Improving Air-Sea Coupling Parameterizations in High-Wind Regimes

PI: Dr. Shuyi S. Chen
Co-PIs: Dr. Mark A. Donelan
Division of Meteorology and Physical Oceanography
Rosenstiel School of Marine and Atmospheric Science, University of Miami
4600 Rickenbacker Causeway Miami, FL 33149-1098, USA
Phone: (305) 361-4048, FAX: (305) 361-4696, E-mail: schen@rsmas.miami.edu

LONG-TERM GOAL

The long-term goal of this PI team is to understand the physical processes of the air-sea interaction and coupling of the atmosphere-ocean system in high-wind maritime regimes, with a particular emphasis on hurricanes. One of the most complex aspects in the air-sea coupling is the effect of surface waves at the air-sea interface that is not clearly defined in the high-wind conditions. We aim to determine the changes that must be made to the coupled atmosphere-wave-ocean models in order to simulate the coupled boundary layers under extreme wind conditions.

OBJECTIVES

The main objectives of this study are 1) to develop and test new parameterizations of wind-wave coupling in high wind conditions, 2) to improve hurricane intensity forecasts in a high-resolution, fully coupled atmosphere-wave-ocean modeling systems, 3) to test the sensitivity of mixing schemes in the ocean mixed layer (OML) and examine the effects of the ocean waves on the OML dynamics, and 4) to develop atmosphere-wave and atmosphere-ocean generic couplers to allow the flexibility of testing various physical parameterizations.

APPROACH

Our current focus is to study the nature of coupled atmosphere-ocean boundary layers and heat and momentum exchange at the air-sea interface in hurricanes. We develop improved parameterizations of subgrid-scale processes, air-sea exchange coefficients, and surface fluxes in coupled atmosphere-wave-ocean models with high-resolution (~1-2 km grid spacing) that can resolve the hurricane eyewall structure. The RSMAS/UM PI team is focusing on the effects of ocean wave "spectral tails" on drag coefficient, wind-wave coupling, and ocean mixed layer parameterizations. In a closely related project (supported by ONR under grant N00014-03-1-0473), the PI (Chen) works with Drs. W. Frank and J. Wyngaard at PSU to develop improved parameterizations of subgrid-scale processes in ABL. The methodology is to use a Large-Eddy Simulation (LES) initialized for hurricane-like conditions, including very high winds, sea spray, and the effects of waves at the lower boundary. These parameterizations would then be installed and tested in the coupled atmosphere-wave-ocean models like the coupled modeling system at RSMAS/UM and the U. S. Navy's COAMPS. We have worked closely with the CBLAST-Hurricane PI team (Dr. P. Black et al.) taking observations during

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the CBLAST-Hurricane field program and using the data to evaluate/validate our coupled modeling results.

WORK COMPLETED

During the year 2005-06, we have complete the development and testing of the CBLAST wind-wave coupling parameterization for the next-generation high-resolution fully coupled atmosphere-wave-ocean model for tropical cyclone research and predictions. Here we summarize the major accomplishments by the PI team:

- A new wind-wave parameterization for fully coupled atmosphere-wave-ocean model developed under the CBLAST-Hurricane is tested and documented in Chen et al (2006a and 2006b) and Zhao and Chen (2006).

- Completed the evaluation/validation of the wind-wave coupling parameterization by comparing the coupled and uncoupled model simulations of Hurricanes Fabian and Isabel (2003) and Frances (2004) with detailed analyses of CBLAST observations including the airborne radar, GPS dropsonde, sea states, and turbulence flux measurements. Coupled simulations of Fabian and Isabel (2003), and Frances (2004), which are observed during the CBLAST-Hurricane field programs.

- Examined the sensitivity of hurricane simulations in the ocean model to the OML parameterizations in collaboration with Dr. Jim Price of WHOI and compared the results with the best upper ocean observations in Hurricane Frances (2004) by Sanford et al. during CBLAST-Hurricane field program.

- Worked in collaboration with other CBLAST PIs, including the PSU group, Dr. Chris Fairall of NOAA and Dr. Shouping Wang of NRL to include the effects of surface waves and an improved sea spray model into the coupling parameterizations. Melicie Desflots, a graduate student working with Dr. Chen, will present this result at the 2006 AGU Fall Meeting.

In addition, over the last year, we have also worked with closely with the HYCOM development team led by Alan Wallcraft of NRL-Stennis and the WRF model development team led by John Michalakes of NCAR on developing and testing a coupled WRF-HYCOM at RSMAS/University of Miami. Dr. Wei Zhao is a key person in this work.

RESULTS

The new scientific findings are summarized in several manuscripts (Chen et al. 2006a, 2006b, Zhao and Chen 2006). Here we include a few highlights:

1) A new CBLAST wind-wave coupling parameterization

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. Existing third generation wave prediction models are unable to do this as their high wavenumber cut-off is about 0.63 m^{-1} or 10 m wavelength while most of the stress is supported by shorter waves. In order to correct this short-coming a new wave and wind stress prediction model has been developed (Donelan, 2004) and is being tested against field and laboratory

data with respect to its wave and stress prediction skill in rapidly changing wind conditions against direct measurements of wave spectra and Reynolds stress. The new wind-wave parameterization calculates directional stress using surface wave directional spectra by parameterizing "spectral tails" (wavelength < 10 m) unresolved by the current wave models (Chen et al. 2006a, 2006b).

One of the issues regarding to the prediction of hurricane intensity changes is the ratio of the enthalpy and drag coefficients (C_k and C_D). Using a simple axisymmetric model with idealized environmental conditions, Emanuel (1995) has proposed that the ratio needs to be at least equal or greater than one for hurricane to intensify. However, the lab experiments of high-winds have shown that the C_D value is max out at high-wind speeds as the so-called flow separation occurs (Donelan et al. 2004). Recent airborne turbulence flux measurements from the CBLAST-Hurricane also support the lab results indicating that this ratio is less than one for intensifying storms such as in Hurricanes Fabian (2003) and Frances (2004). We have conducted a number of fully coupled MM5-WW3-3DUOM simulations to investigate the sensitivity of model simulated hurricane intensity to various coupling parameterizations. Fig. 2 shows model simulated C_k and C_D in Frances using both uncoupled and coupled models. Although the ratio increases from the uncoupled to coupled simulations, the storm continued to intensify while the ratio is less than one, especially near the inner core region of the storm. The difference between the coupled modeling results supported by observations and Emanuel (1995) can be explained by the fact that a gradient wind is used in Emanuel's calculation since his simple model cannot resolve the ABL.
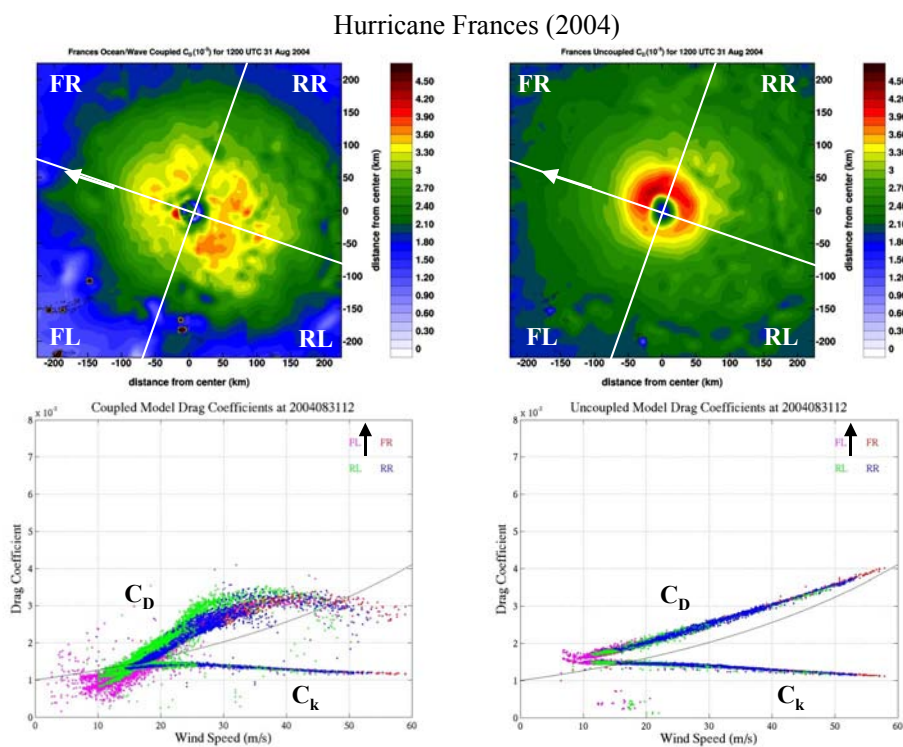
Fig. 1 Comparisons of model simulated air-sea exchange coefficients in Hurricane Frances (2004) using the uncoupled MM5 (right panels) and fully coupled MM5-WW3-3DUOM (left panels). Color scale in the upper panels is the C_D ($\times 10^{-3}$). The lower panels show the enthalpy exchange and the drag coefficients from four different quadrants around the hurricane indicated in the upper panels.

It is important to note that the C_D is explicitly wave-dependent in the coupled model, which can be seen in Fig. 1, as the front quadrants of a hurricane are "smoother" than the rear quadrants where the wavelength is shorter. The uncoupled simulation, in contrast, has the largest C_D value (a function of wind speed) in the front-right.

2) Coupled simulation and comparisons with CBLAST observations

Three EM-APEX floats were deployed near the Caribbean Islands before the passage of Hurricane Frances. A detailed description of the autonomous vertically profiling T, S and V measuring EM-APEX floats and the data collected in Frances is given in Sanford (2004). The observed profile from pre-storm condition is used to initialize the ocean model. The cooling of the upper ocean in the wake of Frances is well reproduced by the coupled A-W-O model simulation. Figure 2 shows the time-series of the observed upper-ocean temperature (T), salinity (S), and current (u, v) data from the EM-APEX float 1633 in pre-, during, and post-Hurricane Frances conditions. The corresponding upper-ocean properties simulated by the A-W-O model are shown in Fig. 3. The model simulates well the hurricane-induced near-inertial current, similar to that documented in Shay and Elsberry (1987) and Price et al. (1994).

The coupling to the ocean circulation model improves the storm intensity by including the storm-induced cooling in the upper ocean and SST, whereas the uncoupled atmosphere model with a constant SST over-intensifies 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 MSLP of especially the atmosphere-ocean coupled model is close to the observed values. The full coupling with the CBLAST wave-wind parameterization clearly improves the model simulated wind-pressure relationship that is a key issue in hurricane intensity forecasting. The improved wind-pressure relationship is showed in all the simulated hurricanes documented in Chen et al. (2006b).

IMPACT/APPLICATIONS

Two recent reports from the NOAA Science Advisory Board Hurricane Intensity Working Group (Snow et al. 2006) and the National Science Board task force on hurricane science and engineering have both identified that improving hurricane intensity forecasts as the highest priority for hurricane research community. The reports have also cited recent science results from the CBLAST-Hurricane program as a key to develop the next-generation hurricane models. This project has and will continue to provide improved physical parameterizations for the coupled atmosphere-wave-ocean models at very high spatial resolution. It will make a significant contribution to improve hurricane intensity predictions.
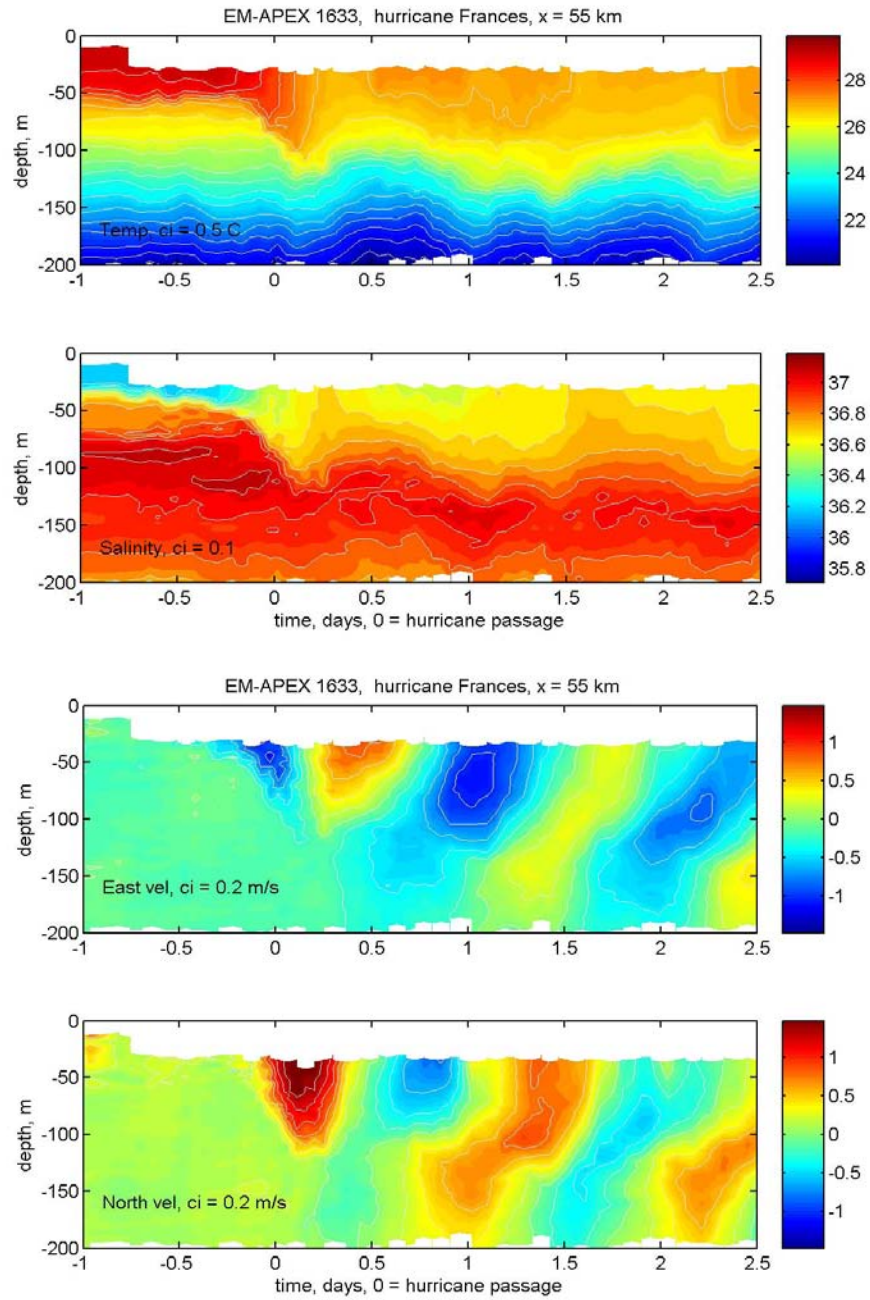
***Fig. 2   Observed upper-ocean temperature (°C) (a), salinity (psu) (b), and current
(u, v, in m s⁻¹) (c and d) from the EM-APEX float 1633. Day 0 marks the passage of Hurricane
Frances at the float at 1200 UTC on 1 September 2004.***
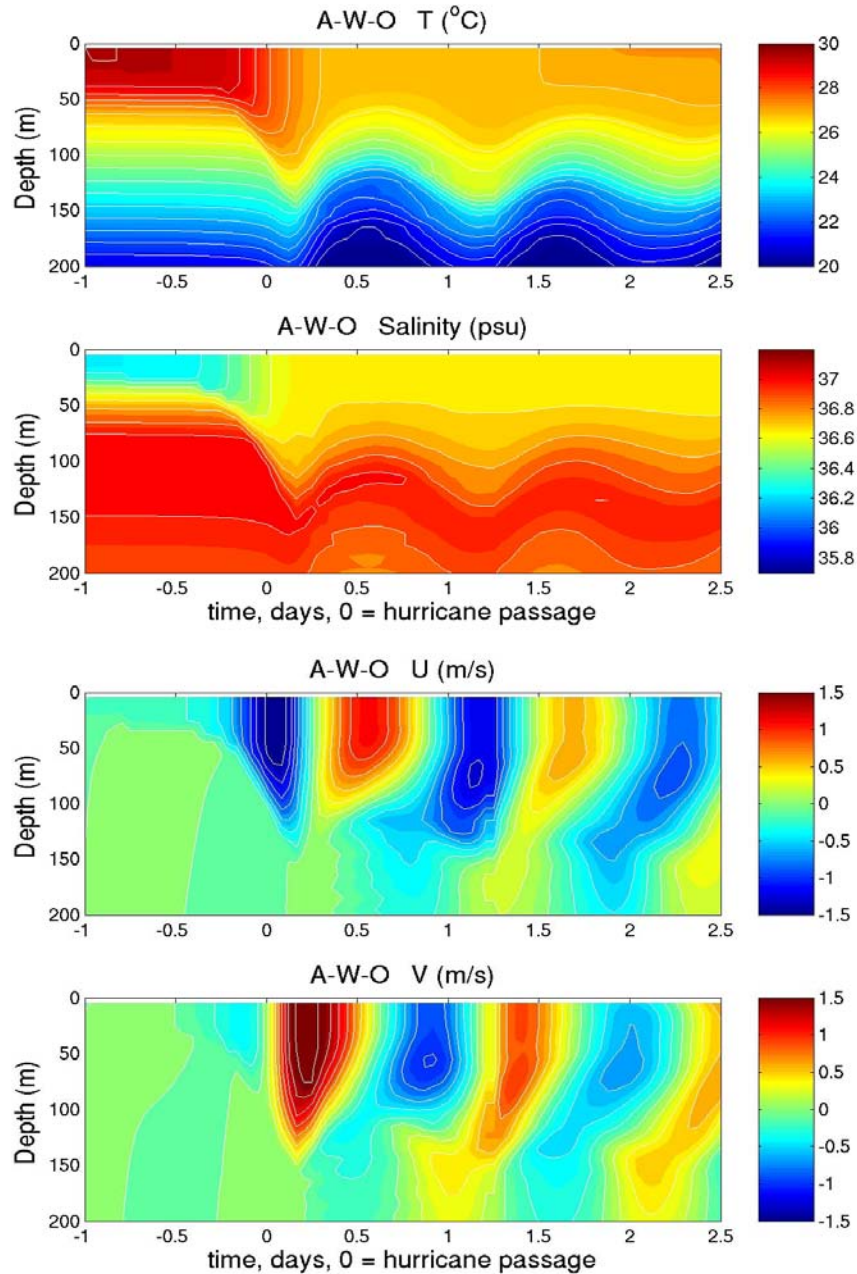
Fig. 3 Same as in Fig. 2, except for the fully coupled model simulated fields.

TRANSITIONS

We will assist in the transitioning of the completed CBLAST wind-wave parameterizations to operational coupled modeling systems including the Navy COAMPS and HWRF. The plan is to have a post-doc associate from NRL-Monterey to be placed at RSMAS/U.Miami to work with Dr. Chen's research group on the coupling parameterization and testing in COAMPS for a period time. These new parameterizations developed at RSMAS/U.Miami and Penn State will be made available for all ONR CBLAST PIs.

RELATED PROJECTS

Related projects include the NSF RAINEX on hurricane rainbands and intensity change (S. Chen), the NASA/JPL QuikSCAT Science Team on data assimilation of the surface winds in tropical cyclones (S. Chen), and ONR CBLAST-Hurricane Observations (P. Black et al.).

PUBLICATIONS (2006)

Chen, S. S., J. F. Price, W. Zhao, M. A. Donelan, and E. J. Walsh, 2006: The CBLAST-Hurricane Program and the next-generation fully coupled atmosphere-wave-ocean models for hurricane research and prediction. *Bull. Amer. Meteor. Soc*, **87**, in press. (Available at http://orca.rsmas.miami.edu/~schen/publications/)

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Zhao, W., and S. S. Chen, 2006: Effects of surface waves and upper ocean on hurricane structure and intensity in a fully coupled model. *The 27th Conf. on Hurricanes and Tropical Meteorology*. 23-27 April 2006, Monterey, CA, Amer. Meteor. Soc. **5C.7**.