Wave-current interaction in the Florida Current in a coupled atmosphere-ocean-wave model

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Abstract-The interaction of waves and currents are investigated in the Florida Current region in two events in early April 2005 using a state-of-the-art coupled atmosphere-ocean forecast model that includes assimilation of observations. During the first event, strong northerly winds force swell southward opposing the Florida Current. Current-wave interaction results in larger significant wave heights than found without currents. The second event has south-easterly winds with a significant component along the current direction. In that case, significant wave heights are smaller for the simulation that includes wave-current interaction than without that feed-back. Wave heights at buoy locations near the coast is generally in good agreement with the models results, which implies that inclusion of wave-current interaction may not be important near the shore . The simulation includes events where the maximum winds reach 20 m/s and significant wave heights exceed 2 m.

I. INTRODUCTION

The Florida Current has currents in excess of 1.5 m/s as it flows pasts the Florida Keys and into the Atlantic Ocean. The strong current is highly sheared, and impacts propagation of swell by refraction and local waves are growing at different rates near the core of the boundary current compared to waves in surrounding regions with weaker current. Off the Atlantic coast of central Florida, the current is northward, so we have chosen a case where the wind primarily is from the north and a case where the wind is from the southeast to examine the wave-current interaction. The study is part of a validation study for a coupled atmosphere-ocean-wave model system and we compare weather station data and wave buoy observations to the model fields.

II. COUPLED OCEAN-ATMOSPHERE MESO-SCALE PREDICTION SYSTEM

We apply the Naval Research Laboratory's Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS®) in a fully coupled mode with very high horizontal and vertical resolutions. The non-hydrostatic atmospheric model is using 3 nested Mercator grids with resolutions of 18 km, 6 km and 2 km, respectively. The coarsest grid cover a region from 85.4°W to 73.5°W and 20.9°N to 32.2°N; the 6-km grid covers the area within 84.00°W to 75.25°W and 22.49°N to 30.47°N; the finest grid is over the region 81.02°W to 78.51°W and 23.40°N to 27.35°N. Fig. 1 shows the areas covered by the three grids bounded by black lines. All atmospheric model grids have 60 vertical levels. The atmospheric models are initialized using the Navy Operational Global Atmospheric Prediction System (NOGAPS) at 0.5° spatial resolution, which also is used to provide boundary conditions during the simulation. The atmospheric model component is described in [9].

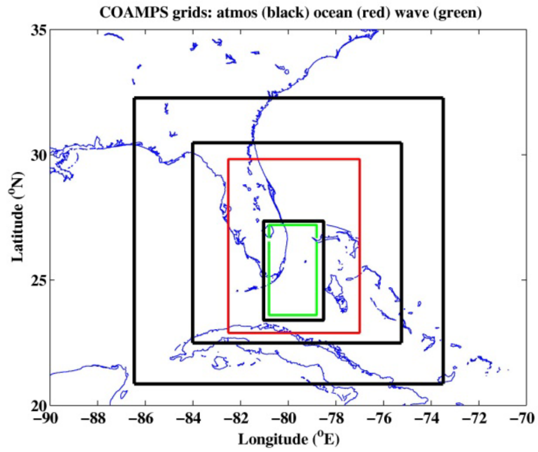

Fig 1. Areas covered by model grids. Boundaries for the three atmospheric grids are show with black lines, with a red line for the 3-km ocean grid and with a green line for the 1-km ocean and wave model grids that were identical.

Details about the ocean model, the Navy Coastal Ocean Model (NCOM), are given in [10]. We use two one-way nested ocean model grids. The coarser model grid covers the area from 82.51°W to 76.99°W and 22.89°N to 29.828°N with a horizontal resolution of 0.03° in the east-west direction and 0.027° in the north-south direction, or about 3 km.

An inner nest with the same vertical levels and a horizontal resolution increased by a factor of three to 1 km covers a region from 82.02°W to 77.45°W and 23.422°N to 26.914°N. Both models are free surface models and use a hybrid sigma-z vertical coordinate with 36 terrain-following sigma levels in the upper 500 m. Below 500 m, up to 15 constant depth z-levels are used to resolve the flow, for a total of up to 51 levels at depths of 5500 m. The initial fields and boundary conditions are provided by Global NCOM using 1/8° spatial resolution and 40 vertical levels [4]. The areas covered by the two ocean models are shown in Fig. 1 bounded by red and green lines.Tides are included as boundary conditions from Oregon State tidal data bases [5][6], and the NCOM forcing includes the tidal potential for the eight primary tidal components : M2, S2, N2, K2, K1, O1, P1 and Q1.

We use the Simulating Waves Nearshore (SWAN) spectral wave model [12], with 33 frequencies in the range 0.0418 Hz – 1Hz and 72 directions, corresponding to a directional resolution of 5°. The wave model covers the area from 80.8°W to 78.8°W and 23.6°N to 27.2°N, the same as the 1-km ocean model and outlined in green in Fig. 1. Boundary conditions are provided by Wavewatch III, which is run in two nested grids. The outer grid has 0.5° resolution, covering the North Atlantic from 17N to 59N. The inner grid has 6.5 km resolution, and covers the area within 90°W to 72°W and 21.2°N to 40°N. SWAN provides wave-induced radiation stress, Stokes drift currents and bottom stress, as additional forcing to the ocean model, which in turn provides mixed layer currents and sea surface height to the wave model. A new formulation of wave dissipation [11] and refraction formulation [13] is used. The coupling between all three model components is done every 6 minutes.

A 12 hour forecast is done using the coupled model, followed by an analysis that includes previous forecasts and data assimilation of new available atmospheric observations. This 12-hour forecast/analysis cycle is repeated throughout the simulation. The coupled ocean-atmosphere model, without waves, has been validated and discussed in early studies [2], including oceanic jets in the open ocean such as the Kuroshio [8]. The fully coupled system including surface waves has recently been described in more detail in [1].

IV. Bathymetry

Global NCOM is using the Navy's Global DBDB2 bathymetry, a 2-minute ($1/30^o$) to calculate ocean depths. For the regional NCOM, DBDB2 was interpolated to a 0.01^o and 0.009^o longitude-latitude grid, which is close to 1 km in resolution (Fig 2, right). The GEODAS grid generator was used to obtain a US Coastal Relief Model in 15-seconds resolution for the coastal region along Florida and part of the Bahamas. The GEODAS data was interpolated to the same 1-km grid as DBDB2 (Fig. 2, left).

Missing data to the south and to the east on the 1-km GEODAS grid were replaced by 1-km DBDB2 data. In a region with a width of 21 km, a linear combination of depths from the two grids was used. Weights on the DBDB2 data decreased linearly from 1 at the missing data location to 0 at a distance 21 km into the GEODAS grid. After interpolation, two passes of a 9-point weighted average filter was used to smooth out the topography in the boundary region. The resulting bottom topography is shown in Fig. 2, center panel. A minimum depth of 5 m is used for the bathymetry used in NCOM, while a 0.1 m minimum depth is used for SWAN since wetting and drying is included.

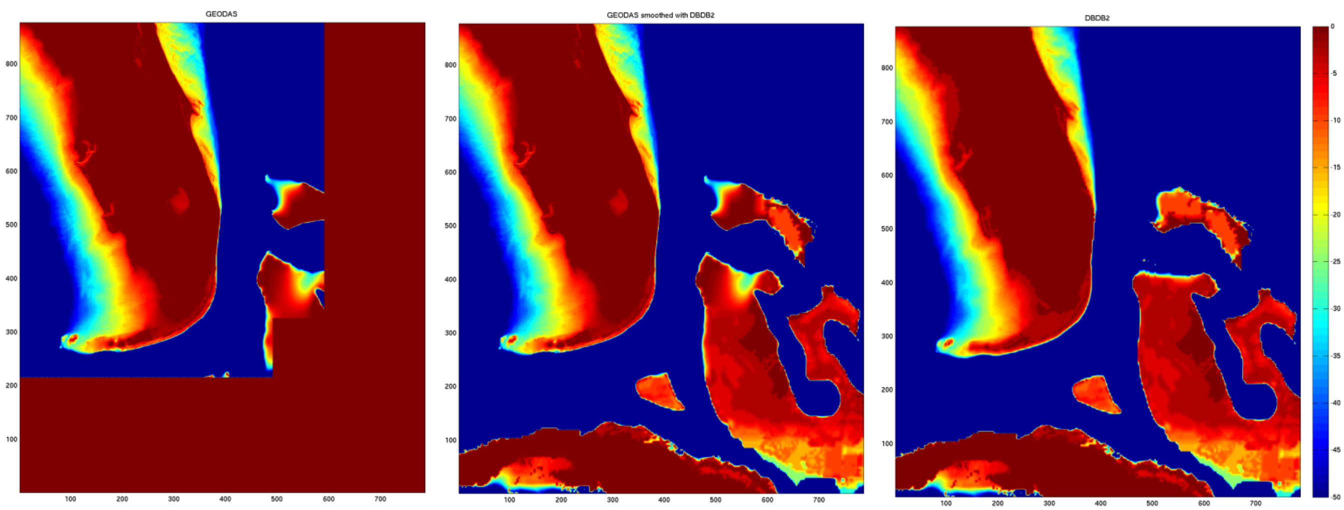

Fig 2. Bathymetry on 1-km from the US Coastal Relief Model using GEODAS (left), combined GEODAS-DBDB2 data (center) and data from DBDB2 (right). The color scale shows depths over 50 m in blue.

V. Spring 2005 Simulation

The coupled model was run to simulate the time period from March 10 to 31 May, 2005 using 12-hourly update cycles. The first 48 hours are used as a spin-up time, and the wave model was run without incoming waves. In this paper we present two wind case scenarios that both generated high waves: The first is a case of northwesterly wind conditions from April 3 to 4, 2005 and a second case were during April 6 to 8 where winds were from the south-southeast. Fig 3. below shows the 10-m winds for all three atmospheric model nests at April 3, 12 UTC, when strong westerlies off the South Carolina and Georgia coast generated large waves.

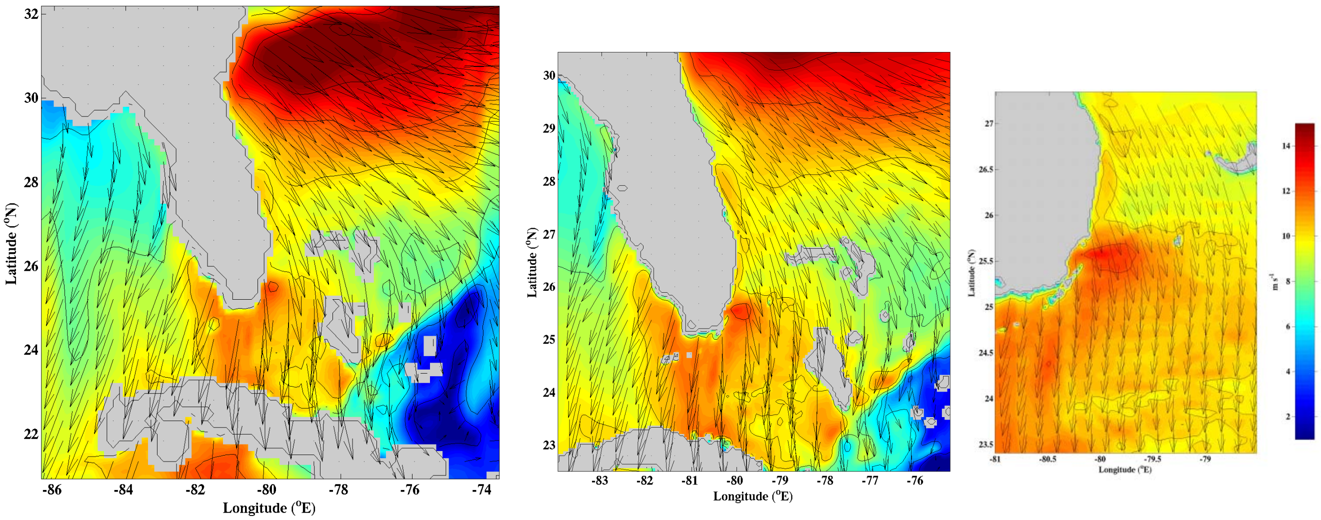

Fig 3. COAMPS atmospheric model 10-m wind vectors and wind speed on April 3, 2005 12UTC Left: The coarse model grid (18 km) showing winds in excess of 15 m/s off the coast of South Carolina and Georgia. Center: 10-m winds on the 6-km grid. Right: wind velocity and wind speed at 10 m shown on nest 3 (2 km grid). The color represents the total wind speed.

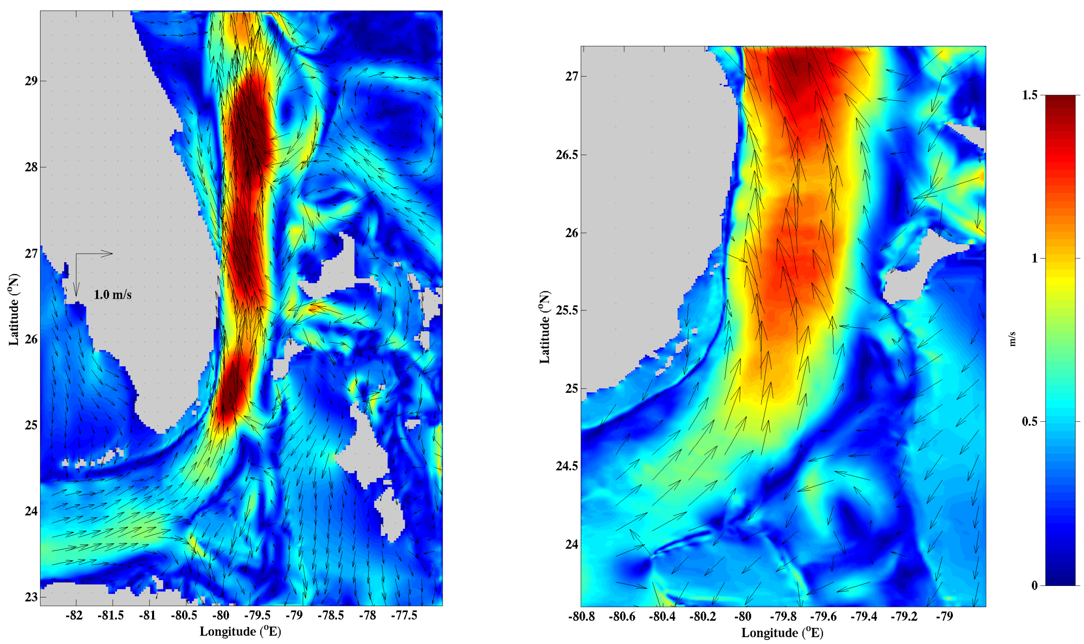

Fig 4. Left: The surface current vector and speed on the 3-km NCOM grid on April 3, 2005 12UTC. Right: Sea surface temperature and current vectors from the 1-km grid NCOM model

In early April, the Florida Current was relatively weak, although current speeds exceeded 1.5 m/s offshore near Cape Canaveral (Fig. 4, left), while exceeding 1 m/s between the south Florida coast and the Bahamas. The flow in the Florida Current has a fairly steady northward component, while the east-west component shows higher variability, mainly in response to the tides.

The largest waves are generated to the north and propagate southward as swell. The significant wave height, H_{sig}, is shown in Fig. 5. The panel to the left shows H_{sig} from a fully coupled run where sea level and surface currents were used for computation of the wave field. Away from the near-shore region, the wave height is larger than if current and sea level feedback to the waves are turned off in the coupled model (right, panel).

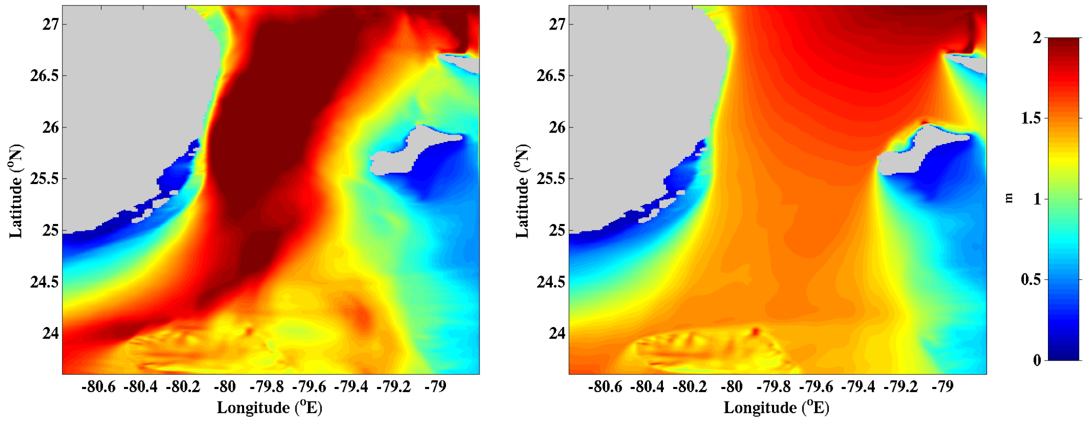

Fig 5. Left: Significant wave height on the 1-km SWAN grid on April 4, 2005 00UTC with current-wave interaction. Right: Significant wave height at the same time but from a run without ocean model feedback to the wave model.

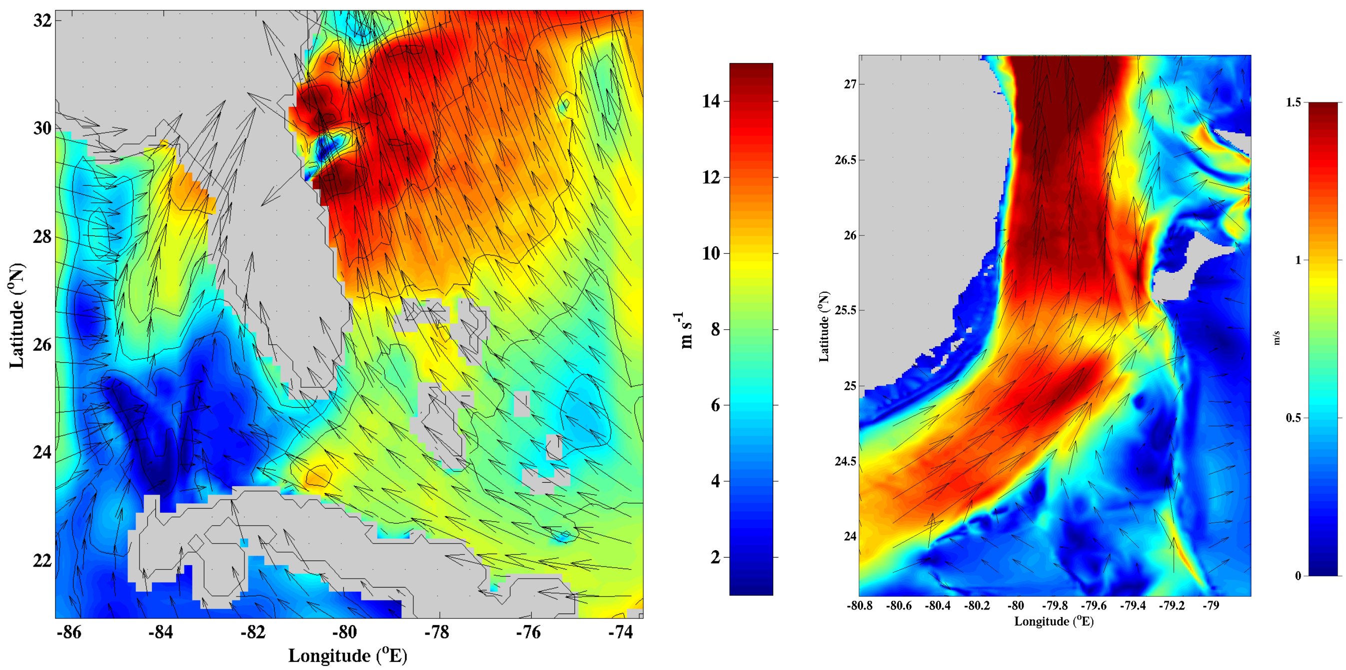

Fig 6. COAMPS atmospheric model 10-m wind vectors and wind speed on April 8, 2005 00UTC on the 18 km grid (Left). The Atlantic off Florida is forced by south-southeasterly winds intensifying poleward. The color represents the total wind speed. Right: Surface currents on the 1-km ocean grid at the same time. Compared to April 3, the Florida Current is intensified.

The swell propagation is against the currents which lead to the larger wave amplitude due to trapping of wave energy [7]. In contrast, for the case of south-south easterly winds (Fig. 6, left), the wave height is reduced when surface currents are active (Fig. 7, left) compared to the model simulation without current feedback (Fig. 7, right).

During this second case from April 6 to 8, the Florida Current is stronger than during April 3 (Fig. 4, right). The strong currents also have a significant impact on the wave period through Doppler shifts and on wave propagation through refraction.

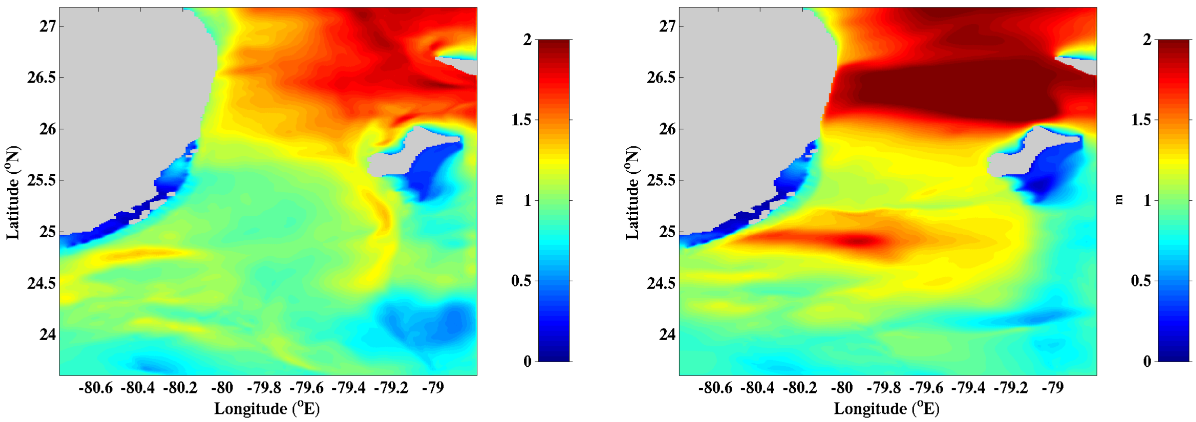

Fig 7. Left: Significant wave height on the 1-km SWAN grid on April 8, 2005 12UTC with current-wave interaction. Right: Significant wave height at the same time but from a run without ocean model feedback to the wave model.

II. OBSERVATIONS

Local wind observations were available at three locations on land shown on Fig. 8 as green triangles: SPGF1, FWFY1 and MLRF1. Ocean in-situ data were provided by buoys at 5 locations: C1 at 80.110°W, 25.501°N; C3 at 80.102°W, 25.499°N; C4 at 80.109°W, 25.499°N; C7 at 80.117°W, 25.436°N, and C8 at 80.113°W, 25.470°N. All buoys are equipped to measure wave height and wave direction. Radar observations of surface currents and wave height are also available, and will be used for future work.

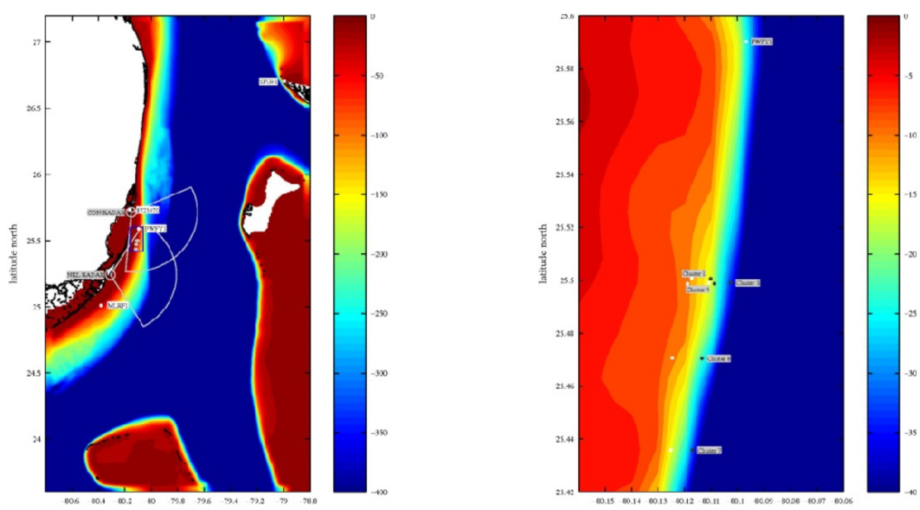

Fig 8. Locations of RSMAS weather stations, buoys and radar observations.

The wind observations were hourly and at 50 m height, but were interpolated to the standard 10-m height using a logarithmic wind-profile assumption and compared to the COAMPS wind field. The result is shown in Fig. 9 for the three meteorological stations. The COAMPS winds are typical within 2 m/s of the observed wind speeds and directions are within 20 degrees for winds above 5 m/s. The high frequency variability of the COAMPS winds is smaller than the observations, which can be expected. For COAMPS, hourly means were computed from a 10 min sampling interval. In general, COAMPS winds compare very well with the three weather stations, which give confidence in the local wind forcing for the wave model.

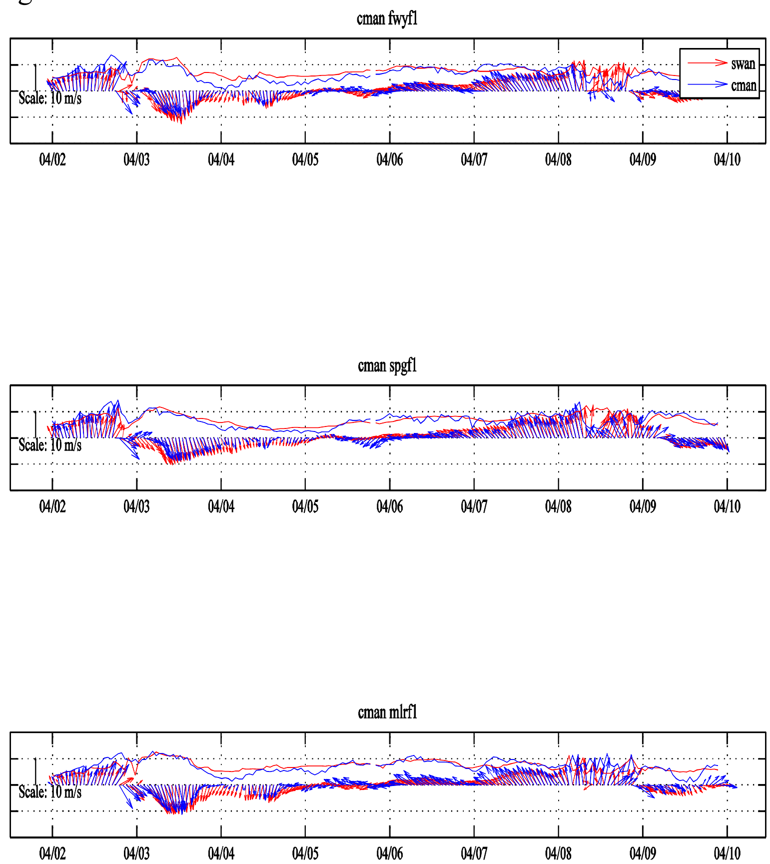

Fig 9. Observations of winds at 50 m interpolated to 10 m using a logarithmic wind profile at station FWYF1 (blue and label cman) and 10 m winds from COAMPS used to force SWAN at the same location (red and label SWAN).

The significant wave height, mean wave direction and peak wave period are shown in Fig. 10 for buoy C1 and C8 and for COAMPS runs with and without current feedback. The model outputs were interpolated to locations where the depths were identical to the actual depths at C1 and C2, rather than using the exact geographical location of those buoys. This was done since the model bottom topography is somewhat smoother and deeper than the actual bathymetry, and the buoy locations are in shallow water in the vicinity of fairly steep bottom topography.

The difference between the two model runs is not as large as expected from the large differences found in open water (Fig. 5 and 7). During April 3, when the wind is from the north, the model waves at the bouy locations are significantly larger than observed although the mean direction is good. We also note that the incidents of swell with periods above 10 sec are seen in the model output, but not in the observations. We suspect that the buoy location is protected by the shallow reef areas to the north, which cover a smaller area and are deeper in the model than in the actual ocean. In contrast, during April 6 to 8, when the wind is from a southerly direction, both wave height, direction and peak period are well simulated. In that case, wave propagation is across the Florida Current, and the wave amplitude is not affected by travelling along a shelf edge. The impact of currents on the waves is smaller.

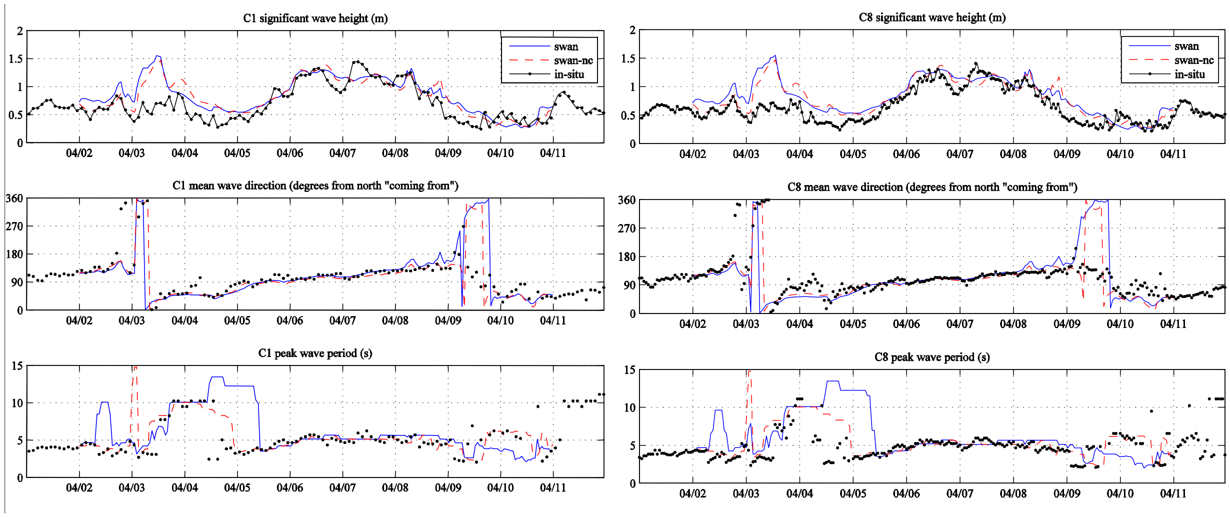

Fig 10. Observations of significant wave height (top), mean wave direction (middle) and peak wave period from buoy C1 at location 80.11°W, 25.50°N and from buoy C8 at 80.12°W, 25.47°N. The observations are shown in black, the model simulation without current in red and simulations including effects of currents is shown in blue.

V. Discussion

The COAMPS model is a practical tool for assimilation of observations, performing atmospheric analyses and forecasting under extreme weather conditions. The system allows for computation of numerous atmospheric and oceanic variables that are not readily observed, and do it consistent with available observations. It provides the state and evolution of the atmosphere and ocean over the entire area of interest. With increasing resolution, model solutions resolve finer scale features that increase the variance of each quantity. Our model simulation is in general consistent with wind and wave observations at the coastal stations, but for waves the agreement depends on the direction of propagation. For the open ocean further investigations are neede. This will be done using high frequency radar observations available from University of Miami [7].

Acknowledgment

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