High-Resolution Simulations of Hurricane Floyd using MM5 Coupled with a Wave Model

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1. Introduction

Over the last a few decades hurricane track forecasts have improved significantly, whereas relatively little progress made in hurricane intensity forecasts. The lack of skill in the intensity forecasting may be attributed to deficiencies in the operational prediction models: insufficient spatial resolution, inadequate surface and boundary layer parameterizations, and no full coupling to the ocean. Recently, it has been demonstrated that hurricane intensity in both idealized, axisymmetric, quasi-balanced models (Emanuel, 1995) as well as "full-physics" nonhydrostatic models (Braun and Tao, 2000) exhibit significant sensitivity to the ratio of the bulk exchange coefficient for enthalpy (C_k) to the exchange coefficient for momentum (C_d). Over the open ocean, roughness length (therefore, Cd) is strongly affected by ocean wave fields. Bao et al. (2000), in their simulation of Hurricane Opal (1995) with MM5 coupled to both a wave model and an ocean model, found modest sensitivity of the simulation to coupling with the wave model, although their simulation was limited to a horizontal grid spacing of 15 km on the finest mesh. In this study we examine the impact of coupling the MM5 to a wave model (WAVEWATCH III) on a high-resolution (1.67 km) six-day simulation of Hurricane Floyd (1999).

2. Methodology

We use a version of MM5 with vortex following mesh refinement scheme described in (Tenerelli and Chen, 2000). As in Tenerelli and Chen (2000), we initialize the model at 0000 UTC 11 September 1999 with the initial fields from the NCEP AVN model on a 1.25^{o}x1.25^o mesh. Instead of using global SST analysis from NCEP, we use the 9-km AVHRR Pathfinder SST data in a manner described in Tenerelli and Chen (2001). We use successive 12-hourly initial NCEP model fields for the lateral boundary conditions.

Four levels of nesting are used, with grid spacings of 45 km on the (fixed) coarsest mesh and 1.67 km on the finest mesh. There are 28 vertical levels in the model, with 9 levels below 900 hPa at the initial time.

We use both an explicit moisture scheme and a slightly modified Kain-Fritsch cumulus parameterization on the 45 and 15 km meshes, and the explicit moisture scheme only on the 5 and 1.67 km meshes. The Blackadar PBL scheme is used on all meshes, but we include the modification of Pagowski and Moore (2001) in which we introduce different roughness scales for temperature (z_t) and moisture (z_q). In the original formulation of the Blackadar scheme, the roughness scales for temperature and moisture are identical to that for momentum (z_0), and this is inappropriate since the physics governing momentum transfer at the surface are different from that governing temperature and moisture.

The wave model is WAVEWATCH III (Tolman and Chalikov, 1996; Tolman, 1999). The basic predicted variable in this model is the wave action spectrum, $N(k, \theta; x, y, t)$, where k is the wavevector magnitude, θ is the wavevector direction, and x, y, and t are space and time coordinates, respectively. We employ a frequency range of 0.0418 - 0.41 s^{-1}, and we use a frequency spacing Δf such that $\Delta f/f = 0.1$. The directional spacing is 7.5^o, and the horizontal grid spacing is 1/6^o both zonally and meridionally.

We modify the sea surface roughness calculation in WAVEWATCH III to the formulation of Donelan et al. (1993), which is based on observations from several field experiments. The roughness length is wave age dependent. It should be noted that there is no observation currently available at high wind ($>$ 25 m s^{-1}) conditions.

We begin all simulations with a 45 km and a 15 km mesh. We introduce a 5 km mesh 24 hours into the simulation, and then a 1.67 km mesh 36 hours after the initial time. All meshes except the coarsest mesh are recentered on the vortex each hour. The big time step for the atmospheric model is 2 minutes. Every ten minutes lowest half-sigma level winds from all active domains are interpolated onto the fixed wave model grid. The interpolated winds are then sent to the wave model and then the wave model is integrated for ten minutes. We then compute a roughness length for the atmospheric model based on the wave age-dependent surface stress associated with the surface waves calculated within the wave model. The atmospheric model is then integrated for ten minutes using the roughness length computed using information from the last call to the wave model.

3. Results

Hurricane Floyd (1999) developed from a tropical depression in the Atlantic on 10 September 1999 and became an intense category 4 hurricane prior to making landfall in the Bahamas, where it recurved and eventually made landfall in North Carolina on 16 September. Tenerelli and Chen (2000) describes the MM5 simulation of Floyd with the original surface flux formulation in the Blackdar PBL. To investigate the sensitivity to the new surface flux calculation and wave coupling, we performed two simulations: one with no coupling and one with coupling to the wave model. Both simulations use the new surface flux

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calculation. Other than the coupling, the two simulations are identical. Below we compare the two simulations and highlight differences between the two simulations.

The minimum sea-level pressure (SLP) for all three simulations and the best estimate of the actual minimum sea-level pressure from NHC is shown in Fig. 1. The most evident feature is the fact that with the original surface flux scheme we obtain a storm that is far deeper than observed. Because both latent and sensible heat fluxes are calculated based on a single roughness length z_0, unrealistically large heat fluxes contribute to the overintensification. With the new scheme the minimum central sea-level pressure attained by the storm is over 30 hPa higher and much closer to the observed minimum pressure. The difference in intensity between the uncoupled and coupled simulations is not as large, but noticeable. The coupled run is about 10 hPa weaker than the uncoupled run at the time of maximum difference, but the minimum pressures attained by the simulations are within 5 hPa. The model simulated storm track is about 100 km too far west than the observed one, which moves over the warmest Gulf Stream water. This explains the difference between the model results and the observations in minimum SLP after 14 September.

There is a large spatial variability in the ocean wave fields around the hurricane. Fig. 2 shows the significant wave heights from WAVEWATCH III and the wind speed at the lowest half sigma level near the vortex center. The significant wave heights are generally larger in the front-right quadrant of the storm, despite the relative symmetry of the wind speed. This is in agreement with the observation of Wright et al. (2000). Fig. 3 shows that the nondimensional drag coefficient for the coupled simulation is not symmetric about the center of the vortex. This is to be expected from the formulation of the wave induced stress, in which the drag coefficient is largest where the wave age is smallest (Donelan et al. 1993).

In contrast, the nondimensional drag coefficient, C_d, for the uncoupled simulation is symmetric about the center of the vortex (Fig. 4). This is not surprising given that, in the uncoupled run, the drag coefficient depends on the roughness length and the stability. The roughness length is a function of friction velocity which is independent of ocean waves. The storm is essentially symmetric in all variables that can influence the stability and roughness length, the drag coefficient must be essentially symmetric as well, which is unrealistic.

The asymmetry in the wave-dependent drag coefficient around a hurricane is mainly associated with the fact that the roughness length is a function of wave age in the coupled simulation. Fig. 5 shows a scatterplot of the roughness length for the coupled simulation, nondimensionalized by a factor g/u_*^2, similar to Doyle (1995). For a given wind speed, the roughness length is significantly larger for young-wind sea waves than the fully developed old waves. This is clearly shown in Fig. 3 that the front-right quadrant of the hurricane is dominated by sea swell, whereas yound waves prevail in the left-rear quadrant. For comparison, the constant roughness length for the uncoupled simulation, corresponding to a Charnock constant of 0.018, is shown as a straight line in Fig. 5.

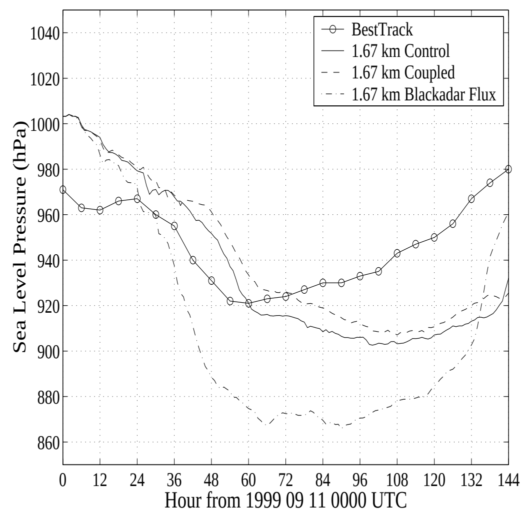

FIG. 1: Hurricane Floyd minimum sea leavel pressure. Best Track (solid with circles); MM5 1.67 km uncoupled run (solid); MM5 1.67 km coupled run (dashed); MM5 1.67 km run with original Blackadar surface flux formulation (dash-dotted).

4. Conclusions

Model simulated Hurricane Floyd intensity is sensitive to the surface parameterizations of heat and momentum fluxes as well as the wind-wave coupling. The new modified sensible and latent heat flux calculation in the Blackdar PBL improves the intensity forecast by about 30 hPa. Comparison of the uncoupled and coupled simulations suggests that the spatial pattern of the nondimensional drag coefficient is substantially altered by the coupling, with higher drag coefficients to the left of the storm, where the wave age is smallest. By contrast, in the uncoupled simulation the drag coefficient is nearly azimuthally symmetric. For a young windsea condition in hurricanes, use of the Charnock formua in the uncoupled simulation underestimates the roughness length. The coupled MM5-WAVEWATCH III simulation seems to improve the overintensification problem in the uncoupled run.

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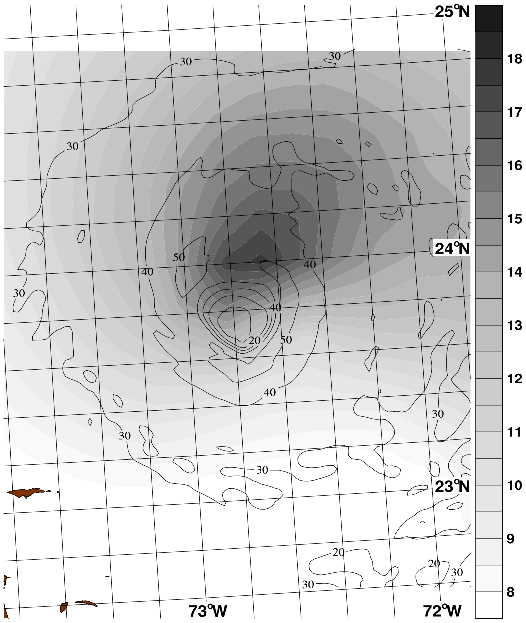

FIG. 2: Significant wave height in meters (shaded) for the coupled simulation; and lowest half-sigma level horizontal wind speed (ms^{-1}, contoured), for Hurricane Floyd at 0000 UTC, 14 Sept 1999.

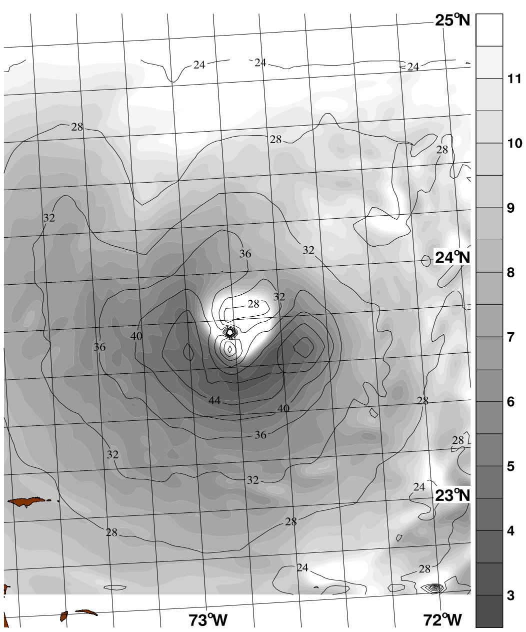

FIG. 3: Wave age, C_p/u_* (shaded), and the nondimensional drag coefficient, C_d (x 10^4, contoured), for the coupled 1.67 km simulation, for the same time as in Fig. 2.

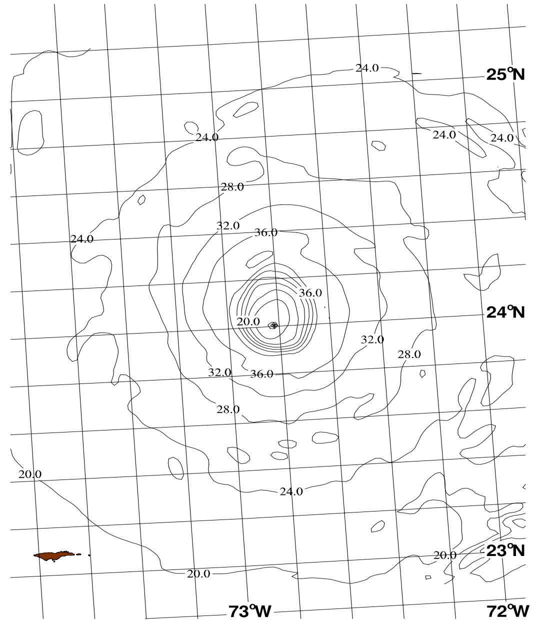

FIG. 4: Nondimensional drag coefficient, C_d (x 10^4, contoured) for the control (uncoupled) 1.67 km simulation, for the same time as in Fig. 2.

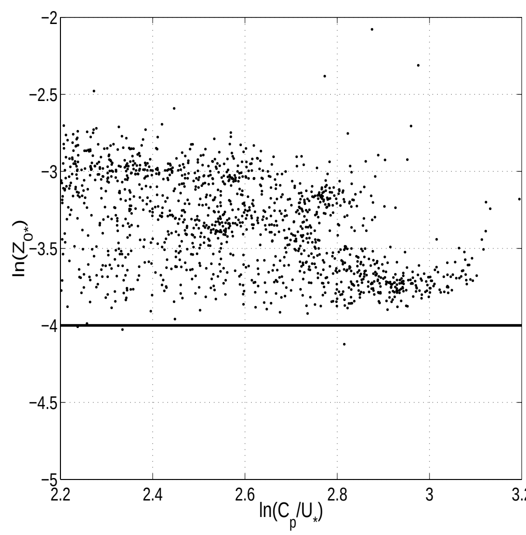

FIG. 5: Scatterplot of nondimensional roughness length (gz_0/u_*^2) versus wave age (C_p/u_*) for the same time as in Fig. 2. Also shown is the nondimensional roughness length corresponding to a Charnock constant of 0.018.

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