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Project Title: Improving the Hurricane WRF-Wave-Ocean Coupled System for Transition to Operations
Recipient Name: The University of Rhode Island
Investigator: Isaac Ginis
Report Type: Annual Report
Reporting Period: 08/01/2007 - 09/30/2008

Work Accomplishments:

1. Tasks scheduled for Year 1:

a) Implementing the URI wave boundary layer model into the HWRF.
b) Improving internal momentum flux parameterization in the WW3 wave model for hurricane conditions.
c) Assimilating mesoscale oceanic features for improved HWRF model initialization.
d) Evaluation and operational implementation of the wave coupling in the HWRF.

2. Tasks accomplished this period

We report here only the tasks completed since 2/01/2008. The prior tasks are reported in our semi-annual report.

a) Implementing the URI wave boundary layer model into the HWRF

We continued the effort towards improving the parameterization of the momentum fluxes in HWRF. Recent observations suggest that the drag coefficient is significantly lower than the traditional bulk parameterization in high wind conditions (Black et al. 2007, Powell, 2007). In fact, the observations are lower than the physics-based parameterization of Moon et al. (2007) implemented in the operational HWRF and GFDL hurricane models in 2007 (Figure 1). This discrepancy is likely because the parameterization based the coupled wind-wave (CWW) model of Moon et al. (2007) does not account for all relevant physical processes. The CWW model is based on an assumption that the form drag at the sea surface is mainly due to smooth non-breaking waves.

We have developed a new coupled wind and wave formulation that includes the enhanced form drag of breaking waves. Breaking and non-breaking waves induce air-side fluxes of momentum and energy in a thin layer above the air-sea interface within the constant flux layer (the wave boundary layer). By imposing momentum and energy conservation in the wave boundary layer and wave energy conservation, we have derived coupled nonlinear advance-delay differential equations governing the wind speed, turbulent wind stress, wave height spectrum, and the length distribution of breaking wave crests. The system of equations is closed by introducing a relation between wave dissipation (due to breaking waves) and the wave height spectrum. Wave dissipation is proportional to nonlinear wave interactions, if the wave curvature spectrum is below the threshold saturation level. Above this threshold, however, wave dissipation rapidly increases, so that the wave height spectrum is limited.

The improved CWW model was first applied for fully grown seas and then was applied for a wide rage of wind wave conditions from laboratories to the open ocean. Kukulka and Hara (2008a,b) investigated the effect of air flow separation due to breaking waves on the air-sea momentum flux and concluded that the contribution of breaking waves is increasingly important for younger seas under higher wind speeds. However, the precise effects of surface breaking waves on the drag coefficient are still under investigation and are not yet explicitly calculated in our model. The other physics missing in the CWW model is the impact of sea sprays generated by breaking waves. Andreas et al. (2004) suggested that sea sprays may significantly reduce the drag coefficient at very high wind speeds. We are collaborating with scientists at NOAA's ESRL Chris Fairall and Jian-Wen Bao to introduce this effect into our CWW model. Since the effects of surface breaking waves and sea sprays on the drag coefficient are still uncertain, we instead introduced two purely empirical parameterizations of the drag coefficient based on the recent observations, shown in Fig. 1. These new formulas are being now tested in the HWRF model.

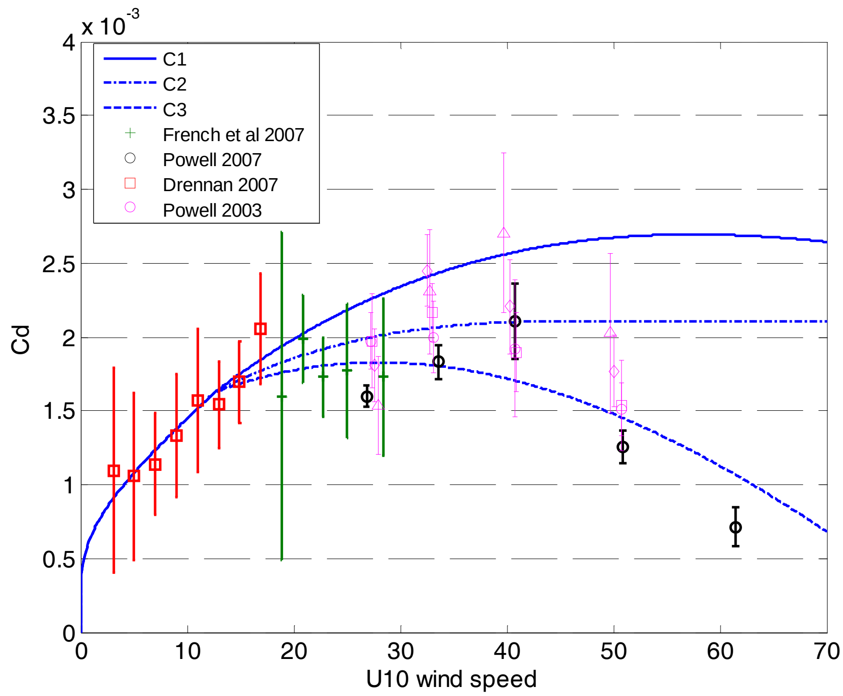

Figure 1. *Three sea state independent drag coefficient formulae (C1: parameterization implemented into the operational HWRF and GFDL model; C2: proposed drag formula to saturate at high winds, C3: proposed drag formula to decrease at high wind) are compared with previous observations (symbols with error bars). Different symbols of Powel (2003) indicate estimates from different wind profile ranges.*

b) Improving internal momentum flux parameterization in the WW3 for hurricane conditions.

We continued to work on improving and testing the momentum flux parameterization in WW3 wave model. The effect of wave-current interaction in WW3 was introduced and investigated under a tropical cyclone wind forcing. The model results were compared with field observations of the surface wave spectra from a scanning radar altimeter, NDBC time series and satellite altimeter measurements in Hurricane Ivan (2004) (Fan et al. 2008d). The results suggest that WW3 with the original drag coefficient parameterization tends to overestimate the significant wave height and the dominant wave length, and produces a wave spectrum that is higher in wave energy and narrower in directional spreading. When an improved drag parameterization is introduced and the wave-current interaction is included, the model yields improved forecast of significant wave height and wave spectral energy, but underestimates the dominant wave length (Figure 2). When the hurricane moves over mesoscale ocean features (warm- and cold-core rings, Loop Current), the current response can be significantly modulated by the non-linear interaction of the storm-induced and pre-existing strong currents in the mixed layer. This modulation also affects surface gravity wave prediction (Fan et al. 2008d).

c) Assimilating mesoscale oceanic features for improved HWRF model initialization.

Coupled hurricane-ocean forecast models require proper initialization of the ocean thermal structure. Yablonsky and Ginis (2008) have created a feature-based (F-B) ocean initialization procedure to account for spatial and temporal variability of mesoscale oceanic features in the Gulf of Mexico, including the Loop Current (LC), warm-core rings (WCRs)] and cold-core rings (CCRs). Using this F-B procedure, near real-time maps of sea surface height and/or the 26°C isotherm depth, derived from satellite altimetry, can be used to adjust the position of the LC and insert WCRs and/or CCRs into the background climatological ocean temperature field prior to hurricane passage. For the 2008 Atlantic hurricane season, the full version of the procedure was implemented in both the GFDL and HWRF models. We worked with TPC staff to implement these changes before the start of the 2008 hurricane season. It is worthwhile to note that the full version can also assimilate real-time in situ data such as AXBT profiles, as discussed in Yablonsky and Ginis (2008).

To evaluate the impact of assimilating mesoscale oceanic features on both the SST cooling under the storm and the subsequent intensity change of the storm GFDL coupled hurricane-ocean model sensitivity experiments for selected hurricanes were run with and without altimeter data assimilation. Simulations of Hurricane Katrina (2005) are shown in Figure 3 and Figure 4. In the CTRL case, the Loop Current and a warm core ring are assimilated using altimetry to accurately represent these features (Figure 3a). In the CLIM case, the Loop Current is initialized instead in its climatological position, and no warm core ring is assimilated (Figure 3b). The presence of the Loop Current and warm-core eddy reduced the SST cooling along the hurricane track in the CTRL case (not shown) and allowed the storm to become more intense (Figure 4). In fact the CTRL case forecasts the intensity of the actual storm much better than the CLIM case does.

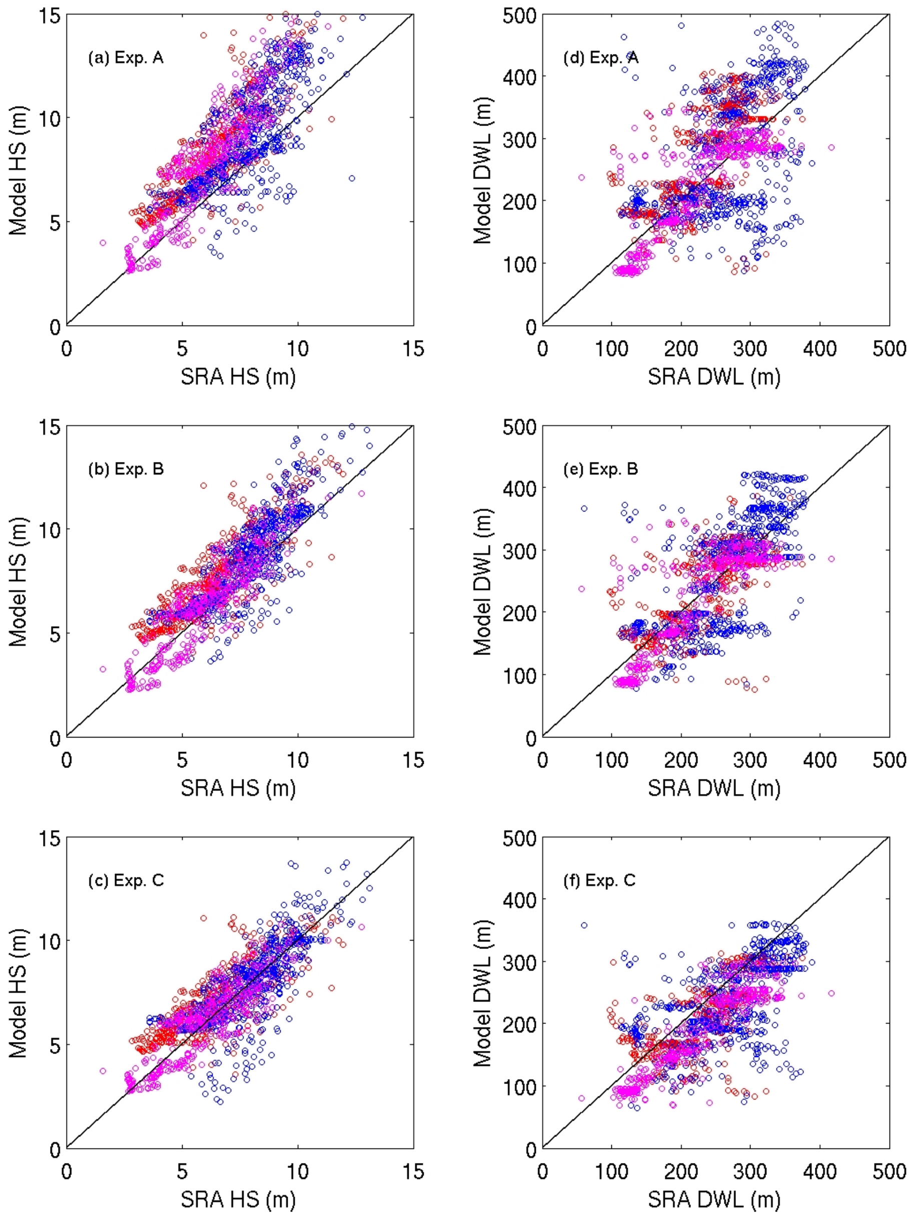

Figure 2. *Model significant wave height (H_s) vs. SRA measurements (left panels); and model dominant wave length (DWL) vs. SRA measurements (right panels) for (d) Exp. A with original WW3 drag coefficient, (e) Exp. B with new drag coefficient based on the coupled wind wave model, and (f) Exp. C with the new drag coefficient and with the effect of ocean currents. The magenta, red, and blue circles correspond to the calculation period of September 9, 12 and 14-15.*

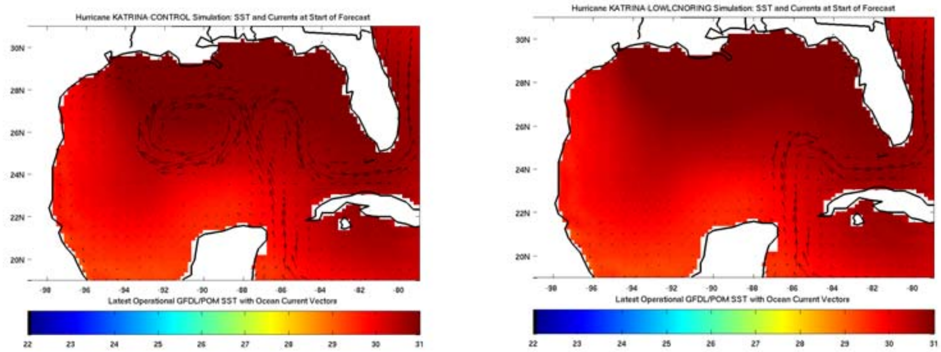

Figure 3. *SST and surface currents for Hurricane Katrina coupled GFDL model forecasts with the Loop Current and a warm core ring initialized based on altimetry to represent the actual location as of 26 August 2005 (left panel) and a modified Hurricane Katrina coupled GFDL model forecast in which the Loop Current is initialized in its climatological position, and no warm core ring is assimilated (right panel).*

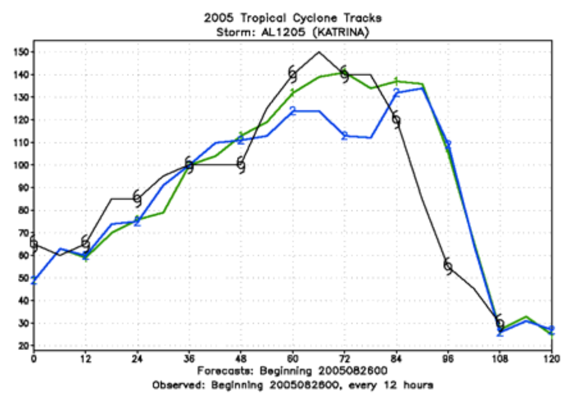

Figure 4. *Hurricane Katrina maximum wind speed (kt) for CTRL (green line; "1" symbols), CLIM (blue line; "2" symbols), and observations (black line; hurricane symbols).*

d) Evaluation and operational implementation of the wave coupling in the HWRF.

In the present operational HWRF and GFDL coupled hurricane models, momentum and kinetic energy fluxes into ocean currents are set to be exactly equal to the fluxes from air, neglecting their dependence on the sea state. However, under hurricane conditions the surface wave field is complex and fast varying in space and time and may significantly affect the fluxes at the air-sea interface. We performed numerical experiments under different idealized TC wind fields using a wind-wave coupled model, and air-sea kinetic energy and momentum flux budget equations (Fan et al. 2008a,b). The model results indicate that spatial and temporal variations of the TC-induced surface waves play an important role in reducing the kinetic energy and momentum fluxes into subsurface currents, mostly in the rear-right quadrant of the TC. For a TC with maximum wind speed of 45 ms^{-1}, the reduction can be as much as 9% (6%) for kinetic energy (momentum) flux in the vicinity of the radius of maximum wind (Figure 5). These results suggest that it is important to explicitly resolve the effect of surface waves for accurate estimations of the momentum and kinetic energy fluxes at the air-sea interface in hurricanes.

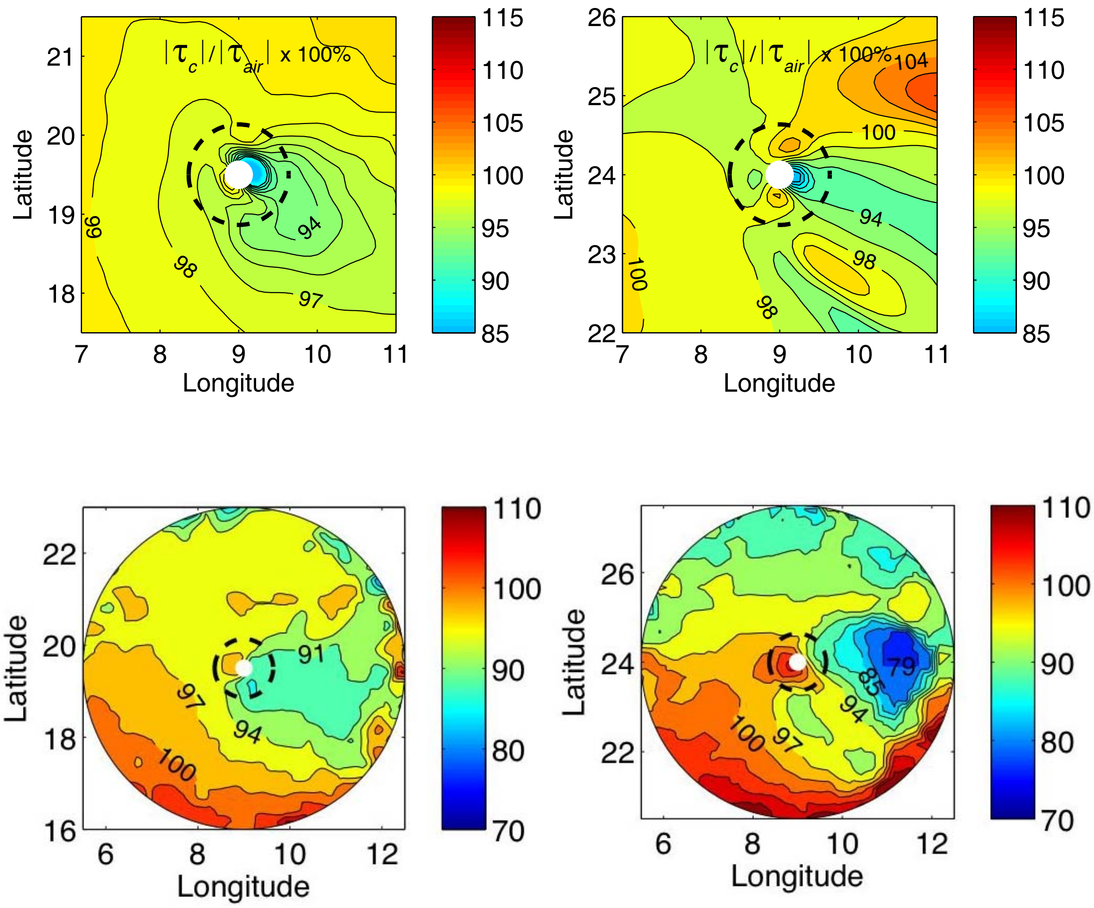

Figure 5. *Percentage of momentum (top) and kinetic energy (bottom) fluxes into subsurface currents relative to air input produced by the idealized moving tropical cyclone with the trnaslation speed of 5ms^{-1} (left) and 10ms^{-1} (right). The dashed circle and white dot represent the radius of maximum wind and the center of the tropical cyclon, respectively.*

We investigated the wind-wave-current interaction mechanisms in tropical cyclones and their effect on the surface wave and ocean responses through a set of numerical experiments (Fan et al. 2008c). The results show that the time and spatial variations in the current field reduces further the momentum flux into the currents, primarily in the rear-right quadrant of the hurricane. The reduction of the momentum flux into the ocean consequently reduces the magnitude of the subsurface current and sea surface temperature cooling to the right of the hurricane track and the rate of upwelling/downwelling in the thermocline (Figure 6). During wind-wave-current interaction, the momentum flux into the ocean is mainly affected by reducing the wind speed relative to currents, while the wave field is mostly affected by refraction due to the spatially varying currents. In the area where the current speed (in the wave propagation direction) has local maximum, the wave spectrum of longer waves is reduced, the peak frequency is shifted to a higher frequency, and the angular distribution of the wave energy is widened.

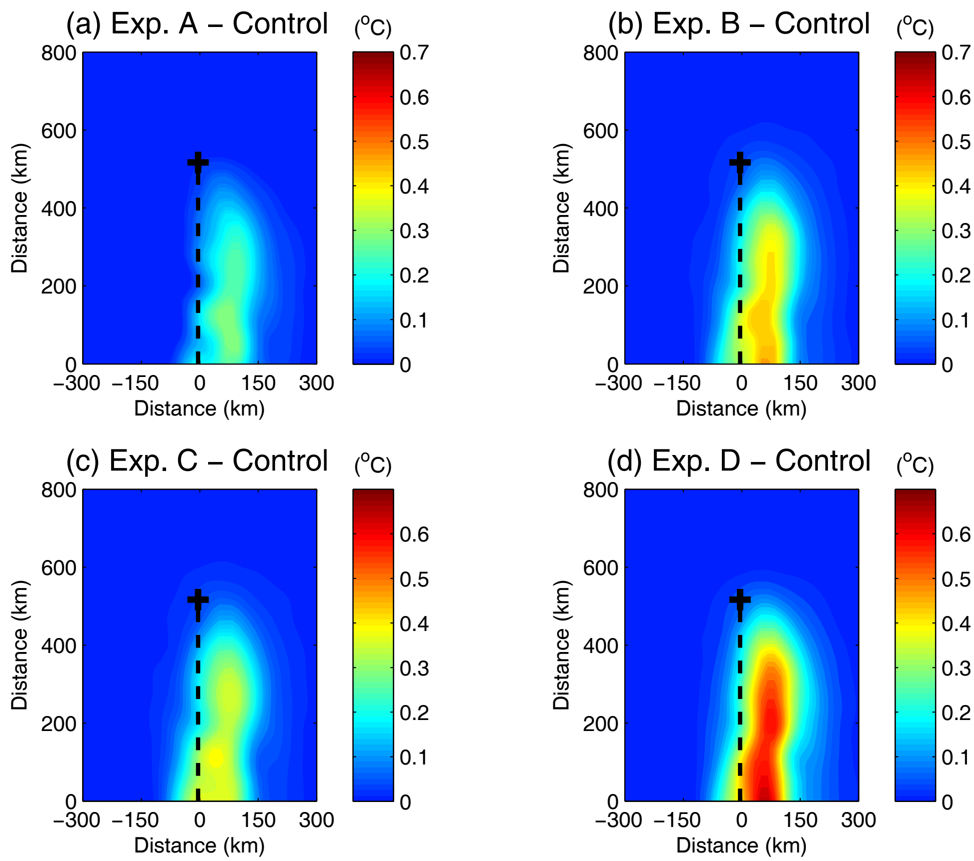

Figure 6. *SST anomaly differences between experiments. (a) effect of air-sea flux budget, (b) effects of current on wind and waves, (c) effect of current on wind only, (d) all effects. The colors scale represents temperature in degrees (°C) with positive/negative denote decrease/increase of SST cooling. The black cross and dashed line on the panels indicate the center and track of the hurricane.*

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