

Climate Science and Climate Risk: A Primer

By Dr. Kerry A. Emanuel

*Professor of Atmospheric Science
Massachusetts Institute of Technology*

email: emanuel@mit.edu

website: <http://eaps4.mit.edu/faculty/Emanuel/>



Considerably more than 90% percent of climate scientists attribute the bulk of the increase in global mean temperature over the past three to four decades to the anthropogenic increase in atmospheric greenhouse gases that commenced with the Industrial Revolution.¹ The great majority of these scientists hold that continued warming presents significant risks to humankind over the coming centuries. What scientific evidence led the scientific community to these conclusions? How robust is that evidence? To what extent should we trust uncertain projections of future climate change based on complicated global climate models? How do we deal with climate change as a problem of risk assessment and management?

This essay summarizes the most important lines of evidence for anthropogenic climate change, confronts some of the stickier questions behind uncertainty in climate projections, and concludes with a discussion of the particular risks entailed by climate change and how they are being quantified.

The essay is structured as follows. First, a brief history of climate science reveals that the most important principles underlying the field were established more than a century ago. A brief tutorial on the greenhouse effect follows and provides evidence that we are altering the concentrations of important greenhouse gases and consequently altering our climate. Trends in global mean temperature over the last century are then set in the context of climate change over much of earth's history, and the causes of past and present climate change are reviewed, addressing the question of whether some of the mechanisms underlying past climate change—such as changing sunlight and orbital forcing—could explain the extraordinarily rapid warming of the past several decades. The concept of a climate model is explained, and the use of such models to estimate future climate change is illustrated. Finally, climate change is presented as a problem of risk assessment and management, and quantitative estimates of individual climate risks to the United States are given.

But, first, a brief note about science itself.

A NOTE ABOUT SCIENCE AND THE SCIENTIFIC METHOD

Put simply, science is the pursuit of objective truth and proceeds under the assumption that there is an objective universe external to the human mind. Scientific inquiry is driven mostly by innate curiosity about how nature works; most scientists I know genuinely love what they do and are in it for discovery.

Sometimes, progress begins with an observation that does

not fit within the existing scientific framework. Scientists then try to repeat and improve on the observation to determine whether it really is an outlier. Next, they may pose one or more hypotheses to explain the observation, and if a hypothesis succeeds in explaining not only that observation but others as well, and especially if it successfully predicts what has not yet been observed, the hypothesis may advance to the status of a theory. In science, *theory* pertains to a principle or set of principles that have been convincingly well established. Thus it is usually not reasonable to say that something is “just a theory” in the realm of science. (However, it may not be unreasonable to say that some idea is “just a hypothesis.”) If the theory of general relativity were “just a theory,” no one's GPS would work.

Scientists rarely refer to “facts” or speak about anything being settled. We are by our very nature skeptical, and a good way for a young scientist to advance is to overturn or significantly modify a generally accepted principle. But well-accepted theories are rarely rejected outright; they are much more likely to be subtly modified. For example, Newton's law of motion was not really overturned by Einstein's theory of relativity; it was modified to be even more precise.

In climate science, the word *skeptic* was hijacked some time ago by the media and certain political groups to denote someone who, far from being skeptical, is quite sure that we face no substantial risks from climate change.

The vast majority of climate scientists, as well as all scientists, are truly skeptical. Science is a deeply conservative enterprise: we hold high bars for reproducibility of observations and experiments, and for detecting signals against a noisy background. Most of us are careful to quantify uncertainty as a matter of intellectual honesty. For example, when a meteorologist says there is a 70% chance of rain tomorrow, that probability is not pulled out of a hat but rather is based on a slew of objective guidance. Cynics often use forecast uncertainty to claim that forecasters do not know what they are talking about, but most of us accept it as

1 Cook et al., 2016: Consensus on consensus: A synthesis of consensus estimates on human-caused global warming. *Environ. Res. Lett.* 11, <http://iopscience.iop.org/article/10.1088/1748-9326/11/4/048002>.

an honest appraisal of the degree of uncertainty. In science, uncertainty must never be confused with ignorance.

Lastly, being conservative about risk is quite different from being conservative about accepting theories and observations. An incautious person will bet on the high probability that his or her house will not burn down. A conservative person buys insurance. Risk assessment is also a science, and the economics of risk demand that we convolve the probability of something happening with its cost to arrive at a true portrait of the risk.

A BRIEF HISTORY OF CLIMATE SCIENCE

It is important first to recognize that progress in climate science dates from more than 200 years ago. By the middle of the 19th century, scientists understood that the earth is heated by sunlight and would keep warming up indefinitely unless it had some way of losing energy. They knew that all objects radiate energy and that the earth radiates it in the form of infrared radiation. Infrared radiation is a form of light but with longer wavelengths than can be seen by the human eye. However, it can be measured by instruments, including infrared glasses that combat soldiers use to “see” in the dark. The hotter the object, the more radiation it emits, and the shorter the wavelength of the emitted radiation. The sun’s surface temperature is about 6,000 kelvins (about 11,000 °F)², and it emits mostly visible light, while the earth’s effective emission temperature is closer to 250 kelvins (−9 °F), and so it emits much less radiation, and at a much longer (infrared) wavelength.

In 1820, the French polymath Jean Baptiste Fourier calculated how warm the earth’s surface had to be to emit as much radiation as it receives from the sun, so that the temperature of the planet could remain constant. He found that his estimate was much too low. He reasoned that the atmosphere must absorb some of the infrared radiation and emit some of it back to the surface, thereby warming it. But he did not have enough information about the atmosphere to test this idea.

It was left to the Irish physicist John Tyndall to solve that problem. He used an experimental apparatus of his own design to carefully measure the absorption of infrared radiation as it passed through a long tube filled with various gases. His measurements astonished him and the whole scientific community of the mid-19th century. Tyndall found that the main constituents of our atmosphere—oxygen and

nitrogen, which together constitute about 98% of air—have essentially no effect on the passage of either visible or infrared radiation. But a few gases he tested, notably water vapor, carbon dioxide, and nitrous oxide, strongly absorb infrared radiation, and water vapor also absorbs some visible light.

Tyndall’s discovery was entirely empirical, based on careful laboratory experiments and measurements. The fundamental physics of the absorption and emission of radiation by matter would not be understood theoretically until the development of quantum mechanics in the early 20th century. According to this physics, symmetrical molecules with only two atoms—nitrogen (N₂) and oxygen (O₂), for example—hardly interact with radiation, but more complex molecules like water vapor (H₂O—two atoms of hydrogen and one of oxygen) and carbon dioxide (CO₂—one atom of carbon and two of oxygen) are not symmetrical and can interact much more strongly with radiation.

Thus by the time of the American Civil War, it was well known that the absorption and emission of radiation in our atmosphere is due to a handful of gases that make up less than 1% of air. We now know that without that 1% the average surface temperature would be near freezing, and we would not be here to measure it. While this phenomenon may seem deeply nonintuitive, it has been verified countless times by theory and experiment. And variations of these greenhouse gases, along with variations in sunlight, volcanoes, and wobbles in the earth’s orbit, have played an important role in climate variations over Earth’s history.

THE ESSENCE OF THE GREENHOUSE EFFECT

Why does the absorption and emission of infrared radiation by the atmosphere warm the planet? This concept is actually quite easy to understand, though it is often explained poorly or even wrongly. When the greenhouse gases (and clouds, which also act as greenhouse agents) absorb infrared radiation, most of which comes from the surface and lower layers of the atmosphere, they must reemit radiation, otherwise the temperature of the atmosphere would increase indefinitely. This reemission occurs in all directions, so that half the radiation is emitted broadly downward and half broadly upward. The downward part is absorbed by the earth’s surface or lower portions of the atmosphere. Thus, in effect, the earth’s surface receives radiant energy from two sources: the sun, and the back-radiation from the greenhouse gases and clouds in the

² A kelvin (abbreviated K) is a measure of absolute temperature; no material can have a temperature of less than 0 K (the so-called absolute zero). The freezing temperature of water is 273 K, and its boiling temperature at sea level pressure is 373 kelvins. The temperature in Celsius is the temperature in kelvins minus 273 (e.g., 373 K − 273 = 100 °C.)

atmosphere, as illustrated in Figure 1. Now here is something surprising: on average the earth's surface receives almost twice as much radiation from the atmosphere as it does directly from the sun, mostly because the atmosphere radiates 24/7, while the sun shines only part of the time. This is how powerful the greenhouse effect is.

The surface must get warm enough to lose enough heat to balance both sunlight and back-radiation from the atmosphere and clouds within it. That is the greenhouse effect.

It should be remarked here that none of the preceding is remotely controversial among scientists, not even those few who express skepticism about global warming.

But not all greenhouse gases are created equal. The most important such gas, because of its relatively high concentrations, is water vapor, which can vary from almost nothing to as much as 3% of a volume of air. Also, condensed water (cloud) strongly absorbs and reemits radiation, and reflects sunlight as well. Next to water, carbon dioxide has the largest effect on surface temperature, followed by methane and nitrous oxide, and a handful of other gases whose concentrations are truly minute.

Water is constantly exchanged between the atmosphere and the earth's surface through evaporation and precipitation. This process is so rapid that, on average, a molecule of water resides in the atmosphere for only about two weeks.

The Greenhouse Effect

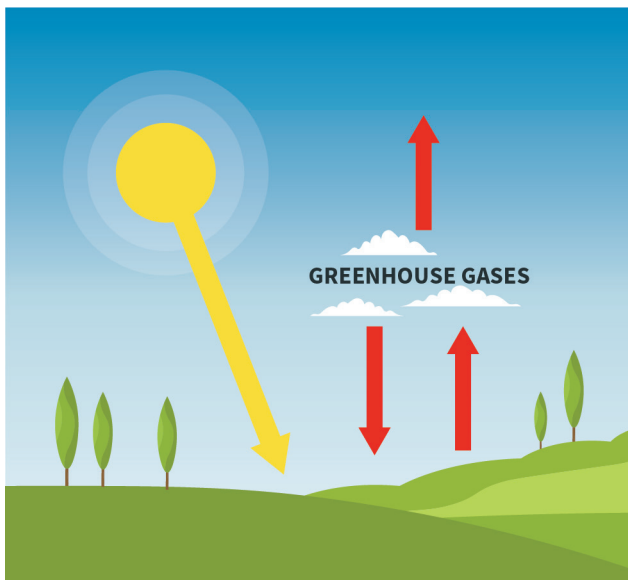


FIGURE 1: The earth's surface receives radiation not just from the sun (yellow arrow) but also from the atmosphere, in the form of infrared radiation (red arrows), which cannot be seen by the eye. Greenhouse gases and clouds in the atmosphere absorb some of the infrared radiation passing upward through them, and reradiate part of it downward.

The concentration of water vapor has an upper limit that is determined by air temperature—warmer air can support larger concentrations of water vapor. This is one reason that moisture varies so wildly from place to place and time to time. Another is that rain and snow can remove water from the air, so that its concentration can and often does fall well below the limit imposed by air temperature. The ratio of the actual amount of moisture in the air to its upper limit is what we refer to as *relative humidity*. Although relative humidity varies greatly, we observe that its long-term average is fairly stable, so to a first approximation, the actual amount of water in the atmosphere changes in tandem with its upper limit, that is, with temperature.

If we were magically to double the water vapor content of the atmosphere without changing its temperature, in roughly two weeks the excess water would be back where it belongs, in oceans, rivers, lakes, and groundwater. This would not be long enough to have much effect on climate. Temperature is the main determinant of the amount of water vapor in the atmosphere.

So, if the temperature rises, the amount of water vapor rises with it. But since water vapor is a greenhouse gas, rising water vapor leads to more back-radiation to the surface, which causes yet higher temperatures. We refer to this process as a *positive feedback*. Water vapor is thought to be the most important positive feedback in the climate system.

At the opposite extreme in terms of atmospheric lifetime is carbon dioxide. It is naturally emitted by volcanoes and absorbed by biological and physical processes that eventually incorporate the carbon into carbonate rocks like limestone. On geologic time scales, these rocks are subducted into the earth's mantle at convergent boundaries of tectonic plates, and the carbon is eventually released back into the atmosphere as carbon dioxide through volcanoes or when the rock is once again exposed to air and weathered. This cycle takes many tens to hundreds of millions of years. But CO₂ is exchanged between the atmosphere, ocean, and land plants on much shorter time scales. The bottom line is that if we were to instantly increase the concentration of CO₂ in the atmosphere, roughly half of it would be absorbed back into plants and the upper ocean after only 100 years or so, but the other half might take many thousands of years to be removed from the air. For this reason, long-lived greenhouse gases like carbon dioxide have an important influence on climate.

OUR EFFECT ON THE GREENHOUSE

Much of the preceding, save for the details of the processes that control atmospheric CO₂, was understood by the end of the 19th century. In particular,

the Swedish chemist and Nobel laureate Svante Arrhenius understood the effect of greenhouse gases on climate and that CO₂ is the most important long-lived greenhouse gas. He also understood that we were beginning to emit prodigious amounts of CO₂ into the atmosphere from industrial processes and was the first to worry that, owing to its long residence time in the atmosphere, we would perceptibly increase its concentration. In 1896 Arrhenius published a paper predicting that if we ever managed to double the concentration of CO₂, the average surface temperature of the planet would rise between 5 and 6 kelvins (9 and 11 °F), a number he revised downward to 4 kelvins (7 °F) in a popular book he published in 1908. Arrhenius arrived at these numbers by performing up to 100,000 calculations by hand, and although he made several incorrect assumptions, the resulting errors partially cancelled each other. It is truly remarkable that his 4 kelvins is within the range of the most recent estimates of 1.5–4.5 kelvins (2.7–8.1 °F). Arrhenius also understood that the radiative effects of CO₂ increase nearly logarithmically (rather than linearly) with its concentration, so that increasing CO₂ by a factor of 8 would produce about three (rather than four) times more warming than doubling it would.

Arrhenius predicted that increasing CO₂ would warm the planet. How did his prediction fare? Figure 2 compares Arrhenius's prediction based on atmospheric CO₂ concentrations with measured global mean surface temperature for the period from 1880 to 2010. The CO₂ content of the atmosphere was measured directly beginning in 1958; before that time (and going back for hundreds of thousands of years) we deduced its abundance by measuring

its concentration in gas bubbles trapped in ice cores.

Over the period of record, the global mean temperature generally follows the natural logarithm of the concentration of CO₂, just as Arrhenius predicted. At the same time, there are obvious deviations from this correlation. The shorter-period deviations mostly reflect the natural, chaotic variability of the climate system (an example of which is El Niño), while longer excursions are mostly due to other influences on climate, such as volcanoes and manmade aerosols. A lawyer may pick apart all these wobbles, but it is hard to avoid the conclusion from Figure 2 that the data largely vindicate a prediction made more than a century ago, based on simple physics and hand calculations. It stands to reason that more warming will occur if we continue to increase the concentration of CO₂ in the atmosphere.

But what if we are fooling ourselves? Correlation is not causation, and perhaps the correspondence of temperature and CO₂ is a coincidence—maybe something else is causing the warming. Or perhaps the rising temperature is causing CO₂ concentrations to increase and not the other way around. How accurate is the green curve in Figure 2—can we really measure the global mean temperature? Climate is always changing, so what is so special about the last 100 years? Are there other predictions of climate science that are verified or contradicted by observations?

These are all legitimate questions and deserve serious consideration; indeed, we would not be good scientists if we did not constantly ask ourselves such questions.

MEASUREMENTS OF TEMPERATURE OVER THE PAST 150 YEARS: HOW GOOD ARE THEY?

Let's begin with the instrumental record of global average surface temperature. Thermometers were invented in the 17th century, but it was not until the 19th century that people started to make systematic, quantitative measurements around the globe. Naturally, most of these were made from land-based stations, but it was not long before measurements were being taken of the temperature of ocean water at and near the surface. (Benjamin Franklin discovered the Gulf Stream by lowering a thermometer into the ocean from a ship.) Sea surface temperature was measured routinely from buckets of water retrieved from the sea, and then, beginning in the 1960s, by taking the temperature of engine intake water. By the late 1960s, these measurements were being augmented by satellite-based measurements of infrared radiation emitted from the sea surface.

In estimating global mean temperature, one must carefully account for the uneven distribution of temperature measurements around the world, changes in the precise

Global Mean Surface Temperature and CO₂

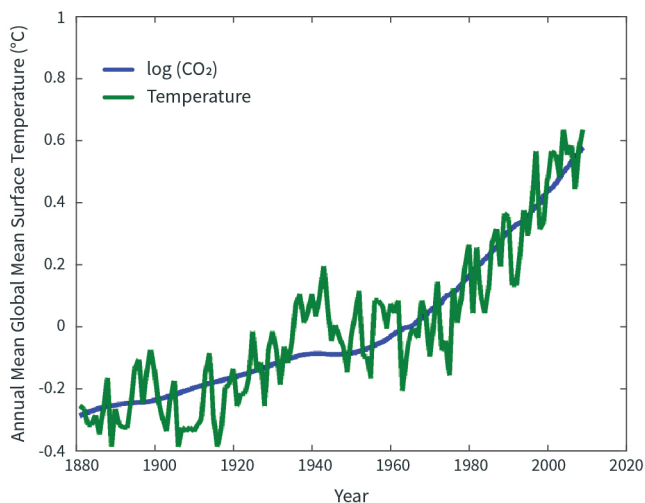


FIGURE 2: Annual, global mean surface temperature (green) and the natural logarithm of atmospheric CO₂ concentration (blue).

location and instruments used to measure temperature, the effects of growing urban areas that create *heat islands* that are warmer than the surrounding countryside, and myriad other issues that can bias global mean temperature. Different groups around the world have tackled these issues in different ways, and one way to assess the robustness of the temperature record is to compare their different results, as shown in Figure 3. The Berkeley Earth estimate, shown in black with gray uncertainty bounds, was undertaken by a group led by a physicist who was skeptical of the way atmospheric scientists had made their estimates. Even so, the four records agree with each other quite well after about 1900 and especially well after about 1950. The better and better agreement reflects the increasing number and quality of temperature measurements around the planet.

Theory and models predict that the air over land and at high latitudes should warm faster than that over the oceans, and this is observed (Figure 4). Global warming is neither predicted nor observed to be globally uniform, and there are even places where the temperature has dropped over the second half of the 20th century, thanks to changing ocean circulation, melting sea ice, and other processes. Note also in Figure 4 that some of the fastest warming is in places far removed from cities, like Siberia and northern Canada; in fact, at most 2%–4% of warming can be attributed to urbanization.³

So the measurements that underlie Figure 2 are pretty accurate. But how does that record of temperature and CO₂

fit with the longer-term climate record? Is it unusual or is it consistent with natural climate variability on 100-year time scales? Since we do not have good global temperature measurements before the 19th century we must turn to the fascinating field of paleoclimate, which seeks proxies for climate variables in the geologic record.

PALEOCLIMATE: EVIDENCE FROM THE GEOLOGICAL RECORD

There are many different proxies for temperature; all have advantages and drawbacks. Some are physical, like the temperature of water in deep boreholes—water that has been isolated from the surface for a long time and reflects a long history of temperature. Some are biological, like the width and density of tree rings. All these are local or at best regional metrics; there is no global “paleothermometer.”

Glacial Cycles in Temperature and Ice Volume

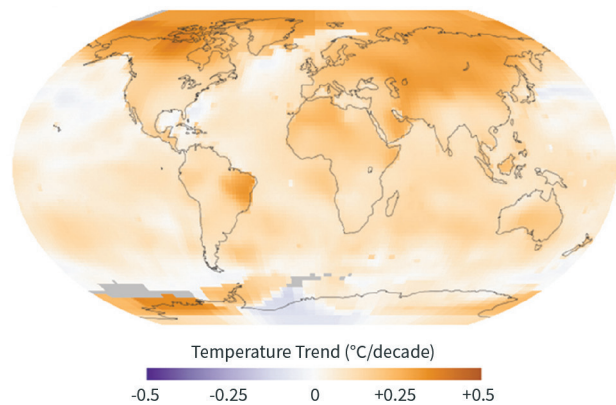


FIGURE 4: World map showing surface temperature trends (°C per decade) between 1950 and 2014. Source: NASA GISS. Also see https://en.wikipedia.org/wiki/Global_warming.

One particularly useful proxy relies on the physics of condensation and evaporation of water. Water (H₂O) is made of one oxygen atom and two hydrogen atoms. A standard oxygen atom consists of a nucleus with 8 protons and 8 neutrons, surrounded by a cloud of 8 electrons. But some oxygen atoms have 9 or 10 neutrons in their nucleus. These variants are called *isotopes*. Standard oxygen, with 8 neutrons, called ¹⁶O to denote the number of protons and neutrons, is by far the most abundant isotope, followed by ¹⁸O with 8 protons and 10 neutrons. A tiny percentage of water contains this heavier oxygen isotope, and it turns out that the

Decadal Land-Surface Average Temperature

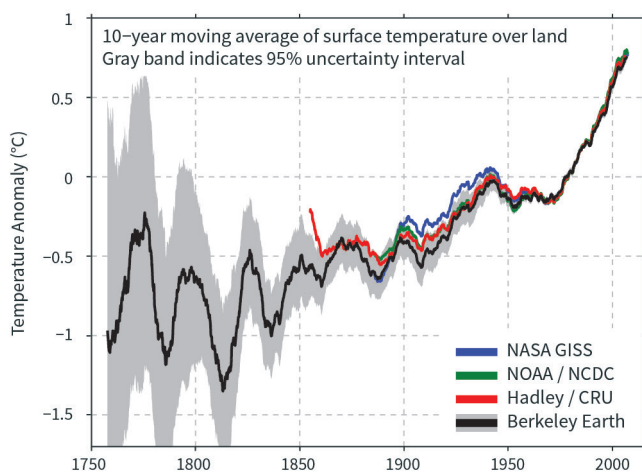


FIGURE 3: 10-year moving average of the global average temperature over land from 1750 to 2012. The blue curve is from the NASA Goddard Institute for Space Studies; the green, from NOAA’s National Climatic Data Center; the red, from the United Kingdom Hadley Center’s Climate Research Unit; and the black curve with gray uncertainty bounds, from the University of California’s Berkeley Earth Project.

3 Jacobson and Ten Hoeve, 2012: Effects of urban surfaces and white roofs on global and regional climate. *J. Climate* 25: 1028–1043.

ratio of the heavy to the light isotope in water contains is a very useful metric.

Ocean water has a particular oxygen isotope ratio. But when seawater evaporates, its molecules containing the lighter isotope evaporate slightly faster than the molecules containing the heavier isotope. So, water vapor is “lighter” than seawater, meaning the ratio of heavy to light isotopes is smaller. Likewise, when the evaporated water begins to condense into clouds, molecules made of the heavier isotope condense first, so that as the cloud rains out, the water vapor left behind becomes progressively “lighter,” as does the precipitation that subsequently forms from it. So the farther away the water vapor is from its source, the “lighter” it is. By “farther” we really mean “colder,” since the amount of water vapor in a cloud falls rapidly as the air cools.

Likewise, standard hydrogen atoms in water have one proton and no neutrons, but a few atoms have one neutron, and there are even a few with two neutrons. A hydrogen atom with one neutron is called *deuterium*, and the ratio of deuterium to normal hydrogen in water can also be used as a paleothermometer.

Thus the isotope ratios in rain and snow reflect the temperature of the cloud in which the rain or snow formed. In places like Greenland and Antarctica, much of the snow that falls accumulates and is progressively compacted by the weight of the snow on top of it, eventually forming ice. The ice is thus progressively older with depth in these ice sheets. Scientists drill down to collect solid cylinders of ice—ice cores—which they can analyze for many properties of the ice, including its isotopes, as a function of depth, or equivalently, age. The isotope ratios give a measure of the temperature of clouds that produced the snow originally. Modern measurements of the isotope ratios of recent snow show that they are highly correlated with surface air temperature, which is in turn correlated with the temperature of clouds above it. Thus we can use the isotope ratios as paleothermometers.

Figure 5 shows the record of temperature inferred from two ice cores in Antarctica, going back 450,000 years, as well as the volume of ice on the planet. You might be wondering how we know how much ice there was on Earth 450,000 years ago. Recall that as seawater evaporates, the lighter isotopes evaporate faster, and thus ice sheets, which form from condensed water vapor, have a higher concentration of lighter isotopes than seawater. As ice sheets grow, the heavier isotopes get left behind in the ocean, and so the ratio of heavier to lighter isotopes in seawater steadily increases. Thus the isotopic composition of seawater is a measure of how much land ice there is on the planet. Marine microorganisms incorporate these isotopic signatures in their shells, and when they die some of them settle to the seafloor, where they get incorporated in sediments. We can analyze these sediment

cores to get isotope ratios as a function of depth, and by other means determine the age of the sediments. Thus we can obtain a record of global ice volume with time.

You can see in Figure 5 that the lower the temperature, the higher the volume of ice on the planet, and vice versa. This makes sense! That the two curves—obtained from entirely different sources of data—agree so well testifies to the basic quality of the data underlying each.

It is plainly obvious that on the 100,000-year time scale, temperature is cyclic. These cycles are the great ice ages and interglacial periods, and the right edge of Figure 5 shows that we are in an interglacial period right now. The last ice age ended about 10,000 years ago—a geologic blink of the eye.

The figure also shows that the Antarctic temperature varied about 9 kelvins (16 °F) between the warmest and coldest periods. Other proxy estimates, models, and theory indicate that the tropics varied quite a bit less, so that the global mean temperature probably varied by about 5 kelvins (9 °F) between peaks and valleys.

WHAT CAUSED THE GREAT ICE AGES?

The cause of these nearly cyclic swings in temperature and the associated growth and retreat of great continental ice sheets was proposed by several scientists, notably by the Serbian mathematician Milutin Milanković in 1912. He recognized that the earth’s rotation axis precesses like a top and that its tilt with respect to the plane in which the earth

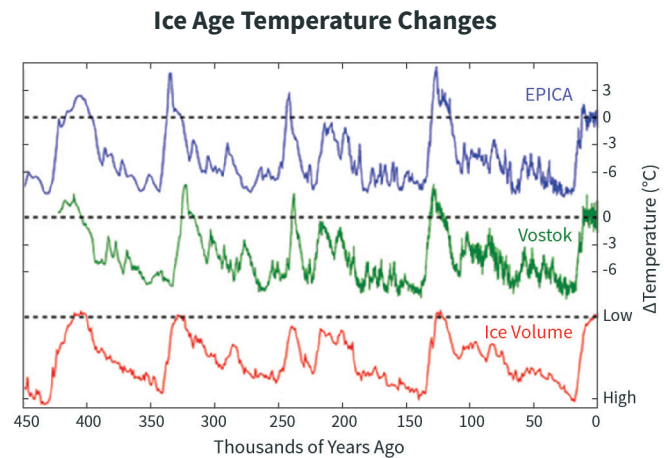


FIGURE 5: Temperature inferred from the deuterium ratios in two Antarctic ice cores (green and blue curves), and ice volume inferred from the oxygen isotope ratios of marine microfossils in ocean floor sediments (red curve). Note that the ice volume curve is flipped, so that high is on the bottom and low on the top, to make it easier to compare with temperature. Source: https://commons.wikimedia.org/wiki/File:Ice_Age_Temperature.png?uselang=en-gb.

orbits the sun also wobbles. Milanković also knew that the degree of elongation of the elliptical path of the earth's orbit around the sun varies cyclically over time. All these factors affect the way sunlight is distributed around the world, even though they hardly affect the total amount of sunlight summed over the planet. He speculated—correctly it turns out—that ice ages are controlled by how much sunlight is received by the Arctic region during summer and set about calculating this value from the basic laws of physics that control the earth's orbit and rotation. After years of hand calculation, Milanković produced a curve showing how ice ages should behave. At that time, data such as those used to produce Figure 5 did not exist, and so there was only rough agreement with what few data there were. But today we know that the great ice ages were caused by the cycles computed by Milanković, though there are gaps in our understanding of the details of how Earth's climate responded to these.

CLIMATE IS ALWAYS CHANGING

So, climate is always changing, at least on time scales of hundreds of thousands of years. Can the orbital mechanism explain the recent warming?

No, because the *Milanković forcing*, that is, the response of climate due to cyclical changes in Earth's orbit, is headed

downward now, and the planet should be cooling. This cooling is illustrated in Figure 6, which zooms in on the last 2000 years of temperatures in the Arctic, deduced using not just one but several proxies for temperature. (Note that the last 2000 years is a tiny, tiny spec on the far right side of Figure 5, so that part of the figure is greatly magnified in Figure 6.) The Arctic is a good place to look, because, as is clear in Figure 4 and from basic climate physics, climate signals are amplified at high latitudes.

The slow, steady cooling trend from the beginning of the record to around AD 1700–1800 probably reflects the slow decline in sunlight reaching the Arctic due to the Milanković orbital mechanism. Unimpeded, this mechanism would lead the earth toward another ice age, with continental ice sheets beginning to grow some thousands of years from now. But note the strong uptick in temperature toward the end of the record, particularly after about 1900. This is quite unusual by the standards of the last few thousand years and reflects the anthropogenic increase in carbon dioxide brought about by rapid consumption of fossil fuels.

Besides chemical proxies for temperature, there are physical proxies as well. Most of the world's alpine glaciers are retreating, and the snows of Kilimanjaro, about which Hemingway wrote so movingly, are on the verge of disappearing for the first time in at least 11,700 years.

2000 Years of Arctic Summer Temperature

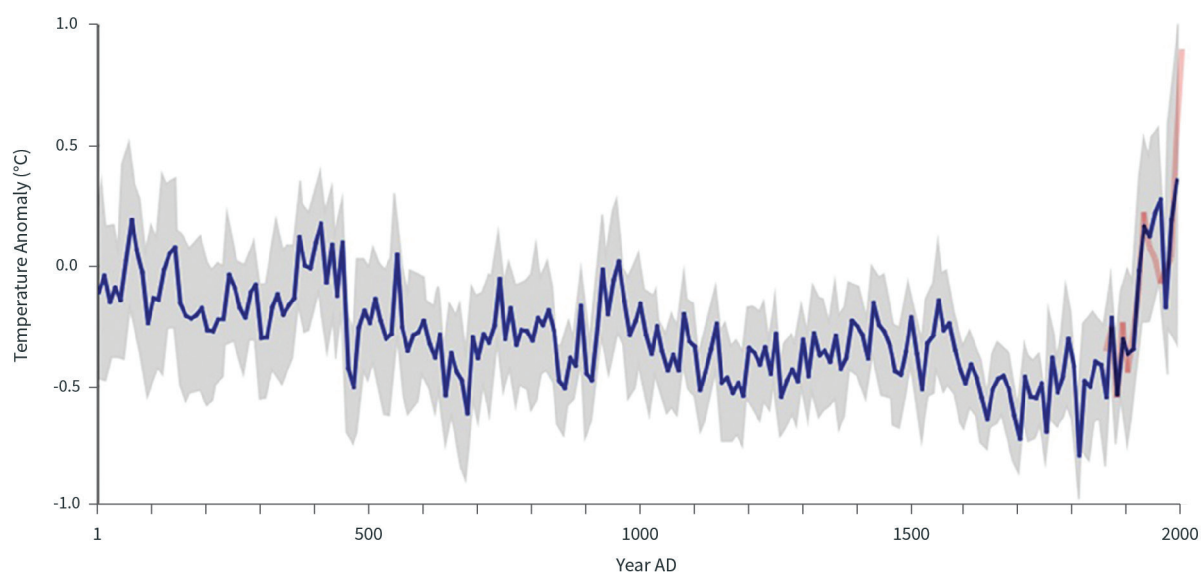


FIGURE 6: Estimated Arctic average summer temperature (°C) over the last 2000 years, based on proxy records from lake sediments, ice cores, and tree rings (blue). The gray shading represents the scatter among the 23 sites used to make this graph. The red line on the right side shows the instrumental Arctic temperature record over roughly the last century. From Kaufman et al., 2009, *Science* 325: 1236–1239.

HOW MUCH OF THE CO₂ INCREASE IS NATURAL?

So the evidence, from both theory and observations (we have not even talked about models yet), suggests that the warming of the last century is unusual by the standards of the last few thousand years and almost certainly caused by increasing atmospheric CO₂ concentrations. But could the trends in CO₂ concentration themselves be natural?

Almost certainly not. Figure 7 shows the history of atmospheric CO₂ and Antarctic temperature going back 800,000 years, thus covering many Milanković cycles. The CO₂ concentration was obtained from bubbles of air trapped in the ice cores.

Clearly, the atmospheric concentration of CO₂ does vary naturally, in tandem with temperature, ranging from about 180 to about 280 parts per million by volume (ppmv). But the Milanković cycles cannot account for the enormous spike at the end of the record, a spike to 400 ppmv that humans put there. There is no evidence that it has been that large for many millions of years. If we do nothing, and there is no global economic meltdown, we may reach well over 1000 ppmv by the end of this century.

A very close and careful analysis of the records of temperature and CO₂ in ice cores shows that during Milanković cycles, CO₂ mostly lags temperature, suggesting that the CO₂ variations were caused by the warming and cooling, not the other way around. In this case, the CO₂ was acting as a positive feedback, amplifying the Milanković oscillations. But in the last 100 years, the huge increase in CO₂

drove the temperature change. (The argument that one has to choose whether CO₂ is a forcing or a response is specious. The same agent can be a forcing in one circumstance and a response in another. Suppose you have a manual transmission car in first gear, pointed downhill, and you release the brake. The downhill motion of your car will spin up its engine. In fact, this is a good way to start your car if its battery is dead and you happen to be pointed downhill. But ordinarily, the engine powers the motion of the car.)

THE SUN

Another argument sometimes heard is that the big uptick in temperature of the last century or so was caused by increasing solar output. Looking at Figure 6, one would wonder why such a big change in our sun did not happen before. More to the point, since about 1980 scientists have been measuring with exquisite precision the amount of energy coming from the sun, using instruments placed in satellites high above the influence of our atmosphere. During that period, when much warming occurred, the satellites actually measured a slight decrease in solar output. While there is evidence that variations in solar output have caused climate to change in the past, these do not appear to explain the recent warming.

CLIMATE SCIENCE, CLIMATE PREDICTION, AND CLIMATE MODELS

The real issue, of course, is what will happen in the future. Although ultimately we want to know what the human and monetary risks are, we should start with something simpler, and it is natural now to ask how global temperature will evolve going forward.

Let's begin with a simple-minded approach. Suppose we just extrapolate the relationship between temperature and CO₂ concentration shown in Figure 2. Doing so gives a temperature increase of about 1.9 kelvins (about 3.5 °F) per doubling of CO₂. What's wrong with that?

There are two problems. First, CO₂ was not the only climate influence that changed over the past century or so. There were changes in other greenhouse gases, small changes in solar output, volcanic eruptions—which spewed sun-reflecting particles into the atmosphere, thereby cooling it—and manmade sulfur pollution, which does the same thing. So the temperature change reflects more than just greenhouse gas increases. Second, the world ocean acts as a huge buffer, absorbing most of the excess energy produced by increasing greenhouse gases. This causes the temperature of the planet

Temperature and CO₂ From Antarctic Ice Cores Over the Past 800,00 Years

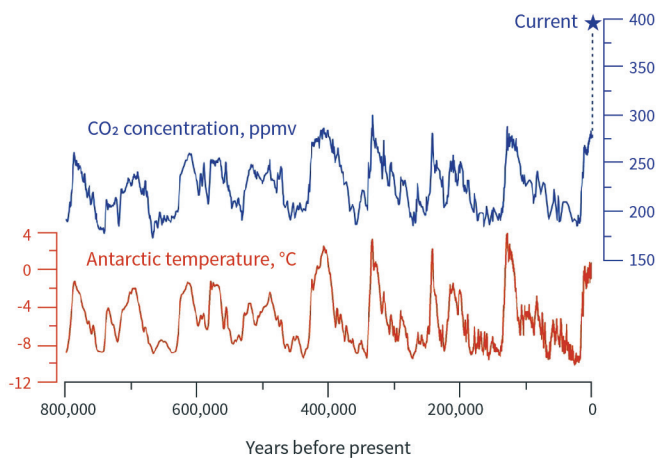


FIGURE 7: Atmospheric CO₂ (blue) and temperature (red) from Antarctic ice cores. The concentration of CO₂ in the year 2015 is shown by the star in the upper right. Data from Lüthi et al., 2008, *Nature*, 453, 379-382, and Jouzel et al., 2007, *Science*, 317, 793-797.

to lag well behind changes in CO₂. So even if the concentration of greenhouse gases leveled off right now, the planet would continue to warm for a while owing to the thermal lag effect of the ocean.

Here is a good way to think about the effect of the oceans. Suppose we have a sealed glass cylinder containing equal volumes of air and water. If it is just sitting at rest with no energy going in or out through the walls of the container, the air and water will settle down to the same temperature. Now heat the bottom of the cylinder for a few minutes and turn off the heater. After a while, once again the temperature of the air and water will be equal, but both will be warmer, say by 1 degree. But because the water is nearly 1,000 times as dense as air and can absorb a little more than 4 times the amount of heat per unit mass, the proportion of energy from the heater that went into warming the water was about 4,000 times more than the amount of energy used to heat the air.

Now let's do a second experiment. This time, add enough black dye to the water to make it opaque and shine a powerful flashlight down through the glass top of the cylinder. The light passes through the air but is absorbed at the very top of the water, heating it. So the top of the water warms up, and since that is the part that is in contact with the air, the air warms up too. But the water below the surface is not heated by the light, which never makes it down below the surface, so it remains at the temperature it had before. But slowly – very slowly—the warmth of the surface water is diffused down into the deep water and this both warms the deep water and cools the surface water and with it, the air.

Thus after we turn on the flashlight there will be an initial fast warming of the air and surface water, followed by a very slow increase in the temperature of the whole system. Eventually, the water and air will reach a new, warmer temperature. How long it takes to do so will depend on how rapidly heat diffuses downward into the deep water.

By analogy, we could account for the lag between heat input and temperature change in the real world if we had a simple theory for how heat penetrates the ocean depths. We know that heat is mixed rapidly downward to a depth of between 20 and 150 meters (60 and 150 feet), depending on location and time of year. If heat did not penetrate deeper, then the 20–150 meter penetration would give a lag of around two years, which would be hardly noticeable in Figure 2. But we know from measurements that heat manages to circulate much deeper in the ocean, taking quite a long time to do so. Just how this happens is complex, and for this and other reasons we turn to comprehensive climate models, about which more in due course.

We are not content, though, merely to extrapolate from the past. We would like to make predictions based on a rigorous understanding of climate science.

The basic theory of the interaction between radiation and the atmosphere has been stable for about 100 years. We can state with almost perfect certainty that if we double CO₂ concentration *and allow nothing but temperature to respond* (clouds, water vapor, vegetation, etc., are held fixed), the earth will warm up by about 1 kelvin (1.8 F). There is no controversy about this conclusion within the scientific community.

The problem, of course, is that these other features of the climate system *do* change. For example, as discussed previously, the water vapor content of the atmosphere varies, mostly in response to temperature itself. As the atmosphere warms, the concentration of water vapor increases. But water vapor is the most important greenhouse gas, and its increase leads to further warming. This is an example of a positive feedback in the system, and current understanding suggests that this factor alone more or less doubles the warming that occurs in response to increasing CO₂. But the true physics of climate is not that simple, and the distribution of water vapor is affected by many other variables besides temperature, so even here there is uncertainty.

Much more problematic are clouds, which, regarding radiation, work both sides of the street. They account for most of the reflection of sunlight by our planet, thereby cooling it. But they also absorb and reradiate infrared radiation (see Figure 1) just like greenhouse gases, thereby exerting a warming effect. Which effect wins depends on the altitude and optical properties of the clouds. At present, there is no generally accepted theory for how clouds respond to climate change.

To this problem we can add many other issues that reflect the immense, almost overwhelming complexity of the climate system. As sea ice melts, a white surface is replaced by dark ocean waters, which absorb more sunlight (another positive feedback). In some places, jungles, which are relatively dark, may be replaced by deserts, which are highly reflective—a negative feedback. The rate at which the oceans absorb excess CO₂ may itself change in response to changes in ocean temperature and concentration of dissolved CO₂.

To deal with the immense complexity of the climate system, scientists turn to comprehensive global climate models. The word *model* means many different things to different people and in different contexts. (I once asked a new graduate student how she had spent her undergraduate years. She told me she had done some modeling. “Computational fluids dynamics?” I asked. Looking puzzled, she replied, “No, clothes.”) Climate models, like models used for predicting weather, are computational devices for solving large sets of equations. These equations include those governing radiative transfer and the fluid equivalent of Newton's laws of motion. Using a computer to solve these equations is very similar to using a computer to, say, precisely land a

spacecraft on Mars. In this case, the computer is primarily solving equations encoding Newton's laws. These laws and equations that describe them are exact, which makes it possible to direct a spacecraft with great precision to a soft landing on a distant planet.

This type of modeling is quite different from, for example, economic modeling. Economic models also solve equations, but unlike with climate models, the equations are not fundamental but rather constructs based mostly on data from past economic behavior. For example, there are no known equations governing human behavior, so we have to, in essence, guess what they might look like if they existed, based on how economies have performed in the past. The reader may judge how successful such models have been. No one pretends that economic models may be made arbitrarily exact, even given many resources and much time over which to improve them.

Yet the comparison of climate models with the "models" used to land spacecraft is a little misleading. Although the equations governing climate are known rather precisely, there is no way they can be solved exactly using present-day computers. We cannot even begin to track each molecule of the climate system but must average over big blocks of space and time. For example, today's climate models typically average over blocks of the atmosphere that are 100 kilometers square and perhaps 1 kilometer thick, and over time intervals of several tens of minutes. This averaging introduces errors and skips over important climate processes. For example, cumulus convection—thunderstorms, for example—is the main way, other than radiation, that heat is transmitted vertically through the atmosphere. But cumulus clouds are only a few kilometers wide and so cannot possibly be simulated by models that average over 100 kilometer squares. Nevertheless, they must be accounted for, and so we turn to a technique awkwardly called *parameterization* to do so. Parameterizations represent processes that cannot be resolved by the model itself, and they attempt to be faithful to the equations underlying those processes. But many assumptions have to be introduced, and their efficacy is usually judged by how well they simulate past events. In many ways, parameterizations are closer in spirit to economic modeling than to programming spacecraft.

Thus climate and weather models are hybrids of strictly deterministic modeling (like programming spacecraft) and somewhat ad hoc parameterizations (closer to economic modeling). Weather models can be tested over and over again, every day, and thereby progressively refined. Today's weather models are far superior to those of a generation ago, partly because of improved computational technology, partly because of increased know-how, and partly because they

can be repeatedly tested against observations and refined. But climate evolves slowly, and so there are not that many climate states against which to test models. So, in contrast with weather forecasting, in climate modeling we have neither the history of success nor the confidence that comes with it. But the fundamentally chaotic nature of weather imposes a predictability horizon on weather forecasting, whereas with climate we are trying to predict the slow response of the long-term average statistics of the weather to changes in sunlight, CO₂, and other factors. For this kind of prediction, there may not be a fundamental predictability horizon. (We can say with confidence that summer will be warmer than winter for as many years in advance as we care to.)

Even here, though, we are on shaky ground. Very simply mathematical models of climate-like systems can exhibit sudden, unpredictable shifts, even though the evolution of the system between these shifts can be quite predictable. (The great mathematician and atmospheric scientist Edward Lorenz, the father of chaos theory, was fascinated by such systems.) We do not know for sure whether our climate is an example of such a system, but there is evidence encoded in ice cores from Greenland that ice age climates can jump rather quickly from one state to another. This evidence, together with behavior of some simple models, puts mathematical teeth on the idea of *tipping points*—sudden and largely unpredictable shifts in the climate state. This idea keeps many a climate scientist awake at night.

So, as the Danish physicist Niels Bohr once remarked, "Prediction is very difficult, especially about the future." There are roughly 40 climate models run by different organizations around the world, and they all give somewhat different predictions about the response of climate to increasing concentrations of greenhouse gases. In addition, we have to estimate just how the greenhouse gas content of the atmosphere will evolve over the coming centuries, which requires not just an understanding of the physics, chemistry, and biology controlling these gases but an assessment of human behavior—how much greenhouse gas will we end up emitting?

This is a problem of economic and behavioral forecasting, including, very importantly, predicting population growth. Will developed nations learn how to better conserve energy? Will the economies of countries like India expand rapidly, as China's did, leading to rapid growth in energy demand? How far will low-carbon energy technologies penetrate the energy sector? There are strong interdependencies among these issues. For example, recent experience shows that as gross national product per capita expands together with per capita energy consumption, population growth tends to level off, ameliorating the growth in energy demand. All these factors strongly affect greenhouse gas emissions.

To deal with all this, the Intergovernmental Panel on Climate Change (IPCC⁴) came up with a set of just four “representative concentration pathways” (RCPs), expressing plausible evolutions of greenhouse gases and other anthropogenic influences on climate, such as aerosols. These are labeled with the associated net radiative forcing in the year 2100; so, for example, RCP 6.0 has a radiative forcing of 6 watts per square meter by the year 2100. (For comparison, doubling CO₂ produces a radiative forcing of about 4 watts per meter squared.) Figure 8 shows the evolutions of these concentration pathways, expressed as though all the forcing is due to CO₂ alone. (That is, we take the radiative forcings associated with other greenhouse gases like methane and nitrous oxide, and with aerosols, and convert them into CO₂-equivalent units.)

The red curve in Figure 8, RCP 8.5, is a pessimistic projection that assumes no serious effort to curtail greenhouse gas emissions, and robust economic growth. By the end of the century, the CO₂ equivalent has quadrupled from preindustrial levels, to around 1230 ppm. To get a feel for how extraordinary such a value is, try plotting it on Figure 7.

4 The IPCC does not perform research, but it coordinates research efforts and periodically summarizes climate research and predictions for the benefit of the public. Researchers from around the world send in their results in standardized formats so they can easily be compared. The series of IPCC reports constitutes singularly the most extensive coherent effort by a scientific discipline to convey research results to the public.

Paleoclimate proxies suggest that such a value has not been seen since at least the Eocene period, roughly 50 million years ago, when alligators roamed Greenland, and sea level was 70 meters (about 230 feet) higher than today’s. If the climate were to equilibrate to the associated radiative forcing of 8.5 watts per meter squared, extrapolation of the IPCC temperature projections would yield a global warming of 3–9 kelvins (about 5–16 °F).

The other three RCPs assume some level of mitigation of greenhouse gas emissions and are useful for estimating how various mitigation strategies might ameliorate climate change.

The projected response of global mean surface temperature depends on both the emissions trajectory and the climate model used to make the projection. In its *Fifth Assessment Report*, the IPCC summarizes this response, shown in Figure 9, which extends to the year 2300. The color shading for each curve in the figure represents the scatter among the various climate models used to make the projections. Note that if nothing is done to curb emissions, and economic growth proceeds rapidly in the developing world, global mean temperature may rise by between 2.5 and 4.5 °C (4.5 to 8 °F)

IPCC Hypothetical CO₂ Concentration Pathways

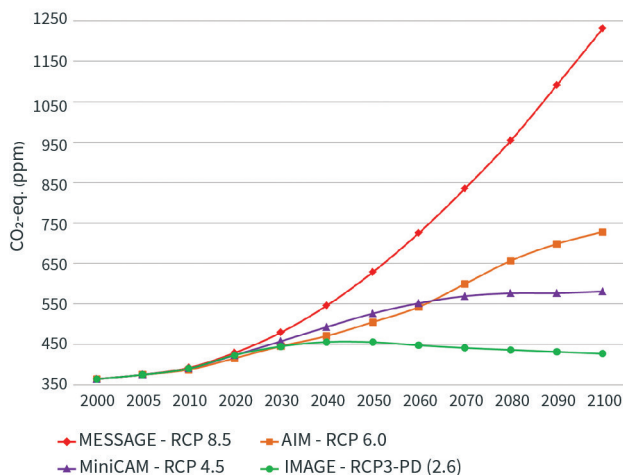


FIGURE 8: Four hypothetical evolutions of greenhouse gases over the 21st century, measured in terms of the CO₂ equivalent of their net radiative forcing. The preindustrial value of the CO₂ equivalent was close to 280 ppm. The red curve is an estimate based on assumptions of population and economic growth with no effort to curtail emissions. Source: https://commons.wikimedia.org/wiki/File:All_forcing_agents_CO2_equivalent_concentration.png

Global Temperature Projections

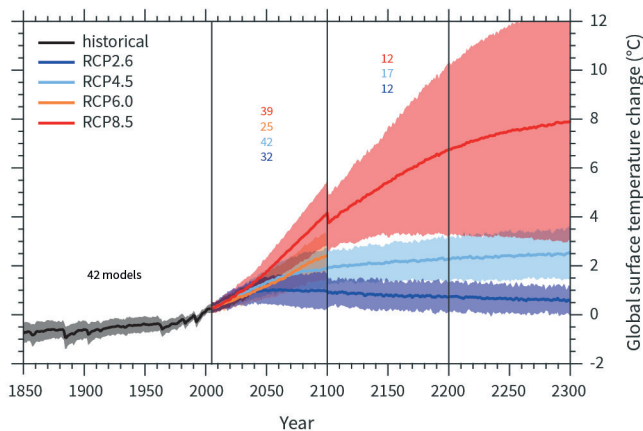


FIGURE 9: Time series of global annual mean surface air temperature anomalies (relative to 1986–2005) from CMIP5 [Coupled Model Intercomparison Project Phase 5, involving at least 20 climate modeling groups] concentration-driven experiments. Projections are shown for each Representative Concentration Pathway (RCP) for the multi-model mean (solid lines) and the 5% to 95% range (± 1.64 standard deviation) across the distribution of individual models (shading). Discontinuities at 2100 are due to different numbers of models performing the extension runs beyond the 21st century and have no physical meaning. Source: Figure and caption from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

by 2100, and between 4 and 13 °C (7 and 23 °F) by 2300.

But what are the consequences of these changes? How will they affect us in human and economic terms? We next consider the set of real risks that climate change poses and how, at least for some risks, we might go about attaching actual numbers to the risks.

CLIMATE RISKS

Besides increasing temperature, which poses its own set of risks, the main risks associated with climate change include rising sea levels; increased volatility of rainfall, which destabilizes food and water supplies; increasing incidence of the strongest hurricanes; and acidification of seawater, which poses significant threats to marine ecosystems and ultimately to populations of fish.

One important goal of climate science is to quantify the risks associated with climate change. This is a complex challenge, as most risks are ultimately local: the flood risks in Boston are not those of Miami, for example. Risks have to be quantified by sector as well as by location. In the private sector, risks to various enterprises have to be considered individually and, if desired, summed over the whole sector. In the public sphere, the effect of climate change on infrastructure, crime, and national security are just a few important considerations. Additionally, some risks, particularly existential risks such as that of nuclear war, are not easily or best described by numbers. The whole enterprise of risk assessment and quantification is far too

large to be summarized in any meaningful way in this short primer. Perhaps the best summary of the field of climate risk quantification for the United States is provided in the recent book *Economic Risks of Climate Change: An American Prospectus*.⁵ Here we provide a brief overview of some of the most important risks.

Sea level rise

We begin by making a simple observation about past sea level rise and human civilization. Look again at the red curve at the bottom of Figure 5, showing changes in the volume of ice sheets on land. All that water locked in the ice came from the ocean, and so when there are extensive ice sheets there is less water in the ocean. Sea level must have been lower. How much lower? The answer is, roughly 130 meters (400 feet). We know this because we know the volume of land ice and also have direct geologic evidence of ancient shorelines.

Figure 10 illustrates sea level rise to modern values from its low point of about 130 meters (roughly 400 feet) below today's level, about 22,000 years ago. Notice that sea level has been remarkably stable for the last 7,000–8,000 years—coincident with the time that human civilization developed.

And that is just the point. Because our prehistoric ancestors were nomadic, they did not build permanent cities. They probably did not even notice the 400 foot rise in sea level over 10,000 years (about 0.5 inch per year). Civilization developed during a time of unusual climatic stability and is exquisitely tuned to the climate of the past 7,000 years. Much damage would be done by a change in sea level of a few feet, let alone 400 feet. It is entirely academic whether the present climate is ideal for human society, as any modest climate shift in either direction will be highly problematic.

Sea level rose through the 20th century and has continued to rise in the present one; its rate has increased to a little more than 0.1 inch per year, mostly owing to thermal expansion as ocean waters warm. Runoff from melting ice in Greenland and West Antarctica is expected to further increase the rate of sea level rise over coming decades, and projections range upward to an increase of around 1 meter (3 feet) by 2100. Elevated sea levels make coastal regions more susceptible to storm-induced flooding, as evidenced by the aftermath of Hurricane Sandy, for example. Rising seas also infiltrate aquifers, putting freshwater supplies at risk. Many cities, such as New York, are weighing the costs and benefits of adaptation strategies such as building massive storm barriers versus hardening individual buildings and reducing exposure over time.

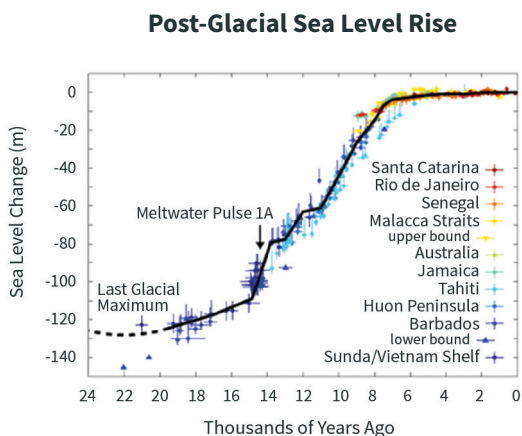


FIGURE 10: Sea level increase (in meters) since the peak of the last ice age, based on detailed geologic evidence from a number of coastal and island locations. Source: https://commons.wikimedia.org/wiki/File:Post-Glacial_Sea_Level.png

5 Houser, T., S. Hsiang, R. Kopp, and K. Larson: *Economic Risks of Climate Change: An American Prospectus*. Columbia University Press, New York (2015), 384 pp.

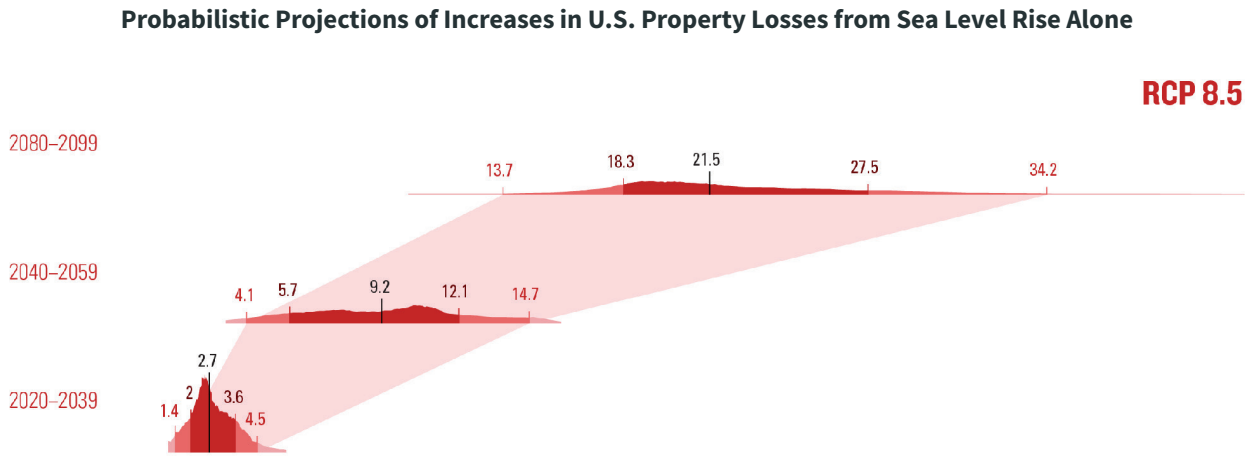


FIGURE 11: Projected probability distributions of increases (billion 2011 USD) in U.S. property losses as a result of sea level rise in the absence of increased hurricane activity. From *Economic Risks of Climate Change: An American Prospectus*.⁵

Figure 11 shows, for three periods during this century, projected probability distributions of annual U.S. property losses owing to sea level rise, assuming that hurricane activity does not change. By the end of the century, annual losses from sea level rise alone may exceed \$20 billion in 2011 dollars.

But sea level will not stop rising in 2100 even if by then we manage to eliminate emissions. The last time Earth’s atmosphere had a concentration of 400 ppm of CO₂ was during the Pliocene period, about 3 million years ago, during which time sea level was about 25 meters (80 feet) higher than it is today. It may take thousands of years, but that is where

sea level is headed, and scientists are not confident about forecasting how fast land ice will melt. There is no way that coastal cities can adapt to that level of change; they will simply have to relocate.

Heat and humidity

Warming is also of direct concern. Advanced civilizations developed mostly in temperate climates; indeed, not one of the 50 nations with the highest standard of living today is in the tropics. Human comfort is better measured by a quantity called the *wet-bulb temperature*, which is the lowest temperature a damp surface can achieve in air of a given temperature and humidity. When the wet-bulb temperature exceeds about 35 °C (95 °F) the human body cannot transmit heat to the surrounding air fast enough to compensate for its internal production of heat, and body temperature rises to lethal values. This limiting wet-bulb temperature is very rarely exceeded in today’s climate, but such values are projected to become common in certain regions, such as the shores of the Persian Gulf, by late in this century. Mortality from heat waves is already of concern; for example, the 2003 heat wave in Europe is estimated to have killed at least 50,000 people. As mean temperatures climb, such heat waves become more common. However, deaths from hypothermia decline with increasing temperature, and as of this writing the data are ambiguous as to the net effect on mortality.

Figure 12 presents an estimate of the number of days each year, by the end of this century, in which the combination of heat and humidity will be extremely dangerous, under emissions scenario RCP 8.5. (By comparison, such conditions today occur no more than once every 10 years, mostly in a small region of the Midwest.)

Heat Stroke Risk Projection

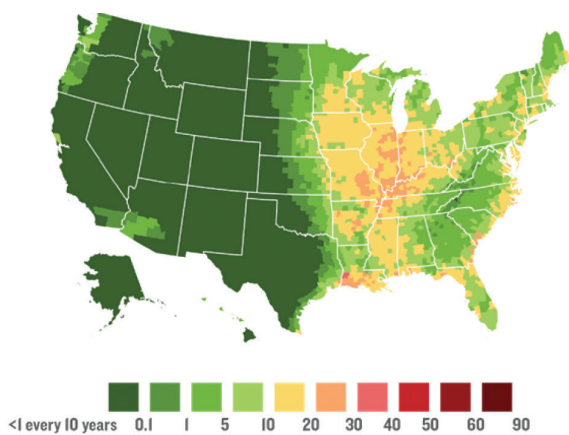


FIGURE 12: Expected number of days per summer of high risk of heat stroke, over the period 2080–2099, under emissions scenario RCP 8.5. Currently, the risk peaks at 1 day per summer in the upper Midwest. From *Economic Risks of Climate Change: An American Prospectus*.⁵

Probabilistic Projections of Increases in U.S. Property Losses from Sea Level Rise and Increased Hurricane Power

RCP 8.5

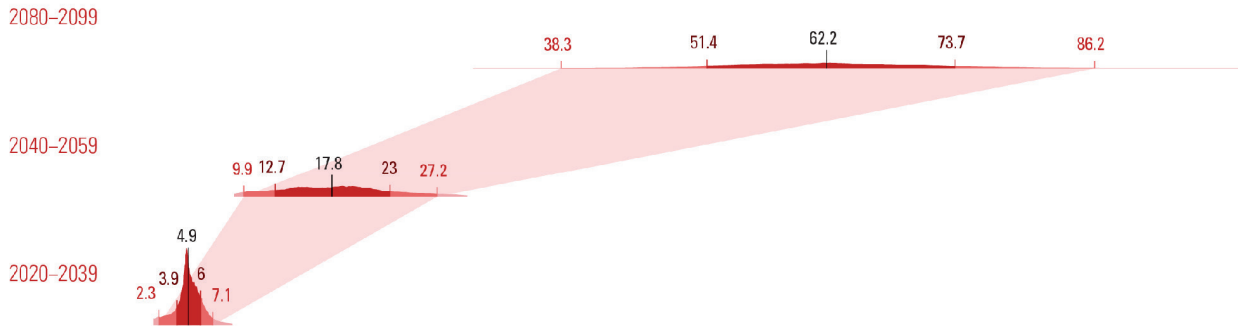


FIGURE 13: Projected probability distributions of the increase in annual U.S. property losses (billions of 2011 USD) from the combination of higher sea levels and increased incidence of intense hurricanes, under emissions scenario RCP 8.5. Compare with Figure 11. From Economic Risks of Climate Change: An American Prospectus.⁵

Destructive storms

Violent storms are another risk to reckon with. Tropical cyclones cause on average more than 10,000 deaths and \$40 billion (U.S.) in damages globally each year. There is now a strong consensus that the incidence of the strongest storms, which although small in number dominate mortality and damage statistics, will increase over time, even though there

may be a decline of the far more numerous weaker events. The jury is still out on what might happen to the incidence and intensity of destructive winter storms and violent local storms such as tornadoes and hailstorms.

Figure 13 shows projected probability distributions of annual U.S. property losses as a result of the combination of higher sea levels and greater incidence of intense hurricanes. A comparison of this graph with Figure 11 shows that accounting for changing hurricane activity roughly doubles the projected losses.

Number of Extreme U.S. Agricultural Loss Events per 20 Years Relative to the Current 1-in-20 Event

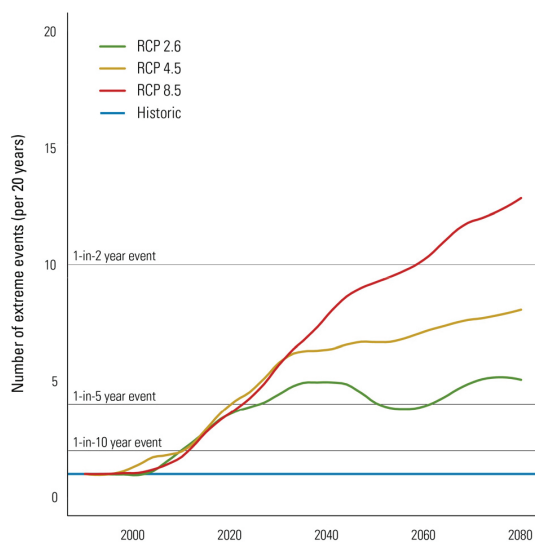


FIGURE 14: Number of extreme U.S. agricultural loss events per 20 years relative to the current 1-in-20 event, for three emissions scenarios. From Economic Risks of Climate Change: An American Prospectus.⁵

Ocean acidification

Increased atmospheric concentrations of CO₂ lead to increases in the concentration of CO₂ dissolved in ocean waters. This makes the oceans more acidic. Laboratory experiments show that as ocean acidity increases, organisms that build shells, including certain mollusks, corals, and plankton, begin to suffer declining ability to build and maintain their shells. Thus ocean acidification poses significant risks to marine ecosystems; but these risks are only now beginning to be quantified.

Food and water

Perhaps the most consequential change will be in the space-time distribution of rainfall. Elementary physics dictates that as the climate warms, rainfall must become increasingly concentrated; that is, when it rains it will rain substantially harder, but the frequency of rainstorms should decline. Also, areas that presently enjoy a wet climate will generally become even wetter, whereas arid regions will become more so,

with only a small increase in globally averaged annual mean precipitation. Flash flooding will become more frequent, as will the incidence of drought. Climate model projections are consistent with these inferences from basic theory.

These changes in the hydrologic cycle, which are already underway, are especially worrying because of their effects on the supply of food and water. These will become apparent first and be most severe in regions, such as the Middle East, that today have only marginal food and/or water supplies

Figure 14 shows a projection of the effect of climate change on U.S. agricultural losses, relative to today's 1-in-20 event. By the end of this century, today's 1-in-20 loss could occur every other year.

Historically, the disappearance of certain civilizations, such as that of the Anasazi in what is today the southwestern U.S., has been attributed to food and water shortages brought on by prolonged drought. Such shortages are also thought to cause or exacerbate mass migrations and armed conflict. The link between climate change and human conflict is well recognized in the defense community. For example, in its 2010 *Quadrennial Defense Review*, the U.S. Department of Defense states that:

climate change could have significant geopolitical impacts around the world, contributing to poverty, environmental degradation, and the further weakening of fragile governments. Climate change will contribute to food and water scarcity, will increase the spread of disease, and may spur or exacerbate mass migration.

Political and social destabilization of a crowded, nuclear-armed world finely adapted to the highly stable climate of the last 7,000 years is perhaps the greatest and least predictable risk incurred by rapid climate change. Such existential risks are difficult to attach numbers to and represent extreme outcomes whose probability is not small under high-emissions scenarios.

HOW LONG CAN WE WAIT TO ACT?

Carbon dioxide is a greenhouse gas of special concern because of its long residence time in the atmosphere. The top panel of Figure 15 shows estimates of the evolution of CO₂ assuming that emissions abruptly stop when concentrations reach various values. Over the first 100 years or so, concentrations fall fairly rapidly, but then the rate of decay drops off and it will take many thousands of years for concentrations to return to preindustrial values. The bottom panel of Figure 15 shows projections of global mean temperature that correspond to the CO₂ concentrations of the top panel. Curiously, the temperature hardly drops at all over the first thousand or so years after emissions cease, reflecting mostly the effects of heat storage in the oceans.

This is a crucial aspect of the challenge we face: absent technology for removing CO₂ from the atmosphere, we will have to live with altered climate for many thousands of years. Thus we have a narrow time window within which to act.

Projections of CO₂ and Temperature Assuming That Emissions Abruptly Stop After Certain CO₂ Levels Are Reached

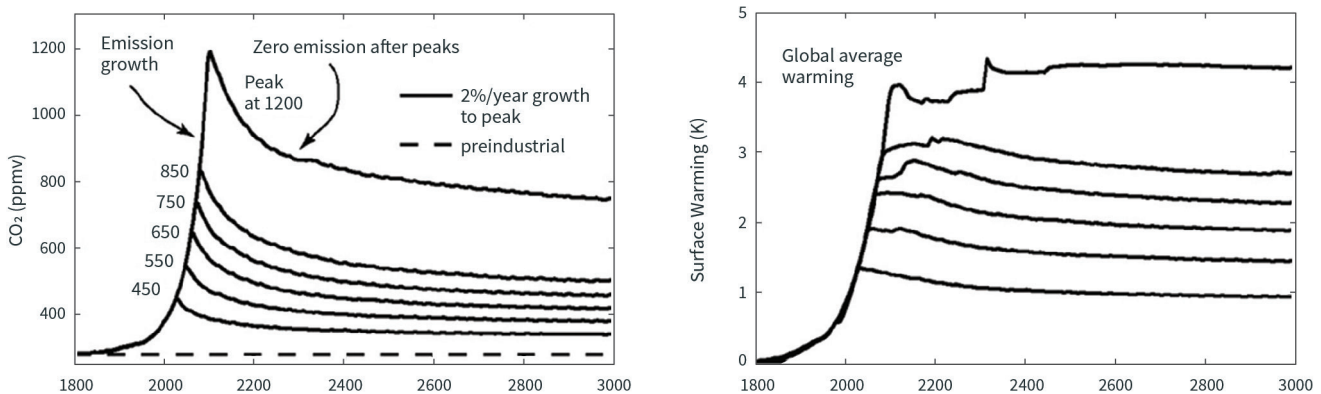


FIGURE 15: Left: Evolution of atmospheric CO₂ over time assuming that emissions abruptly cease when concentrations indicated by the numbers to the left of the curves are reached. Natural processes begin to relax concentrations back toward preindustrial values at the cessation of emissions. Right: Estimates of the evolution of global mean temperature (relative to its preindustrial value) corresponding to the CO₂ concentrations in the top panel. Source: Solomon, S., G.-K. Plattner, R. Knutti, and P. Friedlingstein, 2009, PNAS 106: 1704–1709.

THE BOTTOM LINE

There is overwhelming scientific evidence that the majority of the rapid warming of our planet over the past century has been forced by increasing greenhouse gas concentrations. The concentration of carbon dioxide—the most important long-lived greenhouse gas—is now greater than it has been for at least 800,000 years, and if global economic growth continues and nothing is done to curtail emissions, its level at the end of this century will reach values not seen since the Eocene period, 50 million years ago. Pushing the climate system this hard and this fast entails serious risks to human civilization, engendered in rising sea levels and associated incidence of storm-related coastal flooding, decreasing habitability of tropical and arid regions, increasing acidification of ocean waters and associated risks to marine ecosystems, and destabilization of the hydrologic cycle with attendant increases in food and water shortages. The latter is especially worrying because of the propensity for past fluctuations in food and water supplies to drive civilizational collapse, rapid migrations, and armed conflict.

While climate science is increasingly confident in its attribution of recent climate change to human-caused changes in greenhouse gases and aerosols, the innate skepticism of scientists leads to large uncertainty in climate projections, with possible outcomes ranging from the benign to the catastrophic. There is no scientific justification for the confidence expressed by some that climate change entails little or no risk.

There is some basis for optimism that civilization can greatly reduce climate risk by incentivizing development of carbon-free energy sources and technology for extracting CO₂ from the atmosphere and/or directly from emissions sources. Renewables can power 20%–60% of current demand, or more if better energy-storage technology is invented. Next-generation nuclear fission has many advantages over 1960s nuclear technology and, once developed, can be ramped up to meet a large fraction of demand in 15 years, judging from the experience of countries like France and Sweden. (Nuclear-energy costs over the lifetime of power plants are competitive with coal and oil.) There is also renewed optimism that nuclear fusion, a basically limitless clean source of energy, may become commercially viable in 20 to 30 years. Unfortunately, this will be too late to significantly curtail major climate risk, but it does provide an ultimate target for clean-energy production.

At the present rate of consumption, oil and gas reserves are projected to be exhausted by late in this century, and coal early in the next. Thus in the not-too-distant future fossil fuels will have to be replaced anyway; to mitigate climate risk that transition would need to be advanced by several decades. Other countries, notably China, are investing in advanced carbon-free energy sources, including nuclear fission. Those nations and/or businesses that develop carbon-free energy early and well will gain an important competitive advantage in what is currently a \$6 trillion energy market.

■ *Climate Science and Climate Risk: A Primer* | October, 2016



ABOUT THE AUTHOR

Dr. Kerry Emanuel is the Cecil and Ida Green professor of atmospheric science at the Massachusetts Institute of Technology, where he has been on the faculty since 1981, after spending three years on the faculty of UCLA. Professor Emanuel's research interests focus on tropical meteorology and climate, with a specialty in hurricane physics. His interests also include cumulus convection, and advanced methods of sampling the atmosphere in aid of numerical weather prediction. He is the author or co-author of over 200 peer-reviewed scientific papers, and three books, including *Divine Wind: The History and Science of Hurricanes*, published by Oxford University Press and aimed at a general audience, and *What We Know about Climate Change*, published by the MIT Press. He is a co-director of MIT's Lorenz Center, a climate think tank devoted to basic, curiosity driven climate research.