Modeling the Climate: A New Sense of Urgency

With famine in the drought-stricken regions south of the African Sahara and concern over the size of the U.S. grain crop, the economic and social consequences of even minor changes in climate are increasingly obvious. The world's food supply is now perilously dependent on good weather and prevailing climatic conditions. Abrupt changes in the length of the growing season, annual rainfall, or mean temperature could disrupt modern and primitive agricultural systems alike. Unfortunately, shifts in the earth's climate appear to be the rule rather than the exception.

When and in what direction the climate will change and what effect man's activities will have appear to be the pertinent questions. Hence attempts to understand what controls climatic processes and to construct models capable of predicting climate change have acquired an importance that is reflected in the new sense of urgency among the meteorologists, oceanographers, and other investigators who are involved.

Climatologists point to evidence that, compared to the norm of either the historical or the geological past, the earth's climate has for most of the past 50 years been unusually warm and benign. Sea ice records indicate that Iceland's mean annual temperature was as high or higher during this period than in the past 1000 years. Ocean sediments suggest that the current postglacial epoch is considerably warmer on average than anytime since the last interglacial period about 100,000 years ago. Other evidence establishes, however, that parts of Greenland were once green and fertile and that England was warm and sunny enough to permit the widespread cultivation of grapes—conditions far more favorable than those of the past few decades. Nonetheless, there does seem to have been a trend since 1945 toward cooler temperatures, particularly in the middle latitudes. Some climatologists, reasoning from the past to the future, have warned that a significant global shift in climate may be under way—a shift that could be the forerunner of a new ice age.

The difficulty in forecasting climatic change and in establishing whether a small change represents a trend or a random fluctuation is that climate appears to be the result of a delicate balance among many forces. Some factors, such as the amount of solar radiation reaching the earth, are external to the atmosphere-ocean system, while others, such as the extent of cloudiness, wind and current patterns, sea ice, and snow cover, are themselves affected by atmospheric and oceanic phenomena. There is general agreement among weather scientists that interactions among these many factors are not well understood. If there is reason to be skeptical of claims about the climate based on historical analogies, neither are models of the atmosphere and the ocean sufficiently advanced to allow forecasting of even gross changes in climate. New interest and new activity in modeling the climate, however, have led to better insights into the mechanisms that control the climate, including such immanently practical features as the strength of the Indian monsoon rains and the drought in the sub-Saharan plains. The quickened pace of research has, in fact, given rise to hopes of at least limited attempts at short-range climate forecasting in coming years.

Experiments with Monsoon Rains

At present the research is divided between large, computerized models (known as general circulation models) which attempt to simulate atmospheric motions over the entire globe in some detail and smaller, less comprehensive models of particular processes. General circulation models are so complex that it is often difficult to single out the effects of a particular mechanism, but a good example of what can be done with these models is a numerical experiment conducted by J. Shukla of the Massachusetts Institute of Technology. Using a model developed by S. Manabe and his colleagues at the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, New Jersey, Shukla explored the effect of anomalously cold sea-surface temperatures in the Arabian Sea on the monsoon rains in India. During the summer monsoon season a strong flow of air, known as the Somali jet, flows northward over the eastern coast of Africa and the neighboring reaches of the Indian Ocean. At the same time a northward-moving ocean current, the Somali current, comes into being off the east African coast. Associated with the current is an upwelling of cold water which spreads over much of the Arabian Sea during the peak monsoon months, reducing sea-surface temperatures by about 3°C and sometimes by as much as 10°C. Shukla prescribed this sea-surface temperature change and compared the results of the model with and without this effect.

Shukla found that, in the weather patterns simulated by the model, the sea-surface temperature anomaly had the effect of decreasing the rate of evaporation and the intensity of the northward-moving winds over the Arabian Sea. The result was a reduction in the flux of moisture toward the Indian subcontinent and a sharp decrease in rainfall over India and adjoining areas. In addition, Shukla showed that the differences in the model response with and without the temperature anomaly were statistically significant and not just the result of natural fluctuations in the simulated atmosphere. The experiment does not prove that cold sea-surface temperatures off the African coast cause the failure of the monsoon rains, because other mechanisms that may contribute were not specifically investigated and the response of the ocean to changing wind patterns was not simulated. It does suggest, however, that the region of the Somali current will be important to monitor during a forthcoming field study in the region, and it represents an important step toward understanding a phenomenon on which the food supply of more than half a billion people depends.

Similar studies of the effects of sea-surface temperature anomalies are being conducted with other general circulation models. At the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, for example, Warren Washington and his colleagues are looking at anomalies in the North Pacific and their possible connection with weather patterns over the United States (*Science*, 7 June, page 1064). The NCAR scientists find that simulated weather patterns over the North Pacific itself do seem to show the effects of changes in sea-surface temperature, but they have not yet found any statistically significant effects downstream, over the United States.

Another pertinent numerical experiment, suggested by Jule Charney of the Massachusetts Institute of Technology, is being conducted with a general circulation model at the Goddard Institute of Space Studies (GISS). Charney has proposed that, because deserts have a higher albedo (reflect more of the sun's radiation) than does soil covered by vegetation, they induce sinking motions in the atmosphere which serve to enhance the dryness of the desert climate—in essence that deserts, once started, feed back on themselves. Thus local changes in albedo, whether of natural or man-made origin, might cause substantial local changes in climate. Charney believes that this mechanism may have particular relevance to the current drought in the southern margin of the Sahara, the Sahel, which in summer is largely isolated from global weather patterns that might otherwise contravene the effect.

There is evidence that overgrazing in arid regions can cause large increases in the surface albedo, and hence possibly trigger the onset of desert-like conditions and drought. In the GISS numerical experiment, an increase in albedo of about 0.2 was specified for the Sahel and the effects on the simulated weather patterns were noted. Preliminary results, according to Charney, include a 40 percent reduction in rainfall and cloud cover in the region, consistent with the proposed mechanism. Whether this is indeed the main cause of the Sahelian drought, as Charney suggests, will have to await further work, but the findings do serve to point out the potential importance of biogeophysical feedbacks in establishing climate.

In addition to particular applications, the models themselves are gradually being improved. Among the more important developments with general circulation models is the recent demonstration by both the GFDL and GISS groups that their models are capable of simulating seasonal changes, which are just climate changes on a short time scale. Other efforts are directed to constructing general circulation models of the oceans—a problem that is still far from resolution—which could then be coupled with the atmospheric models. Still other researchers have focused on finding better ways to model the effects of phenomena, such as cumulus clouds, which are too small to appear explicitly in a general circulation model.

The existing models, however, have a number of limitations. Foremost among these is the almost prohibitive amount of computer time required to simulate atmospheric phenomena over the time scales of interest in climate studies. The version of the GFDL model used by Shukla, for example, is global in extent and has 7140 grid points (with a spacing of about 270 kilometers between grid points) at each of 11 separate levels. With each time step of the model, new values for a variety of functions must be computed at each grid point. About 1 or 2 hours of computing is required to simulate a 24-hour day with most general circulation models, and they are thus limited with existing computers to experiments involving periods up to a few years. Smaller one- and two-dimensional models (requiring usually 1 minute or less to simulate a 24-hour day) must be used for studies of long-range climate change.

The computer-time constraints of the larger models are exacerbated by a statistical limitation recently pointed

Speaking of Science

Skunks: On the Scent of a Myth

He was crossing the road, late one night;
He didn't look left, and he didn't look right;
He didn't see the station wagon car;
The skunk got squashed, and there you are,

You've got your dead skunk in the middle of the road,
Dead skunk in the middle of the road,
Dead skunk in the middle of the road,
*Stinkin' to high heaven.**

For ages, it seems, biology textbooks have been telling us that the peculiar odor of the American striped skunk, either squashed or scared, is produced by *n*-butyl mercaptan. But like many another piece of folklore, as another song says, "It ain't necessarily so." In fact, according to Kenneth K. Anderson and David T. Bernstein of the University of New Hampshire, Durham, the striped skunk (*Mephitis mephitis*) doesn't even have *n*-butyl mercaptan. Instead, they last week told the 168th national meeting of the American Chemical Society, the main components are crotyl mercaptan, isopentyl mercaptan, and methyl crotyl disulfide, in the ratio of 4 to 4 to 3.

Anderson is a sulfur chemist with an interest in chemical ecology and communication among animals; he also has a rather puckish sense of humor. Bernstein was a graduate student with the need for a thesis topic. Together they decided that it would be interesting—and fun—to check the work of the late Thomas Bell Aldrich of Johns Hopkins University, who in 1897 first suggested that *n*-butyl mercaptan was the offending substance.

They first tried trapping the skunks themselves but, perhaps luckily, they succeeded in capturing only "a few pussycats." After it was later pointed out to them that skunks carry rabies, and not wanting to take their work home with them, they decided that it would be more discreet to obtain their raw materials from a friend who raised skunks. After that, it was simply a matter of putting the material through a gas chromatograph, obtaining a few spectra, and making some derivatives.

Their findings scarcely represent a major change in the order of things, since the only difference between *n*-butyl mercaptan and crotyl mercaptan is a double bond. But they do have a possible use. Every year, Anderson says, veterinarians and dog owners are plagued by dogs who have met a skunk from the wrong end. Now that the chemical constituents have been properly identified, he adds, it might be possible to develop a chemically sound method to de-scent them. Tomato juice, the traditional remedy, will have to move aside.

—THOMAS H. MAUGH II

* From: "Dead Skunk" by Loudon Wainwright III. © 1972, 1973, Frank Music Corporation. Used by permission.

out by Cecil Leith of NCAR. In order to fully establish the statistical significance of a particular numerical experiment, many repetitions with randomly varying initial data are required—in essence a determination of the climatology of the model—so that particular results can be compared against the average behavior of the simulated weather patterns. This statistical limitation, some investigators believe, may raise the amount of computer time needed by a factor of 10.

Size and computing time are not the only problems. In a review of climate models, Stephen Schneider and Robert Dickinson of NCAR observe that most general circulation models simulate the atmosphere in great detail but treat its interaction with the solar flux, the oceans, and the earth's surface much more crudely. No models, for example, simultaneously calculate the distribution of clouds and sea-surface temperature; instead one or more of these features are specified in the model on the basis of climatological data. This may not be a severe limitation, Schneider and Dickinson believe, for very short range climate predictions (a few weeks to a few months), the period for which they believe general circulation models are ideally suited and which may also be of the greatest social and economic importance. The models also have an important role, they believe, in testing simpler models.

Smaller models need not be at a disadvantage compared to general circulation models for simulating gross climatic features, according to Peter Stone of the Massachusetts Institute of Technology, even though they do not explicitly include all details of atmospheric motions. Much of the atmospheric transport of heat toward the poles is due, in mid-latitudes, to large atmospheric eddies that appear on the weather map as high- and low-pressure systems. This heat transport is climatologically important, since, along with other dynamic processes, oceanic heat transport, and radiative processes, it effectively determines the temperature at the earth's surface. Stone and, independently, J. Green of the Imperial College, London, devised methods of calculating this transport without simulating the eddies themselves.

Stone has compared the calculated heat fluxes to those produced by general circulation models and to observational data, and he finds them qualitatively and quantitatively similar. More significantly, he finds that the eddy fluxes have a strong negative feedback. In response to changes in external climatic forces, Stone believes, the eddies act to increase or decrease the heat transport in such a way as to maintain the stability of the atmosphere, limit its response to the new conditions, and hence inhibit climate change.

Not all climatic processes are stabilizing, however. W. Sellers of the University of Arizona and, independently, M. Budyko of the Main Geophysical Observatory, Leningrad, have modeled the effect of albedo changes due to variations in the ice and snow cover on the earth's surface. They find a positive feedback in response to external changes. According to their models, very small changes in the earth's energy budget, such as a decrease in the sun's output of heat, might increase the ice cover, which would reflect more sunlight back into space and cool the earth still further, leading eventually to an "ice catastrophe"—an ice-covered earth—if not mitigated by other mechanisms.

Other specific mechanisms remain to be investigated. The oceans, for example, are thought to be a stabilizing influence on climate because they undergo change on a time scale about 100 times as long as that of the atmosphere. The uppermost layer of the ocean, however, may have a much shorter time scale and may act to drive change. Because of growing evidence that sea-surface temperature anomalies play an important role in climate over short time periods, there is growing belief that investigations of the upper layer of the oceans ought to have a high priority. Thinking about the climate is a relatively new business for oceanographers, however, and despite pressure from their meteorological colleagues many believe that global monitoring and modeling of the oceans—a necessity for realistic predictions of more than a few years at a time—is simply beyond the present capacity of the field.

However limited at present, climate modeling appears to be the only way to go. Climatic processes, in the opinion of many scientists, are simply too complicated and too interrelated to be amenable to casual analysis. More deductive tests of climate mechanisms, such as models provide, are consequently to be preferred, they believe, to inductive reasoning based on past events. Indeed, for assessing man's impact on climate, there is no alternative to models. And, it would appear, modeling efforts are not far from adding greatly to the understanding of climatic phenomena of no little practical interest.—ALLEN L. HAMMOND

Planetary Science: First Meeting on Moons of the Solar System

The great age of planetary satellites was the 17th century, when the four largest moons of Jupiter were discovered by Galileo and the major satellites of Saturn were discovered by Huygens and Cassini. In the 300 years since then, the moons have been for the most part neglected. But in the last 3 years new observations from the ground and spacecraft have renewed astronomers' interest. Last month, when 150 scientists met at Cornell University, Ithaca, New York, for the First International Conference on Planetary Satellites, it seemed clear that the subject of satellites had become almost as important as the subject of planets.

While most of the efforts of the U.S. space program has been directed toward the earth's moon, which appears to be a unique object with a complex origin, it was not a principal topic of the conference. The two tiny moons of Mars, Phobos and Deimos, were discussed at more length because Mariners 7 and 9 had obtained good pictures of them and raised questions about their composition—whether it is basalt or carbonaceous chondrite. But most of the conference was devoted to the satellites of the outer planets, particularly Jupiter, Saturn, and Uranus. The larger moons of these planets are found in systems with such regular orbits that they look almost like miniature solar systems. Among the 12 moons of Jupiter, the 10 moons of Saturn, and the 5 moons of Uranus, at least 4 of the number for each planet have nearly circular orbits that lie almost in the same plane. The densest Galilean moons of Jupiter are found nearest the center of the satellite system, which is similar to the distribution of the planets from the sun. Perhaps the three satel-