Forecast Cloudy: The Limits of Global Warming Models

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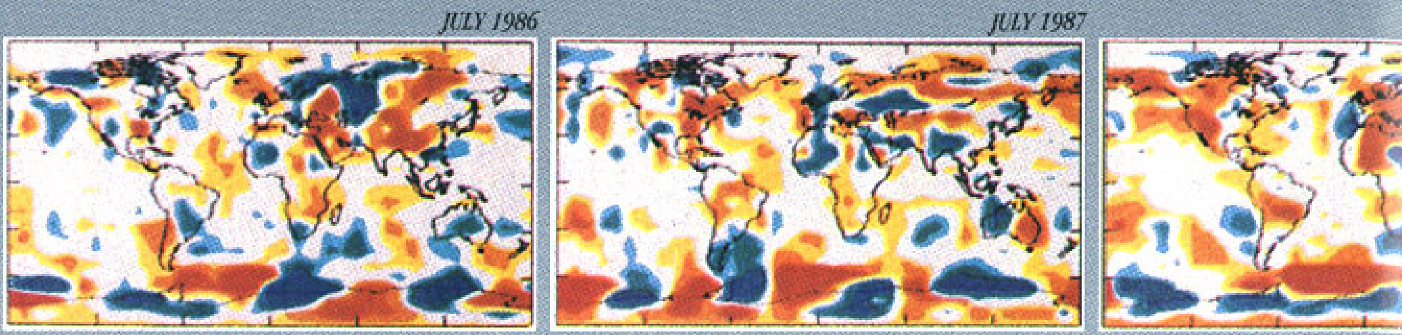


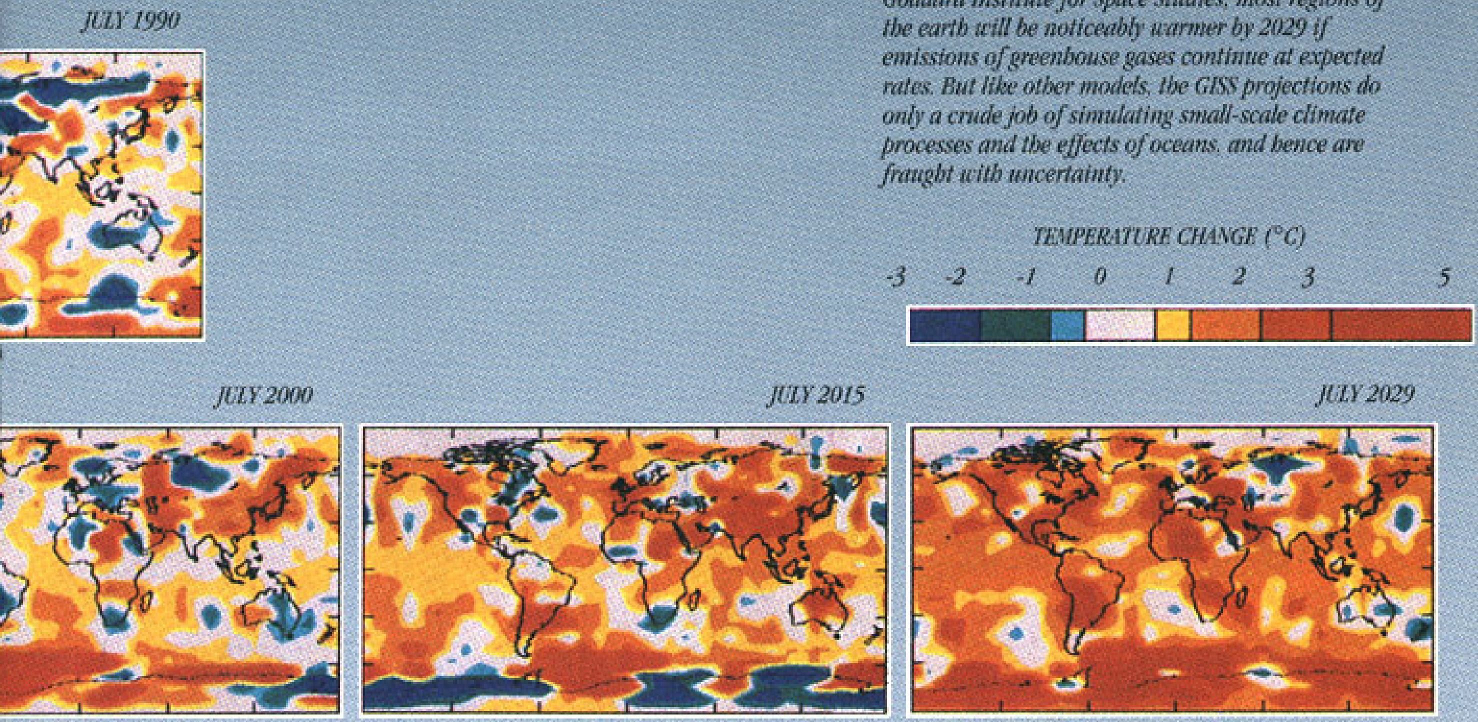
Forecast Cloudy:

The Limits of Global Warming Models

BY PETER H. STONE

A report published in late 1990 by the Intergovernmental Panel on Climate Change (IPCC) warned that global warming could soon force temperatures higher than they have been in hundreds of thousands of years. The report, prepared by 170 scientists from all over the world, concluded that if the world's economies follow a "business-as-usual" scenario, increases in carbon dioxide and other trace gases in the atmosphere will cause the earth's average surface temperature to rise by about 5°F before the end of the next century. Such a rise would come on top of the warming of about 15°F that has already occurred since the last major ice age some 15,000 years ago.

The IPCC report was hardly the first attempt to assign a number to the effect of increases in trace gases. That

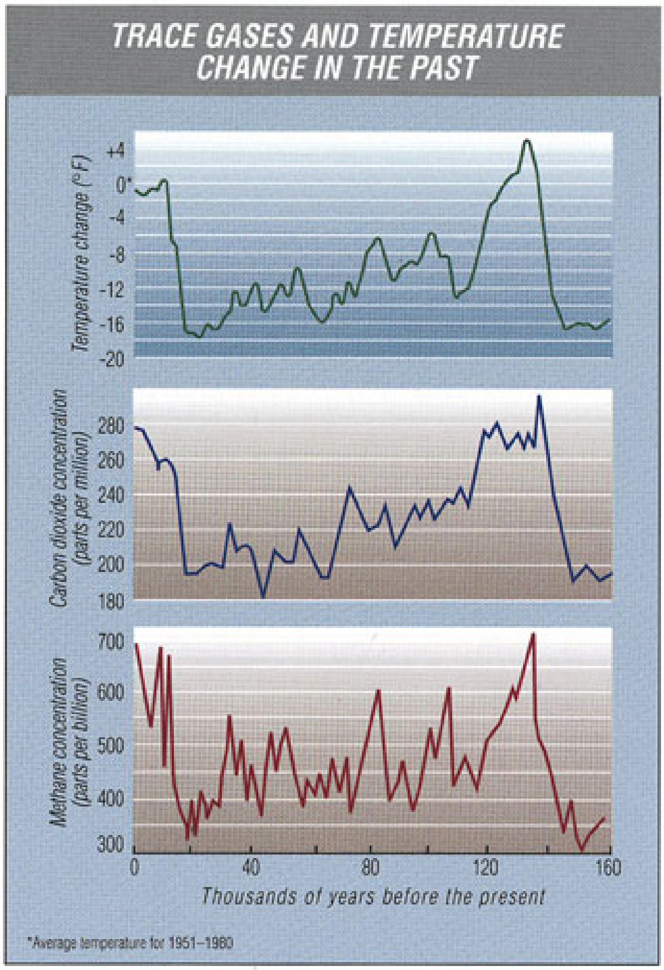


According to a climate model developed at NASA's Goddard Institute for Space Studies, most regions of the earth will be noticeably warmer by 2029 if emissions of greenhouse gases continue at expected rates. But like other models, the GISS projections do only a crude job of simulating small-scale climate processes and the effects of oceans, and hence are fraught with uncertainty.

distinction belongs to the Swedish scientist Arrhenius who, almost 100 years ago, calculated that a doubling of CO_2 would cause a rise of 10°F. Since then, CO_2 doubling has become a standard yardstick for gauging global climate sensitivity. It is also a realistic yardstick, because current trends would produce a level of trace gases equivalent to a doubling of CO_2 by the middle of the next century.

Predictions of climate change rest on models that are far from complete. But better observations, more powerful computers, and improved understanding can help us fill the gaps.

The first modern estimate of the effect of CO_2 doubling was made in 1967 by Syukuro Manabe and Richard Wetherald at the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory in Princeton, N.J. The warming they predicted: 4°F. In 1979 a National Research Council com-



Some of the important greenhouse gases have fluctuated widely in the past because of natural processes that are not fully understood. These natural fluctuations, which have been associated with major changes in global temperature, could alleviate or aggravate global warming, but current climate models do not include them.

mittee chaired by Jule Charney of MIT, recognizing the uncertainties involved, estimated a range of values: 3°F to 8°F. The most recent estimates, including those by the IPCC, still fall within this range. In fact, considering that they benefit from supercomputers and other advances, it is remarkable that the latest predictions are not farther from the figure that Arrhenius arrived at in 1896.

At first glance, this rough consensus might seem to close the book on the issue of global warming: human-produced greenhouse gases such as CO_2 will cause a serious rise in global temperatures, and that's that. Indeed, the apparent robustness of these numbers is why most scientists believe that global warming is a serious threat. But we have much more to learn. The IPCC

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report was quick to point out the many question marks in its predictions, especially regarding the timing, magnitude, and regional patterns of climate change. These uncertainties, common to all climate predictions, stem from the complexity of the physics involved and the coarseness of the models that struggle to simulate it.

A climate model consists of mathematical equations based on the fundamental laws of physics. Solving these equations—a task usually done on large computers—can determine how climate variables such as temperature, humidity, winds, and precipitation will respond to changes in factors like the amount of solar radiation reaching the earth, or the concentrations of trace gases in the atmosphere. The climate system is so complex, however, that a model incorporating all the possible variables for all parts of the globe could not be run on even the fastest supercomputers.

As a result, scientists use a wide variety of models to study climate and climate change. At one extreme are simple models that severely limit the number of variables they try to predict (forecasting only temperature, for example), or that severely restrict the physical and chemical processes they include (omitting, say, heat transport by ocean currents). At the other extreme are the large numerical general circulation models (GCMs) that include as many variables and processes as possible.

Because even these models are not truly comprehensive, the simple models play a valuable role in determining what variables and processes are important, thereby allowing scientists to improve the larger models. Also, there are many problems for which the large models are computationally too inefficient to be practical—for example, problems involving climate changes over hundreds of years. For this reason, the IPCC projections for the next century were based on one of the simplest models. Ultimately, however, only GCMs will be able to yield accurate predictions of changes in all the climate variables anywhere on earth.

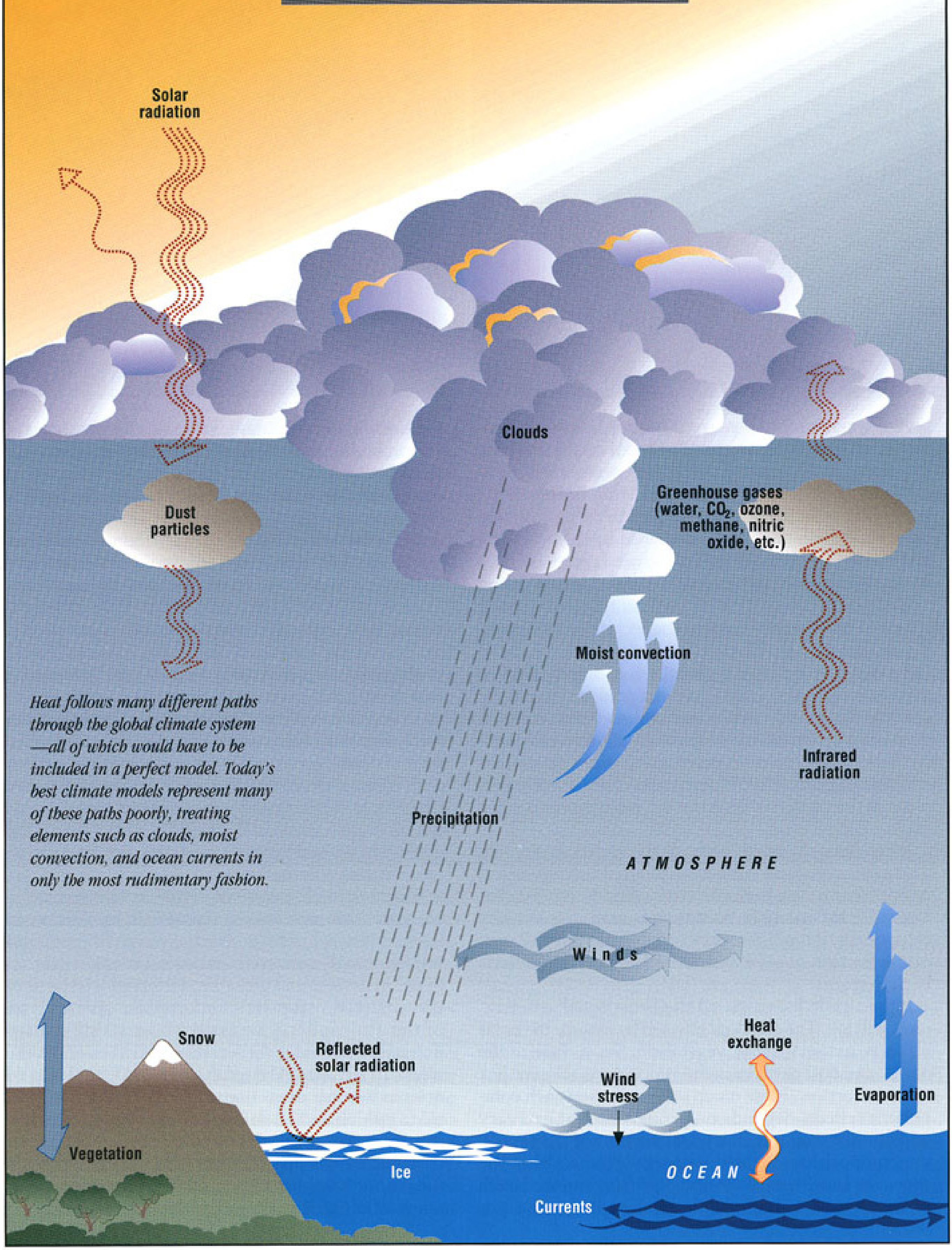
A Complicated Planet

Modeling climate change is inherently difficult. To do so, climatologists must try to simulate the behavior of oceanic and atmospheric systems that are not only fantastically complex in themselves but intricately linked.

Just figuring out how fast greenhouse gases will build up is hard enough. The constituents of the atmosphere that absorb the most infrared radiation, and therefore contribute most strongly to the greenhouse effect, are water vapor and clouds. But other gases contribute as well, and their concentration in the atmosphere is growing, mainly because of human activities that are impossible to predict with certainty even in the short term. In the 1980s, for example, chlorofluorocarbons (CFCs) increased by 40 percent, methane by 10 percent, and CO_2 by 4 percent. At these rates, CFCs would replace carbon dioxide as the major contributor to increases in

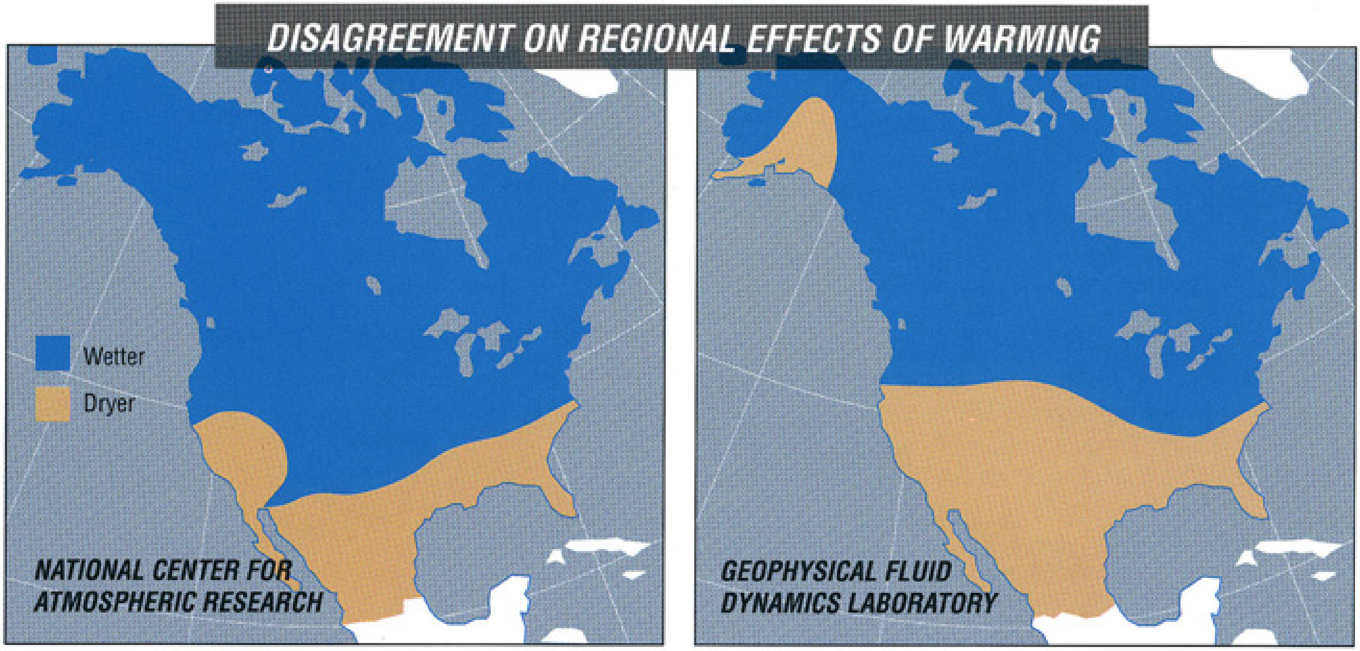
ILLUSTRATIONS: DEBORAH PERUGI

THE GLOBAL CLIMATE SYSTEM



Heat follows many different paths through the global climate system —all of which would have to be included in a perfect model. Today's best climate models represent many of these paths poorly, treating elements such as clouds, moist convection, and ocean currents in only the most rudimentary fashion.

DISAGREEMENT ON REGIONAL EFFECTS OF WARMING



global warming in 25 years. Yet international agreements such as the Montreal Protocol could slow the increase of CFCs, altering the picture considerably.

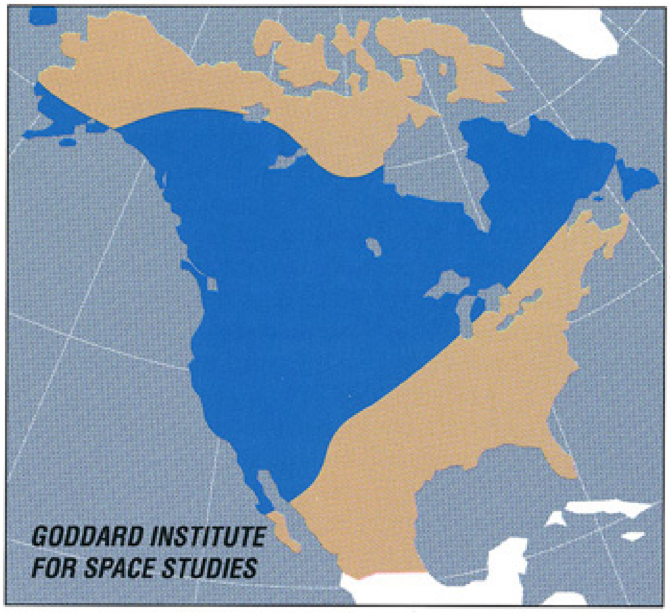
There are also major scientific uncertainties about the buildup. A portion of the gases added to the atmosphere does not remain there but is absorbed by the biosphere and the oceans or destroyed by chemical reactions. This happens to about half the carbon dioxide now being added to the atmosphere, but the fraction that is removed may vary as climate changes, thus modifying the climate change. The natural processes that remove these gases are not well understood, and no GCM has tried to include them. Until we can predict this kind of change, our models will be incomplete. Because analyses of deep ice cores drilled in the Antarctic and Greenland show that major changes in atmospheric concentrations of carbon dioxide and methane have taken place in the past, this defect in the models represents a major uncertainty.

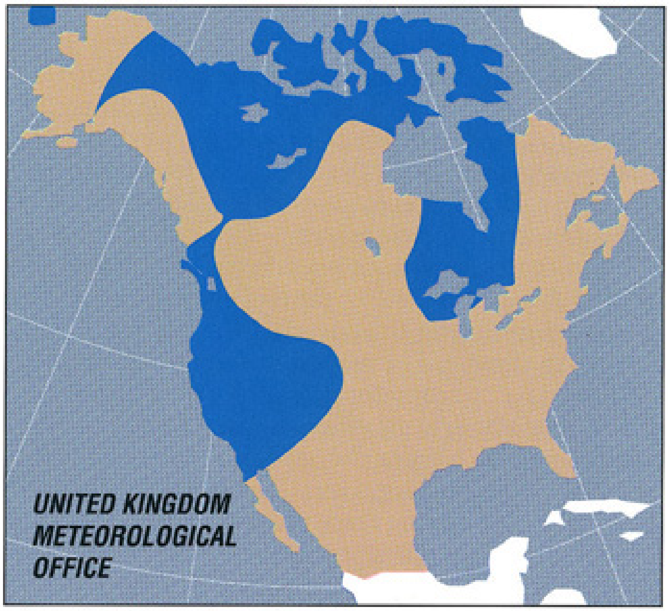
Forecasting the buildup of gases is only the beginning. The next step, predicting how the buildup will affect temperatures, is a task of extraordinary complexity. Consider the many factors that govern just one key component of the climate system: the planetary albedo, or the fraction of solar radiation that the earth reflects back to space.

If the albedo increases, all else being equal, temperatures will fall. The albedo is affected by clouds, the polar ice caps, glaciers, snow, vegetation, the surface of the ocean, and dust particles in the atmosphere, to name just a few influences. How much solar radiation each component reflects depends on properties that can vary widely—for example, the water content of the clouds, the composition of the dust particles, the age of the snow, the roughness of the ocean surface, and the health of the vegetation. In principle, all these details must be predicted if one is to model climate change accurately. To complicate matters, albedo can be affected by unforeseeable events such as volcanic activity. Indeed, the recent eruption of Mount Pinatubo in the Philippines is likely to cause global *cooling* over the next few years until the volcanic particles fall out of the atmosphere.

It is especially difficult to predict the way climate will change in a particular region. For some regions, climate models do not even agree on whether temperatures will rise or fall. A fundamental problem is that the atmosphere and the oceans are fluids that move in response to changes in temperature and pressure. The resulting winds and ocean currents transport heat from one locality to another, modifying temperatures. Because of these fluid motions, every point in the earth-atmosphere-ocean system is coupled to every other point in the system. Climate change at one point cannot be predicted accurately without also predicting changes at other points and changes in the fluid motions that couple them. These fluid motions affect predictions of global average temperatures as well.

Another basic problem is that such motions are chaotic. Although they are governed by the classical laws of physics, which in principle yield predictable results, a small uncertainty in our knowledge of the state of the system at any given time leads to a large uncertainty later. Any gap in our information about the state of the atmosphere, no matter how small, makes it impossible to predict the weather more than about three weeks in advance. The resulting unpredictable fluctuations in weather cause unpredictable fluctuations in climate (which can be defined as the average weather). According to calculations carried out at NASA's Goddard Institute for Space Studies (GISS) in New York City, the chaotic behavior of the atmosphere can cause fluctuations of as much as 1°F over periods of about 30 years.





General circulation models contradict one another on how global warming will affect various regions. Even though the four models represented here agree about the effects of a doubling of CO_2 on average global surface temperatures, they disagree on regional changes in soil moisture. (The projections are for winter).

Although a "noise level" of 1°F is small compared with the projected warming of 5°F before the end of the next century, other possible sources of unpredictable behavior have yet to be assessed. For all we know, chaotic fluid motions in the ocean might produce unpredictable climate changes that are larger still. Indeed, unexplained fluctuations much greater than 1°F have occurred in the past, most recently about 10,000 years ago during the so-called Younger-Dryas cold interval.

Thus any effort to predict climate changes assumes that climate is predictable—but this is not guaranteed. Forecasts of the effects of a rise in greenhouse gases are really just predictions of what will happen in the absence of the unpredictable.

Problems of Scale

Calculating just the predictable part of climate change is still a formidable problem. This is not simply because we don't fully understand the physics of the climate system; it is also because the "resolution" of today's general circulation models is extremely low. Not only are they unable to differentiate between the climates of, say, Buffalo and Boston—a limitation that severely restricts our ability to predict regional climate—but they cannot accurately calculate the effects of a number of important physical phenomena that take place on scales smaller than the models' resolution.

One example is clouds, which contribute greatly to the planetary albedo and the greenhouse effect. Another is moist convection, which both cools the surface of the earth and affects the concentration of water vapor. Also not resolvable are hydrological processes that affect the amount of moisture in the soil—an aspect of climate that is important for agriculture and water resources and that is likely to change as a result of global warming. Because of the complex relationships within the climate system, errors in calculating these processes can seriously compromise a model's ability to simulate climate even on the largest scales.

It is because of doubts over whether the models are simulating the small-scale processes accurately that some scientists, such as Richard Lindzen of MIT, are skeptical of the predictions of global warming. Nevertheless, most scientists, myself among them, believe that the range of values climatologists usually quote—as in the Charney committee's 3°F to 8°F—largely accounts for this uncertainty.

A major reason for the models' shortcomings in calculating the effects of small-scale processes is the limited capacity of computers, which restricts the number of locations in the climate system whose state a general circulation model can describe. All climate models must make trade-offs between the number of locations they simulate, the number of climate processes they calculate, and the accuracy with which they calculate those processes.

Today's highest-resolution climate GCMs specify the state of the atmosphere at the intersections of a three-dimensional grid. This grid is divided into sections that are approximately 250 miles on a side in the horizontal direction—an area the size of New England and New York combined—and about a mile thick in the vertical direction. Since these models incorporate five variables at each intersection of the grid (temperature; wind speed in the latitudinal, longitudinal, and vertical directions; and concentration of water vapor), they must predict about 150,000 numbers to describe the state of the atmosphere at a given time.

To keep up with atmospheric changes, these 150,000 numbers have to be recalculated about eight times an hour. Thus, to determine the evolution of the atmosphere—just one part of the climate system—over one year with such a model requires some 20 to 40 hours of calculation on a supercomputer.

The effects of small-scale phenomena cannot be completely left out of GCMs, or the models could not come close to simulating the current climate, much less changes in climate. The makeshift solution the models employ is to "parameterize" such effects. In other words, they simulate the effects by simplified equations based in part on current climate conditions and in part on approximations deemed reasonable in particular circumstances. By design, these simplified equations can be solved far more efficiently than the exact equations, but at the cost of accuracy; indeed, the simplified equations are often quite crude.

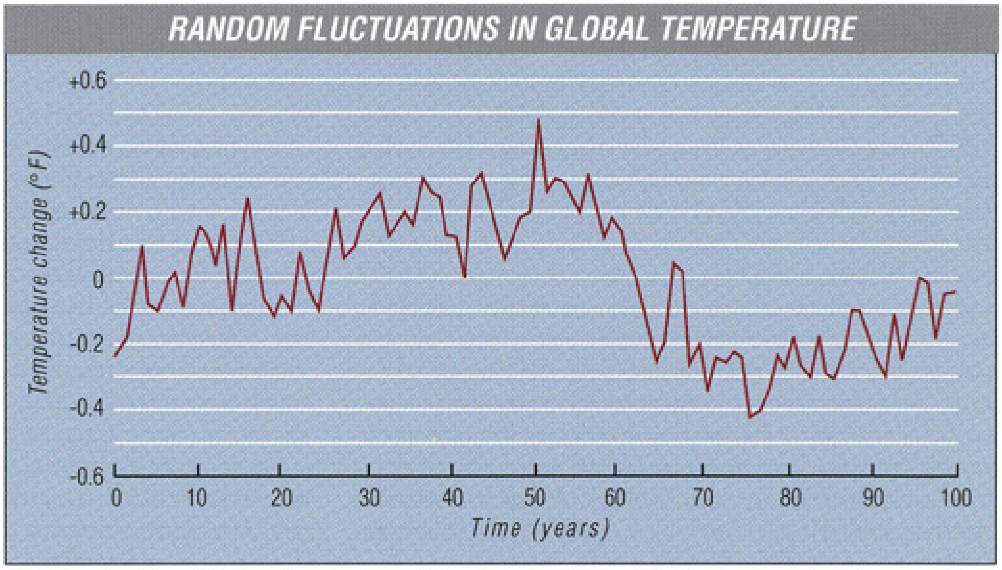
What's more, different models use different parameterizations, which lead to contradictory conclusions about the regional effects of global warming. It's for that reason that GCMs, despite yielding similar predictions for how much global mean temperatures will increase, disagree sharply on the patterns and magnitude of changes in soil moisture. For example, two models—those of the National Center for Atmospheric Research and the Geophysical Fluid Dynamics Laboratory—predict that a doubling of CO_2 would make southern California winters drier, while the GISS and United Kingdom Meteorological Office models indicate that the region's winters would become wetter (*see the diagram on pages 36–37*).

It would be nice if we could get by without parameterizations. Unfortunately, calculating small-scale processes accurately requires much higher resolution than computers will be able to deliver in the near future. For example, the important variations in moist convection occur on scales of 100 yards to half a mile. Resolving these processes would require a grid with a horizontal spacing 1,000 times smaller than today's climate GCMs in both latitude and longitude. And to resolve the rapid evolution of the small-scale features of moist convection, the state of the atmosphere would have to be recalculated about 1,000 times more frequently. Some increase in vertical resolution would also be necessary. All in all, computers would have to be about 10 billion times faster than today's to calculate moist convection accurately. So models must depend on parameterizations for a long time to come.

Even if our models could predict with certainty the ultimate effects of increases in trace gases, such as a doubling of carbon dioxide—and even if we knew precisely how fast the trace gases would increase—we would still need to know how quickly the climate would respond to the buildup. After all, people and ecosystems will adapt to climate change much more easily if it happens slowly.

The oceans play the biggest role in determining the rate of warming, because they are the component of the climate system with the greatest capacity to absorb heat. If warming seeps down only slowly into the ocean's deeper layers, the surface layers—and hence the atmosphere—will heat up rapidly. Conversely, if the deeper layers absorb heat quickly from the surface layers, the atmosphere will take longer to warm up. Thus the 5°F warming predicted by the IPCC report might occur as early as 2040 or as late as 2200.

How fast the warming actually spreads to the deeper layers depends on the ocean's circulations. But because of computer limitations, GCMs that try to calculate this process have inadequate resolution. These models do such a poor job of simulating today's climate—sometimes misrepresenting sea surface temperatures by as much as 15°F—that we cannot have much confidence that they are simulating the physics of heat mixing correctly.



Because fluid motions in the climate system are chaotic, climate is in part unpredictable. Researchers at the Goddard Institute for Space Studies demonstrated this by running a 100-year climate simulation in which trace gases were frozen at 1958 levels. Even with no greenhouse warming, global temperatures fluctuated by nearly 1°F. Thus the 1°F warming noted over the last 100 years cannot be attributed unambiguously to greenhouse warming.

Sidestepping Uncertainty

In the most sophisticated climate projections yet published, researchers at NASA's Goddard Institute for Space Studies (GISS), led by James Hansen, tried to sidestep some of the uncertainties that surround the timing of climate change. The rate of warming depends both on how rapidly the deep oceans will absorb surface heat and on how rapidly trace gases will build up in the atmosphere—neither of which is known.

Instead of attempting to calculate the ocean circulations, the GISS team assumed that heat mixes between the ocean's surface and deeper layers at the same rate that tritium produced by atmospheric nuclear tests mixed into the deep oceans. Although the mixing of a passive tracer like tritium is not necessarily a good proxy for heat mixing, the GISS study, published in 1988, remains the only attempt to use a general circulation model to forecast how climate responds to realistic rates of increase in trace gases. Projections made in 1990 by the Intergovernmental Panel on Climate Change, for example, did not use a general circulation model but relied on a very simple model that represented global climate by a single temperature variable, the global mean surface temperature.

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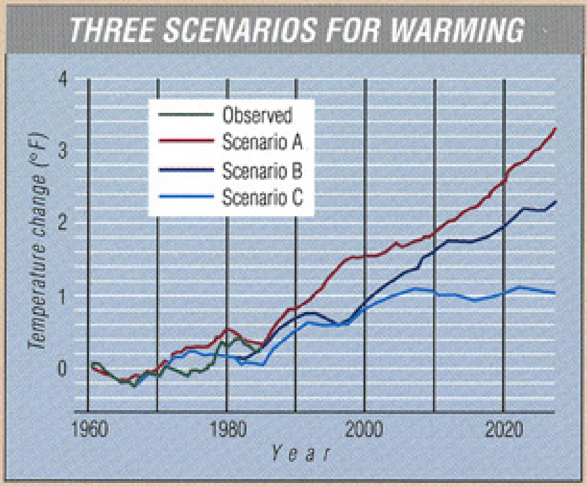


Rather than attempt to predict how fast trace gases will build up, GISS researchers devised three scenarios, each characterized by different rates of increase. Under Scenario B, which assumes the most plausible rates, global temperatures will have risen by more than 2°F by 2025 (0 represents the 1958 average temperature).

Removing Doubt

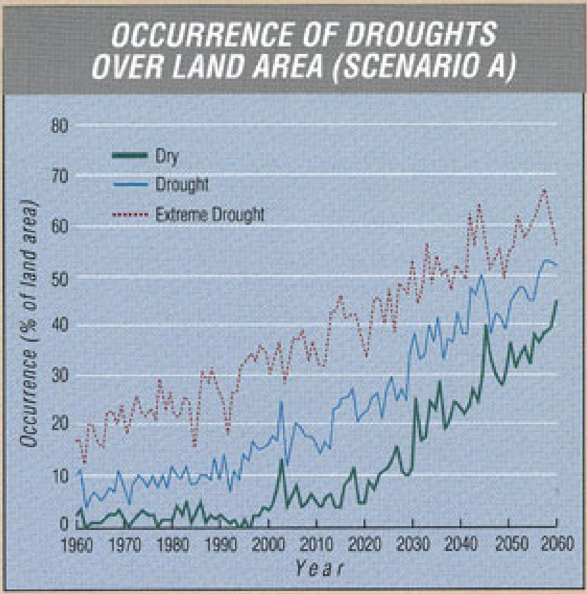
Models may never be able to reproduce all climate processes with absolute fidelity. However, they may not need to. It would be enough to construct a model incorporating only the processes that have a significant impact on climate and using good parameterizations of the processes that the model cannot resolve. Achieving this would require a better understanding of many of the physical and chemical processes involved. To this end, the bigger and faster computers likely to emerge over the next decade will let us carry out many more "sensitivity studies" to narrow down the processes that need to be included in the models. But the key ingredient necessary for improving our understanding—as well as for validating the models—is more comprehensive observations of the climate system.

NASA's proposed Earth Observing System (EOS) could make a major contribution to gathering some of the necessary data. The agency's original proposal called for launching two series of polar-orbiting satellites packed with instruments to monitor many climate processes simultaneously. The first satellite would have been launched in 1998, and EOS orbiters would have continued making observations for 15 years, enough time to monitor long-term changes. Major goals included expanding our knowledge of small-scale hydrological processes and the biological processes that affect CO_2 concentrations. Meeting these goals would improve our ability to predict changes in regional climate and bolster our confidence in predictions of global warming. Because of recent congressional budget cuts, however, EOS will have to be scaled down.

Addressing another big limitation of climate models—their rudimentary treatment of ocean dynamics—will require bigger and faster computers. William Holland and Frank Bryan at the National Center for Atmospheric Research in Boulder, Colo., have already carried out preliminary experiments with high-resolution ocean models that can accurately characterize important large-scale processes. Computers that are about 10,000 times as powerful as today's machines would enable us to include one of these ocean models in a global climate model. With the necessary resources, massive parallel processing machines could allow this soon, perhaps in three or four years.

But the ocean models, too, will still have to be validated against observations. Without good ocean models, our ability to predict regional climate changes and the rate of global warming will be severely limited. A project that could provide the necessary data is the World Ocean Circulation Experiment, a multinational

To avoid the problem of predicting how quickly trace gas concentrations will increase, the GISS researchers posited three different scenarios. Scenario A assumes that concentrations of trace greenhouse gases will continue to grow by the same percentage per year as in recent years. This scenario is similar to the IPCC "business-as-usual" scenario. Scenario C assumes that trace gas concentrations will not increase after the year 2000. This is a rather extreme scenario, requiring that CO_2 emissions be cut by more than 50 percent. Scenario B is an intermediate scenario that assumes concentrations will continue to increase, but in a slower, linear fashion rather than exponentially as in Scenario A. This is perhaps the most plausible of the three scenarios. According to Scenario B, by the year 2025 the global mean surface temperature will have risen 2°F above the average level of 1958.



If greenhouse gas emissions continue growing at the same rate as in recent years (GISS Scenario A), the area of the world stricken by droughts during June, July, and August could increase dramatically.

The rise in temperature predicted by Scenario B would be comparable to historical changes that have had major socioeconomic impacts. For example, a change of 2°F is about the same as the temperature decreases and increases associated with the onset and disappearance of the Little Ice Age, which lasted from about 1400 to 1850. Historical records show that these temperature variations caused significant changes in the severity of European winters, major advances and retreats of alpine glaciers and North Atlantic pack ice, and widescale abandonment of many formerly productive agricultural areas.

Despite their sophistication, however, the Goddard Institute projections are still subject to many of the same uncertainties as other models, such as possible errors in simulating small-scale processes and oceanic heat transports.

—Peter H. Stone

project started in 1985. Plans call for mapping ocean circulations by taking measurements from ships, moored arrays, and subsurface floats over a period of 10 or more years. Unfortunately, funding constraints have already brought about so many cuts in the original program that WOCE may not yield enough data for testing ocean models adequately.

In view of the funding difficulties of large projects like EOS and WOCE, scientists are scurrying to come up with less costly ways of gathering the most crucial information for improving climate predictions. One project that holds great promise is an experiment devised by Walter Munk of the Scripps Institution of Oceanography in La Jolla, Calif., and Andrew Forbes of the Commonwealth Scientific and Industrial Research Organization in Australia.

The two researchers propose placing acoustic sources deep in the oceans at different locations around the world and then listening to the signals at a distance with hydrophones. Since the speed of sound in the ocean depends on the temperature of the water, measurements of the time delay between generating and receiving the acoustic signals will reveal the mean temperature along the path traveled by the sound waves. By measuring the temperature along many paths, it would be possible to determine how rapidly the deep oceans are warming and thereby improve predictions of how rapidly global temperatures will rise.

The project, scheduled to start in 1993, has received initial funding from a U.S. interagency group, and its feasibility has already been tested. If all goes well, accurate measurements of ocean warming will be available sometime in the first decade of the next century.

Although research efforts like Munk and Forbes's could lead to more reliable climate predictions within 15 or 20 years, some of the more extreme projections raise the possibility that global warming will outrun our ability to forecast it accurately. But even if that happened, we would still have compelling reasons to continue working on the climate modeling problem. Global warming, if it does occur, is unlikely to be the last environmental change we bring upon ourselves. So if we are ever to learn to foresee the consequences of our actions, we must improve our understanding of climate and our ability to model it. ■