9.2 **THE IMPACT OF ATMOSPHERIC MODEL RESOLUTION ON A COUPLED WIND/WAVE FORECAST SYSTEM**

Katherine Howard *, Gary Zarillo, Michael Splitt, Steven Lazarus, Sen Chiao
Florida Institute of Technology, Melbourne, Florida

Pablo Santos
National Weather Service, Miami, Florida

David Sharp
National Weather Service, Melbourne, Florida

1. INTRODUCTION

Coastal National Weather Service Forecast Offices (NWSFOs) have responsibility for the nearshore ocean – a region that extends approximately 50 miles from the coastline (Fig. 1). Because the vast majority of human water-related activity occurs within this zone, the quality of wind and wave forecasts are of great importance. At present, NWSFOs receive wave forecast products from the National Centers for Environmental Prediction (NCEP) WAVEWATCH III model (herein referred to as WW3, Tolman 2002). An example of the WW3 coastal product as viewed on the NWS Advanced Weather Interactive Processing System (AWIPS) platform is shown in Figure 1. Despite the relatively high resolution (on the order of 5-10 km) of the coastal product, the WW3 grid spacing remains insufficient to accurately resolve the essential physical processes responsible for wave generation near the coastline. As a result, WW3 products do not extend to the shore (Fig. 1). Presently, NWSFOs extrapolate WW3 output to the shoreline using a Smart Tool (LeFebvre et al. 2001) developed expressly for this purpose (P. Santos, personal communication). Furthermore, the NWS has expressed a direct interest in expanding and improving wave model guidance in the surf zone and offshore waters as well as the full integration of wave model output into the gridded forecast environment (Johnson 2005).

Atmosphere-wave model coupling has become an important component of wave forecasting as the science of air-sea interaction has shown the direct benefits of using accurate high resolution surface winds to drive wave models (e.g., Hodur 1997; Janssen et al. 1997; Makin and Kudryavtsev 1999). In order to better resolve bottom topography, and irregular coastline features, inlets, etc., a wave model should also be of sufficient resolution and include shallow-water effects such as depth-induced wave breaking, triad wave-wave interactions, wave diffraction, and reflection (Cavaleri 2006, Lin et al. 2006).

As a result, an operational high resolution coupled wind/wave forecast system has been developed in collaboration with the NWSFOs in Miami and Melbourne Florida. The project, funded under NOAA's CSTAR program, consists of two basic components that include1) a one-way coupling of wave and atmospheric forecast models and 2) a data assimilation system for QuikSCAT and WSR-88D winds. The latter is discussed in more detail in a companion preprint by Lamberton et al. (2009). A preliminary assessment of the impact of different atmospheric model resolutions on the wave forecasts is presented for the Tropical Storm (TS) Fay wind/wave event that occurred over the period of 18-23 August 2008.

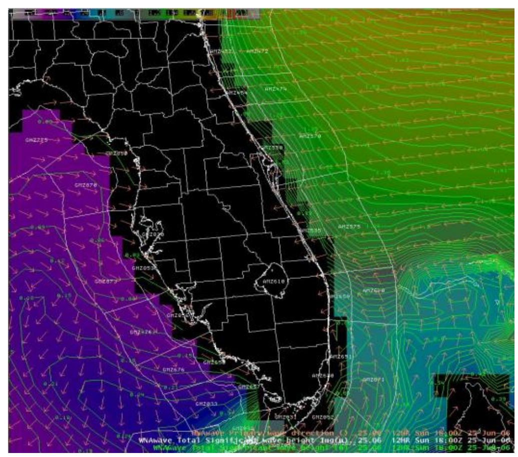

Fig. 1. NOAA WW3 (Western North Atlantic regional wave model) 12 h forecast of primary wave direction (arrows) and significant wave height (m, contours and shading) valid 18 UTC 25 June 2006. Image provided by the Melbourne FL NWS.

2. METHODS

2.1 Atmospheric/Wave Coupling

The forecast system is shown in Figure 3. Results are presented for TS Fay (e.g., Fig. 2) in which the wave model is driven by wind fields from the NAM only, and from the Weather Research and Forecasting model (WRF, red highlight in Fig. 3). Model output from the NAM 218 is used to initialize and provide the boundary conditions for the atmospheric model. Forecasted 10 m winds from various horizontal resolutions of the Weather Research and Forecast - Environmental Modeling System (WRF-EMS) are used to force the Wave-Action Balance Equation and Diffraction (WABED) model.

* Corresponding author address: Katherine L. Howard, Florida Institute of Technology, 150 W. University Blvd, Melbourne, FL 32901. E-mail: khoward@fit.edu.

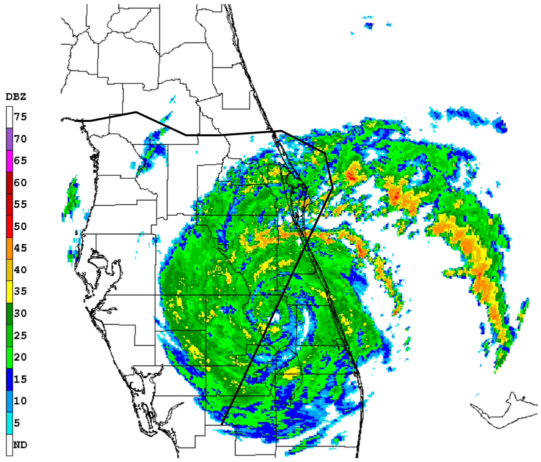

Fig. 2. Melbourne FL National Weather Service WSR-88D reflectivity (0.5 degree) for tropical storm Fay valid 00:12 LST 20 August 2008. Approximate storm path delineated by solid black line.

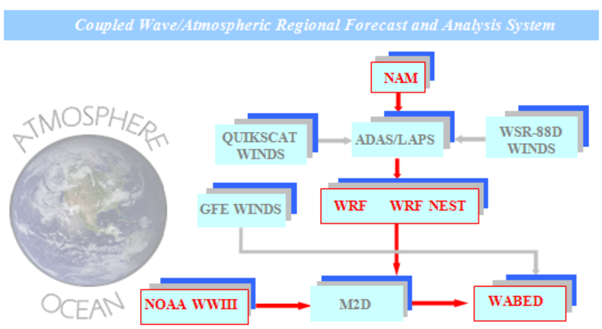

Fig. 3. Flow chart depicting wind/wave forecast system. Red arrows, text and boxes are those components being used and evaluated in this study.

2.2 Atmospheric Model Configuration

The effects of the spatial resolution of the wind forcing on wave forecasts is addressed by examining different model configurations and options, which include varying atmospheric model resolutions (10 km, 4.5 km, and 1.5 km) and the 12 km resolution NAM 218 winds. In order the facilitate the transition of the wind and wave forecast system to the NWS, the Science and Operations Officer (SOO) Science and Training Resource Center (SOO/STRC) Weather Research and Forecasting (WRF) Environmental Modeling System (EMS) version 2.1.2.2e with the ARW core is used. WRF-EMS configuration options are shown in Table 1.

A high resolution domain is set-up that consists of a 4.5 km outer domain and a nested 1.5 km inner domain (Fig. 4). One-way coupling is setup in which the 4.5 km outer domain provides the boundary conditions for the 1.5 km inner nest. The high resolution nested configuration is hereafter referred to as WRF-4.5/1.5.

Table 1. WRF model physics and dynamics configurations.

WRF Model Configurations	
Model Physics	
Cumulus Parameterization	Turned off because of high spatial resolution
Microphysics scheme	Lin et al. scheme, for high spatial resolution dx
Planetary Boundary Layer	Yonsei University scheme
Land Surface	Noah Land Surface Model
Surface Layer	MM5 similarity theory
Long Wave Radiation	RRTM scheme
Short Wave Radiation	Dudhia scheme
Model Dynamics	
Time-integration	Runge-Kutta 3rd Order
Diffusion option	Simple diffusion
Eddy coefficient option	Horizontal Smagorinsky First Order Closure
Upper-level Damping	No damping
Vertical Velocity Damping	Yes

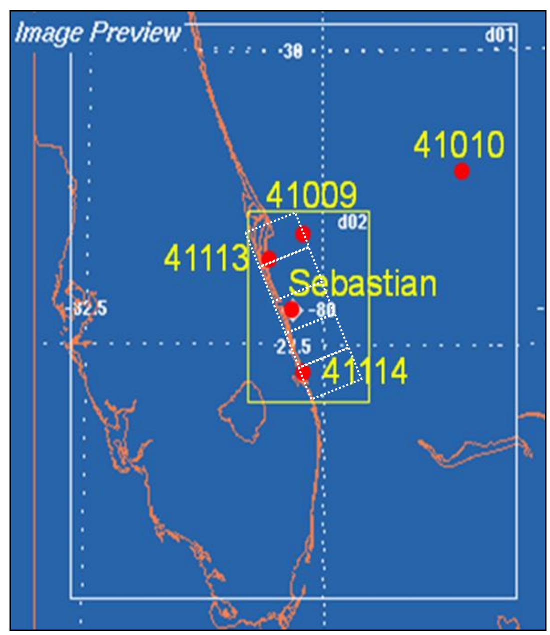

Fig. 4. WRF-EMS domain boundaries showing inner nest (yellow solid line) and outer nest (white solid line). Also shown are the 5 wave model subdomains (dotted boxes) and locations of the validation buoys.

The outer domain of the WRF-4.5/1.5 is referred to as WRF-4.5 and the nest is WRF-1.5. The outer domain is approximately 468 km x 545 km is size and the inner nest is approximately 128 km x 182 km in size. Model output from four NAM 218 tiles provide the initial conditions and three-hourly boundary conditions for the WRF-EMS (obtained from the NCEP server at ftp://ftpprd.ncep.noaa.gov/pub/data/nccf/com/nam/prod). The NAM model data are archived and later used, in lieu of WRF, as an alternative wind forcing for CMS-Wave.

A second lower resolution (10 km) single domain WRF-EMS configuration (herein referred to as WRF-10) with the same physics (Table 1) and outer domain boundaries as the WRF-4.5/1.5 has also been set up.

Forecasts for the TS FAY event are launched using the 00 UTC NAM cycle and are executed on an 8 node cluster. 10 m wind output from the simulations and from NAM are directly used to force the 48 h wave model forecasts.

2.3 Wave Model

CMS-Wave (formerly known as WABED) is one of the components of the Coastal Inlets Research Program's (CIRP's) Coastal Modeling System (CMS) (CMS, Buttolph et al. 2006). The **W**ave-**A**ction **B**alance **E**quation with **D**iffraction or WABED model is a wave model developed for the U.S. Army Engineering Research and Development Center (ERDC) for the purpose of coupling with 2 and 3-dimensional hydrodynamic models designed for high resolution predictions in coastal waters (Mase and Kitano 2000; Mase et al. 2005). CMS-Wave/WABED is a 2-D wave spectral transformation (phase-averaged) model (Lin et al. 2006). Designed for the nearshore region, CMS-Wave is ideal for this study as the wave diffraction scheme in WABED has been shown to be more robust when compared to schemes in other nearshore wave models like SWAN or STWAVE (Mase and Kitano 2000; Mase et al. 2005). The model operates on a coastal half-plane such that primary waves can only propagate from the seaward boundary towards the shoreline. For this study, the CMS-Wave is setup with five high spatial resolution (100 m) grids approximately 50 km^2 in size (Figure 4), oriented coast-parallel from Playlinda Beach, FL north of Cape Canaveral south to Jupiter, FL. The high resolution wave domains lie within the 1.5 km inner WRF-nest.

CMS-Wave is forced by two, single point, time series inputs: initial and boundary wave conditions from WW3 and 10 m winds from the WRF-EMS or NAM 218. For the TS Fay case study, each of the five wave grids are driven by a single independent time series with three hour resolution and are run on the same 8 node cluster as the WRF-EMS.

2.4 Validation

The wave model validation includes significant wave height, primary wave direction, and wave period. The forecast wave parameters are compared to buoy observations within the wave subdomains to help determine an optimal configuration for the real-time forecast system. The impact of forcing the wave model with the different WRF-EMS configurations, as well as the NAM, will be presented in the results section.

Table 2. Wind and wave verification data buoys used in study.

Verification Data Buoys	
10 m Wind Speed and Direction	**Significant Wave Height and Dominant Wave Period**
41009	41009
41010	41113
	41114

Quality controlled buoy data were obtained from the National Data Buoy Center (NDBC) server (http://www.ndbc.noaa.gov/data/) for the buoys shown in Figure 4. If the anemometer on the buoy is not at the WMO standard 10 m, the data from that buoy is adjusted according to the method of Hsu et al. (1994),

$$u_2 = u_1 \, (z_2/z_1)^P \qquad (1)$$

where u_1 is the observed value, u_2 is the value adjusted to the 10 m height, z_1 is the anemometer height, z_2 is the standard height of 10 m, and P is set to 0.11, an empirically determined value shown to be representative over the ocean (Hsu et al. 1994). For the WRF-EMS domain, wind data observations are available at two of the buoy locations shown in Figure 4, while significant wave height is measured at three locations (Table 2).

2.5 Statistics

The statistical quantities employed in this study include the following: RMSE and the scatter index (SI). These statistics are defined in Table 3.

The scatter index (SI) is a standard metric for wave model intercomparison (Clancy et al. 1986). Essentially, it is a normalized measure of error that takes into account the observed wind speed. Lower values of the

Table 3. Statistics used to evaluate the coupled forecast system.

Statistics
Root-mean square error (RMS_{error}): $$\sqrt{\frac{1}{N}\sum_{N}(X_n - Y_n)^2}$$
Scatter Index (SI): $$SI = \frac{standard\ deviation\ of\ errors}{average\ obs} \times 100\%$$

SI are an indication of a better forecast. In the context of significant wave height, reports of the scatter index (SI) in the literature range between 20% for hindcasts with sophisticated models and high quality wind fields to 60% for some operational forecasts with less accurate winds (Janssen and Komen 1984; Clancy et al. 1986). Here, the scatter index is applied to both the wave model output and to gauge the quality of the wind forecasts that drive CMS-Wave as well.

3. RESULTS

RMSE and scatter index are presented for the TS Fay wind event for August 19-22 2008. Each quantity is calculated over the duration of four separate 48 h forecast periods. The SI (Fig. 5) shows noticeable improvement in the 10 m wind forecast when using the WRF-EMS (compare the NAM SI shown in purple with the various WRF-EMS configurations). Horizontal resolution does not appear to significantly impact the wind forecast at buoy 41009 for this event. RMSE for the significant wave height (m) at buoys 41009, 41113, and 41114 are shown in Figures 6a-c respectively. The RMSE is lower for the two buoys that are closer to the coast (Fig. 3). With the exception of the 19 August simulation, the NAM forcing performs quite well compared to the higher resolution WRF and actually produces lower error at 41114 for the 20-22 August period (Fig. 6c). Some of the performance issues are likely tied to the storm location as winds shift during this period from onshore to offshore while the storm tracks to the northeast. This is a subject of further investigation.

The difference between the SI for WW3 and CMS-Wave (i.e., WW3 SI minus CMS-Wave SI) is shown for significant wave height (Fig. 7) and dominant wave period (Fig. 8) for 19-22 August 2008. Positive values indicate that CMS-Wave yields reduced error compared to that of WW3. As one might expect, difference values are small at buoy 41009 which is at the eastern edge of the northernmost wave domain where the WW3 forcing enters the domain. At the coastal buoys (41113, 41114), the forecast significant wave height and dominant wave period is improved over that of WW3 for all model configurations. Improvement is significant at buoy 41114 for dominant wave period. Again, horizontal resolution does not appear to be a factor for this case – rather it is the implementation of the coastal wave model that is the source of the improvement.

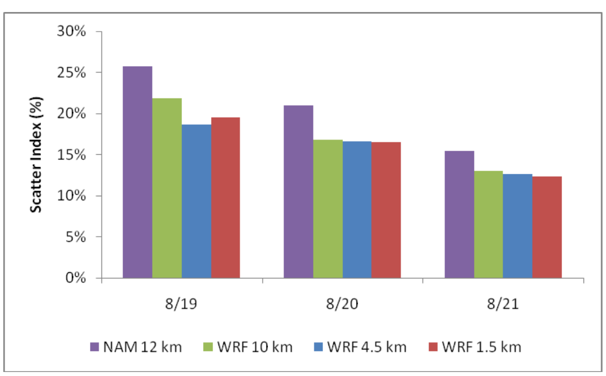

Fig. 5. 10 m wind scatter index (%) for three consecutive 48 h forecasts at buoy 41009. Colors indicate varying atmospheric models and model resolutions.

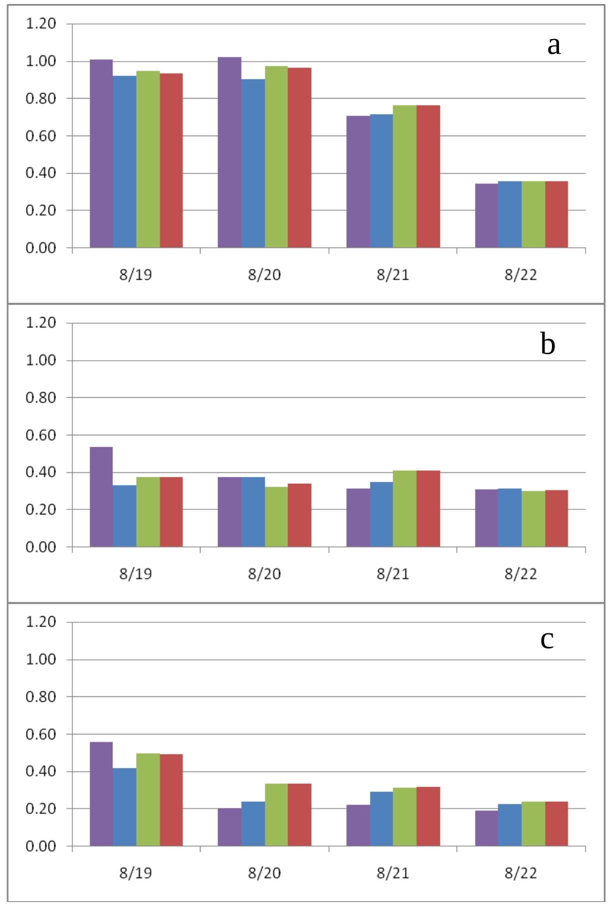

Fig. 6a-c. RMSE for forecast significant wave height (m) for 19-22 August at buoys 41009 (a), 41113 (b), and 41114 (c).

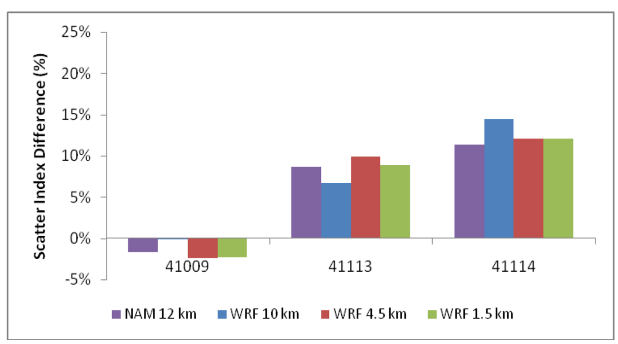

Fig. 7. Scatter Index difference (%) between forecast significant wave height (m) from WW3 and CMS-Wave for the period 19-22 August. Colors indicate varying atmospheric models and model resolutions. Positive values indicate that the CMS-Wave forecast is improved over that of WW3.

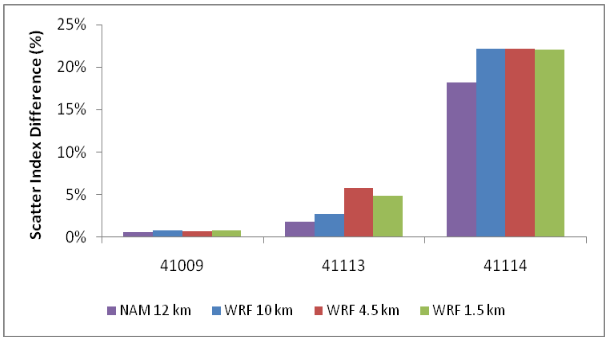

Fig. 8. Same as Figure 7 but for forecast dominant wave period (s).

4. FUTURE WORK

The TS Fay case study is one of a number of wind events that are being used for analysis purposes. Efforts are ongoing to stratify these events based on flow regimes (e.g., onshore versus offshore). Future evaluation will include significant wave height data from satellite altimetry and the incorporation of a flow model into the coupled forecast system.

The wind/wave system is slated for eventual transition and implementation at the National Weather Service (NWS) Forecast Offices in Melbourne and Miami, FL. The intent is to provide quality high resolution short-term gridded wave forecasts for the NWS marine area of responsibility. Taking advantage of the higher resolution, the system will support the creation of enhanced, value-added products. The detailed information will help coastal forecast offices meet the increasing demands of a growing marine industry and boating community.

5. REFERENCES

Buttolph, A. M., Reed, C. W., Kraus, N. C. , Ono, N., Larson, M., Camenen, B., Hansen, H., Wamsley,T., and Zundel, A. K.,. 2006. Two-Dimensional Depth-Averaged Circulation Model CMS-M2D: Version 3.0, Report 2, Sediment Transport and Morphology Change. Coastal Inlets Research Program Technical Report ERDC-CHL-TR-06-, U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.

Cavaleri, L., 2006: Wave Modeling: Where to Go in the Future. *Bull. Amer. Meteor. Soc.*, **87**, 207–214.

Clancy, R., J. Kaitala, and L. Zambresky, 1986: The Fleet Numerical Oceanography Center Global Spectral Ocean Wave Model. *Bull. Amer. Meteor. Soc.*, **67**, 498–512.

Hodur, R.M., 1997: The Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). *Mon. Wea. Rev.*, **125**, 1414–1430.

Hsu, S. A., Eric A. Meindl, and David B. Gilhousen, 1994: Determining the Power-Law Wind-Profile Exponent under Near-Neutral Stability Conditions at Sea, Applied Meteorology, Vol. 33, No. 6, June 1994.

Janssen, P. A. E. M., G. J. Komen, and W. J. P. De Voogt (1984), An Operational Coupled Hybrid Wave Prediction Model, *J. Geophys. Res.*, 89(C3), 3635–3654.

Janssen, P.A.E.M., B. Hansen, and J.R. Bidlot, 1997: Verification of the ECMWF Wave Forecasting System against Buoy and Altimeter Data. *Wea. Forecasting*, **12**, 763–784.

Johnson, D. L., 2005: National Oceanic and Atmospheric Administration memorandum on urgent priorites from the NWS perspective for fiscal years 2008-2012. 8 pp.

Lamberton, N., M. Splitt, S. Lazarus, G. Zarillo, S. Chiao, P. Santos, and D. Sharp, 2009: Assimilation of nearshore winds into a high-resolution atmosphere/wave modeling system. *Preprints, 13th Symposium on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS),* Phoenix, Arizona, Amer. Meteor. Soc., CD-ROM 5B.2.

LeFebvre T. J., M. Mathewson, T. Hansen, and M. Romberg, 2001: Injecting meteorology into the GFE suite. Preprints, *17th Int. Conf. on Interactive information and Processing Systems for Meteorology*, *Oceanography, and Hydrology*, Albuquerque, NM, Amer. Meteor. Soc., 38-41.

Lin, L., H. Mase, F. Yamada, and Z. Demirbilek. 2006. *Wave-action balance diffraction (WABED) model tests of wave diffraction and reflection at inlets.* Coastal Inlets Research Program, ERDC/CHL CHETN-III-73. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Makin, V. K., and V. N. Kudryavtsev (1999), Coupled sea surface-atmosphere model 1. Wind over waves coupling, *J. Geophys. Res.*, 104(C4), 7613–7623.

Mase, H., and T. Kitano. 2000. Spectrum-based prediction model for random wave transformation over arbitrary bottom topography. *Coastal Engineering Journal* 42(1), 111-151.

Mase, H., K. Oki, T. Hedges, and H. J. Li. 2005. Extended energy-balance-equation wave model for multi-directional random wave transformation. *Ocean Engineering* 32, 961-985.

Tolman, H. L., 2002g: User manual and system documentation of WAVEWATCH-III version 2.22. NOAA / NWS / NCEP / MMAB Technical Note **222**, 133 pp.