tivity of the enzyme adenyl cyclase, thereby increasing cyclic AMP synthesis. The name of the game became cyclic AMP, and many workers realized that cyclic AMP might explain how their particular pet hormone might work.

As unicellular organisms evolved into the greater complexity of multicellular life, individual cells began to communicate with each other by chemical signals, such as hormones, and also by developing a nervous system. One problem that has occupied many endocrinologists is how hormones instruct their target tissues to perform their specialized functions. One of Sutherland's contributions is that he has made possible a unifying concept of the mechanism of hormone action. Hormones could be considered as first messengers leaving their site of synthesis and circulating to their target tissues, where they are recognized by specific receptors. Sutherland suggested that, after the hormone combined with receptor, the activity of adenyl cyclase present in the cell membrane increased and the common "second messenger" cyclic AMP was generated inside the cell, where it could stimulate cyclic AMP-sensitive enzymes already present in the tissue to carry out their specialized functions.

Sutherland established a set of criteria to be met to show that a hormone worked through the cyclic AMP system. He indicated that a hormone should increase cyclic AMP levels in tissue, that it should increase the activity of adenyl cyclase, and finally that cyclic AMP itself added to the tissue should mimic the action of the hormone. Unfortunately, cyclic AMP does not readily enter many cells. Theodore Posternak, while visiting Sutherland's laboratory, synthesized a number of cyclic AMP analogs. The most famous of these is dibutyryl cyclic AMP, which appears to enter cells more readily than cyclic AMP itself, because its lipophilic nature allows it to penetrate cell membranes. Thus, if cells treated with dibutyryl cyclic AMP show the same response as cells treated with an appropriate hormone, then this is strong evidence that the hormone works through the cyclic AMP system.

Earl W. Sutherland, Jr.

Cyclic AMP has been found to explain many puzzling biological phenomena. Cyclic AMP acts directly at the gene level in *Escherichia coli* and other bacteria to promote synthesis of many inducible enzymes and even flagella, and the well-known ability of glucose to repress the synthesis of various inducible enzymes in *E. coli* is due to its ability to lower cyclic AMP. Cyclic AMP is a signal for amoebas to aggregate in what constitutes a primitive form of differentiation; cyclic AMP controls the activity of brain cells; and alterations in cyclic AMP metabolism appear to be responsible for some of the altered properties of cancerous connective tissue cells.

One of the most impressive aspects of Sutherland's contribution is that it is truly unique. Today, important discoveries are often made simultaneously in different laboratories. In the case of Earl Sutherland, the rest of us were years behind.

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RESEARCH TOPICS

Global Meteorology (II): Numerical Models of the Atmosphere

Weather in much of the Northern Hemisphere is now routinely forecast for periods up to 72 hours, and fortunately so, because modern man is increasingly dependent on weather information. And while forecasts are often imperfect, they and the computer models on which they are based do predict the weather more accurately than was possible before their advent. Reliable long-range forecasts (from a few days to 2 weeks) would be even more useful, and understanding of average weather patterns on the still longer time scale of several years might help to resolve the question of whether man is inadvertently altering the climate.

Meteorologists have been developing sophisticated models of the atmosphere as one method of coming to grips with these problems, and in recent years they have been conducting numerical experiments with these models to investigate the feasibility of long-range prediction of the weather and simulation of the climate. They have already obtained some interesting results. But achievement of these goals seems to await a better theoretical understanding of meteorological processes, more detailed observational data on the weather, and still faster computers.

Numerical modeling of the weather has always been intimately involved with electronic computers. Among the earliest applications of the first modern computer—built at the Princeton Institute for Advanced Study and completed in the early 1950's—was to the problem of weather prediction. Despite the use of a very simplified atmospheric model, these early attempts—by John von Neumann and Jule Charney—proved so successful that operational use of the technique for weather forecasting began as early as 1954. Since that time the scale and complexity of atmospheric models have increased by several orders of magnitude.

Current operational models, such as that used by the National Meteorological Center of the U.S. National Weather Service, compute wind velocities and temperatures at six levels in the atmosphere with a horizontal resolution of about 300 kilometers. Basically similar although somewhat specialized models are used by the Navy and Air Force. More elaborate research models, such as those developed at the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, New Jersey, or the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, use even finer computational grids involving, in some applications, as many as 18 vertical levels and horizontal resolutions as small as 130 kilometers.* Research groups in England, in the U.S.S.R., and in France are also actively developing such models.

The enormous scale of these models is indicated by the time required to process them with current computers—from a few hours to most of a day, with the largest models, to calculate a 24-hour forecast. Moreover the num- of observations that would be required to describe the atmosphere in this detail, for prescribing initial data or checking model predictions, is not yet available. Nonetheless, many significant atmospheric phenomena, including the details of local weather situations, are so small that they cannot be included directly in present models.

Long-Range Weather Prediction

Atmospheric models are being used both to improve weather prediction and to design a global observational system for that purpose. The consensus among most meteorologists seems to be that present research models provide some information about the weather for as much as 5 days in advance, but that accurate long-range forecasts for even this period are still not possible. Nor is it clear whether the limiting factor is (i) the quantity and quality of observational data needed as input to the model, (ii) the computational grid that is used (and that could be made still smaller when faster computers are available), or (iii) the representation of physical processes in the models. Numerical experiments are being conducted to examine each of these possibilities, but meteorologists agree that much more extensive observational data will be necessary to adequately test the models. Meteorologists are planning a global experiment with a target date of 1976 to obtain this data on a worldwide basis and to test the requirements for future international observing networks as part of the Global Atmospheric Research Program (GARP).

Observational experiments in the atmosphere are costly and logistically complicated. By comparison numerical experiments with computers are much easier to carry out. One question being studied with numerical experiments is the extent to which atmospheric motions are predictable. Meteorologists believe that the atmosphere is, in principle, a deterministic system. But because of the nonlinear character of atmospheric dynamics and the instabilities inherent in atmospheric processes, small errors—whether introduced by observational limitations or by the finite difference approximations that are used in numerical models—are known to grow as the integration of a model proceeds. Hence the effects of even small errors will eventually influence the large-scale features of any model atmosphere. Early numerical experiments by Jule Charney of the Massachusetts Institute of Technology and others indicated that the limit of predictability was about 2 weeks. In these experiments, a prediction was made with a simplified atmospheric model; small random errors were then added to the initial conditions and the calculations were repeated. When the two predictions were compared, they showed good agreement for about a week but only random agreement after about 2 weeks.

More recent predictability experiments by Robert Jastrow and Milton Halem at the Goddard Institute of Space Studies in New York using a model developed by A. Arakawa and Y. Mintz of the University of California at Los Angeles showed that the rate of growth of errors was even faster—and hence the time limit of predictability was even shorter—in models with a smaller grid spacing. But other experiments have shown that the exact rate of growth varies from one model to another; experiments by Joseph Smagorinsky of GFDL with a more sophisticated model indicate that the time limit of predictability is at least 2 weeks. Since the experiments involve the comparison of model predictions to each other, rather than to the real atmosphere, the question is not yet settled.

Some comparison of model predictions with observational data have been done, however. In experiments at GFDL, Kikuro Miyakoda has shown that models with extremely fine grid spacing, despite their more rapid propagation of errors, result in a more realistic atmosphere and a substantially better prediction. As a result, some meteorologists believe that the practical limit of predictability will be about 10 days.

Only a few attempts at long-range global forecasts from observed data have been made because of the scarcity of such data on a global scale. Except for a few specially collected data sets, information from the Southern Hemisphere and from the tropics is not still available in sufficient detail. As part of the GARP effort, atmospheric models are being used to help design an observing system that can gather the required data. Numerical experiments are being done to answer questions about the amount and type of data that are most useful, about the effect on predictability of observational errors in the data, and about the methods by which data are to be incorporated into models.

Meteorologists are investigating, for example, the possibility that wind data are not necessary and that only temperature and sea surface pressure measurements are needed throughout much of the atmosphere. In the conventional meteorological network, both temperatures and wind velocities are reported at fixed intervals. Polar orbiting satellites with infrared observing systems (see *Science*, 18 June 1971, p. 1222), on the other hand, can generate temperature data continuously over what in the course of several orbits is a far larger region. Numerical experiments by Charney and by Halem and Jastrow have indicated that temperature data alone might be sufficient. In their experiments a model case history was first established and then recomputed without the initial wind data but with the "correct" temperature data inserted into the model at regular intervals. Later experiments by A. Kasahara and D. Williamson at NCAR confirmed these results for a more elaborate model and also showed, in the reverse experiment, that the temperature field could be constructed by updating only the wind velocities. The NCAR scien-

* The GFDL is part of the National Oceanic and Atmospheric Administration; NCAR is operated by the University Corporation for Atmospheric Research with funding from the National Science Foundation.

tists found, as expected, that temperature data were preferable in northern and southern latitudes. In the tropics, however, the situation is more complicated, and recent simulations of observing systems by GFDL scientists indicate that wind data will be necessary.

The effects of experimental errors were also simulated in these and other experiments. By incorporating small errors (as compared to the "correct" values from a control case) into the data that was inserted into the model, the scientists found a small, but noticeable effect. A random temperature error as large as 1°C, for example, resulted in slower regeneration of the winds with slightly higher residual errors. But only preliminary work has been done on the problem of continuous updating—the so-called four-dimensional data assimilation problem—that must be solved before satellite data can be readily incorporated into operational models.

Simulation of Climate

Global atmospheric models are also used in an attempt to understand the physical basis of climate. Studies of climate are concerned with variations in meteorological conditions over periods of many years, rather than the short-term variations that constitute weather. In numerical experiments designed to simulate climatic conditions, the models are integrated until they reach statistical equilibrium—a process that takes about a year (on the simulated time scale) for models that include the stratosphere. Transient motions are ignored, and because of the long time periods involved, the initial data set does not influence the equilibrium that is finally obtained. Experiments of this type appear to reproduce typical conditions, and to differentiate, for example, between winter weather patterns and those common in summer.

In experiments at NCAR by Warren Washington and others, these seasonal transitions are produced by changing the model parameters that represent the angle at which the sun's radiation hits the atmosphere and the surface temperatures of the ocean. A fixed distribution of ocean surface temperatures is used, but the distribution is changed monthly to correspond to the climatic average. Among the phenomena that can be studied with seasonally varying models is the flow of moist air across the equator in summer months that is characteristic of the Indian monsoon.

Similar results have been obtained by Syukuro Manabe at GFDL, and a new series of experiments aimed at understanding the annual variability of the atmosphere (why one January differs from another) and the dispersion of inert tracers in the atmosphere are under way. Experiments are also planned to explore the interaction of the atmosphere and the oceans. Scientists have known for some time that the atmosphere and the oceans are strongly coupled and that their interactions have important influences on climate. Wind stress exerted on the ocean surface by the atmosphere helps to drive the major ocean currents, for example, which in turn influence the temperature distribution of the ocean surface and hence the pattern of the weather. Preliminary experiments have been done at GFDL to test the feasibility of climatic simulation with a joint atmosphere-ocean model by Manabe and Kirk Bryan.

Despite a lack of information about oceanic processes, oceanographers have constructed a number of models of the circulations within ocean basins. The GFDL experiment, however, is the first instance in which such a model has been run in tandem with an atmospheric model. The attempt illustrates some of the difficulties involved in simulating climatic processes. The temperature of the ocean surface layers provides an input to the atmospheric model, which in turn computes the supply of heat, momentum, and water (from precipitation and runoff) for the ocean model. But owing to greater heat capacity and the resultant thermal inertia of the oceans, the oceanic model requires several hundred years to come to equilibrium, compared with about 1 year for the atmospheric model. The atmospheric model, on the other hand, is more complicated and requires approximately 40 times more computation than does the oceanic model for an equivalent time step. And in the experiments, the joint model did not attain a complete equilibrium. Nonetheless, according to Manabe and Bryan, it did indicate the role of the ocean currents in changing atmospheric temperature, humidity, and precipitation patterns, and the feasibility of simulating the joint ocean-atmosphere system. More elaborate experiments, with global models, are now in preparation.

One reason for studying the climate is a concern that man's activities may contribute to undesirable climatic changes. But a crucial feature in climatic simulations is the way in which the various physical processes that control the addition of energy to the atmosphere are modeled. Knowledge of these processes is still incomplete—the details of heat and moisture transport at the air-sea interface, for example, are the subject of considerable ongoing research. Other important climatic influences, such as the extent of ice and snow cover at each pole, are also poorly understood; for these reasons meteorologists believe that it is not yet possible to do definitive numerical experiments. Natural variations in the climate, for example, appear too large, and, according to Smagorinsky, director of GFDL, these variations would tend to obscure man's effects on the climate in simulations with present models.

Smagorinsky believes that the development of still better atmospheric models for both weather prediction and climate simulation depends on finding more accurate methods of representing the cumulative effects of physical processes too small to include explicitly in the models; "progress," as he put it, "means dealing more cleverly with small scale processes." Among the problems to be solved are the microphysics and dynamics of individual clouds, overall cloud cover, the effects of small air-borne particles on radiative transfer, and clear air turbulence. The distribution of cloud cover, for example, is related in some models to the distribution of humidity and in others to the vertical velocity. Accuracy is important because meteorologists believe that clouds, depending on their altitude, could have either a net cooling or a net warming effect on the climate. Clear air turbulence, which is sometimes encountered by aircraft downwind of mountain ranges and in the vicinity of the jet stream, is believed by some to play an important role in the transport of energy within the atmosphere, but it is not known how this phenomenon is related to large-scale weather patterns. Atmospheric dust, including that from man's activities, may potentially have important effects on the radiation balance of the atmosphere and hence on the climate, but these effects are not included in present models.

Despite these problems, numerical models have helped to improve prediction of the weather and to advance our understanding of the climate. Their continued development, along with analytical and observational studies of these complex phenomena, offers encouraging prospects for the future.

—ALLEN L. HAMMOND