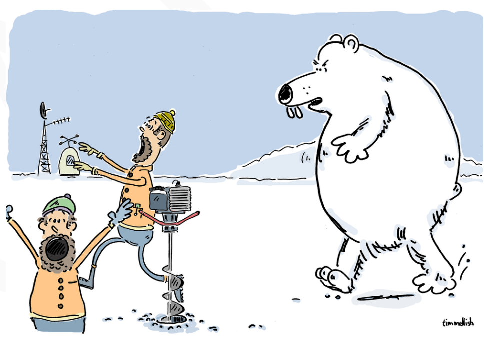
Chapter 4

Climate Science

Solar radiation and greenhouse gases undoubtedly determine the planetary climate. And humans are undeniably altering the greenhouse gas concentration in the atmosphere. So what is the human influence on earth's climate balance and to what extent has it caused warming of the planet?

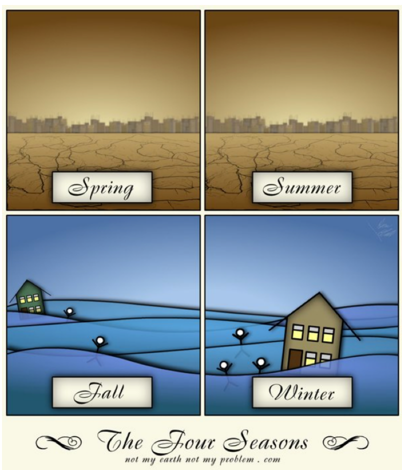


Ironically, it wasn't just the sceptics or the anti-climate movement that obstructed climate change research...

If you follow the media and read books on climate, especially those that set forth only one or the other vantage point for the story's sake, then you may think you already know everything there is to know. We thought we knew it all, too. We didn't. There is a lot more here than meets the eye. Allow yourself to be surprised. We were.

1 Climate Versus Weather

A good way to think of climate is that it is weather averaged over many decades and centuries. These averages remove both seasonal weather variation and interseasonal weather variation (most importantly, the El Niño recurrent multi-year patterns in the Pacific). Climate is then the remaining very slow long-term trend in weather, and conversely weather is the short-term variation around climate.



An intuitive way to distinguish between climate and weather is that humans can far more easily perceive weather changes than climate changes. Short-run weather changes are much larger than climate changes.[1] Weather swamps most people's perceptions. The best way to obtain trustworthy information about climate change is via accurate scientific instruments that can measure averages 24/7, 365 days a year, over many decades. Scientific instruments can then calculate long-term averages precisely enough to smooth out short-term weather variations. Data less than a few decades and the averaged multi-year weather records could be influenced by complicated and random variations unrelated to underlying long-run changes in climate — such as the occasional volcanic eruption or longer weather phenomena that even scientists do not understand.

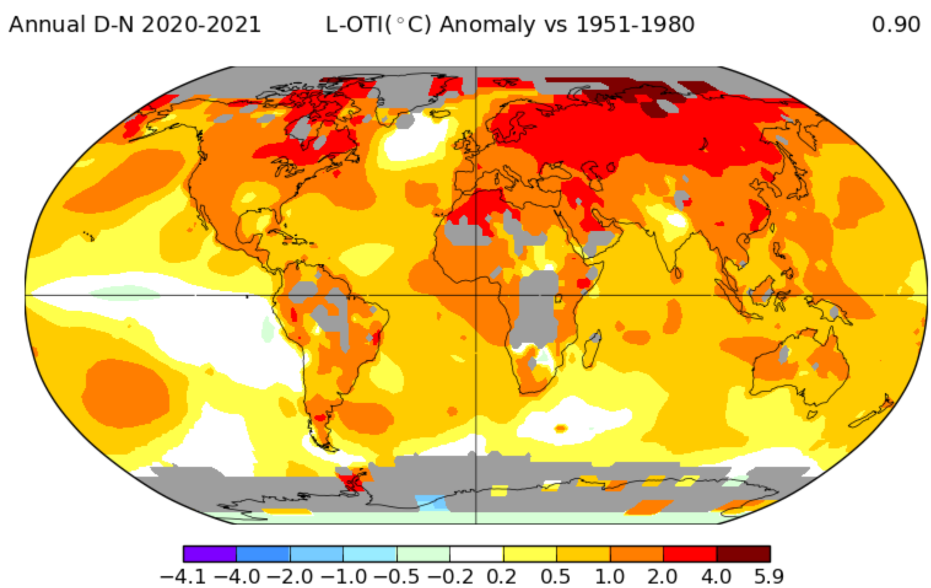
For those of us in our fifties and beyond, maybe — just maybe — we can get some feeling for our *local* climate changes by remembering how weather seemed cooler when we were young. But like many human memories, such perceptions can also be mistaken.

There is another important complication if we want to assess the *global* climate. Local trends are not necessarily representative of global trends. Over millennia or epochs (a few million years), there is good evidence that climate

[1] We casually use the term climate primarily for temperature, but it really includes many other environmental parameters (especially humidity), as well.

trends were distinct in different parts of the globe. The arctic may have gotten colder, while the subarctic may have gotten warmer (or vice-versa).

Figure 1. Temperature Anomaly, 2020-2021



Source: NASA GISS Surface Temperature Analysis (v4). The base years are 1951–1980. Units are in °C. Another version of this map appears in Figure ??.

Even over the last few years, different parts of the globe have warmed at different rates. Warming has been more severe in Russia, North-East Canada, and the Arctic compared to, say, India, the South-Eastern USA, and the Antarctic. To assess *global* climate change, scientists need multi-decade measurements of many aspects of weather not just in a few spots but in many spots all over the globe. The best data is typically from satellites, even though some data sets go back to the 19th century.

As far as human impact is concerned, there is yet another related problem. As we explained in the previous chapter, human emissions have been accumulating slowly. And many planetary responses to those emissions would have been even slower. For instance, it is taking decades or centuries for oceans to warm and for Arctic ice to melt. This "glacial" speed makes our human impact more difficult to gauge. And it makes it more difficult to educate the public about climate change. Our human lives may be short, but our attention spans are even shorter. It is easy to lose a sense of urgency, given all the other pressing problems in our 24-hour news cycle.

Don't worry...The warmer it gets, the less we have to worry about the cold.

When it comes to climate change, humans are like frogs in very slowly warming water. On the plus side, the glacial pace of climate change gives civilization time to react and to adapt. For example, if the sea level rises slowly, our children can move inland towards the new shoreline and build stronger structures, so that damages and deaths from hurricanes will be lower (and they already are *much* lower today than they were a century ago). On the minus side, the glacial pace of climate change makes it an especially insidious threat. Procrastination is just too tempting. By the time humanity may finally get around to reacting appropriately, it may already be too late.

Activist Versus Scientific Views of Extreme Weather Events

What are climate activists to do? How can they catch the public's attention? Some of them try to take advantage of dramatic weather events. Weather changes can attract attention in ways that climate change cannot. This approach of blaming climate for all extreme weather may be well-intended, but it is not entirely honest. And, more importantly, it is not the scientific approach.

➤ Hurricanes (Tropical Cyclones)

Let us give a prominent example. When scientists want to explain that the analysis of climate change is not that simple and push back on over-active imagination, they sometimes discuss hurricanes. Most headlines in the popular media proclaim that hurricanes have been increasing. Indeed, there was a record number of 30 named storms in 2020. Hurricane season also now seems to start about a month earlier than just a few decades ago. Yet, the scientists themselves remain more circumspect. Unlike activists, they do not consider the past hurricane incidence data to be the unconditional smoking gun for global climate change. (There are smoking guns, but they are elsewhere.) The scientists prefer to stress that the evidence is more nuanced.

Kossin et al. (2021) explain that tropical cyclones form not just when (global) air temperature is high, but when many regional influences come together. Local sea temperature — often linked to ocean circulation — is important, but other factors come into to play as well. Temperature gradients (differences) play a role. Dust from volcanic eruptions can play a role. And, in the Atlantic, fossil-fuel aerosol particulates and Saharan dust play a role. Global warming can influence both these factors and hurricanes, but not in straightforward monotonic direction. Their effects can come together regionally in different constellations. Based on the clearly increasing earth temperature (and the clearly but more modestly increasing global ocean temperature), many climate scientists are now predicting more hurricanes of higher intensity[2] and perhaps with different paths. However, this does not mean that they are predicting the number of hurricanes to increase strongly — they do not know. In any case, they will tell you that a few decades of hurricane data are *not* a good measure of global warming. (Scientists have much better ones.) Put differently, although it is not expected (global warming does not predict it one way or another), we could even see a few decades of reduced hurricane activity. If this were to occur, we should not conclude that global warming has subsided.

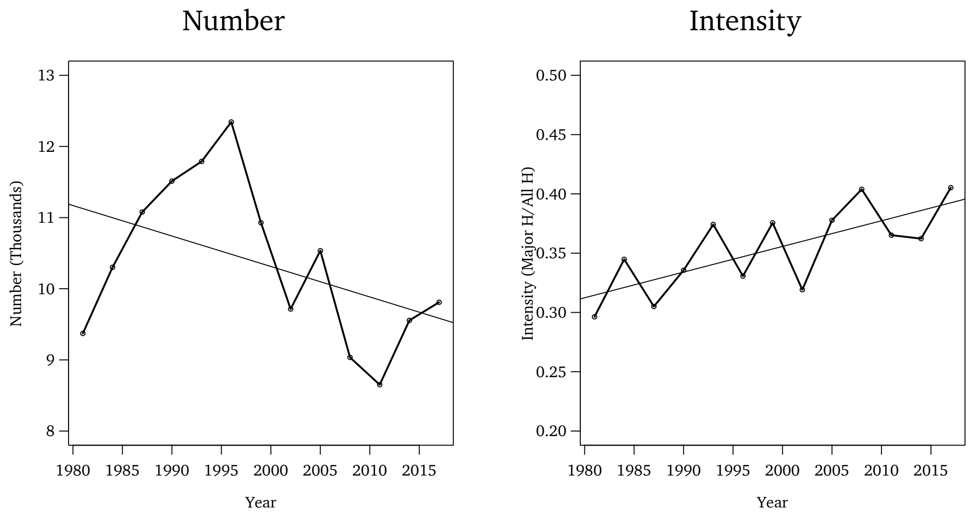
Figure 2 shows the state-of-the-art in tropical cyclone research, using data from six basins in which they occur. The left plot shows that the number worldwide increased from 1980 to 1995 and decreased since. This is sometimes touted as evidence against global warming by skeptics—incorrectly, of course. The models do however predict that when cyclones do form, they will be more intense. The right plot shows that the evidence for this prediction has been slowly accumulating. But our point is not that cyclones do this or that — it is that it requires scientific evidence to draw conclusions, not publicists and news.

➤ Sea Level Temperature and Rise

The evidence of consequences of global warming is stronger in the ocean data. However, some mysteries remain. As the temperature rises, sea-levels

[2] The empirical evidence just passed statistical significance about 2-3 years ago, but the number of hurricanes has been rather low since then, possibly falling back.

Figure 2. Tropical Cyclones (aka Hurricanes)

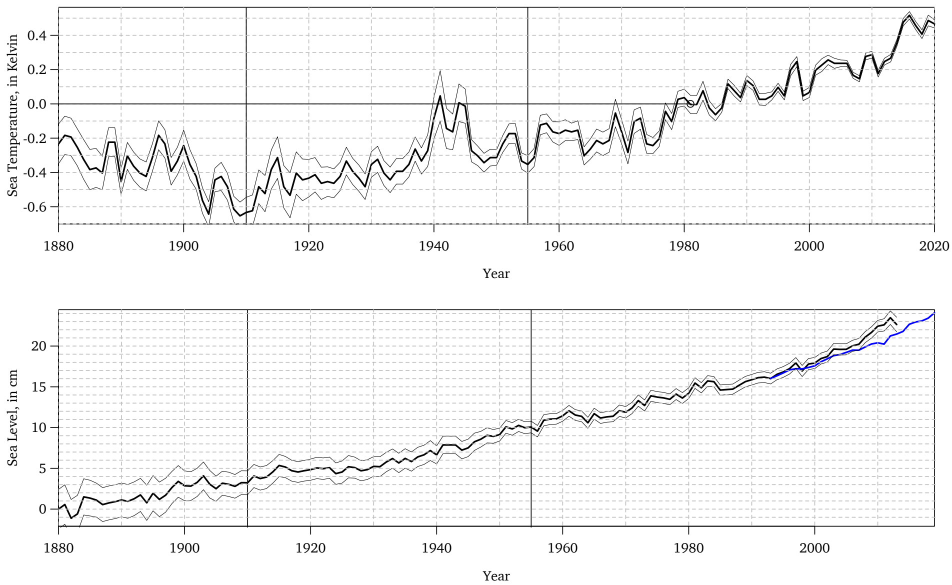


Source: Data were aggregated over all worldwide basins from Kossin et al., PNAS 2020. See also Environmental Protection Agency (EPA), Climate Change Indicators: Tropical Cyclone Activity via the National Oceanic and Atmospheric Administration (NOAA), 2016, and Vecchi and Knutson, 2011. See also Knutson et al., 2019, for a scientific survey.

have and will continue to rise — it is a simple fact of physics. Figure 3 shows the actual evidence. Most activists would just extrapolate the sea-level rise exponentially and call it day. Scientists agonize *both* about the early evidence (that shows a mismatch in temperature and sea-level rise), *and* about whether they should extrapolate past trends linearly or exponentially.

The physicist Steven Koonin has openly questioned how much certainty there is about the IPCC's extrapolative predictions of impending *dramatic* sea-level rise. When scientists disagree, they blame each other for cherry-picking of evidence. Earth is a tough spot to do research in — but the process of science demands exactly such skepticism and debate. (We just wish it were less personal.)

Figure 3. Global Sea-Level Temperature and Rise



Source: The source is the U.S. EPA, both for Sea Temperature and Sea Level. This was the full data set, as available in March 2022. The blue line in the lower graph are based on satellite measurements; the black line on tidal gauges. There were three temperature patterns: 1880–1910, 1910–1955, and 1955–2020. Sea temperature rose most after 1955. Sea level has been steadily increasing (3mm per year), and perhaps slowly accelerating.

➤ Heat and Cold Waves

Conversely, there was an epic cold-wave in the continental United States in February 2021; and Antarctica's 2021 polar winter was the coldest on record. Should this make you think that the climate skeptics may have a point, that the data are ambiguous, or that the world could even be getting colder again? No! Neither a few cold waves nor a few heat waves nor a few hurricanes prove much about global warming.

➤ Don't Misunderstand Us!

To avoid any misunderstanding, our examples do not mean that most other climate-change-blamed phenomena in the news are based merely on click-bait, biased reporting, and incorrect human perception. Furthermore, make no mistake: **All serious scientists agree that earth's temperature has been rising and at an accelerating rate over the last 50 to 100 years.** Climate change is real and it will have stark consequences.

Yet, it is difficult to connect any single specific heat-related event (like Europe's hottest summer on record, 2021) to global warming. This does not imply that heat-related events are necessarily unrelated to global warming, either. Many almost surely are.[3] Increasing temperature *must* eventually lead to increases in many heat-related phenomena — such as heat waves in Europe or Arctic melting.

Our point here is simply that meaningful analysis requires more than just an impression from the news. It requires detailed scientific observations collected over decades with care and appropriate caution in interpretation.

2 The Global Thermostat

A good starting point to understand global temperature is to ask: Why does Earth have the (average) temperature now that it does? Currently, the global mean temperature across day and night and across all latitudes is 14 degrees Celsius (14°C) or 57 degrees Fahrenheit (57°F).

There are two forces maintaining this temperature: solar radiation and greenhouse gases.

Equilibrium

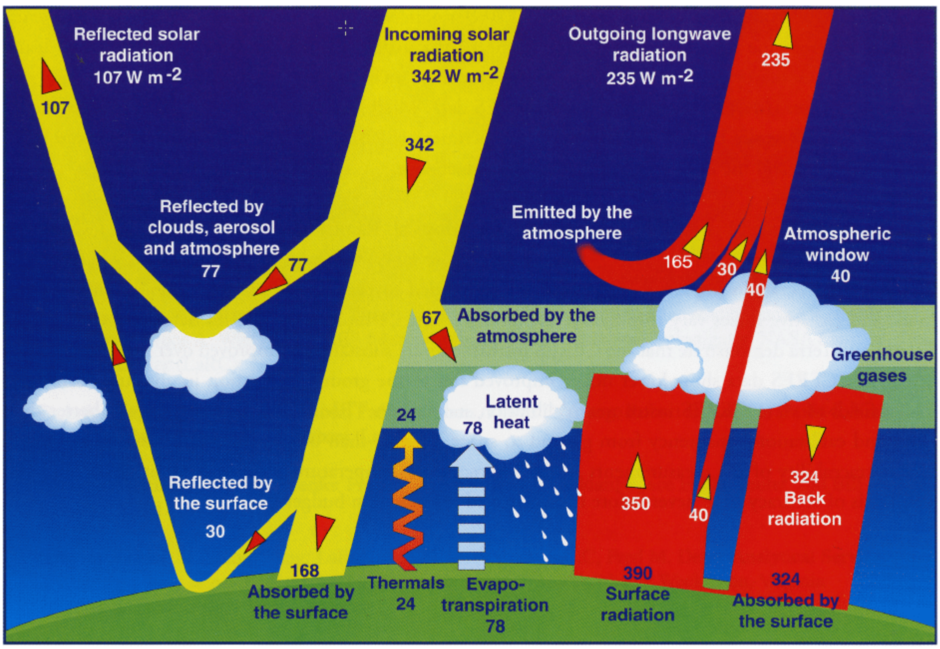
The impact of solar radiation is described by the Stefan-Boltzmann law. When solar radiation increases, the Earth starts to warm. As the ambient temperature rises, the Earth sends more radiation back into space. Eventually, the temperature rises to the "equilibrium" point at which the outgoing radiation from the earth matches the incoming radiation from the sun. If the Earth were an ideal radiator with no greenhouse gases, the Stefan-Boltzmann law implies that the earth's average temperature would be about –18°C (0°F). Most of the world would be an uninhabitable snowball.

Fortunately, greenhouse gases absorb some of the outgoing radiation and re-radiate it back to Earth, thus preventing a "snowball Earth." The greenhouse

[3] Scientists, like Daniel Swain, are beginning to quantify the impact of global warming on the probability of extreme weather events. See our references.

effect works as follows. Gas molecules can be thought of as little oscillators. Each gas has specific frequencies at which it resonates. Any radiation that does not push it at a resonance frequency passes through with little interaction. However, if the radiation frequency matches that of the molecule, then the molecule absorbs the radiation briefly before sending it off again but now in a random direction — and, most importantly for our purposes, some of the radiation is directed back to earth.

Figure 4. Greenhouse Effect



Source: Courtesy of Gregory Bothun strongly based on Trenberth et al, 2016. See also Bothun's more detailed coverage. Yellow is visible light, red is infrared (re-radiated) light.

Figure 4 shows that when visible sunlight hits the surface of the earth, it is absorbed and then re-emitted as lower-frequency infrared light (thermal radiation). The now-infrared light is reflected back into space. Greenhouse gases — that happen to be transparent in the visual spectrum —- resonate in the frequency of infrared light, which makes them absorb and re-radiate some of this infrared light back down to earth. Just as a greenhouse traps the sun's infrared light with glass to warm the plants inside, so do greenhouse gases trap the sun's energy higher up to warm the earth. This process continues until earth reaches a new equilibrium at a higher temperature. That is why earth's global temperature is +14°C (57°F) and not –18°C (0°F).

Despite the beneficial effects of greenhouse gases, there can be too much of a good thing. A horrific example is Venus. Without CO_2, its average temperature would be a reasonable 28°C (82°F). Instead, Venus' actual temperature is 460°C (870°F) — hot enough to melt aluminum and rain sulfuric acid. If you are now concerned that humans could push Earth into a Venus equilibrium, don't worry. Recall from the last chapter that earth's atmosphere is only 0.04% carbon dioxide, possibly reaching as high as 0.1% at the high end of future estimates. Venus's atmosphere is 97% carbon dioxide![4]

Near-Perfect Prediction

Remarkably, it is not only possible to measure Earth's temperature, but it is even possible to measure whether it is already in thermal balance. If you can measure the heat your stove sends to your pot and how much heat your pot emits in turn into your kitchen, the difference is only zero when the pot is in equilibrium. If more heat is going into the pot than coming out, you know the pot is still heating up.

Analogously, NASA satellites can now directly measure both the amount of incoming solar radiation (called the solar constant) and the amount of outgoing thermal radiation. The difference is the heat uptake *dis*equilibrium of Earth (also called radiative forcing). For this reason, scientists know that earth is yet not in an equilibrium. They expect Earth to continue to warm until it reaches its new equilibrium, where incoming and outgoing radiation will again be balanced.. Let us repeat this: **Earth is currently absorbing more energy that it is sending back into space, so it will soon be warmer than it is today**.

How much warmer? In 2005, the planet absorbed a net influx of about 0.5 Watts per square meter. More energy was coming in than going out. Ergo, Earth was heating up. By 2020, the difference had doubled to about 1.0 Watts

[4]Most likely, Venus first ran out of water, because it does not have a magnetic field that would have shielded any water in its atmosphere from the solar wind. Once the atmosphere had run out of water, not only had Venus lost its CO_2 water sinks, but it had also lost its terrestrial sinks because rocks cannot absorb CO_2 through weathering in the absence of water.

per square meter. Ergo, Earth is in the process of warming at a rate that is twice as fast as it was 15 years ago.

Remember that this is a measurement that is independent of whatever Earth's actual temperature is, whatever emissions humans may be releasing, whatever solar or volcanoes may have been doing, etc. It is a direct measure of the rate of temperature change that is currently occurring.

3 The Temperature Record

They want to know whose original climate we're restoring it to.

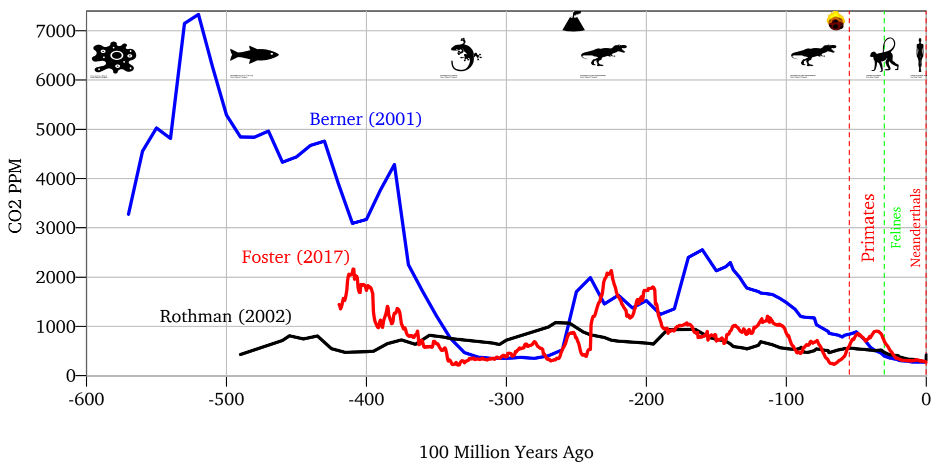
Earth has never been and will never be in an entirely stable equilibrium. When climate activists state that we live in an era with unprecedented higher CO_2 and temperatures, skeptics counter that the Earth used to have both far more CO_2 in its atmosphere and far higher temperatures than it does today. And both are correct!

To understand what this is all about we begin with a brief look at our planet's long-run climate history. (Again, David Archer's The Long Thaw has more detail.) However — *and this is also important to understand* — most of this history is no longer relevant to today's situation. It is remarkably unimportant to the issues facing humanity now.

The scientists' problem is academic. Scientists do not understand all the feedback loops of relevance in the distant past. (In plain English, they are not sure whether the chicken or the egg came first, though they do know that each causes the other.) In contrast, scientists do know that humans have injected significant amounts of CO_2 into the atmosphere over the last century — it was not caused by warming itself or some other unknown influence. Therefore, much of their debate about how to interpret ancient paleo-history (as chicken or egg) is more of academic than of pragmatic interest.

Deep Time: 500 Million Years

Figure 5. Global CO_2 Estimates in Deep Time



Source: Berner-Kothavala (AJS 2001), Foster et al. (Nature, 2017), Rothman (PNAS 2002). (According to Gavin Foster, recent revisions in the revisions in the "Paleosol d13c proxy" may have obsoleted the Berner estimates.)

Scientists have pieced together estimates over about six hundred million years. It seems miraculous that scientists can deduce anything about the continents and climate from hundreds of millions of years ago. But they can. Of course, as should be expected, the farther they go back, the more uncertain the data become.

Such *deep time* seems unimaginably long. Five hundred million years ago, fish were the pinnacle of vertebrate evolution. The first multi-cellular organisms had appeared "only" 50 million years earlier (in the Cambrian era). Not just the current continents, but even the ancestors of our current continents had not yet formed. Modern mammals took over after a measly 6-mile asteroid finished off most dinosaurs on a Tuesday[5] just 66 million years ago.

Let's start with scientists' estimates of deep-time carbon dioxide. Figure 5 presents estimated reconstructions of its atmospheric concentrations, measured in parts per million (ppm). The blue line in Figure 5 represents the

[5] Yes, scientists recently discovered evidence from that one very bad day!

most prominent estimate of CO_2 levels over this time span, although this study may be a little outdated by now. Science has progressed. But comparing the CO_2 estimates from three different studies shows how even the best scientific estimates can disagree.

Not even the most alarmed climate scientists believe that human emissions will push CO_2 concentrations beyond 1,000 ppm — although it is not completely impossible that unknown feedback effects could push the CO_2 concentrations higher for a while. (This would indeed be scary!) Let's say that 800–1,000 ppm is possible *if* humanity burns most available fossil fuels. Despite their large discrepancies, all series in Figure 5 agree that 800–1,000 ppm of CO_2 was not that unusual in deep time. In this comparison, Earth has been in a CO_2 drought for many millions of years. However, towards the right end of the graph, the lines also shows that 800 ppm is very high by human standards — *Homo Sapiens* appeared only about 200,000–300,000 years ago.[6] Thus, depending on the narrator's intent, the increase from 300 ppm to 400 ppm (and soon beyond to 600 or 800 ppm) can be proclaimed as earth returning to normal (by geological standards) or as being unprecedented (by genus-primate standards).

Temperature is even more difficult to reconstruct than CO_2 levels. Unlike CO_2, which is effectively a global gas, temperatures are largely local. If a researcher 500 million years in the future found a temperature record only from the Sahara or only from Mount Kilimanjaro or only from the Antarctic, even the best science could not rescue her from a wrong inference about earth's prevailing climate. Moreover, scientists know that there are not only periods in which all of earth's temperature moved up or down together, but also periods in which earth's temperature gradient changed — it became simultaneously hotter on the equator and colder on the poles or vice-versa.

Here we present today's best scientific estimates of deep history temperature, but do not consider the numbers to be definitive. Scientists may learn more and change them again.

About 600–700 million years ago and lasting for about 20-80 million years, the planet was (for a second time) in a state called "snowball earth." In this

[6] At 800 ppm, as occurs in fully occupied lecture halls, many of us begin to suffer modest adverse health effects — we tend to lose mental acuity and fall asleep. Most of us were not designed for 800 ppm — though some are and/or will be.

so-called Cryogenian period, the entire planet was a frozen wasteland. Ice reflected most sunlight, thereby keeping earth cold. Life was likely limited to a few hearty microbes. After this last snowball earth ended about 540 million years ago, the Cambrian explosion of complex multicellular life began.

Starting around 500 million years ago, and for about 85% of the time since, the earth was in a state called "greenhouse earth" (sometimes also called "hothouse earth"). The average global temperatures exceeded 70°F (21°C) or possibly even 80°F (27°C) at times. Recall that it is 57°F (14°C) today.

For the remaining 15% of the time, the earth was in yet another state that geologists call "ice ages." Formally, an ice age is an era in which there is year-round ice on the polar caps. We are still living in an ice age that started about 50 million years ago. Large primates first evolved during this our current ice age. The first ape appeared about 20 million years ago. Ice ages may be geologically unusual, but they are all that many mammalian orders alive today (including our own) have ever known.[7]

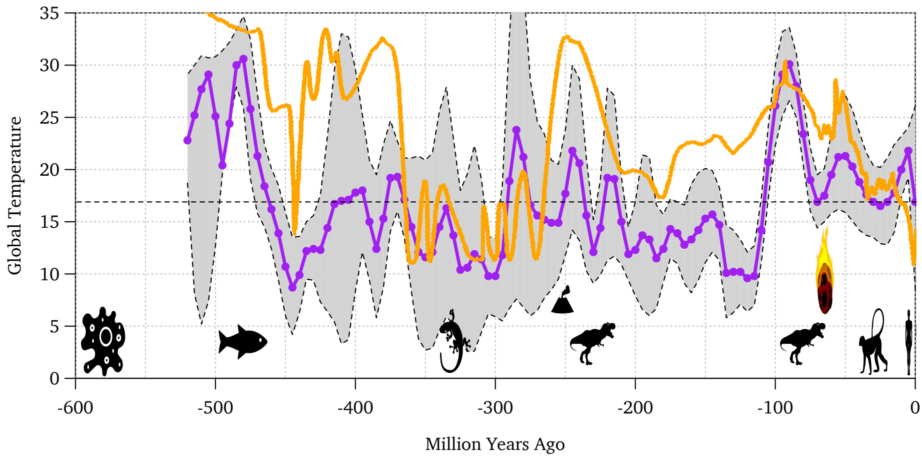
Figure 6 plots estimates of deep-time temperatures over the last 500 million years. The figure shows two different estimates — and, again, clearly, the estimates differ. Wing and Huber place more emphasis on temperature closer to the poles, Verard and Veizer on temperature in oceans closer to the tropics. (And they could both be correct! It is difficult to know.) Our current ice age is at the far right end. The darker purple line suggests that earth's current temperature is near the threshold between an ice-age and a greenhouse earth.

Climate-change skeptics often point out that the connection between planetary greenhouse gas levels and planetary temperature over 500 million years seems weak. And they are right again. However, this observation is not relevant. Why not?

First, over such long time spans, our record of earth's history becomes so uncertain that all estimates must be viewed with a healthy dose of skepticism. Second, the sun was about 5% cooler 500 million years ago. Third, the earth's orbit changes over time and it could have been a little further away from the sun — we will likely never know. Fourth, earth underwent massive geological changes, such as the formation and breakup of continents and mountains.

[7]There is some disagreement among scientists here, too. See Figure 6.

Figure 6. Global *Temperature* Estimates in Deep Time



Source: The graph combines two different estimates of deep-time temperature. The orange line is a preliminary version from a Smithsonian Institution project led by Scott Wing and Brian Huber. It measures closer to the poles. The darker purple curve is from Vérard and Veizer (Geology 2019, Fig 3), with uncertainty in gray. It measures closer to the tropics. The horizontal line is roughly where ice ages might break. The icons denote the appearance of vertebrate orders.

This changed the exposure of different kinds of rocks with different abilities to absorb atmospheric carbon-dioxide. Fifth, not only would 1,000 ppm today have a markedly different impact on temperature than it had 300 million years ago, humans are creatures that evolved in 300 ppm conditions and not in 1,000 ppm conditions. Dragonflies 30 inches long would probably enjoy 1,000 ppm more than humans. And sixth, while scientists do not know what natural forces pushed CO_2 around in deep time, which makes interpreting causality difficult, we know exactly what has pushed CO_2 up in the last 200 years — our human emissions!

Human Time: 500,000 Years

Within ice ages, there are further divisions. There are "glacial periods" and "interglacial periods." During glacial periods, Earth is cooling, and glaciers and ice sheets are advancing. During interglacial periods, Earth is warming, and glaciers and ice sheets are receding. Glacial periods thus end with the coldest interludes within cold ice-age periods. For the last 10,000 years or so — i.e., roughly the time span within which modern civilizations developed — earth has been in a warmer interglacial and also unusually stable period. The fact that glaciers have been receding is not new — they have been doing so for the last few thousand years.

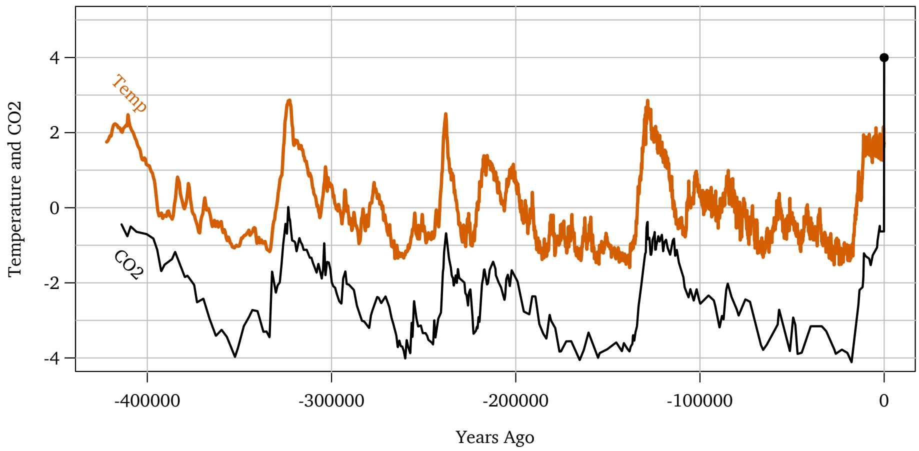
In sum, our ancestors and we have been living near a traditional glacial minimum — a (shorter) interglacial warm era within a (longer) cold ice-age era. This positioning is fortunate. During the last major glacial maximum within our current ice age, conditions were far less hospitable. For example, just 15,000 years ago (well within human existence), the global temperature was 6°C colder and New York City was under a glacier 300 feet thick!

In rebuttal to the skeptics pointing erroneously to the deep-time graph, some climate activists then get to show off their own graph (in Figure 7). They point to the last 400 thousand years, a tiny blip at the end of the graph in Figure 6. This is roughly the time when Homo Sapiens first evolved. The close association between CO_2 and temperature is striking. In some quarters, Figure 7 has obtained a cult-like status as the iconic "smoking gun" — proof that CO_2 drives climate change.

But this simple interpretation is misleading. Although the data correlation patterns are literally correct, they don't mean what the presenter wants to imply. Just as we rejected the lack of co-movement of CO_2 and temperature over the last 500 million years as evidence of absence of a driving role for CO_2 on temperature, so too do we have to reject the co-movement over the last 500 thousand years as evidence of its presence.

The association in Figure 7 does not show (much less prove) that CO_2 drove temperature. Instead, it shows only that CO_2 and temperature moved together — correlation. Whereas correlation means only that there is a mutual relationship between two variables, causation is a much stronger concept. It means that one variable influences another in a *cause-and-effect* relationship. Figure 7 does not show such a cause-and-effect relationship. A deeper analysis of timing suggests that the comovement of the two series reflects feedback effects in both directions. (Higher temperatures can cause CO_2 to be released from their reservoirs.) Moreover, some other unknown variable could have

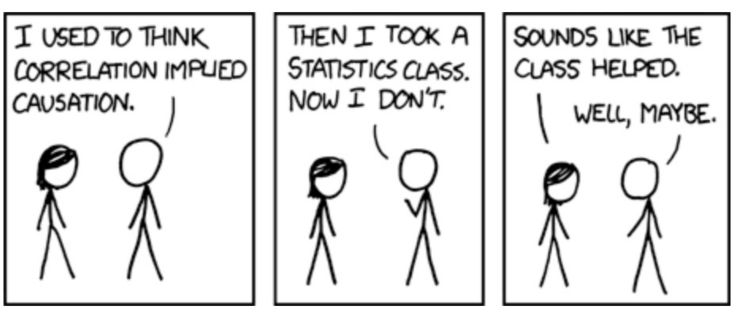
Figure 7. CO_2 and Temperature over 0.5 Million Years



Note: This figure is often *falsely* interpreted as "proving" that CO_2 concentration changes have caused global temperature changes. Instead, data analysis of changes in the two series suggests that it is more likely that some other unknown factor has caused the close association between CO_2 and temperature changes (or even that global temperature changes have caused more CO_2 changes than the other way around).

Source: The figure is based on the famous Vostok ice core data, discussed, e.g. in Petite et al. (Nature 1999).

driven both CO_2 and temperature. The figure is not inconsistent with CO_2 as a driver of temperature; it is just not great evidence.

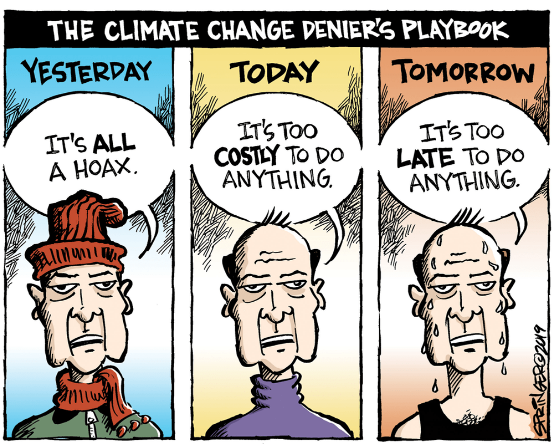


The strongest empirical regularity of this data (again, not easily visible in the figure) is that earth seemed to have had a built-in regulator for these 400,000 years. When temperature was high and had recently increased, then it tended to fall again. When temperature was low and had recently decreased, it tended to increase again.

We do object to one common practice. When Figure 7 is presented to the public, it is usually with a purpose to mislead, suggesting that it is this figure that "proves" that CO_2 strongly drove temperatures over the last 400,000 years. It does not. Better evidence for (and a source of concern regarding) the role of greenhouse gas emissions in causing global warming is elsewhere. It is in the theory of physics and the calculations of radiative forcing.[8] And it is in the empirical evidence of the most recent 100–200 years (covered next).

Historical Time: 1,000 Years

This brings us to today's most "controversial" evidence (according to climate-change skeptics): The famous Hockey Stick Graph by Michael E. Mann (and coauthors) in Figure 8. Think of it as a "zoom" into the last 1,500 years. It shows that the global temperature has been on a sharp upswing beginning around 1800 and accelerating since (especially after 1970) — a hockey-stick-like pattern.



Ironically, this hockey-stick evidence is least controversial among scientists. It is here that the data are most precise. Over the last 100 years, scientists have real-time measurements of temperatures from all over the globe and of deglaciation and sea-level change. There is no longer any reasonable scientific disagreement about Mann's essential temperature observations. It's solid science.

The global temperature has been increasing and indeed accelerating for at least 100 to 200 years. This means that global warming is now faster than

[8]There are some sharp but isolated episodes in Figure 7 for which the culprit can be identified as a CO_2 shock. For these, it is possible to tease out a causal relationship. However, these episodes cannot be generalized to the longer 400,000 year range.

it has been for a thousand years, and scientists can observe it in daily satellite measurements. The last 50 to 100 years is, of course, also the time during which humans could have plausibly been influencing the planetary climate with their slowly accumulating GHG emissions. Before 1900, civilization's accumulated atmospheric emissions were simply too small to matter much. Global warming has accelerated so much that the last 20 years, 2000–2020, alone account for about half of human-induced warming.

The evidence is so clear and uncontroversial, and sometimes so distorted in the press, that it deserves reiterating a second time:

> **Climate-change deniers are simply wrong. Over the last 50 to 100 years, there is no question [1] that the earth has been warming at an accelerating rate and [2] that it has not yet reached a new stable equilibrium. Earth is continuing to heat up.**

Of even greater concern, Figure 9 shows that the temperature rise is still accelerating, in line with the satellite observation that more heat is still coming in than going out. About half of human global warming has occurred in the last 20 years. The single most important point is that all serious scientists agree that earth is now warming at an alarming rate.

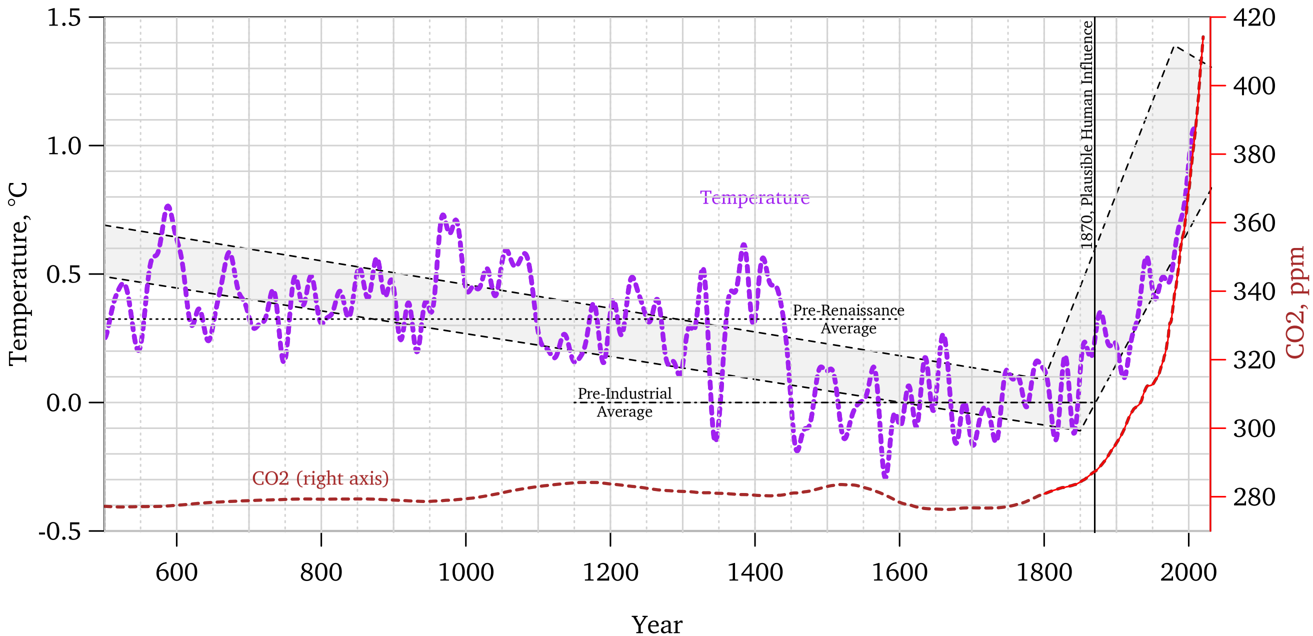
Simultaneously, it is undisputed that it was human activity that has dramatically raised the CO_2 concentration in the atmosphere. CO_2 has been on an analogous increasing and accelerating trajectory. Of course, so have many other observed variables. Correlation is easy to come by. However, there is more than just correlation. The physics of greenhouse gases can explain what causal effects anthropogenic CO_2 should have played in the increasing global temperature.

Yet there are still a few (modest) mysteries. Figure 9 shows that temperature seems to have dropped by about 0.3–0.4°C around the time of the Renaissance (the onset of the "Little Ice Age"[9]). Scientists have some educated guesses as to why, but they do not know for sure.[10] Furthermore, this

[9]The Little Ice Age was not at all an ice age in the geological sense. We were in an ice age before the Little Ice Age and are still in it.

[10]Interestingly, it is not known whether it could have merely been cooler in the Northern Hemisphere. A new hypothesis links cooling to previous warming, that collapsed ocean circulation. Whether true or not, it illustrates the complexity of the climate.

Figure 8. CO_2 and Temperature over 1,500 Years

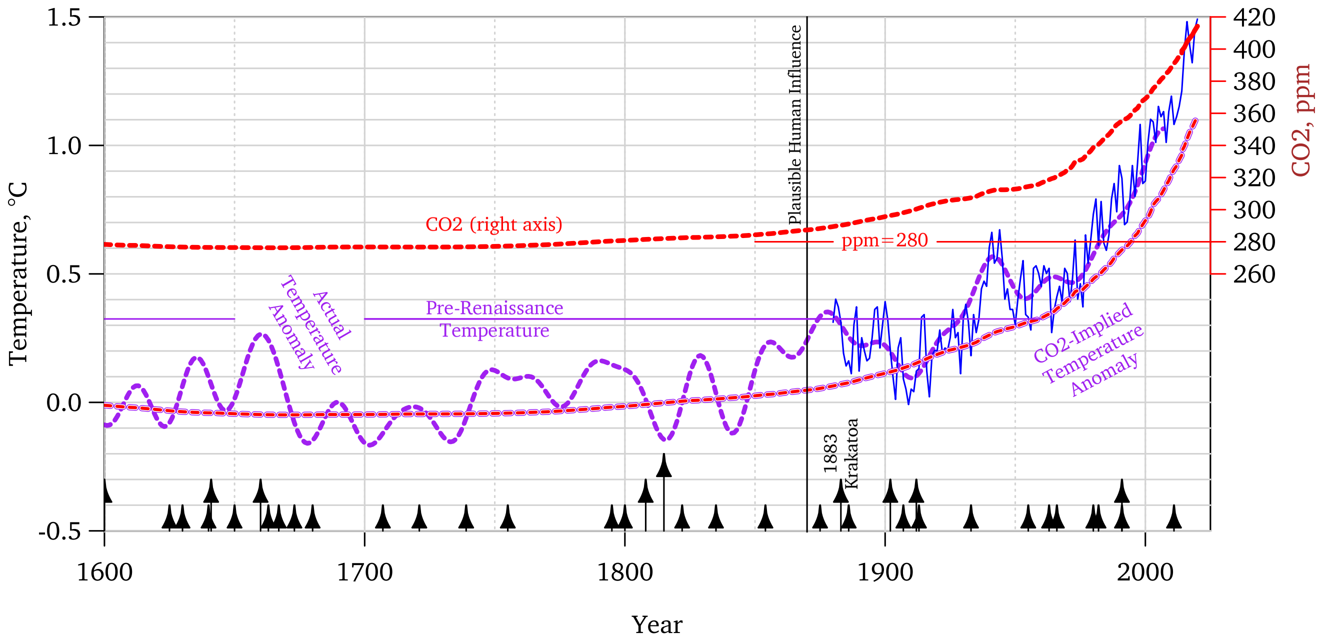


Note: The darker purple curve (mostly inside the "hockey stick") is Michael E. Mann et al.'s global temperature data. The 0°C mark is 1980. The lighter red line is the ETH Zürich CO_2 data. The vertical line shows when humans could have begun to meaningfully contribute to the global CO_2 concentration rise (around 1870). The figure also sketches the famous hockey stick.

The next figure zooms further into the final 500 years.

Source: Mann et al., 2008, "Proxy-Based Reconstructions of Hemispheric and Global Surface Temperature Variations over the Past Two Millennia," PNAS. Volcanoes, VEI 5 or greater, Wikipedia.

Figure 9. CO_2 and Temperature over 500 Years



Note: See previous graph for more explanations. The thin blue line towards the right beginning in 1880 (and continuing Mann's curve) are <u>in-time measured estimates</u> provided by NASA. In addition, this zoom figure adds volcano eruptions at the bottom, with VEIs of 5, 6, and 7 (by arrow length). It also adds a line that sketches what temperature change the CO_2 increase would have predicted if a doubling of CO_2 in the atmosphere increased temperature by about **3°C** (50% immediately, 75% within 30 years, and 100% within 100 years). From 2000 to 2020, it seems too steep. Other reasonable assumptions don't fit slopes both early and late much better.

cold period was also likely *not* caused by a drop in CO_2 levels. Indeed, the temperature first dropped (around 1500) and the CO_2 level fell only later (around 1600). From about 1800 to about 1900, temperatures rebounded from the unusually cold climate of the post-Renaissance. Almost all of this Renaissance temperature decrease and later recovery occurred *before* human emissions could have made much difference. Civilization just had not yet emitted enough GHGs to influence the climate this much.

Finally, a short sidenote: By necessity, all discussions of global warming have to be relative to a benchmark, and the choice of benchmark can make for a meaningful difference in the number of degrees of warming quoted. Earth has warmed about 1.4°C since preindustrial times (say, 1500–1800), but "only" about 1.0°C relative to the middle ages (say, 500–1500). And of the 1.4°C rise in temperature since preindustrial times, only about the last 1.0°C increase could reasonably be due to human-GHG emissions. Therefore, whenever the pundits discuss a (rounded) "1.5°C temperature increase since preindustrial times," you, the audience, have to keep in mind that it would be misleading to connect the full temperature increase to the arrival of industry or human activity. The more plausible human-emission caused abnormal increase *to date* (2020) is 1.0°C. *That's bad enough*, especially in places where temperature changes have stronger localized effects. And remember: human emissions will cause global warming of about 3°C. So far, only about 1°C has occurred. Another 2°C is still heading for us.

Strong Industrial-Age Trend Evidence

To summarize, what makes the recent evidence so much more powerful than evidence from paleo-history is not only that scientists now have satellite measurements, but also that they know that the CO_2 increase was not caused by some unknown phenomenon (or temperature changes themselves, the chicken and egg problem). Instead, the CO_2 increase was caused by human civilization. As we explained in the previous chapter, scientists know this (a) because they can count up how much CO_2 humans have emitted net of how much earth could have scrubbed, and (b) because they can assess the carbon source independently based on the scientific measurement of carbon isotopes. CO_2 from ancient fossil fuel burnt by humans has a different fingerprint than that of recent natural CO_2. Science offers up a unanimous verdict: About

130 ppm of CO_2 out of the total of 410 ppm in the atmosphere today is due to human activity.

We stated earlier that the source of more distant paleo-historic changes in temperatures is largely irrelevant. Even if CO_2 in the past had been caused by temperature changes rather than the other way around (itself an iffy proposition), this is no longer the situation today. Scientists know that human civilization has caused *our* current CO_2 increase. Whatever the causes of the CO_2 and climate-change dynamics may have been a few million years ago, industrial civilization has pumped enough greenhouse gases into the atmosphere in the last 100 years that scientists know it must have had temperature consequences. The basic physics of the greenhouse gas effect demands it.

It's almost as if humanity has been running an experiment to see what an increase in CO_2 would do, and the temperature has duly responded. And both the atmospheric CO_2 concentration and the global temperature are continuing to accelerate — of course, not each and every year, but in a reasonably consistent trending pattern. And neither the temperature rise nor humanity's experiment is done yet.

4 Greenhouse Gases and Temperature

Apologies — we have to circle back briefly to atmospheric gases in order to explain in more detail how they influence temperature.

Greenhouse gases can be grouped into two types. The first type are chemically stable greenhouse gases that stay in the atmosphere for a long time. This first type includes primarily what can be called fossil-fuel GHGs including CO_2 and Methane. The second type is more ordinary — water vapor. Think humidity.

Fossil-Fuel GHGs

We have already explained that carbon dioxide is the most abundant and important fossil-fuel GHG. We have also noted that human activity emits Methane, Nitrous Oxides, and F-gases, too.

➤ Global Warming Potential (GWP)

The three other GHGs are present in much smaller concentrations in the atmosphere than CO_2. However, pound-for-pound, the non-CO_2 gases are much more effective in absorbing and re-emitting infrared energy than CO_2.

To compare the impact of different greenhouse gases, scientists have developed a measure known as the Global Warming Potential (GWP), usually stated in terms of CO_2 equivalents (**CO_2e**). CO_2, by definition, has a GWP CO_2e of 1. We already used the CO_2e measure in the previous chapter, but had not explained it.

The GWP of a gas depends on two factors: (1) how efficiently it absorbs and re-radiates infrared radiation (i.e., how opaque it is to infrared), and (2) how long it stays in the atmosphere. For instance, Methane (CH4) is about 20–100 times more effective in absorbing and re-radiating infrared radiation than CO_2, but it disintegrates with a half life of 9 years. (It then decomposes into trace amounts of CO_2.) The widely accepted GWP figure for Methane is thus 30, meaning that each kg of methane emitted has 30 times the lifetime warming effect of a kg of CO_2.

Despite their higher GWPs, methane, nitrous oxides, and F-gases are so much rarer than CO_2 that CO_2 remains responsible for about 85% of human-caused global warming. CH4 is responsible for about 10%, nitrous oxide for 4%, and the remaining chemical GHGs for 1%. Humans emit about 40 GtCO_2, but the effective emissions rise to 51 GtCO_2e when we take account of the other GHGs (plus another 4–5 GtCO_2e for the land charge). The short-term total temperature effect of human GHG emissions is thus better measured by the 55 GtCO_2e per year; the long-term temperature effect is better measured by the 45 GtCO_2 (emissions plus land charge).

Doubling GHG

Physics can explain how much a specific increase in atmospheric GHG concentrations should raise the global temperature. A typical way to calibrate the temperature effect of a model is to ask how much the global temperature should ultimately rise for every doubling of CO_2 in the atmosphere. In the simplest canonical greenhouse model, doubling CO_2 raises the temperature by **1.2°C**. In a more elaborate model based on the sun's entire absorption spectrum, it is a little lower, **0.8°C**. Thus, roughly speaking, the direct long-term effect of CO_2 is about 1°C for every doubling of the CO_2 atmospheric concentration.

So far, humans have not yet doubled the CO_2 concentration but raised it by about 50% (from 280 ppm to 410 ppm). This implies a direct increase in the long-term equilibrium temperature of Earth of about **0.5°C**. Not all of it can have occurred yet, because the heating process takes a lot of time. More plausibly, the 50% increase in CO_2 has directly raised temperatures so far only by about **0.3°C**, with another 0.2°C on the way.

You should notice that something must be missing. The emissions-caused temperature change of 0.3°C is clearly insufficient to explain the already-observed 1.5°C global temperature change since 1800 (or the 1.0°C increase since 1500). Scientists need to reconcile the larger observed global temperature increase with the smaller theoretical CO_2-predicted temperature increase.

There is widespread agreement that the "missing link" is a second type of greenhouse gas: water vapor.

Water Vapor and Clouds

Think of water vapor as humidity in the air. Unlike CO_2 or the aforementioned GHGs, water is not long-lived in the atmosphere but circulates constantly. It evaporates and rains back down. This process is called the "water cycle."

Nonetheless, water vapor is very important because it is ten times more abundant than CO_2 in the atmosphere (0.4 percent compared to 0.04 percent). Some scientists estimate that, at any given moment, water vapor could have the potential to be responsible for about 85 percent of the atmosphere's ability to block outgoing infrared radiation. (CO_2 blocks "only" 7 percent, but does so for a much longer time. Water vapor also captures and moves heat around, heating the arctic and cooling the tropics.) Civilization has not directly pushed more water into the atmosphere. However, it has done so indirectly. The CO_2 has raised the global temperature, and warmer air holds (almost mechanically) more water vapor.

But the role of water vapor is not that simple. Water is also the essential ingredient in (white) clouds,[11] which reflect incoming solar radiation even before this radiation can reach the ground. Thus, on net, water vapor accounts for much less than 90 percent of global warming — perhaps only 65-85 percent. This range is so wide for two reasons: (1) Some uncertainty arises because the relationship between water vapor and clouds is not one-to-one. Cloud formation also requires seeding with tiny particles. (2) More uncertainty arises because the effect of clouds on temperature is also still not fully understood. It appears that clouds sometimes have a warming effect on the local climate and sometimes a cooling effect — it seems to depend on the type of cloud, the local climate and a variety of other conditions.

NASA has only been measuring and recording global water vapor and clouds across different latitudes for a few decades.[12] Scientists have no direct observational record of clouds over the last few centuries, much less over the last few hundred-thousand years. And local observations are not enough — if it rains more over Illinois, it could easily rain less over New York.

[11] NASA/NOAA report that from 2005 to 2019, the planetary albedo (white cloud layer and sea ice) declined, partly due to the natural Pacific Decadal Oscillation, i.e., El Nino and La Nina.

[12] Dessler et al have now confirmed *with data* that an increase of 1°C seems to trap an additional 2 W/m^2.

5 Scientific Agreement and Disagreement

Let us summarize what we have covered so far. Over the last 50 to 100 years:

1. The global temperature has been sharply increasing at an accelerating rate.
2. The CO_2 concentration in the atmosphere has been sharply increasing at an accelerating rate.
3. This atmospheric CO_2 increase has been overwhelmingly man-made.
4. Some of the global temperature increase has been due to the direct CO_2 (and related chemical gases) greenhouse effect.
5. More of the temperature increase must have been due to water-vapor greenhouse effect, itself caused by rising temperatures, which were in turn caused by the direct GHG heating.

We will now present a version of remaining scientific disagreements as they make sense to us (as scientists but outsiders to the field) without endorsing or denying any specific views. (We cannot be referees.) Here are the two reasonable perspectives: The majority of scientists believes that human GHGs can already account for the heating that we have observed and that they have been, are, and will continue to be the sole driver of global warming over the last and next century. The minority view wonders whether enough "omitted factors" remain that could render human GHG's not entirely responsible.

In addition, both views allow for uncertainty. For example, solar activity could increase or decrease, a large supervolcano could erupt, etc.

The Majority View

The mainstream model is that human GHG emissions have been and will continue to be entirely responsible for forcing the increase in earth's temperature. The long-lived fossil-fuel GHGs do so partly themselves but also (and more importantly) by priming the water cycle. GHGs increase the global temperature, which evaporates more water, which raises the humidity in the air, which is a potent GHG, which again raises the global temperature further. This makes sense: higher temperatures cause more water to evaporate and allow the atmosphere to hold more water. There is no disagreement among majority and minority here.

In the majority view, clouds play a mostly passive role. They are reactive, not proactive. Thus water vapor is a simple temperature multiplier for CO_2 (and then for itself). And the multiplier is not small. Water vapor amplifies the direct CO_2 effect on temperature by a factor of about two to three. This estimate is based on a model that best fits the historical CO_2-temperature data. Recall that CO_2 alone could explain only about 1.0°C for a doubling of CO_2. Calibrated from short-term physical observation of local responses, the models can explain the doubling of the direct temperature effect of CO_2. There is still quite a bit of uncertainty and unexplained variation here, though. Earth is a complex system.

A different approach — perfect if the mainstream is correct — is to take it as given that clouds would have behaved in a way that creates the best fit between (a) measured CO_2 increases in the atmosphere and (b) measured temperature increases on the planet. In this case, the revised predictions for the effect of a doubling of CO_2 is no longer just the direct CO_2-effect of **1°C**, but (including water vapor) the so-called **climate sensitivity**:

- **2.4°C** for the mainstream climate-science model.
- **3.0°C** for simulation models, tended by armies of scientists and running on super-computers. 3°C also the IPCC's preferred number.

These two- to three-fold calibrated amplification factors best reconcile the historically observed CO_2 concentration and temperature data. But climate scientists are not sure. Reasonable climate-sensitivity numbers can range from about 1.5°Cto about 4.5°C— an uncomfortable wide range.

Importantly, one scientific drawback is that these amplification factors are not fully empirical. They are *not* based on two centuries of historical cloud records on Planet Earth. They are fitted, assuming the model is "as assumed." However, they are not arbitrary, either — there are many short-term associations that confirm the predicted local effects. Scientists are hard at work trying to measure the associations better on a global basis.

The Minority Dissent

The minority agrees that humans have caused a sharp increase in CO_2 accumulation in the atmosphere, that there is accelerating global warming, that CO_2 alone can explain at least one-third of global warming, and that water vapor feedback effects can amplify it.

The main disagreements center around the amplification factor of water vapor. The minority argues that aspects of clouds (and perhaps some other aspects of climate change) remain more of an enigma. Such skepticism is the bread and butter of the scientific process. Just like the critiqued model, the skepticism can be wrong. Scientists should remain skeptic about skepticism, too!

The minority notes a standard problem *in almost all fields of science*: the fact that CO_2 can explain most puzzles does not mean that there could not also be some other important omitted influences. What if what mainstream scientists call "natural random background fluctuations" happened not to have been so random over the last 200 years and thus distorted the inference by coinciding with the stark human GHG emission increase?

The minority also argues that the mainstream does not have enough empirical evidence to conclude that *only* CO_2 could have primed the initial temperature increase.[13] This is not an absurd hypothesis. Earth has experienced large and not-fully-understood temperature changes many times over the last 400,000 years even before the advent of large human CO_2 emissions. (Not all are attributable to other factors, like astronomical and solar cycles.)

If the minority view is correct, the carbon-cycle impact on the water cycle could be not the entire story. Even if CO_2-driven temperature increase drives most of the observed climate change, the omitted variables could mean that the cloud-modulated amplification factor could be smaller than three, perhaps even as low as two. If this is so, then harsh action to restrict fossil-fuel emissions would be somewhat less urgent.

[13] For example, geophysicist Jan Veizer writes that "I will argue that it is the other way around, with the tiny carbon cycle piggybacking on the huge water cycle, and the models are therefore reversing the cause and effect relationship." Veizer also suggests that solar activity (more specifically, ionospheric cloud nucleation pathways) could explain some of the changes in the water cycle over the last 500 years. See also Kirkby 2008 and Svensmark et al (2017). Ganopolski et al. suggests that Earth barely escaped a drop from the interglacial maximum around 1900 when solar radiation reached its minimum. It has been increasing since.

The majority points out that it is difficult to conclusively reject the minority view, i.e., to measure the causal effect of the carbon cycle on the water cycle, because it is so broad and unspecific. There is not even one specific alternative mechanism widely agreed upon by critics. However, that is not proof that the minority views are necessarily wrong. Our interpretation is that scientists have the data to confirm that the majority theory could be true, but they lack the data (for now) to test whether the theory could be false: For example, to reject just one specific alternative about cloud formation, scientists would need data regarding whether there have been unusual spikes and systematic changes in cloud cover *unrelated* to CO_2-primed temperature changes that contributed to the planetary temperature response over the last 200 years.

By definition, a minority view is always controversial and not widely accepted. (And what are the consequences if the minority is wrong and civilization fails to act now?) From the perspective of the majority, the minority view has a big hurdle to climb, in that the majority view already has a coherent link from CO_2 to temperature change to humidity change to further temperature change — and with a good amount of evidence. The minority has little evidence to match this. From the perspective of the minority view, the burden of proof is on the majority and the case is not yet closed. Earth is a complex and chaotic enough system that, even lacking a specific alternative mechanism, the majority view could still be wrong. What if some other factor had primed the initial 0.3°C temperature rise?

One important meta-problem is that scientists' motives are difficult to judge. Has some minority dissent been promulgated by the fossil-fuel lobby to mask their own financial motives? The majority views some minority dissent as such (and rightfully so). Will engagement further fan the flames? The minority view wonders whether the majority view has become an echo chamber, with allegiance dictated by ideology and grant money, and with little tolerance for normal scientific skepticism. Scientists are just humans, too.

Widespread distrust has also made it surprisingly difficult for us to ask questions — scientists' first reaction when we question evidence is whether we do so because we are trolls coming to pick bones or whether we do so because we are genuinely curious and apply the same skepticism to their work as we do to our own. At times, this has sadly made it more difficult for us to learn more.

Making Sense of Data

Although there is no century-long global data on the role of clouds, the reader can puzzle over some of the temperature data in Figure 9. Roughly speaking, the overall hockey-stick graphs in CO_2 and temperature are well aligned, both in trend and acceleration. The alignment in trends favors the mainstream view. However, it is possible that the recent acceleration in global temperature could be due to the post-1980 reduction in anthropogenic SO_2 emissions from cleaner coal.

In addition, puzzling observations remain. They can be summarized by the statement that *if CO_2 is such a slowly increasing global gas, then why does global temperature not follow the same smoothly increasing path*, of course with suitable allowances for known solar and volcanic events? A year here or there may be chaotic noise that does not need to be understood, but on a global basis over decades, scientists should be able to explain the big deviations.

For example, from 1810 to 1850, there was an 0.4°C increase (ending the Little Ice Age) without a great change in CO_2 concentration — or for that matter, any other good explanation. Clearly, something other than human CO_2 emissions (which were still negligible) must have been responsible. What was it (and could something similar also be happening now)?

For example, the large Mount Tambora volcano eruption[14] caused the "winter without summer" of 1816, visible in Figure 9 — but what caused the large oscillations in temperature over the following two decades?

From 1860 to 1910, the temperature was stable or mildly declining. Volcanic activity probably contributed, but was it strong enough to nullify the steady increase in CO_2?

From 1910 to 1945, global warming was strong with a sharp 0.5°C temperature increase. This is a large part of what is attributed to increasing GHGs. However, this also coincides with an increase in solar activity. Should we discount this warming?

However, just as it looked like the scientists had picked up a pattern, the temperature increase went on hiatus from 1940–1970 despite only modest volcanic activity. Why?

[14]Not all volcanoes may have emitted similar amounts of SO_2, so our description is not exact. Solar activity variation also does not seem to explain the observed patterns.

The hiatus was clearly over by 1970. For that time forward, there was now a sharp 1.2°C accelerating increase. And this time, solar activity could not have been the culprit because it had been on the decline since 1960! Volcanic activity also was not particularly low. Thus, the recent temperature acceleration seems generally a little too sudden to be attributable solely to the smooth atmospheric CO_2 increases, even giving CO_2 the 3°C power attributed to it by the mainstream models. (The imputed power is plotted in Figure 9.) Was warming delayed to 1970 by some global buffer that had filled up? Or was it delayed by reflective sulfur-dioxide particles from dirty coal that had peaked in 1980 and then declined sharply after 2000?

The majority points to the overall trends of CO_2 and temperature. The "signal" ($CO_2 \rightarrow$Warming) is strongly there and the physics are solid. The satellites' measurement of thermal disequilibrium further tell us more warming lies ahead.

The minority points to some deviations from the trend that are not fully understood. The majority might call this "natural background variation" — but calling it noise does not explain it. Some forces caused these large variations. Climate scientists are not 100% sure what it was. They are collecting more data, trying to find causes for each episode — but this could lead to overfitting the evidence. (Looking harder for confirmation than for rejection of theories also often tends to lead, not surprisingly, to overconfident confirmations.)

Perhaps, stating the argument as a match between "majority" vs "minority" is itself misleading. It could be that the truth lies somewhere in the range. What if mainstream climate scientists are 95% right and 5% wrong? What if something else that we do not yet fully understand still plays an important role?

As economists, we are not in a position to referee debates among the climate-science experts. We can merely present the agreements and disagreements to the best of our abilities. Interested readers can venture out to learn more.

Yet More Puzzles and Chaos

The role of clouds is not the only issue for which scientists desperately need more data. Most of the surface heat on the planet is not stored in the atmosphere, but in the oceans. Unfortunately, scientists have few direct measurements of how global ocean heat has varied over the centuries, especially with respect to the temperature *deep* in the ocean. Scientists can infer a little about deep water temperature indirectly by being clever. For example, with some extra assumptions, the observed increase in sea levels can be used to back out how much warmer the water has become. But with entire continents rising and falling, direct deep-water temperature measurements would be far better.

Here is another puzzle. Scientists do not know why it is primarily the global temperature lows that have risen, not the highs. Put differently, worldwide, climate change has *so far* brought primarily milder winters rather than hotter summers. From the perspective of melting a glacier or the permafrost, it matters less whether the average temperature increase is caused by lows or highs. From the perspective of habitability (and from the perspective of a scientist who really wants to know how the processes work), it does matter. Without understanding the past, scientists are not good at predicting how the highs and lows will react in the future.

Finally, there is a completely different point to consider: the complexity of the large chaotic system that is Planet Earth. Yes, it would be easier to understand Earth if scientists had long histories of all the data they want (which they do not have). But it would still not be easy. The relationships between solar activity, the atmosphere and especially water vapor and clouds, and climate are complex — and scientists do not have any other planets or small-scale systems on our planet that they can experiment with in order to obtain better guidance for the big-scale complex system that is Earth. Computer simulations are no substitutes for experimental evidence. Simulations reflect the assumptions that one puts into them.

What is the Optimal Temperature and Change?

There is no disagreement that earth is warming and increasingly so. Our book is not about refereeing the scientists' modest disagreements. Instead, it is about pragmatic economic responses to climate change. Even so, we still have to grapple with further difficult questions. Here is a short preview:

How should one weigh the costs and benefits of global warming? For example, it is very likely that heat-waves will kill more people in the future — despite migration that will reduce the problem. Realistic reductions of emissions and warming cannot eliminate most of these deaths, but they can (modestly) reduce them. However, how should we count the fact that fewer cold-waves will save lives in the future? Is it appropriate to net one against the other?

Here is an even more basic question that sounds ridiculous at first but is not: What is the earth's optimal temperature? Was the cooler earth temperature 50 years ago better than the temperature today? How much better? What about the much colder temperature 12,000 years ago? If today's 6–7°C warmer temperature is better, how certain are we that another 2–3°C — after an appropriate adaptation interval — would be worse?

Are the costs of climate change so high that the optimal temperature is whatever it is at the moment? Is temperature variation and volatility the problem? In this case, any change would be undesirable. If this is so, then slowing the rate of increase would almost surely be beneficial, although it still would have to be weighed against the cost of doing so.

Our Perspective

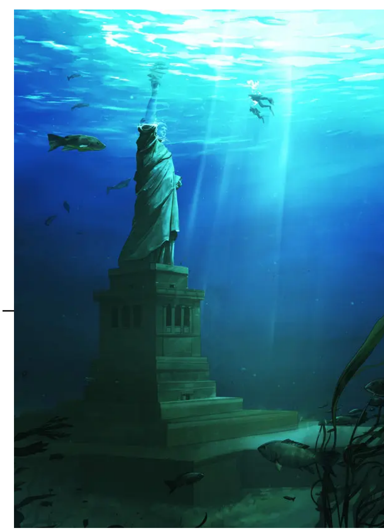
Fortunately, the answers to many of the scientists' and economists' questions are not of as great an importance to our book as they are to other books about climate change. Our book is not primarily about how to eliminate *all* fossil fuels or *all* global warming. Instead, our book is primarily about pragmatic and affordable steps that can be taken to reduce reliance on fossil fuels and slow global warming as soon as possible. It is about the social blockages that have impeded moving the needle and how to get it moving now. We are not writing about planning for policies in 50–100 years; we are writing writing about policies this decade.

Ergo, for us, even in the unlikely case that the majority of scientists are wrong about global warming aspects and the optimal temperature is not today's temperature but 1°C more or less, we would still see no reason not to recommend that civilization curb fossil fuels a lot more (and more urgently) than it has done so far. Collectively, It's way beyond high time.

Our views may be less aggressive than those of the many mainstream earth scientists, but this is unimportant. The world is so far away from the optimal reduction of fossil fuels that our disagreements are small. Thus, we do not need to forecast whether aggressive action should ultimately reduce global warming by 0.3°C or 0.6°C (from 3.0°C to 2.7°C or to 2.4°C) in order to recommend curbing fossil fuels. The solutions that we will recommend in the rest of our book will largely remain the same, either way. They are limited not by the optimal climate path that a non-existing world collective order should follow, but limited by the hard social, political, and economic realities that actual individual decision makers will face.

6 Were the Models Wrong in the Past?

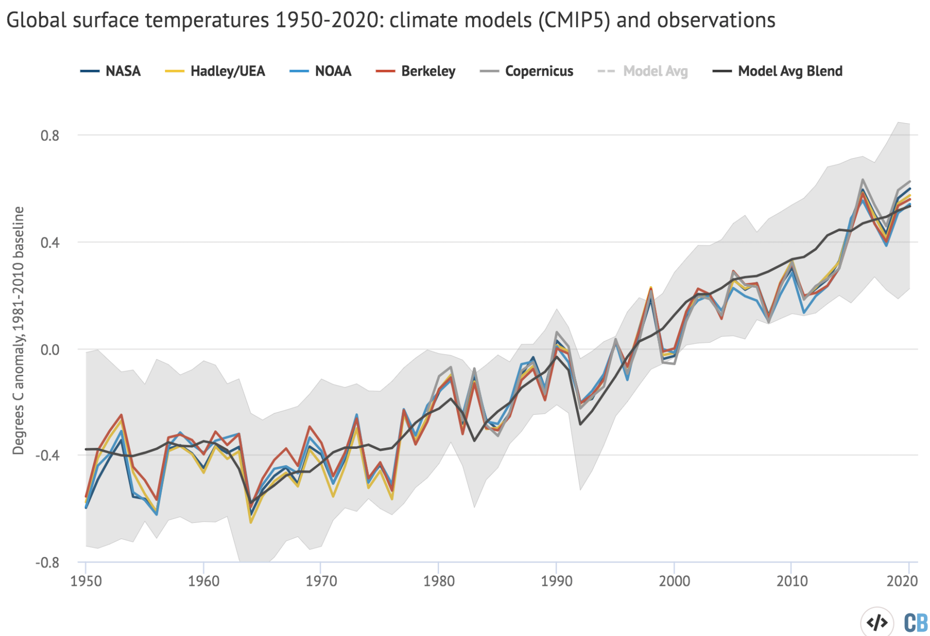
At the start of our chapter, we asked the rhetorical question "What is a climate activist to do?" when climate change is so slow. But we can also ask the rhetorical question "What is a climate-change denier going to do?" when the evidence of global warming is so strong.



New York Times, 2012/11/24 — perhaps a little over the top?

Climate-change deniers can cherry-pick past statements, often of hysterical public pronouncements by some climate alarmists, that have failed to come true — from predictions of an ice age (in the 1960s, long before humans had pumped up their emissions) to predictions of Manhattan's west-side being underwater by now, to imminent predictions of "Peak Oil". (The figure of Lady Liberty is from the New York Times in November 2012.) Yes, these quotes exist; and yes, some scientists held these opinions. But by-and-large this is a misrepresentation of the scientific consensus. The less vocal majority of scientists are not primarily activists. If anything, they typically try to measure better and moderate and report conservative non-extreme estimates. But most new boring findings rarely receive the same attention that more alarming new findings do.

Figure 10. Performance of Temperature Models



Note: Pre-2005 was fitted, post-2005 was predicted.

Source: Hausfather et al., 2019 and Gavin Schmidt, NASA.

But was it true that past models were bad? When skeptics repeat their claims often enough, some audiences become convinced that where there's smoke, there must be fire. But this is false. There is no fire. Figure 10 shows that some skeptics' broad claims are mostly an urban myth. The earlier-generation models were not perfect, but they were pretty good at least since the 1970s.[15] *On the whole* (not each and every one), past models were not hysterical, alarmist, or later contradicted by facts.

What about the models today? Of course, past performance is no guarantee of future performance. Even with much more knowledge, today's models could be wrong. And specific models disagree on precise numbers. However, most agree not only that human emissions have raised atmospheric GHGs and global temperature, but that both will continue (see our next chapter). We have already stated repeatedly that the planet is not yet back in temperature equilibrium. Any disagreement over the precise details should not be viewed as evidence that scientists don't know what they are talking about. They do know, and their disagreement is just the process of good science when the questions are difficult, the system is complex, and not all useful data are available. And, of course, all models contain errors. That is why they are called models.

If someone aims a rifle at you, our best models say you should duck. A prediction of a "zero model" (that the shooter will miss you) is also a model. Current models use the best scientific evidence there is — much better than the zero model that you would reject only after the bullet kills you. The scientists' models say that climate change is real and upon us. Let's not wait until you are dead.

[15]Earlier models were not only less sophisticated, but they also had good reason to predict global cooling. The world may have been on a path towards the next glacial period.

Further Readings

Books

- Archer, David, 2016, The Long Thaw, Princeton University Press, Princeton, NJ. Explains the long-term history and effects of CO_2 and global temperature.
- Dressler, Andrew and Edward Parson, 2019, The Science and Politics of Global Climate Change: A Guide to the Debate, 3rd ed. Cambridge University Press.
- Kenny, Charles, 2012, Getting Better: Why Global Development Is Succeeding — And How We Can Improve the World Even More.
- Koonin, Steven I., 2021, Unsettled, BenBella Books, Dallas, TX, 2021. An opinionated analysis of the science and uncertainty of climate change and the human influence. Discusses much water vapor and sea-level evidence. Gary Yohe has published a critique in Scientific American on May 13, 2021. Yohe objects to cherry-picking, which Koonin similarly objects to in the IPCC. From our perspective, there is more agreement than disagreement on a second factor. Yohe agrees that scientists are still living "in a moving picture." Yohe objects not so much to the climate facts in Unsettled, but to the characterizations of the scientific discourse.[16] A more detailed pushback to Koonin appears in Climatefeedback.org.
- Pinker, Steven, 2018, Enlightenment Now: The Case for Reason, Science, Humanism, and Progress offers a good perspective regarding how people often underestimate human progress and adaptation.

Academic Articles and Reports

- Cruz, Jose-Luis and Esteban Rossi-Hansberg, 2021, The Economic Geography of Global Warming models the effects of climate change on different regions. Because warmer areas are more populated today, the net worldwide human costs can be quite high.
- Foster, Gavin L., et al., 2017, Future climate forcing potentially without precedent in the last 420 million years, Nature Communications.
- Ganopolski et al., 2016, Critical insolation–CO2 relation for diagnosing past and future glacial inception, Nature.
- Knutson et al., 2020, Tropical Cyclones and Climate Change Assessment: Part I: Detection and Attribution, Bulletin of the American Meteorological Society.
- Lenssen, N., et al., 2019: Improvements in the GISTEMP uncertainty model. Journal of Geophysical Research: Atmospheres, NASA GISS Temperature Analysis.

[16] In an interview with Tucker Carlson, Koonin's statements were badly edited and distorted. For example, Koonin *never* disputed the reality of climate change. We also consider both Koonin and his critics to be too harsh. No book and no critique can get everything right. In our opinion, Koonin lays out an important perspective. To the extent that the water cycle is not yet fully understood, one should view his perspective that "the science is not settled" as reasonable — or, in Yohe's words, that scientists are living "in a moving picture."

- Loeb, Norman G. et al., 2021, Satellite and Ocean Data Reveal Marked Increase in Earth's Heating Rate, Geophysical Research Letters. Summarized in The Washington Post.
- Medhaug, Iselin, et al., 2017, Reconciling controversies about the 'global warming hiatus', Nature.
- Sixth IPCC Assessment Report Summary for Policymakers, 2021. A comprehensive and readable summary of the underlying 1,500 AR6 page report.
- AR6 Synthesis Report: Climate Change 2022 The most recent IPCC assessment of the impact of climate change.
- Shaviv, Nir J et al., Nov 2022, The Phanerozoic Climate, Annals of the New York Academy of Sciences. Summary of 540 million years.
- Swain, Daniel et al., June 2020, Attributing Extreme Events to Climate Change: A New Frontier in a Warming World, *One Earth*.
- Trenberth, Kevin E. et al, 2016, Insights into Earth's Energy Imbalance from Multiple Sources, AMS Journal of Climate.
- Vecchi, Gabriel A. and Thomas R. Knutson, 2011, Estimating Annual Numbers of Atlantic Hurricanes Missing from the HURDAT Database (1878–1965) Using Ship Track Density. See also the survey in Knutson et al., 2019, some recent evidence of increasing tropical cyclone strengths in Emmanuel, PNAS, May 2020, and Kossin et al. (2021) from which our hurricane figure was plotted.
- Veizer, Jan, 2011, The role of water in the fate of carbon: Implications for the climate system, 43rd Int. Seminar on Nuclear War and Planetary Emergencies, 313–327. It discusses the perspective that the water cycle is primarily driving the CO_2 cycle rather than the other way around.
- van Wijngaarden and William Happer, 2020, Dependence of Earth's Thermal Radiation on Five Most Abundant Greenhouse Gases. This paper calculates "...from [at least] about 100 ppm to about 800 ppm, the solar energy increase that ends up affecting the troposphere increases roughly the same with each doubling of GHGs (especially CO_2)." We are not going to "enjoy" a situation where further CO_2 suddenly (or more increasingly) stops mattering at some level, because the atmosphere would have already become opaque to the relevant wavelengths.

Shorter Newspaper, Magazine Articles, and Clippings

- Chandler, David R., 2007, Climate myths: Carbon dioxide isn't the most important greenhouse gas, New Scientist.
- Chinchar, Allison, 2021, Antarctica's last 6 months were the coldest on record, CNN.
- Golden Gate Weather Services, 2021, El Niño and La Niña Years and Intensities.
- Lee, Howard, How will our warming climate stabilize? Scientists look to the distant past, 2021/12/20, Ars Technica.
- Lee, Howard, Scientists extend and straighten iconic climate "hockey stick", 2021/11/10.

- Kossin, James et al. Should the official Atlantic hurricane season be lengthened?, RealClimate.org, Apr 2, 2021.
- Lee, Howard, 2021, Scientists extend and straighten iconic climate "hockey stick", Ars Technica.
- Lindsey, Rebecca, updated Oct 7, 2021, Climate Change: Incoming Sunlight, NOAA, `Climate.gov`.
- McCully, Betsy, 2020, Ice Age New York
- Open Source Systems, Science, Solutions. Global Warming Natural Cycle.

Websites

- `https://www.ipcc.ch/`: The *International Panel on Climate Change*. It contains a wealth of information and data. It is also the best expositor of the majority view. More recent reports have ventured more into the social sciences and policy making.
- `https://earth.google.com`: shows Google Earth Climate Change animated over time.
- `https://www.realclimate.org`: climate scientists background for interested non-scientists.
- `https://skepticalscience.com/`: debunks many ill-informed climate skepticism claims.
- `https://www.noaa.gov/`: The National Oceanic and Atmospheric Administration. Hosts the Atlantic Hurricane Data discussed in Section I.
- `https://nsidc.org/`: National Snow & Ice Data Center.

Video / Audio

- Alley, Richard B., 2005, American Geophysical Union Bjerknes Lecture.
- Sobel, Adam, 2021, How Climate Change Fuels Extreme Weather, a podcast analyzing the link between climate change and extreme weather events.

request for select reader feedback

Request for Reader Feedback and Corrections: We have one goal: to present the fairest description of climate change possible. We are *not* wedded to any views. We are not trying to cherry-pick. Where we perceived a *valid* scientific controversy, we have attempted to present both sides. If you believe that we have been misrepresenting the science, please let us know.

sidenote

Skepticism not only from inside the climate-science community but also from beyond is important — as it is in *any* field of science. As outsiders, we want to allow ourselves some liberty commenting on the state of climate science itself.

Like many non-climate researchers (including many physicists), we have often found it difficult to ask probing question. We understand the hesitation of expert climate scientists when dealing with us. Not only have they been the subjects of personal attacks by large fossil-fuel companies (as if they were politicians), they also have had to deal with "trolls" (often paid) whose motives are not to understand the evidence, but to speak to a political audience.

Nevertheless, it seems to us that the emotions have become too high. Although science is (and should be) adversarial by nature, the tone of the debate and mutual (sometimes personal) attacks eevn among the scientists have become excessive to the point of being counterproductive. It seems to us that one source of (remaining) disagreement among good climate scientists has arisen not because climate science is shoddy, or because the scientists are conflicted, evil or stupid — or that those questioning existing explanations are evil. (Yes, there are many charlatans, shills, and trolls, too, but this is not who we are writing about.) Instead, the principal source seems to be that it is difficult to attribute causality to slowly moving variables in an environment as complex as Earth and with the naturally limited data at hand.

The public in particular has difficulties understanding the natural process of science. Science is never certain — but climate science is (probably) as good as it gets. Even Newtonian mechanics, Einstein's relativity, and Darwin's evolution are not "proven" in the mathematical sense. Instead, it is "just" that the scientific evidence is overwhelming.