

An Exchange on Climate Science and Alarm

Introduction

On October 21-22, 2005, the Yale Center for Globalization held a conference on “Global Climate Policy After 2012”. Speakers holding a variety of views addressed the conference, but, as usual, there was little time for actual debate. It was understood that the papers presented at the conference would be published, but, for reasons that I am not privy to, the publication was delayed for over two years¹. During this interval, papers were, apparently modified, and, in particular, the paper by Rahmstorf was turned into a specific attack on my paper. This would not have bothered me, per se. However, the changes were made without informing me, and no opportunity was offered me to defend myself. This is rather unusual – at least outside the topic of climate change. Under the circumstances, I am making available my paper, Rahmstorf’s paper, and my response. In point of fact, the combination of these three documents will, I hope, better convey the nature of the debate that exists on the matter of the science behind global warming alarm. As one will quickly realize, the debate is peculiar in that my paper was devoted to noting the disconnect between global warming, per se, and alarm, while Rahmstorf’s was largely devoted to global warming itself, a matter concerning which there is substantial agreement. The difference is already evident in the titles of the two papers. Mine was “Is Global Warming Alarm Founded on Fact?” while Rahmstorf’s was “Anthropogenic Climate Change: Revisiting the Facts.” Although, Rahmstorf specifically attacks my paper, his own does go beyond this to make many unjustifiable claims and arguments. I should add that time has not permitted me to fully address all the peculiar and unjustified claims in Rahmstorf’s paper. I mention this only because, I would not want the reader to assume that failure to mention constitutes assent.

Richard S. Lindzen
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¹ The book finally appeared as *Global Warming: Looking Beyond Kyoto*, edited by Ernesto Zedillo, and published by the Brookings Institution Press and the Center for the Study of Globalization at Yale. The papers by me and Rahmstorf form Chapters 2 and 3 respectively.

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Is the Global Warming Alarm Founded on Fact?

RICHARD S. LINDZEN

For the sensitive reader or listener, the language used in connection with the issue of “global warming” must frequently sound strange. Weather and climate catastrophes of all sorts are claimed to be the inevitable result of global warming, and global warming is uniquely associated with man’s activities. The reality of the threat of global warming is frequently attested to by reference to a scientific consensus. According to Tony Blair, “The overwhelming view of experts is that climate change, to a greater or lesser extent, is man-made and, without action, will get worse.”¹ Elizabeth Kolbert, in *The New Yorker*, says, “All that the theory of global warming says is that if you increase the concentration of greenhouse gases in the atmosphere, you will also increase the Earth’s average temperature. It is indisputable that we have increased greenhouse gas concentrations in the air as a result of human activity, and it’s also indisputable that over the last few decades average global temperatures have gone up.”²

Given the alarm surrounding the issue, such statements seem peculiarly inconclusive and irrelevant to the catastrophes cited. To be sure, these references are one-sided. They fail to note that there are many sources of climate change and that profound climate change has occurred many times both before and after man appeared on the Earth; given the ubiquity of climate change, it is implausible that all change is for the worse. Moreover, the coincidence of increasing carbon dioxide (CO₂) and the small warming over the past century hardly establishes causality. For the most part, I do not disagree with the consensus, but

I am disturbed by the absence of quantitative considerations. Indeed, I know of no serious split and suspect that the claim that there is opposition to this consensus amounts to no more than setting up a straw man to scoff at. However, I believe that people are being led astray by the suggestion that this agreement constitutes support for alarm.

Let me review the components that constitute this consensus a little more precisely, while recognizing that there is, indeed, some legitimate controversy connected with specific aspects of even these items.

1. The global mean surface temperature is always changing. Over the past sixty years, it has both decreased and increased. For the past century, it has probably increased by about $0.6^\circ \pm 0.15^\circ\text{C}$ (centigrade). That is to say, we have had some global mean warming.

2. CO_2 is a greenhouse gas, and its increase contributes to warming. It is, in fact, increasing, and a doubling would increase the greenhouse effect (mainly due to water vapor and clouds) by about 2 percent.

3. There is good evidence that man is responsible for the recent increase in CO_2 , although climate itself (as well as other natural phenomena) can also cause changes in CO_2 .

In some respects, these three pillars of consensus are relatively trivial. Remaining completely open is the question of whether there is any reason to consider these facts as particularly alarming. Is there any objective basis for considering the approximate 0.6°C increase in global mean surface temperature to be large or small regardless of its cause? The answer to both questions depends on whether 0.6°C is larger or smaller than what we might expect on the basis of models that have led to the present concern. These models are generally called general circulation models (GCMs). We may, therefore, seek to determine how the current level of man-made climate forcing compares with what we would have were CO_2 to be doubled (a common reference level for GCM calculations).

In terms of climate forcing, greenhouse gases added to the atmosphere through man's activities since the late nineteenth century have already produced three-quarters of the radiative forcing that we expect from a doubling of CO_2 .³ There are two main reasons for this. First, CO_2 is not the only anthropogenic greenhouse gas. Others like methane also contribute. Second, the impact of CO_2 is nonlinear in the sense that each added unit contributes less than its predecessor. For example, if doubling CO_2 from its value in the late nineteenth century—from about 290 parts per million by volume (ppmv) to 580 ppmv—causes a 2 percent increase in radiative forcing,⁴ then to obtain another 2 percent increase in radiative forcing we must increase CO_2 by an additional 580 ppmv rather than by another 290 ppmv. At present, the concentration of CO_2 is about 380 ppmv. The easiest way to understand this is to consider adding thin layers of paint to a pane of glass. The first layer cuts out much of the light, the next layer cuts out more, but subsequent layers do less and less because the painted pane is already essentially opaque.

It should be stressed that we are interested in climate forcing and not simply levels of CO₂; the two are most certainly not linearly proportional.

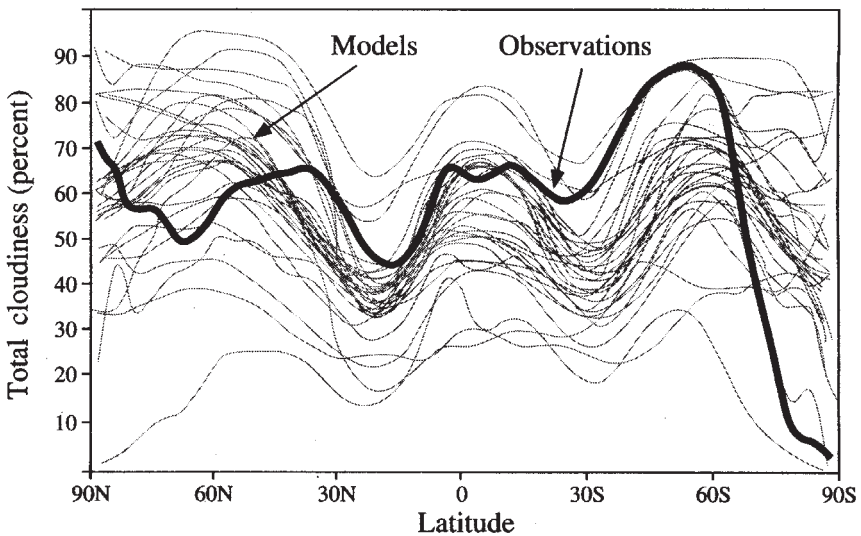
Essential to alarm is the fact that most current climate models predict a response to a doubling of CO₂ of about 4°C (which is much larger than what one expects the simple doubling of CO₂ to produce: that is, about 1°C). The reason for this is that, in these models, the most important greenhouse substances—water vapor and clouds—act in such a way as to amplify the response to anthropogenic greenhouse gases alone (that is, they act as what are called large positive feedbacks). However, as all assessments of the Intergovernmental Panel on Climate Change (IPCC) have stated (at least in the main text, although not in the various summaries for policymakers), the models simply fail to get clouds right. We know this because in official comparisons all models fail miserably to replicate observed distributions of cloud cover. Thus the model predictions are critically dependent on features that we know must be wrong. As shown in figure 2-1, the treatment of clouds involves errors an order of magnitude greater than the forcing from a doubling of CO₂.⁵ While the IPCC allows for the possibility that the models get water vapor right, the intimate relation between water vapor and clouds makes such a conclusion implausible.

Fig 1

Let me summarize the main points thus far:

—It is *not* the level of CO₂ that is important, but rather the impact of man-made greenhouse gases on climate.

Figure 2-1. *Observed and Modeled Percentage Cloud Cover Averaged by Latitude^a*



a. Each thin gray line shows an individual model's hindcast of percentage cloud cover averaged by latitude. The black line shows the observed cloud cover.

—Although we are far from the benchmark of doubled CO₂, climate forcing is already about three-fourths of what we expect from such a doubling.

—Even if we attribute all warming over the past century to man-made greenhouse gases (which we have no basis for doing), the observed warming is only about a third to a sixth of what models project.

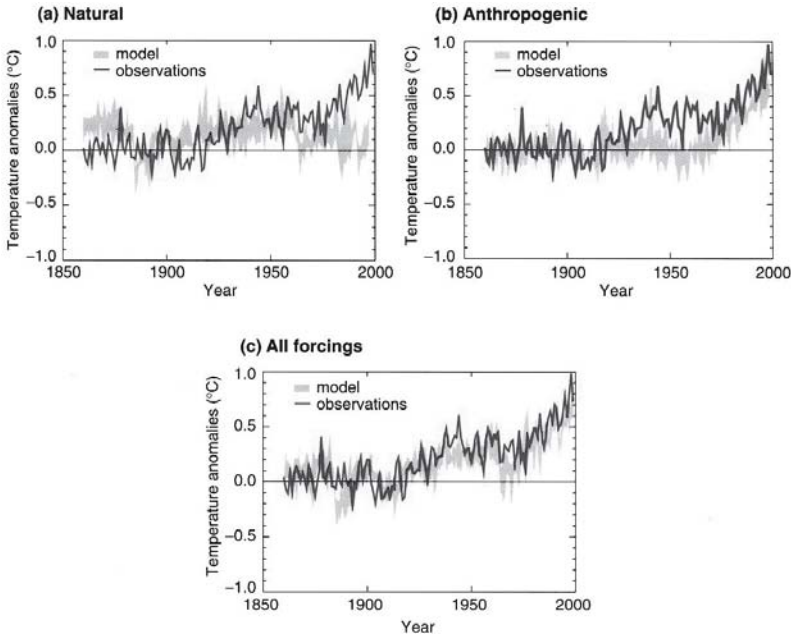
This raises two possibilities: either the models are greatly overestimating the sensitivity of climate to man-made greenhouse gases, or the models are correct, but some unknown process has canceled most of the warming. Calling the unknown process “aerosols” does not change this statement, since aerosols and their impact are unknown to a factor of ten or more; indeed, even the sign is in doubt.

In arguing for climate alarmism, we are choosing the second possibility. Moreover, we are assuming that the unknown cancellation will soon cease. What supports the second possibility, given that it involves so many more assumptions than the first possibility?

The IPCC Third Assessment Report made use of a peculiar exercise in curve fitting using results from the Hadley Centre for Climate Change. It consists of three plots, which are reproduced in figure 2-2. The first panel shows an observed temperature record (without error bars) and the outputs of four model

Fig 2

Figure 2-2. *Simulations of Global Mean Temperature with Various Combinations of “Forcing”*



runs (using the coupled ocean-atmosphere model) with so-called natural forcing for the period 1860–2000. There is a small spread in the model runs (which presumably displays model uncertainty; it most assuredly does not represent natural internal variability). In any event, the models look roughly like the observations until the last thirty years. A second diagram reproduces the observed curve, and the four models are run with anthropogenic forcing. Here there is rough agreement over the last thirty years and less agreement in the earlier period. Finally, the observations and the model runs with both natural and anthropogenic forcing are presented, showing rough agreement over the whole record. The models used have relatively low sensitivity to a doubling of CO₂ of about 2.5°C.

In order to know what to make of this exercise, one must know exactly what was done. The natural forcing consisted of volcanoes and solar variability. Prior to the Pinatubo eruption in 1991, the radiative impact of volcanoes was not well measured, and estimates vary by about a factor of three. Solar forcing is essentially unknown. Thus natural forcing is, in essence, adjustable. Anthropogenic forcing includes not only anthropogenic greenhouse gases, but also aerosols that act to cancel warming (in the Hadley Centre outputs, aerosols and other factors canceled two-thirds of the greenhouse forcing). Unfortunately, the properties of aerosols are largely unknown. In the present instance, therefore, aerosols constitute simply another adjustable parameter (indeed, both the magnitude and the time history are adjustable, and even the sign is in question). This is remarked upon in a recent paper in *Science*,⁶ which notes that the uncertainty is so great that estimating aerosol properties by tuning them to optimize agreement between models and observations (referred to as an inverse method) is probably as good as any other method, but that the use of such estimates to test the models constitutes a circular procedure. This is as strong a criticism of model procedures as is likely to be found in *Science*. The authors are all prominent in aerosol work. The first author is the most junior, and when it was pointed out that the article reflects negatively on model outputs, he vehemently denied any such intent. In the present example, the choice of models with relatively low sensitivity allows adjustments that are not so extreme.

New uncertainties are always entering the aerosol picture. Some are quite bizarre. A recent article in *Science* proposed that airborne dandruff has a significant role.⁷ Other articles suggest that the primary impact of aerosols is actually warming.⁸ Of course, this is the beauty of the global warming issue for many scientists. The issue deals with such small climate forcing and small temperature changes that it permits scientists to argue that everything and anything is important for climate.

In brief, the defense of the models starts by assuming that the model is correct. Then differences between the model behavior in the absence of external forcing and observed changes in “global mean temperature” are attributed to

external forcing. Next “natural” forcing is introduced, and a “best fit” to the observations is obtained. If, finally, it is possible to remove any remaining discrepancies by introducing “anthropogenic” forcing, part of the observed change must be attributable to the greenhouse component of “anthropogenic” forcing.

Of course, the internal variability of the model is not correct, and “anthropogenic” forcing includes not only CO₂ but also aerosols, which are unknown to a factor of ten to twenty (and perhaps even the sign is unknown). Finally, there is little quantitative knowledge of “natural” forcing, so this too is adjustable. Recall that the Hadley Centre acknowledges that the “aerosols” have canceled most of the forcing from CO₂.

The argument just presented is the basis for all popular and scientific claims that man is responsible for much of the observed warming. It would appear that the current role of the scientist in the global warming issue is simply to defend the possibility of ominous predictions so as to justify his belief.

To be fair, the authors of chapter 12 of the *Scientific Assessment of Climate Change*, a volume of the IPCC Third Assessment Report, provided the following for the draft statement of the Summary for Policymakers:

From the body of evidence since IPCC (1996), we conclude that there has been a discernible human influence on global climate. Studies are beginning to separate the contributions to observed climate change attributable to individual external influences, both anthropogenic and natural. This work suggests that anthropogenic greenhouse gases are a substantial contributor to the observed warming, especially over the past thirty years. However, the accuracy of these estimates continues to be limited by uncertainties in estimates of internal variability, natural and anthropogenic forcing, and the climate response to external forcing.

This statement is not too bad, especially the last sentence. To be sure, it does not emphasize the dependence of the results on the model, but the statement is vastly more honest than what the Summary for Policymakers in the IPCC’s Third Assessment Report ultimately presented:

In the light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last fifty years is likely to have been due to the increase in greenhouse gas concentrations.

In point of fact, the impact of man remains indiscernible simply because the signal is too small compared to the natural noise. Claims that the current temperatures are “record breaking” or “unprecedented,” however questionable or misleading, obscure the fact that the observed warming is too small compared to what models suggest. Even the fact that the oceans’ heat uptake capacity leads to

a delay in the response of the surface does not alter this conclusion (especially since the Hadley Centre results are obtained with a coupled model).

Moreover, the fact that we already have three-quarters of the climate forcing expected from a doubling of CO₂ means that if one truly believes the models, then we have long since passed the point where mitigation is a viable strategy. What remains is to maximize our ability to adapt. However, the promotion of alarm does not follow from the science, as is clearly illustrated by the following example.

According to any textbook on dynamic meteorology, one may reasonably conclude that in a warmer world, extratropical storminess and weather variability will decrease. The reasoning is as follows. Judging by historical climate change, changes are greater in high latitudes than in the tropics. Thus in a warmer world, we would expect the temperature difference between high and low latitudes to diminish. However, it is precisely this difference that gives rise to extratropical large-scale weather disturbances. Moreover, when a winter day in Boston is unusually warm, the wind is blowing from the south. Similarly, when the day is unusually cold, the wind is generally blowing from the north. The possible extent of these extremes is determined by how warm low latitudes are and how cold high latitudes are. Given that we expect high latitudes to warm much more than low latitudes in a warmer climate, the difference is expected to diminish, leading to less variance.

Nevertheless, advocates and the media tell us that exactly the opposite is the case: that the models predict this (which, to their credit, they do not) and that the basic agreement discussed earlier signifies scientific agreement on this matter as well. Clearly more storms and greater extremes are regarded as more alarming than not. Thus the opposite of our current understanding is invoked in order to promote public concern. The crucial point here is that once the principle of consensus is accepted, agreement on anything is taken to infer agreement on everything.

The example given focuses on extratropical storms. However, given the relatively heavy hurricane season we have had recently, the emphasis has been on tropical storms. Political activists have seized on recent papers suggesting that, in a warmer world, such storms may become more powerful.⁹ Needless to say, the articles seized upon have been extremely controversial, but more to the point, no such relation was uncovered for storms reaching land—only for those over water.

At this point, it is doubtful that we are even dealing with a serious problem. If this is correct, then no policy addressing this non-problem would be cost-effective. Even if we believe the problem to be serious, we have already reached the levels of climate forcing that have been claimed to be serious. However, when it comes to the Kyoto Protocol, the situation is even worse. Here, there is widespread and even rigorous scientific agreement that complete adherence to the Kyoto Protocol would have no discernible impact on climate.

What about the first possibility—namely, that the models are much too sensitive? Not only is this the possibility that scientists would normally prefer on the basis of Occam’s famous razor, but it is also a possibility for which there is substantial support.¹⁰ I focus here on one line of this evidence: tropical warming in the 1990s was associated with much greater outgoing long-wave radiation than models produce. This discrepancy suggests that current models lack a strong negative feedback.

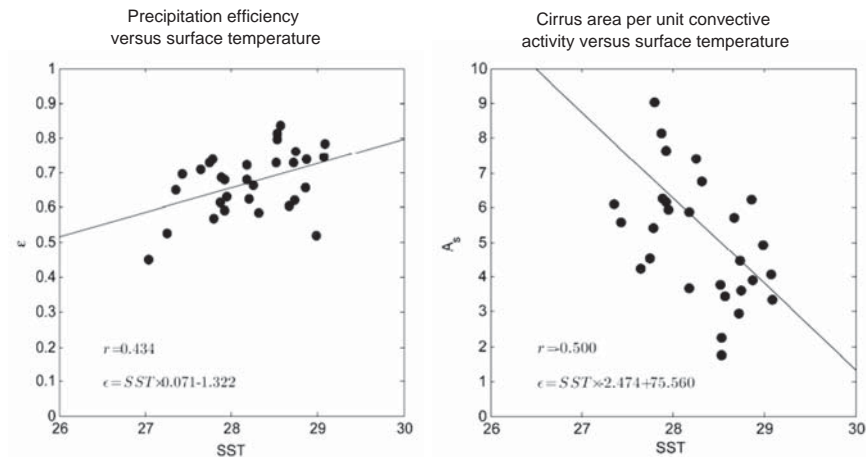
The discrepancy has been confirmed by at least four independent groups: the National Aeronautics and Space Agency’s (NASA’s) Goddard Institute for Space Studies; NASA Langley; State University New York, Stony Brook; and the University of Miami.¹¹

This discrepancy would normally suggest exaggerated model sensitivity. However, the papers attribute it either to circulation changes or to “unknown” cloud properties, except for the paper by Clement and Soden. Using four separate models, they show that changes in dynamics could not produce changes averaged over the tropics. Chou and Lindzen show the discrepancy theoretically, while Clement and Soden show that the discrepancy could be resolved by allowing convective precipitation efficiency to increase with surface temperature.¹² Such dependence is at the heart of the iris effect, which was first found by Lindzen, Chou, and Hou and was theoretically predicted by Sun and Lindzen.¹³ In the first paper, we attempt to examine how tropical clouds respond to changing surface temperature and find that existing satellite data are only marginally capable of dealing with this issue. The results, however, suggest that there are strong negative feedbacks, counter to what models suggest, and that the models in no way replicate the cloud behavior that is observed.

It may turn out that precipitation can be measured rigorously using ground-based radar. Ground-based radar allows the almost continuous measurement of precipitation and the separation of convective precipitation from stratiform precipitation (albeit with remaining questions of accuracy). In the tropics, both types of precipitation originate in condensation within cumulus towers. However, condensation that does not form precipitation is carried aloft as ice, which is detrained to form cirrus from which the condensate eventually falls as stratiform precipitation. Precipitation efficiency is given by the following relation: $e = (\text{convective precipitation}) / (\text{convective precipitation} + \text{stratiform precipitation})$. Using data from Kwajalein Atoll in the western Pacific, we have studied how e varies with sea surface temperature. In addition, the Kwajalein radar makes it possible to look explicitly at the area of stratiform rain per unit of convective mass flux.

Fig 3 Figure 2-3 shows that e increases about 7.1 percent per degree centigrade increase in sea surface temperature (compared with 7.5 percent estimated by Sun and Lindzen in 1993) and that this increase is associated with a decrease in normalized stratiform area of about 25 percent per degree centigrade (which is a bit

Figure 2-3. *Precipitation Efficiency and Cirrus Area per Unit of Convective Activity versus Sea Surface Temperature*



larger than what was estimated from space observations by Lindzen, Chou, and Hou in 2001).¹⁴ If correct, this confirms the iris effect and the fact that models have greatly exaggerated climate sensitivity because, in contrast to models, nature itself acts to limit rather than exaggerate the influence of added greenhouse gases.

What do these simple results imply? The primary implication is that for more than twenty-five years we have based not only our worst-case scenarios but even our best-case scenarios on model exaggeration. This was suggested by previous results, but the present result has the virtue of specifically identifying a basic and crucially relevant error. Under the circumstances, the main question we will be confronting is how long the momentum generated by this issue will prevent us from seeing that it has been an illusion based on model error.

The public discourse on global warming has little in common with the standards of scientific discourse. Rather, it is part of political discourse, where comments are made to secure the political base and frighten the opposition, not illuminate issues. In political discourse, information is to be “spun” to reinforce preexisting beliefs and to discourage opposition. The chief example of the latter is the claim of universal scientific agreement. This claim was part of the media treatment of global cooling (in the 1970s) and has been part of the treatment of global warming since 1988 (well before most climate change institutes were created). The consensus preceded the research.

The fact that media discourse on climate change is political rather than scientific should come as no surprise. However, even scientific literature and institutions have become politicized. Some scientists issue meaningless remarks in what I believe to be the full expectation that the media and the environmental movement will provide the “spin.” Since the societal response to alarm has, so far,

been to generate scientific funding, there has been little reason for scientists to complain. Should scientists feel any guilt, it is assuaged by two irresistible factors: the advocates define public virtue, and administrators are delighted with the growing grant overhead. The situation has been recognized since time immemorial. In Federalist Paper no. 79, Alexander Hamilton brooded about abuses that might arise from legislative tampering with judges' salaries. "In the general course of human nature," he wrote, "a power over a man's subsistence amounts to a power over his will." An indication of such an attitude occurred when, in 2003, the draft of the U.S. National Climate Plan urged giving high priority to improving our knowledge of climate sensitivity (that is, in finding the answer). A National Research Council review panel instead urged giving broader support for numerous groups to study the impacts of warming. The panel apparently was more interested in spreading the wealth than in finding an answer.

A second aspect of politicization of discourse specifically involves scientific literature. Articles challenging the urgent need to address anthropogenic greenhouse gases are met with unusually quick rebuttals. These rebuttals are usually published as independent papers rather than as correspondence concerning the original articles, the latter being the usual practice. When the usual practice is followed, then the response of the original author(s) is published side by side with the critique. However, in the present situation, such responses are delayed by as much as a year. In my experience, criticisms do not reflect a good understanding of the original work. When the original authors' responses finally appear, they are accompanied by another rebuttal that generally ignores the responses but repeats the criticism. This process clearly is not conducive to scientific progress, but it is not clear that progress is what is desired. Rather, the mere existence of criticism entitles the environmental press to refer to the original result as "discredited," while the long delay of the response by the original authors permits these responses to be totally ignored.

A final aspect of politicization is the explicit intimidation of scientists. Intimidation has mostly, but not exclusively, been used against those questioning alarmism. Victims of such intimidation generally remain silent. Congressional hearings have been used to pressure scientists who question the "consensus." These scientists are pitted against carefully selected opponents. The clear intent is to discredit the "skeptical" scientist from whom a "recantation" is sought.

Advocates frequently attempt to use the news media as an instrument for this intimidation. A notable example in the early 1990s was when Ted Koppel announced on *Nightline* that Vice President Al Gore had asked him to find connections between unsavory interests and scientists questioning global warming alarm. After editorializing on the inappropriateness of the request, Koppel proceeded to present a balanced exposure of the debate. Newspaper and magazine articles routinely proclaim that scientists who differ with the consensus view are stooges of the fossil fuel industry. All of this would be bad enough, but the real

source of intimidation is the fact that neither the American Meteorological Society nor the American Geophysical Society sees fit to object to any of this.

These are not isolated examples. Before 1991, some of Europe's most prominent climate experts were voicing significant doubts about climate alarm. The issue has always concerned the basis for alarm rather than the presence of warming (however small). Only the most cynical propagandist could have anticipated that sentient human beings could be driven into panic by the mere existence of some warming. In any event, among these questioners were such distinguished individuals as Sir John Mason, former head of the U.K. Meteorological Office and secretary of the Royal Society; Professor Hubert Lamb, Europe's foremost climatologist and founder of the Climate Research Unit at East Anglia University; Dr. Henk Tennekes, director of research at the Royal Dutch Meteorological Institute; and Dr. Aksel Wiin-Nielsen, professor at the University of Copenhagen, former director of the European Centre for Medium Range Weather Forecasting, and former secretary general of the World Meteorological Organization. All of these figures except Tennekes have disappeared from the public discourse. Lamb is now dead. Tennekes was dismissed from his position, and Wiin-Nielsen was tarred by Bert Bolin (the first head of the IPCC) as a tool of the coal industry. In Russia a number of internationally recognized pioneers of climate science like Kiril Kondratyev (who died in 2006) and Yuri Izrael continue to oppose climate alarm, but Russian scientists eager for connections with the rest of Europe are much more reluctant to express such views.

Not all such situations have ended badly. When a senior Energy Department official, William Happer, was dismissed in 1993 after questioning the scientific basis for global warming, the physics community was generally supportive and sympathetic.¹⁵ In another more bizarre case, an attempt was made to remove the name of Roger Revelle from an already published paper he coauthored with S. Fred Singer and Chauncy Starr, by claiming that Singer had cajoled an allegedly senile Roger Revelle into permitting himself to be so used. This paper discouraged hasty action on ill-understood warming. It should be noted that Revelle was the professor whom Al Gore frequently cites as having introduced him to the horrors of global warming. In any event, Singer took the issue to court and won. His description of the case makes interesting reading.¹⁶

More recent is a controversy over a thousand-year reconstruction of mean temperature purporting to show that the half degree (centigrade) rise of the past century was unprecedented.¹⁷ Because of the extensive use of this work in the politics of global warming, Representative Joe Barton demanded the analytical detail since the research was supported by U.S. funds. Both the American Meteorological Society and the American Geophysical Union protested Barton's request. One need not go into the merits of this controversy to see that the response of professional organizations sends a chilling message. Only the defenders of the orthodoxy will be defended against intimidation.

The *basic agreement* frequently described as representing a global warming “consensus” is entirely consistent with there being virtually no problem. Actual observations suggest that the sensitivity of the real climate is much less than found in computer models whose sensitivity depends on processes that are clearly misrepresented. Attempts to assess climate sensitivity by direct observation of cloud processes, and other means, point to a conclusion that doubling of CO₂ would lead to about 0.5°C warming or less.

Unfortunately, a significant part of the scientific community appears committed to the notion that alarm *may* be warranted. Alarm is felt to be essential to the maintenance of funding. The argument is no longer over whether the models are correct (they are not), but rather *whether their results are at all possible*. It is impossible to prove that something is impossible. The global warming issue parts company with normative science at an early stage. A good indicator of this disconnect is widespread and rigorous scientific agreement that the Kyoto Protocol would have no discernible impact on climate. This clearly is of no importance to the thousands of negotiators, diplomats, regulators, general-purpose bureaucrats, and advocates whose livelihood is tied to climate alarmism.

A rarely asked, but important, question is whether promoting alarmism is good for science. The situation may not be so remote from the impact of Lysenkoism on Soviet genetics. However, I believe that the future will view the response of contemporary society to “global warming” as simply another example of the appropriateness of the fable of the “Emperor’s New Clothes.” For the sake of the science, I hope that future arrives soon. In the meantime, we can continue to play our parts in this modern version of the fable. Our descendents will be amused for generations to come.

Notes

1. *The Economist*, December 24, 2004.
2. Elizabeth Kolbert, “The Climate of Man: I.” *The New Yorker*, April 25, 2005, p. 56.
3. Gunnar Myhre and others, “New Estimates of Radiative Forcing due to Well-Mixed Greenhouse Gases,” *Geophysical Research Letters* 25, no. 14 (1998): 2715–18; James Hansen and Makiko Sato, “Greenhouse Gas Growth Rates,” *Proceedings of the National Academy of Sciences* 101, no. 46 (2004): 16109–14.
4. The term “forcing” refers to the imbalance in radiative energy flux that would be produced by the addition of greenhouse gases. Such forcing is generally described either as a percentage increase in the greenhouse effect or as a flux with units of Watts per square meter. Such a flux acts to warm the Earth.
5. W. Lawrence Gates and others, “An Overview of the Atmospheric Model Intercomparison Project (AMIP I),” *Bulletin of the American Meteorological Society* 80, no. 1 (1999): 29–55.
6. Theodore L. Anderson and others, “Climate Forcing by Aerosols: A Hazy Picture,” *Science* 300, no. 5622 (2003): 1103–04.
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8. Mark Z. Jacobson, "Strong Radiative Heating due to the Mixing State of Black Carbon in Atmospheric Aerosols," *Nature* 409, no. 6821 (February 8, 2001): 695–97. Yang Chen and Joyce E. Penner, "Uncertainty Analysis for Estimates of the First Indirect Aerosol Effect," *Atmospheric Chemistry and Physics* 5, no. 11 (2005): 2935–48.
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11. Junye Chen, Barbara E. Carlson, and Anthony D. Del Genio, "Evidence for Strengthening of the Tropical General Circulation in the 1990s," *Science* 295, no. 295 (2002): 838–41; Anthony D. Del Genio and William Kovari, "Climatic Properties of Tropical Precipitating Convection under Varying Environmental Conditions," *Journal of Climate* 15, no. 18 (2002): 2597–615. Bruce A. Wielicki and others, "Evidence for Large Decadal Variability in the Tropical Mean Radiative Energy Budget," *Science* 295, no. 5556 (2002): 841–44; Bing Lin and others, "Examination of the Decadal Tropical Mean ERBS Nonscanner Radiation Data for the Iris Hypothesis," *Journal of Climate* 17, no. 6 (2004): 1239–46. Robert D. Cess and Petra M. Udelhofen, "Climate Change during 1985–1999: Cloud Interactions Determined from Satellite Measurements," *Geophysical Research Letters* 30, no. 1 (2003): 1019. Amy C. Clement and Brian J. Soden, "The Sensitivity of the Tropical-Mean Radiation Budget," *Journal of Climate* 18, no. 6 (2005): 3189–203.
12. Ming-Dah Chou and Richard S. Lindzen, "Comments on 'Examination of the Decadal Tropical Mean ERBS Nonscanner Radiation Data for the Iris Hypothesis,'" *Journal of Climate* 18, no. 12 (2004): 2123–27. Clement and Soden, "Sensitivity of the Tropical-Mean Radiation Budget."
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14. Sun and Lindzen, "Distribution of Tropical Tropospheric Water Vapor"; Lindzen, Chou, and Hou, "Does the Earth Have an Adaptive Infrared Iris?"
15. This situation is described in William Happer, "Harmful Politicization of Science," In *Politicizing Science: The Alchemy of Policymaking*, edited by Michael Gough (Hoover Institution Press, 2003).
16. S. Fred Singer, "The Revelle-Gore Story: Attempted Political Suppression of Science," in *Politicizing Science*, edited by M. Gough (Hoover Institution Press, 2003).
17. Michael E. Mann, Raymond S. Bradley, and Malcolm K. Hughes, "Northern Hemisphere Temperatures during the Past Millennium: Inferences, Uncertainties, and Limitations," *Geophysical Research Letters* 26, no. 6 (1999): 759–62.

3

Anthropogenic Climate Change: Revisiting the Facts

STEFAN RAHMSTORF

The idea that humans *can* change and *are* in fact changing the climate of our planet has developed gradually over more than a hundred years. A fringe idea in the nineteenth and early twentieth centuries,¹ it is close to a well-established scientific consensus at the turn of the twenty-first century.² The history of this development is grippingly told in a small book, *The Discovery of Global Warming*, by science historian Spencer Weart.³ During the course of this history, the initially outlandish concept of human-caused global warming has won over practically every skeptical climatologist who has cared to look dispassionately at the evidence. But with new developments in the field almost every year—for example, the growing understanding of abrupt climate changes, the record-breaking hurricane season of 2005, or the renewed concerns about the stability of the ice sheets—the “basics” are seldom discussed any more. Few people besides climatologists themselves, even in the climate policy community, could easily recount the main cornerstones of scientific evidence on which the case for anthropogenic warming rests. The goal of this paper is to do just that: to revisit the basic evidence for anthropogenic global warming.

The Meaning of “Anthropogenic Climate Change”

To start, we need to clarify what we mean by “anthropogenic climate change.” It is useful to distinguish two different meanings of the term, since they are

often confounded. The first one, let us call it statement A, can be summed up as follows: *anthropogenic emissions of greenhouse gases will lead to significant global warming*. This is a statement about the future. It is reflected, for example, in the well-known range of future scenarios of the 2001 Intergovernmental Panel on Climate Change (IPCC) report, which concluded that, in the absence of effective climate policies, we must expect a warming of between 1.4 and 5.8°C (centigrade) between the years 1990 and 2100.⁴

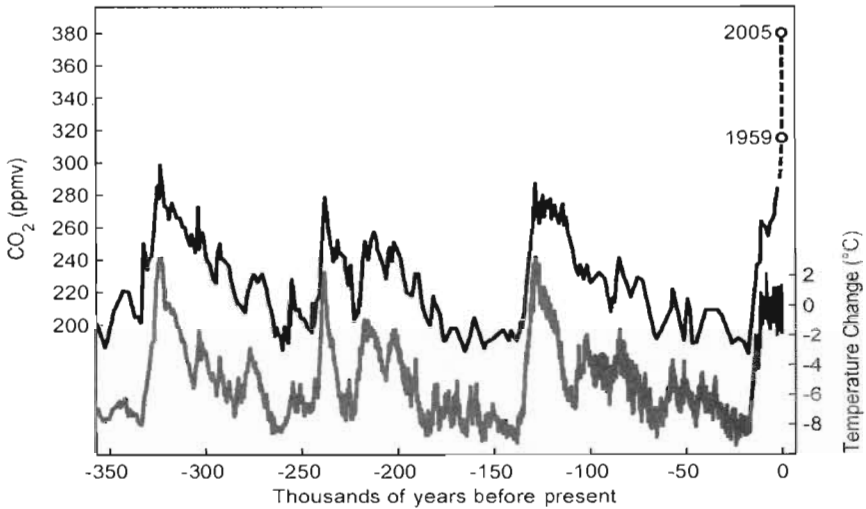
The second meaning, let us call it statement B, can be phrased thus: *human activities already have noticeably changed global climate*. This is a statement about the past and about what we can observe now. It is reflected in the famous IPCC statement of 1996: “The balance of evidence suggests that there is a discernible human influence on global climate.”⁵ It is reinforced considerably in the light of new evidence in the 2001 report: “There is new and stronger evidence that most of the warming observed over the last fifty years is attributable to human activities.”⁶

Only statement A is relevant to policy, because no current or planned policy can affect the past. Such policies are shaped by our expectations for the future. It is important to realize that statement A is not conditional on statement B. Thus, even if too much natural variability was masking any anthropogenic trend or if the quality of the data that we have simply was not good enough to detect any human influence on climate so far, we could (and would) still come to conclusion A. Nevertheless, both statement A and statement B are supported very strongly by the available evidence.

Discussions about climate change in the popular media suggest that many people are misled by fallacious logic, for example, “If the Middle Ages were warmer than temperatures today, then recent warming is perfectly natural (this questions statement B), and we do not need to worry about the effect of our emissions (this questions statement A).” Both these conclusions are, of course, non sequiturs, quite apart from the fact that their premise (warmer Middle Ages) is not supported by the data.

The Carbon Dioxide Effect on Climate

What evidence do we have for statement A—that anthropogenic emissions will lead to significant global warming? I break this into three parts. First, *the carbon dioxide (CO₂) concentration is rising*. This is proven by direct measurement in the atmosphere since the 1950s, set forth as the famous Keeling curve, and it is undisputed.⁷ Current CO₂ data from the Global CO₂ Monitoring Network are made available by the Cooperative Air Sampling Network.⁸ Ice core data, which provide a reliable and accurate record of CO₂ concentration going back hundreds of thousands of years, show further that this rise is, in fact, very unusual.⁹

Figure 3-1. *Climate History of the Past 350,000 Years^a*

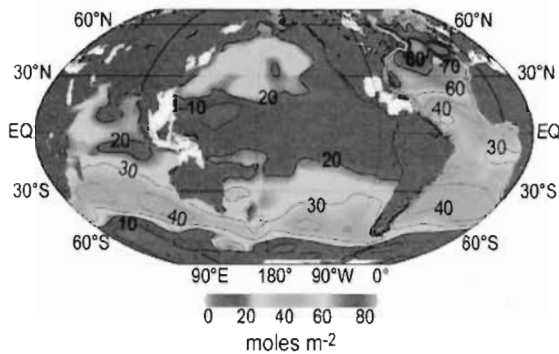
Source: J. R. Petit and others, "Climate and Atmospheric History of the Past 420,000 Years from the Vostok Ice Core, Antarctica," *Nature* 399 (June 1999): 429–36.

a. Based on Vostok ice core in Antarctica. These ice core data end before the onset of anthropogenic changes. Anthropogenic emissions have now increased the CO₂ concentration to 380 ppm (as of 2005).

For at least 650,000 years and probably ever since humans walked the Earth, the carbon dioxide concentration in the atmosphere was never even close to as high as it is at present, as shown in figure 3-1. Current CO₂ concentration has risen above 380 parts per million (ppm), while the preindustrial level back throughout the Holocene (the past 10,000 years) was close to 280 ppm. Similar values apply for previous interglacial periods.

We now come to the second part: *the recent rise in CO₂ is entirely anthropogenic*. This is also undisputed. We have tracked and we know how much fossil fuel has been burned and therefore how much CO₂ we have injected directly into the atmosphere. The observed increase in CO₂ concentration over the past decades is equal to 57 percent of our cumulative emissions. Other parts of the climate system—the ocean and the land biosphere—have absorbed the remaining 43 percent of emissions from the atmosphere. For the ocean, this is documented by around 10,000 oceanographic measurements, which show that the ocean has taken up about 2 gigatons (Gt) of carbon per year, or 30 percent of anthropogenic emissions (see figure 3-2).¹⁰ This CO₂ uptake of the ocean makes the sea water more acidic and threatens marine life, which in itself is sufficient reason to reduce our carbon dioxide emissions significantly, even in the absence of climate change.¹¹

Many other pieces of evidence corroborate the fact that the rise in CO₂ is anthropogenic: the isotope composition, the corresponding decline in

Figure 3-2. *Column Inventory of Anthropogenic CO₂ in the Ocean*

Source: Christopher L. Sabine, "Oceanic Sink for Anthropogenic CO₂," *Science* 305, no. 5682 (2004): 367–71. Ocean measurements are from Hans E. Suess, "Radiocarbon Concentration in Modern Wood," *Science* 122, no. 3166 (1955): 415–17.

atmospheric oxygen as carbon is burned, or the hemispheric gradient in CO₂ concentration.¹²

The third part is the following: *carbon dioxide is a greenhouse gas; doubling its concentration will warm global climate in equilibrium by 3°C ± 1.5°C.* That carbon dioxide acts as a greenhouse gas is hardly a new insight. It is by now well-established nineteenth-century physics. The crucial question is, just how strong is the effect of an increase in CO₂ on climate? This is the only component of statement A about which there can still be legitimate scientific debate, as all the other parts are proven beyond reasonable doubt. So let us spend some time on it.

Swedish Nobel Prize winner Svante Arrhenius made the first estimate in 1896, when he determined a 4–6°C warming for a doubling of atmospheric CO₂.¹³ This number is called "climate sensitivity." It is defined simply as the global mean warming that is reached in equilibrium (that is, after a long time) after doubling the CO₂ concentration in the atmosphere. Strictly speaking, this refers to a doubling from its preindustrial value of 280 ppm to 560 ppm. This is seldom mentioned because the radiative forcing increases with the logarithm of CO₂ concentration due to the near-saturation of the CO₂ absorption bands. This means that a doubling of CO₂ from a different value (say, from the present value or from 560 ppm) gives the same forcing as a doubling from 280 ppm. But the response of the climate system, of course, could differ somewhat for different initial states, which is why "doubling from 280 ppm" should be included in any exact definition.

This climate sensitivity cannot be related directly to the actual warming at a particular time, because the climate system has the capacity to store heat and therefore lags in its response. The warming at a particular time therefore depends on the time history of past CO₂ (and other forcing) changes, not just

on the CO₂ concentration at that point in time. But the climate sensitivity is nevertheless a simple and very useful measure of the strength of the CO₂ effect on climate, because it is a property that characterizes a model (or the real climate system) alone, independent of any particular scenario. Today, there are various independent ways of estimating climate sensitivity, and a great deal of effort is spent on this issue.

One method consists of using radiative forcing (that is, the change in radiation budget in watts per square meter, W/m²), combined with information on the strength of physical feedbacks, to compute the expected temperature change. That is what Arrhenius did with pencil and paper; today, detailed calculations employing computer models are used in order to account for all the feedbacks. Without any feedbacks, a doubling of CO₂ (which amounts to a forcing of 3.7 W/m²) would result in 1°C global warming, which is easy to calculate and is undisputed.¹⁴

The remaining uncertainty is due entirely to feedbacks in the system, namely, the water vapor feedback, the ice-albedo feedback, the cloud feedback, and the lapse rate feedback.¹⁵ The water vapor feedback, for example, amplifies climate warming, because in a warmer climate the atmosphere contains more water vapor, which then acts as a greenhouse gas. While these feedbacks are understood in principle, there is still uncertainty about their exact magnitude, particularly that of the cloud feedback. However, we possess good information about the operation of these feedbacks, gathered from observations of natural variability, including the daily weather variations and the seasonal cycle. These variations are used to measure, for example, how vapor concentration, lapse rate, or cloud properties change with temperature. In many regions of our planet these variations cover a much larger range than is expected for the amplitude of future climate change (in some places, the seasonal cycle exceeds 40°C in amplitude). Getting the seasonal cycle right is therefore a crucial validation test for any climate model, and special observational programs are under way to measure cloud properties in different climatic regions of the world in order to narrow down uncertainties in cloud behavior.

The very first climate model calculations in the 1970s showed climate sensitivities of 2°C and 4°C. When the National Academy of Sciences in 1979 issued its first warning of an approaching global warming as a result of increased CO₂ emissions, it cited an uncertainty range of 1.5 to 4.5°C for climate sensitivity based on those early model results.¹⁶ At that time, this range was on very shaky ground. Since then, many vastly improved models have been developed by a number of climate research centers around the world. Current state-of-the-art climate models span a range of 2.6–4.1°C, most clustering around 3°C. (The claim by Lindzen, in this volume, that “most current climate models predict a response to a doubling of CO₂ of about 4°C” is incorrect.)

Another way to estimate climate sensitivity is by looking at data from past variations of CO₂ and climate. How strongly climate was affected by CO₂ varia-

tions of the past can be estimated from data using correlation analysis. This has been done for the Vostok ice core data for variations over an ice age cycle. Of course, CO₂ is not the primary cause of an ice age, but it provides a feedback in this case. One needs to be very careful to account for all factors, including the presence of large continental ice sheets, methane variations, and atmospheric dust variations. Those data can be obtained from the ice core. The French scientists of the Vostok team that drilled the core performed such a correlation analysis and arrived at 3–4°C for climate sensitivity.¹⁷ That is an estimate made solely on the basis of data.

A third, relatively new approach to estimating climate sensitivity, made possible by the growing power of computing technology, is to study the systematic variation of uncertain parameters in models. This includes, for example, parameters in the equations used to calculate cloud behavior. In this way, many different versions of a climate model are produced, typically up to a thousand versions, in which clouds or other components respond in different ways, to cover the range of current uncertainty in our knowledge. All these models are then checked against observational data, which are used to separate the wheat from the chaff. It is possible to create models with widely differing climate sensitivities—even as high as 11°C—but which of all these versions can stand up to a good reality check? Most of these model versions already fail to reproduce properly the present-day climate and its seasonal cycle. But an even tougher data constraint is one that tests for the response to large CO₂ changes. The two major CO₂ changes in recent climate history are the anthropogenic increase from 280 to 380 ppm since the preindustrial era and the increase from 180 to 280 ppm between the last Ice Age and the Holocene. Both of these have been used to constrain model ensembles to derive climate sensitivity.

The first such studies used twentieth-century data.¹⁸ These provided a good constraint on the lower limit of climate sensitivity, consistent with the original 1.5°C estimate of the National Academy of Sciences. But they also revealed a problem with the constraint of the upper limit of sensitivity. It could not be ruled out on the basis of these data that climate sensitivity could be much higher than 4.5°C. The prime reason for this is the uncertainty in the magnitude of the cooling effect of anthropogenic aerosols (smog particles that reflect sunlight) over the twentieth century. If this cooling effect is large and has canceled a substantial part of the CO₂ warming, then even a very high sensitivity to CO₂ would still be compatible with the observed global temperature rise.

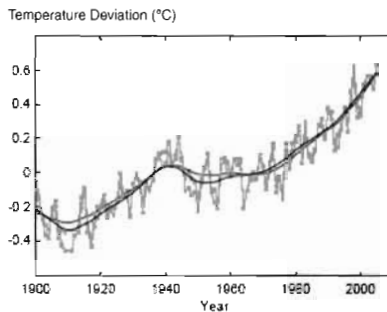
At this point, a comment is put forth in response to a directly related claim made by Richard Lindzen (in chapter 2 of this volume). In his contribution to the Yale Climate Change conference, in his testimony for the British House of Lords, and in media appearances,¹⁹ Lindzen has claimed that the observed global warming is far less than what one would expect from the scientific consensus due to the effect of greenhouse gases. This consensus holds that a doubling of CO₂

causes a radiative forcing of 3.7 W/m^2 , which in equilibrium would cause $3^\circ\text{C} \pm 1.5^\circ\text{C}$ of global warming.²⁰ Lindzen argues that the current radiative forcing due to anthropogenic greenhouse gases (2.6 W/m^2) is already three-fourths of what we would expect from CO_2 doubling and that, “if we attribute all warming over the past century to man-made greenhouse gases, . . . the observed warming is only about one-third to one-sixth of what models project.” He concludes that the “consensus view” must be wrong and claims that climatologists have introduced aerosol cooling as an ad hoc trick to make their numbers match.

This argument is incorrect because it ignores a critical factor: ocean heat uptake. Ocean heat uptake (“thermal inertia”) leads to a time lag of the actual warming behind equilibrium warming. Ocean heat uptake is not just a theoretical or modeled phenomenon, but a measured fact. Data from about 1 million ocean temperature profiles show that the ocean has been taking up heat at a rate of 0.6 W/m^2 (averaged over the full surface of the Earth) for the period 1993–2003.²¹ This rate must be subtracted from the greenhouse gas forcing of 2.6 W/m^2 , as actual warming must reflect the *net* change in heat balance, including the heat flow into the ocean. With an observed temperature increase since the late nineteenth century of 0.8°C (see figure 3-3), and (as Lindzen posits, for the sake of argument) assuming this to be caused by greenhouse gases alone, we would infer a climate sensitivity of $0.8^\circ\text{C} \cdot (3.7 \text{ W/m}^2) / (2.0 \text{ W/m}^2) = 1.5^\circ\text{C}$. This is at the lower end of, but consistent with, the IPCC range.

Of course, we know that anthropogenic aerosols also affect climate; their radiative effect can be estimated, for example, from satellite data.²² It is comparatively uncertain and spatially heterogeneous, but if 1.0 W/m^2 is used as a rough

Figure 3-3. *Global Surface Air Temperature, Over Land and Ocean Combined, since 1900^a*



Source: NASA (data.giss.nasa.gov/gistemp/tabledata/GLB.Ts.txt [May 2007]); British Meteorological Service (hadobs.metoffice.com/hadcrut3/diagnostics/global/nh+sh/annual [May 2007]).

a. The data sets differ in their spatial coverage, interpolation, and quality control techniques. Thin lines and dots show the annual values; the heavy lines show the trend smoothed over eleven years. Deviations are given relative to the 1951–80 average; add 14°C to obtain approximate absolute temperature.

best estimate for the global mean effect (to be subtracted from the denominator), the preceding calculation becomes $0.8^{\circ}\text{C} \cdot (3.7 \text{ W/m}^2) / (1.0 \text{ W/m}^2) = 3.0^{\circ}\text{C}$. For larger aerosol cooling, the denominator gets smaller, and climate sensitivity quickly gets very large. That is why, as just mentioned, the uncertainty in aerosol forcing questions the upper limit of the IPCC range, not the lower limit.

Finally, solar radiation has also increased in the twentieth century, with a best estimate of 0.3 W/m^2 (although recent work argues that this estimate could be much too high).²³ Adding that to the denominator, we obtain $0.8^{\circ}\text{C} \cdot (3.7 \text{ W/m}^2) / (1.3 \text{ W/m}^2) = 2.3^{\circ}\text{C}$. Thus whether we consider greenhouse gases alone, greenhouse gases plus aerosols, or these plus solar forcing, a simple back-of-the-envelope estimate shows that, in each case, observed warming is entirely consistent with the IPCC climate sensitivity range, as long as ocean heat uptake is not ignored. The reverse is also true: climate sensitivity smaller than the IPCC range, as proposed by Lindzen, is in all three cases inconsistent with the observed twentieth-century warming. Thus Lindzen's own argument, if carried out correctly by accounting for ocean heat uptake, disproves the very point he attempts to make.²⁴

Let us come back to ensemble estimates. A recent study conducted by my group has applied this method with data constraints from the last glacial maximum (LGM).²⁵ The LGM climate was simulated with 1,000 versions of the CLIMBER-2 climate model (the first coupled model to realistically simulate Ice Age climate), with key parameters varied within their uncertainty range.²⁶ It turns out that only those model versions with sensitivities between 1.2 and 4.3°C are consistent with the data from the LGM, regardless of whether one uses tropical sea surface temperatures or Antarctic ice core-derived temperatures. The LGM data thus provide the hitherto missing constraint on the upper end of the climate sensitivity range. An important reason for this success is that aerosol cooling and CO_2 cooling work in the same direction for the LGM, so that the large aerosol uncertainty here weakens the constraint on the *lower*, not the upper, climate sensitivity limit. If aerosol cooling had been very large, then the CO_2 effect must have been small: otherwise, the simulated glacial climate would be too cold to be consistent with the data.

Despite allowing for large aerosol uncertainty, even this study suggests a minimum value of 1.2°C for climate sensitivity. I am not aware of any consistency check with observed past climate variations that would be consistent with Lindzen's unsubstantiated claim that "doubling of CO_2 would lead to about 0.5°C warming or less." The fact that the planet cooled strongly in the last glacial maximum, with the tropics cooling by $2\text{--}3^{\circ}\text{C}$, is unfortunately very good evidence against a strong negative feedback in the tropics (Lindzen's hypothetical "iris effect") that would prevent this kind of temperature change. Going back further in climate history, naturally elevated CO_2 levels associated with substantially warmer climates have been documented.²⁷ During the Middle

Pliocene about 3 million years ago, temperatures were 2–3°C warmer than at present, and sea level (due to smaller ice sheets) was 25–35 meters higher.²⁸ Even further back in time, about 35 million years ago in the late Eocene, temperatures were even 3–5°C warmer, and the planet was virtually free of ice for the last time (that is, sea level was about 70 meters higher than now).²⁹ Apparently, no negative feedback prevented these very large climate changes. Another piece of evidence against a strong negative feedback in the tropics is that tropical glaciers are melting away and the tropics are warming.³⁰

Finally, in the ensemble studies, by far most of the climate model versions have climate sensitivity near 3°C, and only a small number of models have sensitivities below 2°C or above 4°C. I have argued here for the “consensus” range of past IPCC reports of 3°C ± 1.5°C, as the goal of this paper is to revisit the basics. But taking all ensemble studies and other constraints together, my personal assessment (and that of a growing number of other researchers) is that the uncertainty range can now be described more realistically as 3°C ± 1°C.³¹

The Observed Climatic Warming

It is time to turn to statement B: human activities are altering the climate. This can be broken into two parts. The first is as follows: *global climate is warming*. This is by now a generally undisputed point (except by novelist Michael Crichton), so we deal with it only briefly.³² The two leading compilations of data measured with thermometers are shown in figure 3-3, that of the National Aeronautics and Space Administration (NASA) and that of the British Hadley Centre for Climate Change. Although they differ in the details, due to the inclusion of different data sets and use of different spatial averaging and quality control procedures, they both show a consistent picture, with a global mean warming of 0.8°C since the late nineteenth century.

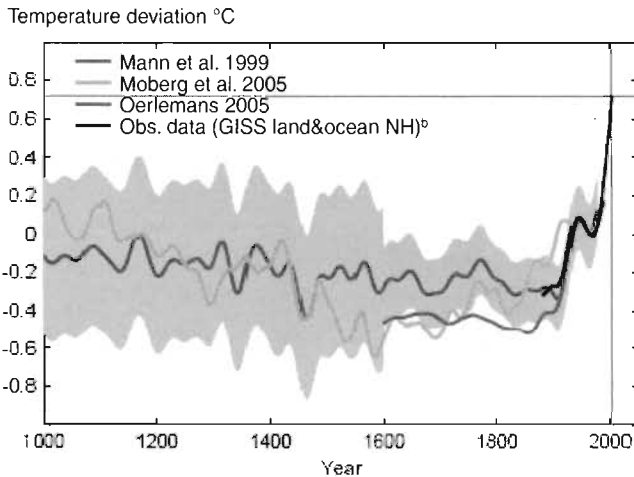
Temperatures over the past ten years clearly were the warmest since measured records have been available. The year 1998 sticks out well above the long-term trend due to the occurrence of a major El Niño event that year (the last El Niño so far and one of the strongest on record). These events are examples of the largest natural climate variations on multiyear time scales and, by releasing heat from the ocean, generally cause positive anomalies in global mean temperature. It is remarkable that the year 2005 rivaled the heat of 1998 even though no El Niño event occurred that year. (A bizarre curiosity, perhaps worth mentioning, is that several prominent “climate skeptics” recently used the extreme year 1998 to claim in the media that global warming had ended. In Lindzen’s words, “Indeed, the absence of any record breakers during the past seven years is statistical evidence that temperatures are not increasing.”)³³

In addition to the surface measurements, the more recent portion of the global warming trend (since 1979) is also documented by satellite data. It is not

straightforward to derive a reliable surface temperature trend from satellites, as they measure radiation coming from throughout the atmosphere (not just near the surface), including the stratosphere, which has strongly cooled,³⁴ and the records are not homogeneous due to the short life span of individual satellites, the problem of orbital decay, observations at different times of day, and drifts in instrument calibration. Current analyses of these satellite data show trends that are fully consistent with surface measurements and model simulations.³⁵

If no reliable temperature measurements existed, could we be sure that the climate is warming? The “canaries in the coal mine” of climate change (as glaciologist Lonnie Thompson puts it) are mountain glaciers. We know, both from old photographs and from the position of the terminal moraines heaped up by the flowing ice, that mountain glaciers have been in retreat all over the world during the past century. There are precious few exceptions, and they are associated with a strong increase in precipitation or local cooling.³⁶ I have inspected examples of shrinking glaciers myself in field trips to Switzerland, Norway, and New Zealand. As glaciers respond sensitively to temperature changes, data on the extent of glaciers have been used to reconstruct a history of Northern Hemisphere temperature over the past four centuries (see figure 3-4).³⁷ Cores drilled in tropical glaciers show signs of recent melting that is unprecedented at least throughout the Holocene—the past 10,000 years.³⁸ Another powerful sign of

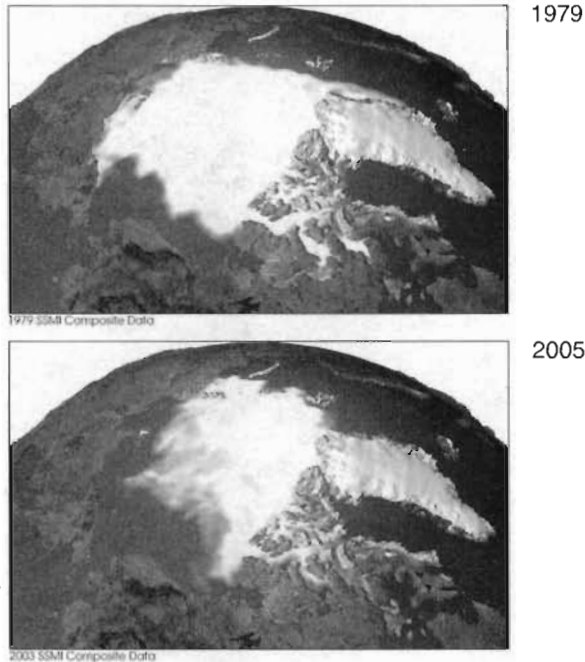
Figure 3-4. *Temperature of the Northern Hemisphere during the Past Millennium^a*



Source: Reconstructed from proxy data. Mann, Bradley, and Hughes, “Northern Hemisphere Temperatures during the Past Millennium,” as shown in IPCC, *Climate Change 2001*; Moberg and others, “Highly Variable Northern Hemisphere Temperatures”; and Oerlemans, “Extracting a Climate Signal.” For full references, see notes 37, 39, and 47. Instrumental data are from NASA up to 2005.

- a. All curves are smoothed over twenty years, and values are given relative to the mean 1951–80.
- b. Goddard Institute for Space Studies (GISS) data for land and ocean, Northern Hemisphere.

Figure 3-5. *Arctic Sea Ice Cover in September (the Summer Minimum Extent) in 1979 and in 2005^a*



Source: NASA (www.nasa.gov/centers/goddard/news/topstory/2005/arcticice_decline.html [May 2007]).

a. The first year of satellite observation was 1979.

warming, visible clearly from satellites, is the shrinking Arctic sea ice cover (figure 3-5), which has declined 20 percent since satellite observations began in 1979.

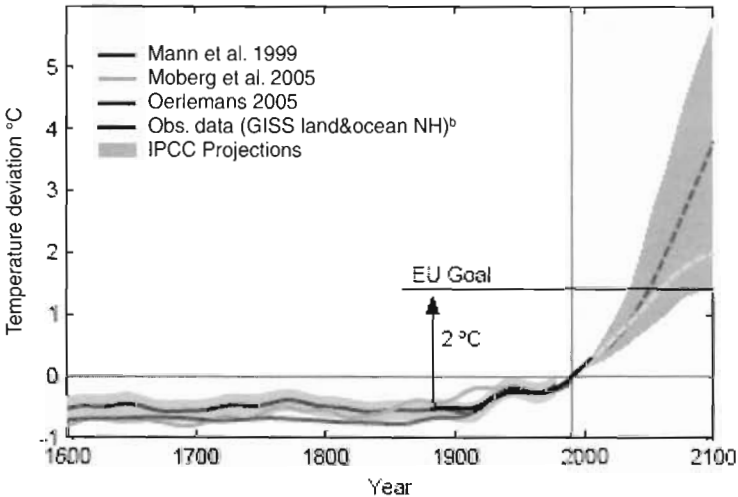
While climate clearly became warmer in the twentieth century, much discussion particularly in the popular media has focused on the question of how “unusual” this warming is in a longer-term context. While this is an interesting question, it has often been mixed incorrectly with the question of causation. Scientifically, how unusual recent warming is—say, compared to the past millennium—in itself contains little information about its cause. Even a highly unusual warming could have a natural cause (for example, an exceptional increase in solar activity). And even a warming within the bounds of past natural variations could have a predominantly anthropogenic cause. I come to the question of causation shortly, after briefly visiting the evidence for past natural climate variations.

Records from the time before systematic temperature measurements were collected are based on “proxy data,” coming from tree rings, ice cores, corals, and other sources. These proxy data are generally linked to local temperatures in some way, but they may be influenced by other parameters as well (for example,

precipitation), they may have a seasonal bias (for example, the growth season for tree rings), and high-quality long records are difficult to obtain and therefore few in number and geographic coverage. Therefore, there is still substantial uncertainty in the evolution of past global or hemispheric temperatures. (Comparing only local or regional temperature, as in Europe, is of limited value for our purposes, as regional variations can be much larger than global ones and can have many regional causes, unrelated to global-scale forcing and climate change.)

The first quantitative reconstruction for the Northern Hemisphere temperature of the past millennium, including an error estimation, was presented by Mann, Bradley, and Hughes and rightly highlighted in the 2001 IPCC report as one of the major new findings since its 1995 report; it is shown in figure 3-6.³⁹ The analysis suggests that, despite the large error bars, twentieth-century warming is indeed highly unusual and probably was unprecedented during the past millennium. This result, presumably because of its symbolic power, has attracted much criticism, to some extent in scientific journals, but even more so in the popular media. The hockey stick-shaped curve became a symbol for the IPCC, and criticizing this particular data analysis became an avenue for some to question the credibility of the IPCC.

Figure 3-6. *Global Temperature Projections for the Twenty-First Century*^a



Source: Data from IPCC, *Climate Change 2001*.

a. The past evolution is shown as in figure 3-5, except that the global (not hemispheric) mean instrumental data are shown, and the temperature origin (0°C anomaly) is placed at the 1990 value of the smoothed instrumental data, since the IPCC projections start in 1990. Two example scenarios (A2, B1) are shown together with the full range (shaded). B1 is a relatively low- and A2 is a relatively high-emissions scenario. The observed temperature rise since 1990 runs along the upper edge of the scenarios.

Three important things have been overlooked in much of the media coverage. First, even if the scientific critics had been right, this would not have called into question the very cautious conclusion drawn by the IPCC from the reconstruction by Mann, Bradley, and Hughes: “New analyses of proxy data for the Northern Hemisphere indicate that the increase in temperature in the twentieth century is likely to have been the largest of any century during the past 1,000 years.” This conclusion has since been supported further by every single one of close to a dozen new reconstructions (two of which are shown in figure 3-6).

Second, by far the most serious scientific criticism raised against Mann, Hughes, and Bradley was simply based on a mistake.⁴⁰ The prominent paper of von Storch and others, which claimed (based on a model test) that the method of Mann, Bradley, and Hughes systematically underestimated variability, “was [itself] based on incorrect implementation of the reconstruction procedure.”⁴¹ With correct implementation, climate field reconstruction procedures such as the one used by Mann, Bradley, and Hughes have been shown to perform well in similar model tests.⁴² Third, whether their reconstruction is accurate or not has no bearing on policy. If their analysis underestimated past natural climate variability, this would certainly not argue for a smaller climate sensitivity and thus a lesser concern about the consequences of our emissions. Some have argued that, in contrast, it would point to a larger climate sensitivity.⁴³ While this is a valid point in principle, it does not apply in practice to the climate sensitivity estimates discussed herein or to the range given by IPCC, since these did not use the reconstruction of Mann, Hughes, and Bradley or any other proxy records of the past millennium. Media claims that “a pillar of the Kyoto Protocol” had been called into question were therefore misinformed. As an aside, the protocol was agreed in 1997, before the reconstruction in question even existed.

The overheated public debate on this topic has, at least, helped to attract more researchers and funding to this area of paleoclimatology; its methodology has advanced significantly, and a number of new reconstructions have been presented in recent years. While the science has moved forward, the first seminal reconstruction by Mann, Hughes, and Bradley has held up remarkably well, with its main features reproduced by more recent work. Further progress probably will require substantial amounts of new proxy data, rather than further refinement of the statistical techniques pioneered by Mann, Hughes, and Bradley. Developing these data sets will require time and substantial effort.

It is time to address the final statement: *most of the observed warming over the past fifty years is anthropogenic*. A large number of studies exist that have taken different approaches to analyze this issue, which is generally called the “attribution problem.” I do not discuss the exact share of the anthropogenic contribution (although this is an interesting question). By “most” I simply mean “more than 50 percent.”

The first and crucial piece of evidence is, of course, that the magnitude of the warming is what is expected from the anthropogenic perturbation of the radiation balance, so anthropogenic forcing is able to explain *all* of the temperature rise. As discussed here, the rise in greenhouse gases alone corresponds to 2.6 W/m^2 of forcing.¹ This by itself, after subtraction of the observed 0.6 W/m^2 of ocean heat uptake, would cause 1.6°C of warming since preindustrial times for medium climate sensitivity (3°C). With a current “best guess” aerosol forcing of 1 W/m^2 , the expected warming is 0.8°C . The point here is not that it is possible to obtain the exact observed number—this is fortuitous because the amount of aerosol forcing is still very uncertain—but that the expected magnitude is roughly right. There can be little doubt that the anthropogenic forcing is large enough to explain most of the warming. Depending on aerosol forcing and climate sensitivity, it could explain a large fraction of the warming, or all of it, or even more warming than has been observed (leaving room for natural processes to counteract some of the warming).

The second important piece of evidence is clear: *there is no viable alternative explanation*. In the scientific literature, no serious alternative hypothesis has been proposed to explain the observed global warming. Other possible causes, such as solar activity, volcanic activity, cosmic rays, or orbital cycles, are well observed, but they do not show trends capable of explaining the observed warming. Since 1978, solar irradiance has been measured directly from satellites and shows the well-known eleven-year solar cycle, but no trend.⁴⁴ There are various estimates of solar variability before this time, based on sunspot numbers, solar cycle length, the geomagnetic AA index, neutron monitor data, and carbon-14 data. These indicate that solar activity probably increased somewhat up to 1940. While there is disagreement about the variation in previous centuries, different authors agree that solar activity did not significantly increase during the last sixty-five years.⁴⁵ Therefore, this cannot explain the warming, and neither can any of the other factors mentioned. Models driven by natural factors only, leaving the anthropogenic forcing aside, show a *cooling* in the second half of the twentieth century (for an example, see figure 2-2, panel a, in chapter 2 of this volume). The trend in the sum of natural forcings is downward.⁴⁶

The only way out would be either some as yet undiscovered unknown forcing or a warming trend that arises *by chance* from an unforced internal variability in the climate system. The latter cannot be completely ruled out, but has to be considered highly unlikely. No evidence in the observed record, proxy data, or current models suggests that such internal variability could cause a sustained trend of global warming of the observed magnitude. As discussed, twentieth-century warming is unprecedented over the past 1,000 years (or even 2,000 years, as the few longer reconstructions available now suggest), which does not support the idea of large internal fluctuations.⁴⁷ Also, those past variations correlate well with past forcing (solar variability, volcanic activity) and thus appear to

be largely forced rather than due to unforced internal variability.⁴⁸ And indeed, it would be difficult for a large and sustained unforced variability to satisfy the fundamental physical law of energy conservation. Natural internal variability generally shifts heat around different parts of the climate system—for example, the large El Niño event of 1998, which warmed the atmosphere by releasing heat stored in the ocean. This mechanism implies that the ocean heat content drops as the atmosphere warms. For past decades, as discussed, we observed the atmosphere warming *and* the ocean heat content increasing, which rules out heat release from the ocean as a cause of surface warming. The heat content of the whole climate system is increasing, and there is no plausible source of this heat other than the heat trapped by greenhouse gases.

A completely different approach to attribution is to analyze the spatial patterns of climate change. This is done in so-called fingerprint studies, which associate particular patterns or “fingerprints” with different forcings. It is plausible that the pattern of a solar-forced climate change differs from the pattern of a change caused by greenhouse gases. For example, a characteristic of greenhouse gases is that heat is trapped closer to the Earth’s surface and that, unlike solar variability, greenhouse gases tend to warm more in winter and at night. Such studies have used different data sets and have been performed by different groups of researchers with different statistical methods. They consistently conclude that the observed spatial pattern of warming can only be explained by greenhouse gases.⁴⁹ Overall, it has to be considered highly likely that the observed warming is indeed predominantly due to the human-caused increase in greenhouse gases.

Discussion and Consequences

This paper discussed the evidence for the anthropogenic increase in atmospheric CO₂ concentration and the effect of CO₂ on climate, finding that this anthropogenic increase is proven beyond reasonable doubt and that a mass of evidence points to a CO₂ effect on climate of 3°C ± 1.5°C global warming for a doubling of concentration. (This is the classic IPCC range; my personal assessment is that, in the light of new studies since the IPCC Third Assessment Report, the uncertainty range can now be narrowed somewhat to 3°C ± 1°C.) This is based on consistent results from theory, models, and data analysis, and, even in the absence of any computer models, the same result would still hold based on physics and on data from climate history alone. Considering the plethora of consistent evidence, the chance that these conclusions are wrong has to be considered minute.

If the preceding is accepted, then it follows logically and incontrovertibly that a further increase in CO₂ concentration will lead to further warming. The magnitude of our emissions depends on human behavior, but the climatic

response to various emissions scenarios can be computed from the information presented here. The result is the famous range of future global temperature scenarios shown in figure 3-6.⁵⁰

Two additional steps are involved in these computations: the consideration of anthropogenic forcings other than CO₂ (for example, other greenhouse gases and aerosols) and the computation of concentrations from the emissions. Other gases are not discussed here, although they are important to get quantitatively accurate results. CO₂ is the largest and most important forcing. Concerning concentrations, the scenarios shown basically assume that ocean and biosphere take up a similar share of our emitted CO₂ as in the past. This could turn out to be an optimistic assumption; some models indicate the possibility of a positive feedback, with the biosphere turning into a carbon source rather than a sink under growing climatic stress.⁵¹ It is clear that even in the more optimistic of the shown (non-mitigation) scenarios, global temperature would rise by 2–3°C above its preindustrial level by the end of this century. Even for a paleoclimatologist like myself, this is an extraordinarily high temperature, which is very likely unprecedented in at least the past 100,000 years. As far as the data show, we would have to go back about 3 million years, to the Pliocene, for comparable temperatures. The rate of this warming (which is important for the ability of ecosystems to cope) is also highly unusual and unprecedented probably for an even longer time. The last major global warming trend occurred when the last great Ice Age ended between 15,000 and 10,000 years ago: this was a warming of about 5°C over 5,000 years, that is, a rate of only 0.1°C per century.⁵²

The expected magnitude and rate of planetary warming is highly likely to come with major risks and impacts in terms of sea level rise (Pliocene sea level was 25–35 meters higher than now due to smaller Greenland and Antarctic ice sheets), extreme events (for example, hurricane activity is expected to increase in a warmer climate), and ecosystem loss.⁵³

The second part of this paper examined the evidence for the current warming of the planet and discussed what is known about its causes. This part showed that global warming is already a measured and well-established fact, not a theory. Many different lines of evidence consistently show that most of the observed warming of the past fifty years was caused by human activity. Above all, this warming is exactly what would be expected given the anthropogenic rise in greenhouse gases, and no viable alternative explanation for this warming has been proposed in the scientific literature.

Taken together, the very strong evidence, accumulated from thousands of independent studies, has over the past decades convinced virtually every climatologist around the world (many of whom were initially quite skeptical, including myself) that anthropogenic global warming is a reality with which we need to deal.

Personal Postscript

When I was confronted with the polemic presented by Lindzen (in this volume), my first reaction was a sense of disbelief. Does Lindzen really think that current models overestimate the observed global warming sixfold? Can he really believe that climate sensitivity is below 0.5°C , despite all the studies on climate sensitivity concluding the opposite, and that a barely correlating cloud of data from one station, as he presents in figure 2-3, somehow proves his view? Does he honestly think that global warming stopped in 1998? Can Lindzen seriously believe that a vast conspiracy of thousands of climatologists worldwide is misleading the public for personal gain? All this seems completely out of touch with the world of climate science as I know it and, to be frank, simply ludicrous.

As a young physicist working on aspects of general relativity theory,⁵⁴ I was confronted with a professor from a neighboring university who claimed in newspaper articles that relativity theory was complete nonsense and that a conspiracy of physicists was hiding this truth from the public to avoid embarrassment and cuts in their funding. (He referred to the “Emperor’s New Clothes,” as does Lindzen.) The “climate skeptics” often remind me of this “relativity skeptic,” and perhaps the existence of people with rather eccentric ideas is not surprising, given the wonderful variety of people. What I find much harder to understand is the disproportionate attention and space that are afforded to such views in the political world and the media.

Notes

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3. Spencer R. Weart, *The Discovery of Global Warming* (Harvard University Press, 2003).
4. IPCC, *Climate Change 2001: Synthesis Report*.
5. IPCC, *Climate Change 1995: The Science of Climate Change*, Contribution of Working Group I to the Second Assessment Report (Cambridge University Press, 1996).
6. IPCC, *Climate Change 2001: Synthesis Report*.
7. Charles D. Keeling, “The Concentration and Isotopic Abundances of Carbon Dioxide in the Atmosphere,” *Tellus* 12 (1960): 200–03.
8. Cooperative Air Sampling Network (<http://www.esrl.noaa.gov/gmd/ccgg/flask.html> [June 2007]).
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10. Christopher L. Sabine and others, "The Oceanic Sink for Anthropogenic CO₂," *Science* 305, no. 5682 (2004): 367–71.
11. James C. Orr and others, "Anthropogenic Ocean Acidification over the Twenty-First Century and Its Impact on Calcifying Organisms," *Nature* 437, no. 7059 (2005): 681–86.
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13. Arrhenius, "On the Influence of Carbonic Acid."
14. IPCC, *Climate Change 2001: Synthesis Report*.
15. Robert Colman, "A Comparison of Climate Feedbacks in General Circulation Models," *Climate Dynamics* 20, no. 7–8 (2003): 865–73.
16. For more on this history, see Weart, *Discovery of Global Warming*.
17. Claude Lorius and others, "The Ice Core Record: Climate Sensitivity and Future Greenhouse Warming," *Nature* 347, no. 6289 (1990): 139–45.
18. Chris E. Forest and others, "Quantifying Uncertainties in Climate System Properties with the Use of Recent Climate Observations," *Science* 295, no. 5552 (2002): 113–17. Reto Knutti and others, "Constraints on Radiative Forcing and Future Climate Change from Observations and Climate Model Ensembles," *Nature* 416, no. 6882 (2002): 719–23.
19. See www.publications.parliament.uk/pa/ld200506/ldselect/ldconaf/12/5012501.htm [May 2007]. National Public Radio, February 16, 2006 (www.kqed.org/epArchive/R602160900 [May 2007]).
20. IPCC, *Climate Change 2001: Synthesis Report*.
21. Josh K. Willis, Dean Roemmich, and Bruce Cornuelle, "Interannual Variability in Upper Ocean Heat Content, Temperature, and Thermosteric Expansion on Global Scales," *Journal of Geophysical Research* 109, no. C12036 (2004): doi:10.1029/2003JC002260.
22. Nicolas Bellouin and others, "Global Estimate of Aerosol Direct Radiative Forcing from Satellite Measurements," *Nature* 438, no. 7071 (2005): 1138–41. IPCC, *Climate Change 2001: Synthesis Report*.
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27. On geologic time scales (millions of years), variations in atmospheric CO₂ concentration are controlled by tectonic processes; see climatology or geology textbooks such as William F. Ruddiman, *Earth's Climate: Past and Future* (New York: Freeman, 2000).

28. H. J. Dowsett and others, "Joint Investigations of the Middle Pliocene Climate I: PRISM Paleoenvironmental Reconstructions," *Global and Planetary Change* 9, no. 3–4 (1994): 169–95.
29. Peter Barrett, "Palaeoclimatology: Cooling a Continent," *Nature* 421, no. 6920 (2003): 221–23. James Zachos and others, "Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present," *Science* 292, no. 274 (2001): 686–93.
30. Lonnie G. Thompson and others, "Kilimanjaro Ice Core Records: Evidence of Holocene Climate Change in Tropical Africa," *Science* 298, no. 5593 (2002): 589–93.
31. James Hansen and others, "Global Temperature Change," *Proceedings of the National Academy of Science* 103, no. 39 (2006): 14288–93.
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35. Thomas R. Karl and others, *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences* (Washington: Climate Change Science Program and the Subcommittee on Global Change Research, 2006). Smaller trends claimed by one group and often cited by "climate skeptics" have turned out to be due to a sign error in a calibration correction. Carl A. Mears and Frank J. Wentz, "The Effect of Diurnal Correction on Satellite-Derived Lower Tropospheric Temperature," *Science* 309, no. 5740 (2005): 1548–51.
36. For a compilation, see IPCC, *Climate Change 2001: Synthesis Report*.
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38. Lonnie G. Thompson and others, "Tropical Glacier and Ice Core Evidence of Climate Change on Annual to Millennial Time Scales," *Climate Change* 59, no. 1–2 (2003): 137–55. Thompson and others, "Kilimanjaro Ice Core Records."
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44. Claus Fröhlich and Judith Lean, "Solar Radiative Output and Its Variability: Evidence and Mechanisms," *Astronomy and Astrophysics Review* 12, no. 4 (2004): 273–320.
45. Raymond Muscheler and others, "How Unusual Is Today's Solar Activity?" *Nature* 436, no. 7050 (2004): E3–E4.
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47. Anders Moberg and others, "Highly Variable Northern Hemisphere Temperatures Reconstructed from Low- and High-Resolution Proxy Data," *Nature* 433, no. 7026 (2005): 613–17.
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50. The fact that observed warming runs along the upper edge of the model scenarios illustrates the absurdity of Lindzen's claim that models overestimate warming by a factor of three to six.
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52. There is good evidence for faster *regional* rates of change—for example, during the abrupt glacial climate changes—but not for faster changes in global mean temperature.
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54. Bernhard Rose, Stefan Rahmstorf, and Heinz Dehnen, "Propagation of Self-Gravitating Density Waves in the deDonder Gauge on a Gravitational Background Field," *General Relativity and Gravitation* 20, no. 11 (1988): 1193–201.

Response to Stefan Rahmstorf's "Anthropogenic Climate Change: Revisiting the Facts."

Richard S. Lindzen

Rahmstorf's paper begins with a recapitulation of the history of the idea of anthropogenic warming¹. Following Al Gore, he suggests that the idea had long been held to be 'outlandish.' Interestingly, this is highly unlikely. There was even a science oriented television series in 1958 that contained an episode astonishingly similar to Gore's movie. The earlier version was titled "The Unchained Goddess," and is still available on Amazon.com. A clip can be seen on <http://motls.blogspot.com/2008/02/unchained-goddess-global-warming-1958.html>. Certainly, the idea was seriously entertained when I was a student in the late 50's and early 60's. It was seriously entertained in the 30's when proposed by Callendar (1938), though careful arguments suggesting it to be minimal were presented by the British pioneers of modern scientific meteorology, George Simpson and David Brunt. Even Arrhenius' suggestion of this possibility much earlier was hardly treated as 'outlandish.' I have occasionally wondered why this issue needs to be artificially presented as a courageous break with conventional wisdom. I suspect that the reason has something to do with the fact that as this idea was being pushed to the forefront of the environmental agenda in the 80's, there was already a determined effort to suppress any opposition. To pose as the suppressed possibly was felt to offer cover for the heavy handed tactics being employed. Indeed, Rahmstorf, true to this tactic, concludes his paper with wistful regret that any attention is given to opposing views. This wish has been loudly expressed by environmental activists since at least as far back as 1988. Given the degree to which the media and the political establishment have yielded to this tactic, one wonders why there is need for wistful regret. One answer is that the intense effort to suppress criticism has not, as yet, led to much in the way of concrete steps to respond to the alarm. Indeed, the focus of the meeting at which these papers were presented was precisely the definition of some action oriented agenda. The common environmental excuse for this situation, as provided by Ross Gelbspan and endorsed by Al Gore, is that there are people like myself who 'deny' global warming and, by our public utterances, are draining the public of its will to take the 'necessary' actions. Needless to add, we are falsely accused of doing this at the behest of the oil industry. It seems never to occur to the acolytes of global warming, that actions haven't been taken since it is unclear what can or should be done.

Be that as it may, Rahmstorf continues with a philosophical meditation on the difference between claims that man has already influenced the climate and claims for what the climate will do in the

¹ Even in this section, Rahmstorf inserts a somewhat pointless reminder of the hurricane season of 2005 and 'renewed' concern for the stability of ice sheets. He wisely avoids specifically endorsing these reminders. The bulk of specialist opinion is that 2005 was not all that special, and that concerns for the major ice sheets are minimal in any reasonable time frame.

future. He plausibly claims that policy can only concern the future, and rather less plausibly argues that the need for future policy is independent of the truth of claims for the past. Nevertheless, Rahmstorf claims that the IPCC claim of attribution for temperature increases of the past 30 years is supported “very strongly by the available evidence.” As I note in my paper, this evidence consists in the argument that current climate models cannot account for the observed increase without including anthropogenic greenhouse warming (significantly cancelled by largely unknown anthropogenic aerosols²). Such argument from failure sounds very reminiscent of the argument for intelligent design (although the correctness of current climate models depends on the presence of destabilizing positive feedbacks that would, as some wag noted, imply unintelligent design). What evidence supports the predictions, I leave to Rahmstorf to state. He continues this paragraph with a peculiar argument for the irrelevance of medieval warm period. Here, his argument depends on phrasing the opposing argument in a particularly naive and silly manner. Quoting Rahmstorf, “‘If the Middle Ages were warmer than temperatures today, then recent warming is perfectly natural (this questions statement B, attribution), and we do not need to worry about the effect of our emissions (this questions statement A, prediction).’ Both these conclusions are, of course, non sequiturs, quite apart from the fact that their premise (warmer Middle Ages) is not supported by the data.” One might note in passing that the last sentence simply glosses over hundreds of peer reviewed papers that document the Medieval Warm Period (or Medieval Optimum, as it was referred to before it became fashionable to fear warmth). We will return to this matter in connection with Rahmstorf’s defense of the hockey stick upon which his claim is based. The artificial claim that Rahmstorf attacks is more usually phrased as a question. Namely, if the Earth’s climate has been warmer than it is at present during the Middle Ages, and existing climate models fail to display this, why should we trust their current attributions (based essentially on their inability to model such things), and their predictions for the future? Such a question is hardly a non sequitur, and the answer is most certainly relevant.

Rahmstorf next launches into a four-part defense of the “Carbon Dioxide Effect on Climate.” To be sure, Rahmstorf says there are only three parts, but he sneaks in the most important part as part of the third part. The first three parts are mostly not contested by anyone, and are therefore largely irrelevant to the debate. Part 1 is that CO₂ in the atmosphere is increasing³. Part 2 is that

² The situation is described in more detail in my paper. The cancellation is sometimes referred to as ‘masking’ the warming, as though the models’ magnitude of warming were certain, and failure to observe what the models predict involved masking rather than overestimation by the model.

³ Rahmstorf typically tries to give this part greater weight by claiming that present values of CO₂ are greater than they have been ‘for at least 650,000 years and probably ever since humans walked the Earth.’ One wonders why he included the word ‘probably’ since homosapiens are generally reckoned to have evolved from homoerectus between 400,000 and 250,000 years BP. While the point of the claim is unclear, it omits the fact that the atmosphere contained much more CO₂ over most of the earths history – including periods of extraordinary

“The recent increase in CO₂ is entirely anthropogenic⁴.” The third part is that CO₂ is a greenhouse gas. It is the fourth part: namely that doubling CO₂ will warm global climate in equilibrium by 3°C±1.5°C, that is the primary point of debate. Rahmstorf acknowledges this, but makes it sound inconsequential since it is only a small part of a larger edifice based on the three relatively trivial points⁵. He then devotes a couple of pages to describing and claiming justification for current model sensitivities. Some of the justification consists in the logically strange idea that the models run often enough constitute a test of themselves. He also refers to the use of the Vostok data to estimate sensitivity as “made solely on the basis of data.” Nothing could be further from the truth. The estimate depends on the assumption that the observed climate change was due to CO₂. However, the cause of the ice ages is generally taken to be due to orbital changes (ie, the Milankovic hypotheses) which, as recently shown by Roe, works very well. At the very least, CO₂ is not operating alone. In such situations, when climate change occurs for reasons other than CO₂, one could well conclude that the climate is infinitely sensitive to CO₂ by incorrectly attributing the cause to CO₂. Similar problems pertain to the use of last glacial maximum or the Eocene to infer climate sensitivity. The concept of simple climate sensitivity is only appropriate to gross global forcings like solar variability and changes in well mixed gases like CO₂. The causes of ice ages and equable climates like the Eocene are clearly more complex, and, not surprisingly, current models do not do a good job of simulating these climates – even with CO₂ levels many times larger than today’s.

Rahmstorf stresses the uncertainties in aerosols permit the possibility of very large sensitivities. To be sure, as the NCAR modeller, J.Kiehl, notes, aerosols are indeed a popular fudge factor for current models, with each model choosing what it needs to achieve plausible simulations. However, as members of the aerosol community have noted, most modelers have chosen much larger values for aerosol cancellation of warming than appear to be justifiable, and they have

biological diversity and evolution. Most current plant life evolved during periods of high CO₂ and are today starved for CO₂. Equally unclear is why Rahmstorf backs his statement up with the famous curves of temperature and CO₂ derived from the Vostok ice core. These curves have temporal resolution of worse than 1000 years, and are thus not very useful for comparing with short period events like the current rise in CO₂. They are also somewhat embarrassing for the global warming issue since they show previous interglacials to be warmer than the present despite lower values of CO₂. They also show that cooling occurred before CO₂ diminished. It took higher temporal resolution to show that warming also preceded increase in CO₂.

⁴ Few would actually agree with the word ‘entirely.’ However, Rahmstorf is somewhat addicted to the use of words like ‘entirely,’ ‘fact,’ ‘irrefutable,’ etc. Such words are inappropriate to a primitive and immature science – which is what climate science is at present.

⁵ This is reminiscent of the old joke about the man who complains of his losses in the stock market to his broker. The broker responds that he (the broker) made money. He adds that his firm also made money. The broker concludes that the customer had little to complain about since two out of three is not a bad record.

therefore exaggerated sensitivity which the aerosol specialists place nearer 1C (Chylek et al, 2007). Rahmstorf, in suggesting much higher sensitivities than any organization has proposed, ignores recent work at the European Centre for Medium Range Weather Forecasting (the world's premier weather forecasting center) which compellingly eliminates sensitivities higher than 4-5C (Rodwell and Palmer, 2007). I shall return to these matters in connection with Rahmstorf's assertions concerning attribution.

Rahmstorf makes two criticisms of my remarks on climate sensitivity. The first is a small technical issue: namely, that I stated that most models I was familiar with actually had a sensitivity of 4C while the IPCC claims that the average among models is closer to 3C. My statement was based on limited personal experience, but as pointed out by Roe and Baker (2007), once models include a large positive water vapor feedback, small changes lead to large changes in model sensitivity, and such changes are readily introduced to produce sensitivities as desired (provided that one starts with a large positive feedback). The more serious criticism is that I ignored 'ocean delay.' This seems to have been a stock reply on Rahmstorf's part since the results I cite in my paper are indeed (as stated) for a coupled atmosphere-ocean model which, therefore, included ocean delay. A more recent consideration of ocean heat uptake by Schwartz (2007) leads to the conclusion of a low climate sensitivity. The issue of ocean delay is more complex than Rahmstorf suggests, since ocean delay is, in fact, proportional to climate sensitivity⁶. With low sensitivity, delay is minimal (a few years); with high sensitivity the delay is on the order of several decades. Observations of the long term climate response to sequences of volcanos suggests that response time is short (Lindzen and Giannitsis, 1998).

Rahmstorf next turns to the temperature record itself. Although he cites two analyses of surface temperature (by Jim Hansen's group at NASA GISS and by the Hadley Centre in the UK), there is a third produced by NOAA. The last, at least, represents an analysis of data by a group that is not also heavily involved in both modeling and the politics of climate. However, although the records vary a bit from each other, the differences amount to no more than the stated uncertainty in the results⁷. The datasets used by all groups are essentially the same, and these datasets all have similar difficulties. For example, data from the oceans is obtained in very different ways from data over land, and large portions of the earth are sparsely sampled. Moreover, there is the longstanding issue of urban heating as well as biases from other changes in land usage. the tendency of NOAA appears to be to reject questionable data. The Hadley Centre seems to prefer to 'correct' questionable stations. Under these circumstances, it is indeed reassuring that the

⁶ The simple argument for this is that climate sensitivity is ultimately a ratio of change of temperature to a change in radiative flux. With high sensitivity, a large equilibrium temperature change is associated with a small flux. However, it is the flux that leads to the change in ocean temperature, so that a small flux takes a longer time to warm the ocean to its equilibrium response.

⁷ Stated uncertainties (or error bars) have a general tendency (as noted by Morgan and Henrion, 1992) to understate the actual uncertainty.

results generally don't differ by more than a couple of tenths of a degree (which, however, is a significant part of the total change). Interestingly, Rahmstorf's comment about Crichton is incorrect in a telling way. Crichton, in his fictional adventure, *State of Fear*, merely had the hero note that individual stations often showed no warming over the past century – which is true. He did not comment much on the global mean. If a reader were to closely examine the records of individual stations or even regions as large as the continental US, he would observe that the variations in the course of a century were far greater than they are for the globe as a whole. This means that individual regions cannot be highly correlated with the global mean; otherwise the global mean variations would have to be much larger.

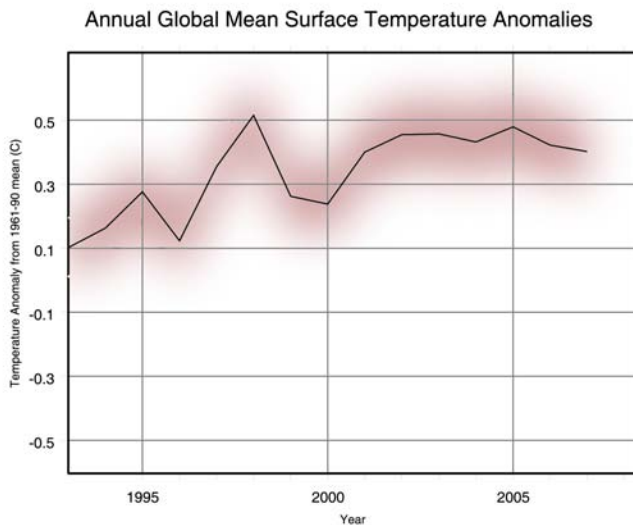


Figure 1. Global mean surface temperature anomalies from 1993-2007. Taken from the Hadley Centre www.metoffice.gov.uk/hadobs.

In his discussion of the surface temperature record, Rahmstorf also refers to what he calls a “bizarre curiosity:” namely, that people have noted that there has been no global warming for over ten years. Rahmstorf falsely associates this claim with the El Nino year of 1998 (ie, he suggests that 1998 was so unusually warm due to El Nino that it would be consistent with warming expectations for subsequent years to be somewhat cooler)⁸. The real situation is shown in Figure 1, which gives the Hadley Centre data. We show the period 1993 to the present. The black curve shows the temperature, while the pink region shows the uncertainty claimed by the Hadley Centre. The reader should first observe the axes. Note that each tick

on the vertical axis represents only 0.2 C. Next, one may compare our Figure 1 with Rahmstorf's Figure 3. We see that the period represented in Figure 1 does, in fact, represent the warmest period in the record. Thus it is reasonable that many of the years in the period 1993-2007 will be among the warmest years in the longer record. However, this tells one nothing about the trend during the last decade and more. If there were a significant trend, then one might reasonably expect that each year would be a record breaking year. No such trend can be seen. As Rahmstorf notes, there is a peak in 1998 that has been associated with El Nino, and there follow a couple of

⁸ A characteristic of many of Rahmstorf's arguments is that they are the commonplace of a website, realclimate.org. This website appears to constitute a support center for global warming believers, wherein any criticism of global warming is given an answer that, however implausible, is then repeated by the reassured believers. A collection of stock responses for believers is featured on <http://gristmill.grist.org/skeptics?source=daily>.

cooler years that are sometimes associated with La Nina. However, if one ignores these events, there is still no statistically significant warming since 1997 or even 1995. The reader might wish to look at the minuscule peak in 2005 that Rahmstorf refers to as ‘rivaling the heat of 1998.’ Counter to Rahmstorf’s assertion, NOAA does list much of 2005 as being part of an El Nino (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/lanina/enso_evolution-status-fcsts-web.pdf). Several things are worth noting in this little exercise. First, if the attribution of the period 1998-2000 to El Nino/La Nina is correct, it shows that such phenomena can perturb global mean temperature on the order of 0.3C which corresponds to most of the warming of the past thirty years. El Nino is not the only such internal (as opposed to externally forced) pattern. Others like the Pacific Decadal Oscillation and the Atlantic Multi-decadal Oscillation represent longer period fluctuations and can be larger than El Nino. I shall discuss this matter further when I turn to Rahmstorf’s defense of the attribution of observed warming to man. Next, one should notice the peculiar use of language by proponents of global warming alarm. Rather than acknowledge that the warming over the past century (or even over the past 150 years) has been small (less than 1C), one speaks of ‘unprecedented’ warming. Rather than note the absence of a trend over the past 11 years, one speaks of the ‘warmest years on record.’ These are really nothing more than semantic stunts designed to befuddle the public.

As I note in my paper, there is not much disagreement over the finding that global mean surface temperature has increased a bit since the 19th Century. As I also note, this is entirely consistent with there being no serious problem (and certainly no crisis). In addition to the above mentioned rephrasing of this unspectacular finding, there is also a persistent tendency to find different measures that purport to show much the same – as though repetition will increase the gravity of the finding. Rahmstorf pursues this approach and again misrepresents the information. Yet, in pointing this out, I have the feeling that the reader may be misled into thinking the issue is more important than it really is. Nevertheless, in going over Rahmstorf’s claims, we will see that some important issues have, indeed, been glossed over.

For example, Rahmstorf mentions the satellite measurements of tropospheric temperature (since 1979). Much confusion surrounds this issue. Original papers by Spencer and Christy (1992) noted that there was no evidence of warming in the troposphere since 1979. Subsequent corrections by Mears and Wentz (2005) led to slight warming – but less than seen at the surface. The report cited by Karl et al (2006), noted that it was possible that other changes in the analysis procedure could bring tropospheric warming up to values seen at the surface (though this was by no means conclusive). What the report also noted was that in the tropical troposphere there was still a significant discrepancy. It turns out that greenhouse warming is characterized by much more warming (2-3 times as much) in the upper tropical troposphere than is found at the surface (Lee et al, 2008), and as noted by myself (Lindzen, 2007) and Douglass et al (2007), the observations, therefore, imply that relatively little of the observed surface warming is due the greenhouse effect. Typical of this field, there is now a paper which uses rather implausible methods (Vinnikov et al, 2007) to conclude that the data can be brought into agreement with the models.

The situation with alpine glaciers is also complex. Rahmstorf's use of the ten thousand year time frame leads to the incontrovertible fact that alpine glaciers have retreated since the end of the last ice age. Turning to more recent times, there is historical evidence that many alpine glaciers advanced from the 14th to the 19th Century. Since the 19th Century, most observed alpine glaciers have been retreating. Counter to what Rahmstorf suggests, alpine glaciers do not respond to global mean surface temperature. Even local annually averaged temperature is not dominant. Summer temperatures and cloud cover matter more, but as the standard text on the matter (Patterson, 1994) notes there are other factors as well. Thus, alpine glaciers are hardly a replacement for thermometers.

This is even true for Arctic sea ice where wind can be as important a factor as temperature in the break up of summer ice. Although summer of 2007 saw a notable reduction of sea ice, there is ample evidence that such reductions have occurred in the 1930's and during other summers of the recent past (before 1979 when satellite observation began). In fact, arctic temperatures were somewhat higher in the 30's (Chylek et al, 2006). Interestingly, sea ice around Antarctica was unusually extensive during the past austral summer. Interpreting this remains difficult, but cherry picking examples and claiming a unique cause hardly helps.

Rahmstorf next moves to a lengthy defense of the Mann et al hockey stick, while continuing to argue that it really doesn't matter. In some ways, I agree with his assessment of the importance. Afterall, nothing in their conclusion changes the fact that current warming is, in fact, small. However, the debate over this paper is interesting for the light it casts on the whole field, and a lengthy description of the affair may be found in Holland (2007). Despite, Rahmstorf's defense, both the Wegman Report (for the US Congress) and the National Research Council report, chaired by G. North (NRC 2006), concluded that the statistical analysis could not reasonably be used for the claims made. The North report attempted to temper its conclusions by suggesting that the approach was possible for the past 400 years (a safe position, given the fact that this period begins within the Little Ice Age). Also, in the press release, it was suggested that the fact that the analysis was inadequate did not necessarily mean that the result was wrong – a baseless and irrelevant assertion, but one which permitted some to claim that the report exonerated Mann. The text certainly showed quite the opposite. Personally, I have long felt that statistics was hardly the most serious problem with the Mann analysis. The approach uses several handfuls of proxy data (mostly tree rings) to infer Northern Hemisphere mean temperatures. (Once one goes further back than about 600 years, the number of proxy time series is substantially reduced.) Now tree rings do not measure annually averaged temperature; rather they represent tree growth which depends on such things as temperature, rainfall, and variance during the growing season. However, one can take a portion of the instrumental record for Northern Hemisphere mean temperature, and find the combination of proxy time series that best fits the instrumental record. This yields essentially weighting functions for each proxy time series, and one can use these weighting functions to extend the temperature record for a thousand years. As it turns out, this approach fails to replicate the rise shown in Rahmstorf's Figure 4 for the last thirty years. This is referred to as the divergence problem. This may not be surprising because there is an important underlying assumption; namely, that as the mean temperature of the Northern Hemisphere varies

that the geographical pattern of variation does not – even on the scale of the surroundings of the individual pine trees used as proxies. The situation becomes more interesting for the Medieval Warm Period. Historical information suggests rather convincingly that there was such a period in the North Atlantic region, but Mann then argued that this was a regional phenomenon that did not hold for the Northern Hemisphere mean. If Mann's point is correct, then it means that the pattern had changed which is inconsistent with his method. Of course, given the statistical problems with Mann's approach, it remains possible that the Medieval Warm Period was characteristic of the Northern Hemisphere. Frankly, we have enough trouble measuring mean surface temperature to tenths of a degree with instruments. Perhaps it is unreasonable to do so for the thousand years preceding instrumental records with a few tree rings.

Finally, Rahmstorf turns to the iconic statement of the last IPCC WG1 Summary: *most of the observed warming over the past 50 years is (likely to be) anthropogenic*. Rahmstorf omits *likely*, but is careful to note that *most* means more than half. At this point warming is really small, and even more remote from alarm. Rahmstorf then presents some seemingly quantitative arguments that essentially show that by manipulating quantities like ocean heat take-up and aerosol forcing, one can bring the models into rough agreement with observations. As already noted in connection with climate sensitivity, Kiehl (2007), a climate modeler at NCAR, is much more up-front on this matter – pointing out that each model has to make different adjustments. Recent attempts to better pin down such things as ocean heat take-up lead to reduced estimates of climate sensitivity (Schwartz, 2007), as does the work of Chylek et al (2007) on aerosols (both papers estimate sensitivities on the order of 1C for a doubling of CO₂). Rahmstorf's second point on this matter is that there is *no viable alternative explanation*. He first justifies this claim with reference to explicit sources of forcing like *solar activity, volcanic activity, cosmic rays, and orbital cycles*. These, he claims, rather controversially, are all well measured, and point to cooling rather than warming. I will leave the discussion of these matters to others, because the main competing process has been omitted from the list. Rahmstorf does finally acknowledge this by referring to the possibility of *a warming trend that arises by chance from an unforced internal variability of the climate system, which cannot be completely ruled out but has to be considered highly unlikely*. To claim that such variability (associated with various indices such as El Nino/La Nina, the Pacific Decadal Oscillation, and the Atlantic Multidecadal Oscillation) is rendered unlikely because it occurs by chance (ie, is unpredictable) is rather illogical⁹. In point of fact, Tsonis et al (2007) are able to account for the changes in global mean temperature over the past 100 years exactly in this manner. As further 'evidence,' Rahmstorf notes that such variability is not found in current models. However, as Smith (2007) (Smith is at the Hadley Centre) notes, their model does not properly display these modes of internal variability. The models do better, Smith claims, if they are initialized for these modes. With 'initialization,' he finds that the model can replicate the observed absence of warming over the past decade. Several

⁹ There is even a joke about the illogic of such an argument that is attributed to Richard Feynman. Feynman walks into a class late, and announces to the class that he has encountered something astounding. While walking through a parking lot, he saw a car with the plate number 186CSC. What, he asks the class, do they think the odds are of seeing that precise number?

things are interesting about the Smith paper. First, it acknowledges that the models do not realistically depict natural internal variability. Second, he acknowledges that global warming has been absent for about a decade. Third, despite the acknowledged shortcoming of the model, Smith uses the model to speculate that warming will resume after 2009. Not surprisingly, it the last item that received emphasis.

Rahmstorf concludes this section with a discussion of ‘fingerprints,’ but as I have already pointed out, the most fundamental fingerprint of greenhouse warming, the greatly enhanced rate of warming in the upper tropical troposphere, does not appear to be observed.

With respect to the iconic attribution claim, what we are arguing may amount to little more than an argument over whether greenhouse warming accounts for 30% rather than 51% of the observed warming that occurred mainly between 1976 and 1993. This, per se, may not be very important. However, much recent work suggests that sensitivity is on the order 1C or less for a doubling of CO₂. This would pretty much rule out alarming consequences, though as my paper notes, the alarming consequences require such a confluence of uncertain conditions that they would be unlikely in any event.

Rahmstorf’s penultimate section, *Discussion and Consequences*, barely touches on the latter. Mostly, it just repeats the earlier faulty arguments while adding an occasional claim of being ‘logical’ and ‘incontrovertible.’ The consequences are in the realm of quickly recited ‘coulds’ and ‘mights.’ However, there are two highly misleading points that Rahmstorf makes, and it may be helpful for readers to be warned of these since they are commonly made assertions.

The first is the claim that the current rate of warming is unprecedented compared to paleoclimatic data. As we have already seen, climate changes on all time scales, and the shorter the period one focuses on, the higher the **rate** of change. To compare rates of change over a few decades in an instrumental record with fine temporal resolution with changes over thousands of years recorded by ice cores with temporal resolution over a thousand years is totally meaningless. The ice core has no information about variations over a few decades.

The second is the claim that the warming over the past 50 years is exactly what was expected. As already noted (twice already), such a claim is based on adjusting aerosols for each model in order to obtain agreement (Kiehl, 2007). Under the circumstances, getting the ‘right’ answer was only achieved by knowing the ‘right’ answer in advance. Even then, as Smith et al (2007), the models failed to anticipate the absence of warming over the past ten years.

To refer to these claims as misleading is, of course, being unduly generous.

This, finally, brings us to Rahmstorf’s *Personal Postscript*. This postscript consists in some rhetorical questions that Rahmstorf assumes the reader will accept as ‘speaking for themselves.’ Of course I think that it is entirely possible that models have greatly exaggerated climate sensitivity. As already pointed out, there are quite a few recent papers that suggest lower

sensitivities. I would certainly not claim that the iris effect is ‘proven,’ but there is increasing independent corroborative evidence in the literature. More important, as noted in Lindzen et al (2001), tropical upper level cirrus have a sufficient impact to enable such a reduction, and current models utterly fail to replicate the observed behavior of such clouds. As to the cessation of warming since 1997 (not 1998), figure 1 does speak for itself, and is corroborated by Smith et al (2007).

Perhaps the most interesting rhetorical question concerns whether I think that “a vast conspiracy of thousands of climatologists worldwide is misleading the public for personal gain.” This accusation, interestingly, has been made against anyone questioning global warming alarm for over 20 years. Recall, that *Newsweek* was already claiming that all scientists agreed on this matter back in 1988. The intent of the accusation is to impugn the credibility of the questioner. Clearly to believe in conspiracies is supposed to be a characteristic of mental imbalance. As I pointed out in Lindzen (1992), there was hardly a need for any conspiracy since it was sufficient for the various parties to simply pursue their obvious self-interest. Indeed, it is quite impossible to involve thousands of individuals in a successful conspiracy. However, to note this leads one to ignore some very well planned activities by environmental activists. Thus, last November, a gentleman named John Firor died. Firor had, for many years been the administrative director of the National Center for Atmospheric Research (where I worked in the mid-60's). Firor remained in this position through several changes of director. His role was administrative rather than scientific, and he readily acknowledged to having no background in the atmospheric sciences. However, by the late 80's he was frequently speaking and writing on the challenge of global warming. As his obituary noted, Firor was also Chairman of the Board of the Environmental Defense Fund (now Environmental Defense) and a trustee and founding board member of the World Resources Institute. Another example concerns the chairman of the governing board of the United Kingdom’s Meteorological Office (the home of the Hadley Centre for Climate Research), Robert Napier, who also happens to be the Chief Executive of World Wildlife Fund - UK. One could give quite a few similar examples of interlocking relations between environmental advocacy organizations and putatively objective academic and research centers. Whether such activities can be said to constitute a conspiracy, is a matter of opinion. However, they clearly provide a well designed academic cover for what is essentially environmental advocacy. The world of climate science as Rahmstorf knows it, may well differ from the one that I belong to. However, Rahmstorf’s world may also be quite different from what outsiders may think it to be.

This finally brings us to Rahmstorf’s absurd, pompous and pretentious association of one the landmarks in modern intellectual history, Einstein’s General Theory of Relativity, with the primitive and crude world of climate modeling. Einstein was pained for much of his life by the fact that his general theory had a single adjustable parameter (the so-called cosmological constant). One can only imagine how he might have felt about this theory being compared with climate models that have almost an uncountable number of adjustable parameters.

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