ATMOSPHERE

Forecasting Hurricane Intensity and Impacts

Hurricane structure and intensity can now be predicted with sufficient accuracy to support quantitative assessment of human and economic impacts.

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In 2005, meteorologists embarked on an ambitious hurricane research project, RAINEX, to investigate how rainbands affect hurricane intensity. Flying radar-equipped aircraft right into the storms—including the infamous Hurricane Katrina—before they made landfall, the scientists recorded wind speed and direction, temperature, humidity, and other data. On page 1235 of this issue, Houze *et al*. report exciting results from this project (*1*). The authors observed Hurricanes Katrina, Ophelia, and Rita and then simulated them numerically on spatial scales of less than 2 km. These highly realistic simulations represent substantial progress on the vexing problem of hurricane intensity prediction.

In the United States, 2004 and 2005 were the most devastating seasons as measured by inflation-adjusted damage, and 2005 was the deadliest since 1928. Forecasts of U.S. hurricane landfalls made as long as 60 hours before the event were excellent, but Earth's atmosphere is still fiendishly unpredictable. It was a meteorologist who instigated the modern appreciation of sensitivity to initial conditions in deterministic mathematical systems (*2*). Thus, both uncertainties in the initial state of the atmosphere and limitations of the numerical models can cause forecasts that started from nearly identical representations of today's weather to diverge after just 3 to 10 days. Hurricane prediction remains an unforgiving enterprise with constant threat of public and costly failure.

There are two crucial aspects to hurricane prediction: forecasting the path it will take (the hurricane track) and forecasting the strongest wind anywhere in the storm (the hurricane intensity). Track forecasts have

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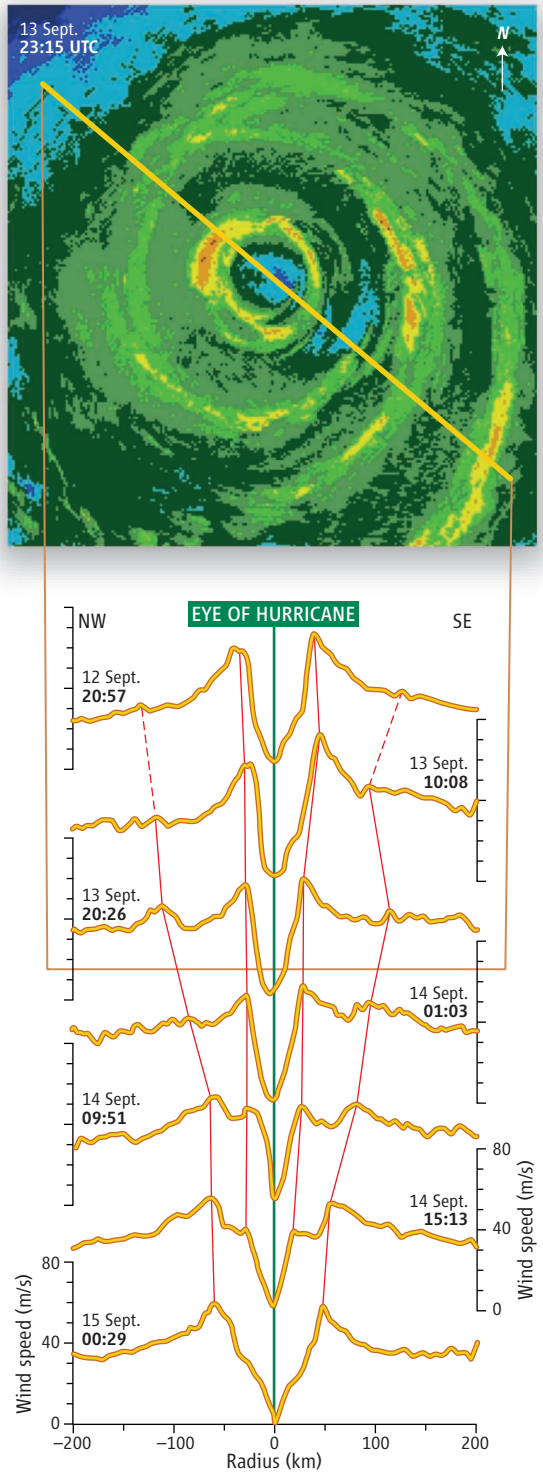
improved steadily over the years, but intensity predictions have lagged a generation behind track forecasts.

Track forecasts are important, because storm surge—flooding by wind-driven water from the sea or lakes—usually causes most hurricane deaths; this was the case also for Hurricane Katrina. Timely evacuation from the surge zone based on track forecasts therefore has the potential to save many lives. Hurricane tracks depend mainly on the steering flow, that is, the prevailing wind around the storm.

Numerical weather prediction models form the basis of modern forecasting. They tabulate meteorological variables on rectangular grids and use the dynamical equations of motion to advance them forward in time. The steering flow has characteristic spatial dimensions of more than 1000 km and takes over 24 hours to change appreciably. Progress in numerical weather prediction and remote sensing has focused on these scales, facilitating advances in track forecasting.

In contrast, to simulate hurricane intensity changes, numerical models need finer grid resolution to represent the small-scale, rapidly evolving organization of convection in the hurricane core. For this reason, improvements of intensity forecasts have been slower. Numerical hurricane simulations (*3*) of individual hurricanes with resolutions of over 5 km predict cyclones that are geometrically larger, weaker cartoons of their counterparts in nature. Intensification and weakening also depend on ocean temperature beneath the storm (*4*), interactions with vertical shear of the steering flow (*5*), and rainbands, eye structure, and other manifestations of the internal dynamics of the storm.

Eyewall replacements, in which a ring of new thunderstorms forms around a preexisting eye, are probably the most difficult phenomena to model. The outer eyewall supplants the inner by intercepting the energy-laden air as it converges toward the original eyewall in contact with the warm ocean. Collapse of the inner eyewall reduces intensity. Subsequently, the hurricane may reintensify if conditions remain favorable.



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Hurricane eyewall replacement. (**Top**) This radar image of Hurricane Floyd shows the eye surrounded by outer and inner concentric eyewalls. The yellow line indicates the approximate aircraft track for the wind profiles below. Image dimensions, 360 km by 360 km. (**Bottom**) Successive profiles in Floyd (yellow curves) of the wind speed at an altitude of 3 km show how an outer eyewall forms, contracts in the course of 51 hours, and replaces the former inner eyewall. Time increases downward and is indicated as date and time next to the axis for each profile. Red lines connect features across time. Image and data from the National Oceanic and Atmospheric Administration's Hurricane Research Division.

Timing and magnitude of these eyewall replacement cycles are crucial to impacts at landfall. In 1992, Hurricane Andrew completed an eyewall replacement, intensified rapidly as it crossed the Gulf Stream, and ripped into Miami-Dade County (*6*). By contrast, eyewall replacements and a less favorable environment reduced Hurricane Floyd of 1999 (see the figure) from a potentially catastrophic windstorm to a rainstorm that caused widespread flooding in the Carolinas. Modeling weakening during eyewall replacements is challenging, but the crucial forecast problem is rapid intensification or reintensification.

The accurate representation of individual bands of convective rainfall in the 1.67-km-resolution RAINEX simulations (*1*) suggests that hurricane modeling may have advanced to the point that sensitivity to initial conditions rather than model shortcomings is the limiting factor. Sensitivity to initial conditions may be overcome by running ensembles of forecasts starting from slightly different initial conditions (*7*). The ensemble mean outperforms individual members, and the ensemble spread provides a measure of forecast reliability.

Windstorm insurers employ catastrophe models based on Monte Carlo simulations of thousands of climatologically representative hurricanes (*8*). The calculated impact of these virtual hurricanes on the actual distribution of insured properties allows insurance companies to estimate underwriting risk on an annual basis. The very realistic RAINEX simulations suggest extension of this well-established technique to predict human and economic impacts of individual, real hurricanes as they approach the coast and pass onshore.

References and Notes

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