Physics-Based Parameterizations of Air-Sea Fluxes at High Winds

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LONG-TERM GOALS

The long term goal of this project is to provide a new set of parameterizations of air-sea fluxes, which can be used as boundary conditions for high-resolution numerical models of ocean, atmosphere, and coupled ocean/atmosphere systems. The new parameterizations will be constructed based on physical processes of the exchange of mass, momentum, heat, moisture, energy at the interface between the ocean and the atmosphere, and will be valid for the whole range of wind speeds.

OBJECTIVES

It is clear intuitively that at high wind speeds breaking waves become increasingly important to air-sea interaction. But the role of these breaking waves on air-sea fluxes is at present almost completely unknown. In this project we develop recent understanding of surface wave processes, and in particular breaking waves and their statistics, to develop a framework for accounting for wave breaking in air-sea fluxes in high winds. The specific objectives are:

- To develop a theoretical model for the statistics of breaking wave coverage, based on the dynamics of the surface waves.

- To use these statistics to formulate a methodology for accounting for the exchange of momentum and kinetic energy between the atmosphere and ocean that results from the breaking waves.

- To integrate this methodology into the framework developed by Makin and co-workers (Makin et al. 1995, Makin and Kudryavtsev 1999) for air-sea exchange for non-breaking waves.

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14. ABSTRACT

The long term goal of this project is to provide a new set of parameterizations of air-sea fluxes, which can be used as boundary conditions for high-resolution numerical models of ocean, atmosphere, and coupled ocean/atmosphere systems. The new parameterizations will be constructed based on physical processes of the exchange of mass, momentum, heat, moisture, energy at the interface between the ocean and the atmosphere, and will be valid for the whole range of wind speeds.

15. SUBJECT TERMS

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- To then develop a model for transfer of scalars, such as heat and moisture, that accounts for both breaking and non-breaking waves.

- To validate, where possible, the components of these models against observational data.

- To clarify limitations of bulk parameterizations and identify improvements.

APPROACH

The approach is

- To validate our recent model results of the equilibrium range of surface wave spectra and breaking wave statistics (Hara and Belcher 2002).

- To develop a model of momentum flux (wave-induced stress and turbulent stress), mean wind profile, and TKE budget in the atmospheric surface under different sea states including hurricane conditions.

- To model effects of breaking waves on transfer of momentum and scalars, such as heat and moisture, in the wave boundary layer.

- To model the effects of waves on the Ekman layer in the ocean, with a view to modeling the vertical profiles of the mean current, TKE, and TKE flux across the wave boundary layer.

- To develop new flux parameterizations in the atmosphere. An important question to be addressed here is how the presence of breaking waves affects the air-sea fluxes in realistic oceanic conditions.

- To compare the new model results with observations conducted under CBLAST.

WORK COMPLETED

We have developed a new model of momentum flux, mean wind profile, and TKE budget in the atmospheric wave boundary layer. The model is based on the conservation of energy and momentum within the wave boundary layer. At the top of the wave boundary layer there is a downward energy flux, which is balanced by the dissipation of the turbulent kinetic energy due to viscosity, and the flux of energy into surface waves. The former determined by the local, reduced turbulent stress at each height. The latter is obtained by integrating the flux into each surface wave spectral component, making use of the equilibrium spectral form obtained by Hara and Belcher (2002). This approach yields an analytical expression for the wind profile, the equivalent surface roughness, and Charnock's constant over mature seas. A manuscript based on the results has been published in Journal of Physical Oceanography (Hara and Belcher, 2004). We have also estimated the drag coefficient and the Charnock coefficient over developing and complex seas by combining ocean wave models and a wave boundary layer model. The combined model estimates the wind stress by explicitly calculating the wave-induced stress. In the frequency range near the spectral peak, WAVEWATCH-III is used to estimate the spectra, and the spectra in the equilibrium range are determined by the analytical model by Hara and Belcher (2002). This approach allows us to estimate the drag coefficient and the equivalent surface roughness for any surface wave fields. Numerical experiments have been performed for constant winds from 5 m/s to 45 m/s to investigate the effect of mature and growing seas on air-sea momentum exchange. For mature seas, the Charnock coefficient is estimated to be about 0.01 ~ 0.02 and the drag coefficient increases as wind speed increases, which are within the range of previous observational data. With growing seas, our results for winds less than 30 m/s show that the drag coefficient is larger with younger seas, being consistent with earlier studies. For winds higher than 30 m/s, however, our results show a different trend, that is, very younger waves yield less drag (Figure 1). This is because the wave-induced stress due to very young waves makes a small contribution to the total wind stress in very high wind conditions.

Next, we have applied the same approach to investigate the Charnock coefficient and the neutral drag coefficient under hurricane wind forcing. The most important finding of these studies is that the drag coefficient levels off or even decreases as the wind speed increases beyond 35-40 m/s, mainly because surface wave fields under such high winds tend to be very young (Figure 2). Our prediction is consistent with the recent field observations by Powell et al. (2003). Two manuscripts based on the results have been published in Journal of Atmospheric Sciences (Moon et al., 2004a,b).

We have developed a new air-sea momentum flux parameterization, which is simple but consistent with the recent results at high wind speeds. The new formula is fitted based on the coupled wave-wind model simulations under ten tropical cyclones in the western Atlantic Ocean during 1998-2003. The new parameterization describes that the roughness length increases linearly with wind speed at high wind speeds; the neutral drag coefficient tends to level off at high wind speeds. The proposed parameterization is then tested for real hurricane predictions using the operational GFDL hurricane prediction model. The impact of the new formula on the hurricane prediction is mainly found in increased maximum wind speeds, which leaded to improved maximum wind forecast for strong hurricanes. A manuscript based on these results is currently in preparation (Moon et al. 2005).

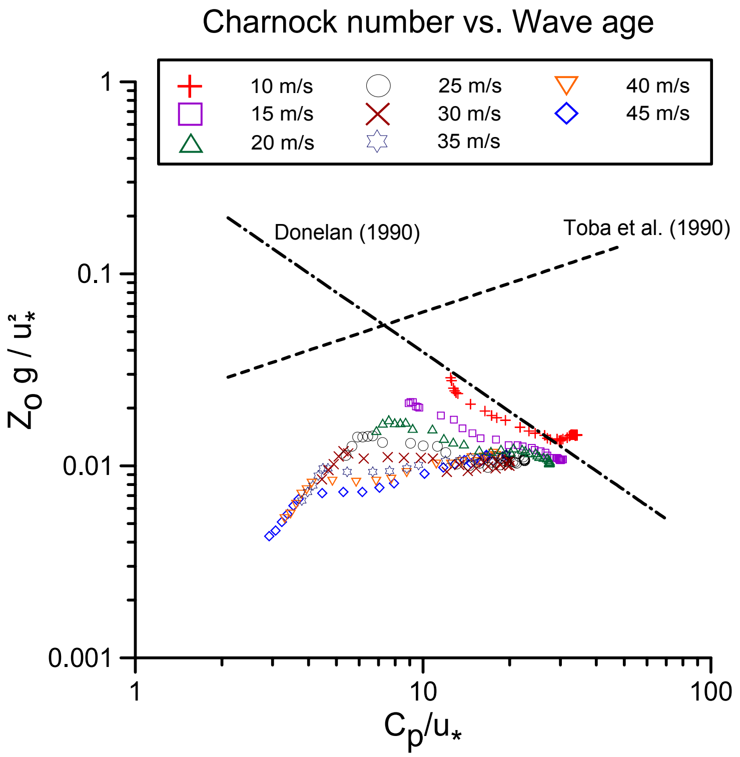

Figure 1: Nondimensional roughness length (Charnock coefficient) versus wave age, which are estimated from the present model for constant winds from 10 m/s to 45 m/s. Dashed line and dash dot line are empirical estimates by Toba et al. (1990) and Donelan (1990), respectively.

An important assumption of the model described above is that wind forcing on shorter waves is reduced in the presence of longer waves (*sheltering effect in spectral domain*). This is because the wind forcing on a particular wave scale is determined by the turbulent wind stress at the height of the inner layer (Belcher and Hunt, 1993), which is reduced from the total wind stress if longer waves support part of the stress as form drag. We examined the validity of this assumption by using laboratory observations. From the measured total wind stress, surface viscous stress and surface wave spectrum, reported by Banner and Peirson (1998), we estimated the wave growth rate coefficient, defined by Plant (1982), with and without the sheltering effect in spectral domain. The results showed that the sheltering effect in spectral domain is real and important, since the growth rate coefficient is significantly underestimated if the effect is neglected. A manuscript based on this finding has been accepted for publication in Journal of Geophysical Research (Kukulka and Hara, 2005).

We have extended the wave boundary layer model to include the effect of breaking waves. Breaking waves support part of the momentum flux as form drag. They also cause air-flow separation behind the breaking crests and shelter shorter waves from direct wind forcing (*spatial sheltering effect*). As a first step we have developed a simple analytical model of the breaking statistics and the wave boundary layer when the entire momentum flux is supported by breaking waves. A manuscript based on the results is currently in preparation.

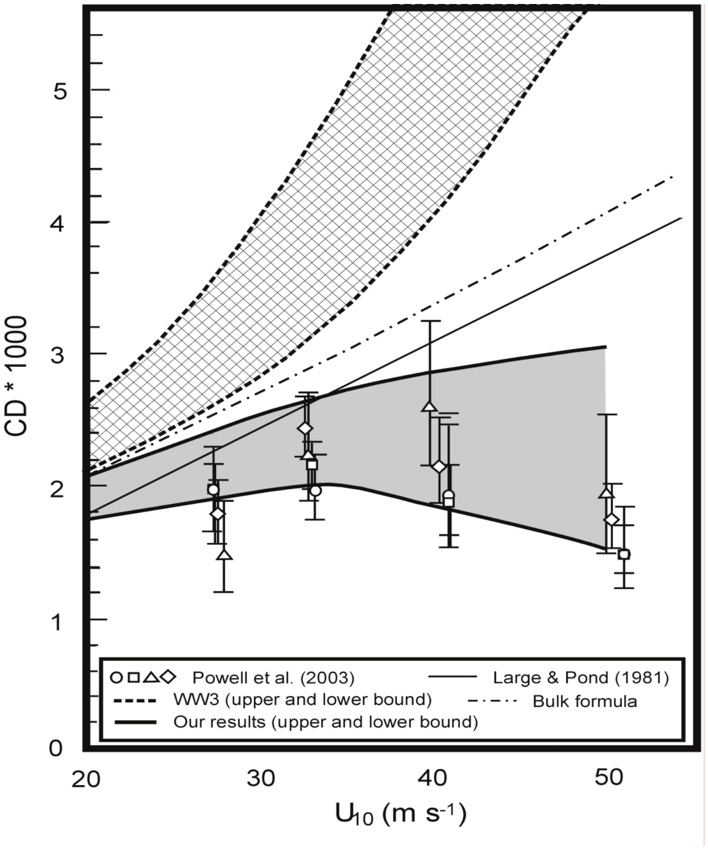

Figure 2: Drag coefficient C_d versus wind speed. Symbols represent C_d estimated by Powell et al. (2003). Vertical bars represent 95% confidence level. Solid line is an extrapolation of Large and Pond (1981). Dashed-dotted line is the bulk formula based on the Charnock coefficient of 0.0185. Shaded and stippled areas represent ranges between upper and lower bound of C_d obtained by our approach and the Wavewatch-III for all experiment cases, respectively.

We have developed a new wavelet analysis methodology to estimate the statistics of steep surface waves. The method has been applied to open ocean wave height data. Results show that high wave slope crests bappear over a wide range of wavenumbers, with a large amount being much shorter than the dominant waves. Unlike the breaking wave statistic, the steep wave statistic does not scale with the cube of the wind speed but is correlated with the wave saturation spectrum at moderate wave slope thresholds. The crest directionality statistic shows that most of steep wave crests are normal to the direction of the mean wind. Two papers based on these results have been published in Journal of Atmospheric and Oceanic Technology (Scott et al., 2005a,b).

We have also made progress in modeling the effects of surface waves on near-surface Ekman layer currents in the water. The Stokes drift associated with the surface waves deforms vorticity in the Ekman layer. This vorticity has two sources: planetary vorticity, and turbulent vorticity. We have developed models for both processes.

Firstly, the deformation of the planetary vorticity by the wave-induced Stokes drift leads to a new force, the Coriolis-Stokes force, that acts in the upper layers of the wind-driven mixed layer. The Coriolis-Stokes force changes the whole mean flow within the Ekman layer. We have developed a quantitative analytical model and performed large eddy simulations of this process. Figure 4 shows a hodograph of the Ekman current calculated with the model both including the effects of Stokes drift on the planetary vorticity, and calculated ignoring this process. Also shown are measurements from the Lotus data (Price & Sundermeyer 1999). Clearly the inclusion of the Stokes drift effect on the planetary vorticity yields very significantly better agreement with the measurements than is obtained when this process is neglected. Comparisons of the model with two other sets of measurements show similar agreement (see Lewis & Belcher 2004). These findings suggest that large-scale ocean models should represent the Coriolis-Stokes force. We have shown how this can be done by modifying the boundary condition at the air-sea interface. This work has led now to two journal articles that are now appeared, namely Lewis & Belcher (*Dynam. Atmos. Ocean*s, 2004, vol 37 313-351) and Polton, Lewis & Belcher (J. Phys. Oceanogr., vol 35 444-457).

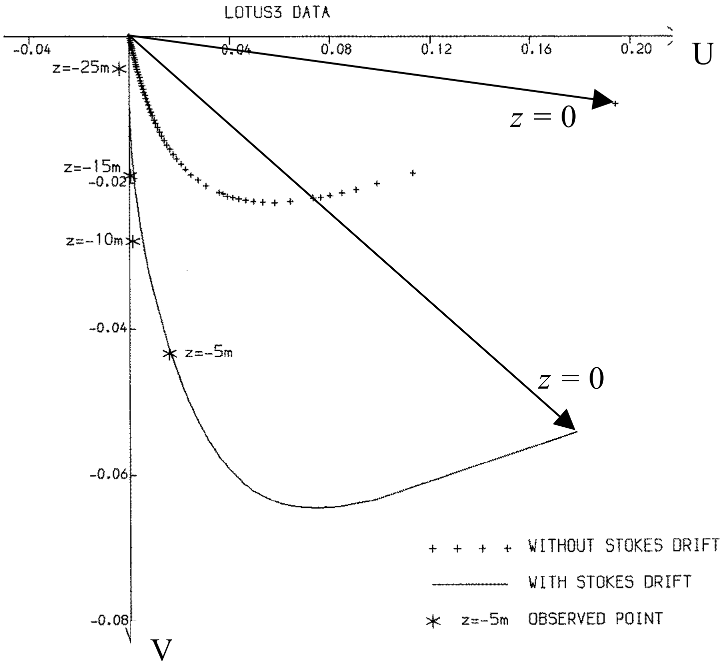

Figure 3. Hodograph of the current profile in the Ekman layer. Solid curve: theoretical solution obtained including the deformation of planetary vorticity by Stokes drift; pluses: conventional theoretical solution obtained by ignoring the effects of Stokes drift; stars: measurements from LOTUS3.

Secondly, we have developed a model for the effects of Stokes drift on the turbulent vorticity in the Ekman layer. This process leads to the development of Langmuir circulations on a whole range of length scales. We have developed a linear analytical model for the deformation of the turbulent vorticity by the Stokes drift. The results of this model compare well with the turbulent statistics computed for Langmuir turbulence by McWilliams et al (1997). This work is being written up for publication (Teixeira & Belcher 2005). The significance of this result is that it shows how any vorticity in the Ekman layer can produce vortices aligned in the wind direction, yielding structures that resemble Langmuir circulations.

RESULTS

In the absence of breaking waves, the mean wind profile inside the wave boundary layer is uniquely determined from the conservation of energy and momentum. The drag coefficient and the equilvalent surface roughness are mainly determined by the (effective) wave age and the sheltering wave age. The former quantity determines the width (in wavenumber) of the equilibrium range, while the latter determines the level of the equilibrium wave spectrum. The drag coefficient also depends on the shape of the spectrum of gravity-capillary waves at lower wind speeds. With growing seas, the drag coefficient is larger with younger seas for winds less than 30 m/s. For winds higher than 30 m/s, however, very younger waves yield less drag. With complex seas under hurricane wind forcing, the drag coefficient levels off or even decreases as the wind speed increases beyond 35-40 m/s, mainly because surface wave fields under such high winds tend to be very young.

The wave boundary layer model can be extended to include the form drag due to breaking waves as well as the airflow separation effect (spatial sheltering) behind breaking wave crests. In particular, the mean wind profile, the breaking wave statistic, and the drag coefficient are all predicted analytically when the entire momentum flux is supported by breaking waves.

The deformation of the planetary vorticity by Stokes drift associated with surface waves is an important process that shapes the mean currents through the depth of the mixed layer. Including this process yields a model for currents in the Ekman layer that agree well with measurements. We recommend that large scale models of ocean circulation include this process. We have shown how this can be done efficiently by modifying the boundary condition at the air sea interface. Any vorticity in the Ekman layer is also deformed by the Stokes drift of the waves and is stretched to produce streamwise vortices that resemble Langmuir vortices.

IMPACT/APPLICATIONS

This program of work promises a one dimensional (1d) model of the atmospheric and oceanic boundary layers in the vicinity of the air--sea interface that accounts for both breaking and non-breaking waves. The model will, given the ten meter wind speed, temperature and humidity and surface wave parameters, produce wave breaking statistics, wind and current profiles, fluxes and flux profiles and the turbulent kinetic energy budgets through the 1d air and water wave boundary layers. These results may be used as a basis for any future modeling efforts of ocean-atmosphere interaction processes.

TRANSITIONS

The results from this project are used to develop a new set of physics-based parameterizations of air-sea fluxes, which are valid for the whole range of wind speeds and can be used as boundary conditions for high-resolution numerical models of ocean, atmosphere, and coupled ocean/atmosphere systems.

RELATED PROJECTS

TH has just completed a NSF project (2000-2005) to address the air-sea momentum flux at high sea. This NSF project has been a subset (atmospheric wave boundary layer only) of this ONR project and therefore these two projects have been fully integrated. TH's main contribution to this ONR project has been in Year 4 and 5 (2004-2005). TH is starting a new NSF project (2005-2008) to validate the new wave boundary layer model including breaking wave effects against laboratory observations performed at University of Miami.

New knowledge gained from our study has been incorporated in coupled atmosphere-wave-ocean numerical models under two NSF(ATM) projects (2000-2004 and 2004-2007) by TH, IG, and IM. Current numerical wave models are not capable of predicting accurately short wind waves at frequencies much higher than the spectral peak. Instead they patch a parameterized form of spectra. More accurate information about short wind wave spectra and their breaking statistics resulting from this study will improve the accuracy of the numerical wave prediction and will thus enhance the performance of coupled numerical models.

SEB has just completed a project funded by the Leverhulme Trust (a UK charity that funds fundamental scientific research) into the dynamics of Langmuir turbulence in the ocean mixed layer. The aim is to develop understanding of the dynamical processes that determine the lifecycle of streamwise vortices in the ocean mixed layer. The model will account for the turbulence injected into the water column from breaking waves. Hence this Langmuir turbulence project will benefit from the parameterization of the oceanic wave boundary layer developed in the work proposed here. SEB has funding from the UK Natural Environment Research Council to pursue this work.

REFERENCES

Banner, M. L. and W. L. Peirson, 1998. Tangential stress beneath wind-driven air-water interfaces. J. Fluid Mech., 364, 115-145.

Belcher, S. E. and J. C. R. Hunt, 1993. Turbulent shear flow over slowly moving waves. J. Fluid Mech., 251, 109–148.

Donelan, M. A., 1990. “Air-sea interaction” in *The Sea: Ocean Engineering Science* 9B, edited by B. le Mehaute and D. M. Hanes, pp. 239-292, Wiley-Interscience, New York.

Hara, T. and S. E. Belcher, 2002. Wind forcing in the equilibrium range of surface wave spectra. J. Fluid Mech., 470, 223-245.

Large, W. G., and S. Pond, 1981. Open ocean momentum flux measurements in moderate to strong wind. J. Phys. Oceanogr., 11, 324–336.

Lewis, D. M. and Belcher, S. E. 2004 Time dependent, coupled, Ekman Boundary layer solutions incorporating Stokes drift. Dynam. Atmos. Oceans, 37 313-351.

Makin V. K. and V. N. Kudryavtsev, 1999. Coupled sea surface-atmosphere model. 1. Wind over waves coupling. J. Geophys. Res., 104(C4), 7613-7623.

Makin V. K., V. N. Kudryavtsev and C. Mastenbroek, 1995. Drag of the sea surface. Boundary Layer Meteorol., 73, 159-182.

McWilliams, J. C., Sullivan, P. P. and Moeng, C. H. 1997. Langmuir turbulence in the ocean. J. Fluid Mech. 334, 1-30.

Moon, I.-J., I. Ginis, T. Hara, and B. Thomas, 2005. Physics-based parameterization of air-sea momentum flux at high wind speeds and its impact on hurricane predictions. Mon. Wea. Rev. In preparation.

Plant, W. J. 1982. A relationship between wind stress and wave slope. J. Geophys. Res., 87, 1961–1967.

Polton, J.A., Lewis, D.M & Belcher, S.E. 2003. Effects of surface waves on the wind-driven Ekman layer. J. Phys. Oceanogr., 35 444-457

Powell, M. D., P. J. Vickery, and T. A. Reinhold, 2003. Reduced drag coefficient for high wind speeds in tropical cyclones. Nature, 422, 279-283.

Teixeira, M. A. C. T. and Belcher, S. E. 2005. The large scale structure of Langmuir turbulence. In preparation.

Toba, Y., N. Iida, H. Kawamura, N. Ebuchi and I. S. F. Jones, 1990. The wave dependence of sea-surface wind stress. J. Phys. Oceanogr., 20, 705-721.

PUBLICATIONS

Hara, T. and S. E. Belcher, 2004. Wind profile and drag coefficient over mature ocean surface wave spectra. J. Phys. Oceanogr., 34(11), 2345-2358, [published, refereed].

Kukulka T. and T. Hara, 2005. Momentum flux budget analysis of wind-driven air-water interfaces, J. Geophys. Res., [in press, refereed].

Lewis, D. M. and Belcher, S. E. 2004. Time dependent, coupled, Ekman Boundary layer solutions incorporating Stokes drift. Dynam. Atmos. Oceans, 37, 313-351, [published, refereed].

Moon, I.J., T. Hara, I. Ginis, S. E. Belcher, and H. L. Tolman, 2004a. Effect of surface waves on air-sea momentum exchange: I. Effect of mature and growing seas. J. Atmos. Sci., 61(19), 2321-2333., [published, refereed].

Moon, I.J., I. Ginis, and T. Hara, 2004b. Effect of surface waves on air-sea momentum exchange: II. Behavior of drag coefficient under tropical cyclones. J. Atmos. Sci., 61(19), 2334-2348, [published, refereed].

Polton, J.A., Lewis, D.M & Belcher, S.E. 2004. Effects of surface waves on the wind-driven Ekman layer. J. Phys. Oceanogr., 35 444-457, [published, refereed].

Scott, N. V., T. Hara, E. J. Walsh, and P. Hwang, 2005. Observations of steep wave statistics in open ocean waters, J. Atmos. Oceanic Tech., 22(3) 258-271, [published, refereed].

Scott, N. V., T. Hara, P. Hwang, and E. J. Walsh, 2005. Directionality and crest length statistics of steep waves in open ocean waters, J. Atmos. Oceanic Tech., 22(3)272-281, [published, refereed].