CURRENT STATE OF CLIMATE SCIENCE:
RECENT STUDIES FROM THE NATIONAL ACADEMIES

Statement of
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Good morning, Mr. Chairman and members of the Committee. My name is Ralph Cicerone, and I am President of the National Academy of Sciences. Prior to this position, I served as Chancellor of the University of California at Irvine, where I also held the Daniel G. Aldrich Chair in Earth System Science. In addition, in 2001 I chaired the National Academies committee that wrote the report, *Climate Change Science: An Analysis of Some Key Questions*, at the request of the White House.

This morning I will summarize briefly the current state of scientific understanding on climate change, based largely on the findings and recommendations in recent National Academies' reports. These reports are the products of a study process that brings together leading scientists, engineers, public health officials and other experts to provide consensus advice to the nation on specific scientific and technical questions.

The Earth is warming. Weather station records and ship-based observations indicate that global mean surface air temperature increased about 0.7oF (0.4oC) since the early 1970's (See Figure). Although the magnitude of warming varies locally, the warming trend is spatially widespread and is consistent with an array of other evidence (including melting glaciers and ice caps, sea level rise, extended growing seasons, and changes in the geographical distributions of plant and animal species). The ocean, which represents the largest reservoir of heat in the climate system, has warmed by about 0.12oF (0.06oC) averaged over the layer extending from the surface down to 750 feet, since 1993. Recent studies have shown that the observed heat storage in the oceans is consistent with expected impacts of a human-enhanced greenhouse effect.

The observed warming has not proceeded at a uniform rate. Virtually all the 20th century warming in global surface air temperature occurred between the early 1900s and the 1940s and from the 1970s until today, with a slight cooling of the Northern Hemisphere during the interim decades. The causes of these irregularities and the disparities in the timing are not completely understood, but the warming trend in global-average surface temperature observations during the past 30 years is undoubtedly real and is substantially greater than the average rate of warming during the twentieth century.

Laboratory measurements of gases trapped in dated ice cores have shown that for hundreds of thousands of years, changes in temperature have closely tracked atmospheric carbon dioxide concentrations. Burning fossil fuel for energy, industrial processes, and transportation releases carbon dioxide to the atmosphere. Carbon dioxide in the atmosphere is now at its highest level in 400,000 years and continues to rise.

Nearly all climate scientists today believe that much of Earth's current warming has been caused by increases in the amount of greenhouse gases in the atmosphere, mostly from the burning of fossil fuels. The degree of confidence in this conclusion is higher today than it was 10, or even 5 years ago, but uncertainties remain. As stated in the Academies 2001 report, "the changes observed over the last several decades are likely mostly due to human activities, but we cannot rule out that some significant part of these changes is also a reflection of natural variability."

One area of debate has been the extent to which variations in the Sun might contribute to recent observed warming trends. The Sun's total brightness has been measured by a series of satellite-based instruments for more than two complete 11-year solar cycles. Recent analyses of these measurements argue against any detectable long-term trend in the observed brightness to date. Thus, it is difficult to conclude that the Sun has been responsible for the warming observed over the past 25 years.

Carbon dioxide can remain in the atmosphere for many decades and major parts of the climate system respond slowly to changes in greenhouse gas concentrations. The slow response of the climate system to increasing greenhouse gases also means that changes and impacts will continue during the twenty-first century and beyond, even if emissions were to be stabilized or reduced in the near future.

Simulations of future climate change project that, by 2100, global surface temperatures will be from 2.5 to 10.4oF (1.4 to 5.8oC) above 1990 levels. Similar projections of temperature increases, based on rough calculations and nascent theory, were made in the Academies first report on climate change published in the late 1970s. Since then, significant advances in our knowledge of the climate system and our ability to model and observe it have yielded consistent estimates. Pinpointing the magnitude of future warming is hindered both by remaining gaps in understanding the science and by the fact that it is difficult to predict society's future actions, particularly in the areas of population growth, economic growth, and energy use practices.

Other scientific uncertainties about future climate change relate to the regional effects of climate change and how climate change will affect the frequency and severity of weather events. Although scientists are starting to forecast regional weather impacts, the level of confidence is less than it is for global climate projections. In general, temperature is easier to predict than changes such as rainfall, storm patterns, and ecosystem impacts.

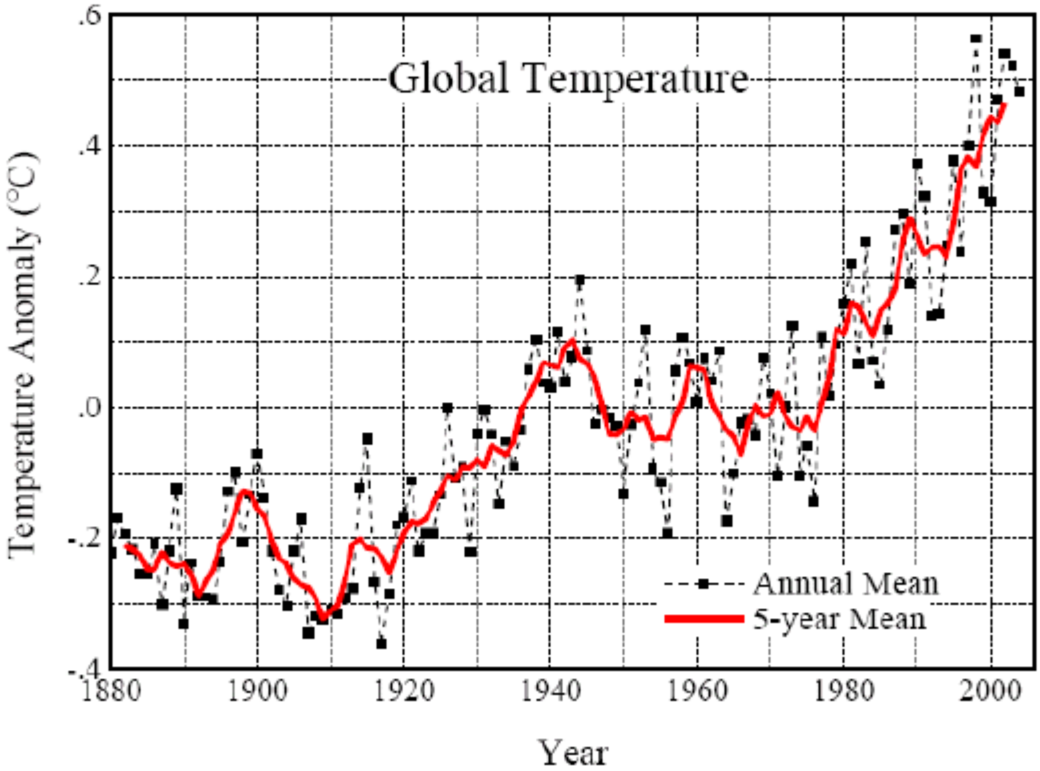
It is important to recognize however, that while future climate change and its impacts are inherently uncertain, they are far from unknown. The combined effects of ice melting and sea water expansion from ocean warming will likely cause the global average sea-level to rise by between 0.1 and 0.9 meters between 1990 and 2100. In colder climates, such warming could bring longer growing seasons and less severe winters. Those in coastal communities, many in developing nations, will experience increased flooding due to sea level rise and are likely to experience more severe storms and surges. In the Arctic regions, where temperatures have risen more than the global average, the landscape and ecosystems are being altered rapidly.

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, those in government at all levels, business leaders and economists. Although the scientific understanding of climate change has advanced significantly in the last several decades, there are still many unanswered questions. Society faces increasing pressure to decide how best to respond to climate change and associated global changes, and applied research in direct support of decision making is needed.

My written testimony describes the current state of scientific understanding of climate change in more detail, based largely on important findings and recommendations from a number of recent National Academies' reports.

The Earth is warming

The most striking evidence of a global warming trend are closely scrutinized data that show a relatively rapid increase in temperature, particularly over the past 30 years. Weather station records and ship-based observations indicate that global mean surface air temperature increased about 0.7oF (0.4oC) since the early 1970's (See Figure). Although the magnitude of warming varies locally, the warming trend is spatially widespread and is consistent with an array of other evidence (e.g., melting glaciers and ice caps, sea level rise, extended growing seasons, and changes in the geographical distributions of plant and animal species).



Global annual-mean surface air temperature change derived from the meteorological station network. Data and plots available from the Goddard Institute for Space Sciences (GISS) at http://data.giss.nasa.gov/gistemp/graphs/.

The ocean, which represents the largest reservoir of heat in the climate system, has warmed by about 0.12oF (0.06oC) averaged over the layer extending from the surface down to 750 feet, since 1993. Recent studies have shown that the observed heat storage in the oceans is what would be expected by a human-enhanced greenhouse effect. Indeed, increased ocean heat content accounts for most of the planetary energy imbalance (i.e., when the Earth absorbs more energy from the Sun than it emits back to space) simulated by climate models with mid-range climate sensitivity.

The observed warming has not proceeded at a uniform rate. Virtually all the 20th century warming in global surface air temperature occurred between the early 1900s and the 1940s and since the 1970s, with a slight cooling of the Northern Hemisphere during the interim decades. The troposphere warmed much more during the 1970s than during the two subsequent decades, whereas Earth's surface warmed more during the past two decades than during the 1970s. The causes of these irregularities and the disparities in the timing are not completely understood.

A National Academies report released in 2000, *Reconciling Observations of Global Temperature Change*, examined different types of temperature measurements collected from 1979 to 1999 and concluded that the warming trend in global-average surface temperature observations during the previous 20 years is undoubtedly real and is substantially greater than the average rate of warming during the twentieth century. The report concludes that the lower atmosphere actually may have warmed much less rapidly than the surface from 1979 into the late 1990s, due both to natural causes (e.g., the sequence of volcanic eruptions that occurred within this particular 20-year period) and human activities (e.g., the cooling of the upper part of the troposphere resulting from ozone depletion in the stratosphere). The report spurred many research groups to do similar analyses. Satellite observations of middle troposphere temperatures, after several revisions of the data, now compare reasonably with observations from surface stations and radiosondes, although some uncertainties remain.

Humans have had an impact on climate

Laboratory measurements of gases trapped in dated ice cores have shown that for hundreds of thousands of years, changes in temperature have closely tracked with atmospheric carbon dioxide concentrations. Burning fossil fuel for energy, industrial processes, and transportation releases carbon dioxide to the atmosphere. Carbon dioxide in the atmosphere is now at its highest level in 400,000 years and continues to rise. Nearly all climate scientists today believe that much of Earth's current warming has been caused by increases in the amount of greenhouse gases in the atmosphere. The degree of confidence in this conclusion is higher today than it was 10, or even 5 years ago, but uncertainties remain. As stated in the Academies 2001 report, "the changes observed over the last several decades are likely mostly due to human activities, but we cannot rule out that some significant part of these changes is also a reflection of natural variability."

Carbon dioxide can remain in the atmosphere for many decades and major parts of the climate system respond slowly to changes in greenhouse gas concentrations. The slow response of the climate system to increasing greenhouse gases also means that changes and impacts will continue during the twenty-first century and beyond, even if emissions were to be stabilized or reduced in the near future.

In order to compare the contributions of the various agents that affect surface temperature, scientists have devised the concept of "radiative forcing." Radiative forcing is the change in the balance between radiation (i.e., heat and energy) entering the atmosphere and radiation going back out. Positive radiative forcings (e.g., due to excess greenhouse gases) tend on average to warm the Earth, and negative radiative forcings (e.g., due to volcanic eruptions and many human-produced aerosols) on average tend to cool the Earth. The Academies recent report, *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 human and natural processes 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 of a degree or more.

One area of debate has been the extent to which variations in the Sun might contribute to recent observed warming trends. *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties* (2005) also summarizes current understanding about this issue. The Sun's brightness—its total irradiance—has been measured continuously by a series of satellite-based instruments for more than two complete 11-year solar cycles. These multiple solar irradiance datasets have been combined into a composite time series of daily total solar irradiance from 1979 to the present. Different assumptions about radiometer performance lead to different reconstructions for the past two decades. Recent analyses of these measurements, taking into account instrument calibration offsets and drifts, argue against any detectable long-term trend in the observed irradiance to date. Likewise, models of total solar irradiance variability that account for the influences of solar activity features—dark sunspots and bright faculae—do not predict a secular change in the past two decades. Thus, it is difficult to conclude from either measurements or models that the Sun has been responsible for the warming observed over the past 25 years.

Knowledge of solar irradiance variations is rudimentary prior to the commencement of continuous space-based irradiance observations in 1979. Models of sunspot and facular influences developed from the contemporary database have been used to extrapolate daily variations during the 11-year cycle back to about 1950 using contemporary sunspot and facular proxies, and with less certainty annually to 1610. Circumstantial evidence from cosmogenic isotope proxies of solar activity (14C and 10Be) and plausible variations in Sun-like stars motivated an assumption of long-term secular irradiance trends, but recent work questions the evidence from both. Very recent studies of the long term evolution and transport of activity features using solar models suggest that secular solar irradiance variations may be limited in amplitude to about half the amplitude of the 11-year cycle.

Warming will continue, but its impacts are difficult to project

The Intergovernmental Panel on Climate Change (IPCC), which involves hundreds of scientists in assessing the state of climate change science, has estimated that, by 2100, global surface temperatures will be from 2.5 to 10.4oF (1.4 to 5.8oC) above 1990 levels. Similar projections of temperature increases, based on rough calculations and nascent theory, were made in the Academies first report on climate change published in the late 1970s. Since then, significant advances in our knowledge of the climate system and our ability to model and observe it have yielded consistent estimates. Pinpointing the magnitude of future warming is hindered both by remaining gaps in understanding the science and by the fact that it is difficult to predict society's future actions, particularly in the areas of population growth, economic growth, and energy use practices.

One of the major scientific uncertainties 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. During a feedback process, a change in one variable, such as carbon dioxide concentration, causes a change in temperature, which then causes a change in a third variable, such as water vapor, which in turn causes a further change in temperature. *Understanding Climate Change Feedbacks* (2003) looks at what is known and not known about climate change feedbacks and identifies important research avenues for improving our understanding.

Other scientific uncertainties relate to the regional effects of climate change and how climate change will affect the frequency and severity of weather events. Although scientists are starting to forecast regional weather impacts, the level of confidence is less than it is 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. The larger and faster the changes in climate, the more difficult it will be for human and natural systems to adapt without adverse effects.

There is evidence that the climate has sometimes changed abruptly in the past—within a decade—and could do so again. Abrupt changes, for example the Dust Bowl drought of the 1930's displaced hundreds of thousands of people in the American Great Plains, take place so rapidly that humans and ecosystems have difficulty adapting to it. *Abrupt Climate Change: Inevitable Surprises* (2002) outlines some of the evidence for and theories of 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. This shutdown could make it much cooler in Northern Europe and warmer near the equator.

It is important to recognize that while future climate change and its impacts are inherently uncertain, they are far from unknown. The combined effects of ice melting and sea water expansion from ocean warming will likely cause the global average sea-level to rise by between 0.1 and 0.9 meters between 1990 and 2100. In colder climates, such warming could bring longer growing seasons and less severe winters. Those in coastal communities, many in developing nations, will experience increased flooding due to sea level rise and are likely to experience more severe storms and surges. In the Arctic regions, where temperatures have risen almost twice as much as the global average, the landscape and ecosystems are being altered rapidly.

Observations and data are the foundation of climate change science

There is nothing more valuable to scientists than the measurements and observations required to confirm or contradict hypotheses. In climate sciences, there is a peculiar relation between the scientist and the data. Whereas other scientific disciplines can run multiple, controlled experiments, climate scientists must rely on the one realization that nature provides. Climate change research requires observations of numerous characteristics of the Earth system over long periods of time on a global basis. Climate scientists must rely on data collected by a whole suite of observing systems—from satellites to surface stations to ocean buoys—operated by various government agencies and countries as well as climate records from ice cores, tree rings, corals, and sediments that help reconstruct past change.

Collecting and archiving data to meet the unique needs of climate change science

Most of the instrumentation and 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. However, collecting climate data is unique because higher precision is often needed in order to detect climate trends, the observing programs need to be sustained indefinitely 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.

Every report on climate change produced by the National Academies in recent years has recommended improvements to climate observing capabilities. A central theme of the report *Adequacy of Climate Observing Systems* (1999) is the need to dramatically upgrade our climate observing capabilities. The report presents ten climate monitoring principles that continue to be 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.

Another key concept for climate change science is the ability to generate, analyze, and archive long-term climate data records (CDRs) for assessing the state of the environment in perpetuity. In *Climate Data Records from Environmental Satellites* (2004), a climate data record is defined 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, ranging from effective, expert leadership to long-term commitment to sustaining the observations and archives.

Integrating knowledge and data on climate change through models

An important concept that emerged from early climate science in the 1980s was that Earth's 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, and plant and animal life. Climate models are built using our best scientific knowledge, first modeling each process component separately and then linking them together to simulate these couplings.

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 deal with 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 affect air quality or influence how nations share technology. Models then offer a range of outcomes based on these different assumptions.

Modeling capability and accuracy

Since the first climate models were pioneered in the 1970s, the accuracy of models has improved as the number and quality of observations and data have increased, as computational abilities have multiplied, and as our theoretical understanding of the climate system has improved. Whereas early attempts at modeling used relatively crude representations of the climate, today's models have very sophisticated and carefully tested treatment of hundreds of climate processes.

The National Academies' report *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 some other countries. The report identified a shortfall in computing facilities and highly skilled technical workers devoted to climate modeling. Federal agencies have begun to centralize their support for climate modeling efforts at the National Center for Atmospheric Research and the Geophysical Fluid Dynamics Laboratory. However, the U.S. could still improve the amount of resources it puts toward climate modeling as recommended in *Planning Climate and Global Change Research* (2003).

Climate change impacts will be uneven

There will be winners and losers from the impacts of climate change, even within a single region, but globally the losses are expected to outweigh the benefits. The regions that will be most severely affected are often the regions that are the least able to adapt. For example, 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 m), displacing tens of thousands of people. Several islands throughout the South Pacific and Indian Oceans will be at similar risk of increased flooding and vulnerability to storm surges. Coastal flooding likely will threaten animals, plants, and fresh water supplies. Tourism and local agriculture could be severely challenged.

Wetland and coastal areas of many developed nations including United States are also threatened. For example, parts of New Orleans are as much as eight feet below sea level today. However, wealthy countries are much more able to adapt to sea level rise and threats to agriculture. Solutions could include building, limiting or changing construction codes in coastal zones, and developing new agricultural technologies.

The Arctic has warmed at a faster rate than the Northern Hemisphere over the past century. *A Vision for the International Polar Year 2007-2008* (2004) reports that this warming is associated with a number of impacts including: melting of sea ice, which has important impacts on biological systems such as polar bears, ice-dependent seals, and local people for whom these animals are a source of food; increased snow and rainfall, leading to changes in river discharge and tundra vegetation; and degradation of the permafrost.

Preparing for 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 could apply it to inform their decisions. Such efforts, often called "climate services," are analogous to the efforts of the National Weather Service to provide useful weather information. Climate is becoming increasingly important to public and private decision making in various fields such as emergency management planning, water quality, insurance premiums, irrigation and power production decisions, and construction schedules. *A Climate Services Vision* (2001) outlines principles for improving climate services that include making climate data as user-friendly as weather services are today, and active and well-defined connections among the government agencies, businesses, and universities involved in climate change data collection and research.

Another avenue would be to develop practical strategies that could be used to reduce economic and ecological systems' vulnerabilities to change. Such "no-regrets" strategies, recommended in *Abrupt Climate Change: Inevitable Surprises* (2002), provide benefits whether a significant climate change 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; slow biodiversity loss; improve water, land, and air quality; and make institutions—such as the health care enterprise, financial markets, and transportation systems—more resilient to major disruptions.

Reducing the causes of climate change

The climate change statement issued in June 2005 by 11 science academies, including the National Academy of Sciences, stated that despite remaining unanswered questions, the scientific understanding of climate change is now sufficiently clear to justify nations taking cost-effective steps that will contribute to substantial and long-term reduction in net global greenhouse gas emissions. Because carbon dioxide and some other greenhouse gases can remain in the atmosphere for many decades and major parts of the climate system respond slowly to changes in greenhouse gas concentrations, climate change impacts will likely continue throughout the 21st century and beyond. Failure to implement significant reductions in net greenhouse gas emissions now 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.

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 contribute to stabilizing greenhouse gas concentrations.

Meeting energy needs is a major challenge to slowing climate change

Energy—either in the form of fuels used directly (i.e., gasoline) or as electricity produced using various fuels (fossil fuels as well as nuclear, solar, wind, and others)—is essential for all sectors of the economy, including industry, commerce, homes, and transportation. Energy use worldwide continues to grow with economic and population growth. 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. Carbon emissions from energy can be reduced by using it more efficiently or by switching to alternative fuels. It also may be possible to capture carbon emissions from electric generating plants and then sequester them.

Energy efficiency in all sectors of the U.S. economy could be improved. The 2002 National Academies' report, *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards*, evaluates car and light truck fuel use and analyzes how fuel economy could be improved. Steps range from improved engine lubrication to hybrid vehicles. The 2001 Academies report, *Energy Research at DOE, Was It Worth It?* addresses the benefits of increasing the energy efficiency of lighting, refrigerators and other appliances. Many of these improvements (e.g., high-efficiency refrigerators) are cost-effective means to significantly reducing energy use, but are being held back by market constraints such as consumer awareness, higher initial costs, or by the lack of effective policy.

Electricity can be produced without significant carbon emissions using nuclear power and renewable energy technologies (e.g., solar, wind, and biomass). In the United States, these technologies are too expensive or have environmental or other concerns that limit broad application, but that could change with technology development or if 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.

Several technologies are being explored that would collect CO_2 that would otherwise be emitted to the atmosphere from fossil-fuel-fired power plants, and then sequester it in the ground or the ocean. Successful, cost-effective sequestration technologies would weaken the link between fossil fuels and greenhouse gas emissions. The 2003 National Academies' report, *Novel Approaches to Carbon Management: Separation, Capture, Sequestration, and Conversion to Useful Products*, discusses the development of this technology.

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. 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 2004 National Academies' report, *The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs*, 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 efficient use in fuel cell vehicles.

Continued scientific efforts to address a changing climate

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, those in government at all levels, business leaders, and economists. Although the scientific understanding of climate change has advanced significantly in the last several decades, there are still many unanswered questions. Society faces increasing pressure to decide how best to respond to climate change and associated global changes, and applied research in direct support of decision making is needed.

National Academies' Reports Cited in the Testimony

Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties (2005)
Climate Data Records from Environmental Satellites (2004)
Implementing Climate and Global Change Research (2004)
A Vision for the International Polar Year 2007-2008 (2004)
The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs (2004)
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