10.14 A TWO-WAY COUPLED MODELING STUDY OF ATMOSPHERE-OCEAN INTERACTIONS DURING HURRICANE FRANCES (2004)

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1. INTRODUCTION

It remains a challenging task to improve tropical cyclone intensity forecasts. One of the constraints is due to a lack of understanding of the coupled ocean-atmosphere system, particularly with regard to air-sea interaction processes on the mesoscale under high-wind conditions. The sea surface temperature (SST) cooling induced by hurricane have been observed up to 6 °C (Black 1983) and is closely related to the translation speed of the hurricane (Bender el al. 1993). The amount of SST cooling underneath a hurricane can significantly reduce the heat and moisture fluxes at ocean surface, which may play an important role in the storm evolution (Bender and Isaac 2000). For example, Schade and Emanuel (1999) found that the SST feedback can significantly reduce the hurricane intensity using a simple coupled model.

The objective of this study is to gain a better understanding of air-sea interaction processes during Hurricane Frances (2004). In this study, we apply the Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS[@1]) (Hodur 1997), which is comprised of a nonhydrostatic atmospheric model, the NRL Coastal Ocean Model (NCOM) as the ocean modeling component, and a coupler for information transfer between the atmosphere and ocean. The Coupling System Infrastructure Framework (CSIF) (Jin and Hodur 2006) is used here to facilitate the ocean-atmosphere coupling. The emphasis of this study is to investigate impact of the atmospheric surface forcing at various resolutions on the tropical cyclone induced SST cooling. We also examine hurricane intensity forecasts from the fully coupled system and compare them with forecasts with temporally-invariant SSTs, which is typically the case for most operational NWP models.

2. DESCRIPTION OF THE COUPLED SYSTEM

2.1 *Framework*

The CSIF has been designed to provide a streamlined, flexible, and efficient modeling framework for coupled models, such as atmosphere and ocean modeling codes. The COAMPS and NCOM codes are coupled under the CSIF and tested in one-way and two-way modes. COAMPS provides surface heat, moisture, momentum fluxes, sea level pressure and rainfall for NCOM forcing, while NCOM provides the updated SSTs for COAMPS. The data transfers between atmosphere and ocean models are controlled by a flux coupler.

2.2 *Atmosphere Model*

COAMPS is a fully compressible, nonhydrostatic primitive equation model. The equations are discretized on a staggered, scheme C grid and solved using the time splitting technique with a semi-implicit formulation for the vertical acoustic modes. Robert time filter is used to damp the computational mode. All derivatives are computed with second-order accuracy with the exception of fourth-order horizontal diffusion. The micro-physics scheme in COAMPS consists of a single-moment bulk prediction for water vapor, cloud water, cloud ice, rain water, snow, and graupel/hail. The shortwave and longwave radiative transfers are formulated following Harshvardhan et al (1987). A 1.5 order TKE closure is used for turbulence. The atmospheric model has an option for moving nested grids that follow a feature, such as a vortex, which is particularly useful for tropical cyclone simulations.

2.3 *Ocean Model*

The ocean component of COAMPS, NCOM, is based on the hydrostatic primitive equations and includes a free surface upper boundary condition (Martin, 2000). The equations are solved on a staggered Arakawa C grid and use the Boussinesq and incompressible approximations. A hybrid coordinate system is used in the vertical, with terrain following coordinates in the upper layers and z-level coordinates in the lower layers, which can accurately resolve flows along steep bathymetry, such as the continental shelf. An implicit method is used for the barotropic component. The time integration is leapfrog with an Asselin filter to suppress the computational mode. A second-order centered scheme is used for spatial differencing and a third-order upwind scheme is used for advection. Mellor-Yamada level 2.5 turbulence model is used to parameterize the vertical mixing and a Smagorinsky-type scheme is to represent the horizontal mixing processes. A radiation condition is used at the open lateral boundaries.

2.4 *Coupler*

The coupler facilitates all data transfer between different models. The coupler is generalized so that configurations can vary considerably (grid resolution, number of domains and their locations). The coupler automatically collects the configuration of each model and then facilitates the transfer of data between models accounting for based on domain resolution and location (including the complex of a moving nest). The coupler also provides an option to control the method of data transfer at the different resolutions for the nested simulations.

[1] COAMPS® is a registered trademark of the Naval Research Laboratory

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3. HURRICANE FRANCES (2004)

In this study, COAMPS is applied to study the air-sea interaction processes operating during Hurricane Frances. All model components are initialized at 1200UTC 1 Sept 2004 and run for 48 hours. Three nested domains (27km/9km/3km) in the horizontal and 30 levels in vertical are used. The third mesh translates with the hurricane vortex. The NOGAPS forecast fields are used as a first guess. The NCOM simulations are performed at 10 km and 3km resolutions in horizontal as sensitivity tests. NCOM uses initial and boundary conditions from a 1/8 degree resolution global NCOM forecasts provided by the Naval Oceanographic Offices (NAVO).

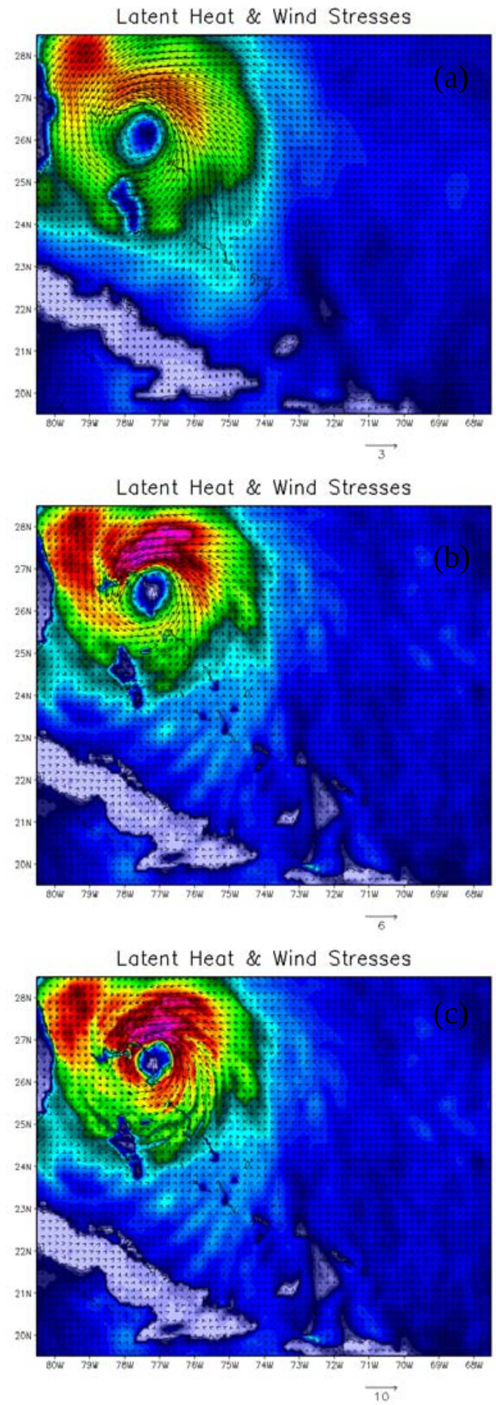

Figure 1. Surface latent heat (Wm^{-2}) and surface wind stress (m^2s^{-2}) distributions at the 48-hour simulation time with a resolution of (a) 27km, (b) 9km and (c) 3km.

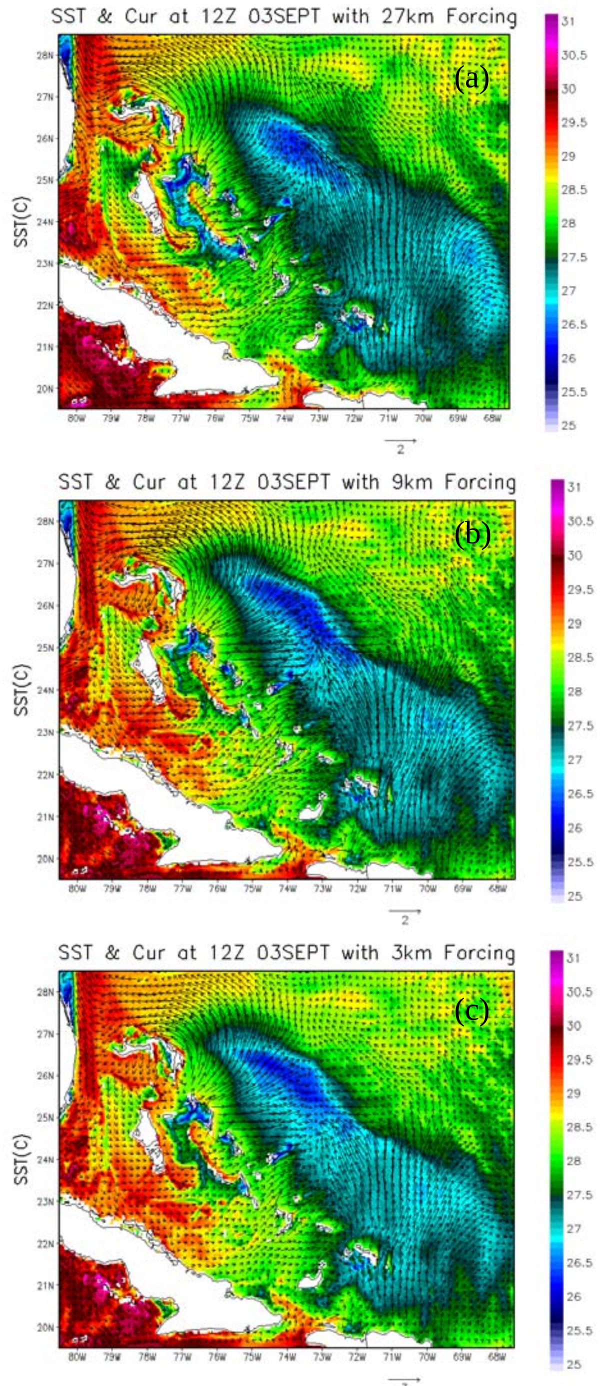

Figure 2. SST (K) and surface current (ms^{-1}) distributions at the 48-hour simulation time with atmospheric forcing at resolutions of (a) 27km, (b) 9km and (c) 3km, respectively

3.1 *Influence of Grid Resolution on Ocean Responses*

It has been well established in previous studies that it is necessary to have high grid resolutions (< 10 km) for numerical models to produce skillful TC intensity forecasts (Liu et al 1997). One of our objectives is to evaluate the impact of atmospheric forcing at various horizontal resolutions on the SST and ocean surface currents. Figure 1 shows the latent heat flux from COAMPS at 48 h for horizontal resolutions of 27-km, 9-km, and 3-km respectively. The latent heat flux at the 27-km resolution is much weaker than that at the 9-km and 3-km resolutions, primarily because of weaker wind speeds on the coarser meshes. The strongest latent heat flux is found surrounding the eyewall of Hurricane Frances on the 3-km resolution mesh, associated with the strong surface wind stresses (as shown from the value of the reference scale as 3, 6 and 10).

Figure 2 shows the SST and surface currents after 48 h using atmospheric surface forcing at 27 km (F1), 9 km (F2), and 3 km (F3) respectively. The 3-km forcing produced the largest area of SST cooling on the right side of the Frances path. SST cooling is as large as 3 K. The SST difference between F2 and F3 is relatively small (about 0.5 K). SST differences between F1 and F3 are about 1 K. In the F3 experiment, SST was cooled to about 26K and SST anomaly is located behind the tropical cyclone and to the right of track. This is consistent with the observed satellite SST from AMSR_E and TMI (not shown). A 2.4 ms^{-1} anomaly in the surface ocean current occurs after the hurricane passage. Surface current differences between F2 and F3 are as large as 1 ms^{-1} and near 2 ms^{-1} between F1 and F3. Strong divergence of the surface currents is found to be associated surface cooling, which is conducive for upwelling and cooling in that area.

A vertical cross section of ocean temperature (Fig. 3) is constructed perpendicular to the hurricane track 6 h following the passage of Frances. With the 3-km forcing, a deep mixed layer (~60m) is formed and due to the large surface wind stress. The currents are enhanced by up to 2.4 ms^{-1} near the surface in F3. The strong surface current divergence forces localized regions of upwelling to the right side of the hurricane track (about 100 km away) with SSTs of 26K. With the 9-km forcing, the 26K SSTs do not reach the ocean surface and the currents are about 2 ms^{-1}. With the 27 km forcing, is the SST and current anomalies due to the hurricane are much smaller.

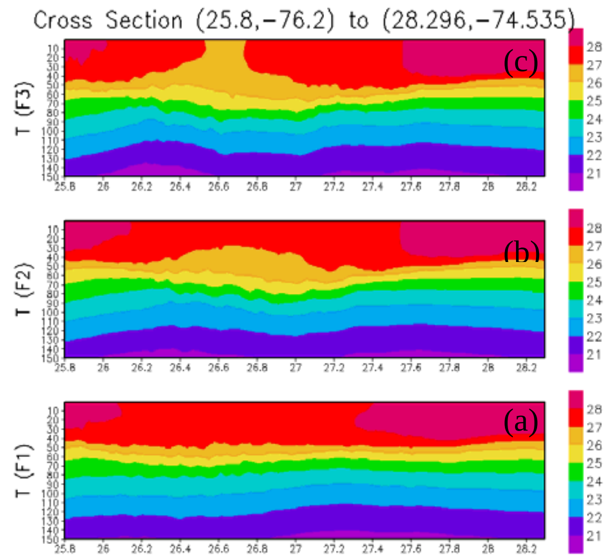

Figure 3. A vertical cross section (6 h after the hurricane passage and perpendicular to the hurricane track) of ocean temperature (K) at 48 h using surface forcing at horizontal resolutions of (a) 27km, (b) 9km and (c) 3km).

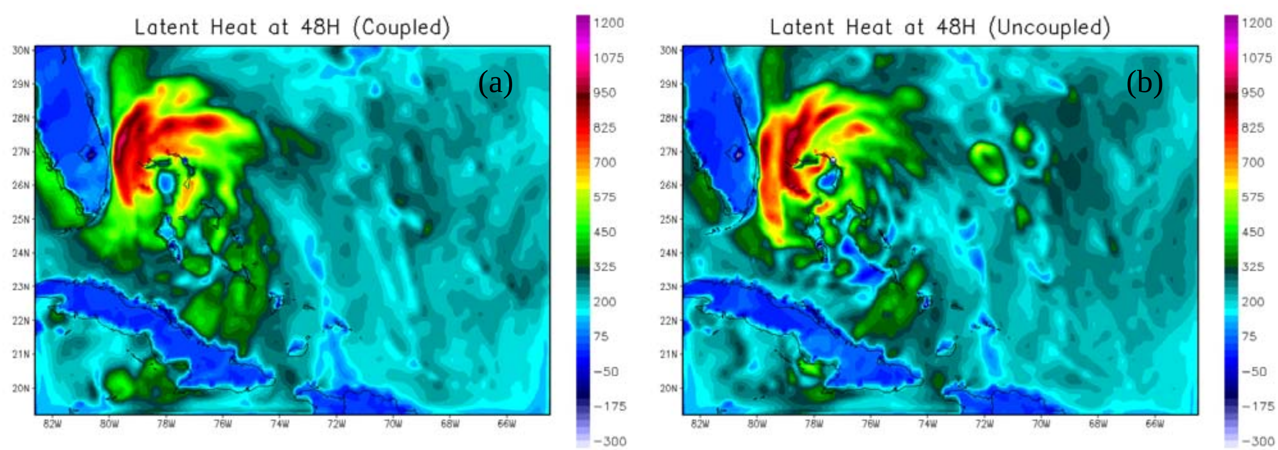

Figure 4. Surface latent heat flux (Wm^{-2}) at 48 h for the (a) coupled and (b) uncoupled simulations.

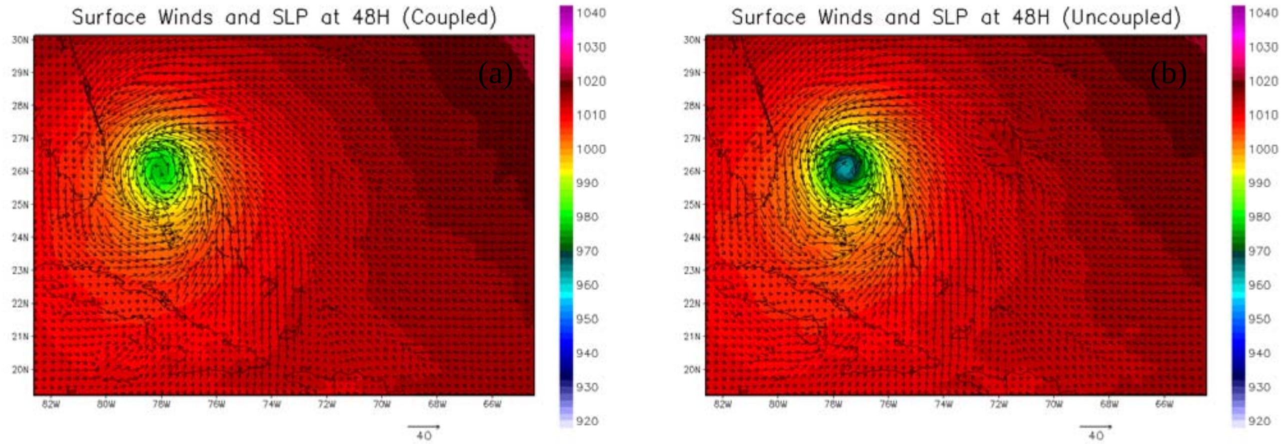

Figure 5. Sea level pressure (mb) after 48-h of the (a) coupled and (b) uncoupled simulations.

3.2 *Coupled vs. Uncoupled Simulations*

The coupled and uncoupled simulations are conducted using the CSIF framework at 10 km resolution. The only difference between the coupled and uncoupled simulations is that the SST in the coupled run is updated every five minutes. The surface latent heat fluxes after 48-h simulations from the uncoupled and coupled runs are shown in Fig. 4. The latent heat flux is weaker in the coupled simulation. Associated with the reduced latent heat flux in the coupled run, the minimum sea level pressure reaches only 978 hPa, about 13 hPa higher than that from an uncoupled run using temporally invariant SSTs (Fig. 5).

4. RESULTS AND CONCLUSIONS

A newly developed coupling framework, the Coupling System Infrastructure Framework (CSIF), designed for efficient coupling of models within COAMPS, has been used to simulate Hurricane Frances (2004) at various horizontal resolutions and in uncoupled (one-way) and coupled (two-way) modes. The results show that the circulation of Hurricane Frances induces a SST cooling to the right of the hurricane path extending outward to about 100 km. The center of the cold SST anomaly trails the hurricane center by 8-10 h. The cooling is forced by the vertical turbulent mixing and ocean upwelling. The simulated SST cooling in the wake of Hurricane Frances is consistent with the AMSR/TMI satellite SST imagery.

Our simulations suggest that the SST and surface currents are very sensitive to the resolution of the atmospheric forcing. The 3-km resolution forcing results in a cold pool that is larger than those found with the 9 km and 27 km surface forcing. A stronger hurricane circulation is simulated on the 3 km grid and as a result of the rapid ocean responses, a larger area of cooling, and a deeper ocean mixed layer ensues relative to the coarser resolution meshes. Comparisons of coupled vs. uncoupled simulations show that the atmosphere responds rapidly to the change of SST and has an important impact on the intensity of Hurricane Frances. The results suggest that two-way interactive coupling is necessary for more realistic intensity forecasts for Hurricane Frances.

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6. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the Battlespace Environment Institute sponsored by the DoD High Performance Computing Modernization Program. Computations were performed on SGI O2K at the Naval Research Laboratory.