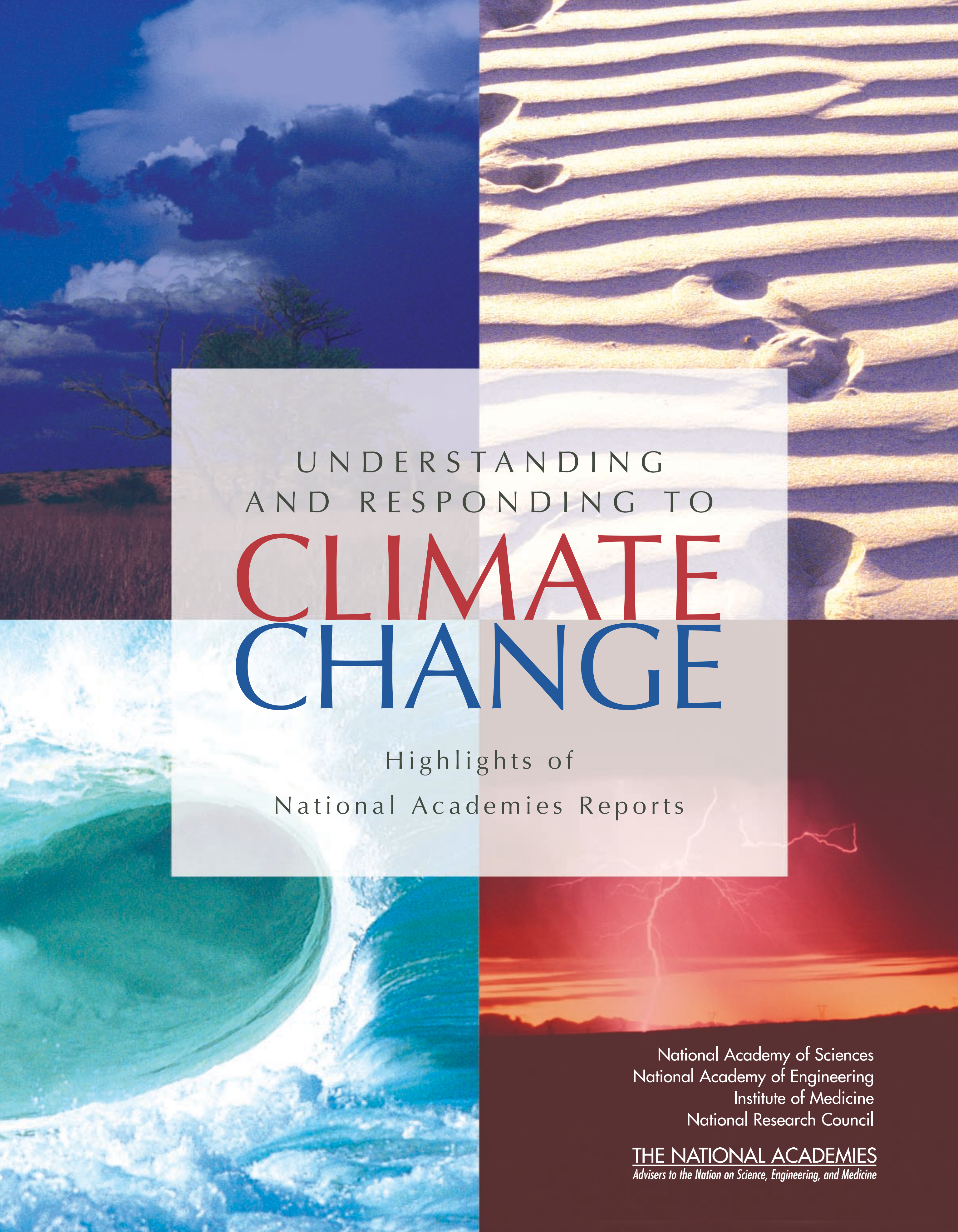


UNDERSTANDING AND RESPONDING TO CLIMATE CHANGE

Highlights of National Academies Reports

National Academy of Sciences
National Academy of Engineering
Institute of Medicine
National Research Council

THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

UNDERSTANDING AND RESPONDING TO

CLIMATE CHANGE

A GROWING BODY OF EVIDENCE

indicates that the Earth's atmosphere is warming. Records show that surface temperatures have risen about 1.4ºF (0.7ºC) since the early twentieth century, and that about 0.9ºF (0.5ºC) of this increase has occurred since 1978. Observed changes in oceans, ecosystems, and ice cover are consistent with this warming trend.

The fact is that Earth's climate is always changing. A key question is how much of the observed warming is due to human activities and how much is due to natural variability in the climate. In the judgment of most climate scientists, Earth's warming in recent decades has been caused primarily by human activities that have increased the amount of greenhouse gases in the atmosphere *(see Figure 1)*. Greenhouse gases have increased significantly since the Industrial Revolution, mostly from the burning of fossil fuels for energy, industrial processes, and transportation. Greenhouse gases are at their highest levels in at least 400,000 years and continue to rise.

Global warming could bring good news for some parts of the world, such as longer growing seasons and milder winters. Unfortunately, it could bring bad news for a much higher percentage of the world's people. Those in coastal communities, many in developing nations, will likely experience increased flooding due to sea-level rise and more severe storms and surges. In the Arctic regions, where temperatures have increased almost twice as much as the global average, the landscape and ecosystems are rapidly changing.

Although the potential effects of climate change are widely acknowledged, there is still legitimate debate regarding how large, how fast, and where these effects will be. Climate science is just beginning to project how climate change might affect regional weather. Estimating climate change impacts also requires projecting society's future actions, particularly in the areas of population growth, economic growth, and energy use.

GLOBAL WARMING OR CLIMATE CHANGE?

The phrase "climate change" is growing in preferred use to "global warming" because it helps convey that there are changes in addition to rising temperatures.

Extreme weather events over the past several years—the record-breaking hurricane season of 2005 including Katrina, the first ever hurricane in the South Atlantic in 2004, a sustained drought in the U.S. West, and the 2003 heat wave in Europe—have raised a question: Are these events possibly associated with climate change? It is very difficult to point to any one single event and ascribe its cause to climate change. However, the collection of such events may indicate a contribution from climate change, and the likelihood of extreme events could increase in the future.

This brochure highlights important themes and recommendations from National Academies' reports on climate change. These reports are the products of the National Academies' study process, which brings together leading scientists, engineers, public health officials, and other experts to address specific scientific and technical questions. On climate change, such reports have assessed consensus findings on the science, identified new avenues of inquiry and critical needs in the observing and computational research infrastructure, and explored opportunities to use scientific knowledge to more effectively respond to climate change.

How climate will change in the future is inherently uncertain, but far from unknown. If scientific uncertainty about climate change is used to delay action, the risks and costs of adverse effects of climate change could increase significantly.

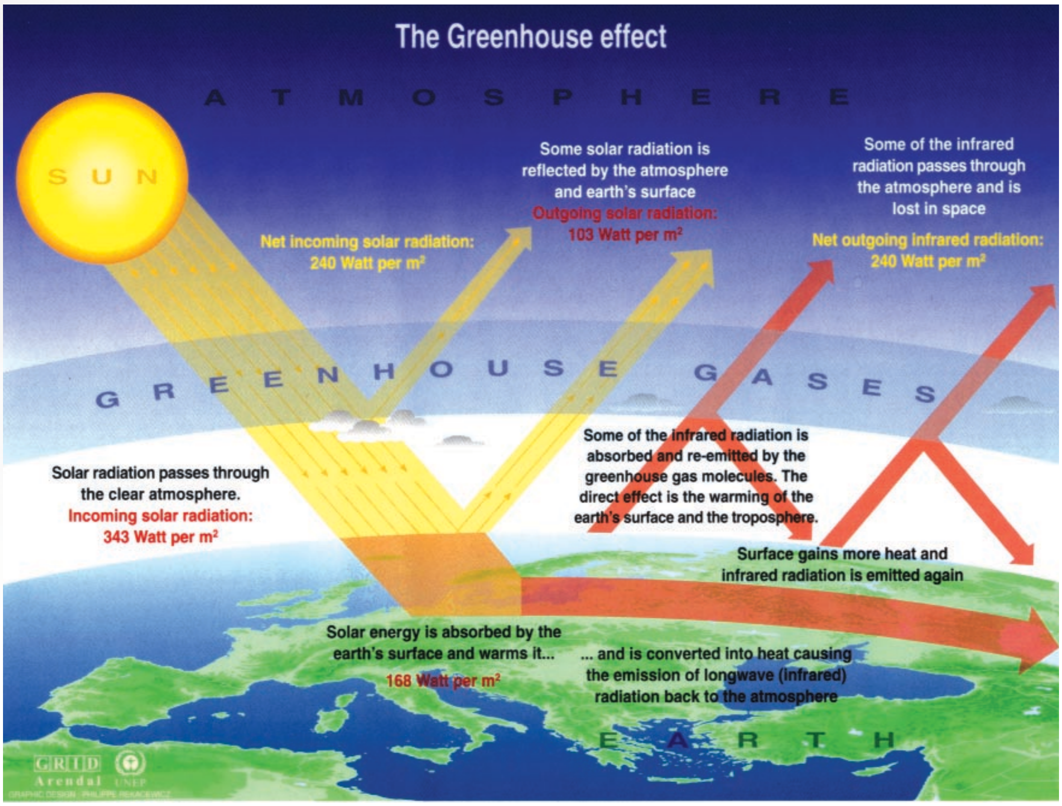
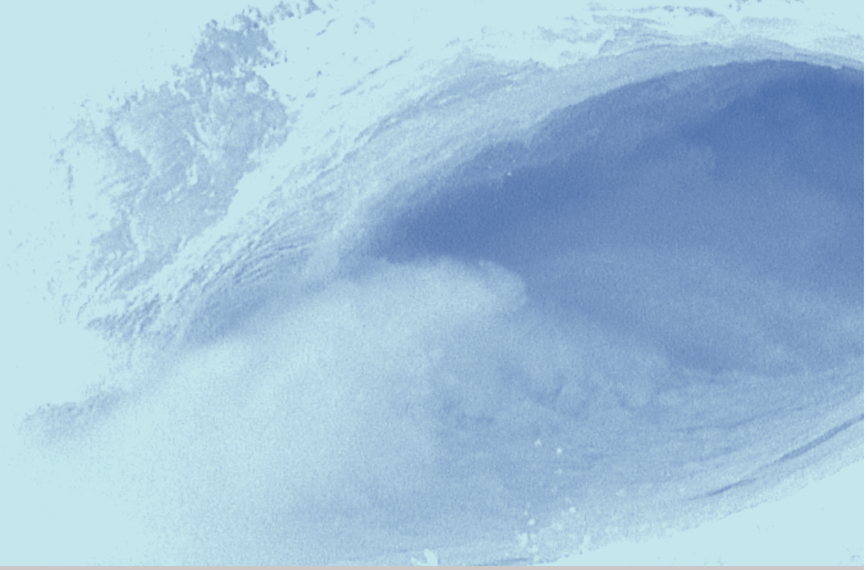


Figure 1. The greenhouse effect is a natural phenomenon that is essential to keeping the Earth's surface warm. Without it, there would not be life as we know it. Like a greenhouse window, greenhouse gases allow sunlight to enter and then prevent heat from leaving the atmosphere. Water vapor (H_2O) is the most important greenhouse gas, followed by carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halocarbons, and ozone (O_3). However, much higher concentrations of greenhouse gases than naturally occur—mostly from burning fossil fuels—are trapping excess heat in the atmosphere and are warming Earth's surface faster than at any time in recorded history. Source: Okanagan University College, Canada; University of Oxford; U.S. Environmental Protection Agency; United Nations Environment Programme (UNEP) and World Meteorological Organization (WMO).



Changes observed over the last several decades are likely mostly due to human activities.

—National Research Council, 2001

ABOUT THE SCIENCE

The Earth is warming.

Climate is conventionally defined as the long-term average of weather conditions, such as temperature, cloudiness, and precipitation; trends in these conditions for decades or longer are a primary measure of climate change. The most striking evidence of a global warming trend is closely scrutinized data that show a relatively rapid and widespread increase in temperature during the past century *(see Figure 2)*.

The rising temperatures observed since 1978 are particularly noteworthy because the rate of increase is so high and because, during the same period, the energy reaching the Earth from the Sun had been measured precisely enough to conclude that Earth's warming was not due to changes in the Sun. Scientists find clear evidence of this warming trend even after removing data from urban areas where an urban heat-island effect could influence temperature readings. Furthermore, the data are consistent with other evidence of warming, such as increases in ocean temperatures, shrinking mountain glaciers, and decreasing polar ice cover.

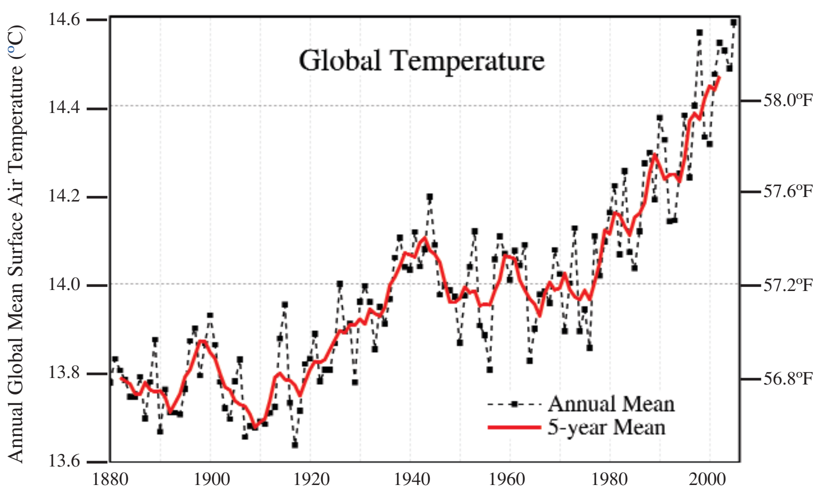


Figure 2. Global annual-mean surface air temperature derived from measurements at meteorological stations has increased by 1.4° F (0.7°C) since the early 20th century, with about 0.9°F (0.5°C) of the increase occurring since 1978. Figure courtesy of Goddard Institute for Space Studies.

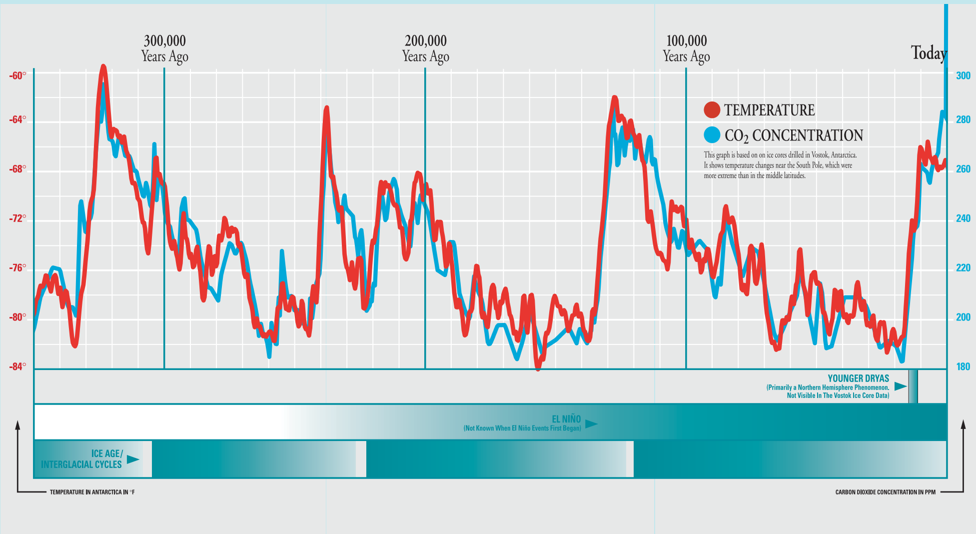


Figure 3. As recorded in ice cores from Vostok, Antarctica, the temperature near the South Pole has varied by more than 20º F during the past 350,000 years, and the temperature has corresponded closely with CO_2 concentrations. There have been peaks of warmth approximately each 100,000 years. The rise and fall of temperatures constitute the ice age/interglacial cycle. Image courtesy of the Marian Koshland Science Museum of the National Academy of Sciences.

One issue that had emerged in the climate change debate is whether temperature measurements are reliable. Temperature readings of the lower atmosphere taken with satellites appeared to show less warming than thermometer readings taken near the surface of the Earth. Some scientists interpreted this discrepancy to mean that global warming is not occurring and that the surface data are flawed.

A report released in 2000, *Reconciling Observations of Global Temperature Change,* examined this conflict in detail and concluded that the warming trend in global-average surface temperature observations during the past 20 years is undoubtedly real. The report spurred other groups to examine the discrepancy; they found that trends in satellite data were affected by instrument calibration and difficulties in interpreting temperature readings. Recent satellite and surface data are in better agreement, largely resolving the dispute.

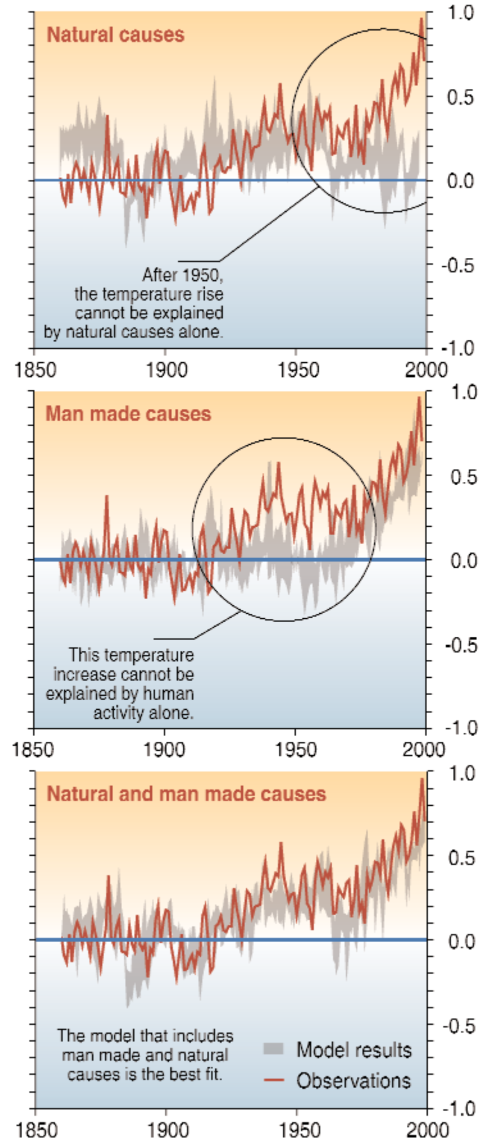
Humans have had an impact on climate.

In May 2001, the White House asked the National Academy of Sciences to assess our current understanding of climate change by answering several key questions related to the causes of climate change, projections of future change, and critical research directions to improve understanding of climate change. *Climate Change Science: An Analysis of Some Key Questions* responded directly to those questions. The report's often-cited conclusion is that "changes observed over the last several decades are likely mostly due to human activities" with some contribution from natural variability.

How do we know this to be true? The role of atmospheric carbon dioxide (CO_2) in warming the Earth's surface was first demonstrated by Swedish scientist Svante Arrhenius more than 100 years ago. Scientific data have since established that, for hundreds of thousands of years, changes in temperature have

Figure 4. Simulations of past temperature more closely match observed temperature when both natural and human causes are included in the models. The gray lines indicate model results. The red lines indicate observed temperatures. Source: Intergovernmental Panel on Climate Change.

Temperature anomalies in °C



closely tracked with atmospheric CO_2 concentrations *(see Figure 3)*. The burning of fossil fuels (oil, natural gas, and coal) releases carbon dioxide to the atmosphere. About 80% of the energy used in the United States is derived from fossil fuels. The recent rapid rise in both surface temperature and CO_2 is one of the indications that humans are responsible for some of this unusual warmth. In addition, model predictions of temperature change have been shown to closely match observed temperature changes when data from both natural and human-induced causes are used together *(see Figure 4)*.

There are several factors that contribute to Earth's warming and cooling. To compare the contributions of various factors, scientists have devised the con-

Forcing of the climate for the year 2000, relative to 1750

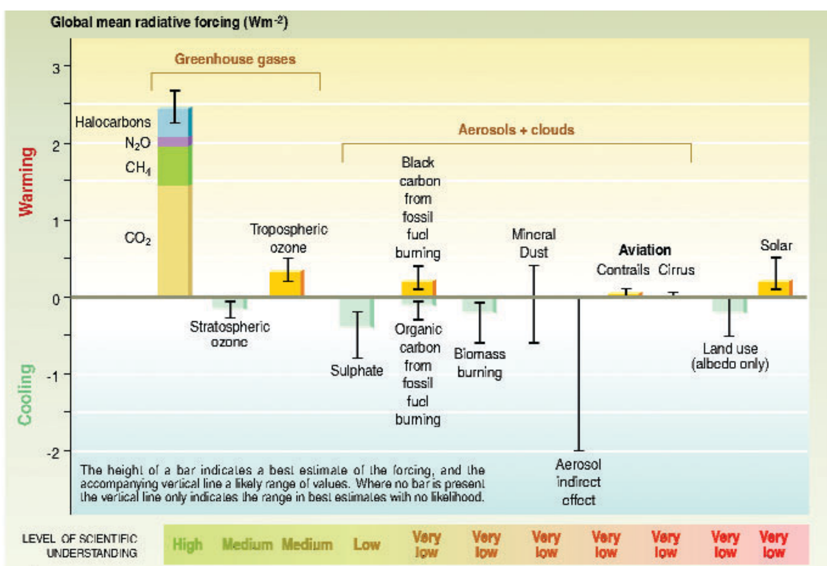


Figure 5. Various climate drivers, or radiative forcings, act to either warm or cool the Earth. Positive forcings, such as those due to greenhouse gases, tend to warm the Earth, while negative forcings, such as aerosols from industrial processes or volcanic eruptions, tend on average to cool it. If positive and negative forcings remained in balance, there would be no warming or cooling. Source: Intergovernmental Panel on Climate Change.

cept of "radiative forcing." Radiative forcing is the change in the balance of radiation (i.e., energy) coming into the atmo-sphere and radiation going back out. Positive radiative forcings, such as excess greenhouse gases, warm the Earth, while negative radiative forcings, such as volcanic eruptions and many human-produced aerosols, cool the Earth *(see Figure 5)*.

Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties (2005) takes a close look at how climate has been changed by a range of forcings. A key message from the report is that it is important to quantify how these forcings cause changes in climate variables other than temperature. For example, climate-driven changes in precipitation in certain regions could have significant impacts on water availability for agriculture, residential and industrial use, and recreation. Such regional impacts will be much more noticeable than projected changes in global average temperature.

Warming will continue, but its impacts are difficult to project.

The Intergovernmental Panel on Climate Change (IPCC), which involves hundreds of scientists from the United States and other nations in assessing the state of climate change science, concluded in a 2001 report that, by 2100, average global surface temperatures will rise 2.5 to 10.4°F (1.4 to 5.8°C) above 1990 levels. IPCC also

WHAT WARMS AND COOLS THE EARTH?

The Sun is Earth's main energy source. Its output appears nearly constant, but small changes during an extended period of time can lead to climate changes. In addition, slow changes in the Earth's orbit affect how the Sun's energy is distributed across the Earth, creating another variable that must be considered.

Greenhouse gases warm the planet:

Water vapor (H_2O), supplied from oceans and the natural biosphere, accounts for two-thirds of the total greenhouse effect, but acts primarily as a feedback (see page 8). Water vapor introduced directly to the atmosphere from agricultural or other activities does not stay there very long, and so does not have much warming effect.

Carbon dioxide (CO_2) has natural and human sources. Co_2 levels are increasingly due to burning of fossil fuels.

Methane (CH_4) has been rising due to an increase in several human activities including raising livestock, growing rice, use of landfills, and the extraction, handling, and transport of natural gas.

Ozone (O_3) has natural sources especially in the stratosphere, where changes caused by ozone-depleting chemicals have been important; ozone also is produced in the troposphere (lower part of the atmosphere) when hydrocarbons and nitrogen oxide pollutants react.

Nitrous oxide (N_2O) has been rising from agricultural and industrial sources.

Halocarbons, including chlorofluorocarbons (CFCs), remain from refrigerants in appliances made before CFCs were banned and various similar gases were developed as CFC replacements.

Some aerosols (airborne particles and droplets) warm the planet:

Black carbon particles or "soot," produced when fossil fuels or vegetation are burned, generally have a warming effect by absorbing solar radiation.

Some aerosols cool the planet:

Sulfate (SO_4) aerosols from burning fossil fuels reflect sunlight back to space.

Volcanic eruptions emit gaseous SO_2, which, once in the atmosphere, forms sulfate aerosol and ash. Both reflect sunlight back to space.

Changes in land cover and ice extent can warm or cool the Earth:

Deforestation produces land areas that reflect more sunlight back to space; replacement of tundra by coniferous trees that create dark patches in the snow cover may increase absorption of sunlight.

Sea ice reflects sunlight back to space; reduction in sea ice extent allows more sunlight to be absorbed into the dark ocean, causing warming.

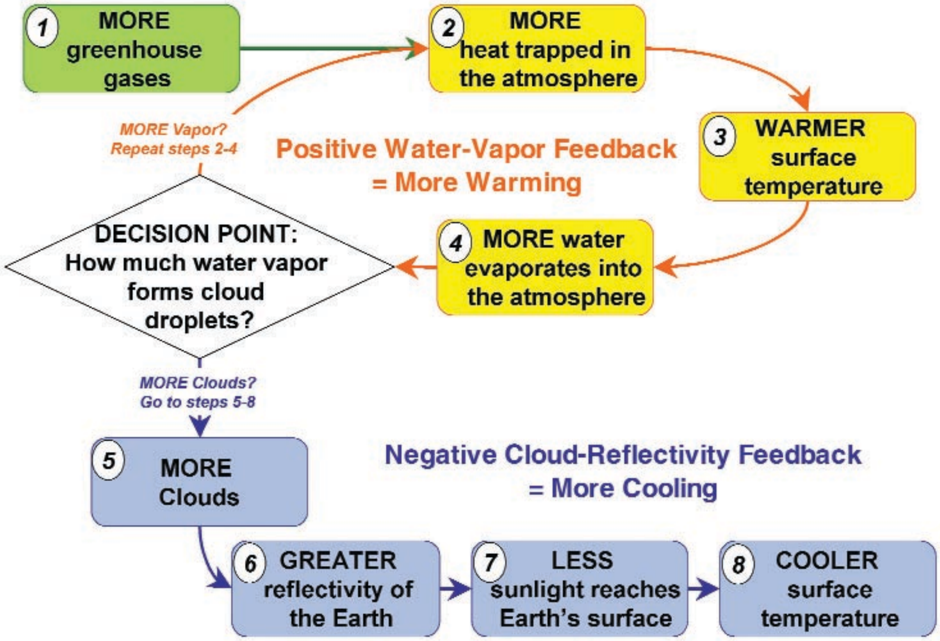


Figure 6. More vapor or more clouds? This schematic illustrates just two out of the dozens of climate feedbacks identified by scientists. The warming created by greenhouse gases leads to additional evaporation of water into the atmosphere. But water vapor itself is a greenhouse gas and can cause even more warming (steps 2-4 are repeated). Scientists call this the "positive water-vapor feedback." On the other hand, if the water vapor leads to the formation of more clouds, some warming may be counteracted because clouds reflect solar radiation (steps 5-8). Clouds also trap heat in the atmosphere. A major research question is how many and what type of clouds will form—low clouds tend to cool (reflect more energy than they trap) and high clouds tend to warm (trap more energy than they reflect).

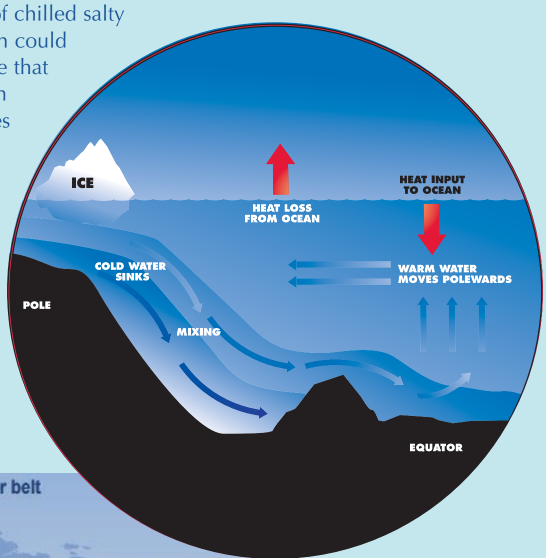
concluded that the combined effects of melting glaciers, melting ice caps, and sea water expansion from ocean warming will likely cause the global average sea-level to rise approximately 0.1 to 0.9 meters between 1990 and 2100. Uncertainties remain about the magnitude, rate, and impacts of future climate change, largely due to gaps in understanding climate and the difficulty in predicting future societal choices.

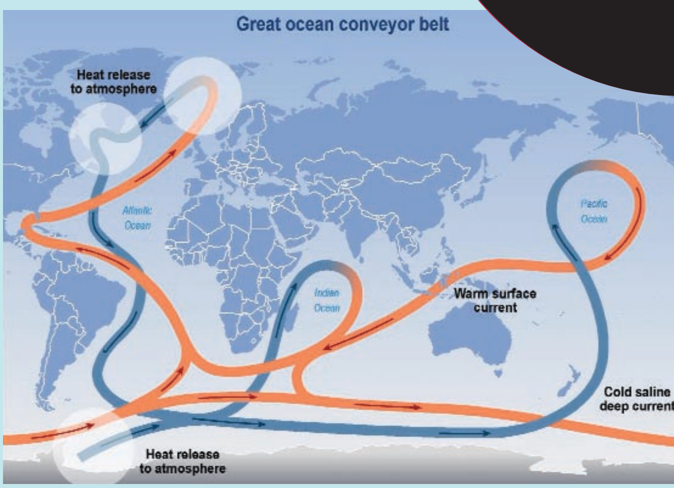
One of the major scientific uncertainties currently being investigated is how climate could be affected by what are known as "climate feedbacks." Feedbacks can either amplify or dampen the climate response to an initial radiative forcing *(see Figure 6)*. During a feedback loop, a change in one factor, such as temperature, leads to a change in another factor, such as water vapor, which then causes a change in the first factor. *Understanding Climate Change Feedbacks (2003)* examines what is known and not known about climate change feedbacks and identifies important research avenues for improving our understanding.

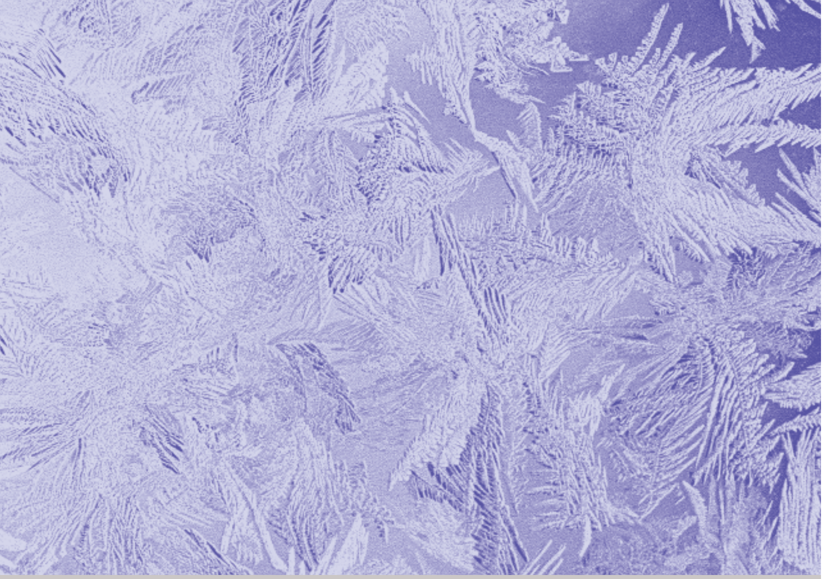
Another uncertainty is exactly how climate change will affect different regions. Although scientists are starting to project regional climate impacts, their level of confidence is less than for global climate projections. In general, temperature is easier to predict than changes such as rainfall, storm patterns, and ecosystem impacts. It is very likely that increasing global temperatures will lead to higher maximum temperatures and fewer cold days over most land areas. Some scientists believe that heat waves, such as those experienced in Chicago and central Europe in recent years, will continue and possibly worsen.

Evidence shows that the climate has sometimes changed abruptly in the past—within a decade—and could do so again. Abrupt changes, such as the Dust Bowl drought of the 1930s that displaced hundreds of thousands of people in the American Great Plains, take place so rapidly that humans and ecosystems have difficulty adapting to them. *Abrupt Climate Change: Inevitable Surprises (2002)* outlines some of the evidence for and theories about abrupt change. One theory is that melting ice caps could “freshen” the water in the North Atlantic, shutting down the natural ocean circulation that brings warmer Gulf Stream waters to the north and cooler waters south again *(see Figure 7)*. This shutdown could make it much cooler in northern Europe.

Figure 7. A key mechanism in the circulation of water through the world's oceans is the sinking of cold saltwater. Large oceanic currents transport warm, saline water to the North Atlantic where the waters become denser as they are cooled by cold Arctic air. The chilled seawater sinks to the bottom, forming a southward-moving water mass that flows around Antarctica and fills the world’s ocean basins. Gradually the water warms, becoming less dense, and returns to the surface, completing the cycle as it travels northward again. It has been hypothesized that less dense “freshened water” from melting ice caps could disrupt ocean circulation by preventing the formation of chilled salty water. Such a disruption could trigger a climate change that would make it cooler in northern Europe. Images courtesy of the Marian Koshland Science Museum of the National Academy of Sciences and the Intergovernmental Panel on Climate Change.







HOW THE SCIENCE IS DONE

Our ability to look at the Earth as a whole and model the complex interactions of the Earth, the ocean, and the atmosphere is a very young science, barely 20 years old. Only in the past few years have we been able to start making the links in our science across climate change, climate variability, regional climate impacts, to changes in extreme and episodic events.

—Antonio Busalacchi, Professor, University of Maryland

Observations and data are the foundation of climate change science.

In 1958, long before the idea of human-induced climate change was prevalent, a scientist named Charles Keeling began collecting canisters of air a couple times a week at the Mauna Loa Observatory on the big island of Hawaii. Dr. Keeling's goal was to measure carbon dioxide concentrations to better understand the carbon cycle—essentially how carbon is exchanged between plants, animals, the ocean, and the atmosphere. This remarkable 50-year dataset has been a boon for climate change science, and similar observations are now routinely made at stations across the globe *(see Figure 8)*.

Unlike many other sciences, where measurements can be carefully controlled in the laboratory, climate change research requires observations of numerous naturally occurring phenomena over long periods of time and on a global basis. Climate scientists must rely on data collected by a wide array of observing systems—from satellites to surface stations to ocean buoys—operated by various government agencies and countries, as well as indicators of past climate from ice cores, tree rings, corals, and sediments that help reconstruct past changes *(see Figure 9)*.

Data should be collected and archived to meet the unique needs of climate change science.

Most of the observing systems used to monitor climate today were established to provide data for other purposes, such as predicting daily weather; advising farmers; warning of hurricanes, tornadoes, and floods; managing water resources; aiding ocean and air transportation; and understanding the ocean. Data for climate research, however, have unique requirements. Higher accuracy is often needed to detect gradual climate trends, the observing programs must be sustained over long periods of time and accommodate changes in observing technology, and observations are needed at both global scales and at local scales to serve a range of climate information users.

Many National Academies' reports on climate change recommend improvements to climate observing capabilities. A central theme of *Adequacy of Climate Observing Systems (1999)* is the need to dramatically upgrade our climate observing capabilities. The report presents 10 climate monitoring principles that form the basis for designing climate observing systems, including management of network change, careful calibration, continuity of data collection, and documentation to ensure that meaningful trends can be derived.

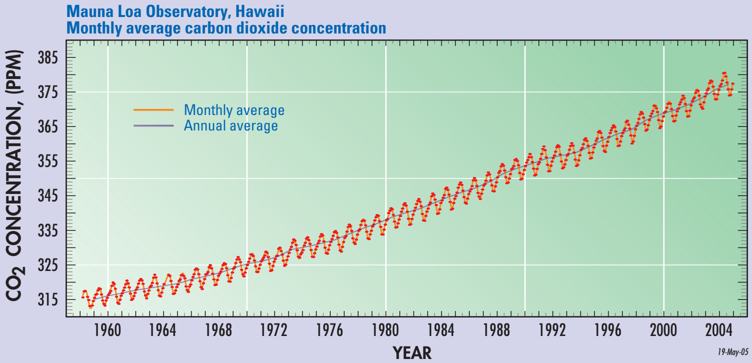


Figure 8. Charles Keeling's Mauna Loa Curve provides a remarkable set of data on atmospheric carbon dioxide (CO_2) concentrations collected since 1958 that are now an integral part of climate change science. The steady upward trend shows increases in annual average CO_2 concentrations due mostly to fossil fuel burning and the saw-tooth line shows the yearly cycle in CO_2 concentrations mostly burning due to seasonal changes in Northern Hemisphere vegetation. Data source: Carbon Dioxide Information Analysis Center.

Another key requirement for climate change science is the ability to generate, analyze, and archive long-term climate data records for assessing the state of the environment in perpetuity. *Climate Data Records from Environmental Satellites (2004)* defines a climate data record as a time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change. The report identifies several elements of successful climate data record generation programs that range from effective, expert

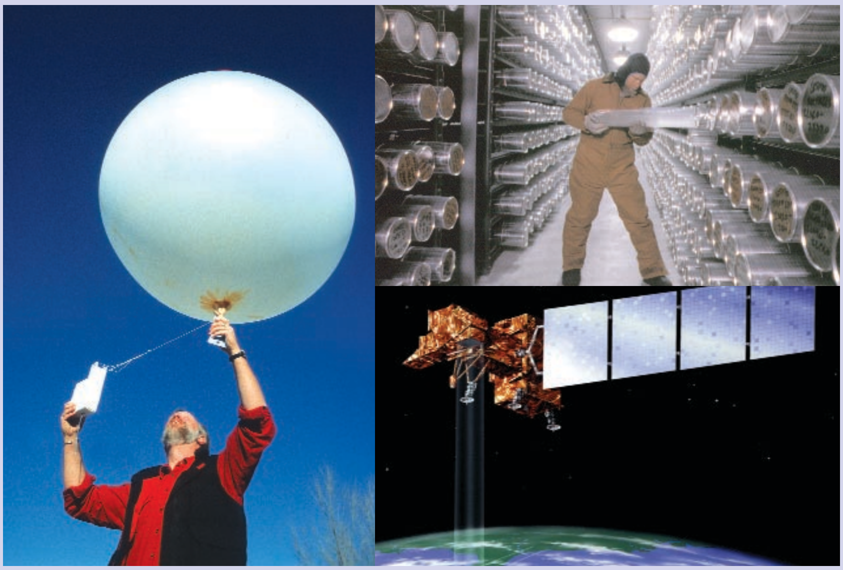


Figure 9. (left) Weather balloons, which carry instruments known as radiosondes, measure temperature, humidity, gases, and other properties throughout the vertical extent of the atmosphere. Image © University Corporation for Atmospheric Research. (top right) Ice is one of Earth's best record keepers of very long-term changes, revealing features of the climate when the ice was deposited. Tree rings and sediments also hold past climate information. (bottom right) The Landsat satellite series provides the longest continuous record of the Earth's continental surfaces—dating back to 1972—providing critical information for global change research. Image courtesy of the NASA Goddard Space Flight Center.

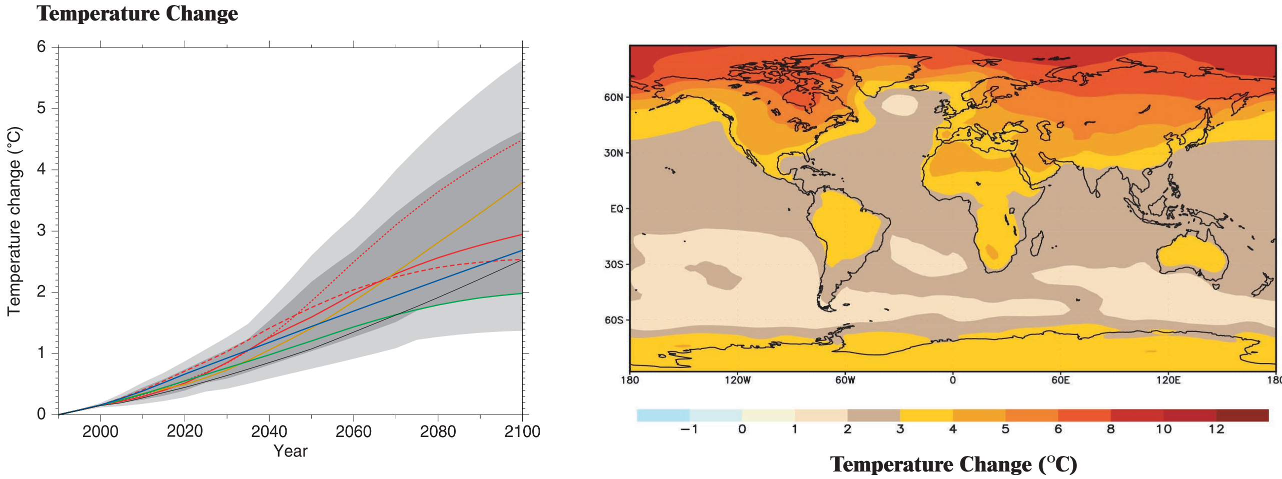


Figure 10. Climate models are often used to help inform policy decisions. The graph on the left shows the projected global mean temperature change for several different scenarios of future emissions based on assumptions of future population growth, economic development, life style choices, technological change, and availability of energy alternatives. Each line represents the average of many different models run for the same scenario. Each model incorporates different assumptions to handle uncertainties in our understanding of natural climate processes. The figure on the right shows the temperature changes that different regions of the world might experience by the end of this century, based on a model run with a midrange set of assumptions. The difference between the model temperature averaged from 2071 to 2100 and the observed temperature in 1990 is shown. Land areas are expected to warm more than oceans, and the greatest warming is projected at high latitudes. Source: Intergovernmental Panel on Climate Change (IPCC).

leadership to a long-term commitment to sustaining observations and archives.

Models integrate our knowledge and data on climate change.

An important concept that emerged from early climate science was that Earth's natural climate is not just a collection of long-term weather statistics, but rather the complex interactions or "couplings" of the atmosphere, the ocean, the land, ecosystems, and human life. Climate models use mathematical equations and our best scientific knowledge to represent the climate system, first modeling each system component separately and then linking them to simulate these couplings. The most complex of these models can only be run on some of the world's most advanced supercomputers.

Climate models are important tools for understanding how the climate operates today, how it may have functioned differently in the past, and how it may evolve in the future in response to forcings from both natural processes and human activities. Climate scientists can better characterize uncertainty about future climate by running models with different assumptions of future population growth, economic development, energy use, and policy choices, such as those that influence how nations share technology. Such models offer a range of outcomes based on differing assumptions *(see Figure 10)*.

Modeling capability and accuracy keep improving.

Since the late 1960s and 1970s when

climate models were pioneered, their accuracy has improved as the number and quality of observations have increased, as computational abilities have multiplied, and as our theoretical understanding of the climate system has grown. Today's models are very sophisticated and able to simulate hundreds of climate processes.

The long time scales of climate change make it difficult to verify models against actual climate conditions. In contrast, the accuracy of weather models that forecast conditions only days to weeks in advance can more easily be checked against observed conditions and improved. Climate scientists are now using models to work toward "seamless" predictions from weather (days) to long-term climate change (centuries). Successful predictions of multiyear variabilities known to influence weather, such as the El Niño phenomenon—a natural variation that affects weather during a 3-7 year cycle—could provide a needed link to more confidently projecting climate changes to a decade or longer.

Improving Effectiveness of U.S. Climate Modeling (2001) offers several recommendations for strengthening climate modeling capabilities, some of which have already been adopted in the United States. At the time the report was published, U.S. modeling capabilities were lagging behind several other nations. The report identified a shortfall in computing facilities and highly skilled technical workers devoted to climate modeling as two primary causes. Federal agencies have begun to centralize their support for climate modeling efforts at the National Center for Atmospheric Research (NCAR) and the Geophysical Fluid Dynamics Laboratory (GDFL). However, as recommended in *Planning Climate and Global Change Research (2003)*, the United States could still make good use of additional resources for climate modeling.

FEDERALLY COORDINATED RESEARCH ON CLIMATE CHANGE

More than a dozen federal agencies are involved in producing and using climate change data and research. The first efforts at a coordinated government research strategy culminated in the creation of the U.S. Global Change Research Program (GCRP) in 1989. The GCRP coordinated research at these agencies with the aim of "understanding and responding to global change, including the cumulative effects of human activities and natural processes on the environment." GCRP made substantial investments in understanding the underlying processes of climate change, documenting past and ongoing global change, improving modeling, and enhancing knowledge of El Niño and the ability to forecast it.

In February 2002, President George W. Bush formed the U.S. Climate Change Science Program (CCSP) (http://www.climatescience.gov/) as a new management structure intended to incorporate the work of the GCRP as well as a new Climate Change Research Initiative (CCRI) that was created to focus on priority research areas and provide useful information for policy decisions. In fall 2002, the CCSP asked the National Academies to review its draft 10-year strategic plan for climate and global change research. *Planning Climate and Global Change Research* (2003) offered many recommendations for improving the draft plan. The revised plan, reviewed in *Implementing Climate and Global Change Research* (2004), was found to be significantly improved.

HOW THE SCIENCE INFORMS DECISION-MAKING

Policymakers look to climate change science to answer two big questions: what could we do to prepare for the impacts of climate change, and what steps might be taken to slow it?

—Richard Alley, Professor, Pennsylvania State University

Climate change impacts will be uneven.

Climate change will affect ecosystems and human systems—such as agricultural, coastal, transportation, and health infrastructure—in ways that we are only beginning to understand *(see Figure 11)*. There will be winners and losers from the impacts of climate change, even within a single region, but globally the losses are expected to far outweigh the benefits. The larger and faster the changes in climate, the more difficult it will be for human and natural systems to adapt without adverse effects.

Unfortunately, the regions that will be most severely affected are often the regions that are the least able to adapt. Bangladesh, one of the poorest nations in the world, is projected to lose 17.5% of its land if sea level rises about 40 inches (1 meter), displacing millions of people. Several islands throughout the South Pacific and Indian oceans will be at similar risk of increased flooding and

The Chinstrap penguin: a regional winner.
Even within a single regional ecosystem, there will be winners and losers. For example, the population of Adélie penguins has decreased 22% during the last 25 years, while the Chinstrap penguin population increased by 400%. The two species depend on different habitats for survival: Adélies inhabit the winter ice pack, whereas Chinstraps remain in close association with open water. A 7–9° F rise in midwinter temperatures on the western Antarctic Peninsula during the past 50 years and associated receding sea-ice pack is reflected in their changing populations.

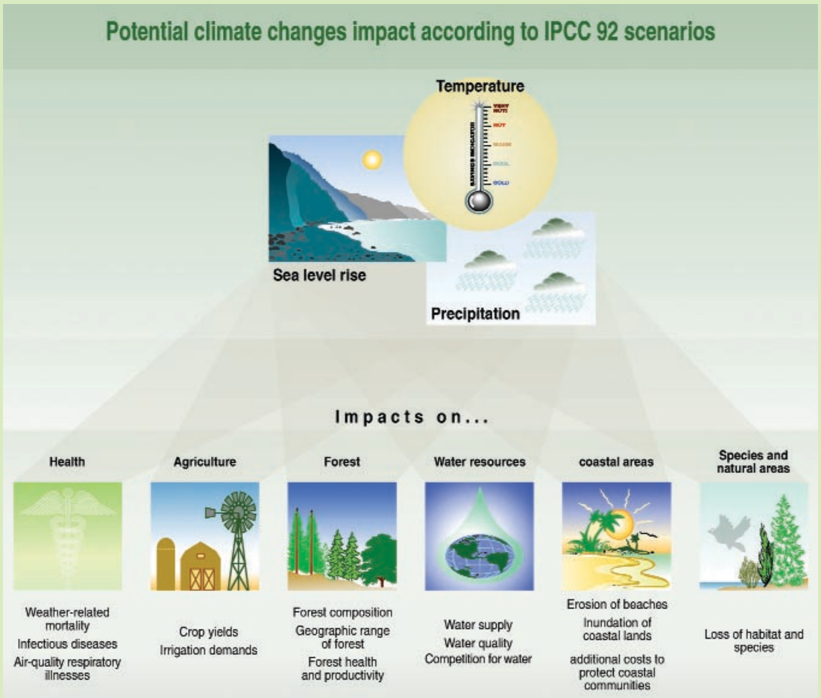


Figure 11. Climate changes could have potentially wide-ranging effects on both the natural environment and human activities and economies. Source: U.S. Environmental Protection Agency.

vulnerability to storm surges. Coastal flooding will likely threaten animals, plants, and fresh water supplies. Tourism and local agriculture could be severely challenged.

Many developed nations, including the United States, are also threatened. Nations with wealth have a better chance of using science and technology to anticipate, mitigate, and adapt to sea-level rise, threats to agriculture, and other climate impacts. Adaptations could include revising construction codes in coastal zones or developing new agricultural technologies. The developed world will need to assist the developing nations to build their capacity to meet the challenges of adapting to climate change.

We can better prepare for climate variability and change.

Climate information is becoming increasingly important to public and private decision making in various sectors, such as emergency management, water quality, insurance, irrigation, power production, and construction. *Making Climate Forecasts Matter (1999)* identifies research directions toward more useful seasonal-to-interannual climate forecasts and how to use forecasting to better manage the human consequences of climate change.

One way to begin preparing for climate change is to make the wealth of climate data and information already collected more accessible to a range of users who can apply it to make informed decisions. Such efforts, often called "climate services," are analogous to the efforts of the National Weather Service to provide useful weather information. *A Climate Services Vision (2001)* outlines principles for improving climate services: climate data should be made as user-friendly as weather information is today, and the government agencies, businesses, and universities involved in climate change data collection and research today should establish active and well-defined connections.

Another way to prepare for climate change is to develop practical strategies that could be used to reduce economic and ecological systems' vulnerabilities to change. Some of these are "no-regrets" strategies that will provide benefits whether a significant climate change

CLIMATE AND HUMAN HEALTH

Climate change will likely affect human health in the future. Potential impacts include heat stress, increased air pollution, and lack of food due to drought or other agricultural stresses. Climate change can also influence the spread of infectious diseases. Temperature, precipitation, and humidity can affect the lifecycle of many disease pathogens and carriers, modifying the timing and intensity of disease outbreaks. For example, some studies have predicted that global climate change could lead to a widespread increase in malaria transmission by expanding mosquito habitat and range.

Current strategies for controlling infectious disease epidemics rely primarily on surveillance and response. *Under the Weather: Climate, Ecosystems, and Infectious Disease (2001)* recommends a shift toward prediction and prevention, such as developing early warning systems. The report recommends that, in order to better understand the linkages between climate change and disease, efforts be focused on improving disease transmission models and epidemiological surveillance programs, and increasing interdisciplinary collaboration among climate modelers, meteorologists, ecologists, social scientists, and medical and health professionals. Overall vulnerability to infectious disease could be reduced through water treatment systems, vaccination programs, and enhanced efforts to control disease carriers.

ultimately occurs or not, potentially reducing vulnerability at little or no net cost. No-regrets measures could include low-cost steps to improve climate forecasting; to slow biodiversity loss; to improve water, land, and air quality; and to make our health care enterprise, financial markets, and transportation systems more resilient to major disruptions.

Steps can be taken to reduce greenhouse gases in the atmosphere.

Despite remaining unanswered questions, the scientific understanding of climate change is now sufficiently clear to justify taking steps to reduce the amount of greenhouse gases in the atmosphere. Because carbon dioxide and some other greenhouse gases can remain in the atmosphere for many decades, centuries, or longer, the climate change impacts from concentrations today will likely continue well beyond the 21st century and could potentially accelerate. Failure to implement significant reductions in net greenhouse gas emissions will make the job much harder in the future—both in terms of stabilizing their atmospheric abundances and in terms of experiencing more significant impacts.

Governments have proven they can work together successfully to reduce or reverse negative human impacts on nature. A classic example is the successful international effort to phase out of the use of chlorofluorocarbons (CFCs) in aerosol sprays and refrigerants that were destroying the Earth's protective ozone layer. At the present time there is no single solution that can eliminate future warming. As early as 1992, *Policy Implications of Greenhouse Warming* found that there are many potentially cost-effective technological options that could help stabilize greenhouse gas concentrations. Personal, national, and international choices could have an impact; for example driving less, regulating emissions, and sharing energy technologies could be beneficial.

Meeting energy needs is the single greatest challenge to slowing climate change.

Energy—either in the form of fuels used directly (such as gasoline) or as electricity produced using various fuels (such as fossil fuels, nuclear, solar, wind, and others)—is essential for all sectors of the economy including industry, commerce, homes, and transportation. Worldwide energy use continues to grow with economic and population expansion. Developing countries, China and India in particular, are rapidly increasing their use of energy, primarily from fossil fuels, and consequently their emissions of CO_2 *(see Figure 12)*. Carbon emissions from energy can be reduced by using it more efficiently or by switching to alternative fuels.

Energy efficiency in all sectors of the U.S. economy could be improved. Gains made in response to the oil price shocks of the 1970s slowed as energy prices fell, but many technologies could be implemented, especially if current high oil prices prove permanent. *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards (2002)* evaluates car and light truck fuel use and analyzes how fuel economy could be improved. Steps range from improved engine lubrication to hybrid vehicles. *Energy Research at DOE: Was It Worth It? (2001)* addresses the benefits of increasing the energy efficiency of lighting, refrigerators, and other appliances. Many of these improvements are cost-effective means to significantly reduce energy use, but are being held back by market constraints such as consumer awareness, higher initial costs, and the lack of industry incentives and effective policy.

Electricity can be produced without significant carbon emissions using nuclear power and renewable energy technologies, such as solar, wind, and biomass. In the United States, these technologies are currently too expensive or have environmental or other concerns that limit broad application; however, this could change if new technologies develop or as the costs of fossil fuels increase. Replacing coal-fired electric power plants with more efficient, modern natural-gas-fired turbines would reduce carbon emissions per unit of electricity produced.

Another way to reduce emissions is to collect CO_2 emitted to the atmosphere from fossil-fuel-fired power plants, and then sequester it in the ground or the ocean. *Novel Approaches to Carbon Management: Separation, Capture,*

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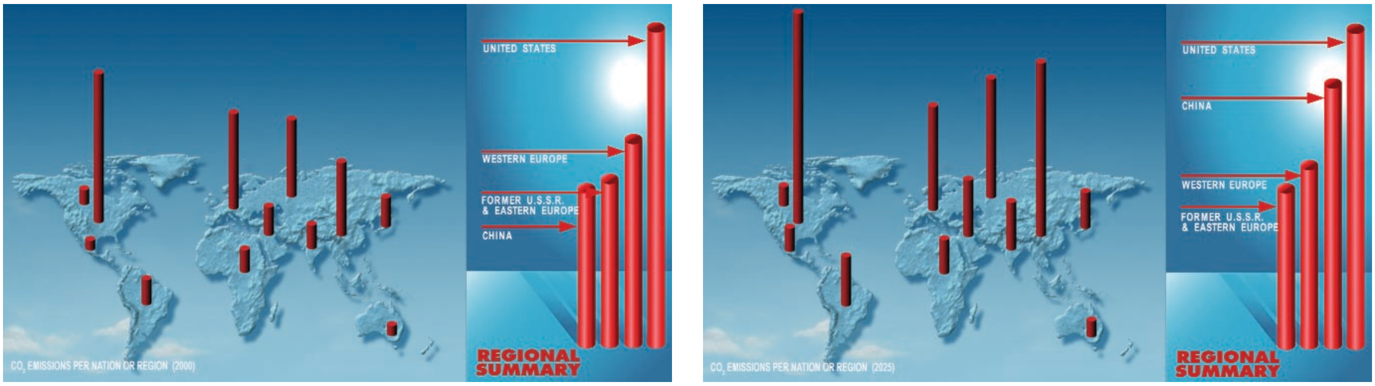

Figure 12. The two panels compare CO_2 emissions per nation in 2000 and projections for 2025. In 2000, the largest emitter of CO_2 was the United States, which is responsible for 25% of global emissions. In 2025, China and the developing world may significantly increase their CO_2 emissions relative to the United States. Image courtesy of the Marian Koshland Science Museum of the National Academy of Sciences.

Sequestration, and Conversion to Useful Products (2003) discusses the development of this technology. If successful, carbon sequestration could weaken the link between fossil fuels and greenhouse gas emissions.

Capturing CO_2 emissions from the tailpipes of vehicles is essentially impossible, which is one factor that has led to considerable interest in hydrogen as a fuel. However, as with electricity, hydrogen must be manufactured from primary energy sources. Significantly reducing carbon emissions when producing hydrogen from fossil fuels (currently the least expensive method) would require carbon capture and sequestration. Substantial technological and economic barriers in all phases of the hydrogen fuel cycle must first be addressed through research and development. *The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs (2004)* presents a strategy that could lead eventually to production of hydrogen from a variety of domestic sources—such as coal with carbon sequestration, nuclear power, wind, or photo-biological processes—and its efficient use in fuel-cell vehicles.

Continued Scientific Efforts to Address a Changing Climate

Although society's understanding of climate change has advanced significantly during the past few decades, many questions remain unanswered. The task of mitigating and preparing for the impacts of climate change will require worldwide collaborative inputs from a wide range of experts, including natural scientists, engineers, social scientists, medical scientists, business leaders, and economists. Society faces increasing pressure to decide how best to respond to climate change and associated global changes. Building upon our ever expanding understanding of climate change, the next wave of research should more fully address the needs of decision makers, not only those who shape our climate policy, but for all who will be affected by climate change impacts.

SELECTED CLIMATE CHANGE AND RELATED REPORTS FROM THE NATIONAL ACADEMIES

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For more studies and related information see http://dels.nas.edu/globalchange and http://dels.nas.edu/basc. National Academies reports are available from the National Academies Press, 500 Fifth Street, NW, Washington, DC 20001; 800-624-6242; http://www.nap.edu. Reports are available online in a fully searchable format.

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At a time when responding to our changing climate is one of the nation's most complex endeavors, reports from the National Academies provide thoughtful analysis and helpful direction to policymakers and stakeholders. These reports are produced by committees organized by the Board on Atmospheric Sciences and Climate, its Climate Research Committee, and numerous other entities within the National Academies. With support from sponsors, the National Academies will continue in its science advisory role to the agencies working on understanding changing climate, documenting its impacts, and developing effective response strategies.

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