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"The Changing Climate"

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The Changing Climate

Global warming should be unmistakable within a decade or two. Prompt emission cuts could slow the buildup of heat-trapping gases and limit this risky planetwide experiment

by Stephen H. Schneider

In 1957 Roger Revelle and Hans E. Suess of the Scripps Institution of Oceanography observed that humanity is performing a "great geophysical experiment," not in a laboratory, not in a computer, but on our own planet. The outcome of the experiment should be clear within decades, but it essentially began at the start of the Industrial Revolution. Since then human beings have increased the atmospheric content of carbon dioxide by about 25 percent by burning coal, oil and other fossil fuels and by clearing forests, which releases carbon dioxide as the litter is burned or decays.

Carbon dioxide makes up only a thirtieth of 1 percent of the atmosphere, but together with water vapor and other gases present in much smaller quantities, such as methane and the chlorofluorocarbons (CFC's), it plays a major role in determining the earth's climate. As early as the 19th century it was recognized that carbon dioxide in the atmosphere gives rise to a greenhouse effect. The glass of a greenhouse allows sunlight to stream in freely but blocks heat from escaping, mainly by preventing the warm air inside the greenhouse from mixing with outside air. Similarly, carbon dioxide and other greenhouse gases are relatively transparent to sunshine but trap heat by more efficiently absorbing the longer-wavelength infrared radiation released by the earth.

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By now the atmosphere's heat-trapping ability has been well established. For example, as seen from space, the earth radiates energy at wavelengths and intensities characteristic of a body at -18 degrees Celsius. Yet the average temperature at the surface is some 33 degrees higher: heat is trapped between the surface and the level, high in the atmosphere, from which radiation escapes. There is virtually no doubt among atmospheric scientists that increasing the concentration of carbon dioxide and other gases will increase the heat trapping and warm the climate.

What, then, is the question that the ongoing geophysical experiment will settle? Even though there is virtually no debate among scientists about the greenhouse effect as a scientific proposition, there is controversy. Will the rising concentrations of greenhouse gases raise the earth's temperature by one, five or eight degrees C? Will the increase take 50, 100 or 150 years? Will it be drier in Iowa or wetter in India? There is still more controversy when it comes to policy: Should steps be taken to reduce the greenhouse warming or to anticipate its effects? What steps, and when? In the face of so much controversy, an understanding of what is well known, known slightly and not known at all about the greenhouse warming is essential.

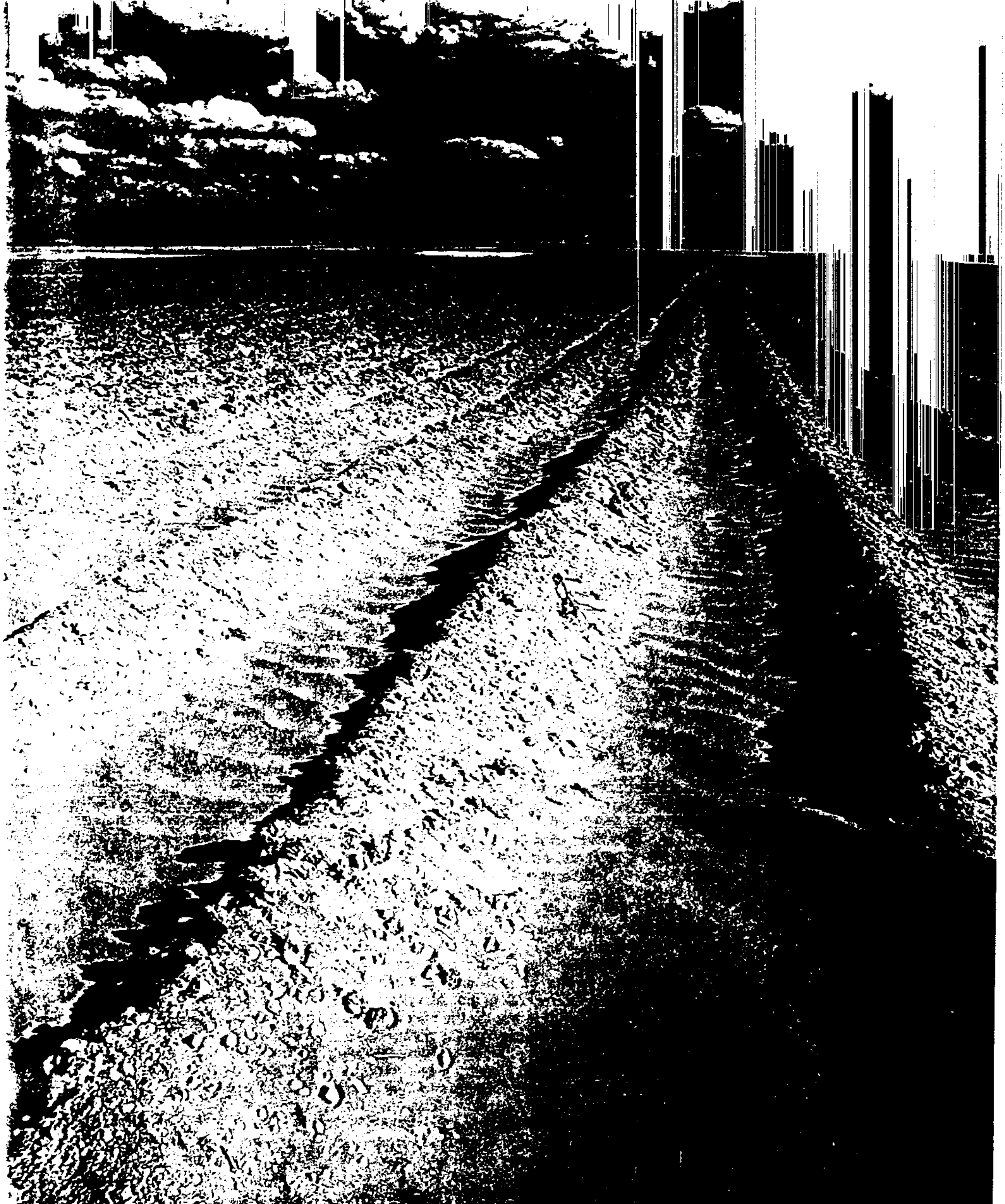
Circumstantial evidence from the geologic and historical past bears out a link between climatic change and fluctuations in greenhouse gases. Between 3.5 and four billion years ago the sun is thought to have been about 30 percent fainter than it is today. Yet life evolved and sedimentary rock formed under the faint young sun: at least some of the earth's surface was above the freezing point of water. Some workers have proposed that the early atmosphere contained as much as 1,000 times today's level of carbon dioxide, which compensated for the sun's feeble radiation by its heat-trapping effect.

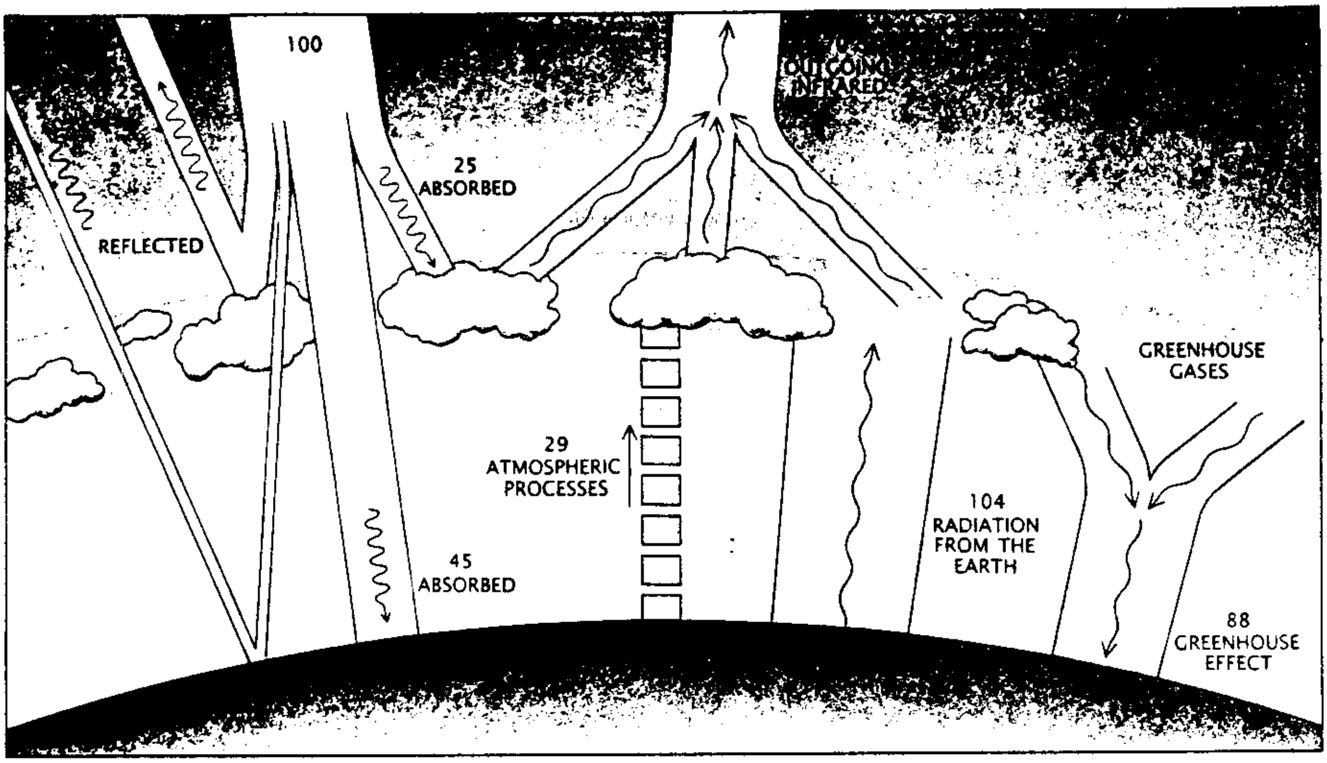
Later an enhanced greenhouse effect may have been partly responsible for the warmth of the Mesozoic era—the age of the dinosaurs—which fossil evidence suggests was perhaps 10 or 15 degrees C warmer than today. At the time, 100 million years ago and more, the continents occupied different positions than they do now, altering the circulation of the oceans and perhaps increasing the transport of heat from the Tropics to high latitudes. Yet calculations by Eric J. Barron, now at Pennsylvania State University, and others suggest that paleocontinental geography can explain no more than half of the Mesozoic warming.

Increased carbon dioxide can readily explain the extra heating, as Aleksandr B. Ronov and Mikhail I. Budyko of the Leningrad State Hydrological Institute first proposed and as Barron, Starley L. Thompson of the National Center for Atmospheric Research (NCAR) and I have calculated. A geochemical model constructed by Robert A. Berner and Antonio C. Lasaga of Yale University and the late Robert M. Garrels of the University of South Florida suggests that the carbon dioxide may have been released by unusually heavy volcanic activity on the mid-ocean ridges, where new ocean floor is created by upwelling magma [see "The Geochemical Carbon Cycle," by Robert A. Berner and Antonio C. Lasaga; SCIENTIFIC AMERICAN, March].

Direct evidence linking greenhouse gases with the dramatic climatic changes of the ice ages comes from bubbles of air trapped in the Antarctic ice sheet by the ancient snowfalls that

PARCHED FIELDS turn to sand during a 1983 dry spell in Texas. Such images could multiply if, as several computer models predict, global warming reduces soil moisture in midcontinental regions, where grain production is concentrated.





HEAT TRAPPING in the atmosphere dominates the earth's energy balance. Some 30 percent of incoming solar energy is reflected (*left*), either from clouds and particles in the atmosphere or from the earth's surface; the remaining 70 percent is absorbed. The absorbed energy is reemitted at infrared wavelengths by the atmosphere (which is also heated by updrafts and cloud formation) and by the surface. Because most of the surface radiation is trapped by clouds and greenhouse gases and returned to the earth, the surface is currently about 33 degrees Celsius warmer than it would be without the trapping.

built up to form the ice. A team headed by Claude Lorius of the Laboratory of Glaciology and Geophysics of the Environment, near Grenoble, examined more than 2,000 meters of ice cores—a 160,000-year record—recovered by a Russian drilling project at the Vostok Station in Antarctica. Laboratory analysis of the gases trapped in the core showed that carbon dioxide and methane levels in the ancient atmosphere varied in step with each other and, more important, with the average local temperature (determined from the ratio between hydrogen isotopes in the water molecules of the ice).

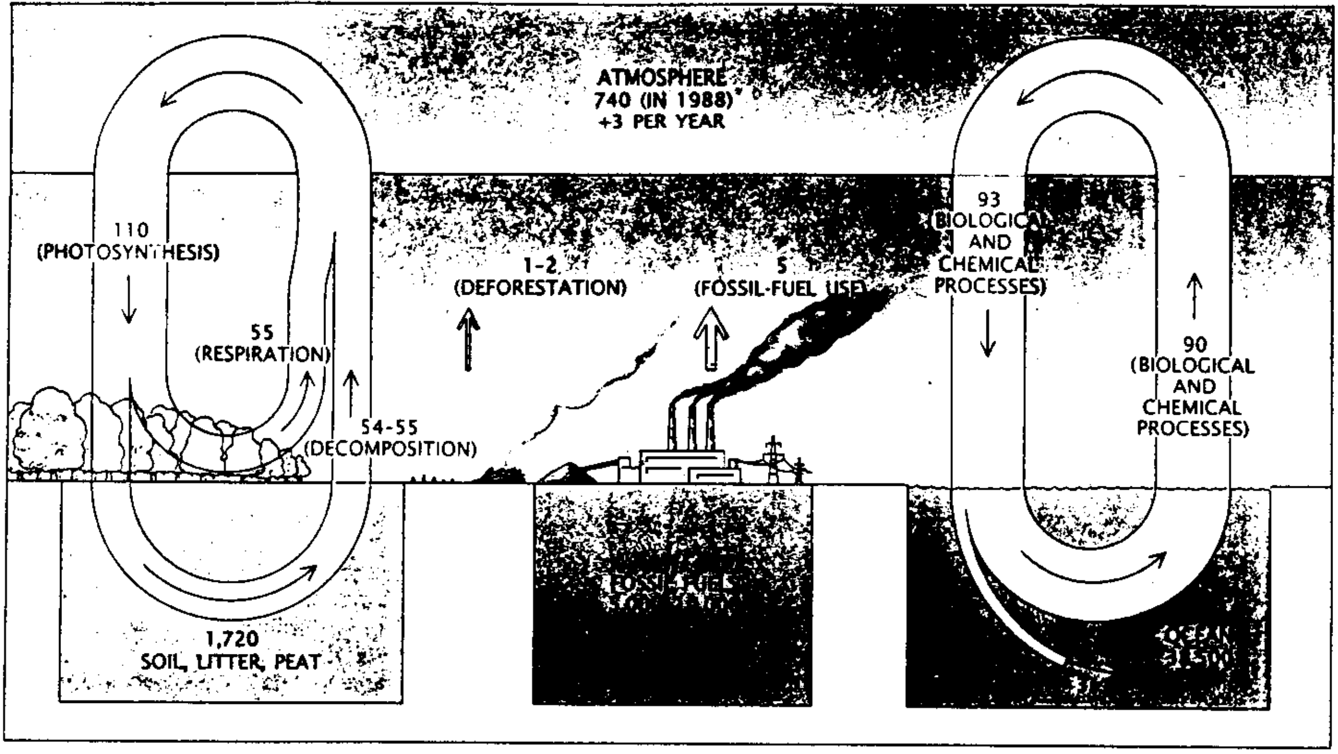
During the current interglacial period (the past 10,000 years) and the previous one, a 10,000-year period around 130,000 years ago, the ice recorded a local temperature about 10 degrees C warmer than at the height of the ice ages. (The earth as a whole is about five degrees warmer during interglacials.) At the same time, the atmosphere contained about 25 percent more carbon dioxide and 100 percent more methane than during the glacial periods. It is not clear whether the greenhouse-gas variations caused the climatic changes or vice versa. My guess is that the ice ages were paced by other factors, such as changes in the earth's orbital parameters and the dynamics of ice buildup and retreat, but biological changes and shifts in ocean circulation in turn affected the atmosphere's trace-gas content, amplifying the climatic swings.

A still more detailed record of greenhouse gases and climate comes from the past 100 years, which have seen a further 25 percent increase in carbon dioxide above the interglacial level and another doubling of atmospheric methane. Two groups, one led by James E. Hansen at the National Aeronautics and Space Administration's Goddard Institute for Space Studies and the other by T. M. L. Wigley at the Climatic Research Unit of the University of East Anglia, have constructed records of global average surface temperature for the past century. The workers drew on data from many of the same recording stations around the globe (the Climatic Research Unit also included readings made at sea), but they had different techniques for analyzing the records and compensating for their shortcomings. Certain recording stations were moved over the course of the century, for example, and readings from city centers may have been skewed by heat released by machinery or stored by buildings and pavement.

This "urban heat island" effect is likely to have been disproportionately large in developed countries such as the U.S., but even when the same correction calculated for the U.S. data (by Thomas R. Karl of the National Climatic Data Center in Asheville, N.C., and P. D. Jones of East Anglia) is applied to the global data set, about half a degree C of unexplained "real" warming over the past 100 years remains in both records. In keeping with the trend, the 1980's appear to be the warmest decade on record and 1988, 1987 and 1981 the warmest years, in that order.

Is this the signal of the greenhouse warming? It is tempting to accept it as such, but the evidence is not definitive. For one thing, instead of the steady warming one might expect from a steady buildup of greenhouse gases, the record shows rapid warming until the end of World War II, a slight cooling through the mid-1970's and a second period of rapid warming since then.

What trajectory will the temperature curve follow now? Three basic questions must be answered in forecasts of the climatic future: How much carbon dioxide and other greenhouse gases will be emitted? By how much will atmospheric



CARBON IS EXCHANGED between the atmosphere and reservoirs on the earth. The numbers give the approximate annual fluxes of carbon (in the form of carbon dioxide) and the approximate amount stored in each reservoir in billions of metric tons. The existing cycles—one on land and the other in the oceans—remove about as much carbon from the atmosphere as they add, but human activity (deforestation and fossil-fuel burning) is currently increasing atmospheric carbon by some three billion metric tons yearly. The numbers are based on work by Bert Bolin of the University of Stockholm.

levels of the gases increase in response to the emissions? What climatic effects will the resulting buildups have, after natural and human factors that might mitigate or amplify those effects are taken into account?

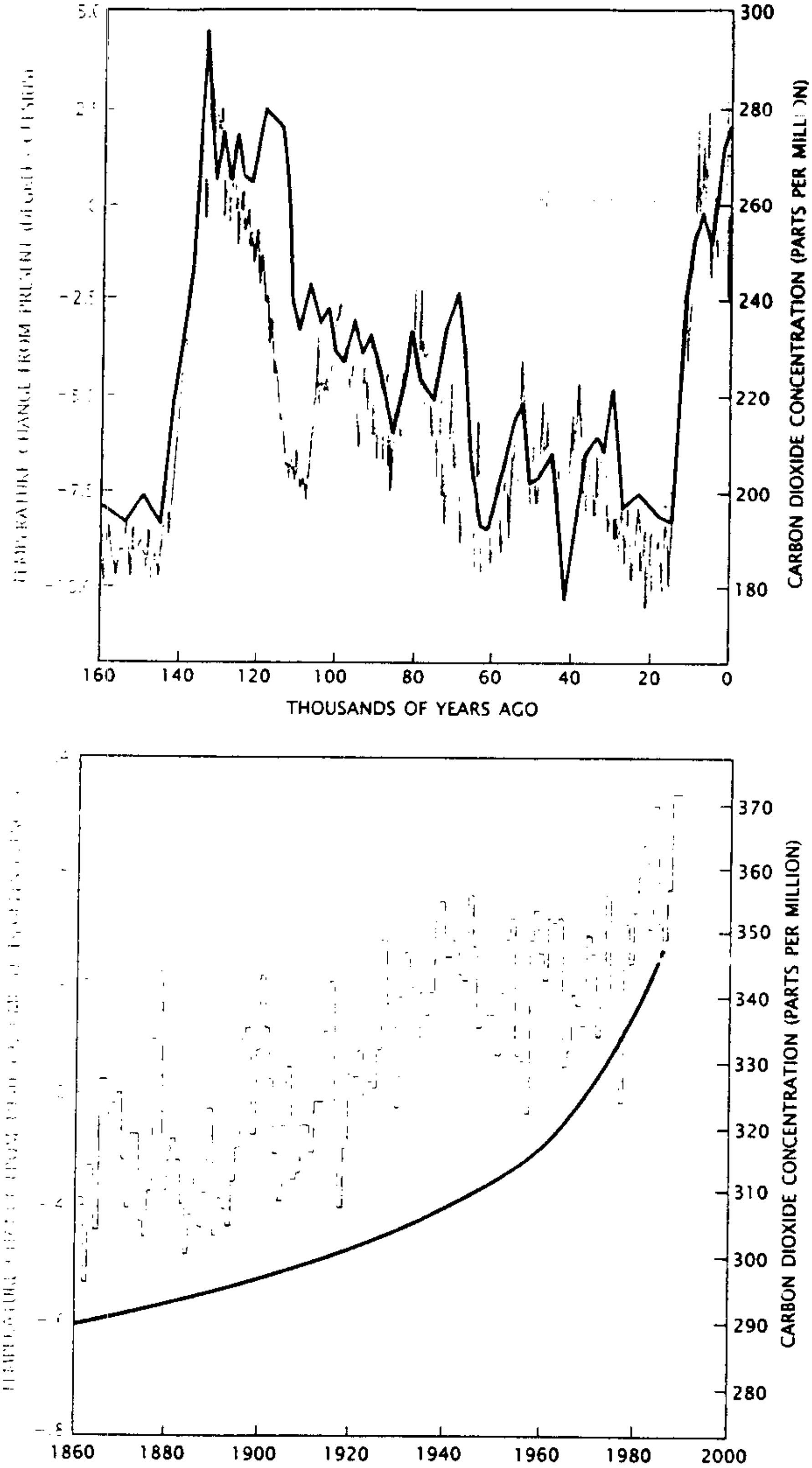
Projecting emissions is an intricate exercise in social science. How much carbon dioxide humanity as a whole will be emitting in the future depends primarily on the global consumption of fossil fuels and the rate of deforestation (which accounts for perhaps half of the buildup since the year 1800 and 20 percent of current emissions). Each factor in turn is affected by many others. Growth in fossil-fuel use, for example, will reflect population growth, the rate at which alternative energy sources and conservation measures are adopted and the state of the world economy. Typical projections assume that global fossil-fuel consumption will continue increasing at about its current pace—much slower than it grew before the energy crisis of the 1970's—yielding increases in carbon dioxide emissions of between .5 and 2 percent a year for the next several decades at least.

Other greenhouse gases, such as methane, the CFC's, oxides of nitrogen and low-level ozone, together could contribute as much to global warming as carbon dioxide, even though they are emitted in much smaller quantities: they are much better at absorbing infrared radiation. But predicting future emissions for these gases is even more complicated than it is for carbon dioxide. The sources of some gases, such as methane, are not well understood; the production of other gases, such as the CFC's and low-level ozone, could rise or fall sharply depending on whether specific technological or policy steps are taken.

Given a plausible scenario for future carbon dioxide emissions, how fast will the atmospheric concentration increase in response? Atmospheric carbon dioxide is continuously being absorbed by green plants and by chemical and biological processes in the oceans. The rate of carbon dioxide uptake is likely to change as the atmospheric concentration changes; that is, feedback processes will enter the equation. Because carbon dioxide is a raw material of photosynthesis, an increased concentration might speed the uptake by plants, counteracting some of the buildup. Similarly, because the carbon dioxide content of the oceans' surface waters stays roughly in equilibrium with that of the atmosphere, oceanic uptake will slow the buildup to some extent. (The slower the buildup is in the first place, the more effective, proportionally, oceanic uptake is likely to be.)

It is also possible, however, that an increased concentration of carbon dioxide and other greenhouse gases will trigger positive feedbacks that would add to the atmospheric burden. Rapid change in climate could disrupt forests and other ecosystems, reducing their ability to draw carbon dioxide down from the atmosphere. Moreover, climatic warming could lead to rapid release of the vast amount of carbon held in the soil as dead organic matter. This stock of carbon—at least twice as much as is stored in the atmosphere—is continuously being decomposed into carbon dioxide and methane by the action of soil microbes. A warmer climate might speed their work, releasing additional carbon dioxide (from dry soils) and methane (from rice paddies, landfills and wetlands) that would enhance the warming. Large quantities of methane are also locked up in continental-shelf sediments and below arctic permafrost in the form of clathrates—molecular lattices of methane and water. Warming of the shallow waters of the oceans and melting of the permafrost could release some of the methane.

In spite of all these uncertainties,



CARBON DIOXIDE AND TEMPERATURE are very closely correlated over the past 160,000 years (*top*) and, to a lesser extent, over the past 100 years (*bottom*). The long-term record, based on evidence from Antarctica, shows how the local temperature (*color*) and atmospheric carbon dioxide rose nearly in step as an ice age ended about 130,000 years ago, fell almost in synchrony at the onset of a new glacial period and rose again as the ice retreated about 10,000 years ago. The recent temperature record shows a slight global warming (*color*), as traced by workers at the Climatic Research Unit of the University of East Anglia. Whether the accompanying buildup of carbon dioxide in the atmosphere caused the half-degree warming is hotly debated.

many workers expect uptake by plants and by the oceans to moderate the carbon dioxide buildup, at least for the next 50 or 100 years. Typical estimates, based on current or slightly increased emission rates, put the fraction of newly injected carbon dioxide that will remain in the atmosphere at about one half. Under that assumption, the atmospheric concentration will reach 600 parts per million, or about twice the level of 1900, by sometime between the years 2030 and 2080. Some other greenhouse gases are expected to build up faster than carbon dioxide, however.

What effect will a doubling of atmospheric carbon dioxide have on climate? The historical record offers no clear quantitative guidance. Nor can climate—the product of complicated interactions involving the atmosphere, the oceans, the land surface, vegetation and polar ice—be physically reproduced in a laboratory experiment. In exploring the future of the earth's climate, my colleagues and I rely on mathematical climate models.

The models, which have been built at Princeton University's Geophysical Fluid Dynamics Laboratory, the Goddard Institute for Space Studies, here at NCAR and elsewhere, consist of expressions for the interacting components of the ocean-atmosphere system and equations representing the basic physical laws governing their behavior, such as the ideal gas laws and the conservation of mass, momentum and energy. Given values for, say, the input of energy from the sun and the composition of the atmosphere, a model calculates "climate"—temperature and, in sophisticated models, pressure, wind speed, humidity, soil moisture and other variables.

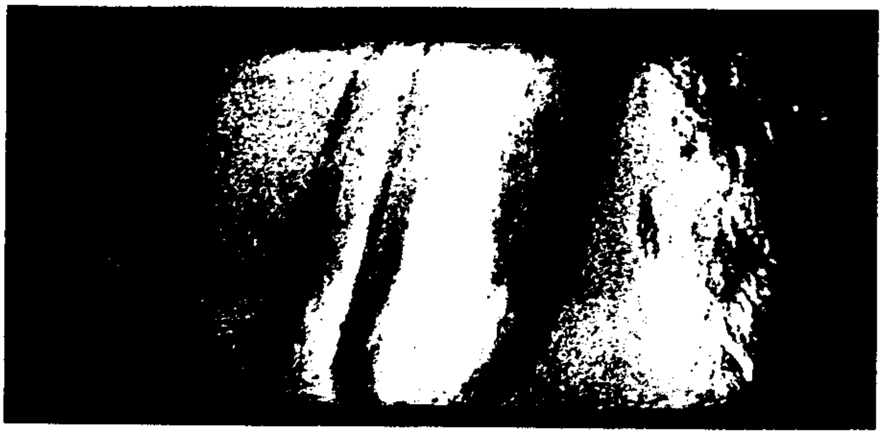
To keep the task computationally manageable, the calculations are done at discrete points in a simplified version of the real world. In the most complicated models—global-circulation models (GCM's), which were first developed for long-term weather forecasts—the atmosphere is represented as a three-dimensional grid with an average horizontal spacing of several hundred kilometers and an average vertical spacing of several kilometers; climate is calculated only at the intersections of the grid lines. In spite of the simplification, running such a GCM for only one simulated year can take many hours on the fastest available supercomputers.

To study the effect of a trace-gas buildup, a modeler simply specifies the projected amount of greenhouse gases and compares the model results with a control simulation of the existing climate, based on the present atmospheric composition. The results of the most recent GCM's are in rough agreement: a doubling of carbon dioxide, or an equivalent increase in other trace gases, would warm the earth's average surface temperature by between 3.0 and 5.5 degrees C. Such a change would be unprecedented in human history; it would match the five-degree warming since the peak of the last ice age 18,000 years ago but would take effect between 10 and 100 times faster.

The shortcomings of computer models limit the reliability of such forecasts. Many processes that affect global climate are simply too small to be seen at the coarse resolution of a model. Such climatically important processes as atmospheric turbulence, precipitation and cloud formation take place on a scale not of hundreds of kilometers (the scale of the grid in a GCM) but of a few kilometers or less. Since such processes cannot be simulated directly, modelers must find a way of relating them to variables that can be simulated on the model's coarse scale. They do so by developing a parameter—a proportionality coefficient—that relates, say, the average cloudiness within a grid cell to the average humidity and temperature (something the model can calculate).

This strategy, known as parameterization, has the effect of aggregating small-scale phenomena that could act as feedbacks on climatic change, either amplifying or moderating it. Clouds, for example, reflect sunlight back to outer space (tending to cool the climate) and also absorb infrared radiation from the earth (tending to warm it). Which effect dominates depends on the clouds' brightness, height, distribution and extent. Recent satellite measurements have confirmed two-decade-old calculations showing that clouds currently have a net cooling effect; the earth as a whole would be much warmer under cloudless skies. But climatic change might cause incremental changes in cloud characteristics, altering the nature and amount of the feedback. Present models, crudely reproducing only average cloudiness, can say little that is reliable about cloud feedback—or about the many other feedbacks that depend on parameterized processes.

Another shortcoming of present models is their crude treatment of the oceans. The oceans exert potent effects on the present climate and will surely influence climates to come. Their enormous thermal mass will act as a "thermal sponge," slowing any initial increase in global temperature while the oceans themselves warm up. The magnitude of the effect will depend on ocean circulation, which in turn may change as the earth warms. In principle, a climate model should couple a simulated atmosphere with oceans whose dynamics are simulated in equal detail. The computational challenge is staggering, however, and in most GCM's applied to greenhouse warming the dynamics of the oceans are simplified, treated at coarse resolution or left out.



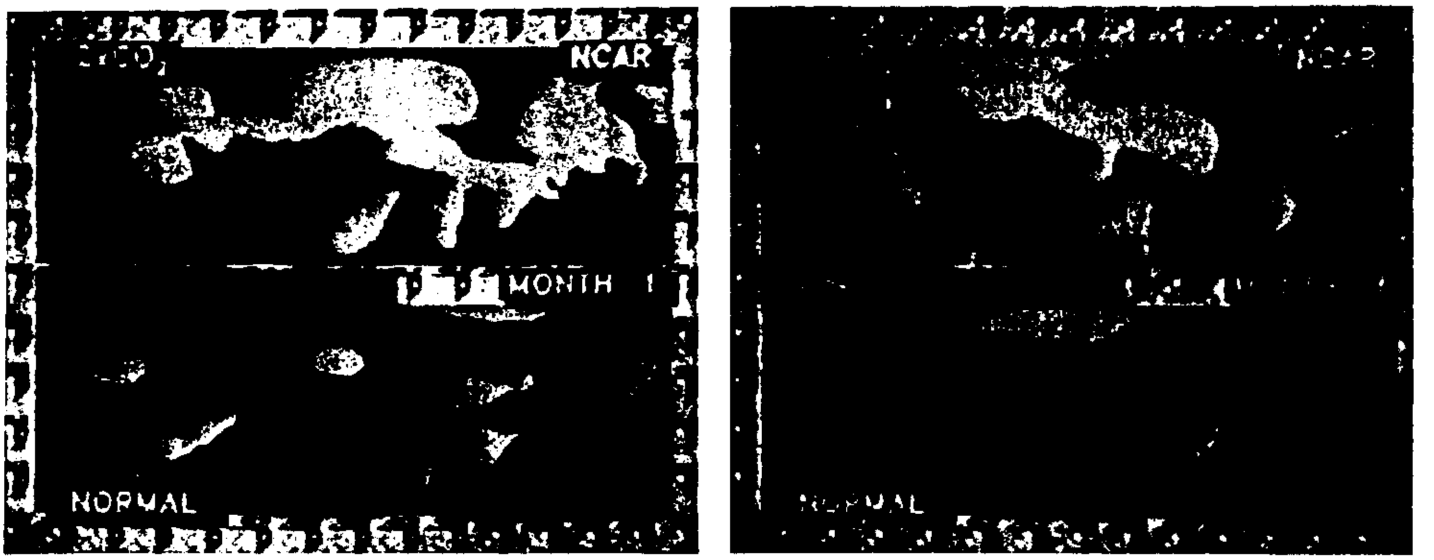
ICE CORE—a segment of a two-kilometer core drilled from the Antarctic ice sheet at the Soviet Union's Vostok Station—contains trapped bubbles of ancient air. Analysis of the bubbles and of the ratio of hydrogen isotopes in the ice, which varies with local temperature, enabled Claude Lorius and his colleagues at the Laboratory of Glaciology and Geophysics of the Environment, near Grenoble, to reconstruct a 160,000-year record of trace gases and temperature (*see top illustration on opposite page*).

In addition to limiting the reliability of global forecasts, the simplified treatment of the oceans also prevents the models from giving a definitive picture of how climate will change over time in specific regions. Ideally one would like to know not only how much the world as a whole will warm but also whether it will, say, get drier in Iowa, wetter in India or more humid in New York City. Yet, as long as the oceans are out of equilibrium with the atmosphere, their thermal effects will be felt differently at different places. An area in which there is little mixing between surface waters and cold, deep waters might warm quickly; high-latitude regions where deep water is mixed up to the surface might warm more slowly. These thermal effects could in turn affect wind patterns, thereby altering other regional variables, including humidity and rainfall. (Regional forecasts are also compromised in many models by simplified representations of vegetation, which ignore climatically important processes such as the release of water vapor by plants and their effect on surface albedo, or reflectiveness.)

Nevertheless, climatologists have grounds for considerable confidence in their models' forecasts of global surface-temperature change. Individual model elements can be verified by comparing them with the results of a more detailed submodel—a smaller, finer-scale simulation—or with real data. Cloud parameterizations, for example, can be tested against actual measurements of the relation of temperature and humidity to cloudiness within an area corresponding to a cell in the model.

The skill of a model as a whole, and in particular its ability to account for relatively fast processes, such as changes in atmospheric circulation or average cloudiness, can be verified by checking its ability to reproduce the seasonal cycle—a twice-yearly change in hemispheric climate that is larger than any projected greenhouse warming. In spite of parameterization, most GCM's map the seasonal cycle of surface temperature quite well, but their ability to simulate seasonal changes in other climatic variables, including precipitation and relative humidity, has not been studied as thoroughly.

During the course of decades (the expected time scale for unmistakable global warming), other, slower processes that do not affect the seasonal cycle come into play: changes in ocean currents or in the extent of glaciers, for instance. Simulations of past climates—the ice ages or the Mesozoic hothouse—serve as a good check on the long-term accuracy of climate



SNAPSHOTS OF A GREENHOUSE WORLD come from a climate model used by the author and Starley L. Thompson at the National Center for Atmospheric Research. The model traced surface temperatures over the year for an atmosphere with twice the present level of carbon dioxide (*top*); the findings were compared with the results of a yearlong simulation for

models. To such tests of overall validity can be added simulations of the climates of other planets, such as Venus, where a dense greenhouse atmosphere maintains a surface temperature of about 450 degrees C.

The record of the past 100 years provides the only direct test of the models' ability to simulate the effects of the ongoing greenhouse-gas increase. When a climate model is run for an atmosphere with the composition of 100 years ago and then run again for the historical 25 percent increase in carbon dioxide and doubling in methane, does it "predict" the observed half-degree warming? Actually most models yield a somewhat larger warming, of at least a degree.

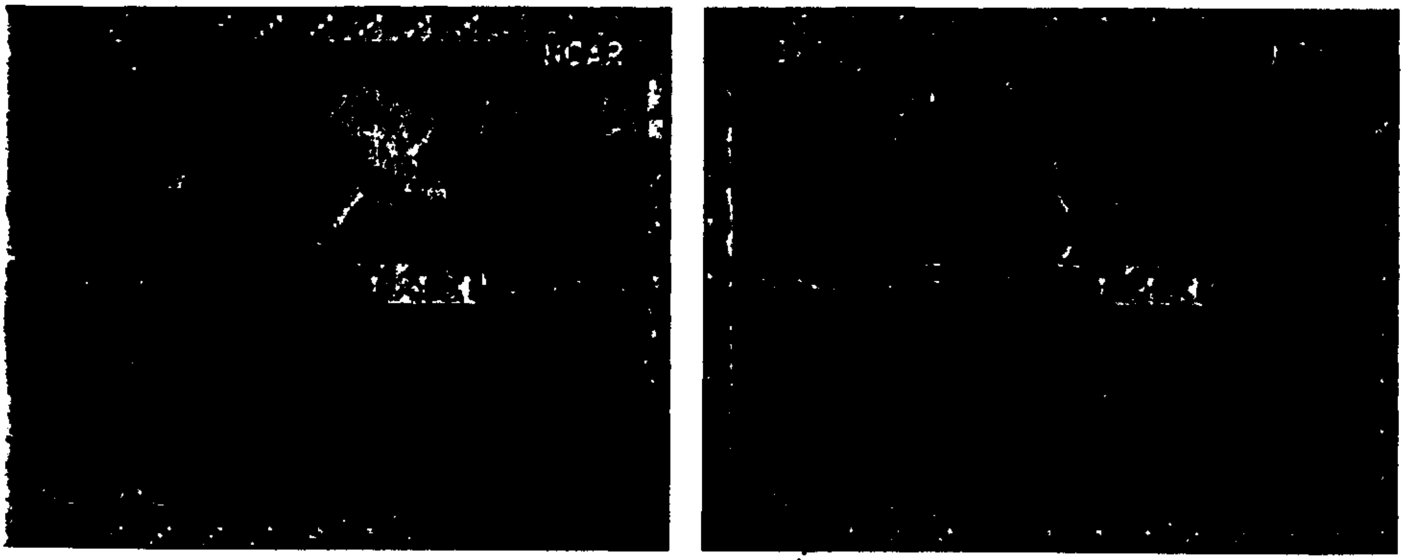
If the observed temperature increase really is a greenhouse warming and not just "noise"—a random fluctuation—one might account for the disparity in various ways. Perhaps the models are simply twice too sensitive to small increases in greenhouse gases, or perhaps the incomplete and inhomogeneous network of thermometers has underestimated the global warming. Conceivably some other factor, not well accounted for in the models, is delaying or counteracting the warming. It might be that the heat capacity of the oceans is larger than current models calculate, that the sun's output has declined slightly or that volcanoes have injected more dust into the stratosphere than is currently known, thereby reducing the solar energy reaching the ground.

It may be significant that the transient cooling interrupting the warming trend began around 1940 and was most pronounced in the Northern Hemisphere, coinciding in time and place with a sharp increase in emissions of sulfur from coal- and oil-burning factories and power plants. The sulfur, a major cause of acid rain, is emitted as a gas, sulfur dioxide, but is transformed into fine sulfate particles once in the atmosphere. The particles can travel long distances and serve as condensation nuclei for the formation of cloud droplets, and so they may make some clouds denser and brighter, increasing their cooling effects. In addition, if no soot is bound to the sulfate, it forms a reflective haze even in cloudless skies. Sulfur emissions could be one factor that has held a greenhouse warming down somewhat in the Northern Hemisphere, especially since World War II.

The discrepancy between the predicted warming and what has been seen so far keeps most climatologists from saying with great certainty (99 percent confidence, say) that the greenhouse warming has already taken hold. Yet the discrepancy is small enough, the models are well enough validated and other evidence of greenhouse-gas effects on climate is strong enough, so that most of us believe that the increases in average surface temperature predicted by the models for the next 50 years or so are probably valid within a rough factor of two. (By "probably" I mean it is a better-than-even bet.) Within a decade or so, warming of the predicted magnitude should be clearly evident, even in the noisy global temperature record. But waiting for such conclusive, direct evidence is not a cost-free proposition: by then the world will already be committed to greater climatic change than it would be if action were taken now to slow the buildup of greenhouse gases. Of course, whether or not to act is a value judgment, not a scientific issue.

Why worry about changes in climate on the scale predicted by the models? Changes in temperature and precipitation could threaten natural ecosystems, agricultural production and human settlement patterns. Particular forest types, for example, grow in geographic zones defined largely by temperature. The belt of spruce and fir that now spans Canada grew far to the south at the end of the last ice age 10,000 years ago, hugging the edge of the ice sheet. As the climate warmed by one or two degrees every 1,000 years and the ice retreated, the forest belt migrated northward, at perhaps one kilometer a year. Forests probably could not sustain the much faster migration required by the projected warming, and many ecosystems cannot migrate in any case: they exist only in preserves, which might become marooned in a newly inhospitable climate zone.

Human activities could be affected directly if a warming speeded the evaporation of moisture, reducing stream runoff; in the western U.S. a temperature increase of several degrees C could decrease runoff in the Colorado basin substantially even if precipitation held steady. As water ran short, faster evaporation would in-



the present atmosphere (*bottom*). The red areas were more than six degrees C warmer than the model-calculated normal for that time of year under existing conditions; the light blue areas were more than six degrees colder. The weather anomalies steadily changed position, shape and size, but heating always predominated in the greenhouse simulation.

crease the demand for irrigation, adding to the strain on water supplies. At the same time, water quality might suffer as the same waste volume was diluted in lower stream volumes.

What is more, several climate models predict that summer precipitation will actually decline in midcontinental areas, including the central plains of the U.S. The late Dean F. Peterson, Jr., of Utah State University and Andrew A. Keller of Keller-Bliesner Engineering in Logan, Utah, estimated the effects on crop production of a three-degree warming combined with a 10 percent drop in precipitation. They found that based on increased crop water needs and a reduction in available water, the viable acreage in arid regions of the western states and the Great Plains would fall by nearly a third. (A western drying might also result in an increased frequency of wildfires.)

Coastal areas, meanwhile, might face a rise in sea level. Most workers expect a global temperature increase of a few degrees C over the next 50 or 100 years to raise sea level by between .2 and 1.5 meters as a result of the thermal expansion of the oceans, the melting of mountain glaciers and the possible retreat of the Greenland ice sheet's southern margins. (Ice could actually build up in Antarctica owing to warmer winters, which would probably increase snowfall.) The rising sea would endanger coastal settlements and ecosystems and might contaminate groundwater supplies with salt. In spite of many local factors that make it difficult to isolate a consistent global signal, one group of workers recently claimed to have found a uniform worldwide rise in sea level of about two millimeters a year in long-term tide-gauge records. That rise is somewhat larger, however, than one would have expected from the warming seen so far.

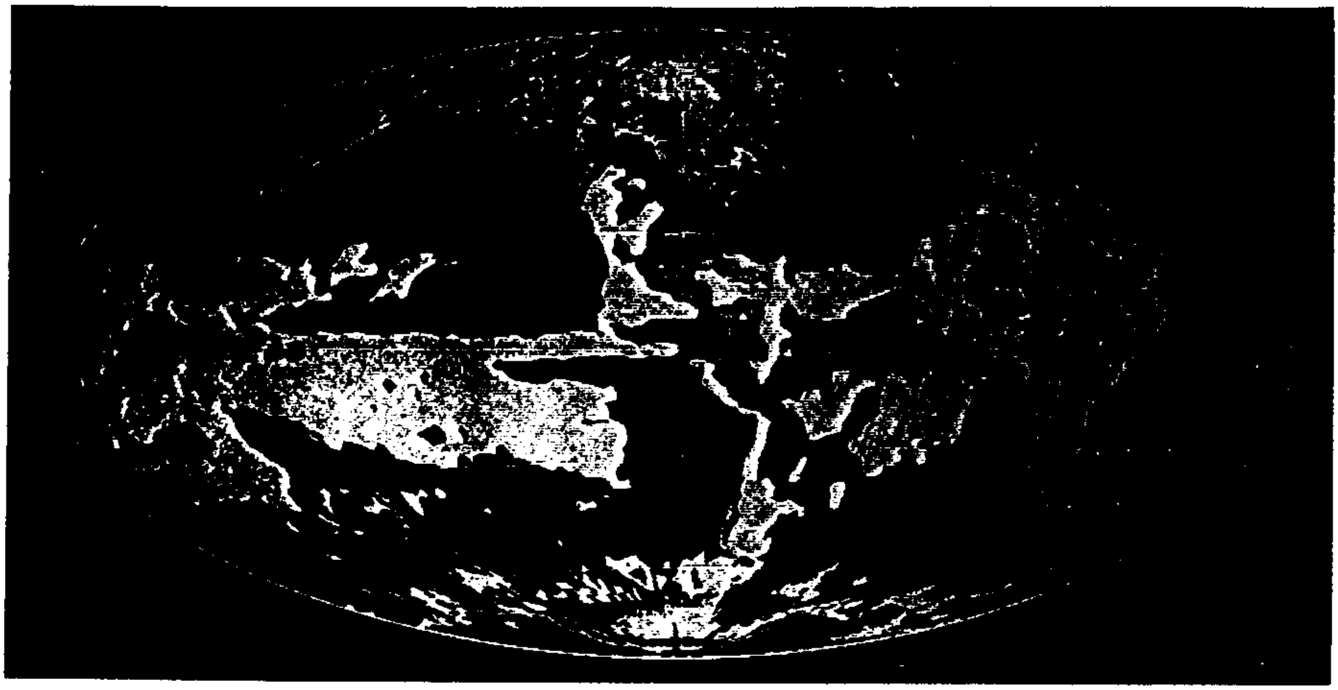
Clearly these direct effects of climatic change would have powerful economic, social and political consequences. A decline in agricultural productivity in the Middle West and Great Plains, for example, could be disastrous for farmers and the U.S. economy. By cutting into the U.S. grain surplus, it might also have serious implications for international security.

To be sure, not everyone would lose. If the corn belt simply moved north by several hundred kilometers, for example, Iowa's billion-dollar loss could become Minnesota's billion-dollar gain. But how could the losers be compensated and the winners charged? The issue of equity would become still more thorny if it spanned borders—if the release of greenhouse gases by the economic activities of one country or group of countries did disproportionate harm to other countries whose activities had contributed less to the buildup.

In the face of this array of threats, three kinds of responses could be considered. First, some workers have proposed technical measures to counteract climatic change—deliberately spreading dust in the upper atmosphere to reflect sunlight, for instance. Yet if unplanned climatic changes themselves cannot be predicted with certainty, the effects of such countermeasures would be still more unpredictable. Such "technical fixes" would run a real risk of misfiring—or of being blamed for any unfavorable climatic fluctuations that took place at the same time.

Many economists tend to favor a second class of action: adaptation, often with little or no attempt to anticipate damages or prevent climatic change. Adaptive strategists argue that the large uncertainties in climate projections make it unwise to spend large sums trying to avert outcomes that may never materialize. They argue that adaptation, in contrast, is cheap: the infrastructure that would have to be modified in the face of climatic change—such as water-supply systems and coastal structures—will have to be replaced in any case before large climatic changes are due to appear. The infrastructure can simply be rebuilt as needed to cope with the changing environment.

Passive adaptation relies mostly on reacting to events as they unfold, but some active adaptive steps could be taken now to make future accommodation easier. An American Association for the Advancement of Science panel on climatic change made a strong, potentially controversial but, I believe, compelling suggestion for active adaptation: governments at all levels should reexamine the technical features of water systems and the economic and legal aspects of water-supply management in order to increase the systems' efficiency and flexibility. As the climate warms and precipita-



CLOUDS AFFECT SURFACE TEMPERATURES because they both reflect sunlight, preventing it from warming the earth, and absorb infrared radiation from the surface, contributing to the greenhouse effect. In this image, based on satellite data gathered in April, 1985, clouds had a net cooling effect in some regions (*blues and green*) and a heating effect in others (*red*). On the whole, clouds cool the planet more than they warm it, but the characteristics of clouds and their effect on climate might change unpredictably in a greenhouse world. The image was provided by V. Ramanathan of the University of Chicago.

tion and runoff change, water shortages may grow more common and needs for regional transfers more complex. Even if climate did not change, more flexible water systems would make it easier to cope with the normal extremes of weather.

The third and most active category of response is prevention: curtailing the greenhouse-gas buildup. Energy-conservation measures, alternative energy sources or a switch from coal to natural gas and other fuels with a lower carbon content could all reduce carbon dioxide emissions, as could a halt to deforestation. Stopping the production of CFC's, already notorious because of their ability to erode the stratospheric ozone layer, would eliminate another component of the buildup. A far-reaching proposal for an international framework for reducing emissions was put forward in 1976 by Margaret Mead and William W. Kellogg of NCAR: a "law of the air," which would keep emissions of carbon dioxide below a global standard by assigning polluting rights to each nation.

Proposals for immediate action are controversial because they often entail large immediate investments as insurance against future events whose details are far from certain. Is there some simple principle that can help us to choose which preventive or adaptive measures to spend our resources on? I believe it makes sense to take actions that will yield "tie-in" benefits even if climatic changes do not materialize as forecast.

Pursuing energy efficiency is a good example of this tie-in strategy. More efficient fossil-fuel use will slow the carbon dioxide buildup, but even if the sensitivity of climate to carbon dioxide has been overstated, what would be wasted by taking this step? Efficiency usually makes economic sense, and a reduction in fossil-fuel use would curb acid rain and urban air pollution and lessen the dependence of many countries on foreign producers. Developing alternative energy sources, revising water laws, searching for drought-resistant crop strains, negotiating international agreements on trade in food and other climate-sensitive goods—all these steps could also offer widespread benefits even in the absence of any climatic change.

Often such steps will nonetheless be costly and politically controversial. Regulations or incentives to foster energy-efficient technologies might burden some groups—coal miners and the poor, perhaps—more than others, and the costs may be proportionally greater for poor countries than for rich ones. Actions to prevent a greenhouse warming will have to be coupled with domestic- and foreign-policy measures that attempt to balance fairness and effectiveness. Still, I believe it is better to fight poverty and foster development through direct investment rather than through artificially low energy prices that neglect the costs of the resulting environmental disruptions.

Some people argue that the free market, not government regulation or tax incentives, should dictate increases in energy efficiency, say, or the elimination of CFC's. But it cannot be logically argued that the market is "free" when it does not include some of the potential costs of environmental damage caused by goods or services. Moreover, even political conservatives agree that an economic calculus must give way to a strategic consciousness when national or global security is at stake.

Security is indeed at stake here, as the implications of a global temperature rise of several degrees or more over the next century make clear. Adding to the predicted threats are surprises that may be lurking in the greenhouse century: a sharp positive feedback in the greenhouse-gas buildup from accelerated decay of soil organic matter, dramatic changes in regional climates because of a shift in ocean circulation, or the outbreak of new diseases or agricultural pests as ecosystems are disrupted. In my value system—and this is a political and not a scientific judgment—effective tie-in actions are long overdue.

I am often asked whether I am pessimistic because it will be impossible to avert some global change: at this stage, it appears, no plausible policies are likely to prevent the world from warming by a degree or two. Actually I see a positive aspect: the possibility that a slight but manifest global warming, coupled with the larger threat forecast in computer models, may catalyze international cooperation to achieve environmentally sustainable development, marked by a stabilized population and the proliferation of energy-efficient and environmentally safe technologies. A much larger greenhouse warming (together with many other environmental disruptions) might thereby be averted.

The developed world might have to invest hundreds of billions of dollars every year for many decades, both at home and in financial and technical assistance to developing nations, to achieve a stabilized and sustainable world. It is easy to be pessimistic about the prospects for an international initiative of this scale, but not long ago a massive disengagement of NATO and Warsaw Pact forces in Europe also seemed inconceivable. Disengagement now seems to me to be possible, even likely. Perhaps the resources such an agreement would free and the model of international cooperation it would provide could open the way to a world in which the greenhouse century exists only in the microchips of a supercomputer.

FURTHER READING

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