



INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE



UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION



INTERNATIONAL CENTRE FOR SCIENCE AND HIGH TECHNOLOGY

c/o INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS 34100 TRIESTE (ITALY) VIA GRIGNANO, 9 (ADRIATICO PALACE) P.O. BOX 586 TELEPHONE 040-224572 TELEFAX 040-224575 TELEX 460449 APH I

SMR.648 - 7

SECOND AUTUMN WORKSHOP ON MATHEMATICAL ECOLOGY

(2 - 20 November 1992)

"Climate Modeling"

S. Schneider
National Center for Atmospheric Research
P.O. Box 3000
Boulder, Colorado 80307-3000
U.S.A.

These are preliminary lecture notes, intended only for distribution to participants.

Climate Modeling

Will the "greenhouse effect" bring on another Dust Bowl? Would nuclear war mean "nuclear winter"? Computer models of the earth's climate yield clues to its future as well as to its checkered past

by Stephen H. Schneider

The earth's climate changes. It is vastly different now from what it was 100 million years ago, when dinosaurs dominated the planet and tropical plants thrived at high latitudes; it is different from what it was even 18,000 years ago, when ice sheets covered much more of the Northern Hemisphere. In the future it will surely continue to evolve. In part the evolution will be driven by natural causes, such as fluctuations in the earth's orbit. But future climatic change, unlike that of the past, will probably have another source as well: human activities. We may already be feeling the climatic effects of having polluted the atmosphere with gases such as carbon dioxide. The effects of a nuclear war would be far more dramatic.

How can human societies prepare for so uncertain a climatic future? Clearly it would help to predict that future in some detail, but therein lies a problem: the processes that make up a planet's climate are too large and too complex to be reproduced physically in a laboratory. Fortunately they can be simulated mathematically with the help of a computer. In other words, instead of building a physical analogue of the land-ocean-atmosphere system, one can devise mathematical expressions for the physical principles that govern the system—energy conservation, for example, and Newton's laws of motion—and then allow the computer to calculate how the climate will evolve in accordance with the laws. Mathematical climate models cannot simulate the full complexity of reality. They can, however, reveal the logical consequences of plausible assumptions about the climate. At the very least they are a big step beyond purely speculative "hand waving."

Mathematical models have been used to simulate the present climate—to study, for instance, the effects on the atmosphere of volcanic eruptions such as El Chichón. They are also helping to explain the evolution of past

climates, including those of the ice ages and the Cretaceous period (the final age of the dinosaurs). The accuracy of paleoclimatic simulations in turn lends confidence to workers who employ the same models to simulate future climates, and who in particular try to gauge the potential impacts of human pollution and of nuclear war. In this context climate modeling is emerging as a fundamental tool for assessing public policy.

Although all climate models consist of mathematical representations of physical processes, the precise composition of a model and its complexity depend on the problem it is designed to address. In particular they depend on how long a period of the past or future is to be simulated. Some of the processes that influence climate are very slow: the waxing and waning of glaciers and forests, for example, or the motions of the earth's crust, or the transfer of heat from the surface of the ocean to its deeper layers. A model designed to forecast next week's weather ignores these variables, treating their present values (the extent of ice coverage, for instance) as external, unchanging "boundary conditions." Such a model simulates only atmospheric change. On the other hand, a model designed to simulate the dozen or so ice ages and interglacial periods of the past million years must include all the above processes and more.

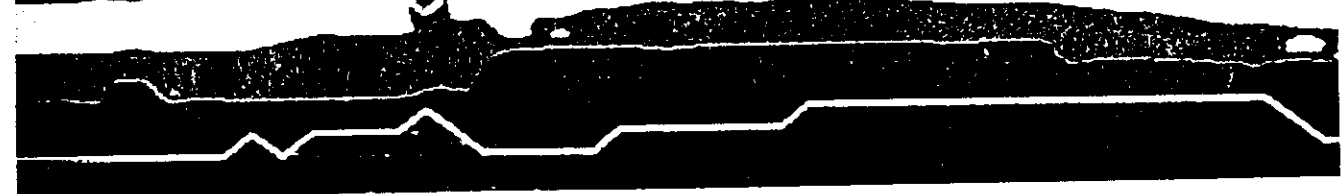
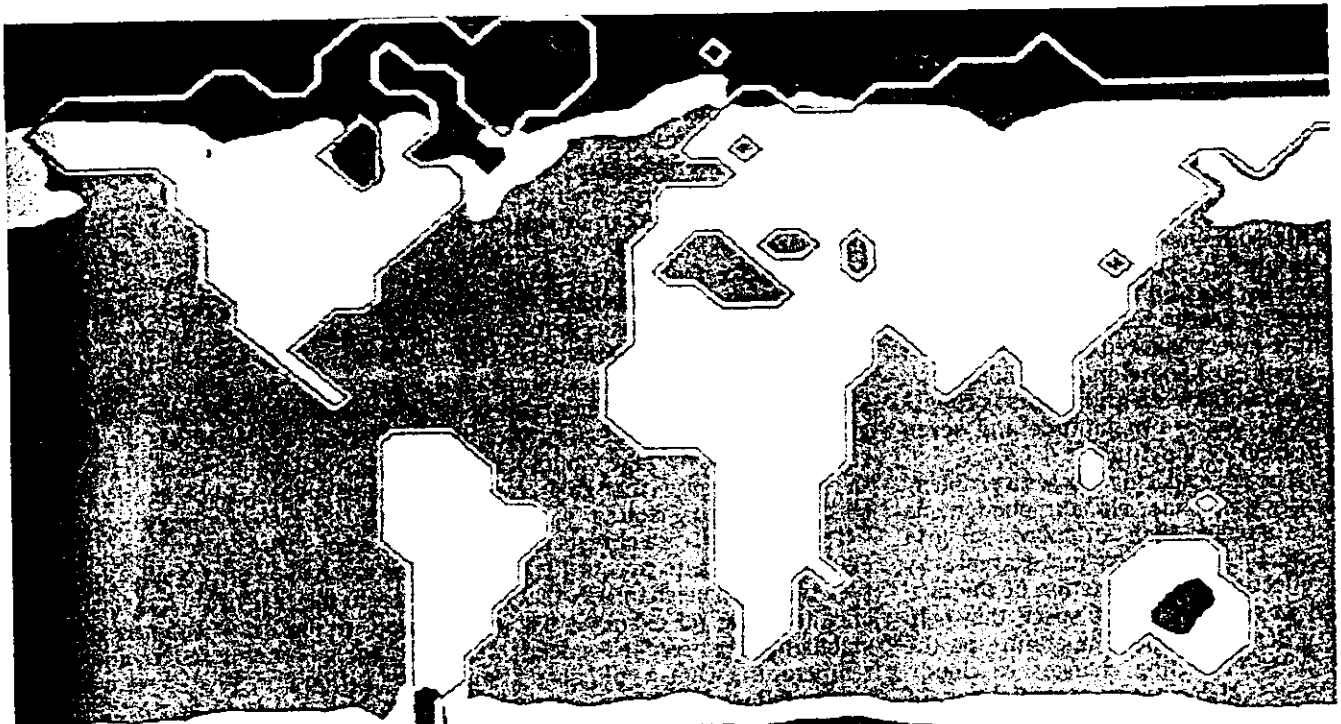
Climate models vary also in their spatial resolution, that is, in the num-

ber of dimensions they simulate and the amount of spatial detail they include. An example of an extremely simple model is one that calculates only the average temperature of the earth, independent of time, as an energy balance arising from the earth's average reflectivity and the average "greenhouse" properties of the atmosphere. Such a model is zero-dimensional: it collapses the real temperature distribution on the earth to a single point; a global average. In contrast, three-dimensional climate models reproduce the way temperature varies with latitude, longitude and altitude. The most sophisticated of them are known as general-circulation models. They predict the evolution with time not only of temperature but also of humidity, wind speed and direction, soil moisture and other variables.

General-circulation models are usually more comprehensive than simpler models in terms of the detail they include, but they are also much more expensive to design and run. The optimal level of complexity for a model depends on the problem and on the resources available to address it; more is not necessarily better. Often it makes sense to attack a problem first with a simple model and then employ the results to guide research at higher resolution. Deciding how complicated a model to use for a given task—in other words, at what level to trade completeness and accuracy for tractability and economy—is more a value judgment than a strictly scientific one.

Even the most complex general-cir-

NUCLEAR WAR in July would trigger widespread but transient "quick freezes" in the Northern Hemisphere, according to simulations by the author and Starley L. Thompson of the National Center for Atmospheric Research. The maps show model-computed surface temperatures (in degrees Celsius) on a normal day in July (*top*) and on the 10th day of a 10-day nuclear war (*bottom*). The simulation assumes that fires started by 6,500 megatons of bombs produced 180 million metric tons of sunlight-blocking smoke. Cooling is localized because the smoke is patchy and because it depends on local weather. Hence one simulation cannot forecast temperature for a given time and place; it can only convey types of change a nuclear war could cause.



5 to 10
0 to 5
<0

ulation model is sharply limited in the amount of spatial detail it can resolve. No computer is fast enough to calculate climatic variables everywhere on the earth's surface and in the atmosphere in a reasonable length of time. Instead calculations are executed at widely spaced points that form a three-dimensional grid at and above the surface. The model my colleagues and I at the National Center for Atmospheric Research use has a grid with nine layers stacked to an altitude of about 30 kilometers. The horizontal spacing between grid points is roughly 4.5 degrees of latitude and seven degrees of longitude.

The wide spacing creates a problem: many important climatic phenomena are smaller than an individual grid box. Clouds are a good example. By reflecting a large fraction of the incident sunlight back to space, they help to determine the temperature on the earth. Predicting changes in cloudiness is therefore an essential part of reliable climate simulation. Yet no global climate model now available or likely to be available in the next few decades has a grid fine enough to resolve individual clouds, which tend to be a few kilometers rather than a few hundred kilometers in size.

The solution to the problem of sub-grid-scale phenomena is to represent them collectively rather than individually. The method for doing so is known

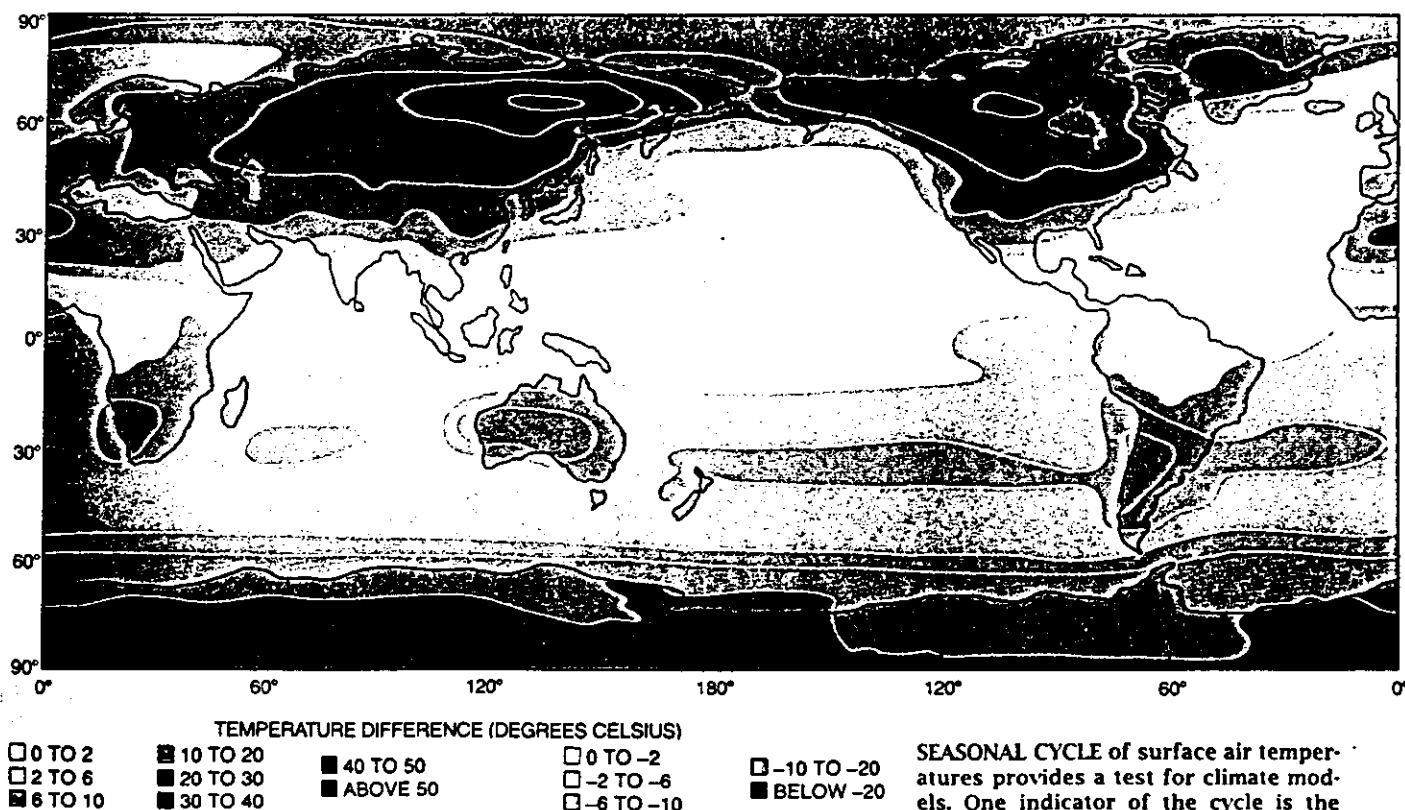
as parameterization. It consists, for example, in searching through climatological data for statistical relations between variables that are resolved by the grid and ones that are not. For instance, the average temperature and humidity over a large area (the size of one grid box, say) can be related to the average cloudiness over the same area; to make the equation work one must introduce a parameter, or proportionality factor, that is derived empirically from the temperature and humidity data. Since a model can calculate the temperature and humidity in a grid box from physical principles, it can predict the average cloudiness in the grid box even though it cannot predict individual clouds.

To fully simulate a climate the models must take into account the complex feedback mechanisms that influence it. Snow, for example, has a destabilizing, positive-feedback effect on temperature: when a cold snap brings a snowfall, the temperature tends to drop further because snow, being highly reflective, absorbs less solar energy than bare ground. This process has been parameterized fairly well in climate models. Unfortunately other feedback loops are not as well understood. Again clouds are a case in point. They often form over warm, wet areas of the earth's surface, but depending on the circumstances they may have either a stabilizing, negative-feedback

effect (cooling the surface by blocking sunlight) or a positive one (warming the surface further by trapping heat).

Uncertainty about the nature of important feedback mechanisms is one reason the ultimate goal of climate modeling—forecasting reliably the future of key variables such as temperature and rainfall patterns—is not yet realizable. Another source of uncertainty that is external to the models themselves is human behavior. To forecast, for example, what impact carbon dioxide emissions will have on climate one would need to know how much carbon dioxide is going to be emitted.

What the models can do is analyze the sensitivity of the climate to various uncertain or unpredictable variables. In the case of the carbon dioxide problem one could construct a set of plausible economic, technological and population-growth scenarios and employ a model to evaluate the climatic consequences of each scenario. Climatic factors whose correct values are uncertain (such as the cloud-feedback parameter) could be varied over a plausible range of values. The results would indicate which of the uncertain factors is most important in making the climate sensitive to a carbon dioxide buildup; one could then focus research on those factors. The results would also give some idea of the range



of climatic futures to which societies may be forced to adapt. How to respond to such information, of course, is a political issue.

Perhaps the most perplexing question about climate models is whether they can ever be trusted enough to provide grounds for altering social policies, such as those governing carbon dioxide emissions. How can models so fraught with uncertainties be verified? There are actually several methods. None of them is sufficient on its own, but together they can provide significant (albeit circumstantial) evidence of a model's credibility.

The first method is to check the model's ability to simulate today's climate. The seasonal cycle is one good test because the temperature changes involved are large—several times larger, on the average, than the change from an ice age to an interglacial period. General-circulation models do remarkably well at mapping the seasonal cycle, which strongly suggests they are on the right track. The seasonal test, however, does not indicate how well a model simulates slow processes, such as changes in ice cover, that may have important long-term effects.

A second method of verification is to isolate individual physical components of the model, such as its parameterizations, and test them against real data from the field. For exam-

ple, one can check whether the model's parameterized cloudiness matches the level of cloudiness appropriate to a particular grid box. The problem with this test is that it cannot guarantee that the complex interactions of many individual model components are properly treated. The model may be good at predicting average cloudiness but bad at representing cloud feedback. In that case the simulation of the overall climatic response to, say, increased carbon dioxide is likely to be inaccurate.

For determining overall, long-term simulation skill there is a third method: checking the model's ability to reproduce the climates of the ancient earth or even of other planets. The paleoclimatic simulations I shall describe below are intrinsically interesting as exercises in understanding the earth's history. As checks on climate models, however, they are also crucial to estimating its future.

One of the most successful paleoclimatic simulations to date was done by John E. Kutzbach and his colleagues at the University of Wisconsin at Madison. Kutzbach attempted to explain the warmest period in recent history: the climatic optimum that took place between about 9,000 and 5,000 years ago. During that period, judging from fossil and other geologic evidence, summer tempera-

tures on the northern continents were several degrees Celsius higher than they are now. In Africa and Asia the monsoons were more intense.

Kutzbach's simulation showed that the climatic differences could be explained by two small differences in the earth's orbit: a slightly greater tilt of its spin axis and the fact that it made its closest approach to the sun in June rather than in January, as it does now. Both these differences would have increased the amplitude of the seasonal cycle in the Northern Hemisphere. Nine thousand years ago the Northern Hemisphere received about 5 percent more solar heat during the summer and about 5 percent less during the winter than it does today. Because the summer temperature difference between land and sea was greater, the wind patterns were different and the monsoon rainfall was more intense.

Kutzbach's success was particularly encouraging to my colleagues and me at NCAR because he used the same basic three-dimensional model we do. Stanley L. Thompson and I applied the model to the problem of explaining the strikingly dissimilar climate that prevailed just two millennia before the climatic optimum. About 11,000 years ago the earth had emerged from the grip of the last ice age. Much of the warm-weather flora and fauna had begun to return to the northern lati-



difference between summer and winter temperatures. Here the observed temperature differences between August and February (left) are compared with the differences computed by

a three-dimensional model (right) devised by S. Manabe and R. Stouffer of the Geophysical Fluid Dynamics Laboratory. The model reproduces most features with remarkable accuracy.

tudes, particularly in western Europe. Then suddenly that part of the planet was struck again by a dramatic cooling of nearly ice-age intensity. The cold period lasted for almost 1,000 years; it is known as the Younger Dryas, after an arctic flower.

The cooling during the Younger Dryas was most intense in the North Atlantic region, particularly on the western coast of Europe and in England. The pattern suggests an oceanic cause. A number of paleoclimatologists, including William F. Ruddiman and Andrew McIntyre of Columbia University's Lamont-Doherty Geological Observatory, have argued that, ironically, the ultimate cause of the Younger Dryas was the rapid breakup of the European and North American ice sheets between 12,000 and 10,000 years ago. The breakup would have dumped a vast amount of fresh water into the North Atlantic. Since fresh water freezes more readily than salt water, the "meltwater spike" might have produced a broad cover of sea ice that would have blocked the northern leg of the Gulf Stream, which ordinarily warms northwestern Europe.

To test this hypothesis Thompson and I ran a simulation in which the surface of the North Atlantic to a latitude of 45 degrees was assumed to be frozen—not because we believe that was what happened during the Younger Dryas but as a way of determining the sensitivity of climate to sea ice. Our results support the hypothesis. During the summer the cooling effect of the frozen North Atlantic is felt primarily along the coast of Europe;

the dominant influence on inland temperatures is the sun. During the winter, however, when solar heating is reduced and when the Gulf Stream normally maintains an equable climate in western Europe by generating warm onshore breezes, the sea-ice cover leads to more widespread and severer cooling.

Other workers, notably a group at the Goddard Institute for Space Studies, have obtained similar results using different models. The temperature maps produced by the models are roughly consistent with the available geologic data. They even suggest where paleoclimatologists should dig for evidence that would further buttress the sea-ice hypothesis and the models too. The models predict, for instance, that a sea-ice increase would have had only a slight cooling effect during the summer in the Soviet Union; the Goddard model, which included the effects of the remnant European ice sheet, actually predicts warmer summers in the Soviet Union. These predictions could be tested by analyzing fossilized pollen to determine what kind of plants thrived in that region during the Younger Dryas.

In the middle of the Cretaceous period, about 100 million years ago, tropical plants grew in the mid-latitudes, in what are now the temperate zones. Alligators lived near the Arctic Circle, which like Antarctica appears to have been free of permanent ice. Sea levels were hundreds of meters higher. The evidence suggests that the temperature in the interiors

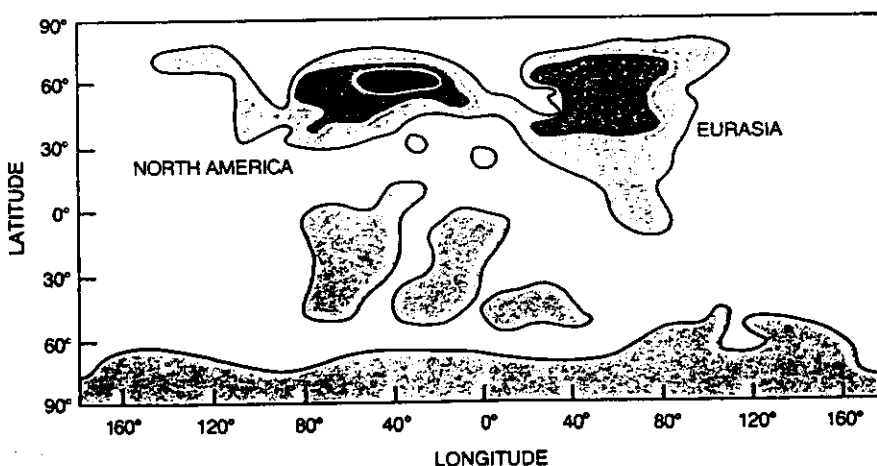
of continents usually remained above freezing even in winter.

What could explain such a warm era? One hypothesis is that heat transport by oceanic currents, which help to spread the excess solar energy received near the Equator around the earth, was more efficient in the Cretaceous. The continents then were in different positions, and so the ocean currents must have been different too.

Eric J. Barron, now at Pennsylvania State University, and Warren M. Washington of NCAR were the first to test this hypothesis with a three-dimensional climate model. They did not explicitly model the transport of heat in the ocean; instead they assumed that the sea-surface temperature everywhere was at least 10 degrees C., which implies a large poleward heat transport. They found that, contrary to the usual interpretation of the geologic evidence, the continental mid-latitudes still got cold in winter and the temperature fell well below freezing in the Antarctic. When Barron, Thompson and I ran a simulation incorporating a more extreme (and unrealistic) assumption—an ocean that transported heat with perfect efficiency, so that its temperature everywhere was a warm 20 degrees C.—the discrepancy between model and evidence got worse: the middle of the northern continents got even colder in winter.

Actually that is not surprising. By fixing the sea-surface temperature at a globally uniform 20 degrees, we had eliminated the temperature gradient between the Equator and the poles that is the chief driving force of the earth's atmospheric circulation. Consequently the winds in our model became too feeble to carry much heat onto the continents. In order to test adequately the hypothesis that enhanced oceanic heat transport produced the warm climate of the Cretaceous, we needed to devise a more realistic model.

Hence we did an additional set of simulations in which sea-surface temperatures were explicitly calculated but were never allowed to drop below 20 degrees C. even at the poles. With the temperature of the tropical oceans now between 25 and 30 degrees C., the model incorporated a substantial temperature gradient. Accordingly its winds were more vigorous. And yet, even though the model planet as a whole was considerably warmer than the real earth is today, it was not warm enough. Below-freezing temperatures were still widespread within the continents. Evidently the warm oceans and



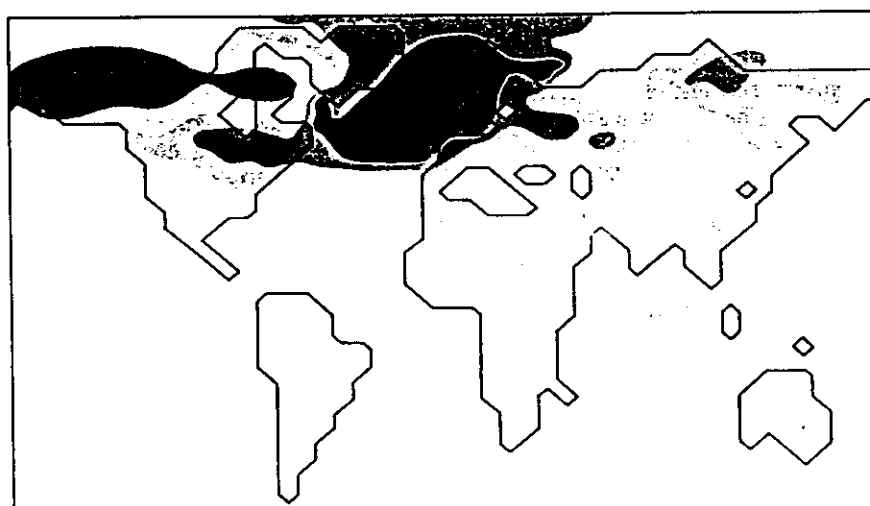
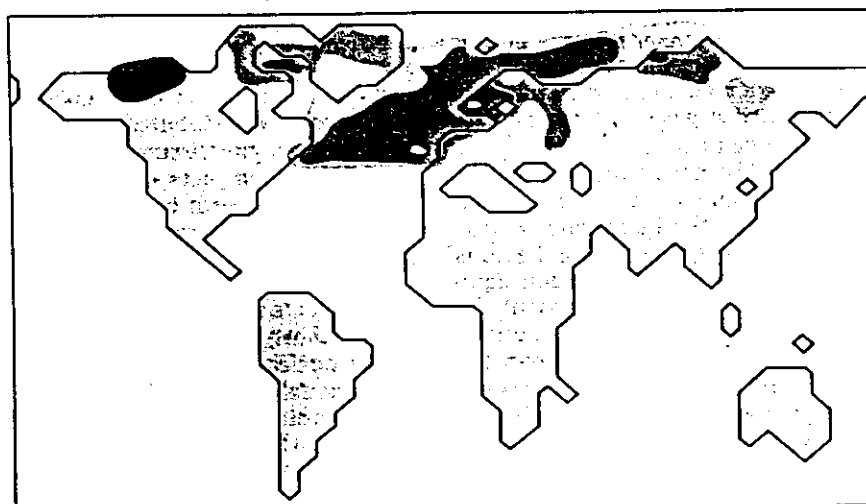
CRETACEOUS CLIMATE was warmer than today's, and fossil evidence suggests that temperatures on the northern continents remained above freezing even in winter. (The continents are shown in roughly the positions they occupied 100 million years ago.) The map attempts to model this warm climate by assuming that ocean currents transported more heat than they do now, so that the sea-surface temperature was at least 20 degrees Celsius. Under this extreme assumption the air temperature in January would still have dropped to almost the freezing point (light color) or even well below freezing (dark color) in North America and Eurasia.

enhanced heat transport we had hypothesized were still not enough to overcome the fact that in winter the continents receive little sunlight and radiate a lot of heat out to space.

My colleagues and I strongly suspect that some other mechanism must have helped to keep the Cretaceous climate warm. The best candidate, it seems to us, is an enhanced greenhouse effect due to the presence in the atmosphere of elevated levels of carbon dioxide. Recent geochemical models support this view. Carbon dioxide and other gases escape from the earth's interior, notably at mid-ocean rifts, where two of the plates that make up the earth's surface spread apart and molten rock rises into the gap. The mid-Cretaceous, most investigators agree, was an era of rapid plate motion, and so it should have been an era of high carbon dioxide emissions. The geochemical models suggest that the atmosphere then may have had between five and 10 times more carbon dioxide than it has now. In an extreme form the Cretaceous period may have foreshadowed the type of climate that human beings are in the process of creating today.

There is no doubt that the concentration of carbon dioxide in the atmosphere is rising; it is roughly 25 percent higher now than it was a century ago. It is also broadly accepted that when the carbon dioxide concentration rises, the temperature at the earth's surface must rise too. Carbon dioxide is relatively transparent to visible sunlight, but it is more efficient at absorbing the long-wavelength, infrared radiation emitted by the earth. Hence it tends to trap heat near the surface. That is the greenhouse effect. It explains the very hot temperatures on Venus (whose thick atmosphere is mostly carbon dioxide) as well as the frigid conditions on Mars (whose carbon dioxide atmosphere is very thin).

What is not certain is the precise amount of warming and the regional pattern of climatic change that can be expected from a significant increase in the atmospheric concentration of carbon dioxide and other greenhouse gases. (The cumulative effect of chlorofluorocarbons, nitrogen oxides, ozone and other trace gases could be comparable to that of carbon dioxide over the next century.) It is the regional pattern of changes in temperature, precipitation and soil moisture that will determine what impact the greenhouse effect will have on ecosystems, agriculture and water supplies.



TEMPERATURE CHANGE (DEGREES CELSIUS)
 ■ 5 TO 30 WARMER
 □ 5 TO 10 COLDER
 □ 10 TO 20 COLDER
 ■ 20 TO 30 COLDER

YOUNGER DRYAS was a period of dramatic cooling that began about 11,000 years ago, as the earth was warming up after the last ice age. The relapse, most intense along the northwestern coast of Europe, may have been triggered by the formation of a broad ice cover in the North Atlantic. The maps show NCAR simulations of the changes that would result if the surface of the Atlantic were frozen as far south as 45 degrees north. In summer (*top*) the cooling effect of the sea ice would be felt primarily along the coast; in winter (*bottom*) it would be more widespread.

A number of workers have attempted to model the possible climatic impacts of carbon dioxide. Most of them have followed the same approach: they give the model an initial jolt of carbon dioxide (usually doubling the atmospheric concentration), allow it to run until it reaches a new thermal equilibrium and then compare the new climate to the control climate. In one of the most widely cited results, Syukuro Manabe, Richard T. Wetherald and Ronald Stouffer of the Geophysical Fluid Dynamics Laboratory at Princeton University have found that both a doubling and a quadrupling

of atmospheric carbon dioxide would produce a summer "dry zone" in the North American grain belt, but that soil moisture in the monsoon belts would increase. The GFDL model reached its new equilibrium after several decades of simulated time.

In reality, however, the approach to equilibrium would probably be much slower. The GFDL model omitted both the horizontal transport of heat in the ocean and the vertical transport of heat from the well-mixed surface layer to the ocean depths. Both processes would slow the approach to thermal equilibrium; the real transi-

tion would probably take more than a century. Heat transport in the oceans would also affect the temperature response to a realistic, gradual increase in greenhouse gases, as opposed to the one-time injection.

In 1980 Thompson and I developed simple one-dimensional models that demonstrated the importance of the transient phase of warming. Regions at different latitudes approach equilibrium at different rates, essentially because they vary in their amount of land; land warms up faster than the oceans. Hence during the transient phase the warming and other climatic effects induced by the enhanced greenhouse effect could well display worldwide patterns significantly different from the ones inferred on the basis of equilibrium simulations. Furthermore, the social impact of climatic changes would probably be greatest rather early, before equilibrium has been reached and before human beings have had a chance to adapt to their new environment.

To represent the transient phase adequately one would need to couple a three-dimensional model of the atmosphere with a three-dimensional model of the ocean that includes the effects of horizontal and vertical heat transport. A handful of coupled models have been run, but they are still too uneconomical to simulate the next century, and they are also not yet

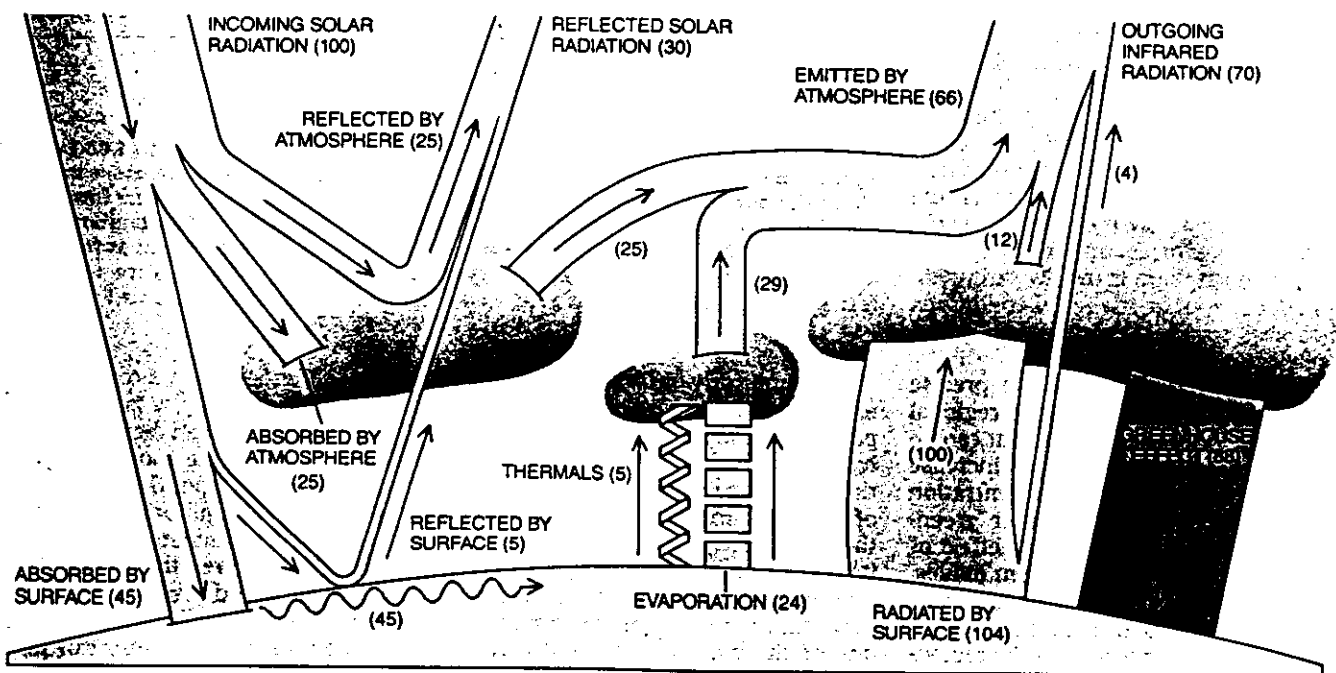
trustworthy enough. When they are improved, one will be able to state with more confidence how the impacts of rising levels of greenhouse gases might be distributed. Until then one can only cite circumstantial evidence that the impacts are likely to be significant: the earth is already more than .5 degrees C. warmer than it was a century ago.

Efforts to model the comparatively short-term climatic effects of a nuclear war do not share the ocean-model problems of the greenhouse studies, but those results too are laden with uncertainty. Since the first calculations were made in 1982 by Paul J. Crutzen of the Max Planck Institute for Chemistry in Mainz and John W. Birks of the University of Colorado at Boulder, it has been clear that smoke from the thousands of fires ignited by nuclear explosions might block a significant amount of sunlight. The first and best-known attempt to model the resulting changes in surface temperature was a study called the TTAPS study, after the names of its authors: Richard P. Turco, Owen B. Toon, Thomas P. Ackerman, James B. Pollack and Carl Sagan. The TTAPS study predicted that temperatures over land would drop between 20 and 40 degrees C. in the aftermath of a large but plausible war involving a 5,000-megaton nuclear exchange.

Since the cooling was projected to persist for many months, it seemed to justify the epithet "nuclear winter."

From the start the authors of the TTAPS study acknowledged deficiencies in their model. There were three major ones. First, the model ignored winds: it was a one-dimensional model that represented only the vertical structure of the atmosphere. Second, it ignored oceans: the predictions of cooling over land were made for an all-land planet and thus omitted the warming effect of heat carried inland from the oceans. Finally, the model ignored the seasons by using an annual average for the solar energy input. In short, the TTAPS study was a first-generation assessment whose conclusions were bound to be modified.

Some of the first modifications came from a study done by Curt Covey, Thompson and me using the three-dimensional NCAR model. As expected, we found that the oceans moderate the chilling effect of the nuclear smoke cloud. In mid-latitude, mid-continental areas of the Northern Hemisphere, the average temperature drop in our July simulation was about half the drop predicted by the TTAPS study; along western coasts the cooling was less by a factor of 10. Moreover, the temperature change showed seasonal dependence. The cooling was pronounced only if the nuclear war was assumed to take place in the



GREENHOUSE EFFECT arises because the earth's atmosphere tends to trap heat near the surface. Carbon dioxide, water vapor and other gases are relatively transparent to the visible and near-infrared wavelengths (blue) that carry most of

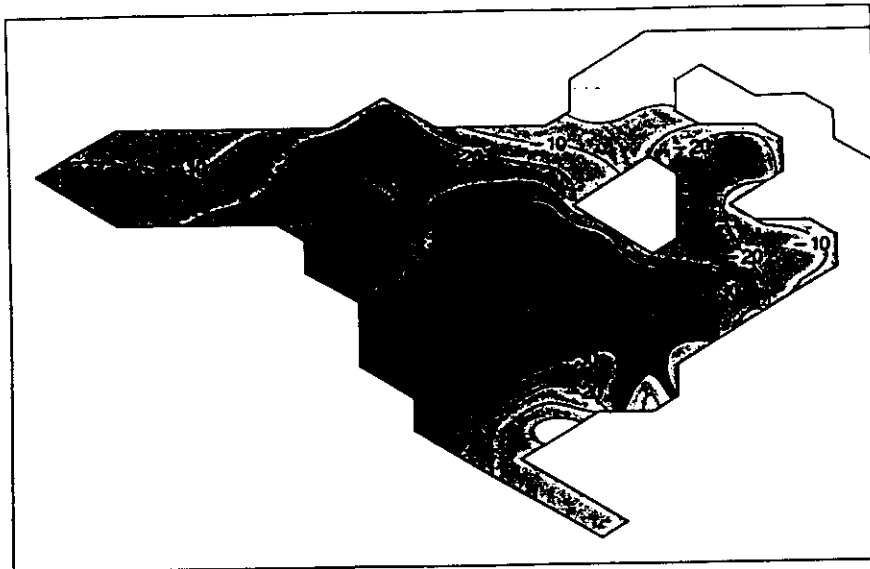
the sun's energy, but they readily absorb the longer, infrared wavelengths (red) emitted by the earth. Most of this energy is radiated back (dark red). Hence an increase in atmospheric concentration of greenhouse gases tends to warm the surface.

northern spring or summer. If the war were to start in the fall or winter, when northern latitudes receive little sunlight anyway, its climatic consequences would be relatively small.

Nevertheless, our most important finding was to confirm the basic TTAPS conclusion that the climatic effects of a nuclear war could be severe. Although the average decrease in temperature would be much smaller than the TTAPS study had predicted, our model showed that localized cooling could be dramatic. Even a few days of dense smoke high overhead could drop the surface temperature on land to near freezing in midsummer. Such transient "quick freezes" could strike anywhere in the war latitudes—in Texas, for instance—even if the overall size of the nuclear smoke cloud was several times smaller than the TTAPS group had assumed. The location of the quick freezes would depend on local weather conditions. Specifically, the freezes would strike wherever the air was not humid enough to produce ground fog and the winds were not strong enough to disrupt surface inversions (stable air layers). The war's climatic effects would thus be distributed by a kind of weather roulette.

More recent studies (by Thompson, by Michael C. MacCracken's group at the Lawrence Livermore National Laboratory and by Robert C. Malone's group at the Los Alamos National Laboratory) have confirmed our basic results. We had found localized freezes even though the limitations of our model forced us to assume that the initial smoke cloud would be uniformly distributed between 30 and 70 degrees north. In the later, more realistic simulations, the war generates thick, patchy clouds that carry freezing conditions with them as they drift around the Northern Hemisphere.

The most plausible of the recent calculations show an average temperature drop over land of between 10 and 15 degrees C. for a summer war. Elsewhere I have suggested that "nuclear fall" might be more appropriate than "nuclear winter" as a metaphor for such climatic changes, but in using that phrase I certainly did not mean to conjure up pleasant images of colorful autumn leaves. A nuclear fall in July could, as autumn does each year, end the growing season in much of the Northern Hemisphere. Even in areas where the temperature does not drop below freezing, the disruption of monsoon rainfall might have a disastrous effect on food supplies. Indeed, while refined climate models have been lowering the original estimates of a nu-



DOUBLING OF ATMOSPHERIC CARBON DIOXIDE would turn the Great Plains into a dry zone in the summer, according to a model devised by Manabe and Wetherald. The map shows the percentage change in soil moisture (from June through August) that would result once the model atmosphere reached a new thermal equilibrium.

clear war's cooling effects, a general awareness has been growing that the earth's biota can be highly sensitive even to small climatic disturbances.

Moreover, the climatic effects of a nuclear war might not be limited to the first weeks after it ended. Particularly in the summer some of the patchy smoke would tend to rise into the stratosphere, eventually producing a thin, fairly uniform veil that could cover the entire Northern Hemisphere for months. Some smoke would probably spread across the Equator as well. The veil could lead to abnormal killing frosts in the late spring or early fall. By slightly cooling the northern continents it might also cause a substantial reduction in the life-giving monsoon rains. In the aftermath of a nuclear war, present scientific knowledge suggests, the earth would not be consigned to the insects, and the human species would almost certainly not become extinct. But the climatic effects might nonetheless be calamitous, and they could extend the impact of the war to billions of people who live far from the blast zones.

That said, I do not want to minimize the uncertainties that surround all the nuclear-winter simulations. The accuracy of a climate model, as I have explained above, can never be proved conclusively; it can only be verified by circumstantial evidence, such as the model's ability to simulate past climates or the seasonal cycle. In the case of nuclear winter the greatest source of uncertainty lies not

in what the models include but in what they must leave out.

For example, no climate model can predict how much smoke there will be on the first day of a nuclear war or how high the plumes will rise; the values of such crucial variables have to be assumed. If the bulk of the smoke rises to an altitude of several kilometers, it will lie above most of the water vapor in the atmosphere, and the rate at which it is rained out will be slow. In that case the likelihood of severe, hemispherewide climatic effects would be high. Conversely, if smoke is washed out at a higher rate than most models have assumed, a climate disaster on a hemispheric scale would be much less likely.

The nuclear-winter issue illustrates a general point I want to stress again. Climate models do not yield definitive forecasts of what the future will bring; they provide only a dirty crystal ball in which a range of plausible fortunes can be glimpsed. They thereby pose a dilemma: we are forced to decide how long to keep cleaning the glass before acting on what we think we see inside.

The dilemma is perhaps less acute in the case of nuclear war, whose consequences would in any event be catastrophic, than it is in the case of atmospheric pollution. At present we are altering our environment at a rate that is too fast to understand the resulting climatic changes. If the trend does not stop, we shall eventually either verify or disprove the climate models—by means of a real, global experiment whose consequences we shall not escape.

