Reply

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Jones and Toba (1995) have raised some objections to our attempts (Donelan et al. 1993) to resolve the discrepancy between their view of the effect of wave development on the surface roughness and our own. They point out that "we all agree that, at a constant wave height, old waves have a lower aerodynamic roughness than young waves." We do indeed. Where exactly, then, is the disagreement? Perhaps this is best illustrated by constructing the corresponding figure to their Fig. 2 from our Eqs. (9) and (10) (Donelan et al. 1993). This is shown in Fig. 1, in which we have limited the wave age range to that which is covered by our field data. In this figure, moving along an iso-height line (dotted) from right to left, corresponding to decreasing wind speed and increasing wave age, yields a lower roughness (z_0 or equivalently C_D). The same is true in Jones and Toba (1995), Fig. 2. Note, however, that in their figure, in contrast to ours, higher wave ages occur at the top of the figure so that the essential difference is that *at constant wind speed* they show roughness increasing with wave age or wave height (as they point out), while we indicate the opposite. For example, at a wind speed of 15 m s^{-1}, their drag coefficient increases from 2.28×10^{-3} to 2.87×10^{-3} as wave height increases from 0.5 to 5 m—that is, as the wave age increases. By contrast, our drag coefficient reduces from 2.40×10^{-3} to 1.83×10^{-3}, so that while we are in good agreement for the 0.5-m height, their drag coefficient is 57% greater than ours for the 5-m waves. For stronger winds the differences are much larger. For example, at 25 m s^{-1}, wind speed and wave age equal 1.0 (near full development; wave height of

about 14 m), they offer 4.17×10^{-3} as the drag coefficient, while we are much lower at 2.29×10^{-3}. These are substantial differences particularly at high winds and high waves, conditions that obtain over significant areas of the deep oceans.

How do these differences arise? It is our contention that the Toba et al. (1990) result, reproduced by Jones and Toba (1995), is a direct consequence of the way they treat the laboratory and field data as a "continuum." This can be clearly seen in their Fig. 1, reproduced here, with some additions, as Fig. 2. Their regression line through both field and laboratory data (shown solid) does indeed indicate a pronounced decrease of the normalized roughness, z_0/H_s, with wave age (here represented by C_p/u_*). However, each data type (laboratory and field) taken separately has a greater slope than the line through the sets taken together. It is this difference in slopes that determines whether the roughness length (not normalized, or the drag coefficient) increases or decreases with wave age at a constant wind speed. To see this, we replace H_s by a combination of u_* and C_p as given by the 3/2 power law of Toba (1972). The line of slope 3/2 is shown (dashed) on Fig. 2 drawn through the field data points used by Toba et al. (1990). If the normalized roughness length, z_0/H_s, changes more rapidly with wave age than the line of slope 3/2, then our result obtains. If the change is less rapid than the 3/2 line, then this gives support to the Toba et al. (1990) contention. The field data taken alone clearly support a greater slope than the 3/2 line. The disagreement between Jones and Toba (1995) and us thus comes down to the question of whether to include laboratory data with the field data. We have given our arguments against fitting a simple power law to laboratory and field data together (Donelan et al. 1993) and need not repeat them here.

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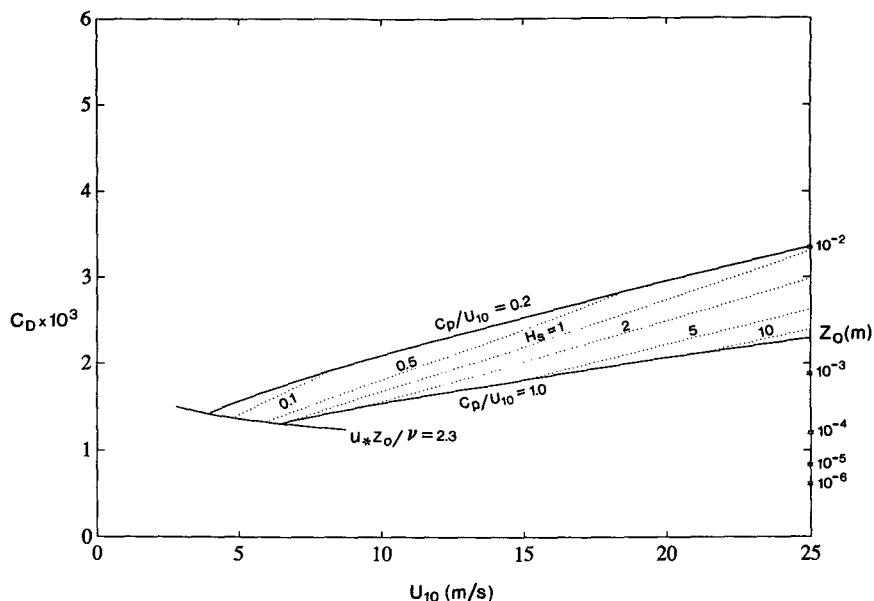E-mail: mark.donelan@cciw.ca

FIG. 1. The relationship between drag coefficient and wind speed for "equilibrium" waves developed from Eqs. (9) and (10) of Donelan et al. (1993). Here U_{10} is the wind speed and ν is viscosity. The solid lines are for wave ages of 0.2 and 1.0, and the fully rough limit $u_* z_0/\nu = 2.3$. The dotted lines are lines of constant significant height; the values indicated in meters. The corresponding roughness lengths are shown on the right-hand ordinate.
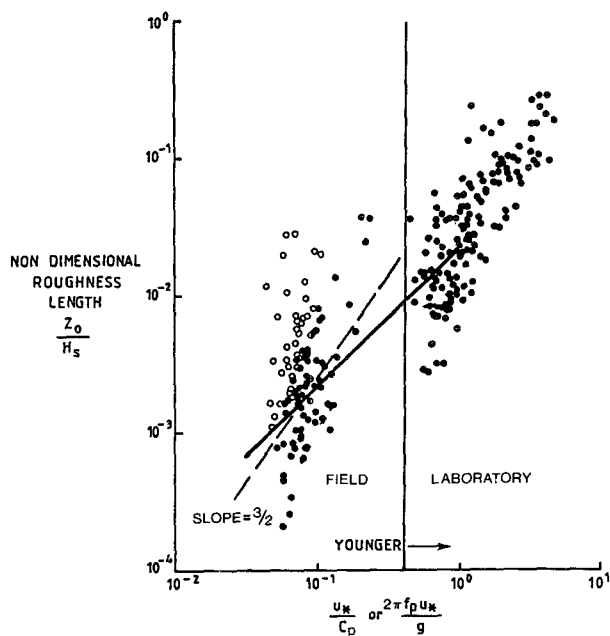

FIG. 2. The relationship between aerodynamic roughness and wave age for a set of measurements that have satisfied the criteria set out in Toba et al. (1990). Open symbols are data collected in Bass Strait that were not used in Toba et al. (1990) Eq. (30). The solid line is Eq. (3) of Jones and Toba (1995). The dashed line has a slope of 3/2.

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