Climate Science, Risk & Solutions

Climate Knowledge for Everyone

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More than 90% of climate scientists attribute the increase in global temperature over the past 30-40 years to greenhouse gases that humans have been adding to the atmosphere since the beginning of the Industrial Revolution in the 1700s.[1] The great majority of these scientists agree that if this warming continues, it presents significant risks to humankind and all life on Earth: to our cities and towns, our water and food supplies, and our health. How do we know that this warming is happening and that it's caused by humans? How strong is the evidence? What risks can we expect and what can we do about them?

A note about 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; scientists 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 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 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.

[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.

Part 1

Climate Science

A brief history of climate science

Climate science is not a new field. By the time of the American Civil War, it was well-known that a handful of gases that make up less than 1% of the air absorb radiation from the sun and the earth, and emit some of it back to Earth. We now know that without those gases, the average surface temperature of the planet would be well below freezing, and human life would not exist. How did these early scientists study this? What else affects our Earth's climate, and what does it have to do with recent warming?

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°C (11,000°F), and it emits mostly visible light, while the earth's effective emission temperature is closer to -18°C (0°F) and so it emits much less radiation, and at a much longer (infrared) wavelength.

In 1820, the French mathematician and physicist Jean Baptiste Fourier came to understand that warmer surfaces emit more radiation than colder surfaces and 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 would neither increase nor decrease over time. He found that his estimate was much colder than the observed temperature. He reasoned that the atmosphere must absorb some of the infrared radiation from the earth's surface 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

1824

Jean Baptiste Fourier calculated that the average temperature of Earth should be much colder than observed. He reasoned that the atmosphere must absorb some infrared radiation from the Sun and Earth and emit it back to the planet's surface.

1856

Eunice Foote became the first to suggest that variations in atmospheric carbon dioxide content might have been responsible for past variations in climate.

1859

John Tyndall proved that water vapor, carbon dioxide, and nitrous oxide (1% of our atmosphere) strongly absorbs infrared radiation.

1896

Svante Arrhenius published a paper predicting that if we ever doubled the concentration of CO_2, the average surface temperature of the planet would rise between 5 and 6°C (9 and 11°F) a number he revised downward to 4°C (7°F) in 1908.

1930

Milutin Milanković linked ice age cycles to Earth's orbital characteristics.

1938

The first observed connection between global warming and carbon dioxide levels is made by Guy Callendar.

1958

Systematic carbon dioxide data collection begins at Mauna Loa Observatory by Charles Keeling in Hawaii.

tested, notably water vapor, carbon dioxide, and nitrous oxide, strongly absorb infrared radiation, and water vapor also absorbs some visible light. These gases are called "greenhouse gases" because, like the greenhouses we use to grow plants, they trap heat (although the way they do so is very different from the way actual greenhouses work).

Tyndall's discovery was entirely 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 (N_2) and oxygen (O_2), for example—hardly interact with radiation, but more complex molecules like water vapor (H_2O—two atoms of hydrogen and one of oxygen) and carbon dioxide (CO_2—one atom of carbon and two of oxygen) can interact much more strongly with radiation.

The greenhouse effect and us

How it works

Why does the absorption and emission of infrared radiation by the atmosphere warm the planet? When the greenhouse gases (and clouds, which also act as greenhouse agents) absorb infrared radiation, they must re-emit radiation, otherwise the temperature of the atmosphere would increase indefinitely. This re-emission occurs in all directions, so that half the radiation is emitted broadly downward and half broadly upward. The downward part ("back-radiation") is absorbed by the earth's surface or lower portions of the atmosphere. Thus, in effect, Earth's surface receives radiant energy from two sources: the Sun, and the back-radiation from the greenhouse gases and clouds in the atmosphere, as illustrated in Figure 1.

The warmer a surface, the more radiation it emits. Earth's surface must get warm enough to lose enough heat to balance both sunlight and back-radiation from the atmosphere and clouds. 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.

> Earth's surface receives almost twice as much radiation from the atmosphere as it does directly from the Sun. This is partly because the atmosphere radiates 24/7, while the Sun shines only part of the time.

Figure 1

Earth's surface receives radiation from both the Sun, and the greenhouse gases and clouds in the atmosphere.

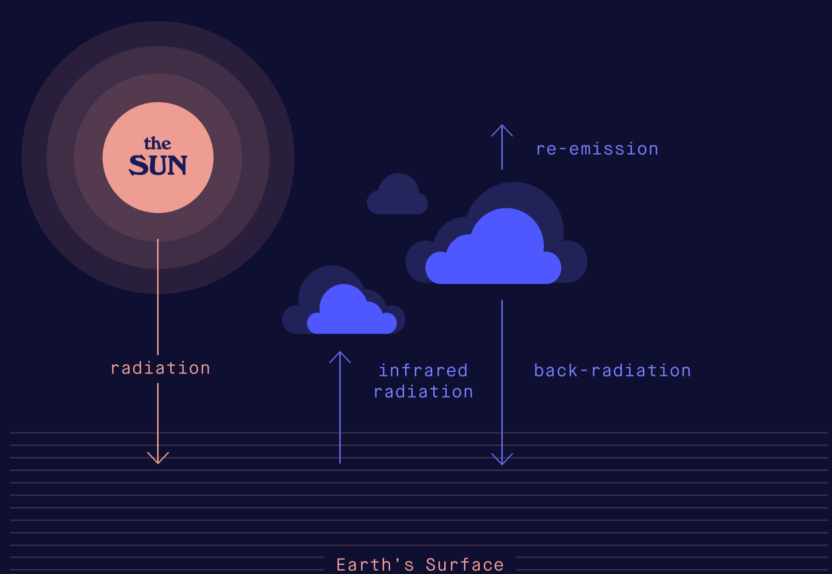


Figure 2

It takes longer for some gases to leave the atmosphere. This is why carbon dioxide has such a strong influence on climate.

Our atmosphere

Not all greenhouse gases are the same. The most important such gas in our climate system, 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 re-emits 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 temperature of the air limits how much water vapor it can hold: warmer air can support more vapor, whereas colder air holds less. Because rain and snow remove water from the air, there is often less water vapor in the air than there could be.

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.

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. (It is important here to distinguish between a "feedback" and a "forcing." When we discuss climate, a "feedback" is a process that strongly reacts to the climate itself, whereas a "forcing," like changing solar radiation, CO_2 or volcanoes, is not controlled by the climate itself, at least not on the time scales of concern in the problem of global warming.)

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 carbonate rocks are pushed down into the earth's mantle at convergent boundaries, where one tectonic plate slides beneath another, 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 CO_2 also cycles through the atmosphere, ocean, and land plants on a different time scale, on the order of hundreds—not millions—of years.

Water vapor and carbon dioxide (CO_2) both contribute to the greenhouse effect, but CO_2 has an important influence on climate change because CO_2 stays in the atmosphere for a long time. If we were to magically double just the amount of water vapor in the atmosphere, in roughly two weeks the excess water would rain and snow back into oceans, ice sheets, rivers, lakes, and groundwater. Because water vapor leaves the atmosphere so quickly, extra vapor doesn't have much of a long-term warming effect. But if we were to instantly increase the concentration of CO_2, it would take roughly 100 years for about half of it to cycle back into plants and the ocean. The other half? Thousands of years. This is why long-lived greenhouse gases like carbon dioxide have an important influence on Earth's climate.

Figure 3

Water vapor is the most important positive feedback in the climate system.

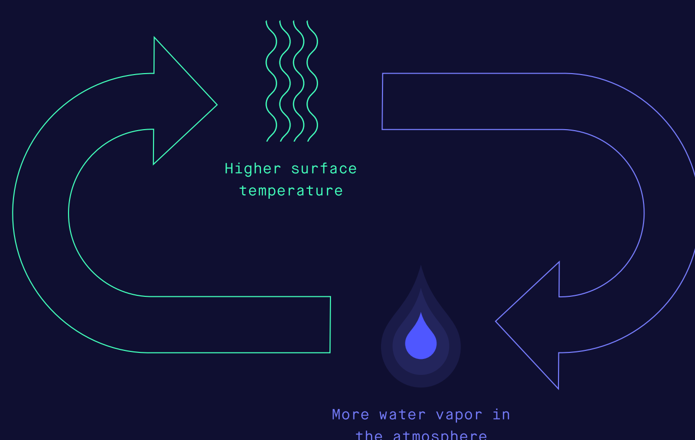
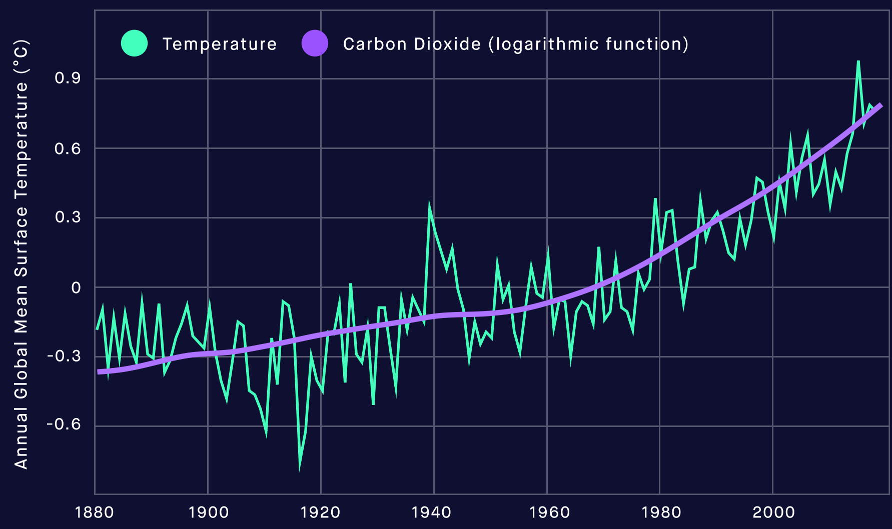


Figure 4

Annual global mean surface temperature correlates to CO_2 concentration.



The impact of increased CO_2

Much of the preceding, save for the details of the processes that control atmospheric CO_2, 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 CO_2 is the most important long-lived greenhouse gas.

He also understood that we were beginning to emit large amounts of CO_2 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. (Well before Arrhenius's time, Eunice Foote speculated that past variations in CO_2 might have played a role in past variations in climate.) In 1896, Arrhenius published a paper predicting that if we ever managed to double the concentration of CO_2, the average surface temperature of the planet would rise between 5 and 6°C (9 and 11°F), a number he revised downward to 4°C (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 canceled each other. It is truly remarkable that his 4°C (7°F) is within the range of the most recent estimates of 1.5–4.5°C (2.7–8.1°F).

Arrhenius also understood that the radiative effects of CO_2 increase nearly logarithmically (rather than linearly) with its concentration, so that increasing CO_2 by a factor of 8 would produce about three (rather than four) times more warming than would doubling it.

Arrhenius predicted that increasing CO_2 would warm the planet. How did his prediction fare? Figure 4 compares Arrhenius's prediction based on atmospheric CO_2 concentrations with measured global mean surface temperature for the period from 1880 to 2018. The CO_2 content of the atmosphere was measured directly beginning in 1958. Before that time (and going back for hundreds of thousands of years) scientists deduced its abundance by measuring CO_2 concentration in gas bubbles trapped in ice cores, as we explore in the next section. Over the period of record, the global mean temperature generally follows the logarithm of the concentration of CO_2, just as Arrhenius predicted. But you'll notice in the graph that Earth's average temperature is jagged; it's not a smooth rising line like CO_2 concentration. The shorter-period deviations mostly reflect the natural, chaotic variability of the climate system (an example of which is El Niño), while longer departures are mostly due to other influences on climate, such as volcanoes and human-made aerosols. While we may not be able to account for each little wobble, it is hard to avoid the conclusion from Figure 4 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 CO_2 in the atmosphere.

But what if we are fooling ourselves? Correlation is not causation, and perhaps the correspondence of temperature and CO_2 is a coincidence—maybe something else is causing the warming. Or perhaps the rising temperature is causing CO_2 concentrations to increase and not the other way around. How accurate is the curve in Figure 4—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.

Measuring past temperatures

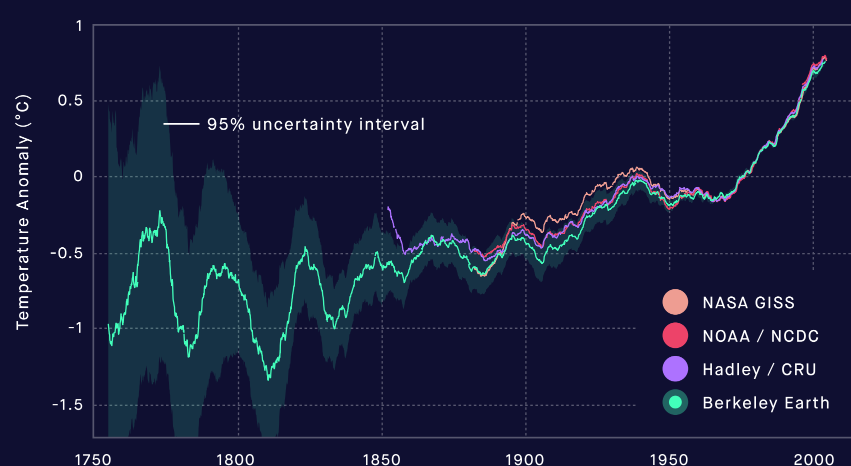
Historic temperatures

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 from ships, including measurements 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

Figure 5

Over time, global temperature estimates from different research groups have become more and more aligned.



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

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 5. One of these records, the Berkeley Earth estimate, shown in green with transparent 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 indeed what we observe when measuring air temperature over land and sea. 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. Some of the fastest warming is in places far removed from cities, like Siberia and northern Canada; in fact, at most 2%–4% of the earth's total warming can be attributed to urbanization[2].

So the measurements that underlie Figure 4 are pretty accurate. But how does that record of temperature and CO_2 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.

> **Different scientific groups have tackled measurement issues in different ways, yet their results agree with each other quite well. We are therefore very confident that these records are accurate.**

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

Prehistoric records

How do we know what the earth was like before humans existed? Tree rings, ice sheets, and sediments on the ocean floor reveal how our planet's temperature and ice cover have changed over the course of hundreds of thousands of years. For example, scientists can determine prehistoric temperatures by drilling deep into the ice (in places like Greenland and Antarctica) and analyzing the makeup of ancient snow. Similarly, scientists have figured out that the shells of marine microorganisms carry indicators of how salty the ocean is. By looking at shells that have decomposed and settled on the ocean floor, they can estimate the volume of ice on the planet thousands of years ago.

There are many different proxies for determining historical 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 of these are local or at best regional metrics; there is no global "paleothermometer."

One particularly useful proxy makes use of the fact that ice sheets and seawater contain different "flavors" (or isotopes) of water. Water (H_2O) 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 ^{16}O to denote the number of protons and neutrons, is by far the most abundant isotope, followed by ^{18}O with 8 protons and 10 neutrons. A tiny percentage of water contains this heavier oxygen isotope, and it turns out that the ratio of the heavy to the light isotope in water 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.

Figure 6

We can determine historical temperatures from ice core samples. The deeper the ice, the older the cloud that made the snow.

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.

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 7 shows the record of temperature inferred from two ice cores in Antarctica, going back 450,000 years, as well as from 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.

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 7 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.

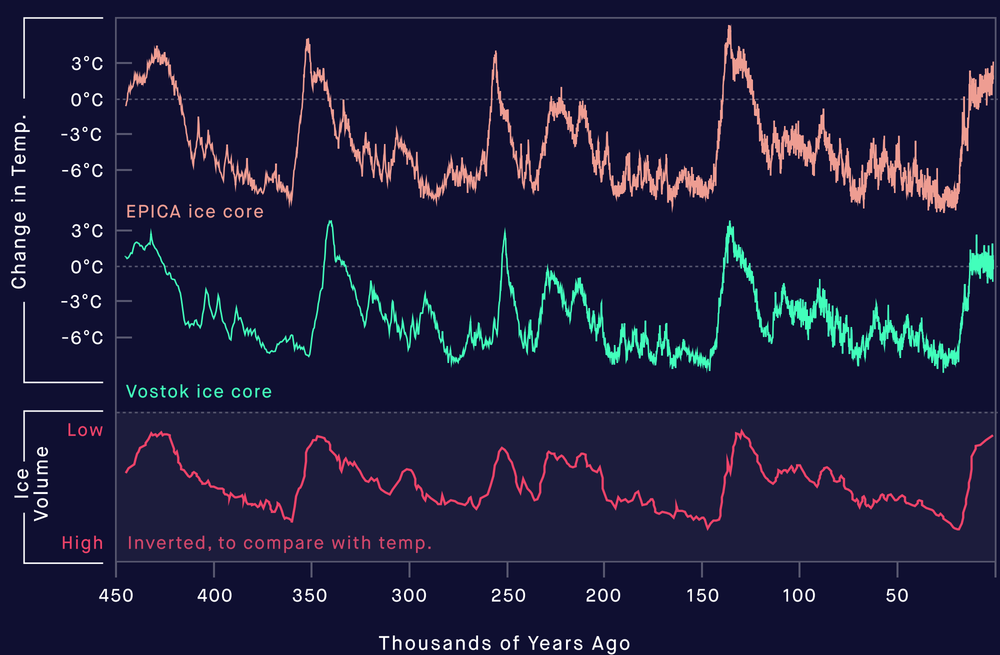
It is plainly obvious that on the 100,000-year time scale, temperature is cyclic. These cycles are the great ice ages and interglacial periods, and the right edge of Figure 7 shows that we are in an interglacial period right now. The last ice age ended about 10,000 years ago—a geologic blink of the eye.

The figure also shows that the Antarctic temperature varied about 9°C (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°C (9°F) between peaks and valleys.

On a 100,000-year time scale, temperature is cyclic. These cycles are the great ice ages and interglacial periods, and we are in an interglacial period right now.

Figure 7

Historically, as temperature goes up, ice volume on Earth goes down.



Temperature inferred from the deuterium ratios in two Antarctic ice cores (peach and green curves), and ice volume inferred from the oxygen isotope ratios of marine microfossils in ocean floor sediments (pink 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

Part 2

Climate Change

The climate is always changing

Earth's orientation in space isn't constant: our planet's tilt, wobble, and the shape of its orbit around the sun cycles over the course of tens of thousands of years. These cycles are what cause the natural fluctuations between global ice ages and warmer periods. Our planet's climate is also affected by volcanic activity and changes in how much energy from the sun hits the earth. One way that we know that the current warming is caused by human activity is because we are currently in a cycle that should be cooling the planet.

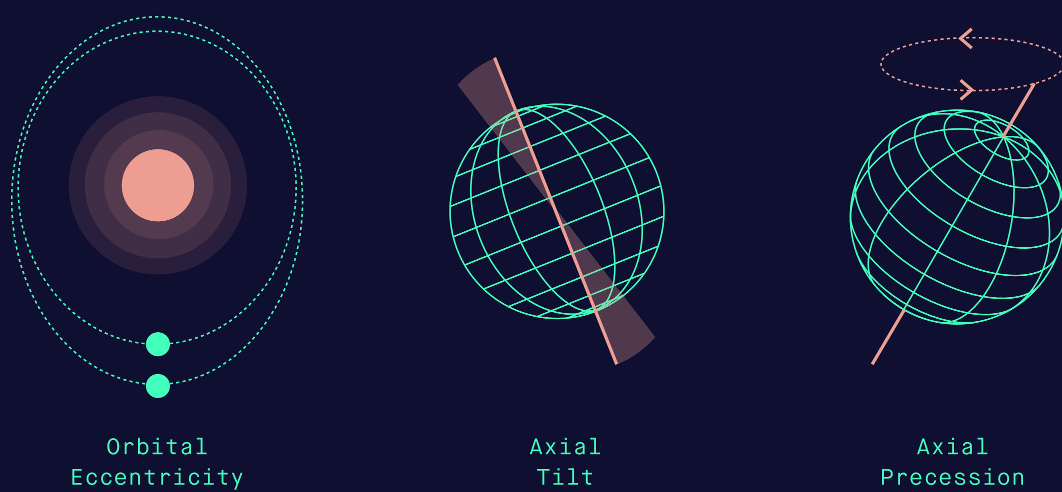
The cause of these cyclic swings in temperature and the associated growth and retreat of great continental ice sheets was proposed by several scientists, notably by the Serbian mathematician Milutin Milanković in 1912. He recognized that the shape of Earth's orbit around the sun varies cyclically over time—back and forth from more circular to more oval—with a period of about 100,000 years. Milanković also knew that Earth's tilt with respect to the plane in which it orbits the sun wobbles over a cycle of 41,000 years, and that Earth's rotation axis precesses like a top with periods of 19,000 and 23,000 years. These three factors—our planet's tilt, wobble, and orbit—affect the way sunlight is distributed around the world, even though they hardly affect the total amount of sunlight received by the planet as a whole.

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 7 did not exist, and so there was only rough agreement with what little information there was. 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.

> **Ice ages are controlled by how much sunlight is received by the Arctic region during summer. In the early twentieth century, mathematician Milutin Milanković calculated (by hand) how the distribution of sunlight varies and speculated that variations in arctic sunlight caused the ice ages.**

Figure 8

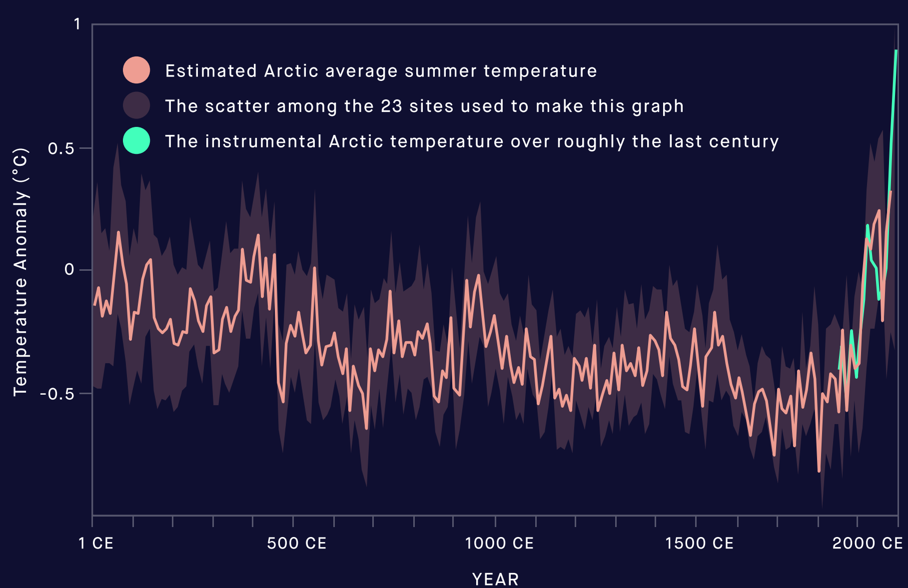
Earth's orbital eccentricity, axial tilt, and axial precession change in cycles. These cycles work together to trigger ice ages.



This expected cooling is illustrated in Figure 9, which zooms in on the last 2,000 years of temperatures in the Arctic. The slow, steady cooling trend from the beginning of the record to around 1700–1800 CE probably reflects the slow decline in sunlight reaching the Arctic due to the Milanković orbital cycles. Unimpeded, this mechanism would lead the earth toward another ice age, with continental ice sheets beginning to grow 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 increase in carbon dioxide and other greenhouse gases brought about by humanity's rapid consumption of fossil fuels. We are certain that this increase in CO_2 concentrations was caused by human activities because the isotopes of carbon in ice show that it comes from fossil fuel burning and the clearing of forests. Over the course of a few hundred years, humans rapidly burned fossil fuels that nature created over tens of millions of years.

Figure 9

Until about 1900, the summer temperature in the Arctic was going down.



Estimated Arctic average summer temperature (°C) over the last 2000 years, based on proxy records from lake sediments, ice cores, and tree rings (peach). The transparent shading represents the scatter among the 23 sites used to make this graph. The green 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 CO_2 increase is natural?

So, the evidence suggests that the warming of the last one hundred years—over 100 ppm between 1918 and 2018—is unusual compared to the last few thousand years and is almost certainly caused by higher concentrations of CO_2. But could the increased CO_2 concentrations themselves be natural?

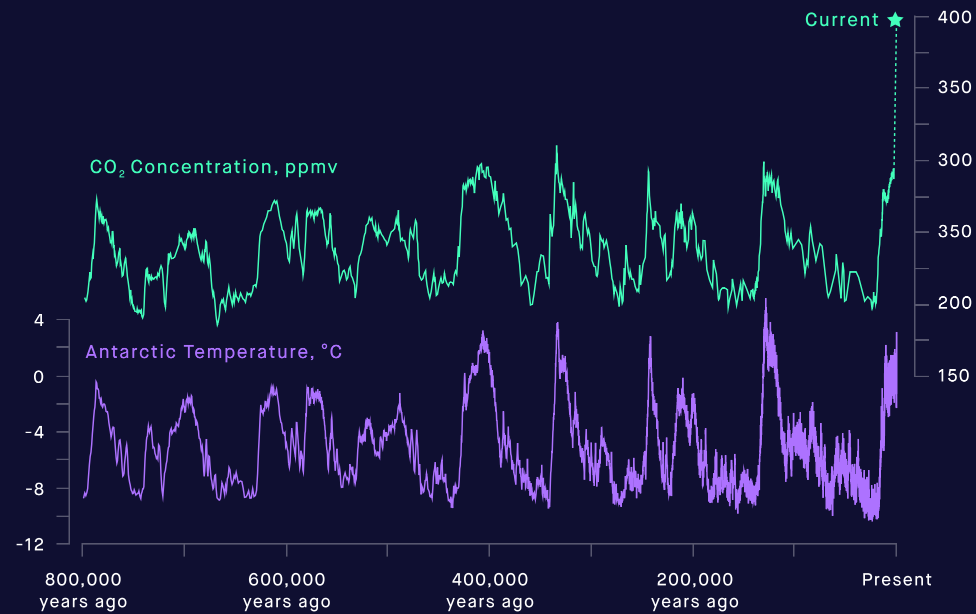
Almost certainly not. Figure 10 shows the history of atmospheric CO_2 and Antarctic temperature going back 800,000 years, thus covering many Milanković cycles. Clearly, the atmospheric concentration of CO_2 does vary naturally, in tandem with temperature, ranging from about 180 to about 280 parts per million by volume (ppmv). But the Milanković cycles cannot account for the enormous spike at the end of the record, a spike to over 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 CO_2 in ice cores shows that during Milanković cycles, CO_2 mostly lags temperature, suggesting that the CO_2 variations were caused by the warming and cooling, not the other way around. In this case, the CO_2 was acting as a positive feedback, amplifying the Milanković oscillations. But in the last 100 years, the huge increase in CO_2 drove the temperature change.

The argument that one has to choose whether CO_2 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.

Figure 10

Current CO_2 levels are well beyond anything our planet has seen for the past 800,000 years.



Atmospheric CO_2 (green) and temperature (purple) from Antarctic ice cores. The concentration of CO_2 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.

Predicting climate

The real issue, of course, is what will happen in the future. Although ultimately we want to understand what the human and monetary risks are, we should start with something simpler: how global temperature will evolve going forward. But the Earth's climate system is immensely, almost overwhelmingly complex. Clouds both reflect and absorb energy from the sun, oceans absorb heat as it radiates back from the atmosphere, volcanoes erupt and spew sun-reflecting particles, ice melts and causes once highly reflective surfaces to turn into dark ocean waters. To deal with this complexity, scientists have created computer models to map these interactions and simulate how the Earth might respond under different scenarios and assumptions—and we're getting an increasingly clear picture of what kind of temperature changes we can expect in the coming decades.

What are climate models?

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. Models used for predicting weather, for example, are computational devices for solving large sets of equations. Using a computer to solve these equations is very similar to using a computer to, say, precisely land a spacecraft on Mars. This type of modeling is quite different from something like economic modeling. Economic models also solve equations, but unlike weather models, the equations are constructs based mostly on past economic data and records of human behavior.

But this 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.

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, CO_2, 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.) Instead, we have to deal with remaining uncertainties in the physics of climate.

Uncertainty

Scientists face tremendous challenges when attempting to model the Earth's climate system. While there is a solid understanding of how many parts of the system work, our incomplete understanding of several aspects of the highly complex climate system introduces uncertainty into our attempts to forecast how climate will change.

To take one example, 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 CO_2. But the true physics of climate is not that simple, and the distribution of water vapor is affected by many other variables besides temperature. Our incomplete understanding of water vapor is thus one source of uncertainty in modeling climate.

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 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. Clouds are now considered the main source of uncertainty in climate projections.

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 CO_2 may itself change in response to changes in ocean temperature and concentration of dissolved CO_2. Incomplete understanding of these processes also introduces uncertainty in climate projections.

Another source of uncertainty is the response of the deep ocean to climate change. The oceans act as a buffer to temperature change and delay the response of global temperature to increasing greenhouse gases. 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. 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.

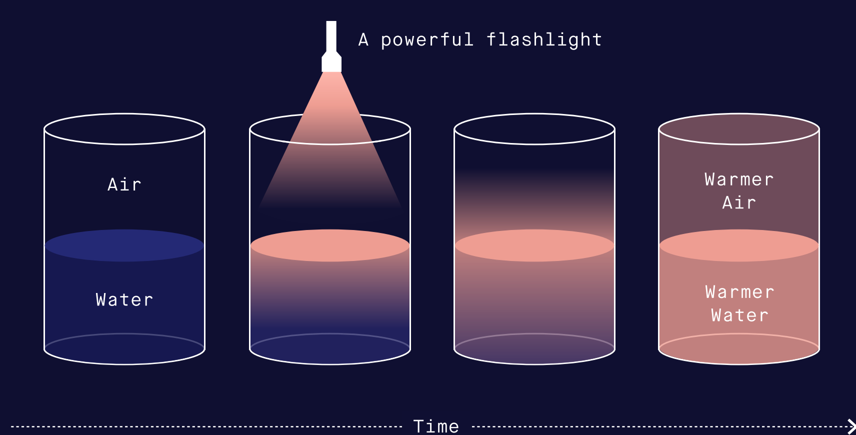
Thus after we turn on the flashlight there will be an initial fast warming of the air and surface water, followed by a very slow increase in the temperature of the whole system. Eventually, the water and air will reach a new, warmer temperature. How long it takes to do so will depend on how rapidly heat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

Our models 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 500 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. But we know from measurements that heat manages to circulate much deeper in the ocean, taking quite a long time to do so, perhaps as much as 1,000 years. Just how this happens is complex, and is a source of uncertainty for longer range climate projections.

Finally, mathematical models of climate-like systems can exhibit sudden, unpredictable shifts. We don't 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 our 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.

Figure 11

It takes time for the temperature of a system to increase after an initial burst of warmth.



Dealing with uncertainty

As the Danish physicist Niels Bohr once remarked, "Prediction is very difficult, especially about the future." Scientists have developed a number of strategies to account for uncertainty, and have used these to estimate the range of possible temperatures that we will see in the coming century. 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?

Estimating future emissions 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[3]) came up with a set of just four "representative concentration pathways" (RCPs), expressing plausible evolutions of greenhouse gases and other man made influences on climate, such as aerosols. These are labeled with the associated radiative forcing (the excess

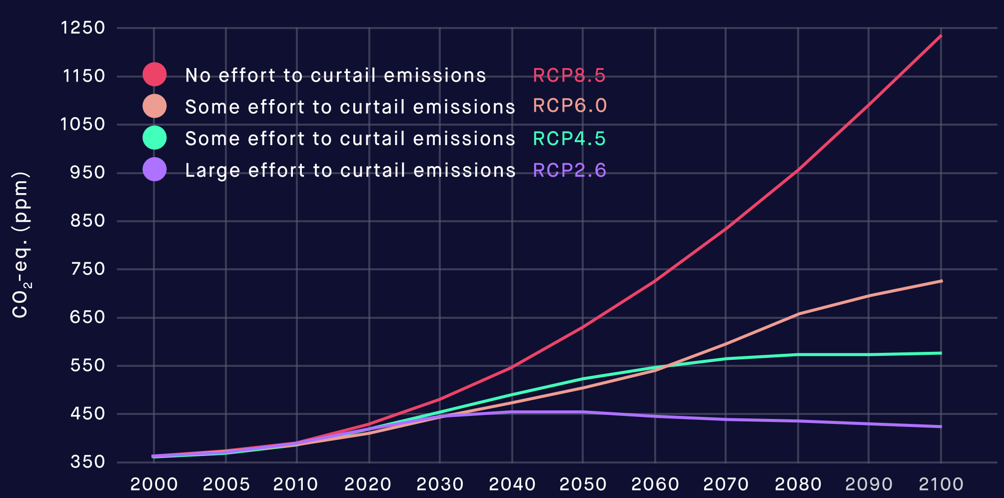
[3] The IPCC does not perform research, but it coordinates research efforts and periodically summarizes climate research and predictions for the benefit of the public. Researchers from around the world send in their results in standardized formats so they can easily be compared. The series of IPCC reports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

heating caused by human-made greenhouse gases) 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 CO_2 produces a radiative forcing of about 4 watts per meter squared.) Figure 12 shows the evolutions of these concentration pathways, expressed as though all the forcing is due to CO_2 alone. (That is, we take the radiative forcings associated with other greenhouse gases like methane and nitrous oxide, along with aerosols, and convert them into CO_2-equivalent units.)

In addition to the uncertainty surrounding the emissions there is inherent uncertainty in the models themselves. Many important processes such as turbulence, convection, and the interaction of radiation with clouds have to be represented indirectly in the models and this is one of many sources of model error. One strategy to account for this important source of uncertainty is to run many different models and to run each of them many times with different initial states to produce a large ensemble of projections. While imperfect, comparing the results of the many members of such an ensemble gives us some idea of the inherent uncertainty in model projections. This strategy is also used in running weather prediction models and has proved valuable in quantifying the uncertainty of weather forecasts.

Figure 12

The effort we make to curtail emissions today will impact greenhouse gas concentrations for the rest of the century.



Four hypothetical evolutions of greenhouse gases over the 21st century, measured in terms of the CO_2 equivalent of their net radiative forcing. The CO_2 equivalent is a measure of total greenhouse gas emissions expressed in terms of the amount of CO_2 having the same global warming potential over a specified timescale (generally 100 years). The preindustrial value of the CO_2 equivalent was close to 280 ppm. The pink curve is an estimate based on assumptions of population and economic growth with no effort to curtail emissions.

What the models say

The news isn't good. If nothing is done to curb emissions, and economic growth proceeds rapidly in the developing world, by 2100, global mean temperature may rise by between 2.5°C and 4.5°C (that's 4.5°F to 8°F), and by 2300, by between 4°C and 13°C (that's 7°F and 23°F).

The pink curve in Figure 12, RCP 8.5, is a pessimistic projection that assumes no serious effort to curtail greenhouse gas emissions and robust economic growth. In this projection, by the end of the century, the CO_2 equivalent has quadrupled from preindustrial levels, to around 1,230 ppm. 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°C (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.

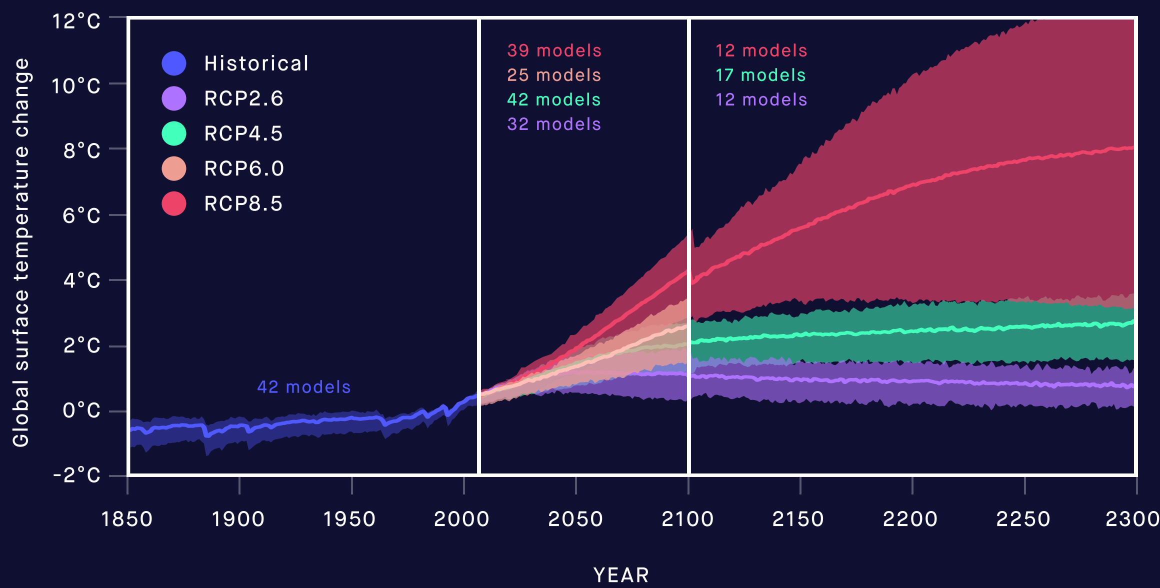
The projected response of global mean surface temperature depends on both the emissions trajectory and the climate model used to make the projection. In its Fifth Assessment Report, the IPCC summarizes this response, shown in Figure 13, which extends to the year 2300. The color shading for each curve 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) by 2100, and by 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.

> **Unless humanity makes substantial changes in emissions or their capture, by the end of the century we could see CO_2 concentrations not seen for 50 million years. This was when alligators roamed Greenland and sea levels were 230 feet higher than today.**

Figure 13

If nothing is done to curb emissions global mean temperature may rise by between 4°C and 13°C by 2300.



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

Part 3

Risk

Understanding risk

When considering what to do about climate change, it's helpful to think about it in terms of managing risk. Every one of us confronts various kinds of risks on a regular basis, from mundane risks like climbing a stepladder to replace a lightbulb, to highly consequential risks, like undergoing open-heart surgery. Whether or not we're aware of it, each of these decisions involves two steps: estimating how likely something is to happen, and assessing the costs and benefits, both in human and monetary terms. What do we know about the probabilities and costs of climate change? And how should we consider tail risks: unlikely scenarios with potentially catastrophic outcomes?

In essence, risk is about probabilities and about costs, measured in human and monetary terms. For example, in deciding to ascend a stepladder to replace a lightbulb, we may estimate that the probability of falling off the ladder is small but of potentially great consequence, and weigh that against the large probability of successfully changing the bulb, with the attendant benefit of having light. This may be an easy one, but then there are the tough ones. A surgeon tells me that I have a 90% chance of surviving open-heart surgery. But if I do, I might have only a few years left to live. Given that the procedure will cost my family dearly whether it succeeds or not, should I go forward with it?

The assessment of risk therefore requires that we multiply the cost of the outcome by the probability of that outcome. We are then in a position to decide how much, if anything at all, we would be willing to spend to avoid that outcome. Quite often, the very worst outcomes have very low probability, and it is often quite difficult to assess the true probability of very low probability events. Economists call this the problem of "tail risk", because it relates to the risks associated with the far ends—"tails"—of probability curves. The probabilities of tail risks might be very small, but we cannot ignore them because the costs can be very high.

For example, if you were told by a reliable source that there is a 1% probability that your child would be run over if you let them cross a busy highway, you would almost certainly not take that risk even though the odds are vastly in your favor. The costs are just way too high, particularly when weighed against the relatively low cost of walking to a pedestrian crossing.

When we confront the risks associated with climate change, we need to know something about the probabilities of different climate outcomes, the costs those outcomes might impose on society, and the costs and benefits of mitigating climate change. We also need to confront the tail risks associated with low probability but potentially catastrophic outcomes, such as large and rapid sea level rise due to a collapsing ice sheet.

But there are strong cultural biases running against any discussion of this kind of tail risk, at least in the realm of climate science. The legitimate fear that the public will interpret any discussion whatsoever of tail risk as a deliberate attempt to scare people into action, or to achieve some other ulterior or nefarious goal, is enough to make most climate scientists shy away from any talk of tail risk and stick to the safe high ground of the middle of the probability distribution. The accusation of "alarmism" is often quite effective in making scientists skittish in conveying tail risk, and talking about the tail of the distribution is a sure recipe to be so labeled.

After all, by their very definition, such risks are unlikely to be the outcome. If we want to be admired by our descendants, the best strategy is to stick with the most probable outcomes and with high probability we can then ridicule those "alarmists" who warned of the tail risks, just as the adult who advises the child to cross the street will, in all likelihood, be able after the fact to chastise the one who counseled against it.

As we explain in the next chapter, in the case of climate change, the most probable outcomes over the next century, barring any action to curtail the emission of greenhouse gases, incur serious costs to society. But if climate change is worse than what we currently think is the most likely outcome, we face the possibility of catastrophic outcomes, so catastrophic that it might be difficult to really attach any definite number to the likely costs. It becomes almost a philosophical question how much we might be willing to spend to avoid the unlikely, but not so comfortably improbable possibility of truly catastrophic outcomes.

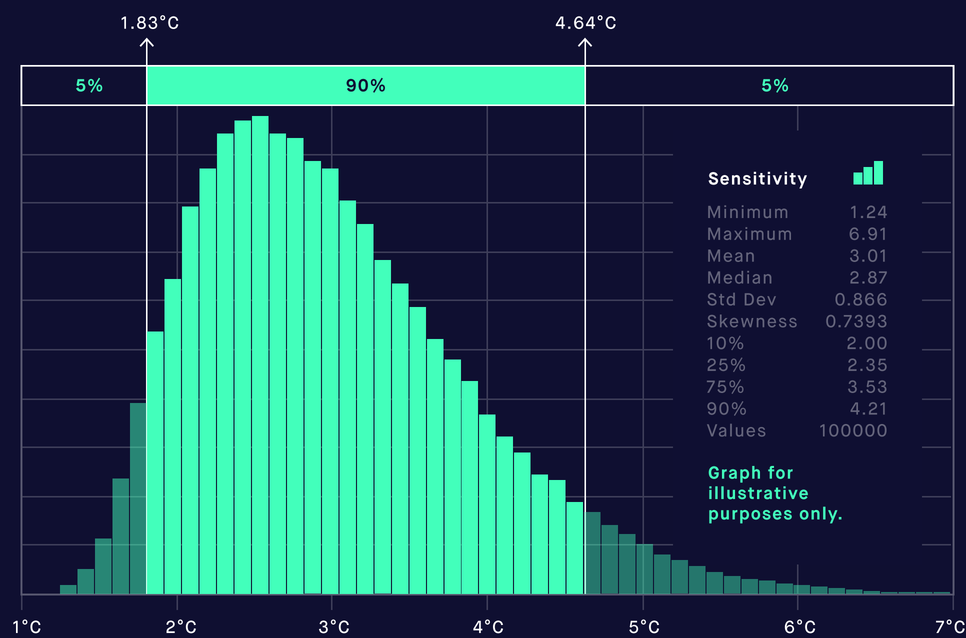
To illustrate this a bit more concretely, take a look at figure 14, which shows an estimate of the probability distribution of global mean temperature resulting from a doubling of CO_2 relative to its pre-industrial value, made from 100,000 simulations with a particular climate model. We use this here as an illustration; it should not be regarded as the most up-to-date estimate of the probabilities of global temperature increases.

More or less in agreement with the most recent report of the Intergovernmental Panel on Climate Change (IPCC), the most probable "middle" of the distribution runs from about 1.5°C to about 4.5°C, while there is a roughly 5% probability of temperature increases being less than about 1.8°C and more than about 4.6°C. But, given the corresponding distributions of rainfall, storms, sea level rise, etc., the 5% high-end may be so consequential, in terms of outcome, as to be justifiably called catastrophic. It is vitally important that we account for this tail risk as well as the most probable outcomes.

So far it has been difficult to quantify tail risk beyond that implied by figures such as figure 14. We have also tried to use paleoclimate data and the observed response of climate to large volcanic eruptions to narrow down the probability distribution. A wild card in climate risk assessment is the problem of abrupt, irreversible climate change, which evidence in ice cores and deep sea sediments suggests has occurred in the past. We also have to be mindful that the graph in figure 14 and many risk assessment studies use doubling of CO_2 as a benchmark, whereas we are currently on track to triple CO_2 content by the end of this century. Unless we find a way to extract carbon from the atmosphere (which we discuss in the chapter on Solutions) the climate risks would become alarmingly high (and not just in the tails) in the 22nd century, even if we stopped emissions by the end of this century. Let's explore those risks now.

Figure 14

The extreme scenarios—massive or only little warming—are unlikely but possible. This is what we mean by "tail risk".



Please note that this graph is for illustrative purposes only. It should not be regarded as the most up-to-date estimate of the probabilities of global temperature increases. Figure from Chris Hope, University of Cambridge.

What are the risks?

Sea level rise

We begin by making a simple observation about past sea level rise and human civilization. Remember that as ice volume on Earth goes down, sea level goes up and vice versa. 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.

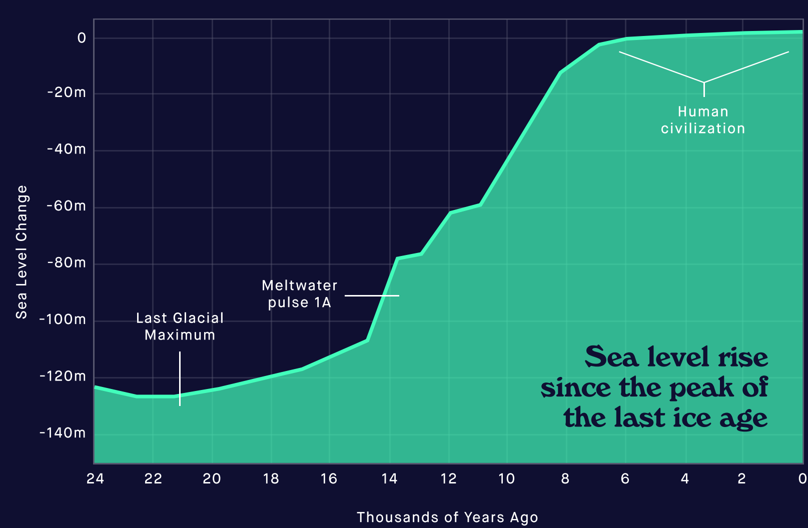
Figure 15 illustrates sea level rise to modern values from its low point of about 130 meters (roughly 400 feet) below today's level, about 22,000 years ago. Notice that sea level has been remarkably stable for the last 7,000–8,000 years—coincident with the time that human civilization developed.

And that is just the point. Because our prehistoric ancestors were nomadic, they did not build permanent cities. They probably didn't 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 7,000-8,000 years. But in our time, much damage would be done by a change in sea level of a few feet, let alone 400 feet. A 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

Figure 15

Sea level rose considerably after the last ice age but has been remarkably stable for the last 7,000–8,000 years.



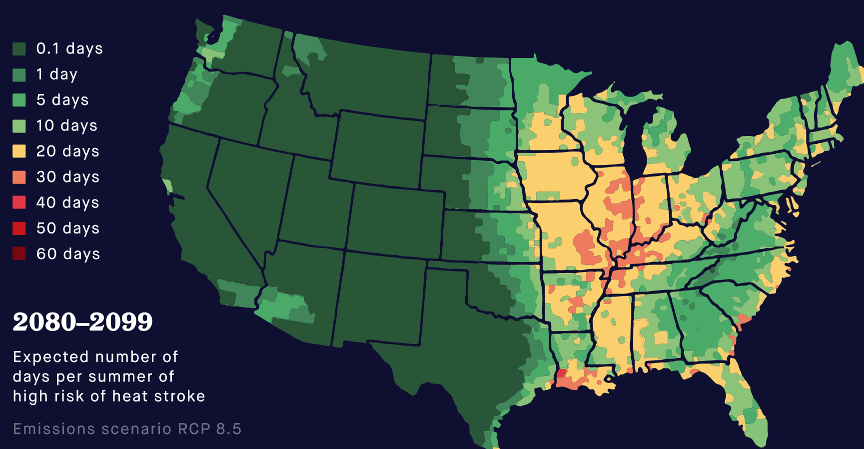
of sea level rise over coming decades, and projections range upward to an increase of around 1 meter (3 feet) by 2100, with a few estimates ranging as high as 2 meters (6 feet). Most of the thermal expansion effect and at least some of the glacial melting has been directly attributed to anthropogenic warming.

Elevated sea levels make coastal regions more susceptible to storm-induced flooding, as evidenced by the aftermath of Hurricane Sandy in 2012, 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.

But owing to the slow heating of the oceans, 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 over 400 ppm of CO_2 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 would simply have to relocate.

Figure 16

The number of days each summer with extremely dangerous levels of heat and humidity is expected to go up.



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: 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.

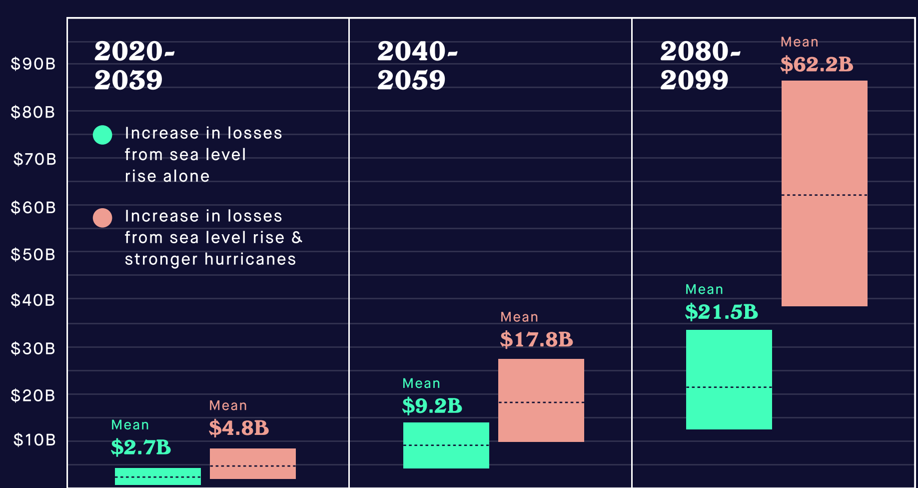
Heat and humidity

Warming is also of direct concern. Human comfort is measured by a quantity called the wet-bulb temperature, which is the lowest temperature a damp surface can have 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 16 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.)

Figure 17

U.S. property losses due to sea level rise and stronger hurricanes are projected to increase.



Projected increases (billion 2011 USD) in U.S. property losses as a result of sea level rise in the absence of increased hurricane activity, and from the combination of higher sea levels and increased incidence of intense hurricanes, under emissions scenario RCP 8.5. From: 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.

Destructive storms

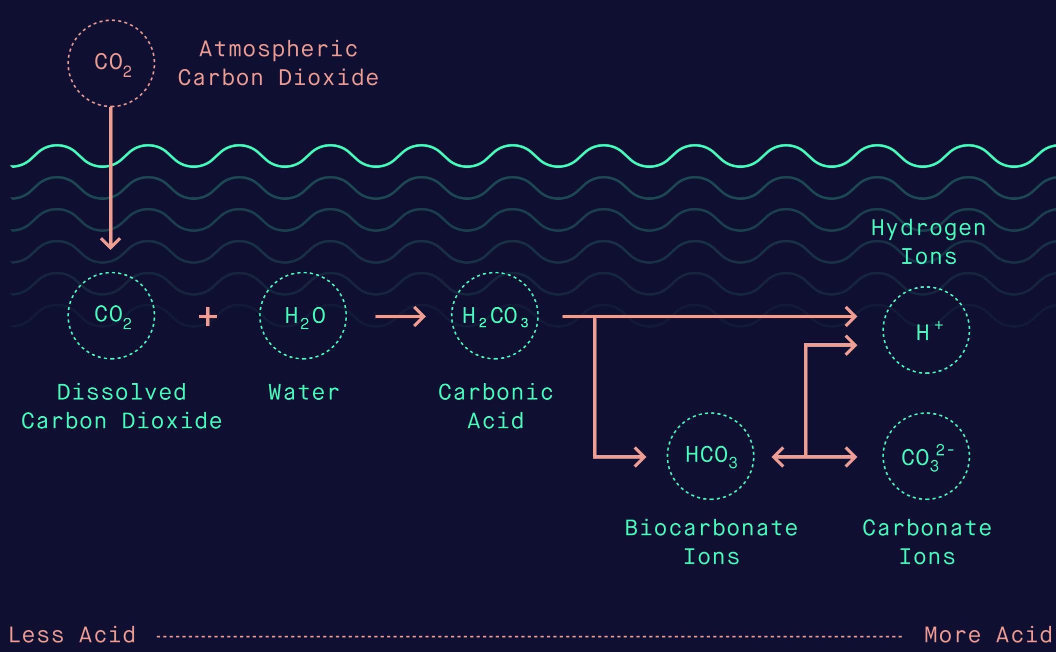
Violent storms are another risk to reckon with. Tropical cyclones cause on average more than 10,000 deaths and $700 billion (U.S.) in damages globally each year. There is now a strong consensus that the incidence of the strongest storms, which although small in number dominate mortality and damage statistics, 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 17 shows projections of annual U.S. property losses as a result of the combination of higher sea levels and greater incidence of intense hurricanes.

Ocean acidification

Increased atmospheric concentrations of CO_2 lead to increases in the concentration of CO_2 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.

Figure 18

In more acidic environments, mollusks, corals, and plankton have trouble building and maintaining their shells.



Food and water

Perhaps the most consequential change, however, will be the change in where and when rain falls. Physics tells us that as the climate warms, the frequency of storms will decline, but that when it rains it will rain substantially harder. Wet climates will generally become even wetter, while arid regions will become more so, meaning that flash flooding and drought will be more frequent. These changes in the water cycle, which we are already starting to see, are especially worrying because of their impacts on our food and water resources.

These changes 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 19 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 once in 20 years agricultural loss events could occur every other year.

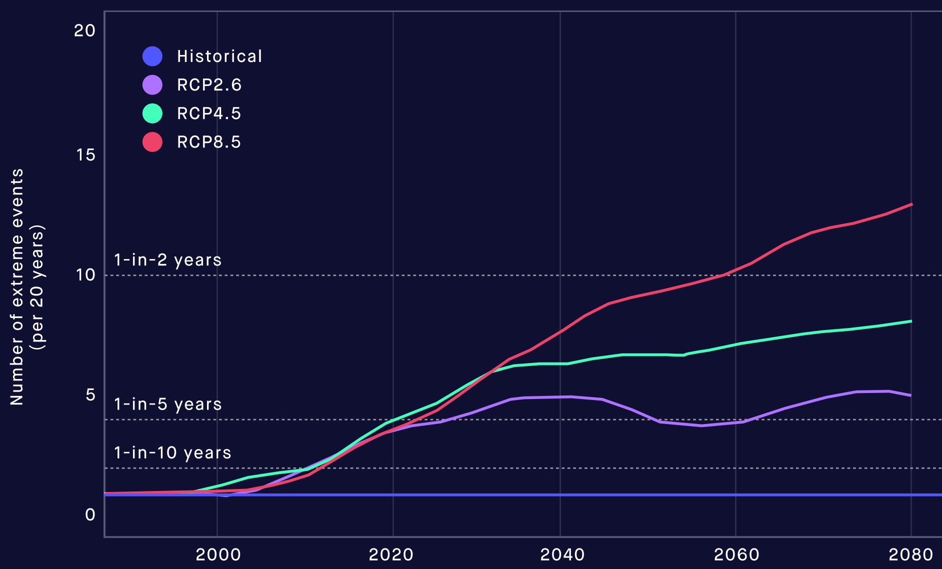
Historically, the disappearance of certain civilizations, such as that of the Anasazi in what is today the southwestern U.S., has been attributed to food and water shortages brought on by prolonged drought. Such shortages are also thought to cause or exacerbate mass migrations and armed conflict. The 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 7,000-8,000 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.

> Political and social destabilization is perhaps the greatest and least predictable risk incurred by rapid climate change.

Figure 19

By the end of this century, today's once in 20 years agricultural loss events could occur every other year.



Number of extreme U.S. agricultural loss events per 20 years relative to the current 1-in-20 event, for three emissions scenarios. From: 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.

How long can we wait to act?

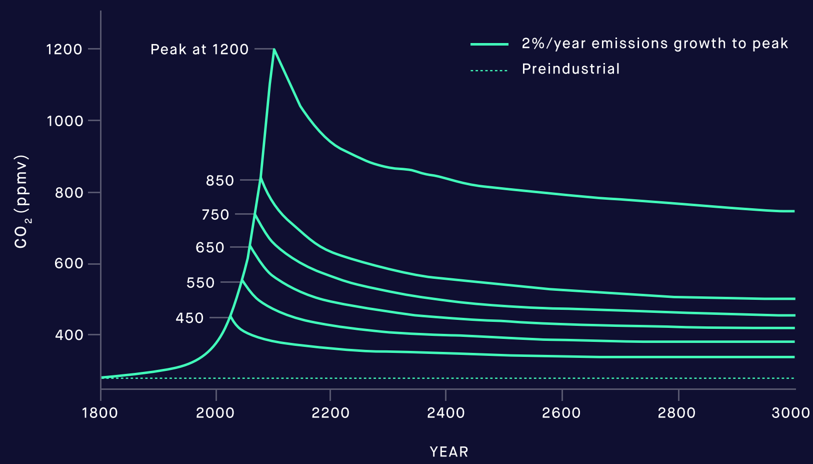
Global climate change presents us with unprecedented challenges. Since climate science can do no more than estimate a broad set of possible outcomes ranging from the concerning to the catastrophic, society must treat the problem as one of risk assessment and management. At one extreme, we could elect to do nothing and gamble on an only moderately challenging outcome. But if we are wrong we will saddle children and their descendants with enormous problems. At the other extreme, we could make serious economic and other tangible sacrifices that might prove unnecessary. Unfortunately, waiting much longer to see which way things go is not a viable option since it takes thousands of years for CO_2 levels in our atmosphere to decline once emissions stop. In fact, even if we were to magically cut all emissions today, we would still see CO_2 levels of over 400 ppm until the year 3000. By the time the consequences of climate change become unequivocally clear, it will almost certainly be too late to do much about it. We must decide very soon.

Carbon dioxide is a greenhouse gas of special concern because of its long residence time in the atmosphere. Figure 20 shows estimates of the decline of CO_2 levels 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.

Figure 21 shows projections of global mean temperature that correspond to the CO_2 concentrations in Figure 20. 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 CO_2 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.

Figure 20

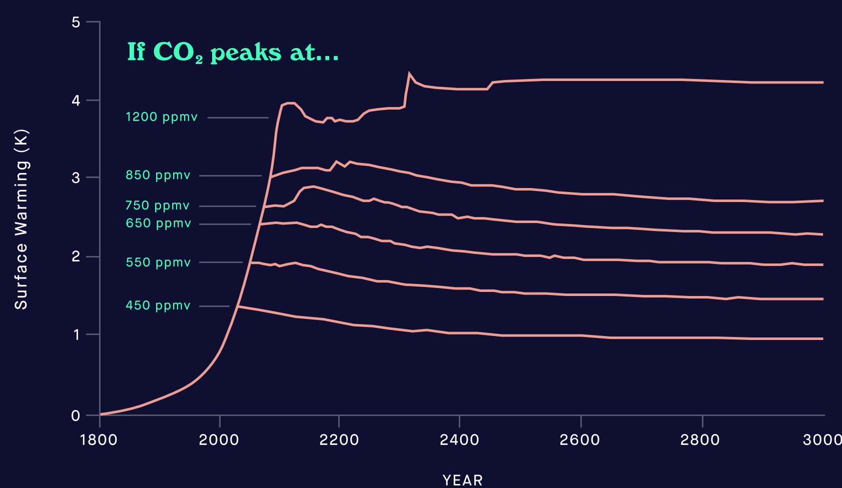
Even if emissions abruptly stopped, CO_2 concentration will remain high for thousands of years.



Evolution of atmospheric CO_2 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. Source: Solomon, S., G.-K. Plattner, R. Knutti, and P. Friedlingstein, 2009, PNAS 106: 1704–1709.

Figure 21

Even if emissions abruptly stopped, temperature will also remain high for thousands of years.



Estimates of the evolution of global mean temperature (relative to its preindustrial value) corresponding to the CO_2 concentrations in figure 20 of this site. Source: Solomon, S., G.-K. Plattner, R. Knutti, and P. Friedlingstein, 2009, PNAS 106: 1704–1709.

What can we do?

Which solutions we deploy to deal with climate change is not decided by scientists, engineers, or economists—it's decided by society as a whole. After we understand the climate risks and the options for dealing with them, it is up to us to choose how much risk we're willing to assume on behalf of future generations, and therefore which actions to take.

This is a terrifically difficult decision because the costs of action may be high and those paying them are not likely to reap the benefits themselves. Indeed, there are few historical examples of civilizations consciously making sacrifices on behalf of descendants two or more generations removed. Yet, if we are to stave off the worst impacts of climate change, this generation must decide what actions it will take, and the following chapter briefly introduces the kinds of large-scale technological solutions that are available to us.

Options for dealing with climate change fall into three broad categories: curtailing the emissions of greenhouse gases and/or taking greenhouse gases out of the atmosphere (mitigation), learning to live with the consequences (adaptation), and engineering our way around the problems that greenhouse gases produce (geoengineering).

> **Broadly speaking, there are three strategies: Reduce emissions of greenhouse gases, compensate for them through climate engineering, and adapt to climate change.**

Curtailing emissions

Of these three options, mitigation has the most straightforward effect on climate because it attacks the source of the problem. Some aspects of mitigation might be worth undertaking anyway. For example, consumers might spend extra money on a high-efficiency car if the excess cost is paid back in fuel cost savings over a few years. Similarly, the costs of constructing or retrofitting buildings to conserve energy might also be paid back in a short time. Such conservation measures would not only help reduce emissions but would also prove economically beneficial for consumers.

But given the actual and expected growth in the economies of developing nations such as China and India, conservation alone cannot begin to reduce greenhouse gas emissions to safe levels. Experience has shown unequivocally that rapid economic growth can only be achieved with large increases in per capita energy consumption.

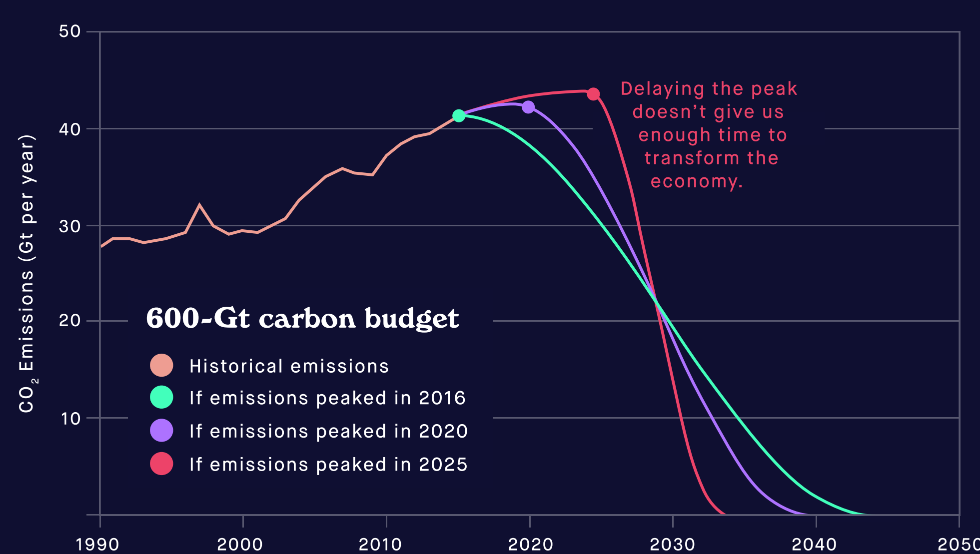
The alleviation of the wrenching poverty of poor nations is, of course, a highly desirable goal, and it also appears to be a necessary condition for the reduction of population increase, which is a key driver of energy growth. Thus the global problems of climate, energy, poverty and population are inextricably linked.

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. Fortunately, the means of decarbonizing energy are at hand. The growth in solar and wind power in recent decades has been truly impressive, and the price of these energy sources has fallen as demand increases and technology improves. Even so, solar and wind provide only 6% of global electrical power today, and most energy experts believe that the inherent intermittency of these sources will limit their market penetration to 30-40%, barring a true breakthrough in energy storage and/or transmission technologies.

Nuclear fission provides about 10% of global electrical energy, but today relies entirely on light-water reactors that

Figure 22

We have about 600 gigatonnes of carbon dioxide left to emit before the planet warms dangerously, by more than 1.5-2°C.



produce radioactive waste. Even so, nuclear fission is far and away the safest form of energy mankind has ever produced. The mortality per kilowatt hour generated is less than that of most other energy sources, and comparable to solar and wind. While much is made of events such as that at the Fukushima facility in Japan, petrochemical accidents brought about by the earthquake and tsunami killed many while no deaths resulted from Fukushima's release of radioactive material. Indeed, it is estimated that nuclear fission has saved about 1.8 million lives by displacing fossil fuels, whose combustion is the source of numerous health problems.

Yet nuclear technology has advanced significantly since light-water reactors were introduced more than a half-century ago. Advanced reactors operate at ambient pressure and are passively safe, so they are inherently incapable of melting down. They burn fuel far more efficiently, resulting in greater power production per unit input of fuel, and much less radioactive waste. They are far more environmentally benign than solar or wind, requiring much less land, and some of the new designs require very little water for cooling.

Actual experience in countries such as Sweden and France shows that fission power can be ramped up to supply a large fraction of electrical energy in less than 15 years. What is now lacking more than anything else is political will.

The implementation of nuclear fission, higher efficiency vehicles and buildings, and other mitigation measures could be accelerated by a variety of governmental actions, such as carbon taxes, cap-and-trade policies, subsidies for carbon-free energy, and removing existing subsidies for the coal, oil, and natural gas industries. While it is beyond the scope of this primer to discuss policy, it is clear that these approaches could greatly accelerate the implementation of these climate mitigation solutions.

> **Nuclear fission is the safest form of energy humans have ever produced. The mortality per kilowatt hour generated is less than that of most other energy sources, and comparable to solar and wind.**

Removing carbon

Another mitigation strategy is to reduce the effect of emissions by capturing and storing their greenhouse gas components. Such technology exists today but is not currently considered to be economically viable. There is some hope that technological developments might bring these costs down.

Capturing carbon at its industrial source is perhaps the best of all solutions if it can be done economically, because fossil fuels are so abundant and affordable and because extensive infrastructure already exists for producing and distributing them. It is also possible to capture CO_2 directly from the atmosphere, but this is currently much more expensive because atmospheric concentrations of the gas are far lower than those at the emissions sources.

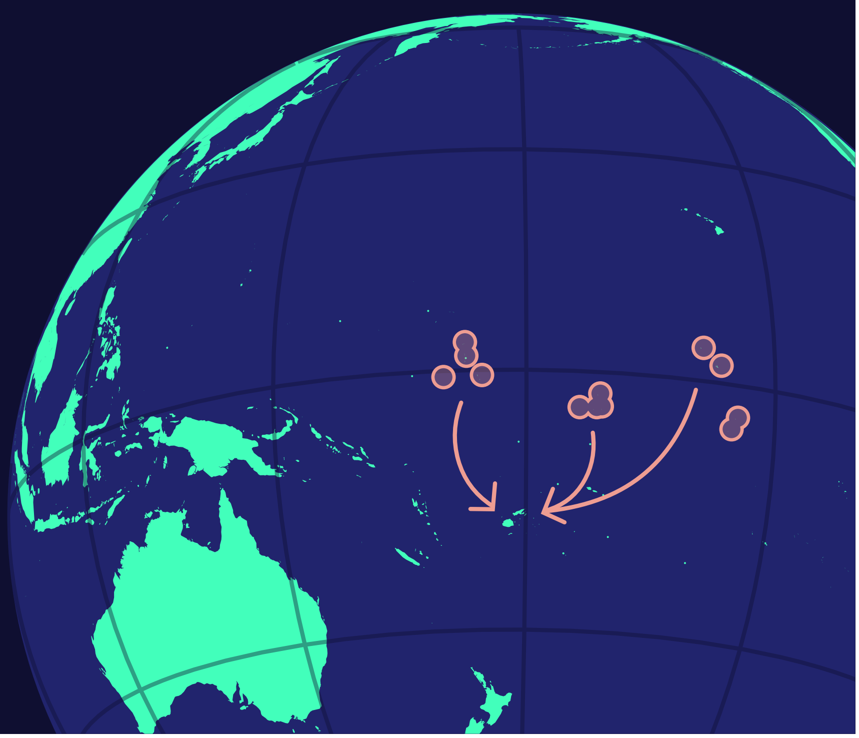
Adaptation

Whereas the costs of mitigation fall mostly on the largest emitters of greenhouse gases, the costs of adaptation are more broadly distributed over the world. For example, the low-lying Pacific island nation of Kiribati, with a population of just over 110,000, is threatened by rising sea levels, and there has been talk of moving the entire population to Fiji. At the other extreme, countries such as Russia and Canada might profit from a warmer climate as, for example, melting ice allows for new ocean passageways and reveals mineral resources. But most nations will need to adapt to climate change, entailing measures ranging from crop substitutions to beefing up seawalls and levees and planning for shifting demands for and supplies of water and food.

A key but complex issue is the relative costs and benefits of adaptation and mitigation, all of which must be estimated in an environment of considerable uncertainty. An optimal strategy will no doubt involve doing some of both.

Figure 23

The island nation of Kiribati, with a population of just over 110,000, is threatened by rising sea levels. In 2012, there was talk of moving the entire population to Fiji.



Geoengineering

The third approach, geoengineering, seeks to actively counter greenhouse gas-induced warming. Proposals aimed at cooling the earth focus primarily on managing the net amount of solar radiation the planet absorbs by increasing the reflectivity (albedo) of the surface and/or the atmosphere. A popular technique involves injecting modest amounts of sulfur into the stratosphere, resulting in the formation of sulfate aerosols that reflect sunlight and thereby cool the climate system. The technology to do this pretty much exists today, and the cost of doing so is small enough that a small nation or even a wealthy individual could pull it off.

But there are many technical, legal, and political problems with solar radiation management. On the technical side, cooling the mean surface temperature back to some desired point (say, enough to prevent damaging sea level rise) while leaving atmospheric concentrations of CO_2 unabated would not necessarily repair other important aspects of the climate system. In particular, canceling a long-wave radiative effect (greenhouse gas warming) with a short-wave fix (reflecting solar radiation) does not necessarily restore variables other than temperature. For example, bringing the temperature back to some desired level would almost certainly result in a reduction of global precipitation.

Moreover, engineering solar radiation does nothing to address the CO_2-induced acidification of the oceans that may prove to be among the most serious consequences of greenhouse gas emissions.

Furthermore, any entity, whether an individual or a nation, that undertook geoengineering would do so within a largely undeveloped legal framework, leaving it exposed to legal or even military action. For all these reasons, most of those who work seriously on geoengineering regard it as an option to be developed and then kept in our collective back pocket, to be used only if the effects of climate change become catastrophic.

> **Most of those who work seriously on geoengineering regard it as an option to be kept in our collective back pocket.**

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, remaining uncertainties in climate physics and climate models lead to large uncertainty in climate projections, with possible outcomes ranging from the challenging to the catastrophic.

The science suggests that we may be able to avoid the greatest risks of climate change by removing carbon emissions from our world's energy supply very soon, within the next 10-15 years. And there are many reasons to be optimistic that we can do this. We can scale carbon-free energy sources, technology for capturing CO_2 from power plants and industry, and ways to extract CO_2 directly from the atmosphere. Renewable energy can power 20%-60% of current energy needs, and more if better energy-storage technology is invented. Nuclear fission has improved remarkably since the 1960s and, once developed, can be ramped up to meet a large fraction of demand in less than 15 years. There is also renewed optimism that nuclear fusion, a basically limitless clean source of energy, may become commercially viable in 15 to 25 years. While this may be too late to significantly curtail major climate risk, 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 businesses that develop carbon-free energy early and well will gain an important competitive advantage in what is currently a $6 trillion energy market.

> **There is no scientific justification for the confidence expressed by some that climate change entails little or no risk.**

Conclusion

This concludes our introduction to climate science, and the risks and solution areas for climate change. It's now up to society to consider both the climate risk that lies ahead of us and also the opportunities we can seize: to create a pollution-free energy system; to form an adaptable and resilient society; to keep human, animal, and plant life flourishing; and to create a better world for generations to come.

Dispelling Myths

A Q&A from Climate Communication

By Susan Joy Hassol
Director of Climate Communication

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Q

Is Earth's climate warming?

Yes, it is an unequivocal fact that, since the early 20th century, Earth's average temperature has risen and continues to rise, despite some natural year-to-year fluctuations. Each of the past few decades has been substantially warmer than the decade prior to it. The hottest five years on record are 2014-2018.

All analyses of all surface temperature data sets compiled by major climate centers around the world show a clear warming trend. Besides these thousands of thermometer readings from weather stations around the world, there are many other clear indicators of global warming such as rising ocean temperatures, sea level, and atmospheric humidity, and declining snow cover, glacier mass, and sea ice.

Because temperatures vary from year to year, scientists measure trends in running averages and analyze trends over decades rather than expecting every year to be hotter than the previous year. Some years have particular factors that make them hotter than those just before and after. For example, a major El Niño event combined with the persistent rise in heat-trapping gases made 1998 one of the hottest years on record. That has caused some people to claim that Earth has been "cooling" since then. But as the data clearly show, this claim is false.

Q

Do climate scientists agree that the world is warming and that humans are the cause?

More than 90% of climate scientists have concluded that human-caused global warming is happening. It is well-established that human activity is the dominant cause of the warming experienced over the past 50 years. This conclusion is based on multiple lines of evidence, from basic physics to the patterns of climate change through the layers of the atmosphere. The warming of global climate and its causes are not matters of opinion, they are matters of scientific evidence, and that evidence is clear.

These two basic conclusions, that the world is warming and that humanity is the primary cause, are well-documented in the reports of the Nobel prize-winning Intergovernmental Panel on Climate Change. Further, these major conclusions have been objectively reviewed and independently verified by the National Academies of Sciences of all major countries including the U.S., and all relevant scientific organizations such as the American Geophysical Union, American Meteorological Society, American Association for the Advancement of Science, and the Royal Society of the United Kingdom.

Q

How do we know recent climate change is caused by human factors rather than natural factors?

Climate changes observed over recent decades are inconsistent with trends caused by natural forces but are totally consistent with the increase in human-induced heat-trapping gases. In fact, without human influences, Earth's climate actually would have cooled slightly over the past 50 years.

Natural forces cause Earth's temperature to fluctuate on long timescales due to slow changes in the planet's orbit and tilt. Such forces were responsible for the ice ages. Other natural forces sometimes cause temperatures to change on short timescales. For example, major volcanic eruptions can cause short-term cooling lasting two to three years. Changes in the sun's output over the past 30 years have followed the typical 11-year cycle, with no net increase, while temperatures were warming strongly.

Many independent lines of evidence (from basic physics to the patterns of temperature change through the layers of the atmosphere) have shown that the warming of the past 50 years is primarily due to the human-caused increase in heat-trapping gases.

Q

What do ice cores tell us about the relationship between temperature and carbon dioxide?

We know from ice core records that temperature and carbon dioxide (CO2) levels are closely correlated. In the distant past, warming episodes appear to have been initiated by cyclical changes in Earth's orbit around the sun that caused more summer sunlight to fall in the northern hemisphere. This caused snow and ice on land and sea to melt, revealing darker land and water, which caused more warming, in a self-reinforcing cycle. As the planet continued to warm, more CO2 was released from the oceans, and this increase in heat-trapping gas caused even more warming. Thus, while CO2 did not initiate those warming episodes, it did contribute to them.

In the current warming episode, it is clear that CO2 and other human-induced heat-trapping gases are driving the warming. We know with certainty that the increase in CO2 concentrations since the Industrial Revolution was caused by human activities because the isotopes of carbon show that it comes from fossil fuel burning and the clearing of forests.

So even though past warming episodes may have been initiated by orbital changes that caused warming and thus caused CO2 to rise, which then led to more warming, we know that the current warming episode is being driven by increasing CO2 due to the burning of fossil fuels and the clearing of forests. The orbital changes that caused the ice ages are far too weak and slow to cause a warming as rapid as the current one.

Q

How can we trust predictions about our climate for decades or centuries in the future?

When people wonder about the degree of certainty in global warming predictions versus next week's weather report, they are confusing climate and weather. Predicting weather and predicting climate are different and pose different challenges.

Weather is individual, day-to-day atmospheric events; climate is the statistical average of those events. Weather is short-term and chaotic and is thus inherently unpredictable beyond a few days. Climate is long-term average weather and is controlled by larger forces, such as the composition of the atmosphere, and is thus more predictable on longer timescales. For the same reasons, a cold winter in one region does not disprove global warming.

As an analogy, while it is impossible to predict the age at which any particular man will die, we can say with high confidence that the average age of death for men in industrialized countries is about 75. The individual is analogous to weather, whereas the statistical average is analogous to climate.

Q

How reliable are climate models?

Climate models are mathematical representations of the interactions between the various aspects of the climate system including the atmosphere, oceans, land surface, ice, and the sun. The complex task of simulating Earth's climate is carried out by computer programs designed to detect long-term climate trends based on large-scale forces. Unlike weather prediction models, climate models are not intended to predict individual storm systems.

Climate models are tested against what we know happened in the past and they do accurately map past climate changes. Climate models have also been proven to make accurate predictions. For example, the eruption of Mt. Pinatubo provided an opportunity for such a test. The models successfully predicted the climatic response after the eruption, a cooling influence that lasted a couple of years.

Models have also been applied to the question of how the climate system will react to additional greenhouse gases. These models have correctly predicted effects subsequently confirmed by observation, including greater warming in the Arctic and over land, greater warming at night, and stratospheric cooling.

What did most climate scientists in the 1970s predict about future climate?

The vast majority of published climate science papers in the 1970s were related to the same concern that prevails today: warming due to the increase in heat-trapping gases. There were a few papers published at that time on the issue of particle pollution (mostly from coal plants which did not yet have scrubbers) blocking out some of the incoming sunlight and exerting a short-term cooling influence. Some media outlets picked up on this and sensationalized the notion of global cooling, contrary to the concerns of most climate scientists.

Because it has been a persistent myth that scientists warned of cooling in the 1970s, researchers examined this question and published their findings in 2008 in the Bulletin of the American Meteorological Society. They concluded: "There was no scientific consensus in the 1970s that the earth was headed into an imminent ice age. Indeed the possibility of anthropogenic [human-caused] warming dominated the peer-reviewed literature even then."

How do we know recent warming is NOT caused by the sun?

Since 1978, scientists have been using sensors on satellites to measure the amount of the sun's energy reaching the top of Earth's atmosphere. Since that time, global temperatures have risen sharply, while there has been no significant change in the amount of the sun's energy reaching Earth.

In addition, if the warming had been caused by an increase in the sun's energy, we would expect to see warming throughout the layers of the atmosphere, from the surface all the way up through the stratosphere. On the other hand, warming caused by a buildup of heat-trapping gases from human activities would cause warming at the surface but cooling in the stratosphere, and this is in fact what we observe.

Q

Do warmer cities affect the global temperature record?

No. The "urban heat island" effect is undoubtedly a real phenomenon that has been recorded in major cities around the world. It results from the large amounts of concrete and asphalt in cities absorbing and holding heat and the minimal amount of vegetation to provide shade and evaporative cooling. However, scientists have accounted for these local effects and have verified that they do not skew the global temperature record. For example, one test scientists have done is to remove all the urban stations from the global temperature record. When this is done, the global warming of the past 50 years is still apparent.

Q

How do volcanoes influence climate?

Volcanoes can and do influence global climate, exerting a cooling influence for a few years. This cooling influence occurs when large, explosive volcanic eruptions inject sun-reflecting sulfate particles into the high reaches of the atmosphere (the stratosphere). For example, the four major volcanic eruptions of the 20th century caused short-term interruptions in the long-term warming trend caused by human induced emissions of heat-trapping gases.

Contrarians have asked whether the CO2 emissions from volcanoes might impact climate. But in fact, this is insignificant compared to human activities. Burning fossil fuels releases several hundred times more CO2 than volcanoes do each year. Fossil fuel burning results in the emission of approximately 35 gigatons of CO2 into the atmosphere per year worldwide. This obviously dwarfs the estimated annual release of CO2 from volcanoes, which is 0.15 to 0.26 gigatons per year.

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