Brian's Kindle for Mac 5 - What We Know about Climate Change (The MIT Press)

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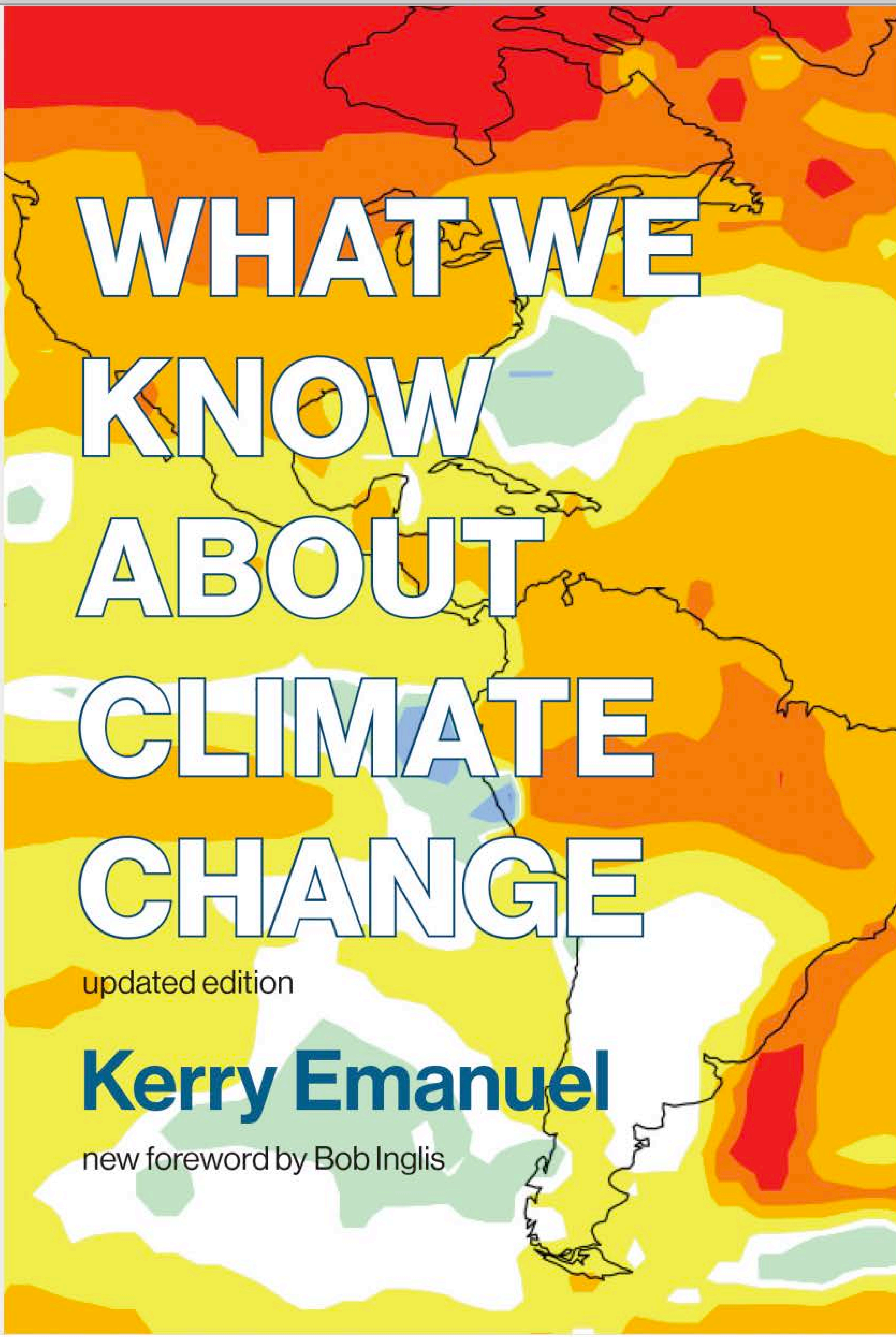

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1

The Myth of Natural Stability

Two strands of environmental philosophy run through the course of human history. The first holds that the natural state of the universe is one of infinite stability, with an unchanging earth anchoring the predictable revolutions of the sun, moon, and stars. Every scientific revolution that challenged this notion, from Copernicus's heliocentricity to Hubble's expanding universe, from Wegener's continental drift to Heisenberg's uncertainty and Lorenz's macroscopic chaos, met with fierce resistance from religious, political, and even scientific hegemonies.

The second strand also sees stability as the natural state of the universe but holds that human beings destabilize it. The great floods described in many religious traditions are portrayed as attempts by a god or gods to cleanse the earth of human corruption. Deviations from cosmic order, such as meteors and comets, were more often viewed as omens than as natural phenomena. In Greek mythology, the blistering heat of Africa and the burnt skin of its inhabitants were attributed to Phaëthon, an offspring of the sun god Helios. Having lost a wager to his son, Helios was obliged to allow him to drive the sun chariot across the sky. In this primal environmental catastrophe, Phaëthon lost control and scorched the earth, killing himself in the process.

These two fundamental ideas—cosmic stability and man-made disorder—have permeated many cultures through much of history. They strongly influence views of climate change even today.

In 1837 Louis Agassiz provoked public outcry and scholarly ridicule when he proposed that many enigmas of the geologic record, such as peculiar scratch marks on rocks, and boulders far removed from their bedrock sources, could be explained by the advance and retreat of huge sheets of ice. His proposal marked the beginning of a remarkable endeavor, today known as paleoclimatology.

Paleoclimatology uses physical and chemical evidence from the geological record to deduce changes in the earth's climate over time. This field has produced among the most profound yet least celebrated scientific advances of our era. We now have exquisitely detailed knowledge of how climate has varied over the last few million years and, with progressively less detail and certainty, how it has changed going back to the age of the oldest rocks on our 4.5-billion-year-old planet.

For those who take comfort in stability, there is little consolation in this history. In just the past three million years, our climate has swung between mild states—similar to today's and lasting 10,000 to 20,000 years—and periods of 80,000 years or so in which giant ice sheets, in some places several miles thick, covered northern continents. Even more unsettling is the suddenness with which the climate can change, especially as it recovers from glacial periods.

Over longer intervals of time, the climate has changed even more radically. During the early part of the Eocene era, around 50 million years ago, the earth was free of ice, and giant trees grew on islands near the North Pole, where the annual mean temperature was about 60°F, far warmer than today's mean of about 30°F. There is also some evidence that the earth was almost entirely covered with ice at various times around 500 million years ago. These "snowball earths" alternated with exceptionally hot climates.

What explains these changes? For climate scientists, ice cores in Greenland and Antarctica provide intriguing clues about the great glacial cycles of the past three million years. As the ice formed it trapped bubbles of atmosphere, whose chemical composition—including, for example, its carbon dioxide and methane content—can now be analyzed. Moreover, it turns out that the ratio of two isotopes of oxygen locked up in the molecules of ice is a good indicator of the air temperature when and where the ice was formed. And the age of the ice can be determined by counting the layers that mark the seasonal cycle of snowfall and melting.

Relying on such analyses of ice cores and similar analyses of sediment cores from the deep ocean, researchers have learned something remarkable: the ice-age cycles of the past three million years were almost certainly caused by periodic oscillations of the earth's rotation and orbit that affect primarily the orientation of its axis. These oscillations do not much affect the *amount* of sunlight that reaches the earth, but they do change the *distribution* of sunlight with latitude. Ice ages occur when, as a result of orbital variations, arctic regions intercept relatively little summer sunlight so that ice and snow do not melt as much as they otherwise would.

The timing of the ice ages, then, is the result of the earth's orbit. It is discomfiting that these large climate swings—from glacial to interglacial and back—are caused by relatively small changes in the distribution of sunlight with latitude. Thus, on the time scale of ice ages, climate seems exquisitely sensitive to small perturbations in the distribution of sunlight.

And yet for all this sensitivity, the earth never suffered a permanent catastrophe of fire or ice. In the fire scenario, the most effective greenhouse gas—water vapor—accumulates in the atmosphere as it warms. The warmer the atmosphere, the more water vapor it can contain; as more water vapor accumulates, more heat gets trapped, and the warming spirals upward. This feedback, unchecked, is called the runaway greenhouse effect, and it continues until the oceans have all evaporated, by which time the planet is unbearably hot. One has to look only as far as Venus to see the end result. Any oceans that may have existed on that planet evaporated eons ago, yielding a super greenhouse inferno and an average surface temperature of about 900°F.

Death by ice can result from another runaway feedback. As snow and ice accumulate progressively equatorward, they reflect an increasing amount of sunlight back to space, further cooling the planet until it freezes into a snowball earth. As discussed above, there is some evidence that this actually happened to the earth several times around 500 million years ago. It used to be supposed that once the planet reached such a frozen state, reflecting almost all sunlight back to space, it could never recover. More recently it has been theorized that without liquid oceans to absorb the carbon dioxide continuously emitted by volcanoes, the gas would accumulate in the atmosphere until its greenhouse effect was finally strong enough to start melting the ice. Once begun, the positive feedback between temperature and reflectivity would work in reverse, rapidly melting the ice and leading to a hothouse climate in a short time. It would not take much change in the amount of sunlight reaching the earth to cause a snowball or runaway greenhouse catastrophe.

But solar physics informs us that the sun was about 25 percent dimmer early in the earth's history, which should have led to an ice-covered planet, a circumstance not supported by geological evidence from that era. So what saved the earth from an ice catastrophe?

Life itself, perhaps. Our atmosphere is thought to have originated in gases emitted from volcanoes, but the composition of volcanic gases bears little resemblance to air as we know it today. We believe that the early atmosphere consisted mostly of water vapor, carbon dioxide, sulfur dioxide, chlorine, and nitrogen. There is little evidence of much oxygen before the advent of cyanobacteria, a phylum of bacteria that produced oxygen through photosynthesis and began the transformation of the atmosphere into something like today's, consisting mostly of nitrogen and oxygen with trace amounts of water vapor, carbon dioxide, and other gases. Carbon dioxide content probably decreased slowly over time owing to chemical weathering—chemical reactions involving rainwater and rocks—possibly aided by biological processes. As the composition of the atmosphere changed, the net greenhouse effect weakened, compensating for the slow but inexorable brightening of the sun.

This compensation may not have been an accident. In the 1960s James Lovelock proposed that life actually exerts a stabilizing influence on climate by producing feedbacks favorable to it. He called his idea the Gaia hypothesis, named after the Greek earth goddess. But even according to this view, life is preserved only in the broadest sense: individual species, such as those that transformed the early atmosphere, altered the environment at their peril.

Clearly life has profoundly altered our climate. We humans are merely the most recent species to do so.

2
Greenhouse Physics

As the last chapter's sketch of the planet's early climatic history shows, the greenhouse effect plays a critical role in the earth's climate, and no sensible discussion of climate could proceed without grasping its nature.

The greenhouse effect has to do with radiation—in this context meaning energy carried by electromagnetic waves—which include such phenomena as visible light, radio waves, and infrared radiation. All matter with a temperature above absolute zero emits radiation. The hotter the substance, the more radiation it emits and the shorter the average wavelength of that radiation. A fairly narrow range of wavelengths constitutes visible light. The average surface temperature of the sun is about 10,000°F, and the sun emits much of its radiation as visible light, with an average wavelength of about half a micron. (A micron is one millionth of a meter; there are 25,400 microns in an inch.) The earth's atmosphere emits radiation as though its average temperature were around 0°F, at an average wavelength of about 15 microns. Our eyes cannot detect this infrared radiation. It is important to recognize that the same object can both emit and absorb radiation: when an object emits radiation, it loses energy, cooling it; absorption, on the other hand, heats it.

Most solids and liquids absorb much of the radiation they intercept, and they also emit radiation rather easily. Air is another matter. It is composed almost entirely of oxygen and nitrogen, each in the form of two identical atoms bonded together in a single molecule. Such molecules barely interact with radiation: they allow free passage to both solar radiation moving downward to the earth and infrared radiation moving upward from the earth's surface.

If that were all there is to the atmosphere, it would be a simple matter to calculate the average temperature of the earth's surface: it would have to be just warm enough to emit enough infrared radiation to balance the shortwave radiation it absorbed from the sun. (Were it too cool, it would emit less radiation than it absorbed and would heat up; conversely, were it too warm it would cool down.) Accounting for the sunlight reflected back to space by the planet, this works out to be about 0°F, far cooler than the observed mean surface temperature of about 60°F.

Fortunately for us, our atmosphere contains trace amounts of other substances that do interact strongly with radiation. Foremost among these is water, H_2O, consisting of two atoms of hydrogen bonded to a single atom of oxygen. Because of its more complex geometry, it absorbs and emits radiation far more efficiently than molecular nitrogen and oxygen. In the atmosphere water exists both in its gas phase (water vapor) and its condensed phase (liquid water and ice) as clouds and precipitation.

Water vapor and clouds absorb sunlight and infrared radiation, and clouds also reflect sunlight back to space. The amount of water vapor in a sample of air varies greatly from place to place and time to time but does not usually exceed about three percent of the mass of the sample. Besides water, there are other gases that interact strongly with radiation, including carbon dioxide (CO_2, presently about 405 molecules for each million molecules of air) and methane (CH_4, around 1.9 molecules for each million molecules of air).

Collectively the greenhouse gases—water vapor, carbon dioxide, methane, and several others—are nearly transparent to sunlight. Were it not for the presence of clouds, short-wavelength radiation would pass virtually unimpeded to the surface, where most of it would be absorbed. On the other hand, these same gases absorb much of the long-wavelength, infrared radiation that passes through them. To compensate for the heating this absorption causes, the greenhouse gases must also emit radiation, and each layer of the atmosphere thus emits infrared radiation upward and downward.

As a result, the surface of the earth receives radiation from the atmosphere as well as from the sun. It is an extraordinary fact that, averaged over the planet, the surface receives almost twice as much radiation from the atmosphere as it does from the sun. To balance this extra input of radiation—the radiation emitted by atmospheric greenhouse gases and clouds—the earth's surface warms up and thereby emits more radiation itself. This is the essence of the greenhouse effect.[1]

If air were not in motion, the observed concentration of greenhouse gases and clouds would raise the average temperature of the earth's surface to around 85°F, much warmer than observed. In reality, hot air from near the surface rises upward and is continually replaced by cold air moving down from aloft. These convection currents lower the surface temperature to an average of 60°F while warming the upper reaches of the atmosphere. So the downward emission of radiation by greenhouse gases keeps the earth's surface warmer than it would otherwise be, and, at the same time, the convective movement of air dampens the warming effect and keeps the surface temperature bearable, while warming the upper atmosphere

The greenhouse gases collectively comprise roughly 0.3% of the mass of the atmosphere. Almost all of this is water vapor, which while highly variable in space and time, makes up on average about 0.25% of the atmosphere. But the concentration of water vapor is mostly just a function of temperature, and it adjusts to an equilibrium value in just a few weeks. Thus water vapor is properly considered a feedback in the climate system: warmer air has more water vapor, which through its greenhouse effect makes the system yet warmer.

By contrast, it takes hundreds to thousands of years for CO_2 concentrations to adjust naturally, so it is really long-lived greenhouse gases like CO_2 that exert a controlling influence on climate.

It is truly astonishing that, as the great Irish physicist John Tyndall discovered in the mid-nineteenth century, the tolerably warm conditions we enjoy are thanks to long-lived greenhouse gases like CO_2 that together constitute only about 0.04% of our atmosphere. On time scales of millions of years and greater, these long-lived greenhouse gases act as a kind of thermostat. For example, if the planet were to warm up appreciably, chemical weathering of rocks would accelerate, taking CO_2 out of the atmosphere, cooling the climate back toward it original equilibrium. Conversely, were the planet to cool, weathering would slow, allowing CO_2 to accumulate in the atmosphere thus warming it back to equilibrium.

In 1897, the Swedish chemist and Nobel laureate Svante Arrhenius realized that increasing combustion of fossil fuels would eventually raise CO_2 concentrations, simply because human emissions were far too large for the natural system to deal with on human time scales. By 1906 he had calculated that doubling the concentration of CO_2 would raise the earth's surface temperature by about 4°C, a number well within contemporary estimates of 2–4.5°C per doubling of CO_2. It is important to note that Arrhenius did this without the benefit of computers, relying on basic physics already fairly well quantified by his time. Figure 1 tests Arrhenius's prediction by comparing the observed natural logarithm of the CO_2 concentration with observed global mean temperature. While there are many natural influences on climate, such as small variations in solar output and

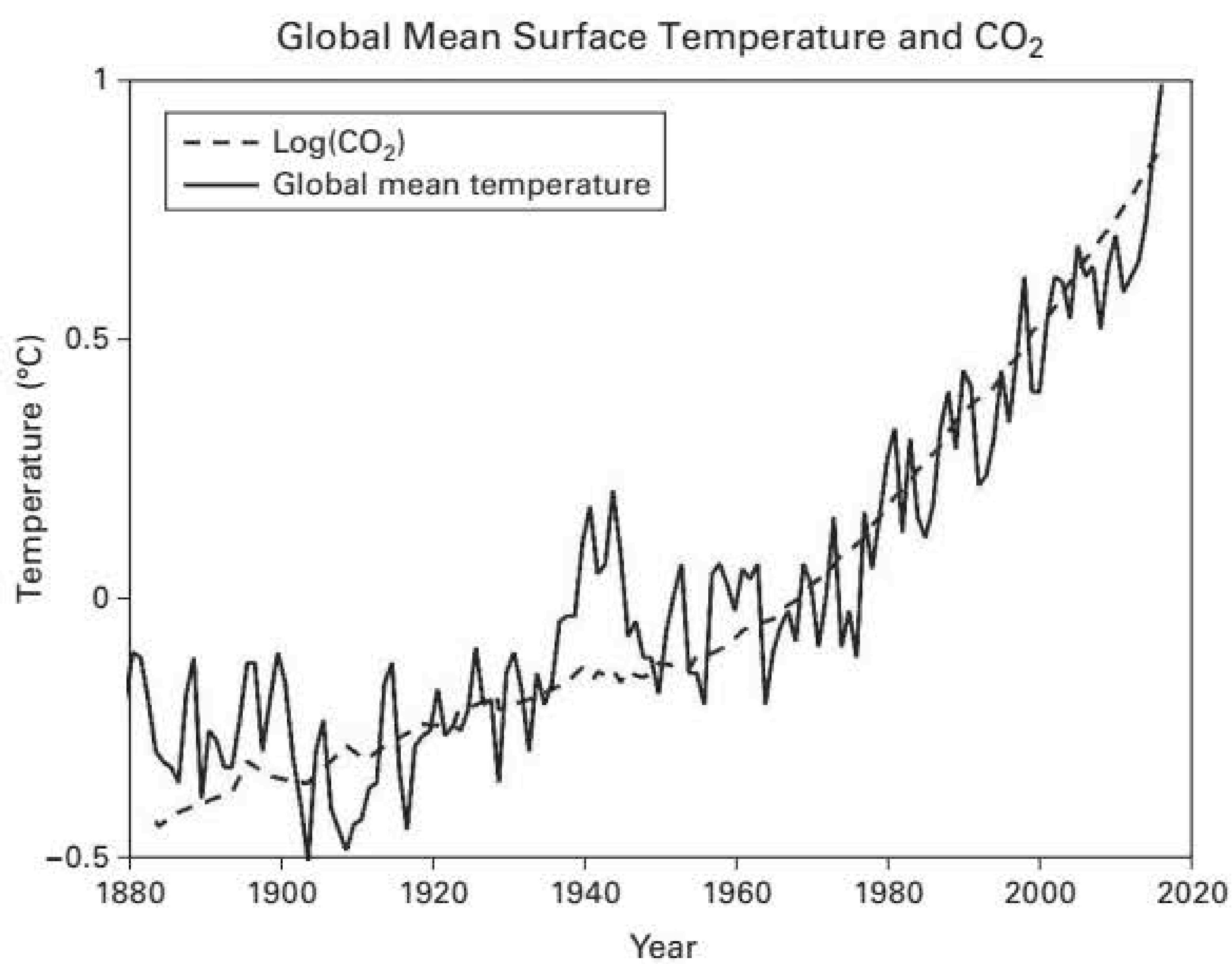

Figure 1
Natural logarithm of atmospheric CO_2 concentration (dashed), from ice cores and, after 1958, from direct measurements, compared to global mean temperature (solid) from the NASA Goddard Institute for Space Studies.

large volcanic eruptions, one can see that Arrhenius's prediction as so far been well verified.

The long residence time of CO_2 in the atmosphere implies that unless we can figure out an artificial way to remove it from the atmosphere, we will be stuck with increased levels of this important greenhouse gas and its associated climate anomalies for several millennia.

3

Why the Climate Problem Is Difficult

Basic climate physics is entirely uncontroversial among scientists.[1] And if one could change the concentration of a single greenhouse gas while keeping the rest of the system (except its temperature) fixed, it would be fairly simple to calculate the corresponding change in surface temperature. For example, doubling the concentration of CO_2 would raise the average surface temperature by about 1.9°F, enough to detect but probably not enough to cause serious problems.

But, of course, it's not actually that simple. Almost all of the uncertainty in climate science arises from the fact that, in reality, changing any single component of the climate system will indirectly cause other components of the system to change as well. These knock-on effects are known as feedbacks, and the most important and uncertain of these involves water.

There is a fundamental difference between water and most other greenhouse gases. Whereas a molecule of carbon dioxide or methane might remain in the atmosphere for hundreds or thousands of years, water is constantly recycled between the atmosphere, land surface, and oceans, so that a particular molecule of water resides in the atmosphere for, on average, about two weeks. On climate time scales, which are much longer than two weeks, atmospheric water vapor is tightly controlled by temperature and by physical processes operating within clouds. If one were to deposit a huge pulse of water vapor in the atmosphere, it would be gone in a few weeks.

Water vapor and clouds are the most important greenhouse substances in the atmosphere; clouds affect climate not only by emitting infrared radiation toward the surface and warming it up but also by reflecting sunlight back into space, thus cooling the planet.

Water is carried upward from its source at the surface by convection currents, which themselves result from greenhouse-induced warming of the surface. Simple physics as well as detailed calculations using computer models of clouds show that the amount of water vapor in the atmosphere is sensitive to the details of the physics by which tiny cloud droplets and ice crystals combine into larger raindrops and snowflakes, and how these in turn fall and partially re-evaporate on their way to the surface. The devil in these details seems to carry much authority with climate.

This complexity is limited, however, because the amount of water in the atmosphere is subject to a fundamental and important constraint. The concentration of water vapor in any sample of air has a strict upper limit that depends on its temperature and pressure. In particular, this limit rises very rapidly with temperature. The ratio of the actual amount of water vapor in a sample to this limiting amount is the familiar quantity called *relative humidity*. Calculations based on a large variety of computer models and observations of the atmosphere all show that as climate changes, relative humidity remains approximately constant. This means that as atmospheric temperature increases, the actual amount of water vapor increases as well. Water vapor is a greenhouse gas, though, and so increasing temperature increases water vapor, which leads to further increases in temperature. This positive feedback in the climate system is the main reason that the global mean surface temperature is expected to increase somewhat more than the 1.9°F that doubling CO_2 would produce in the absence of feedbacks. (At very high temperatures, the water vapor feedback can run away, leading to the catastrophe of a very hot planet with no oceans. This apparently happened on Venus, whose mean surface temperature is about 900°F, despite the fact that it absorbs less sunlight than earth, thanks to its very extensive and reflective cloud cover.)

The amount and distribution of water vapor in the atmosphere is also important in determining the distribution of clouds, which play a complex role in climate. On the one hand, they reflect about 22 percent of incoming solar radiation back to space, thereby cooling the planet. On the other hand, water vapor and clouds absorb solar radiation, and both absorb and emit infrared radiation, thus contributing to greenhouse warming. As anyone who has spent time gazing at the sky knows, clouds can assume beautiful and intricate patterns; capturing such patterns in computer models is challenging, to say the least. Thus it is hardly surprising that different global climate models produce different estimates of how clouds might change with changing climate. This is the largest source of uncertainty in climate-change projections.

A further complication in this already-complex picture comes from aerosols: minute solid or liquid particles suspended in the atmosphere. Industrial activity and biomass burning have brought about large increases in the aerosol content of the atmosphere, which most researchers agree have had a large effect on climate. Of the anthropogenic aerosols, the main objects of concern are sulfate aerosols, which are created through atmospheric chemical reactions involving sulfur dioxide, a gas produced by the combustion of fossil fuels. These tiny particles reflect incoming sunlight and, to a lesser degree, absorb infrared radiation. Perhaps more important, they also serve as condensation nuclei for clouds. When a cloud forms, water vapor does not form water droplets or ice crystals spontaneously but instead condenses onto preexisting aerosol particles. The number and size of these particles determine whether the water condenses into a few large droplets or many small ones, and this in turn strongly affects the amount of sunlight that clouds reflect and the amount of radiation they absorb.

It is thought that aerosols, in the aggregate, cool the planet because the increased reflection of sunlight to space—both directly by the aerosols themselves and through their effect on increasing the reflectivity of clouds—is believed to outweigh any increase in their greenhouse effect. Unlike the greenhouse gases, however, sulfate aerosols remain in the atmosphere for only a few weeks before they are washed out by rain and snow. Their abundance is proportional to their rate of production: as soon as their production decreases, concentrations of sulfate aerosols in the atmosphere drop. Since the late 1980s, improved technology and evermore stringent regulations, aided by the collapse of the USSR and the subsequent reduction and modernization of industrial output there, have diminished sulfate aerosol pollution in developed countries. On the other hand, sources of sulfate aerosols have been increasing in such rapidly developing countries as China and India, so the net aerosol content of the atmosphere may increase again.

Besides the uncertainties in the clouds and airborne particles that affect our climate system, there is another important source of uncertainty in attributing both past and future climate change to changes in solar radiation and atmospheric composition: our climate would change with time even if all of these factors were unchanging. This is because, like weather, climate varies all on its own. It is, on some level, a chaotic system.

The essential property of chaotic systems is that small differences tend to magnify rapidly. Think of two autumn leaves that have fallen next to each other in a turbulent brook. Imagine following them as they move downstream on their way to the sea: at first, they stay close to each other, but then the eddies in the stream gradually separate them. At some point, one of the leaves may get temporarily trapped in a whirlpool behind a rock while the other continues downstream. It is not hard to imagine that one of the leaves arrives at the mouth of the river days or weeks ahead of the other. It is also not hard to imagine that a mad scientist, having equipped our brook with fancy instruments for measuring the flow of water and devised a computer program that uses the measurements to predict where the leaves would go, would nevertheless find it almost impossible to pinpoint where the leaves would be even an hour after they started their journey.

Let's go back to the two leaves just after they have fallen in the brook and say that at this point they are 10 inches apart. Suppose that after 30 minutes they are 10 feet apart, and this distance increases with time. Now suppose that it were possible to rewind to the beginning but this time start the leaves only five inches apart. It would not be surprising if it took longer—say an hour—before they are once again 10 feet apart. Keep rewinding the experiment, each time decreasing the initial distance between the leaves. You might suppose that the time it takes to get 10 feet apart keeps increasing indefinitely. But for many physical systems (probably including brooks), this turns out not to be the case. As you keep decreasing the initial separation, the increases in the amount of time it takes for the leaves to be separated by 10 feet get successively smaller, so much so that there is a definite limit: no matter how close the leaves are when they hit the water, it will not take longer than, say, six hours for them to be 10 feet apart.

The same principle applies if, instead of having two leaves, we have a single leaf and a computer model of the leaf and the stream that carries it. Even if the computer model is perfect and we start off with a perfect representation of the state of the brook, any error—even an infinitesimal one—in the timing or position of the leaf when it begins its journey will lead to the forecast being off by at least 10 feet after six hours, and greater distances at longer times. *Prediction beyond a certain time is impossible*. It is important to understand that this limit to our ability to predict chaotic systems is a fundamental property of such systems; it is not possible, even in principle, to foresee the outcomes of such chaotic systems in detail beyond certain time limits.

Not all chaotic systems have this property of limited predictability, but our atmosphere and oceans, alas, almost certainly do. As a result, it is thought that the upper limit of the predictability of weather is around two weeks. (Our failure thus far to have reached this limit speaks to the imperfection of our models and our measurements.)

While the day-to-day variations of the weather are perhaps the most familiar examples of environmental chaos, variations at longer time scales can also behave chaotically. El Niño is thought to be chaotic in nature, making it difficult to predict more than a few months in advance. Other chaotic phenomena involving the oceans have even longer time scales.

On top of the natural, chaotic variability of weather and climate are changes brought about by variable "forcings," a term for agents of climate change that are not themselves strongly affected by climate. The most familiar of these is the march of the seasons, brought about by the tilt of the earth's axis, which itself is nearly independent of climate.[2] The effects of this particular forcing are not hard to separate from the background climate chaos: we can confidently predict that in New York, say, January will be colder than July, even though we cannot predict detailed weather there six months in advance. Other examples of natural climate forcing include variations in solar output and volcanic eruptions, which inject aerosols into the stratosphere and thereby cool the climate.

Some of this forcing is predictable on long time scales. For example, barring some catastrophic collision with a comet or asteroid, variations of the earth's orbit are predictable many millions of years into the future. On the other hand, volcanic activity is unpredictable. In any event, the climate we experience reflects a combination of "free" (unforced), chaotic variability, and changes brought about by external forcings, some of which, like volcanic eruptions, are themselves chaotic. Part of the recent forced climate variability has been brought about by human beings.

Distinguishing the forced response of the climate system from its chaotic natural variability requires a detailed understanding of the character of the latter, often referred to as "climate noise." Current estimates of this noise come largely from climate models run for a long time with constant forcing. These estimates suggest that the current global warming trend is clearly distinguishable from climate noise on time scales of around 30 years and longer. Just as a particular week in mid-spring may be colder than a particular week in late winter, there can be stretches as long as 30 years during which, owing to natural chaotic variability, the global mean temperature cools. Thus, for example, the lack of appreciable global warming over the first decade of the current millennium is, contrary to the claims of some, entirely consistent with the simultaneous occurrence of climate noise and greenhouse gas-induced warming. The record high temperatures of 2014, 2015, and 2016 put a predictable end to this "hiatus" (see figure 1).

4

Determining Humanity’s Influence

How do we tell the difference between natural climate variations—both free and forced—and those that are caused by our own activities?

One way to tell the difference is to make use of the fact that the increase in greenhouse gases and sulfate aerosols dates back only to the Industrial Revolution of the nineteenth century: before that, the human influence is probably small. If we can estimate how climate changed before this time, we will have some idea of how the system varies naturally. Unfortunately, detailed measurements of climate did not themselves begin in earnest until the nineteenth century, but there are "proxies" for certain climate variables such as temperature. These proxies include the width and density of tree rings, the chemical composition of ocean and lake plankton, and the abundance and type of pollen.

Plotting the global mean temperature derived from actual measurements and from proxies going back a thousand years or more reveals that the recent upturn in global temperature is truly unprecedented: the graph of temperature with time shows a characteristic hockey-stick shape, with the business end of the stick representing the upswing of the last 50 years or so. The proxies are imperfect, however, and have large margins of error, so any hockey-stick trends of the past may be masked, but the recent upturn in global temperature still stands above even a liberal estimate of such errors.[1]

Another way to tell the difference is to simulate the climate of the last hundred years or so using computer models. Computer modeling of global climate is perhaps the most complex endeavor ever undertaken by humankind. A typical climate model consists of millions of lines of computer instructions designed to simulate an enormous range of physical phenomena, including the flow of the atmosphere and oceans; condensation and precipitation of water inside clouds; the transport of heat, water, and atmospheric constituents by turbulent convection currents; the transfer of solar and terrestrial radiation through the atmosphere, including its partial absorption and reflection by the surface, clouds, and the atmosphere itself; and vast numbers of other processes. There are by now a few dozen such models, but they are not entirely independent of one another, often sharing common pieces of computer code and common ancestors.

Although the equations representing the physical and chemical processes in the climate system are well known, they cannot be solved exactly. It is computationally impossible to keep track of every molecule of air and ocean, so to make the task viable, the two fluids must be divided up into manageable chunks. The smaller and more numerous these chunks, the more accurate the result, but with today's computers the smallest we can make these chunks in the atmosphere is around 50 miles in the horizontal and a few hundred yards in the vertical. We model the ocean using somewhat smaller chunks. The problem here is that many important processes happen at much smaller scales. For example, cumulus clouds in the atmosphere are critical for transferring heat and water upward and downward, but they are typically only a few miles across and so cannot be simulated by the climate models. Instead, their effects must be represented in terms of quantities such as wind speed, humidity, and air temperature that are averaged over the whole computational chunk in question. The representation of these important but unresolved processes is an art form known by the awkward term *parameterization*, and it involves numbers, or parameters, that must be tuned to get the parameterizations to work in an optimal way. Because of the need for such artifices, a typical climate model has many tunable parameters that one might think of as knobs on a large, highly complicated machine. This is one of many reasons that such models provide only approximations to reality. Changing the values of the parameters or the way the various processes are parameterized can change not only the climate simulated by the model, but also the sensitivity of the model's climate to, say, greenhouse gas increases.

How, then, can we go about tuning the parameters of a climate model so that it serves as a reasonable facsimile of reality? Here important lessons can be learned from our experience with those close cousins of climate models, weather-prediction models. These are almost as complicated and must also parameterize key physical processes, but because the atmosphere is measured in many places and quite frequently, we can test the model against reality several times per day and keep adjusting its parameters (that is, tuning it) until it performs as well as it can. In the process we come to understand the inherent accuracy of the model. But in the case of climate models, there are precious few tests. One obvious test is whether the model can replicate the current climate, including key aspects of its variability, such as weather systems and El Niño. It must also be able to simulate the seasons in a reasonable way: summers must not be too hot or winters too cold, for example.

Beyond a few simple checks such as these, however, there are not many ways to assess the models, and so projections of future climates must be regarded as uncertain. The amount of uncertainty in such projections can be estimated to some extent by comparing forecasts made by many different models, given their different parameterizations (and, very likely, different sets of coding errors). We operate under the expectation that the real climate will fall among the projections made with the various models—that the truth, in other words, will lie somewhere between the higher and lower estimates generated by the models. It is not inconceivable, though, that the actual solution will fall outside these limits.

While it is easy to stand on the sidelines and take shots at these models, they represent science's best effort to project the earth's climate over the next century or so. At the same time, the large range of possible outcomes is an objective quantification of the uncertainty that remains in this enterprise. Still, those who proclaim that the models are wrong or useless usually are taking advantage of science's imperfections to promote their own prejudices. Uncertainty is an intrinsic feature of prediction, and it works in both directions.

Figure 2 shows the results of two sets of computer simulations of the global average surface temperature during the twentieth century, using a particular climate model. In the first set, denoted by the dotted line and lighter shade of gray, only natural, time-varying forcings are applied. These consist of variable solar output and "dimming" owing to aerosols produced by known volcanic eruptions. The second set (dashed line and darker shade of gray) incorporates human influence on sulfate aerosols and greenhouse gases. Each set of simulations is run four times beginning with slightly different initial states, and the range of outcomes produced is denoted by the shading in the figure. This range reflects the random fluctuations of the climate produced by this model, while the bold curves show the average of the four ensemble members. The observed global average surface temperature is depicted by the black curve. The two sets of

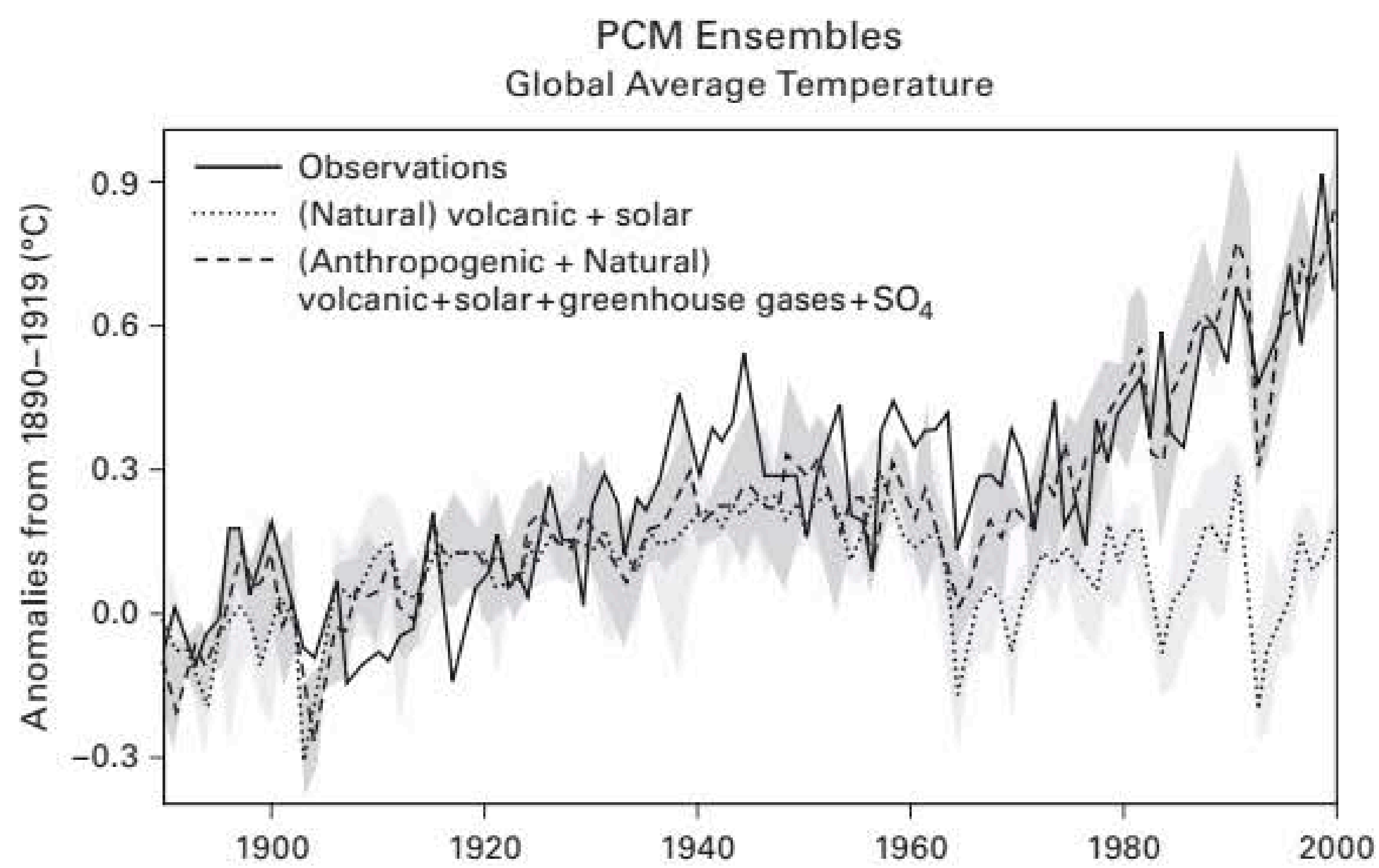

Figure 2

Showing the results of two sets of computer simulations of the global average surface temperature of the twentieth century using a climate model. In the first set, denoted by the dotted line and lighter shade of gray, only natural, time varying forcings are applied. The second set (dashed line and darker gray) adds in the man-made influences. In each set, the model is run four times beginning with slightly different initial states, and the range among the four ensemble members is denoted by the shading in the figure while the gray curves show the average of the four ensemble members. The observed global average surface temperature is depicted by the black curve.

simulations diverge during the 1970s and have no overlap at all today. The observed global temperature also starts to fall outside the envelope of the all-natural simulations in the 1970s.

This exercise has been repeated using many different climate models, with the same qualitative result: one cannot accurately simulate the evolution of the climate over the last 30 years without accounting for the human input of sulfate aerosols and greenhouse gases. This is one (but by no means the only) important reason that almost all climate scientists today believe that man's influence on climate has emerged from the background noise of natural variability. But the main reason remains the elementary physics that Arrhenius used to predict the global response to increasing greenhouse gases, long before the computer age.

5
The Consequences