P6.11

A FRAMEWORK FOR COUPLED MODELING

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1. INTRODUCTION

To accurately forecast coastal weather, tropical cyclones and storm surge, a coupled model system, including atmosphere model, ocean model, wave model and storm surge model, is required to study the complex and intensive interactions among atmosphere, ocean and wave. Coupled numerical modeling is becoming more popular and affordable with increased computer powers in recent years. Since most existing atmosphere, ocean and wave models usually have different designs and architectures, it is found to be a challenging job to couple them, especially to run them efficiently across vector, parallel, or symmetric multi-processor machines, using the Message Passing Interface (MPI).

Recently, the Earth System Modeling Framework (ESMF) has been developing to serve the coupled numerical modeling needs. ESMF requires that all models coupled under its framework to meet its standard. It is proved to be an extremely hard and time consuming to restructure complicated numerical models. The framework proposed in this study provides a coupling environment and is very similar to ESMF. The major differences between this framework and ESMF are: ESMF requires restructuring each model to its standard and generates a simple executable, while this framework does not require major changes to each model structure, and let each model run with its own executable. Only minimum code and script changes are required for each model under this framework. In this study, the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®[1]) (Hodur, 1997 and Hodur, et al. 2002) developed by the Naval Research Laboratory (NRL), the NRL Coastal Ocean Model (NCOM), and Wave Watch III (WW3) have been coupled and tested for the Hurricane Frances (2004) case.

2. DESCRIPTION OF THE COUPLED SYSTEM

2.1 *Framework*

A coupling system infrastructure framework (CSIF) has been built to provide a streamlined, flexible, and efficient modeling environment in which to couple models, such as atmosphere, ocean, and wave models. Atmosphere, ocean and wave models have been tested with one-way and two-way options. To couple COAMPS and NCOM under ESMF framework, the structures of COAMPS and NCOM need to rewritten. Our new approach is to couple several models with separate executables.

The CSIF (Figure 1) contains COAMPS, NCOM, WW3 and a coupler. Atmospheric model and ocean model coupled in one-way and two-way modes at different coupling frequencies. COAMPS provides surface heat fluxes, wind stress, sea level pressure and rainfall to NCOM, while NCOM feeds back the updated SST to COAMPS. The atmospheric model and wave model coupled in one-way coupled mode. COAMPS provide 10-m winds and air temperature to WW3. The interaction between NCOM and WW3 is realized through exchanging information about SST, sea surface height, currents and wave-induced stress. As shown in Figure 1, the exchange processes denoted in black have been implemented. The red ones are to be done in the future study. All data transfers between different models are handled by the coupler.

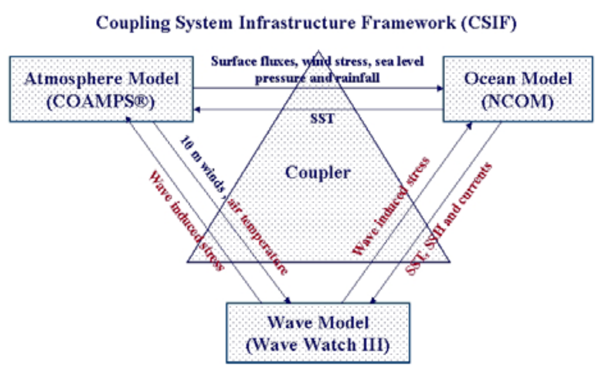

Figure 1. A framework for the coupled modeling.

2.2 *Atmospheric Model*

The Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) (Hodur, 1997 and Hodur, et al. 2002) is a fully compressible, nonhydrostatic primitive equation model. The equations are based 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 to the second-order accuracy and the options are provided for forth-order accurate horizontal advection and diffusion. The micro-physics scheme in COAMPS consists of a single-moment bulk prediction. The shortwave and longwave radiative transfers are following the methods of Harshvardhan et al. A 1.5 order TKE closure is used for

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

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turbulence. A moving inner nest feature following the vortex is particularly useful for the Hurricane simulations.

2.3 ***Ocean Model***

NCOM, the ocean component of COAMPS, is based on hydrostatic primitive equations and is a three-dimensional, free surface model (Martin, 2000). The equations are solved on the staggered Arakawa C grid and using the Boussinesq and incompressible approximations. A hybrid coordinate system is used in the vertical, with sigma coordinates in the upper layers and z-level coordinates in the low layers. An implicit method is used for the barotropic component. The time integration is leapfrog with the Asselin filter to suppress the time-splitting. The second-order centered scheme is used for spatial differencing and a third-order upwind scheme for advection. Mellor-Yamada level 2.5 turbulence model is used for vertical mixing and Smagorinsky scheme is used for horizontal mixing. Radiation schemes are used at the open lateral boundaries.

2.4 ***Wave Model***

The ocean surface wave model is the third generation wave model, WAVEWATCH III (Tolman, 1991). This wave model accounts for wave dispersion within discrete spectral bins by adding diffusion terms to the propagation equation (Booij and Holthuijsen 1987) and uses the Chalikov and Belevich formulation for wave generation and the Tolman and Chalikov formulation for wave dissipation. A third order finite difference method is employed by utilizing a split-mode scheme with a total variance diminishing limiter to solve wave propagation. This model is suitable for wind waves of slowly varying, unsteady and inhomogeneous depths and currents. 25 frequencies wave spectrum (from 0.0418 to 041 Hz) and 48 directional bands are used.

2.5 ***Coupler***

The coupler handles all data transfer between different models. Configurations (grid resolution, number of domains and their locations) for each model can be different. Coupler collects the model configuration of each model and transfer data from one model to another based on domain resolution and location (including the moving nest). The coupler also provides options to control the way of data transfer at the different resolutions for the nested simulations. For example, we can control how to transfer the flux data from COAMPS to NCOM. One way is to transfer the flux data in domain 1 of COAMPS to NCOM. Another is the transfer both domain 1 and domain 2 data to NCOM. We can also combine all three domain information and transfer them to NCOM. By doing this, we test the sensitivity of the ocean simulation to the resolution of atmospheric forcing (see section 4 for discussions).

Namelist or environment variables are used to set exchange frequency (cplflx- for flux and cplsst- for SST) for the coupled modeling. At every cplflx step, COAMPS provides the fluxes and Coupler transfers the data to NCOM. At every cplsst step, NCOM provides SST to all the nested domains of COAMPS through Coupler. Coupler acts as a traffic controller and gives a green light when it finishes the data transfer. NCOM waits at every cplflx step for data and continues to run when Coupler gives a green light. COAMPS waits at every cplsst step for data and continues to run when Coupler gives a green light. We can use cplflx and cplsst to conduct standalone, one-way and two-way interaction studies. This technique is also used for the COAMPS and WW3 coupling.

3. FEATURES OF FRAMEWORK

As stated earlier, this CSIF provides an easy, simple, flexible and efficient model environment to couple numerical models. Since it uses separate executables for the different models, there is no need to change each model structure. Different models start and end at the same time, and exchange information during the simulations. Only a generalized clock needed to add to each model. It is easy to use this system to couple several models and easy to control the exchange frequency between models during the simulation. Table 1 shows the comparison of the uncoupled COAMPS and NCOM simulations with the fully coupled simulations at the different coupling frequencies. It costs less than 3% extra CPU time comparing with the uncoupled simulations.

	CPU Time Ratio	Wall Time Ratio
Uncoupled (cplflx=3600s)	1.000	1.000
Coupled (cplflx=150s)	1.009	1.058
Coupled (cplflx=300s)	1.029	1.064
Coupled (cplflx=600s)	1.017	1.048
Coupled (cplflx=3600s)	1.010	1.027
Coupled (cplflx=10800s)	1.025	1.046
Coupled (cplflx=21600s)	1.013	1.032

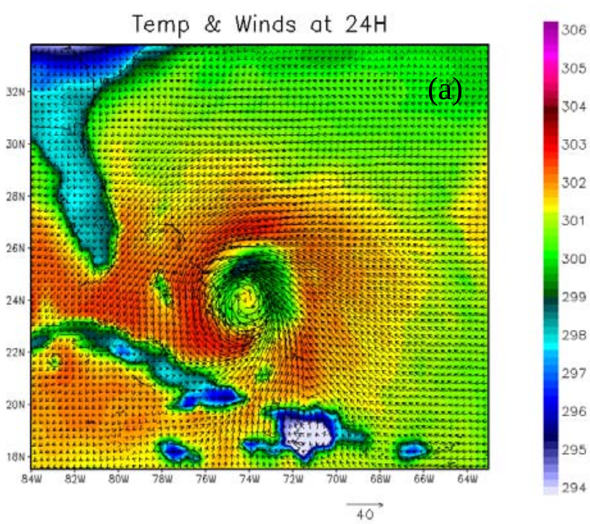
Table 1. CPU and wall time ratios for the uncoupled and the fully coupled simulations with the different coupling frequency.

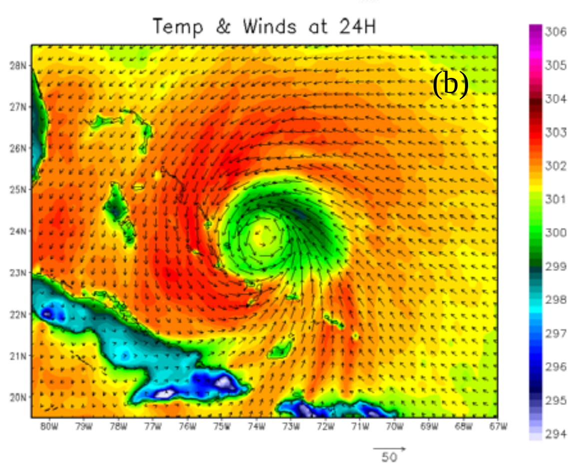
The most important CSIF component is the time management. One clock needs to be created and implemented in each coupled component (atmosphere model, ocean model, wave model and coupler). Each model will update the clock time of its clock hosted at CSIF and check the clock time of other models. Actions taken by each model (such as write out, read in, wait) are based on the clock time and command directions (what actions need to take at the specified time). CSIF provides an environment that allows different models to exchange clock information when the models are running. All clocks will be destroyed when the jobs are done.

4. HURRICANE FRANCES (2004)

CSIF is being used to study the Hurricane Frances case. All models are initialized at 12Z 1 Sept 2004 and run for 48 hours. Three nested domains (27km/9km/3km) in horizontal and 30 levels in vertical with the third mesh moving with the hurricane are constructed for COAMPS. NOGAPS forecasts are used as the first guess. The NCOM simulations are performed at 9km and 3km resolutions in horizontal in the different tests. The NCOM uses the initial and boundary conditions from the 1/8 degree resolution global NCOM forecasts provided by the Naval Oceanographic Offices (NAVO). The WW3 simulation is performed at 9 km resolution and is driven by the surface winds from COAMPS.

Figure 2 shows the COAMPS 24-hour forecasts of temperature and winds at surface in three nested domains. The coarse domain (at 27 km) simulation provides a big picture of hurricane movement and location, while the fine domain (at 3 km) simulation provides the detailed hurricane structures with the lower sea level pressure and the higher surface maximum wind. The surface maximum winds reach 33, 41, and 45 m/s in the 27-km, 9-km, and 3-km resolution domains, respectively. All three domains capture the surface features of the Hurricane, although the maximum surface winds are under estimated.





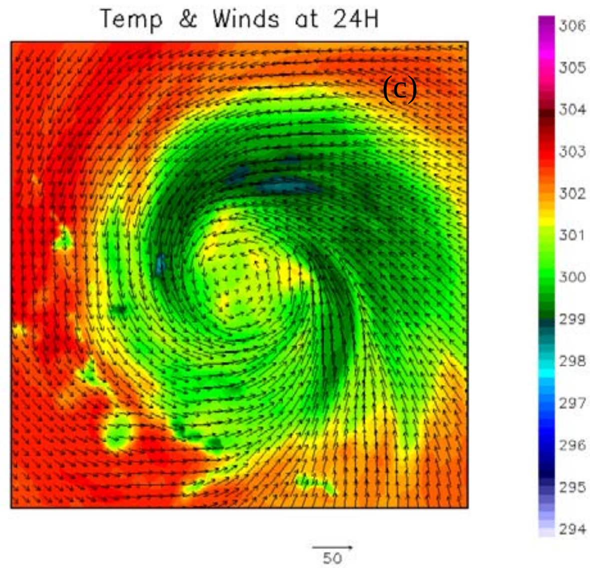


Figure 2. Surface air temperature and surface wind distributions at 24 hour simulation time of (a) domain 1 (27km), (b) domain 2 (9km) and (c) domain 3 (3km). The 3 km resolution domain moves along with the Hurricane.

The simulated waves respond to the high winds of hurricane quickly and the highest significant wave height (SWH) area moves along with the hurricane (Figure 3). The high wave area is located about 80 km away from the hurricane core and on the right side of the hurricane path. The simulated highest SWH reaches 15 feet, which is consisted with the observations. The high waves are dissipated quickly without the continuous high wind forcing after the hurricane's passage. The small islands on the left side of the hurricane path block the wave propagations in that direction.

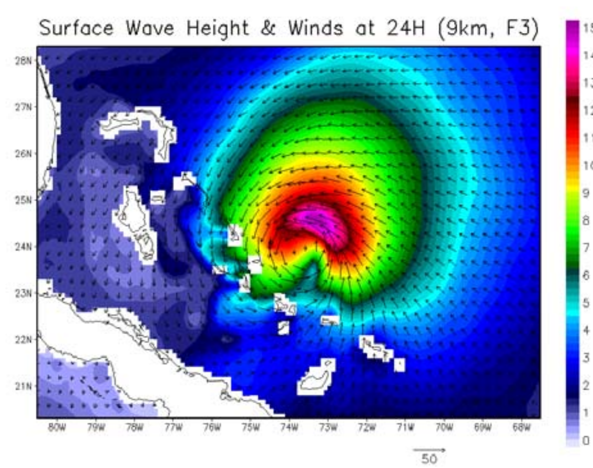


Figure 3. Sea surface significant wave height from WW3 simulations (of 9km resolution) at 24 hours under the wind forcing at the 3km (case F3) resolution.

The coupler combines the surface latent fluxes from three domains and provides a high resolution latent heat field base on the NCOM grid (Figure 4a). The NCOM 24-hour forecast SST and surface currents (Figure 4b) show that the ocean surface responds to the hurricane Frances with the cold SST on the right side of the hurricane path extending for about 100km. The center of the cold SST area is about 8-10 hours behind of the hurricane core and is associated with the ocean vertical mixing and upwelling. The strong winds increase the ocean mixed layer depths to about 60 meter. The simulated SST cooling after the hurricane Frances is consisted with the AMSR_E satellite SST imagery.

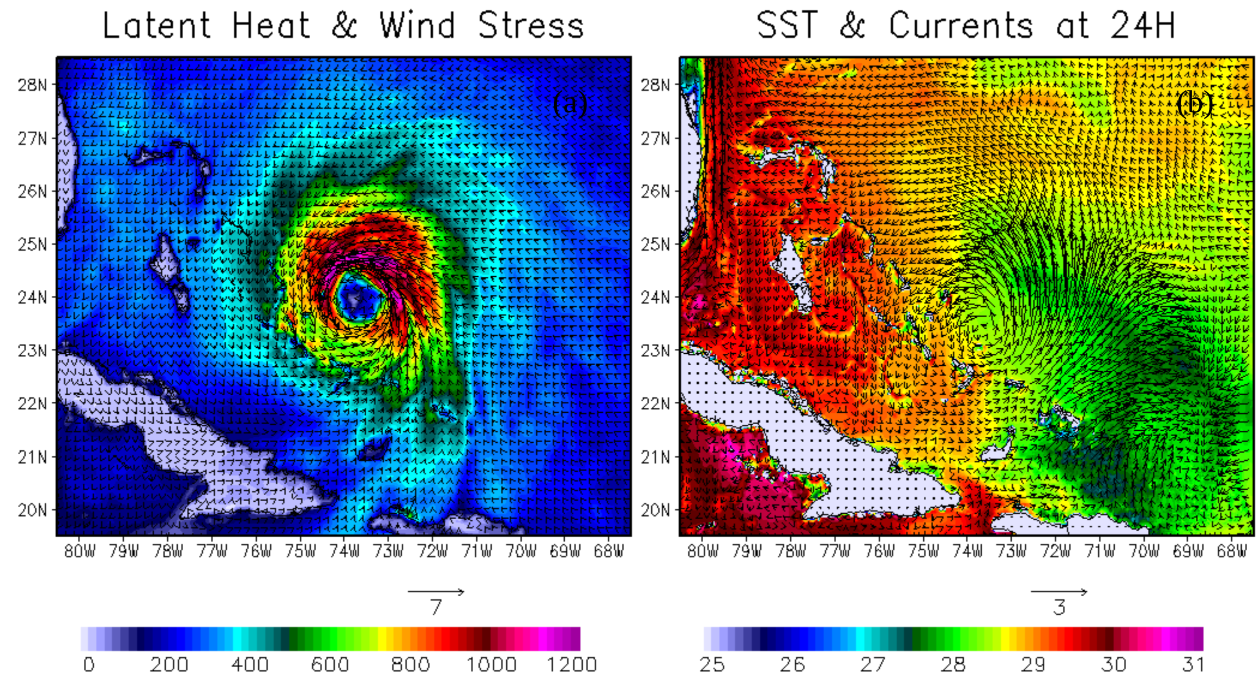


Figure 4. Latent heat and wind stress (a), SST and surface currents (b) distributions at 24 hour simulation time.

5. RESULTS AND CONCLUSIONS

A coupling framework has been built to provide a streamlined, flexible, and efficient modeling environment in which to couple models. This coupling framework does not require any changes to any of the model structures, and only minimal code and script changes are required for each model. Under this framework, separate executables are used for different models, and the models exchange information during the simulation. COAMPS, NCOM, and WW3 have been coupled successfully under this framework and have been tested for Hurricane Frances (2004). Results show that the coupling framework adds less than 3% overhead to the cost of running the systems.

The coupler has been created to control all the data transfer between the different models. Since configurations (grid resolution, number of domains and their locations) for each model can be different, the coupling framework collects the model configuration of each model and transfers data from one model to another model based on domain resolution and location (including moving nests). One-way and two-way coupled COAMPS-NCOM, and one-way coupled COAMPS-WW3 forecasts have been performed using this framework.

6. REFERENCE

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7. ACKNOWLEDGEMENTS

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