STRUCTURE AND INTENSITY CHANGES IN HURRICANES OPHELIA AND KATRINA (2005): COUPLED ATMOSPHERE-OCEAN MODELING AND RAINEX OBSERVATIONS

Andrew W. Smith* and Shuyi S. Chen
Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, Florida

1. Introduction

Intensity and intensity change remain one of the most challenging issues in tropical cyclone (TC) prediction. Complex interactions between the storm itself and the atmosphere-ocean environment facilitate changes in intensity vis-à-vis storm structure, which are difficult to both observe and model. Hurricanes Ophelia and Katrina (2005) demonstrate well the impact of this storm-environment coupling and its consequences for TC strength and organization. Katrina, Ophelia, and Rita were well observed during the Hurricane Rainband and Intensity Change Experiment (RAINEX, see *Houze et al. 2006*) in 2005. Although previous studies have explored linkages between convective structure evolution and intensity in TCs observed during RAINEX (*Houze et al. 2006, 2009; Judt and Chen, 2010*), the role of coupling between the TC and large-scale atmosphere-ocean environment to structure-intensity dynamics has not been examined. Understanding this is important to explaining both how Hurricane Ophelia survived extreme storm-induced ocean cooling and why Ophelia and Katrina became very different mature TCs despite both originating in favorable environments.

To address these questions, we investigate structure and intensity changes in Hurricanes Ophelia and Katrina using a high-resolution coupled atmosphere-wave-ocean model and unprecedented NOAA and U.S. Navy ELDORA Doppler radar and satellite observations gathered during the RAINEX field campaign. With the goal of improving hurricane intensity prediction, RAINEX comprised a series of flight missions through Hurricanes Katrina, Ophelia, and Rita to study eyewall-rainband interactions (e.g. eyewall replacement cycles, see *Judt and Chen,* 2010).

Hurricane Ophelia originated from a weak tropical storm north of the Bahamas mired in weak environmental steering flow. With limited forward movement, Ophelia induced strong upper-ocean cooling beneath the circulation that persisted near the storm's inner core and was likely responsible for extremely shallow vertical and asymmetric convection. By contrast, Hurricane Katrina intensified to hurricane intensity in the southeastern Gulf of Mexico (GOM) where the storm propagated over a warm eddy of the Loop Current with a strong upper-tropospheric outflow. As a result of this favorable environment and sustained forward movement, Katrina became a major hurricane with intense, deep and symmetric inner core and convection.

* *Corresponding author address:* Andrew Wyatt Smith, RSMAS, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149; email: andrew.smith@rsmas.miami.edu

2. Coupled Model and Experiments

The University of Miami Unified Wave Interface-Coupled atmosphere-wave-ocean Model (UWIN-CM) consists of component models Weather Research and Forecasting (WRF) v3.7.1 for the atmosphere, HYbrid Coordinate Ocean Model (HYCOM) v2.2.98 and University of Miami Wave Model (UMWM) v1.3 UWIN-CM is configured with 12-,4-, and 1.3 km nested grids and 44 vertical levels for WRF and 4 km grids for HYCOM and UMWM. Six-hourly 0.5° NCEP FNL (Ophelia) and GFS (Katrina) fields and the daily 1/12° global HYCOM analysis are used for initial and boundary conditions. Three model couplings were used for experiments: uncoupled atmosphere (UA), atmosphere-ocean (AO) and atmosphere-wave-ocean (AWO).

3. Effects of Air-Sea Interaction on Storm Structure and Track in Hurricane Ophelia

a. Track and intensity

Six-hourly storm tracks from UWIN-CM UA and AO simulations reflect very different TC evolutions (*Fig 1*). The UA TC lacks ocean coupling, altering the large-scale environment felt by the storm and prohibiting awareness or response to ocean cooling. Differences between the UA and AO steering flow as a result produced very different tracks. During Ophelia's anticyclonic loop, pressure and wind intensity are overestimated in UA whereas AO responds to storm-induced cooling with gradual weakening (*Fig 2*).

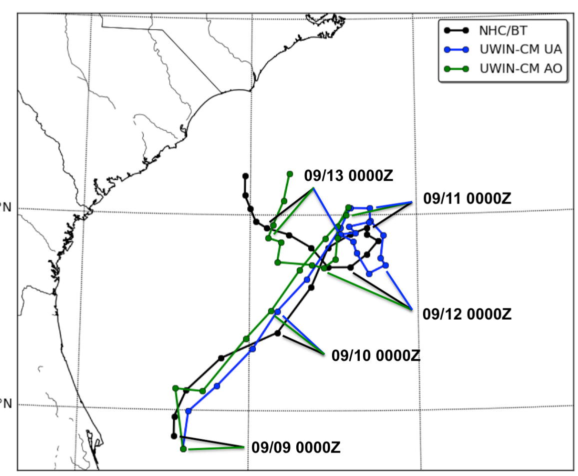

Fig 1. Storm tracks for Hurricane Ophelia, September 9-14 with NHC-determined best track compared to the UWIN-CM simulations.

Fig 2. Minimum sea-level pressure (upper) and maximum wind speed (lower) for Hurricane Ophelia, September 9-14 with NHC-determined best track compared to the UWIN-CM simulations.

b. Storm-induced Upper Ocean Cooling

Prolonged wind stress forcing by TC winds at the ocean surface induces upwelling of colder sub-surface waters; consequential impact on storm intensity depends upon forward speed of the TC. Satellite observations of SST from the TRMM Microwave Imager Advanced Microwave Scanning Radiometer (TMI AMSR) confirm Ophelia cooled SST by 3-5°C while executing its slow counter-clockwise loop beginning late on September 10 (*Fig 3)* with the cooling remaining within 60 (100) km of the storm center September 11-12 (13) (*Fig 4*).

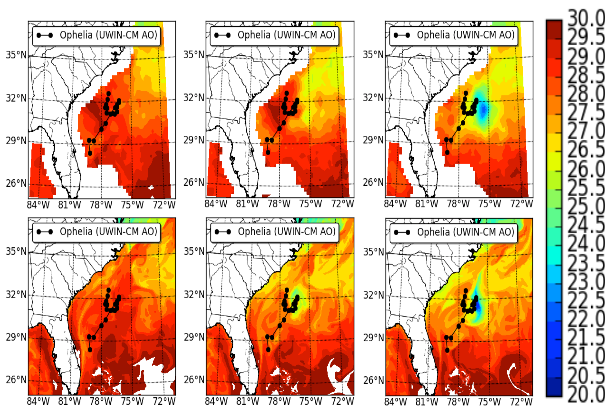

Fig 3. Sea-surface temperature (deg. C) near Hurricane Ophelia, from TMI AMSR-E satellite observations (upper) and from UWIN-CM simulations (1200 Z) for September 9 (l), 11 (c), and 13 (r). Ophelia's track included as reference with cooling starting late September 10 and remaining near the storm's center through September 13.

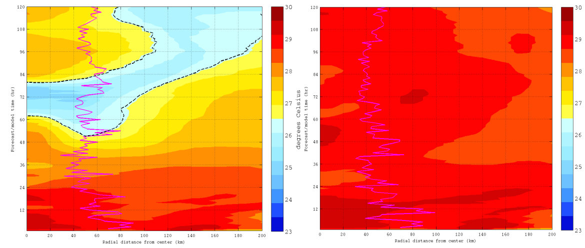

Fig 4. Azimuthally-averaged SST (deg C) and radius of maximum wind (RMW) at 3-km altitude in Hurricane Ophelia UWIN-CM AO (left) and UA (right) simulations for September 9-14.

c. Symmetry & Vertical Structure

Symmetry of the eyewall and distribution of convection both at and beyond the RMW reflect not only a storm's inertial stability but also the environment the TC is interacting with. AO model flight-level radar reflectivity snapshots from Ophelia show an asymmetric and weak eyewall consistent with the disorganized, incomplete structure to convection observed in the TC's eyewall by RAINEX September 11-12. Conversely, the UA vortex has a smaller, more symmetric, and intense eyewall ring (*Fig 6*). Unusually shallow and asymmetric vertical structure was also observed by ELDORA during this time, with convective returns reaching maximum altitudes less than 10 km (*Fig 5*). Azimuthally averaged 35-dBZ echo-top height time-radius diagrams verify ocean cooling induced by Ophelia likely impacted the vertical extent and symmetry of deep convection via reduction of surface heat fluxes (*Fig 7*).

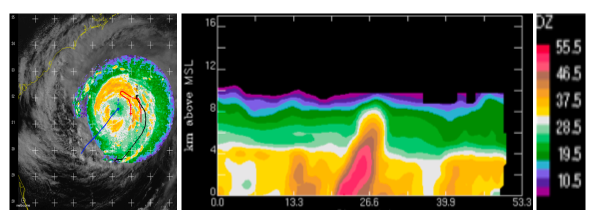

Fig 5. RAINEX ELDORA Doppler radar reflectivity snapshots from September 11 1900Z. Convective returns show an incomplete and disorganized eyewall with vertical extent less than 8 kilometers.

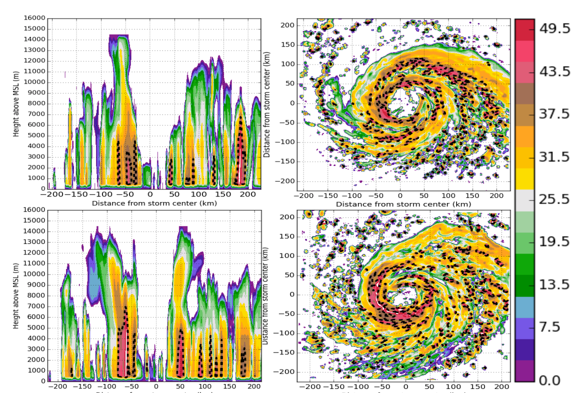

Fig 6. Horizontal and vertical radar reflectivity snapshots from UWIN-CM simulations, taken September 11 1900Z. Dotted contours outline 40 dBZ returns. Asymmetrical, shallow (less than 6 km) organization of the eyewall convection can be seen in AO (top) while a smaller, more intense eyewall and 7-8 km vertical depth of convection appear in UA simulations (bottom).

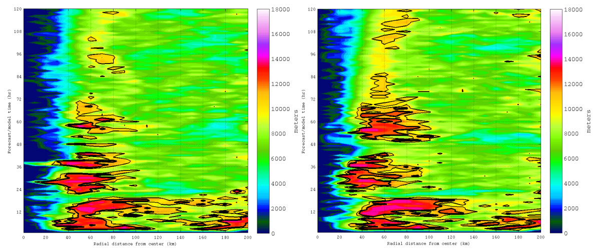

Fig 7. Azimuthally-averaged 35-dBZ echo-top heights in UWIN-CM AO (left) and UA (right) simulations. Contours indicate 10.25 (light) and 12 (heavy) kilometers. Echo-top height and symmetry decrease during the SST cooling experienced by Ophelia AO September 11-13.

Contoured-frequency by altitude diagrams showing percentage difference in the intensity of convection per dBZ for UA-AO UWIN-CM simulations demonstrate a shift toward higher convective returns through greater vertical depth in the UA vs. AO storm as SST cooling greatly impacted Ophelia's structure by the evening of September 12 (*Fig 8*).

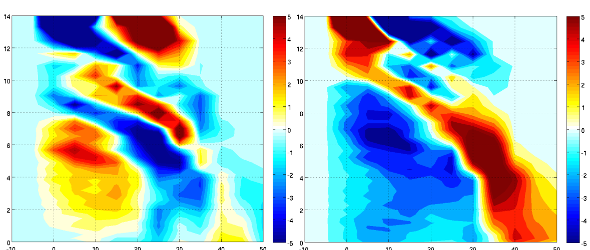

Fig 8. Contoured-frequency by altitude (CFAD) difference (UA-AO) from UWIN-CM simulations (% difference per dBZ per km) for September 10 2100Z (left) vs. September 12 2100Z (right).

4. Hurricane Impact at Landfall from Coupled Atmosphere-Wave-Ocean Model Forecast of Katrina

In light of the 10-year anniversary of Hurricane Katrina, UWIN-CM was used to simulate the storm as was done previously using the 5th-generation National Center for Atmospheric Research Mesoscale Model (NCAR MM5, *Dudhia* 1993; *Grell et al.* 1994, *Judt and Chen* 2010) following RAINEX. Tracks, pressure, and wind intensities from NHC and UWIN-CM simulations are given below (*Fig 9,10)*. With the advancement of UWIN-CM coupling to atmosphere, ocean and wave domains, updated model wind, rain, wave, and current fields will be used in future work to retrospectively assess storm surge, wind and precipitation impacts of Katrina at landfall which were not previously possible (*Fig 11*).

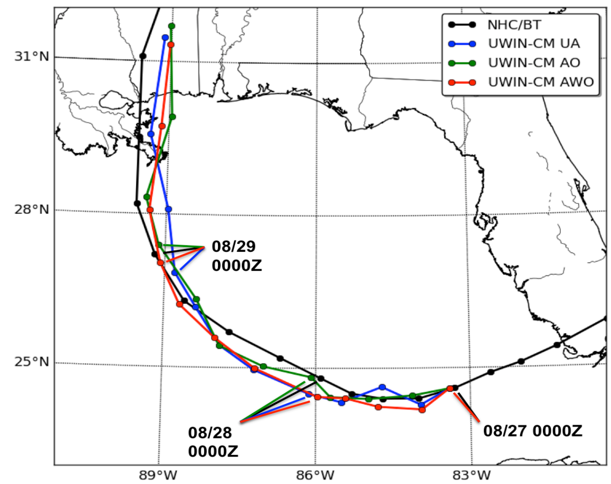

Fig 9. Storm tracks for Hurricane Katrina, August 27-29 with NHC-determined best track compared to the UWIN-CM simulations.

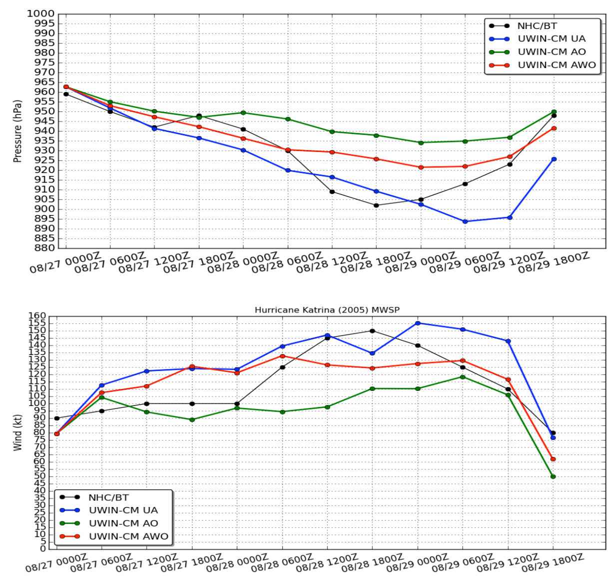

Fig 10. Minimum sea-level pressure (upper) and maximum wind speed (lower) for Hurricane Katrina, August 27-29 with NHC-determined best track compared to the UWIN-CM simulations.

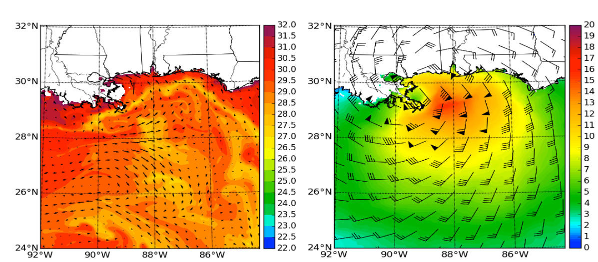

Fig 11. Updated SST (deg C) and surface currents (m/s)

(left) and significant wave height (m) and surface wind (kt) (right) fields from Hurricane Katrina UWIN-CM AWO simulation near landfall on August 29 1200Z.

5. Summary and Conclusions

Improving prediction of hurricane intensity requires better understanding of how storm-environment interactions incite changes in TC convective structure. Hurricanes Ophelia and Katrina are two well-observed storms from RAINEX that demonstrate the importance of these interactions. Weak large-scale environmental flow facilitated prohibitive SST cooling beneath Ophelia captured only by AO simulations. This cooling likely contributed to extremely shallow and asymmetric vertical structure confirmed by field observations. Coupling to atmosphere, ocean, and wave domains gives us the opportunity to re-examine the role of air-sea interactions in Hurricane Katrina and model landfall impacts using updated rain, wind, wave and current fields not available during RAINEX.

6. Acknowledgments

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