The Race to Predict Next Week's Weather

Increasingly powerful computers are helping to push the limits of medium-range forecasting beyond a week

For the past few years, the United States has had to settle for being second best in medium-range weather forecasting, the prediction on Monday or Tuesday of what the weekend weather will be like. The upstart European Center for Medium Range Weather Forecasts has surpassed the computer forecasting skill of the U.S. National Weather Service's National Meteorological Center (NMC) since the beginning of 1980.* That was only a few months after the European Center began producing forecasts. By the usual measures of forecasting skill, the European Center has been forecasting at least half a day farther ahead than NMC with the same accuracy. It has maintained that lead by adding a day or more of useful forecast during its first 3 years.

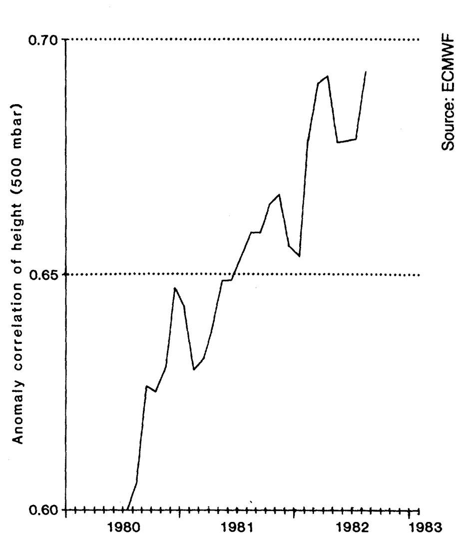
So far, the race has gone to the swift—those forecasters possessing the fastest, most powerful computer. The more powerful the computer, the more realistic the simulation of global weather. The European Center's unimposing Cray-1 is at least ten times faster than NMC's 10-year-old IBM 360/195. The Cray needs its speed of 50 million arithmetic operations per second, as well as a gymnasium-size room of lesser computers and peripheral equipment, to handle the 80 million bits of weather data received each day, transform them into a usable picture of that day's weather over the entire globe, and then perform the 500 billion arithmetic operations needed to predict what the atmosphere's behavior will be 10 days later.

NMC's less powerful IBM 360/195 copes with the same flood of data by creating a fuzzier, less precise picture of the present weather and assuming that the weather is even less complicated than the Cray assumes it is. Inevitably the less realistic the computer model of the atmosphere, the sooner the forecast will bear no resemblance to the real world.

While waiting for the next, more powerful computer, both groups of forecasters have been trying to squeeze better forecasts from their fixed computer power. The result has been more realistic forecast models and, sometimes, improved forecasts.

One way to look farther ahead is to look farther away around the globe. A 1-day forecast for western Europe need not take account of present conditions much beyond Greenland, West Africa, and the Urals. But a 7-day forecast must include today's weather over Buenos Aires, Djakarta, Kabul, Honolulu, and the North Pole. Conventional wisdom holds that any improvements in the data from even the most distant part of the observation network will improve medium-range forecasts in Europe. Despite the use of 9000 surface weather stations, 750 sites from which instrument-laden balloons (radiosondes) are launched, ships at sea, and commercial planes in flight, there are still gaping holes in the surface-based global observation network, especially over the vast ocean areas of the Southern Hemisphere. Satellite measurements are filling some of these gaps, but they provide only wind speeds and temperature soundings that have lower accuracies than radiosonde observations.

Researchers filled more observational gaps, if only temporarily, during the First GARP Global Experiment (FGGE) in 1979. Five geostationary satellites imaged the entire globe, two polar orbiting satellites probed atmospheric properties, hundreds of weather buoys reported from southern oceans, and long-lived balloons drifted along the equator. These additional observations extended useful forecasts for the Southern Hemisphere from about 4 days to more than 5 days, according to Lennart Bengtsson, the director of the European Center, and his colleagues there.



Increasing forecasting skill

The upward trend in this measure of the accuracy of 5-day forecasts begins at the 0.6 level, which is considered to be the minimum for useful forecasting.

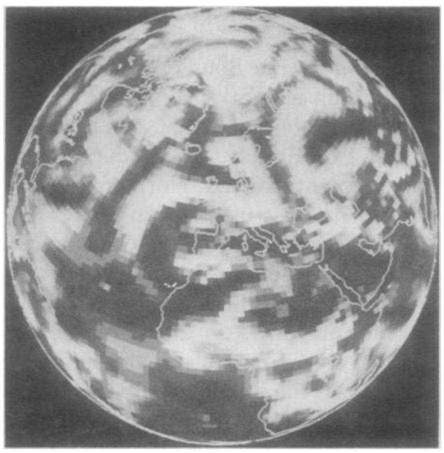
Beefing up the Southern Hemisphere observation network may improve forecasts there, but even the special effort during FGGE failed to produce much improvement in the Northern Hemisphere. At least in their ten test cases, Bengtsson reported, the FGGE data did not extend useful predictability in the Northern Hemisphere beyond the then-typical limit of 5 to 6 days. In another study by Milton Halem and his colleagues at the Goddard Space Flight Center, Greenbelt, Maryland, satellite data alone improved 4- and 5-day forecasts of atmospheric pressure over Australia. According to their study, though, the effect of FGGE observations on 3-day forecasts over North America and Europe was much smaller, more variable, and at times negligible. It would appear that whatever improvements FGGE made in the observing network, they were not sufficient to improve substantially Northern Hemisphere forecasts. Since the cost of the observation network already runs over $1 billion per year, forecasters see an improvement of satellite accuracy as the most practical means of bettering the observations used in their computer models. So far, the accuracy of satellite temperature soundings and wind speed estimates has fallen short of initial expectations.

Once a forecasting center receives observations for a given time, the next step is to create an accurate picture of the atmosphere so that the computer can use it as a starting point for its forecast calculations. This process, called analysis, must transform the randomly scattered observations into a uniform, three-dimensional network of data points, the best form that the computer can use to develop its forecast. Each grid point is a surrogate for the atmosphere surrounding it; whatever happens in that parcel of air is summed up by that point. The

*The European Center was established by 17 member countries and is headquartered in Reading, England; NMC is located in Camp Springs, Maryland.

closer the points are spaced and the more good observations represented by each point, the sharper and more accurate the picture of the weather.

As is usually the case in computer forecasting, the better way takes more computer power. The European Center's model has grid points spaced about 200 kilometers apart in the horizontal and at 15 levels in the vertical, a total of 273,630 points in all. The slower NMC computer model cannot handle such a detailed picture of the weather. Its horizontal resolution is half that of the European Center and it has only 12 vertical levels. The European Center's analysis includes about 200 of the surrounding observations in determining the value at a grid point. The NMC system allows only 20 observations to influence the grid point value. Until recently, only eight observations entered the calculation.


ECMWF

A forecasting model's clouds

Even after all of the grid is filled, forecast calculations cannot begin until meteorologically insignificant, small-scale disturbances in the analysis—both real atmospheric phenomena and noise—are removed. The trick is to filter them out and bring the system into balance during this process, called initialization by meteorologists, without losing useful information. NMC found how mischievous their initialization procedure could be after a 21 October 1979 forecast failed to anticipate the development of a strong vortex in the Gulf of Alaska. Researchers eventually found that the initialization procedure would simply throw out satellite data. That data appeared to be an unwanted disturbance, so the initialization adjusted the analysis to redress the imbalance by the wholesale rejection of satellite data.

Having a complete, understandable atmosphere to start with, a model can begin simulating future atmospheric behavior. Working with equations stating basic physical principles, such as the gas law and Newton's second law of motion, a model calculates what the conditions will be in 15 minutes, given the initial wind speed and direction, temperature, and surface pressure at each grid point. The calculation is done repeatedly with the new conditions used as a base until the desired forecast time is reached. Before 1980, NMC forecast beyond 3 days on the basis of a simpler, barotropic model rather than this baroclinic or primitive equation model. Applied at a single, crucial level in the atmosphere in order to allow simplifying assumptions, the old barotropic model allowed initial conditions to influence the atmosphere but not the potential energy stored within it. When the barotropic model was replaced by the more realistic primitive equation model, NMC forecasters extended useful predictions by about a full day.

Researchers have known all along that solving the nonlinear components of the primitive equations for a grid that is stretched over a sphere involves unavoidable errors. A grid would be fine if the earth were flat; atmospheric properties on a sphere would be easier to calculate if they were represented by a set of waves of varying amplitude. The catch was that such spectral calculations required 100 times more computer power to achieve the same resolution. Fourier transform methods solved that problem in the early 1970's, allowing forecasters to transform the grid mesh into a wave representation, perform the nonlinear calculations, and transform the results back to a grid with no substantial penalty in computing time. NMC has been running a spectral model for almost 4 years, having found that it solved a pesky noise problem in their grid model. The European Center is now switching to a spectral model after having found that it extended their useful forecasts an average of 6 hours. One in ten of their test forecasts gained a full day.

The atmosphere is not the closed system that a collection of physical laws would imply. To be realistic, the primitive equations must also incorporate terms to account for the addition and removal of water, heat energy, and momentum. The possible routes for these fluxes are numerous and complex. For example, water's movement through the atmosphere—from oceans, through clouds, to precipitation—carries heat energy that can drive the atmospheric circulation, but the actual flux of water and heat depends on diverse properties of the earth and the atmosphere, from the wetness of the ground to the stability of the overlying air. The horizontal extent of this process can be as small as a puffy, cumulus cloud, but a global model is too myopic to "see" this convective-scale activity.

Faced with the problem of representing a huge, complex world in a powerful but still simple-minded computer model, forecasters have tried to distill the effect of these small-scale physical processes into imperfect but computationally practical mathematical descriptions. Individual convective clouds cannot show up in a global model, but when conditions dictate that they should, equations called physical parameterizations can convey the effects of convection, such as atmospheric heating, to the large-scale processes occurring on the grid. A guiding principle of medium-range forecasting is that the more and better the physical parameterizations in a model, the more accurate the forecast.

Although their smaller computing capacity has limited NMC forecasters to simpler physical parameterizations, U.S. forecasts may not suffer as much as might be presumed. The NMC model has less sophisticated descriptions of precipitation and processes near the surface, like drag and evaporation, and no parameterization whatsoever of radiation processes. The model cranks out weather in perpetual darkness. Despite these and other disadvantages, the European Center's model does not seem to reap any additional benefits when forecasting much beyond 4 days or so, according to NMC studies. John Stackpole and Steven Tracton of NMC compared a year's forecasts in the 1- to 5-day range for each center. The European Center's forecasting lead grew from day 1 through day 3 or so but did not grow any more through day 5. Comparing forecasts of 5-day means that were centered near day 8, Francis Hughes of NMC found that the European Center's lead was no larger after 8 days than at about 4 days.

The European Center has identified one physical aspect of their model whose improvement should have a substantial effect on their forecasts. In the past, Atlantic lows in the model tended to become too intense and to plough into the continent instead of sweeping farther to the north. After pursuing some blind alleys, Adrian Simmons and Stefano Tibaldi of the European Center, and John Wallace, a visitor from the University of Washington, traced the cause of this systematic error back to the heights of mountains in the Rockies and Alps. These mountain chains can deflect and help steer weather systems around the globe, but in the model the 4000-meter peaks and 3000-meter passes of the Alps, for example, sink into a grid-size plateau only 1000 meters high. Even topography must be averaged over a grid space, one of which takes in the entire French Alps. But the real winds slamming into the Alps must go over or around the highest barrier, which could be the highest mountains, passes, or even valleys filled with stagnant air.

The European Center's researchers have alleviated most of their shrunken mountain problem with their own version of a technique called envelope orography. In their revision of the model, rough mountain chains are made higher and valleys are filled in when air stagnates within them. The changes, which European forecasters are now inserting into their operational model, have extended experimental forecasts at least 6 to 12 hours on average, according to Wallace. Under some circumstances, they added 2 to 3 days.

The forecasts finally produced by these models come in a variety of forms. The standard for comparison is the forecast of atmospheric pressure distribution, the highs and lows that generally correspond to fair weather and foul. Such forecasts by the European Center are useful out to about 6 days, according to standard statistical tests. No one's temperature forecasts extend quite so far, though they are improving, and precipitation forecasts, the most difficult to make, fall apart after about 3 days. Meteorologists believe that they have more skill than that in forecasting the major weather events of special interest to the public, but they have yet to develop valid statistical tests for such events.

The race for the lead in medium-range forecasting may close to neck-and-neck later this year as NMC brings on its Control Data CYBER 205, at about 80 million instructions per second the computational equal of the Cray-1. Most NMC personnel expect to achieve equivalency with the European Center within about a year of taking delivery of the CYBER this April. The Americans will also be competing with the United Kingdom, which is already operating a CYBER 205 of its own.

The Americans may have little time to savor their newly won equality. According to Bengtsson, the European Center is eyeing Cray's X-MP for acquisition in early 1984. The X-MP is a multiprocessor having three to five times the computing power of the Cray-1. The most obvious step to take with such a machine, says Woods, would be to increase the model's resolution.

How long this race may run is not certain, but the end cannot be too far off. Computer power may have no immediately obvious bounds, but the predictability of the atmosphere must have inherent limits. Edward Lorenz of the Massachusetts Institute of Technology has estimated this upper limit of predictability by comparing a number of the European Center forecasts made for a particular day and the actual conditions of that day. His best estimate is that forecasts as skillful as the Center's present 7-day forecast can be extended to perhaps 10 or 12 days. The barrier to detailed, long-range forecasts, he says, is the tendency of the inevitable errors in describing the smallest-scale structure of the atmosphere to cascade into large-scale weather patterns. There is a limit, it appears, to what even a supercomputer can do about the weather.

—RICHARD A. KERR

Plants' Resistance to Herbicide Pinpointed

The change of a single nucleotide in a chloroplast gene can make plants resistant to the widely used herbicide atrazine

A group of investigators at Michigan State University (MSU) recently found that a single change in a chloroplast gene can account for the development of resistance to the herbicide atrazine in certain weeds. According to Charles Arntzen of MSU, who presented the results at the Miami Winter Symposium,* the discovery could lead to the introduction of similar herbicide resistance into important crop plants. Since this endeavor requires the transfer of just one gene, it may achieve success more readily than many other potential projects for the genetic engineering of plants.

One likely target for genetic manipulation is the soybean, which is currently very susceptible to atrazine. Soybeans are often planted in rotation with corn, a crop which is tolerant to the herbicide. If atrazine residues remain in the field from the previous season, soybean yields may be markedly reduced.

Around 1970 farmers first noticed that weeds were becoming resistant to atrazine, principally in areas where it had been applied repeatedly without switching periodically to other herbicides. Now more than two dozen different weed species in Europe, southern Canada, and several states in this country are resistant.

Corn is tolerant because it naturally contains enzymes that detoxify atrazine. Investigators originally assumed that weeds became resistant because they acquired the ability either to detoxify atrazine or to prevent its uptake by plant cells. But that turned out not to be the case. "There was no difference in anything until we looked at the site of atrazine action," Arntzen says.

Research in his and other laboratories has shown that atrazine blocks electron transport in chloroplasts, killing weeds by depriving them of the energy and reducing power needed for photosynthesis. "Atrazine displaces a quinone from a specific protein involved in electron transport in the chloroplast and shuts off electron flow," Arntzen explains.

Attempts to isolate and characterize the protein, which is tightly bound to chloroplast membranes, proved futile. To detect the protein in a preparation of chloroplast membranes, Arntzen and Gary Gardner, who is now at Shell Development Company in Modesto, California, labeled it with a radioactive atrazine derivative. Atrazine itself does not covalently bind to its target, but the derivative becomes covalently attached to the binding site when illuminated with ultraviolet light. The investigators found that chloroplasts from susceptible plants contain a 32- to 34-kilodalton protein that is labeled by the atrazine derivative. The protein is present in resistant plants but does not become labeled.

Because atrazine and the quinone compete for the same binding site, it was possible to conclude that this protein is the photosynthetic quinone-binding protein. The mutation that confers atrazine resistance apparently prevents binding

*Held in Miami on 17 to 21 January under the auspices of the Department of Biochemistry of the University of Miami and the Papanicolaou Cancer Research Institute.