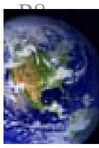
Global Climate Change

Key Messages:

- Human activities have led to large increases in heat-trapping gases over the past century.
- Over the last 100 years, global average temperature and sea level have increased, and precipitation patterns have changed.
- Numerous independent lines of evidence show that many of the climatic changes of the past 50 years are primarily human-induced.
- Global temperatures will continue to rise over this century; by how much and for how long depends on a number of factors, including the amount of heat-trapping emissions and how sensitive the climate is to those emissions.

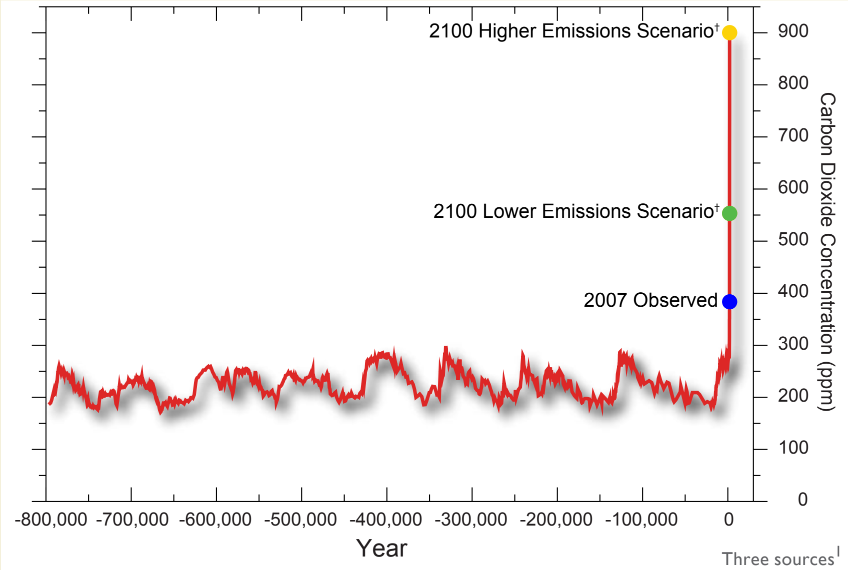
Key Sources

- CCSP 1.1 Temperature Trends
- CCSP 2.1 GHG Emissions
- CCSP 2.2 Carbon Cycle
- CCSP 2.4 Ozone Trends
- CCSP 3.1 Climate Models
- CCSP 3.2 Climate Projections
- CCSP 3.3 Extremes
- CCSP 3.4 Abrupt Climate Change
- CCSP 4.3 Impacts
- IPCC WG-1
- IPCC WG-3



This introduction to global climate change explains very briefly what has been happening to the world's climate and why, and what is projected to happen in the future. While this Report focuses on climate change impacts in the United States, understanding these changes and their impacts necessarily requires an understanding of the global climate system.

800,000 Years of Carbon Dioxide Concentrations



Three sources[1]

An Antarctic ice core provides a look at the past 800,000 years of Earth's carbon dioxide concentrations, a central factor in our planet's climate. Over this long period, atmospheric carbon dioxide levels varied within a range of about 170 to 300 parts per million. The carbon dioxide concentration is now far outside of that range, 30 percent higher than the highest point in at least the last 800,000 years, at over 380 parts per million. Civilization is now on a path that is moving us rapidly toward even higher levels.

Many changes have been observed in global climate over the past century. The nature and causes of these changes have been comprehensively chronicled in a variety of recent reports, such as those by the Intergovernmental Panel on Climate Change (IPCC) and the U.S. Climate Change Science Program (CCSP). This Section does not intend to duplicate these comprehensive efforts, but rather to provide a brief synthesis, and to integrate more recent work with the assessments of the IPCC, CCSP, and others.

Human activities have led to large increases in heat-trapping gases over the past century.

The Earth's climate depends on the functioning of a large natural "greenhouse effect". The greenhouse effect is the result of gases like water vapor, carbon dioxide, ozone, methane, and nitrous oxide, which absorb heat radiated from the Earth's surface and lower atmosphere and then radiate much of the energy back towards the surface. Without this natural greenhouse effect, the average surface temperature of the Earth would be about 60°F colder. However, human activities release additional heat-trapping gases into the atmosphere, particularly through the burning of fossil fuels (coal, oil, and natural gas). This intensifies the natural greenhouse effect, thereby changing the climate of our planet.

Earth's climate is influenced by a variety of factors, both human-induced and natural. The increase in the carbon dioxide concentration has been the principal factor causing warming over the past 50 years. Its concentration has been building up in the Earth's atmosphere since the beginning of the industrial era, primarily due to the burning of fossil fuels and the clearing of forests. Human activities have also increased the emissions of other greenhouse gases, such as methane, nitrous oxide, and halocarbons[2]. These emissions are thickening the blanket of heat-trapping gases in Earth's atmosphere, causing surface temperatures to rise.

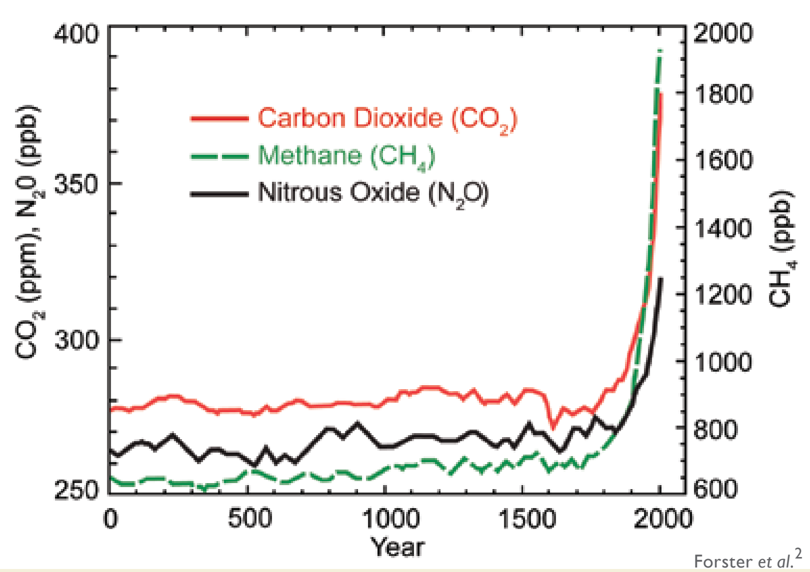
Heat-trapping gases

Carbon dioxide concentration has increased due to the use of fossil fuels in electricity generation, transportation, industrial processes, and space and water heating. It is also produced as a by-product during the manufacturing of cement. Deforestation provides a source of carbon dioxide, and reduces its uptake by trees and other plants. Globally, over the past several decades, about 80 percent of human-induced carbon dioxide emissions came from the burning of fossil fuels, while about 20 percent resulted from deforestation. The concentration of carbon dioxide in the atmosphere has increased by roughly 35 percent since the industrial revolution[2].

Methane concentration has increased mainly as a result of agriculture, raising livestock (which produce methane in their digestive tracts), mining, transportation, and use of certain fossil fuels, sewage, and decomposing garbage in landfills. About 70 percent of the emissions of atmospheric methane are now related to human activities.

Nitrous oxide concentration is increasing as a result of fertilizer use and fossil fuel burning.

2,000 Years of Greenhouse Gas Concentrations



Forster *et al.*[2]

Increases in concentrations of these gases since 1750 are due to human activities in the industrial era. Concentration units are parts per million (ppm) or parts per billion (ppb), indicating the number of molecules of the greenhouse gas per million or billion molecules of air.

Halocarbon emissions come from the release of manufactured chemicals to the atmosphere. Examples include chlorofluorocarbons (CFCs), which were used extensively in refrigeration and other industrial processes before their presence in the atmosphere was found to cause stratospheric ozone depletion. The abundance of these gases in the atmosphere is now decreasing as a result of international regulations designed to protect the ozone layer. Continued decreases in halocarbon emissions are expected to reduce their effect on climate change in the future[2,3].

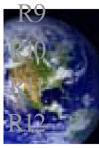
Ozone itself is a greenhouse gas, and is continually produced and destroyed in the atmosphere by chemical reactions. In the troposphere, the lowest 5 to 10 miles of the atmosphere near the surface, human activities have increased ozone concentration through the release of gases such as carbon monoxide, hydrocarbons, and nitrogen oxides. These gases undergo chemical reactions to produce ozone in the presence of sunlight. In addition to trapping heat, excess ozone in the troposphere causes respiratory illnesses and other human health problems. In the stratosphere, the layer above the troposphere, ozone exists naturally and protects life on Earth from exposure to excessive ultraviolet radiation from the Sun. As mentioned previously, halocarbons released by human activities destroy ozone in the stratosphere and have caused the ozone hole over Antarctica. Changes in the stratospheric ozone layer have contributed to changes in wind patterns and regional climates.

Water vapor is the most important and abundant greenhouse gas in the atmosphere. Human activities produce only a small increase in water vapor through combustion processes and irrigation. However, the surface warming caused by human-produced increases in other greenhouse gases leads to a large increase in water vapor, since a warmer climate increases evaporation and allows the atmosphere to hold more moisture. This in turn leads to more warming, creating a "feedback loop".

Other human influences

In addition to the global-scale climate effects of heat-trapping gases, human activities also produce additional local and regional effects. Some of these activities partially offset the warming caused by greenhouse gases, while others increase the warming. One such influence on climate is caused by tiny particles called "aerosols" (not to be confused with aerosol spray cans). For example, the burning of coal produces emissions of sulfur-containing compounds. These compounds form "sulfate aerosol" particles, which reflect some of the incoming sunlight away from the Earth, thus leading to local or regional cooling influence. Sulfate aerosols also tend to make clouds more efficient at reflecting sunlight, causing an additional indirect cooling effect. Another type of aerosol, often referred to as soot or black carbon, absorbs incoming sunlight and traps heat in the atmosphere. Thus, depending on their type, aerosols can either mask or increase the warming caused by increased levels of greenhouse gases. At the global scale, the sum of these aerosol effects offsets some of the warming caused by heat-trapping gases and, in some locations with large amounts of aerosol particles, can even cause a net cooling.

The effects of various greenhouse gases and aerosol particles on Earth's climate depend in part on how long these gases and particles remain in the atmosphere. After emission, the atmospheric concentration of carbon dioxide remains elevated for many centuries, while the elevated concentrations of aerosols and methane would persist for only days to decades if emissions were reduced. Reductions in some of these shorter-lived gases and particles can thus have relatively rapid and potentially complex effects on climate[4,5]. In contrast, while the concentrations of carbon dioxide and other long-lived gases go up rapidly after their emission, the climate effects of reductions in their emissions will not become apparent for at least several decades.



Human activities have also changed the land surface in ways that alter how much heat is reflected or absorbed by the surface. Such changes include the cutting and burning of forests, the replacement of other areas of natural vegetation with agriculture and cities, and large-scale irrigation. These transformations of the land surface can cause local (and even regional) warming or cooling. Globally, the net effect of these changes has probably been a slight cooling of the Earth's surface over the past 100 years[6,7].

Natural influences

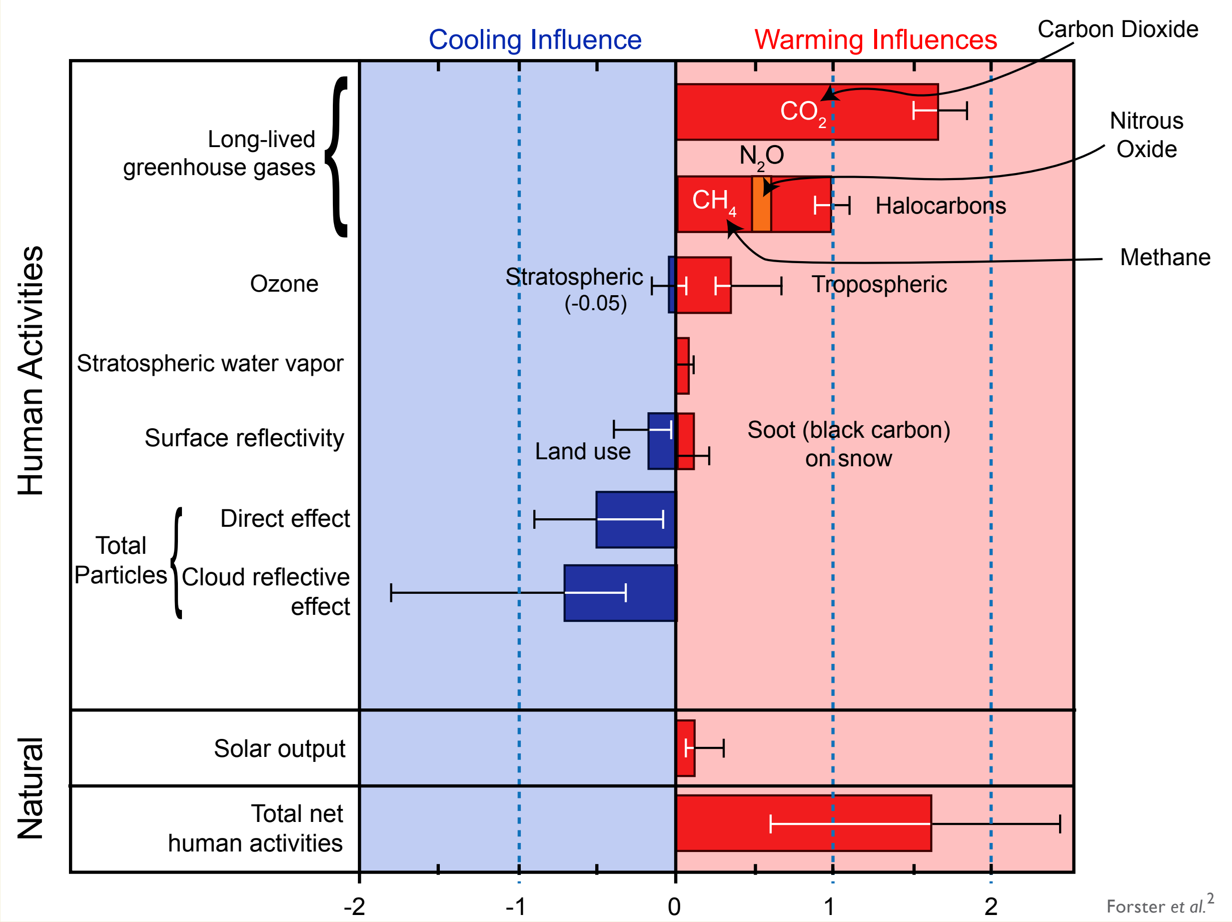
Two important natural factors also influence climate: the Sun and volcanic eruptions. Over the past three decades, human influences on climate have become increasingly obvious, and global temperatures have risen sharply. During the same period, the Sun's energy output (as measured by satellites since 1979) has followed its historic 11-year cycle of small ups and downs, but with no net increase[8]. The two major volcanic eruptions of the past 30 years have had short-term cooling effects on climate, lasting 2 to 3 years[5]. Thus, these natural factors cannot explain the warming of recent decades; in fact, their net effect on climate has probably been a slight cooling influence over this period. Slow changes in Earth's orbit around the Sun and its tilt toward or away from the Sun are also a purely natural influence on climate, but are only important on timescales from thousands to many tens of thousands of years.

The climate changes that have occurred over the last century are not solely caused by the human and natural factors described above. In addition to these influences, there are also purely natural fluctuations in climate (often called "climate noise") that occur even in the absence of changes in human activities, the Sun, or volcanoes. One example is the El Niño phenomenon, which has important influences on many aspects of regional and global climate. Many other modes of natural internal variability have been identified by climate scientists and their effects on climate occur at the same time as the effects of human activities, the Sun, and volcanoes.

Carbon release and uptake

Once carbon dioxide is emitted to the atmosphere, some of it is absorbed by the oceans and by vegetation on land; about 45 percent of the carbon dioxide emitted by human activities in the last 50 years has been taken up by these natural "sinks". The rest has remained in the air, increasing the atmospheric concentration[1,2,9]. It is thus important to understand not only how much carbon dioxide is emitted, but also how much is taken up, over what time scales, and how these sources and sinks of carbon dioxide might change as climate continues to warm.

Major Factors Affecting Climate



Forster *et al.*[2]

The figure above shows the amount of warming influence (red bars) or cooling influence (blue bars) that different factors have had on Earth's climate over the industrial age (from about 1750 to the present). Results are in watts per square meter. The longer the bar, the greater the influence on climate. The top part of the box includes all the major human-induced factors, while the second part of the box includes the Sun, the only major natural factor with a long-term effect on climate. The cooling effect of individual volcanoes is also natural, but is relatively short-lived (2 to 3 years). The bottom part of the box shows that the total net effect of human activities is a strong warming influence. The thin lines on each bar provide an estimate of the range of uncertainty.

The rate of rise in global emissions of carbon dioxide has been accelerating. The growth rate increased from 1.3 percent per year in the 1990s to 3.3 percent per year between 2000 and 2006[10]. The increasing emissions of carbon dioxide have clearly contributed to the observed increased concentration of carbon dioxide in the atmosphere, but are perhaps not the only factor. There is some evidence that a recent decrease in the rate of uptake of carbon dioxide by the oceans and by land vegetation contributed to the observed increased carbon dioxide concentration in the atmosphere[10].

Over the last 100 years, global average temperature and sea level have increased, and precipitation patterns have changed.

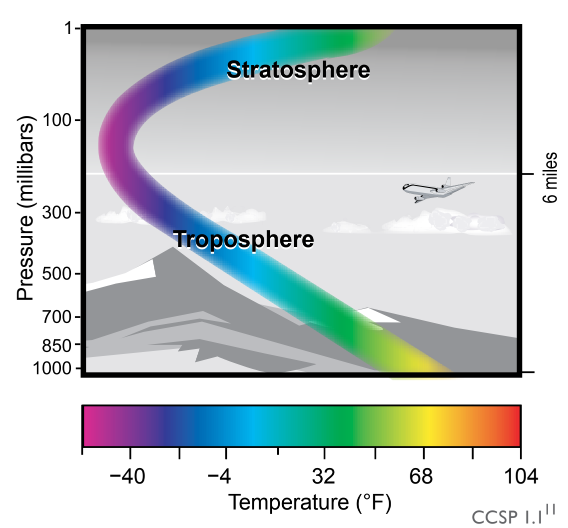
Temperatures are rising

Global average surface air temperature has been increasing rapidly since 1970[12]. The estimated change in the average temperature of Earth's surface is based on measurements made by satellites and at thousands of weather stations, ships, and buoys around the world. These measurements are independently compiled, analyzed, and processed by different research groups. An important step in the data processing is to identify and adjust for the effects of changes in the instruments used to measure temperature, the measurement times and locations, and the local environment around the measuring site (such as the growth of cities, and the development of so-called "urban heat island" effects) or within a satellite's field of view. A number of research groups around the world have produced estimates of global-scale changes in surface temperature.

The warming trend that is apparent in all of these temperature records is confirmed by other independent observations, such as the melting of Arctic sea ice, the retreat of mountain glaciers on every continent[13], reductions in the extent of snow cover, earlier blooming of plants in spring, and increased melting of the Greenland and Antarctic ice sheets[14].

Additionally, temperature measurements above the surface have been made by weather balloons since the late 1940s, and from satellites since 1979. These measurements show warming of the troposphere, consistent with the surface warming[16,17]. They also

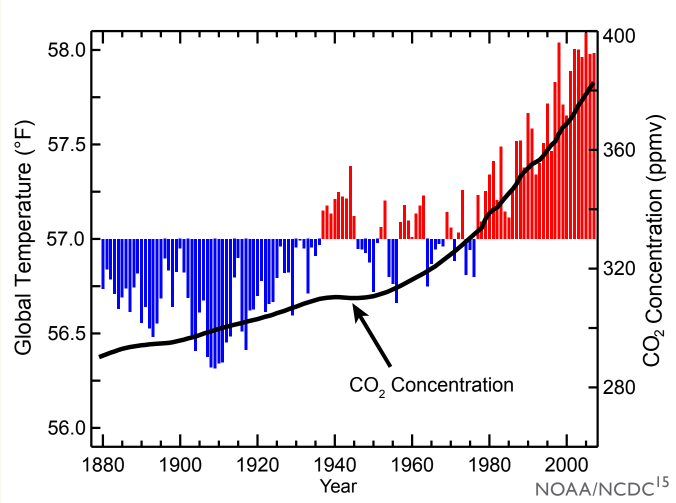
Layers of the Atmosphere Closest to the Earth's Surface



CCSP 1.1[11]

The illustration shows the layers of the atmosphere closest to Earth's surface. The troposphere extends from the surface up to roughly 6 miles above the surface and the stratosphere is above that. The colored band shows the average temperature of the atmosphere at different altitudes. In the troposphere, temperatures generally decrease with height, while in the stratosphere temperatures increase with height.

Global Temperature and CO_2



NOAA/NCDC[15]

Global annual average temperature (as measured over both land and oceans). Red bars indicate temperatures above the 1901-2000 average, blue bars are below average temperatures. The black line shows carbon dioxide concentration. While there is a clear long-term global warming trend, each individual year does not show a temperature increase relative to the previous year, and some years show greater changes than others. These year-to-year fluctuations in temperature are due to natural processes, such as the effects of El Niños and La Niñas.

reveal cooling in the stratosphere[16]. This pattern of tropospheric warming and stratospheric cooling agrees with our understanding of how atmospheric temperature would be expected to change in response to increasing greenhouse gas concentrations and the observed depletion of stratospheric ozone[6].

Precipitation patterns are changing

Precipitation is not distributed evenly over the globe. Its average distribution is governed primarily by atmospheric circulation patterns and the availability of moisture, which in turn are influenced by temperature. Because of human-caused changes in atmospheric temperature, changes are expected in atmospheric circulation, and therefore in precipitation patterns.

Observations show that such shifts are occurring. Changes have been observed in the amount, intensity, frequency, and type of precipitation. Pronounced increases in precipitation over the past 100 years have been observed in eastern North America, southern South America, and northern Europe. Decreases have been seen in the Mediterranean, most of Africa, and southern Asia. The geographical distribution of droughts and flooding has been complex. In some regions, there have been increases in the occurrences of both droughts and floods[14]. As the world warms, northern regions and mountainous areas are experiencing more precipitation falling as rain rather than snow[18]. Widespread increases in heavy precipitation events have occurred, even in places where total amounts have decreased. These changes are associated with the fact that warmer air holds more water vapor evaporating from the world's oceans and land surface[17]. This increase in atmospheric water vapor has been observed from satellites, and is primarily due to human influences[19,20].

Sea level is rising

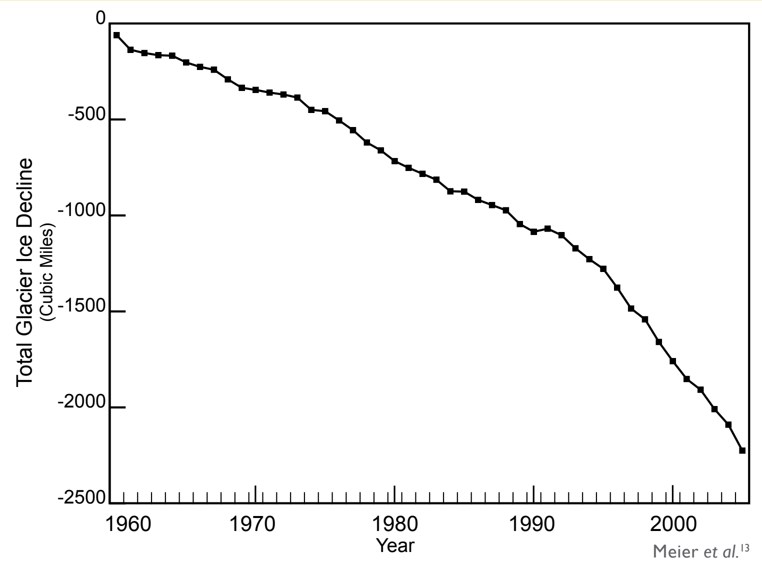
After at least 2000 years of little change, sea level rose by roughly 8 inches over the past 100 years. Satellite data available over the past 15 years shows sea-level rising at a rate roughly double the rate observed over the past century[21].

Global warming causes sea level to rise in two ways. First, ocean water expands as it warms, and therefore takes up more space. Warming has been observed in each of the world's major ocean basins, and has been directly linked to human influences[22,23].

Second, warming leads to the melting of glaciers and ice sheets, which raises sea level by adding water to the oceans. Glaciers have been retreating worldwide, and the rate of retreat has increased in the past decade[24]. Only a few glaciers are actually advancing (in locations that were well below freezing, and where increased precipitation has outpaced melting). The total volume of glaciers on Earth is declining sharply. The progressive disappearance of glaciers has implications not only for the rise in global sea level, but also for water supplies in certain densely-populated regions of Asia and South America.

The Earth has two major ice sheets. The Greenland Ice Sheet contains enough water to raise sea level by about 20 feet. Melting of the entire Antarctic Ice Sheet would raise sea levels by over 200 feet. Both of these ice sheets are currently melting around parts of their edges. Complete melting of either of these ice sheets over this century or the next is

Cumulative Decrease in Global Glacier Ice



Meier *et al.*[13]

As temperatures have risen, glaciers around the world have shrunk. The graph shows the cumulative decline in glacier ice worldwide.

virtually impossible. The Greenland Ice Sheet has also been experiencing record amounts of surface melting, and a large increase in the rate of mass loss in the past decade[25].

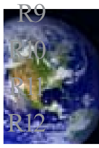
Numerous independent lines of evidence show that many of the climatic changes of the past 50 years are primarily human-induced.

In 1996, the IPCC Second Assessment Report[26] cautiously concluded that "the balance of evidence suggests a discernible human influence on global climate". Since then, a number of national and international assessments have come to much stronger conclusions about the reality of human effects on climate. Recent scientific assessments find that most of the warming of the Earth's surface over the past 50 years has been caused by human activities[27,28]. What evidence allowed scientists to identify human influences as the major cause of the observed warming? How can we be sure that "it's mostly us"?

This conclusion rests on multiple lines of evidence. Like the warming "signal" that has gradually emerged from the "noise" of natural climate variability, the scientific evidence for a human influence on global climate has accumulated slowly over the past several decades, from many hundreds of studies. No single study is a "smoking gun". Nor has any single study undermined the large body of evidence supporting the conclusion that human activity is the primary driver of recent warming.

The first line of evidence is our basic physical understanding of how greenhouse gases trap heat, how the climate system responds to increases in greenhouse gases, and how other human and natural factors influence climate. The second line of evidence is from indirect estimates of climate changes over the last 1,000 to 2,000 years. These so-called "paleodata" are obtained from living things (like tree rings and corals) and from physical quantities (like the ratio between lighter and heavier isotopes of oxygen in ice cores) which change in measurable ways as climate changes. The lesson from paleodata is that global surface temperatures over the last several decades are clearly unusual, in that they were higher than at any time during at least the past 400 years[29]. For the Northern Hemisphere, recent temperature rises are clearly unusual in at least the last 1,000 years[29,30].

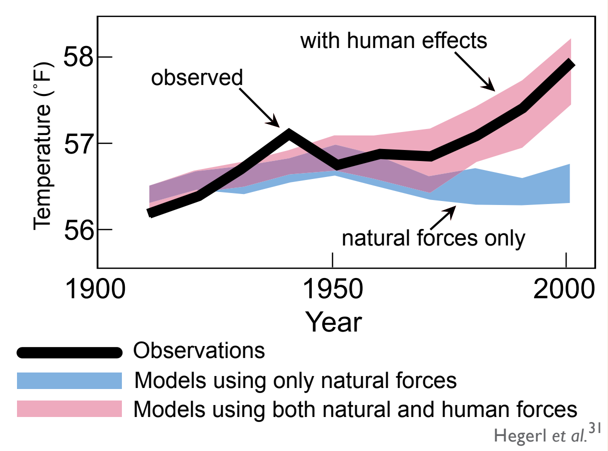
The third line of evidence is based on the broad, qualitative consistency between observed changes in climate and the computer model predictions of how climate would be expected to change in response to human activities. For example, when climate models are run with historical increases in greenhouse gases, they show gradual warming of the Earth and ocean surface, increases in ocean heat content and the temperature of the lower atmosphere, a rise in global sea level, retreat of sea-ice and snow cover, cooling of the stratosphere, an increase in the amount of atmospheric water vapor, and changes in large-scale precipitation and pressure patterns. These and other aspects of modeled climate change are in agreement with observations[6,31].



Finally, there is statistical evidence from so-called "fingerprint" studies. Each factor that affects climate produces a unique pattern of climate response, much as each person has a unique fingerprint. Fingerprint studies exploit these unique signatures, and make detailed comparisons of modeled and observed climate change patterns[31]. Scientists rely on such studies to attribute observed changes in climate to a particular cause or set of causes. In the real world, the climate changes that have occurred since the Industrial Revolution are due to a complex mixture of human and natural causes. The importance of each individual influence in this mixture changes over time. Of course, there are not multiple Earths, which would allow an experimenter to change one factor at a time on each Earth, thus helping to isolate different fingerprints. Climate models can be used to perform the systematic experiments that are not possible in the real world: a single factor (like greenhouse gases) or a set of factors can be varied, and the response of the climate system to these individual or combined changes can thus be studied[32].

For example, when climate model simulations of the last century include all of the major influences on climate, both human-induced and natural, they can reproduce many important features of observed

Separating Human and Natural Influences on Climate



The blue band shows how global average temperatures would have changed due to natural forces only, as simulated by climate models. The red band shows model projections of the effects of human and natural forces combined. The black line shows actual observed global average temperatures. As the blue line indicates, without human influences, temperature over the past century would actually have first warmed and then cooled slightly over recent decades.

climate change patterns. When human influences are removed from the model experiments, results suggest that the surface of the Earth would actually have cooled slightly over the last 50 years. The clear message from fingerprint studies is that the observed warming over the last half-century cannot be explained by natural factors alone[6,33].

Another fingerprint of human effects on climate has been identified when one looks at a slice through the layers of the atmosphere, and studies the pattern of temperature changes from the surface up through the stratosphere. In all climate models, increases in carbon dioxide cause warming at the surface and in the troposphere, but lead to cooling of the stratosphere. Models also show that the human-caused depletion of stratospheric ozone has a strong cooling effect in the stratosphere. There is a good match between the model fingerprint in response to combined carbon dioxide and ozone changes and the observed pattern of tropospheric warming and stratospheric cooling[6].

In contrast, if most of the observed temperature change had been due to an increase in solar output rather than an increase in greenhouse gases, Earth's atmosphere would have warmed throughout its full vertical extent, including the stratosphere[6]. The observed pattern of atmospheric temperature changes, with its pronounced cooling in the stratosphere, is therefore inconsistent with the hypothesis that changes in the Sun can explain the warming of recent decades. Moreover, direct satellite measurements of solar output show slight decreases during the recent period of warming.

The earliest fingerprint work[34] focused on changes in surface and atmospheric temperature. Scientists then applied fingerprint methods to a whole range of climate variables[31,35], identifying human-caused climate signals in the heat content of the oceans[22,23], the height of the tropopause[36] (the boundary between the troposphere and stratosphere, which has shifted upward by hundreds of feet in recent decades), the geographical patterns of precipitation[37], drought[38], surface pressure[39], and the runoff from major river basins[40].

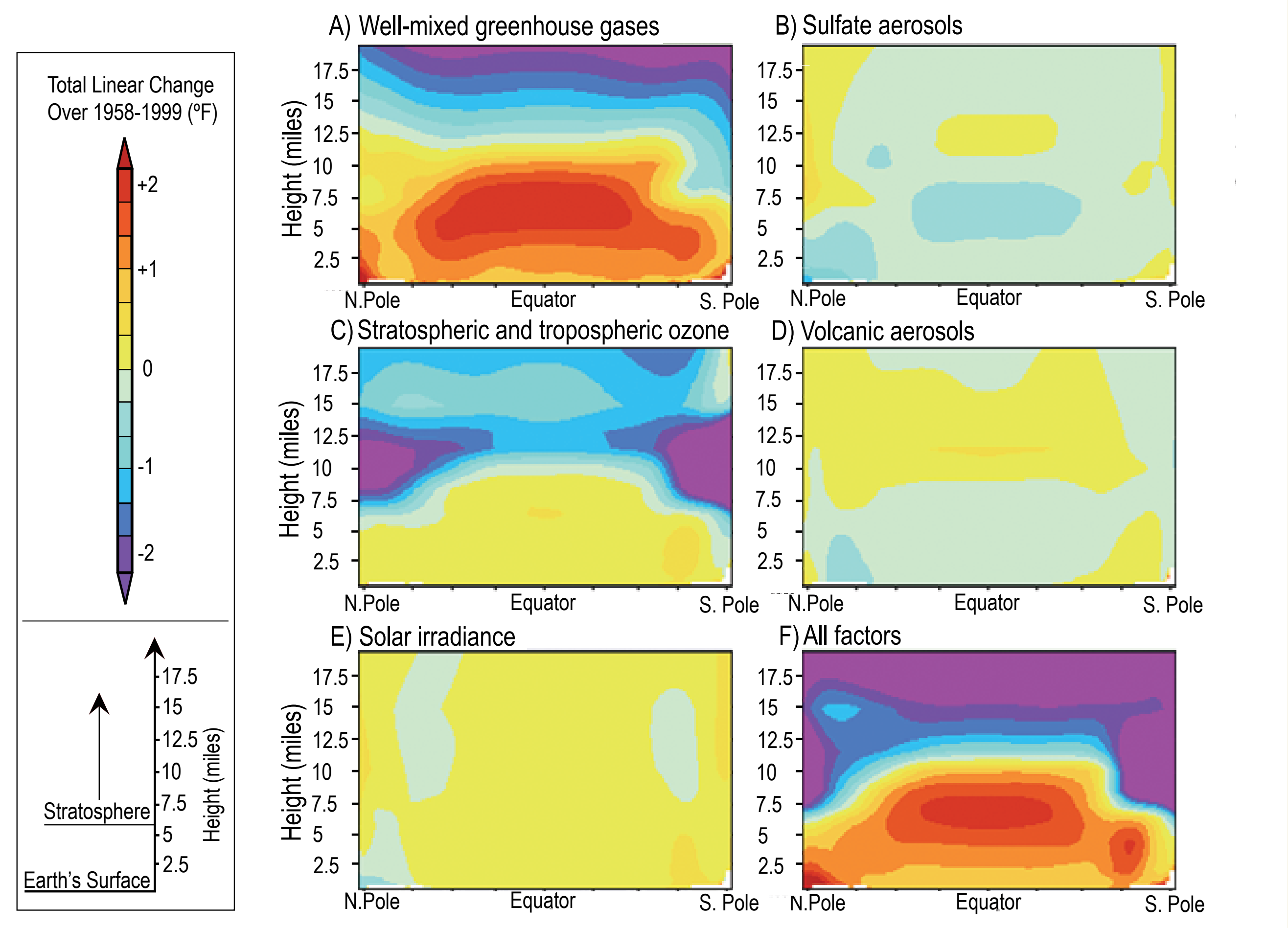
Studies published after the appearance of the IPCC Fourth Assessment Report in 2007 have found human fingerprints in the increased levels of atmospheric moisture[19,20] (both close to the surface and over the full extent of the atmosphere), in the decline of Arctic sea ice extent[41], and in the patterns of changes in Arctic and Antarctic surface temperatures[42]. The message from this entire body of work is that the climate system is telling a consistent story of increasingly dominant human influence—the changes in temperature, ice extent, moisture, and circulation patterns fit together in a physically consistent way, like pieces in a complex puzzle.

Increasingly, this type of fingerprint work is shifting its emphasis. As noted, clear and compelling scientific evidence supports the case for a pronounced human influence on global climate. Much of the recent attention is now on climate changes at continental and regional scales[43,44], and on variables that can have large impacts on societies. For example, scientists have established causal links between human activities and the changes in snowpack, maximum and minimum temperature, and the seasonal timing of runoff over mountainous regions of the western United States[18]. A large human component has been identified in the ocean surface temperature changes in hurricane formation regions[45,46]. Researchers are also looking beyond the physical climate system, and are beginning to tie changes in the distribution and seasonal behavior of plant and animal species to human-caused changes in temperature and precipitation[47,48].

For over a decade, one aspect of the climate change story seemed to show a significant difference between models and observations[6]. In the tropics, all models predicted that with a rise in greenhouse gases, the troposphere would be expected to warm more rapidly than the surface. Observations from weather balloons, satellites, and surface thermometers seemed to show exactly the opposite behavior (more rapid warming of the surface than the troposphere). This issue was a stumbling block in our understanding of the causes of climate change. It is now largely resolved[49]. Research showed that there were large uncertainties in the satellite and weather balloon data. When uncertainties in models and observations are properly accounted for, newer observational datasets (with better treatment of known problems) are in agreement with climate model results[17,50-53].

This does not mean, however, that all remaining differences between models and observations have been resolved. The observed changes in some climate variables, such as Arctic sea ice[41], some aspects of precipitation[37,55], and patterns of surface pressure, appear to be proceeding much more rapidly than models have projected. The reasons for these differences are not well understood. Nevertheless, the bottom-line conclusion from climate fingerprinting is that most of the observed changes studied to date are consistent with each other, and are also consistent with our scientific understanding of how the climate system would be expected to respond to the increase in heat-trapping gases resulting from human activities[6,31].

Patterns of Temperature Change Produced by Various Atmospheric Factors



Modified from CCSP 1.1[54]

Climate simulations of the vertical profile of temperature change due to various factors, and the effect due to all factors taken together.

Scientists are sometimes asked whether extreme weather events can be linked to human activities[56]. Scientific research has concluded that human influences on climate are indeed changing the likelihood of certain types of extreme events. For example, an analysis of the European summer heat wave of 2003 found that the risk of such a heat wave is now roughly four times as great due to human influences on climate[57,58].

Like fingerprint work, such analyses of human-caused changes in the risks of extreme events rely on information from climate models, and on our understanding of the physics of the climate system. All of the models used in this work have imperfections in their representation of the complexities of the "real world" climate system[59,60]. These are due to both limits in our understanding of the climate system, and in our ability to represent its complex behavior with available computer resources. Despite this, models are extremely useful, for a number of reasons.

First, despite the existence of systematic errors, the current generation of climate models accurately portrays many important aspects of today's weather patterns and climate[59,60]. Models are constantly being improved, and are routinely tested against many observations of Earth's climate system. Second, the fingerprint work shows that models capture not only our present-day climate, but also key features of the observed climate changes over the past century[29]. Third, many of the large-scale observed climate changes (such as the warming of the surface and troposphere, and the increase in the amount of moisture in the atmosphere) are driven by very basic physics, which is well-represented in models[19]. Fourth, climate models can be used to predict changes in climate that can be verified in the real world. Examples include the global cooling subsequent to the eruption of Mount Pinatubo and the stratospheric cooling with increasing carbon dioxide. Finally, models are the only tools that exist for trying to understand the climate changes likely to be experienced over the course of this century. No period in Earth's geological history provides an exact analogue for the climatic conditions that will unfold in the coming decades.

Global temperatures will continue to rise over this century; by how much and for how long depends on a number of factors, including the amount of heat-trapping emissions and how sensitive the climate is to those emissions.

Some continued warming of the planet is inevitable over the next few decades. The amount of future warming will be determined largely by choices made now and over the next few decades. Lower levels of heat-trapping emissions will yield less future warming, while higher levels will result in more warming, and more severe impacts on society and the natural world.

Rising global temperature

All climate models project that human-caused emissions of heat-trapping gases will cause further warming in the future. Based on scenarios that do not assume explicit climate policies to reduce greenhouse gas emissions, global average temperature is projected to rise by 2 to 11.5°F by the end of this century[61] (relative to the 1980-1999 time period). Whether the actual warming in 2100 will be closer to the low or the high end of this range depends primarily on two factors: first, the future level of emissions of heat-trapping gases, and second, how sensitive climate will be, that is, how much climate will change in response to those emissions. The range of possible outcomes has been explored using a range of different emissions scenarios, and a variety of climate models that encompass the known range of climate sensitivity.

The IPCC developed a set of scenarios in a Special Report on Emissions Scenarios (SRES)[62]. These have been extensively used to explore the potential for future climate change. None of these scenarios assumes explicit policies to limit climate change. Rather, emissions in these scenarios vary based on different assumptions about changes in population, adoption of new technologies, economic growth, and other factors. None of them involve stabilizing atmospheric concentrations of heat-trapping gases at a level that would avoid dangerous human interference with the climate system as required by the United Nations' Framework Convention on Climate Change, which was signed in 1992 by the United States and most other countries.

Changing precipitation patterns

Projections of changes in precipitation largely follow recently observed patterns of change, with overall increases in the global average but substantial shifts in where and how precipitation falls[61]. Generally, higher latitudes are projected to receive more precipitation, while the sub-tropics expand further poleward[63] and also receive less rain. Increases in tropical precipitation are projected during rainy seasons (such as monsoons), and especially over the tropical Pacific. Certain regions, including the U.S. West (especially the Southwest) and the Mediterranean, are expected to become drier. The trend towards more heavy downpours is expected to continue, with precipitation becoming less frequent but more intense[61]. More precipitation is expected to fall as rain rather than snow.

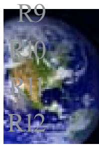
Currently rare extreme events are becoming more common

In a warmer future climate, models project there will be an increased risk of more intense, more frequent and longer-lasting heat waves[61]. The European heat wave of 2003 is an example of the type of extreme heat event that is likely to become more common[61], with the likelihood of such a heat wave projected to increase 100-fold in the next 40 years. If greenhouse gas emissions continue to increase, by the 2040s more than half of European summers will be hotter than the summer of 2003, and by the end of this century, a summer as hot as that of 2003 will be considered unusually cool[57].

Increased extremes of summer dryness and winter wetness are projected for much of the globe, meaning a generally greater risk of droughts and floods. This has already been observed[38], and is projected to continue, because in a warmer world, precipitation tends to be concentrated into more intense events, with longer periods of little precipitation in between[61].

Models project a general tendency for more intense but fewer storms overall outside the tropics, with more extreme wind events and higher ocean waves in a number of regions in association with those storms. Models also project a shift of storm tracks toward the poles in both hemispheres[61].

Changes in hurricanes are difficult to project because there are countervailing forces. Higher ocean temperatures lead to stronger storms with higher wind speeds and more rainfall[64]. But changes in wind speed and direction with height are also projected to increase in some regions, and this tends to work against storm formation and growth[65]. It currently appears that stronger, more rain-producing tropical storms and hurricanes are generally more likely, though more research is required on these issues.



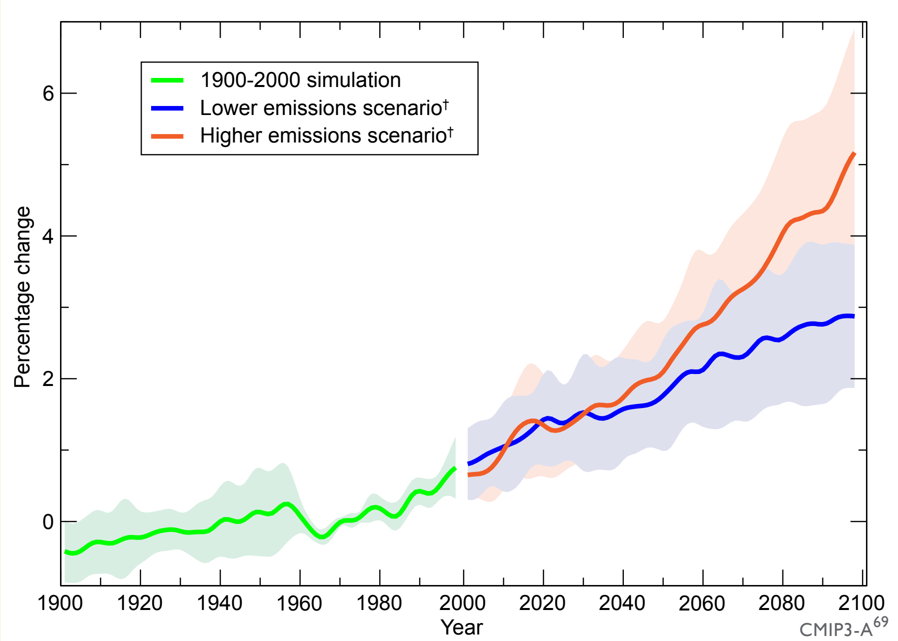
Sea level will continue to rise

Projecting future sea-level rise presents special challenges. Scientists have a well-developed understanding of the contributions of thermal expansion and melting glaciers to sea-level rise, so the models used to project sea-level rise include these processes. However, recent observations of the polar ice sheets show that additional processes are operating that affect the responses of ice sheets to warming. Although these processes are not well understood, they are already producing substantial additional loss of ice mass, but it is difficult to predict their future contributions to sea-level rise.

Thus, most current estimates offer only a likely lower bound for future sea-level rise projections, with a highly uncertain upper bound. The 2007 assessment by the IPCC, for example, which did not attempt to include the highly uncertain contributions to sea-level rise due to changes in ice sheet dynamics, projected a rise of the world's oceans from 8 inches to 2 feet by the end of this century[61].

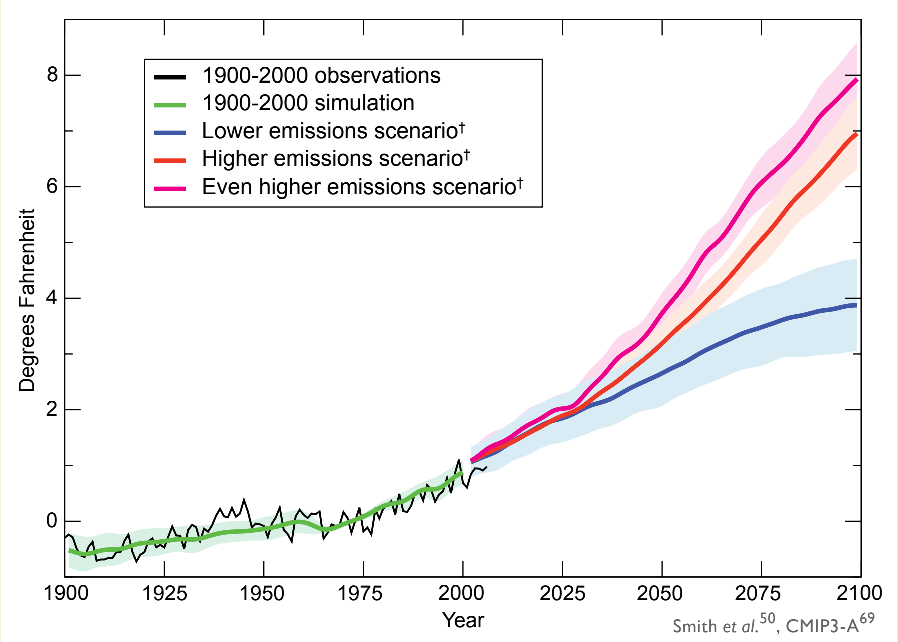
Recent research has led to more comprehensive estimates of the accelerated flow to the sea of ice sheets in a warmer climate and how this contributes to sea-level rise. This work suggests that the upper and lower limits on sea-level rise over this century are substantially greater than previously projected[13,66-68].

The changes in sea level experienced at any particular location along the coast depend not only on the increase in the global average sea level, but also on changes in regional currents and winds and, particularly, on the vertical movements of the land due to geological forces. The consequences of sea-level rise at any particular location depend on the amount of sea-level rise relative to the adjoining land. Although some parts of the U.S. coast are undergoing uplift (rising), most shorelines are subsiding (sinking) to various degrees—from a few inches to over 2 feet per century.


Global Increase in Heavy Precipitation

CMIP3-A[69]

Observed and projected changes in the heaviest 5 percent of precipitation events. The shaded areas show the possible ranges while the lines show the central projections from a set of climate models.


Observed and Projected Global Average Temperature

Smith *et al.*[50], CMIP3-A[69]

Observed and projected changes in the global average temperature under three IPCC no-policy emissions scenarios. The shaded areas show the possible ranges while the lines show the central projections from a set of climate models.

Emissions scenarios

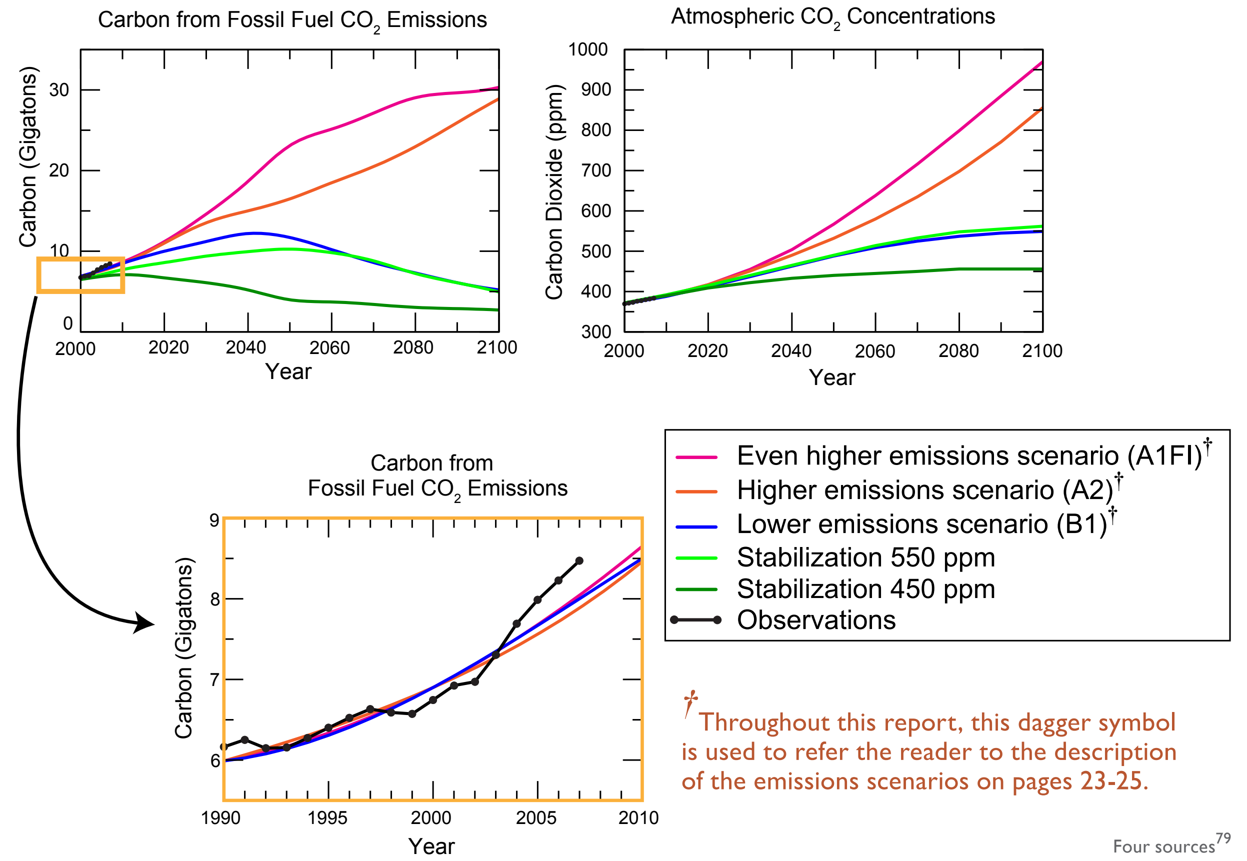
The IPCC emission scenarios do not encompass the full range of possible futures: climate can change less than those scenarios imply, or it can change more. Current carbon dioxide emissions are, in fact, above the highest emissions scenario† developed by the IPCC[70] (see figure on page 25). Whether this will continue is uncertain.

There are also lower possible emissions paths than those put forth by the IPCC. The Framework Convention on Climate Change, to which the United States and most other countries are signatories, calls for stabilizing concentrations of greenhouse gases in the atmosphere at a level that would avoid dangerous human interference with the climate system. What exactly constitutes such interference is subject to interpretation.

A variety of research studies suggest that a further 2°F increase (relative to the 1980-1999 period) would lead to severe, widespread, and irreversible impacts[71-73]. To have a good chance (but not a guarantee) of avoiding temperatures above those levels, it has been estimated that atmospheric concentrations of carbon dioxide would need to stabilize in the long term at around today's levels[74-77].

The graphs above show emissions scenarios and resulting CO_2 concentrations for three IPCC scenarios[†,61] and two stabilization scenarios[78]. The stabilization scenarios are aimed at stabilizing atmospheric CO_2 at roughly 450 and 550 parts per million (ppm); this is 70 to 170 ppm above the current concentration of about 380 ppm. Resulting temperature changes depend on the level of CO_2, how sensitive the climate system is, and

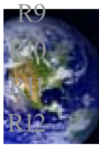
Scenarios of Future Carbon Dioxide Emissions and Concentrations



† Throughout this report, this dagger symbol is used to refer the reader to the description of the emissions scenarios on pages 23-25.

Four sources[79]

The graphs show recent and projected global emissions of carbon dioxide in gigatons of carbon, on the left, and atmospheric concentrations on the right under five emissions scenarios. The top three in the key are IPCC scenarios that assume no explicit climate policies (these are used in model projections that appear throughout this report). The bottom two are "stabilization scenarios," designed to stabilize atmospheric carbon dioxide concentrations at 450 or 550 parts per million. The inset expanded below these charts shows emissions for the current two decades under these five scenarios along with actual emissions (in black).



the amount of particles in the atmosphere[75]. Only the 450 ppm stabilization target has the potential to keep the global temperature rise at or below about 3.5ºF from pre-industrial and 2ºF above current, a level beyond which many concerns have been raised about dangerous human interference with the climate system[76,77].

A further complication is that carbon dioxide is not the only greenhouse gas of concern. Concentrations of other heat-trapping gases like methane and nitrous oxide and particles like soot will also have to be stabilized at low enough levels to prevent global temperatures from rising higher than the level mentioned above. When these other gases are added, including the offsetting cooling effects of sulfate aerosol particles, analyses suggest that stabilizing concentrations around 400 parts per million of equivalent CO_2 would yield about an 80 percent chance of avoiding exceeding the 2ºF above present temperature threshold. This would be true even if concentrations temporarily peaked as high as 475 parts per million and then stabilized at 400 parts per million roughly a century later[50,69,76,77,80,81].

Rapid climate change

There is also the possibility of even larger climate change than current scenarios and models project. Not all changes in the climate are gradual. The long record of climate found in ice cores, tree rings, and other natural records show that Earth's climate patterns have undergone rapid shifts from one stable state to another within as short a period as a decade. The occurrence of rapid climate changes becomes increasingly more likely as the human disturbance of the climate system grows[61]. Such changes can occur so rapidly that they would challenge the ability of human and natural systems to adapt[82]. Examples of such changes are rapid shifts in drought frequency and duration. Ancient climate records suggest that in the United States, the Southwest may be at greatest risk for this kind of change, but that other regions including the Midwest and Great Plains have also had these kinds of rapid shifts in the past and could experience them again in the future.

Rapid ice sheet collapse with related sea-level rise is another type of rapid change that is not well understood or modeled that poses a risk for the future. Recent observations show that melting on the surface of an ice sheet produces water that flows down through large cracks that create conduits through the ice to the base of the ice sheet where it lubricates ice previously frozen to the rock below[82]. Further, the interaction with warm ocean water, where ice meets the sea, can lead to sudden losses in ice mass and accompanying rapid global sea-level rise. Observations indicate that ice loss has increased dramatically over the last decade, though scientists are not yet confident that they can project how the ice sheets will respond in the future.