A NOTE ON A PARAMETERIZATION OF THE SEA DRAG

Research Note

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Abstract. A new parameterization of the sea drag is based on a wind-over-waves coupling theory. The parameterization accounts for the wind speed, wave age and finite depth dependencies of the sea drag. The latter two are introduced through the integral parameters of the wind-wave field: the dominant wave height and the wavenumber at the spectral peak, and the water depth. The parameterization is checked against the wind-over-waves model results and two field datasets obtained in a wide range of the wind speed and wave age. The comparison is encouraging. The parameterization is aimed for use in operational ocean-state and atmosphere models.

Keywords: Air–sea interaction, Parameterization, Sea drag, Wind-over-waves coupling, Wind waves.

1. Introduction

Wind-over-waves coupling (WOWC) is a modern theory of microscale air-sea interaction, which allows to relate the sea drag (surface stress) directly to the properties of wind waves and peculiarities of their interaction with the wind. A modern WOWC theory was recently developed by Makin et al. (1995), Makin and Kudryavtsev (1999, 2002), Kudryavtsev et al. (1999), and Kudryavtsev and Makin (2001). The recent WOWC model is based on the conservation equation for integral momentum, which relates the friction velocity to the sea surface stress. The surface stress is supported by viscous stress and the form drag, the latter being the correlation of the wave-induced pressure field with the wave slope. The form drag is supported by the wave-induced stress described in terms of the non-separated sheltering mechanism, and by stress due to separation of the air flow from breaking wind waves. The theory provides a clear understanding of the physical mechanisms forming the surface stress, and an explanation on what causes the stress dependence on the wind speed, wave age, finite bottom depth, and other ocean and atmosphere parameters.

The relation (Charnock, 1955) for the roughness parameter z_0

$$z_0 = z_* \frac{u_*^2}{g} \tag{1}$$

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is used traditionally here in the analysis. The roughness parameter is defined through the logarithmic wind profile extending to the surface from a height where the mean wind speed u is not influenced by the wave motions

$$u(z) = \frac{u_*}{\kappa} \ln \frac{z}{z_0}. \tag{2}$$

The height $z = 10$ m is sufficient to fulfil this condition. In (1) and (2) u_* is the friction velocity, g is acceleration of gravity, κ is the von Karman constant, and z_* is the dimensionless Charnock parameter. The Charnock parameter was originally introduced as a constant and is referred to as the Charnock constant. In that form the Charnock relation was, and is widely, used in all kinds of oceanographic and meteorological applications. However, in general, the Charnock parameter is not a constant but could depend, for example, on the wind speed as was shown by measurements (e.g., Yelland and Taylor, 1996).

The surface stress or the sea drag defined as

$$\frac{\tau}{\rho_a} = u_*^2, \tag{3}$$

where ρ_a is density of air, follows directly as a result of the WOWC model. By using (1) and (2) these results could be presented in terms of the Charnock parameter. In particular, we have shown (Makin et al., 1995; Kudryavtsev and Makin, 2001) that the wave-induced stress supported mainly by short waves provides the Charnock relation with the Charnock parameter being a constant. When the separation of the air flow from short gravity waves is accounted for in the WOWC model it provides the Charnock relation with the Charnock parameter dependent on the wind speed (Kudryavtsev and Makin, 2001). The parameter increases with an increase in the wind speed. The separation of the air flow from dominant waves (waves at the spectral peak of the wave spectra) explains then the wave age and finite bottom dependence of the Charnock parameter and thus the sea drag (Makin and Kudryavtsev, 2002). It was shown that the stress supported by the air flow separation from dominant waves is proportional to the breaking probability of dominant waves and a reference wind speed specified at the level just above the breaking dominant wave. The breaking probability of dominant waves in turn is defined by the dominant wave steepness (see Banner et al., 2000). With the dominant wave steepness increasing, the breaking probability of dominant waves is increased, and so is the 'separation' stress. This mechanism explains why steep young waves exert more stress than waves in a fully developed sea. The same mechanism explains the finite bottom dependence of the sea drag: long waves propagating into shallow waters begin to feel the bottom and become shorter and steeper enhancing the air flow separation and thus the sea drag. The dependence of the separation stress on the reference wind speed, which is a difference of the mean wind speed taken just above the breaking wave and its phase velocity, provides a quenching mechanism for fast long waves and very short slow moving waves. The fast waves propagating at the phase speed close to the mean wind speed could not induce the air flow separation because the reference wind speed is too small to trigger the separation. This explains why long fast waves propagating into the shallow water at the phase speed exceeding the wind speed have no impact on the surface stress. For the short waves the reference velocity drops because their reference level is too low. That explains the drop in the surface stress for very young waves typical for the laboratory conditions (see Figure 2 in Donelan et al., 1993). The WOWC model was verified on several experimental data sets (Makin and Kudryavtsev, 2002).

This understanding provides a ground for building a parameterization of the sea drag. The parameterization is aimed for use in operational ocean state and atmosphere models, for example, in wave prediction models. In that respect the parameterization should meet a number of requirements. The wave models provide accurate information on dominant waves only. The high frequency tail is crudely parameterized and it cannot be used to calculate the stress supported by short wind waves. The use of the physical short wave model (Kudryavtsev et al., 1999) to calculate this stress is not feasible in the operational environment. This suggests the following strategy: The parameterization should include only integral parameters of the wind field that can be easily obtained from the wave models or measurement. It should provide a simple and time effective numerical implementation. The WOWC model (already verified on field data) will be viewed here as a generator of model data against which the parameterization can be tested. Keeping in mind that the overall typical error in stress measurements is about 20% (e.g., Donelan, 1990) the parameterization will be considered good if it provides stress that deviates from the WOWC model results by not more than 20%. It is then tested on several field data sets.

Finally, it is important to note that the proposed parameterization is applicable to pure sea situations under stationary and spatially homogeneous wind conditions. Thus, no potential aerodynamic impact of swell on the sea drag is currently accounted for. There is experimental evidence (though limited) by Donelan et al. (1997) and Drennan et al. (1999) that the presence of counter- or cross-swells under light winds can result in drag coefficients that are much larger than the value for a pure wind sea. This could be of importance for applications to the open ocean, where swell is always present. A proper parameterization of the potential impact of swell on the sea drag requires understanding of physical mechanisms that could provide this impact and further extended experimental study in the open ocean.

2. The Parameterization

The resistance law of the sea surface can be written in a general form as (Makin and Kudryavtsev, 2002)

$$u_*^2 = \tau^\nu + \tau^w + \tau_{eq}^s + \tau_d^s, \tag{4}$$

where τ^ν is the viscous stress at the sea surface, τ^w is the wave-induced stress at the surface, τ_{eq}^s is the surface stress supported by the air flow separation (AFS) from short waves, and τ_d^s is the surface stress supported by the AFS from dominant waves. All stresses are normalized by the density of air.

Viscous stress provides the increase of the Charnock parameter at low wind speeds, and the wave-induced stress provides the 'constant' Charnock type dependence of the sea drag. Their sum can be parameterized by a generalized relation for the roughness scale

$$z_0^t = 0.1\frac{\nu}{u_*} + c\frac{u_*^2}{g}, \tag{5}$$

where ν is kinematic molecular viscosity and c is a constant.

An increase of the Charnock parameter with increasing wind speed, a fact confirmed by measurements, e.g., by Yelland and Taylor (1996), is explained by the WOWC model as a result of the separation stress due to short waves. It is parameterized simply by a statistical fit to model results. Here a function (which carries no physical basis)

$$f_{u_{10}} = 0.02\max[0, \tanh(0.075u_{10} - 0.75)] \tag{6}$$

is chosen (u_{10} is the wind speed at 10-m height) and the relation (5) is rewritten in the form

$$z_0^t = 0.1\frac{\nu}{u_*} + (c + f_{u_{10}})\frac{u_*^2}{g}. \tag{7}$$

The comparison of the stress, which follows from (7) (c is taken as 0.0075), with the WOWC model is shown in Figure 1 for a fully developed sea characterized by the inverse wave-age parameter $u_{10}/c_p = 0.83$, where c_p is the phase speed at the spectral peak.

For a fully developed sea the separation stress from dominant waves does not contribute to the sea drag because they propagate faster than the wind, as explained in the Introduction. In Makin and Kudryavtsev (2002) it was shown that when the stress τ_d^s is not accounted for by the WOWC model the sea drag appears to have only a marginal dependence on wave age, i.e., relation (7) reproduces the model

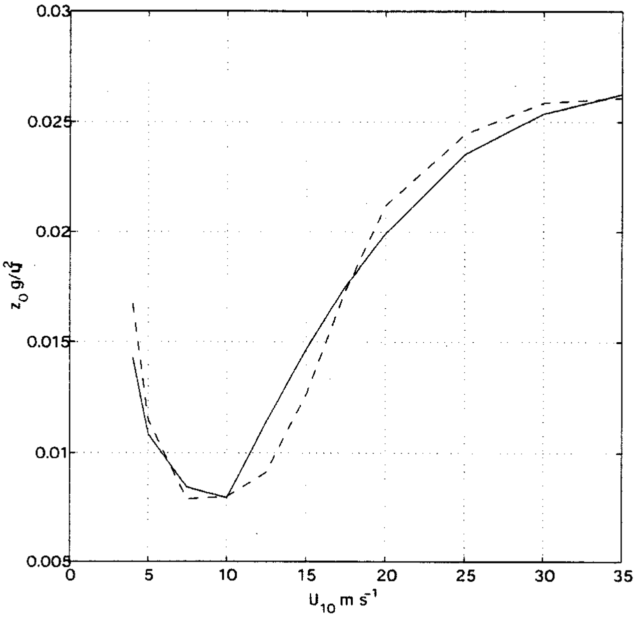

Figure 1. Charnock parameter versus the wind speed. Solid line, the parameterization; dashed line, the WOWC model. The inverse wave-age parameter $u_{10}/c_p = 0.83$.

stress for all wave ages (with τ_d^s switched off). The stress, which corresponds to relation (7), can be calculated through (2) as

$$\tau^t = \frac{\kappa^2}{\ln^2(10/z_0^t)} u_{10}^2. \tag{8}$$

This relation parameterizes the contribution of the viscous stress, wave-induced stress and separation stress supported by short waves to the surface stress. The remaining surface stress component in (4), the separation stress due to AFS from dominant waves τ_d^s, is parameterized via integral wind-wave field parameters and the reference wind speed as suggested by Makin and Kudryavtsev (2002)

$$\tau_d^s = \frac{\varepsilon_b \gamma}{2\pi} u_r^2 \exp\left(-\frac{\varepsilon_T^2}{\varepsilon_d^2}\right), \tag{9}$$

where $\varepsilon_b = 0.5$ is the characteristic slope of the breaking wave, $\gamma = 0.8$ is an empirical constant, $\varepsilon_d = H_s k_p/2$ is the dominant wave steepness, H_s is the dominant significant wave height obtained as an integral around the spectral peak of the wind-wave spectrum, k_p is the peak wavenumber of the wind-wave spectrum, and $\varepsilon_T = 0.24$ is a threshold level constant. Both parameters H_s and k_p could be obtained from a wave model or measurements. (In the mixed wind-wave – swell seas characterized by a doubled spectral peak only the wind-wave part of

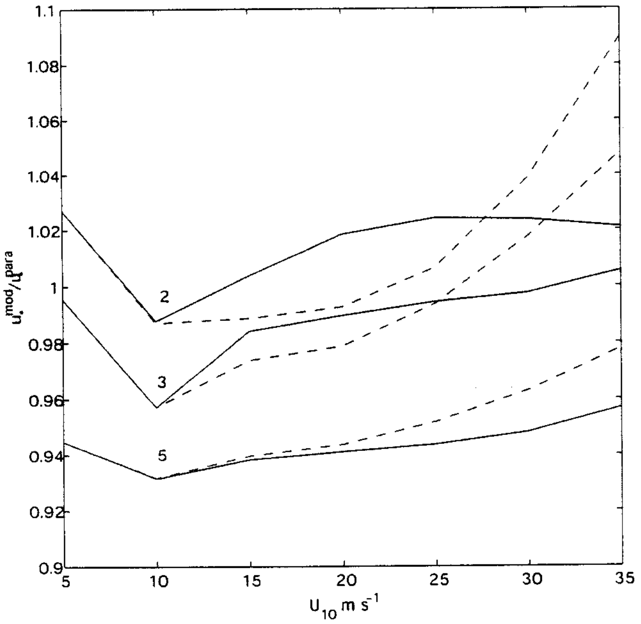

Figure 2. Ratio of the friction velocity resulting from the WOWC model and the parameterization versus the wind speed. Solid lines, deep water; dashed lines, the depth is 10 m. Digits above the lines indicate the inverse wave-age parameter u_{10}/c_p.

the spectra should be taken to obtain H_s and k_p.) It is a common practice that the peak frequency ω_p rather than the peak wavenumber is known/measured. These are related via the dispersion relation

$$\omega_p^2 = gk_p \tanh(k_p d), \tag{10}$$

where d is the water depth, and $c_p = \omega_p/k_p$. The reference wind speed for dominant waves u_r

$$u_r = u(\frac{\varepsilon_b}{k_p}) - c_p \tag{11}$$

is specified at the level just above breaking dominant waves, i.e., at $z = \varepsilon_b/k_p$. Given the wind speed u_{10}, the significant wave height H_s, the peak frequency ω_p and the depth d,

$$u_*^2 = \tau^t + \tau_d^s \tag{12}$$

is solved by iteration to obtain the friction velocity.

The resulting friction velocity is checked against the solution of the WOWC model. In Figure 2 the ratio between the modelled friction velocity u_*^{mod} and the friction velocity resulting from the parameterization u_*^{para} is shown for the inverse

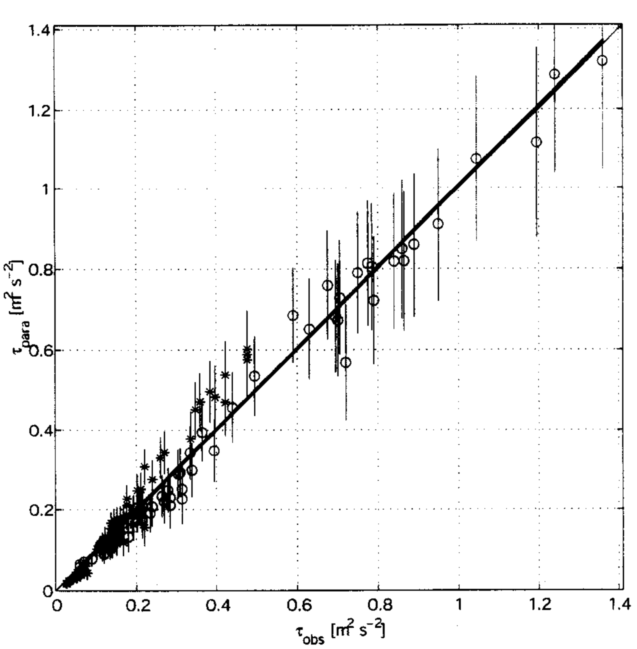

Figure 3. Calculated stress τ_{para}, Equation (12), against HEXMAX (open circles) and RASEX (stars) measured stress τ_{obs} in m^{2}s^{-2}. Bars correspond to the overall error of 20% in measured stress. Thick solid line indicates the regression line.

wave-age parameter $u_{10}/c_p = 2$, 3 and 5, for a deep ocean and depth of 10 m. The difference does not exceed 10% in terms of the friction velocity, which is less than 20% in terms of the stress. Three iterations were required to obtain the result.

The parameterization is then tested against two field datasets: The HEXMAX, the HEXOS Main Experiment (where HEXOS refers to Humidity Exchange Over the Sea), as reported by Janssen (1997), and RASEX (Risø Air–Sea EXchange) as reported by Johnson et al. (1998) (for details see original papers). Here it is mentioned only that the first dataset is characterized by the wind speed in the range of $6 < u_{10} < 20$ m s^{-1}and the inverse wave-age parameter in the range of $0.8 < u_{10}/c_p < 2$, while for the second dataset the ranges are: $4 < u_{10} < 17$ m s^{-1} and $1 < u_{10}/c_p < 3.5$. Both datasets correspond to intermediate water depth characterized by $0.8 < \tanh(k_p d) < 1$. Parameters that enter the parameterization, the wind speed u_{10}, the significant wave height H_s, the water depth d and the peak wavenumber k_p, were taken from the Tables found in the above references (the wavenumber was calculated from the peak phase speed c_p listed in the first dataset and from the peak period $T_p = 2\pi/\omega_p$ listed in the second). The scatter plot between measured stress and stress obtained by the parameterization is shown in Figure 3, the error bars correspond to 20% error in measured stress (Donelan, 1990; Janssen, 1997; Johnson et al., 1998). The comparison is encouraging. The slope of the regression line is 1.008, while the intercept is 0.002, and most of the calculated stress is within the scatter in measurements.

It is concluded that the suggested parameterization of the sea drag (surface stress) is accurate enough and can be used in ocean-state and atmospheric models.

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References

Banner, M. L., Babanin, A. V., and Young, I. R.: 2000, 'Breaking Probability for Dominant Waves on the Sea Surface', *J. Phys. Oceanog.* **30**, 3145–3160.

Charnock, H.: 1955, 'Wind Stress on a Water Surface', *Quart. J. Roy. Meteorol. Soc.* **81**, 639–640.

Donelan, M. A.: 1990, 'Air–Sea Interaction', *The Sea: Ocean Engineering Science* **9**, 239–292.

Donelan, M. A., Dobson, F. W., Smith, S. D., and Anderson, R. J.: 1993, 'On the Dependence of Sea Surface Roughness on Wave Development', *J. Phys. Oceanog.* **23**, 2143–2149.

Donelan, M. A., Drennan, W. M., and Katsaros, K. B.: 1997, 'The Air-Sea Momentum Flux in Conditions of Wind Sea and Swell', *J. Phys. Oceanog.* **27**, 2087–2099.

Drennan, W. M., Graber, H. C., and Donelan, M. A.: 1999, 'Evidence for the Effects of Swell and Unsteady Winds on Marine Wind Stress', *J. Phys. Oceanog.* **29**, 1853–1864.

Janssen, J. A. M.: 1997, 'Does Wind Stress Depend on Sea–State or Not? – A Statistical Error Analysis of HEXMAX Data', *Boundary-Layer Meteorol.* **83**, 479–503.

Johnson, H. K., Højstrup, J., Vested, H. J., and Larsen, S. E.: 1998, 'On the Dependence of Sea Surface Roughness on Wind Waves', *J. Phys. Oceanog.* **28**, 1702–1716.

Kudryavtsev, V. N. and Makin, V. K.: 2001, 'The Impact of Air-Flow Separation on the Drag of the Sea Surface', *Boundary-Layer Meteorol.* **98**, 155–171.

Kudryavtsev, V. N., Makin, V. K., and Chapron, B.: 1999, 'Coupled Sea Surface-Atmosphere Model 2. Spectrum of Short Wind Waves', *J. Geophys. Res.* **104**, 7625–7639.

Makin, V. K. and Kudryavtsev, V. N.: 1999, 'Coupled Sea Surface-Atmosphere Model 1. Wind over Waves Coupling', *J. Geophys. Res.* **104**, 7613–7623.

Makin, V. K. and Kudryavtsev, V. N.: 2002, 'Impact of Dominant Waves on Sea Drag', *Boundary-Layer Meteorol.* **103**, 83–99.

Makin V. K., Kudryavtsev, V. N., and Mastenbroek, C: 1995, 'Drag of the Sea Surface', *Boundary-Layer Meteorol.* **79**, 159–182.

Yelland, M. and Taylor, P. K.: 1996, 'Wind Stress Measurements from the Open Ocean', *J. Phys. Oceanog.* **26**, 541–558.