5C.7 Effects of Surface Waves and Upper Ocean on Hurricane Structure and Intensity in a Fully Coupled Model

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1. INTRODUCTION

One of the uncertainties in tropical cyclone prediction is that the air-sea interaction is the inner core region is largely unknown with very little observations. The extreme high winds, large ocean waves, and copious sea spray push the surface-exchange parameters for temperature, water vapor, and momentum into untested new regimes. The objective of this study is, through numerical simulations using a nested-grid high-resolution, coupled atmosphere-wave-ocean model, to understand the physical processes governing the storm structure and intensity. We developed a model evaluation and validation procedure using observations including both satellite remote sensing and in situ measurements from the Coupled Boundary Layer Air-Sea Transfer (CBLAST) Hurricane field programs in 2003 and 2004. The components of the coupled model system are the PSU/NCAR MM5, WAVEWATCH III, the WHOI 3DUOM and the UM HYCOM. The coupled modeling system has have tested in a number of Atlantic hurricanes including Bonnie (1998), Floyd (1999), Fabian (2003), and Frances (2004). To better understand the effects of air-sea coupling on hurricanes, we first conducted an uncoupled control simulation for each storm using MM5 only. The fully coupled simulations are compared with the observations and the uncoupled simulations. In general, the coupled model improves the simulated storm intensity over the uncoupled simulations that tend to overestimate storm intensity in all cases. It is because of the storm-induced cooling due to vertical mixing in the upper ocean in the coupled model, whereas the uncoupled MM5 uses a constant SST through out of the simulation. The storm-induced cold wake in the SST is well simulated in the coupled model compared with the coupled model compared with the satellite observations. The maximum cool is to the rear right of the storm as observed in Frances and many other storms previously. The storm-induced surface wave field is high complex and asymmetric around a hurricane. It is clearly evident in the coupled simulation of Hurricanes Floyd and Frances, in terms of both significant wave height (SWH) and wave length. The highest SWH and largest wave length are found in the front right quadrant as observed in CBLAST-Hurricane field program. These characteristics in the wave fields will produce a relatively weaker surface stress in the front right quadrant and a stronger stress in the rear left quadrant of the storm. The combined effects of the atmosphere-wave-ocean coupling give a rise in the asymmetry in the air-sea fluxes. The uncoupled MM5 simulation produced a more symmetric net heat flux compared to that of coupled model simulation. The asymmetry in surface heat flux has also been observed in CBLAST-Hurricane 2003-2004.

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2. COUPLED ATMOSPHERE-WAVE-OCEAN MODELING SYSTEM

2.1 Atmospheric Model

The atmosphere model in the coupled modeling system are the Fifth Generation of the Penn State University-National Center for Atmospheric Research atmospheric nonhydrostatic mesoscale model (MM5) (Dudhia 1993, Grell et al. 1994). For studying hurricanes and coastal storms, we have developed a vortex-following nested grid that allows for long integration (7-10 days or longer) of the model with cloud-resolving resolution of 1-2 km in the inner most domain (Tenerelli and Chen 2001, Rogers et al. 2003, Chen and Tenerelli 2005). In this study, we use 4-level nests with 45, 15, 5, and 1.67km resolutions, respectively.

2.2 Wave Model

The ocean surface wave models are the third-generation wave model, namely the NOAA WAVEWATCH III (or WW3) developed by Tolman (1991) for wind waves on slowly varying, unsteady and inhomogeneous depths and currents. In this study, we use WW3 using the action density wave spectrum with 25 frequencies logarithmically spaced from 0.0418 to 0.41 Hz and 48 directional bands.

2.3 Ocean Models

The ocean circulation models used in the coupled system are the WHOI's three-dimentional upper ocean model with the PWP mixing scheme (3DUOM, Price 1994) and the U. Miami/NRL Hybrid Coordinate Ocean Model (HYCOM, Bleck et al. 2002). The ocean model grid resolution vary from 1/12 degree in HYCOM to 15 km in 3DUCOM.

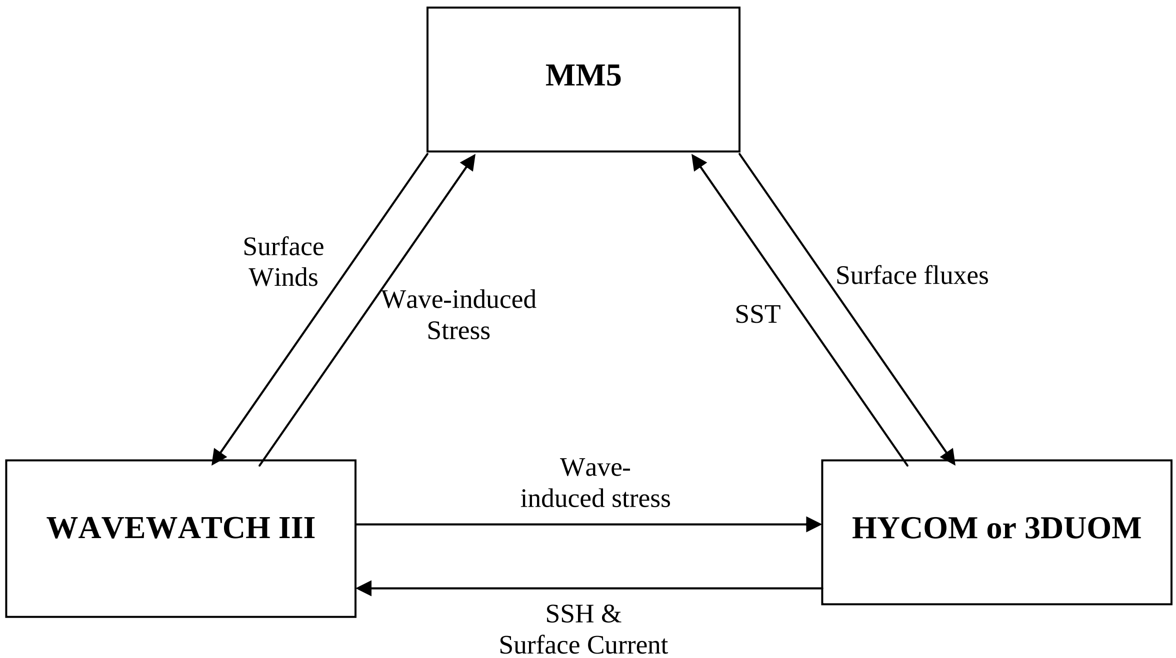


Fig. 1 A schematic of the coupled atmosphere-wave-ocean modeling framework.

2.4 Coupling Framework

A generic coupled modeling framework is demonstrated in a schematic diagram in Fig. 1. We have developed physically-based couplers between each of the model components. Most previous coupled parameterizations do not work well in high-wind conditions. One of the issues is related to the wind-wave coupling is critically depended on the high frequency of the wave spectra that cannot be fully resolved by the current wave models. We first developed a new wind-wave coupling method that parameterizes the special tail and integrates the total wave spectra to calculate surface stress (Chen et al. 2004). It is based the lab measurements described in Donelan et al. (2004b). Another issue is related to the lack of accurate SST field from current ocean models on short time and small spatial scales, which is required for hurricane prediction. Before an improved data assimilation is available, we have adopted a method that uses a combined high-resolution satellite observed SST and model produced SST anomaly for the coupled system. It works well in the highly wind-driven environment.

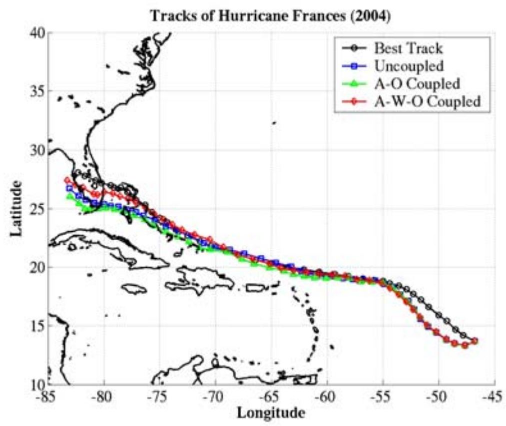
3. HURRICANE FRANCES (2004)

The coupled modeling system has have tested in a number of Atlantic hurricanes including Bonnie (1998), Floyd (1999), Fabian (2003), and Frances (2004). Here we present some results from Hurricanes Frances (2004) that one of the best observed storms during the CBLAST-Hurricane 2004 field program. To better understand the effects of the surface waves and upper-ocean circulation including SST on hurricanes, we conducted three separated model simulations, including the uncoupled MM5, coupled MM5-3DUOM or A-O, and fully coupled MM5-WW3-3DUOM or A-W-O.

3.1 Track and Intensity

Fig.2 shows the comparisons of model simulated tracks, maximum surface windspeed and minimum sea-level-pressure (SLP) with the best track data from the National Hurricane Center (NHC). Hurricane tracks are mostly affected by the environmental steering flow. The comparisons (Fig. 2a) of the uncoupled, coupled A-O, and fully coupled A-W-O model simulated storm tracks indicate that the effects of the coupled wave and ocean are not large insofaras the storm track is concerned. While the uncoupled and coupled A-O model simulated tracks are almost the same, the fully coupled A-W-O model simulations improved tracks slightly near the landfall. However, the coupled model improves the model simulated storm intensity significantly over the uncoupled MM5. It is mostly because of the storm induced cooling due to vertical mixing in the upper ocean in the coupled model, whereas the uncoupled MM5 uses a constant SST through out of the simulation. The storm-induced cold wake in the SST is well simulated in the coupled model compared with the satellite observations (Fig. 3). The maximum cool is to the rear right of the storm as observed in Frances and many other storms previously.

(a)



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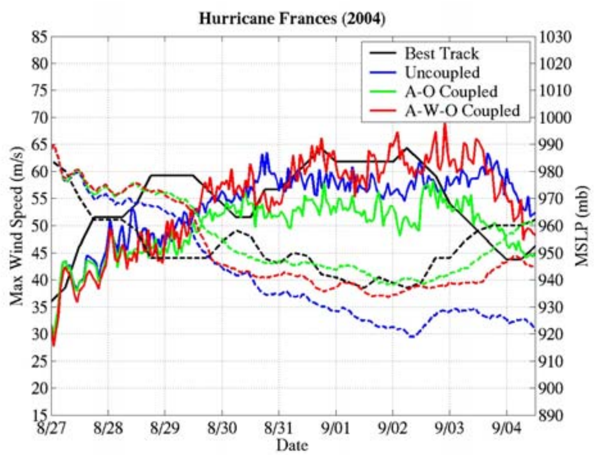
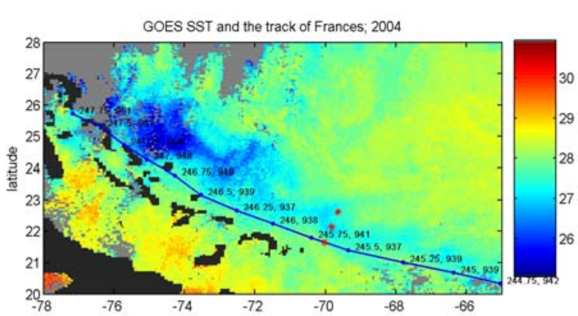


Fig. 2 Model simulated (a) storm tracks and (b) simulated MSLP (dashed lines) and maximum wind speed (solid lines) from the fully coupled atmosphere-wave-ocean model (red), coupled atmosphere-ocean model (green), and uncoupled atmosphere model (blue) of Hurricane Frances in comparison with the NHC best track data (black) over a 10-day period from 0000 UTC on 27 August – 0000 UTC on 6 September 2004.

(a)



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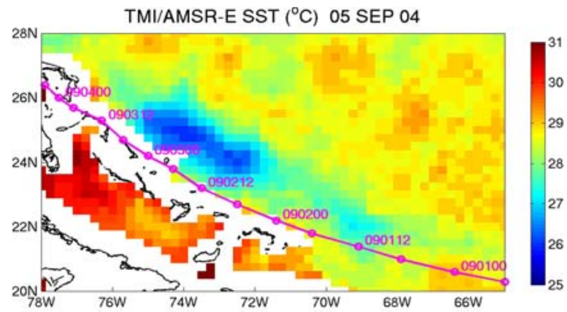

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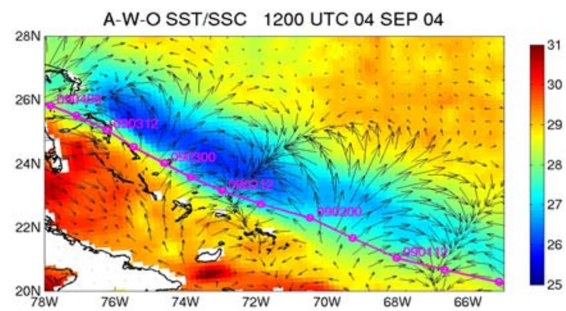


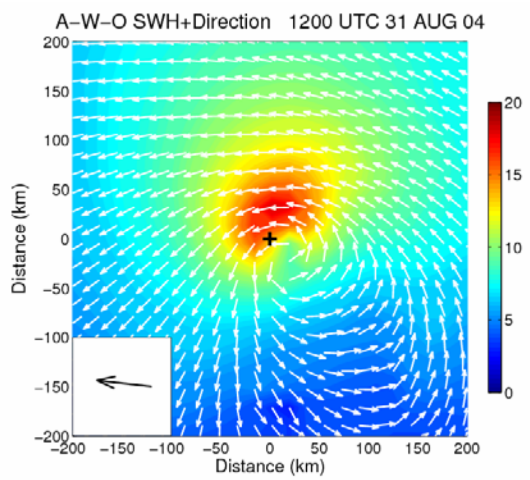
Fig. 3 Observed SST from (a) the GOES and (b) the TRMM TMI-AMSRE daily composite on 5 September 2004, respectively, and (c) fully coupled model simulated SST and ocean surface current in Hurricane Frances at 1200 UTC 4 September 2004. Storm tracks are overlaid on each of the SST maps.

3.2 Surface Fluxes

The storm-induced surface wave field is high complex and asymmetric around a hurricane. It is clearly evident in the coupled simulation of Hurricane Frances, in terms of both significant wave height (SWH) and wave length (Fig. 4). The highest SWH and largest wave length are found in the front right quadrant as observed in CBLAST-Hurricane field program and previously by Walsh et al. (2002). These characteristics in the wave fields will produce a relatively weaker surface stress in the front right quadrant and a stronger stress in the rear left quadrant of the storm (Fig. 5).

On the other hand, the SST cooling is also asymmetric around the storm. The combined effect of the atmosphere-wave-ocean coupling gives a rise in the asymmetry in the air-sea fluxes as shown in Fig. 5. The uncoupled MM5 simulation produced a more symmetric net heat flux (Fig. 6c) compared to that of coupled model simulations (Figs. 6a and b). The asymmetry in surface heat flux has also been observed in CBLAST-Hurricane 2004. The storm-induced upper ocean cooling in the right-rear quadrant not only contributes to the asymmetry, but also reduces the overall surface heat fluxes in Frances from the inner core to the outer rainband regions as a result of reduced storm intensity (Figs. 6a and b). The enhanced surface wind in the fully coupled A-W-O, as a result of the sea-state-dependent stress that is reduced in extreme high winds compared with the uncoupled MM5 and coupled A-O, contributes to the increased surface heat (mostly latent) flux in the eyewall and front-right quadrant of Hurricane Frances (Fig. 6) and similarly in Hurricanes Floyd and Bonnie.

(a)



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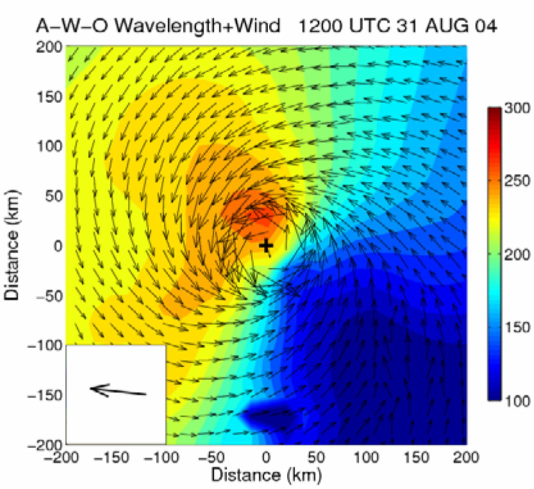
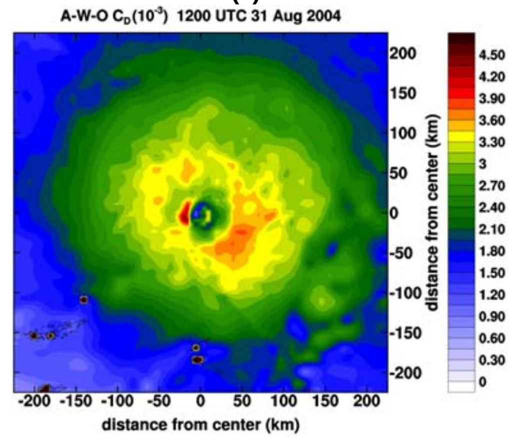


Fig. 4 A-W-O model simulated (a) SWH (color, m) and wave propagation direction (white vectors) and (b) mean wavelength (color, m) and surface wind (black vectors) at 1200 UTC on 31 August 2004. The black "+" indicates the storm center of Hurricane Frances. The arrow in the lower left corner indicates the direction of the storm motion.

(a)



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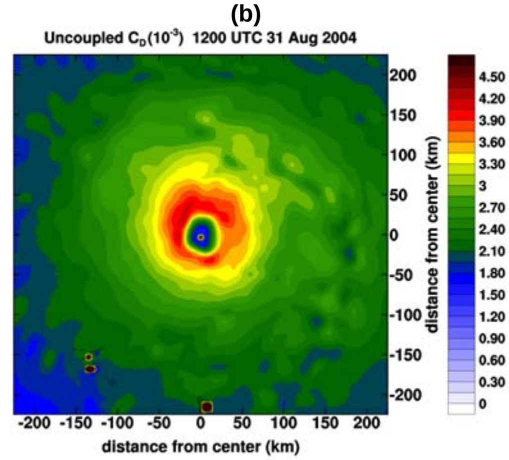
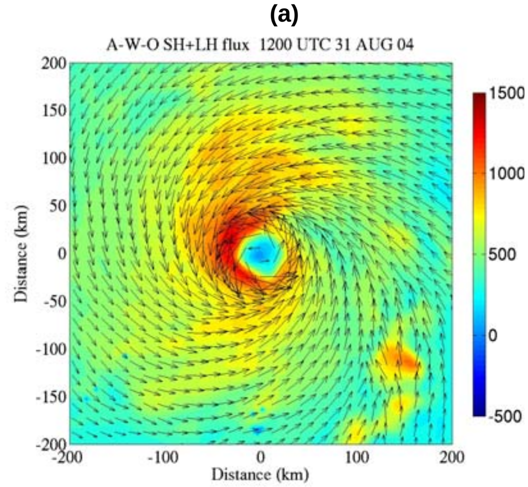


Fig. 5 The (a) fully coupled and and (b) uncoupled model simulated drag coefficient in Hurricane Frances at 1200 UTC 31 August 2004.

(a)



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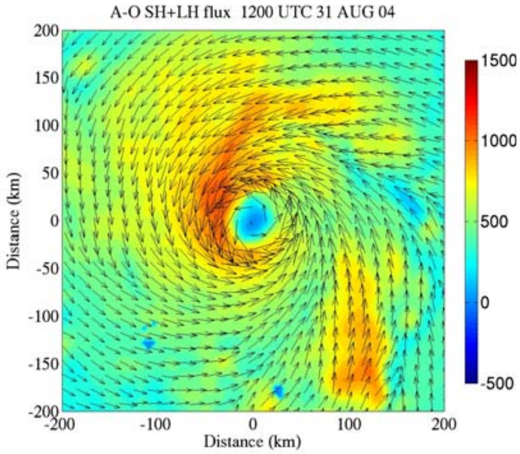

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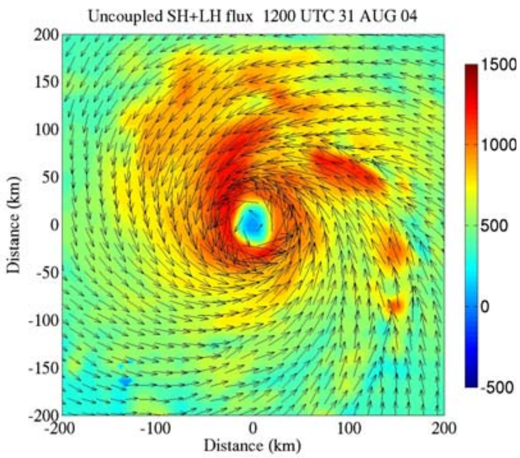

Fig. 6 Simulated enthalpy (sensible+latent) flux (color, W m^{-2}) and surface wind (vector) in Hurricane Frances at 1200 UTC 31 August 2004 from (a) fully coupled atmosphere-wave-ocean, (b) coupled atmosphere-ocean, and (c) uncoupled atmosphere models.

3.3 Pressure-wind Relationship

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 fully coupled model with the new wind-wave parameterization improves the surface pressure-wind relationship compared with the observations of Landsea et al. (2004) shown in Fig. 7. The uncoupled atmospheric model over-predicts the MSLP by 10-30 hPa, and under-predicts the MWS by 10-15 m s^{-1}, while the A-O coupled model improves the MSLP but still under-predicts the surface wind.

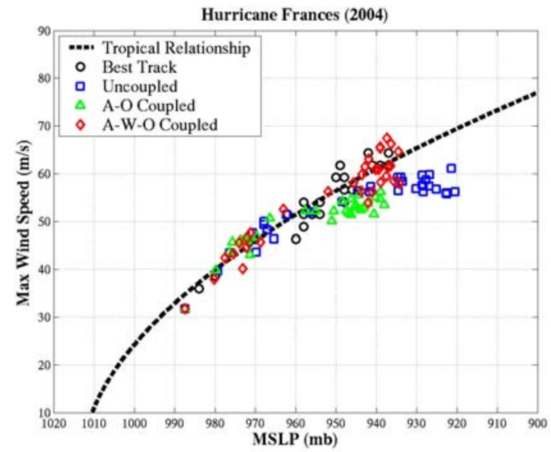

Fig. 7 Observed (the NHC best track data, black circles) and simulated pressure-wind relationship from the fully coupled atmosphere-wave-ocean model (red), the coupled atmosphere-ocean model (green), and the uncoupled atmosphere model (blue) for Hurricanes Frances.

4. CONCLUSIONS

The coupled atmosphere-wave-ocean modeling system has been tested successively in a number of Atlantic hurricanes. Model simulations are compared and evaluated with available in-situ and satellite observations. In general, the coupled model improves model simulated storm structure, air-sea fluxes, and storm intensity changes compared to that uncoupled atmospheric model simulations. 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 A-O 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.

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