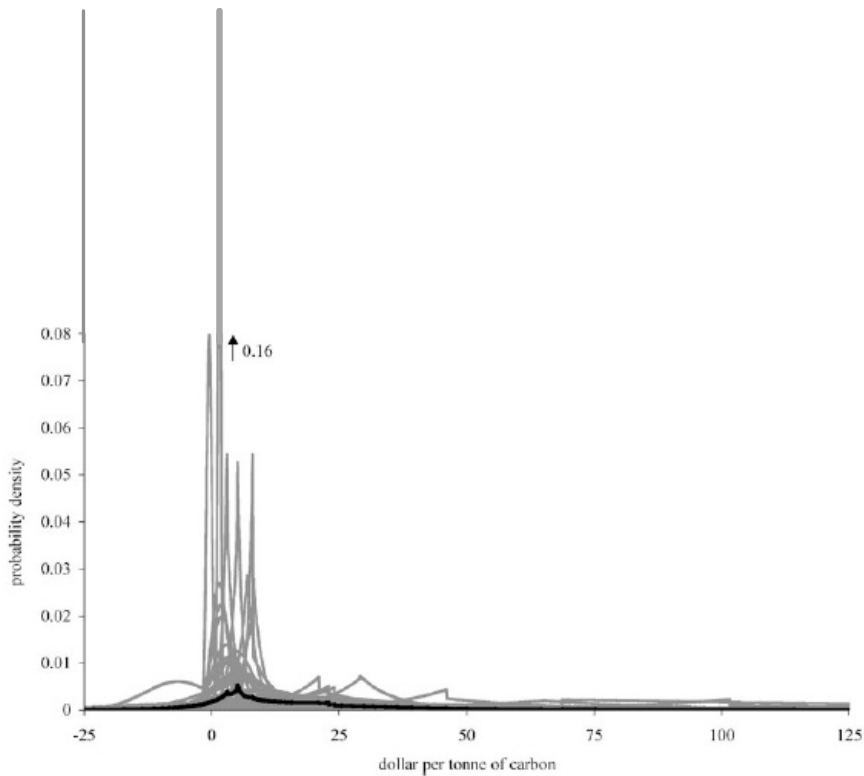
FIGURE 7: Histogram of estimates of marginal or average damage costs per tonne of carbon, in $US. Source: Tol (2005).

The mode is $2/tonne of carbon, the median is $14/tonne and the mean is $93/tonne. Tol initially included some gray literature in his sample, with cost estimates up to $800 per tonne. If we only consider peer-reviewed literature, the mean falls to $43 and the mode falls to $1.50 per tonne; Tol reports the latter number is robust to many configurations of quality-weighting. If we further remove papers that apply a pure rate of time preference below 3% the median falls to about $6/tonne (Tol, 2005, Fig. 5). In other words, half the peer-reviewed studies put the costs at or below $6/tonne.

So even if we ignore the fundamental uncertainty about the effect of CO_2 on the climate, there is not a lot of uncertainty about the marginal damages of carbon. The social cost of carbon, at the global level, is almost certainly less than $50/tonne, and likely less than $10/tonne. A price of, say, $5/tonne of carbon (US) would be a reasonable starting point for a carbon tax, given current damage estimates, if CO_2 really does cause global warming.

A number of studies looking at time paths of carbon taxes have emphasized that they ought to start low, but slowly increase over time. The 'DICE' and 'RICE' models of William Nordhaus[47] are well-known in this regard. These analyses embed an assumption that the effect of CO_2 concentrations on the 'global temperature' is known with certainty. The slow increase in the carbon price reflects the trade-off between investing in income-enhancing capital and emissions-abating capital. At present, the rate of return to productive investment is high relative to the rate of return to investing in CO_2 abatement. But in the dynamic models popular among economists ('Integrated Assessment Models') the damages of global warming begin to over-ride the return to ordinary capital accumulation at some future point, and more aggressive abatement policy becomes optimal a few decades hence.

This prescription—a low initial carbon tax that ramps up over time at something like the rate of interest[48]—has detractors on two sides. Environmentalists want hard caps on emissions right away,[49] or at least a sufficiently high carbon price to force deep emission cuts early on,[50] while skeptics like me don't think the government should commit to a long-range schedule of rising carbon taxes without some objective feedback loop in place to account for the possibility that future information may reveal the social damages of CO_2 emissions to be small or zero. In light of the range of views on this issue, the next section explains a carbon tax proposal that conceivably could make (just about) everybody happy.

3   The T3 tax

3.1   The unique role of the tropical troposphere

I explained in Section 1 above that the tropical troposphere plays a unique role as the locus of warming under GHG-forcing mode runs. The other regions that potentially exhibit amplified response in model projections are the North and South poles.

In the 2001 IPCC Report, models predicted an amplified warming over Antarctica,[51] but both surface and MSU temperature data show no upward trend since 1960 for the Antarctic region.[52] Climate models seem

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[47] Nordhaus, W., and J. Boyer. (2000). *Warming the World: Economic Modeling of Global Warming*, Cambridge, Mass: MIT Press. D.L. Kelly and C.D. Kolstad (1999) "Integrated Assessment Models For Climate Change Control," Henk Folmer and Tom Tietenberg (eds.), *International Yearbook of Environmental and Resource Economics 1999/2000: A Survey of Current Issues,* Cheltenham, UK, Edward Elgar, 1999.

[48] The best known of these proposals results from Nordhaus' DICE model. In a recent book-length manuscript describing the model and its optimal policy path (available at http://www.econ.yale.edu/~nordhaus/DICEGAMS/dice_mss_060707_pub.pdf) Nordhaus proposes a tax beginning at about $27 per tonne of carbon in 2005, rising at a rate of 2—3% per year in real terms, reaching $90 per tonne as of 2050 and $200 per tonne by 2100, as the optimum response to climate change as parameterized in his model.

[49] E.g. "Market Certainty in a Carbon Constrained World", *Environmental Defense* brief to Congress, 2005.

[50] For example, the Canadian Green Party is calling for a $50 per tonne carbon tax, to rise as high as $100 per tonne by 2020. But they want to supplement it with hard caps on large emitters. http://www.greenparty.ca/en/releases/06.06.2007?origin=redirect.

[51] IPCC Working Group I Report *Climate Change 2001: The Scientific Basis* Figure 9.8, top panel.

to have been modified since then and there is now no predicted GHG warming over the South pole (see IPCC Figure 10.7, references in discussion for Figure 5 above).

Models continue to predict an amplified warming over the Arctic region, as shown in Figure 5. However, the intensification of the Arctic Oscillation since the late 1980s (see Section 1.2.1 above) makes it hard to interpret whether this is a signal of anthropogenic global warming. Also, the collapse of the surface-based climate monitoring network, especially in Russia, means that monitoring of the Arctic region at the Earth's surface is impaired by serious data quality problems.

That leaves the tropical troposphere. It is unique for three reasons. First, models all show that warming occurs strongest and earliest there. Second, it is continuously monitored by weather satellites, with two independent teams producing highly correlated mean temperature estimates. Third, there are no rival mechanisms other than GHG forcing that would lead modelers to predict strong tropical tropospheric warming. In the IPCC Fourth Assessment Report Figure 9.1[53] the pattern associated with solar intensification over the 20th century does not have the strong tropical tropospheric hotspot. While some scientists propose that future solar changes of sufficient strength could, potentially, lead to a warming of that region of the atmosphere, the IPCC considers the sun to play only a minor role in overall climate change (see 2007 IPCC Working Group I Summary for Policy Makers). Moreover solar output is projected to decline over the coming few decades. NASA reports[54] that, while the current solar cycle, which will peak around 2011, will be intense, the one to follow, which will peak around 2022, could be one of the weakest in hundreds of years.

Consequently, the current mean temperature in the tropical troposphere, and its trend over the next few decades, is a good metric for the reliability of climate models, and the strength of the underlying GHG-induced global warming hypothesis itself. And by implication, it provides a convenient way to build a feedback loop into a time-path of carbon taxes, so that policy makers do not have to gamble an extremely expensive policy agenda on one side being right in a complex and contentious scientific battle. If the tropical troposphere does not start 'heating' up at a rapid rate in the next few years, the models and the larger hypotheses which they embody will be refuted. Held and Soden (2000), referring to the necessity of observing an accumulation of water vapor in the tropical troposphere, remark as follows (p. 471):

> Given the acceleration of trends predicted by many models, we believe that an additional 10 years may be adequate, and 20 years will very likely be sufficient, for the combined satellite and radiosonde network to convincingly confirm or refute the predictions of increasing vapor in the free troposphere and its effects on global warming.

Many partisans in the global warming debate have said, for years, that the 'debate is over,' or 'there is no debate.' But it is more accurate to say that the debate will not go on forever. There are now two rival predictions firmly on the table. If the sun controls climate, we are in for a strong cooling trend after 2011.

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[52] See, for example, http://cdiac.esd.ornl.gov/trends/temp/angell/graphics/spolar.gif for a compilation of surface and tropospheric data series; also IPCC Fourth Assessment Report Figure 3.7, bottom panel.

[53] See http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Pub_Ch09.pdf, page 675.

[54] http://science.nasa.gov/headlines/y2006/10may_longrange.htm.

If GHG's control climate, we are in for warming. Either way, it will show up first, and most clearly, in the troposphere over the tropics.

3.2   The T3 tax formula

I propose that a carbon tax be implemented that would be calibrated to begin at around the median damage estimates in the survey by Richard Tol (2005, *op. cit.*). If global warming proceeds as projected it would rise at approximately the optimal pace as computed by Nordhaus' DICE model. But it would follow the 'T3' path – the tropical tropospheric temperature, so as to build in a direct feedback loop, ensuring a more self-correcting path than other proposals.

Using the Spencer-Christy method to analyse MSU data, the mean tropical tropospheric temperature anomaly (its departure from the 1979-1998 average) over the past three years is 0.18 degrees C. The corresponding RSS estimate is 0.29. Suppose every country implements the T3 tax, whose US dollar rate, per tonne of carbon, is set as follows:

$$T3 = 20 \times \tfrac{1}{36} \sum_{i=0}^{35} \tfrac{1}{2}\big(SC(t-i) + RSS(t-i)\big) \tag{1}$$

where *SC*(*t*) is the Spencer-Christy monthly mean tropical tropospheric temperature anomaly and *RSS*(*t*) is the same from the RSS lab. (1) says that the tax rate is equal to 20 times the three-year moving average of the mean of the RSS and UAH estimates of the mean tropical tropospheric temperature anomaly. In (1), and all ensuing discussion, I am assuming the dollar values are inflation-adjusted. By using a three-year trailing average the movements would be smoothed out, avoiding spikes or drops due to, e.g. volcanic activity or strong El Nino events.

The rate could be frozen for 12 month intervals if that much stability is desired, but the rate is not very volatile. The reconstructed historical rate is shown in Figure 8. It exhibits far less volatility than, e.g., the European carbon market price, which has swung about $30 (US) per year since inception. Based on current data (as of May 2007) the T3 tax would be US $4.70 per tonne of carbon, roughly matching the median estimate from Tol, though below the starting value advocated by Nordhaus. As explained in Section 2, the tax would be implemented on all domestic carbon emissions, all the revenues would be recycled into domestic income tax cuts to maintain fiscal neutrality, and there would be no accompanying cap on total emissions.
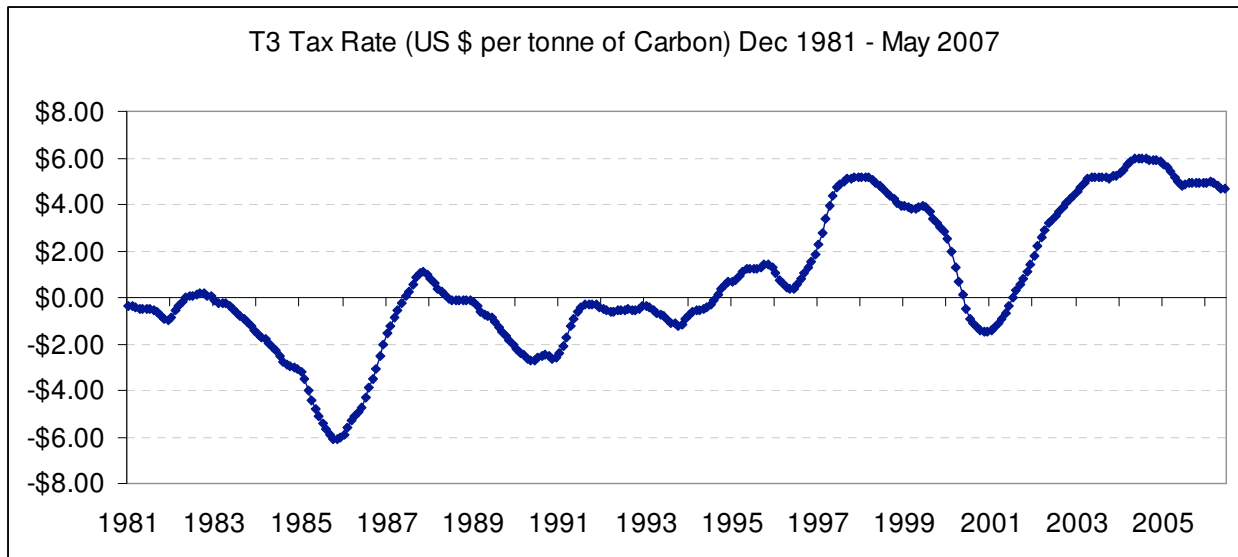
Figure 8: Values the T3 Tax would have taken historically (up to May 2007) had it been implemented in December 1981.

The IPCC predicts a globally-averaged warming rate of 0.1 to 0.6 degrees per decade at the surface (some modelers predict even more), implying an increase of at least 0.2 to 1.2 degrees C per decade in the mean tropical troposphere temperature under greenhouse forcing scenarios. That implies the tax will climb by $4 to $24 per tonne per decade. This would not hit the Green Party of Canada's goal ($100 by 2020), but at the upper end of warming forecasts, the tax would reach $200 per tonne of CO_2 by 2100, mirroring Nordhaus' optimal path, and forcing major carbon emission reductions and a global shift to non-carbon energy sources.

Many proponents of global warming mitigation policy would like this. But presumably so would skeptics, because they believe the models are exaggerating the warming forecasts. After all, as shown in Figure 6, the Spencer-Christy tropical troposphere series went up only 0.08 degrees per decade since 1979. Nor is it accelerating: the average of the Spencer-Christy and RSS tropical troposphere series went up only about 0.08 degrees C over the past decade, and has been going down since 2002. If those who consider the sun to be the primary influence on climate change are right, the T3 tax could fall back below zero within a few years, turning into a subsidy for carbon emissions.

At this point the global warming alarmists would be tempted to denounce the proposal. But they need to pause before doing so, and consider what they would be saying. The tax would only stabilize as a carbon subsidy if all the climate models are wrong, if greenhouse gases are not warming the atmosphere, and if the sun actually controls the climate. Alarmists have in the past denounced such claims as 'denialism' so they can hardly reject the T3 proposal on the belief that they are actually true.

Under the T3 tax, the regulator gets to call everyone's bluff at once, without gambling in advance on who is right. If the tax goes up, it ought to have. If it doesn't go up, it shouldn't have. Either way we get a sensible outcome, though I wouldn't necessarily call it an 'optimal' outcome. To show that it is the optimal outcome would require development of a proper intertemporal model that incorporates the relevant economic considerations: discounting, lags between emissions and effects, capital accumulation, etc.

An appropriate model would also include parameter uncertainty. The Nordhaus DICE model assumes the key parameters are known with certainty, namely the effect of CO_2 on the climate, and the effect of the "global temperature" on productivity. Some authors have introduced parameter uncertainty in the DICE framework, with surprising results. Kelly and Kolstad[55] (1999) allowed the effect of GHG levels on the mean temperature to be known only as an estimated mean and variance, which were then updated each period based on observations, leading to a re-optimization of the policy path. They found that, for reasonable parameter choices, it would take about 90 years for a policymaker to acquire enough knowledge to rule out the wrong climate sensitivity parameter, during which time the policy deviates from the optimal path due to use of an incorrect estimate of climate sensitivity. Andrew Leach[56] developed the model further by allowing uncertainty in one more dimension: the extent of autocorrelation of temperature shocks in the climate record, i.e. the degree to which a random fluctuation in one year affects the climate in future years. Adding this one form of uncertainty extended the learning horizon by several centuries, stretching over a thousand years, depending on the circumstances. The learning problem arises because, with uncertainty about the persistence of random fluctuations over time, it is more difficult to determine whether trends over short intervals are natural in origin or not. Again, the time-to-learn was defined as the time required to assimilate (via Bayesian updating) the information contained in each year's new data to refine the estimates of key policy model parameters sufficiently to rule out false values of the key climate parameters. All along the learning path the policy maker cannot set an optimal tax because the parameters are not known with sufficient accuracy. The precision in the Nordhaus model is illusory, since it simply assumes away the parameter uncertainty.

A short digression, not entirely off-topic: Taking account of the uncertainty about the autocorrelation of climate processes is quite pertinent in light of the substantial literature that has developed in recent years on the subject of Long Term Persistence (LTP) in climatic data.[57] Persistence models arose in hydrology following Hurst's investigation of long-term Nile River depth records.[58] Mandelbrot proposed the Fractional Gaussian Noise (FGN) model a few years later[59] to quantify the Hurst phenomena. Hurst noted

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[55] Kelly, D.L. and C.D. Kolstad (1999) "Bayesian Learning, Growth and Pollution" *Journal of Economic Dynamics and Control* 23:491—518.

[56] Leach, A. (2007) "The Climate Change Learning Curve" *Journal of Economic Dynamics and Control* 31 (5), pp.1728-1752.

[57] For a recent example see Koutsoyiannis, D., A. Efstratiadis and K. P. Georgakakos (2007) "Uncertainty Assessment of Future Hydroclimatic Predictions: A Comparison of Probabilistic and Scenario-Based Approaches." *Journal of Hydrometeorology* 8:261—281.

[58] Hurst H.E. (1951) "Long term storage capacity of reservoirs," *Transactions of the American Society of Civil Engineers,* **116,** 770-808.

[59] Mandelbrot, B. B. (1965) "Une classe de processus stochastiques homothétiques a soi: application à la loi climatologique de H. E. Hurst." *C. R. Acad. Sci. Paris* 260, 3284–3277.

that hydrological events (droughts, floods) tended to cluster together over time, causing long-term excursions in the data that appeared as pseudo-trends over short intervals. Standard time series analysis based on autoregressive models do not adequately capture the apparently slowly-decaying influence of a temporary random shock over a long interval. The FGN model uses a single parameter *h* (the Hurst coefficient) to model the complex decay rate of autocovariances over time, and embeds classical autoregressive processes as a special case. Values of *h* estimated on long term hydrological data suggests that many basic climatic processes exhibit LTP.[60] A generalization of the Hurst model to allow for nonstationarity has led to discovery of Hurst phenomena in numerous temperature and solar flux series.[61] These models are closely related to fractional integration methods familiar to econometricians. The new results show that applying classical statistical methods to climate processes will lead to under-estimation of the extent of natural variability. Cohn and Lins (2005)[62] recently developed a test for the significance of trends in geophysical data that is robust to the presence of LTP. They showed that what appears to be a highly significant upward trend in a common 'global temperature' series under the autoregressive assumption falls to insignificance when the test allows for persistence. 25 orders of magnitude of significance disappears under the revised testing method. They conclude:

> "[With respect to] temperature data, there is overwhelming evidence that the planet has warmed during the past century. But could this warming be due to natural dynamics? Given what we know about the complexity, long-term persistence and non-linearity of the climate system, it seems the answer might be yes…natural climatic excursions may be much larger than we imagine."

In my capacity as an expert reviewer of the recent IPCC report, I objected to the report authors' use of simplistic, obsolete methods to evaluate the significance of trends in their temperature data sets. In response to the first draft of the report, I and another reviewer drew attention to the literature on LTP phenomena, asked that it be properly referenced, and that the temperature trend significance calculations (which were done by applying a first-order autocorrelation correction then calculating a Durbin-Watson statistic to check that the problem was 'fixed') be re-done using up-to-date methods following the peer-reviewed literature. The chapter authors were obviously antagonistic to this suggestion and refused to change their methods, but the second draft of the IPCC report did, at least, include a short discussion of the LTP issue and an acknowledgment that over-estimation of the significance of trends in climate data can be expected to be a typical problem. Then, despite the fact that reviewers had made no objections to this addition, it was deleted from the final edition, and a few disputatious claims (unsupported by any published studies) were inserted regarding the Cohn and Lins paper. The episode is recounted on-line at http://www.climateaudit.org/?p=1805.

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[60] Koutsoyiannis, Demetris (2004) "Hydrologic Persistence and the Hurst Phenomenon." In *Water Encyclopedia, Vol. 4, Surface and Agricultural Water,* edited by J. H. Lehr and J. Keeley, Wiley, New York.

[61] Kärner O. (2002) "On nonstationarity and antipersistency in global temperature series." *Journal of Geophysical Research* D107; doi:10.1029/2002JD002024. Kärner O. (2005) "Some examples of negative feedback in the earth climate system." *Central European Journal of Physics,* 3**,** 190-208.

[62] Cohn, T.A. and H.F. Lins, (2005) "Nature's style: Naturally trendy." *Geophysical Research Letters* **32,** L32402, doi:10.1029/2005GL024476.

The point of this digression was to note that Andrew Leach's extension of the Kelly-Kolstad model ties to a very current issue in empirical climatology, namely the persistence of shocks in temperature/climatic data. Evidence suggests the form of persistence in hydrological and climatic data tends to exaggerate the significance of classically-estimated trends. While the IPCC is not yet willing to confront the issue, in the real world, climatic shocks are persistent, and climate sensitivity is uncertain. According to both the Kelly-Kolstad and Leach analyses, it could take hundreds of years for policymakers to learn enough to reject incorrect hypotheses about key policy model parameters and thereby formulate the optimal policy.

Consequently, I do not mind noting that the T3 tax rule does not qualify as an optimal tax. Instead I point to the evidence that no one knows what the optimal policy rule for global warming should be, and the 'first best' strategy will not be knowable for decades or centuries. So, realistically, we are not going to know the optimal policy any time soon, but we might at least be able to find a sensible policy, hopefully one that gains wide support.

3.3   An alternative T3 formula

Equation (1) uses a coefficient of 20 to calibrate the tax to the temperature record. Critics who want a more aggressive schedule of increases might say that this coefficient it too low, and propose another coefficient, say 50. However, that would imply a starting value of \$11.75. Now suppose there is no change in the temperature for 100 years. This would obviously indicate that CO_2 was inert as regard to climate, yet the tax would remain in place. So we could increase the sensitivity of the tax by scaling up the slope parameter, but we should also shift the rate down so that if there is no warming, there is also no tax. This would imply a revised T3 formula, denoted T3*, as follows:

$$T3^* = -11.75 + 50 \times \tfrac{1}{36} \sum_{i=0}^{35} \tfrac{1}{2} \big(SC(t-i) + RSS(t-i) \big) \qquad (2).$$

Table 1 lists the rates that would emerge for the T3 tax under both formulas, for a range of temperature trends, assuming the system begins in 2010 and runs through 2100.

Coefficient	T3 trend	2010	2025	2050	2075	2100
20	-0.1	\$4.70	\$1.70	-\$3.30	-\$8.30	-\$13.30
	0.0	\$4.70	\$4.70	\$4.70	\$4.70	\$4.70
	0.1	\$4.70	\$7.70	\$12.70	\$17.70	\$22.70
	0.2	\$4.70	\$10.70	\$20.70	\$30.70	\$40.70
	0.3	\$4.70	\$13.70	\$28.70	\$43.70	\$58.70
	0.4	\$4.70	\$16.70	\$36.70	\$56.70	\$76.70
	0.5	**\$4.70**	**\$19.70**	**\$44.70**	**\$69.70**	**\$94.70**
	0.6	\$4.70	\$22.70	\$52.70	\$82.70	\$112.70
	0.7	\$4.70	\$25.70	\$60.70	\$95.70	\$130.70
	0.8	\$4.70	\$28.70	\$68.70	\$108.70	\$148.70

	0.9	$4.70	$31.70	$76.70	$121.70	$166.70
	1.0	$4.70	$34.70	$84.70	$134.70	$184.70
	1.1	$4.70	$37.70	$92.70	$147.70	$202.70
50	-0.1	$0.00	-$7.50	-$20.00	-$32.50	-$45.00
	0.0	$0.00	$0.00	$0.00	$0.00	$0.00
	0.1	$0.00	$7.50	$20.00	$32.50	$45.00
	0.2	$0.00	$15.00	$40.00	$65.00	$90.00
	0.3	$0.00	$22.50	$60.00	$97.50	$135.00
	0.4	$0.00	$30.00	$80.00	$130.00	$180.00
	0.5	**$0.00**	**$37.50**	**$100.00**	**$162.50**	**$225.00**
	0.6	$0.00	$45.00	$120.00	$195.00	$270.00
	0.7	$0.00	$52.50	$140.00	$227.50	$315.00
	0.8	$0.00	$60.00	$160.00	$260.00	$360.00
	0.9	$0.00	$67.50	$180.00	$292.50	$405.00
	1.0	$0.00	$75.00	$200.00	$325.00	$450.00
	1.1	$0.00	$82.50	$220.00	$357.50	$495.00

TABLE 1: Rates for the T3 Tax (per tonne of carbon) under formulas (1) and (2). T3 trend (second column) is degrees C/decade. Tax is assumed to begin in 2010. A negative value indicates a subsidy. Row associated with 0.5 C/decade is in bold for ease of presentation.

By way of comparison, if the tax rate were to begin at $4.70 and increase at 4 percent per year it would rise to over $160 by 2100. Formula (1) would only yield a $200/tonne carbon tax by the end of the century under the high-end of warming scenarios. Formula (2) would top $200 per tonne under the middle scenario (0.5 degrees C/decade). Under the high end scenario the tax would go to nearly $500 per tonne. Of course under that scenario, GHG's are assumed to be so tied to global warming, that at carbon tax rates of over $200 per tonne, emissions would fall and the high end warming scenarios would likely not be attained.

However the drawback for proponents of a higher T3 coefficient is that if the tropospheric temperature record goes below zero for a long period of time, e.g. after the forecasted drop in solar activity in the early 2020s, formula (2) would prescribe a large subsidy for CO_2 emissions. Advocates of an aggressive pricing ramp for carbon should be careful what they wish for. However it would not be acceptable to make the tax rule asymmetrical, so that if temperatures go up then the tax goes up, but if they go down then the tax stays the same. This would be a heads-I-win-tails-you-lose dodge. The essence of the T3 proposal is that it requires advocates to make a commitment based on the view they claim to hold about future climate change. If the advocates of greenhouse gas controls really believe the case for warming is so strong as to warrant committing to a costly international effort to scale back energy consumption, they cannot also advocate for a safety net in the form of a floor value for the tax in the event of global cooling.

3.4 Advantages of the T3 tax

3.4.1 Inducing private sector climate modeling

Investors planning major industrial projects will need to forecast the T3 tax rate many years ahead, thereby taking into account the most likely path of global warming a decade or more in advance. This will have the beneficial effect of encouraging private sector climate forecasting. Firms will need good estimates of future tax rates, which will force them to look deeply, and objectively, into the question of whether existing climate forecasts are credible. The financial incentives will lead to independent re-assessments of global climate modeling, without regard to what politicians, the IPCC or climatology professors want to hear.

One simple outcome might be the emergence of a financial contract based on the long-term future value of the tropical tropospheric temperature record. I suggested the development of this contract at the on-line forecasting market www.intrade.com. So far it hasn't appeared, but I hope they consider it, and I would find it very interesting to compare it to IPCC projections.

In a similar vein, Wharton School Marketing Professor J. Scott Armstrong, who specializes in evaluating forecasting methods, recently coauthored a review of IPCC forecast methodology[63] and concluded that there was no 'scientific' basis for the forecasts of global warming, in the sense that the IPCC projections and supporting documentation violated many key principles that guide forecasting methodology outside climatology. In June 2007, after concluding that there was no more reason to expect global warming than global cooling, Armstrong made a public challenge (http://theclimatebet.com/) to Al Gore, betting him $10,000 that any climate model he chose would do worse at predicting the global climate over the coming decade than simply assuming there would be no change. Gore replied on July 7, 2007, declining the bet.

The issue of forecasting raises the question of how expectations play a role in resolving parameter uncertainty. The standard treatment of this in dynamic economic models (such as models of investment behaviour, monetary policy etc.) uses the concept of "rational expectations." This simply means that if making a mistake is costly, agents who make decisions based on forecasts will not persistently make the same mistake over and over. For example, if a forecasting method consistently yields over-estimates, people will eventually compensate by reducing the estimates. A rational forecasting process subject to market constraints will, on average, be accurate, in the sense that errors will be unsystematic and will converge to a zero mean. Right now, the IPCC and other such groups do not face market constraints. If they persistently overestimate warming, they face no consequences, and indeed may find it easier to get their papers published. The Kelly-Kolstad and Leach models did not solve for a rational expectations equilibrium.[64] In their models, policymakers make optimal use of new information to update their estimates of one or two model parameters, but the model structure itself is assumed to be true. This creates the possibility that they could make persistent and systematic forecast errors over time, potentially overstating the length of the learning process. My conjecture is that the T3 tax, by establishing market constraints that select for greater forecast accuracy, would induce an efficient, rational-expectations process for climate forecasting. Persistent errors would be costly, and accurate

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[63] Armstrong, J.S. and K. Green (2007) "Global Warming: Forecasts by Scientists versus Scientific Forecasts" forthcoming, *Energy and Environment*, available at http://www.forecastingprinciples.com/Public_Policy/WarmAudit31.pdf.

[64] See, e.g., Kelly and Kolstad *op. cit.* p. 501. The Leach model finds a Markov-Perfect Equilibrium.

forecasts would be financially rewarding, and that would be the incentive for private sector efforts in climate modeling. Hence the learning horizon might not be as long as current literature suggests.

3.4.2 Inducing forward-looking behaviour

Global warming is a long-term problem. The intertemporal aspects arise not only because of inertia in the climate system but also because of inertia in the economy. Capital investments in energy consumption (such as large industrial plants and power generating stations) need to be planned years, or decades in advance, and can have operating lives of 30—50 years, or more. If the government makes a credible commitment to the T3 tax, a firm planning to build a power plant that will operate for 40 years will need to consider the T3 tax liability over its entire lifetime. In this way, the T3 tax solves a problem that advocates for global warming policy often draw attention to: the need to be forward-looking. The argument is usually expressed along the following lines: *We cannot wait until global warming is happening. By then it will be too late. We need to act now to prevent the damages from happening down the road.*

This argument asks too much of policymakers and society. We cannot commit to an expensive and radical policy path without firm evidence that it is necessary, and without an effective feedback loop that refines the policy in light of future information. Uncertain model forecasts are an inadequate basis for making the policy commitment, especially in light of their conspicuous problems in the tropical troposphere. The T3 tax gets around this by putting the onus on individuals to weigh their willingness to gamble on the forecasts. If a firm is building an emissions-intensive smelter, for example, they can ignore global warming forecasts if they like, but they cannot ignore the emissions tax rate they will be paying in ten years. If the best forecast is that carbon emissions will be expensive by 2025, that will affect investment decisions today. In this sense the T3 tax is forward-looking.

To put it another way, a likely objection to the T3 tax is that the formula uses past and current temperature data, rather than future warming, hence it does not internalize the future damages of a tonne of carbon emissions, as would a tax based on, e.g., the DICE model analysis. But the DICE tax rate ramp is the correct path only if carbon emissions have the assumed large effect on climate. If not, the model prescribes the wrong tax path. In other words, it is only optimal by assumption, but it might be quite wrong. And according to the models that allow for learning, we will not know which is the case for a century or more. So it is important not to compare the T3 mechanism to a non-existent ideal alternative.

Also, while the T3 tax formula is based on current and past temperature measures, investment decisions will be based on expected future values of the tax, and therefore expected future temperatures; including changes due to current emissions. In that sense the T3 tax system does build in forward-looking behaviour, based on the workings of the actual climate, not a computer model. Also, rather than the government being the sole forecaster for the purpose of setting the tax rate, investors themselves do the forecasting, with the highest payoff going to those who make the most accurate forecast. An investor evaluating a major capital investment must consider what the expected value of the tax will be in ten or twenty years, not just what it is today. If today's emissions cause future warming, that will be factored in the planning decisions for current and future investments. In that way the T3 tax evolves as if it built in the (discounted) present value of future carbon emissions.

Of course the effects go the other way too. Consider a firm that is thinking of developing a large alternative energy project on the expectation that global warming will be so bad that carbon-based energy will start to be priced out of the market. They can invoke the most alarmist forecasts they like in order to convince investors to back their project. But if the policy in 10 years' time is the T3 tax, there will be an objective outcome, which might include no financial incentive for wind power, and even a small subsidy for burning coal. They will need to assess the likelihood of that outcome before sinking money into the project.

3.5 A T3 pricing equivalent for tradable permits

Despite economists' preference for carbon taxes over tradable permits, policy makers in Canada and the US have talked almost exclusively about using tradable permits. The T3 concept can be introduced into a tradable permits system as the basis of a backstop price. If policymakers have some emissions target in mind (for example, five percent below 1990 emissions), they can auction that quantity of permits off, but add to the market a stipulation that firms can choose either to hold permits for their emissions, or pay a safety-valve price per tonne as a penalty for not holding permits (see Section 2.2). If the price is set using the T3 formula, it effectively becomes a price ceiling in the permits market, and once the ceiling is hit the permits policy would be formally equivalent to a carbon tax.

Tradable permits systems that have been proposed in Canada and the US sometimes apply a safety-valve pricing rule. However they tend to be arbitrary, such as increasing at the rate of GDP growth, or at a set percentage level each year. Using the T3 principal would simply put the pricing rule on a proper, objective basis.

4 Conclusions

At the recent G8 Summit in Berlin, after long negotiations, world leaders agreed to "stabilize greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system." This is identical to the wording in Article Two of the UN Framework Convention on Climate Change, signed in 1992. In other words, world leaders have agreed to a text they had already ratified 15 years earlier.

Such is the stalemate in global warming policy. The Kyoto Protocol was signed 10 years ago, and expires in just over 5 years, but none of the participating countries have shown any enthusiasm for complying with it, unless by accident they happen to be within its emission limits (as is the case for Russia, for instance, following the economic collapse of the early 1990s). Fundamentally, the flaw in the Kyoto Protocol was that it requires participants to act against their own interests, and not surprisingly they turned out to be reluctant to do so.[65] Perhaps the threat of global warming is so severe that deep emission

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[65] For a perceptive discussion of this issue see Boehmer-Christiansen, S. and A. Kellow (20020 *International Environmental Policy: Interests and the Failure of the Kyoto Process* Cheltenham: Edward Elgar.

cuts really *are* in our interest. There are certainly some impressive names who take this view, such as Sir Nicholas Stern, Kenneth Arrow and Joseph Stiglitz.[66] But I think the reader who looks at their essays, and I especially draw attention to those by Arrow and Stiglitz, will see that they follow from the popular picture of global warming outlined in Section 1, and as such are characteristic of the kind of thinking that has led into the stalemate, rather than providing guidance for the way out.

It may be too much to hope that an instrument like the T3 tax would appeal to people on far sides of the climate policy discussion. On June 15, 2007, the Green Party of Canada issued the following reaction to my newspaper op-ed on the subject. It was written by Green Party climate critic Guy Dauncey and sent to me from a party member:

> Ross McKitrick's proposal for a "T3" carbon tax based on a measurement of global warming in the troposphere is premised on his belief that there are still important divisions of opinion as to whether humanity is having an influence on the climate.
>
> It is true there are a few who are determined not to accept what the world's climate scientists are telling us, but the inability of the G-8 to come up with binding commitments to reduce emissions is due to Neroesque obstinacy in the White House, not to any uncertainties in the science.
>
> McKitrick's proposal would have us tax carbon at a level that is low enough to be completely ineffective, and wait for further signs of danger before increasing it. This is like waiting until you can see an approaching tsunami with your eyes before agreeing to invest in an early-warning system.
>
> He would also like "independent" private companies to develop their own global climate modelling, in order to avoid having to accept what the climate scientists are saying.
>
> With this line of reasoning, if he can tolerate the prayer meeting, I'm sure there is a job waiting for him in the White House, where his prejudices against science would surely be very welcome.

I hope that this extended discussion has answered some of the misconceptions exemplified by the above response. For example, while I have made my own views on some of the scientific issues clear, I have also stressed that people holding quite different views ought to support the T3 mechanism, since on their assumptions it would ramp up into a strong abatement incentive over the coming decades. The T3 tax would start low because current estimates of marginal damages are low—the fact that this would result in very little abatement reflects conditions in the market for energy, and underscores the fact that policymakers can pick a price or a quantity, but not both. The tsunami metaphor gets the matter

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[66] Stern, Sir Nicholas (2007) *The Economics of Climate Change*. Cambridge, UK: Cambridge University Press. Available at: http://www.hm-treasury.gov.uk/Independent_Reviews/stern_review_economics_climate_change/sternreview_index.cfm.; Arrow, K. (2007), *op. cit.* Stiglitz, J. (2006) "A New Agenda for Global Warming," *The Economists' Voice*: Vol. 3 : Iss. 7, Article 3. Available at: http://www.bepress.com/ev/vol3/iss7/art3.

backwards. The T3 tax *is* an early-warning system, in that it is intrinsically forward-looking. Investors do not merely look at present-day prices and tax rates, they form expectations about future prices. Those who take the most accurate account of future changes will have the biggest advantage. Private sector climate models would therefore not be a ploy to avoid sound scientific predictions, but a means to sharpen the incentives to get the predictions right. But—and here is the rub for those who fancy themselves on the side of unprejudiced science—increased accuracy and objectivity in climate forecasts may or may not lead to an expectation of higher T3 rates. Perhaps the Green Party spokesman is uneasy with independent forecasts for this reason. Future levels of the T3 tax would ultimately be decided by the atmosphere, and that is exactly where the decision should be made.