The CBLAST-Hurricane Program and the Next-Generation Fully Coupled Atmosphere–Wave–Ocean Models for Hurricane Research and Prediction

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The record-setting 2005 hurricane season has highlighted the urgent need for a better understanding of the factors that contribute to hurricane intensity, and for the development of corresponding advanced hurricane prediction models to improve intensity forecasts. The lack of skill in present forecasts of hurricane intensity may be attributed, in part, to deficiencies in the current prediction models—insufficient grid resolution, inadequate surface and boundary-layer formulations, and the lack of full coupling to a dynamic ocean. The extreme high winds, intense rainfall, large ocean waves, and copious sea spray in hurricanes push the surface-exchange parameters for temperature, water vapor, and momentum into untested regimes.

The Coupled Boundary Layer Air–Sea Transfer (CBLAST)-Hurricane program is aimed at developing improved parameterizations using observations from the CBLAST-Hurricane field program (described by Peter Black and colleagues elsewhere in this issue) that will be suitable for the next generation of hurricane-prediction models. The most innovative aspect of the CBLAST-Hurricane modeling effort is the development and testing of a fully coupled[1] atmosphere–wave–ocean modeling system that is capable of resolving the eye and eyewall at ~1-km grid resolution, which is consistent with a key recommendation for the next-generation hurricane-prediction models by the NOAA Science Advisor Board Hurricane Intensity Research Working Group. It is also the National Centers for Environmental Prediction (NCEP) plan for the new Hurricane Weather Research and Forecasting (HWRF) model to be implemented operationally in 2007–08.

[1] The so-called fully coupled model here refers to two-way coupling with simultaneous communication between the two models.

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AIR–SEA INTERACTION AND HURRICANES. Hurricanes rarely reach their maximum potential intensity (MPI, as defined by Kerry Emanuel and Greg Holland). Many factors can prevent a given storm from reaching MPI, including environmental vertical wind shear, distribution of troposphere water vapor, hurricane internal dynamics, and air–sea interactions. The effect of air–sea interactions on hurricane structure and intensity change is the main focus of the CBLAST-Hurricane program. Intensification of a hurricane depends upon two competing processes at the air–sea interface—the heat and moisture fluxes that fuel the storm and the dissipation of kinetic energy associated with wind stress on the ocean surface. Air–sea interaction is especially important within the extremely high winds (up to 75 m s^{-1}) and strong gradient zones of temperature and pressure located in the inner core (eye and eyewall) of a hurricane. The enthalpy and momentum exchange coefficients under the extreme high-wind conditions are, of course, very difficult to determine in precisely the regions where they are most important. The stress is supported mainly by waves in the wavelength range of 0.1–10 m, which are an unresolved "spectral tail" in present wave models.

In the November 1995 *Journal of the Atmospheric Sciences*, Emanuel proposed that storm intensity is largely controlled by the ratio of the air–sea enthalpy

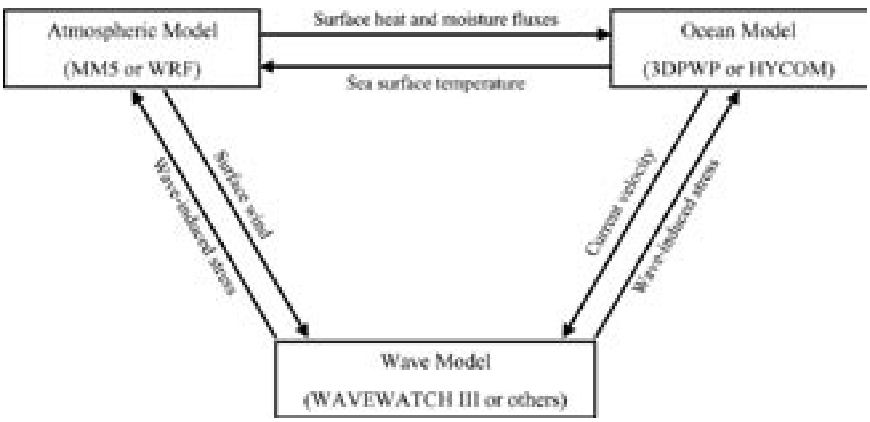


Fig. 1. Schematics of a coupled atmosphere–wave–ocean modeling system with the component atmosphere, surface wave, and ocean circulation models, as well as the coupling parameter exchanges between each of the component models.

and momentum flux exchange coefficients, C_k/C_D. Using a simple axisymmetric model with idealized environmental conditions, Emanuel showed that this ratio needs to be equal to or greater than one for hurricanes to intensify. As shown in many studies, C_D is sea state dependent while C_k has relatively little sensitivity to sea state. Other research shows that the effects of sea spray on the air–sea exchange may also be important. Recent laboratory experiments conducted at hurricane wind speeds by Donelan and colleagues have shown that C_D reaches a saturation point at high-wind speeds greater than about 33 m s^{-1}, when flow separation begins to occur, and that C_k remains relatively constant. The airborne turbulence flux measurements from CBLAST-Hurricane reported in the *Journal of the Atmospheric Sciences* by Drennan and colleagues also support these laboratory results, indicating that C_k/C_D is less than 1 for intensifying storms (e.g., Hurricane Fabian in 2003). The rapid increase in computer power and recent advances in observation technology have made it possible for us to develop a strategy for the next generation of high-resolution hurricane prediction models.

A COUPLED MODELING SYSTEM. This paper describes the strategy and current activity in developing and testing a new, high-resolution, coupled atmosphere–wave–ocean model for hurricane research and prediction. The fully coupled atmosphere–wave–ocean modeling system includes the following three components: the atmospheric model, a surface wave model, and an ocean circulation model. The basic coupling parameters—that is, the data passed between the models—are noted in a schematic in Fig. 1. A specific issue we emphasize here is the determination and parameterization of the air–sea momentum and enthalpy fluxes in conditions of extremely high and time-varying hurricane winds.

The atmospheric model. The atmospheric component of the coupled modeling system will be either the nonhydrostatic fifth-generation Pennsylvania State University (PSU)–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5) or the Weather Research and Forecasting (WRF) model. A special property of the atmospheric model is that it must support very high horizontal resolution. The radius of maximum wind (RMW)—that is, the distance from the center of the eye to the ring of the maximum wind speed—is typically 15–30 km, although occasionally it is as small as 5–10 km, as observed in Hurricanes Lili (2002) and Wilma (2005). To resolve the eye and eyewall structures in a hurricane, the horizontal resolution (or grid spacing) in numerical models needs to be on the order of ~1 km. Figure 2 shows an example of model-simulated Hurricane Floyd (1999) with various grid resolutions and a comparison with the observations (this figure and much of the work described here can be found in more detail in a paper submitted by Chen and Tenerelli to *Monthly Weather Review*). Only the 1.67-km simulation can reproduce the observed inner-core structure, whereas the simulations with 5- and 15-km resolution clearly do not (Fig. 2).

To capture the long life cycle of hurricanes and resolve the inner-core structure, we developed a vortex-following nested grid that allows the model to be integrated for 5 days or longer at a very high resolution (~1 km) in the innermost domain. The high-resolution elevation and land-use data are refreshed on the fine meshes each time they are initialized or moved. We use four nests with 45-, 15-, 5-, and 1.67-km grid spacing. The three inner domains move automatically with the storm. The same vortex-following moving-nest capability has been adapted in WRF. The model has been used to simulate Hurricanes Bonnie (1998) and Floyd (1999). The inner core of hurricanes is simulated explicitly in the cloud-resolving mode.

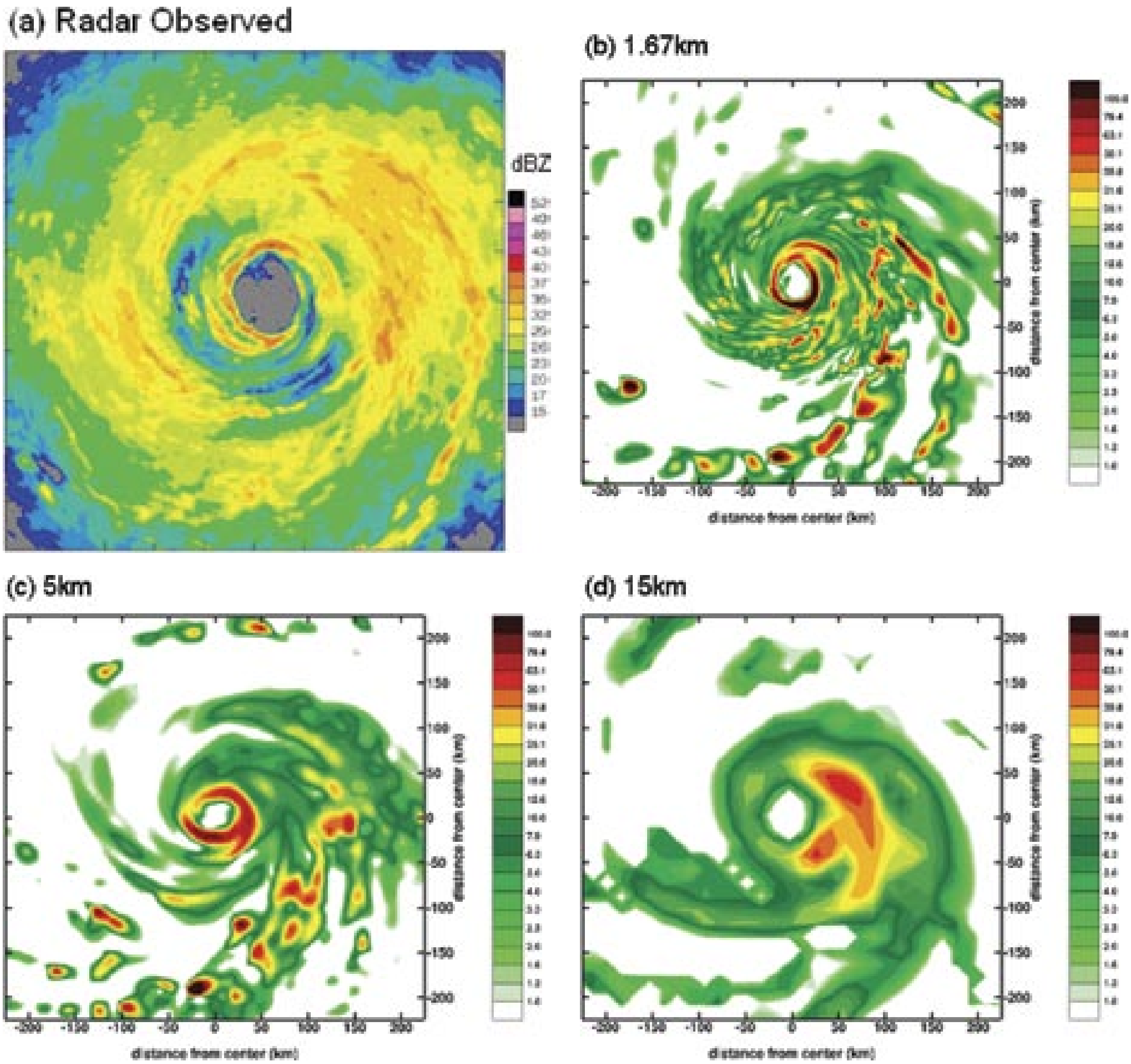


Fig. 2. (a) The NOAA/Atlantic Oceanographic and Meteorological Laboratory (AOML)/HRD airborne radar-observed reflectivity (dB*Z*, over an area of 360 km x 360 km) and the MM5-simulated rain rate (mm h^{-1}) using (b) 1.67-, (c) 5-, and (d) 15-km grid resolution in Hurricane Floyd at 0000 UTC 14 Sep 1999.

The microphysics scheme is based on the work of Wei-Kuo Tao and Joanne Simpson. The Blackadar PBL scheme is used on all grids, but over water we include a modification (based upon Garratt's 1992 book, *The Atmospheric Boundary Layer*) in which we introduce different roughness scales for temperature z_t and moisture z_q. In the uncoupled MM5 and WRF applications, the momentum roughness length z_o over the open ocean is calculated from the relationship described in Charnock's 1955 article in the *Quarterly Journal of the Royal Meteorological Society*. The NCEP global analysis fields (6 hourly and 1° × 1°) and the high-resolution (~9 km) Advanced Very High Resolution Radiometer (AVHRR) Pathfinder SST analysis as well as the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) Advance Microwave Sounding Radiometer (AMSR) SST (~25 km) are used to initialize the uncoupled MM5 and provide continuous lateral and lower boundary conditions.

Ocean model. Hurricanes draw energy from the ocean surface, and they cool the ocean by wind-induced

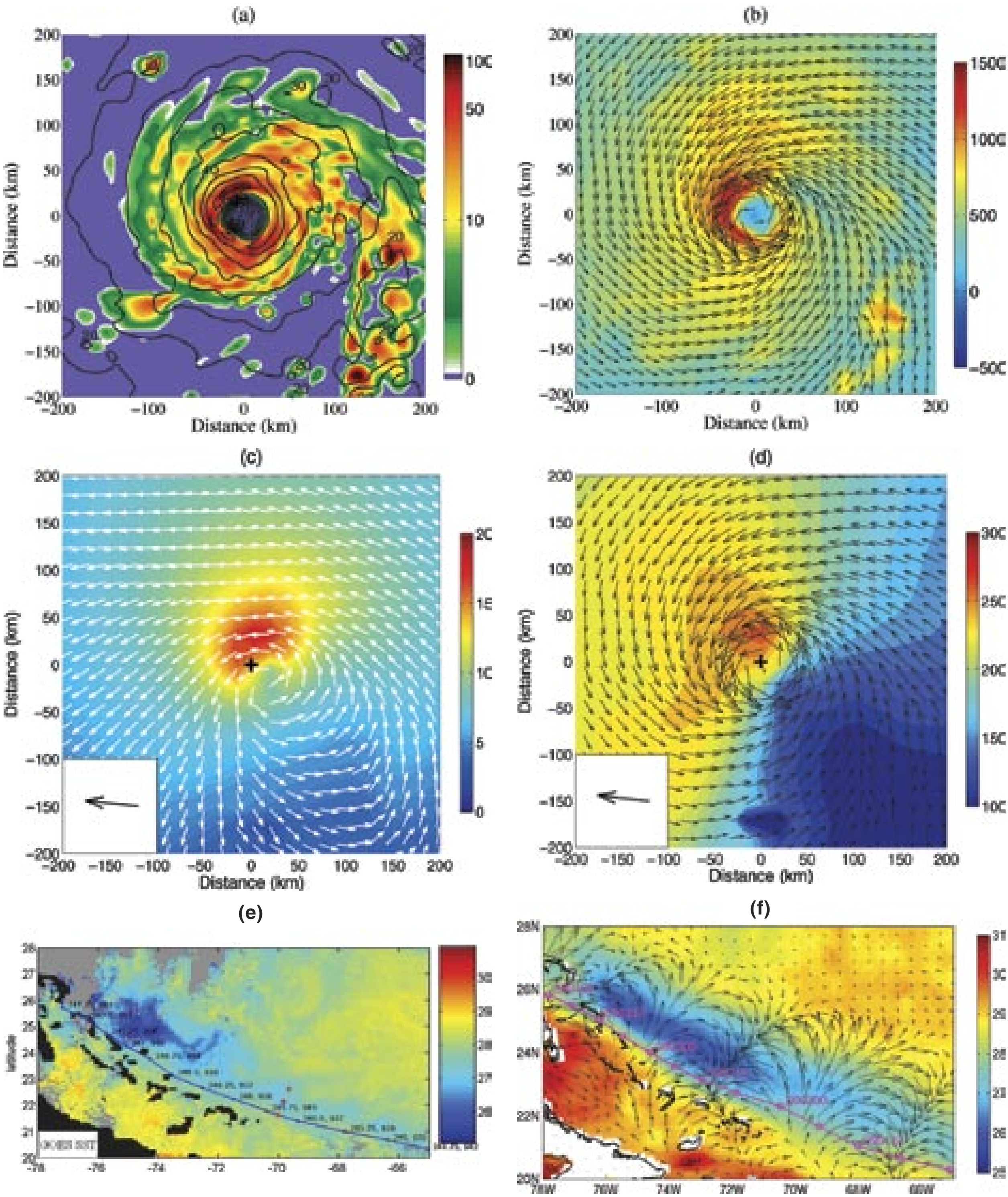
Fig. 3 (opposing page). Coupled model-simulated (a) rain rate (color, mm h^{-1}) and surface wind speed (black contour with 10 m s^{-1} interval); (b) enthalpy (sensible + latent) flux (color, W m^{-2}) and surface wind (vector); (c) significant wave height (SWH) (color, m) and wave propagation direction (white vectors); and (d) mean wavelength (color, m) and surface wind (black vectors) in Hurricane Frances at 1200 UTC 31 Aug 2004. The black "+" indicates the storm center of Hurricane Frances. The arrow in the lower-left corner indicates the direction of the storm motion. (e) Observed and (f) model-simulated SST (color, °C) and ocean surface current (vectors) in Hurricane Frances at 1200 UTC 4 Sep 2004. Storm tracks are overlaid on each of the SST maps. The red stars indicate the locations of the Electromagnetic-Autonomous Profiling Explorers (EM)-APEX floats: 1636 (on the storm track), 1633, and 1634 (50 and 100 km away from the storm center, respectively). The observed vertical temperature and salinity profiles from the EM-APEX floats are used in the ocean model initialization and evaluation.

surface fluxes, which are crucial to the hurricane, and by vertical mixing, which is dominant with the ocean surface layer. This vertical mixing occurs as a response to the large-amplitude near-inertial currents generated within the oceanic mixed layer (OML). Upward vertical motion generated by the wind-driven currents (upwelling) may also enhance SST cooling by lifting the base of the OML and bringing cooler water closer to the sea surface. The amplitude of SST cooling resulting from a given hurricane thus depends in part upon the thermal stratification of the upper ocean, which is sometimes represented by an integrated heat content. The oceanic part of a coupled modeling system then should include a realistic thermal stratification, an appropriate parameterization of vertical mixing, and the possibility of upwelling to achieve an accurate representation of the SST cooling.

The ocean model in the coupled system will be a three-dimensional, primitive equation, hydrostatic upper-ocean model (the 3DPWP of Price et al.'s 1994 *Journal of Physical Oceanography* paper) or the Hybrid Coordinate Ocean Model (HYCOM; developed by Chassignet et al.). It is used to simulate the upper-ocean current and temperature fields underneath the hurricane. The 3DPWP model domain is the same as the outer domain of the atmospheric model with 15-km grid spacing. It has 30 vertical levels with grid spacings of 5–10 m for the top 20 levels and 20 m for the remaining levels. It is initialized using observed and climatological temperature and salinity profiles. The temperature profile is blended from selected prestorm airborne expendable bathythermograph (AXBT) observations from Hurricane Research Division (HRD) aircraft missions and LEVITUS94 climatological temperature data for depths greater than those sampled by AXBT observation. At each time step of the ocean model (10 min), the ocean model takes surface stress and heat and moisture fluxes from the atmospheric and wave models and steps ahead the ocean dynamics. At the same time interval, the ocean model passes back the SST anomaly (the difference between the initial and current SST) to the atmospheric model, and passes back the ocean surface current to the wave model.

Surface wave model. The coupling of the atmosphere through waves to the ocean is best served by a direct calculation of the evolution of the wave field and the concomitant energy and momentum transfer from wind to waves to upper-oceanic layers. A third-generation wave model, the WAVEWATCH III (WW3), is used to simulate ocean surface waves in the atmospheric–ocean–wave coupling system. It was developed by Tolman in *Weather and Forecasting* (2002) for wind waves in slowly varying, unsteady, and inhomogeneous ocean depths and currents. WW3 is extensively evaluated and validated with observations. The wind waves are described by the action density wave spectrum $N(k, \theta, x, y, t)$. We use 25 frequency bands, logarithmically spaced from 0.0418 to 0.41 Hz at intervals of $\Delta f/f = 0.1$, and 48 directional bands at 7.5° intervals. The water-depth data used in the wave model are the 5-min gridded elevation data from the National Geophysical Data Center. In the coupled system, the wave model inputs the surface-wind and ocean-surface current fields from the atmospheric and ocean models and outputs surface stress integrated from a new wind–wave coupling parameterization developed by the CBLAST modeling team.

Most of the wind stress is supported by surface waves with a wavelength that is less than the cutoff, typically 10 m, of existing third-generation wave prediction models. In order to correct this shortcoming, a new wave and wind-stress prediction model has been developed and is being tested against both field data, with respect to its prediction skill in rapidly changing wind conditions, and laboratory



data of direct measurements of wave spectra and Reynolds stress. We developed a new wind–wave parameterization that includes effects of the wave spectral tail on the drag coefficient. It calculates directional stress using surface-wave directional spectra by parameterizing "spectral tails" (frequency > cutoff frequency) unresolved by the wave models. The wind–wave parameterization incorporates an important feature shown in the 2004 Donelan et al. article in *Geophysical Research Letters*: that the drag coefficient becomes saturated once the wind speed exceeds 33 m s^{-1}. Beyond this speed, the surface simply does not become any rougher in an aerodynamic sense. In the range of wind speeds from 10 to 26 m s^{-1} these laboratory measurements parallel the open-ocean measurements of Large and Pond published some 25 years ago in the *Journal of Physical Oceanography*, but are a little lower. Donelan et al. attributed a change in flow characteristics leading to saturated aerodynamic roughness to a flow separation resulting from continuous wave breaking, where the flow is unable to follow the wave crests and troughs (as shown by Reul et al. in the July 1999 issue of *Physics of Fluids*). Others have indicated that C_D may decrease in very high wind speeds.

In most coupled wind–wave models, such as those described by Bao et al. in 2000 and Doyle in 2002 in *Monthly Weather Review*, the surface roughness is treated as a scalar. However, the swirling winds in both extratropical and tropical cyclones are highly variable, and hence the stress vector is not necessarily in the same direction as that of the local wind vector. Instead of computing a scalar roughness from the total stress, we use a method of directionally coupling the wind and waves. Although the stress vector was used in an uncoupled, one-way-forced wave model by Moon et al. in the October 2004 *Journal of the Atmospheric Sciences*, its impact on hurricanes has not been tested in a high-resolution, fully coupled model until now.

COUPLED SIMULATIONS AND FUTURE PLANS. The CBLAST-Hurricane coupling parameterizations are currently being tested in the fully coupled modeling system. Model-simulated storm tracks, structure, and intensity for several Atlantic hurricanes—including Hurricane Frances (2004), which is one of the best-observed storms during the CBLAST-Hurricane 2004 field program—are compared with observations. To isolate the effects of the surface waves from that of upper-ocean circulation, including SST, we conducted three separate model simulations for each storm, including the uncoupled atmosphere, coupled atmosphere–ocean, and fully coupled atmosphere–wave–ocean simulations. Model simulations are evaluated with observations of directional wave spectra, SST, air–sea fluxes, profiles of the atmospheric boundary layer, ocean temperature, salinity, and current from various in situ, airborne, and satellite data. Figure 3 shows an example of the fully coupled model simulation in comparison with observations in Hurricane Frances (2004). The high-resolution, fully coupled hurricane simulations show details of the hurricane inner-core structure, as well as surface waves and fluxes that have not been possible in the current operational forecast models. Hurricane-induced surface waves are highly asymmetric (Figs. 3c and 3d) as observed during the CBLAST-Hurricane field program and in Hurricane Bonnie (1998). The complex wave field that determines the surface stress and the storm's interaction with a dynamic ocean (Figs. 3e and 3f) in the coupled model can significantly affect the storm structure and intensity.

Observations from the CBLAST-Hurricane field program provided a unique dataset to evaluate and validate fully coupled models. The high-resolution, fully coupled model is capable of capturing the complex hurricane structure and intensity change. The coupling to the ocean-circulation model can improve the storm intensity forecast by including the storm-induced cooling in the upper ocean and SST, whereas the uncoupled atmosphere model with a constant SST may overintensify the storms. However, without coupling to the surface waves explicitly, both the uncoupled atmospheric model and the coupled atmosphere–ocean model underestimate the surface wind speed, even though the sea level pressure may be close to that of the observed values. The pressure and wind-speed relationship of a hurricane is one of the most complex and difficult parameters to predict, because it is quite sensitive to the details of the treatment of surface roughness and momentum flux. The full coupling with the CBLAST wave–wind parameterization will improve the model-predicted wind–pressure relationship, which is a key issue in hurricane intensity forecasting. The fully coupled model simulations will be compared with the observations of Landsea et al. (from *The Atlantic Hurricane Database Reanalysis Projects,* published by Columbia University Press) and the CBLAST data. Other factors affecting surface heat and moisture fluxes, such as sea spray, will be explored in the fully coupled modeling system.

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