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# EFFECT OF OCEAN WAVES ON AIR-SEA MOMENTUM FLUXES AND HURRICANE INTENSITY

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## 1. INTRODUCTION

Recent observational studies demonstrate that air-sea momentum flux at high wind conditions in hurricanes strongly depends on the wave field and that the drag coefficient ($C_d = u_*^2/U_{10}^2$) levels off or even decreases at very high winds (Powell et al. 2003). Yet most hurricane research and forecast model utilize the bulk parameterization, i.e., the boundary layer parameterization based on the Monin-Obukhov similarity theory with the behavior of the drag coefficient based on extrapolations from field measurements in much weaker winds. It assumes that the Charnock coefficient ($z_{ch}$) is constant, i.e., is independent of the sea state. (Here, the Charnock coefficient is defined as $z_{ch} = z_0 g/u_*^2$, and $z_0$ is the equivalent surface roughness.) Therefore, this parameterization implicitly assumes that the surface wave field is fully developed. These extrapolations describe a monotonic increase in $C_d$ with wind speed.

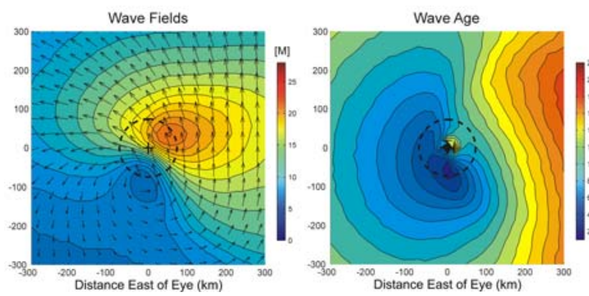
In this study, we will investigate the effect of ocean waves on air-sea momentum fluxes and hurricane intensity using a newly developed Coupled Wave-Wind (CWW) model (Moon et al. 2004a & 2004b).

## 2. THE COUPLED WAVE-WIND MODEL

The CWW model estimates the wind stress vector by explicitly calculating the wave-induced stress vector and the surface viscous stress vector. It is designed to estimate $C_d$ and the equivalent surface roughness for mature and growing seas as well as for complex seas forced by hurricane-force winds.

In CWW model, the complete wave spectrum is constructed by merging the NCEP WAVEWATCH III (WW3) wave model 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 (WBL) model of Hara and Belcher (2004) to explicitly calculate the wave-induced stress vector, the mean wind profile, and the drag coefficient. Here, the stress is treated as a vector quantity since we assume that the wave field is generated by non-uniform and nonstationary winds. The WBL model of Hara and Belcher (2004) consists of the lowest part of the atmospheric boundary layer that is influenced by surface waves, based on the conservation of momentum and energy. Energy conservation is cast as a bulk constraint, integrated across the depth of the wave boundary layer, and the turbulence closure is achieved by parameterizing the dissipation rate of turbulent kinetic energy.

The accuracy of momentum flux estimation strongly depends on how realistic ocean wave spectra can be simulated by the wave model in complex seas forced by hurricanes. The performance of the WW3 in the hurricane conditions was evaluated from a hindcast of hurricane Bonnie in 1998 (Moon et al., 2003).



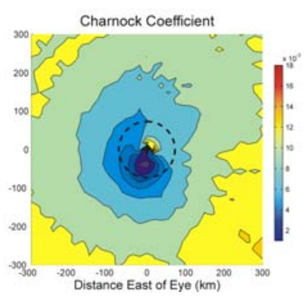




**Figure 1.** Wave fields (upper left panel) simulated by the WW3 for a northward fast-moving hurricane. The arrow direction indicates the direction of dominant waves and the arrow length is proportional to the mean wavelength. Contours show the significant wave height. Wave age (upper right panel), is determined by the phase speed at peak frequency and the friction velocity. The Charnock coefficient $z_{ch}$ (lower left penal) is calculated using the CWW model. Dashed lines are radii of the maximum wind speeds.

## 3. NUMERICAL EXPERIMENTS FOR IDEALIZED HURRICANES

The CWW model was applied for idealized hurricanes moving northward with various hurricane translation speeds: stationary, slow-moving (2.5 m/s), typical-speed (5 m/s), fast-moving (10 m/s), and varying. In these experiments, waves to the right and front of the hurricane track become trapped as the hurricane translation speed becomes faster and waves are exposed to prolong forcing from the wind. As a result, higher, longer and more developed waves are formed to the right and front of the track and yield higher drag

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coefficients, while lower, shorter and younger waves to the rear and left yield lower drag coefficients (Fig. 1). The upper and lower bounds of $C_d$ (Fig. 2), which are estimated from the $C_d$ scatterplot for hurricane Bonnie experiments as a function of wind speed, show the tendency of leveling-off and even decrease of $C_d$ at high winds, being consistent with the recent observations of Powell et al. (2003). These results thus clearly show that the behavior of drag coefficient (and Charnock coefficient) at high wind conditions forced by hurricanes is completely different from that at weak wind speeds and that the drag coefficient varies significantly depending on the relative position from the storm center.

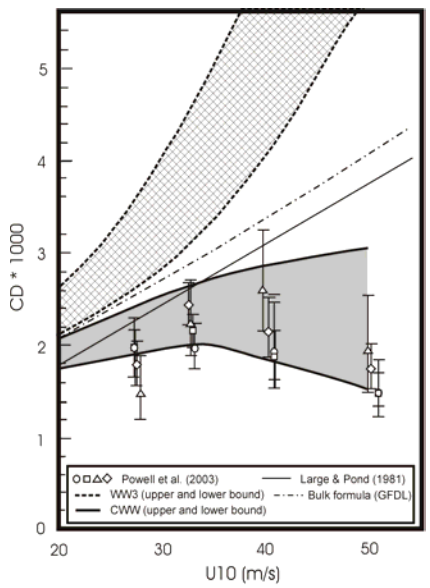


**Figure 2**. Drag coefficient ($C_d$) as a function of $U_{10}$. Symbols are data from Powell et al. (2003). Vertical bars represent 95% confidence limits. Solid line is the Large and Pond (1981) formula. Dash-dot line is the bulk formula used in GFDL hurricane model. Shaded and hatched areas represent ranges between upper and lower bound of $C_d$ obtained by the coupled wave-wind model and internal estimation of WW3 for hurricane Bonnie in 1998, respectively.

## 4. SENSITIVITY OF HURRICANE INTENSITY TO MOMENTUM FLUX PARAMETERIZATION

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. If the roughness length is set constant (capped) for wind speeds > 35 m/s, consistent with the results from our coupled wave-wind model, it leads to a substantial increase of maximum surface wind (Fig. 3). The changes of the wind speed extend through the boundary layer. These results strongly suggest that the proper estimation of momentum flux in hurricane conditions can be only achieved by a coupled-wave-ocean model. They also suggest that the GFDL/URI model intensity predictions could be significantly affected by improved parameterization of the air-sea exchange at high wind speeds.

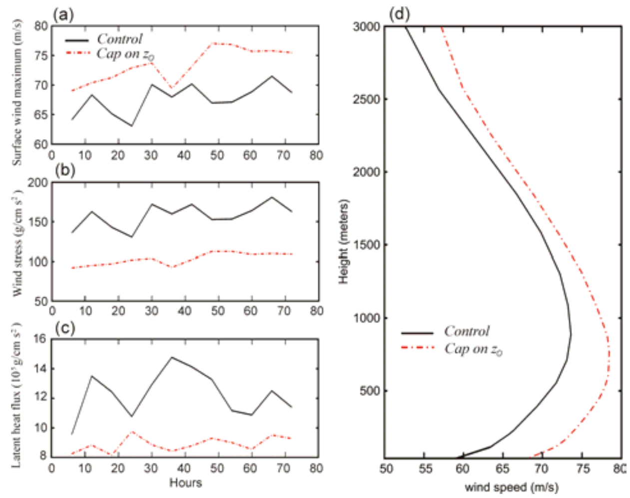


**Figure 3.** Evolution with time of (a) surface wind maximum, (b) wind stress, and (c) latent heat flux, and (d) vertical wind profiles (at 24 hours, averaged around the maximum wind point), obtained by two idealized sensitivity simulations using the GFDL/URI hurricane model. The "Control" run uses the air-sea exchange coefficients as in the operational GFDL hurricane model. The "Cap on $z_0$" run uses the same coefficients, but $z_0$ is kept constant at wind speeds of above 35 m/s.

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