



About this Report



What is this report?

This report summarizes the science of climate change and the impacts of climate change on the United States, now and in the future. It is largely based on results of the U.S. Global Change Research Program (USGCRP),^a and integrates those results with related research from around the world. This report discusses climate-related impacts for various societal and environmental sectors and regions across the nation. It is an authoritative scientific report written in plain language, with the goal of better informing public and private decision making at all levels.

Who called for it, who wrote it, and who approved it?

The USGCRP called for this report. An expert team of scientists operating under the authority of the Federal Advisory Committee Act, assisted by communication specialists, wrote the document. The report was extensively reviewed and revised based on comments from experts and the public. The report was approved by its lead USGCRP Agency, the National Oceanic and Atmospheric Administration, the other USGCRP agencies, and the Committee on the Environment and Natural Resources on behalf of the National Science and Technology Council.^b This report meets all Federal requirements associated with the Information Quality Act, including those pertaining to public comment and transparency.

What are its sources?

The report draws from a large body of scientific information. The foundation of this report is a set of 21 Synthesis and Assessment Products (SAPs), which were designed to address key policy-relevant issues in climate science (see page 161); several of these were also summarized in the *Scientific Assessment of the Effects of Climate Change on the United States* published in 2008. In addition, other peer-reviewed scientific assessments were used, including those of the Intergovernmental Panel on Climate Change, the U.S. National Assessment of the Consequences of Climate Variability and Change, the Arctic Climate Impact Assessment, the National Research Council's Transportation Research Board report on the Potential Impacts of Climate Change on U.S. Transportation, and a variety of regional climate impact assessments. These assessments were augmented with government statistics as necessary (such as population census and energy usage) as well as publicly available observations and peer-reviewed research published through the end of 2008. This new work was carefully selected by the author team with advice from expert reviewers to update key aspects of climate change science relevant to this report. The icons on the bottom of this page represent some of the major sources drawn upon for this synthesis report.

On the first page of each major section, the sources primarily drawn upon for that section are shown using these icons. Endnotes, indicated by superscript numbers and compiled at the end of the book, are used for specific references throughout the report.

See page 161 for descriptions of these sources.

^a. The U.S. Global Change Research Program (USGCRP), which was established in 1990 by the Global Change Research Act, encompasses the Climate Change Science Program (CCSP).
^b. A description of the National Science and Technology Council (NSTC) can be found at www.ostp.gov/cs/nstc.



U.S. Global Change Research Program

Does this report deal with options for responding to climate change?

While the primary focus of this report is on the impacts of climate change in the United States, it also deals with some of the actions society is already taking or can take to respond to the climate challenge. Responses to climate change fall into two broad categories. The first involves “mitigation” measures to reduce climate change by, for example, reducing emissions of heat-trapping gases and particles, or increasing removal of heat-trapping gases from the atmosphere. The second involves “adaptation” measures to improve our ability to cope with or avoid harmful impacts and take advantage of beneficial ones, now and in the future. Both of these are necessary elements of an effective response strategy. These two types of responses are linked in that more effective mitigation measures reduce the amount of climate change, and therefore the need for adaptation.

This report underscores the importance of mitigation by comparing impacts resulting from higher versus lower emissions scenarios. The report shows that choices made about emissions in the next few decades will have far-reaching consequences for climate change impacts. Over the long term, lower emissions will lessen both the magnitude of climate change impacts and the rate at which they appear.

While the report underscores the importance of mitigation as an essential part of the nation’s climate change strategy, it does not evaluate mitigation technologies or undertake an analysis of the effectiveness of various approaches. These issues are the subject of ongoing studies by the U.S. Government’s Climate Change Technology Program and several federal agencies including the Department of Energy, Environmental Protection Agency, National Oceanic and Atmospheric Administration, Department of Transportation, and Department of Agriculture. The range of mitigation responses being studied includes more efficient production and use of energy, increased use of non-carbon-emitting energy sources, and carbon capture and storage.

Adaptation options also have the potential to moderate harmful impacts of current and future climate variability and change. While this report does address adaptation, it does not do so comprehensively.

Global Climate Change Impacts in the United States

Rather, in the context of impacts, this report identifies examples of actions currently being pursued in various sectors and regions to address climate change, as well as other environmental problems that could be exacerbated by climate change such as urban air pollution and heat waves. In most cases, there is currently insufficient peer-reviewed information to evaluate the practicality, effectiveness, costs, or benefits of these measures, highlighting a need for research in this area. Thus, the discussion of various public and private adaptation examples should not be viewed as an endorsement of any particular option, but rather as illustrative examples of approaches being tried.

How is the likelihood of various outcomes expressed given that the future is not certain?

When it is considered necessary to express a range of possible outcomes and identify the likelihood of particular impacts, this report takes a plain-language approach to expressing the expert judgment of the author team based on the best available evidence. For example, an outcome termed “likely” has at least a two-thirds chance of occurring; an outcome termed “very likely,” at least a 90 percent chance.¹ In using these terms, the Federal Advisory Committee has taken into consideration a wide range of information, including the strength and consistency of the observed evidence, the range and consistency of model projections, the reliability of particular models as tested by various methods, and most importantly, the body of work addressed in earlier synthesis and assessment reports. Key sources of information used to develop these characterizations of uncertainty are referenced in endnotes.

How does this report address incomplete scientific understanding?

This assessment identifies areas in which scientific uncertainty limits our ability to estimate future climate change and its impacts. The section on *An Agenda for Climate Impacts Science* at the end of this report highlights some of these areas.



Executive Summary



Observations show that warming of the climate is unequivocal. The global warming observed over the past 50 years is due primarily to human-induced emissions of heat-trapping gases. These emissions come mainly from the burning of fossil fuels (coal, oil, and gas), with important contributions from the clearing of forests, agricultural practices, and other activities.

Warming over this century is projected to be considerably greater than over the last century. The global average temperature since 1900 has risen by about 1.5°F. By 2100, it is projected to rise another 2 to 11.5°F. The U.S. average temperature has risen by a comparable amount and is very likely to rise more than the global average over this century, with some variation from place to place. Several factors will determine future temperature increases. Increases at the lower end of this range are more likely if global heat-trapping gas emissions are cut substantially. If emissions continue to rise at or near current rates, temperature increases are more likely to be near the upper end of the range. Volcanic eruptions or other natural variations

could temporarily counteract some of the human-induced warming, slowing the rise in global temperature, but these effects would only last a few years.

Reducing emissions of carbon dioxide would lessen warming over this century and beyond. Sizeable early cuts in emissions would significantly reduce the pace and the overall amount of climate change. Earlier cuts in emissions would have a greater effect in reducing climate change than comparable reductions made later. In addition, reducing emissions of some shorter-lived heat-trapping gases, such as methane, and some types of particles, such as soot, would begin to reduce warming within weeks to decades.

Climate-related changes have already been observed globally and in the United States. These include increases in air and water temperatures, reduced frost days, increased frequency and intensity of heavy downpours, a rise in sea level, and reduced snow cover, glaciers, permafrost, and sea ice. A longer ice-free period on lakes and rivers, lengthening of the growing season, and increased water vapor in the atmosphere have also been observed. Over the past 30 years, temperatures have risen faster in winter than in any other season, with average winter temperatures in the Midwest and northern Great Plains increasing more than 7°F. Some of the changes have been faster than previous assessments had suggested.

These climate-related changes are expected to continue while new ones develop. Likely future changes for the United States and surrounding coastal waters include more intense hurricanes with related increases in wind, rain, and storm surges (but not necessarily an increase in the number of these storms that make landfall), as well as drier conditions in the Southwest and Caribbean. These changes will affect human health, water supply, agriculture, coastal areas, and many other aspects of society and the natural environment.

This report synthesizes information from a wide variety of scientific assessments (see page 7) and recently published research to summarize what is known about the observed and projected consequences of climate change on the United States. It combines analysis of impacts on various sectors

U.S. Global Change Research Program

Global Climate Change Impacts in the United States



such as energy, water, and transportation at the national level with an assessment of key impacts on specific regions of the United States. For example, sea-level rise will increase risks of erosion, storm surge damage, and flooding for coastal communities, especially in the Southeast and parts of Alaska. Reduced snowpack and earlier snow melt will alter the timing and amount of water supplies, posing significant challenges for water resource management in the West.

Society and ecosystems can adjust to some climatic changes, but this takes time. The projected rapid rate and large amount of climate change over this century will challenge the ability of society and natural systems to adapt. For example, it is difficult and expensive to alter or replace infrastructure designed to last for decades (such as buildings, bridges, roads, airports, reservoirs, and ports) in response to continuous and/or abrupt climate change.

Impacts are expected to become increasingly severe for more people and places as the amount of warming increases. Rapid rates of warming would lead to particularly large impacts on natural ecosystems and the benefits they provide to humanity. Some of the impacts of climate change will be irreversible, such as species extinctions and coastal land lost to rising seas.

Unanticipated impacts of increasing carbon dioxide and climate change have already occurred and more are possible in the future. For example, it has recently been observed that the increase in atmospheric carbon dioxide concentration is causing an increase in ocean acidity. This reduces the ability of corals and other sea life to build shells and skeletons out of calcium carbonate. Additional impacts in the future might stem from unforeseen changes in the climate system, such as major alterations in oceans, ice, or storms; and unexpected consequences of ecological changes, such as massive dislocations of species or pest outbreaks. Unexpected social or economic changes, including major shifts in wealth, technology, or societal priorities would also affect our ability to respond to climate change. Both anticipated and unanticipated impacts become more challenging with increased warming.

Projections of future climate change come from careful analyses of outputs from global climate models run on the world's most advanced computers. The model simulations analyzed in this report used plausible scenarios of human activity that generally lead to further increases in heat-trapping emissions. None of the scenarios used in this report assumes adoption of policies explicitly designed to address climate change. However, the level of emissions varies among scenarios because of differences in assumptions about population, economic activity, choice of energy technologies, and other factors. Scenarios cover a range of emissions of heat-trapping gases, and the associated climate projections illustrate that lower emissions result in less climate change and thus reduced impacts over this century and beyond. Under all scenarios considered in this report, however, relatively large and sustained changes in many aspects of climate are projected by the middle of this century, with even larger changes by the end of this century, especially under higher emissions scenarios.

In projecting future conditions, there is always some level of uncertainty. For example, there is a high degree of confidence in projections that future temperature increases will be greatest in the Arctic and in the middle of continents. For precipitation, there is high confidence in projections of continued increases in the Arctic and sub-Arctic (including Alaska) and decreases in the regions just outside the tropics, but the precise location of the transition between these is less certain. At local to regional scales and on time frames up to a few years, natural climate variations can be relatively large and can temporarily mask the progressive nature of global climate change. However, the science of making skillful projections at these scales has progressed considerably, allowing useful information to be drawn from regional climate studies such as those highlighted in this report.

This report focuses on observed and projected climate change and its impacts on the United States. However, a discussion of these issues would be incomplete without mentioning some of the actions society can take to respond to the climate challenge. The two major categories are "mitigation" and "adaptation." Mitigation refers to options for limiting climate change by, for example, reducing

heat-trapping emissions such as carbon dioxide, methane, nitrous oxide, and halocarbons, or removing some of the heat-trapping gases from the atmosphere. Adaptation refers to changes made to better respond to present or future climatic and other environmental conditions, thereby reducing harm or taking advantage of opportunity. Effective mitigation measures reduce the need for adaptation. Mitigation and adaptation are both essential parts of a comprehensive climate change response strategy.

Carbon dioxide emissions are a primary focus of mitigation strategies. These include improving energy efficiency, using energy sources that do not produce carbon dioxide or produce less of it, capturing and storing carbon dioxide from fossil fuel use, and so on. Choices made about emissions reductions now and over the next few decades will have far-reaching consequences for climate-change impacts. The importance of mitigation is clear in comparisons of impacts resulting from higher versus lower emissions scenarios considered in this report. Over the long term, lower emissions will lessen both the magnitude of climate-change impacts and the rate at which they appear. Smaller climate changes that come more slowly make the adaptation challenge more tractable.

However, no matter how aggressively heat-trapping emissions are reduced, some amount of climate change and resulting impacts will continue due to the effects of gases that have already been released. This is true for several reasons. First, some of these gases are very long-lived and the levels of atmospheric heat-trapping gases will remain elevated for hundreds of years or more. Second, the Earth's vast oceans have absorbed much of the heat added to the climate system due to the increase in heat-trapping gases, and will retain that heat for many decades. In addition, the factors that determine emissions, such as energy-supply systems, cannot be changed overnight. Consequently, there is also a need for adaptation.

Adaptation can include a wide range of activities. Examples include a farmer switching to growing a different crop variety better suited to warmer or drier conditions; a company relocating key business centers away from coastal areas vulnerable to sea-level rise and hurricanes; and a community

altering its zoning and building codes to place fewer structures in harm's way and making buildings less vulnerable to damage from floods, fires, and other extreme events. Some adaptation options that are currently being pursued in various regions and sectors to deal with climate change and/or other environmental issues are identified in this report. However, it is clear that there are limits to how much adaptation can achieve.

Humans have adapted to changing climatic conditions in the past, but in the future, adaptations will be particularly challenging because society won't be adapting to a new steady state but rather to a rapidly moving target. Climate will be continually changing, moving at a relatively rapid rate, outside the range to which society has adapted in the past. The precise amounts and timing of these changes will not be known with certainty.

In an increasingly interdependent world, U.S. vulnerability to climate change is linked to the fates of other nations. For example, conflicts or mass migrations of people resulting from food scarcity and other resource limits, health impacts, or environmental stresses in other parts of the world could threaten U.S. national security. It is thus difficult to fully evaluate the impacts of climate change on the United States without considering the consequences of climate change elsewhere. However, such analysis is beyond the scope of this report.

Finally, this report identifies a number of areas in which inadequate information or understanding hampers our ability to estimate future climate change and its impacts. For example, our knowledge of changes in tornadoes, hail, and ice storms is quite limited, making it difficult to know if and how such events have changed as climate has warmed, and how they might change in the future. Research on ecological responses to climate change is also limited, as is our understanding of social responses. The section titled *An Agenda for Climate Impacts Science* at the end of this report offers some thoughts on the most important ways to improve our knowledge. Results from such efforts would inform future assessments that continue building our understanding of humanity's impacts on climate, and climate's impacts on us.



Key Findings

1. Global warming is unequivocal and primarily human-induced.

Global temperature has increased over the past 50 years. This observed increase is due primarily to human-induced emissions of heat-trapping gases. (p. 13)

2. Climate changes are underway in the United States and are projected to grow.

Climate-related changes are already observed in the United States and its coastal waters. These include increases in heavy downpours, rising temperature and sea level, rapidly retreating glaciers, thawing permafrost, lengthening growing seasons, lengthening ice-free seasons in the ocean and on lakes and rivers, earlier snowmelt, and alterations in river flows. These changes are projected to grow. (p. 27)

3. Widespread climate-related impacts are occurring now and are expected to increase.

Climate changes are already affecting water, energy, transportation, agriculture, ecosystems, and health. These impacts are different from region to region and will grow under projected climate change. (p. 41-106, 107-152)

4. Climate change will stress water resources.

Water is an issue in every region, but the nature of the potential impacts varies. Drought, related to reduced precipitation, increased evaporation, and increased water loss from plants, is an important issue in many regions, especially in the West. Floods and water quality problems are likely to be amplified by climate change in most regions. Declines in mountain snowpack are important in the West and Alaska where snowpack provides vital natural water storage. (p. 41, 129, 135, 139)

5. Crop and livestock production will be increasingly challenged.

Many crops show positive responses to elevated carbon dioxide and low levels of warming, but higher levels of warming often negatively affect growth and yields. Increased pests, water stress, diseases, and weather extremes will pose adaptation challenges for crop and livestock production. (p. 71)

6. Coastal areas are at increasing risk from sea-level rise and storm surge.

Sea-level rise and storm surge place many U.S. coastal areas at increasing risk of erosion and flooding, especially along the Atlantic and Gulf Coasts, Pacific Islands, and parts of Alaska. Energy and transportation infrastructure and other property in coastal areas are very likely to be adversely affected. (p. 111, 139, 145, 149)

7. Risks to human health will increase.

Harmful health impacts of climate change are related to increasing heat stress, waterborne diseases, poor air quality, extreme weather events, and diseases transmitted by insects and rodents. Reduced cold stress provides some benefits. Robust public health infrastructure can reduce the potential for negative impacts. (p. 89)

8. Climate change will interact with many social and environmental stresses.

Climate change will combine with pollution, population growth, overuse of resources, urbanization, and other social, economic, and environmental stresses to create larger impacts than from any of these factors alone. (p. 99)

9. Thresholds will be crossed, leading to large changes in climate and ecosystems.

There are a variety of thresholds in the climate system and ecosystems. These thresholds determine, for example, the presence of sea ice and permafrost, and the survival of species, from fish to insect pests, with implications for society. With further climate change, the crossing of additional thresholds is expected. (p. 76, 82, 115, 137, 142)

10. Future climate change and its impacts depend on choices made today.

The amount and rate of future climate change depend primarily on current and future human-caused emissions of heat-trapping gases and airborne particles. Responses involve reducing emissions to limit future warming, and adapting to the changes that are unavoidable. (p. 25, 29)



Global Climate Change

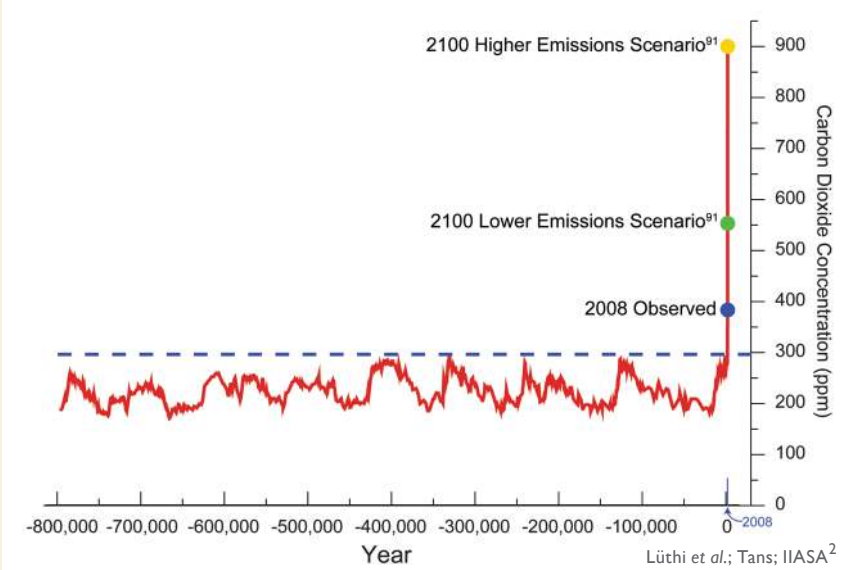
Key Messages:

- Human activities have led to large increases in heat-trapping gases over the past century.
- Global average temperature and sea level have increased, and precipitation patterns have changed.
- The global warming of the past 50 years is due primarily to human-induced increases in heat-trapping gases. Human “fingerprints” also have been identified in many other aspects of the climate system, including changes in ocean heat content, precipitation, atmospheric moisture, and Arctic sea ice.
- Global temperatures are projected to 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 gas emissions and how sensitive the climate is to those emissions.

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 requires an understanding of the global climate system.

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.

800,000 Year Record of Carbon Dioxide Concentration



Analysis of air bubbles trapped in an Antarctic ice core extending back 800,000 years documents the Earth’s changing carbon dioxide concentration. Over this long period, natural factors have caused the atmospheric carbon dioxide concentration to vary within a range of about 170 to 300 parts per million (ppm). Temperature-related data make clear that these variations have played a central role in determining the global climate. As a result of human activities, the present carbon dioxide concentration of about 385 ppm is about 30 percent above its highest level over at least the last 800,000 years. In the absence of strong control measures, emissions projected for this century would result in the carbon dioxide concentration increasing to a level that is roughly 2 to 3 times the highest level occurring over the glacial-interglacial era that spans the last 800,000 or more years.



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 natural “greenhouse effect.” This effect is the result of heat-trapping gases (also known as greenhouse 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 toward the surface. Without this natural greenhouse effect, the average surface temperature of the Earth would be about 60°F colder. However, human activities have been releasing additional heat-trapping gases, intensifying the natural greenhouse effect, thereby changing the Earth’s climate.

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 in the mid-1700s, primarily due to the burning of fossil fuels (coal, oil, and natural gas) and the clearing of forests. Human activities have also increased the emissions of other greenhouse gases, such as methane, nitrous oxide, and halocarbons.³

These emissions are thickening the blanket of heat-trapping gases in Earth’s atmosphere, causing surface temperatures to rise.

Heat-trapping gases

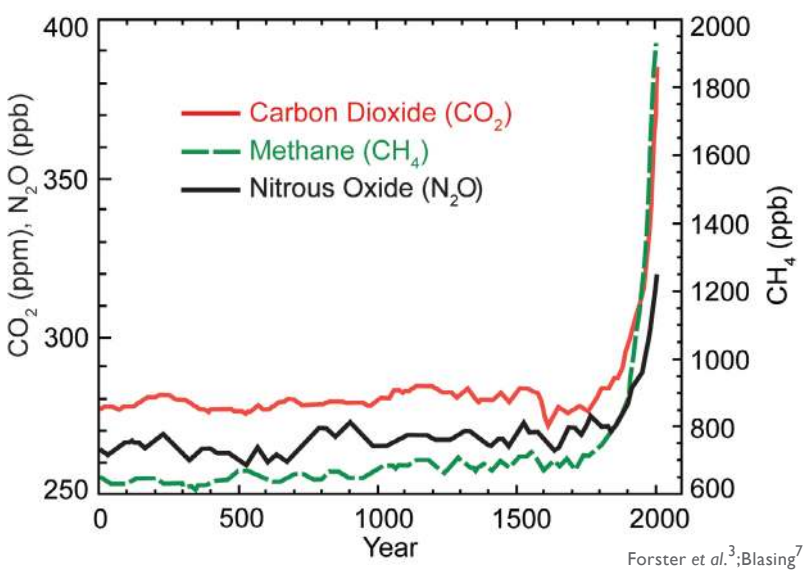
Carbon dioxide concentration has increased due to the use of fossil fuels in electricity generation, transportation, and industrial and household uses. It is also produced as a by-product during the manufacturing of cement. Deforestation provides a source of carbon dioxide and reduces its uptake by trees 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 and associated agricultural practices. The concentration of carbon dioxide in the atmosphere has increased by roughly 35 percent since the start of the industrial revolution.³

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.⁴

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

Halocarbon emissions come from the release of certain manufactured chemicals to the atmosphere. Examples include chlorofluorocarbons (CFCs), which were used extensively in refrigeration and for 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 ozone-depleting halocarbon emissions are expected to reduce their relative influence on climate change in the future.^{3,5} Many halocarbon replacements, however, are potent greenhouse gases, and their concentrations are increasing.⁶

2,000 Years of Greenhouse Gas Concentrations



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.

Ozone 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 the 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.⁸ Changes in the stratospheric ozone layer have contributed to changes in wind patterns and regional climates in Antarctica.⁹

Water vapor is the most important and abundant greenhouse gas in the atmosphere. Human activities produce only a very small increase in water vapor through irrigation and combustion processes.³ However, the surface warming caused by human-produced increases in other greenhouse gases leads to an increase in atmospheric water vapor, since a warmer climate increases evaporation and allows the atmosphere to hold more moisture. This creates an amplifying “feedback loop,” leading to more warming.

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, causing a cooling influence at the surface. 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.¹³ On a globally averaged basis, the sum of these aerosol effects offsets some of the warming caused by heat-trapping gases.¹⁰

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 thousands of years, and that of methane for decades, while the elevated concentrations of aerosols only persist for days to weeks.^{11,12} The climate effects of reductions in emissions of carbon dioxide and other long-lived gases do not become apparent for at least several decades. In contrast, reductions in emissions of short-lived compounds can have a rapid, but complex effect since the geographic patterns of their climatic influence and the resulting surface temperature responses are quite different. One modeling study found that while the greatest emissions of short-lived pollutants in summertime by late this century are projected to come from Asia, the strongest climate response is projected to be over the central United States.¹³

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.^{14,15}

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 historical 11-year cycle





of small ups and downs, but with no net increase (see figure page 20).¹⁶ The two major volcanic eruptions of the past 30 years have had short-term cooling effects on climate, lasting 2 to 3 years.¹⁷ 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 fluctuations in climate 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 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.

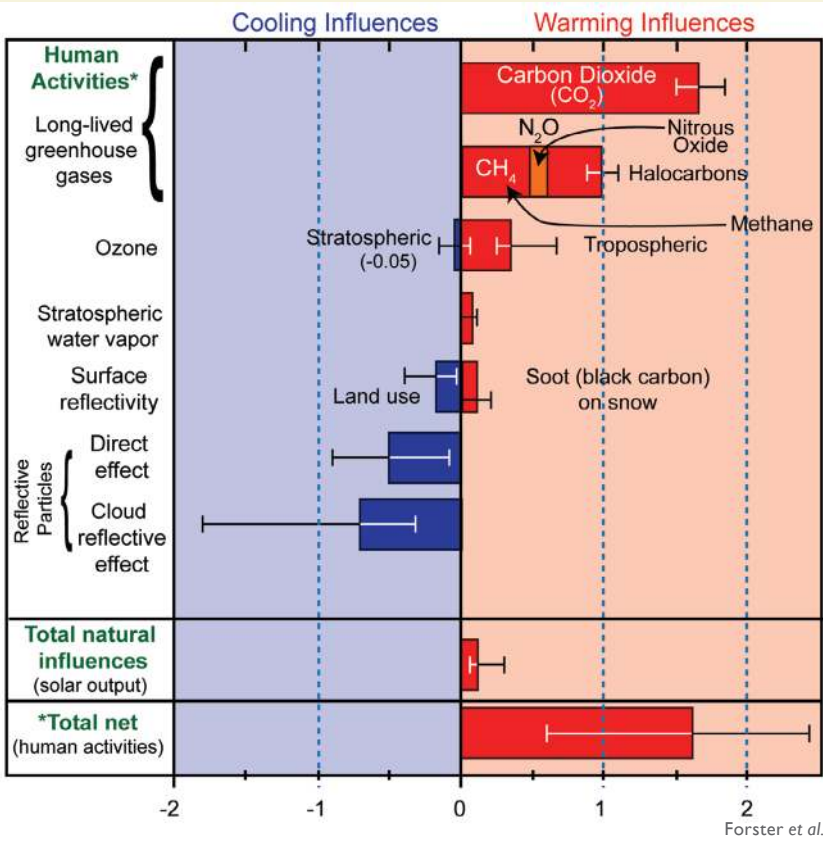
Carbon release and uptake

Once carbon dioxide is emitted to the atmosphere, some of it is absorbed by the oceans and taken up by vegetation, although this storage may be temporary. About 45 percent of the carbon dioxide emitted by human activities in the last 50 years is now

stored in the oceans and vegetation. The rest has remained in the air, increasing the atmospheric concentration.^{2,3,18} 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. For example, it is known from long records of Earth’s climate history that under warmer conditions, carbon tends to be released, for instance, from thawing permafrost, initiating a feedback loop in which more carbon release leads to more warming which leads to further release, and so on.^{19,20}

Global emissions of carbon dioxide have been accelerating. The growth rate increased from 1.3 percent per year in the 1990s to 3.3 percent per year between 2000 and 2006.²¹ The increasing emissions of carbon dioxide are the primary cause of the increased concentration of carbon dioxide observed in the atmosphere. There is also evidence that a smaller fraction of the annual human-induced emissions is now being taken up than in the past, leading to a greater fraction remaining in the atmosphere and an accelerating rate of increase in the carbon dioxide concentration.²¹

Major Warming and Cooling Influences on Climate
1750-2005



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), thus their influence is not included in this figure. The bottom part of the box shows that the total net effect (warming influences minus cooling influences) of human activities is a strong warming influence. The thin lines on each bar provide an estimate of the range of uncertainty.