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Briefing Paper

Climate Science: A Guide to the Public Debate

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Introduction

The foundations of climate science date back to the early 19th century,[1] when scientists—using their newfound sophistication in chemistry and physics—became aware that heat trapping gases in the atmosphere maintained global temperatures above freezing. Despite continued scientific study, the field was of little public interest until the 1960s, when scientists became increasingly concerned that greenhouse gas emissions might dangerously interfere with the planet's climate.[2] Such concerns have inspired growing volumes of scientific research into the causes and potential effects of climate change ever since.

The contemporary state of knowledge regarding climate science is compiled by the International Panel on Climate Change (IPCC)[3] and other scientific societies.[4] Just as basic chemistry and physics would predict, industrial activity has indeed increased the amount of greenhouse gases in the atmosphere (primarily CO2), trapped heat, and warmed the climate. Associated changes have been measured in temperatures, rainfall, sea level, and other basic ecological and physical conditions around the world. According to the IPCC AR5, these effects should be expected to continue with additional emissions, "increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems."

To reduce the likely impacts of climate change, governments across the globe have forwarded policies to cut future greenhouse gas (GHG) emissions, reduce the cost of low-carbon energy, and prepare society for the negative impacts of climate change. Some are now in the early stages of implementing those policies. These actions and plans coalesced in 2015 under negotiations for the Paris Climate Agreement, which signaled the global intent to restrain climate change to less than 2°C of average global temperature increase over pre-industrial times,[5] a feat that will require even more significant reductions in expected GHG emissions.[6]

As a result of both the complexity of projecting into the future and the political and economic challenges of reducing GHG emissions, political debates about how society should respond to

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[1] For a book length exploration of the history of major papers in climate science, see Archer and Pierrehumbert in references; for a web presentation visit http://history.aip.org/climate/index.htm.

[2] President's Science Advisory Committee Report 1965: Appendix Y4: Atmospheric Carbon Dioxide, pp. 111-133 in *Restoring the Quality of our Environment*, Report of the Environmental Pollution Panel. The White House, Washington DC, November 1965. https://dge.carnegiescience.edu/labs/caldeiralab/Caldeira%20downloads/PSAC,%201965,%20Restoring%20the%20Quality%20of%20Our%20Environment.pdf.

[3] International Panel on Climate Change. Fifth Assessment Report (AR5) 2015. https://www.ipcc.ch/report/ar5/.

[4] The Royal Society and the U.S. National Academies of Sciences, Engineering and Medicine, Climate Change: Evidence and Causes. 2014 http://nas-sites.org/americasclimatechoices/events/a-discussion-on-climate-change-evidence-and-causes/.

[5] United Nations Framework Convention on Climate Change. The Paris Agreement. 2015. http://unfccc.int/paris_agreement/items/9485.php.

[6] Massachusetts Institute of Technology Joint Program on the Science and Policy of Global Change. 2016 Food, Water, Energy, and Climate Outlook. Massachusetts Institute of Technology. (2016) https://globalchange.mit.edu/publications/signature/2016-food-water-energy-climate-outlook.

the risks of climate change have brought an intense political spotlight on the science of climate change. Statements in the public debate about climate science, however, range from legitimate to dubious. The lines between what we know with confidence and what is still a puzzle are not always clear to non-specialists. Even to specialists, local perspectives on risk and the burden of proof necessary to compel a public policy response vary between countries, states, and individuals. Thus the public debate can make it difficult for climate science to appropriately inform judgments about energy and environmental policy.

This brief does not take a stand on particular policy options for the United States.[7] Instead, it aims to explain what the scientific debate about climate change is (and is not) about, examine some of the more common objections to the narratives offered by mainstream science (including 5 commonly asked questions), and provide context for what is known about the current state of the climate and what remains to be discovered. This paper does not aim to resolve every scientific dispute. The scientific community does that through experimentation, peer review, and replication of results. Rather, we will examine how scientific conclusions about climate change have formed and how those conclusions are reflected in the public debate about the reality and risks of climate change.

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[7] The Niskanen Center, however, supports market-based and efficient measures to reduce greenhouse gas emissions in the United States. c.f. Taylor, Jerry. The Conservative Case for a Carbon Tax. The Niskanen Center. 2015. http://niskanencenter.org/wp-content/uploads/2015/03/The-Conservative-Case-for-a-Carbon-Tax1.pdf

Contents

What Changes the Climate?

The conditions that keep the Earth's climate livable are well known. The Earth orbits the Sun. Light from the Sun falls on the Earth; some passes through the atmosphere and warms the surface of the Earth.[8] Gravity keeps Earth's atmosphere from drifting off into space, and a mix of GHGs (e.g., water vapor, CO2, methane, ozone and others) trap heat close to the surface because of the greenhouse effect.[9] It is warmer in Chicago than on the Moon because Earth's atmosphere blankets the planet and keeps energy near the surface of the planet.

Anything that causes the amount of energy trapped by the atmosphere to go up or down over long periods of time changes the climate. Some of these climate agents are well known and familiar. For example, more sunshine means warmer surface temperatures and more heat for greenhouse gases to keep near the surface. It feels warmer in Miami than in Chicago, in part, because places near the equator get more sunlight.

Over any particular epoch in Earth's history, the combination of factors determining the climate or causing it to change has varied. Long-term changes in the brightness of the Sun, the shape of the orbit of the Earth around the Sun, the distribution of the continents, the reflectivity of the land surface, eruptions of large volcanoes, and the chemical composition of the atmosphere are all known to have affected the climate. Over Earth's history, changes in these primary drivers of climate have led to conditions drastically different from today—both colder and hotter[10].

Much of the challenge of climate science comes in discerning how these different effects have accentuated or offset each other. For example, what is the ultimate effect of increasing the solar output of the Sun (warming), making the Earth's surface brighter by deforestation (cooling), and intensifying the greenhouse effect (warming) when all occur together? In most cases, the interactions between these factors make their relationships with global climate too difficult to understand through simple qualitative analysis. This is why scientific and quantitative analysis is important.

Developing a scientific understanding of the climate of the last 800,000 years is an example of that challenge. During that period the climate cycled naturally between cold ice ages and warm periods at irregular intervals lasting thousands of years. Figure 1 shows temperatures near the South Pole changed by as much as 10 °C between cold glacial periods and warmer interglacial periods. The corresponding global temperature changes were about half that, on the order of

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[8] Not all of the light inbound from the Sun reaches the surface of the Earth. Some is reflected or absorbed by the atmosphere itself and some reflects off reflective surfaces like the tops of clouds or large expanses of ice on the ocean or land.

[9] Greenhouse gases in the atmosphere absorb heat (infrared) radiation coming from the surface and from within the atmosphere. They then reradiate it both up and down. The downward portion radiates back toward the surface, causing further temperature increases near the surface.

[10] Global temperature has ranged between cold ice ages (4-6 °C colder than today) and hot greenhouses (up to 6 °C warmer during the Cretaceous).

4-6°C.[11] As the climate moved between hot and cold periods, the atmospheric CO2 concentration also went up and down. This clear relationship in measurements prompted scientists to ask whether CO2 was driving temperature changes, or whether temperature changes were driving CO2 concentrations.

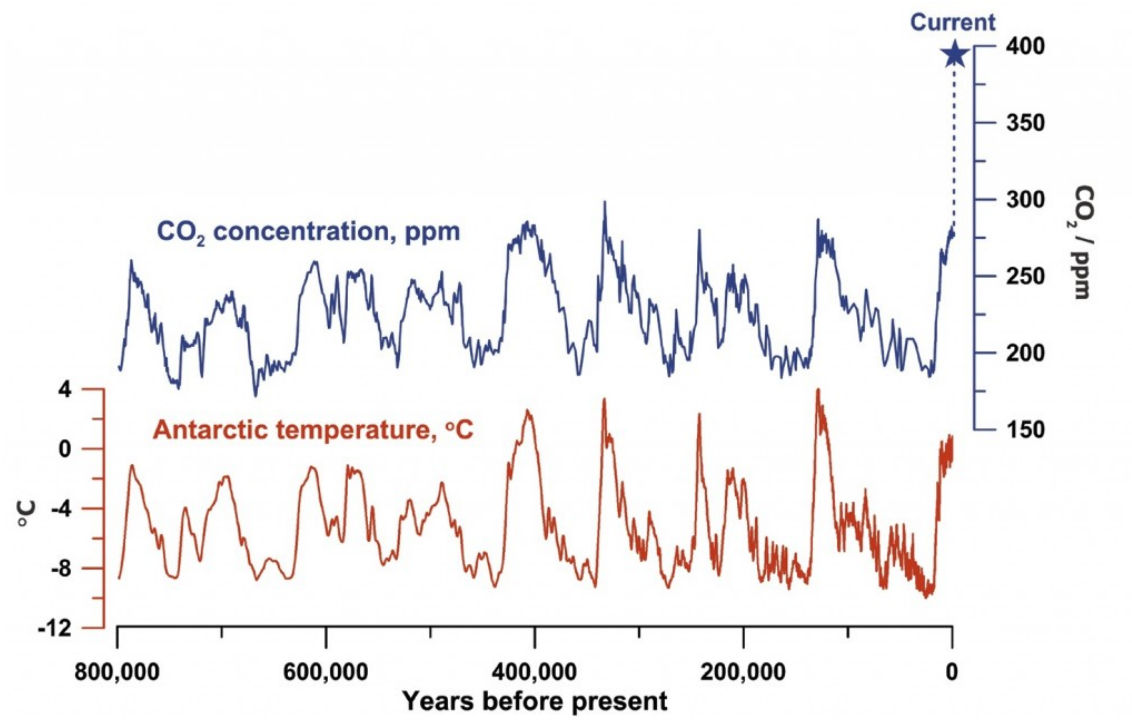

Figure 1: The co-evolution of temperature and CO2 concentration from the last 800,000 years. The temperature record in red captures the air temperature in Antarctica by measuring the ratio oxygen isotopes trapped in air bubbles taken from ice formed in the deep past. CO2 levels are measured from the same air bubbles and are shown in blue. The rapid increase of atmospheric CO2 in the recent past is shown as a dotted blue line. Source: United States National Academies of Sciences, Climate Change: Evidence and Causes

Research has revealed that both are true. Scientists found that the increase in CO2 concentrations followed temperature changes, indicating something else must be contributing. The leading explanation now holds that temperature changes from wobbles in the Earth's orbit caused warming[12], which increased CO2 levels and caused additional warming. To exit each ice age, changes in Earth's orbit tipped the ice-covered Northern Hemisphere toward the sun, causing ice to melt at the poles, the surface reflectivity to decrease, and global temperatures to increase. CO2 was then released into the atmosphere from the warmer oceans, which hold a lot

[11] Annan and Hargreaves 2013.
[12] These wobbles are really changes in three distinct orbital parameters that together determine how sunlight falls on the Earth: the circularity of the planet's orbit, the tilt of Earth's axis with respect to the Sun, and the time of year when Earth is closest to the Sun.

of dissolved carbon.[13] The warming effect of increased CO_2 helped give warm periods an extra temperature boost. As geological time wore on, changes in the orbit of the planet favored cooling and the released CO_2 was eventually recaptured by the oceans. Cooling at high Northern latitudes led to ice formation, and again the world fell into an ice age.

Right now, we're deep (about 10,000 years[14]) into a natural warm spell. Assuming our understanding is correct, the Earth would still be relatively warm today had humans never evolved or never learned how to clear land for agriculture or burn coal, oil, and gas for energy. Without a substantial human role in the climate, then, climate would probably be slowly cooling over thousands of years, continuing the cycle of warm to cold periods.

However, the current amount of CO_2 in the atmosphere is far greater than at any other period in the last 800,000 years (see the starred endpoint in Figure 1), as a result of human activity. Given the role that the greenhouse effect plays in climate, we should expect this increase in atmospheric greenhouse gases to profoundly alter the previous rhythm of warming and cooling, and push temperatures even higher. While the precise conditions that instigate the fall into an ice age are not well known, some scientists believe that the human climate footprint already delayed the next ice age[15] and conditions for another may not arrive for 100,000 years.[16]

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[13] Cold ocean waters can hold more CO_2 than warmer ones, so as changes in the Earth's orbit instigated warming, CO_2 bubbled out of the ocean and into the atmosphere, causing the global average temperature to go up further. This type of amplification has caused a positive (or amplifying) feedback effect, and appears to have played an important role in the transitions between cold and warm climates.

[14] Marcott et al. 2013.

[15] Ruddiman et al. 2014; for a popular account of this idea see Ruddiman "How did humans first alter global climate?" *Scientific American* https://www.scientificamerican.com/article/how-did-humans-first-alte/.

[16] Ganopolski et al. 2016.

Human Influence on the Climate

Carbon Dioxide Increase

In the centuries before the industrial revolution, CO_2 levels in the atmosphere were around 280 parts per million (ppm), a value near the upper end of the range of values from the last million years. Current observations indicate that the CO_2 concentration has recently risen past 400 ppm—a 43 percent increase over preindustrial levels—and is growing at about 2 ppm per year.[17]

There is little doubt that the increase in atmospheric CO_2 is due to human emissions, as fossil fuel burning and forestry and agriculture have released more CO_2 into the atmosphere than has accumulated since the 19th century.[18] Since 1870, human activities have released about 2,000 billion metric tons of CO_2 ($GtCO_2$) into the atmosphere through the burning of fossil fuels and clearing of land. If all of that CO_2 had accumulated in the atmosphere, then concentrations would already be approaching 550 ppm (i.e., a doubling of the preindustrial concentration). Instead, the amount of CO_2 in the atmosphere has only increased by about 110 ppm or about 850 $GtCO_2$ since the late 19th century. The rest has been captured by plants (via photosynthesis) and the oceans (which dissolves CO_2 in seawater). Together, these natural processes have removed about 60 percent of human CO_2 emissions from the atmosphere.

Were emissions to suddenly stop, those same natural processes would capture and remove excess CO_2 from the atmosphere. However, these processes will take hundreds of years to significantly reduce atmospheric CO_2, and thousands of years to completely capture CO_2 from fossil fuel burning back into the natural geochemical cycle by depositing the emitted carbon into the ocean and ocean sediments. Accordingly, any climate change associated with emissions from CO_2 should be expected to last tens of thousands of years, all else being relatively equal.[19]

Measurements of Recent Climate Change

The most central measure of climate change is the increase in the global average surface temperature. [20] Thermometer networks regularly measure temperature around the world and these measurements are combined to make a global average. While the number and quality of

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[17] Global Carbon Project (2016) Carbon budget and trends 2016. [www.globalcarbonproject.org/carbonbudget] published on 14 November 2016.

[18] A second line of evidence proves that the CO_2 accumulating in the atmosphere comes from industrial activities. The chemical signature of fossil fuels, which are low in the unstable isotope Carbon-14, is detectable in the atmosphere.

[19] Archer et al. 2009.

[20] Whether or not global surface temperature ought to be the most central measure of climate change, or human-caused climate change, is a matter of some debate—even within the scientific community. It is considered central here because the length of the record, dating back to the 19th century, and the policy context implied by the Paris Agreement.

surface thermometers has increased with time, precise global records can be assembled stretching back to the 19th century. While there is some disagreement on the margins, research groups around the world have found that the global average surface temperature has increased by about 1 °C since the middle of the 19th century, as shown by Figure 2.[21]

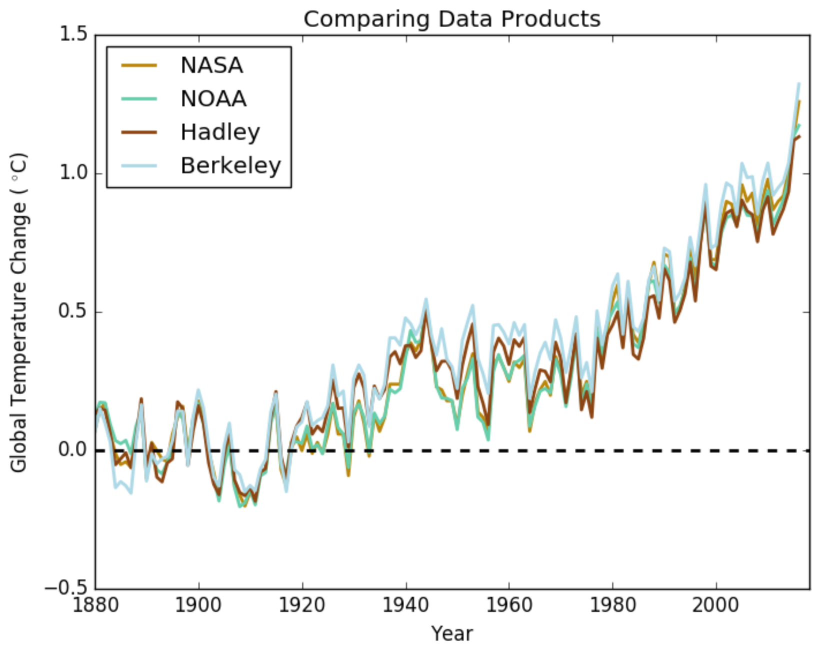

Figure 2: Annual average temperature records from 1880-2016, shown as a departure from the 1880-1920 average. The colored lines show the temperatures as estimated by four different research groups: NASA GISS (brown), NOAA (green), Hadley Centre (red), and Berkeley Earth (blue). See text for references.

The average increase in global temperatures has manifested itself in a host of temperature records. Each of the last three decades was hotter than the previous decade, with the hottest decade in the instrumental record so far being 2000 to 2010. Since 2010, temperatures have reached even higher levels, with the years 2014, 2015, and 2016 each successively registering as the hottest year since monitoring global temperatures with thermometers began in the mid 19th century (the so-called "instrumental record").[22]

During the course of this century-long warming, there have been periods where the rise in temperatures slowed or stopped for up to 10- to 15-year periods, but risen again such that the overall warming has continued.[23] Explanations for these decadal variations in temperature invoke short-term changes in natural climate drivers (e.g., volcanic eruptions or solar activity), human climate drivers (e.g., changes in emissions of sulfur dioxide, a particulate pollutant that has a cooling effect on climate) or random fluctuations on the part of the climate from changes in the large-scale circulation of the ocean (e.g., changes in the exchange of heat between the

[21] IPCC AR5 WGI Chapter 2. Observations: Surface and Atmosphere.
[22] See discussion: Are global temperature records reliable?
[23] See discussion: A hiatus, a pause, a slowdown?

ocean and the atmosphere resulting from the El Niño/La Niña oscillations or large scale ocean circulation in the Pacific Ocean).

Along with temperature, sea level rise is a sensitive indicator of climate change. Warm periods in Earth's history featured much higher sea levels, a result of ice sheets and glaciers melting and warming ocean temperatures. Over the 20th century, global average sea level increased by about 8 inches after not having changed very much over at least the last several thousand years.[24] As for temperature, there is not much technical disagreement about the extent or causes of total sea level rise over the last century,[25] which is the result of warming of the global ocean (which causes water to expand) and melting ice from glaciers and polar regions (adding water).

A larger body of evidence shows other components of the climate system undergoing significant changes, including the warming of the lower part of the atmosphere (known as the troposphere, which has been observed since the mid-20th century), cooling of the stratosphere[26] (observed since the mid-20th century), the warming of the oceans (observed globally since the 1970s), the retreat of glaciers (observed at many glaciers since the 19th century), the retreat of snow cover (observed by satellites since the 1970s), and receding sea ice in the Arctic (observed by satellite since the 1980s).[27]

Determining the Extent of Human Influence

Global CO2 and temperature records show that CO2 in the atmosphere has increased dramatically with coinciding temperature increases, sea level rise, and other warming signals. Intuitively, it makes sense that these are related; as the greenhouse gas blanket gets thicker, the surface warms up. However, as with the cycles between ice ages and warm periods, to estimate the relative effects of humans and other factors on recent climate change we have to consider the full range of climate drivers.

The major human drivers of climate change include emissions of greenhouse gases, changes in land use affecting the local land surface (warm or cool), and the effect of sulfate-producing particulate pollution (cooling) and soot (warming) from burning fossil fuels.[28] Over time periods of decades to a few centuries, the natural drivers meriting consideration include changes in the brightness of the Sun (e.g., due to sunspots) and volcanic eruptions, which loft small particles into the sky.

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[24] Kopp et al. 2016.

[25] IPCC AR5 WG1 Chapter 13. Sea Level Change.

[26] In the stratosphere, CO2 contributes to cooling as it emits radiation to space at high altitudes. Stratospheric cooling coherent with warming of the troposphere is a signature of an increased greenhouse effect from increasing CO2.

[27] IPCC AR5 WG1 Chapter 2. Observations: Atmosphere and Surface; IPCC AR5 WG1 Chapter 3. Observations: Oceans, IPCC AR5 WG1 Chapter 4. Observations: Cryosphere.

[28] The most significant of these is SO2, from burning of fossil fuels, which forms sulfate in the atmosphere. The white haze of sulfate makes the atmosphere more reflective and exerts a cooling effect.

Current research shows that natural drivers cannot adequately explain the timing, amount, or pattern of warming that has been observed over the second half of the 20th century. Figure 3 illustrates the expected effects of natural drivers, and natural and human drivers combined, on global temperature in the 20th century. Note that only when human influences are included do the temperature increases calculated by climate models reasonably represent the amount of warming in the observed record, as well as its timing. More sophisticated studies of the relative weighting of human and natural climate drivers take into account regional variations in temperature as well as the vertical distribution of temperature change to separate human and natural signals.[29]

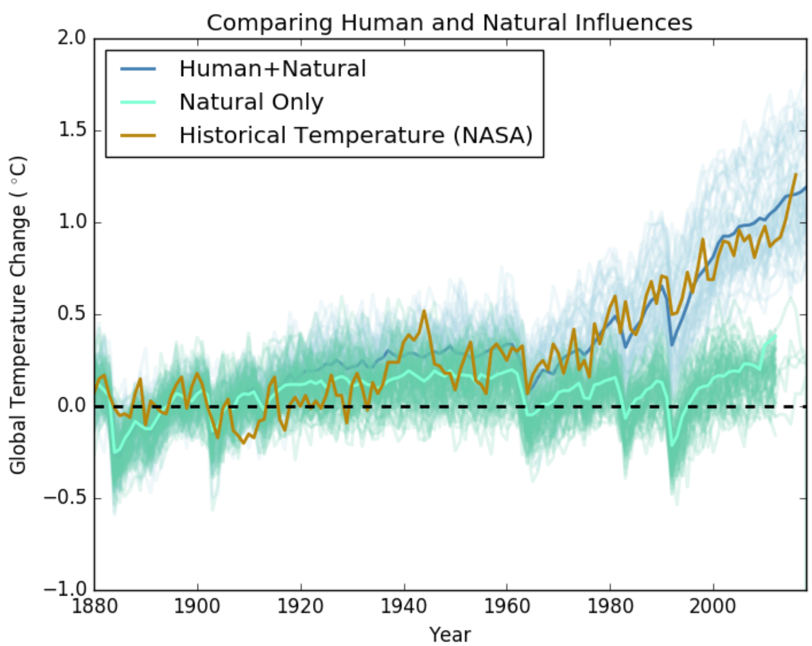

Figure 3: The contribution to 20th century climate change from natural and human factors. The green band shows how model simulations estimate temperature when only natural factors work to alter the climate. The blue band shows how model simulations estimate temperature when both natural and human factors are in play. The width of each band shows the range in climate due to different model characteristics and internal variability. The black line shows one estimate of observed surface temperature.

Individual studies that calculate how much of the recent change is due to human activity find that nearly all of the warming observed over the late 20th century was the result of human influence[30]. Taking a cautious estimate of error in such calculations, scientists writing the summary for the last IPCC report concluded that at least half of the temperature increase since the mid-20th century (total 0.6° C) was the result of human influence[31]. Their best estimate was that *all* of the recent temperature increase was human-caused. Without the cooling effect of

[29] Hegerl and Zwiers 2011.
[30] IPCC AR5 WG1 Chapter 10. Detection and Attribution of Climate Change: from Global to Regional.
[31] Ibid.

particulate aerosol pollution, we probably would have experienced greater warming from increases in CO2 and other greenhouse gas concentrations.

Disentangling the combined effects of natural variability, external factors, and human influence on the temperature changes before 1950 is more difficult, because the observations themselves are more uncertain, data coverage is less complete and conclusions are necessarily less confident.[32] However, there is little doubt that, the largest changes to agents that warm and cool the climate since the 18th century have come from human influences, and they favor warming.[33]

Other climate changes that are consistent with greenhouse gas warming include sea level rise, warming oceans, retreating glaciers and sea ice, and cooling of the upper atmosphere (stratosphere). All of which have been observed to some degree already. This consilience of evidence is cited by the IPCC and others to confidently assert not just the reality of global warming, but its human causes. [34] However, the conclusion about human influence for each type of phenomena weakens at regional scales and for specific phenomena (such as drought and extreme weather events like Hurricanes), as data and physical understanding get noisier, subject to more variability, and the amount of data coverage declines.

Future Human Influence on Climate

The primary question for policymakers, is how much warming we should expect in the future and if future emissions will play a major role in the future climate. These questions define how much climate change their planning should take into account and how much can be avoided by reducing GHG emissions. Basic theory and climate models predict that temperature will continue to increase in response to GHG emissions. The amount of climate change we should expect depends on how the climate will respond to continuing human activities and natural events (a scientific matter) and the extent of future greenhouse gas emissions (a matter of technological development, economic growth, and policy choices). For all but the lowest emissions scenarios, we should expect quite a bit more temperature change than has already been experienced. But the extent of the warming by the end of the 21st century appears to strongly depend on how much greenhouse gases we emit in the future.

Recently, scientists have identified a convenient way to think about the connection between emissions and warming without relying upon competing assumptions about economic and technological trends. For as long as CO2 emissions continue, we can expect the average increase in temperature to be proportional to the total amount of CO2 released into the atmosphere. Since large scale emissions began in the 18th century, we can already see indications of this proportionality in historical climate change.[35]

[32] Huber and Knutti 2012.
[33] IPCC AR5 WG1 Chapter 8. Anthropogenic and Natural Radiative Forcing.
[34] Oreskes 2007.
[35] IPCC AR5 WG1 Chapter 12. Long-term Climate Change: Projections, Commitments, and Irreversibility.

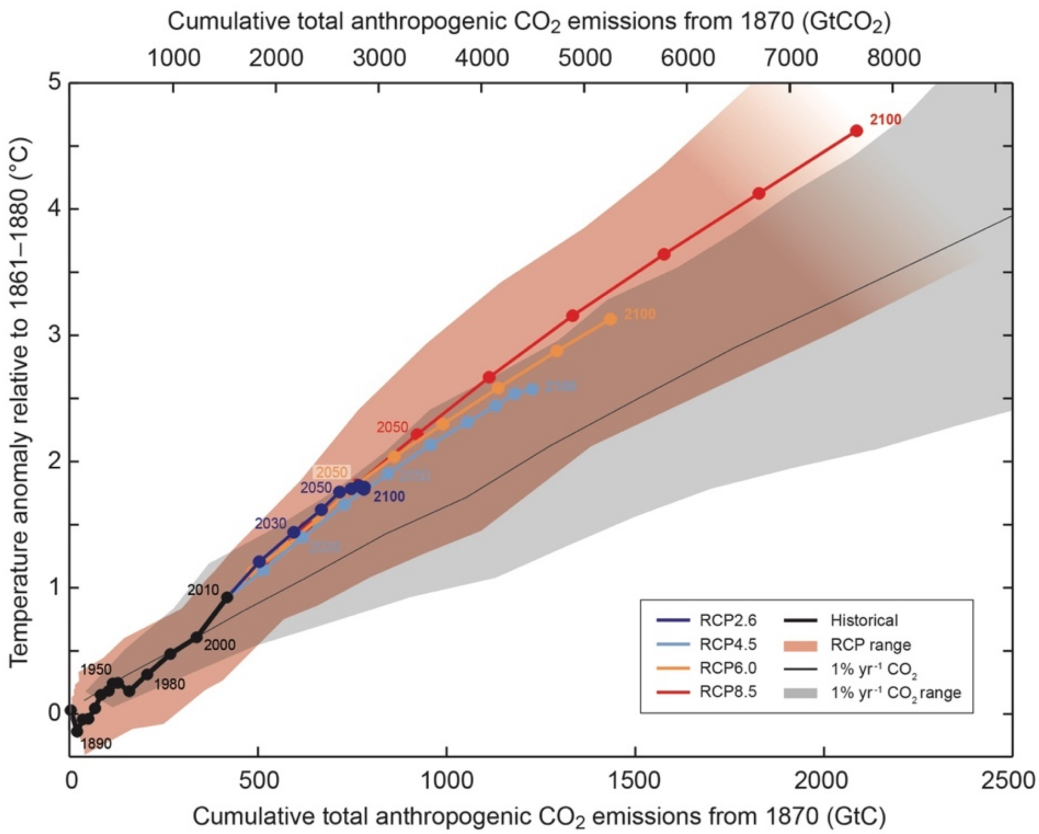

Figure 4: The increase in surface temperature compared to the total amount of CO2 emitted since 1870, calculated with climate models. The black line shows averaged model results through 2005, where historical emissions are known. The blue, orange, red lines show different scenarios for CO2 emissions in the 21st century, (the Representative Concentration Pathways). Circles show the average temperature in each decade. The grey band shows the temperature evolution when only CO2 is increased in a model. Source: IPCC Assessment Report 5, Summary for Policymakers

We cannot forecast future emission levels with high confidence, because we cannot predict how society will evolve over the 21st century and beyond. Instead, scientists and energy experts have developed different scenarios for what CO2 concentrations and other human activities may be in the future—scenarios called Representative Concentration Pathways (RCPs)—that reflect different possible futures for human influence on the climate. In the highest emissions case (RCP8.5, shown by red line in figure 4) temperatures increase by an additional 2.6-4.8 °C by 2100, and continue to increase thereafter. In the lowest emissions case (RCP2.6, shown by dark blue line in figure 4) temperatures increase by 0.3-1.7 °C and do not rise much further thereafter. [36]

Uncertainties regarding these projections still exist, of course, as demonstrated by the fairly wide range of temperature change projected by models for any amount of total emissions. The

[36] Ibid.

most important of which relate to what fraction of CO2 emissions accumulates in the atmosphere rather than being sequestered in plants, trees, soils, or the oceans (an issue known as *airborne fraction*), and the temperature increase that follows from increased CO2 concentrations in the atmosphere (an issue known as *climate sensitivity)*. Both the airborne fraction and the climate sensitivity are important topics of continuing inquiry in climate research.[37] The public debate about climate projections, however, has focused almost entirely on the correct value of climate sensitivity.[38]

The term climate sensitivity is defined as the increase in the global average surface temperature as a result of a doubling of the atmospheric CO2 concentration, considered both at the moment the CO2 doubles (transient sensitivity) or the climate adjusts to the permanently doubled CO2 concentration (equilibrium sensitivity).[39] The IPCC reports that the most likely range for transient sensitivity is between 1-2.5 °C and the most likely range for the equilibrium sensitivity is between 1.5-4.5 °C. These estimates are informed by information from studies of paleoclimate records (like the transitions between warm and cool periods shown in Figure 1), climate models, basic physics, and the observed change in global temperature since the 19th century.

This presumed proportional relationship between temperature and total CO2 emissions implies that, to prevent warming over a threshold—for example the 2 °C goal adopted in the Paris Climate Accord—only a finite amount of CO2 can be emitted. That number is commonly referred to as the remaining carbon budget. Given the present range of estimates in warming projected by models, the Paris goal would require limiting total emissions to about 3700 GtCO2, more than half of which has already been emitted. Presently, global emissions from fossil fuels and deforestation are just about 40 GtCO2 per year, allowing for about 4 decades at today's emissions levels. The presence of other human climate influences means that budget is probably more like three decades, if the standard estimates of climate sensitivity are correct.[40]

The range of future warming exhibited by climate models approaches 2 °C for all of the emission scenarios considered by the IPCC and other groups. In low emissions scenarios, temperatures approach that level toward the end of the century. In high emissions scenarios, temperatures pass through 2 °C sometime in the middle to late 21st century. And insofar as the global surface temperature is an indicator of change in other parts of the climate system— e.g. changes in temperature extremes, global amounts of precipitation, and sea level rise—further changes should be expected in them as well.[41]

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[37] Marotzke et al. 2017.

[38] See Question: Are climate models too sensitive?

[39] Technical definitions: Transient Climate Sensitivity-The change in global averaged surface temperature at the moment that atmospheric CO2 doubles, after increasing at 1 percent per year from pre-industrial values. Equilibrium Climate Sensitivity is the surface temperature increase after the climate system has fully adjusted to a doubling of atmospheric CO2 over preindustrial levels.

[40] https://www.carbonbrief.org/analysis-only-five-years-left-before-one-point-five-c-budget-is-blown.

[41] NAS Board on Atmospheric Sciences and Climate. "Warming World : Impacts by Degree" The National Academy of Sciences. 2011. http://dels.nas.edu/materials/booklets/warming-world.

Understanding Risks

Basic physical theory and climate models indicate we should expect a suite of physical effects will advance with continued global warming. Temperature increases will likely be larger over land and in polar regions and smaller over the oceans. Weather and natural variability will continue to modulate local and global temperatures, but as average temperatures increase, extremes and records will favor hot spells over cold snaps. Warming will be accompanied by increasing amounts of total global precipitation and the amount of precipitation that falls in individual events, because warmer air holds more water vapor. Despite projections of globally increasing rainfall, some areas most likely face a higher tendency toward dry and hot conditions, or drought, as the atmospheric circulation changes. Continued heating of the oceans and melting ice from glaciers will contribute to sea level rise that will likely go on for centuries.

Coincident with the physical effects of climate change, the geochemical impacts of higher CO2 levels will otherwise affect environmental conditions in the oceans and land. As the oceans absorb excess CO2 from the atmosphere, ocean pH will decrease, leading to ocean acidification. Higher CO2 concentrations in the atmosphere will make more available for photosynthesis and could act as a fertilizer, aiding plant growth and agriculture in some regions.

The risks of climate change come from the effects of climate change clashing with the natural world or human infrastructure and lifestyles. Since climate change implies changes to the background conditions against which society and ecosystems do their work, understanding the potential for positive and negative impacts throughout the planet is challenging. Formal efforts to understand local impacts of climate change have been performed for the world at different levels of global warming, the United States[42], and vulnerable parts of the world for 4 °C of global warming.[43]

Risk assessments of climate change are complicated and relatively uncertain. As we have seen, projections of the future are not certain even for global temperatures. We don't know with much confidence how regional conditions or extreme weather events will change and likewise how human and natural systems will respond or adapt. The expected pace of 21st century climate change has almost no geological analog. The capacity of society and ecosystems to adapt or adjust to climate change at the rate and size human activities are inciting is untested.

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[42] United States Global Change Research Program. *Third National Climate Assessment* 2014. http://nca2014.globalchange.gov/.

[43] Schellnhuber, Hans Joachim, et al. "Turn down the heat: climate extremes, regional impacts, and the case for resilience." *Turn down the heat: climate extremes, regional impacts, and the case for resilience* 2013. http://documents.worldbank.org/curated/en/975911468163736818/pdf/784240WP0Full00D0CONF0to0June19090L.pdf.

In its fifth assessment report, the IPCC compiled a summary of different studies into the local, regional, and global effects of climate change, the vulnerability of different regions and sectors to change, and the capacity for different systems to adapt to change. Combining those different concepts, the IPCC rated how climate change created additional risks across five different areas.[44]

- Unique and threatened systems are systems that have little capacity to adapt to rapid climate changes, such as low-lying coastal areas or isolated ecosystems.
- Extreme weather events include record heat, more intense precipitation, droughts, and tropical storms.
- The distribution of impacts refers to the geographical distribution of the effects of climate.
- Global aggregate impacts are the combined effects of climate change on biological diversity and economic growth.
- Large-scale singular events are qualitative changes to the climate system such as the possible shutdown of ocean circulation, changes in monsoon behavior, melting Arctic permafrost, or the collapse of major ice sheets leading to a meter or more of sea level rise in the next century.

The IPCC's ratings are subjective, but they describe the character of additional risk associated with each level of warming. At a medium level of additional risk, the climate change signature will begin to be detectable in specific events or regions or sporadically harmful. As risks move from high to very high, the effects of climate change become more pervasive, harmful, or permanent.

The temperature increase at which each area of concern transitions to higher levels of additional risk varies, but there is general agreement that risks increase with temperature. At this time, we are only edging into moderate levels of additional risk to *unique and threatened systems* and *extreme weather*. However, once we surpass 2 °C of warming, the additional risk in each category will range from medium to high. At 4 °C of warming over preindustrial levels, the additional risk is high to very high across all sectors.

[44] IPCC AR5 WG2 Summary for Policymakers.

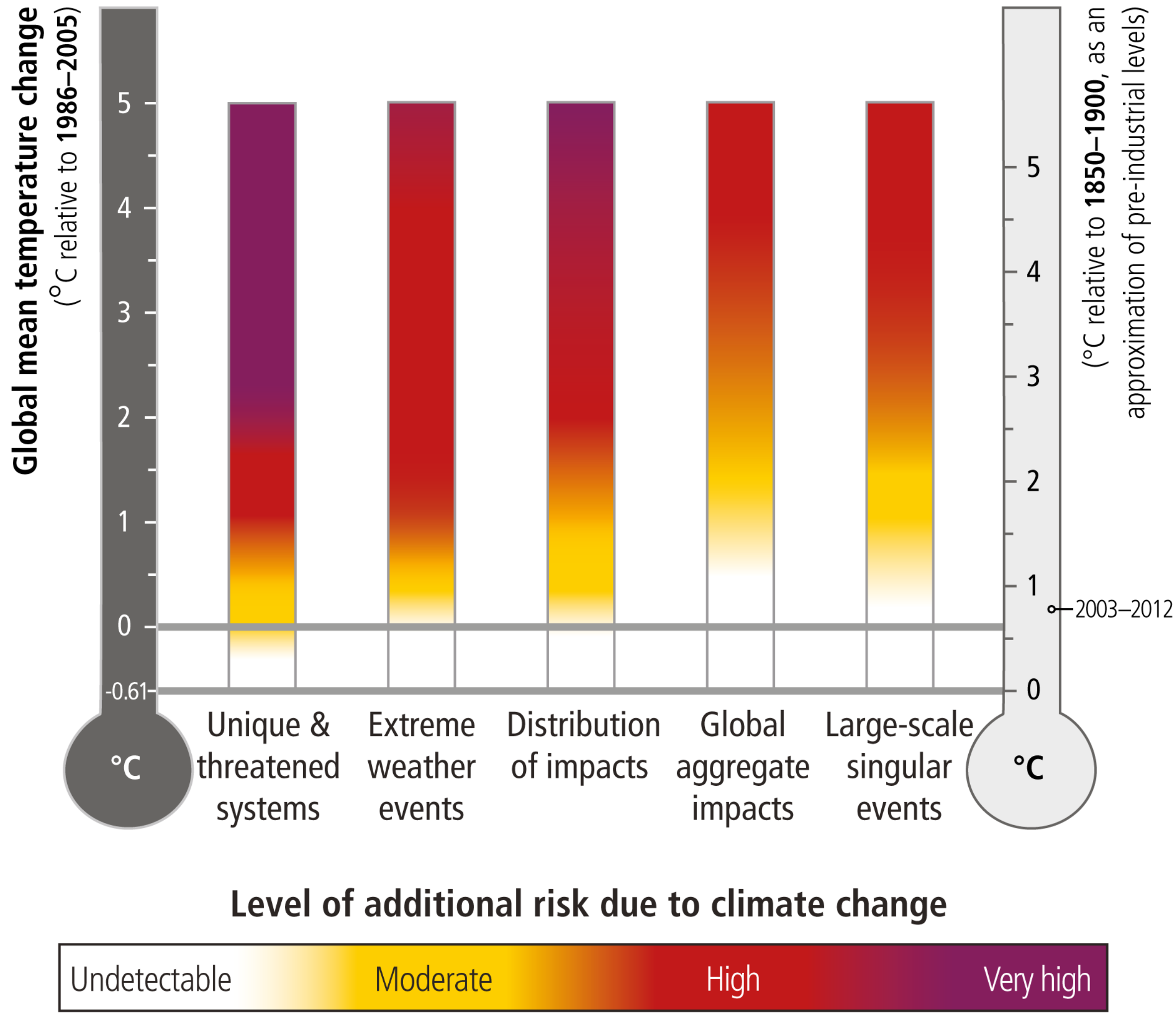

Figure 5: Risks of global temperature increases to different areas of concern. Temperature increase over preindustrial (right) and near present (left) are shown by the thermometer graphics. Each bar represents a different area of concern. The different levels of additional risk are shown as transitioning colors, going from undetectable (white) to very high (purple). Source: IPCC AR5 Working Group 2. Impacts, Adaptation, and Vulnerability: Summary for Policymakers

Question 1: Are temperature records reliable?

Unfortunately, we do not have a global thermometer to measure the planet-wide surface temperature. And we certainty did not have one looking 100 years into the past. Instead, surface temperature has been recorded at individual weather stations and by ships at sea. Those measurements are combined and averaged to make global records. Because the number of stations, local conditions, and measurement equipment have changed over time, combining individual temperature measurements into a global temperature record requires data processing and some scientific judgment.

As of now, four research groups create major global temperature records by combining local thermometer readings. Three of those records are produced by government labs in the United States (NASA[45] and NOAA[46]) and the United Kingdom (Hadley Centre[47]). The fourth was produced as an independent group, (Berkeley Earth[48]) which originally set out to critically examine the work of the others. Each uses different data processing techniques to combine the measurements from different instruments, time periods, and locations. These groups, working independently, find similar global temperature increases over the instrumental period, as illustrated in Figure 2, which is an important check of their reliability.

Global temperature records are a frequent subject of critique and controversy. Critics claim that these temperature records are unreliable because the underlying measurements are potentially biased, or human biases in analysis skew the results. However, scientists are constantly on the lookout for potential secondary effects introducing error in the data. To wit, the data processing supporting the current datasets have been subject to significant scientific scrutiny and have been refined with subsequent revisions of these data products.

The global temperature records are revised as scientists accumulate new observations, new types of temperature data, and improve analytical techniques. These revisions typically involve small alterations to the data processing tools that correct biases in the raw measurements. Figure Q1 shows a recent example with the NOAA dataset, where the absolute change between subsequent versions of the temperature record are small. It also shows, however, that the absolute effect of the processing of the raw measurements is noticeable before about 1940, when data was sparser. After correction, the global temperature record shows less warming than naive treatment of the measurements would indicate.

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[45] NASA Goddard Institute for Space Studies, https://data.giss.nasa.gov/gistemp/.
[46] NOAA National Climatic Data Center, https://www.ncdc.noaa.gov/data-access/marineocean-data/noaa-global-surface-temperature-noaaglobaltemp.
[47] Hadley Center and University of East Anglia, https://crudata.uea.ac.uk/cru/data/temperature/.
[48] Berkeley Earth, http://berkeleyearth.org/land-and-ocean-data/.

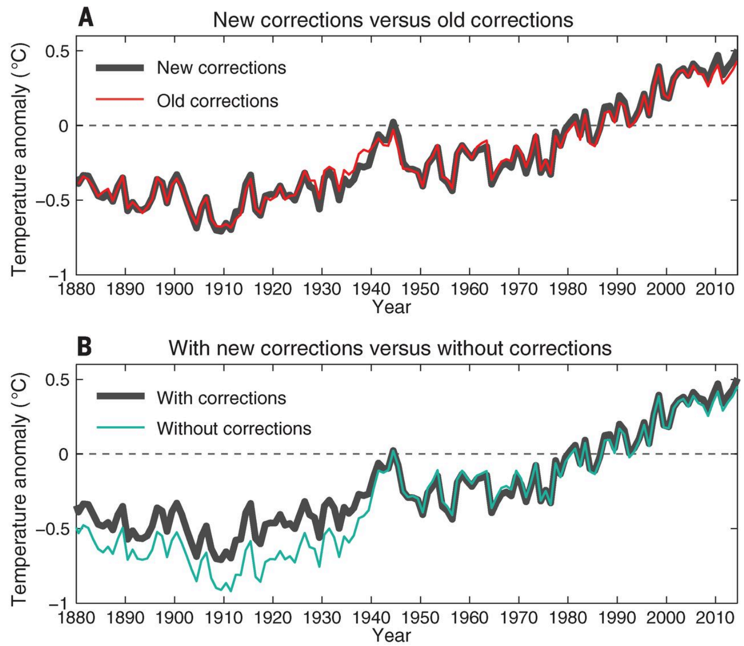

Figure Q1: Comparisons of temperature records produced by NOAA show the effect of data revisions. Panel (a) compares two subsequent iterations of the NOAA record, with the new corrections to its data processing. Panel (b) shows the difference between the global temperature record with no corrections and the NOAA corrections. Source: Karl et al. 2015, Possible artifacts of data biases in the recent global surface warming hiatus. Science.

Question 2: Has global warming stopped, paused, or slowed down?

In the early part of the 21st century, global average surface temperature increased more slowly than it had over the previous several decades. This event is referred to alternatively as the global warming hiatus, pause, or slowdown. Since it occurred at a time when atmospheric CO2 was growing in concentration, and so too its warming effect, the warming slowdown has led some to question predictions of ongoing and accelerating warming.

It is important to note that over the early 21st century, global warming—energy accumulation in the atmosphere and oceans—continued. Measurements of ocean temperatures and satellite measurements at the top of the atmosphere show that warming of the climate system, as a whole, has continued.[49] However, these measurements cannot resolve confidently if heat accumulation has increased as a result of higher levels of CO2.

It is also hard to argue that surface temperature did not increase in the early 21st century. However, the rate of increase was slower than it had been over the past few decades and was also slower than had been predicted by climate models (by about half, 0.1 °C instead of 0.2°C).[50] Understood as a departure from expected warming, the slowdown exists despite some

[49] Johnson et al. 2016.
[50] Fyfe et al. 2016.

recent revisions to surface temperature datasets that show more warming over this period than we had previously thought.[51]

Over the last few years, a substantial body of research has helped scientists understand why real world temperature departed from what the models suggest should have been the case. A cooling phase in the Pacific Ocean, driven by strong trade winds bringing cold water to the ocean surface, appears to be behind much of the slowdown.[52] A series of small volcanic eruptions, that were not included in climate models, also played a role in reducing the global temperature increases that we might otherwise have seen.[53]

At this point, there is little evidence that the warming slowdown should lessen projections of future warming. Modeling studies show that when such slowdowns are associated with random variations on the part of the climate, they do not indicate less warming than might be expected over the 21st century.[54] It is possible that revisions to future predictions might be appropriate in the future, but that would require not just observations of a warming slowdown, but a theoretical understanding of why such revisions would be necessary.

Question 3: Could these changes be natural?

The large changes in global temperature and atmospheric CO2 from deep Earth history prove that natural changes in the climate should be expected over long time periods. Climate change on human timescales, season-to-season and year-to-year, also occurs for reasons that have nothing to do with human influence.

In gauging the human influence on climate, the strongest conclusions from climate scientists have been for the last half-century or so. Multiple studies find that most of the warming over that period can be chalked up to human influence, because solar and volcanic effects, and the biggest climate oscillations were mostly neutral over that period. Additionally, the pattern of temperature increase (global changes, larger near over land than ocean, concurrent with ocean warming) is inconsistent with the temperature patterns that accompany the known sources of variability on the scale of half centuries (high latitude oceans).

Some experts are critical of the conclusion that human activities are the primary cause of the most recent warming and argue that it discounts plausible alternative explanations. There are minority concerns that natural variability could account for a significant fraction of the observed temperature increase and mainstream climate science is overstating the role of human activities in recent climate change.

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[51] Karl et al. 2015; Hausfather et al. 2017.
[52] Kosaka and Xie 2014.; England et al. 2014.
[53] Schmidt et al. 2014.
[54] England et al. 2015.

One set of concerns holds that some unknown external factor—excluded from computer experiments like those shown in Figure 4, and unaccounted for in studies of modern climate change—has contributed to the recent temperature increase. However, the major external factors that scientists think have affected climate over the late 21st century are already included in such simulations. Other potential influences have been proposed, but not proven to be important to climate over the late 20th century.[55]

Another set of concerns holds that random oscillations in climate system could have caused a significant amount of the measured global temperature increase. Such large internal variability, moreover, is inconsistent with observations and scientific understanding to date. Internal variability in climate models and statistical analyses of historical global temperature is smaller than the warming observed in the late 20th century over the same time periods. The change in temperature over that period was about 0.6 °C. While there is not much confidence that climate models have the right amount of internal variability, because of limited observational evidence, internal variability would have to be three times larger than in the models to disturb the conclusion that human influence was the leading climate driver over the last half-century.[56] No mechanism that could provide such large variability, but would have escaped detection over the last century, has been articulated.

Question 4: Are there measurements that challenge this picture?

Despite the apparent consilience of physical evidence surrounding climate change, it is a natural impulse, and scientific obligation, to ask if there are measurements that show different changes than expected or might refute model predictions of climate change. If so, then it is important to understand how such measurements might call us to revise future projections or reexamine the consensus of scientific view of climate change.

To date, the retrieval of temperatures by satellites are the most significant datasets that challenge mainstream interpretation of climate warming. Some experts have argued that satellite data offer a fundamental critique of our present understanding of climate change, because they show much less warming than climate model predictions, and may indicate the need to lower temperature projections of climate change.[57] There is not a agreement, however, over whether satellite temperatures actually do refute the predictions of climate models; as alternative explanations for the apparent disagreement have been closely examined, other possible explanations have emerged.

Since the late 1970s, satellites have measured radiation emitted by the atmosphere. In the 1990s, scientists developed methods for using these measurements to estimate the

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[55] Solomon, NRC 2007.

[56] IPCC AR5 Chapter 10.

[57] Christy, J. R., 2015: Testimony. Data or dogma? Promoting open inquiry in the debate over the magnitude of human impact on Earth's climate. Hearing in front of the U.S. Senate Committee on Commerce, Science, and Transportation, Subcommittee on Space, Science, and Competitiveness (2015), http://docs.house.gov/meetings/SY/SY00/20160202/104399/HHRG-114-SY00-Wstate-ChristyJ-20160202.pdf.

temperatures. The resulting datasets represent the temperature over tall bands of the atmosphere, several miles in height, with lots of uniform horizontal detail, but with errors from drifts in satellite orbit and the calibration between subsequent satellites making measurements. That is distinct from surface measurements, which offer a high level of vertical detail (temperature at 2 meters above the ground or at the surface of the ocean) but with limited spatial coverage, quality, and measurement type. Both kinds of data require data processing and scientific scrutiny before adding to our information about climate change.

Earlier, flawed, versions of satellite temperature records showed slight cooling of the atmosphere,[58] a result wildly against model expectation and surface measurements of warming. Subsequent revisions have made these measurements less discordant with other evidence of climate change, but there is still a fairly good body of evidence climate models show larger temperature increases than the satellites. Whether that difference is against expectation or indicates a problem with climate models or theory depends on statistical tests and physical interpretation.

Figure Q2 shows different visual comparisons of atmospheric temperatures from satellites and computer models. The casual reader could justifiably see a modeling failure or relative coherence between models and satellite data from interpreting these graphics in isolation. The way the different lines are plotted against each other yields very different qualitative interpretations. If the intent is to understand if the satellite measurements are vastly different from climate models, then quantitative analysis is necessary.

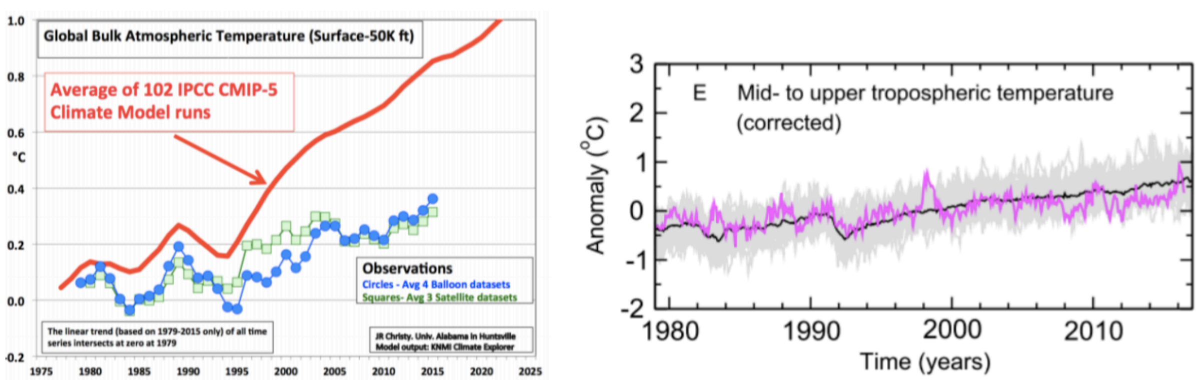

Figure Q2: Two comparisons of atmospheric temperatures measured from satellites with computer model simulations. The chart on the left shows the average prediction of 102 computer model simulations against averages of satellite and weather balloon datasets. The chart on the right shows the average computer model in black with a grey confidence interval against the average of satellite data in purple. Dataset versions and details vary between the two charts, but the difference between the two shows how graphical design can influence perception. The chart on the left comes from Congressional testimony and was not formally peer reviewed, while the chart on the right is excerpted from a peer-reviewed journal article.

[58] Spencer and Christy 1990

There are three research groups that produce satellite temperature records for the whole globe. On average, they show that climate models have warmed faster than observations in the lower atmosphere.[59] However, they do not agree if that difference is statistically significant, given the range in warmings projected by climate models.[60] Without strong agreement on statistical significance between different scientific interpretations of satellite data, it is hard to draw a strong conclusion that these measurements are an indictment of our understanding of climate change.

Even without statistical significance, different interpretations might explain faster warming in climate model projections. The list is similar to the set of factors that could influence the global warming slowdown including, models being, on average, too sensitive to enhanced CO2 warming is one possibility. Other candidates include the climate models misrepresenting, by accident of experimental design, the true solar intensity and volcanic activity of the early 21st century or natural variability (the slowdown in the early 21st century) that reduced warming in the real world, common errors in the satellite data products, or some combination of these things.

The search for measurements that run contrary to the standing view on climate change is ongoing, as a matter of scientific discipline and as we enter a time when the expected signals of climate change should be detectable above natural variability in many parts of the climate. Satellite data, in particular, have historically confronted climate science with questions about the true temperature trends in the atmosphere and the basic physical understanding predicting that increase. However, recent developments in the scientific literature and repeated studies have lead us to a better understanding of the flaws in early processing of satellite data and an increasing reconciliation with climate models and theory. Details and refinements will continue to be worked out, but do not appear to fundamentally challenge the picture of developed by climate change science.

[59] Christy testimony from 2015.
[60] Santer et al. 2016.

Question 5: Are climate model projections too hot?

Basic theory and fundamental understanding help us understand that global warming will continue in the 21st century. But climate model simulations help us identify how much warming we might expect in the future and how much other climate variables like sea level will change. The degree of climate sensitivity is central to the predictions of climate change. While the range of sensitivity found in climate models is similar to the values that come from other lines of evidence, 1.5-4.5 °C for a doubling of atmospheric CO2, some argue that these estimates are too high.

In recent years, a series of studies that compared the measured change in global average temperature with the increase in CO2 found lower values of climate sensitivity than the average climate model simulates; for equilibrium climate sensitivity these studies typically suggest values that are less than 2 °C.[61] This has led some to argue that projections of future climate change should be revised downward.[62] The conclusion that the real world is much less sensitive to CO2 emissions than climate models has been directly challenged by recent studies showing that comparing the data-based methods with climate models was fraught with inadequate treatment of statistics and examination of the sensitivity of their assumptions.

The data-based methods in question use historical temperature records as an input, calculating the sensitivity of climate by comparing the difference between CO2 warming effects early and late in the records and the change in global temperature. That comparison may be biased toward too low values, because global temperature records poorly represent changes in the Arctic and record changes in sea surface temperature instead of the faster warming air above the sea level. When those errors are compensated for, by appropriately sampling climate models to reflect the actual temperature record, there is no statistically significant difference in the estimates of climate sensitivity that come from data and models.[63]

Additionally, there is some evidence that the methods used to estimate climate sensitivity from data do not properly account for other external factors that influence climate change. The cooling effect from pollution in the Northern Hemisphere might have the same cooling effect, globally averaged, as a decline in solar intensity, but different outcomes in terms of global temperature. Studies that are able to distinguish these factors are rare, but when those factors are brought into account, the average climate sensitivity from data-based methods is well inside the IPCC range.[64]

It has proven difficult for scientists to narrow the wide range of values for climate sensitivity because of limits in the records of past changes and the relative influence of different climate

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[61] For two examples, see Otto et al. 2013; Lewis and Curry 2015.

[62] Lewis, Nicholas and Crok, Marcel. "A Sensitive Matter: How the IPCC buried evidence showing good news about global warming," The Global Warming Policy Foundation Report 13 (2014), http://www.thegwpf.org/content/uploads/2014/03/A-Sensitive-Matter-download.pdf.

[63] Richardson et al. 2016.

[64] Marvel et al. 2015.

agents. Different lines of evidence (e.g., basic physics, comparisons to past ice ages, and the temperature response to human influence) strongly refute sensitivities much higher or lower than the IPCC. However, viewing only one type of evidence in isolation can lead to logical errors when different lines of evidence refute very high and very low values, for instance.[65]

To convincingly refine our estimates of climate sensitivity will likely require both breakthroughs in climate physics (particularly, a better understanding of how cloud cover will act to accentuate or reduce temperature trends[66]) and enough time to pass that we can accumulate more high-quality measurements of the real-world response to today's climate drivers. Both outcomes likely lie a couple decades hence;[67] until then decisions will have to be made with some ambiguity in the potential climate response.

[65] Stevens et al. 2016.
[66] Sherwood et al. 2014.
[67] Urban et al. 2014.

Conclusion

Climate science began with the discovery of basic physical and chemical principles of the Earth system and the desire to understand the large changes in the past evidenced in the geological record. The climate changes of the past provide a foundation for understanding what might be in store in our future. Indeed, if the climate had been relatively stable in the past, despite similar changes in atmospheric CO_2 concentrations or other climate agents, there would be less call for considering the potential risks of human activities. However, the response to human activities that is already apparent reinforces the idea that human activities have had a significant climate effect.

There is little doubt that human activities have increased the amount of CO_2 and other greenhouse gases in the atmosphere. Likewise, there is little doubt that this has had a noticeable effect on the climate—and therefore the weather, sea level, and other physical and chemical conditions. Measurements of these changes paint a mostly consistent picture and strongly implicate human activities as the largest single driver of change over the last century. Looking forward, the potential for human emissions to add 1-3 °C to global temperatures in the next century is consistent with what we know from basic physics, past climate change, and climate models.

The findings that large changes to the climate will create risks for humans and nature are also not particularly under debate. Evaluations of the risks associated with climate change suggest that they will increase dramatically as the global average temperature approaches and then exceeds 2 °C of warming over the preindustrial average. While it is not exactly clear how society or ecological systems would respond to those effects, standing wisdom says it will be near that point that they will probably become widespread, easily distinguishable from historical variability, and largely irreversible.

Within public policy debates, the active questions are over whether or not we have sufficient skill to measure and interpret changes now and project changes in the future. These are related to how large the risks of climate change really might be later in this century. In particular, there are fair questions about the value of climate sensitivity and how much warming we should expect over the coming century given any emissions pathway.

But even at the lowest reasonable values for climate sensitivity, the relationship between total CO_2 emissions and temperature explains why the scope of future climate change, and the associated risks, are potentially so large and the sense of urgency from climate advocates so strong. Central values of climate response say that we will achieve "dangerous" warming within a few decades. But even if the sensitivity to emissions is on the lower end, total temperature increases will be sufficient to introduce significant risks by the second half of the century under almost any emissions scenario.

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