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AIR-SEA MOMENTUM FLUX AT HIGH WINDS

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1. INTRODUCTION

The mean wind profile and the Charnock coefficient, or the drag coefficient, over mature and growing seas are investigated. The complete surface wave spectrum is constructed by combining a numerical wave model output near the spectral peak and an analytical model of the equilibrium (tail) part of the spectrum. The wave spectrum is then introduced to a model of the wave boundary layer, which consists of the lowest part of the atmospheric boundary layer that is influenced by surface waves. The model is based on the conservation of momentum and energy within the wave boundary layer.

2. MODEL OF WAVE BOUNDARY LAYER

We begin by assuming that the total wind stress is a sum of the turbulent stress, the (nonbreaking) wave induced stress, and the breaking wave induced stress;

$$\tau_{tot} = \tau_t(z) + \tau_w(z) + \tau_b(z) \qquad (1)$$

where z is the height above the water surface. As in Hara and Belcher (2002) the wave induced stress $\tau_w(z)$ is obtained by integrating the momentum input to waves in all angles and up to a wavenumber $k = \delta / z$, where δ is the normalized depth of the inner region (Belcher and Hunt, 1993). The local turbulent stress $\tau_t^l(k)$, which forces waves at a wavenumber k, is then set equal to $\tau_t(z = \delta / k)$, that is, the turbulent stress evaluated at the top of the inner region.

It is assumed that the wave drag (momentum flux) due to a single breaking wave of a wavenumber k is determined by the length of its breaking crest and the wind speed evaluated at $z = \delta' / k$ (height that is equal to a set fraction of the wavelength) relative to the wave phase speed. The breaking statistic Λ is defined such that $\Lambda(\vec{k})d\vec{k}$ is the total length of breaking wave crests with wavenumbers between $\vec{k}$ and $\vec{k} + d\vec{k}$ per unit surface area. The breaking wave induced stress $\tau_b(z)$ is obtained by integrating the momentum input to breaking wave crests in all angles and up to a wavenumber $k = \delta' / z$.

Following Hara and Belcher (2004), the vertical wind profile $u(z)$ is determined from the energy conservation in the wave boundary layer:

$$\tau_{tot} \frac{du}{dz} + \frac{d\Pi}{dz} - \rho_a \varepsilon(z) = 0 \qquad (2)$$

Here, the vertical energy flux Π due to wave induced motion is set equal to a sum of the energy flux into nonbreaking surface waves integrated up to the wavenumber $k < \delta / z$ and the energy flux into breaking waves integrated up to the wavenumber $k < \delta' / z$. The viscous dissipation rate $\rho_a \varepsilon(z)$ of the turbulent kinetic energy is parameterized in terms of the local turbulent stress $\tau_t(z)$ following the approach used in one-equation models of turbulence.

3. MOMENTUM FLUX OVER MATURE SEAS

We first neglect the effect of breaking waves and estimate the Charnock coefficient $z_0 g / u_*^2$ over mature seas, where z_0 is the equivalent surface roughness length, g is the gravitational acceleration, and u_* is the wind friction velocity. Since the wind forced part of the wave spectrum is described by the analytical model of Hara and Belcher (2002), it is possible to obtain a simple analytical form of the Charnock coefficient. In particular, the Charnock coefficient approaches a constant if the effect of surface tension and viscosity is small and majority of the stress is supported by waves, and if the spectrum is proportional to u_* not too far from the spectral peak (Hara and Belcher 2004).

4. MOMENTUM FLUX OVER GROWING SEAS

Over growing seas the spectrum near the peak is estimated using the WAVEWATCH III numerical model and the spectral tail is parameterized using the analytical model of Hara and Belcher (2002). In Figure 1 the results of the Charnock coefficient at different wind speeds are shown against the wave age c_p / u_*, where c_p is the phase speed at the spectral peak. At lower wind speeds (less than 30 m/s) the Charnock coefficient decreases as the wave field develops, being consistent with the parameterization by Donelan (1990), which is based on recent field observations. However, at higher wind speeds the Charnock coefficient increases as the wave age increases. In particular, very young seas under strong winds yield much lower drag than fully developed seas. This trend is qualitatively consistent with the parameterization by Toba et al. (1990).

5. EFFECT OF BREAKING WAVES

We first estimate the breaking wave statistic Λ by assuming that the energy input from wind is balanced by the energy dissipation by breaking at each wavenumber and that the energy dissipation rate is

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related to the breaking wave statistic (Phillips, 1985). The results are then introduced to the wave boundary layer model to estimate the wind profile and the Charnock coefficient. Although the results depend on a few empirical parameters, whose values are not well constrained, our calculation suggests that the effect of breaking waves is weak over mature seas. This is mainly because as the form drag supported by breaking waves increases the spectrum of (nonbreaking) waves and its contribution to the form drag decrease.

We are currently investigating the breaking effect over growing and complex seas.

6. REFERENCES

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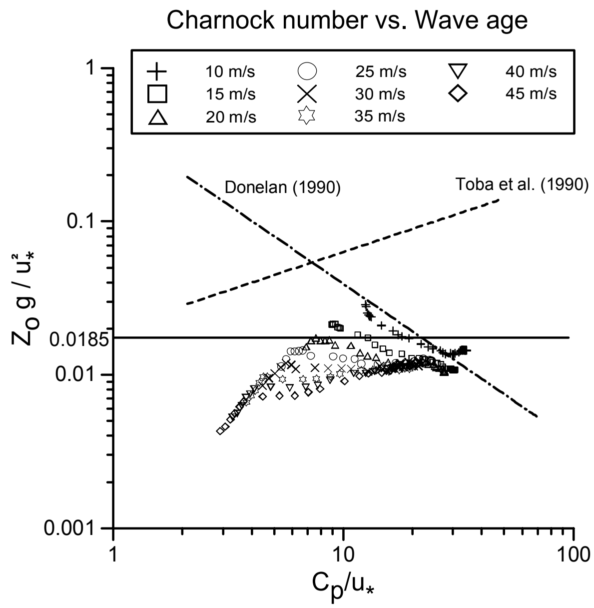

Figure 1. Charnock coefficient vs. wave age for different wind speeds. Different symbols indicate different wind speeds. Short dashed and long dashed lines are parameterizations by Toba et al. (1990) and Donelan (1990), respectively.