

## Effect of surface waves on Charnock coefficient under tropical cyclones

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[1] The dependence of the air-sea momentum flux on surface wave fields is investigated at very high winds under tropical cyclones. A coupled wave-wind model is applied to estimate the momentum flux under ten hurricanes in the western Atlantic Ocean during 1998–2003. The model explicitly calculates the wave-induced stress vector and the total wind stress vector from a given wind speed vector and a calculated wave spectrum. It is found that the neutral drag coefficient levels off at high wind speeds under tropical cyclones, being consistent with recent observations and previous modeling studies. The most important finding of this study is that the Charnock coefficient is mainly determined by two parameters: the input wave age (wave age determined by the peak frequency of wind energy input) and the wind speed, regardless of the complexity of the wave field under a real hurricane, and that the Charnock coefficient increases with the input wave age at very high winds.

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### 1. Introduction

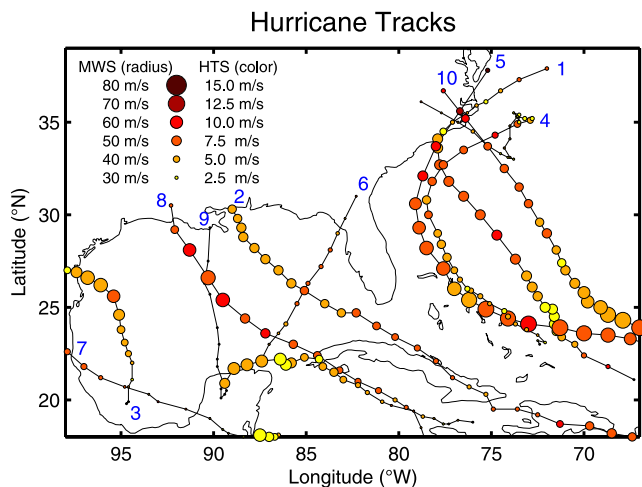
[2] Estimation of air-sea momentum flux (drag coefficient  $C_d$  or roughness length  $z_0$ ) in high wind conditions is one of the most important subjects in hurricane and storm surge modeling and prediction. In most operational models the air-sea momentum flux is parameterized with a constant non-dimensional surface roughness (or Charnock coefficient,  $z_{ch} = z_0 g / u_*^2$ , where  $z_0$  is the roughness length,  $u_*$  is the friction velocity and  $g$  is the gravitational acceleration) and the stability correction based on the Monin-Obukhov similarity theory [Monin and Obukhov, 1954], regardless of wind speeds or sea states. However, a number of studies suggested that the value of the Charnock coefficient depends on the sea state [Toba et al., 1990; Smith et al., 1992; Johnson et al., 1998; Komen et al., 1998; Oost et al., 2001; Drennan et al., 2003]. These studies showed different, often conflicting, relationships between  $z_{ch}$  and the wave age ( $c_p / u_*$ , where  $c_p$  is the phase speed at the peak frequency). Toba et al. [1990] suggested that  $z_{ch}$  increases with the wave age based on observations of mostly young waves in a wave flume, while Donelan's [1990] data obtained in the open sea showed that  $z_{ch}$  decreases with

the wave age. Yelland and Taylor [1996] found a constant  $z_{ch}$  between 0.01 and 0.02 regardless of the wave age. None of these studies, however, investigated  $z_{ch}$  in very high wind conditions mainly due to insufficient observational data.

[3] Recently, Moon et al. [2004a] investigated the dependence of the Charnock coefficient on the wave age at high winds using a numerical model. In their study the surface wave directional frequency spectrum near the spectral peak was calculated using the WAVEWATCH III [Tolman, 2002] model and the high frequency part of the spectrum was parameterized using the theoretical model of Hara and Belcher [2002]. The wave spectrum was then introduced to the wave boundary layer model of Hara and Belcher [2004] to estimate the Charnock coefficient at different wave evolution stages. The study found that under a uniform and stationary wind speed the Charnock coefficient depends on both the wind speed and the wave age; it decreases with the wave age at lower wind speeds but increases with the wave age at very high (>30 m/s) wind speeds.

[4] In their subsequent study [Moon et al., 2004b] the numerical approach was extended to account for misalignment between wind and wave directions and was used to estimate the Charnock coefficient under idealized hurricane wind forcing. Although the wave field under a hurricane is extremely complex, the study showed that the Charnock coefficient mainly depends on the same two parameters, the wind speed and the wave age, as in steady uniform wind forcing provided that the wave age is replaced by the input wave age [Tolman, 2002]. The latter is defined as the peak frequency of the positive part in the input source term of the WAVEWATCH III model. It allows obtaining more consistent estimation of the wave age, even in complex multimodal spectra, rather than using the peak frequency from one-dimensional frequency spectrum [Tolman and Chalikov, 1996]. Moon et al. [2004b] also emphasized that at very high winds under hurricanes the surface wave field is mostly young and the input wave age is small, hence the neutral Charnock coefficient and drag coefficient tend to be much smaller than the bulk estimates.

[5] The main objective of this study is to investigate the Charnock coefficient under real hurricanes in the western Atlantic Ocean during 1998–2003. It is designed to further substantiate the conclusions of Moon et al. [2004b], which were derived from limited numerical experiments with highly idealized hurricane wind forcing. In particular, this study examines whether the dependence of the Charnock coefficient on the wind speed and the input wave age is robust under a wide range of wind and wave conditions encountered during real tropical cyclone events. Since the Charnock coefficient is mainly determined by these two parameters we explore the possibility of constructing a simple and yet much improved parameterization of the



**Figure 1.** Tracks, maximum wind speeds (MWS), and translation speeds (HTS) of tropical cyclones occurred in the western Atlantic Ocean during 1998–2003: 1. Bonnie (1998), 2. George (1999), 3. Bret (1999), 4. Dennis (1999), 5. Floyd (1999), 6. Gordon (2000), 7. Keith (2000), 8. Lili (2002), 9. Isidore (2002), 10. Isabel (2003).

air-sea momentum flux that can be used under a wide range of wind forcing including hurricane winds.

## 2. The Coupled Wave-Wind (CWW) Model

[6] The estimation of the Charnock coefficient is made using the same numerical approach as in *Moon et al.* [2004b]. Since the details of the method are provided in *Moon et al.* [2004a, 2004b], only a brief summary is given below.

[7] In the CWW model, the complete wave spectrum is constructed by merging the WAVEWATCH III [Tolman, 2002] 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 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. Therefore, the method allows us to estimate the wind stress for any given surface wave field, even for the complex seas encountered under tropical cyclones. As in *Moon et al.* [2004b], the calculated wind stress vector in this study is always aligned with the local wind vector within a few degrees. Therefore, we may calculate the neutral drag coefficient and the effective surface roughness as scalar quantities. For each storm, the spatial distributions of the input wave age and the Charnock coefficient are calculated by the CWW model every six hours.

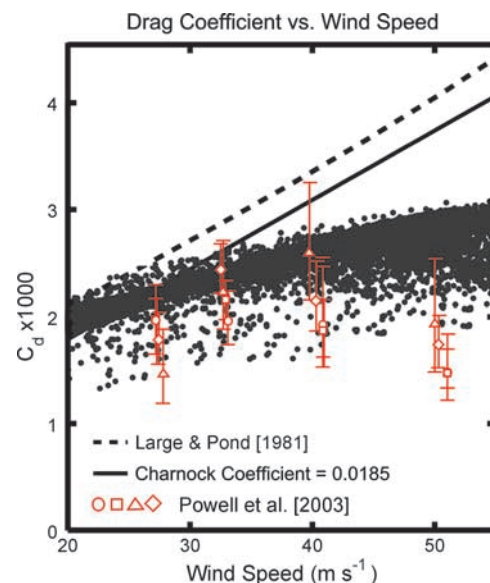
## 3. Tropical Cyclone Wind Field Specification

[8] For this study we selected ten tropical cyclones which occurred in the western Atlantic Ocean during 1998–2003. Figure 1 shows the tracks, maximum wind speeds, and translation speeds of these storms. These tropical cyclones made landfalls in the U.S. and had highly variable intensities

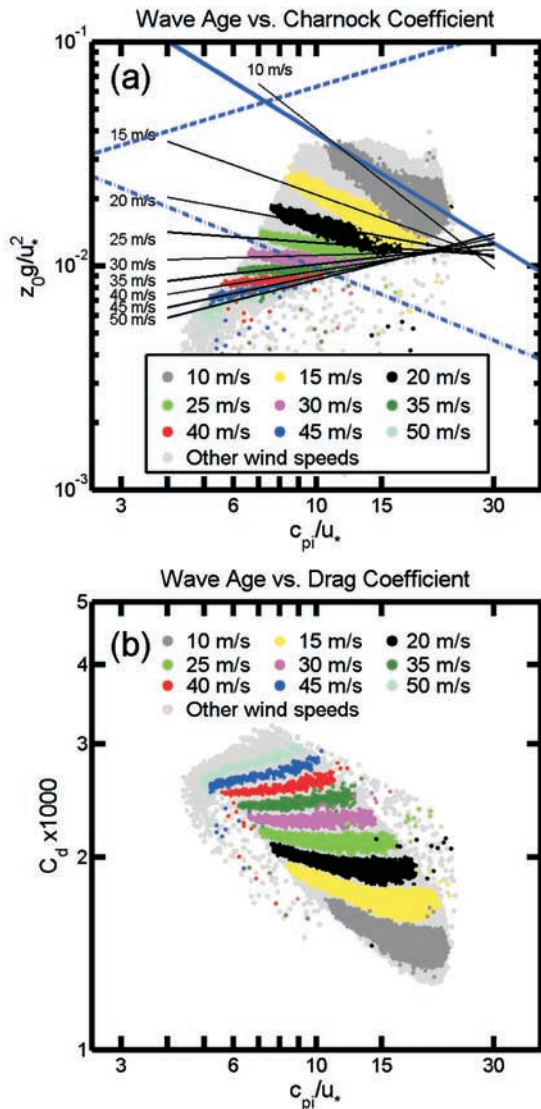
and forward speeds. Therefore, our simulations cover a wide range of wind and wave conditions under real tropical cyclones. The hurricane wind fields used as input to the wave model are calculated from an analytical model used for hurricane vortex initialization in the NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) hurricane prediction system [Kurihara *et al.*, 1998]. The computed wind fields are based on the hurricane message files from the National Hurricane Center (NHC) and have been validated against buoy and station measurements and NOAA's Hurricane Research Division (HRD) wind fields [Moon *et al.*, 2003].

## 4. Neutral Drag Coefficient Under Tropical Cyclones

[9] Figure 2 shows a scatterplot of the drag coefficient ( $C_d$ ) against wind speed obtained during the passage of ten tropical cyclones. The results are compared with two existing surface flux parameterizations that are widely used in a variety of numerical weather prediction models. In this figure,  $C_d$  shows a large scatter so that it is difficult to find a unique relationship between  $C_d$  and wind speed. However, there is an overall tendency to level-off with increasing wind speed. This trend is significantly different from that of the two surface flux parameterizations (solid and dot lines) showing a monotonic increase of  $C_d$  with wind speed. One plausible explanation for this discrepancy, as well as the large scatter, is that the surface wave field under hurricane wind forcing is not fully developed (i.e., the Charnock coefficient is not constant) and is not determined uniquely by the local wind condition. Note that the existing parameterizations implicitly assume that the surface wave field is fully developed and are based on extrapolations from measurements obtained at lower winds. The lower  $C_d$  in



**Figure 2.** A scatterplot of  $C_d$  as a function of the wind speed obtained from the CWW model for ten tropical cyclones. Symbols represent field observations of *Powell et al.* [2003] from GPS sondes in hurricanes for various layers (O, 10–100 m; □, 10–150 m; △, 20–100 m; ◇, 20–150 m). Vertical bars represent the range of estimates based on 95% confidence limits.



**Figure 3.** Scatterplots of (a)  $z_{ch}$  and (b)  $C_d$  as a function of the  $w_{age}$  obtained from the CWW model for ten tropical cyclones in the western Atlantic Ocean. The computed  $z_{ch}$  and  $C_d$  are plotted using different color circles according to wind speed in 5-m/s intervals. Black solid lines are the best fits of each wind speed group for equation (1). Blue solid line and dash-dot line represent empirical estimates by Donelan [1990] in the open ocean and laboratory respectively. A dotted line represents the formula of Toba et al. [1990].

high wind speeds is consistent with the recent field observations of Powell et al. [2003], also shown in Figure 2, as well as the laboratory experiments of Alamaro et al. [2002] and Donelan et al. [2004], the theoretical study of Emanuel [2003], and the idealized hurricane simulations of Moon et al. [2004b].

## 5. Dependence of Charnock and Drag Coefficient on the Input Wave Age

[10] In this section, we investigate the relationship between the hurricane-generated surface wave fields and momentum fluxes using a non-dimensional surface rough-

ness (Charnock coefficient) and a sea state parameter (input wave age). Figure 3 shows scatterplots of  $z_{ch}$  and  $C_d$  as a function of the input wave age ( $w_{age}$ ) obtained from the CWW model during the passage of ten tropical cyclones. In Figure 3a, the distribution of  $z_{ch}$  against  $w_{age}$  shows a large scatter, but the majority of data points (except very young seas and high wind speeds) are within two empirical lines given by Donelan [1990] in the open ocean (blue solid line) and in the laboratory (blue dash-dot line). Because of the large scatter, it is difficult to find a unique relationship between the Charnock coefficient and the input wave age. However, if we choose subsets of data at wind speeds (within  $\pm 0.1$  m/s) of every 5 m/s and highlight them using different color symbols, we find that there is a strong (and roughly power law) correlation between  $z_{ch}$  and  $w_{age}$  for each wind speed. For example, for the 40 m/s wind speed (representing winds between 39.9 m/s and 40.1 m/s), denoted by the red circles, the relationship between  $z_{ch}$  and  $w_{age}$  can be fitted by the following simple form,

$$z_{ch} = n(w_{age})^m, \quad (1)$$

where  $(m, n)$  is  $(0.2607, 0.0052)$  and the regression coefficient ( $r$ ) is 0.82. Using the same form, the fitting constants  $(m, n)$  and the regression lines for other wind speeds are given in Table 1 and Figure 3a, respectively.

[11] Many past studies suggested that there is a unique relationship between the Charnock coefficient and the wave age. Various relationships were proposed and these are summarized by Jones and Toba [2001]. Our results, however, suggest that the Charnock coefficient is determined by two parameters – the input wave age and the local wind speed – regardless of the complexity of the wave field. We find that while for high wind speeds  $z_{ch}$  increases with the input wave age, for low wind speeds  $z_{ch}$  decreases with the input wave age.

[12] Another interesting result of our analysis is that all regression lines between  $z_{ch}$  and  $w_{age}$  converge at a point around  $20 < w_{age} < 30$  and  $0.01 < z_{ch} < 0.015$ , suggesting that the Charnock coefficient is roughly independent of wind speed for fully developed seas. This result is qualitatively consistent with the theoretical analysis of Hara and Belcher [2004].

[13] Figure 3b shows that there is a strong correlation between  $C_d$  and  $w_{age}$  for each wind speed as seen between  $z_{ch}$  and  $w_{age}$ . It is clearly seen that at very high winds  $C_d$  is lower for younger waves, which may explain the leveling-off of  $C_d$  with wind speed. In a recent wind tunnel study,

**Table 1.** Regression Constants for Equations (1) and Their Regression Coefficients ( $r$ )

Wind Speed [m/s]	Equation (1)		
	$m$	$n$	$r$
9.9 < W < 10.1	-1.30182	0.817809	0.64
14.9 < W < 15.1	-0.594894	0.082168	0.71
19.9 < W < 20.1	-0.302122	0.0307755	0.72
24.9 < W < 25.1	-0.118524	0.0166773	0.76
29.9 < W < 30.1	0.0483266	0.0099775	0.75
34.9 < W < 35.1	0.186318	0.0066187	0.79
39.9 < W < 40.1	0.260749	0.0052136	0.82
44.9 < W < 45.1	0.3540439	0.0039632	0.86
49.9 < W < 50.1	0.441526	0.0030941	0.79

Donelan *et al.* [2004] gave another explanation of the latter effect, suggesting that flow separation from steep waves reduces the drag coefficient in very strong winds.

## 6. Summary and Concluding Remarks

[14] It is clear that the sea state has significant influence on air-sea momentum fluxes. A number of previous studies suggested that there is a certain relationship between the non-dimensional roughness length (or Charnock coefficients) and the sea state represented by the wave age. However, there are still lively debates in the research community over this relationship. The major reason leading to the discrepancies among different studies is the paucity of observation data, especially in high wind speeds and very young seas. Therefore, theoretical and numerical approaches provide a very useful and complementary way for investigation of a wide range of wind forcing and wave conditions without the limitations associated with measurements.

[15] In this paper, we used a coupled wave-wind (CWW) model to examine the Charnock coefficient under hurricane wind forcing. Since this model was successfully used over mature and growing seas, as well as for idealized hurricanes [Hara and Belcher, 2004; Moon *et al.*, 2004a, 2004b], we applied it to ten simulations of hurricanes that occurred in the western Atlantic Ocean during 1998–2003. We found that the neutral drag coefficient levels off at very high wind speeds, consistent with recent field observations [Powell *et al.*, 2003], the laboratory experiments of Alamaro *et al.* [2002] and Donelan *et al.* [2004], and the idealized hurricane simulations of Moon *et al.* [2004b].

[16] The most important finding of this study is that the relationship between the Charnock coefficient and the input wave age (wave age determined by the peak frequency of wind energy input) is not unique, but strongly depends on wind speed. The relationship between the Charnock coefficient and the input wave age and wind speed is robust regardless of the complexity of the wave field.

[17] The regression lines between the input wave age and the Charnock coefficient show a negative slope at low wind speeds, as proposed by Donelan [1990], but a positive slope at high wind speeds, as proposed by Toba *et al.* [1990]. This behavior of the Charnock coefficient in high winds provides a plausible explanation why the drag coefficient under tropical cyclones, where seas tend to be extremely young, is significantly reduced in high wind speeds.

[18] In high wind conditions, breaking waves, sea spray, and foam may play a significant role in determining the wind stress [Andreas and Emanuel, 2001; Makin and Kudryavtsev, 2002; Powell *et al.*, 2003]. Flow separation from the surface may also contribute to the limiting aerodynamic roughness at extreme wind speeds [Donelan *et al.*, 2004]. We expect that inclusion of these processes in the CWW model may modify the wind stress over young seas. However, although our model results may not include all relevant processes, our main conclusion – the dependence of the Charnock coefficient on the wind speed and the input wave age – is likely to be robust.

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