Numerical simulations and observations of surface wave fields under an extreme tropical cyclone

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Abstract

The performance of the wave model WAVEWATCH III under a very strong, Category 5, tropical cyclone wind forcing is investigated with different drag coefficient parameterizations and ocean current inputs. The model results are compared with field observations of the surface wave spectra from a scanning radar altimeter, NDBC time series and satellite altimeter measurements in Hurricane Ivan (2004). The results suggest that the model with the original drag coefficient parameterization tends to overestimate the significant wave height and the dominant wave length and produces a wave spectrum that is higher in wave energy and narrower in directional spreading. When an improved drag parameterization is introduced and the wave-current interaction is included, the model yields improved forecast of significant wave height and wave spectral energy, but underestimates the dominant wave length. When the hurricane moves over a pre-existing mesoscale ocean feature, such as the Loop Current in the Gulf of Mexico and a warm- and cold-core ring, the current associated with the feature can accelerate or decelerate the wave propagation and significantly modulate the wave spectrum.
1. Introduction

Tropical cyclone-generated wave fields are of interest both scientifically for understanding wind–wave interaction physics and operationally for predicting potentially hazardous conditions for ship navigation and coastal regions. There have been considerable efforts made to understand the characteristics of tropical cyclone-generated surface waves through both measurements and numerical modeling. Wright et al. (2001) and Walsh et al. (2002) studied the spatial variation of hurricane directional wave spectra for both open ocean and landfall cases using the National Aeronautics and Space Administration (NASA) Scanning Radar Altimeter (SRA). These measurements have provided detailed wave characteristics at a specific place and time. Moon et al. (2003) conducted a detailed comparison between WAVEWATCH III (WW3) wave model simulations and observations of the spatial distribution of hurricane directional wave spectra obtained from NASA SRA in Hurricane Bonnie (1998), a Category 2-3 tropical cyclone on the Saffir-Simpson hurricane intensity scale (SSHS). Excluding shallow areas near the shore, the model results yielded an excellent agreement with observations of directional spectrum as well as significant wave height, dominant wavelength, and wave direction under hurricane wind forcing. Later studies of Chao et al. (2005); Tolman and Alves (2005); Tolman et al. (2005) found that WW3 overestimates the significant wave height under very high wind conditions in strong hurricanes. Moon et al. (2007) suggested that one of the reasons for the overestimation of the significant wave height is overestimation of the drag coefficient used in WW3 at very high winds. Comparing with buoy wave measurements during Hurricane Katrina in 2005 (SSHS Category 5 in the Gulf of
Mexico), they found that WW3 simulations with a reduced drag coefficient yielded more accurate simulations.

During Hurricane Ivan (SSHS Category 4-5 in the Caribbean Sea and Gulf of Mexico) in 2004 three sets of detailed SRA wave spectra measurements were collected by NASA through a joint effort between the NASA/Goddard Space Flight Center and NOAA/Atlantic Oceanographic and Meteorological Laboratory/Hurricane Research Division (HRD). These observations, together with satellite measurements and NDBC buoy time series, are used in this study to evaluate the WW3 predictions in extreme tropical cyclones. In particular, we investigate if an improved drag coefficient parameterization and inclusion of the effect of wave-current interaction may improve the wave predictions using WW3.

The outline of this paper is as follows. The wave and ocean models are described in section 2. The available observations are presented in section 3. Section 4 provides a new method for wind field specification. The results are presented and discussed in section 5. A summary and conclusions are given in section 6.

2. Methodology

2.1 The wave model

The ocean surface wave model, WAVEWATCH III (Tolman 1998), has been used operationally at the National Oceanic and Atmospheric Administration–National Centers for Environmental Prediction (NOAA–NCEP) for more than a decade. The model was validated over a global-scale wave forecast and a regional wave forecast (Tolman 1998, 2002; Tolman et al. 2002; Wingeart et al. 2001). WAVEWATCH III
(WW3) explicitly accounts for wind input, wave–wave interaction, and dissipation due to white-capping and wave–bottom interaction, and solves the spectral action density balance equation for directional wave number spectra. The wave spectrum of the model is discretized using 24 directions and 40 intrinsic (relative) frequencies extending from 0.0285 to 1.1726 Hz, with a logarithmic increment of $f_{n+1} = 1.1 f_n$, where $f_n$ is the nth frequency. The intrinsic frequency is related to the wave number (magnitude) $k$ through the dispersion relation. The model domain is set to 5°N to 32°N in the latitudinal direction and 95°W to 48°W in the longitudinal direction, with a grid increment of 1/12° in both directions for all experiments.

Moon et al. (2004a, b) have shown that the drag coefficient used in WW3 is significantly larger than estimates based on a coupled wave-wind model (CWW) that explicitly integrates the wave form drag. The CWW results are more consistent with recent field and laboratory observations of the drag coefficient (Powell et al. 2003, Donelan et al. 2004, Black et al. 2007)). Moon et al. (2007) found that using the CWW model in WW3 yielded improved wave predictions during Hurricane Katrina (2005).

In this study, we have conducted three sets of experiments with the WW3 model. In Exp. A, the original drag coefficient parameterization in WW3 is used to force the wave model. In Exp. B, the original drag coefficient parameterization has been replaced by the CWW model in calculating the wind input term in WW3. In the CWW model, the complete wave spectrum is constructed by merging the WW3 spectrum in the vicinity of the spectral peak with the spectral tail parameterization based on the equilibrium spectrum model of Hara and Belcher (2002). The resulted spectrum is then incorporated into the wave boundary layer model of Hara and
Belcher (2004) to explicitly calculate the wave-induced stress vector, the mean wind profile, and the drag coefficient. The CWW model treats the wind stress as a vector quantity to consider the influence of dominant waves that propagate at a large angle to the local wind. It makes thus possible the estimation of the wind stress for any given surface wave field, even for the complex seas encountered under tropical cyclones.

In Exp. C, we use the same set up for the wave model as in Exp. B, but also introduce ocean currents that are produced by the ocean model described below in response to hurricane forcing. There are two ways the ocean current \( \vec{U}_c \) impacts the wave field in WW3 model. First, through the wind input term in the calculation of the wind stress. When ocean current is present, the 10 meter wind velocity input \( \vec{U}_{10} \) is replaced by the relative wind velocity \( \vec{U}_{10} - \vec{U}_c \). Second, the wave action equation, which is solved in WW3, accounts for the modulation by the surface current such that

\[
\frac{\partial N}{\partial t} + \nabla_x \cdot \left[ \left( \vec{U}_c + \vec{C}_g \right) N \right] - \frac{\partial}{\partial k} \left( \vec{k} \cdot \frac{\partial \vec{U}_c}{\partial s} N \right) + \frac{\partial}{\partial \theta} \left( \frac{1}{k} \vec{k} \cdot \frac{\partial \vec{U}_c}{\partial m} N \right) = F \tag{1}
\]

where \( N = \psi / \omega \) is the wave action spectrum, \( \vec{C}_g \) is group velocity vector, \( \vec{k} \) is the wave number vector, \( k \) is the wave number, \( \theta \) is the wave direction, \( s \) is a coordinate in the wave direction, \( m \) is the coordinate perpendicular to \( s \), \( F \) is forcing, and \( \vec{U}_c \) is the ocean current at depth of \( L/4\pi \) (\( L \) is the mean wave length). Please refer to Fan et al. (2008c) for explanation of why the current at depth \( L/4\pi \) is used. The variable ocean current not only modifies the speed of the wave action flux (second term of equation (1)) but also modifies the wave number of a particular wave packet as it propagates (third and fourth terms of equation (1)).
2.2 The ocean model

In this study, the ocean currents are calculated using the Princeton Ocean Model (POM). POM is a three-dimensional, primitive equation model with complete thermohaline dynamics, sigma vertical coordinate system, and a free surface (Blumberg and Mellor, 1987). We employed the version of POM used operationally in the GFDL/URI hurricane prediction system (Bender et al. 2007).

A realistic initialization of the 3-D density and velocity fields in the ocean model is critical for proper simulation of the ocean response to a hurricane (Ginis 2002). The initialization method implemented in the GFDL/URI system is described in detail in Falkovich et al. (2005) and Yablonsky and Ginis (2008) and includes a realistic representation of the Loop Current (LC) and warm- and cold-core eddies in the Gulf of Mexico. In this method, the initial condition is first generated using the Generalized Digital Environmental Model (GDEM) monthly ocean temperature and salinity climatology (Teague et al. 1990), which has 1/4° horizontal grid spacing and 33 vertical z levels at depths range from 0 to 5500 m. Then, a feature-based modeling procedure (Yablonsky and Ginis 2008) is conducted to incorporate sea surface height anomaly (SSHA) observations. Positive SSHA features (also refer to as warm features) are regions where warm upper ocean layer (warm ocean layer is often defined as from surface down to the depth of the 26°C isotherm) (Shay et al. 2000) is deeper than climatology. On the other hand, negative SSHA features are regions where warm upper ocean layer shoals from climatology. These positive and negative SSHA features are frequently associated with warm- and cold-core mesoscale eddies, respectively. In the feature-based procedure,
multiple points along the LC path are specified, allowing the LC shape to be adjusted to match the observed shape derived from satellite altimetry. Then, the warm- and cold-core eddies in the Gulf of Mexico are incorporated by assuming they are elliptical in shape, with major and minor axes defined based on the SSHA data. For this study, we utilize the altimetry data from the Colorado Center for Astrodynamics Research (CCAR) Real-Time Altimetry Project through their website: (http://argo.colorado.edu/~realtime/welcome/). The CCAR altimetry map on September 12, 2004, shown in Figure 15 (a), is used to initialize the position and structure of the LC and a warm-core ring in the Gulf of Mexico, shown in Figure 15 (b).

3. Wave observations during Hurricane Ivan

Hurricane Ivan in 2004 was a classical, long-lived Cape Verde hurricane that reached SSHS Category 5 strength three times. The hurricane track from September 8 12:00 UTC to 16 12:00 UTC is shown in Figure 1. Three sets of detailed SRA wave spectra measurements were collected by NASA through a joint effort between the NASA/Goddard Space Flight Center and NOAA/HRD. The flight tracks of the NOAA aircraft carrying the SRA are shown in Figure 1. Two sets of measurements were collected from 16:15 to 20:10 UTC on September 9th and from 10:40 to 15:40 UTC on September 12th when Ivan was crossing the Caribbean Sea and at its maximum intensity of Category 5. The third set of measurements was done from Sept. 14 20:30 UTC and Sept. 15 03:30 UTC when Ivan entered the Gulf of Mexico.

The SRA measurements covered the region within about 2° of the hurricane eye. The SRA scanned a radar beam across the aircraft ground track to measure the
elevation at 64 points on the sea surface. Sea surface topographic maps were produced from groups of SRA cross-track scan lines. The topography was then interpolated to a north- and east-oriented 256 by 256 rectangular grid of 7 m spacing centered on the data. The elevations in the uniform grid were transformed by a two-dimensional Fast Fourier Transform (FFT) with wave number spectral resolution of 0.0035 radian/m. The encounter wave spectra were Doppler corrected and the 180° ambiguous spectral lobes were deleted. Wright et al. (2001) and Walsh et al. (2002) describe the process in detail.

Two satellites, Envisat-1 and ERS-2 (in the same orbit as Envisat-1 and trailing it by about 28 minutes), approached within about 90km of the eye of Hurricane Ivan at 03:38 UTC and 04:06 UTC on September 15 (Figure 1). Both satellites carried radar altimeters which documented wind speed and wave height along their ground track. Also, five National Data Buoy Center buoys, located within 4° of the hurricane track (Figure 1), documented significant wave height time series through the passage of the hurricane. All these data will be used to evaluate our model results.

4. Hurricane wind field specification

The wind fields during Hurricane Ivan are obtained from the NOAA/HRD real-time wind analysis (HWIND) and interpolated into 0.5-hour intervals to input into both the WW3 and POM models. HWIND is an integrated tropical cyclone observing system in which wind measurements from a variety of observation platforms are used to develop an objective analysis of the distribution of wind speeds in a hurricane (Powell et al. 1998). The wind data in gridded form are available at the HRD website
for all hurricanes in the Atlantic basin since 1994 (www.aoml.noaa.gov/hrd/data_sub/wind.html). The HRD winds with the spatial resolution of about 6 km × 6 km, covering an area of about 8° × 8° in latitude-longitude around the hurricane’s center are provided at intervals of every 3 or 6 hours. This frequency is not sufficient to force a numerical model and therefore the wind data need to be interpolated in space and time.

If a hurricane rapidly intensifies or its size undergoes significant changes in a short period of time, direct time/space interpolation may result in distortion of wind fields. Any error in the input wind field will result in an error in the computed wave field because wind waves are very sensitive to small variations in the wind input. To illustrate this sensitivity, let us consider fully developed wave conditions in which the significant wave height $H_s$ is roughly proportional to the square of the wind speed and wave energy is roughly proportional to the wind speed cubed. A 10% bias in the surface wind speed may cause ~20% error in $H_s$ and ~35% in wave energy.

Here, we introduce an interpolation method (hereafter called “normalized interpolation”) of the HRD wind fields in time/space with minimum distortions of the hurricane wind field. For simplicity, we illustrate below the normalized interpolation method along one radial direction of the hurricane, which can easily be applied to a 2-D hurricane wind field. Consider two radial profiles of wind speed $W_1(r_1)$ and $W_2(r_2)$ at two different times $t_1$ and $t_2$ with their maximum wind speed located at $R_1$ and $R_2$ correspondingly (Figure 2a). A simple averaging of the two profiles at time $(t_1 + t_2)/2$ would result in the dashed line in Figure 2a, which is clearly not a good approximation of the hurricane radial wind profile. In our method we first normalize the radial
distance from the hurricane center by the radius of the maximum wind speed, so that in the normalized coordinate, both W1 and W2 have their maximum wind speed at the normalized distance 1.0 (Figure 2b). If we interpolate these two wind profiles at time \((t_1+t_2)/2\) (dashed line in Figure 2b), the wind profile is not distorted like the one in Figure 2a. Since the radius of the maximum wind speed for the interpolated wind profile is simply \((R_1+R_2)/2\), we use this radius to obtain the desired interpolated wind speed profile at time \((t_1+t_2)/2\) in the dimensional coordinate as illustrated by the dashed line in Figure 2c. An example of the 2-D interpolated wind field at Sep. 9 18:00 UTC and the HRD winds at Sep. 9 13:30 UCT and 19:30 UTC are showed in Figure 3.

5. Results and Discussion

5.1 Wave parameters

We first compare the significant wave height \(H_s\), dominant wave length (DWL) and dominant wave propagation direction (DWD) in WW3 with the SRA measurements. The significant wave height \(H_s\) is the standard output of the wave model. To obtain the DWL and DWD, the model directional frequency spectrum is transformed into the same wave number space as the SRA measurements using Jacobian transformation, and the location of the wave spectrum peak, which corresponds to the DWL and DWD, is determined using a parabolic interpolation. The DWL, DWD and \(H_s\), are interpolated from the uniform model grid in WW3 to the non-uniformly spaced SRA measurement locations using the cubic interpolation
method. For each SRA location, these parameters are then linearly interpolated in time to obtain the DWL, DWD, and \( H_s \) at the measurement time.

Comparisons between the model results in Exp. A, B and C and the observations at all the SRA measurement locations along the flight tracks are shown in Figure 4 for the measurements on September 9\(^{th} \), Figure 5 for the measurements on September 12\(^{th} \), and Figure 6 for the measurements on September 14-15. The model significant wave height and the dominant wave length in Exp. A, B and C are plotted in Figure 7 against the corresponding SRA data for all SRA measurement locations for the periods of September 9, 12 and 14-15. The root mean square errors, defined as

\[
\text{rms} = \sqrt{\frac{1}{N} \sum (x_{\text{Model}} - x_{\text{Observation}})^2},
\]

between the SRA measurements and the model results are presented in Table 1.

The model DWD in all three experiments are very close to each other and match very well with the SRA observations during all three flight periods (Figures 4b, 5b and 6d). This indicates that the wind stress parameterization based the CWW model and wave-current interaction have negligible effects on the DWD predictions. The locations where the wave propagation directions differ by more than 10\(^{\circ} \) are generally in the rear right quadrant of the hurricane where there can be two or three comparable peaks in the observed spectrum while the model spectrum has a smooth, one peak structure.

From the \( H_s \) comparison along the flight track on September 9\(^{th} \), we can see that at the locations in the rear quadrants of the hurricane, where the \( H_s \) values are small (less than 5m), the model predictions in Exp. A agree very well with the SRA observations (Figure 4d and 7a). This is consistent with the fact that WW3 has been
extensively calibrated and validated under low and moderate wind conditions. The $H_s$ values from Exp. B. and Exp. C are also very similar to those from Exp. A at these locations (Figure 4d), indicating that neither the new wind stress parameterization nor the wave-current interaction has any effect when the waves are small.

Along the other flight track sections during the September 9th flight and the entire flights on September 12th and September 14th-15th, the results show that Exp. A significantly overestimates $H_s$ almost everywhere (Figure 4d, 5d, and 6d), and the error increases as $H_s$ increases (Figure 7a). The $H_s$ prediction in Exp. B is generally lower compared to Exp. A. Take the September 9th flight for example; the root mean square error of $H_s$ in Table 1 is reduced from 2.25 m in Exp. A to 1.67 m in Exp. B (the reduction is about 26%). This is because the new parameterization reduces the wind stress at higher wind speeds, and hence reduces the wind input to waves in the model. However, the $H_s$ values are still considerably larger than observations (Figure 7b).

When the ocean current is introduced to the wave model in Exp. C, the root mean square error is further reduced to 0.9 m for the September 9th flight (about 60% error reduction), and the overall agreement with the observations is significantly improved (Figure 7c). This is consistent with the finding in Fan et al. (2008c) indicating that the wave-current interaction tends to significantly reduce the magnitude of simulated $H_s$. In the next subsection a detailed analysis is given to explain why ocean currents tend to reduce $H_s$ under tropical cyclone conditions.

The $H_s$ comparison for the September 9th flight in Figure 4d shows that the results from Exp. C almost overlap with the observations everywhere except for a
small section along the flight track in front of the hurricane (shown by the red dashed line in Figure 4a). Although the $H_s$ prediction is significantly improved in this section compared to Exps. A and B, the differences between the model results and observations are still significant. Furthermore, the $H_s$ comparison along the September 12\textsuperscript{th} flight also showed large differences between the model results from Exp. C and observations along most sections of the flight track. However, the $H_s$ comparison for the September 14\textsuperscript{th}-15\textsuperscript{th} flight doesn’t seem to have this problem. This discrepancy could be due to the influence of the pre-existing mesoscale variability of the ocean current in the Caribbean Sea on surface waves which is not considered in this study. Our ocean model initialization methodology provides a realistic representation of the Loop Current and mesoscale eddies in the Gulf of Mexico, but no real-time data assimilation is done in the Caribbean Sea. Instead, the GDEM monthly climatology data is used to initialize the 3-D temperature and current fields. Since the climatology data smooth out most of mesoscale features, the modeled current field also shows a smooth structure in the Caribbean area. The effect of mesoscale features, such as the Loop Current and a warm-core ring in the Gulf of Mexico, on the wave predictions will be discussed in detail in section 5.4.

The model results in all three experiments indicate consistent underestimation of $H_s$ within the hurricane eye region, except on September 9\textsuperscript{th} when the radius of maximum wind was small (13 km) and Hurricane Ivan was moving with a relatively fast forward speed (6 m/s). On September 14\textsuperscript{th}-15\textsuperscript{th}, when the radius of maximum wind was three times larger (39 km) and Ivan was moving about three times slower (2m/s), Figures 6d and 14 show significant downward excursions in the model $H_s$,
each of the six times the aircraft passed through the eye. We speculate that a possible reason of the degraded $H_s$ predictions near the hurricane eye can be due to not very accurate representation of the inflow angle in the HRD surface wind fields in these instances. From idealized experiments (not shown here), we found that variations of the inflow angle in the surface wind have very small effect on the surface wave prediction when the hurricane has a small eye and moves relatively fast, like Hurricane Ivan on September 9th. But for slowly moving hurricanes with large eyes, the $H_s$ prediction can be significantly affected by even small changes in the wind inflow angle. HRD surface wind analysis is based on available surface wind observations from buoys, Coastal–Marine Automated Network (CMAN) platforms, ships, and other surface facilities. Because these data are often sparse near hurricanes, aircraft flight-level observations adjusted to the surface with a planetary boundary layer model (Powell 1980) are used to supplement the in situ surface measurements. Based on examination of the inflow angle change from the launch levels to the surface the wind directions in HWIND for surface-adjusted flight level winds over water are given a constant angle of about 20°, (Powell et al 1996). It is possible that the real inflow angles in the Ivan surface wind field near the eye wall were quite different from the values assigned by HWIND.

The model $H_s$ from all three different experiments are also compared with NDBC Buoy data from September 13th to 16th in the Gulf of Mexico (Figure 8). With accurate wind forcing, the WW3 simulations show good agreement with observations. At buoys 42003 and 42039, WW3 with the original $C_d$ parameterization (Exp. A) overestimates the maximum $H_s$ by about 1.5-2 m, while the simulations in Exp. B and
Exp. C yield much reduced errors. Buoy 42040 was adrift after 15 September, 21:00 UTC which introduces some uncertainty in the accuracy of the comparison with the data. Over all, despite the buoy drift, the observations are in a reasonably good agreement with the model predictions. On September 15th, Hurricane Ivan passed directly over six wave-tide gauges deployed by the Naval Research Laboratory north of buoy 42040 (~29.3°N, 87°W). Three moorings observed waves with $H_s$ reaching maximum values of 17.9, 16.1 and 17.1 m (Wang et al., 2005). These values are in good agreement with the model-produced $H_s$ in Exp. C, as seen in the significant wave height wave swath (Figure 10).

Figure 9 shows $H_s$ measured by the radar altimeters on the Envisat and ERS-2 satellites at 03:38 UTC and 04:06 UTC, respectively, on September 15 (tandem track shown in Figure 1) compared with WW3 results from Exp. C on September 14 at 22:00 UTC, September 15 at 02:00 UTC and 04:00 UTC. The open circles show SRA $H_s$ observations between 21:04 UTC on September 14 and 02:57 UTC on September 15 which were within 10 km of the satellite track. The simulated $H_s$ on September 15th, the closest time to the satellite measurements, compares well to the satellite data, although the altimeter shows higher maximum $H_s$ values by 1-2 meters compared to both the model results and SRA data. The comparison between the predicted $H_s$ and satellite measurements confirms that including wave-current interaction improves wave forecast skill.

The swath pictures of $H_s$ in all three experiments are shown in Figure 10, which represent maximum values at each grid point throughout the hurricane passage. In this figure, results at shallow-water seas below 30-m depth are removed because of
limitations of the resolving depth in the wave model. It is seen that the highest waves are found when Ivan reached SSHS Category 5 intensity in the northern Caribbean and when the hurricane approached shallow seas before making landfall. The values of $H_s$ in the swaths produced in Exps. B and C are progressively lower than those in Exp. A. The difference plot between Exp. A and Exp. C shows that the larger reduction of $H_s$ appears to the right of the hurricane along its track. The maximum difference reached 5.7 m north-west of Cuba where Ivan passed over the Loop Current. The effect of the Loop Current on wave prediction is discussed below.

The DWL model results show very similar values among all three experiments when the wave field is less developed in the rear-left quadrant of the hurricane (Figure 4c, 5c, and 6c). The same tendency was found for the $H_s$ simulations. Unlike the $H_s$ results, however, the dominant wave lengths are noticeably shorter than those in the SRA measurements. To the right of the hurricane, where the waves are more developed, the three experiments yield very different DWL values (Figure 4c, 5c, and 6c). In Exp. A, DWL are mostly longer than those in the SRA observations (Figure 7d), while in Exp. C they are shorter (Figure 7f).

Overall, WW3 seems to underestimate DWL when $H_s$ is correctly predicted. Fan et al. (2008a) have also noticed this tendency when their results are compared with DWL empirical formulas from other studies. The underestimation of DWL is most likely due to the nonlinear wave interaction term calculated within WW3. Tolman (2004) (also private communication with Dr. Hendrik Tolman) shows that the present WW3 nonlinear interaction calculation based on the Discrete Interaction Approximation (DIA) systematically overestimates the wind sea spectral peak
frequency by roughly 10% (i.e., underestimates the DWL of wind seas by roughly 20%). For swell, such biases are not obvious in WW3.

5.2 Reduction of significant wave height by surface currents

A significant finding in the previous section is that inclusion of the ocean current systematically reduces $H_s$ prediction. There are two ways the ocean current ($\bar{U}_c$) impacts the wave field as described in the Methodology section, that is, the subtraction of the current from the 10 meter wind speed, and the modification of the wave action equation. Both effects are included in Exp. C. In order to determine which current effect is more important, Exp. D is designed. This experiment is the same as Exp. C, except the effect of current in the wave action equation is not considered. The results of the wave field simulation corresponding to the time/location of the SRA measurement on September 9th 18:00UTC are presented in Fig. 11.

Starting from Exp. B (without current effects), if the 10 meter wind speed input is modified by the current but the wave action equation is not affected (Exp. D), the resulting simulation of $H_s$ indicates small changes, as seen in Fig. 11(d). Notice that $H_s$ is reduced in the area where the wind and current vectors have similar directions and increased where the wind and current vectors misaligned, as seen from Fig. 11(b) and Fig. 11(d). When the current effect in the wave action equation is also included (Exp. C), $H_s$ is significantly reduced, especially where $H_s$ reaches its maximum, as shown in Fig. 11(c). These figures clearly indicate that the current effect on the wave field is mainly through the wave action equation. The relative wind speed effect is significantly smaller.
Let us next examine why including the ocean current in the wave action equation tends to reduce $H_s$. Since the direction of the dominant wave is mostly within $30^\circ$ of the direction of the current (Figure 11 and Figure 12), we can consider for simplicity a one-dimensional approximation of the wave action equation. Furthermore, the wave action equation is expressed in the coordinate system moving with the hurricane, and the time tendency term is neglected (i.e., the wave field is assumed stationary in the moving coordinate). Then, the wave action equation used in Exp. C (equation (1)) is simplified to

$$\frac{\partial N}{\partial s} (U_c + C_g - U_t) - k \frac{\partial N}{\partial k} \frac{\partial U_c}{\partial s} = F,$$

where $C_g$ is group velocity, and $U_t$ is the hurricane translation speed projected onto the wave propagation direction $s$. If we only consider the current effect on relative wind speed (Exp. D), then (2) is further simplified to

$$\frac{\partial N_0}{\partial s} (C_g - U_t) = F_0,$$

here, the subscript 0 in $N$ and $F$ denotes no current. Subtracting (2) from (3) yields

$$\frac{\partial (N_0 - N)}{\partial s} (C_g - U_t) = -k \frac{\partial N}{\partial k} \frac{\partial U_c}{\partial s} + \frac{\partial N}{\partial s} U_c + (F_0 - F)$$

Then, the equation (4) shows that the reduction of the wave action spectrum $(N_0 - N)$ from Exp. D to Exp. C, shown in Figure 11(c), is caused by three factors. First, when waves are compressed or stretched by a spatially varying current, the resulting modulation of the wave action is expressed by the term $-k \frac{\partial N}{\partial k} \frac{\partial U_c}{\partial s}$. Second, the term $\frac{\partial N}{\partial s} U_c$ is the modulation to the wave field due to horizontal current advection. This
term can be interpreted as follows. If the forcing term is set such that the wave field grows with fetch \( \frac{\partial N}{\partial s} > 0 \), then the spatial wave growth is reduced by a positive current simply because the wave packet propagates faster. The third effect is the modification of the forcing term \( (F_0 - F) \), which is expected to be more important for shorter waves (spectral tail).

Let us consider a wave pathway (pink arrow) in Figure 11. Along this path the reduction of \( H_s \) (i.e., \( (N_0 - N) \) near the spectral peak) rapidly increases (Fig. 11(c)). Along the same path, \( H_s \) (and therefore \( N \) near the spectral peak) increases (Figure 11(a)) and the surface current \( U_c \) remains large (Figure 11(b)). After close examination of the spectral output along this path (not shown), we have found that the compression/stretching term is relatively unimportant near the spectral peak and that the advection term \( \frac{\partial N}{\partial s} U_c \) is mainly responsible for the reduction of the significant wave height, i.e., waves become lower when the wave group propagates faster due to the positive surface current. Although this simplified 1-D analysis is not likely to apply everywhere, it is nevertheless noteworthy that the significant reduction of \( H_s \) persists over a large area where the current is strong and is roughly aligned with the wave propagation.

This analysis also highlights the significance of the hurricane translation speed \( U_t \). The equation (4) indicates that the reduction of \( N \) is enhanced as \( (C_g - U_t) \) decreases, i.e., as the translation speed increases. In fact, when \( C_g \), which is typically ~9-10 m s\(^{-1}\), is close to \( U_t \) (near resonance), the reduction of \( N \) becomes the largest.
5.3 Wave spectrum

Next, we compare individual model spectra obtained at various positions along the September 9th flight track with those of the SRA measurements. Five spectra are selected for the comparisons (white points A to E shown in Figure 4a). Figure 12 shows the SRA directional wave spectra and the model spectra in all three experiments at location A to E. All three experiments show excellent agreement with the observations in simulating the peak wave direction. From Figure 4a, we can see that locations A to D are in front of the hurricane, and the waves there are actually swells propagated in the tangential direction from the radius of maximum wind at an earlier position of the storm due to the resonance (Moon et al. 2003). We can see that at all 5 locations, the model produces higher peak energy in Exp. A and B, but similar peak energy to observations in Exp. C. Also notice that the angular distribution of the wave energy in Exp. C is widened. The directional spreading tends to become wider when the surface current is included in the WW3 simulation, being consistent with the Tolman et al. (1996) study of wave interference with the Gulf Stream. This is likely caused by spatial variation of the surface current, although it is difficult to quantitatively examine the current effect on directional spreading.

At locations A, C and D, the model produces narrower directional spreading than in the observations in Exp. A and B, but similar directional spreading to observations in Exp. C. However, at locations B and E, the model produces similar directional spreading in Exp. B, but larger directional spreading in Exp. C. This discrepancy may be related to some overestimation of the ocean current. In this study,
we used the bulk formula for calculating wind stress in POM with the drag coefficient parameterization based on the CWW model. Fan et al. (2008a, and 2008b) have pointed out that the momentum flux into the ocean can be significantly reduced due to the spatial and temporal variations of the hurricane-induced surface waves. Fan et al. (2008c) have also shown that the coupled wind-wave-current processes can significantly reduce the momentum flux into the ocean in the right-rear quadrant of the hurricane. Since these processes are not considered in our experiments, the momentum flux input to the ocean is likely overestimated. As a result, the currents and current divergence are overestimated too, especially at locations to the right of the hurricane track. Because both B and E are located close to the right of the hurricane track, the overestimation of the directional spreading in the model may be caused by the overestimation of the current.

The frequency spectrums at locations A to E are shown in Figure 13. We can see that the frequency spectrums in Exps. A and B are much higher than the observations at all 5 locations. When the wave-current interaction is introduced in Exp. C, the peak of the frequency spectrum is reduced and shifted to higher frequency, which greatly improves the comparison of peak energy with observations.

5.4 Effect of Loop Current on wave prediction

To investigate the effect of pre-existent currents due to mesoscale ocean features on wave prediction, we modified Exp. C such that the Loop Current and its warm core ring in the Gulf of Mexico are removed from the ocean initialization. Figure 14(c) shows $H_s$ comparison between Exp. C results with and without the Loop
Current initialization along the September 14th – 15th flight. The SRA measurements are also shown for reference. The $H_s$ difference between the two experiments is clearly seen along some of the flight sections. Let us examine two such periods highlighted by the gray areas in Figure 14(c).

At 21:00 UTC on September 14, $H_s$ is significantly larger with the Loop Current initialization. The spatial snapshot of the $H_s$ difference with and without the Loop Current initialization is shown at the corresponding time in Figure 14(a). Figure 15(c) shows the spatial distribution of the ocean temperature at 70 m depth and current field at $L/4\pi$ depth also at the same time. At this time the aircraft is over the edge of the Loop Current (Figure 15(c)), where a strong northward current is added due to the LC initialization (Figure 16(a)). The wave field at the same time (Figure 16(b)) indicates that the dominant waves are propagating southward at this location. If we consider the evolution history of these dominant waves (along the pink arrows in Figures 16(a) and 16(b)), it is evident that a strong opposing current persisted (i.e., the packet propagation was slower) throughout the wave evolution such that the overall wave spectrum was enhanced. This explains why the predicted $H_s$ at this location is increased when the Loop Current initialization is included.

At 02:40 UTC on September 15, the predicted $H_s$ is significantly smaller with the Loop Current initialization (Figure 14(c)). Figure 15(d) shows that the flight is passing through the southern edge of the warm core ring at this time. Due to the initialization of the warm core ring, a strong westward current is added at that location (Figure 15(c)). The wave field at the same time (Figure 16(d)) shows that the dominant waves are propagating westward. Again, the evolution history of these
dominant waves (along the pink arrows in Figures 16(c) and 16(d)) is such that a strong positive (aligned) current accelerated the wave packet propagation and reduced the spectral level throughout the wave evolution.

These two examples clearly demonstrate that strong currents due to pre-existing mesoscale ocean features may significantly modify the wave field prediction mainly because such currents accelerate or decelerate the wave propagation.

6. Summary and Conclusions

It has been known in previous studies that the operational wave model WW3 overestimates the significant wave height under very high wind conditions such as under strong hurricanes. In this study we have investigated how the performance of WW3 is affected by different drag coefficient parameterizations and by including the effect of wave-current interaction. Hurricane Ivan in 2004 has been used as a test case since several observations were available for comparison including the detailed direct observations of wave spectra from the NASA Scanning Radar Altimeter, NDBC buoy and satellite measurements.

The drag coefficient has been parameterized by either using the original formulation in WAVEWATCH III or the Coupled Wave-Wind model, which is based on the explicit integration of the wave form drag. The effect of wave-current interaction has been included by passing the hurricane-induced currents calculated by the Princeton Ocean Model into the Coupled Wave-Wind model. The real-time wind analysis during Hurricane Ivan produced by the NOAA Hurricane Research Division has been used to force both the wave model and the ocean model.
The results can be summarized as follows:

1. All experiments in this study show excellent prediction of wave direction, indicating that the effects of the wind stress parameterization and wave-current interaction on wave direction prediction are negligible.

2. The original WAVEWATCH III drag parameterization tends to overestimate the significant wave height, wave energy and the dominant wave length under very strong wind forcing, and the error seems to increase as the significant wave height increases.

3. The improved stress parameterization, together with including the wave-current interaction, is shown to improve forecast of significant wave height and wave energy.

4. The hurricane-induced ocean current tends to reduce the significant wave height mainly because it increases the advection velocity of the wave packet. Spatial variation of the current widens the directional spreading of the wave spectrum.

5. When the hurricane moves over a pre-existing mesoscale ocean feature, such as the Loop Current in the Gulf of Mexico and a warm- and cold-core ring, the wave field may be significantly modified. This is mainly because strong currents associated with these features accelerate or decelerate the wave propagation and thus causing the modulation of the wave spectrum.

The results presented in this paper confirm that a fully coupled wind-wave-ocean system as suggested in Fan et al. (2008c) is necessary to accurately forecast wave fields in hurricanes.
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References


Table 1. Root mean square error of model significant wave height ($H_s$) and dominant wave length (DWL) relative to the SRA observation. The room mean square error is defined as \[ \sqrt{\frac{1}{N} \sum (x_{\text{Model}} - x_{\text{Observation}})^2} \].
Figure 1. Available measurements along Hurricane Ivan track. The color and size of the circle represents the maximum wind speed of the hurricane. The black lines in the vicinity of the hurricane track represent the flight tracks during the SRA measurements. The red line to the left of the hurricane track overlaps with the September 14-15 SRA measurements shows the satellite tracks of Envisat-1 and ERS-2. The red triangles in the Gulf of Mexico show National Data Buoy Center buoy locations along Hurricane Ivan track.
Figure 2. Diagrams of wind profile interpolations. (a) Solid lines are wind profile W1 and W2 vs. radial distance at time t1 and t2 with maximum wind speed at R₁ and R₂; dashed line is wind profile obtained at time (t₁+t₂)/2 using direct time/space interpolation. (b) Solid lines are wind profile W1 and W2 vs. radial distance normalized by the radius of maximum wind at time t₁ and t₂; dashed line is wind profile obtained at time (t₁+t₂)/2 using normalized interpolation. (c) Solid lines are wind profile W1 and W2 vs. radial distance at time t₁ and t₂ with maximum wind speed at R₁ and R₂; dashed line is wind profile obtained at time (t₁+t₂)/2 using normalized interpolation.
Figure 3. HRD wind speed within 100 km of the hurricane center at (a) Sept. 9 13:30 UTC and (b) Sept. 9 19:30 UTC. (c) The interpolated wind field at Sept. 9 18:00 UTC. The white line in the figures shows the hurricane track, and the color scale gives the magnitude of wind speed.
Figure 4. (a) Significant wave height field (color) at Sept. 9 18:00 UTC. The thick black line is the flight track and the thick white line is the hurricane track. (b) Wave propagation direction relative to true north rotating clockwise, (c) dominant wave length, and (d) significant wave height comparison between SRA measurements and model results in Exp. A, B and C.
Figure 5. SRA observations and WW3 results comparison for experiments A, B and C for Sept. 12 flight. (a) Significant wave height field (color) at Sept. 12 13:00 UTC. The thick black line is the flight track and the thick white line is the hurricane track. (b) Wave propagation direction relative to true north rotating clockwise, (c) dominant wave length, and (d) significant wave height comparison between SRA measurements and model results from Exp. A, B and C.
Figure 6. The same as in Fig. 5, except for Sept. 14-15 flight.
Figure 7. Model significant wave height ($H_s$) vs. SRA measurements for (a) Exp. A, (b) Exp. B, and (c) Exp. C; and model dominant wave length (DWL) vs. SRA measurements for (d) Exp. A, (e) Exp. B, and (f) Exp. C. The magenta, red, and blue circles correspond to the calculation period of September 9, 12 and 14-15.
Figure 8. Comparison of model significant wave height (Hs) for experiment A, B, and C with NDBC buoy measurements shown in figure 1.
Figure 9. Significant wave height measured by the radar altimeters on the Envisat (red dots) and ERS-2 (blue dots) satellites at 03:38 UTC and 04:06 UTC, respectively, on September 15 (tandem track shown in Figure 1) compared with WW3 results from experiment C on September 14 at 22:00 UTC (dotted line), September 15 at 02:00 UTC (dash line) and 04:00 UTC (solid line). The open circles show SRA wave height observations between 21:04 UTC on September 14 and 02:57 UTC on September 15 which were within 10 km of the satellite track.
Figure 10. Swaths of $H_s$ produced by WW3 in Exp. A, Exp. B, and Exp. C and the difference of the swath of $H_s$ between Exp. A and Exp. C during the passage of Hurricane Ivan. The solid line is the storm track with dots indicating the positions of the storm center every 12 hours. Gray colors represent shallow-water seas below 30-m depth.
Figure 11. (a) Significant wave height ($H_s$) in color and dominant wave length and direction in black arrows in Exp. C corresponding to the time/location of the SRA measurement on September 9th 18:00UTC. (b) Ocean current magnitude (color) and vector (black arrow) at depth of $L/4\pi$. (c) $H_s$ in Exp. C minus $H_s$ in Exp. D. (d) $H_s$ in Exp. D minus $H_s$ in Exp. B. The thick magenta arrow in (a), (b) and (c) shows a pathway of wave packets discussed in the text and the cross denotes the Hurricane Ivan center
Figure 12. SRA directional wave spectra and WW3 spectra for Exp. A, B, and C at selected locations along the aircraft track indicated in Figure 4. The dashed circles (outer to inner) correspond to wavelengths of 150, 250, and 350 m. The solid circles indicate wavelengths of 200 and 300 m. The color scales represent spectral density, and each spectrum contains nine contours, linearly spaced from 10% to 90% of the
peak spectral density. The black arrow and red arrow show wind and current (if available) vectors. They extend in the downstream direction with their length proportional to their magnitude. The wind speed of 30 ms$^{-1}$ corresponds to a length of 0.03 rad. The significant wave height and the dominant wave length are shown in the upper-right corner of the SRA and the WW3 spectrum. The location of SRA measurement in latitude and longitude and observation time is shown in the lower-right and lower-left corner of the SRA spectrum.

Figure 13. Comparison of frequency spectrum for different experiments at locations A to E shown in Figure 4.
Figure 14. WW3 significant wave height ($H_s$) in experiment C with Loop current initialization in the ocean model minus the $H_s$ without Loop current initialization at (a) 21 UTC on September 14, and (b) 2:40 UTC on September 15. (c) $H_s$ with Loop current (black line) and without Loop current (red line) initialization in the ocean model compared with SRA observations (black cross).
Figure 15. Satellite altimetry map in the Gulf of Mexico on September 12, 2004 (a), and ocean temperature at 70 m depth with current vectors at L/4π depth in the ocean model at 12 UTC on September 12 (b), 21 UTC on September 14 (c), and 2:40 UTC on September 15 (d). On figure (c) and (d), the black line is flight track, the white line is hurricane track, the red dot shows the location of the flight at this time.
Figure 16. (a) Ocean current difference between the experiments with and without the Loop Current initialization at 21:00 UTC on September 14. (b) Significant wave height ($H_s$) in color and dominant wave length and direction in black arrows at 21:00 UTC on September 14. (c) Ocean current difference between the experiments with and without the Loop Current initialization at 2:40 UTC on September 15. (d) Significant wave height ($H_s$) in color and dominant wave length and direction in black arrows at 2:40 UTC on September 15. The black line shows the flight track and the red dots show the location of the flight at the time that the current and wave field are shown. The pink arrow shows the wave propagation path.