Hurricane Prediction and Control: Impact of Large Computers

This is the third is a continuing series of articles on natural disasters, their prediction and modification, and progress in understanding the physical bases of these phenomena. Two earlier articles (Science, *25 May, p. 851, and 1 June, p. 940) reported advances in earthquake prediction. Hurricanes are the subject here. Generally less devastating than major earthquakes—although a single hurricane in 1970 killed an estimated 200,000 persons in Bangladesh—these storms are still the most destructive of all atmospheric phenomena. A recent report of the National Academy of Sciences (see box) recommends that efforts to modify hurricanes and other severe storms become a national goal.*

Weather satellites each year track about 100 small disturbances—dust clouds leaving Africa, rain squalls originating near the equator—in the atmosphere over the tropical Atlantic. About ten of these disturbances grow into tropical storms, and five or six reach the size (hundreds of kilometers across), degree of organization, and intensity (peak winds ranging from 33 to more than 90 meters per second) characteristic of hurricanes. During the 1960's hurricanes caused an average of 50 deaths and $420 million property damage annually in the United States, and their destructiveness is increasing as more and more houses and marinas are built in vulnerable coastal areas.

In recent years satellite coverage of the regions in which hurricanes form has improved, making it easier to locate these storms and follow their movements; and there has been considerable progress in understanding the physics of these potent atmospheric phenomena. But predicting where a hurricane will go is still an inexact science at best, and modifying these storms to reduce their peak winds remains an uncertain prospect. The most promising development seems to be a new generation of numerical models that may improve prediction and may help to resolve questions about modification.

Warnings to coastal residents and shipping are now based on predictions made by meteorologists at the Miami hurricane center of the National Weather Service of the path a particular storm will follow. These predictions rely on statistical methods, on climatological inference, on analogs with the tracks of earlier hurricanes, and on calculations with a very simplified dynamic model of the storm (*1*). In practice, hurricane forecasting involves choosing among the often conflicting predictions of these different methods and depends heavily on the experience and judgment of the forecasters. The resulting accuracy leaves much to be desired; for Atlantic hurricanes in southern regions (near Florida), the average error is about 180 km for a 24-hour forecast of the location of the storm center and nearly 390 km for a 48-hour projection. Farther north the forecast errors are larger still. One practical consequence of this inaccuracy is that, because of the considerable cost of evacuation and other disaster preparations, official warnings (as opposed to preliminary bulletins) are rarely given out sooner than 12 to 18 hours before the storm's onset. Reliably more precise forecasts of the hurricane track would also reduce the size of the coastal region that must be evacuated. Most damage and loss of life are caused by the wind-driven surge of water that occurs as the storm hits land; the height and extent of the storm surge can now be quite accurately predicted if the landfall and intensity of the storm are known.

With present techniques, some forecasters believe, hurricane prediction has reached a plateau. The accuracy of 24-hour forecasts has improved only 30 percent since the 1950's. The prospect for the future is for increased use of dynamic models in hurricane prediction, a prospect made possible by larger and faster computers.

Until recently, attempts to model hurricanes were severely limited by the time necessary to compute the model. Numerical models (that is, models consisting of sets of equations solved by repeated numerical calculations on a computer) of hurricanes had usually been either of the type used to represent the general circulation of the atmosphere or of more specific type that models a storm isolated from its environment. General circulation models, because of computational grid points so widely spaced that details of the simulated storm were not resolved and because of ineffectiveness in representing the behavior of the tropical atmosphere, had found little application in hurricane research. More specific models of the storms, however, had been largely restricted to idealized, two-dimensional treatments that, because they did not include the interaction between the storm and its environment, could not simulate its motion.

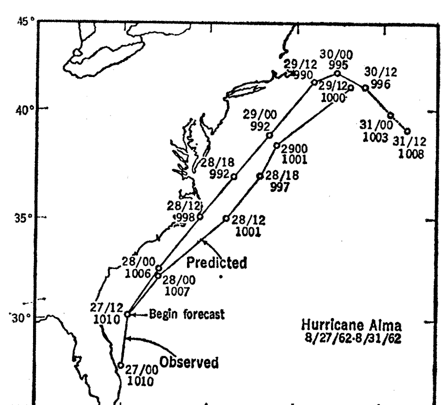

Fig. 1. Observed and predicted track of Hurricane Alma as forecast by a numerical model. Day, hour, and atmospheric pressure (in millibars) at the storm center (a measure of the storm's intensity) are indicated at each position. Observed and predicted storm positions deviated by less than 140 km over the first 36 forecast hours. (Source: B. F. Ceselski, National Center for Atmospheric Research)

With larger computers, however, more ambitious models are now being attempted. One of the most sophisticated, three-dimensional models of a hurricane is that developed in various forms by T. Krishnamurti of Florida State University in Tallahassee, M. Mathur (now with the National Meteorological Center in Washington, D.C.), and B. F. Ceselski (now with the National Center for Atmospheric Research in Boulder, Colorado). Their model is regional in scope, and includes an area about 6000 km². It is similar in concept to the general circulation models used by the Weather Service for daily weather forecasting, but has been adapted for tropical conditions and is equipped with a finer computational grid (30 km between data points). When tested against the recorded behavior of several past hurricanes, the model was able in most cases to predict the intensity and the movement of the storms with surprising accuracy (Fig. 1). Although it has yet to be tested against a wide range of past cases, the model appears to give results that compare favorably with existing forecast methods. Ceselski believes that the success of the model, in spite of its relatively sparse specification of hurricane dynamics, indicates that general environmental conditions, and not just internal features of the storm itself, are determinants of hurricane motion and intensity.

Perhaps the first of the new generation of hurricane models, and the most extensively tested, is that developed by B. Miller of the National Hurricane Center (NHC) in Miami. His model, although similar to that later developed by the Florida State team, differs in some details and currently uses a coarser computational grid (100-km spacing). It is, however, correspondingly faster to compute and has made reasonably accurate forecasts when run against half a dozen documented cases. Like the Florida State model, it requires more input data than is commonly available —reconnaissance flights through hurricanes ordinarily gather data at only one altitude, and they generally do not include a large region outside the storm. Nonetheless, NHC plans to use Miller's model for hurricane forecasting on an experimental basis this year, and plans are under way at the National Meteorological Center to develop a much larger and more ambitious model for operational forecasting in coming years.

The outlook for controlling hurricanes or modifying their strength is less clear and far more controversial than for prediction. For one thing, the rain produced by these storms supplies the water needs of large areas in the southern and eastern United States. Steering hurricanes away from land—if it could be done—would thus also change rainfall patterns, perhaps dramatically. Modification experiments have instead tried to reduce the intensity of the storm by seeding its clouds with Dry Ice or silver iodide.

In what appears to have been an unfortunate coincidence, however, the

Speaking of Science

Weather and Climate Modification: Progress and Problems

Surveying the field of weather modification some 7 years after an earlier study, a National Academy of Sciences panel in a new report (*1*) finds both progress and problems. Progress comes in the form of more statistically valid evidence that cloud seeding can increase precipitation under some circumstances and more detailed knowledge of what those circumstances are. Problems, to judge by the recommendations contained in the report, have to do in the first instance with the lack of research funding and organizational muscle given weather modification by the federal government. To remedy this situation, the panel proposes three national goals with a target date of 1980: (i) to put rainmaking and other precipitation modifications on a sound basis; (ii) to develop means of mitigating the effects of the most severe storms and weather hazards; and (iii) to determine the extent of inadvertent modification of local weather and the global climate by man-made pollutants.

To reach these goals, the panel recommends research funding of no less than $50 million annually—a figure the report compares with federal spending of about $12 million for weather modification in recent years—and the establishment of a national laboratory for weather modification, among other programs. The panel did not, however, tackle the sticky job of recommending what programs should have top priority in the all too likely event that $50 million is not forthcoming.

Among the specific advances cited by the panel was confirmation of the effectiveness of seeding orographic clouds—those produced by topographic features. More than 14 years of randomized experiments near Climax, Colorado, showed that seeding clouds in which the temperature ranged between −11° and −20°C at the cloud tops could increase the snowfall in this mountainous region by 10 to 30 percent. The results of seeding convective clouds such as the ordinary cumulus rain cloud, according to the panel, are more mixed. Seeding experiments in Missouri and Arizona seem to have reduced rainfall in the experimental area, while other experiments in Israel, Australia, and the Soviet Union have yielded positive results. In Florida, numerical models of cumulus clouds were used to select "seedable" clouds, which did produce significantly more rain. The panel notes, however, that questions have been raised about the downwind effects of cloud seeding (outside the intended target area) and recommends more serious study of these effects.

In regard to modifications of weather hazards, the panel reports that means of dissipating warm fogs over airports or of reducing the intensity of tornadoes do not yet exist and that attempts to reduce forest fires caused by lightning have been inconclusive. On preventing hailstorms, the panel notes the spectacular successes claimed by Soviet scientists and, on a lesser scale, by investigators in France and Kenya, but bemoans the lack of statistical controls that would make the results more convincing.

Opinions differ as to the prospects for modifying hurricanes (see accompanying story), but for that reason, the panel believes, randomization of seeding experiments on these storms in some form is all the more important, despite the expense and operational difficulties such procedures might involve. Indeed, concern over statistical methods and the impact of criticism by statisticians of early weather modification experiments is obvious all through the report. Some researchers believe that the panel may in fact have gone overboard in its concern for statistical rigor, neglecting the extent to which knowledge of physical processes can lead to very specific predictions to be tested in weather modification experiments. It is generally agreed, however, that predictions based on numerical models will be increasingly closely coupled with modification experiments.

Inadvertent weather modification now receives little attention, a circumstance the panel regrets. But despite a suggestion that monitoring of pollutants should be undertaken, the panel's report does not spell out specific new programs or funding recommendations. It does step into the arena of international policy, citing with approval a proposed ban on military use of weather modification techniques. That such concerns are now germane may be one of the best indicators that weather modification is no longer an esoteric bag of tricks but is rapidly approaching the status of an operational technology.—A.L.H.

References

1. Review Panel on Weather and Climate Modification, T. E. Malone, chairman, *Weather and Climate Modification, Problems and Progress* (National Academy of Sciences, Washington, D.C., 1973). $6.25, paperbound.

first attempt to seed a hurricane, in 1947, was followed by disaster. A storm that had passed over Florida and was headed east into the Atlantic when seeded by scientists (the General Electric Research group) abruptly turned around and struck the coastline with renewed fury. In the light of what is now known about hurricanes, it seems unlikely to most meteorologists that the seeding had anything to do with its change in path, but the incident nonetheless gave seeding experiments on hurricanes a bad reputation and led to restrictions, still in effect, on seeding any storms within reach of land. In subsequent efforts to modify hurricanes under project Stormfury—a cooperative U.S. Navy–National Oceanic and Atmospheric Administration (NOAA) program begun in 1962—only three suitable hurricanes have occurred within reach of the project's airplanes.

The most imposing feature of a hurricane is the ring of towering clouds around the eye, or center, of the storm. These clouds generate the heat and ultimately the pressure differences that drive the storm's winds. Stormfury experiments were originally based on the hypothesis that seeding within the eyewall clouds would change the distribution of atmospheric pressure within the storm and reduce maximum winds by 10 to 15 percent. Although it is generally agreed that seeding clouds containing supercooled water can induce freezing and addition of latent heat to the cloud air, most meteorologists believe subsequent modification of the hurricane as postulated by the original Stormfury hypothesis to be scientifically groundless. Indeed, some hurricane researchers now believe that seeding within the eyewall clouds would, if anything, increase the storm's intensity.

Modification experiments on Hurricane Debbie in 1969 in which maximum winds decreased by 30 percent after massive seeding on 18 August and decreased 15 percent after a second seeding period on 20 August, however, have stimulated new interest in the technique. Hurricanes display a wide range of natural variability, but Stormfury director R. Gentry of the National Hurricane Research Laboratory (NHRL) in Miami believes that the changes were in part due to the seeding in that they were larger than the average variations expected for storms of this type on the basis of previous data. Other researchers are more skeptical; they find that data "unconvincing" or "promising, but not reliable evidence."

Since the Debbie experiments, a growing understanding of hurricane dynamics and computer simulations of hurricane seeding experiments have led to a revised theoretical rationale for modification. The simulations were done by S. Rosenthal of NHRL with a two-dimensional model of an isolated storm. Because the model's computational grid is too coarse to include phenomena on the scale of individual clouds, heat is added to the model atmosphere at appropriate locations to represent the effects of seeding. In a series of numerical experiments, Rosenthal found that this simulated seeding was most effective in reducing peak winds if it was done at some distance from the storm's center, outside the eyewall. The smaller clouds found outside the eyewall—according to the revised Stormfury hypothesis—will grow when seeded, in the process feeding on and diverting some of the warm, moist air from the flow near the sea surface which would otherwise fuel the eyewall clouds that drive the storm. By depriving the storm center of some of its moist air, the argument goes, peak winds will be reduced.

Although still a questional hypothesis in the sense that it has not been proved, several meteorologists involved in hurricane research believe that modification along these lines is at least a theoretical possibility. In practical terms, modifications would involve striking a balance between seeding far enough from the center of the storm to disrupt the eyewall and the logistical difficulties of covering larger and larger areas and finding enough seedable clouds at these distances. Present plans would be to seed just outside the eyewall and hope for a large enough effect. Since with present models these effects cannot be reliably predicted, there appear to be grounds for further experimental trials.

During the next few years, however, there will be no experimental hurricane seeding. Military support for Stormfury was abruptly terminated last year, apparently more as a belated response to the Mansfield amendment forbidding sponsorship of research unrelated to military purposes than because of any disenchantment with the project itself. The NOAA Stormfury budget, which had been running at nearly $2 million annually in recent years, has also been cut in return for promises of money for badly needed new planes and upgraded instrumentation in coming years. Because of the paucity of suitable storms in the Atlantic, operations, when they resume in 1976, may well be moved to the western Pacific, a more prolific breeding ground for hurricanes.

In the meantime, modeling efforts are continuing in the hope of having more detailed numerical experiments to compare with field experiments. Rosenthal and R. Anthes at NHRL have developed what is to date the most detailed three-dimensional model of a hurricane. In progress are efforts to construct models with very fine computational grids and correspondingly detailed representation of the storm near its center, but with coarser grids outside this region.

A second approach is the incorporation of better ways of representing the effects of clouds in numerical models. This problem is common to much of meteorology, not just to hurricane research. More accurate descriptions of cloud microphysics and more self-consistent attempts to classify and quantify the effects of these small-scale processes on larger phenomena have appeared in recent years, perhaps the most comprehensive of which is that developed by A. Arakawa of the University of California at Los Angeles. Rosenthal plans to test Arakawa's scheme in hurricane models in the hope it will lead to more meaningful simulations of seeding experiments.

As larger computers make possible better models of hurricanes, it seems likely that hurricane forecasts will be improved. The key limitations, as is true with weather forecasting generally, will be the cost of gathering enough data and the difficulties of incorporating the data into the model. In view of the cost of modification experiments and the sheer impossibility of enough trials to judge their efficacy on purely statistical grounds, numerical experiments will become of increasing importance here too. Indeed, despite continuing skepticism about the possibility of modifying hurricanes, there is growing agreement that modification and prediction are closely linked. Although numerical models are not yet the primary source of decision-making information about where storms will hit land, how seeding would affect them, and when and where to seed, they will certainly dominate research on these questions.—ALLEN L. HAMMOND

References

1. R. H. Simpson (*Science*, in press) discusses these methods and the problems encountered in hurricane prediction in greater detail.