A Sea Surface Stress Parameterization Dependent on Directional Sea State

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1. INTRODUCTION

A physically based model is developed for the dependency of surface turbulent stress on directional wave characteristics. The physical impacts of sea state are parameterized through the influences of the surface's orbital motion induced by waves. Such a model has been successfully applied to capillary-wave related surface stress (*Bourassa et al.*, 1999); however, such wave dominate stress for ten meter wind speeds (U_{10}) < ~5 ms^{-1}. The mechanism was not applied to gravity wave related surface stresses, which dominate greater wind. A minor improvement (10% reduction in RMS differences) over *Bourassa* (2004) is made through a more detailed consideration of the lower boundary condition in the modified log-wind profile. Another advantage of this physically-based mechanism is that it considers directional sea state (i.e., the wind direction relative to the direction of wave propagation).

2. DATA

A preliminary version of observations from the Storm Wave Study experiment (SWS-2; *Dobson et al.*, 1999; *Taylor et al.*, 1999) was kindly provided by Peter K. Taylor. These observations were gathered in the North Atlantic Ocean, with the goal of gathering a high quality data set for severe wind conditions. The constraints applied for quality assurance are discussed in *Bourassa* (2004).

3. FLUX MODEL

The downward momentum flux ($\boldsymbol{\tau}$) can be modeled in terms of the friction velocity ($\mathbf{u}_*$):

$$\boldsymbol{\tau} = \rho\, \mathbf{u}_* \,|\, \mathbf{u}_* \,|, \tag{1}$$

where ρ is the density of the air. The influence of surface waves on stress is usually determined by the relation between $\mathbf{u}_*$ and roughness length (z_o). The modified log–wind relation is

$$\mathbf{U}(z) - \mathbf{U}_s = \frac{\mathbf{u}_*}{\kappa}\left[\ln\left(\frac{z-d}{z_o}+1\right) + \varphi(z, z_o, L)\right], \tag{2}$$

where $\mathbf{U}$ is the wind vector at height z above the local mean surface, k is von Kârmân's constant, d is the displacement height (the height at which the log wind profile extrapolates to zero wind speed), and L is the Monin-Obukhov stability length. The influence of atmospheric stratification in the boundary-layer is modeled through the Monin-Obukhov stability length. The parameterization of L is identical to that used in the BVW (Bourassa-Vincent-Wood) flux model (*Bourassa et al.*, 1999).

3.1 Momentum Roughness Length

The form of the momentum roughness length parameterization (3) used herein (*Bourassa* 2004) is a modification of BVW (*Bourassa et al.* 1999). This roughness length (*Bourassa* 2004) can be written with no explicit dependence on sea state, where the gravity wave roughness length is a two-dimensional version of Charnock's equation (*Charnock*, 1955). The influence of sea state on stress enters solely through the modification of vertical shear in wind speed (4), due to a non-zero lower boundary condition: the wave-induced surface motion. The roughness length is anisotropic, with unit vectors parallel ($\hat{e}_1$) and perpendicular ($\hat{e}_2$) to the mean direction of wave motion. It considers contributions to surface roughness from three types of surface features

$$z_{o_i} = \beta'_v \frac{0.11\nu}{\left|u_{*_i}\right|} + \left[\left(\beta'_c \frac{b\ \sigma}{\rho_w \left|\mathbf{u}_*\right|\left|\mathbf{u}_* \bullet \hat{\mathbf{e}}_i\right|}\right)^2 + \left(\beta'_g \ \frac{a\left|\mathbf{u}_*\right|\left|\mathbf{u}_* \bullet \hat{\mathbf{e}}_i\right|}{g}\right)^2\right]^{0.5} \tag{3}$$

where the β terms are binary weights for the roughness lengths associated with (from left to right, an aerodynamically smooth surface, capillary waves, and gravity waves), where ν is the molecular viscosity of air, b is a dimensionless constant (determined from laboratory observations; *Bourassa et al.* 1999), σ is surface tension, ρ_w is water density, c_p is the phase speed of the dominant waves, and g is gravitational acceleration. The orbital velocity (U_{orb}) changes the velocity frame of reference to that of a fraction f of the orbital velocity of the dominant waves. Laboratory studies (*Okuda et al.*, 1997) have shown that most of the interactions between wind and waves occur near the crest of the dominant waves).

$$\left[\mathbf{U}(z) - f\,\mathbf{U}_{orb} - \mathbf{U}_{current}\right]\bullet\hat{\mathbf{e}}_i = \frac{\mathbf{u}_*\bullet\hat{\mathbf{e}}_i}{\kappa}\left[\ln\left(\frac{z-d}{z_{o_i}}+1\right)+\varphi\left(z, z_{o_i}, L\right)\right] \quad (4)$$

The orbital speed of gravity waves is approximated by

$$U_{orb} = \pi H_s / T_p \quad (5)$$

where H_s is the significant wave height, and T_p is the period of the significant waves. The fraction of the orbital velocity (f) that modifies the surface condition was set at 80% (*Bourassa* 2004). Herein, a non-zero displacement height is considered. The displacement height, 60% of the significant wave height, is determined by assuming circular orbital motion and a height corresponding to a horizontal velocity of 80% of the orbital velocity. Consideration of displacement height reduced the rms difference by almost 10%. Charnock's constant is highly dependent on the velocity frame of reference ($f\mathbf{U}_{\text{orb}}$ – $\mathbf{U}_{\text{current}}$) and displacement height (d): a small change in $|\mathbf{u}_*|$ corresponds to a large percentage change in z_o. This approach reduced the root-mean-square (rms) differences between modeled at observed friction velocity from 0.078 to 0.041 ms^{-1}. Without displacement height, it was found that a = 0.064 resulted in an excellent fit to the SWS2 data. Herein, considering d, results in a = 0.035, and improves the fit for the highest wind speeds (fig. 1).

The lack of wave directional information in the preliminary release of the SWS2 data, and hence the lack of consideration in this study, presumably accounts for a substantial fraction of the unaccounted for variability in the SWS2 data.

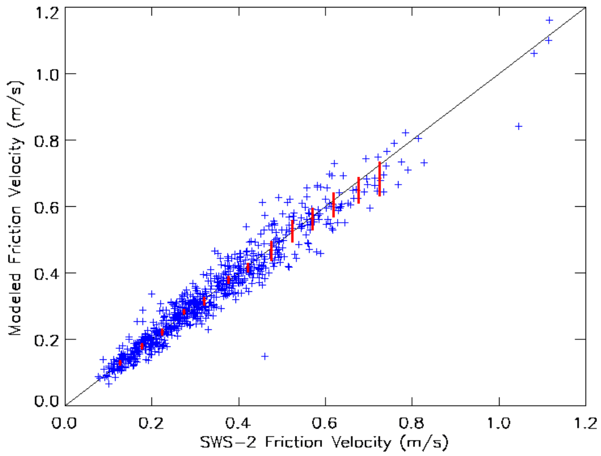

Fig. 1. Comparison of modeled and observed friction velocity magnitudes. The observations are from the SWS2 experiment. The red bars are centered on the mean, and extend for ±3 standard deviations in the mean.

4. COMPARISONS TO OBSERVATIONS

The model is evaluated with SWS-2 observations, as this data set is deemed the best for calibration purposes. In particular, all the required meteorological data, flux data, and wave data were recorded (however, wave directional information is not available at this time), and the surface water is well mixed, allowing the differences between bulk and skin temperature to safely be ignored.

The comparison (fig. 1) to the SWS2 friction velocity observations is good, particularly in the mean. The rms difference between modeled and observed values is 0.041 ms^{-1} when the orbital velocity and displacement height are considered, and increases to 0.078 ms^{-1} when these considerations are ignored (and a is tuned accordingly). The median value of the absolute value of the relative error is 11% when orbital velocity and displacement height are considered.

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