CLIMATE CHANGE SCIENCE

AN ANALYSIS OF SOME KEY QUESTIONS

Committee on the Science of Climate Change

Division on Earth and Life Studies

National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C.

NATIONAL ACADEMY PRESS 2101 Constitution Avenue, N.W. Washington, D.C. 20418

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International Standard Book Number 0-309-07574-2

Additional copies of this report are available from:

National Academy Press
2101 Constitution Avenue, N.W.
Lockbox 285
Washington, D.C. 20055
(800) 624-6242
(202) 334-3313 (in the Washington metropolitan area)
http://www.nap.edu

Printed in the United States of America

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Foreword

This study originated from a White House request to help inform the Administration's ongoing review of U.S. climate change policy. In particular, the written request (Appendix A) asked for the National Academies' "assistance in identifying the areas in the science of climate change where there are the greatest certainties and uncertainties," and "views on whether there are any substantive differences between the IPCC [Intergovernmental Panel on Climate Change] Reports and the IPCC summaries." In addition, based on discussions with the Administration, the following specific questions were incorporated into the statement of task for the study:

- *What is the range of natural variability in climate?*
- *Are concentrations of greenhouse gases and other emissions that contribute to climate change increasing at an accelerating rate, and are different greenhouse gases and other emissions increasing at different rates?*
- *How long does it take to reduce the buildup of greenhouse gases and other emissions that contribute to climate change?*
- *What other emissions are contributing factors to climate change (e.g., aerosols, CO, black carbon soot), and what is their relative contribution to climate change?*
- *Do different greenhouse gases and other emissions have different draw down periods?*
- *Are greenhouse gases causing climate change?*
- *Is climate change occurring? If so, how?*
- *Is human activity the cause of increased concentrations of greenhouse gases and other emissions that contribute to climate change?*
- *How much of the expected climate change is the consequence of climate feedback processes (e.g., water vapor, clouds, snow packs)?*
- *By how much will temperatures change over the next 100 years and where?*
- *What will be the consequences (e.g., extreme weather, health effects) of increases of various magnitudes?*
- *Has science determined whether there is a "safe" level of concentration of greenhouse gases?*
- *What are the substantive differences between the IPCC Reports and the Summaries?*
- *What are the specific areas of science that need to be studied further, in order of priority, to advance our understanding of climate change?*

The White House asked for a response "as soon as possible" but no later than early June—less than one month after submitting its formal request.

The National Academies has a mandate arising from its 1863 charter to respond to government requests when asked. In view of the critical nature of this issue, we agreed to undertake this study and to use our own funds to support it.

A distinguished committee with broad expertise and diverse perspectives on the scientific issues of climate change was therefore appointed through the National Academies' National Research Council (see Appendix B for biographical information on committee members). In early May, the committee held a conference call to discuss the specific questions and to prepare for its 2-day meeting (May 21-22, 2001) in Irvine, California. The committee reviewed the 14 questions and determined that they represent important issues in climate change science and could serve as a useful framework for addressing the two general questions from the White House.

For the task of comparing IPCC Reports and Summaries, the committee focused its review on the work of IPCC Working Group I, which dealt with many of the same detailed questions being asked above. The committee decided to address the questions in the context of a brief document that also could serve as a primer for policy makers on climate change science. To aid in the presentation, the questions have been organized into seven sections, with the questions addressed in each section listed in *italics* at the beginning of that section.

While traditional procedures for an independent NRC study, including review of the report by independent experts, were followed, it is important to note that tradeoffs were made in order to accommodate the rapid schedule. For example, the report does not provide extensive references to the scientific literature or marshal detailed evidence to support its "answers" to the questions. Rather, the report largely presents the consensus scientific views and judgments of committee members, based on the accumulated knowledge that these individuals have gained—both through their own scholarly efforts and through formal and informal interactions with the world's climate change science community.

The result is a report that, in my view, provides policy makers with a succinct and balanced overview of what science can currently say about the potential for future climate change, while outlining the uncertainties that remain in our scientific knowledge.

The report does not make policy recommendations regarding what to do about the potential of global warming. Thus, it does not estimate the potential economic and environmental costs, benefits, and uncertainties regarding various policy responses and future human behaviors. While beyond the charge presented to this committee, scientists and social scientists have the ability to provide assessments of this type as well. Both types of assessments can be helpful to policy makers, who frequently have to weigh tradeoffs and make decisions on important issues, despite the inevitable uncertainties in our scientific understanding concerning particular aspects. Science never has all the answers. But science does provide us with the best available guide to the future, and it is critical that our nation and the world base important policies on the best judgments that science can provide concerning the future consequences of present actions.

I would especially like to thank the members of this committee and its staff for an incredible effort in producing this important report in such a short period of time. They have sacrificed many personal commitments and worked long weekends to provide the nation with their considered judgments on this critical issue.

Bruce Alberts
President
National Academy of Sciences

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

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Grace Wahba, University of Wisconsin, Madison

Although the reviewers listed above have provided constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Richard M. Goody (Harvard University) and Robert A. Frosch (Harvard University). Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

We would also like to thank the following individuals for their input regarding the IPCC process: John Christy, Haroon Kheshgi, Michael Mann, Jerry Meehl, Berrien Moore, Michael Oppenheimer, Joyce Penner, Ray Pierrehumbert, Michael Prather, Venkatachalam Ramaswamy, Ben Santer, Piers Sellers, Susan Solomon, Ron Stouffer, Kevin Trenberth, and Robert Watson.

Contents

Summary

Greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise. Temperatures are, in fact, rising. 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. Human-induced warming and associated sea level rises are expected to continue through the 21st century. Secondary effects are suggested by computer model simulations and basic physical reasoning. These include increases in rainfall rates and increased susceptibility of semi-arid regions to drought. The impacts of these changes will be critically dependent on the magnitude of the warming and the rate with which it occurs.

The mid-range model estimate of human induced global warming by the Intergovernmental Panel on Climate Change (IPCC) is based on the premise that the growth rate of climate forcing[1] agents such as carbon dioxide will accelerate. The predicted warming of 3°C (5.4°F) by the end of the 21st century is consistent with the assumptions about how clouds and atmospheric relative humidity will react to global warming. This estimate is also consistent with inferences about the sensitivity[2] of climate drawn from comparing the sizes of past temperature swings between ice ages and intervening warmer periods with the corresponding changes in the climate forcing. This predicted temperature increase is sensitive to assumptions concerning future concentrations of greenhouse gases and aerosols. Hence, national policy decisions made now and in the longer-term future will influence the extent of any damage suffered by vulnerable human populations and ecosystems later in this century. Because there is considerable uncertainty in current understanding of how the climate system varies naturally and reacts to emissions of greenhouse gases and aerosols, current estimates of the magnitude of future warming should be regarded as tentative and subject to future adjustments (either upward or downward).

Reducing the wide range of uncertainty inherent in current model predictions of global climate change will require major advances in understanding and modeling of both (1) the factors that determine atmospheric concentrations of greenhouse gases and aerosols, and (2) the so-called "feedbacks" that determine the sensitivity of the climate system to a prescribed increase in greenhouse gases. There also is a pressing need for a global observing system designed for monitoring climate.

The committee generally agrees with the assessment of human-caused climate change presented in the IPCC Working Group I (WGI) scientific report, but seeks here to articulate more clearly the level of confidence that can be ascribed to those assessments and the caveats that need to be attached to them. This articulation may be helpful to policy makers as they consider a variety of options for mitigation and/or adaptation. In the sections that follow, the committee provides brief responses to some of the key questions related to climate change science. More detailed responses to these questions are located in the main body of the text.

What is the range of natural variability in climate?

The range of natural climate variability is known to be quite large (in excess of several degrees Celsius) on local

[1] A climate forcing is defined as an imposed perturbation of Earth's energy balance. Climate forcing is typically measured in watts per square meter (W/m2).

[2] The sensitivity of the climate system to a prescribed forcing is commonly expressed in terms of the global mean temperature change that would be expected after a time sufficiently long for both the atmosphere and ocean to come to equilibrium with the change in climate forcing.

and regional spatial scales over periods as short as a decade. Precipitation also can vary widely. For example, there is evidence to suggest that droughts as severe as the "dust bowl" of the 1930s were much more common in the central United States during the 10th to 14th centuries than they have been in the more recent record. Mean temperature variations at local sites have exceeded 10°C (18°F) in association with the repeated glacial advances and retreats that occurred over the course of the past million years. It is more difficult to estimate the natural variability of global mean temperature because of the sparse spatial coverage of existing data and difficulties in inferring temperatures from various proxy data. Nonetheless, evidence suggests that global warming rates as large as 2°C (3.6°F) per millennium may have occurred during retreat of the glaciers following the most recent ice age.

Are concentrations of greenhouse gases and other emissions that contribute to climate change increasing at an accelerating rate, and are different greenhouse gases and other emissions increasing at different rates? Is human activity the cause of increased concentrations of greenhouse gases and other emissions that contribute to climate change?

The emissions of some greenhouse gases are increasing, but others are decreasing. In some cases the decreases are a result of policy decisions, while in other cases the reasons for the decreases are not well understood.

Of the greenhouse gases that are directly influenced by human activity, the most important are carbon dioxide, methane, ozone, nitrous oxide, and chlorofluorocarbons (CFCs). Aerosols released by human activities are also capable of influencing climate. (Table 1 lists the estimated climate forcing due to the presence of each of these "climate forcing agents" in the atmosphere.)

Concentrations of carbon dioxide (CO_2) extracted from ice cores drilled in Greenland and Antarctica have typically ranged from near 190 parts per million by volume (ppmv) during the ice ages to near 280 ppmv during the warmer "interglacial" periods like the present one that began around 10,000 years ago. Concentrations did not rise much above 280 ppmv until the Industrial Revolution. By 1958, when systematic atmospheric measurements began, they had reached 315 ppmv, and they are currently ~370 ppmv and rising at a rate of 1.5 ppmv per year (slightly higher than the rate during the early years of the 43-year record). Human activities are responsible for the increase. The primary source, fossil fuel burning, has released roughly twice as much carbon dioxide as would be required to account for the observed increase. Tropical deforestation also has contributed to carbon dioxide releases during the past few decades. The excess carbon dioxide has been taken up by the oceans and land biosphere.

Like carbon dioxide, methane (CH_4) is more abundant in Earth's atmosphere now than at any time during the 400,000 year long ice core record, which dates back over a number of glacial/interglacial cycles. Concentrations increased rather smoothly by about 1% per year from 1978, until about 1990. The rate of increase slowed and became more erratic during the 1990s. About two-thirds of the current emissions of methane are released by human activities such as rice growing, the raising of cattle, coal mining, use of land-fills, and natural gas handling, all of which have increased over the past 50 years.

A small fraction of the ozone (O_3) produced by natural processes in the stratosphere mixes into the lower atmosphere. This "tropospheric ozone" has been supplemented during the 20th century by additional ozone, created locally by the action of sunlight upon air polluted by exhausts from motor vehicles, emissions from fossil fuel burning power plants, and biomass burning.

Nitrous oxide (N_2O) is formed by many microbial reactions in soils and waters, including those acting on the increasing amounts of nitrogen-containing fertilizers. Some synthetic chemical processes that release nitrous oxide have also been identified. Its concentration has increased approximately 13% in the past 200 years.

Atmospheric concentrations of CFCs rose steadily following their first synthesis in 1928 and peaked in the early 1990s. Many other industrially useful fluorinated compounds (e.g., carbon tetrafluoride, CF_4, and sulfur hexafluoride, SF_6), have very long atmospheric lifetimes, which is of concern, even though their atmospheric concentrations have not yet produced large radiative forcings. Hydrofluorocarbons (HFCs), which are replacing CFCs, have a greenhouse effect, but it is much less pronounced because of their shorter atmospheric lifetimes. The sensitivity and generality of modern analytical systems make it quite unlikely that any currently significant greenhouse gases remain to be discovered.

What other emissions are contributing factors to climate change (e.g., aerosols, CO, black carbon soot), and what is their relative contribution to climate change?

Besides greenhouse gases, human activity also contributes to the atmospheric burden of aerosols, which include both sulfate particles and black carbon (soot). Both are unevenly distributed, owing to their short lifetimes in the atmosphere. Sulfate particles scatter solar radiation back to space, thereby offsetting the greenhouse effect to some degree. Recent "clean coal technologies" and use of low sulfur fuels have resulted in decreasing sulfate concentrations, especially in North America, reducing this offset. Black carbon aerosols are end-products of the incomplete combustion of fossil fuels and biomass burning (forest fires and land clearing). They impact radiation budgets both directly and indirectly; they are believed to contribute to global warming, although their relative importance is difficult to quantify at this point.

How long does it take to reduce the buildup of greenhouse gases and other emissions that contribute to climate change? Do different greenhouse gases and other emissions have different draw down periods?

TABLE 1 Removal Times and Climate Forcing Values for Specified Atmospheric Gases and Aerosols

Forcing Agent	Approximate Removal Times[3]	Climate Forcing (W/m^2) Up to the year 2000
Greenhouse Gases		
Carbon Dioxide	>100 years	1.3 to 1.5
Methane	10 years	0.5 to 0.7
Tropospheric Ozone	10-100 days	0.25 to 0.75
Nitrous Oxide	100 years	0.1 to 0.2
Perfluorocarbon Compounds (Including SF_6)	>1000 years	0.01
Fine Aerosols		
Sulfate	10 days	–0.3 to –1.0
Black Carbon	10 days	0.1 to 0.8

[3]A removal time of 100 years means that much, but not all, of the substance would be gone in 100 years. Typically, the amount remaining at the end of 100 years is 37%; after 200 years 14%; after 300 years 5%; after 400 years 2%.

Is climate change occurring? If so, how?

Weather station records and ship-based observations indicate that global mean surface air temperature warmed between about 0.4 and 0.8°C (0.7 and 1.5°F) during the 20th century. Although the magnitude of warming varies locally, the warming trend is spatially widespread and is consistent with an array of other evidence detailed in this report. The ocean, which represents the largest reservoir of heat in the climate system, has warmed by about 0.05°C (0.09°F) averaged over the layer extending from the surface down to 10,000 feet, since the 1950s.

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 during the past few 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. One striking change of the past 35 years is the cooling of the stratosphere at altitudes of ~13 miles, which has tended to be concentrated in the wintertime polar cap region.

Are greenhouse gases causing climate change?

The IPCC's conclusion that most of the observed warming of the last 50 years is likely to have been due to the increase in greenhouse gas concentrations accurately reflects the current thinking of the scientific community on this issue. The stated degree of confidence in the IPCC assessment is higher today than it was 10, or even 5 years ago, but uncertainty remains because of (1) the level of natural variability inherent in the climate system on time scales of decades to centuries, (2) the questionable ability of models to accurately simulate natural variability on those long time scales, and (3) the degree of confidence that can be placed on reconstructions of global mean temperature over the past millennium based on proxy evidence. Despite the uncertainties, there is general agreement that the observed warming is real and particularly strong within the past 20 years. Whether it is consistent with the change that would be expected in response to human activities is dependent upon what assumptions one makes about the time history of atmospheric concentrations of the various forcing agents, particularly aerosols.

By how much will temperatures change over the next 100 years and where?

Climate change simulations for the period of 1990 to 2100 based on the IPCC emissions scenarios yield a globally-averaged surface temperature increase by the end of the century of 1.4 to 5.8°C (2.5 to 10.4°F) relative to 1990. The wide range of uncertainty in these estimates reflects both the different assumptions about future concentrations of greenhouse gases and aerosols in the various scenarios considered by the IPCC and the differing climate sensitivities of the various climate models used in the simulations. The range of climate sensitivities implied by these predictions is generally consistent with previously reported values.

The predicted warming is larger over higher latitudes than over low latitudes, especially during winter and spring, and larger over land than over sea. Rainfall rates and the frequency of heavy precipitation events are predicted to increase, particularly over the higher latitudes. Higher evaporation rates would accelerate the drying of soils following rain events, resulting in lower relative humidities and higher daytime temperatures, especially during the warm season. The likelihood that this effect could prove important is greatest in semi-arid regions, such as the U.S. Great Plains. These predictions in the IPCC report are consistent with current understanding of the processes that control local climate.

In addition to the IPCC scenarios for future increases in greenhouse gas concentrations, the committee considered a scenario based on an energy policy designed to keep climate change moderate in the next 50 years. This scenario takes into account not only the growth of carbon emissions, but also the changing concentrations of other greenhouse gases and aerosols.

Sufficient time has elapsed now to enable comparisons between observed trends in the concentrations of carbon dioxide and other greenhouse gases with the trends predicted in previous IPCC reports. The increase of global fossil fuel carbon dioxide emissions in the past decade has averaged 0.6% per year, which is somewhat below the range of IPCC scenarios, and the same is true for atmospheric methane concentrations. It is not known whether these slowdowns in growth rate will persist.

How much of the expected climate change is the consequence of climate feedback processes (e.g., water vapor, clouds, snow packs)?

The contribution of feedbacks to the climate change depends upon "climate sensitivity," as described in the report. If a central estimate of climate sensitivity is used, about 40% of the predicted warming is due to the direct effects of greenhouse gases and aerosols. The other 60% is caused by feedbacks. Water vapor feedback (the additional greenhouse effect accruing from increasing concentrations of atmospheric water vapor as the atmosphere warms) is the most important feedback in the models. Unless the relative humidity in the tropical middle and upper troposphere drops, this effect is expected to increase the temperature response to increases in human induced greenhouse gas concentrations by a factor of 1.6. The ice-albedo feedback (the reduction in the fraction of incoming solar radiation reflected back to space as snow and ice cover recede) also is believed to be important. Together, these two feedbacks amplify the simulated climate response to the greenhouse gas forcing by a factor of 2.5. In addition, changes in cloud cover, in the relative amounts of high versus low clouds, and in the mean and vertical distribution of relative humidity could either enhance or reduce the amplitude of the warming. Much of the difference in predictions of global warming by various climate models is attributable to the fact that each model represents these processes in its own particular way. These uncertainties will remain until a more fundamental understanding of the processes that control atmospheric relative humidity and clouds is achieved.

What will be the consequences (e.g., extreme weather, health effects) of increases of various magnitude?

In the near term, agriculture and forestry are likely to benefit from carbon dioxide fertilization and an increased water efficiency of some plants at higher atmospheric CO_2 concentrations. The optimal climate for crops may change, requiring significant regional adaptations. Some models project an increased tendency toward drought over semi-arid regions, such as the U.S. Great Plains. Hydrologic impacts could be significant over the western United States, where much of the water supply is dependent on the amount of snow pack and the timing of the spring runoff. Increased rainfall rates could impact pollution run-off and flood control. With higher sea level, coastal regions could be subject to increased wind and flood damage even if tropical storms do not change in intensity. A significant warming also could have far reaching implications for ecosystems. The costs and risks involved are difficult to quantify at this point and are, in any case, beyond the scope of this brief report.

Health outcomes in response to climate change are the subject of intense debate. Climate is one of a number of factors influencing the incidence of infectious disease. Cold-related stress would decline in a warmer climate, while heat stress and smog induced respiratory illnesses in major urban areas would increase, if no adaptation occurred. Over much of the United States, adverse health outcomes would likely be mitigated by a strong public health system, relatively high levels of public awareness, and a high standard of living.

Global warming could well have serious adverse societal and ecological impacts by the end of this century, especially if globally-averaged temperature increases approach the upper end of the IPCC projections. Even in the more conservative scenarios, the models project temperatures and sea levels that continue to increase well beyond the end of this century, suggesting that assessments that examine only the next 100 years may well underestimate the magnitude of the eventual impacts.

Has science determined whether there is a "safe" level of concentration of greenhouse gases?

The question of whether there exists a "safe" level of concentration of greenhouse gases cannot be answered directly because it would require a value judgment of what constitutes an acceptable risk to human welfare and ecosystems in various parts of the world, as well as a more quantitative assessment of the risks and costs associated with the various impacts of global warming. In general, however, risk increases with increases in both the rate and the magnitude of climate change.

What are the substantive differences between the IPCC Reports and the Summaries?

The committee finds that the full IPCC Working Group I (WGI) report is an admirable summary of research activities in climate science, and the full report is adequately summarized in the *Technical Summary*. The full WGI report and its *Technical Summary* are not specifically directed at policy. The *Summary for Policymakers* reflects less emphasis on communicating the basis for uncertainty and a stronger emphasis on areas of major concern associated with human-induced climate change. This change in emphasis appears to be the result of a summary process in which scientists work with policy makers on the document. Written responses from U.S. coordinating and lead scientific authors to the committee indicate, however, that (a) no changes were made without the consent of the convening lead authors (this group represents a fraction of the lead and contributing authors) and (b) most changes that did occur lacked significant impact.

It is critical that the IPCC process remain truly representative of the scientific community. The committee's concerns focus primarily on whether the process is likely to become less representative in the future because of the growing voluntary time commitment required to participate as a lead or coordinating author and the potential that the scientific process will be viewed as being too heavily influenced by governments which have specific postures with regard to treaties, emission controls, and other policy instruments. The United States should promote actions that improve the IPCC process while also ensuring that its strengths are maintained.

What are the specific areas of science that need to be studied further, in order of priority, to advance our understanding of climate change?

Making progress in reducing the large uncertainties in projections of future climate will require addressing a number of fundamental scientific questions relating to the buildup of greenhouses gases in the atmosphere and the behavior of the climate system. Issues that need to be addressed include (a) the future usage of fossil fuels, (b) the future emissions of methane, (c) the fraction of the future fossil-fuel carbon that will remain in the atmosphere and provide radiative forcing versus exchange with the oceans or net exchange with the land biosphere, (d) the feedbacks in the climate system that determine both the magnitude of the change and the rate of energy uptake by the oceans, which together determine the magnitude and time history of the temperature increases for a given radiative forcing, (e) details of the regional and local climate change consequent to an overall level of global climate change, (f) the nature and causes of the natural variability of climate and its interactions with forced changes, and (g) the direct and indirect effects of the changing distributions of aerosols. Maintaining a vigorous, ongoing program of basic research, funded and managed independently of the climate assessment activity, will be crucial for narrowing these uncertainties.

In addition, the research enterprise dealing with environmental change and the interactions of human society with the environment must be enhanced. This includes support of (a) interdisciplinary research that couples physical, chemical, biological, and human systems, (b) an improved capability of integrating scientific knowledge, including its uncertainty, into effective decision support systems, and (c) an ability to conduct research at the regional or sectoral level that promotes analysis of the response of human and natural systems to multiple stresses.

An effective strategy for advancing the understanding of climate change also will require (1) a global observing system in support of long-term climate monitoring and prediction, (2) concentration on large-scale modeling through increased, dedicated supercomputing and human resources, and (3) efforts to ensure that climate research is supported and managed to ensure innovation, effectiveness, and efficiency.

1

Climate, Climate Forcings, Climate Sensitivity, and Transient Climate Change

CLIMATE

Climate is the average state of the atmosphere and the underlying land or water, on time scales of seasons and longer. Climate is typically described by the statistics of a set of atmospheric and surface variables, such as temperature, precipitation, wind, humidity, cloudiness, soil moisture, sea surface temperature, and the concentration and thickness of sea ice. The statistics may be in terms of the long-term average, as well as other measures such as daily minimum temperature, length of the growing season, or frequency of floods. Although climate and climate change are usually presented in global mean terms, there may be large local and regional departures from these global means. These can either mitigate or exaggerate the impact of climate change in different parts of the world.

A number of factors contribute to climate and climate change, and it is useful to define the terms climate forcings, climate sensitivity, and transient climate change for discussion below.

CLIMATE FORCINGS

A climate forcing can be defined as an imposed perturbation of Earth's energy balance. Energy flows in from the sun, much of it in the visible wavelengths, and back out again as long-wave infrared (heat) radiation. An increase in the luminosity of the sun, for example, is a positive forcing that tends to make Earth warmer. A very large volcanic eruption, on the other hand, can increase the aerosols (fine particles) in the lower stratosphere (altitudes of 10-15 miles) that reflect sunlight to space and thus reduce the solar energy delivered to Earth's surface. These examples are natural forcings. Human-made forcings result from, for example, the gases and aerosols produced by fossil fuel burning, and alterations of Earth's surface from various changes in land use, such as the conversion of forests into agricultural land. Those gases that absorb infrared radiation, i.e., the "greenhouse" gases, tend to prevent this heat radiation from escaping to space, leading eventually to a warming of Earth's surface. The observations of human-induced forcings underlie the current concerns about climate change.

The common unit of measure for climatic forcing agents is the energy perturbation that they introduce into the climate system, measured in units of watts per square meter (W/m^2). The consequences from such forcings are often then expressed as the change in average global temperature, and the conversion factor from forcing to temperature change is the sensitivity of Earth's climate system. Although some forcings—volcanic plumes, for example—are not global in nature and temperature change may also not be uniform, comparisons of the strengths of individual forcings, over comparable areas, are useful for estimating the relative importance of the various processes that may cause climate change.

CLIMATE SENSITIVITY

The sensitivity of the climate system to a forcing is commonly expressed in terms of the global mean temperature change that would be expected after a time sufficiently long for both the atmosphere and ocean to come to equilibrium with the change in climate forcing. If there were no climate feedbacks, the response of Earth's mean temperature to a forcing of 4 W/m^2 (the forcing for a doubled atmospheric CO_2) would be an increase of about 1.2°C (about 2.2°F). However, the total climate change is affected not only by the immediate direct forcing, but also by climate "feedbacks" that come into play in response to the forcing. For example, a climate forcing that causes warming may melt some of the sea ice. This is a positive feedback because the darker ocean absorbs more sunlight than the sea ice it replaced. The responses of atmospheric water vapor amount and clouds probably generate the most important global climate feedbacks. The nature and magnitude of these hydrologic feedbacks give rise to the largest source of uncertainty about climate sensitivity, and they are an area of continuing research.

As just mentioned, a doubling of the concentration of carbon dioxide (from the pre-Industrial value of 280 parts per million) in the global atmosphere causes a forcing of 4 W/m^2. The central value of the climate sensitivity to this change is a global average temperature increase of 3°C (5.4°F), but with a range from 1.5°C to 4.5°C (2.7 to 8.1°F) (based on climate system models: see section 4). The central value of 3°C is an amplification by a factor of 2.5 over the direct effect of 1.2°C (2.2°F). Well-documented climate changes during the history of Earth, especially the changes between the last major ice age (20,000 years ago) and the current warm period, imply that the climate sensitivity is near the 3°C value. However, the true climate sensitivity remains uncertain, in part because it is difficult to model the effect of cloud feedback. In particular, the magnitude and even the sign of the feedback can differ according to the composition, thickness, and altitude of the clouds, and some studies have suggested a lesser climate sensitivity. On the other hand, evidence from paleoclimate variations indicates that climate sensitivity could be higher than the above range, although perhaps only on longer time scales.

TRANSIENT CLIMATE CHANGE

Climate fluctuates in the absence of any change in forcing, just as weather fluctuates from day to day. Climate also responds in a systematic way to climate forcings, but the response can be slow because the ocean requires time to warm (or cool) in response to the forcing. The response time depends upon the rapidity with which the ocean circulation transmits changes in surface temperature into the deep ocean. If the climate sensitivity is as high as the 3°C mid-range, then a few decades are required for just half of the full climate response to be realized, and at least several centuries for the full response.[1]

Such a long climate response time complicates the climate change issue for policy makers because it means that a discovered undesirable climate change is likely to require many decades to halt or reverse.

Increases in the temperature of the ocean that are initiated in the next few decades will continue to raise sea level by ocean thermal expansion over the next several centuries. Although society might conclude that it is practical to live with substantial climate change in the coming decades, it is also important to consider further consequences that may occur in later centuries. The climate sensitivity and the dynamics of large ice sheets become increasingly relevant on such longer time scales.

It is also possible that climate could undergo a sudden large change in response to accumulated climate forcing. The paleoclimate record contains examples of sudden large climate changes, at least on regional scales. Understanding these rapid changes is a current research challenge that is relevant to the analysis of possible anthropogenic climate effects.

[1]The time required for the full response to be realized depends, in part, on the rate of heat transfer from the ocean mixed layer to the deeper ocean. Slower transfer leads to shorter response times on Earth's surface.

2

Natural Climatic Variations

What is the range of natural variability in climate?

Climate is continually varying on time scales ranging from seasons to the lifetime of Earth. Natural climate changes can take place on short time scales as a result of the rapid alterations to forcings (as described in section 1). For example, the injection of large quantities of sulfur dioxide (SO_2), which changes to sulfuric acid droplets, and fine particulate material into the stratosphere (the region between 10 and 30 miles altitude where the temperature rises with increasing altitude) by major volcanic eruptions like that of Mt. Pinatubo in 1991 can cause intervals of cooler than average global temperatures. Climate variability also can be generated by processes operating within the climate system—the periodic rapid warming trend in the eastern Pacific Ocean known as El Niño being perhaps the best known example. Each of these different processes produces climate variability with its own characteristic spatial and seasonal signature. For example, El Niño typically brings heavy rainstorms to coastal Ecuador, Peru, and California and droughts to Indonesia and Northeast Brazil.

Over long time scales, outside the time period in which humans could have a substantive effect on global climate (e.g., prior to the Industrial Revolution), proxy data (information derived from the content of tree rings, cores from marine sediments, pollens, etc.) have been used to estimate the range of natural climate variability. An important recent addition to the collection of proxy evidence is ice cores obtained by international teams of scientists drilling through miles of ice in Antarctica and at the opposite end of the world in Greenland. The results can be used to make inferences about climate and atmospheric composition extending back as long as 400,000 years. These and other proxy data indicate that the range of natural climate variability is in excess of several degrees C on local and regional space scales over periods as short as a decade. Precipitation has also varied widely. For example, there is evidence to suggest that droughts as severe as the "dust bowl" of the 1930s were much more common in the central United States during the 10th to 14th centuries than they have been in the more recent record.

Temperature variations at local sites have exceeded 10°C (18°F) in association with the repeated glacial advances and retreats that occurred over the course of the past million years. It is more difficult to estimate the natural variability of global mean temperature because large areas of the world are not sampled and because of the large uncertainties inherent in temperatures inferred from proxy evidence. Nonetheless, evidence suggests that global warming rates as large as 2°C (3.6°F) per millennium may have occurred during the retreat of the glaciers following the most recent ice age.

3

Human Caused Forcings

Are concentrations of greenhouse gases and other emissions that contribute to climate change increasing at an accelerating rate, and are different greenhouse gases and other emissions increasing at different rates?

Is human activity the cause of increased concentrations of greenhouse gases and other emissions that contribute to climate change?

What other emissions are contributing factors to climate change (e.g., aerosols, CO, black carbon soot), and what is their relative contribution to climate change?

How long does it take to reduce the buildup of greenhouse gases and other emissions that contribute to climate change?

Do different greenhouse gases and other emissions have different draw down periods?

Are greenhouse gases causing climate change?

GREENHOUSE GASES

The most important greenhouse gases in Earth's atmosphere include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), water vapor (H_2O), ozone (O_3), and the chlorofluorocarbons (CFCs including CFC-12 (CCl_2F_2) and CFC-11 (CCl_3F)). In addition to reflecting sunlight, clouds are also a major greenhouse substance. Water vapor and cloud droplets are in fact the dominant atmospheric absorbers, and how these substances respond to climate forcings is a principal determinant of climate sensitivity, as discussed in Section 1. The CO_2, CH_4, N_2O and H_2O are both produced and utilized in many biological processes, although the major source of gaseous water is evaporation from the oceans. Ozone is created in the atmosphere by reactions initiated by sunlight. The CFCs are synthetic compounds developed and released into the atmosphere by humankind. In addition, sulfur hexafluoride (SF_6) and perfluorocarbon gases such as carbon tetrafluoride (CF_4) are very potent and nearly inert greenhouse gases with atmospheric lifetimes much longer than 1000 years.

The natural atmosphere contained many greenhouse gases whose atmospheric concentrations were determined by the sum of the ongoing geophysical, biological, and chemical reactions that produce and destroy them. The specific effects of humankind's activities before the industrial era were immersed in all of the natural dynamics and became noticeable only in the immediate vicinity, as with the smoke from small fires. The theoretical realization that human activities could have a global discernible effect on the atmosphere came during the 19th century, and the first conclusive measurements of atmospheric change were made during the last half of the 20th century. The first greenhouse gas demonstrated to be increasing in atmospheric concentration was carbon dioxide, formed as a major end product in the extraction of energy from the burning of the fossil fuels—coal, oil, and natural gas—as well as in the burning of biomass.

The common characteristics of greenhouse gases are (1) an ability to absorb terrestrial infrared radiation and (2) a presence in Earth's atmosphere. The most important greenhouse gases listed above all contain three or more atoms per molecule. Literally thousands of gases have been identified as being present in the atmosphere at some place and at some time, and all but a few have the ability to absorb terrestrial infrared radiation. However, the great majority of these chemical compounds, both natural[1] and anthropogenic, are removed in hours, days, or weeks, and do not accumulate in significant concentrations. Some can have an indirect greenhouse effect, as with carbon monoxide (CO).[2] If the average survival time for a gas in the atmosphere is a year or longer, then the winds have time to spread it throughout the lower atmosphere, and its absorption of terrestrial infrared radiation occurs at all latitudes and longitudes. All the listed greenhouse gases except ozone are released to the atmosphere at Earth's surface and are spread globally throughout the lower atmosphere.

The lifetime of CH_4 in the atmosphere is 10-12 years. Nitrous oxide and the CFCs have century-long lifetimes before they are destroyed in the stratosphere. Atmospheric CO_2 is not destroyed chemically, and its removal from the atmosphere takes place through multiple processes that transiently store the carbon in the land and ocean reservoirs, and ultimately as mineral deposits. A major removal process depends on the transfer of the carbon content of near-surface waters to the deep ocean, which has a century time scale, but final removal stretches out over hundreds of thousands of years. Reductions in the atmospheric concentrations of these gases following possible lowered emission rates in the future will stretch out over decades for methane, and centuries and longer for carbon dioxide and nitrous oxide.

Methane, nitrous oxide, and ozone all have natural sources, but they can also be introduced into the atmosphere by the activities of humankind. These supplementary sources have contributed to the increasing concentrations of these gases during the 20th century.

Carbon Dioxide

While all of the major greenhouse gases have both natural and anthropogenic atmospheric sources, the nature of these processes varies widely among them. Carbon dioxide is naturally absorbed and released by the terrestrial biosphere as well as by the oceans. Carbon dioxide is also formed by the burning of wood, coal, oil, and natural gas, and these activities have increased steadily during the last two centuries since the Industrial Revolution. That the burning of fossil fuels is a major cause of the CO_2 increase is evidenced by the concomitant decreases in the relative abundance of both the stable and radioactive carbon isotopes[3] and the decrease in atmospheric oxygen. Continuous high-precision measurements have been made of its atmospheric concentrations only since 1958, and by the year 2000 the concentrations had increased 17% from 315 parts per million by volume (ppmv) to 370 ppmv. While the year-to-year increase varies, the average annual increase of 1.5 ppmv/year over the past two decades is slightly greater than during the 1960s and 1970s. A marked seasonal oscillation of carbon dioxide concentration exists, especially in the northern hemisphere because of the extensive draw down of carbon dioxide every spring and summer as the green plants convert carbon dioxide into plant material, and the return in the rest of the year as decomposition exceeds photosynthesis. The seasonal effects are quite different north and south of the equator, with the variation much greater in the northern hemisphere where most of Earth's land surface and its vegetation and soils are found.

The atmospheric CO_2 increase over the past few decades is less than the input from human activities because a fraction of the added CO_2 is removed by oceanic and terrestrial processes. Until recently, the partitioning of the carbon sink between the land and sea has been highly uncertain, but recent high-precision measurements of the atmospheric oxygen:nitrogen (O_2:N_2) ratio have provided a crucial constraint: fossil fuel burning and terrestrial uptake processes have different O_2:CO_2 ratios, whereas the ocean CO_2 sink has no significant impact on atmospheric O_2. The atmospheric CO_2 increase for the 1990s was about half the CO_2 emission from fossil fuel combustion, with the oceans and land both serving as important repositories of the excess carbon, i.e., as carbon sinks.

Land gains and loses carbon by various processes: some natural-like photosynthesis and decomposition, some connected to land use and land management practices, and some responding to the increases of carbon dioxide or other nutrients necessary for plant growth. These gains or losses dominate the net land exchange of carbon dioxide with the atmosphere, but some riverine loss to oceans is also significant. Most quantifiable, as by forest and soil inventories, are the above- and below-ground carbon losses from land clearing and the gains in storage in trees from forest recovery and management. Changes in the frequency of forest fires, such as from fire suppression policies, and agricultural practices for soil conservation may modify the carbon stored by land. Climate variations, through their effects on plant growth and decomposition of soil detritus, also have large effects on terrestrial carbon fluxes and storage on a year-to-year basis. Land modifications, mainly in the middle latitudes of the northern hemisphere, may have been a net source of carbon dioxide to the atmosphere over much of the last century. However, quantitative estimates have only been possible over the last two decades, when forest clearing had shifted to the tropics. In the 1980s land became a small net sink for

[1]While the activities of mankind are part of the natural world, the convention exists in most discussions of the atmosphere that "natural processes" are those that would still exist without the presence of human beings; those processes that are significantly influenced by humans are called "anthropogenic".

[2]Both carbon monoxide and methane are removed from the atmosphere by chemical reaction with hydroxyl (OH). An increase in the carbon monoxide uses up hydroxyl, slowing methane removal and allowing its concentration and greenhouse effect to increase.

[3]Fossil fuels are of biological origin and are depleted in both the stable isotope ^{13}C and the radioactive isotope ^{14}C, which has a half-life of 5600 years.

carbon, that is, the various processes storing carbon globally exceeded the loss due to tropical deforestation, which by itself was estimated to add 10-40% as much carbon dioxide to the atmosphere as burning of fossil fuels. In the 1990s the net storage on land became much larger, nearly as large as the ocean uptake. How land contributes, by location and processes, to exchanges of carbon with the atmosphere is still highly uncertain, as is the possibility that the substantial net removal will continue to occur very far into the future.[4]

Methane

Methane is the major component of natural gas and it is also formed and released to the atmosphere by many biologic processes in low oxygen environments, such as those occurring in swamps, near the roots of rice plants, and the stomachs of cows. Such human activities as rice growing, the raising of cattle, coal mining, use of land-fills, and natural-gas handling have increased over the last 50 years, and direct and inadvertent emissions from these activities have been partially responsible for the increase in atmospheric methane. Its atmospheric concentration has been measured globally and continuously for only two decades, and the majority of the methane molecules are of recent biologic origin. The concentrations of methane increased rather smoothly from 1.52 ppmv in 1978 by about 1% per year until about 1990. The rate of increase slowed down to less than that rate during the 1990s, and also became more erratic; current values are around 1.77 ppmv. About two-thirds of the current emissions of methane are released by human activities. There is no definitive scientific basis for choosing among several possible explanations for these variations in the rates of change of global methane concentrations, making it very difficult to predict its future atmospheric concentrations.

Both carbon dioxide and methane were trapped long ago in air bubbles preserved in Greenland and Antarctic ice sheets. These ice sheets are surviving relics of the series of ice ages that Earth experienced over the past 400,000 years. Concentrations of carbon dioxide extracted from ice cores have typically ranged between 190 ppmv during the ice ages to near 280 ppmv during the warmer "interglacial" periods like the present one that began around 10,000 years ago. Concentrations did not rise much above 280 ppmv until the Industrial Revolution. The methane concentrations have also varied during this 400,000 year period, with lowest values of 0.30 ppmv in the coldest times of the ice ages and 0.70 ppmv in the warmest, until a steady rise began about 200 years ago toward the present concentrations. Both carbon dioxide and methane are more abundant in Earth's atmosphere now than at any time during the past 400,000 years.

[4]The variations and uncertainties in the land carbon balance are important not only in the contemporary carbon budget. While the terrestrial carbon reservoirs are small compared to the oceans, the possibility of destabilizing land ecosystems and releasing the stored carbon, e.g. from the tundra soils, has been hypothesized.

Other Greenhouse Gases

Nitrous oxide is formed by many microbial reactions in soils and waters, including those processes acting on the increasing amounts of nitrogen-containing fertilizers. Some synthetic chemical processes that release nitrous oxide have also been identified. Its concentration remained about 0.27 ppmv for at least 1,000 years until two centuries ago, when the rise to the current 0.31 ppmv began.

Ozone is created mainly by the action of solar ultraviolet radiation on molecular oxygen in the upper atmosphere, and most of it remains in the stratosphere. However, a fraction of such ozone descends naturally into the lower atmosphere where additional chemical processes can both form and destroy it. This "tropospheric ozone" has been supplemented during the 20th century by additional ozone—an important component of photochemical smog—created by the action of sunlight upon pollutant molecules containing carbon and nitrogen. The most important of the latter include compounds such as ethylene (C_2H_4), carbon monoxide (CO), and nitric oxide released in the exhaust of fossil-fuel-powered motor vehicles and power plants and during combustion of biomass. The lifetime of ozone is short enough that the molecules do not mix throughout the lower atmosphere, but instead are found in broad plumes downwind from the cities of origin, which merge into regional effects, and into a latitude band of relatively high ozone extending from 30°N to 50°N that encircles Earth during Northern Hemisphere spring and summer. The presence of shorter-lived molecules, such as ozone, in the troposphere depends upon a steady supply of newly formed molecules, such as those created daily by traffic in the large cities of the world. The widespread practice of clearing forests and agricultural wastes ("biomass burning"), especially noticeable in the tropics and the Southern Hemisphere, contributes to tropospheric ozone.

The chlorofluorocarbons (CFCs) are different from the gases considered above in that they have no significant natural source but were synthesized for their technological utility. Essentially all of the major uses of the CFCs—as refrigerants, aerosol propellants, plastic foaming agents, cleaning solvents, and so on—result in their release, chemically unaltered, into the atmosphere. The atmospheric concentrations of the CFCs rose, slowly at first, from zero before first synthesis in 1928, and then more rapidly in the 1960s and 1970s with the development of a widening range of technological applications. The concentrations were rising in the 1980s at a rate of about 18 parts per trillion by volume (pptv) per year for CFC-12, 9 pptv/year for CFC-11, and 6 pptv/year for CFC-113 (CCl_2FCClF_2). Because these molecules were identified as agents causing the destruction of stratospheric ozone,[5] their production was banned in the industrial countries as of January 1996 under the terms of the 1992 revision of the Montreal Protocol, and further emissions have almost stopped. The atmospheric concentrations of CFC-11 and CFC-113 are now slowly decreasing, and that of CFC-12 has been essentially level for the past several years. However, because of the century-long lifetimes of these CFC molecules, appreciable atmospheric concentrations of each will survive well into the 22nd century.

Many other fluorinated compounds (such as carbon tetrafluoride, CF_4, and sulfur hexafluoride, SF_6), also have technological utility, and significant greenhouse gas capabilities. Their very long atmospheric lifetimes are a source of concern even though their atmospheric concentrations have not yet produced large radiative forcings. Members of the class of compounds called hydrofluorocarbons (HFCs) also have a greenhouse effect from the fluorine, but the hydrogen in the molecule allows reaction in the troposphere, reducing both its atmospheric lifetime and the possible greenhouse effect. The atmospheric concentrations of all these gases, which to date are only very minor greenhouse contributors, need to be continuously monitored to ensure that no major sources have developed. The sensitivity and generality of modern analytic systems make it unlikely that any additional greenhouse gas will be discovered that is already a significant contributor to the current total greenhouse effect.

AEROSOLS

Sulfate and carbon-bearing compounds associated with particles (i.e., carbonaceous aerosols) are two classes of aerosols that impact radiative balances, and therefore influence climate.

Black Carbon (soot)

The study of the role of black carbon in the atmosphere is relatively new. As a result it is characterized poorly as to its composition, emission source strengths, and influence on radiation. Black carbon is an end product of the incomplete combustion of fossil fuels and biomass, the latter resulting from both natural and human-influenced processes. Most of the black carbon is associated with fine particles (radius <0.2 μm) that have global residence times of about one week. These lifetimes are considerably shorter than those of most greenhouse gases, and thus the spatial distribution of black carbon aerosol is highly variable, with the greatest concentrations near the production regions. Because of the scientific uncertainties associated with the sources and composition of carbonaceous aerosols, projections of future impacts on climate are difficult. However, the increased burning of fossil fuels and the increased burning of biomass for land clearing may result in increased black carbon concentration globally.

Sulfate

The precursor to sulfate is sulfur dioxide gas, which has two primary natural sources: emissions from marine biota and volcanic emissions. During periods of low volcanic activity, the primary source of sulfur dioxide in regions downwind from continents is the combustion of sulfur-rich coals; less is contributed by other fossil fuels. In oceanic regions far removed from continental regions, the biologic source should dominate. However, model analyses, accounting for the ubiquitous presence of ships, indicate that even in these remote regions combustion is a major source of the sulfur dioxide. Some of the sulfur dioxide attaches to sea-salt aerosol where it is oxidized to sulfate. The sea salt has a residence time in the atmosphere on the order of hours to days, and it is transported in the lower troposphere. Most sulfate aerosol is associated with small aerosols (radius <1 μm) and is transported in the upper troposphere with an atmospheric lifetime on the order of one week. Recent “clean coal technologies” and the use of low sulfur fossil fuels have resulted in decreasing sulfate concentrations, especially in North America and regions downwind. Future atmospheric concentrations of sulfate aerosols will be determined by the extent of non-clean coal burning techniques, especially in developing nations.

CLIMATE FORCINGS IN THE INDUSTRIAL ERA

Figure 1 summarizes climate forcings that have been introduced during the period of industrial development, between 1750 and 2000, as estimated by the IPCC. Some of these forcings, mainly greenhouse gases, are known quite accurately, while others are poorly measured. A range of uncertainty has been estimated for each forcing, represented by an uncertainty bar or “whisker.” However, these estimates are partly subjective, and it is possible that the true forcing falls outside the indicated range in some cases.

Greenhouse Gases

Carbon dioxide (CO_2) is probably the most important climate forcing agent today, causing an increased forcing of about 1.4 W/m^2. CO_2 climate forcing is likely to become more dominant in the future as fossil fuel use continues. If fossil fuels continue to be used at the current rate, the added

[5]Eighty-five percent of the mass of the atmosphere lies in the troposphere, the region between the surface and an altitude of about 10 miles. About 90% of Earth’s ozone is found in the stratosphere, and the rest is in the troposphere.

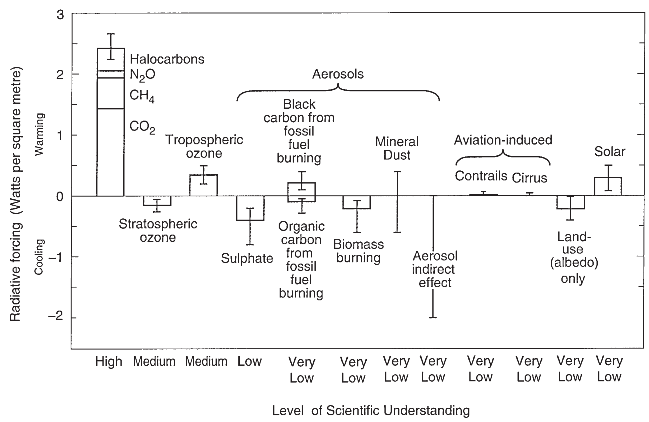

FIGURE 1 The global mean radiative forcing of the climate system for the year 2000, relative to 1750, and the associated confidence levels with which they are known. (From IPCC, 2001; reprinted with permission of the Intergovernmental Panel on Climate Change.)

CO_2 forcing in 50 years will be about 1 W/m^2. If fossil fuel use increases by 1-1.5% per year for 50 years, the added CO_2 forcing instead will be about 2 W/m^2. These estimates account for the non-linearity caused by partial saturation in some greenhouse gas infrared absorption bands, yet they are only approximate because of uncertainty about how efficiently the ocean and terrestrial biosphere will sequester atmospheric CO_2. The estimates also presume that during the next 50 years humans will not, on a large scale, capture and sequester the CO_2 released during fossil-fuel burning.

Other greenhouse gases together cause a climate forcing approximately equal to that of CO_2. Any increase in CH_4 also indirectly causes further climate forcing by increasing stratospheric H_2O (about 7% of the CH_4 is oxidized in the upper atmosphere), as well as by increasing tropospheric O_3 through reactions involving OH and nitrogen oxides. The total climate forcing by CH_4 is at least a third as large as the CO_2 forcing, and it could be half as large as the CO_2 forcing when the indirect effects are included.

Methane is an example of a forcing whose growth could be slowed or even stopped entirely or reversed. The common scenarios for future climate change assume that methane will continue to increase. If instead its amount were to remain constant or decrease, the net climate forcing could be significantly reduced. The growth rate of atmospheric methane has slowed by more than half in the past two decades for reasons that are not well understood. With a better understanding of the sources and sinks of methane, it may be possible to encourage practices (for example, reduced leakage during fossil-fuel mining and transport, capture of land-fill emissions, and more efficient agricultural practices) that lead to a decrease in atmospheric methane and significantly reduce future climate change. The atmospheric lifetime of methane is of the order of a decade, therefore, unlike CO_2, emission changes will be reflected in changed forcing rather quickly.

Tropospheric ozone (ozone in the lower 5-10 miles of the atmosphere) has been estimated to cause a climate forcing of about 0.4 W/m^2. Some of this is linked to methane increases as discussed above, and attribution of the ozone forcing between chemical factors such as methane, carbon monoxide, and other factors is a challenging problem. One recent study, based in part on limited observations of ozone in the late 1800s, suggested that human-made ozone forcing could be as large as about 0.7-0.8 W/m^2. Surface level ozone is a major ingredient in air pollution with substantial impacts on human health and agricultural productivity. The potential human and economic gains from reduced ozone pollution and its importance as a climate forcing make it an attractive target for further study as well as possible actions that could lead to reduced ozone amounts or at least a halt in its further growth.

Aerosols

Climate forcing by anthropogenic aerosols is a large source of uncertainty about future climate change. On the basis of estimates of past climate forcings, it seems likely that aerosols, on a global average, have caused a negative climate forcing (cooling) that has tended to offset much of the positive forcing by greenhouse gases. Even though aerosol distributions tend to be regional in scale, the forced climate response is expected to occur on larger, even hemispheric and global, scales. The monitoring of aerosol properties has not been adequate to yield accurate knowledge of the aerosol climate influence.

Estimates of the current forcing by sulfates fall mainly in the range –0.3 to –1 W/m^2. However, the smaller values do not fully account for the fact that sulfate aerosols swell in size substantially in regions of high humidity. Thus, the sulfate forcing probably falls in the range –0.6 to –1 W/m^2. Further growth of sulfate aerosols is likely to be limited by concerns about their detrimental effects, especially acid rain, and it is possible that control of sulfur emissions from combustion will even cause the sulfate amount to decrease.

Black carbon (soot) aerosols absorb sunlight and, even though this can cause a local cooling of the surface in regions of heavy aerosol concentration, it warms the atmosphere and, for plausible atmospheric loadings, soot is expected to cause a global surface warming. IPCC reports have provided a best estimate for the soot forcing of 0.1-0.2 W/m^2, but with large uncertainty. One recent study that accounts for the larger absorption that soot can cause when it is mixed internally with other aerosols suggests that its direct forcing is at least 0.4 W/m^2. It also has been suggested that the indirect effects of black carbon—which include reducing low-level cloud cover (by heating of the layer), making clouds slightly "dirty" (darker), and lowering of the albedo of snow and sea ice—might double this forcing to 0.8 W/m^2. The conclusion is that the black carbon aerosol forcing is uncertain but may be substantial. Thus there is the possibility that decreasing black carbon emissions in the future could have a cooling effect that would at least partially compensate for the warming that might be caused by a decrease in sulfates.

Other aerosols are also significant. Organic carbon aerosols are produced naturally by vegetation and anthropogenically in the burning of fossil fuels and biomass. Organic carbon aerosols thus accompany and tend to be absorbed by soot aerosols, and they are believed to increase the toxicity of the aerosol mixture. It is expected that efforts to reduce emissions of black carbon would also reduce organic carbon emissions. Ammonium nitrate (not included in Figure 1) recently has been estimated to cause a forcing of –0.2 W/m^2.

Mineral dust, along with sea salt, sulfates, and organic aerosols, contributes a large fraction of the global aerosol mass. It is likely that human land-use activities have influenced the amount of mineral dust in the air, but trends are not well measured. Except for iron-rich soil, most mineral dust probably has a cooling effect, but this has not been determined well.

The greatest uncertainty about the aerosol climate forcing—indeed, the largest of all the uncertainties about global climate forcings—is probably the indirect effect of aerosols on clouds. Aerosols serve as condensation nuclei for cloud droplets. Thus, anthropogenic aerosols are believed to have two major effects on cloud properties: the increased number of nuclei results in a larger number of smaller cloud droplets, thus increasing the cloud brightness (the Twomey effect), and the smaller droplets tends to inhibit rainfall, thus increasing cloud lifetime and the average cloud cover on Earth. Both effects reduce the amount of sunlight absorbed by Earth and thus tend to cause global cooling. The existence of these effects has been verified in field studies, but it is extremely difficult to determine their global significance. Climate models that incorporate the aerosol-cloud physics suggest that these effects may produce a negative global forcing on the order of 1 W/m^2 or larger. The great uncertainty about this indirect aerosol climate forcing presents a severe handicap both for the interpretation of past climate change and for future assessments of climate changes.

Other Forcings

Other potentially important climate forcings include volcanic aerosols, anthropogenic land use, and solar variability. Stratospheric aerosols produced by large volcanoes that eject gas and dust to altitudes of 12 miles or higher can cause a climate forcing as large as several watts per square meter on global average. However, the aerosols fall out after a year or two, so unless there is an unusual series of eruptions, they do not contribute to long-term climate change.

Land-use changes, especially the removal or growth of vegetation, can cause substantial regional climate forcing. One effect that has been evaluated in global climate models is the influence of deforestation. Because forests are dark and tend to mask underlying snow, the replacement of forests by crops or grass yields a higher albedo surface and thus a cooling effect. This effect has been estimated to yield a global cooling tendency in the industrial era equivalent to a forcing of –0.2 W/m^2. Land use changes have been an important contributor to past changes of atmospheric carbon dioxide. However, the impacts of such changes on climate may be much more significant on regional scales than globally, and largely act through changes of the hydrologic cycle. Such impacts are currently poorly characterized because they depend on complex modeling details that are still actively being improved.

Solar irradiance, the amount of solar energy striking Earth, has been monitored accurately only since the late 1970s. However, indirect measures of solar activity suggest that there has been a positive trend of solar irradiance over the industrial era, providing a forcing estimated at about 0.3 W/m^2. Numerous possible indirect forcings associated with solar variability have been suggested. However, only one of these, ozone changes induced by solar ultraviolet irradiance variations, has convincing observational support. Some studies have estimated this indirect effect to enhance the direct solar forcing by 0.1 W/m^2, but this value remains highly uncertain. Although the net solar forcing appears small in comparison with the sum of all greenhouse gases, it is perhaps more appropriate to compare the solar forcing with the net anthropogenic forcing. Solar forcing is very uncertain, but almost certainly much smaller than the greenhouse gas forcing. It is not implausible that solar irradiance has been a significant driver of climate during part of the industrial era, as suggested by several modeling studies. However, solar forcing has been measured to be very small since 1980, and greenhouse gas forcing has certainly been much larger in the past two decades. In any case, future changes in solar irradiance and greenhouse gases require careful monitoring to evaluate their future balance. In the future, if greenhouse gases continue to increase rapidly while aerosol forcing moderates, solar forcing may be relatively less important. Even in that case, however, the difference between an increasing and decreasing irradiance could be significant and affect interpretation of climate change, so it is important that solar variations be accurately monitored.

4

Climate System Models

Climate system models are an important tool for interpreting observations and assessing hypothetical futures. They are mathematical computer-based expressions of the thermodynamics, fluid motions, chemical reactions, and radiative transfer of Earth climate that are as comprehensive as allowed by computational feasibility and by scientific understanding of their formulation. Their purpose is to calculate the evolving state of the global atmosphere, ocean, land surface, and sea ice in response to external forcings of both natural causes (such as solar and volcanic) and human causes (such as emissions and land uses), given geography and initial material compositions. Such models have been in use for several decades. They are continually improved to increase their comprehensiveness with respect to spatial resolution, temporal duration, biogeochemical complexity, and representation of important effects of processes that cannot practically be calculated on the global scale (such as clouds and turbulent mixing). Formulating, constructing, and using such models and analyzing, assessing, and interpreting their answers make climate system models large and expensive enterprises. For this reason, they are often associated, at least in part, with national laboratories. The rapid increase over recent decades in available computational speed and power offers opportunities for more elaborate, more realistic models, but requires regular upgrading of the basic computers to avoid obsolescence.

Climate models calculate outcomes after taking into account the great number of climate variables and the complex interactions inherent in the climate system. Their purpose is the creation of a synthetic reality that can be compared with the observed reality, subject to appropriate averaging of the measurements. Thus, such models can be evaluated through comparison with observations, provided that suitable observations exist. Furthermore, model solutions can be diagnosed to assess contributing causes of particular phenomena. Because climate is uncontrollable (albeit influenceable by humans), the models are the only available experimental laboratory for climate. They also are the appropriate high-end tool for forecasting hypothetical climates in the years and centuries ahead. However, climate models are imperfect. Their simulation skill is limited by uncertainties in their formulation, the limited size of their calculations, and the difficulty of interpreting their answers that exhibit almost as much complexity as in nature.

The current norm for a climate system model is to include a full suite of physical representations for air, water, land, and ice with a geographic resolution scale of typically about 250 km. Model solutions match the primary planetary-scale circulation, seasonal variability, and temperature structures with qualitative validity but still some remaining discrepancies. They show forced responses of the global-mean temperature that corresponds roughly with its measured history over the past century, though this requires model adjustments. They achieve a stable equilibrium over millennial intervals with free exchanges of heat, water, and stress across the land and water surfaces. They also exhibit plausible analogues for the dominant modes of intrinsic variability, such as the El Niño/Southern Oscillation (ENSO), although some important discrepancies still remain. At present, climate system models specify solar luminosity, atmospheric composition, and other agents of radiative forcing. A frontier for climate models is the incorporation of more complete biogeochemical cycles (for example, for carbon dioxide). The greater the sophistication and complexity of an atmospheric model, the greater the need for detailed multiple measurements, which test whether the model continues to mimic observational reality. Applications of climate models to past climate states encompass "snapshots" during particular millennia, but they do not yet provide for continuous evolution over longer intervals (transitions between ice ages).

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Observed Climate Change During the Industrial Era

Is climate change occurring? If so, how?

Are the changes due to human activities?

THE OCCURRENCE OF CLIMATE CHANGE

A diverse array of evidence points to a warming of global surface air temperatures. Instrumental records from land stations and ships indicate that global mean surface air temperature warmed by about 0.4-0.8°C (0.7-1.5°F) during the 20th century. The warming trend is spatially widespread and is consistent with the global retreat of mountain glaciers, reduction in snow-cover extent, the earlier spring melting of ice on rivers and lakes, the accelerated rate of rise of sea level during the 20th century relative to the past few thousand years, and the increase in upper-air water vapor and rainfall rates over most regions. A lengthening of the growing season also has been documented in many areas, along with an earlier plant flowering season and earlier arrival and breeding of migratory birds. Some species of plants, insects, birds, and fish have shifted towards higher latitudes and higher elevations. The ocean, which represents the largest reservoir of heat in the climate system, has warmed by about 0.05°C (0.09°F) averaged over the layer extending from the surface down to 10,000 feet, since the 1950s.

Pronounced changes have occurred over high latitudes of the Northern Hemisphere. Analysis of recently declassified data from U.S. and Russian submarines indicates that sea ice in the central Arctic has thinned since the 1970s. Satellite data also indicate a 10-15% decrease in summer sea ice concentration over the Arctic as a whole, which is primarily due to the retreat of the ice over the Siberian sector. A decline of about 10% in spring and summer continental snow cover extent over the past few decades also has been observed. Some of these high latitude changes are believed to be as much or more a reflection of changes in wintertime wind patterns as a direct consequence of global warming per se. The rate of warming has not been uniform over the 20th century. Most of it occurred prior to 1940 and during the past few decades. The Northern Hemisphere as a whole experienced a slight cooling from 1946-75, and the cooling during that period was quite marked over the eastern United States. The cause of this hiatus in the warming is still under debate. The hiatus is evident in averages over both Northern and Southern Hemispheres, but it is more pronounced in the Northern Hemisphere. One possible cause of this feature is the buildup of sulfate aerosols due to the widespread burning of high sulfur coal during the middle of the century, followed by a decline indicated by surface sulfate deposition measurements. It is also possible that at least part of the rapid warming of the Northern Hemisphere during the first part of the 20th century and the subsequent cooling were of natural origin—a remote response to changes in the oceanic circulation at subarctic latitudes in the Atlantic sector, as evidenced by the large local temperature trends over this region. Suggestions that either variations in solar luminosity or the frequency of major volcanic emissions could have contributed to the irregular rate of warming during the 20th century cannot be excluded.

The IPCC report compares the warming of global mean temperature during the 20th century with the amplitude of climate variations over longer time intervals, making use of recent analyses of tree ring measurements from many different sites, data from the Greenland ice cores, and bore hole temperature measurements. On the basis of these analyses, they conclude that the 0.6°C (1.1°F) warming of the Northern Hemisphere during the 20th century is likely to have been the largest of any century in the past thousand years. This result is based on several analyses using a variety of proxy indicators, some with annual resolution and others with less resolved time resolution. The data become relatively sparse prior to 1600, and are subject to uncertainties related to spatial completeness and interpretation making the results somewhat equivocal, e.g., less than 90% confidence. Achieving greater certainty as to the magnitude of climate variations before that time will require more extensive data and analysis.

Although warming at Earth's surface has been quite pronounced during the past few decades, satellite measurements beginning in 1979 indicate relatively little warming of air temperature in the troposphere. The committee concurs with the findings of a recent National Research Council report,[1] which concluded that the observed difference between surface and tropospheric temperature trends during the past 20 years is probably real, as well as its cautionary statement to the effect that temperature trends based on such short periods of record, with arbitrary start and end points, are not necessarily indicative of the long-term behavior of the climate system. The finding that surface and troposphere temperature trends have been as different as observed over intervals as long as a decade or two is difficult to reconcile with our current understanding of the processes that control the vertical distribution of temperature in the atmosphere.

THE EFFECT OF HUMAN ACTIVITIES

Because of the large and still uncertain level of natural variability inherent in the climate record and the uncertainties in the time histories of the various forcing agents (and particularly aerosols), a causal linkage between the buildup of greenhouse gases in the atmosphere and the observed climate changes during the 20th century cannot be unequivocally established. The fact that the magnitude of the observed warming is large in comparison to natural variability as simulated in climate models is suggestive of such a linkage, but it does not constitute proof of one because the model simulations could be deficient in natural variability on the decadal to century time scale. The warming that has been estimated to have occurred in response to the buildup of greenhouse gases in the atmosphere is somewhat greater than the observed warming. At least some of this excess warming has been offset by the cooling effect of sulfate aerosols, and in any case one should not necessarily expect an exact correspondence because of the presence of natural variability.

The cooling trend in the stratosphere, evident in radiosonde data since the 1960s and confirmed by satellite observations starting in 1979, is so pronounced as to be difficult to explain on the basis of natural variability alone. This trend is believed to be partially a result of stratospheric ozone depletion and partially a result of the buildup of greenhouse gases, which warm the atmosphere at low levels but cool it at high levels. The circulation of the stratosphere has responded to the radiatively induced temperature changes in such a way as to concentrate the effects in high latitudes of the winter hemisphere, where cooling of up to 5°C (9°F) has been observed.

There have been significant changes in the atmospheric circulation during the past several decades: e.g., the transition in climate over the Pacific sector around 1976 that was analogous in some respects to a transition toward more "El Niño-like" conditions over much of the Pacific, and the more gradual strengthening of the wintertime westerlies over subpolar latitudes of both Northern and Southern Hemispheres. Such features bear watching, lest they be early indications of changes in the natural modes of atmospheric variability triggered by human induced climate change. To place them in context, however, it is worth keeping in mind that there were events of comparable significance earlier in the record, such as the 1930s dust bowl.

[1] *Reconciling Observations of Global Temperature Change,* 2000.

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Future Climate Change

How much of the expected climate change is the consequence of climate feedback processes (e.g., water vapor, clouds, snow packs)?

By how much will temperatures change over the next 100 years and where?

What will be the consequences (e.g., extreme weather, health effects) of increases of various magnitude?

Has science determined whether there is a "safe" level of concentration of greenhouse gases?

ESTIMATING FUTURE CLIMATE CHANGE

Projecting future climate change first requires projecting the fossil-fuel and land-use sources of CO_2 and other gases and aerosols. How much of the carbon from future use of fossil fuels will be seen as increases in carbon dioxide in the atmosphere will depend on what fractions are taken up by land and the oceans. The exchanges with land occur on various time scales, out to centuries for soil decomposition in high latitudes, and they are sensitive to climate change. Their projection into the future is highly problematic.

Future climate change depends on the assumed scenario for future climate forcings, as well as upon climate sensitivity. The IPCC scenarios include a broad range of forcings. One scenario often used for climate model studies employs rapid growth rates such that annual greenhouse gas emissions continue to accelerate. This is a useful scenario, in part because it yields a reasonably large "signal/noise" in studies of the simulated climate response. More important, it provides a warning of the magnitude of climate change that may be possible if annual greenhouse gas emissions continue to increase. There are sufficient fossil fuels in the ground to supply such a scenario for well over a century.

IPCC scenarios cover a broad range of assumptions about future economic and technological development, including some that allow greenhouse gas emission reductions. However, there are large uncertainties in underlying assumptions about population growth, economic development, life style choices, technological change, and energy alternatives, so that it is useful to examine scenarios developed from multiple perspectives in considering strategies for dealing with climate change. For example, one proposed growth scenario[1] for the next 50 years notes that CO_2 emissions have grown by about 1% annually in the past 20 years and assumes a zero growth rate for CO_2 emissions until 2050 (that is, constant emissions). The scenario also focuses on forcings from non-CO_2 greenhouse gases such as methane, and assumes a zero growth rate for them (that is, atmospheric amounts in 2050 similar to those in 2000). Plausible assumptions for technological progress and human factors were proposed to achieve this trajectory for radiative forcing. This scenario leads to a predicted temperature increase of 0.75°C by 2050, approximately half of that resulting from more conventional assumptions. One rationale for focusing first on 2050 rather than 2100 is that it is more difficult to foresee the technological capabilities that may allow reduction of greenhouse gas emissions by 2100.

Scenarios for future greenhouse gas amounts, especially for CO_2 and CH_4, are a major source of uncertainty for projections of future climate. Successive IPCC assessments over the past decade each have developed a new set of scenarios

[1]Hansen, J., M. Sato, R. Ruedy, A. Lacis, and V. Oinas, Global warming in the twenty-first century: an alternative scenario, *Proceedings of the National Academy of Sciences*, 97: 9875-9880, 2000.

with little discussion of how well observed trends match with previous scenarios. The period of record is now long enough to make it useful to compare recent trends with the scenarios, and such studies will become all the more fruitful as years pass. The increase of global fossil fuel CO_2 emissions in the past decade, averaging 0.6% per year, has fallen below the IPCC scenarios. The growth of atmospheric CH_4 has fallen well below the IPCC scenarios. These slowdowns in growth rates could be short-term fluctuations that may be reversed. However, they emphasize the need to understand better the factors that influence current and future growth rates.

Global warming will not be spatially uniform, and it is expected to be accompanied by other climate changes. In areas and seasons in which there are large temperature changes, feedbacks may be much larger than their global values. An example of such regionally large effects is the ice-albedo feedback. Reduced snow cover and sea and lake ice will be important at high latitudes and higher elevations, especially during winter and spring. In the presence of the higher temperatures, atmospheric water vapor concentration and precipitation will also be higher. Determining the net ice-albedo feedback effect is complicated by its connections to other aspects of the hydrologic and energy cycles. Clouds may change to amplify or reduce its effect. Increased precipitation with warming at the margin of ice and snow may act to either reduce or amplify this effect, e.g., reducing the effect by increasing snow levels where it is below freezing. Changing vegetation cover likewise can introduce major modification.

An increase in the recycling rate of water in the hydrologic cycle is anticipated in response to higher global average temperatures. Higher evaporation rates will accelerate the drying of soils following rain events, thereby resulting in drier average conditions in some regions, especially during periods of dry weather during the warm season. The drier soils, with less water available for evapotranspiration, will warm more strongly during sunlight hours resulting in higher afternoon temperatures, faster evaporation, and an increase in the diurnal temperature range. The effect is likely to be greatest in semi-arid regions, such as the U.S. Great Plains. The faster recycling of water will lead to higher rainfall rates and an increase in the frequency of heavy precipitation events.

There is a possibility that global warming could change the behavior of one or more of the atmosphere's natural modes of variability such as ENSO or the so-called North Atlantic or Arctic Oscillation. Such changes could lead to complex changes in the present-day patterns of temperature and precipitation, including changes in the frequency of winter or tropical storms. Higher precipitation rates would favor increased intensity of tropical cyclones, which derive their energy from the heat that is released when water vapor condenses.

Temperatures are expected to increase more rapidly over land compared to oceans because of the ocean's higher heat capacity and because it can transfer more of the trapped heat to the atmosphere by evaporation. Over land, the warming has been—and is expected to continue to be—larger during nighttime than during daytime.

Consequences of Increased Climate Change of Various Magnitudes

The U.S. National Assessment of Climate Change Impacts, augmented by a recent NRC report on climate and health, provides a basis for summarizing the potential consequences of climate change.[2] The National Assessment directly addresses the importance of climate change of various magnitudes by considering climate scenarios from two well-regarded models (the Hadley model of the United Kingdom and the Canadian Climate Model). These two models have very different globally-averaged temperature increases (2.7 and 4.4°C (4.9 and 7.9°F), respectively) by the year 2100. A key conclusion from the National Assessment is that U.S. society is likely to be able to adapt to most of the climate change impacts on human systems, but these adaptations may come with substantial cost. The primary conclusions from these reports are summarized for agriculture and forestry, water, human health, and coastal regions.

In the near term, agriculture and forestry are likely to benefit from CO_2 fertilization effects and the increased water efficiency of many plants at higher atmospheric CO_2 concentrations. Many crop distributions will change, thus requiring significant regional adaptations. Given their resource base, the Assessment concludes that such changes will be costlier for small farmers than for large corporate farms. However, the combination of the geographic and climatic breadth of the United States, possibly augmented by advances in genetics, increases the nation's robustness to climate change. These conclusions depend on the climate scenario, with hotter and drier conditions increasing the potential for declines in both agriculture and forestry. In addition, the response of insects and plant diseases to warming is poorly understood. On the regional scale and in the longer term, there is much more uncertainty.

Increased tendency toward drought, as projected by some models, is an important concern in every region of the United States even though it is unlikely to be realized everywhere in the nation. Decreased snow pack and/or earlier season melting are expected in response to warming because the freeze line will be moving to higher elevations. The western part of

[2]Except where noted, this section is based on information provided in the U.S. National Assessment. U.S. Global Change Research Program, "Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change", 2001, Cambridge University Press, 612 pp.

the nation is highly dependent on the amount of snow pack and the timing of the runoff. The noted increased rainfall rates have implications for pollution run-off, flood control, and changes to plant and animal habitat. Any significant climate change is likely to result in increased costs because the nation's investment in water supply infrastructure is largely tuned to the current climate.

Health outcomes in response to climate change are the subject of intense debate. Climate change has the potential to influence the frequency and transmission of infectious disease, alter heat- and cold-related mortality and morbidity, and influence air and water quality. Climate change is just one of the factors that influence the frequency and transmission of infectious disease, and hence the assessments view such changes as highly uncertain.[3] This said, changes in the agents that transport infectious diseases (e.g., mosquitoes, ticks, rodents) are likely to occur with any significant change in precipitation and temperature. Increases in mean temperatures are expected to result in new record high temperatures and warm nights and an increase in the number of warm days compared to the present. Cold-related stress is likely to decline whereas heat stress in major urban areas is projected to increase if no adaptation occurs. The National Assessment ties increases in adverse air quality to higher temperatures and other air mass characteristics. However, much of the United States appears to be protected against many different adverse health outcomes related to climate change by a strong public health system, relatively high levels of public awareness, and a high standard of living. Children, the elderly, and the poor are considered to be the most vulnerable to adverse health outcomes. The understanding of the relationships between weather/climate and human health is in its infancy and therefore the health consequences of climate change are poorly understood. The costs, benefits, and availability of resources for adaptation are also uncertain.

Fifty-three percent of the U.S. population lives within the coastal regions, along with billions of dollars in associated infrastructure. Because of this, coastal areas are more vulnerable to increases in severe weather and sea level rise. Changes in storm frequency and intensity are one of the more uncertain elements of future climate change prediction. However, sea level rise increases the potential damage to coastal regions even under conditions of current storm intensities and can endanger coastal ecosystems if human systems or other barriers limit the opportunities for migration.

In contrast to human systems, the U.S. National Assessment makes a strong case that ecosystems are the most vulnerable to the projected rate and magnitude of climate change, in part because the available adaptation options are very limited. Significant climate change will cause disruptions to many U.S. ecosystems, including wetlands, forests, grasslands, rivers, and lakes. Ecosystems have inherent value, and also supply the country with a wide variety of ecosystem services.

The impacts of these climate changes will be significant, but their nature and intensity will depend strongly on the region and timing of occurrence. At a national level, the direct economic impacts are likely to be modest. However, on a regional basis the level and extent of both beneficial and harmful impacts will grow. Some economic sectors may be transformed substantially and there may be significant regional transitions associated with shifts in agriculture and forestry. Increasingly, climate change impacts will have to be placed in the context of other stresses associated with land use and a wide variety of pollutants. The possibility of abrupt or unexpected changes could pose greater challenges for adaptation.

Even the mid-range scenarios considered in the IPCC result in temperatures that continue to increase well beyond the end of this century, suggesting that assessments that examine only the next 100 years may well underestimate the magnitude of the eventual impacts. For example a sustained and progressive drying of the land surface, if it occurred, would eventually lead to desertification of regions that are now marginally arable, and any substantial melting or breaking up of the Greenland and Antarctic ice caps could cause widespread coastal inundation.[4]

"Safe" Level of Concentration of Greenhouse Gases

The potential for significant climate-induced impacts raises the question of whether there exists a "safe" level of greenhouse gas concentration. The word "safe" is ambiguous because it depends on both viewpoint and value judgment. This view changes dramatically if you are part of an Eskimo community dependent on sea ice for hunting, or an inhabitant of a coastal city, or a farm community. It depends on whether an industry is robust or sensitive to climate change. The viewpoint changes distinctly between countries with sufficient resources for adaptation and poorer nations. Value judgments become particularly important when assessing the potential impacts on natural ecosystems. The question can be approached from two perspectives. The first issue is whether there is a threshold in the concentration of greenhouse gases that, if exceeded, would cause dramatic or catastrophic changes to the Earth system. The second issue

[3] *Under the Weather: Climate, Ecosystems, and Infectious Disease*, 2001.

[4] Appreciable desertification on a regional scale could take place within a decade or two. Many centuries would be required for substantial melting of the ice sheets to occur and the likelihood of a breakup during this century is considered to be remote.

is whether the consequences of greenhouse warming, as a function of the concentration of greenhouse gases, are sufficiently well known that the scientific community can define "an acceptable concentration" based on an analysis of potential risks and damages. The first issue is best addressed by examining Earth's history. Guidance for the second issue can be derived from assessments of the impacts of climate change.

A variety of measurements demonstrate that CO_2 has varied substantially during Earth's history, reaching levels between three and nine times pre-industrial levels of carbon dioxide prior to 50 million years ago. During the periods of hypothesized high carbon dioxide concentrations, there are strong indicators of warmth (although many different factors have contributed to climate change during Earth's history). These indicators include warm deep-sea temperatures and abundant life within the Arctic Circle. There are also some records of abrupt warming (thousands of years) in Earth's history that may be related to atmospheric greenhouse concentrations, which caused significant perturbations to the Earth system. The global temperature increases determined for some of these warm periods exceed future projections from all climate models for the next century. These changes are associated with some extinctions, and both the periods of warmth and abrupt transitions are associated with the large-scale redistribution of species. However, a substantial biosphere is evident (i.e., no catastrophic impact tending toward wholesale extinctions) even with substantially higher CO_2 concentrations than those postulated to occur in response to human activities.

The course of future climate change will depend on the nature of the climate forcing (e.g., the rate and magnitude of changes in greenhouse gases, aerosols) and the sensitivity of the climate system. Therefore, determination of an acceptable concentration of greenhouse gases depends on the ability to determine the sensitivity of the climate system as well as knowledge of the full range of the other forcing factors, and an assessment of the risks and vulnerabilities. Climate models reflect a range of climate sensitivities even with the same emission scenario. For example, the consequences of climate change would be quite different for a globally-averaged warming of 1.1°C (2.0°F) or a 3.1°C (5.6°F) projected for the IPCC scenario in which CO_2 increases by 1% per year leading to a doubling from current levels in the next 70 years.

Both climate change and its consequences also are likely to have a strong regional character. The largest changes occur consistently in the regions of the middle to high latitudes. Whereas all models project global warming and global increases in precipitation, the sign of the precipitation projections varies among models for some regions.

The range of model sensitivities and the challenge of projecting the sign of the precipitation changes for some regions represent a substantial limitation in assessing climate impacts. Therefore, both the IPCC and the U.S. National Assessment of Climate Change Impacts assess potential climate impacts using approaches that are "scenario-driven." In other words, models with a range of climate sensitivities are used to assess the potential impacts on water, agriculture, human health, forestry, and the coastal zones, nationally and region by region. The differences among climate model projections are sufficiently large to limit the ability to define an "acceptable concentration" of atmospheric greenhouse gases. In addition, technological breakthroughs that could improve the capabilities to adapt are not known. Instead, the assessments provide a broader level of guidance:

- The nature of the potential impacts of climate change increases as a function of the sensitivity of the climate model. If globally-averaged temperature increases approach 3°C (5.4°F) in response to doubling of carbon dioxide, they are likely to have substantial impacts on human endeavors and on natural ecosystems.
- Given the fact that middle and high latitude regions appear to be more sensitive to climate change than other regions, significant impacts in these regions are likely to occur at lower levels of global warming.
- There could be significant regional impacts over the full range of IPCC model-based projections.
- Natural ecosystems are less able to adapt to change than are human systems.

In summary, critical factors in defining a "safe" concentration depend on the nature and level of societal vulnerability, the degree of risk aversion, ability and/or costs of adaptation and/or mitigation, and the valuation of ecosystems, as well as on the sensitivity of the Earth system to climate change.

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Assessing Progress in Climate Science

What are the substantive differences between the IPCC Reports and the Summaries?

What are the specific areas of science that need to be studied further, in order of priority, to advance our understanding of climate change?

The committee was asked to address these two questions. The first involved evaluating the IPCC Working Group I report and summaries in order to identify how the summaries differ from the report. The second question involved characterizing areas of uncertainty in scientific knowledge concerning climate change, and identifying the research areas that will advance the understanding of climate change.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

The full text of the IPCC Third Assessment Report on *The Scientific Basis* represents a valuable effort by U.S. and international scientists in identifying and assessing much of the extensive research going on in climate science. The body of the WGI report is scientifically credible and is not unlike what would be produced by a comparable group of only U.S. scientists working with a similar set of emission scenarios, with perhaps some normal differences in scientific tone and emphasis.

However, because the IPCC reports are generally invoked as the authoritative basis for policy discussions on climate change, we should critically evaluate this effort so that we can offer suggestions for improvement. The goal is a stronger IPCC that will lead to better definitions of the nature of remaining problems, a clarity in expressing both robust conclusions and uncertainties, and thus aid achievement of the best possible policy decisions. We must also consider options for an improved process, given the enormous and growing investment required by individual scientists to produce this assessment. Three important issues directed to this goal are described below.

The IPCC Summary for Policy Makers

The IPCC WGI *Summary for Policymakers* (SPM) serves an obviously different purpose than the scientific working group reports. When one is condensing 1,000 pages into 20 pages with a different purpose in mind, we would expect the text to contain some modifications. After analysis, the committee finds that the conclusions presented in the SPM and the *Technical Summary* (TS) are consistent with the main body of the report. There are, however, differences. The primary differences reflect the manner in which uncertainties are communicated in the SPM. The SPM frequently uses terms (e.g., likely, very likely, unlikely) that convey levels of uncertainty; however, the text less frequently includes either their basis or caveats. This difference is perhaps understandable in terms of a process in which the SPM attempts to underline the major areas of concern associated with a human-induced climate change. However, a thorough understanding of the uncertainties is essential to the development of good policy decisions.

Climate projections will always be far from perfect. Confidence limits and probabilistic information, with their basis, should always be considered as an integral part of the information that climate scientists provide to policy and decision makers. Without them, the IPCC SPM could give an impression that the science of global warming is "settled," even though many uncertainties still remain. The emission scenarios used by the IPCC provide a good example. Human decisions will almost certainly alter emissions over the next century. Because we cannot predict either the course of human populations, technology, or societal transitions with any clarity, the actual greenhouse gas emissions could be either greater or less than the IPCC scenarios. Without an understanding of the sources and degree of uncertainty, decision makers could fail to define the best ways to deal with the serious issue of global warming.

Modification of the Scientific Text After Completion of the SPM

The SPM results from a discussion between the lead authors and government representatives (including also some non-governmental organizations and industry representatives). This discussion, combined with the requirement for consistency, results in some modifications of the text, all of which were carefully documented by the IPCC. This process has resulted in some concern that the scientific basis for the SPM might be altered. To assess this potential problem, the committee solicited written responses from U.S. coordinating lead authors and lead authors of IPCC chapters, reviewed the WGI draft report and summaries, and interviewed Dr. Daniel Albritton who served as a coordinating lead author for the IPCC WGI *Technical Summary*. Based on this analysis, the committee finds that no changes were made without the consent of the convening lead authors and that most changes that did occur lacked significant impact. However, some scientists may find fault with some of the technical details, especially if they appear to underestimate uncertainty. The SPM is accompanied by the more representative *Technical Summary* (TS). The SPM contains cross-references to the full text, which unfortunately is not accessible until a later date, but it does not cross-reference the accompanying TS.

The IPCC as Representative of the Science Community

The IPCC process demands a significant time commitment by members of the scientific community. As a result, many climate scientists in the United States and elsewhere choose not to participate at the level of a lead author even after being invited. Some take on less time-consuming roles as contributing authors or reviewers. Others choose not to participate. This may present a potential problem for the future. As the commitment to the assessment process continues to grow, this could create a form of self-selection for the participants. In such a case, the community of world climate scientists may develop cadres with particularly strong feelings about the outcome: some as favorable to the IPCC and its procedures and others negative about the use of the IPCC as a policy instrument. Alternative procedures are needed to ensure that participation in the work of the IPCC does not come at the expense of an individual's scientific career.

In addition, the preparation of the SPM involves both scientists and governmental representatives. Governmental representatives are more likely to be tied to specific government postures with regard to treaties, emission controls, and other policy instruments. If scientific participation in the future becomes less representative and governmental representatives are tied to specific postures, then there is a risk that future IPCC efforts will not be viewed as independent processes.

The United States should promote actions that improve the IPCC process while also ensuring that its strengths are maintained. The most valuable contribution U.S. scientists can make is to continually question basic assumptions and conclusions, promote clear and careful appraisal and presentation of the uncertainties about climate change as well as those areas in which science is leading to robust conclusions, and work toward a significant improvement in the ability to project the future. In the process, we will better define the nature of the problems and ensure that the best possible information is available for policy makers.

RESEARCH PRIORITIES

The underlying scientific issues that have been discussed in this report and the research priorities that they define have evolved over time. For this reason, many have been identified previously in NRC reports.[1]

Predictions of global climate change will require major advances in understanding and modeling of (1) the factors that determine atmospheric concentrations of greenhouse gases and aerosols and (2) the so called "feedbacks" that determine the sensitivity of the climate system to a prescribed increase in greenhouse gases. Specifically, this will involve reducing uncertainty regarding: (a) future usage of fossil fuels, (b) future emissions of methane, (c) the fraction of the future fossil fuel carbon that will remain in the atmosphere and provide radiative forcing versus exchange with the oceans or net exchange with the land biosphere, (d) the feedbacks in the climate system that determine both the magnitude of the change and the rate of energy uptake by the oceans, which together determine the magnitude and time history of the temperature increases for a given radiative forcing, (e) the details of the regional and local climate change consequent to an overall level of global climate change, (f) the nature and causes of the natural variability of climate and its interactions with forced changes, and (g) the direct and indirect effects of the changing distributions of aerosol. Because the total change in radiative forcing from

[1]*Decade-to-Century-Scale Climate Variability and Change: A Science Strategy*, 1998; *The Atmospheric Sciences Entering the Twenty-First Century*, 1998; *Adequacy of Climate Observing Systems*, 1999; *Global Environmental Change: Research Pathways for the Next Decade*, 1999; *Improving the Effectiveness of U.S. Climate Modeling*, 2001; *The Science of Regional and Global Change: Putting Knowledge to Work*, 2001.

other greenhouse gases over the last century has been nearly as large as that of carbon dioxide, their future evolution also must be addressed. At the heart of this is basic research, which allows for creative discoveries about those elements of the climate system that have not yet been identified, or studied.

Knowledge of the climate system and projections about the future climate are derived from fundamental physics and chemistry through models and observations of the atmosphere and the climate system. Climate models are built using the best scientific knowledge of the processes that operate within the climate system, which in turn are based on observations of these systems. A major limitation of these model forecasts for use around the world is the paucity of data available to evaluate the ability of coupled models to simulate important aspects of past climate. In addition, the observing system available today is a composite of observations that neither provide the information nor the continuity in the data needed to support measurements of climate variables. Therefore, above all, it is essential to ensure the existence of a long-term observing system that provides a more definitive observational foundation to evaluate decadal- to century-scale variability and change. This observing system must include observations of key state variables such as temperature, precipitation, humidity, pressure, clouds, sea ice and snow cover, sea level, sea-surface temperature, carbon fluxes and soil moisture. Additionally, more comprehensive regional measurements of greenhouse gases would provide critical information about their local and regional source strengths.

Climate observations and modeling are becoming increasingly important for a wide segment of society including water resource managers, public health officials, agribusinesses, energy providers, forest managers, insurance companies, and city planners. In order to address the consequences of climate change and better serve the nation's decision makers, the research enterprise dealing with environmental change and environment-society interactions must be enhanced. This includes support of (a) interdisciplinary research that couples physical, chemical, biological, and human systems, (b) improved capability of integrate scientific knowledge, including its uncertainty, into effective decision support systems, and (c) an ability to conduct research at the regional or sectoral level that promotes analysis of the response of human and natural systems to multiple stresses.

Climate research is presently overseen by the U.S. Global Change Research Program (USGCRP). A number of NRC reports[2] have concluded that this collection of agencies is hampered organizationally in its ability to address the major climate problems. The ability of the United States to assess future climate change is severely limited by the lack of a climate observing system, by inadequate computational resources, and by the general inability of government to focus resources on climate problems. Efforts are needed to ensure that U.S. efforts in climate research are supported and managed to ensure innovation, effectiveness, and efficiency. These issues have been addressed by NRC reports, but more examination is needed.

[2]*Global Environmental Change: Research Pathways for the Next Decade*, 1999; *Improving the Effectiveness of U.S. Climate Modeling*, 2001; *The Science of Regional and Global Change: Putting Knowledge to Work*, 2001

Appendixes

A

Letter from the White House

THE WHITE HOUSE
WASHINGTON

May 11, 2001

Dr. Bruce Alberts
National Academy of Sciences
2101 Constitution Avenue, NW
Washington, D.C. 20418

Dear Dr. Alberts:

The Administration is conducting a review of U.S. policy on climate change. We seek the Academy's assistance in identifying the areas in the science of climate change where there are the greatest certainties and uncertainties.

We would also like your views on whether there are any substantive differences between the IPCC Reports and the IPCC summaries.

We would appreciate a response as soon as possible.

Sincerely yours,

John M. Bridgeland
Deputy Assistant to the President
for Domestic Policy and
Director, Domestic Policy Council

Gary Edson
Deputy Assistant to the
President for International
Economic Affairs

B

Biographical Sketches of Committee Members and Staff

Dr. Ralph J. Cicerone *(Chair)* is the chancellor of the University of California at Irvine and the Daniel G. Aldrich Professor in the Department of Earth System Science and the Department of Chemistry. His areas of research include atmospheric chemistry; sources of gases that affect climate and the composition of the global atmosphere, especially methane and nitrous oxide; and the ozone layer and human influence on it. He is a member of the National Academy of Sciences. Dr. Cicerone received his Ph.D. from the University of Illinois.

Dr. Eric J. Barron is Director of the Earth and Mineral Sciences Environment Institute and Distinguished Professor of Geosciences at Pennsylvania State University. His specialty is paleoclimatology/paleoceanography. His research emphasizes global change, specifically numerical models of the climate system and the study of climate change throughout Earth's history. Dr. Barron is a fellow of the American Geophysical Union and the American Meteorological Society. He has served on several National Research Council committees, including, most recently, the Grand Challenges in the Environmental Sciences and the Task Group on Assessment of NASA Plans for Post-2000 Earth Observing Missions. He is currently the chair of the Board on Atmospheric Sciences and Climate. Dr. Barron received his Ph.D. from the University of Miami.

Dr. Robert E. Dickinson is a professor of dynamics and climate in the School of Earth and Atmospheric Sciences at the Georgia Institute of Technology. His research interests include the dynamics of atmospheric planetary waves, stratospheric dynamics, models of global structure and dynamics of terrestrial and planetary thermosphere, NLTE infrared radiative transfer in planetary mesopheres, global climate modeling and processes, the role of land processes in climate systems, the modeling role of vegetation in regional evapotranspiration, and the role of tropical forests in climate systems. Dr. Dickinson is a member of the National Academy of Sciences and the recipient of the Revelle medal of the American Geophysical Union (AGU) and the Rossby award of the American Meteorological Society. He is currently president-elect of the AGU. Dr. Dickinson received his Ph.D. from the Massachusetts Institute of Technology.

Dr. Inez Y. Fung is the Richard and Rhoda Goldman Distinguished Professor for the Physical Sciences, Director of the Center for Atmospheric Sciences, and a professor in the Department of Earth and Planetary Science and the Department of Environmental Sciences, Policy and Management at the University of California at Berkeley. Her research expertise is in large-scale numerical modeling of biogeochemical cycles and their interaction with climate. Her research also includes climate change, remote sensing of earth systems, investigations of atmosphere-ocean interactions, and atmosphere-biosphere interactions. She is a member of the National Academy of Sciences, a fellow of the American Geophysical Union and the American Meteorological Society, and a recipient of NASA's Exceptional Scientific Achievement Medal. Dr. Fung received her Sc.D. from the Massachusetts Institute of Technology.

Dr. James E. Hansen is head of the NASA Goddard Institute for Space Studies. His research interests include radiative transfer in planetary atmospheres, interpretation of remote sounding of planetary atmospheres, development of simplified climate models and three-dimensional global climate models, current climate trends from observational data, and projections of man's impact on climate. He is a member of the National Academy of Sciences and a fellow of the

American Geophysical Union. Dr. Hansen received his Ph.D. from the University of Iowa.

Mr. Thomas R. Karl is Director of the National Climatic Data Center of the National Oceanic and Atmospheric Administration. Before this he served as the senior scientist where his research interests included global climate change, extreme weather events, and trends in global and U.S. climate over the past 100 years. Mr. Karl is a fellow of the American Meteorological Society and the American Geophysical Union and served as the chair of the National Research Council's Climate Research Committee. He was a coordinating lead author for the IPCC Working Group I Third Assessment Report. Mr. Karl received his M.S. from the University of Wisconsin.

Dr. Richard S. Lindzen is the Alfred P. Sloan Professor of Meteorology in the Department of Earth, Atmospheric and Planetary Sciences at the Massachusetts Institute of Technology. His research interests include dynamic meteorology and climatology, specifically upper atmosphere dynamics, waves and instability, climate sensitivity, regional and interannual variability of weather, tropical meteorology, monsoons, mesoscale systems, clear air turbulence, climate dynamics, and general circulation. He is a member of the National Academy of Sciences and a fellow of the American Association for the Advancement of Science. He was a lead author for the IPCC Working Group I Third Assessment Report. Dr. Lindzen received his Ph.D. from Harvard University.

Dr. James C. McWilliams is the Slichter Professor of Earth Sciences in the Department of Atmospheric Sciences and the Institute for Geophysics and Planetary Physics at the University of California at Los Angeles. His research focuses on the fluid dynamics of Earth's oceans and atmosphere, both their theory and computational modeling. Particular subjects of interest include the maintenance of general circulations; climate dynamics; geostrophically and cyclo-strophically balanced dynamics in rotating, stratified fluids; vortex dynamics; the planetary boundary layers; planetary-scale thermohaline convection, the roles of coherent structures of turbulent flows in geophysical and astrophysical regimes; numerical methods; coastal ocean modeling and statistical estimation theory. He is a fellow of the American Geophysical Union and has served on the National Research Council's Climate Research Committee and Board on Atmospheric and Sciences. Dr. McWilliams received his Ph.D. from Harvard University.

Dr. F. Sherwood Rowland is the Donald Bren Research Professor of Chemistry and Earth System Science at the University of California at Irvine. His research interests include atmospheric chemistry (stratospheric ozone, trace compounds in the troposphere on a global basis); chemical kinetics, in particular, gas phase reactions of chlorine, fluorine, and hydrogen; and radiochemistry, specifically tracer studies with radioactive isotopes. Dr. Rowland is a member of the National Academy of Sciences where he currently serves as Foreign Secretary. He is also a member of the Institute of Medicine. He has received numerous awards including the Nobel Prize in Chemistry in 1995 and the Revelle medal of the American Geophysical Union. Dr. Rowland received his Ph.D. from the University of Chicago.

Dr. Edward S. Sarachik is a professor in the Department of Atmospheric Sciences and an adjunct professor in the School of Oceanography at the University of Washington. His research interests focus on large-scale atmosphere-ocean interactions, seasonal variations in the tropical oceans, the role of the ocean in climate change, and biogeochemical cycles in the global ocean. Dr. Sarachik is a fellow of the American Geophysical Union, the American Meteorological Society, and the American Association for the Advancement of Science. He has served on numerous National Research Council committees including the Climate Research Committee, the Tropical Ocean/Global Atmosphere (TOGA) Advisory Panel (chair), and the Panel on Improving U.S. Climate Modeling (chair). Dr. Sarachik received his Ph.D. from Brandeis University.

Dr. John M. Wallace is a professor of atmospheric sciences and co-director of the University of Washington Program on the Environment. From 1981-98 he served as director of the (University of Washington/NOAA) Joint Institute for the Study of the Atmosphere and the Ocean. His research specialties include the study of atmospheric general circulation, El Niño, and global climate. He is a member of the National Academy of Sciences; a fellow of the American Association for the Advancement of Science, the American Geophysical Union (AGU), and the American Meteorological Society (AMS); and the recipient of the Rossby medal of the AMS and Revelle medal of the AGU. Dr. Wallace received his Ph.D. from the Massachusetts Institute of Technology.

Dr. Vaughan C. Turekian *(Study Director)* is a Program Officer with the Board on Atmospheric Sciences and Climate. He received his B.S. from Yale University, where he specialized in Geology and Geophysics and International Studies. He received his Ph.D. in Environmental Sciences from the University of Virginia in 2000 where he used stable bulk and compound-specific isotope analyses to characterize the sources and processing of aerosols in marine air.