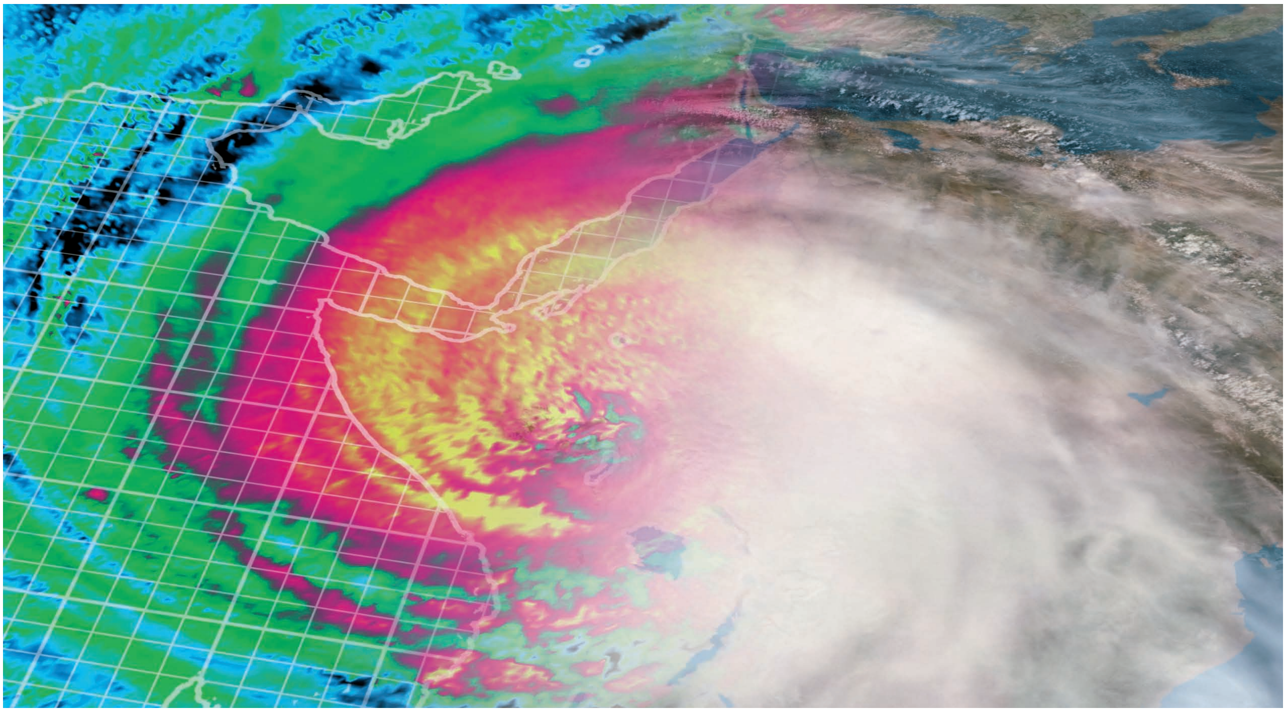
GUEST EDITOR'S INTRODUCTION

The Future of Hurricane Prediction

Future hurricane prediction systems will use high-resolution inner-core observations to perform cloud-resolving analysis and forecasting in massively parallelized high-performance computing facilities.



Hurricanes are strong tropical storms with maximum surface winds greater than 64 meters per second that originate from equatorial oceans. The eye of a hurricane is usually 30 to 50 kilometers wide, but the storm's overall extent might exceed 600 km or more. The damaging winds, torrential rains, storm surges, and flooding caused by hurricanes make them one of the deadliest and costliest natural disasters. Given how destructive hurricanes can be to both human lives and property, the demand for faster and more precise warnings is ever increasing; to provide these, we need more accurate forecast guidance with longer lead times. Over the past few decades, we've made significant progress in short-range predictions of tropical cyclones. This is most notable in track forecasts: today's average 72-hour forecast position is as accurate as a 36-hour track forecast was 15 years ago. However, there's little improvement in our ability to predict hurricane intensity in terms of maximum surface wind speed during

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the same period, and our skill at predicting tropical cyclone formation or rapid intensity changes is quite limited.

Hurricane intensity forecasts are difficult for several reasons; possible factors include:

- deficiencies in the current generation of operational forecast models, which are key tools used by hurricane forecasters;
- a lack of sufficient observations within the hurricane vortex (that is, the inner-core area) or on larger scales over the ocean; and
- the limited ability of operational forecast models to efficiently ingest available observations for initializing the model.

For example, the highest-resolution US National Oceanic and Atmospheric Administration (NOAA) operational forecast models have a horizontal grid-size ranging from six to nine kilometers, which is insufficient to resolve cloud and eyewall dynamics, both of which are key to hurricane intensity change. The use of coarser grid resolution is constrained largely by limited computing resources. Moreover, NOAA's high-resolution intensity forecast guidance models rely heavily on initializing the storms through some form of vortex initialization devoid of observations within the vortex (with the exception of central pressure); neither current generation operational model can assimilate high-resolution hurricane inner-core observations such as those from ground-based or airborne Doppler radars.

The Hurricane Forecast Improvement Program's goal is to significantly improve guidance for hurricane track, intensity, and storm-surge forecasts, and to engage and align interagency and larger scientific community efforts to improve hurricane forecasts and address related challenges.

Recently, NOAA established the Hurricane Forecast Improvement Program (HFIP), a 10-year effort to provide a basis for NOAA and other agencies to coordinate national hurricane research. HFIP's goal is to significantly improve guidance for hurricane track, intensity, and storm-surge forecasts, and to engage and align interagency and larger scientific community efforts to improve hurricane forecasts and address related challenges. Plans include the development of two integral components: improved coupling of atmosphere-ocean-land processes, high-resolution nonhydrostatic regional models, and advanced data assimilation systems that can efficiently assimilate all available observations. Both components will be addressed in this special issue.

In This Issue

In "HWRFx: Improving Hurricane Forecasts with High-Resolution Modeling," Xuejin Zhang, Thiago S. Quirino, Kao-San Yeh, Sundararaman G. Gopalakrishnan, Frank D. Marks, Jr., Stanley B. Goldenberg, and Sim Aberson from NOAA's Hurricane Research Division introduce the development and infrastructure of an experimental system for next-generation hurricane weather research and forecasting. Specifically, they've designed high-resolution hurricane tests to examine whether the increase of horizontal resolution will positively impact the accuracy of both track and intensity forecasts through more realistic structural evolution, including the eyewall replacement process and storm size.

The impact of model resolution and the challenges of predicting hurricanes are further discussed in "High-Resolution Hurricane Forecasts," by Christopher A. Davis, Wei Wang, Steven Cavallo, James Michael Done, Jimy Dudhia, Sherrie Fredrick, John Michalakes, Ginger Caldwell, and Tom Engel. Their experimental hurricane research and forecasting modeling system can resolve a hurricane's deep convective motions, as well as the storm's eye and eyewall. Running at a massively parallel computing facility, the model with finer resolution has the potential to improve intensity prediction.

In "Diagnosing Tropical Cyclone Sensitivity," the US Naval Research Laboratory's James D. Doyle, Carolyn A. Reynolds, and Clark Amerault examine hurricane forecast sensitivity to the initial state using adjoint modeling based on the Navy's next-generation regional-scale hurricane prediction system. As their article describes, using adjoint sensitivity also provides insight into the potential for targeted observations; the design of hurricane monitoring and observing systems; and hurricane dynamics and predictability limits.

Data assimilation produces the best estimate of the model's initial state (initial conditions) by combing all available information sources, including the current observations, the background

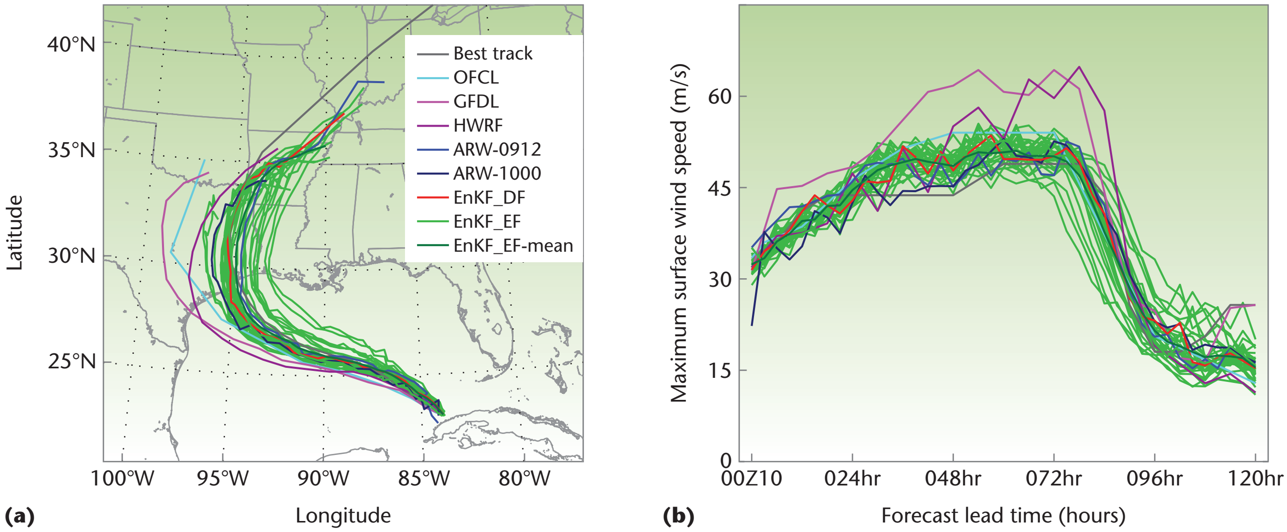

Figure 1. Experimental Hurricane Ike forecasts. (a) The track and (b) intensity forecasts by the 4.5-km weather research and forecasting (WRF) model run with (EnKF) and without (ARW) the ensemble Kalman filter assimilation of airborne Doppler velocity; the ensemble forecast initialized with EnKF perturbations ("EnKF EF"); the NOAA operational forecasts by the Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model and the hurricane weather research and forecast (HWRF) model; the US National Hurricane Center (NHC) official operational forecast model (OFCL) initialized at 0000 UTC 10 September 2008; and the NHC best-track observational analysis (OBS).

information (usually propagated through short-term forecasts), and the inherent uncertainties associated with each source of information. Initial condition errors are another primary source of uncertainties in hurricane prediction. In "Advanced Data Assimilation for Cloud-Resolving Hurricane Initialization and Prediction," Pennsylvania State University's Yonghui Weng, Meng Zhang, and I introduce and compare three of the state-of-the-art initialization and data assimilation approaches. They demonstrate that the ensemble Kalman has greater promise for delivering more accurate forecasts and realistic forecast uncertainties. They also showed a clear advantage in using a 4D variational data assimilation method over a 3D variational method, the latter of which is used in the current-generation of US operational hurricane prediction models.

Outlook for the Future

The studies in this special issue provide insights into hurricane prediction, as well as potential future solutions—especially in terms of intensity forecasts. Among the solutions discussed are

- the development of better numerical models, with improved understanding and parameterization of subgrid scale physical processes;
- the necessity of running the model at cloud-resolving resolutions;
- the need for enhanced surveillance through ground-based and airborne Doppler radars, rawindsondes and dropsondes, and satellite observations;
- the design of better data assimilation techniques to more effectively use observations;
- the need for probabilistic analysis and forecasting given hurricane predictability's inherent limit; and
- the demand for massively parallel advanced computing capabilities.

Since 2008, I've been working with Yonghui Weng at Pennsylvania State University to explore the feasibility of developing a future clouding-resolving ensemble analysis and forecasts system in collaboration with hurricane specialists John Gamache and Frank Marks at NOAA's HRD. As our article in this issue describes, this prototype hurricane prediction system, developed with HFIP support and implemented at the Texas Advanced Computing Center (TACC) high-performance computing facility, uses an ensemble Kalman filter to assimilate high-resolution airborne radar observations from the NOAA P-3 hurricane surveillance aircrafts in real-time.

Figure 1 shows highlights of the prototype's real-time performance for Hurricane Ike, one of the most high-impact landfalling events of 2008. It represents the first time that airborne Doppler radar observations were assimilated in real-time into hurricane prediction models. It also represents the first time that hurricane cloud-resolving ensemble analyses and forecasts were performed in real-time. Finally, our project also featured the unprecedented real-time, simultaneous coordination, parallelization, and on-demand usage of more than 23,000 cluster cores on the TACC high-performance computers.

As Figure 1 shows, the prototype's forecast compared favorably against deterministic operational forecast models, as well as the NOAA official forecasts issued at similar times. In addition, the ensemble system provides clear evidence of flow- or event-dependent uncertainty in hurricane analysis and prediction, which current operational practice still assumes is the climatological average.

This case study—along with all articles in this special issue—highlights the need for more in-depth investigations of how we might use advanced data assimilations techniques, airborne Doppler observations, and cloud-resolving ensemble analysis and forecasts for future hurricane prediction.

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