The Wind Drift and Wave Breaking

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27 October 1975

ABSTRACT

When the wind blows across the water, a highly sheared current develops which extends a few millimeters into the water and amounts, at the surface, to 3–4% of the wind speed. Banner and Phillips (1974) have pointed out that the wind drift, as this thin surface current layer is called, may be sufficiently augmented by interaction with the orbital velocity field of the wave that the maximum particle speed may exceed the phase speed and the wave breaks. If a longer gravity wave is also present, the wind drift may be further augmented and the short gravity wave may break prematurely. We have examined both the basic breaking condition and the diminution (straining) of the short gravity waves by longer waves experimentally in wave tanks. We find that actual wave breaking occurs at substantially higher winds than predicted and that the diminution is substantially less at the higher winds. The observed wind speed dependence of this diminution appears to be contrary to prediction and points to direct coupling between wind and short gravity waves as an important factor in the response of these waves to straining.

1. The augmented wind drift

When the wind blows across the water, a very thin, highly sheared current develops near the surface extending a few millimeters into the water. The surface speed of this current, or wind drift as it is often called, amounts to 3–4% of the wind. The influence of the wind drift on the phase speed of wind-generated, short gravity and capillary waves is clear enough (e.g., Wright and Keller, 1971; Shemdin, 1972; Keller *et al.*, 1974). Now Banner and Phillips (1974) have pointed out that the wind drift may also act to limit the amplitude of short waves. The idea is that the wind drift is sufficiently augmented by interaction with the orbital velocity field of the wave that the maximum particle speed may exceed the phase speed, so that the wave breaks.

Banner and Phillips (1974) calculate the modifications produced in the wind drift by an underlying irrotational wave. They neglect the effect of the wind on the linear dynamics of the wave (e.g., the change in phase speed) but find that the surface drift is also augmented in the mean and by an oscillating component. The total augmented surface drift is given by

$$q=(C_0-U)-[(C_0-U)^2-q_0(2C_0-q_0)]^{\frac{1}{2}}, \qquad (1)$$

where U is the tangential component of orbital velocity just under the wind drift, C_0 is the phase speed of the irrotational wave, and q_0 is, for practical purposes, the surface drift in the absence of the wave. The total horizontal particle velocity is then, very nearly, $q+U$, and when this equals C_0 the wave breaks. Thus, using (1), the breaking condition is

$$(C_0-U_0)^2=q_0(2C_0-q_0), \qquad (2)$$

where U_0 is the first-order orbital speed. For waves with circular orbits the modulus of the slope, S_m, is approximately U_0/C_0, so that (2) can be rewritten

$$S_m=1-[x(2-x)]^{\frac{1}{2}}, \qquad (3)$$

where $x=q_0/C_0$.

2. Wave slopes and orbital speeds at short fetch

Eq. (3) is a relationship between wave slope at breaking and the wind drift which is readily compared with experiment. The rms dominant wave slope for wind-generated waves of a fetch of 2.7 m is given by Keller *et al.* (1974) together with corresponding phase speeds. The curve through the dominant wave slopes in Fig. 6 (center) of Keller *et al.* is redrawn in Fig. 1 together with the relationship (3). The intersection of the two curves yields the predicted air friction velocity u_* and the slope at breaking. The parameters used in the calculation of the curve from (3) are listed in Table 1. The second column in Table 1 is

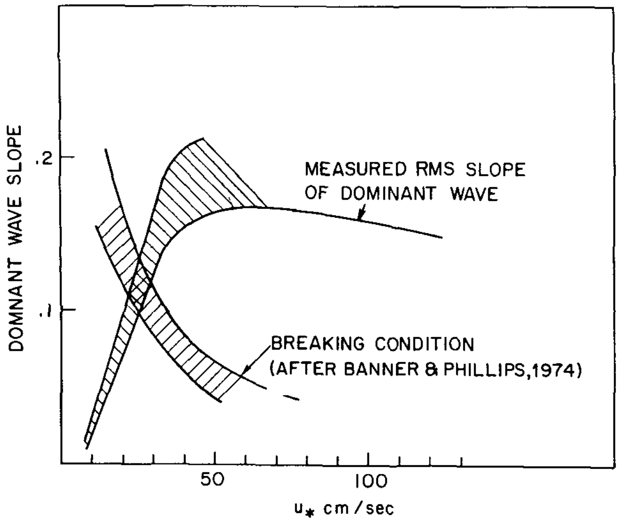

FIG. 1. Prediction of wind speeds and wave slopes at wave breaking.

the wind speed W at the center of the wind tunnel. The measured crest speed has been used rather than C_0. This probably slightly exceeds C_0 over most of the range of winds and results in a prediction of breaking at slightly higher winds than would the use of C_0. Furthermore S_m is the modulus of the slope of a monochromatic wave whereas the measured slopes are rms values of a narrow band wave. An attempt to take this factor into account broadens the curves into the swaths shown. The predicted wind speed for breaking is substantially less than that at which the dominant wave slope saturates.

The value of slope at which breaking is predicted is quite small, and it is perspicuous to expand (1) in a Taylor series in U/C_0. To second order

$$q+U=q_0+\frac{U}{1-x}+\frac{x(1-x/2)}{(1-x)^3}(U^2/C_0)+\cdots. \quad (4)$$

The linear term on the right of (4) is the horizontal component of surface speed of the wave obtained from a first-order perturbation of the wind drift (Keller *et al.*) provided C_0 is replaced by C, the phase speed obtained from the boundary value problem. The quantity $U/(1-x)$ is plotted in Fig. 2 (solid line) together with the rms horizontal float speeds and vertical float speeds taken from Wright and Keller (1971). It is seen that the measured horizontal speeds of 0.64 cm diameter by 0.185 cm thick paraffin disks substantially exceed the vertical speeds made with spheres but are nonetheless smaller than the first-order particle speeds and hence substantially smaller than would be obtained from (1). Of course, the floats may not respond fully to fluctuations in the wind drift. Note, however, that the rms vertical velocities of spheres agree very well with the product

TABLE 1. Speeds at 2.7 m fetch.

u_* (cm s^{-1})	W (m s^{-1})	q_0* (cm s^{-1})	C (cm s^{-1})	$C-q_0$ (cm s^{-1})
15	3.1	11	30	19
20	3.9	14	32	18
30	5.5	19	37	18
40	6.5	22	42	20
50	7.8	27	46	19
60	9.2	32	50	18
80	11.3	40	59	19
100	13.1	47**	66	19
125	15.0	54**	75	21

* Measured in the NRL wave tank and associated with the corresponding values of u_* measured at the University of Florida, by the author.
** Extrapolated from lower winds.

of rms dominant wave slope and crest speed (dashed line, Fig. 2) given by Keller *et al.*

Another measure of the fluctuating speed is the Doppler bandwidth in microwave scattering from the waves. Measurements of this bandwidth (Keller *et al.*) made at a fetch on 1 m, a depression angle of 30°, and a wavelength of 3.2 cm are given in Fig. 3. It is seen that the Doppler bandwidth increases uniformly from low winds up to a wind speed of about 10 m s^{-1}. At this point, the equivalent rms horizontal velocity is 7–8 cm s^{-1}. At a wind of 10 m s^{-1} the bandwidth begins to increase much more rapidly reaching, eventually, an equivalent horizontal speed of 35–40 cm s^{-1}. Thus both the saturation of the dominant wave slope and the rapid increase of bandwidth occur at about the same wind speed at short fetch. Both these indi-

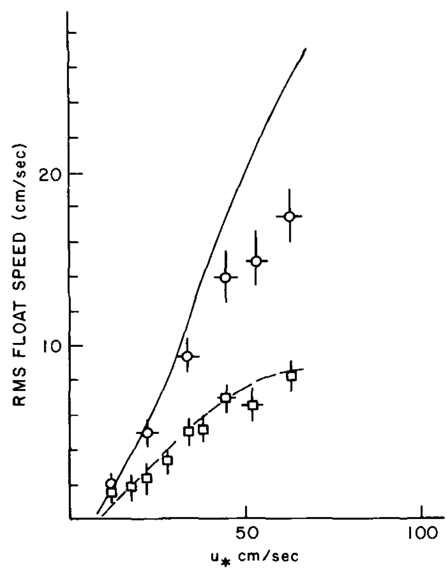

FIG. 2. Measured float velocities and first-order orbital speeds: circles, rms horizontal velocity of 0.64 cm diameter by 0.185 cm thick paraffin disks; squares, rms vertical velocity of 0.64 cm diameter spheres.

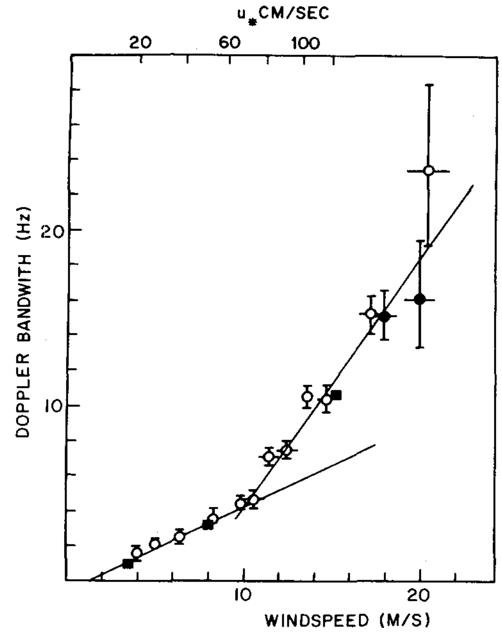

FIG. 3. Doppler bandwidth at 1 m fetch.

cators of wave breaking occur at higher winds than predicted by (3).

3. Straining of wind waves

The aforementioned wave-breaking mechanism has been invoked to explain the reduction, and in some cases near obliteration, of wind waves by longer, larger waves (Phillips and Banner, 1975). The idea is that larger waves further augment the wind drift causing premature breaking of the shorter gravity waves. Phillips and Banner estimate that the ratio r of wind wave amplitude in the presence of a longer wave to the undiminished amplitude is

$$r=(g/g')\left(\frac{C_c-q_{\max}}{C_0-q_0}\right)^2, \tag{5}$$

where g and g' are the acceleration of gravity and the effective acceleration of gravity at the large wave crest, respectively, C_c is the phase speed of the short wave at the large wave crest, and $q_{\max}$ the maximum value of the augmented wind drift.

We have measured wind wave spectra as a function of large-wave amplitude and frequency using a capacitance wire probe in conjunction with the microwave scattering measurements described by Keller and Wright (1975). We obtained the mean squared surface displacement of the wind waves by numerical integration of these spectra. The ratio of this mean squared displacement in the presence of mechanically generated waves to that in the absence of these waves is plotted in Figs. 4–6. In the case of the data of Figs. 4 and 5 the wind speed was 10 m s^{-1} ($u_*=64$ cm s^{-1}) and the wave amplitude was nearly constant at 2.9 cm and 5.5 cm, respectively, while the wave frequency was varied. The value of r^2 calculated from (5) is the solid curve in both cases. It is evident that the predicted diminution is much too great. In the case of the data of Fig. 6 the wave frequency was kept constant at 0.575 Hz and the amplitude varied at two lower wind speeds ($u_*=16.5$ and 30 cm s^{-1}). The solid and dotted lines are again the predictions calculated from (5). The predicted values at the lower wind speed are now too small. At $u_*=30$ cm s^{-1} the predicted and observed values are very close and this is the same wind speed at which Phillips and Banner (1975) obtained a reasonable agreement between theory and experiment. Data from Figs. 4

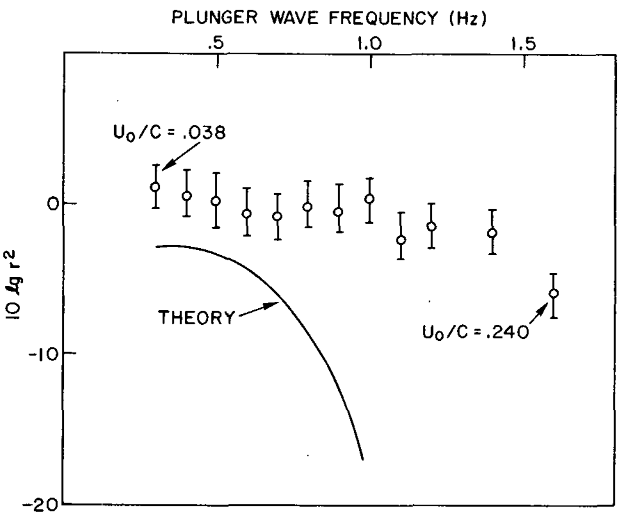

FIG. 4. Measured and calculated diminution of wind waves by plunger-generated waves: $u_*=64$ cm s^{-1}, plunger wave amplitude=2.9 cm, peak wind wave frequency=3.2 Hz, phase speed of dominant wind wave=49 cm s^{-1}, $q_0=35$ cm s^{-1}.

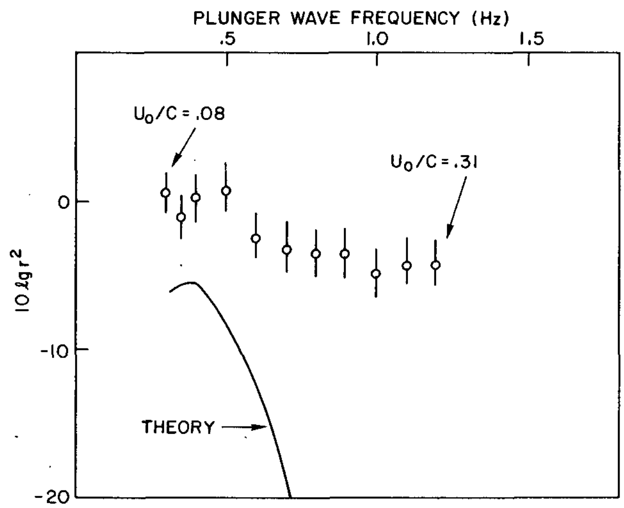

FIG. 5. Measured and calculated diminution of wind waves. Plunger wave amplitude=5.5 cm. Other parameters as in Fig. 4.

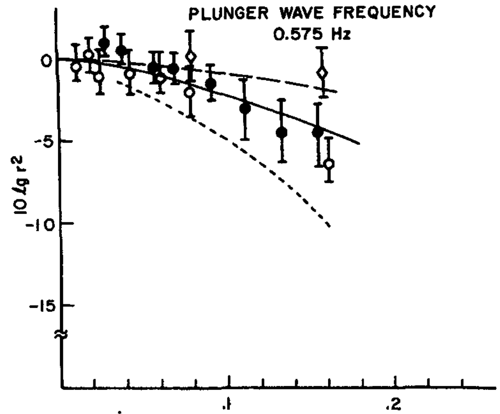

FIG. 6. Measured and calculated diminution of wind waves by 0.575 Hz plunger-generated waves:

u_* (cm s^{-1})	Measured r^2	Theoretical r^2	Peak frequency of wind waves (Hz)
16.5	○	----	4.2
30	●	——	3.4
64	◇	-----	3.0

and 5 at 0.575 Hz are shown again in Fig. 6 to emphasize that the wind-speed dependence of the measured diminution of wind wave amplitude is opposite to that predicted.

4. Summary and conclusions

In this note we have compared predictions of augmented wind drift and wind-drift-induced wave breaking with available measurements. There is little doubt that the wind drift is indeed augmented. There is some question, however, whether the augmented drift is as large as predicted and considerable question whether wave breaking resulting from such augmentation is energetically sufficiently dominant over the direct input from the wind to limit the amplitude of short gravity waves in the manner envisioned by Banner and Phillips (1974). This latter factor is the probable cause of the failure of most of the measurements reported here to conform to a theory which neglects the direct coupling of waves to wind.

Acknowledgments. The capacitance probe measurements were made jointly with my colleague, W. C. Keller, at the Wave Tank Facility of the University of Florida, Gainesville. The cooperation of Prof. Omar Shemdin and the staff of that facility is gratefully acknowledged. These data were taken under Contract NA-756-73 with the National Environmental Satellite Service.

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