# 3

# *Anthropogenic Climate Change: Revisiting the Facts*

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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]

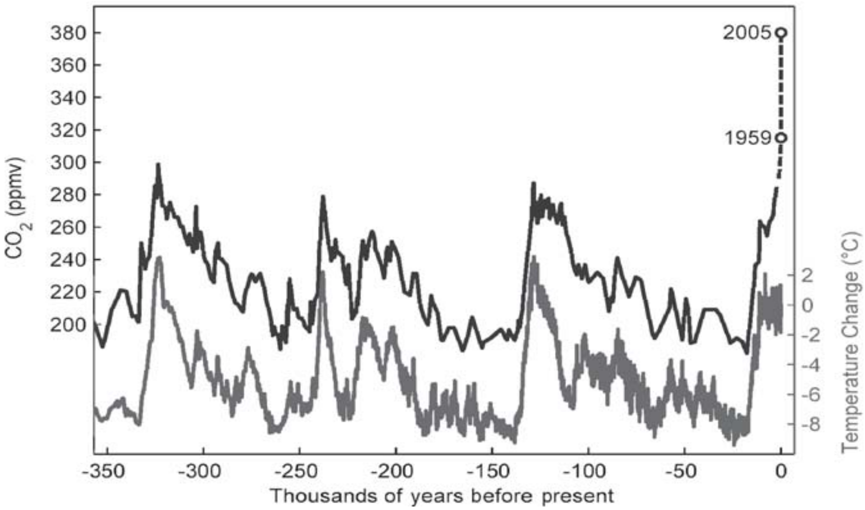
Only statement A is relevant to policy, because no current or planned policy can affect the past. Such policies are shaped by our expectations for the future. It is important to realize that statement A is not conditional on statement B. Thus, even if too much natural variability was masking any anthropogenic 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 ($CO_2$) 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 $CO_2$ data from the Global $CO_2$ Monitoring Network are made available by the Cooperative Air Sampling Network.[8] Ice core data, which provide a reliable and accurate record of $CO_2$ 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.

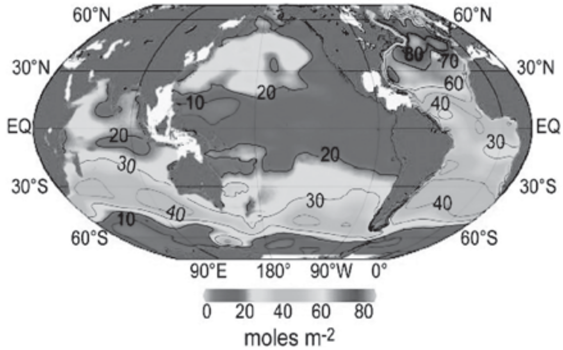
a. Based on Vostok ice core in Antarctica. These ice core data end before the onset of anthropogenic changes. Anthropogenic emissions have now increased the $CO_2$ concentration to 380 ppm (as of 2005).

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 $CO_2$ 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 $CO_2$ is entirely anthropogenic.* This is also undisputed. We have tracked and we know how much fossil fuel has been burned and therefore how much $CO_2$ we have injected directly into the atmosphere. The observed increase in $CO_2$ 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 $CO_2$ 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 $CO_2$ is anthropogenic: the isotope composition, the corresponding decline in

Figure 3-2. *Column Inventory of Anthropogenic $CO_2$ in the Ocean*




Source: Christopher L. Sabine, "Oceanic Sink for Anthropogenic $CO_2$," *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 $CO_2$ 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 $CO_2$ 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 $CO_2$.[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 $CO_2$ 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 $CO_2$ concentration due to the near-saturation of the $CO_2$ absorption bands. This means that a doubling of $CO_2$ 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 $CO_2$ (and other forcing) changes, not just on the $CO_2$ concentration at that point in time. But the climate sensitivity is nevertheless a simple and very useful measure of the strength of the $CO_2$ 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, $W/m^2$), 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 $CO_2$ (which amounts to a forcing of 3.7 $W/m^2$) 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 $CO_2$ 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 $CO_2$ of about 4°C” is incorrect.)

Another way to estimate climate sensitivity is by looking at data from past variations of $CO_2$ and climate. How strongly climate was affected by $CO_2$ variations 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, $CO_2$ 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 $CO_2$ changes. The two major $CO_2$ 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 $CO_2$ warming, then even a very high sensitivity to $CO_2$ would still be compatible with the observed global temperature rise.

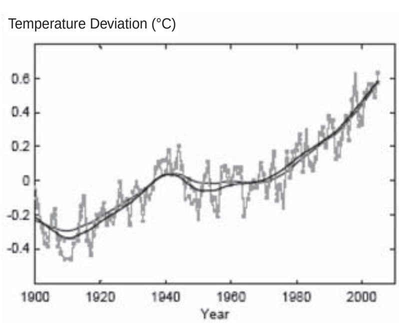
At this point, a comment is put forth in response to a directly related claim made by Richard Lindzen (in chapter 2 of this volume). In his contribution to the Yale Climate Change conference, in his testimony for the British House of Lords, and in media appearances,[19] Lindzen has claimed that the observed 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 $CO_2$

causes a radiative forcing of 3.7 W/m$^2$, which in equilibrium would cause 3°C ± 1.5°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°C · (3.7 W/m$^2$) / (2.0 W/m$^2$) = 1.5°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 $0.8°C \cdot (3.7\ W/m^2)\ /\ (1.0\ W/m^2) = 3.0°C$. 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 $0.8°C \cdot (3.7\ W/m^2)/(1.3\ W/m^2) = 2.3°C$. 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 2–3°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

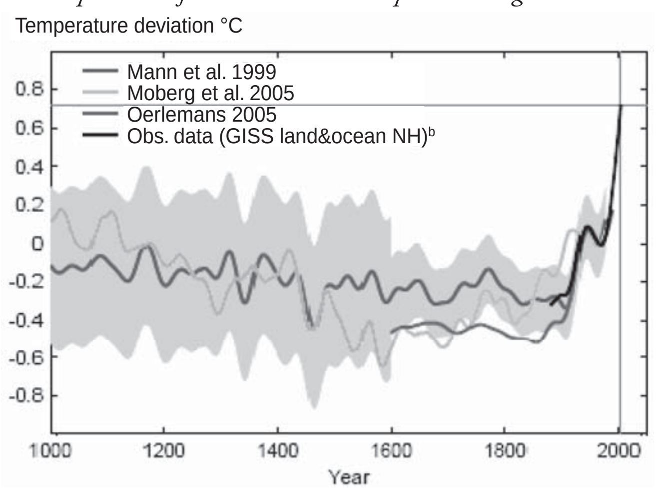
It is time to turn to statement B: human activities are altering the climate. This can be broken into two parts. The first is as follows: *global climate is warming.* This is by now a generally undisputed point (except by novelist Michael Crichton), so we deal with it only briefly.[32] The two leading 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]

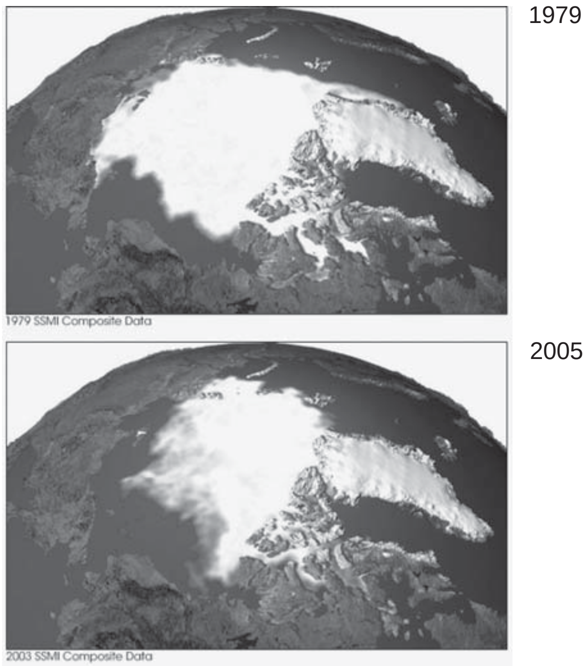



Source: Reconstructed from proxy data. Mann, Bradley, and Hughes, "Northern Hemisphere Temperatures during the Past Millennium," as shown in IPCC, *Climate Change 2001*; Moberg and others, "Highly Variable Northern Hemisphere Temperatures"; and Oerlemans, "Extracting a Climate Signal." For full references, 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.

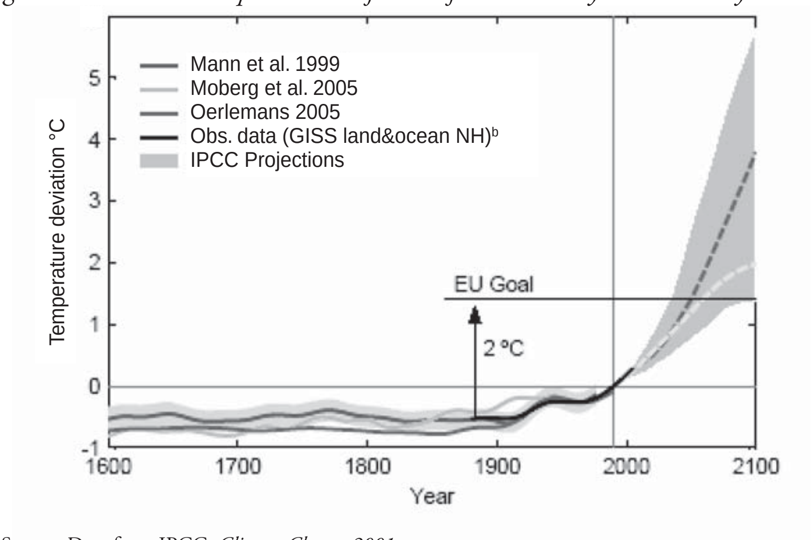
warming, visible clearly from satellites, is the shrinking Arctic sea ice cover (figure 3-5), which has declined 20 percent since satellite observations began in 1979.

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. 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 $CO_2$ concentration and the effect of $CO_2$ on climate, finding that this anthropogenic increase is proven beyond reasonable doubt and that a mass of evidence points to a $CO_2$ 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 $CO_2$ 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 $CO_2$ (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. $CO_2$ 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 $CO_2$ 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 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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