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Drag coefficient comparisons between observed and model simulated directional wave spectra under hurricane conditions

Yalin Fan*, W. Erick Rogers

Oceanography Division, Naval Research Laboratory, Stennis Space Center, MS 39529, United States

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ABSTRACT

In this study, Donelan, M.A., Babanin, A.V., Young, I.R., Banner, M.L., 2006. J. Phys. Oceanogr. 36, 1672–1688 source function is used to calculate drag coefficients from both the scanning radar altimeter (SRA) measured two dimensional wave spectra obtained during hurricane Ivan in 2004 and the WAVEWATCH III simulated wave spectra. The drag coefficients disagree between the SRA and model spectra mainly in the right/left rear quadrant of the hurricane where the observed spectra appear to be bimodal while the model spectra are single peaked with more energy in the swell frequencies and less energy in the wind sea frequencies. These results suggest that WAVEWATCH III is currently not capable of providing sensible stress calculations in the rear quadrants of the hurricane.

1. Introduction

Tropical cyclones, also popularly known as hurricanes or typhoons, are among the most spectacular and deadly geophysical phenomena. Both the most lethal and the most expensive natural disasters in U.S. history were tropical cyclones (Emanuel 2003). Tropical cyclones are driven by enthalpy fluxes from the sea and limited mostly by surface drag, but there is little understanding of the behavior of these fluxes at very high wind speeds. Direct measurements of the fluxes have been made at wind speeds as large as 25 m/s, but technical problems have thus far prevented reliable estimates at higher speeds. As a result, momentum transfer under extreme wind conditions has been extrapolated from these field measurements in a variety of modeling applications, including hurricane risk assessment and prediction of storm motion, intensity, waves and storm surges. However, work by Powell et al. (2003) and Donelan et al. (2004) suggests that in those extreme circumstances the drag decreases with wind speed or saturates. But, the understanding of the physics of such extreme events is only beginning.

Makin (2005) argues that spray production may give rise to the reduction of drag coefficient, C_d, by suppressing the air turbulence for increasing wind speed during hurricanes. On the other hand, Andreas (2004) has proposed that when spray returns to the water, short waves will be extinguished. This will no doubt reduce the drag considerably as the short waves carry most of the wave-induced stress (Makin and Kudryavtsev, 1999). Donelan et al. (2004) also suggest that flow separation may be the reason for drag reduction since the outer airflow does not "see" the troughs of the waves during such events and thus unable to follow the wave surface, and skips from breaking crest to breaking crest. All these hypotheses are standing on one common ground – the momentum flux is closely coupled with the sea state in the ocean.

Thus, fully coupled Atmosphere-wave-ocean model is suggested for accurate hurricane predictions as well as corresponding ocean responses (Chen et al., 2007; Fan et al., 2009a; Liu et al., 2011; Chen et al., 2013). Third generation wave models [e.g., WAVEWATCH III (Tolman, 1998), the Wave Model (WAM; Hasselmann et al., 1988), and Simulating Waves Nearshore (SWAN; Booij et al., 1999)] have been used to study surface wave responses during hurricanes, and the modeled wave parameters (significant wave height, mean/dominant wave length, mean/dominant wave direction) are shown to compare well with observations (Phadke et al., 2003; Moon et al., 2003; Xu et al., 2007; Fan et al., 2009b; Allard et al., 2014). Thus, there is desire in the modeling community to calculate momentum flux using the source function from the wave model. However, the wave energy spectrum computed by the models is from a balance between input and dissipation, and the wave parameters that are usually validated against observations are weighted by energy thus depend primarily on long waves around the peak. Since the momentum flux depends mainly on short wind waves, one may ask whether the model spectra represent real spectra well enough to provide reasonable momentum flux to atmosphere and ocean models in a coupled system for hurricane predictions, or is there a stronger argument for using parameterized fluxes?

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* Corresponding author. Tel.: +0012286884655.
E-mail address: yalin.fan@nrlssc.navy.m, yalin.fan@gmail.com (Y. Fan).

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During Hurricane Ivan (SSHS category 4–5 in the Caribbean Sea and Gulf of Mexico) in 2004, detailed scanning radar altimeter (SRA) wave spectra measurements were collected by NASA through a joint effort between the NASA Goddard Space Flight Center and National Oceanic and Atmospheric Administration (NOAA)/ Atlantic Oceanographic and Meteorological Laboratory/Hurricane Research Division (HRD). The integrated parameters (significant wave height, dominant/mean wavelength and direction) calculated from the SRA spectra are used to evaluate WAVEWATCH III® by Fan et al. (2009) together with NDBC and satellite measurements, but the actual two-dimensional wave spectra produced by the wave models are not validated against observations.

In this study, these measured wave spectra will be used to calculate C_d using the source functions proposed by Donelan et al. (2006). The same source functions are applied to calculate C_d using model *simulated* wave spectra at the same time and location as the SRA spectra. Magnitude and spatial distribution of the C_d from both calculations are compared in detail. In particular, we investigate if the model spectra are suitable to provide reliable C_d for coupled models.

2. Methodology

2.1. The wave model

The wind-wave model, WAVEWATCH III® (WWIII) version 4.18, developed and used operationally at the National Centers for Environmental Prediction (NCEP) (Tolman et al., 2014) is used for this study. WWIII computes the evolution in space and time of the wave spectrum, which for the present study is discretized using 45 directions and 38 intrinsic (relative) frequencies extending from 0.02855 to 0.97 Hz, with a logarithmic increment of $f(n+1)=1.1f(n)$, where $f(n)$ is the n^{th} frequency. The wave model is built on a latitude-longitude grid with a horizontal resolution of $1/12^\circ$.

Ocean currents obtained from the HYCOM+NCODA Global $1/12^\circ$ Reanalysis database (https://hycom.org/dataserver/glb-reanalysis) are introduced into WWIII. There are two significant ways the ocean current (U_c) impacts the wave field. First, through the wind input term in the calculation of the wind stress. When ocean current is present, the 10-m wind velocity input (U_{10}) is replaced by the relative wind velocity U_{10}–U_c. Second, the wave action equation, solved in WWIII accounts for the modulation by the ocean current such that the variable ocean current not only modifies the speed of the wave action flux but also any horizontal shear in the currents modifies the wave number of a particular wave packet as it propagates (Holthuijsen and Tolman, 1991, Fan et al., 2009b).

2.2. SRA measurements

Three sets of detailed SRA wave spectra measurements were collected by NASA. The flight tracks of the aircraft carrying the SRA are shown in Fig. 1. Two sets of measurements were collected from 1615 to 2010 UTC on September 9 and from 1040 to 1540 UTC on September 12 when Ivan was crossing the Caribbean Sea and at its maximum intensity of category 5. The third set of measurements was done from 2030 to 2353 UTC on September 14 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 × 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 wavenumber spectral resolution of 0.0035 rad m^{-1}. The wave spectra were Doppler corrected and the 180° ambiguous spectral lobes were deleted (more details on the data process are given in Wright et al., 2001 and Walsh et al., 2002).

The horizontal resolution of the spectra is based on the altitude of the aircraft, and can resolve waves equal or longer than 50 m (~ 0.17 Hz) for the Hurricane Ivan measurements. Diagnostic tails need to be added in order to use these spectra for source function and momentum flux calculations. The method for adding the diagnostic tails and how this will affect the momentum flux calculations are discussed in Section 3.

2.3. Hurricane wind specification

The wind fields during Hurricane Ivan are obtained from the NOAA/HRD real-time wind analysis (HWIND) and interpolated into 0.5-h intervals using the normalized interpolation method given by Fan et al. (2009b). 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 1-minute sustained wind speeds in a hurricane (Powell et al., 1998). It has the spatial resolution of about 6 × 6 km, covering an area of about $8^\circ \times 8^\circ$ in latitude–longitude around the hurricane's center, and are provided at intervals of every 3 or 6 h. This frequency is not sufficient to force a numerical model and therefore the wind data are interpolated in space and time using the normalized interpolation method developed by Fan et al. (2009b).

2.4. Wind stress and drag coefficient calculation

The Janssen (1991) wind input parameterization is widely used in many studies and wave models including WWIII and the WAM model. In his theory, both the effects of waves and the effect of air turbulence on the mean wave profile are taken into account. An effective roughness z_e is proposed, which is used together with the friction velocity u_*, to determine the growth rate and hence the input source function. In numerical models, z_e and u_* from previous time step is used to determine the input source function, then the roughness length z_0, z_e, and u_* are solved using iterations of the wind speed log profile equation, expression of z_e, and the Charnock relationship (see details in Mastenbroek et al., 1993). This procedure is possible with the WWIII generated spectrum, but not practical for the SRA measurements. Thus a stress calculation based on the wave spectra and wind only is used for this study: Donelan et al. (2006). The authors proposed a wind input source function $S_{in}(f,\theta)$, based on field measurements collected during the Australian Shallow Water Experiment (AUSWEX):

$$S_{in}(f,\theta) = B(f,\theta)E(f,\theta) \tag{1}$$

where

$$B(f,\theta) = \gamma(f,\theta)\sigma\frac{\rho_a}{\rho_w} \tag{2}$$

and

$$\gamma(f,\theta) = G\sqrt{B_n'(f)}W(f,\theta) \tag{3}$$

The sheltering coefficient G is given by

$$G = 2.8 - \left\{1 + tanh\left[10\sqrt{B_n'(f)}W(f,\theta) - 11\right]\right\} \tag{4}$$

with

$$W(f,\theta) = \left\{max\left[0, \frac{U_{10}}{C}cos(\theta_{wv} - \theta_{wn}) - 1\right]\right\}^2 \tag{5}$$

Where, σ is the angular frequency, θ is the wave direction, $f=\sigma/2\pi$ is the frequency in hertz, ρ_a and ρ_w are air and water densities, θ_{wv} and θ_{wn} are wave and wind directions, and C is the