From Michael Mann, "The Hockey Stick and the Climate Wars"

Chapter 2

Climate Science Comes of Age

The ice we skate is getting pretty thin
The waters getting warm so you might as well swim*

—Smashmouth, "All Star" (1999)

When I entered the field of climate research in the early 1990s, the science was just coming of age. Major research centers around the world were using some of the fastest supercomputers available to run ever-more sophisticated models of Earth's climate. Important new observations were coming in. Thermometer measurements showed that the globe—both land and ocean—had by that time warmed approximately 1 degree Fahrenheit over the past century. The accumulated loss of ice during the previous four decades from melting glaciers around the world could fill Lake Huron. An increasing number of climate measurements were painting a picture of a climate that was changing in much the way models had been predicting it would if we continued to emit greenhouse gases. By the mid-1990s, enough evidence had accumulated to convince the IPCC, as we've seen, that there was a "discernible human influence on climate." While the jury had been out when I began my studies in the early 1990s, it had come in with a judgment by the time I was completing them in the mid-1990s. What had led to that verdict can be described in five easy steps.

Climate Change in Five Easy Steps

By the mid-1990s, scientists were able to connect the dots when it came to establishing a human impact on our climate.

(1) We knew for one thing that human activity—primarily the burning of fossil fuels—had increased carbon dioxide (CO_2) concentrations in the atmosphere. The legendary atmospheric scientist Charles Keeling first began to make direct measurements of atmospheric CO_2 in 1958 at a pristine location far from any pollution sources—nearly three miles above sea level at the top of Mauna Loa in Hawaii. Thanks to Keeling's work, we had an instrumental record of CO_2—the so-called

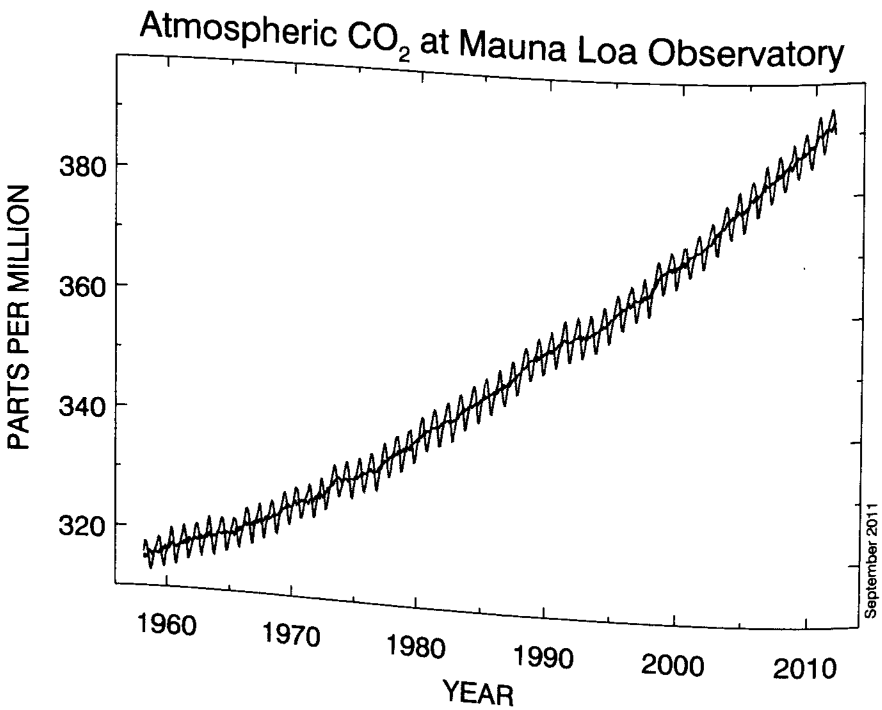

Figure 2.1: The Keeling Curve
Monthly measurements of atmospheric CO_2 concentrations from Mauna Loa, Hawaii, dating back to 1958. The original measurements were made by Charles Keeling. The record is maintained and updated by scientists with the Scripps Institution of Oceanography. [From Scripps Institute of Oceanography/NOAA Earth System Research Laboratory.]

Keeling curve—going back nearly half a century. But we could go back even farther by analyzing CO_2 content in samples of the ancient atmosphere recovered from the layers of ice in ice cores stretching back hundreds of thousands of years.

These records indicate a steady two-century–long rise in CO_2 concentrations coincident with the Industrial Revolution, culminating in modern levels that appear unprecedented in hundreds of thousands of years at least, long before modern humans arrived on the scene. The CO_2 that was building up in the atmosphere as the Industrial Revolution progressed, moreover, had humanity's fingerprints all over it; analysis of the carbon isotopes indicated that the source lay in the burning of fossil fuels. At current rates of fossil fuel burning, CO_2 concentrations, it was estimated, would reach twice preindustrial levels within about four decades. We'd potentially need to reach back tens of millions of years, halfway to the age of dinosaurs, to find previous levels that high.

(2) Scientists also knew that this increase in atmospheric CO_2 (and other trace gases produced by human activity, such as methane) must have a warming effect on Earth's surface. In fact, that had been known for nearly two centuries. The esteemed French scientist and mathematician Joseph Fourier (1768–1830) is generally credited with discovery of the warming effect of these gases. Other great nineteenth-century scientists such as Ireland's John Tyndall (1820–1893) and Sweden's Svante Arrhenius (1859–1927) helped work out the basic physics and chemistry.

Earth is heated from above by the Sun. The only thing keeping the planet from getting hotter and hotter is its ability to cool off by emitting its own invisible form of radiation (infrared radiation) to space. Certain gases in our atmosphere such as carbon dioxide, however, impede this heat loss mechanism by absorbing a fraction of that radiation and reradiating some of it back down toward the surface, rather than allowing it to escape to space. This requires Earth's surface to send even more infrared radiation out to space. And that it can only do by warming up.

This effect, which in some respects resembles how a greenhouse works, is known as the "greenhouse effect," and the gases responsible for it are thus termed "greenhouse gases." The greenhouse effect is hardly controversial. Indeed, without a natural greenhouse effect, Earth would be a frozen planet lacking life as we know it. By increasing the concentrations of these gases in the atmosphere, it was only logical that we should be further warming Earth's surface.

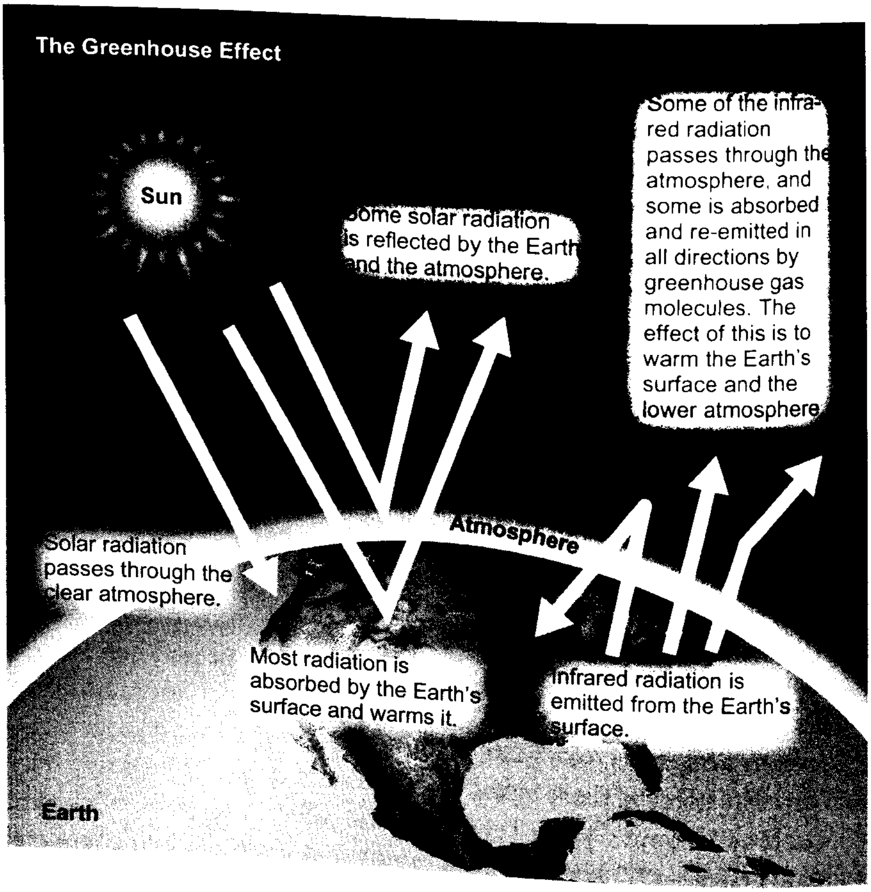

Figure 2.2: The Atmospheric Greenhouse Effect
Earth is warmed by the incoming radiation from the Sun, and its temperature can stabilize only by producing its own invisible outgoing (infrared) radiation. The greenhouse effect involves the absorption of some of that outgoing radiation by greenhouse gases in our atmosphere. The greenhouse effect warms the surface by sending some of this radiation back toward Earth rather than allowing it to escape to space.

(3) Indeed, as mentioned earlier, thermometer measurements told us that by the mid-1990s Earth had already warmed a little more than a degree Fahrenheit (roughly 0.6°C) since the dawn of industrialization. The globe was in fact warming. This observation alone may not seem that decisive; after all, the warming might have been at least partly natural in origin. However, the observation did not exist in isolation. There was now evidence as to the probable cause.

(4) By the mid-1990s, it was possible to investigate the causal mechanisms behind changes in Earth's climate using relatively sophisticated mathematical models of Earth's climate. These models solved the same complex equations of atmospheric physics that numerical weather prediction models did. But they also took into account components of the climate system other than the atmosphere, including the oceans, the continental ice sheets, and even life on Earth (collectively known as the "biosphere"), and they attempted to account for the physical, chemical, and biological interactions among these components. Of course, no theoretical model is ever perfect; even the best model is only an idealization of the actual world. There are always real-world processes that cannot be captured—for example, in the case of a numerical climate model, individual clouds or small-scale air currents like dust devils—that are simply too small for the model to resolve. The key question is, can the model be shown to be useful? Can it make successful predictions?

Climate models had passed that test with flying colors by the mid-1990s. James Hansen, in the late 1980s, successfully predicted the continuing warming that would be observed by the mid-1990s.[1] Even something the model couldn't have predicted in advance—the 1991 eruption of Mount Pinatubo in the Philippines—provided yet another key test. As soon as the eruption occurred, Hansen put what was known about the reflective qualities of volcanic sulfur particulates (known as "sulfate aerosols") into the simulations. The aerosols cooled surface temperatures for several years in the model by shielding the surface from a fraction of incoming sunlight, leading Hansen to make what turned out to be a successful prediction of the temporary cooling that was seen over the ensuing few years.[2]

(5) Finally, perhaps most significant of all, only when human factors were included could the models reproduce the observed warming—both its overall magnitude and, equally important, its geographical pattern over Earth's surface and its vertical pattern in the atmosphere. The primary such human factor was increasing greenhouse gas concentrations due to fossil fuel burning and other human activities. A secondary human factor, sulfate aerosols emitted from industrial smokestacks, also played a role, however. Like volcanic sulfate aerosols, these industrial aerosols have a cooling effect. Unlike volcanic aerosols, which reach the lower stratosphere, allowing them to spread out into a layer covering the globe, industrial aerosols remain confined to the lower atmosphere,

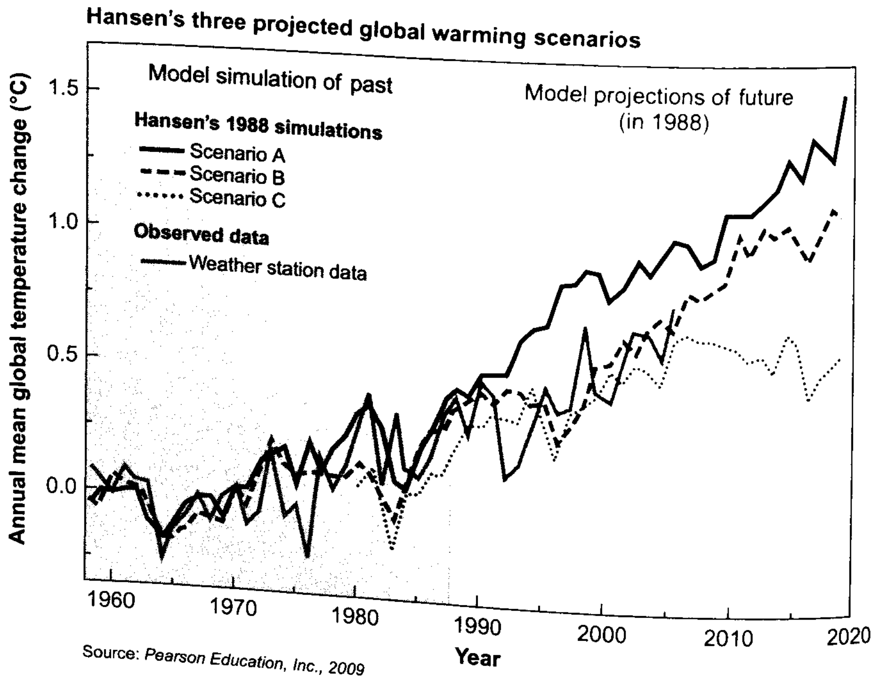

Figure 2.3: Testing Climate Models
A comparison of three different simulations of global warming through 2020 made by James Hansen in 1988. The curve made up of weather station observations (available through 2005 in this analysis) closely matches the curve of the middle scenario (B)—the one that is based on the trajectory of an emissions scenario that most closely matches actual greenhouse gas emissions over the preceding twenty years. The upper and lower curves correspond to scenarios A and C, which assume higher and lower emissions respectively.

leading to localized patterns of cooling that offset global warming in some regions. The pattern of warming predicted by the models from the combination of these two human effects on the climate provide a unique "fingerprint" of what the human influence on climate should look like if the models were correct—and the fingerprint matched. The surface and lower atmosphere showed an irregular pattern of warming, while the atmosphere aloft was cooling, just as the models indicated it should.[3] The fingerprint predicted for natural factors alone—for example, from fluctuations in solar output—on the other hand, failed to match the observations. It was the work of Ben Santer and other climate scientists during the mid-1990s in establishing this fingerprint of human influence that provided the "smoking gun," the fifth and final link in the chain of reasoning that allowed the IPCC to declare in 1995 that there was indeed at least a "discernible" human influence on climate.

So the case could be made by the mid-1990s—in just five easy steps—that human activity was changing our climate. The case became stronger over the next decade and a half as increasingly more sophisticated models were developed and a wider array of data was collected that confirmed unprecedented changes taking place in our climate. It is fair to say, though, that even by the mid-1990s there was no longer reason for real scientific debate over the proposition that humans had warmed the planet and changed the climate. That conclusion was now supported by the efforts of thousands of scientists around the world whose work contributed to the various pillars of evidence detailed above. What scientists were still debating with each other at scientific meetings and in the professional journals was the precise balance of human versus natural causes in the changes observed thus far, and just what further changes might loom in our future.

Answers to these more specific questions were far less clear. Climate scientists could surmise that if human civilization continued to follow its current upward trajectory of fossil fuel burning, we would likely see a near doubling of preindustrial atmospheric CO_2 levels by the mid-twenty-first century. Furthermore, we could estimate that such an increase would lead to an additional warming of anywhere between 1.5 and 4.5° C (roughly 3–8°F).

The large spread in estimated temperature increase arose primarily from uncertainty about the effects of so-called feedbacks, responses of the system that can either further amplify or diminish the warming. Certain feedbacks are almost certainly positive, amplifying the given effect; for example, a warmer atmosphere holds more water vapor, and water vapor is itself a greenhouse gas, further warming the surface. The melting of ice as Earth warms exposes more of the ground and ocean surface. These surfaces absorb sunlight more effectively than does ice, which further amplifies the warming. But other factors, such as how clouds change under warmer conditions and to what effect, were highly uncertain, and remain so still.

Most models indicate a tendency for more low clouds in a warmer climate; low clouds mimic the effect of surface ice, for example, reflecting solar radiation back to space. Thus, in these models, clouds play the role of a negative feedback, diminishing the warming. Yet in other credible climate models, clouds behave differently, effectively enhancing the overall greenhouse effect and acting as yet another positive feedback. Representing cloud effects is perhaps the most daunting challenge for climate models, because they occur at scales too small to capture explicitly in the models, and their effects must therefore be represented only through approximations.

What's All the Fuss About?

By the mid-1990s, larger questions regarding the potential societal and environmental impacts of climate change were beginning to receive more attention as well. Did climate change pose a threat to the future welfare of our civilization, and even possibly to our species? And if so, what, if anything, should we do about it, and when? Science alone could not, of course, answer many of these questions. They are as much matters of policy (and risk management, economics, and ethics) as they are matters of science. The science could, however, *inform* matters of policy.

There was increasing recognition by the mid-1990s that another 1.5°C (2.5°F) warming beyond current levels (for a total of 2°C or 3.5°F warming relative to preindustrial times) could represent a serious threat to our welfare.[4] Precisely what limitations in global greenhouse gas emissions would be required to avoid that amount of warming remained uncertain, and still does, because of the spread of predictions among models. If we choose to take the midrange model estimates as a best guess, avoiding a total of 2°C of warming would require stabilizing atmospheric CO_2 concentrations at no higher than about 450 parts per million (ppm).

Preindustrial levels were about 280 ppm, reflecting a long-term balance between natural processes that produce (sources) and those that take up (sinks) CO_2 from the atmosphere. Humans, through extensive fossil fuel burning and other practices, have upset that natural balance, causing CO_2 concentrations to rise steadily. Indeed, those concentrations will continue to rise until human emissions are brought essentially to zero.[5] The carbon we emit into the atmosphere today has an extended legacy; it will potentially reside there for centuries.

Levels, as of 2011, are nearly 390 ppm and are increasing by 2 to 3 ppm per year as a result of annual carbon emissions. The average

American, through various actions and activities, emits roughly 20 tons—the weight of two very large adult male African elephants—of carbon per year. Globally, human beings emit the equivalent of more than 400 million of those elephants—roughly 8.5 billion tons—of carbon per year. A 450 ppm stabilization target would require greenhouse gas emissions be brought to a peak of no more than about 9 billion tons (450 million elephants) per year within the next decade, be lowered to mid-twentieth-century levels of roughly 1 billion tons (50 million elephants) per year by midcentury, and brought to near zero by the end of the century, to avoid breaching 450 ppm. That is a daunting task, as global population continues to increase, developing nations such as China and India continue to ramp up their own emissions, and industrial nations like the United States continue with business as usual. Given the enormity of the challenge, it was convenient for some to simply deny that climate change was happening at all, especially those who were profiting handily from civilization's addiction to fossil fuels.

Some leading climate scientists such as NASA's James Hansen have argued that CO_2 not only needs to be stabilized below 450 ppm, but in fact must be brought back to a level even lower than present. Based on geological evidence regarding ice amounts and sea levels that prevailed in past warm climates, Hansen argues that we need to bring CO_2 down to levels lower than those that persisted when I first entered into climate research in the early 1990s—to 350 ppm, to be specific.[6] In the December 2009 climate change negotiations in Copenhagen, Denmark, a consortium of low-lying island nations already threatened by rising sea levels lobbied for such a target.[7] This target has even been incorporated into the name of the grassroots climate change campaign founded a few years ago by environmental writer Bill McKibben: 350.org. Lowering atmospheric CO_2 concentrations from current levels would require not only dramatically reducing emissions, but in fact making them negative—that is, actively taking ambient CO_2 from the air through expensive and, as yet, largely untested technologies such as open air carbon capture (which attempts to suck the CO_2 out of the air, mimicking what plants do naturally, but at a greatly accelerated rate and without releasing carbon into the atmosphere as plant matter does when it dies and decomposes).

Suppose we were instead to continue with business as usual, shunning efforts to curtail carbon emissions. The impacts on our civilization and environment could be profound. By doing so, we might well be committing ourselves to the melting of the major ice sheets, resulting in a sea level rise as much as six feet by the end of this century[8] and, eventually, twenty feet or more, thus ensuring extensive loss of coastal settlements around the world, including the East and Gulf Coasts of the United States, and the potential disappearance of many low-lying island nations. Many coastal regions, including the U.S. East and Gulf Coasts, might feel the double whammy of inundation from sea level rise and increased erosion and destruction from potentially more powerful hurricanes fueled by warmer oceans. Increasingly widespread and severe droughts would likely take hold over the major continents, including North America, as precipitation became increasingly intermittent and moisture evaporated more readily from warmer soils. Many regions would likely also see increased flooding from more intense rainfall events.

Among the potential impacts would be greater social conflict resulting from movements of large numbers of environmental refugees and increased competition for available resources within and among nations, more widespread famine due to declining agricultural productivity in developing tropical nations already struggling with hunger and malnutrition, and threats to human health and even mortality from potential increases in the spread of infectious disease and stress-related deaths from more frequent and extreme heat waves. Key ecosystems may be lost, including coral reefs and the summer Arctic sea ice environment critical to the survival of polar bears.

Of course, there could be potential benefits in some cases. Agricultural productivity, for example, might increase in some midlatitude regions owing to longer growing seasons, as long as freshwater supply remains available—an important caveat. However, when all the various potential impacts of the climate changes are taken into account, the weight of impacts have been shown to be decidedly negative, and increasingly so as warming progresses.[9] It is possible that the models that indicate a temperature rise of only 3°F or so for CO_2 doubling are right, that the changes will be modest enough that we, and many other living things, might be able to adapt. That appears unlikely, however, given the evidence, and in the worst case scenario, where considerably greater temperature rises occur, Earth will, as NASA's James Hansen bluntly put it, resemble "another planet."[10] Environmental author Bill McKibben has even given a name to this planet: Eaarth.[11] Ultimately the question boils down to this: Are we willing to roll the dice, with Earth lying in the balance? And is it within our rights to imperil future generations should we be wrong?

Given the wealth of scientific evidence amassed by the mid-1990s, one might rightly wonder how there could be a viable opposing position on controlling our carbon emissions. It was already difficult for any scientist to credibly argue that Earth wasn't warming, or that there was no impact on our climate by human activity (though a few still did, nonetheless, and still do). However, even among those who accepted the facts of global warming, there was still an awareness that much uncertainty exists, as we have seen. How much warming would there be? How much of the warming that had occurred could we confidently attribute to human activity? And precisely what impacts would the forecasted changes have on our daily lives? These were still wide-open questions. And while we continue to refine our understanding of climate change, many of these questions remain open to this day.

Taking steps to reduce emissions to levels that would avoid breaching 450 ppm would have been far easier in 1995 than it is now, given that we have emitted more than 100 billion tons of carbon into the atmosphere in the meantime. But even then, it would have been challenging and potentially costly. Those opposed to action could point to that uncertainty for justification. Why should we engage in potentially expensive measures to reduce greenhouse gas emissions, they could say, when the benefits are unclear? The impacts of continued fossil fuel burning in the decades ahead might be mild, some asserted; they might even be favorable. Back when I was working on my Ph.D., I would sometimes encounter such an argument from friends and acquaintances who knew that my research, at least vaguely, had something to do with the topic of global warming.

In fact, I wasn't completely unreceptive to this argument at the time. It was at least an honest, if somewhat flawed, line of reasoning. The flaw, as I would gently point out, is that the logic could just as easily work the other way. What if the problem was actually worse than our current prevailing best estimates? What if the true response of the climate instead lay at the high end of the uncertainty range? The effects in that case could be catastrophic and the costs to civilization and our environment incalculable. In fact, the argument was not my own. I had seen it advanced by Stanford University climate scientist Stephen Schneider in an article that had left an impression on me. Schneider had used the analogy of buying an insurance policy.[12] We don't purchase fire insurance for our homes because we believe our homes are going to burn down. We purchase it because if our house did burn down, it could ruin our lives. We purchase fire insurance to hedge against a perhaps quite low-probability, but undeniably catastrophic, potential outcome. It is useful to think of climate change mitigation the same way. I find Schneider's analogy as compelling today as I did then.

But even in the mid-1990s, as the scientific case had become persuasive, some critics weren't content to engage in the worthy debate to be had over climate change policy, cost-benefit analysis, and risk management. They were instead intent on preempting that debate by continuing to argue that climate change itself, if not a massive and deliberate hoax, was based on bad science. Perhaps they were afraid that general acceptance of the facts behind global warming and the risks it poses would lead the public to demand action to protect the future. Whatever their motive, they sought to deny the science altogether.

The Six Stages of Climate Change Denial

A leaked 2002 memo from leading Republican consultant Frank Luntz warned that the party had nearly "lost the environmental communications battle" and urged its politicians to double down in their efforts to deny the scientific consensus behind global warming.[13] Luntz sounded an alarm: "The scientific debate is closing [against those who deny the reality of climate change] but not yet closed. There is still a window of opportunity to challenge the science. . . . Voters believe that there is no consensus about global warming within the scientific community. Should the public come to believe that the scientific issues are settled, their views about global warming will change accordingly." Luntz suggested a full frontal attack: "you need to continue to make the lack of scientific certainty a primary issue in the debate."

Luntz has been heavily criticized for the now-infamous memo, but in his defense, he was simply the messenger. He was merely communicating the wisdom derived from careful polling and focus groups. From a purely pragmatic standpoint, he was also likely correct; the best tactic for those advocating inaction on climate change seemed to be to continue to attack the science supporting a human influence on climate, as they had for well over a decade.

The climate change denial campaign has always seemed to enjoy the same advantage as the defense in a criminal trial. Those opposed to limiting carbon emissions recognized long ago they need only cast "reasonable doubt" to convince members of the public that it is too expensive to take action. They need not present a logically consistent case. It suffices for them to attempt to simply pick holes in the scientific evidence, however inconsequential. The greater burden lies with those making the scientific case. They must present a case so persuasive that even the most skilled artists of sophistry cannot undermine it. Critics frequently argue that until science is able to offer proof of the reality of human-caused climate change, it is too early to act. Yet this is a red herring. Science can only ever offer weights of evidence, degrees of confidence, and estimated risk. "Proof" is reserved for mathematical theorems and alcoholic beverages.

While there has been little consistency over the years among the various arguments climate change contrarians have made, there is nonetheless a hierarchy to the denialist canon—what I refer to as the "six stages of denial." It goes something like this:

1. CO_2 is not actually increasing.
2. Even if it is, the increase has no impact on the climate since there is no convincing evidence of warming.
3. Even if there is warming, it is due to natural causes.
4. Even if the warming cannot be explained by natural causes, the human impact is small, and the impact of continued greenhouse gas emissions will be minor.
5. Even if the current and projected future human effects on Earth's climate are not negligible, the changes are generally going to be good for us.
6. Whether or not the changes are going to be good for us, humans are very adept at adapting to changes; besides, it's too late to do anything about it, and/or a technological fix is bound to come along when we really need it.

Contrarians have tended to retreat up the ladder of denial as the scientific evidence has become more compelling. With the ever upwardly

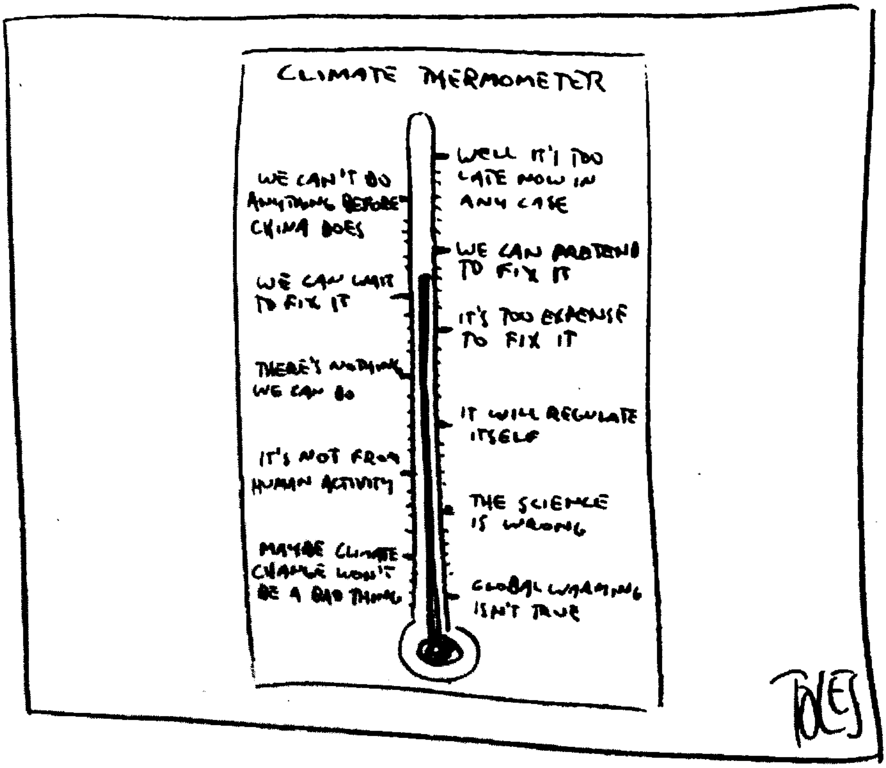

Figure 2.4: The Stages of Denial
A cartoon that uses a thermometer to gauge one conception of the various stages of climate change denial. [TOLES ©2009 The Washington Post. Reprinted with permission of UNIVERSAL UCLICK. All rights reserved.]

trending Keeling curve of CO_2 levels plain for anyone to see, few were calling into question the rise in atmospheric CO_2 by the time I had entered climate science in the early 1990s. But you could still find claims that there was no evidence of warming. John Christy and Roy Spencer of the University of Alabama at Huntsville, for example, argued in a series of papers in the early 1990s that the satellite temperature measurements they had analyzed demonstrated an absence of warming in the atmosphere.[14] Problems with their estimation procedures were established by the late 1990s, however.[15] When their original findings were found to have been almost entirely in error, they did acknowledge that Earth is warming. Spencer still contends, nonetheless, that humans are not to blame for the increase,[16] while Christy accepts that there is a detectable human contribution to the warming, but argues that future warming will be less than standard climate models project.[17]

Contrarians in the climate change debate, oddly enough, have been known to jump several rungs of the ladder of denial at once. For example, S. Fred Singer appeared to leap from warming is not occurring (stage 2) all the way to it is warming but there is nothing we can do about it anyway (stage 6) with the book *Unstoppable Global Warming: Every 1500 Years* that he coauthored in 2006.[18]

Yet one can still find some clinging to that lowest rung of the ladder, the rung I term "CO_2 denial." In a 2007 article in the social science journal *Energy and Environment*, a high school teacher in Germany, Ernst-Georg Beck, argued against there having been any increase in atmospheric CO_2 over the past two centuries.[19] It was an extraordinary claim, given the overwhelming evidence from the work of Keeling and others. What was the evidence that Beck pointed to? A hodgepodge of CO_2 records that were either compromised by systematic errors or taken from heavily polluted urban locations, where CO_2 levels are not representative of the overall ambient global levels. Keeling's son Ralph, a respected atmospheric scientist in his own right, charitably assessed Beck's paper as having "serious conceptual oversights that would have been spotted by any reasonably qualified reviewer."[20] Other commentators weren't as kind.[21]

To return to where things stood when I was completing my Ph.D. in the mid-1990s: No serious, well-credentialed, actively publishing climate scientists could be found clinging to the lower rungs of the ladder of denial. But you could find quite a few legitimately standing on the middle and upper rungs: Yes, there is warming, and some of it almost certainly is anthropogenic in nature. But just how much of it is due to human activity? How much of it might simply be due to natural variability? The implications of these very legitimate questions were potentially far-reaching. If the "noise"—that is, the natural variability—was large enough to have explained a substantial share of twentieth-century warming, it might mean that a relatively small amount of warming could be attributed to human influence. That would in turn imply that the sensitivity of the climate to increasing greenhouse gas concentrations might be at the lower end of the range of uncertainty. Some of this uncertainty persists today.