# Wind Over Waves II:
# Forecasting and Fundamentals of Applications

**Shahrdad G Sajjadi**, Professor of Oceanography,
John C Stennis Space Centre, Mississippi
and
**Lord Julian Hunt**, Professor of Space and Climate Physics,
University College London

**Horwood Publishing**
**Chichester**

**The Institute of Mathematics**
**and its Applications**

**HORWOOD PUBLISHING LIMITED**
International Publishers, Coll House, Westergate, Chichester, West Sussex, PO20 3QL, England
First published in 2003

**COPYRIGHT NOTICE**
All Rights Reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the permission of Horwood Publishing.

© Shahrdad G Sajjadi and Lord Julian Hunt 2003

**British Library Cataloguing in Publication Data**
A catalogue record of this book is available from the British Library

**ISBN 1-898563-81-0**

Printed in Great Britain by Antony Rowe Ltd, Eastbourne

# Preface

The study of waves on surfaces of liquids continues to throw up new phenomena and new theoretical questions that are of great interest to many scientific and engineering disciplines. Fluid mechanics, meteorology, oceanography, geology and civil, chemical and electrical engineering being some of those that feature in the contribution to this volume. Here we particularly focus on surface waves driven by the gas flow over the surface with the main emphasis being on ocean winds force by the natural wind. However many of the results are certainly applicable to waves of engineering importance near the coast or in confined or open channels.

Because of the scientific importance of these topics and the growing interest in their applications, an extended programme of lectures and seminars was held on the 'Mathematics of Surface Water Waves' at the Isaac Newton Institute (INI) for Mathematical Sciences in Cambridge. On the organising committee of the programme, held in August and September 2001, were T. Bridges, S.E. Belcher, S.G. Sajjadi. This was followed (from September 3–5) by a conference organised by the Institution of Mathematics and its Applications (IMA) of Churchill College on the subject of 'Wind over waves; fundamentals, forecasting and applications'.

This second volume in the IMA series of wind over waves is based on the excellent theoretical and experimental papers presented at the conference and on the new ideas and discussions at both meetings, (probably the longest and largest ever held on this topic). The opening remarks of Julian Hunt setting the scene for the programme and the conference are included here on pp 1–2.

During the conference the annual Theoretical and Applied Mechanics Day (August 27) was celebrated. This was recently instituted by the state of Illinois. Professor Moffatt, Director of INI composed some suitable verse after Robbie Burns (following the tradition of Maxwell who illustrated his dynamics lectures in Cambridge in the 1870's with such lines from Burns' poems, as 'when a body meets a body'!)

The first paper in this volume by Craik is based on extensive historical research into how Stokes' basic linear and non-linear theory of small amplitude waves emerged from the considerable number of earlier studies. But, as Craik, whose own work on waves is well known, remarks, none of these had the clarity and correctness of Stokes' analysis. Stokes spent some of his career (as did one of the editors) involved in the administration of the Meteorological Office which is why he developed great interest in the interaction between waves and weather. He was not always so far sighted in his views on scientific development, making the mistake that O. Reynolds work on turbulence was unimportant - as Prof. B.E. Launder FRS has recently discovered in Royal Society archives).†

† In a personal communication, Prof. Launder wrote to Dr Sajjadi: 'My remarks

# Wind-Over-Waves Coupling

**V.K. Makin[1] and V.N. Kudryavtsev[2]**

[1] Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands,
[2] Marine Hydrophysical Institute, Sebastopol, Ukraine

## ABSTRACT

Wind-over-waves coupling is a modern theory of microscale air-sea interaction, which allows to relate the sea drag directly to the properties of wind waves and peculiarities of their interaction with the wind. Interaction of waves with ocean surface phenomena explains variability of fluxes. Role of short and dominant waves in supporting the sea drag is discussed.

## 1. INTRODUCTION

Interaction between Earth's atmosphere and the oceans occurs at the air-sea interface, via surface fluxes of momentum, heat, moisture and gases. These surface fluxes serve as lower boundary conditions for the general circulation models of the atmosphere and provide upper boundary conditions for general circulation models of the ocean. Any natural or anthropogenic impact on the air-sea interface will therefore change the surface fluxes and influence the global and mesoscale atmosphere and ocean circulations, that is, climate and weather. Correct description of surface fluxes is thus of importance to predict long and short term climate changes. That requires the understanding of the physics of the microscale air-sea interaction, which is to a great extent determined by the wind-wave interaction.

The last decade has seen tremendous progress in modelling air-sea fluxes, with the emergence of new ideas of, inter alia, how the wind generates waves, how a spectrum of waves mediates momentum and other transfer, and how breaking waves impact exchanges between the atmosphere and oceans. The common thread running through these new ideas is the strong dependence of the fluxes on the wave properties. Hence current understanding shows how any changes to the waves will have impacts on the surface fluxes. These developments mean that we are now in a position to study systematically the impacts of currents, swell, slicks and other complicating factors on surface fluxes. A theory which allows the assessment is called the wind-over-waves coupling (WOWC) theory. A modern WOWC theory was recently developed by Makin *et al.* (1995), Makin & Kudryavtsev (1999), Kudryavtsev *et al.* (1999), Kudryavtsev & Makin (2002), and Makin & Kudryavtsev (2002). Here a concise description of this theory is given.



## 2. CONCEPT OF WIND-OVER-WAVES COUPLING

Wind-over-waves coupling is a modern theory of microscale air-sea interaction, which allows to relate the sea drag directly to the properties of wind waves and peculiarities of their interaction with the wind and ocean surface phenomena, and to explain the formation of fluxes and their variability. The approach is based on the conservation equation for integral momentum:

$$u_*^2 = \tau^\nu + \overline{p\frac{\partial\eta}{\partial x}}, \tag{2.1}$$

where $u_*$ is the friction velocity, $\tau^\nu$ is the viscous surface stress, $\tau^f = \overline{p\partial\eta/\partial x}$ is the form drag at the sea surface, and a bar denotes statistical averaging. Equation (2.1) reflects a fundamental fact that the stress $\tau = u_*^2$ at the surface is formed by viscous stress and the form drag $\tau^f$. The form drag of the sea surface $\eta$ is a correlation of the wave-induced surface pressure field $p$ with the wave slope $\partial\eta/\partial x$. As a matter of fact the second term on the right-hand side of equation (2.1) becomes dominant for moderate and high winds. It becomes immediately clear that that are waves that are responsible for formation of the stress and its variation. We keep in mind the following scheme. The atmosphere provides the energy input to the wave field. Waves grow and adjust themselves to the atmosphere. As waves support the stress the atmosphere in turn is adjusted to waves. So, the atmosphere and waves form a self-consistent system, which is in equilibrium. If any ocean surface pheonomenon such as currents of any origin, swell, slicks or even rain changes the property of the wave field the balance in the system atmosphere-waves is broken, and the system adjusts itself to a new equilibrium. This explains the variability of fluxes as a result of interaction of waves with the ocean surface phenomena.

## 3. THE MODEL

Equation (2.1) preassumes stationary and spatial homogeneous conditions. The sea surface is described statistically in terms of the directional wave variance spectrum $F(\mathbf{k})$,where $\mathbf{k}$ is the wavenumber vector. The wind direction coincides with the mean direction of waves propagation and the wave spectrum is symmetrical relative to that direction. Relating the form drag in (2.1) to geometrical properties of the surface (described in terms of the wave spectrum) and to the properties of the energy exchange between waves and the wind, the stress at the surface is related or coupled directly to the sea state.

### 3.1. *The form drag*

Two main mechanisms of the wind-wave interaction that support the form drag are distinguished. When the wavy surface is regular (in a sense that there are no wave breaking events) the wind flows over the wave smoothly, i.e. the surface is streamlined. This regime of wind-wave interaction is described in terms of the non-separeted sheltering mechanism (Belcher & Hunt 1993), which provides the energy flux to waves from the wind. A part of the form drag supported by the non-separated sheltering mechanism: the wave-induced stress $\tau_w^f$ can be written

$$\tau_w^f = \int_k \int_\theta \beta c^2 B(k,\theta) \cos\theta d \ln k d\theta, \tag{3.1}$$

where $B = k^4 F$ is the saturation wave spectrum, $c$ is the phase speed, $\theta$ is the angle, and $\beta$ is the dimensionless energy flux to waves or the growth rate parameter. The growth rate parameter is taken in the form

$$\beta = C_\beta \left(\frac{u_*}{c}\right)^2, \tag{3.2}$$

where the proportionality coefficient is dependent on wave parameters

$$C_\beta = c_\beta \kappa^{-1} \ln \frac{\pi}{k z_c}, \tag{3.3}$$

$z_c = \exp[\kappa c/(u_* \cos\theta)]$, and $c_\beta$ is a constant close to 2. Notice, that $C_\beta \to 0$ both for very long waves ($c/u_*$ is large) and for very short waves($k$ is large).

It is a common knowledge that waves intensively break on the sea surface. There is increasing experimental evidence that breaking waves play a significant role in the dynamics of the lower atmosphere (e.g. Melville 1996). A significant augmentation of the surface local stress above breaking waves is reported in laboratory experiments (e.g. Banner 1990; Giovanangeli *et al.* 1999). In these studies it has been established that the air flow separation (AFS) from the crest of breaking waves is responsible for this augmentation. The impact of the air flow separation from breaking waves on the sea drag was accounted for in Kudryavtsev & Makin (2001). They assumed that the sea surface can be presented as a streamlined surface covered by areas, where the air flow separation takes place. The air flow separation occurs intermittently on the sea surface, where wave breaking fronts arise. It was further assumed that the stress due to separation is proportional to the pressure drop $\Delta p_s$ on the forward side of the breaking front and to the total length of wave breaking fronts $\sum l_i$ (details see in Kudryavtsev & Makin 2001). The quantity $1/S \sum l_i$ is the average total length of breaking fronts per unit surface introduced originally by Phillips (1985)

$$\frac{1}{S} \sum l_i = \Lambda(\mathbf{c}) d\mathbf{c}, \tag{3.4}$$

where the distribution $\Lambda(\mathbf{c})$ represents the surface density of the total length of wave breaking fronts that have velocities in the range $\mathbf{c}$ to $\mathbf{c} + d\mathbf{c}$. The drop of pressure induced by the separation acts on the wave breaking front during a short period of time and then disappears. The pressure drop can be estimated by using the analogy between the AFS from breaking waves and separated flows typical of the backward facing step. It can be thus parameterized as

$$\Delta p_s = \frac{1}{2} \gamma {u_s}^2, \tag{3.5}$$

where $\gamma$ is an empirical constant close to 1, $u_s$ is the reference speed defined as a positive difference between the mean wind speed at a reference level specified



here at $z = 1/k$ and the phase speed of the wave

$$u_s = \frac{u_*}{\kappa} \cos\theta \ln \frac{1}{k z_0} - c, \tag{3.6}$$

where $z_0$ is the roughness parameter defined through the logarithmic wind profile

$$U(z) = \frac{u_*}{\kappa} \ln \frac{z}{z_0} \tag{3.7}$$

extending to the surface from a height where the wind velocity is not influenced by wave motions. Introducing these assumptions it was shown that the separation stress supported by the AFS from all waves has a general form

$$\tau_s^f = \varepsilon_b \gamma \int_{\mathbf{c}} u_s^2 \cos\theta k^{-1} \Lambda(\mathbf{c}) d\mathbf{c}, \tag{3.8}$$

where $\varepsilon_b = 0.5$ is the characteristic slope of the breaking wave. Notice, that even if a fast wave propagating with the phase velocity close to or faster than the mean wind speed breaks it will not support the stress because the separation cannot take place under these conditions.

### 3.1.1. *Stress supported by the AFS from equilibrium range of short gravity waves*

The separation stress supported by short gravity waves in the equilibrium range of the spectrum $\tau_{s_{eq}}^f$ was obtained by Kudryavtsev & Makin (2001). Following the approach by Phillips (1985) the distribution function $\Lambda(\mathbf{c})$ is directly related to the average rate of the energy dissipation per unit area by breakers with velocities between $\mathbf{c}$ and $\mathbf{c}+d\mathbf{c}$. It was further assumed that under the steady condition the energy dissipation due to wave breaking is equal or proportional to the energy input from the wind in the equilibrium range of the wind wave spectrum. The total length of wave breaking fronts can be then expressed in terms of the saturation spectrum as

$$\Lambda(\mathbf{c}) \sim \frac{\beta}{b} B(\mathbf{c}) k^{-1} \tag{3.9}$$

with $b = 0.01$ being an empirical constant. With (3.9) the separation stress (3.8) can be written as

$$\tau_{s_{eq}}^f = \varepsilon_b \gamma b^{-1} \int_\theta \int_{k<k_m} u_s^2 \beta(k,\theta) B(k,\theta) \cos\theta d\theta d \ln k. \tag{3.10}$$

The integration over the wavenumber $k$ in (3.10) is done in the wavenumber range satisfying the condition $k < k_m$, where $k_m = 2\pi/\lambda_m$ rad m$^{-1}$ and the wavelength $\lambda_m = 0.1$ m. This condition reflects the fact that waves shorter than $\lambda_m$ rather generate parasitic capillaries than break as discussed by Kudryavtsev *et al.* (1999). The generation of parasitic capillaries prevents the formation of the sharp surface slope and hence prevents the separation of the air flow from these short waves.

3.1.2. *Stress supported by the AFS from dominant waves*

When seas are young dominant waves (waves at the spectral peak) break intensively (Babanin *et al.* 2001). They contribute to the separation stress and impact the sea drag. The range of dominant waves is defined here by the condition $k \leq 2k_p$, where $k_p$ is the spectral peak wavenumber. The assumption that dissipation is balanced by wind input is not valid in the range of the spectral peak and Equation (3.9) does not hold there. The statistics of dominant waves breaking will be described by a breaking wave model based on a concept of a threshold level. The model is based on the description of statistical properties of a Gaussian wave surface, where it is assumed that the wave breaking event takes place when the sea surface exceeds some threshold level. The detailed analysis of statistical properties for a random, moving, Gaussian surface is given by Longuet-Higgins (1957). He derived a general expression for the mean length of a contour for the crossection of the wavy surface by a plane of a constant height $\zeta_0$ per unit area $\overline{s}$ (his Equation 2.3.16). $\zeta_0$ is defined as the height of a counter above which the onset of dominant wave breaking occurs. It is assumed that when the surface level exceeds the 'threshold' level $\zeta_0$, a strong and sudden (explosive) instability erupts and causes the onset of breaking. Assuming further that dominant waves can be presented as a superposition of narrow band random surface waves it can be shown (Makin & Kudryavtsev 2002) that the length of the contours of the breaking zone is

$$\overline{s} = \frac{1}{\pi} k \exp\left(-\frac{\varepsilon_T^2}{\varepsilon_d^2}\right), \tag{3.11}$$

where $\varepsilon_d = H_d k_p/2$ is the dominant wave steepness ($H_d$ is their significant wave height) and $\varepsilon_T = \sqrt{2}\zeta_0 k_p$ is a tuning constant. Taking into account that the length of breaking fronts is approximately twice less than $\overline{s}$, the average total length per unit surface area of breaking fronts of dominant waves is

$$\Lambda(\mathbf{c})d\mathbf{c} = \frac{1}{2}\overline{s} \tag{3.12}$$

and the separation stress (3.8) supported by dominant waves is

$$\tau^f_{s_d} = \frac{\varepsilon_b \gamma}{2\pi} u_{sd}^2 \exp\left(-\frac{\varepsilon_T^2}{\varepsilon_d^2}\right). \tag{3.13}$$

Here the reference wind speed for dominant waves $u_{sd}$

$$u_{sd} = \frac{u_*}{\kappa} \ln \frac{\varepsilon_b}{k_p z_0} - c_p \tag{3.14}$$

is specified at the level just above breaking dominant waves, i.e. at $z = \varepsilon_b/k_p$, and $c_p$ is the phase speed at the spectral peak.

### 3.2. *Viscous stress*

Patching the linear wind profile inside the viscous layer with the logarithmic wind profile above it, the viscous stress can be written

$$\tau^\nu = (\kappa d)^{-1} \ln\left(\frac{\delta}{z_0}\right) u_*^2, \tag{3.15}$$



where

$$\delta = d\frac{\nu}{u_*} \tag{3.16}$$

is the thickness of the viscous sublayer, $\nu$ is the molecular viscosity, $d = 12$ is a constant.

### 3.3. *Resistance law of the sea surface*

Equation (2.1), where viscous stress is calculated according to (3.15) and the form drag $\tau^f$ can be evaluated through (3.1), (3.10) and (3.13), describes the resistance law of the sea surface relating the stress to properties of the wave field. Given the wind speed at a specified height and a wave spectrum Equation (2.1) is solved by iterations to provide the sea surface stress.

### 3.4. *Specification of the wave spectrum*

To obtain the stress the wave spectrum should be known. It can be described by an empirical model or by a physical model of the wave spectrum. The former will provide a 'one-way' coupling: adjustment of the atmosphere to a given wave field. To study the self-consistent adjustment of the atmosphere and waves, and potentially the variability of fluxes a physical model of the wave spectrum is necessary. To calculate the stress due to the AFS supported by short gravity waves $\tau^f_{s_{eq}}$, the equilibrium part of the wave spectrum defined at $k < k_m$ has to be known. The calculation of the separation stress supported by dominant waves $\tau^f_{s_d}$ requires the shape of the spectrum at the spectral peak, while the calculation of the wave-induced stress $\tau^f_w$ requires the shape of the spectrum in the wavenumber range from capillary waves to the spectral peak. A composite model of the wave spectrum (Kudryavtsev *et al.* 1999) describes the saturation spectrum $B(k,\theta)$ in the full wavenumber range from few millimeters up to the spectral peak. It consists of two parts: the low and the high wavenumber spectrum

$$B(k,\theta) = B_l(k,\theta) + B_s(k,\theta). \tag{3.17}$$

The shape of the low wavenumber (at the spectral peak) spectrum $B_l$ defined by the inverse wave age parameter $U_{10}/c_p$ is given by the empirical model by Donelan *et al.* (1985). The shape of the high wavenumber spectrum $B_s$ results from the physical model developed by Kudryavtsev *et al.* (1999). The model is based on the energy balance equation and accounts for wind input, viscous dissipation, dissipation due to wave breaking (including energy losses due to generation of parasitic capillaries by short gravity waves), and nonlinear three-wave interaction. As it will be shown the short waves support most of the sea drag, that is why their description through a balance of physical mechanism is crucial. The stress is defined by the saturation spectrum $B$. The saturation equilibrium spectrum $B_s$ in turn depends on the stress via the wind input. Thus the wind waves and the atmospheric boundary layer are strongly coupled forming a self-consistent dynamical system.

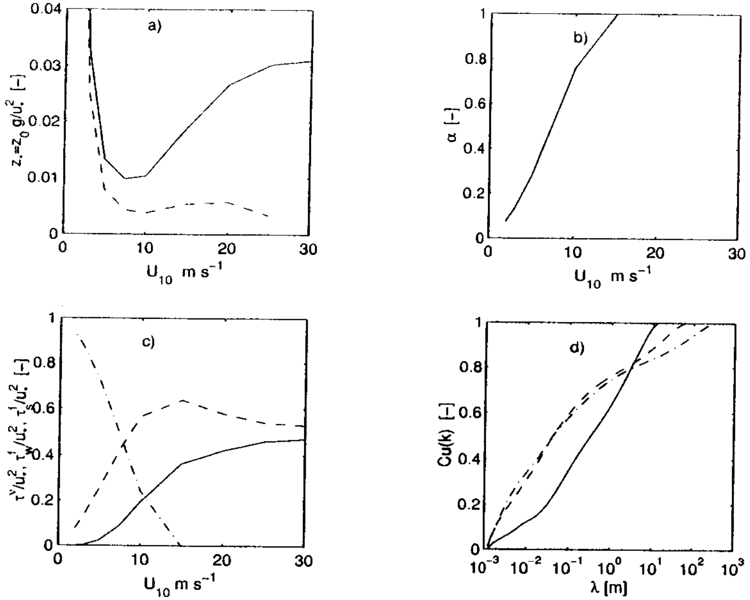


FIGURE 1. (a) Charnock parameter $z_0 g/u_*^2$ versus $U_{10}$. Model results: solid line, separation stress is accounted for; dashed line, separation stress is not accounted for. (b) The same as in (a) but for the coupling parameter $\alpha$. (c) Stress contributions. Solid line, stress due to separation $\tau_s^f/u_*^2$; dashed line, wave-induced stress $\tau_w^f/u_*^2$; dashed-dotted line, viscous stress $\tau^\nu/u_*^2$. (d) Cumulative spectrum $Cu(k)/\tau^f$ of the form drag $\tau^f$ versus the wavelength $\lambda$. Solid line, wind speed $U_{10} = 5\text{ms}^{-1}$; dashed line, $U_{10} = 10\text{ms}^{-1}$; dashed-dotted line, $U_{10} = 20\text{ms}^{-1}$.

## 4. Role of short waves in supporting the sea drag

We first analyze a case of a fully developed sea specified by the inverse wave age parameter $U_{10}/c_p = 0.83$. In Figure 1a the dimensionless roughness length or the Charnock parameter $z_0 g/u_*^2$ is shown as a function of the wind speed. The solid line represents the solution of the full model (the stress due to the AFS is accounted for), while the dashed - the model solution when the stress due to the AFS is not accounted for. The additional stress supported by the AFS is responsible for a well pronounced wind speed dependence of the Charnock parameter shown in Figure 1a. In the range of the wind speed from 10 ms$^{-1}$ to 20 ms$^{-1}$ the Charnock parameter increases twice in correspondence with field measurements (e.g. Yelland & Taylor 1996). A strong increase of the Charnock parameter at low winds reflects the transition of the sea surface from the aerodynamically rough to the smooth condition.The coupling parameter $\alpha$ defined as the ratio of the form drag to the total drag $\alpha = \tau^f/u_*^2$ is shown in Figure 1b. At high wind speeds most of the drag is due to the form drag, while at low wind speeds the viscous stress dominates. To show the role of the air flow separation in the momentum transfer the contribution to the total stress $u_*^2$ of viscous stress $\tau^\nu/u_*^2$, the wave-induced stress $\tau_w^f/u_*^2$, and the stress due to the AFS $\tau_s^f/u_*^2$ as a function of the wind speed is shown in Figure 1c. Notice, that $\tau^\nu/u_*^2 + \tau_w^f/u_*^2 + \tau_s^f/u_*^2 = 1$. For low wind speeds $U < 5$ ms$^{-1}$ viscous stress dominates the sea surface drag while the role of the form drag is negligible. With the increase of the wind speed the role of the form drag becomes pronounced. At the wind speed $U > 10$ ms$^{-1}$ the surface drag is mainly supported by the wave-induced and the AFS stresses. The relative role of the stress due to the AFS increases with increasing the wind speed and for high wind speeds it supports about 50% of the total stress.In Figure 1d the cumulative spectrum of the form drag $\tau^f$ as a function of the wavelength $\lambda$ is shown to illustrate the role of waves from different ranges of the wavenumber in supporting the stress. For all wind speeds shown about 80% of the form drag is supported by waves shorter than few meters. Short gravity-capillary and capillary waves support a significant part of the stress especially for higher winds. If these waves are damped by e.g. oil, so does the stress which they support. That will results in lower values of the drag coefficient as compared to a case of a clean sea surface (Grodskii *et al.* 1999) This is an example how an ocean surface phenomenon changing the properties of waves impacts the stress.

For a fully developed sea dominant waves do not contribute to the stress. Though their breaking occurs (Banner *et al.* 2000) they propagate with the phase speed exceeding the mean wind speed. The separation cannot occur under such conditions. All the separation stress due to the AFS comes from waves in the equilibrium range. The wave-induced flux to dominant waves is also very small because the growth rate parameter is small ($C_\beta \to 0$).



## 5. Role of dominant waves in supporting the sea drag

For young seas characterized by increased inverse wave age parameter, the role of dominant waves in forming the sea drag becomes more and more important (Makin & Kudryavtsev 2002). Supporting about 10% of the total stress at $U_{10}/c_p = 2$, and about 20% at $U_{10}/c_p = 3$, their contribution becomes dominant for very young seas $U_{10}/c_p = 5$.

### 5.1. *Wave age dependence of the sea drag*

The Charnock parameter $z_0 g/u_*^2$ as a function of the inverse wave age parameter based on the friction velocity $u_*/c_p$ is shown in Figure 2. Calculations are done for the wind speed $U_{10} = 7.5$ m s$^{-1}$ and $U_{10} = 20$ m s$^{-1}$ and the inverse wave age parameter $0.83 < U_{10}/c_p < 25$. Data are compiled from Donelan *et al.* (1993), their Figure 2. Model results (as well as data) show a clear increase of the Charnock parameter with increasing the inverse wave age. This increase is explained by the model by the increased steepness of young waves and thus increased separation stress due to the AFS from dominant waves. The Charnock parameter has a maximum around $u_*/c_p = 0.3 \div 0.4$ ($U_{10}/c_p = 7$). For higher values of the inverse wave age parameter corresponding to very young waves typical for small water bodies and laboratory conditions, the Charnock parameter decreases. This is explained by the fact that the wind wave spectrum is very narrow in the wavenumber space, and the separation stress from the equilibrium range becomes smaller. The dominant waves are very peaked but small in height, and the reference speed (3.14) is rapidly dropping reducing the separation stress from dominant waves. Both effects lead to decreasing of the

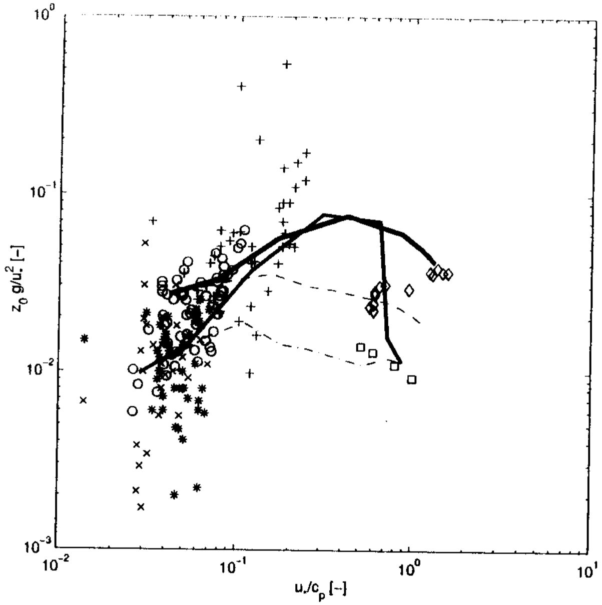


FIGURE 2. Charnock parameter $z_0 g/u_*^2$ versus inverse wave age $u_*/c_p$. Model results: thin solid line - $U_{10} = 7.5$ ms$^{-1}$; thick solid line - $U_{10} = 20$ ms$^{-1}$; dashed-dotted line - $U_{10} = 7.5$ ms$^{-1}$ for $\tau_d^s = 0$; dashed line - $U_{10} = 20$ ms$^{-1}$ for $\tau_d^s = 0$. Symbols indicate data: circles - North Sea; pluses - Lake Ontario; stars - Atlantic Ocean, long fetch; x-marks - Atlantic Ocean, limited fetch; diamonds and squares - wave tanks.

Charnock parameter. Despite the scatter of the data is huge, the model results in general agree well with measurements.

To outline the role of separation from dominant waves we switched off this stress in the model and plot results in the same Figure. There is only a marginal increase of the Charnock parameter with increasing inverse wave age. This suggests that the separation from dominant waves is responsible for the observed behavior of the Charnock parameter with inverse wave age. It is also clear that for waves close to a fully developed $u_*/c_p < 0.1$ ($U_{10}/c_p < 1.5$) the dominant waves do not support the separation stress as already explained in the previous section.

### 5.2. *Depth dependence of the sea drag*

The fact that the AFS from dominant waves contribute a noticeable part to the total stress (sea drag) suggests a mechanism, which could explain a known experimental fact that the drag coefficient is higher in the shallow waters as compared to the open ocean data (e.g. Geernaert 1990). When waves propagate into the shallow water long waves begin to feel the bottom and become steeper. Hence, the depth limited spectra is expected to be more peaked compared to spectra in the deep water (Young & Verhagen 1996). That leads to the enhanced breaking of dominant waves. The enhanced breaking leads to the enhanced separation of the air flow from dominant waves, which gives rise to the total stress (Makin & Kudryavtsev 2002).

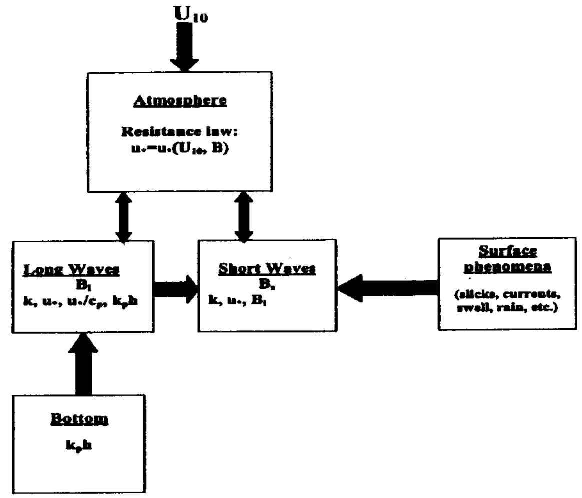


FIGURE 3. Schematic description of wind-over-waves coupling. Arrows indicate impacts.

## 6. SUMMARY

Wind-over-waves coupling - a modern theory of microscale air-sea interaction is presented. The theory allows to relate the sea drag directly to the properties of wind waves and peculiarities of their interaction with the wind and to explain the formation of fluxes. Waves interact with ocean surface phenomena, change their properties - and thus the stress they support. This explains the variability of fluxes. Schematic description of wind-over-waves coupling is presented in Figure 3. Waves play a crucial role in supporting the sea drag. In a fully developed sea almost all the stress is supported by short waves at moderate and high winds. The air flow separation from short waves plays a significant role supporting to about 50% of the stress at high wind speeds. The wind speed dependence of the Charnock parameter is explained by the separation from short waves, while the role of dominant waves is negligible. However, the separation of the air flow from dominant waves begin to play a significant role in supporting stress for young seas and explains the wave age and the finite bottom depth dependencies of the sea drag. WOWC theory provides a framework to study sea surface fluxes and their variability.

REFERENCES

BABANIN, A.V., YOUNG, I.R. & BANNER, M.L. 2001 Breaking probability for dominant waves on water of finite constant depth. *J. Geophys. Res.* **106**, 11659-11676.

BANNER, M.L. 1990 The influence of wave breaking on the surface pressure distribution in wind wave interaction. *J. Fluid Mech.* **211**, 463-495.

BANNER, M.L., BABANIN, A.V. & YOUNG, I.R. 2000 Breaking probability for dominant waves on the sea surface. *J. Phys. Oceanogr.*, **30**, 3145-3160.

BELCHER, S.E. & HUNT, J.C.R. 1993 Turbulent shear flow over slowly moving waves. *J. Fluid Mech.* **251**, 109-148.

DONELAN, M.A., HAMILTON, J. & HUI, W.H. 1985 Directional spectra of wind generated waves. *Phil. Trans. R. Soc. London, Ser. A* **315**, 509-562.

DONELAN, M.A., DOBSON, F.W., SMITH, S.D. & ANDERSON, R.J. 1993 On the dependence of sea surface roughness on wave development. *J. Phys. Oceanogr.*, **23**, 2143-2149.

GEERNAERT, G.L. 1990 Bulk parameterizations for the wind stress and heat fluxes. In *Surface Waves and Fluxes, Vol. 1*, G.L. Geernaert & W.J. Plant (eds.), Kluwer Academic Publishers, Dordrecht, pp. 91-172.

GIOVANANGELI, J.P., REUL, N., GARAT, M.H. & BRANGER, H. 1999 Some aspects of wind-wave coupling at high winds: an experimental study. In *Wind-Over-Wave Couplings*, S.G. Sajjadi *et al.* (eds.), Oxford University Press, pp. 81-90.

GRODSKII, S.A., KUDRYAVTSEV, V.N. & MAKIN, V.K. 1999 An estimate of the influence of the sea surface pollution on short wind waves and parameters of the atmospheric boundary layer. *Morskoy Gidrophizicheskiy Zhurnal*, **6**, 3-14, (in Russian). (Engl. transl.: GRODSKII, S.A., KUDRYAVTSEV, V.N. & MAKIN, V.K. 2001 Evaluation of the influemce of surface films on short wind waves and the characteristics of the boundary layer of the atmosphere. *Physical Oceanography.* **11**, No. 6, 495-508.

KUDRYAVTSEV, V.N. & 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. & CHAPRON, B. 1999 Coupled sea surface-atmosphere model 2. Spectrum of short wind waves. *J. Geophys. Res.* **104**, 7625-7639.

LONGUET-HIGGINS, M.S. 1957 The statistical analysis of a random moving surface. *Phil. Trans. R. Soc. London, Ser. A* **249**, 321-387.

MAKIN, V.K. & KUDRYAVTSEV, V.N. 1999 Coupled sea surface-atmosphere model 1. Wind over waves coupling. *J. Geophys. Res.* **104**, 7613-7623.

MAKIN V.K. & KUDRYAVTSEV, V.N. 2001 Impact of dominant waves on sea drag. *Boundary-Layer Meteorol.*, **103**), 83-99.

MAKIN V.K., KUDRYAVTSEV, V.N. & MASTENBROEK, C 1995 Drag of the sea surface. *Boundary-Layer Meteorol.* **79**, 159-182.

MELVILLE, W.K. 1996 The role of surface-wave breaking in air-sea interaction. *Ann. Rev. Fluid Mech.* **28**, 279-321.

PHILLIPS, O.M. 1985 Spectral and statistical properties of the equilibrium range in wind generated gravity waves. *J. Fluid Mech.* **156**, 505-531.

YELLAND, M. & TAYLOR, P.K. 1996 Wind stress measurements from the open ocean. *J. Phys. Oceanogr.* **26**, 541-558.

YOUNG, I.R. & VERHAGEN, L.A. 1996 The growth of fetch limited waves in water of finite depth. Part 2. Spectral evolution. *Coastal Eng.* **29**, 79-99.

# Sea Surface Roughness Parameterization

**I. Papadimitrakis and A.I. Papaioannou**

National Technical University of Athens Department of Civil Engineering
Hydraulics, Water Resources and Maritime Engineering

## ABSTRACT

The contribution of wind-generated waves to the deep-sea surface roughness, in the absence of a swell, is examined under neutral stability conditions. Based on a modified Banner and Melville wave breaking mechanism, a critical frequency is determined for partitioning the spectrum of surface waves among 'short' and 'long' wave components, where the latter do not (always) contribute to the surface roughness. This partitioning allows estimation of an effective sea surface roughness as a fraction of the sea surface variance (i.e. a fraction of the zero order moment of the spectrum). When extensive, large-scale, wave breaking occurs near the spectral peak frequency the entire wave spectrum contributes to the surface roughness.

The proposed model for estimating the critical-partitioning frequency, and thereafter the effective sea surface roughness and drag coefficient, utilizes both observed spectra collected from North Aegean and other Greek seas and theoretical formulations of the latter.

The critical frequency, as well as the surface roughness ($z_0$) and the drag coefficient ($C_d$) appear to be functions of two essential parameters of the wave field, namely the wave age and the significant slope. The critical frequency is found to decrease with (increasing) the inverse wave age and the significant slope approaching asymptotically the spectral peak frequency and causing a greater part of the spectrum to contribute to the sea surface roughness (as expected).

Results are compared with other field observations of both $z_0$ and $C_d$. Similarities and discrepancies among the various data sets, as well as among our results and theoretical considerations are discussed. The importance of the significant wave slope and of the stage of wave development in determining the drag coefficient is also examined.

## 1. INTRODUCTION

The influence of surface wave condition on the wind-stress (or drag) coefficient above an air-water interface, in the absence (and in fewer cases in the presence) of a swell and under neutral stability conditions, has been long recognized by a number of investigators, as for example: Kitaikorodskii & Volkov (1965), Melville (1977), Donelan (1982), Huang *et al.* (1986) and more recently by Donelan *et al.* (1993), Makin *et al.* (1995), Anctil & Donelan (1996), Makin (1999), Makin & Kudryavtchev (1999), Kudryavtchev & Makin (2001) and Taylor & Yelland (2001). The associated research efforts span over a period of almost four decades and have analyzed the subject matter from different perspectives.

Such interfacial effects are usually incorporated in the roughness length ($z_0$)