In *Proceedings 'Waves 2001'*, San Francisco, 2001 September 2–6

DO STRONG WINDS BLOW WAVES FLAT?

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Abstract: Seafarers have traditionally reported that under heavy seas, a rapid increase of wind force tends to reduce the height of the waves. This phenomenon is at variance with common scientifically-accepted ideas of the behavior of wind waves, since the wave height in a wind sea increases with wind speed, the rate of wave growth increases with wind stress and with sea-surface roughness, and wave breaking, which should increase during severe wind conditions, tends to increase the sea-surface roughness.

However, it has been shown, for example by Banner and Phillips, that a vertically-sheared current reduces the maximum steepness a water wave can have before breaking, Since the shear in the surface current will respond more rapidly than the wave height to a sudden increase in wind speed, an increase in the intensity of wave breaking should then occur, leading to a temporary decrease in wave height until the sheared current distributes itself through the water column.

The simple model described in this paper reproduces this effect, although the reduction in the wave height is predicted to be rather modest, of the order of 5 per cent. Although it is applied for deep water, the results are consistent with the laboratory observations of Douglass on the effect of on-shore and off-shore winds on nearshore wave breaking.

INTRODUCTION

Seafarers have traditionally reported that under heavy seas, a rapid increase of wind force tends to reduce the height of the waves, in other words 'violent winds blow the waves flat'. This reported phenomenon is at variance with common scientifically-accepted ideas of the behaviour of wind waves, in the following respects: (i) the wave height in a wind sea is a strictly increasing function of wind speed; (ii) the rate of wave growth increases with wind stress and with sea-surface roughness; and (iii) wave breaking, which can be expected to increase during severe wind conditions, tends to increase the hydrodynamic roughness of the water surface (Banner 1990).

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However, a possible mechanism does exist. strong gusts of wind blowing in the same direction as the wind-wave propagation will cause the surface current to increase rapidly. The extra momentum supplied by the wind will take some time to diffuse downward from the surface, and the resulting vertical current shear and associated vorticity field will reduce the limiting height for non-breaking waves (Banner and Phillips 1974; Dalrymple 1974). Thus, existing wind waves will tend to break more vigorously, and their amplitude will be reduced for a while. Conversely, wind blowing in the direction against the wave propagation will tend to increase the limiting height, so that the waves will be able to reach a greater amplitude before they break.

The effect of wind blowing with or against the wave propagation direction was studied for near-shore breaking waves by Douglass (1990) in laboratory experiments. His results confirm that a wind blowing with the waves, i.e. on-shore, tends to make the waves break sooner, in deeper water. If the wind blows off-shore, against the wave propagation, the wave breaking is delayed, and the waves tend to form plunging breakers closer to the shore.

In the present paper we will consider the deep-water case, and concentrate on the time-dependent effects of changing winds on wave breaking.

MODELING THE PHENOMENON

Predicting the interaction of wind, waves, near-surface currents, and wave breaking can potentially involve the use of sophisticated and computationally intensive numerical models involving wave interaction and turbulence closure schemes with many variable parameters. In this study we will restrict ourselves to the simplest possible schemes, with as few externally specified parameters as possible.

To parameterize the momentum flux from air to water we employ a simple wind-speed-dependent drag coefficient formula:

$$\tau = \rho_w {u_*}^2 = \rho_a {U_*}^2 = \rho_a C_D U^2, \tag{1}$$

where τ is the wind stress, ρ_a the air density, ρ_w the water density, U the wind speed (referred, say, to a height of 10 meters above the water surface), and C_D is the drag coefficient, given by the following formula (Wu 1980):

$$C_D = A + BU, \tag{2}$$

where $A = 0.8 \times 10^{-3}$ and $B = 0.065 \times 10^{-3}$ m^{-1} s.

To compute the current near the sea surface, we make the following assumptions:

1. The momentum transferred from the atmosphere to the ocean by the wind stress acts to increase the momentum of the water column, which is given by

the vertically integrated current velocity. We assume that the system is two-dimensional, and that the wind, waves, and current are all directed in the same horizontal direction.

2. The current speed at the sea surface is a fixed fraction λ of the wind speed U—we choose $\lambda = 0.02$ which is approximately the value used in oil spill simulation models if we neglect the effect of the wave-induced Stokes drift. We neglect the wave momentum, given by the vertically-integrated Stokes drift. For a more detailed discussion of these points, see e.g. Jenkins (1987).
3. We assume that the current profile is described using exponential functions of the vertical coordinate z. For example, if a wind of speed U_0 starts to blow after initially calm conditions, the current u evolves with time t according to the following formula:

$$u(z,t) = u_{0s} e^{\mu_0(t)\,.\,z}, \tag{3}$$

where the surface current $u_{0s} = \lambda U_0$, and, in order to obey condition 1 above, μ_0 will decrease with time, corresponding to the exponential profile reaching to greater and greater depths. Here, we have the z coordinate pointing upwards, with $z = 0$ at the sea surface.

In order to satisfy the above conditions, we find that after a wind of speed U has been blowing for a time t, the current is given by

$$u(z,t) = \lambda U \exp[\lambda U z/({u_*}^2 t)]. \tag{4}$$

This in fact obeys the equation

$$\frac{\partial u}{\partial t} = -\frac{{u_*}^2 z}{\lambda U}\frac{\partial^2 u}{\partial z^2}. \tag{5}$$

We have neglected the Coriolis force, which may be significant for time scales of over ≈ 2 h). It is, however, straightforward to include the Coriolis terms in a version of (5) which contains both x- and y-components of the current vector.

Waves and Wave Breaking

We represent the evolution of the wind-wave spectrum by using the fetch-dependent formula of Donelan et al. (1985) (see Komen et al. (1994), p. 187). This gives a peak enhancement and a "Phillips constant" which depend on the ratio of wind speed to the phase speed at the spectral peak. The fetch-dependence is converted to time-dependence by dividing the fetch by the group velocity of the waves at the spectral peak.

To determine the effect of current shear on wave breaking, we start with the criterion of Banner and Phillips (1974) for the crest elevation $\zeta_{\max}$ at which a wave will break, given the current u_s at $\zeta = 0$:

$$\zeta_{\max} = \frac{c^2}{2g}\left(1 - \frac{u_s}{c}\right)^2. \tag{6}$$

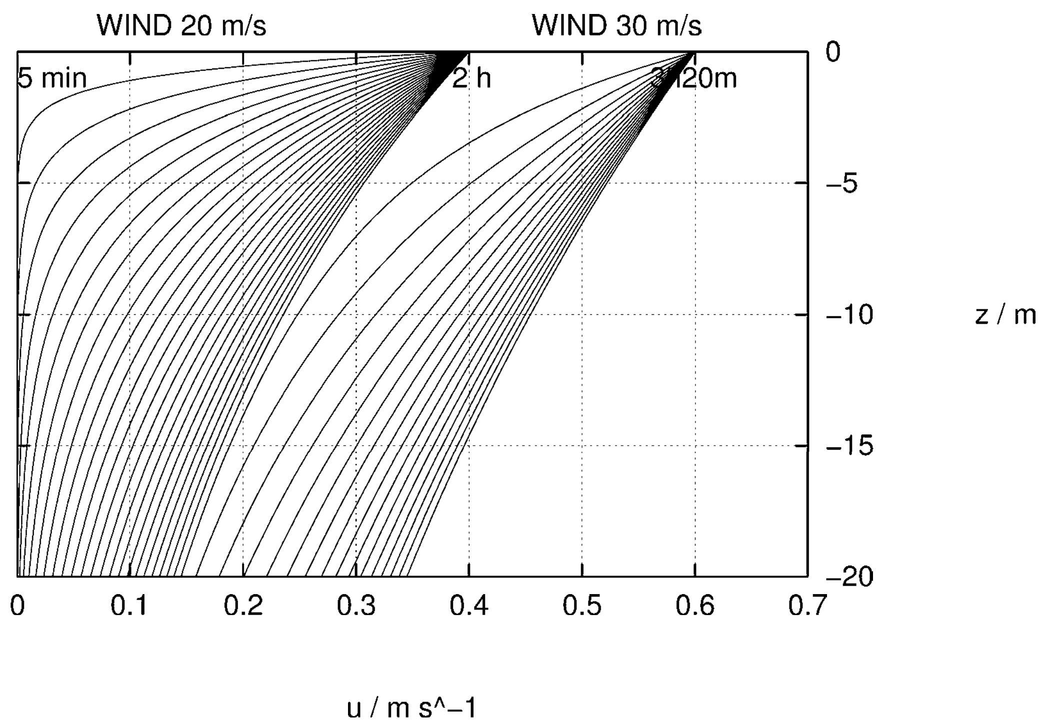

Fig. 1. Computed currents

The factor $(1 - u_s/c)^2$ is thus the reduction factor due to the surface current on the maximum wave amplitude before breaking. In fact, since the current will also increase the phase speed of the waves (see Teague 1986), we use a modified factor $(1 - (u_s - u_b)/c)^2$, where u_b is the current at a depth of $1/(2k)$, where k is the wavenumber.

RESULTS

Figure 1 shows the currents computed every 5 minutes for a wind blowing initially at $20\,\mathrm{m\,s^{-1}}$ for 2 hours, and then at $30\,\mathrm{m\,s^{-1}}$ for another 1 h 20 min. Figure 2 shows in the upper graph the evolution of the wind-wave spectra for wind speeds of 20 and $30\,\mathrm{m\,s^{-1}}$ blowing over initially calm seas. The changeover from the wave spectrum due to the $20\,\mathrm{m\,s^{-1}}$ wind to that for the $30\,\mathrm{m\,s^{-1}}$ wind is not shown—this would require a numerical wave prediction model to be run, rather than the application of the Donelan *et al.* formulas.

The lower graph of Figure 2 shows the predicted reduction in the highest amplitude of non-breaking waves as a function of wave frequency, due to the current shear in Figure 1, at 5-minute intervals, with extra one-minute intervals shown in the five minute period just after the wind increase to $30\,\mathrm{m\,s^{-1}}$ at $t = 2\,\mathrm{h}$. (The solid lines show the situation for the $20\,\mathrm{m\,s^{-1}}$ wind, and the dashed lines are for the $30\,\mathrm{m\,s^{-1}}$ wind.) It can

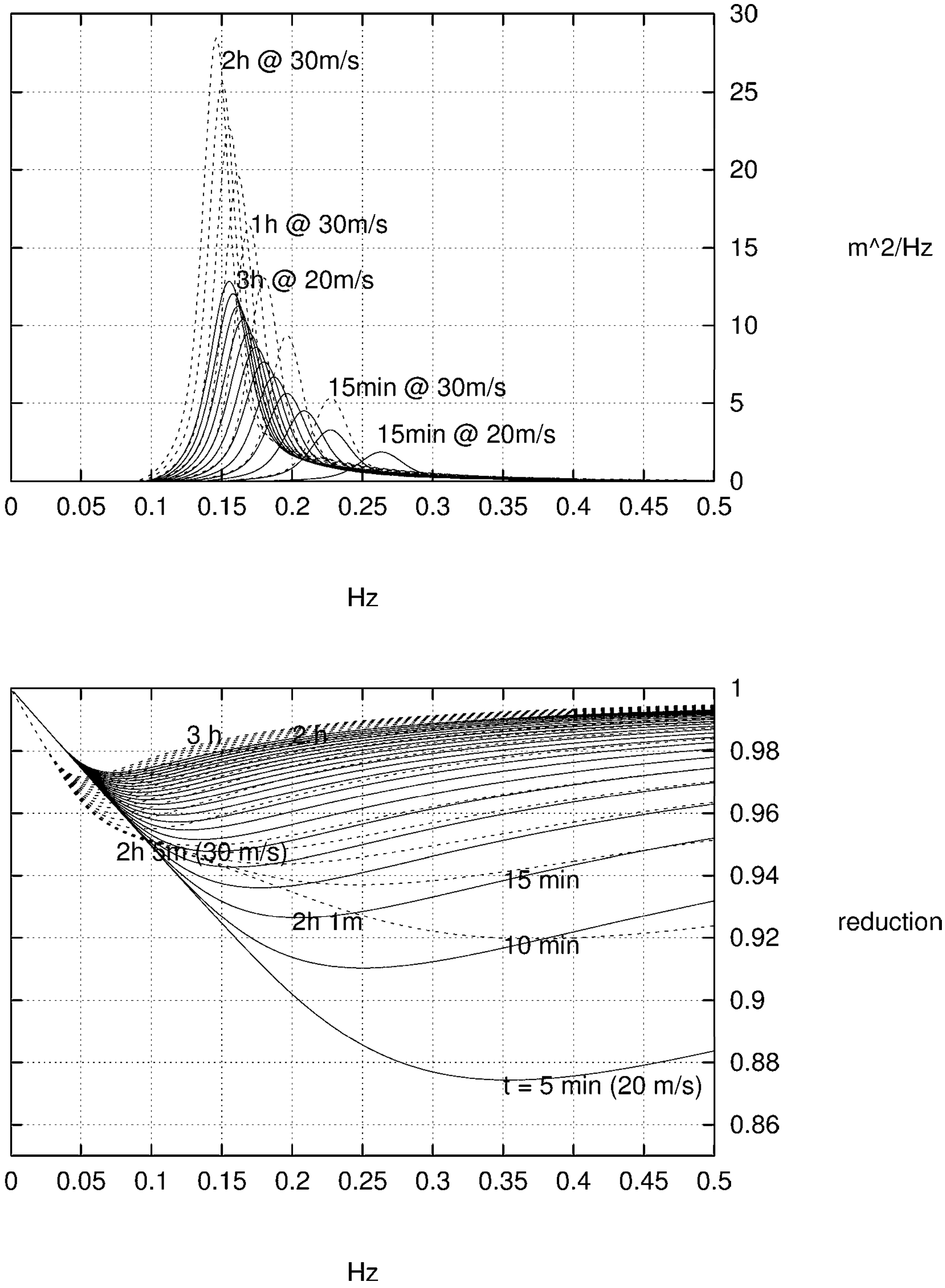

Fig. 2. Wave spectra from Donelan/Hamilton/Hui model, and computed reduction in amplitude of maximum non-breaking waves.

be seen that the reduction in the breaking wave height criterion applies over the whole frequency range of the energy-containing spectral components, and that the greatest reductions occur a very short period—within the first few minutes—after the wind speed increase. The precise details of the changeover of the wave spectra after the increase in the wind speed are not in fact important for the wave reduction factor in the lower part of the figure, since the reduction factor depends only upon the current and not the wave spectrum itself.

CONCLUSION

The calculated reduction in the wave height due to shear-induced breaking is rather modest, being of the order of 5 per cent. However, the computations assumed that the wave crest orbital velocities were given by wave theory, which is a rather crude approximation. Detailed time-dependent nonlinear numerical computations by Banner and Tian (1998) indicate that the presence of a surface shear of $0.2\ s^{-1}$ (corresponding to $60\,cm\,s^{-1}$ in a distance of 3 m) reduces the steepness at breaking by 16 percent. The 5 per cent reduction is in fact the same order of magnitude as the change in near-shore breaker height observed in the laboratory experiments of Douglass (1990). Further investigations of this phenomenon should employ more detailed spectral wave modeling and quantitative comparison with laboratory measurements.

ACKNOWLEDGEMENTS

This work was supported by the Commission of the European Communities under contract EVK3-CT-2000-00026 of the Fifth Framework Programme (MAXWAVE project), and the Norwegian Research Council under the project “Measurement and modelling of controlling factors for air–sea fluxes”. The author is solely responsible for the work and it does not represent the opinion of the sponsors. The sponsors are not responsible for any use that may be made of the data appearing herein.

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Keywords: Wave breaking, wind-induced currents, surface shear, wind waves, wave modeling, current modeling