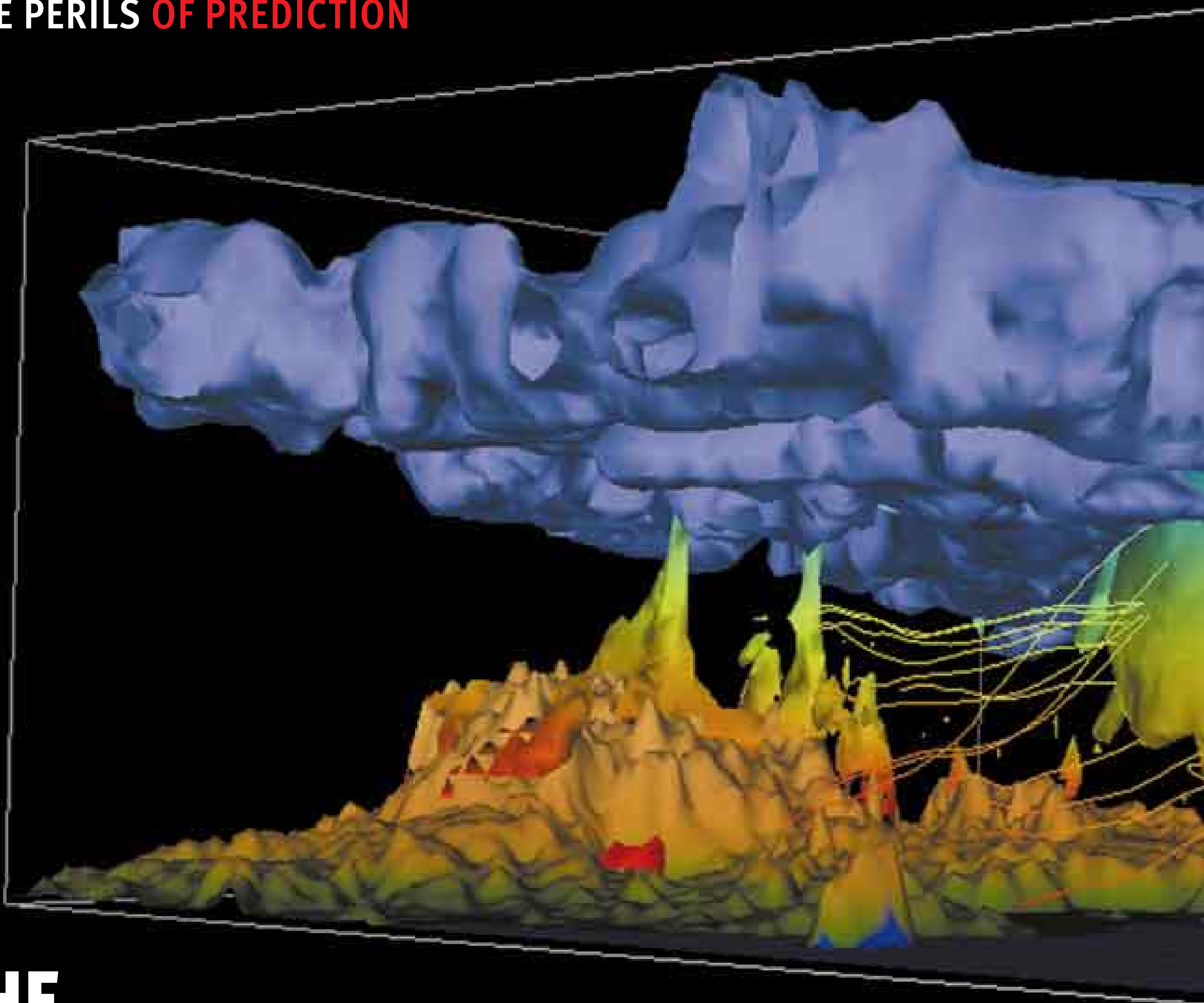
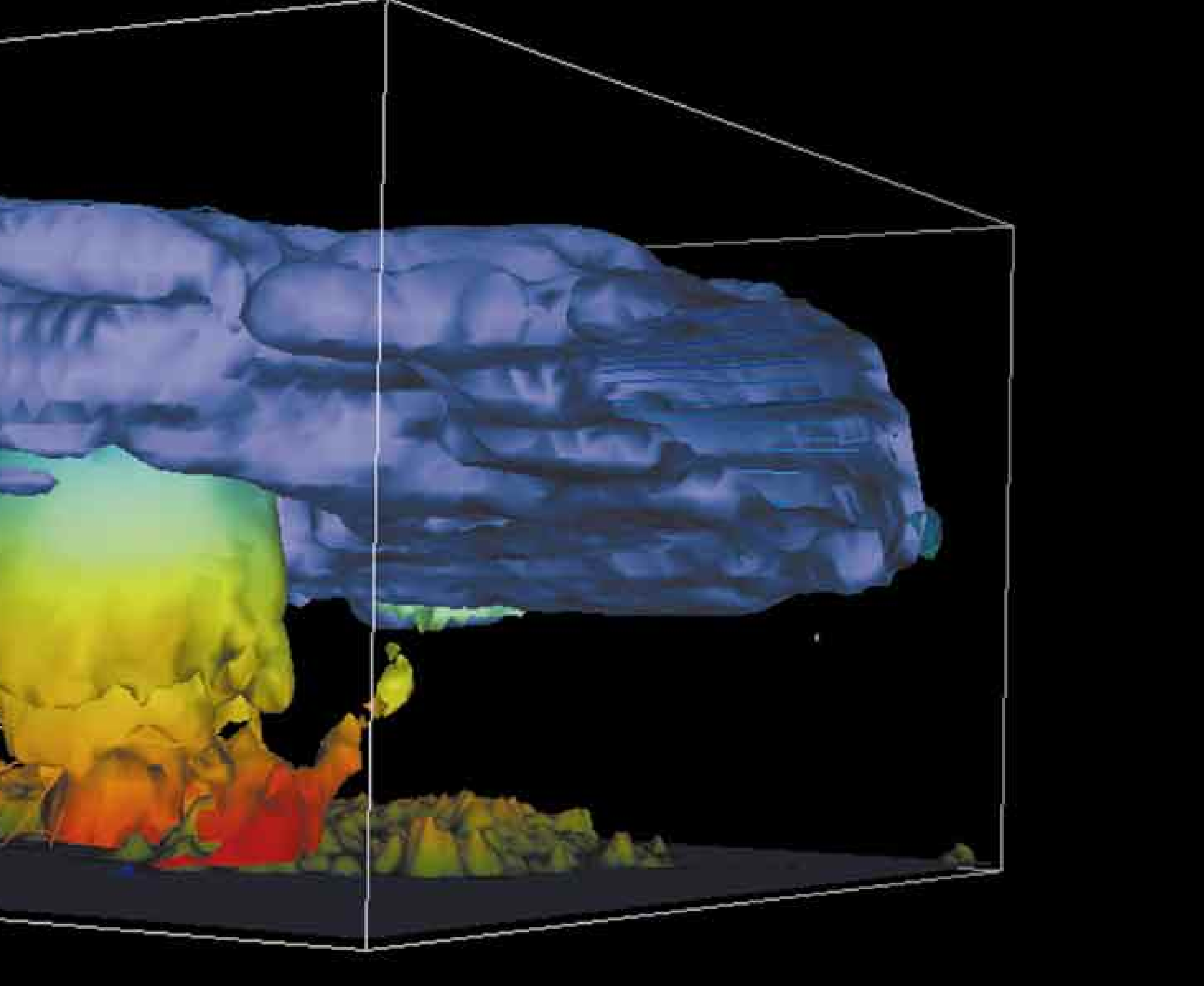


THE BUTTERFLY THAT ROARED

by JEFFREY ROSENFELD

To improve weather forecasting, meteorologists have learned to pay attention to the effects of chaotic airflows in the atmosphere



CYCLONE OFF ASIA: **This computer model, developed at Pennsylvania State University and the National Center for Atmospheric Research, shows a storm brewing over the Yellow Sea off the coast of China. Beneath the upper deck of icy clouds, the model creates an imaginary cloudscape (the tints represent temperature) that shows the areas where airflow is most contorted.**

BILL KUO *NCAR Mesoscale and Microscale Meteorology Division (computational modeling)*; HONGQING WANG *University of Peking* AND TIM SCHEITLIN *NCAR Scientific Computing Division (visualization)*

Weather forecasters are a frequently humbled bunch. No matter how far their science advances, the atmosphere finds ways to defy prediction. In 1998, for example, sophisticated computer models helped the National Weather Service (NWS) achieve the highest forecast accuracy in its 130-year history. But a disturbing number of meteorological events that same year proved how fragile that achievement was.

Take what happened on Thursday, February 19, 1998. The models predicted a stormy weekend in Louisiana. Fortunately, though, meteorologists were flying over the Pacific Ocean for a special research mission and reported one small correction. The jet stream was moving much faster than expected far off the coast of Alaska. Rerunning the models with the new information, NWS meteorologists saw that storms would probably strike central Florida, not Louisiana.

By Sunday at 2 P.M., confident forecasters issued a tornado watch—seven hours ahead of a deadly tornado outbreak in the Orlando area. A little discrepancy in the pattern of air flowing more than 4,000 miles away had made the difference between an accurate forecast and a bust. The change in the winds in Alaska had displaced storms in the southeast by several hundreds of miles—endangering people living near Orlando, not New Orleans. Blame what happened on chaos, the way small uncertainties in atmospheric conditions in one place can produce enormous consequences at a huge distance. Chaos is the bane of weather forecasters because it adds untold complexity to the models they use to make predictions.

Through the 1970s, few meteorologists anticipated the impact of chaos on the accuracy of forecasting. They had once assumed that they could gain a handle on the weather simply by accumulating a better understanding of such phenomena as lunar phases and solar cycles. The growing use of the computer facilitated this search by making it possible to construct statistical models that made predictions based on historical trends. Ironically, however, the computer age quickly displaced these models as a tool for day-to-day forecasting. Statistical models took a backseat with the rise of another type of computer prediction called dynamic modeling.

Like a motion picture, a dynamic model consists of a series of frames, each one a slight alteration of the previous one. The first frame is a numerical snapshot of the weather—the "initial conditions," a collection of the latest temperatures, pressures and other observations. The initial conditions are entered for each of a series of evenly spaced points of a grid that is superimposed onto a map of the area for which a forecast is being made. Then the model subjects the conditions at each grid point to basic equations describing motions (dynamics) of air and heat. The results of these calculations form the next frame, a simulation of the atmosphere usually a few minutes into the future. Each subsequent frame is produced by running the conditions in the previous frame through the equations of the model. As in a movie, time passes in small jumps from frame to frame. Eventually the computer arrives at the frame representing the time in the future that meteorologists are hoping to forecast—say, a day ahead. Meteorologists interpret this last grid of forecast conditions to predict whether tomorrow will be sunny or gray.

The growing use of dynamic models paved the way for the discovery of chaos. In 1961 Edward N. Lorenz of the Massachusetts Institute of Technology made a pivotal finding. Lorenz's dynamic model proved surprisingly sensitive to fluctuations in initial conditions. Slightly altered initial conditions changed the model results drastically. Lorenz realized that the real atmosphere, too, has this strange characteristic, which scientists now call chaos. Because of chaos, the weather never repeats itself exactly, so forecasting based solely on past trends is doomed. In addition, because it is impossible to know initial conditions perfectly, chaos forces dynamic models to spit out gibberish if stepped forward too far into the future.

Over time, Lorenz formulated a limit: beyond about two weeks, no one can tell where it will rain on a given day. Most of the time forecasters can't even get close to the two-week limit. Even the short-term predictions are dicey: tornado warnings—now averaging a lead time of about 12 minutes—are often false alarms. And most experts think chaos will bar warnings even a few hours in advance. Yet that hasn't discouraged meteorologists. By developing a savviness about chaos—even exploiting it—forecasts can continue to improve despite limits.

Breaking Up Gridlock

Lorenz described sensitivity to initial conditions as the "butterfly effect." Theoretically, a butterfly flapping its wings in Beijing could cause a storm over New York City. Such small motions slip through most model grids. Computer power has improved enough to take models from 200-mile spacing between points on a grid in the 1950s to 20-mile spacing in the finest resolution used today at the NWS. Anything in the 20 miles between grid points is lost to the computer. In other words, a butterfly as big as Manhattan could elude detection. But continued efforts to narrow grid spacings—with improvement in specification of initial conditions—is one way meteorologists can minimize the impact of chaos on forecasts.

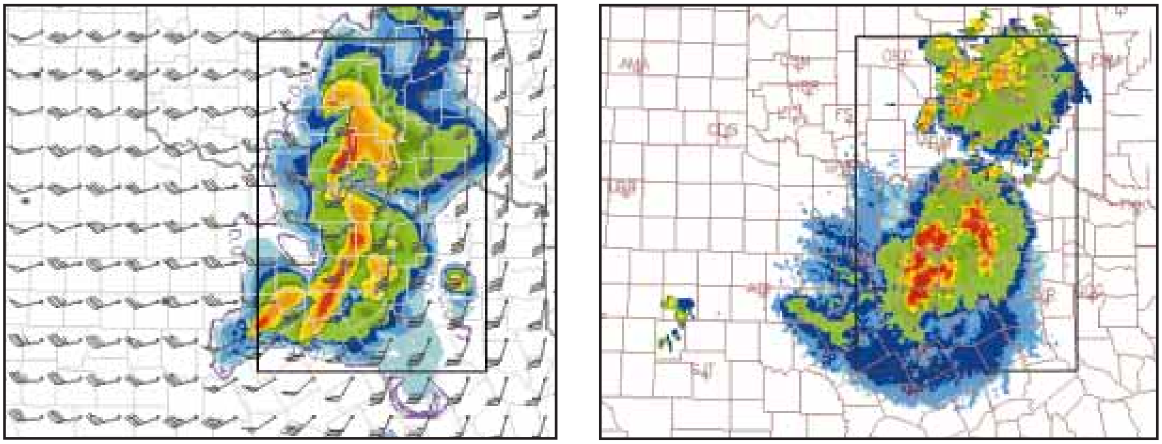
Already model grids have tightened enough to handle big storms like East Coast blizzards of up to 1,000 miles across. Sometimes meteorologists can project their development five days in advance. Until recently, model forecasts of thunderstorms have not had much success. These storms—usually about 10 miles across—respond quickly to subtle motions.

Finer grids should assist models in forecasting severe storms. But devising better grids requires improving observations (the initial conditions). Right now so few observations represent the roughly 25 million cubic miles of U.S. weather that an accurate forecast for any given small area seems miraculous. For upper air conditions, 108 balloons rise simultaneously twice a day and radio back data. A few

M.I.T. MUSEUM

FATHER OF CHAOS: Edward N. Lorenz came up with crucial insights that place a theoretical limit on how far in the future it is possible to predict the weather.

ADVANCED REGIONAL PREDICTION SYSTEM



CENTER FOR ANALYSIS AND PREDICTION OF STORMS, UNIVERSITY OF OKLAHOMA

A high-resolution computer model devised at the Center for Analysis and Prediction of Storms at the University of Oklahoma predicts weather conditions over a very localized area. It forecast where thunderstorms that generated tornadoes would crop up over Oklahoma on May 3, 1999 (*left*). The projections corresponded closely to where the storms actually occurred (*right*).

dozen upward-pointing microwave beams add information about what winds are aloft. These beams are supplemented by automatic readings from commercial airliners that cover temperature, pressure and winds at high altitudes along popular routes. Information gathering is rarely as good elsewhere, especially over the oceans, long the Achilles' heel of global models.

To obtain better information, the National Oceanic and Atmospheric Administration experiments with getting better data out of observing systems, such as one that tracks clouds with satellites to derive wind speeds. Signals from the Global Positioning System can also roughly index atmospheric moisture content. Unfortunately, explains Thomas Schlatter of NOAA's Forecast Systems Laboratory, data are sustenance for models: if they eat too much, they can get sick; if too little, they can die. Most of these new data sources provide only indirect information and thus lack much nutritional value. Satellites, for instance, measure various wavelengths of radiation from the atmosphere, ranging from the infrared to the microwave end of the spectrum. From these emissions, meteorologists can detect the presence of moisture, but they then have to make a cumbersome conversion to derive humidity, the parameter to be input into the model. Even then, to ensure that the humidity figure is accurate, the scientists must adjust the model or the data to get usable results—unappetizing fare for those seeking to minimize errors in the initial conditions that lead to chaos.

In some cases, new uses of observing systems can help tighten grids to heretofore unheard-of resolution. At the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma, meteorologists recently made a breakthrough in their ability to model initial conditions. CAPS uses NWS radar data routinely to run a grid with five-mile spacing over the central U.S. The CAPS model also benefits from special observations across Oklahoma that track moisture and heat exchange between the soil and the atmosphere, which helps show where sunshine might trigger new updrafts for storms. On May 3, 1999, in the worst outbreak of tornadoes in Oklahoma history, CAPS predicted correctly where individual thunderstorms (though not the tornadoes themselves) would pop up over the landscape—two hours before they actually appeared on radars.

Benefits of a Better Diet

For three years, CAPS teamed up with American Airlines to test the new storm modeling. On January 6, 1999, for example, NWS models led forecasters to believe that the early morning might be clear at American's hub at the Dallas/Fort Worth airport. The fine-scale grid in the CAPS model picked up a small disturbance nearby, however, so the airline meteorologist predicted that fog would begin at the hub at 6 A.M. With three hours' warning, some incoming planes had time to add fuel for holding over Dallas/Fort Worth, thereby saving American at least $4.5 million in costs to divert flights to other airports.

Fine-scale models such as CAPS that make forecasts for a limited area are a proliferating breed. The most widely used fine-scale forecasting model is distributed by the National Center for Atmospheric Research (NCAR). With it, meteorologists at the University of Washington forecast Pacific Northwest weather daily. Part of the area is resolved by two-mile grid spacings. This grid resolution allows simulation of important terrain features that determine local atmospheric properties. "The mountains produce all kinds of features," explains Clifford F. Mass, an atmospheric sciences professor at the University of Washington. The fine-scale model can forecast local events, such as winds that collide behind mountains, the paucity of rain or snow on slopes sheltered from storms, and winds that pick up velocity and temperature as they descend a mountain.

In the central U.S., terrain effects are less pronounced. But there the storms themselves cause complicated local winds. Thunderstorm outflows—cool air spreading from rain shafts—

can kick up new storms. To model this, says CAPS director Kelvin K. Droegemeier of the University of Oklahoma, it seems likely that grid points about a mile apart are necessary. But Mass points out that increased resolution yields diminishing returns if the observations needed to specify initial conditions aren't plentiful. In the West, bordered by the sparsely observed Pacific, the absence of atmospheric readings is already a problem for fine-scale modeling. "If you aim a very fine rifle well enough but in the wrong place, then you don't hit the target," Mass says. Without better initial conditions, "the models are frequently not aimed in the right place."

Another difficulty with high-resolution modeling is that the results can mystify meteorologists. At five-mile resolution, Droegemeier says, a model might produce a storm that, unrealistically, does not dissipate. Increase the resolution to 500 yards, and the simulation might create a storm that oddly varies its strength. At even finer resolutions, the simulated storm can exhibit behavior that scientists have yet to see in nature. Meteorologists have trouble determining whether these results are caused by chaos, by model errors or by the weather itself.

One reason for this confusion is that no one is sure what limits chaos imposes on fine-scale modeling. Lorenz studied the atmosphere on a global scale, in which turbulence is distributed relatively evenly. But thunderstorms are concentrated areas of frenetic activity, with relatively vast spaces of minimal turbulence in between. "It's kind of scary," Droegemeier says. "We're not sure what resolution we need."

Increasing resolution decreases uncertainty only to a point: for every model, meteorologists ultimately must devise shortcuts to stand in for some hard-to-resolve atmospheric phenomena. A global model (a name for a model that usually has a grid with more than 30-mile spacing) simulates shifts in the jet stream and large storms, such as blizzards. But the model does not represent thunderstorms. Instead it must use a shortcut that consists of a simple calculation to approximate the effects of a thunderstorm on existing weather conditions. Even the sophisticated CAPS model—which uses basic equations of heat and motion to simulate thunderstorms—must resort to shortcuts. At one-mile resolution, it must take into account individual raindrops, a task beyond the capabilities of the modeling software. So it uses a shortcut to calculate the effects of rainfall evaporation, an important model input.

Shortcuts don't just fill the gaps in the grid—they also incorporate new knowledge from researchers, another way meteorologists improve forecasts despite the limits of chaos. One hazard that models do not resolve is supercooled drizzle—liquid droplets less than half a millimeter in diameter that float in clouds at subfreezing temperatures. Undetected supercooled drizzle iced the wings of a commuter plane over Roselawn, Ind., in 1994 and caused it to crash, killing all 68 people on board. At NCAR, Ben Bernstein and his colleagues subsequently developed an algorithm that incorporated human expertise at forecasting aircraft icing from supercooled drizzle, knowledge developed during recent National Aeronautics and Space Administration test flights. This software considers many different variables, such as cloudtop temperatures and surface precipitation, then weighs the evidence as an expert would.

Another team of NCAR researchers, led by Rita Roberts, James Wilson and Cynthia Mueller, recently developed an automated system to predict the motion of thunderstorms about half an hour ahead. They combined satellite and radar information, local surface observations and a model that analyzes thunderstorm outflows, the cooled air that emerges from areas where rain is falling. The system improved severe-weather warnings in tests at the NWS.

One of the most elaborate meteorological expert systems

ENSEMBLE MODEL

ENVIRONMENTAL MODELING CENTER, NATIONAL CENTERS FOR ENVIRONMENTAL PREDICTION

Each colored line on these maps represents a separate prediction for the same atmospheric pressure pattern. Combined, the lines constitute an ensemble of forecasts. Every prediction is slightly different because the computer runs the model each time with slightly different input conditions. At first the tiny differences in input conditions matter little: the resulting lines trace nearly identical paths (*left*). In later predictions (*center* and *right*), however, the lines diverge. If the divergence occurs rapidly, as it does here, meteorologists know that atmospheric conditions are chaotic and that their predictions may be uncertain.

consists of real flesh and blood: the forecasters of the Hydrometeorological Prediction Center (HPC) at the National Centers for Environmental Prediction (NCEP), the NWS's modeling hub. They tell the local forecasters how much rain to expect—not just where and when—by interpreting the models carefully. One NCEP model, for instance, approximates thunderstorms in a way that makes too much rain on the East Coast and too little in the High Plains and West. The HPC staff members adjust accordingly at the times they think storms will appear.

New techniques for improving forecasts take into account the inherent limits of scientific certainty.

The HPC forecasters are attuned to theoretical advances that might improve on the model output. In recent years, researchers have characterized the interaction of the high-altitude jet stream with low-level channels of moist air. These interactions elude most models, so the HPC must predict these rainy areas and then adjust the model results.

Ensemble Work

The HPC forecasters have learned that their expertise can tempt them to become overly precise in making predictions. In April 1997 the Red River began to rise at Grand Forks, N.D. Based in part on HPC outlooks, the NWS predicted a record flood of 49 feet. Unfortunately, citizens of Grand Forks didn't pile the sandbags high enough for what turned out to be a 54-foot flood, and the city's downtown district was overwhelmed, forcing more than 5,000 people to evacuate.

Forecasters correctly foresaw that the river would reach a record crest, but critics assert that predicting the full range of possible water levels might have saved Grand Forks. New techniques for improving forecasts take into account the inherent limits of scientific certainty. HPC will begin issuing advisories estimating the chance—either 75, 50 or 25 percent—that a given prediction is likely to be exceeded. Probabilities help people decide how much risk they wish to take.

Assessing the likelihood of a meteorological event has grown easier with a technique called ensemble forecasting, which makes it possible to assess the atmospheric uncertainties produced by chaos. An ensemble is a collection of nearly identical simulations using a particular model. For example, the ensemble of NCEP's two-week model includes 14 different versions of the forecast, each with slightly different initial conditions. Scientists check the ensemble's predictions every few hours against observations of the actual weather to gauge accuracy. In a sense, they are intentionally breeding chaos. If the ensemble forecasts diverge from the real weather quickly, the forecasters know that the atmosphere is particularly sensitive to its initial conditions and that the forecast is uncertain.

Errors in prediction that result from chaos can often render the four-day outlook meaningless, says Zoltan Toth, a General Sciences Corporation modeler at NCEP. But sometimes the atmosphere seems relatively insensitive to initial conditions. "In some cases, we can actually get to the two-week limit," Toth says.

Ensemble studies and similar analyses show that predictions are often enhanced when the environment forces the atmosphere to behave in a consistent manner—limiting the influence of chaos. Recent El Niño–based climate predictions have been successful, partly because of the overwhelming influence (or "forcing") of the ocean on wind patterns. Once a strong El Niño (periodic warming of the equatorial Pacific off South America) appears, the atmosphere above it settles into a reasonably predictable routine, affecting winds elsewhere around the world as well.

Such oceanic forcing may determine hurricane intensity. Hurricane Opal in 1995 gained 20 miles per hour in wind strength in just 14 hours over the Gulf of Mexico, only to weaken again before landfall. A recent modeling study by scientists at M.I.T. suggests that warm ocean waters triggered Opal's intensification. The hurricane's winds then forced cool water to rise to the surface, which would have quelled the storm quickly if Opal had not moved so fast. Researchers with the University of Rhode Island and NOAA have now coupled an ocean circulation model to a hurricane model to simulate the upwelling. In 1999 the new coupled model—which also boasts more realistic cloud simulations—showed it could improve intensity forecasting by 30 percent.

Ensembles not only reveal which environmental features—a warm ocean eddy, for instance—can enhance prediction but also help meteorologists isolate where uncertainty is overwhelming a model. Then scientists can try to improve predictions by obtaining more observations from a critical area. The flights over the Pacific that discovered the strong jet stream in February 1998 tested this strategy.

But chaos can fool even the ensembles. Once at NCEP, two of the 14 simulations in the ensemble nearly began to duplicate each other day after day. With the varying initial conditions, each simulation, as it progresses, is supposed to differ increasingly from other simulations—an essential characteristic of chaos. When the rogue pair began to dance too closely together, Toth and his fellow chaos breeders had to stop the music, ending the simulations. Somehow the chaos they had created had lost its way. The NCEP model masters had to start over with a fresh set of initial conditions. "We didn't understand why it was happening," Toth says. So researchers faced another puzzle among the unanswered questions related to chaos. Finding answers may help scientists avoid the destruction that can be unleashed by a storm misplaced on a computer model grid. W

JEFFREY ROSENFELD is a freelance writer who lives in El Cerrito, Calif. He is the author of the book *Eye of the Storm: Inside the World's Deadliest Hurricanes, Tornadoes and Blizzards* (Plenum Trade, 1999) and a contributing editor at *Weatherwise* magazine.