



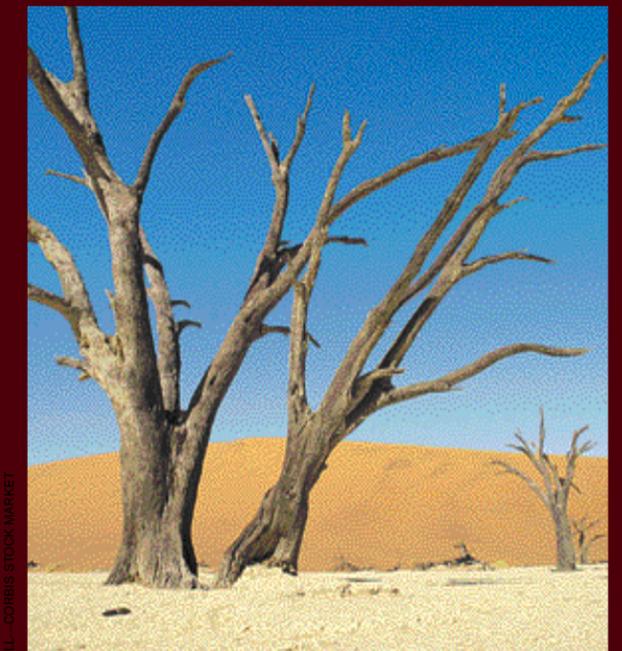
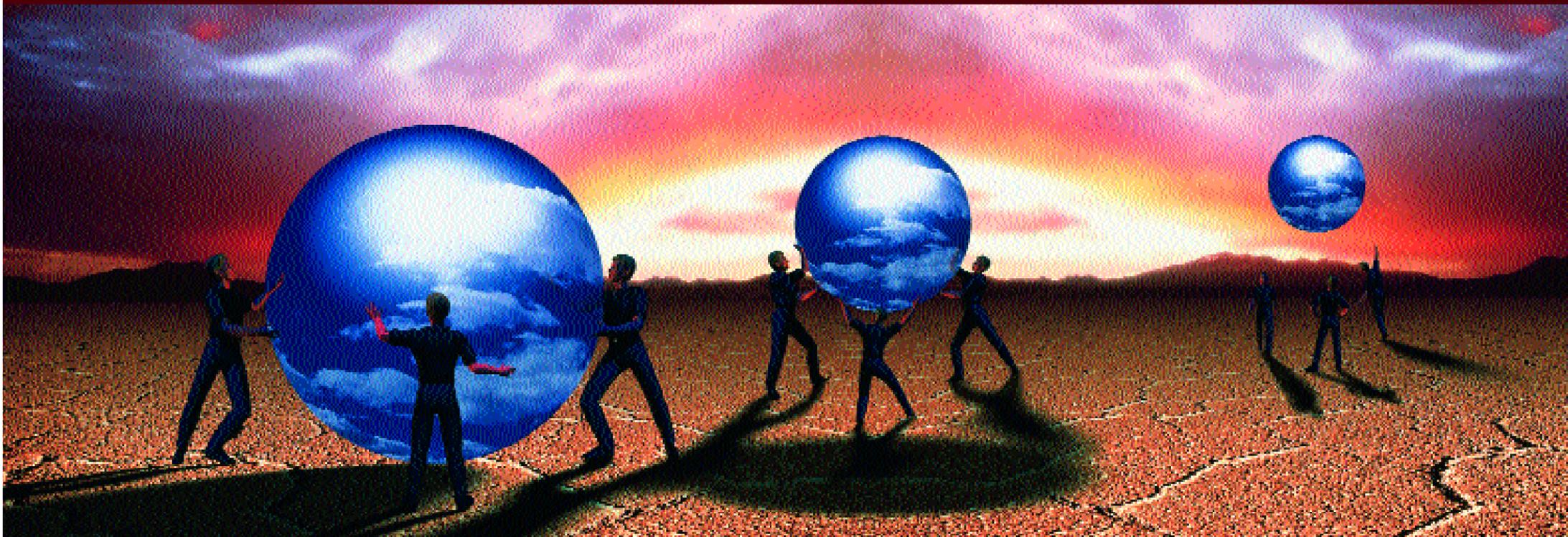
Stronger Evidence of Human Influences on Climate

The 2001 IPCC Assessment

by Kevin E. Trenberth



The third assessment from Working Group I of the Intergovernmental Panel on Climate Change (IPCC),¹ issued in January 2001, reaffirmed previous findings but with much stronger language. Its message is clear: The Earth's climate is changing in ways that cannot be accounted for by natural variability—"global warming" is indeed happening. This article provides an outline of the IPCC process (see the box on page 11), as well as a summary of and commentary on the main findings of Working Group I.



IPCC reports on the evolving science of global climate change, focusing special attention on the ways in which human activities affect the climate. IPCC reviews the evidence for climate change and the possible causes and considers how the climate system responds to various agents of change. Because our climate models are simplified versions of the real world and are still being improved upon, IPCC evaluates the ability of models to describe the processes involved in the climate system and the functioning of the system as a whole. The panel seeks to attribute recent observed changes to possible causes, especially the human influences, and then, using climate models, projects future change from those causes.

Climate changes have occurred in the past naturally for various reasons, over periods ranging from decades to millennia. Fluctuations in the sun's energy output and other factors that influence the amount and fate of the energy that reaches the Earth's surface have caused natural climate change. And now, by greatly changing the composition of the atmosphere, humankind is performing an enormous geophysical experiment.² Human actions alter the Earth's environment in ways that cause climate change.³ Legitimate debates go on about the extent and rate of change and what, if anything, can be done about it, but that the experiment is underway is not in doubt.

Land use (e.g., farming and building cities), storage and use of water (e.g., dams, reservoirs, and irrigation), generation of heat (e.g., furnaces), and the use of fossil fuels are the human-induced environmental changes that most influence the climate. The use of fossil fuels introduces visible particulate pollution (called aerosols) and gases such as carbon dioxide (CO₂) into the

atmosphere, both of which alter the balance of radiation on Earth. These gases are relatively transparent to incoming solar radiation, yet they absorb and reemit outgoing infrared radiation. The resulting blanketing effect is known as the greenhouse effect, and the gases involved are called greenhouse gases. Not all greenhouse gases are the result of human activities. There is a large natural greenhouse effect that makes the Earth habitable. The increase in CO₂ levels over the last century or two from human activities, as well as the introduction of other greenhouse gases more recently, mean that more energy stays in the system. Global warming and the associated climate change are the expected results.

Observed Climate Change

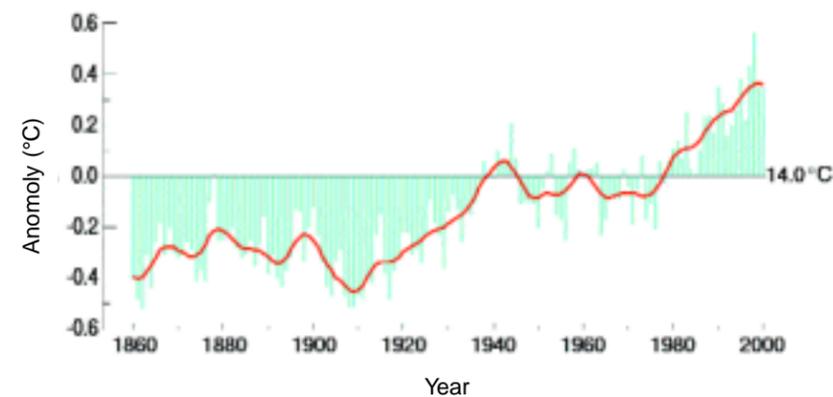
Records of surface temperature show that a global mean warming of about 0.7°C has occurred over the past 100 years. IPCC reports this change as 0.6 ± 0.2°C, but this is a linear fit to what is

obviously not a linear trend (see Figure 1 below for the instrumental record of global mean temperatures). Temperatures increased most noticeably from the 1920s to the 1940s; they then leveled off from the 1950s to the 1970s and took off again in the late 1970s. The 1990s mark the warmest decade on record, and 1998 is by far the warmest year on record, exceeding the previous record held by 1997. Preliminary annual global mean temperatures in the year 2000 were about the same as for 1999. Synthesis of information from tree rings, corals, ice cores,



The final plenary of the IPCC Working Group I, with the co-chairs, Sir John Houghton of the United Kingdom (right) and Y. Ding of China (left).

Figure 1. Departures of global annual mean temperature from 14°C, 1860–2000



NOTE: This figure shows the departures of the global mean temperature from 14°C (the mean from 1961–1990) for the years 1860–2000.

SOURCE: Data provided by Hadley Center, United Kingdom Meteorological Office, and Climate Research Unit, University of East Anglia.

The IPCC and Its Latest Report

The Intergovernmental Panel on Climate Change (IPCC) is a body of scientists from around the world convened by the United Nations jointly under the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO). Initiated in 1988, its mandate is to provide policy makers with an objective assessment of the scientific and technical information available on climate change, the expected environmental and socioeconomic impacts of the changes, and possible response options. The assessment should be policy relevant but not policy prescriptive.

IPCC has performed three major assessments of the state of knowledge and degree of understanding of climate science. The first and second were completed in 1990 and 1995, respectively, and the third in January to March 2001. IPCC is made up of three major working groups, each of which includes participants from the United Nations countries. In the 2001 assessment, Working Group (WG) I reported on the science of climate change, WG II enumerated the impacts of climate change and options for adaptation to such changes, and WG III spelled out the options for mitigating and slowing climate change, including possible policy options (see the figure below).

For the third assessment, WG I included 123 lead authors, 516 contributors, 21 review editors, and more than 700 reviewers. The report is about 1,000 pages, including a *Technical Summary*, a short *Summary for Policy Makers* (SPM), and 14 chapters.¹

Each new IPCC report reviews all the published literature over the previous five years or so, assesses the state of knowledge, and tries to reconcile disparate claims, resolve discrepancies, and highlight uncertainties. The IPCC process is very open. Two major reviews were carried out in producing the most recent report. Skeptics can and do participate, some as authors. The strength of the process is that it yields a consensus report. It is not necessarily the latest or greatest science. It is too long for readability, but because it does sort out what can be reliably stated, it serves as a useful reference. The weakness in the process is that the writing of all chapters and the operations of each working group are done in parallel. This means that, because the results

from one chapter and group cannot be readily used by the others, the impacts of climate change, for example, might be assessed based on dated estimates of what might happen. Several plenary sessions of all authors help to cut down on conflicts, gaps, and duplication, but some of those problems are almost inevitable. The summaries provide more digestible material for most readers and are available on the Internet.²

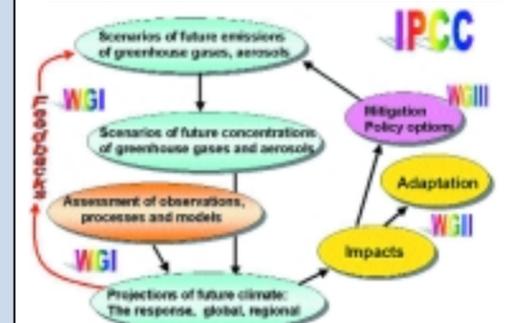
The WG I *Summary for Policy Makers* was approved line by line by governments in a major meeting, which took place over four days in Shanghai in January 2001.³ Governments officials participate in the process along with scientists. The rationale here is that the scientists determine what can be said, but the governments determine how it can best be said. Negotiations occur over wording to ensure accuracy, balance, clarity of message, and relevance both to understanding the science and to policy.

In Shanghai, there were about 100 countries represented by delegations, roughly 10 nongovernmental organizations, and about 42 scientists. Simultaneous translation occurred throughout the meeting into English, French, Spanish, Russian, Chinese, and Arabic. The IPCC process depends on the goodwill of the participants to produce a balanced assessment. However, in Shanghai, it appeared that there were attempts to blunt and perhaps obfuscate the messages in the report, most notably by Saudi Arabia. This led to very protracted debates over wording on even bland and what should have been uncontroversial text. For instance, the opening introductory paragraph of five lines took more than an hour and a half to work out, and then with a small group spun off to recommend revised wording. The draft sentence—"Many hundred of scientists contributed to its preparation and review"—was the primary focus. The sentence is factual but was challenged on grounds that it implied that all of these scientists endorsed the report in every respect. Of course it does not say that, but reviewing the many alternative proposed wordings took

inordinate amounts of time. The final wording stated, "Many hundreds of scientists from many countries participated in its preparation and review." These kinds of delays quickly disrupted the schedule, and arrangements for extra evening sessions had to be made. During the limited breaks, authors of the report worked with delegates in side meetings to craft revised text for submission to the plenary. There were no coffee breaks at any time. The chairman, Sir John Houghton of the United Kingdom, and those who helped run the meeting showed fortitude in their unflagging commitment to continue without taking a break. On the second day, following a one and a half-hour break to quickly consume the evening meal, the session ran until 10:45 p.m. The days began for most of the participants at 8:00 a.m. with sidebar meetings. Adjournment on the third day was at 11:30 p.m., and the SPM was finally approved at 12:45 a.m. on the final day. The meeting closed just after 1:00 a.m. In many ways the meeting became one of endurance. In spite of these trials and tribulations, the result is a reasonably balanced consensus summary. However, the *Summary for Policy Makers* did grow to about double the initial draft length during the course of the meeting and became more technical than desirable for policy makers.

1. IPCC, *Climate Change 2001: The Scientific Basis*, J. T. Houghton et al., eds. (Cambridge U.K.: Cambridge University Press, 2001) (in press).
2. For details, see <http://www.ipcc.ch>.
3. Working Groups II and III had not yet completed their work at the time this article was written.

IPCC components and working group responsibilities



NOTE: WG = Working Group.
SOURCE: K. Trenberth.

and historical data further indicates that the 1990s are the warmest decade in at least the past 1,000 years for the Northern Hemisphere, which is as far back as annual-resolution hemispheric estimates of temperatures can be made.⁴ The melting of glaciers over most of the world and rising sea levels confirm the reality of the global temperature increases.

There is good evidence from measurements of sea level pressure, wind, and temperature over the twentieth century for decadal changes in the atmospheric circulation and some evidence for similar ocean changes. For instance, these include changes in winds over the North Atlantic and Europe related to the phenomenon known as the North Atlantic Oscillation and changes in El Niño.⁵ Such observations signal that increases in temperature are not uniform or monotonic. For example, some places warm more than the average, while other places cool. Changes in precipitation and other components of the hydrological cycle also vary considerably geographically. For instance, it is likely that precipitation has increased by perhaps 1 percent per decade during the twentieth century over most mid- and high-latitude continents of the Northern

Hemisphere. Changes in climate variability are also being seen and changes in extremes are beginning to emerge. Perhaps of greatest note are the observed increases in the heat index (which measures humidity and temperature effects on comfort) and the observed trend toward more intense precipitation events.

One persistent controversy in climate change science has been the discrepancy between the trend seen in the so-called satellite temperature record and that seen in the temperature record from the Earth's surface. The controversy stems in part from the fact that the two data sets do not measure the same phenomenon. The satellite record, which begins in 1979, measures microwave radiation from the lowest 8 kilometers of the Earth's atmosphere and thus depicts temperatures in that part of the atmosphere, which are quite different from those at the surface. Climate models that assess the scenario of increasing greenhouse gases suggest that warming in the lower atmosphere should be greater than that at the surface. But here is the point of contention for skeptics: The observed satellite record shows less warming from 1979–1999. Consequently, doubt has been cast on the

veracity of both the surface temperature record and the models. However, when the observed stratospheric ozone depletion is included in the models, the models predict that the surface and tropospheric temperatures increase at about the same rate. In fact, this is what has happened from about 1960 to the present based on balloon observations, which replicate the satellite record after 1979. Because the satellite record includes only two decades, the influence of El Niño and the eruption of Mt. Pinatubo in 1991 leads to a disproportionate relative downward trend in temperatures observed in the lower atmosphere. Other effects, such as changes in cloud cover, have not been accounted for by the models and may also affect the two records differently. Accordingly, the different short-term trend in the satellite record is not at odds with the warming in the surface record.

The Climate System and Its Driving Forces

Because we humans live in and breathe the atmosphere, it is natural for us to focus on the atmospheric changes. But the atmosphere is only one element of a greater climate system that involves interactions among various internal components and external forcings. The internal, interactive components include the atmosphere, the oceans, sea ice, the land and its features (including the vegetation, albedo, biomass, and ecosystems), snow cover, land ice, and the hydrology of the land (including rivers, lakes, and surface and subsurface water). The factors that are normally regarded as external to the system include the sun and its output, the Earth's rotation, sun-Earth geometry and the slowly changing orbit, the physical components of the Earth system such as the distribution of land and ocean, the topographic features on the land, the ocean-bottom topography and basin configurations, and the mass and basic composition of the atmosphere and the oceans. These factors determine the mean climate, which may vary from natural causes. Climate variations arise naturally when the atmos-

phere is influenced by and interacts with other internal components of the system and "external" forcings.

The continual flow of radiation from the sun provides the energy that drives the Earth's climate. About 31 percent of that radiation gets reflected back into space by molecules, tiny airborne particles (aerosols), clouds, or by the Earth's surface and thus plays no part in the climate. The sun's massive energy input leads to warming. To maintain a balance, the Earth radiates back into space, in the form of "long-wave" or infrared radiation, roughly the same amount of energy that it receives. The amount of radiation lost from the top of the atmosphere to space corresponds to a global mean surface temperature of about -19°C, much colder than the annual average global mean temperature of about 14°C. The higher mean temperature of the Earth, given the amount of energy radiated from its surface, can be explained by the existence of the atmosphere. The Earth's atmosphere intercepts the bulk of energy emitted at the surface and, in turn, reemits energy both toward space and back to the Earth. The energy that escapes into space is emitted from the tops of clouds at various atmospheric levels (which are almost always colder than the surface) or by atmospheric gases that absorb and emit infrared radiation. These greenhouse gases, notably water vapor and CO₂, produce a blanketing effect known as the natural greenhouse effect. Water vapor gives rise to about 60 percent of the current greenhouse effect and CO₂ accounts for about 26 percent.⁶ Clouds also absorb and emit infrared radiation and have a blanketing effect similar to that of the greenhouse gases. But because clouds also reflect solar radiation, they act to cool the surface. Though on average the two opposing effects offset one another to a large degree, the net global effect of clouds in our current climate, as determined by space-based measurements, is a small cooling of the surface.

Human Influences

The amount of CO₂ in the atmosphere has increased by about 31 percent since the beginning of the Industrial Revolution,

from 280 parts per million (ppm) by volume to 367 ppm. This increase is due mainly to combustion of fossil fuels and the removal of forests. Projections of future CO₂ concentrations suggest that, in the absence of controls, the rate of increase may accelerate and thus double the concentrations of CO₂ from pre-industrial levels within the next 50 to 100 years. Human activities (especially biomass burning; agriculture; animal husbandry; fossil fuel extraction, distillation, and use; and the creation of landfills and rice paddies) have increased the atmospheric concentrations of several other greenhouse gases (methane, nitrous oxide, chlorofluorocarbons (CFCs)) and tropospheric ozone. These other greenhouse gases tend to reinforce the changes caused by increased CO₂ levels. However, the observed decreases in lower stratospheric ozone since the 1970s, caused principally by human-introduced CFCs and halocarbons, contribute a small cooling effect.

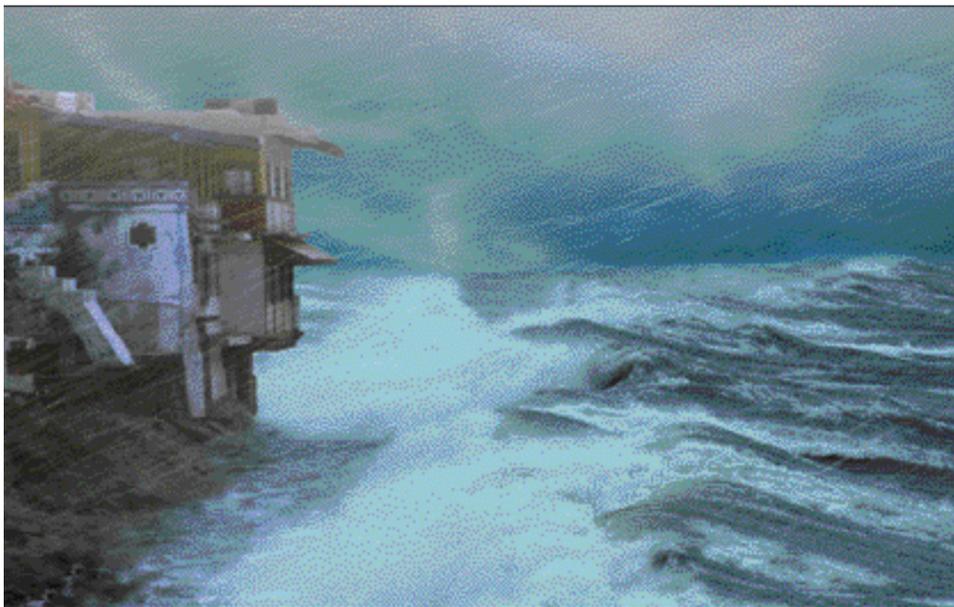
Aerosols enter the atmosphere naturally when they are blown off the surface of deserts or dry regions, blasted into the atmosphere during volcanic eruptions, or released during forest fires. They impact climate in various ways. For instance, the aerosols introduced into the atmosphere during the eruption of Mt. Pinatubo in the Philippines in June 1991 blocked enough radiation for two years to cause observable cooling. Human activities contribute to aerosol particle formation mainly through emissions of sulfur dioxide (SO₂) (a major source of acid rain), particularly from coal-burning power stations and through biomass burning. Sulfate aerosols, visible as a milky, whitish haze from airplane windows, reflect a fraction of solar radiation back to space and hence work to cool the Earth's surface. Some aerosols, like soot, absorb solar radiation and lead to local warming of the atmosphere. Other

aerosols absorb and reemit infrared radiation. Aerosols play still another role. By acting as the nuclei on which cloud droplets condense, they affect the number and size of droplets in a cloud and thereby alter the reflective and absorptive properties of clouds.⁷ Aerosols from human activities are mostly introduced near the Earth's surface and are often washed out of the atmosphere by rain. They typically remain aloft for only a few days near their sources. Aerosols therefore have a very strong regional affect on the climate, usually producing cooling.

The determination of the climatic response to the changes in heating and cooling is complicated by feedbacks. Some of these feedbacks amplify the original warming (positive feedback) and others serve to reduce warming (negative feedback). If, for instance, the amount of CO₂ in the atmosphere were suddenly doubled while all other factors remained constant, the amount of energy absorbed by the atmosphere would increase. With additional energy trapped in the system, a new balance would have to be reached. To accomplish this balance the atmosphere would have to warm up. In the absence of other changes, the warming at the surface and throughout the troposphere would be about 1.2°C.⁸ In reality, many other factors could change as a result of doubled CO₂ concentrations, and various feedbacks would



Reductions in vegetative cover can affect the amount of moisture in a region as well as the amount of solar radiation reflected from the Earth's surface.



Global warming is likely to amplify weather extremes. More powerful weather events, such as storm surges associated with hurricanes, have the potential to cause increased damage to infrastructure.

come into play. When the positive and negative feedbacks are considered, the best IPCC estimate of the average global warming for doubled CO₂ is 2.5°C. The net effect of the feedbacks is positive and, in fact, roughly doubles the global mean temperature increase otherwise expected. Increases in water vapor that accompany warming contribute the strongest positive feedback.

Modeling of Climate Change

To quantify the response of the climate system to changes in forcing, the complex interactions and feedbacks among the components must be accounted for (see Figure 2 on this page). Numerical models of the climate system based upon sound, well-established physical principles are the tools used to estimate climate change. Experiments can be run with climate models in which concentrations of greenhouse gases or other influences, like aerosols, are varied. The best models capture the current understanding of the physical processes involved in the climate system, the interactions among the processes, and the performance of the system as a whole. The predictive powers of a model can be tested by running the model with known forcings from the past

through it and then comparing the results to actual climate records. Though models are exceedingly useful tools for carrying out numerical climate experiments, they do have limitations and must be used carefully.⁹ The latest models have been able to reproduce the climate of the past century or so with increasing accuracy (see Figure 3 on page 15). Thus the global mean temperature record is well replicated within limits imposed by natural fluctuations merely by specifying the changes in atmospheric composition and changes in the sun.

Detection and Attribution

Two main issues that must be settled before politicians are likely to take action: First, it must be discerned whether the recent climate has changed more than expected from natural variability; second, observed climate changes must be attributed to various causes, including human influences. Several key points that emerged from the recent IPCC assessment address these issues:

- The magnitude and rate of change of mean surface temperature globally, or at least in the Northern Hemisphere, over the past few decades is outside the range of anything deduced from

paleo-climate records of the last 1,000 years. Data are inadequate before that.

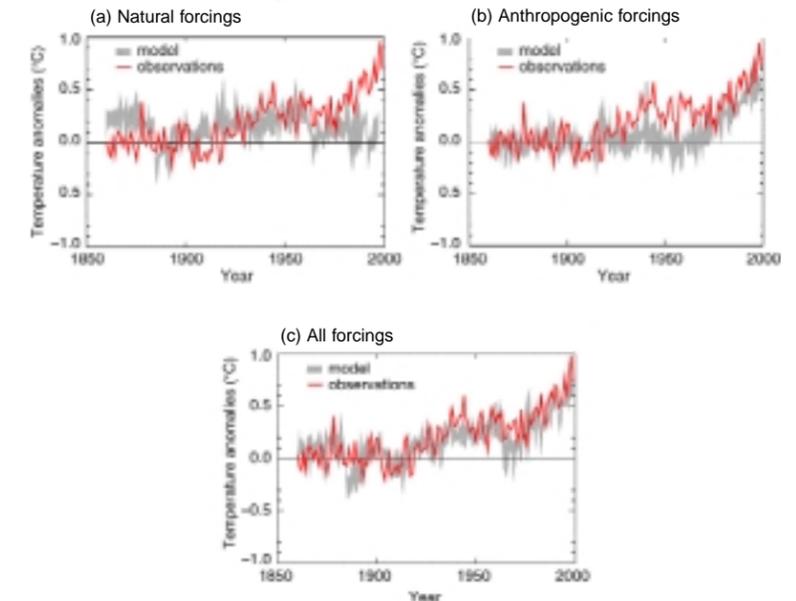
- Estimates of internal climate variability (how much climate can vary from natural causes not including changes in the sun) derived from models are reasonably consistent with the pre-industrial variability deduced from paleo-climate data. Together, the estimates from model and paleo-climate observations provide more reliable estimates of the natural variability.
- Consequently, given the better sense of natural climate variability, detection of climate change is much clearer now than it was five years ago. Hence, it is very unlikely that recent climate change is natural in origin.
- The natural forcing agents (e.g., solar and volcanoes) over the last two to four decades are likely to have had a net cooling effect and, thus, cannot be a cause of the recent increase in temperature.
- A combination of internal climate variability, natural forcing, and perhaps small anthropogenic forcing can account for the increases in the observed globally averaged surface temperature up until about 1970. Increases in solar radiation may account, in part (perhaps 0.15 to 0.2°C), for the warming between about 1920 and 1940, even though solar changes are poorly known before 1979 when satellite observations began (see Figure 3). However, it is also probable that a natural component related to changes in North Atlantic Ocean circulation may have played a role.
- The rate and magnitude of the warming over the last few decades cannot be explained unless the net human influence is one of warming over the last 30 years. Uncertainties in cooling by aerosol forcing (especially the effects on clouds) are therefore constrained.
- The nearer the “balance” or the offset between positive anthropogenic greenhouse gas forcing and negative anthropogenic aerosol forcing over the last 50 years, the larger the climate responsiveness needs to be to explain

warming over recent decades. For instance, if the net warming is small, the climate system must be quite sensitive to that warming to produce the observed temperature change. But if the warming is larger, the climate system must be less sensitive to produce the same temperature change. This has implications for future predictions.

The line of argument shown by these points is open to the criticism that there is some circular reasoning involved. The objective of attributing climate change to specific causes is to account for the change in temperature, but the temperature change itself is invoked as part of the argument. Ideally, only the knowledge of forcings and responsiveness of the system, as given by models, are used to replicate the observed temperature. Neither the forcings nor the true sensitivity of the systems are known well enough to proceed in this manner. Climate modelers attempt to avoid such a trap by basing their models on sound physical principles. However, many parameters have to be chosen when developing models. Although the choices are based on knowledge of the processes, and the parameters are physically based, there is ample scope for unintentional tuning. For example, the brightness of clouds depends on the size and number of cloud droplets but varies from cloud to cloud and is not known well. Choice of a particular value for the model clouds may compensate for shortcomings in the amount of clouds in the model. Inevitably, running a model with two different sets of parameters yields different results, and the set that brings the model into best agreement with observations is chosen for further use in the model. It is important, therefore, to recognize that the procedure is not as objective as it might appear and that uncertainties remain.

The most contentious section in the *Summary for Policy Makers* proved to be the concluding paragraph on attribution. After much debate, a carefully crafted statement was agreed upon: “In the light of new evidence, and taking into account the remaining uncertainties, most of the observed warming over

Figure 3. Simulation of temperature change under three forcing mechanisms



NOTE: Climate models can be used to simulate the temperature changes that result from natural and anthropogenic causes. The simulations represented in Figure 3a were done with only natural forcings: solar variation and volcanic activity. Figure 3b represents simulations with only anthropogenic forcings: greenhouse gases and aerosols. Figure 3c represents simulations with both natural and anthropogenic forcings. Notice that when human and natural forcings are included, the simulations most closely match the observed temperature changes. Such comparisons suggest that anthropogenic forcings provide a plausible explanation for a substantial part of the observed temperature change over the past century.

SOURCE: IPCC, *Climate Change 2001: The Scientific Basis*, J. T. Houghton et al., eds. (Cambridge U.K.: Cambridge University Press, 2001) (in press). Based on P. A. Stott et al., “External Control Of Twentieth-century Temperature Variations by Natural and Anthropogenic Forcings,” *Science* 281, 15 December 2000, 2133-37.

the last 50 years is likely to have been due to the increase in greenhouse gas concentrations.” Moreover, although not highlighted by IPCC, increasing evidence suggests that the signal of human influence on climate emerged from the noise of natural variability in about 1980 and will only get larger.

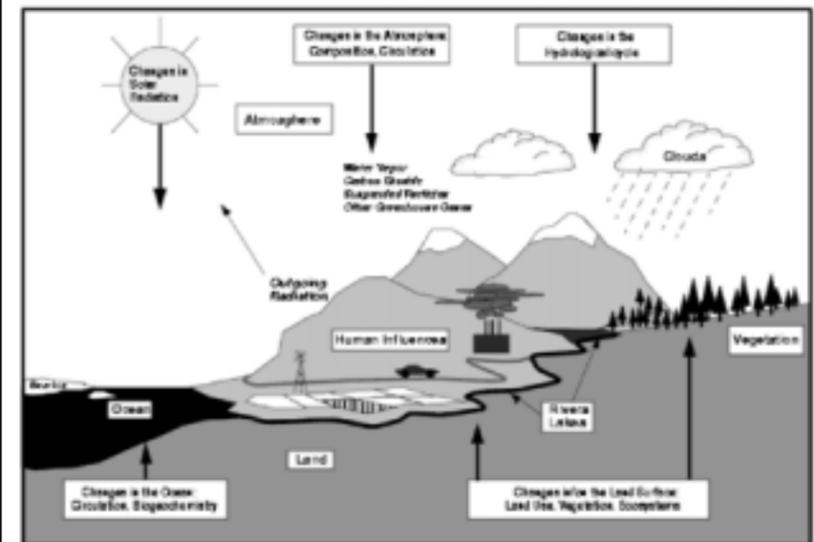
The implications of these findings may be felt in the near future. The models predict that global temperature increases of 0.1 to 0.2°C over the next decade are likely unless volcanic eruptions interfere.¹⁰ Time will tell whether the assessment is correct, perhaps within a decade.

Prediction of Climate Change

Climate models have been used to project the effects of future global warming

to the year 2100. Because human activities are not predictable in any deterministic sense, “predictions” based on human influences necessarily contain a “what if” emissions scenario. IPCC presumes that these predictions will be used for planning purposes, including actions to prevent undesirable outcomes, consistent with the Framework Convention on Climate Change. Such actions, which are a consequence of the prediction, may change the outcome and thus make the prediction wrong. Accordingly, they are not truly predictions but rather projections that are tied to particular emissions scenarios. This is an important point, because some skeptics have ignored the distinction and misused it to challenge findings. For example, in 1990, only scenarios with increasing greenhouse gases

Figure 2. The climate system and its driving forces



SOURCE: K. Trenberth.

were used. Then, in 1995, the first primitive scenarios with aerosols were included, which produced a cooling. Some skeptics, pointing to this difference, claimed that the models had changed and were therefore suspect, when, in fact, it

was the scenarios that had changed, not the models. In addition, for a given scenario, the rate of temperature increase depends on the model used and how, for instance, the model depicts features such as clouds. It is for this reason that a range

of possible outcomes exists. About half of the spread in range of values at 2100 is due to uncertainties in models. The spread in values is unrelated to the scenarios and should not be considered as representative of anything real. The rest of the spread in range can be accounted for by the different scenarios.

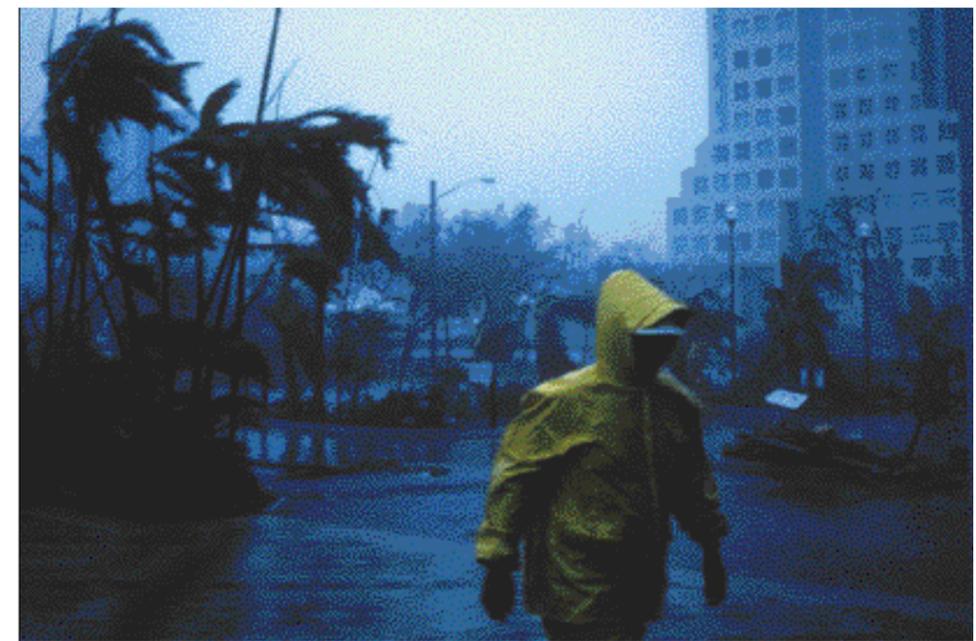
In 2001, the future emissions scenarios were set up by the *Special Report on Emissions Scenarios (SRES)*¹¹ (see the box on this page) and included 35 scenarios. The projections for six “illustrative” CO₂ emission scenarios are given in Figure 4a on page 18. For each emissions scenario, IPCC calculates expected concentrations of CO₂. In the year 2100, the projected values range from about 550 ppm to almost 1,000 ppm, compared with 367 ppm at present. Projections of temperature change and sea-level rise for these same scenarios are shown in Figures 4b and 4c on page 18. When the range of uncertainties is factored in and the projections for 2100 across all 35 scenarios are analyzed, there is an increase in the global mean temperature from 1.4°C to 5.8°C (see Figure 4b). Most increases fall between 2°C to 4°C. These numbers exceed those in the 1995 IPCC report, which showed temperature changes ranging from about 1°C to 3.5°C.¹² The increase is higher mainly because the new emissions scenarios include lower sulfur emissions (which are likely to be reduced for air quality reasons). The 35 scenarios also expand the range of possibilities from the last report and contribute to the range in temperature projected in 2100. Modifications in carbon cycle models that convert emissions to concentrations and in climate models account for less than 20 percent of the deviation between the 1995 IPCC report and this year’s report and thus do not account for much change in the range.

Figure 4c also shows the corresponding sea-level rise. Because heat penetrates slowly into the voluminous oceans, sea-level rise is expected to be manifested over a longer period of time than temperature change. Because the heat inputs that have already occurred will only

work their way through the system slowly, even in the unlikely scenario of a massive reduction in greenhouse gas emissions, sea-level rise will continue unabated. Note again that though these projections include crude estimates of the effects of sulfate aerosol, they deliberately omit other possible human influences, such as changes in land use.¹³ A major concern is that the projected rates of climate change in Figures 4b and 4c exceed anything seen in nature in the past 10,000 years.

An increase in global mean temperature logically follows increased heating. But temperature increase, often thought of as the sole indicator of “global warming,” is not the only possible outcome. For example, rising concentrations of greenhouse gases enhance the hydrological cycle by furnishing additional energy for the evaporation of surface moisture. Because the water-holding capacity of the atmosphere is greater at higher temperatures, increased atmospheric moisture should accompany global temperature increases. Because water vapor is also a powerful greenhouse gas, it contributes a strong positive feedback, amplifying global warming. Naturally occurring droughts are also liable to be exacerbated by enhanced drying. Thus droughts, such as those set up by El Niño, are likely to take hold more quickly, wilt plants sooner, and become more extensive and longer-lasting with global warming. When the land is dry, the energy that would ordinarily drive the hydrological cycle goes into raising temperatures, bringing on sweltering heat waves. Further, globally there will have to be an increase in precipitation to balance the enhanced evaporation. More moisture in the atmosphere implies stronger moisture flow converging into all precipitating weather systems—such as thunderstorms or extratropical rain or snow storms—and rain or snow events of greater intensity.¹⁴

For any change in mean climate, there is likely to be an amplified change in extremes. Because of the wide range of natural variability associated with day-to-day weather, most small climate



Rising concentrations of greenhouse gases enhance the hydrological cycle by furnishing additional energy for evaporation of surface moisture. Increased moisture in the atmosphere leads to weather events of greater intensity and duration.

changes will probably go unnoticed; the extremes, however, will be easily detected. Extremes play an exceedingly important role for natural and human systems and infrastructure. All living organisms are adapted to a range of natural weather variations. New extremes could be devastating to ecosystems. Extremes that exceed tolerances of a system can cause nonlinear effects: the so-called “straw that breaks the camel’s back.” For instance, floods that historically have had an expected return period of 100 years may now recur in 50 or 30 years.¹⁵ More frequent extreme floods may overstress dams and levees, causing breaks and the consequent damage to infrastructure, loss of human life, and contamination of drinking water.

The changes in extremes of weather and climate observed to date have only recently been compared to the changes projected by models, many of which agree with recent observed trends. Models project that higher maximum temperatures, more hot days, and more heat waves are all likely. The largest temperature increases are expected mainly in areas where soil moisture decreases are apt to occur. Increases of daily minimum temperatures are projected to occur over most land areas and are generally larger where snow and ice retreat. A decreased number of frost days and cold waves is

likely. Changes in surface air temperature and surface humidity will mean increases in the heat index and increased discomfort. Increases in surface air temperature will lead to a greater number of days during which cooling (such as from air conditioning) might be considered desirable for comfort and fewer days during which space heating is required for comfort. Precipitation extremes are expected to increase more than the mean, as will the frequency of extreme precipitation events. A general drying is projected for the mid-continental areas during summer, as a result of higher temperatures and increased drying not offset by increased precipitation in these regions. Theoretical and modeling studies project increases in the upper limit of intensity of tropical cyclones in addition to appreciable increases in their average and peak precipitation intensities. Changes in El Niño are also likely, but their nature is quite uncertain.¹⁶

Humans Are Changing the Climate

In 1995, the IPCC assessment concluded that “the balance of evidence suggests a discernible human influence on global climate.”¹⁷ Since then the evidence has become much stronger—the recent record warmth of the 1990s, the

The IPCC Special Report on Emissions Scenarios (SRES)

To build projections of carbon dioxide (CO₂) emissions into the atmosphere that are consistent with each other, rather than extrapolating past values, different scenarios are created for how the countries of the world develop. The following factors are used when formulating the future scenarios: population growth, economic growth, technology development, diversity, and inter-country equity in standard of living. Within a given scenario, many possibilities, referred to as “storylines,” can occur. The storyline actually realized often depends upon capricious happenings such as the outcome of the vote in the 2000 U.S. presidential election.

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, a global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are reduction in disparities of standards of living among regions, capacity-building through education and training, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family branches out into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), nonfossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies).

A2. The A2 storyline and scenario family describe a very heterogeneous world. The underlying theme is self-

reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in a continuously increasing population. Economic development is primarily regionally oriented, with per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline and scenario family describe a world with reduction in disparities in standards of living, a global population that peaks in mid-century and declines thereafter, like the A1 storyline, but with rapid change in economic structures toward a service and information economy, reductions in use of raw materials, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental problems, sustainability, and improved equity among nations and their peoples, but without additional initiatives designed to address climate change issues.

B2. The B2 storyline and scenario family describe a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, with less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

These six scenario groups branch out further into a total of 35 emissions scenarios in all, but A1B, A1FI, A1T, A2, B1, and B2 are illustrative of the spread of possible futures (see Figure 4 on page 18 for projections of CO₂ concentrations, temperature change, and sea level rise under these scenarios).

historical context provided by the improved paleo-record, improved modeling and simulation of the past climate, and improved statistical analysis. Thus the headline in the new IPCC report states, "There is new and stronger

evidence that most of the warming observed over the last 50 years is attributable to human activities."¹⁸ The best assessment of global warming is that the human contribution to climate change first emerged from the noise of back-

ground variability in the late 1970s. Hence, climate change is expected to continue into the future. The amplification of extremes is likely to cause the greatest impact. Although some changes arising from global warming may be

benign or even beneficial, the economic effects of more extreme weather will be substantial and clearly warrant attention in policy debates.

Because of the long lifetime of CO₂ in the atmosphere and the slow heat penetration and equilibration of the oceans, there is already a substantial commitment to further global climate change, even in the absence of further emissions of greenhouse gases. IPCC considered implications for stabilizing CO₂ and greenhouse gases at various concentrations up to four times pre-industrial levels, and concluded that substantial reductions in emissions, well below current levels, would be required sooner or later in all cases. Even full implementation of the Kyoto Protocol would merely slow the time of doubling of CO₂ concentrations from pre-industrial values by perhaps 15 years (for instance from 2060 to 2075).¹⁹ Moreover, these projections emphasize that even stabilizing concentrations would not stop climate change because of the slow response of the system; for this reason, temperature increases and especially sea-level rise would continue for many decades thereafter. As we begin to understand that our geophysical experiment might turn out badly, we are also discovering that it cannot be turned off abruptly.

The IPCC report provides the evidence that global warming is happening and now the question arises, *What, if anything, should be done about these findings?* The options include: do nothing, mitigate or stop the problem, adapt to the changes as they happen, or find some combination of these options. Different value systems come into play in deciding how to proceed. Considerations include those of population growth, equity among developed and developing countries, intergenerational equity, stewardship of the planet, and the precautionary principle ("better to be safe than sorry"). Those with vested interests in the current situation frequently favor the first option, extreme environmentalists favor the second, and those who have a belief that technology can solve all problems might favor the third. In rationally

discussing options, it is helpful to recognize the legitimacy of these different points of view. This problem is truly a global one because the atmosphere is a global commons. These immense problems cannot be solved by one nation acting alone. Unfortunately, to date, international progress toward mitigating and preparing for the possible outcomes of global warming is inadequate.

The evidence presented by the IPCC report suggests that there is a strong case for slowing down the projected rates of climate change caused by human influences. Any climate change scenario is fraught with uncertainties. But a slowing in the warming process would allow researchers to improve projections of climate change and its impacts. Actions taken to slow down climate change would provide time to better prepare for and adapt to the changes as they appear. Natural systems and human systems, many of which have long amortization lifetimes (e.g., power stations, dams, and buildings), are then less likely to be dislocated or become obsolete quickly. Therefore, we must plan ahead. Greater energy efficiency and expanding use of renewable resources, such as solar power, are clearly key steps toward slowing the rate of climate change.

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NOTES:

1. IPCC, *Climate Change 2001: The Scientific Basis*, J. T. Houghton et al., eds. (Cambridge U.K.: Cambridge University Press, 2001) (in press).
2. R. Revelle and H. E. Suess, "Carbon Dioxide Exchange between Atmosphere and Ocean and Question of an Increase of Atmospheric CO₂ during the Past Decades," *Tellus* 9 (1957): 18–27.
3. F. S. Rowland, "Climate Change and Its Consequences: Issues for the New U.S. Administration," *Environment*, March 2001, 28–34.
4. Reconstructions of temperature and rainfall make use of multiple proxy indicators at individual sites around the world but have to be merged, reconciled, and combined to give regional and larger area averages. Sufficient data with annual resolution now exist to do this for the Northern Hemisphere for the past 1,000

years but not for the Southern Hemisphere or for beyond the past millennium. See M. E. Mann, R. S. Bradley, and M. K. Hughes, "Global-scale Temperature Patterns and Climate Forcing over the Past Six Centuries," *Nature* 392, 23 April 1998, 779–87; and M. E. Mann, R. S. Bradley, and M. K. Hughes, "Northern Hemisphere Temperatures during the Past Millennium: Inferences, Uncertainties, and Limitations," *Geophysical Research Letters* 26 (1999): 759–62.

5. J. W. Hurrell, "1995: Decadal Trends in the North Atlantic Oscillation Regional Temperatures and Precipitation," *Science* 269 (1995): 676–9; K. E. Trenberth and T. J. Hoar, "The 1990–1995 El Niño–Southern Oscillation Event: Longest on Record," *Geophysical Research Letters* 23 (1996): 57–60; and K. E. Trenberth and T. J. Hoar, "El Niño and Climate Change," *Geophysical Research Letters* 24 (1997): 3057–60.

6. J. T. Kiehl and K. E. Trenberth, "Earth's Annual Global Mean Energy Budget," *Bulletin of the American Meteorological Society* 78 (1997): 197–208.

7. Recent evidence highlights the possible importance of this effect, although the magnitude is very uncertain. See J. M. Hansen, M. Sato, A. Lacis, and R. Ruedy, "The Missing Climate Forcing," *Philosophical Transactions of the Royal Society of London* 352 (1997): 231–40.

8. K. E. Trenberth, J. T. Houghton, and L. G. Meira Filho, "The Climate System: An Overview," in J. T. Houghton et al., eds., *Climate Change 1995: The Science of Climate Change* (Cambridge, U.K.: Cambridge University Press, 1996), 51–64.

9. K. E. Trenberth, "The Use and Abuse of Climate Models in Climate Change Research," *Nature* 386, 13 March 1997, 131–33.

10. IPCC, note 1 above.

11. IPCC, *Special Report on Emissions Scenarios, Summary for Policy Makers* (2000).

12. IPCC, *Climate Change 1995: The Science of Climate Change*, J. T. Houghton et al., eds., (Cambridge, U.K.: Cambridge University Press, 1996). For a review of the second IPCC assessment, see *Climate Change 1995: The Science of Climate Change*, reviewed by W. C. Clark and J. Jäger, *Environment*, November 1997, 23–8; *Climate Change 1995: Impacts, Adaptations, and Mitigation*, reviewed by R. W. Kates, *Environment*, November 1997, 29–33; and *Climate Change 1995: Economic and Social Dimensions*, reviewed by T. O'Riordan, *Environment*, November 1997, 34–39.

13. It is estimated that conversion from forests to agriculture in the United States makes the surface much brighter, especially in the late summer and fall after crops are harvested. This means more solar radiation is reflected, which results in cooling.

14. K. E. Trenberth, "Atmospheric Moisture Residence Times and Cycling: Implications for Rainfall Rates with Climate Change," *Climatic Change* 39 (1998): 667–94.

15. K. E. Trenberth, "The Extreme Weather Events of 1997 and 1998," *Consequences* 5 (1999): 2–15.

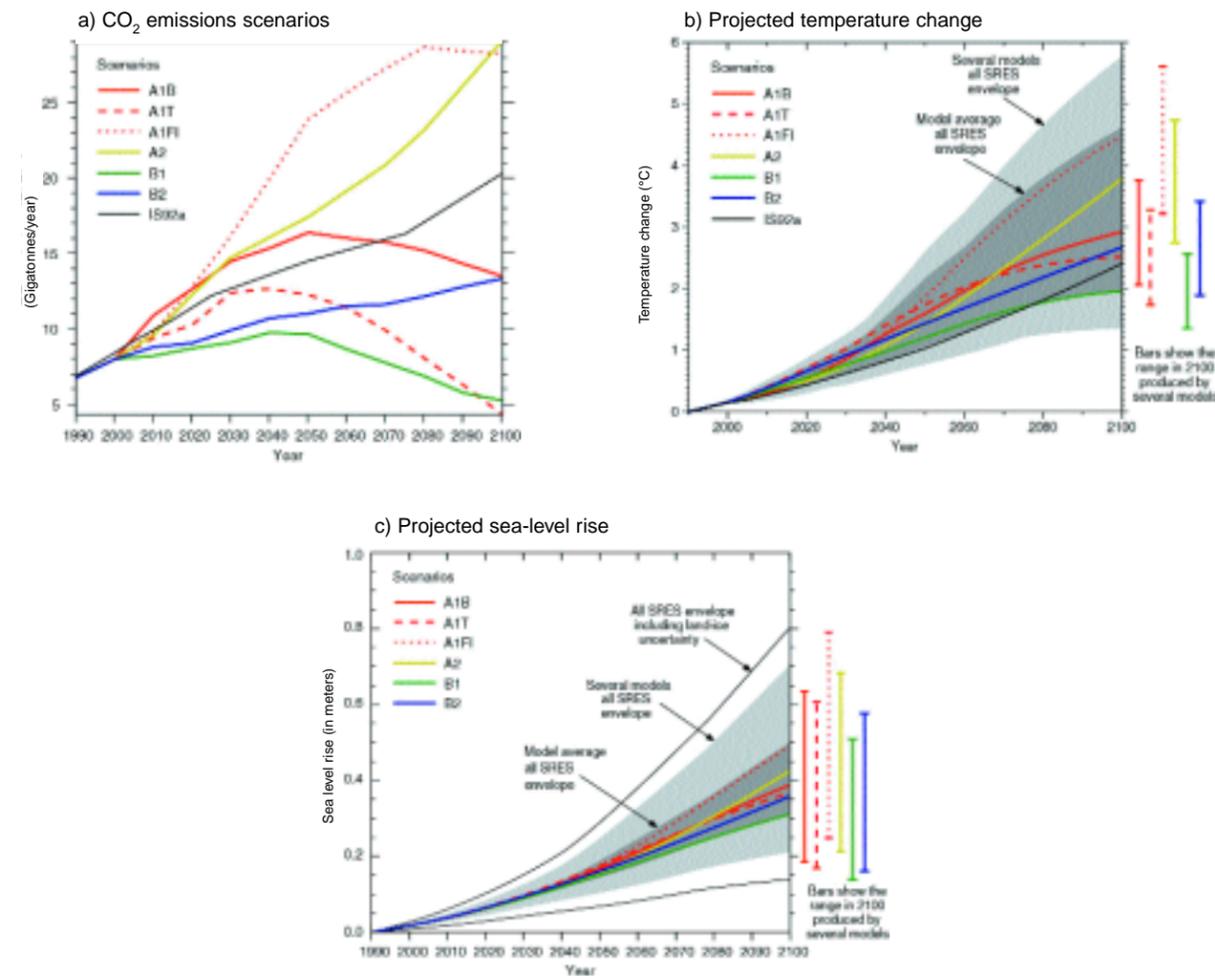
16. The 1997–1998 El Niño is the biggest recorded event by several measures. The last two decades have been marked by unusual El Niño activity. See Trenberth and Hoar, 1996 and 1997, note 5 above. A key question is how is global warming influencing El Niño? Because El Niño is involved with movement of heat in the tropical Pacific Ocean, it is conceptually easy to see how increased heating from the build up of greenhouse gases might interfere. Climate models certainly show changes with global warming, but none simulate El Niño with sufficient fidelity to have confidence in the results. So the question of how El Niño may change with global warming is a current research topic.

17. Trenberth, note 14 above.

18. IPCC, note 1 above.

19. T. M. L. Wigley, "The Kyoto Protocol: CO₂, CH₄ and Climate Implications," *Geophysical Research Letters* 25 (1998): 2285–8.

Figure 4. Projections under several IPCC scenarios, 1990–2100



NOTE: The following scenarios were used by IPCC to project CO₂ emissions. The A1FI scenario is a fossil fuel intensive energy system. The A1T scenario is a nonfossil fuel energy system. In the A1B scenario, no one energy source is relied upon too heavily. The A2 scenario is characterized by self-reliant economies and preservation of local identities with fast population growth. The B1 scenario is a service- and information-based economy with reductions in the use of raw materials and introduction of clean and resource-efficient technologies, with emphasis on global solutions to economic, social, and environmental problems. The B2 scenario emphasizes local solutions to economic, social, and environmental problems with continuously increasing populations, at a rate lower than A2, with more diverse and less rapid technological change than in the B1 and A1 storylines. The IS92 scenario, an emissions scenario used in the 1995 IPCC assessment, is included for comparison. (See the box on page 16 for more details on IPCC scenarios.)

SOURCE: IPCC, *Climate Change 2001: The Scientific Basis*, J. T. Houghton et al., eds. (Cambridge U.K.: Cambridge University Press, 2001) (in press).