Comments on "The Dependence of Sea Surface Roughness on Wave Development"

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While it is agreed that the sea state influences the aerodynamic drag coefficient, the manner in which it exerts this influence is far from clear, as witnessed by the recent workshop report by Toba and Jones (1992). Donelan et al. (1993) have drawn to our attention some of the dilemmas of attempting to describe drag over the whole range of wind-driven surface gravity waves from the wavelets of the laboratory tank to the monsters of the Southern Ocean.

Most of the previous literature fails to clearly make the point that at least two variables, not one, are needed to describe the statistics of the wind-driven ocean topography. Only in a wave field "in local equilibrium with the wind" can *one* of the pair of wave height and wave period be used. This, of course, is known and is illustrated by the probability distribution of significant wave height H_s and wave period T_s of ocean waves presented, for example, by Ezraty et al. (1978). When the wave height spectrum can be represented as

$$\phi(k) = f(k/k_p)F\left[\frac{u_*^2 k}{g}\right], \qquad (1)$$

where k_p is the wavenumber of the most energetic component, then there is a relationship between the standard deviation σ, k_p, gravity, and the friction velocity u_*. Toba's (1972) three-halves power law is an example of such a relationship. It was used in Toba et al. (1990, hereafter called TIKEJ90), to define a wave field "in local equilibrium with the wind"—that is, one that approximately satisfied

$$H_s^2 = B^2(gu_*)T_s^3, \qquad (2)$$

where T_s is a significant wave period defined in TIKEJ90. For such waves, only one wave variable, such as H_s, together with the wind, u_*, must be specified to define the gross properties of the topography.

The concept of the aerodynamic roughness, z_o, of a solid surface have proved to be an effective simplification for parameterizing the complex range of turbulent processes that are involved in transferring stress from the atmosphere to a solid boundary. Aerodynamists quickly found empirical relationships between z_o and the topography of the surface over which the air flows. However, for waves, the roughness elements are not fixed relative to the sea surface, but propagate relative to the surface. All components take part in the momentum transfer process; however, the phase speed of the most energetic wave components present, as a parameter representing the whole spectral range, can be used to form a nondimensional number, wave age.

It is important now to recognize that most authors predict (for waves in equilibrium with the wind) that aerodynamic roughness normalized by wave height decreases with wave age. The data from TIKEJ90 has been replotted in Fig. 1 to show it also follows this trend. This, however, is not the salient point of the exception Donelan et al. (1993) take to TIKEJ90, where both laboratory and field data has been treated as single dataset.

By using an expression such as Eq. (1), one variable can be eliminated from the plot of Fig. 1. In TIKEJ90 and Donelan et al. (1993) this is wave height σ. (Gravity g is introduced but is constant in these discussions.) The use of the "local equilibrium" criteria to reduce the number of variables is justified only in certain physical situations. A fetch-limited steady wind situation is one such situation. Rapidly decreasing wind stress, for example, is not one. (In the latter the wave height will be larger than appropriate for equilibrium.)

Donelan et al. (1993) suggest that young laboratory waves are much smoother (lower z_o) than their field

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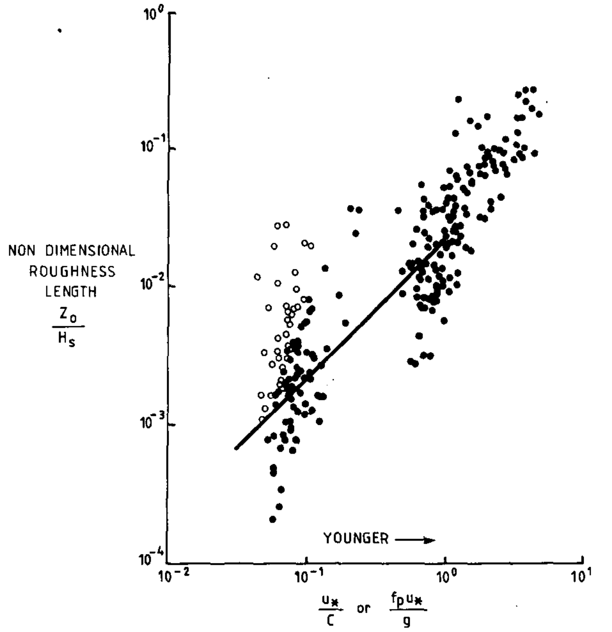

FIG. 1. The relationship between aerodynamic roughness and wave age for a set of measurements that have satisfied the criteria set out in TIKEJ90. Open symbols are data collected in Bass Strait and are not used in TIKEJ90 Eq. (30). The solid line is Eq. (3).

equivalents. However, they do not present any data at equivalent wave age to support this assertion. What is true is that the regression lines of z_o/σ over the short ranges of wave age, when extrapolated outside the data range, show lower normalized roughness than the field results for their tank experiments. The distinction is not nearly so clear when the ranges of c/u_* are increased by the use of the other datasets, as in TIKEJ90. By using both sets of data, on the assumption that they are part of a continuum, Donelan et al. (1993) argue that the conclusions about roughness length normalized by u_*, as a function of wave age (*for equilibrium waves*) is "incorrect" in TIKEJ90. They chose not to use in their Fig. 2 the "conservative expression"

$$\frac{gz_o}{u_*^2} = 0.02\left[\frac{\sigma_p u_*}{g}\right]^{-1/2} \quad (3)$$

advocated in the conclusion of TIKEJ90 in order to heighten the difference between their approach and the approach of TIKEJ90. Equation (3) is an empirical fit to the data collected together in TIKEJ90 and shows a negative dependence on inverse wave age. This is in sharp contrast to the positive power law proposed by Donelan et al.

Most people agree that flumes represent a different set of boundary conditions to the open ocean. Donelan et al. (1993) correctly point out that tank end reflections, different spectral shape, and directional spectral distributions occur in the tank experiments, compared with the field results. However, their observation that laboratory waves are steeper than ocean waves, may be the result of different wave ages, as discussed, for example, by Bailey et al. (1991). It is not established *at all* that differences in airflow separations and nonlinear effects that they speculate about are the result of the presence of the tank itself rather than wave age.

It is our point of view that wind waves can profitably be thought of as a continuum. Some variables that may be important change between laboratory tanks and the open ocean. We need to see if variables other than wave age are needed to model this transition. The results presented by Donelan et al. (1993) suggest this may be so. We await a young wave experiment in the natural environment to help resolve this important issue. The issue is of general importance because many of the concepts in air–sea interaction are derived from laboratory tank results.

Finally, we would like to take exception to the assertion by Donelan et al. (1993) that TIKEJ90 contend that "old waves are rougher than young waves." They are referring, not to Fig. 1, but to z_o normalized by u_*. We all agree that, at a constant wave height, old waves have a lower aerodynamic roughness than young waves. What we presented was the regression through a large number of experimental results that represented waves "in equilibrium with the wind." Statistically, the wave height increases with wave age and wind stress for such waves. In such a situation, changing from u_* to σ scaling does not help with the problem of spurious correlation (if there is one), rather it disguises it. If a log-law wind profile has been assumed, then the role of wave age, wind speed, and wave height in the proposed expression of TIKEJ90 can be seen in a drag coefficient diagram. When the class of waves that satisfy Eq. (2) is expressed as a function of wind speed, as in

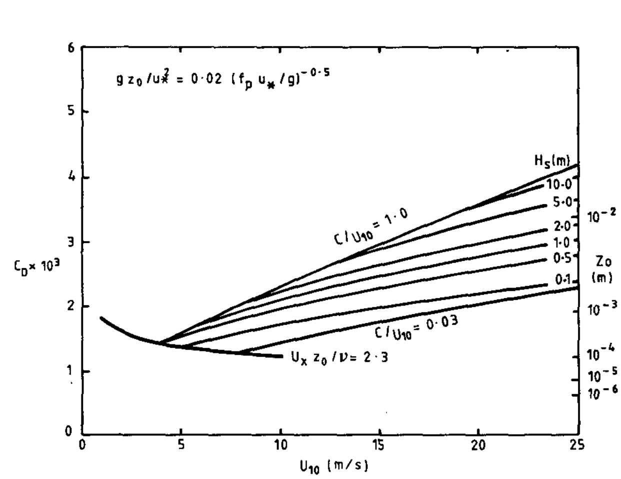

FIG. 2. The relationship between drag coefficient and wind speed for "equilibrium" waves developed from Eq. (30) of TIKEJ90. Here U_{10} is wind speed and ν is viscosity.

Fig. 2, we see for Eq. (3) an increasing drag coefficient at constant wind speed with wave age (and consequent wave height).

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