GEORGE C. Marshall INSTITUTE

Climate Issues & Questions

updated and revised edition

The Marshall Institute – Science for Better Public Policy

The George C. Marshall Institute
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Climate Issues & Questions

The debate over the state of climate science and what it tells us about past and future climate has been going on for more than fifteen years. It is not close to resolution, in spite of assertions to the contrary. What is often referred to as a “consensus” is anything but. Many of those making this claim hold a particular point of view that is based on their “expert judgment,” not established scientific fact. For others, especially those engaged in advocacy, the claim of consensus is used to advance their agenda.

Although humanity has been interested in climate since prehistoric times, climate science is, in fact, a relatively new field. It is only since the 1970s, when models were developed to connect atmospheric and oceanic climate processes, that scientists have had the tools to study climate as a system.

Concerns about climate change have resulted in some scientists entering the policy debate because of alarm about either the potential impacts of climate change or the economic impact of ill-conceived policies. Others, unfortunately, have entered the debate to advance political or economic agendas, gain funding for research, or enhance their personal reputations. To the extent that the debate is carried out in the public policy arena or media, the rigors of the scientific process are short-circuited.

This state of affairs creates misunderstandings and confusion over what we know about the climate system, past climate changes and their causes, human impacts on the climate system and how human activities may affect future climate. Policy needs are better served by clarity and accuracy.

The purpose of this document is to address a set of fundamental questions about climate change by summarizing the best available scientific information. The information provided is not intended to rebut claims about human impacts on climate or the potential for adverse impacts later this century. It is intended to separate fact from speculation and to demonstrate that while concerns are legitimate, there is not a robust scientific basis for drawing definitive and objective conclusions about the extent of human influence on future climate. The presentation moves from what is well established, to what is not certain, to what is unknown, and may be unknowable.

This is the second edition of *Climate Issues and Questions*. Here we update the 2004 edition with new information where available, as well as considering new questions, including:

- Is the Arctic is warming faster than the rest of the Earth? It is, but not as fast as recently claimed, and the rate of warming is neither unusual nor attributable solely to human activities.
- Are satellite and surface temperature trends different? They still are, even though the differences are smaller than they used to be.
- Is evidence of increased ocean heat storage a “smoking gun” indicating climate change? No, the publication reporting these results is based on an unverified

model and does not make use of satellite measurements for the property (the Earth's energy balance) it is simulating.

- Will climate change cause an increase in the number or intensity of hurricanes? The evidence supporting these claims is insufficient.
- Will there be an increase in other extreme weather events? If the Earth warms there will be an increase in what is now considered hot weather and a decrease in cold weather, but there is insufficient evidence to claim that other extremes (e.g. tornadoes) will increase.

QUESTIONS

1. How is the atmospheric concentration of carbon dioxide (CO_2) determined and how accurate are the measurements?

Atmospheric concentrations of CO_2 have been measured directly since 1958. The CO_2 concentration in air bubbles trapped in ice sheets is used to determine atmospheric concentration for earlier times. The measurements are consistent and accurate.

Direct, continuous measurement of atmospheric CO_2 concentrations began in 1958 at Mauna Loa, Hawaii. Additional measurement points have been added since that time.[1] These measurements are extremely accurate and show a seasonal variation in CO_2 concentration, in part due the growth and decay of plant matter over the course of the year. They also show that atmospheric CO_2 concentrations are essentially constant around the world.

CO_2 is long-lived in the atmosphere, and emissions during any single year are a small fraction of the total amount of atmospheric CO_2. As a result, CO_2 emissions are well mixed in the atmosphere, and a ton of CO_2 emitted anywhere in the world has the same effect on atmospheric concentrations. This fact demonstrates the importance of focusing more attention on CO_2 emissions in developing countries where reducing their growth can be highly cost-effective.

The record of atmospheric CO_2 concentrations for periods before 1958 has been reconstructed using ice core data. The ice sheets that cover Antarctica, Greenland, the islands north of Canada and Russia, and the tops of some mountainous areas represent the accumulation of as much as several hundred thousand years of snow fall. In very cold, dry areas, such as the interior of Greenland and Antarctica, the record is particularly good because there is little year-to-year evaporation or melt, and snow compresses into annual layers of ice. These annual layers of ice contain small bubbles of air that were trapped when the snow fell. By carefully analyzing the air in these bubbles, it is possible to determine atmospheric composition over time. The longest time series of atmospheric CO_2 concentration, from the Vostok Station in Antarctica, is over 700,000 years long.[2] Ice core data on CO_2 concentration from Greenland and Antarctica are in good agreement, indicating that the measurements are accurate reflections of past conditions.

For still longer times in the past, atmospheric concentration of CO_2 is estimated by studying the balance among geochemical processes, including organic carbon burial in sediments, silicate rock weathering, and the effects of volcanic activity.[3] These studies provide estimates for atmospheric concentration of CO_2 for as far back as 25 million years. Data from geochemical studies are less certain than data from ice cores or direct measurement.

2. How much of today's atmosphere is CO_2?

The atmosphere is comprised of many gases. CO_2, a greenhouse gas, represents 0.038% of today's atmosphere, while the concentration of water vapor, the most important of the greenhouse gases, varies from near zero in cold, dry polar air to more than 6% in humid, tropical air.

Over 99.9 percent of the dry atmosphere is nitrogen, oxygen, and argon, which are not greenhouse gases. The amount of water vapor in the atmosphere depends on temperature and relative humidity, ranging from near zero in cold, dry polar air, to more than 6 percent, in high humidity, tropical air. The other greenhouse gases, carbon dioxide, etc., account for less than a tenth of a percent of the atmosphere.

3. What has been the history of atmospheric CO_2 concentrations?

Atmospheric concentration of CO_2 has varied greatly over time, from a high of more than 380 parts-per-million (ppm) 25 million years ago, to a low of about 180 ppm during several periods of glaciation over the past 400,000 years. The atmospheric concentration of CO_2 was relatively constant at about 280 ppm for 1,000 years before 1750. Since 1750, CO_2 concentration has risen, reaching about 380 ppm in 2004.

Geochemical studies indicate that atmospheric concentrations of CO_2 may have been 500 parts-per-million (ppm) or higher 25 million years ago, well above today's level of 380 ppm.[4] Since that time they have varied greatly, dropping to as low as 180 ppm during several periods of glaciation over the past 400,000 years. These drops were followed by rises to 300 ppm or more during inter-glacial periods. Careful analyses of proxy temperature and proxy CO_2 concentration data indicates that the rise in CO_2 concentration followed the rise in temperature, and was probably the result of increased plant growth during the warmer periods.

Ice core data show that atmospheric CO_2 concentration was constant at about 280 ppm from 1000 to about 1750. After that it began rising, very slowly at first, then somewhat more rapidly, reaching about 380 ppm in 2004.[5] Recently atmospheric CO_2 concentration has been rising at about 1.8 ppm per year or about 0.5 percent per year. This rate of increase would lead to doubling of atmospheric CO_2 concentration in about 140 years. Scenarios that reach a doubling of atmospheric CO_2 concentration in the latter half of this century are unrealistic. (This topic is discussed in more detail in Question 12.)

4. Do we know why CO_2 concentrations are rising?

The increase in CO_2 concentration <u>appears</u> to be the result of human activities, though only about half of the CO_2 emissions that result from human activity accumulate in the atmosphere. The rest accumulates in the oceans or is stored in the biosphere.

Large amounts of CO_2 (about 550 billion metric tons per year) are continually exchanged between the atmosphere, oceans, and biosphere (the plants and animals of the world). This exchange is roughly in balance. Human emissions from fossil fuel combustion, deforestation, and other land-use changes emit about 30 billion metric tons of CO_2 per year. About half of this CO_2 is accumulating in the atmosphere. The rest accumulates in the oceans or is stored in the biosphere as enhanced plant growth. While deforestation and land-use changes result in the emission about 6 billion tons of CO_2 per year, the biosphere takes up over 8 billion tonnes of CO_2 per year, a net absorption of over 2 billion tons of CO_2 per year.[6]

There is no doubt that humans have contributed to the recent increase in atmospheric CO_2 concentrations. Similar arguments can be made for the role of human activities in the increases observed in the atmospheric concentrations of other greenhouse gases, e.g., methane, nitrous oxide, and fluorinated compounds. However, as the next question examines, the relationship between these changes in the atmospheric concentrations and observed changes in climate is not simple. Many other factors affect climate and their roles must be considered in determining the effect of human emissions of greenhouse gases on climate

5. What do we know about the relation between increases in the atmospheric concentrations of CO_2 and other greenhouse gases and temperature?

During the 20th century atmospheric concentrations of CO_2 and other greenhouse gases rose steadily, but global average surface temperature rose, then fell, then rose again in a pattern that showed no relationship to greenhouse gas concentration. CO_2 and other greenhouse gas concentrations were relatively constant from 1000 to 1750, but the Earth experienced a warm period from 800 to 1200, followed by a cold period from 1400 to about 1850.

Human emissions of CO_2 and other greenhouse gases rose steadily through the 20th century. These emissions resulted in increases in atmospheric concentrations of greenhouse gases. However, global average temperature did not follow the same pattern. While there are problems in interpreting the surface temperature database,[7] there is much evidence showing that temperature rose over much of the globe between 1910 and 1940, fell between 1940 and 1975, and has been rising since 1975.[8] The fall in temperatures between 1940 and 1975 was sufficient to raise concerns in the scientific community about the start of a new ice age.[9]

The observed pattern of surface temperature change cannot be explained by greenhouse gas emissions alone. In fact, the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report concluded that the rise in temperature during the first half of the 20th century was due to solar variability.[10]

If greenhouse gases were the only factor affecting climate, temperature should have been stable between 1000 and 1750, followed by continual warming. Since there is insufficient direct temperature measurement data prior to 1861 to make an estimate of global temperature, climatologists use proxy measures, such as tree ring thickness, to estimate temperature.

Proxy measurements provide evidence that from about 800 to 1200, during a period called the Medieval Climate Optimum, substantial regions of the Earth were warmer than they are today. By 1400, a cold period, known as the Little Ice Age, had begun. This cold period lasted well into the 19th century. The warming of the late 19th and early 20th century seems to be a natural recovery from the Little Ice Age.[11] With their detailed analyses of well over 200 proxy climate studies from all parts of the world, Soon and his co-workers have shown that these two periods were global in nature and represented significant shifts in the Earth's climate.[12] These changes in climate are not explained by changes in the atmospheric concentrations of CO_2 and other greenhouse gases, since these concentrations were relatively constant during most of that period.

6. **If temperature changes cannot be correlated with the increase in atmospheric concentrations of CO_2 and other greenhouse gases, what is causing them?**

   The climate system is a complex set of interactions between solar energy, clouds, particulates, water vapor and other greenhouse gases, and the absorption and reflection of solar radiation at the Earth's surface. The general nature of these interactions is understood by climate scientists, but their details are highly uncertain.

   Climate is the result of a complex set of interactions between natural, and more recently, human drivers. The most important natural driver is the intensity of solar radiation reaching the Earth, which is determined by changes in the Sun itself and by shifts in the Earth's orbit and tilt. Satellite measurements indicate that the intensity of solar radiation reaching the Earth changes over the 11-year sunspot cycle. Astronomers have also determined that the Earth's orbit and tilt change in cycles that last up to 100,000 years. These cycles appear to be the cause of ice ages and interglacial periods, but are not of concern when discussing climate on short time-scales.

   Solar energy reaches the Earth as short-wave energy. Not all of it penetrates the atmosphere to the surface. Atmospheric gases are essentially transparent to short-wave energy, but about one-third of solar energy is reflected off clouds and particulate material in the atmosphere. However, not all clouds and particulates reflect solar radiation; some absorb it. The two-thirds of solar energy that reaches the surface can either be absorbed by the surface or reflected. Bright surfaces, such as ice or snow, reflect a large portion of the energy that hits them; dark surfaces, such as bare soil, absorb most of the energy that hits them.

The second most important natural driver of climate is the Greenhouse Effect. The Earth has to have a mechanism for getting rid of the energy that it absorbs, or else it would heat up and eventually melt. It gets rid of energy by emitting long-wave, or thermal, radiation. The oxygen, nitrogen and argon that make up 99.9% of the dry atmosphere are transparent to this long-wave radiation. However, water vapor and some trace gases in atmosphere, such as carbon dioxide and methane, absorb long-wave radiation, heating the atmosphere. This process is known as the Greenhouse Effect,[13] and the water vapor and the trace gases that can absorb long-wave radiation are known as greenhouse gases.

A third natural driver is the presence of particulate matter in the atmosphere. Some particulates, such as sulfate aerosols, reflect incoming solar radiation and have a cooling effect. Others, such as the black carbon resulting from fossil fuel combustion, absorb incoming solar radiation and have a warming effect. These effects are referred to as the direct effects of particulates. However, particulates also can have indirect effects. Fine particulates act as nuclei for cloud formation. Low-level clouds reflect solar radiation and thus have a cooling effect. Some high level clouds can absorb solar radiation and have a warming effect. Understanding the role of particulates in the climate system is a major research priority because of the high level of uncertainty about their effects, e.g., it is not known whether their net effect is warming or cooling.

Volcanic eruptions can change the level of natural climate drivers by adding both greenhouse gases and particulates to the atmosphere. Eruptions that throw large amounts of sulfate particulate into the lower stratosphere have the largest effect. One such eruption, Mt. Pinatubo in 1992, lowered global average temperature by about 0.5°C (about 0.9°F) in the following year, and affected global climate for up to three years.[14]

Human activities can also affect the climate system by adding both greenhouse gases and particulates to the atmosphere and by changing the Earth's surface, which in turn changes the amount of incoming solar radiation that the surface reflects. Combustion of both fossil and biomass fuels is the biggest human source of greenhouse gas emissions, but other activities also contribute. Cement manufacture emits CO_2. Agriculture and landfills are sources of methane emissions. Fertilizer use and nylon manufacture are sources of nitrous oxide emissions, and air conditioners and refrigerators can emit fluorine-containing greenhouse gases. Land-use changes also can affect the climate system. Clearing land for agricultural use increases the amount of dark surface that absorbs rather than reflects incoming solar energy; it also removes trees and plants that absorb and store CO_2.

The drivers that affect the climate system are not independent. They are connected by a complex set of feedbacks, the most important of which is the water vapor feedback. If the Earth warms, more water will evaporate and the atmospheric concentration of water vapor will increase. Water vapor is a greenhouse gas, so increasing its atmospheric concentration will further increase warming. However, higher atmospheric concentrations of water vapor will also result in more cloud formation, which can lead either to cooling or warming. Another feedback is the sea ice effect. If the Earth warms, some sea ice will melt. Sea ice reflects most of the incoming solar radiation that falls on it, but the ocean that is exposed when sea ice melts absorbs most of the radiation that falls on it. Shrinking sea ice creates further warming.

If there were no other changes in the climate system, climate sensitivity, which is the change in equilibrium global average temperature in response to a doubling of atmosphe-ric concentration of CO_2,[15] is estimated to be 1.2°C. (2.2°F)[16] However, when feedbacks are taken into account, a high level of uncertainty is created. Climate sensitivity is usually quoted as lying between 1.5 and 4.5°C (2.7-8.1°F).[17]

A further complication to our understanding of the climate system is the cyclic behavior that it exhibits. The quickest of these cyclical behaviors, ENSO (El Niño—Southern Oscillation), which occurs on a 3-7 year period, is well known, but not well understood or predictable.

On a longer time scale, the Interdecadal Pacific Oscillation (IPO) warms the sea surface in the Pacific during its positive periods and cools it during its negative period. The IPO was negative from 1947 to 1976, roughly corresponding to the 20th century period of cooling in global average surface temperature, and positive from 1978 to at least 1998, corresponding to a period of rising global average surface temperature.[18] The IPO appears to be superimposed on the shorter ENSO cycle, which causes changes in sea surface temperatures in the tropical Pacific, but the relationship between the two is not understood. To further complicate relationships, the Pacific Decadal Oscillation affects sea surface temperatures in the northern Pacific, but it is unclear whether this is an independent cycle or merely the Northern Pacific part of the IPO.

The Atlantic also exhibits cyclic behavior. The North Atlantic Oscillation (NAO) has a positive phase, which is:

> … associated with cold winters over the north-west Atlantic and warm winters over Europe, Siberia and eastern Asia as well as wet conditions from Iceland to Scandinavia and dry winters over southern Europe.[19]

The NAO turned positive in about 1970 and has been strongly positive since 1985. As will be discussed below, climate models do not project or back-cast these cyclical behaviors.

7. Is the Arctic warming faster than the rest of the Earth?

Like the rest of the Earth, the Arctic is warming. The best available evidence suggests that over the 20th century, it warmed at a somewhat faster rate than the global average, but less than would be projected by climate models and less than claimed by the 2004 *Arctic Climate Impact Assessment* (ACIA). Understanding temperature trends in the Arctic is complicated by limited data and the fact that conditions in the Arctic can change much more rapidly than over the rest of the Earth,

Independent of temperature measurements, there is much evidence that, along with the rest of the Earth, that the Arctic has warmed over the past few decades. Satellite measurements since 1978 indicate that the area covered by sea ice at the summer minimum has declined by 9.2% per decade,[20] and there are many reports of warming and increased melting of permafrost.[21] The questions are whether this warming is unusual, and if so, can it be attributed to human emissions of greenhouse gases?

The most widely quoted source for statements indicating unusual warming of the Arctic is the *Arctic Climate Impact Assessment* (ACIA)[22] published in 2004 by the Arctic Council, an intergovernmental group of the eight countries, including the U.S., with land above the Arctic Circle. A key figure in the ACIA report shows the five-year running average for land-based weather station above 60°N. This choice of weather stations includes a large area which is south of the Arctic Circle (66.5°N), the usual boundary of the Arctic, but more importantly includes data from Siberian weather stations of questionable accuracy. Nevertheless, the pattern of average temperature rise and fall in the Arctic mimics that of the global average with a slight offset in time. Average temperature rises from about 1915 to about 1935, then falls until about 1965, then rises through the rest of the century. The changes in temperature are more abrupt, during both the rising and falling periods, than for the Earth as a whole. As discussed above in Question 6, neither the rise in temperature for the early part of the century nor the fall in temperature during the middle of the century can be explained by human activities.

ACIA makes much of the fact that for 1966-2002, the average temperature at land-based weather stations above 60°N rose 0.38°C per decade, four times the global average. 1966 represents the temperature low after three decades of cooling, so any trend based on that starting year would be exaggerated. Had one looked at a five-year running average from 1934 to 2002, for land-based weather stations above 70°N, the true Arctic, the trend line would have shown a small decline in temperature.[23]

Paleoclimate data show that the Arctic has experienced wide swings in temperature over short periods of time independent of any possible human influence. As discussed below in Question 21, about 11,500 years ago the average temperature in Central Greenland rose 7°C in a few decades. Such rapid changes have also occurred more recently. During the decade of the 1920s, average annual temperature for coastal stations in Greenland rose 2-4°C, with peak temperatures occurring in the 1930s.[24] Paleoclimatic data from the Taimyr Peninsula above 70°N in Siberia indicates that both the 3rd and the 10th to 12th centuries were warmer than the 20th, and the warmest period of the 20th century was around 1940.[25]

Taken together, these results show that the recent warming in the Arctic is not unusual, nor can it be attributed solely to human activities.

8. Do satellites and surface temperature measurements give different results?

Differences between temperature trends in the lower atmosphere measured by satellites and temperature trends from surface weather stations have been narrowed, but the differences still exist. There are several estimates of both satellite and surface temperature trends. Most temperature trends measured by satellites still show less warming than most temperature trends measured at the surface, but the estimates overlap. In addition, the range of model projections of temperature trends overlaps both sets of measurements. Both sets of measurements are subject to error, as are the model results, and further data and analyses are needed to resolve the remaining differences.

Two approaches have been used to determine recent trends in the Earth's temperature. The first has been to develop weighted averages of data from the thousands of land-based weather stations and ocean temperature measurements around the world. This is not as simple as it sounds. While weather station coverage is dense and well-maintained in the world's richer countries, it is sparse and poorly-maintained in many poorer countries, affecting the accuracy of information from these regions. Also, as with any measurement, changes in the technique used to make the measurement and systematic errors affect the results. Balling (2003),[26] estimates that these problems could lead to total errors of 0.2-0.3°C. While errors of this size have no impact on day-to-day weather reports, they are a third to a half of the reported global average surface temperature trend for the 20th century and critical in judging the importance of these changes.

The second approach has been to use satellite measurements of microwave radiation from the lower atmosphere, from the surface to about five miles above the surface, as a proxy for temperature. Satellites measurements have an advantage over surface measurements in that they provide equal coverage of a very high percentage of the Earth's surface. They have the disadvantage of being indirect measurements that have to be calibrated. In addition, satellite orbits decay with time, complicating the calibration problem, and since the satellites used for these measurements have limited lifetimes, the series of satellites used to generate temperature history for several decades have to be calibrated against each other.

As has been well publicized, for many years there was a significant disagreement between surface and satellite measurements of temperature trends. Satellites measurements first showed cooling, then much less warming than surface measurements. In 2000, the National Research Council of the National Academy of Sciences concluded that the difference between the two sets of measurements was real and could not be explained.[27] A more recent paper explores the reasons for uncertainty in temperature measurements and concludes that reducing uncertainty requires a minimum of three independent data sets.[28]

Additional data and data analysis since 2000 has narrowed the difference between satellite and surface estimates of temperature change. Both sets of data have been subjected to multiple analyses and there are a range of estimates for each trend, which overlap. However, most analyses still show less warming in the lower atmosphere than at the surface. There is also a range of model estimates of temperature trends, which overlaps both data sets. This situation has lead the Climate Change Science Program to conclude in a draft report now undergoing review: "Given the range of observed results and the range of model results, there is no inconsistency at the global scale."[29]

While there is "no inconsistency" between model results and observations, there is still no agreement. Most models predict more warming in the lower atmosphere than at the surface, and most observations indicate less warming. Further data and analyses are needed to resolve these remaining difference and to improve our understanding of the dynamics of the weather system.

9. Is evidence of increased ocean heat storage a "smoking gun" indicating climate change?

Media reports of a paper by James Hansen and 14 co-authors that appeared in the June 3, 2005 issue of *Science*[30] claimed that it represented the "smoking gun" evidence for climate change. The smoking gun claim is surprising, since there can be no doubt that climate has been changing. While there is a debate over the amount of change, and an even greater debate over the causes of that change, there is no evidence to argue that the world as a whole is not warmer than it was a century ago. In light of this warming, the authors' conclusion that the Earth is absorbing more energy than it is emitting is obvious. As discussed below, the authors used indirect evidence to test their model, rather than the direct satellite measurements of the Earth's energy balance. Finally, their finding that the Earth is committed to additional warming is also not surprising, since this concept has been well understood since at least 1990.

The Hansen, *et al* paper focuses on the Earth's energy balance. To provide some background to this topic: on average, the Earth receives about 342 watts per square meter of incoming solar radiation. About a third of this radiation (107 watts per square meter) is reflected by clouds and aerosols in the atmosphere, the balance (235 watts per square meter) penetrates to the surface, where some of it is reflected and the rest absorbed.[31] On average, all of the solar energy that reaches the surface must be emitted back into space. If not, the Earth would heat up and eventually melt. However, on a short term basis, the Earth can absorb more or less energy than it emits. If it absorbs more, the Earth will warm; if it absorbs less, the Earth will cool. Since the Earth has been warming for most of the past century, it is reasonable to expect that the Earth is absorbing more solar energy than it is emitting.

The specific claims made in the Hansen *et al* paper are that

- the the model the authors used calculated that the Earth was currently absorbing 0.85 ± 0.15 watts per square meter more energy than it was emitting,
- the this calculation was "confirmed" by measurements of the increasing heat content of the oceans, and
- the even if the current energy imbalance were eliminated, the Earth would warm by an additional 0.6°C.

The approach that Hansen *et al* have used to confirm their model calculation of the Earth's energy balance ignores a much more pertinent set of data: satellite measurements of the Earth's radiation budget. These have been analyzed in a number of studies[32] and would seem to be a much more direct means of evaluating the accuracy of the climate model projections. The comparison the authors make does not preclude the real possibility that compensating errors in their unvalidated model could be the reason for the apparent agreement.

The fact that the oceans are warming, and thus their heat content increasing, is not surprising. The atmosphere has been warming, on average, for a century, and since the oceans are in equilibrium with the atmosphere, they, too, should be warming. Nor is it surprising that the Earth is committed to additional warming. The climate system has inertia and continues either warming or cooling for a period of time even after the driver has been removed. This topic was discussed in the IPCC's First Assessment Report,[33] published in 1990, and well understood before that.

10. What influence does the Sun have on global climate?

The Sun provides the energy that drives the climate system. Long-term variations in the intensity of solar energy reaching the Earth are believed to cause climate change on geological time-scales. New studies indicate that changes in the Sun's magnetic field may be responsible for shorter-term changes in climate, including much of the climate of the 20th century.

The Sun provides the energy that drives the climate system, but as described above, solar energy interacts with the other components of the climate system in complex ways. Clouds, particulates, and the Earth's surface can either absorb or reflect solar energy. Absorption of solar energy has a warming effect, while reflection of solar energy has a cooling effect. The climate system is further complicated by the effects of greenhouse gases which absorb solar energy that was earlier absorbed and then re-radiated by the Earth's surface. While the climate system is complex, it is certain that any change in the amount of solar energy reaching the Earth will have an effect on climate.

The brightness of the Sun, a measure of the amount of solar energy being emitted, varies with the Sun's magnetism over the 11-year sunspot cycle. In 2001, the IPCC cited satellite measurements that indicate that changes in the intensity of solar energy are too small, about ± 0.08 percent,[34] to account for climate change. Recent research, however, challenges that conclusion. In 2003, two researchers from Columbia University chal-lenged the then consensus view that there had been no upward trend in solar irradiance in the past few decades. Their data, using a different set of satellite measurements than had been used, showed an upward trend in the amount of energy being emitted by the Sun.[35] In 2005, two Duke University researchers,[36] using the Columbia University data, concluded that changes in solar intensity could have accounted for a minimum of 10-30% of the surface warming observed between 1980 and 2002. These finding are important not only in explaining recent warming, but in estimating the potential of greenhouse gases to create future warming. If recent increases in greenhouse gas concentrations have led to a smaller amount of the observed warming than calculated by climate models, future increases in greenhouse gas concentrations will also lead to less warming than calculated by climate models.

Other researchers have studied potential feedbacks that would allow small changes in solar irradiance to be amplified into larger changes in climate. In 1997, two Danish researchers, Svensmark and Friis-Christiansen, showed that from 1983 to 1994, there was a high degree of correlation between total cloud cover and the intensity of cosmic rays striking the Earth, which in turn is correlated with the intensity of the Sun's magnetic field.[37] The changes in cloud cover, 3-4 percent, were large enough to explain much of climate change. While this correlation has to be tested with further observation and theoretical analysis, it suggests that the Sun plays an important role not only in climate change on geological time-scales, but also on climate variations on a much shorter time-scale.

Scientific interest in potential feedbacks that could amplify the small observed changes in the intensity of solar energy has been growing. In its First Assessment Report, the IPCC dismissed the possibility that changes in solar intensity could have had a significant impact on climate on a decade- or century-long period.[38] However, in its Third Assessment Report, the IPCC devoted a whole section to mechanisms for the amplification of solar forcing, i.e., feedbacks.[39] The IPCC concludes that these mechanisms are not well established, but the attention IPCC has paid to the solar feedbacks is likely to stimulate further scientific research on this question.

11. What is known with a high degree of certainty about the climate system and human influence on it?

We know, with a high degree of certainty, that:

- the the surface of the Earth warmed over the past century;
- the increases in the atmospheric concentrations of CO_2 and other greenhouse gases will have a warming effect;
- the human emissions of CO_2 and other greenhouse gases are responsible for much of the increase in atmospheric concentrations of these gases; and
- the economic growth trends, particularly in the developing nations, will increase human emissions of CO_2, at least over the next few decades because economic growth requires energy use and the dominant source of energy will remain fossil fuels.

These facts are the basis for concern about potential human impacts on the climate system.

12. What major climate processes are uncertain and how important are these processes to understanding future climate?

Key uncertainties in our understanding of the climate system include the details of ocean circulation, the hydrological (water) cycle, and the properties of aerosols. The cumulative effect of these and other uncertainties in our understanding of the climate system is an inability to accurately model the climate system. Since models are the only way to project future climate, our lack of understanding of key climate processes means we lack the ability to accurately project future climate.

Many important climate processes are highly uncertain, including roles of:

- the ocean currents,
- the clouds and water vapor feedbacks, and
- the aerosols

in the climate system. As a result of these deficiencies in our understanding, we lack the ability to accurately model the climate system or project its future behavior.

We know that over 90% of the energy in the climate system is in the ocean currents which play an important role in distributing this energy around the globe. However, there is a high level of uncertainty about the mechanisms by which this occurs. Ocean circulation is often referred to as "thermohaline circulation," which some scientists argue is driven by differences in the temperature and salinity of different regions of the ocean. If this is the case, then changes in global surface temperature could disrupt ocean circulation patterns, bringing climate changes to various parts of the globe.[40] However, other scientists argue that ocean circulation is driven by tidal forces.[41] This argument is supported by satellite measurements that show the Moon slowly moving away from the Earth, creating enough energy to drive the ocean currents.[42] If this argument is correct, warming will have no effect on the ocean currents.

Whichever mechanism drives ocean currents, we lack detailed understanding of their operation. The Strategic Plan of the U.S. Climate Change Science Program (CCSP), which was reviewed and endorsed by the National Research Council, documents this by stating that:

> All major U.S. climate models fail to adequately simulate several climate processes and their associated feedbacks in response to natural or anthropogenic perturbations. The oceans store and transport energy, carbon, nutrients, salt, and freshwater on multiple time scales and help to regulate and determine climate changes on a continuum of time scales. Yet some critical ocean phenomena, including ocean mixing and large-scale circulation features that determine the rate of storage and transport, remain as key challenges to understand, assess, and model.[43]

The CCSP Strategic Plan does not include a specific focus on ocean circulation, but treats the area as one of the uncertainties that need to be resolved.

We know that the hydrological (water) cycle, including cloud formation and dynamics, plays an important role in the climate system, but again we lack detailed understanding of its operation. The CCSP Strategic Plan states:

> Other critical processes that are inadequately represented in climate models include atmospheric convection, the hydrological cycle, and cloud radiative forcing processes.[44]

The Strategic Plan devotes a full chapter to the water cycle and lists a number of research questions aimed at elucidating the role of clouds in the climate system.[45]

Aerosols are a third major area of uncertainty in our understanding of the climate system. Again quoting the CCSP Strategic Plan:

> Research has demonstrated that atmospheric particles (aerosols) can cause a net cooling or warming tendency within the climate system, depending on their physical and chemical characteristics. Sulfate-based aerosols, for example, tend to cool, whereas black carbon (soot) tends to warm the system. In addition to these direct effects, aerosols can also have indirect effects on radiative forcing (e.g., changes in cloud properties). When climate models include the effects of sulfate aerosols, the simulation of global mean temperature is improved. One of the largest uncertainties about the net impacts of aerosols on climate is the diverse warming and cooling influences of very complex mixtures of aerosol types and their spatial distribution. Further, the poorly understood impact of aerosols on the formation of both water droplets

> and ice crystals in clouds also results in large uncertainties in the ability to project climate changes. More detail is needed globally to describe the scattering and absorbing optical properties of aerosols from regional sources and how these aerosols impact on other regions of the globe.[46]

The Strategic Plan calls for addressing a number of research questions to reduce these uncertainties.

The cumulative effect of these and other uncertainties in our understanding of the climate system is an inability to accurately model the climate system. As the National Academies of Science observed:

> … climate models are imperfect. Their simulation skill is limited by uncertainties in their formulation, the limited size of their calculations, and the difficulty in interpreting their answers that exhibit almost as much complexity as in nature.[47]

Since models are the only way to project future climate, our lack of understanding of key climate processes means we lack the ability to accurately project future climate.

13. **What tools are available to separate the effects of the different drivers that contribute to climate change?**

Climate scientists use general circulation models (GCMs) to try to separate the effects of the different drivers that affect the climate system. These models use mathematical equations to describe the different processes known to occur in the climate system. GCMs are extremely complex because they must try to model all of the processes occurring in both the atmosphere and the oceans, neither of which are homogeneous, by dividing them into small grid boxes, then modeling change in small time increments. The resulting computational demand exceeds the capacity of even the best super-computers.

Scientists have two general sets of tools for separating the effects of variables in a complex system: statistical analysis and modeling. The climate system is too complex and climate data too limited for statistical approaches to work. This leaves modeling.

Climate models are an attempt to develop mathematical equations to describe the individual processes that are known to occur in the climate system, and then solve all of these equations simultaneously to obtain a description of the overall behavior of the system. For example, we know that the climate system must obey the fundamental laws of physics, e.g., that mass and energy must be conserved. We also know that many processes such as the reflection of radiation from the Earth's surface and the warming effect of greenhouse gases will occur. Climate models attempt to express all of these phenomena as a set of mathematical equations.

While climate models are relatively simple in concept, their use is extraordinarily complex for several reasons:

a. The climate system consists of two inter-connected sub-systems, the atmosphere and the oceans. While the importance of the atmosphere in the climate system is obvious, it is the oceans that contain the overwhelming share of the energy in the system. Change in the atmosphere can be rapid, but change in the oceans is slow. Any calculation of future climate must take this slow change in the oceans into account.

   The physical processes taking place in the atmosphere and the oceans are different. The most advanced climate models, called coupled atmosphere-ocean general circulation models (abbreviated AOGCMs, or just GCMs), attempt to model all the major climate processes in both the atmosphere and the oceans.

b. Neither the atmosphere nor the oceans are homogeneous. To deal with the complexity of the real world, many climate models use a Cartesian grid approach, dividing both the atmosphere and oceans into a set of boxes or cells.[48] The most advanced climate models use a three-dimensional (3-D) approach in which the atmosphere is divided into cells that are about 200 miles square and vary in height from a few thousand feet close to the surface to several miles in the stratosphere. The oceans are also divided into cells, though the size of ocean cells need not be the same as the size of atmospheric cells.

   Conditions within a single cell are assumed to be uniform, but we know from practical experience that both the weather and climate can be very different over a distance of 200 miles, particularly in mountainous or coastal regions. Computer simulations have shown that for areas with highly diverse climate, such as Britain, it is necessary to reduce cell size by a factor of about 7, to about 30 miles on a side, to accurately simulate some aspects of climate.[49] Reducing the length and width of cells by a factor of 7 increases the computing requirement by a factor of almost 50, assuming that no reduction is made in the height of the cells. This is beyond the current capacity of even the best supercomputers.

c. Running a climate model also requires a set of initial conditions, i.e., the weather conditions around the globe at a specific time. Climate is a chaotic system, which means that small changes in initial conditions can result in large changes in output conditions. One of the ways of handling this problem is to run the model using an ensemble of varying initial conditions. Output results which are relatively independent of the initial conditions are probably more robust and believable than output results which are dependent on initial conditions. While there is agreement among climate modelers that using the ensemble approach is highly desirable, the practicalities of computer capacity and availability mean that it is rarely used.

d. The climate model is run by calculating the changes indicated by the model's equations over a short increment of time—20 minutes in the most advanced GCMs—for one cell, then using the output of that cell as inputs for its neighboring cells. The process is repeated until the change in each cell around the globe has been calculated. In a perfect model, results for the initial cell at the end of the calculation would be the same as those determined at the start of the calculation. However, climate models are far from perfect, so the whole process must be repeated and smoothed using standard numerical calculation techniques. Eventually, a consistent set of results is determined for the first time step. The whole process is repeated for the next time step until the model has been run for the desired amount of time.

14. How accurate are climate models?

Current climate models have many shortcomings. They cannot accurately model the atmosphere's vertical temperature profile, their estimates of natural climate variability are highly uncertain, and there are large differences in the response of different models to the same forcing. No climate model has been scientifically validated.

A model's output is only as good as its equations and inputs. There is general agreement among climate scientists on the shortcomings of current climate models and their outputs. Many lists of these shortcomings exist; the following is taken from the UN's Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report. The term "forcing" used several times in this list means a factor that can drive climate change.

- Discrepancies between the vertical profile of temperature change in the troposphere seen in observations and models.
- Large uncertainties in estimates of internal climate variability (also referred to as natural climate variability) from models and observations.
- Considerable uncertainty in the reconstructions of solar and volcanic forcing which are based on limited observational data for all but the last two decades.
- Large uncertainties in anthropogenic forcings associated with the effects of aerosols.
- Large differences in the response of different models to the same forcing.[50]

Other lists typically add uncertainties about the roles of clouds and ocean currents in the climate system, the inability to model El Niño and other observed cyclic phenomena in the climate system, and the sensitivity of the climate system to changes in greenhouse gas concentrations to the IPCC's list.

The last point on the IPCC's list, large differences in the response of different models to the same forcing, is perhaps the most indicative of the limitations of current climate models. These differences occur because different climate models use very different mathematical representations of the same climate processes.

They do this because there still is no agreement among climate scientists about the physics of some key climate processes, such as cloud formation. The quality of climate models cannot improve until there is a better understanding of these key climate processes.

The *Summary for Policymakers* of the science portion of the IPCC's Third Assessment Report claims: "Some aspects of model simulations of ENSO, monsoons and the North Atlantic Oscillation, as well as selected periods of past climate, have improved."[51] However, the underlying report gives a much less positive view of the state of climate models:

> Considerable improvements have taken place in modeling ocean processes. … These improvements have contributed to better simulations of natural large-scale circulation patterns such as El Niño – Southern Oscillation (ENSO) and the oceanic response to atmospheric variability associated with the North Atlantic Oscillation (NAO). *However, significant deficiencies in ocean models remain* (emphasis added). Boundary currents in climate simulations are much weaker and wider than in nature, though the consequences of this fact for global climate sensitivity are not clear. Improved parameterization of important sub-grid processes, such as mesoscale eddies, have increased the realism of simulations, but important details are still under debate. Major uncertainties still exist with the representation of small-scale processes, such as overflows and flows through narrow channels, western boundary currents, convection, and mixing.[52]

Elsewhere the Third Assessment Report details the problems with climate model simulations of El Niño,[53] concluding as the summary statement did that while models have improved, there are still significant shortcomings in their simulations. Given the importance of the El Niño cycle in the world's climate, the ability of climate models to accurately simulate its behavior is a critical test of their reliability. And longer-term cyclic behavior, such as the NAO and the IPO (Interdecadal Pacific Oscillation), are likely to be even greater modeling challenges, since the understanding of their current behavior is even weaker than the understanding of El Niño.

Because of these shortcomings, most climate model outputs do not closely simulate conditions observed in the real world.[54] However, some climate models have been adjusted, or calibrated, to where they provide a reasonable simulation of some aspects of climate. Advocates use these simulations to claim that the models are valid representations of the climate system. They are not.

The difference between *calibration* and *validation* of models is critical. Climate models are routinely calibrated, or adjusted, to make their output look more like the real world. However, calibrating a model to produce a realistic simulation of current climate conditions does not ensure that it will provide realistic projections of future climate conditions. Realistic representations of current climate or projections of future climate require a model that has been validated and an accurate set of inputs. Validation requires that the model be developed using one set of data, then its output shown to match an independent set of data. At this time, no climate model has been validated.

The effects of model calibration can be seen in the results of research being carried out at MIT, where an on-going project is testing climate models against real world observations. Rather than trying to compare model projections of temperature and precipitation, which has to be done on a point-by-point basis around the globe, the MIT researchers have looked at some of the internal parameters which can be derived from model calculations. One such internal parameter is the rate of heat transfer to the deep ocean. This parameter is important because the faster heat is transferred to the deep ocean, the slower the surface will warm. The MIT researchers found that almost all commonly used climate models have higher rates of heat transfer to the deep ocean than seen in observations.[55] Since the models have been calibrated to match the surface temperature record of the past century, they must also contain other, compensating errors. These compensating errors will not necessarily have the same impact on projections of future climate, raising questions about the validity of those projections.

15. What is the basis for forecasts of large temperature increases and adverse climate impacts between 1990 and 2100?

Forecasts of large temperature increases and adverse climate impacts between 1990 and 2100 are based on the output of climate models using the IPCC SRES (*Special Report on Emissions Scenarios*) Scenarios as input. Concerns about the quality of climate model output have been discussed in Question 11. Large increases in temperature depend on three assumptions, none of which are likely:

a. **No overt action is taken to control greenhouse gas emissions. However, a variety of actions, some voluntary, some mandatory, are currently being taken to control greenhouse gas emissions.**

b. **Greenhouse gas emissions grow at the high end of the range of the IPCC emissions scenarios, i.e., CO_2 emissions in 2100 that were over five times current CO_2 emissions. These high emission scenarios have been broadly criticized as unrealistic.**[56]

c. **The climate system shows a high sensitivity to changes in greenhouse gas concentrations. Reports from a recent IPCC workshop indicate that while there is still a great deal of uncertainty, climate modelers now believe that the climate system is less responsive to greenhouse gas concentrations than would be required for a 5.8°C temperature rise.**[57]

Forecasts of large temperature increases and adverse climate impacts between 1990 and 2100 are based on the output of climate models. The output of a climate model is only as good as the model's ability to accurately represent the climate system and the quality of inputs used. As discussed above, climate models have many shortcomings and none has been scientifically validated. Equally important, the inputs needed to project climate for the next 100 years, as is typically attempted, are unknowable. Human emissions of greenhouse gases and aerosols will be determined by the rates of population and economic growth and technological change. Neither of these is predictable for more than a short period into the future.

Faced with an inability to predict future human emissions, climate scientists use the scenario approach. The IPCC defines a scenario as "an image of the future" and a set of scenarios as alternate images of the future.[58] Currently, the most widely used set of emissions scenarios for projecting future climate are the so-called SRES scenarios published by the IPCC in 2000 in its *Special Report on Emissions Scenarios*. This report presents emissions projections for 35 scenarios and recommended that climate modelers use a sub-set of six "marker" scenarios for climate projections. These marker scenarios vary dramatically in their projections of future emissions. Cumulative CO_2 emissions between 1990 and 2100, which will determine atmospheric concentration of CO_2, vary by a factor of more than two. Sulfur emissions in 2100, which will determine sulfate aerosol concentration in 2100, vary by a factor of three.[59] If all 40 scenarios are considered the range of variability is much greater, a factor of more than three in cumulative CO_2 emissions and a factor of nearly 8 in sulfate emissions in 2100.

In its Third Assessment Report, the IPCC used the full range of emissions scenarios and seven different climate models to project temperature in 2100. This exercise yielded the oft-quoted projection of 1.4-5.8°C (2.5-10.4°F) temperature rise between 1990 and 2100.[60] It also concluded:

> By 2100, the range in the surface temperature response across the group of climate models run with a given scenario is comparable to the range obtained from a single model run with the different SRES scenarios.[61]

In other words, the uncertainty due to differences in models was as large as the uncertainty due to the difference in emissions scenarios.

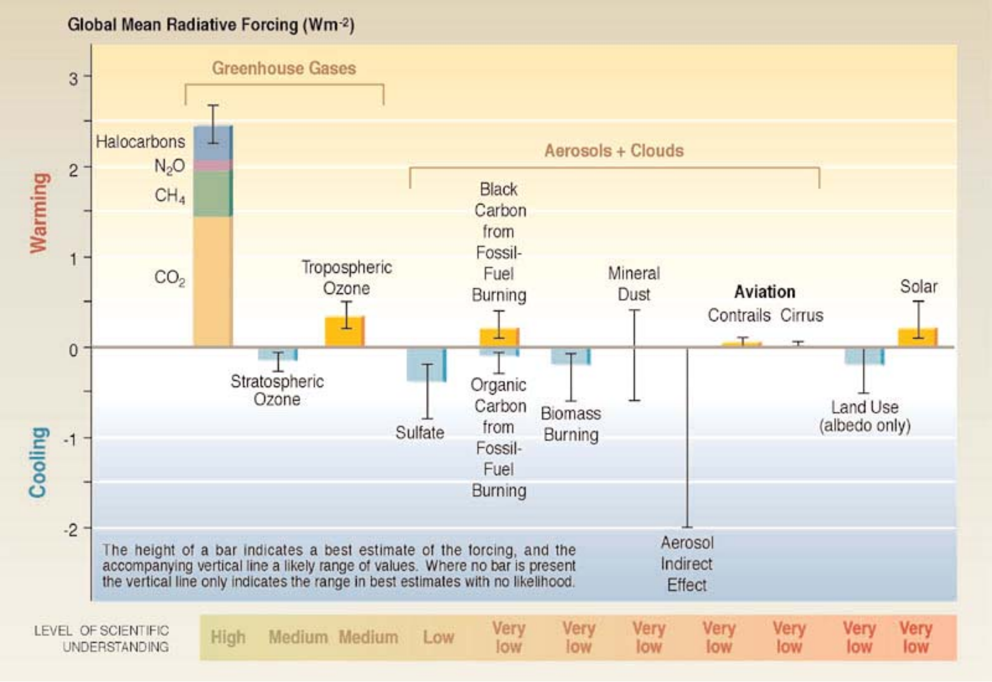
Most of the attention paid to these projections has focused on the upper end of the temperature range, since it would result in the most dramatic impacts. The upper end of the range depends on the three assumptions described at the beginning of this question, none of which are likely.

Climate models are not currently capable of accurately projecting future climate and furthermore it is clear that the upper end of their climate change projections is unrealistic.

16. How accurate are the parameters used in climate models?

The scientific level of understanding of the direct effects of greenhouse gases is high, but the scientific understanding of the other drivers of the climate system is low or very low.

A version of the following figure first appeared in the IPCC's Third Assessment Report. This version was published in the CCSP Strategic Plan.[62]



The height of a bar indicates a best estimate of the forcing, and the accompanying vertical line a likely range of values. Where no bar is present the vertical line only indicates the range in best estimates with no likelihood.

The figure shows that the direct effects of greenhouse gases are understood with a high level of accuracy, but the level of understanding of the other drivers of the climate system is either low or very low. In some cases, understanding of potentially large effects, i.e., the indirect effects of aerosols, is so poor that it is not even possible to make a best estimate of its value.

17. How well have models done in "back-casting" past climate?

Model results that match global average surface temperature for the past 140 years have been published, but they are suspect because of: (1) the quality of the surface temperature data used to determine global average surface temperature; and (2) the quality of the models themselves.

In its Third Assessment Report (TAR), the IPCC concluded: "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."[63] Much of the underpinning for this conclusion was found in a climate model study that attempted to "back-cast" the global average surface temperature of the past 140 years using only natural forcings (solar variability and volcanic eruptions), only anthropogenic, i.e., man-made, forcings (greenhouse gas and sulfate emissions), or a combination of both natural and man-made forcings. The key results of this study are shown in the following figure, first published in the TAR, but then reproduced in the CCSP Strategic Plan. [64]

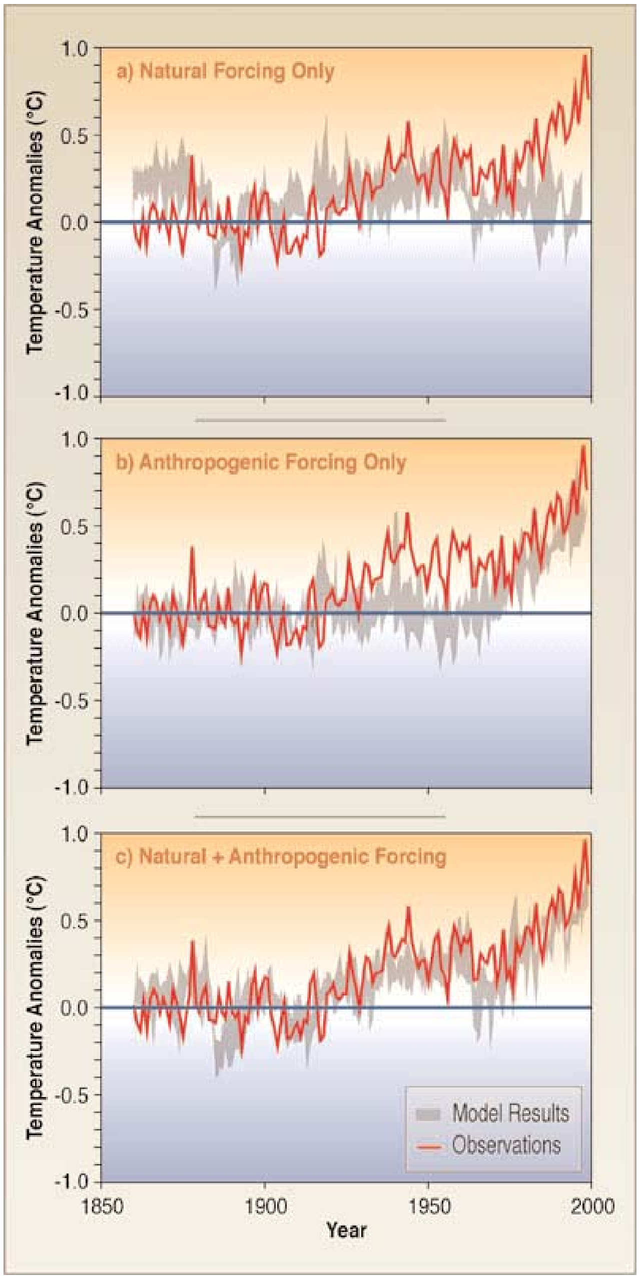


Figure 4-2: Climate model simulations of the Earth's temperature variations compared with observed changes for (a) natural forcing due to solar variations and volcanic activity; (b) anthropogenic forcing from greenhouse gases and an estimate of sulfate aerosols; and (c) both natural and anthropogenic forcing included. The model results show that the forcings included are sufficient to explain the observed changes, but do not exclude the possibility that other forcings may also have contributed.

The figure purports to show that natural forcings alone cannot explain the rise in global average surface temperature over the last 50 years, that anthropogenic forcings do a poor job of explaining the surface temperature pattern of the first half of the 20th century, and that, when both types of forcing are taken into account, the model provides a good fit to the observations.

While the IPCC conclusion attributing the temperature rise of the late 20th century to human activities is stated as fact, elsewhere in its report, the IPCC characterizes it as *likely*, which is defined as a 66-90% judgmental estimate of confidence that the statement is true. This represents the collective judgment of the authors, typically the 10–20 Lead Authors responsible for the Chapter in which the conclusions appears, using the observational evidence, modeling results, and theory they examined. Such judgmental estimates are not proof, nor do they provide information about the sources and degree of uncertainty. And as the NAS points out: "… without an understanding of the sources and degree of uncertainty, decision-makers could fail to define the best ways to deal with the serious issue of global warming."[65]

Significant uncertainties in the IPCC's conclusion arise from:

- the quality of the data used to determine the global average surface temperature; and
- the models used to simulate that surface temperature.

The surface temperature data base has several limitations, including:

- uneven geographic coverage—most of the data are for industrialized nations, with sparse coverage over much of the developing world;[66]
- sea surface temperature measurements that are more scattered and require more adjustment than the land-based measurements;[67]
- the urban heat island effect that IPCC indicates could account for up to 0.12°C. temperature rise during the 20th century, one-fifth of the total bserved;[68] and
- numerous possible errors created by instrument calibration and siting problems.[69]

Concerns about the accuracy and meaning of climate model results were discussed above in Question 11.

18. Is the global warming over the past century unique in the past 1,000 years or longer?

The IPCC Third Assessment Report conclusion that the warming of the 20th century unique in at least 1,000 years was based on a study (by Mann, *et al.*) that has been shown to be incorrect by three studies recently published in the peer-reviewed literature. These studies show

that many parts of the world have experienced warmer temperatures at some time during the last 1,000 years than they did during the second half of the 20th century and that climate variability is much greater than indicated by the IPCC.

In its Third Assessment Report, the IPCC concluded:

> … the increase in temperature in the 20th century is *likely* to have been the largest of any century during the past 1,000 years. It is also *likely* that, in the Northern Hemisphere, the 1990s was the warmest decade and 1998 the warmest year.[70]

The IPCC defined *likely* as having a 66-90% chance of being true in the expert judgment of the authors who drew the conclusion.

The main support for this conclusion was a proxy study published by Mann, *et al.*, purporting to show slowly declining surface temperature for the Northern Hemisphere between 1000 and 1900, followed by a sharp rise in temperature during the 20th century.[71] Their curve has been referred to as the "hockey stick." Subsequent scientific work has shown the Mann, *et al.* study to be deeply flawed and its conclusions unjustified.[72]

In 2003, McIntyre and McKitrick published a reanalysis of the data used by Mann, *et al.*, which showed that the "hockey stick" was based on four categories of error: collation errors, unjustified truncation and extrapolation, use of obsolete data, and calculation mistakes.[73] Correcting for these errors, they found that the proxy data showed higher temperatures for the early 15th century than for the 20th century.

Also in 2003, Soon and his co-workers published a detailed analysis of over 200 proxy studies from all parts of the world that demonstrated the existence of both a warm period (the Medieval Climate Optimum) from about 800 to about 1200 and a cool period (the Little Ice Age) from about 1400 to about 1850.[74] Data providing evidence of these warm and cool periods argues strongly again the slowly declining temperature from 1000 to 1900 shown by Mann, *et al.* The proxy data also show that many parts of the world have experienced higher temperatures at some point in the last 1000 years than they experienced during the second half of the 20th century. Soon, *et al.* did not believe that the proxy data they collected was of sufficient quality to construct a global average temperature history for the last 1000 years.

In 2004, von Storch, *et al.* published the results of a climate modeling study which showed that the empirical methods used by Mann, *et al.* systematically underestimate the variability of climate.[75] Von Storch, *et al.* concluded that "variations may have been at least a factor of two larger than indicated by empirical reconstructions."

These three studies, all of which were published in the peer-reviewed literature, raise serious questions about the Mann, *et al.* study and the IPCC conclusion that was based on it. They also offer a practical example of both the scientific process and the risks of short-circuiting it. The scientific process worked as it should in the debate over the temperature history of the last 1,000 years. One group of scientists, Mann, *et al.*, published their data and analysis. The analysis had flaws and those flaws were identified by other scientists who published corrections. Scientists have long recognized that "it isn't science until it's been done twice," that is, scientific results should not be considered valid until they have been replicated or until they have been tested the way Mann, *et al.*'s results were tested.

In the case of Mann, *et al.*, the correction process took 5-6 years. For most scientific questions this would have caused no problem. However, during that time the IPCC chose to highlight the Mann, *et al.* findings, *before they had been validated through the normal scientific process*, and some policy-makers made the conclusions from Mann, *et al.* a key part of the policy debate. What should have been an ordinary scientific question became a political one, to the detriment of the scientific process.

19. How much does the global climate vary naturally?

Climate scientists don't know the answer to this question, but the available data suggest that there is considerable natural variation on a time-scale of decades to centuries.

Climate varies naturally on timescales ranging from seasons to tens of thousands of years between ice ages. Knowledge of the natural variability of the climate system is needed to assess the extent of human impact on the climate system. At present there are no robust estimates for climate variability on the decades to centuries timescale that is essential for evaluating the extent to which human activities have already affected the climate system, and to provide the baseline of knowledge needed to assess how they might affect it in the future.

During the last 10,000 years the climate has remained relatively warm and stable, allowing humans to advance and prosper. But even during this generally warm period temperature has fluctuated significantly. About 6,500 years ago, during a period known as the Holocene Climate Optimum, the climate was warmer than it is today. There is also evidence that roughly a thousand years ago, during a period called the Medieval Climate Optimum, regions of the Earth were substantially warmer than they are today. By 1400 A.D., a cold period, known as the Little Ice Age, had begun. This cold period lasted well into the 19th century. The warming of the late 19th and early 20th century seems to be a natural recovery from the Little Ice Age.[76]

Closer to the present, in 2001, the IPCC concluded that the 1990s were very likely the warmest decade, and 1998 the warmest year, since the beginning of the instrumental temperature record in 1861.[77] However, the rate of temperature rise between from 1980 to 2000 was similar to that experienced between 1920 and 1940, and seems well within the bounds of natural climate variation.

Climate scientists do not have a good estimate of natural climate variability on a decade- or century-long timescale. In 1999, the National Research Council identified obtaining such an estimate as one of the major challenges in climate science.[78] That challenge is likely to remain unmet for a considerable period into the future. Yet having a good estimate of natural variability is critical in evaluating whether projected changes in future climate are significant.

The climate system varies naturally as the result of four factors:

- mathematically, the climate system exhibits “chaotic” (i.e., complex and non-linear) behavior, which means that it has limited predictability;
- important parts of the climate system exhibit oscillating behavior, e.g., the El Niño-Southern Oscillation (ENSO) cycle that repeats every 2-8 years in the tropical Pacific, and the North Atlantic Oscillation that has a cycle length of 60-80 years;
- variability in solar intensity, a key driver of the climate system, which occurs in cycles varying in length form the familiar 11-year sunspot cycle to shifts in the Earth’s orbit that occur in cycles of 100,000 years; and
- the random nature of volcanic eruptions, which emit both greenhouse gases and aerosols, both of which impact the climate system.

Two approaches have been used to estimate natural climate variability, climate models and analysis of paleoclimatic data. To date, neither has provided an adequate estimate of decadal to centennial variability. Comparisons of estimates of temperature variability calculated from climate model simulations with the actual variability observed in temperature measurements for periods of up to 40 years, show that that the climate models do a poor job of simulating actual variability.[79] This poor performance is probably the result of problems in both the ocean and land-surface components of the models, including their inability to accurately simulate the ENSO cycle. Furthermore, the currently available climate models do not provide the independent evaluation needed to estimate variability. Paleoclimatic data derived from proxies such as tree rings and coral reefs are subject to error and uncertainties that limit their precision. However, the few attempts that have been made to estimate the natural variability of surface temperature on decadal to centennial timescales from paleoclimatic data indicate that natural variability is significantly greater than the changes observed during the 20th century.

More detail on research on the causes and magnitude of natural climate variability can be found in the Marshall Institute report *Natural Climate Variability.*[80]

20. What do we know about the extent of human influence on climate? To what extent has the temperature increase since 1975 been the result of human activities?

The best answer to these questions is “We don’t know.” Human activities have a number of potential impacts on climate. Greenhouse gas emissions contribute to warming, as do some particulate emissions. Other particulate emissions produce cooling. Land-use changes can produce either warming or cooling, depending on the change. The direct effects of greenhouse gas emissions are relatively easy to determine, but their indirect effects, through water vapor and other feedbacks, are poorly understood. The impacts of other human activities—particulate emissions and land-use changes—are poorly understood.

21. Could climate change abruptly?

Over the last million years, the Earth’s climate has shifted dramatically between ice ages and warmer periods like the present one, called the Holocene. The glacial periods, with major advances of ice sheets, have generally lasted about 100,000 years, while the interglacial periods have lasted about 10,000 years. The transition between glacial and interglacial conditions can take place in less than a thousand years—sometimes in as little as decades. Such dramatic climatic shifts occurred near the end of the last major ice age, about 15,000 years ago. First, a brief warming occurred, and then the ice age returned for roughly a thousand years. Finally, by 11,500 years ago, the climate quickly warmed again.[81] Ice core data indicate that temperatures in central Greenland rose by 7°C or more in a few decades. Other proxy measurements indicate that broad regions of the world warmed in 30 years or less.[82]

Recently attention has focused on the potential for climate to change abruptly as the result of human activities. A common scenario is the onset of an ice age as the result of human greenhouse gas emissions.

It is now generally agreed that changes in the Earth’s orbit, which result in changes in the amount of solar energy reaching the Earth’s surface, are responsible for both ice ages and the warm interglacial periods between them. This theory was first popularized in the 1920s by Milutin Milankovitch, a Serbian astrophysicist. He theorized that three factors controlled the amount of solar energy reaching the Earth’s surface:

- the eccentricity, or shape, of the Earth’s orbit, which varies on a cycle of about 100,000 years;
- the tilt of the Earth’s axis, which varies on a cycle of about 41,000 years; and
- the precession of the equinoxes, which varies on a cycle of about 22,000 years.

Milankovitch's theory was largely ignored for 50 years until a study of deep-sea sediment cores published in 1976 showed that his cycles did explain large-scale climate changes.[83] Subsequent studies of ice core samples from Greenland and Antarctica showed that in some cases over the past 250,000 years, changes in atmospheric levels of carbon dioxide followed, rather than preceded, changes in temperature.[84]

Since increases in greenhouse gases concentrations should cause warming rather than cooling, the obvious question is how could warming trigger an ice age? In response to this question, climate disaster theorists have come up with the following scenario. Warming will lead to melting of glaciers and ice sheets in Greenland and Antarctica, which, in turn, will lead to the release of large amounts of fresh water into northern and southern oceans. These releases of fresh water will shut down the thermohaline circulation (such as the Gulf Stream) that currently carries large amounts of heat from the semi-tropics to higher latitudes. Deprived of this transfer of heat, the higher latitudes will cool, triggering the next ice age.

While this scenario may sound convincing, it is not supported by scientific fact. Carl Wunsch, an oceanographer at MIT, points out, the term thermohaline circulation, which implies that currents like the Gulf Stream are driven by differences in the temperature and salinity of sea water through the ocean, is a misnomer. These differences are not strong enough. What drives ocean currents is the tidal force exerted by the Moon.[85] Wunsch's argument is supported by satellite data indicating that the Moon is slowly moving away from the Earth creating the tidal energy necessary to drive ocean currents.[86]

Even climate scientists who disagree with Wunsch and argue that warming could weaken thermohaline circulation reject the disaster scenario. In a letter to *Science*, Wallace Broecker of Lamont-Doherty Earth Observatory, who first raised concerns about the effect of warming on thermohaline circulation, rejected both the speed and the severity of disaster scenario.[87]

A number of modeling studies have been conducted on thermohaline circulation in the North Atlantic. The models used have significant shortcomings, and their output should be viewed cautiously. Some of these models studies show that warming could cause a weakening of thermohaline circulation, but the effect of this weakening was far from an ice age. To quote the IPCC: "… even in models where the thermohaline circulation weakens, there is still a warming over Europe."[88]

In summary, all available evidence indicates that ice ages are the result of changes in the amount of solar energy reaching the Earth's surface, not changes in greenhouse gas concentrations.

Another "abrupt" climate change scenario involves massive species extinctions as a result of climate change. One recent paper by Thomas, *et al.* studied 1,100 species with limited geographic range and concluded that a temperature rise of 0.8-1.7°C by 2050 would commit 18 percent of them to extinction.[89] However, Thomas and his co-authors also report that climate change was implicated in the extinction of only one species during the 20th century, when according to the IPCC, global average temperature rose by 0.6°C. Is it reasonable to assume that if and 0.6°C temperature rise caused the extinction of only one species, that 0.8-1.7°C temperature rise will cause the extinction of 18 percent of the millions of species on Earth?[90] We think not.

22. Will sea level rise abruptly?

There currently is no scientific evidence to support concern about rapid sea level rise during this century. Longer term, the dynamics of glacier and ice sheet melting are too poorly understood to make reasonable projections.

In a warming climate sea level will rise for two reasons: (1) melting glaciers and ice sheets will add more water to the oceans, and (2) the water in the oceans will expand as it warms. However, as with all parts of the climate system, there are complicating factors. Sea level also rises and falls due to geological shifts in the land underlying the ocean and the coast. The polar regions are very dry. However, if they warm, more moisture can fall as snow and result in more, not less, accumulation of ice. Finally, the amount of water that is stored in reservoirs and not allowed to flow to the ocean has to be subtracted from potential sea level rise.

The IPCC estimates that sea level rose between 1 and 2 millimeters per year during the 20th century, or about 4 to 8 inches for the century, but that no acceleration of sea level rise was detected over the century.[91] It projects a sea level rise between 4 and 35 inches between 1990 and 2100.[92] The upper end of this range depends on temperature rising to the upper end of IPCC projections to 2100. As discussed in Question 12, projections of large increases in temperature are dependent on three assumptions, none of which are likely.

Larger increases in sea level rise would require rapid melting of either the Greenland or Antarctic ice sheets. Modeling studies indicate that the Antarctic ice sheets are likely to gain mass because of increased precipitation, contributing to a decline in sea level, during the next century. The Greenland ice sheet is projected to lose mass, but not sufficiently to cause a rapid increase in sea level. Both the increase in mass of the Antarctic ice sheet and loss of mass of the Greenland ice sheet are included in the IPCC's estimate of sea level rise to 2100.

Concern has also been expressed about breakup to the West Antarctic Ice Sheet (WAIS) because it is grounded below sea level. IPCC concludes:

> However, loss of grounded ice leading to substantial sea level rise form this source is now widely agreed to be *very unlikely* (italics in original) during the 21st century … [93]

Very unlikely is defined as having a 1–10 percent chance of occurring. IPCC also points out that the dynamics of the WAIS are poorly understood, especially for longer time frames, and that disintegration of the of the Antarctic ice sheets would require conditions that are far beyond those projected by worst case climate model scenarios. Current understanding of the behavior of ice sheets is too poor to allow reasonable estimates of their behavior beyond 2100 to be made.

23. Will the number of tropical cyclones (hurricanes, typhoons) increase and will they become more intense?

It is well established that tropical cyclones will not form unless the sea surface temperature in 26°C (79°F) or higher. However, tropical cyclone formation depends on a parameter known as Convective Available Potential Energy (CAPE), which is a function of both sea surface temperature and atmospheric circulation. The atmosphere can either collect the energy available from the warm ocean, leading to cyclone formation, or dissipate it, in which case a cyclone will not form. Since sea surface temperatures are often above 26°C, but tropical cyclones are relatively rare events, dissipative conditions predominate. The same parameter controls tropical cyclone intensity.

The large number of hurricanes and weaker tropical cyclones in the North Atlantic during the 2004 and 2005 hurricane seasons has been attributed by some to an effect of human-induced climate change. The atmospheric conditions that lead to cyclone formation are controlled by the cyclic conditions in the various ocean basins. The positive phase of the North Atlantic Oscillation (NAO), which began in 1995, leads to more hurricane formation (See Question 6 for more detail on the NAO and other cyclic climate phenomena). El Niño also has an impact, suppressing hurricane formation in the North Atlantic. Compared with the 1970–1995 period, which was the negative phase of the NAO, all years since 1995 have had above average Atlantic hurricane activity except for 1997 and 2002, which were years with strong El Niños.

Interestingly, there is a strong negative correlation between hurricane activity in the North Atlantic and typhoon activity in the North Pacific; years with high hurricane activity tend to be years with low typhoon activity, and globally the number of tropical cyclones tends to be fairly constant. This, too, argues that atmospheric circulation is a far more important factor in tropical cyclone formation that sea surface temperature.[94] 1997, a year with strong El Niño activity and weak hurricane activity in the North Atlantic, saw the highest ever recorded number of typhoons in the North Pacific.[95] While this was "the highest ever recorded number of typhoons" care must be taken in interpreting this and other statistics for tropical cyclones. Prior to the satellite era, observation of these storms was incomplete. They were reported only if they hit land or a ship encountered them and reported their occurrence.

Another concern is that even if the number of tropical cyclones does not increase, the ones that are formed will become more intense. Such intensification is predicted by some climate models.[96] This concern was heightened by the recent paper suggesting that tropical cyclones had become more destructive over the past 30 years.[97] However, the same set of conditions that controls the formation of tropical cyclones controls their strength, i.e., whether atmospheric conditions lead to the collection or dissipation of convective energy. Just as there is no evidence to determine whether climate change has or will lead to a greater number of storms, there is no evidence to determine whether the storms that do form will become more intense.

While a full scientific analysis of the 2005 hurricane season has yet to be published, hurricane experts are cautioning against attributing the record number of storms to climate change. For example, Kevin Trenberth of the (U.S.) National Center for Atmospheric Research (NCAR) said:

> (1) … there is no sound theoretical basis for drawing any conclusions about how anthropogenic climate change affects hurricane numbers or tracks, and thus how many may hit land.
>
> (2) … it is not yet possible to say how El Niño and other factors affecting hurricane formation may change as the world warms.
>
> (3) … our physical understanding suggests that the intensity of rainfall from hurricanes is probably increasing even if this increase cannot yet be proven…[98]

24. Will other extreme weather events, such as heat waves, increase?

If the Earth warms, some types of extreme weather events will increase, others will decrease, and still others will remain unchanged. The occurrence of what is now defined as extreme heat will increase, while extreme cold will decrease,

If the Earth warms, some types of extreme weather events will increase, others will decrease, and still others will remain unchanged. The frequency of extreme temperature events will change. What constitutes a "heat wave" is a function of location; 90°F is an extreme temperature for Boston, but not an unusual summer event in Dallas or Phoenix. If average temperature increases, the likelihood of surpassing the local definition of extreme heat will also increase. Conversely, the likelihood of surpassing the local definition of extreme cold will decrease. In time, it is likely that these definitions would be changed to reflect the change in long-term climate.

If the Earth warms, precipitation patterns will change, which will lead to a change in the frequency of floods and droughts. Some areas will see increases in either floods or droughts, other will see decreases. However, since climate models do an even poorer job of projecting precipitation changes than they do for temperature changes, it is not possible to say whether the net change will be positive or negative.[99]

The last class of weather extremes is small-scale (on a global basis) events such as tornadoes, and hail and thunderstorms. The IPCC could find no evidence of systematic changes in the frequency of these events,[100] and made no projections about their future frequency.

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