Effect of surface waves on air-sea momentum exchange: II. Behavior of drag coefficient under tropical cyclones

IL-JU MOON, ISAAC GINIS, AND TETSU HARA

Graduate School of Oceanography, University of Rhode Island, Narragansett, Rhode Island

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Corresponding author: Il-Ju Moon, Graduate School of Oceanography, University of Rhode Island, Narragansett, Rhode Island, 02882.
Email: mij@gso.uri.edu

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ABSTRACT

Present parameterizations of air-sea momentum flux at high wind speed, including hurricane wind forcing, are based on extrapolation from field measurements in much weaker wind regimes. They predict monotonic increase of drag coefficient ($C_d$) with wind speed. Under hurricane wind forcing, the present numerical experiments using a coupled ocean wave and wave boundary layer model show that $C_d$ at extreme wind speeds strongly depends on the wave field. Higher, longer and more developed waves in the right front quadrant of the storm produce higher sea drag; lower, shorter and younger waves in the rear left quadrant produce lower sea drag. Hurricane intensity, translation speed, as well as the asymmetry of wind forcing are major factors that determine the spatial distribution of $C_d$. At high winds above 30 m s$^{-1}$, the present model predicts an overall trend of $C_d$ leveling off and even decreasing with wind speed in certain sectors. This trend is consistent with recent observational, experimental, and theoretical results at very high wind speeds.
1. Introduction

The air-sea momentum fluxes (or wind stress) over ocean are key boundary parameters for atmospheric, oceanic and wave models. In severe storm situations such as tropical cyclones, accurate estimation of the fluxes is crucial in predicting storm track and intensity, storm surges, and ocean wave fields (Ooyama 1969; WAMDI Group 1988; Emanuel 1995; Doyle 2002; Moon et al. 2003c). It has long been recognized that the wind stress (or the drag coefficient \( C_d \) or the roughness length \( z_0 \)) depends on wind speed as well as on sea states and atmospheric stability (Monin Obukhov, 1954; Charnock 1955; Large and Pond (1981); Smith et al. 1992). However, the bulk formula that is widely used in many numerical models assumes that the wind stress magnitude is a unique function of the wind speed, being independent of the sea state, after the stability correction is made. The roughness length is expressed in terms of the air friction velocity \( u_* \) and the acceleration of gravity \( g \) based on the dimensional argument by Charnock (1955). The parameterizations are mostly based on field measurements in weak to moderate wind regimes less than 25 m s\(^{-1}\) and predict monotonic increase of the drag coefficient with wind speed.

Recently, a number of observational studies indicated that \( C_d \) strongly depends on the sea state (Toba et al. 1990; Smith et al. 1992; Johnson 1998; Drennan et al. 2003). In most cases, the sea state has been represented by a dimensionless wave age (\( c_p/u_* \)), where \( c_p \) is the phase speed at the peak frequency. However, the dependency of \( C_d \) (or nondimensional roughness, i.e., Charnock coefficient) on wave ages are still remains controversial, especially in high wind and very young sea conditions (Komen et al. 1988; Jones and Toba 2001).

In severe storm conditions, especially forced by tropical cyclones, the surface wave field is quite complex and fast varying in space and time and generates. This cause to produce many extreme young waves as well as complex spectra with swell propagating at large and sometimes conflicting angles to the local wind (Moon et al. 2003a). The existence of the swell may influence both the magnitude of the wind stress and the angle between the wind stress and the mean wind (Smith 1980; Geernaert 1988; Rieder et al. 1994; Grachev et al. 2003). For the complex seas, therefore, the wind stress must be
treated as a vector quantity and the proper estimation of the stress can be archived by using two-dimensional wave spectrum, not a single parameter like wave ages.

There have been a number of studies that attempted to predict air-sea momentum flux (in particular, roughness length) by explicitly calculating the wave-induced stress (i.e., the stress supported by surface waves) with the two-dimensional wave spectrum (Janssen 1989; Chalikov and Makin 1991; Makin et al. 1995; Makin and Matenbroek 1996; Markin and Kudryavtsev 1999; Hara and Belcher 2004). Among them, Janssen’s (1989) theory is most widely used in surface wave models (WAMDI Group 1988) and coupled models between atmosphere (or ocean) and surface waves (Weber et al. 1993; Lionello et al. 1998; Johnson et al. 1999; Bao et al. 2000: Desjardins et al. 2000: Doyle 2002; Moon 2004). However, the most studies have never attempted to estimate the wind stress as a vector quantity and to apply over the extreme wind speeds above 35 m s\(^{-1}\).

In the companion paper (Moon et al. 2004), we investigated the effect of surface waves on air-sea momentum exchange for mature and growing seas forced by steady uniform winds. Here, the complete wave spectrum was constructed by merging the WAVEWATCH-III (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 result was 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. A merit of this method is to allow estimating wind stress vectors over any given complex seas. This study basically follows the approach of Moon et al. (2004) in calculating the wave-induced stress vectors and the wind profile, but focusing on investigating the effect of surface waves on air-sea momentum exchange in extreme complex seas forced by tropical cyclones. In particular, behavior of drag coefficient (or nondimensional roughness) depending on hurricane’s characteristics will be examined mainly as a function of wind speed or wave age. For this purpose, various idealized hurricanes with different translation speeds, intensities, and structures are applied in numerical experiments and the results are compared with other stress formulas currently in use.

A brief outline of the stress vector estimation is given in section 2. Experimental design and method to investigate drag behaviors under hurricane forcing are introduced
in section 3. Section 4 describes results of the experiments and they are compared with available observational data. The summary and conclusion are given in the last section.

2. Estimation of wind stress vector

For a given 10-meter wind speed, the wind stress vector is estimated by explicitly calculating the wave-induced stress. The wave spectrum is estimated by combining the Wave Watch III (WW3) model results near the spectral peak and the parameterization of the spectral tail based on Hara and Belcher (2002). The spectrum is then incorporated to the wave boundary layer model of Hara and Belcher (2004) to estimate the wind stress vector. Full descriptions of this approach are given in the companion paper (Moon et al. 2004).

3. Experimental designs

The present experiments are designed to investigate the effects of the storm translation speed, intensity, structure, and varying storm speed on the stress behavior under hurricane wind forcing (Table 1). Firstly, three idealized hurricanes with different translation speeds are used to examine the effect of the hurricane translation speed (HTS). In these experiments, the maximum wind speed (MWS) is fixed at 45 m s$^{-1}$ and spatially symmetric wind forcing is applied. Secondly, the influence of the storm intensity is investigated by two fast-moving symmetric hurricanes with different MWS. The effect of storm structure is investigated by two asymmetric hurricanes moving with the HTS of 5 m s$^{-1}$ (typical speed) and 10 m s$^{-1}$ (fast moving). Finally, to examine the effect of a time varying translation speed, the observed translation speed of Hurricane Bonnie (1998) is used for the experiment.

The wind fields for these experiments are obtained from an analytical model proposed by Holland (1980). The model requires the centered and ambient pressure and the radius of maximum wind speed (RMW) as inputs. In these experiments, we fix the RMW as 74
km and ambient pressure as 1012 hPa but centered pressures vary depending on the storm intensity. Fig. 1 shows a wind field of a symmetric hurricane estimated by the Holland model. The wind fields are moved northward with various HTS over the deep ocean of 2000-m depth, extending 3000 km in the south-north direction and 1500 km in the east-west direction. The model domain, resolution, and grid system of the WW3 used for these experiments are identical to those used in Moon et al. (2004).

In the following discussions, the results of all numerical experiments except Exp. D are presented after a spin-up time of 54 hours, when a quasi-steady state is achieved. The experiment D using the Hurricane Bonnie’s translation speed is designed for a more realistic simulation of the wind stress and therefore allows an analysis of time varying translation speeds.

4. Results and discussion

a. Effect of storm translation speed on wind stress

1) SURFACE WAVE FIELDS

Figures 2a–2c represent spatial distributions of the significant wave height, $H_s$ (contours) and the dominant wave direction and wavelength, $L$ (arrows) produced by idealized tropical storms (Exp. A) with the HTS of 0 m s$^{-1}$, 5 m s$^{-1}$, and 10 m s$^{-1}$, respectively. The figures are plotted for locations within distance of 300 km from the storm center. The arrow length is proportional to the dominant wavelength and a dashed circle is the RMW. As the HTS increases, waves in the front right quadrant of the storm track become higher and longer, while those in the rear left quadrant become lower and shorter. The maximum values of $H_s$ and $L$ in the fast-moving hurricane reach up to 23 m and 420 m, respectively, which are almost twice the values observed in the stationary hurricane.

In this study, the “input” wave age ($c_{pi} / u_*$) is determined from the peak input frequency $f_{pi}$, which is defined as the peak frequency of the wind sea (waves directly forced by wind) part of the spectrum. It is different from the conventional peak frequency
$f_p$ calculated from the one-dimensional spectrum. With a hurricane-generated complex multimodal wave field, it is essential to find the peak frequency of the wind sea in order to establish a reliable value of the wave age. Estimation of the $f_{pi}$ is made within the WW3 (Tolman and Chalikov, 1996). Distributions of the input wave age representing the state of growth of wind waves relative to local wind forcing are shown in Figs. 2d–2f. As the HTS increases it becomes comparable to the group speed of dominant waves. In particular, waves to the front right of the hurricane’s track are exposed to prolonged forcing from wind, i.e., become “trapped” within the hurricane. The trapped waves produce higher, longer and older waves in the front right quadrant. On the other hand, waves to the rear left of the track experience limited fetch and duration of wind forcing. These waves become lower, shorter, and younger as the HTS increases.

Moon et al. (2003a) have concluded that the hurricane-generated wave field is mostly determined by two factors: the distance from the hurricane center and the HTS. They show that for a hurricane with a low translation speed, the wave field is everywhere dominated by swell generated in the vicinity of the RMW, whose direction then depends on the distance from the hurricane center. For a fast-moving hurricane, the dominant waves are mostly determined by resonance (or trapped waves). When the group velocity of dominant waves is close to the HTS, their growth may be significantly enhanced by the resonance effect, and the swell produced by the resonance may dominate the wave system over its propagating areas.

Figure 3 shows the directional wave spectra obtained at east, north, west, and south points of the RMW. For the stationary hurricane, the spectra have the same shapes in all directions and the dominant waves are locally generated and roughly aligned with the wind. As the storm moves faster, the wave spectra in the east and north point of the hurricane show a unimodal swell due to a resonance effect, while the spectra in the west and south of the hurricane display a more complex structure with both swell and wind-wave peaks.

2) DIRECTIONAL CHARACTERISTICS OF WIND, WIND STRESS AND WAVES
Under the influence of hurricanes, the misalignment of winds and waves is common, as seen in Fig. 3, due to the curvature of hurricane-generated wind fields and their translation. Dominant waves generated near the RMW frequently propagate at a large angle to the local wind, sometimes even opposing it. In all existing wind stress parameterizations it is assumed that the surface wind and wind stress vectors are collinear. However, if there is swell propagating at a large angle to the local wind, the surface wind and stress vectors may not be aligned (Smith 1980; Geernaert 1988). In this section, we investigate the directional characteristics of wind, wind stress and waves.

Figure 4 compares directions of wind, dominant waves, and wind stress, which are produced by the idealized hurricanes with different translation speeds. For the stationary hurricane (Fig. 4a), the dominant waves are mainly determined by the swell generated near the RMW, and consistently propagate to the right of the local wind direction. As the HTS increases, the dominant waves are mostly determined by the swell produced by resonance effect, propagating in the hurricane track direction or to the left of the track (Moon, et al. 2003a). The maximum directional difference between dominant waves and wind is found in the front left quadrant of the hurricane, especially in the fast-moving case (Fig. 4c). At these locations, the misalignment between the wind and wind stress is also the largest (the wind stress vectors always lie between the mean wind direction and dominant wave direction), but it never exceeds a few degrees. This is mainly because dominant waves that are misaligned with wind support little momentum flux; that is, the misaligned dominant waves may reduce the wind stress magnitude (compared to the stress with aligned dominant waves) but they cannot affect the stress direction appreciably. Our results show that the WW3 spectrum at the cut-off frequency is always very much aligned with the wind direction even if the peak region is not aligned. This implies that the equilibrium range that supports the majority of the stress is always aligned with the wind. However, note that this result does not imply that the two-dimensional (vector) stress estimation is unnecessary. If the wind and waves are assumed to be always aligned and the stress is treated as a scalar quantity, the stress magnitude may be significantly overestimated.

Observations of Geernaert (1988), Rieder et al. (1994), and Grachev et al. (2003) showed more distinct angle differences between wind stress and mean wind velocity.
vectors than our results. This may be because their observations were made with much weaker wind speed and well-developed swell. In such conditions, the effect of (misaligned) swell (negative momentum flux from waves to wind) may be more enhanced relative to the effect of (aligned) wind seas. The present approach only considers the positive flux and neglects negative flux from swell mainly because we are interested in strong wind regime forced by tropical cyclones. If we include the negative fluxes in this model, the misalignment might be more significant at positions away from the hurricane center where strong misaligned swell and very weak wind forcing exist.

Since the wind and wind stress directions are mostly aligned (with misalignment of less than a few degrees), it is possible to calculate the drag coefficient $C_d$, the roughness length $z_0$, and the Charnock coefficient $z_{ch} = gz_0/u^2$ from the magnitude of the 10-m wind speed and the wind friction velocity. Such results are discussed next.

3) CHARNOCK COEFFICIENT AND DRAG COEFFICIENT

Figures 2g–2i show the spatial distribution of the Charnock coefficient $z_{ch}$, estimated from the idealized medium strength tropical storm experiments with the HTS of 0 m s$^{-1}$, 5 m s$^{-1}$, and 10 m s$^{-1}$, respectively. For all cases, $z_{ch}$ is less than 0.018 within 300 km from the storm center, which is the value used in the NOAA’s operational hurricane model. As the HTS increases, a significant decrease of $z_{ch}$ is found in the rear left quadrant of the track where younger waves exist.

Figure 5 shows the scatterplot of $z_{ch}$ as a function of the input wave ages at all grid points of the WW3 simulation (except where the estimated $f_c$ is outside the WW3-resolving range). The results are color coded according to the local wind speed at each grid point. The figure clearly shows that most of the decreased $z_{ch}$ values are found in very young seas (input wave age less than 10) and with strong winds (higher than 30 m s$^{-1}$). For a fast-moving hurricane (Fig. 5c), the drop of $z_{ch}$ with decreasing input wave age is further enhanced. Here, thin solid lines represent the results of numerical experiments with growing seas (Moon et al. 2004) under steady uniform winds at four different wind speeds. Our results under the hurricane wind forcing is roughly consistent with the pure growing sea results, i.e., the Charnock coefficient is mainly determined by the two
parameters - the input wave age and the local wind speed - regardless of the complexity of the wave field.

Figures 2j–2l show spatial distributions of $C_d$ for three different translation speeds. In the stationary hurricane, the maximum of $C_d$ appears near the RMW. As the HTS increases, the maximum moves to the front right quadrant of the track.

In Fig. 6, $C_d$ is plotted against wind speed at all grid points as in Fig. 5, with different colors assigned according to the relative position from the storm center. The figure shows that $C_d$ in the front right quadrant monotonically increases with the wind speed (but not as fast as the mature sea results of Moon et al. (2004) denoted by the dash-dot lines), while that in the rear left quadrant is leveling off or even decreasing at higher winds for the fast-moving hurricane. The latter trend is similar to the very young sea results (wind duration of 1 hour) of Moon et al. (2004) under steady uniform wind, denoted by the solid lines. This is because in extremely high wind conditions, the equilibrium range of very young waves in the rear left quadrant is quite low and makes a relatively smaller contribution to the total wind stress than more developed waves in the front right quadrant.

Next we compare the obtained drag coefficient distributions (Figs. 2j–2l) with those of bulk formula based on a constant $z_{ch} (0.0185)$ (Figs. 2m–2o) and the internal prediction of the WW3 (Figs. 2p–2r). The distributions from the bulk formula show that $C_d$ is independent of the HTS because it is independent of the sea state. The $C_d$ values from the WW3 are estimated parametrically with their dependence on the input wave age (Tolman 2002), i.e., younger waves yield higher drag. The distributions of $C_d$ from the WW3 (Figs. 2p–2r) are consistent with those of wave age (Figs. 2d–2f) as expected. In Fig. 6, our drag coefficient values are compared with the bulk formula (dashed line) and the WW3 estimates. It is seen that the bulk formula and the WW3 significantly overestimates the drag coefficient compared to our results, particularly at higher wind speeds and for faster moving hurricanes.

In many oceanic and atmospheric models, the bulk formula based on the constant Charnock coefficient (mostly 0.0185) is widely used even at high winds (Kurihara 1998; Johnson et al. 1998). This parameterization is based on extrapolations from field measurements obtained under moderate winds; it has not been validated against
observations at high winds. The extrapolation yields monotonic increase of $C_d$ with wind speed (Fig. 6). Our results, on the other hand, show that at high winds above $30 \text{ m s}^{-1}$, $C_d$ levels off and even decreases with wind speed in certain sectors. Therefore, they suggest that the choice of $z_{ch} = 0.0185$ is a good approximation only in the moderate winds; at high wind speeds the bulk formula may lead to significant overestimation of the momentum exchange across the air-sea interface.

\textit{b. Effect of storm intensity}

We next examine how the wind field and the drag coefficient vary with different storm intensity. Typical hurricanes produce MWS in the range from $30 \text{ m s}^{-1}$ to $60 \text{ m s}^{-1}$. In this section, we investigate the effect of the storm intensity on wind stress using two fast-moving (HTS = $10 \text{ m s}^{-1}$) hurricanes (Exp. B) with different intensities, i.e., the MWS of $35 \text{ m s}^{-1}$ (weak storm) and $55 \text{ m s}^{-1}$ (strong storm).

Figure 7 shows $C_d$ against wind speed for the weak and strong storms, which should be compared with the result of the medium strength storm shown in Fig. 6c. These figures show that the dependence of $C_d$ on wind speed is very similar except that the leveling off and decrease of the $C_d$ in the rear left quadrant occur at different wind speeds (at wind speeds just below the MWS). The decrease of $C_d$ becomes more distinct as the MWS increases.

\textit{c. Effect of storm structure}

When a hurricane moves, actual wind speeds in the right (left) of its track become higher (lower) than those in the left due to addition (subtraction) of the translation speed to the wind speed determined by the hurricane pressure field. The maximum wind speed is always found in the right hand side. In all previous experiments, axisymmetric wind fields (i.e., same wind speeds in all directions from the storm center) are used. Here, we
examine the effect of asymmetric wind fields on wind stress, when the hurricane translation speed is added in the applied wind speed.

Figure 8 shows the distribution of the applied wind speed with the HTS of 5 and 10 m s\(^{-1}\) and the MWS of 45 m s\(^{-1}\). In Fig. 9 the distributions of waves, wave age, Charnock coefficient, and drag coefficient are shown. These figures can be compared with the symmetric wind field results shown in Fig. 2. The asymmetric effect yields further increase of the wave height, length, and the drag coefficient in the front right quadrant of the hurricane’s track and further decrease of these quantities in the rear left quadrant. Figure 10 shows \(C_d\) against wind speed with asymmetric wind forcing. Comparison between Fig. 10 and Figs. 6b–6c (with symmetric wind forcing) shows that leveling-off of \(C_d\) starts at lower wind speeds with asymmetric wind forcing compared to the symmetric wind cases.

d. Effect of varying storm speed

Results presented so far have been obtained after a spin-up time of 54 hours with a fixed HTS. This allows us to investigate the behavior of \(C_d\) under a steady-state condition (i.e., steady relative to an observer moving with the hurricane). However, as a real hurricane develops, its translation speed often changes significantly. Wind stress fields produced by a varying storm translation speed may differ from the stead-state results with a fixed HTS. In this section, we investigate the effect of a varying HTS on wind stress using the observed translation speed time record of a real hurricane.

Figure 11 shows the translation speed of Hurricane Bonnie (1998) used in this experiment. The speed varies from 2 m s\(^{-1}\) to 8 m s\(^{-1}\) during the 7-day period. For this simulation, an asymmetric wind field, resulting from the summation of the translation speed and an axisymmetric wind field with the MWS of 45 m s\(^{-1}\), is applied.

Shown in Fig. 12 are distributions of \(C_d\) when Bonnie moved at the same HTS of 5 m s\(^{-1}\) but was accelerating (Fig. 12a, corresponding to Pt. A in Fig. 11) and was decelerating (Fig. 12b, corresponding to Pt. B in Fig. 11). Comparing these figures with Fig. 9g (the steady-state result with the same HTS of 5 m s\(^{-1}\)) as well as Fig. 2j (HTS = 0 m s\(^{-1}\)) and
Fig. 9h (HTS = 10 m s\(^{-1}\)), one can see that \(C_d\) during the acceleration is slightly lower than the constant HTS result (Fig. 9g), i.e., slightly closer to the HTS = 0 m s\(^{-1}\) result (Fig. 2j), while \(C_d\) during the deceleration is higher than the constant HTS result (Fig. 9g), i.e., closer to the HTS = 10 m s\(^{-1}\) result (Fig. 9h). The same trend is also found in the scatterplots of \(C_d\) against the wind speed (not shown here). This is mainly because the surface wave field is not determined by the instantaneous wind forcing but by the time history of wind forcing, i.e., the wave field retains memory of the wind forcing history. Consequently, the drag coefficient, which is influenced by the surface wave field, responds to varying wind forcing with some time delay.

\textit{e. Comparison with other studies}

Figure 13 compares our results of \(C_d\) against wind speed with two existing parameterizations (the formula by Large and Pond (1981) and the bulk formula with a constant Charnock coefficient of 0.0185), the WW3 prediction, and the estimate based on observations of Powell et al. (2003). The latter is the only observation reported under hurricane forcing of wind speed over 40 m s\(^{-1}\). Our upper and lower bounds are determined by combining all grid points at every minute from all experiments described earlier. Most data points are located near the upper bound. Data points near the lower bound are from the rear left quadrant of the hurricane.

At high wind speeds, the leveling off and decreasing trend of our \(C_d\) with wind speed is significantly different from that of the two surface flux parameterizations that are widely used in a variety of models, including those used for forecasting hurricanes and storm surges. The existing parameterizations yield monotonic increase of \(C_d\) with wind speed because they are based on extrapolations from the measurements obtained at lower winds. The internal prediction of the WW3 based on the sea-state-dependent \(C_d\) shows even faster increase in high wind speeds, because it assumes that younger waves yield higher drag regardless of wind speeds, while our model predicts lower drag with younger waves at high wind speeds.
Powell et al. (2003) estimated $C_d$ using a dataset from hundreds of Global Positioning System (GPS) sondes that were dropped in the vicinity of hurricane eyewalls, where the strongest wind occurs, in the Atlantic, and Eastern and Central Pacific basins since 1997. This is the first observation of $C_d$ in tropical cyclones under high wind speeds over 40 m s$^{-1}$. Figure 13 shows that for high wind speeds above 35 m s$^{-1}$, their estimation is much less than the two existing parameterizations. The overall trend of the observed $C_d$, i.e., increase with wind speeds at lower wind speeds and decrease with wind speeds at very higher winds, is qualitatively consistent with our model results.

A leveling-off and decrease of $C_d$ at high wind speeds was also found in laboratory experiments by Alamaro et al. (2002). In addition, Emanuel (2003) predicts that the drag coefficients should be capped at a constant value at sufficiently high wind speeds based on his theoretical study of the energy balance of a hurricane system. Our model results are consistent with these recent studies as well. Moreover, our model results provide a plausible explanation why the drag coefficient ceases to increase at very high wind speeds.

5. Summary and conclusion

Effect of surface waves on air-sea momentum exchange under hurricane wind forcing has been investigated by combining the WAVEWATCH-III ocean wave model, the spectral tail parameterization based on the equilibrium spectral model by Hara and Belcher (2002), and the wave boundary layer model of Hara and Belcher (2004). The combined model estimates the wind stress vector by explicitly calculating the wave-induced stress vector. This approach allows us to estimate the drag coefficient and the equivalent surface roughness for any surface wave fields, even for complex seas driven by hurricanes. From the numerical experiments using idealized hurricanes with different translation speeds, intensities, and structures, we have investigated the behavior of the drag coefficient $C_d$ and the Charnock coefficient $z_{ch}$ under hurricane wind forcing. The results can be summarized as follows:
(1) Under hurricane wind forcing, swell often propagates with a large angle to the local wind. However, the misalignment between the wind stress direction and the wind direction is always small (less than a few degrees). This is mainly because under strong wind forcing, enough wind-forced waves are generated and they are aligned with local wind and support a significant amount of stress. Consequently, the longer waves that are misaligned with local wind support little momentum flux; they may affect the wind stress magnitude but may not affect the wind stress direction significantly. Therefore, it is possible to define and calculate the drag coefficient and the equivalent surface roughness using the wind stress magnitude and the wind speed magnitude.

(2) As the HTS increases, higher, longer and more developed waves in the right front quadrant of the storm track produce higher sea drag; lower, shorter and younger waves in the rear left quadrant produce lower sea drag.

(3) The Charnock coefficient $z_{ch}$ is mainly determined by the local wind speed and the local input wave age (wave age of local wind seas) regardless of the complexity of the wave field. For lower wind speeds, $z_{ch}$ tends to decrease with the input wave age; for strong winds above 30 m s$^{-1}$, $z_{ch}$ tends to decrease as waves become younger. The latter trend is different from those found in most previous observations because such a trend is found only in extreme young seas, which does not last long and cannot be observed at moderate winds.

(4) The drag coefficient increases with wind speed at lower winds but it levels off and even decreases in certain sectors at very high winds. This is because young waves produced in high winds (especially in the rear left quadrant of the storm track) generate small drags. The spatial variability of the drag coefficient increases as the HTS increases.

(5) As the intensity of storm increases, the leveling-off of the drag coefficient occurs at higher wind speed. This is because very young waves, which lead to the dropping of $C_d$, are produced around the RMW.

(6) Asymmetric wind forcing (resulting from adding the HTS to an axisymmetric wind speed) contributes to further increase of the wave height, length, and sea drag in
the front right quadrant of the storm track and further decrease of these in the rear left quadrant.

(7) When the HTS changes, $C_d$ responds with some time delay because the surface wave field retains memory of wind forcing history.

(8) Our numerical experiments with different hurricane conditions generally predict that $C_d$ increases with wind speed at low winds and levels off with wind speed at very high winds. This overall trend is consistent with the recent laboratory study by Alamaro et al. (2002) and the theoretical study by Emanuel (2003). An even reduced $C_d$ with wind speed, which is found in certain sectors of very high wind regime, is also consistent with the result of Powell et al. (2003) obtained from various tropical cyclones. The existing parameterizations and the WW3 internal calculations significantly overestimate the drag coefficient at high winds.

An important conclusion that follows from this study is that accurate hurricane forecasting requires coupling between a hurricane model and a surface wave model, since accurate prediction of surface fluxes are crucial for hurricane forecasting, in particular, for storm intensity and track prediction. Experiments with the GFDL/URI coupled hurricane-ocean model indicate important sensitivity of the hurricane intensity to the momentum flux parameterization at the sea surface (Ginis et al. 2004). In these experiments, if the roughness length is set constant (capped) for wind speeds $> 35$ m/s, consistent with our results, it leads to a substantial increase of maximum surface wind. The changes of the wind speed extend through the boundary layer. These results strongly suggest that the hurricane intensity predictions (as well as corresponding track forecast) could be significantly affected by the improved parameterization of the air-sea momentum flux at high wind speeds.

Hurricane winds produce a large number of breaking waves and sea spray. Breaking waves and spray may significantly change the wind stress. Makin and Kudryavtsev (2002) predicted that breaking waves significantly enhance the sea drag over younger seas. Andreas and Emanuel (2001) considered spray effects on momentum transfer and concluded that this effect could be large as well. Powell et al. (2003) pointed out the possible importance of the breaking waves and spray on the stress behavior. It is our
intension to include these processes in our future modeling efforts. It is important to realize, however, that estimating quantitatively the effect of breaking waves and spray is very difficult because our quantitative understanding of such processes is extremely limited at present. The modeling study presented here, although it neglects breaking waves and spray, provides a plausible and quantitative explanation why the drag coefficient levels off and even decreases at very high winds.
REFERENCES


Figure Captions

Fig. 1. Wind fields for the idealized experiment, which are moving with various HTS. These are obtained from an analytic model proposed by Holland (1980). Center pressure (953 hPa) and RMW (74 km) are used as inputs of the model. Thick solid circle represents the radius of maximum wind speed.

Fig. 2. Spatial distributions of significant wave height and mean wave direction (a–c), wave age (d–f), Charnock coefficient $z_{ch}$ (g–i), drag coefficient $C_d$ by the present approach (j–l), $C_d$ by the bulk formula with $z_{ch}$ of 0.0185 (m–o), and $C_d$ by the internal prediction of the WW3 (p–r). All figures are produced by idealized medium-strength tropical storms with HTS of 0 m s$^{-1}$, 5 m s$^{-1}$, and 10 m s$^{-1}$. Dashed circle and plus symbol represent the RMW and the center of storm, respectively.

Fig. 3. Directional wave spectra of the WW3 at (a) East, (b) North, (c) West, and (d) South points from storm center over RMW produced by idealized tropical storms with HTS of 0 m s$^{-1}$ (left), 5 m s$^{-1}$ (center), and 10 m s$^{-1}$ (right). Dashed circles (outer to inner) correspond to wave lengths of 150 m, 250 m, and 350 m. The solid circles indicate wavelengths of 100 m, 200 m, and 300 m. Each spectrum contains eighteen contours, linearly spaced from 10% to 90% (thick contours) and from 1% to 9% (thin contours) of the peak spectral density, which is shown in the second number in the upper right corner. The thick arrows extend in the downwind direction the distance being proportional to the wind speed. A wind speed of 30 m s$^{-1}$ corresponds to a length of 0.03 rad m$^{-1}$. The total $H_s$ is shown in the upper right corner. The mean wavenumber and group velocity are in the lower right corner and in the lower left corner, respectively.

Fig. 4. Comparison of directions among wind (red arrows), dominant wave (black arrows), and wind stress (blue arrows), which are produced by idealized medium-strength tropical storms with translation speeds of (a) 0 m s$^{-1}$, (b) 5 m s$^{-1}$, and (b) 10 m s$^{-1}$. Dashed circle represents the RMW. Plus symbol represents the center of storm.

Fig. 5. Scatterplots of the $z_{ch}$ as a function of wave ages in all grid points for storms with translation speeds of (a) 0 m s$^{-1}$, (b) 5 m s$^{-1}$ and (c) 10 m s$^{-1}$. Moderate winds (circle
s), medium-speed winds (filled circles), and strong winds (plus) are plotted using different symbols. Dashed line represents the \( z_{ch} \) of 0.0185. Solid lines are results of Moon et al. (2004) obtained using steady uniform winds of 10, 15, 30, and 40 m s\(^{-1}\) speeds.

Fig. 6. Scatterplots of the \( C_d \) as a function of the wind speed in all grid points for storms with translation speeds of (a) 0 m s\(^{-1}\), (b) 5 m s\(^{-1}\) and (c) 10 m s\(^{-1}\). Solid line and dash-dot line represent results of Moon et al. (2004) obtained at 1 and 72 hours after the onset of the steady uniform wind, respectively. Dashed line is the bulk formula based on \( z_{ch} \) of 0.0185. Our results and WW3’s prediction are plotted using different symbols according to the relative position from storm center (right front quadrant: +, \( \times \), left rear quadrant: \( \circ \), \( \diamond \), other quadrants: \( \bullet \), \( \star \)).

Fig. 7. Same format as in Fig. 7c but for fast-moving (HTS = 10 m s\(^{-1}\)) storms with the MWS of (a) 35 m s\(^{-1}\) and (b) 55 m s\(^{-1}\).

Fig. 8. Spatial distributions of wind produced by asymmetric hurricanes with translation speeds of (a) 5 m s\(^{-1}\) and (b) 10 m s\(^{-1}\). Asymmetric hurricanes are calculated from the addition (or subtraction) of the translation speed to wind speed determined by the hurricane pressure field.

Fig. 9. Same format as in Figs. 3b-3l but for asymmetric hurricanes with translation speeds of 5 m s\(^{-1}\) and 10 m s\(^{-1}\).

Fig. 10. Same format as in Figs. 7b and 7c but for asymmetric hurricanes with translation speeds of 5 m s\(^{-1}\) and 10 m s\(^{-1}\).

Fig. 11. Variation of Hurricane Bonnie translation speed. Two points (A and B) with the HTS of 5 m s\(^{-1}\) but accelerating or decelerating speed are chosen to compare with the steady-state results with the same speed.

Fig. 12. Spatial distributions of \( C_d \) produced by an idealized storm using the translation speeds of Hurricane Bonnie at (a) 06 h 25 August and (b) 06 h 26 August 1998, which correspond with the times identified as A and B in Fig. 12.

Fig. 13. Comparison of \( C_d \) between various observation-based values (or formulas) and model outputs as a function of wind speed. Symbols represent \( C_d \) estimated from GPS sonde data in various hurricanes (Powell et al., 2003). Vertical bars represent the range of estimates based on 95% confidence. Solid line is an extrapolation of
Large and Pond (1981). Dashed-dotted line is the bulk formula based on $z_{ch}$ of 0.0185. Shaded and stippled areas represent ranges between upper and lower bound of $C_d$ obtained by the present approach and the WW3 for all experiment cases, respectively.
Table Captions

Table 1. Experimental designs.
Fig. 1. Wind fields for the idealized experiment, which are moving with various HTS. These are obtained from an analytic model proposed by Holland (1980). Center pressure (953 hPa) and RMW (74 km) are used as inputs of the model. Thick solid circle represents the radius of maximum wind speed.
Fig. 2. Spatial distributions of significant wave height and mean wave direction (a–c), wave age (d–f), Charnock coefficient $z_{ch}$ (g–i), drag coefficient $C_d$ by the present approach (j–l), $C_d$ by the bulk formula with $z_{ch}$ of 0.0185 (m–o), and $C_d$ by the internal prediction of the WW3 (p–r). All figures are produced by idealized medium-strength tropical storms with HTS of 0 m s$^{-1}$, 5 m s$^{-1}$, and 10 m s$^{-1}$. Dashed circle and plus symbol represent the RMW and the center of storm, respectively.
Fig. 2. Continued.
Fig. 3. Directional wave spectra of the WW3 at (a) East, (b) North, (c) West, and (d) South points from storm center over RMW produced by idealized tropical storms with HTS of 0 m s\(^{-1}\) (left), 5 m s\(^{-1}\) (center), and 10 m s\(^{-1}\) (right). Dashed circles (outer to inner) correspond to wavelengths of 150 m, 250 m, and 350 m. The solid circles indicate wavelengths of 100 m, 200 m, and 300 m. Each spectrum contains eighteen contours, linearly spaced from 10% to 90% (thick contours) and from 1% to 9% (thin contours) of the peak spectral density, which is shown in the second number in the upper right corner. The thick arrows extend in the downwind direction the distance being proportional to the wind speed. A wind speed of 30 m s\(^{-1}\) corresponds to a length of 0.03 rad m\(^{-1}\). The total \(H_s\) is shown in the upper right corner. The mean wavenumber and group velocity are in the lower right corner and in the lower left corner, respectively.
Fig. 4. Comparison of directions among wind (red arrows), dominant wave (black arrows), and wind stress (blue arrows), which are produced by idealized medium-strength tropical storms with translation speeds of (a) 0 m s\(^{-1}\), (b) 5 m s\(^{-1}\), and (b) 10 m s\(^{-1}\). Dashed circle represents the RMW. Plus symbol represents the center of storm.
Fig. 5. Scatterplots of the $z_{ch}$ as a function of wave ages in all grid points for storms with translation speeds of (a) 0 m s$^{-1}$, (b) 5 m s$^{-1}$ and (c) 10 m s$^{-1}$. Moderate winds (circles), medium-speed winds (filled circles), and strong winds (plus) are plotted using different symbols. Dashed line represents the $z_{ch}$ of 0.0185. Solid lines are results of Moon et al. (2004) obtained using steady uniform winds of 10, 15, 30, and 40 m s$^{-1}$ speeds.
Fig. 6. Scatterplots of the $C_d$ as a function of the wind speed in all grid points for storms with translation speeds of (a) 0 m s$^{-1}$, (b) 5 m s$^{-1}$ and (c) 10 m s$^{-1}$. Solid line and dash-dot line represent results of Moon et al. (2004) obtained at 1 and 72 hours after the onset of the steady uniform wind, respectively. Dashed line is the bulk formula based on $z_{ch}$ of 0.0185. Our results and WW3’s prediction are plotted using different symbols according to the relative position from storm center (right front quadrant: $+$, $\times$, left rear quadrant: $\bigcirc$, $\lozenge$, other quadrants: $\bullet$, $\star$).
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Fig. 13. Comparison of $C_d$ between various observation-based values (or formulas) and model outputs as a function of wind speed. Symbols represent $C_d$ estimated from GPS sonde data in various hurricanes (Powell et al., 2003). Vertical bars represent the range of estimates based on 95% confidence. Solid line is an extrapolation of Large and Pond (1981). Dashed-dotted line is the bulk formula based on $z_{ch}$ of 0.0185. Shaded and stippled areas represent ranges between upper and lower bound of $C_d$ obtained by the present approach and the WW3 for all experiment cases, respectively.
Table 1. Experimental designs

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<tr>
<th>Exp. Name</th>
<th>Storm Type</th>
<th>HTS</th>
<th>Maximum Wind Speed (Intensity)</th>
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