On the Dependence of Sea Surface Roughness on Wave Development

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ABSTRACT

The aerodynamic roughness of the sea surface, z_0, is investigated using data from Lake Ontario, from the North Sea near the Dutch coast, and from an exposed site in the Atlantic Ocean off the coast of Nova Scotia. Scaling z_0 by rms wave height gives consistent results for all three datasets, except where wave heights in the Atlantic Ocean are dominated by swell. The normalized roughness depends strongly on wave age: younger waves (traveling slower than the wind) are rougher than mature waves. Alternatively, the roughness may be normalized using the friction velocity, u_*, of the wind stress. Again, young waves are rougher than mature waves. This contradicts some recent deductions in the literature, but the contradiction arises from attempts to describe z_0 in laboratory tanks and in the field with a single simple parameterization. Here, it is demonstrated that laboratory waves are inappropriate for direct comparison with field data, being much smoother than their field equivalents. In the open ocean there is usually a mixture of swell and wind-driven sea, and more work is needed before the scaling of surface roughness in these complex conditions can be understood.

1. Introduction

Wind stress τ on the sea surface is a driving force for ocean circulation. Accurate representation of this stress is important in modeling and forecasting both atmospheric and oceanic dynamics and, more recently, in interpreting the remotely sensed radar and microwave signatures of the sea surface.

The wind stress is parameterized by a drag coefficient $C_D = \tau/\rho U^2$ or by an aerodynamic surface roughness z_0. Generally z_0 is not measured directly, but is calculated from the measured wind speed and friction velocity. The wind profile law for neutral stratification is

$$U_N(z) = (u_*/\kappa)\ln(z/z_0), \tag{1}$$

where $u_* = (\tau/\rho)^{1/2}$ is the friction velocity, ρ is air density, and $\kappa = 0.4$ is the von Kármán constant. Throughout this manuscript the term "roughness" refers to the aerodynamic surface roughness z_0 rather than the physical size of the perturbations that cause it. There is a unique relationship between z_0 and the neutral drag coefficient,

$$z_0 = z/\exp(\kappa U/u_*) = z/\exp[\kappa/(C_{DN})^{1/2}], \tag{2}$$

so specifying the roughness specifies the drag coefficient and vice versa.

There has been a gradual evolution of understanding of the roughness and drag coefficient of the sea surface (Donelan 1992). During the decade of 1965–1975 the implementation of more direct eddy correlation methods led to reliable values of wind stress at moderate wind speeds. During the next decade (1975–1985) it became evident that the drag coefficient increases with wind speed. Over the open ocean the rate of increase is as predicted by the theory of Charnock (1955), who argued on dimensional grounds that for well-developed seas the roughness should be proportional to the wind stress τ,

$$z_0 = \alpha u_*^2/g. \tag{3}$$

Smith (1980, 1988) found a value $\alpha = 0.011$. Where younger waves prevail, at shallow or coastal sites, α is somewhat greater, about 0.018 (e.g., Garratt 1977; Wu 1980).

It is obvious that the roughness is due mainly to surface waves, but it has been difficult to relate the roughness to wave parameters in a quantitative way. Stewart (1974) proposed an extension of the Charnock relation, making the roughness an arbitrary function of wave age

$$z_0 = u_*^2/g \times fn(C_p/U_\lambda), \tag{4}$$

where C_p is the phase speed of the waves at the spectral

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peak, and the wind speed U_λ is measured at height λ, the wavelength of the longer waves. Donelan (1982) proposed that the roughness was proportional to the rms height of the shorter waves at and above twice the frequency of the spectral peak, and tested this model with data from Lake Ontario. Geernaert et al. (1987) proposed an empirical relation for dependence of the drag coefficient on wave age C_p/u_*. However, lacking wave spectral data, they had to estimate the wave field from the wind speed and fetch, and although they were on the right track this circular argument may have predetermined their result.

Representing the waves by wave age C_p/u_* or C_p/U_{10N} implies "spectral similarity," that is, that the wave spectrum has a consistent shape for a given wave age. Janssen (1989) used the Miles–Phillips wave growth theory to calculate wind profiles and stresses over growing waves. Nordeng (1991) proposed a "wave-age dependent Charnock constant" $\alpha = z_* \equiv gz_0/u_*^2$ based on theoretical development from the ideas of Kitaigorodskii (1973) and of Janssen (1989). From wind stress and wave data at a platform in the North Sea during the Humidity Exchange over the Sea (HEXOS) Program Smith (1992) found the dimensionless roughness z_* to be inversely proportional to wave age. Blake (1991) empirically fitted measured wind stress values to a five-term polynomial with terms in wind speed and significant wave height, U^nH^m, with $n = 2$, 3, and 4, and $m = 0$ and 1. (The significant wave height, in this context taken as $H = 4\sigma$, is the average height of the highest one-third of the waves.) Although no single description of the wave age dependence of the roughness emerges, these authors share a conviction that the roughness decreases with increasing wave age.

Toba et al. (1990) assembled a dataset with a wide range of wave ages by combining open ocean data from an oil platform in Bass Strait, Australia, with a collection of published coastal, lake, and laboratory data. In Bass Strait the wind stress was not measured; instead u_* was estimated from wave height and period using an empirical formula, and certain periods judged to be anomalous were deleted. Except for a few points from Lake Ontario the field u_* measurements used by Toba et al. (1990) were taken at depths of only 3–6 m, where C_p is limited to 5–8 m s^{-1}. At these sites, except in light winds, the effective wave age is less than that of deep-water ocean waves having the same peak frequencies. More important, waves propagating into shoaling water become steeper and eventually break, strongly enhancing their roughness. As noted above, even coastal ocean sites have higher roughness than open ocean sites. In spite of this, most of the Bass Strait estimates of z_* are substantially higher than the values from shallow sites. Toba et al. concluded that roughness is proportional to wave age, and fitted a power law,

$$z_* = 0.025(C_p/u_*), \qquad (5)$$

to the combined data because their youngest waves of all (laboratory waves) were considerably smoother for a given wave age than field waves. Their dependence of z_* on wave age reduced to $(C_p/u_*)^{1/2}$ if the Bass Strait values were deleted. It is our contention that the conclusions of Toba et al. (1990) on the wave age dependence of the roughness are incorrect. They arise through an inappropriate juxtaposition of laboratory data with field data, and to a lesser degree through using field data that are not directly relevant to the ocean and to overestimation of u_* in Bass Strait.

In the following we will demonstrate the separation of the populations of roughness estimates obtained in the field and in the laboratory. We will suggest several reasons for the differences; however, lacking an overall theory for the momentum transfer at the air–sea interface, we are unable to reconcile the differences. Nonetheless, it is apparent that simple parameterization schemes based on nondimensional combinations of interfacial parameters must treat the two populations differently.

2. Relationship between surface roughness and waves

In Fig. 1 the eddy wind stress measurements of Donelan (1990), from an anemometer bivane at a platform in 12 m of water in Lake Ontario, clearly show an increase of roughness scaled with rms wave height, σ, for younger waves. The regression line

$$z_0/\sigma = 5.5 \times 10^{-4}(U_{10}/C_p)^{2.7} \qquad (6)$$

from Donelan agrees quite well with the regression line

$$z_0/\sigma = 5.3 \times 10^{-4}(U_{10}/C_p)^{3.5} \qquad (7)$$

fitted to selected HEXOS eddy correlation data (Smith et al. 1992) from sonic and pressure anemometers (Oost et al. 1992) on a platform in 18 m of water in the North Sea 9 km off the Dutch coast. Cases with single-peaked wave spectra were selected, where the wave height was believed to be determined by locally generated sea. The idea that the roughness length z_0 should be well correlated with the height of the roughness elements (waves) depends on the concept of aerodynamically rough flow. Consequently we have restricted our attention—as did Toba et al. (1990)—to cases where the roughness Reynolds number, u_*z_0/ν, exceeds 2.2; here ν is the kinematic viscosity of air.

Donelan's data and the selected HEXOS data are for pure wind seas and, as such, permit a direct comparison between the roughness length and wave properties. Also shown in Fig. 1 are data from Smith (1980), with wind stress measured using a thrust anemometer on an unmanned stable platform exposed to the full fetch of the North Atlantic Ocean. At this site the rms wave height was usually dominated by swell and in many cases the sea peak in the one-dimensional wave spectra (directional wave spectra were not obtained) could not even be identified to determine the phase velocity. For onshore winds (long fetch) the roughness

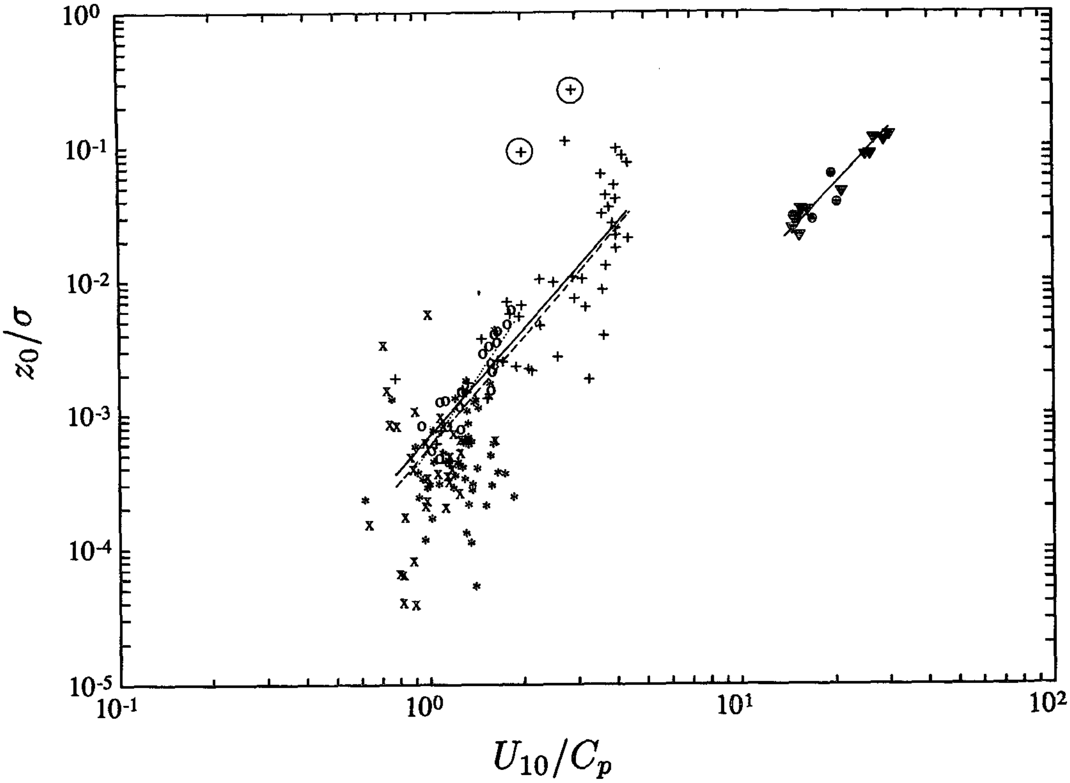

FIG. 1. The ratio of measured roughness length z_0 to rms wave height σ versus inverse wave age U_{10}/C_p. Roughness Reynolds number > 2.2. Symbols: Lake Ontario +; HEXOS O; Atlantic Ocean, long fetch *; limited fetch ×; Donelan (1990) wave tank ▼, Keller et al. (1992) wave tank ●. Lines: ——, overall regressions to field data [Eq. (8)] and to laboratory data; – – – Eq. (6) Lake Ontario (Donelan 1990); · · · · · Eq. (7), HEXOS (Smith et al. 1992).

values lie mainly on or below the lines from Eqs. (6) and (7), illustrating that for the open ocean the rms wave height is often determined not by local processes but by swell, and is not an appropriate parameter for scaling the roughness. The points for offshore and alongshore winds are more scattered but follow the same pattern. All datasets are for nearly neutrally stratified conditions and are converted to equivalent neutral values. In addition a small correction due to the vertical stress gradient has been applied to recover the surface stresses from those measured near 10 m (Donelan 1990).

The overall regression line through both the HEXOS and Donelan field datasets, indicated in Fig. 1, is given by

$$z_0/\sigma = 6.7 \times 10^{-4}(U_{10}/C_p)^{2.6}. \qquad (8)$$

Two of Donelan's data points, excluded from the regression calculation by the "Chauvenet criterion" (cf. Maat et al. 1991), are circled in the figure.

The roughness length may be expressed in terms of the wind speed and wave age by application of an empirical relationship between σ and U/C_p from Lake Ontario field data (Donelan et al. 1985, Fig. 16), $\tilde{\epsilon} = \sigma^2 g^2/(U\cos\theta)^4 = 0.00274(U\cos\theta/C_p)^{-3.3}$, where θ is the angle between the waves and the wind. If $\cos\theta \approx 1$,

$$\sigma = 0.055(U^2/g)(U/C_p)^{-1.7}, \qquad (9)$$

so that for fully rough field conditions

$$z_0 = 3.7 \times 10^{-5}(U^2/g)(U/C_p)^{0.9}. \qquad (10)$$

This demonstrates that the roughness length for field waves depends on the wind quadratically and approximately inversely on the wave age, C_p/U_{10}. [The use of a "3/2 power law" (as in Toba et al. 1990) instead of (9) leads to a similar result.]

Roughness lengths from laboratory data shown on Fig. 1 are from two sources in which the measurements of the friction velocity were made by direct eddy correlation methods using X-film anemometry. The regression line through the more extensive dataset (Donelan 1990) is also indicated.

Although both field and laboratory datasets show strong positive dependence of the normalized roughness length z_0/σ on the wind forcing parameter U_{10}/C_p (inverse wave age), various attempts to find a common parameterization of z_0/σ on other wave age related parameters (u_*/C_p, U_λ/C_p) were unsuccessful (Donelan 1990). The field and laboratory data are distinctly separated: extrapolation of the laboratory results to typical field conditions yields roughness lengths smaller than the field results by a factor of 20. If the field and laboratory data are treated as samples from the same population, as in Toba et al. (1990), the dependence of z_0/σ on U_{10}/C_p is much weaker (roughly linear instead of 2.6 power), and when equation (9) is applied, z_0 then shows dependence on wave age opposite to (10).

In Fig. 2 the same data are scaled in a different way, which is often used in studies of sea surface roughness. The dimensionless roughness is in the form $z_* \equiv gz_0/u_*^2$ and the inverse wave age parameter u_*/C_p is also scaled with the friction velocity u_*. This avoids the problem of not knowing the contribution of the swell: but, with both parameters scaled by the same variable, self-correlation can give rise to spurious regression results (e.g., Perrie and Toulany 1990). Smith et al. (1992) argued that in spite of this there is a significant dependence of the residual drag coefficient (after removing the dependence on wind speed) on the wave age, approximately doubling the drag coefficient for the youngest waves in the HEXOS dataset. Allowing for local flow distortion and using averaged wind stress from sonic and pressure anemometers, the HEXOS result (solid line),

$$z_0 = 0.48u_*^3/gC_p, \quad (11)$$

gives the opposite dependence on wave age from Toba et al. (dashed line). The separation of field and laboratory data is again apparent in Fig. 2.

Other choices of nondimensional variables with which to examine the effect of waves on roughness length have been tried. For example, Toba (1979) and Toba and Koga (1986) have argued that the dimensionless combination $u_*^2/\nu\omega_p$ (where ω_p is the frequency of the wave spectrum peak) is well correlated with the roughness Reynolds number, u_*z_0/ν (Fig. 3). The line of linear proportionality, $z_0 = 0.025u_*/\omega_p$ (solid line), does follow the trend of the laboratory data from several sources and the field and laboratory data do overlap. The dashed line that we have fitted to their field data, with a slope of 1.9, shows a more rapid (approximately quadratic) dependence of u_*z_0/ν on $u_*^2/\nu\omega_p$; there is still a systematic difference between the roughnesses of field and laboratory waves. Again there is a possibility of spurious self-correlation through the use of common scaling parameters.

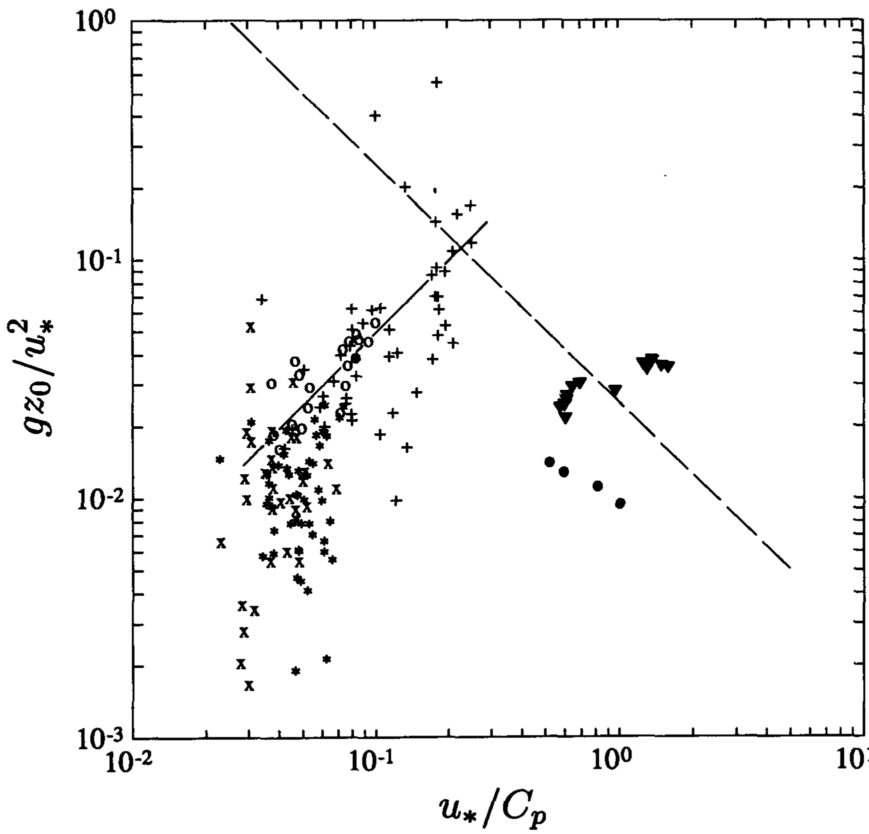

FIG. 2. Dimensionless roughness gz_0/u_*^2 versus inverse wave age u_*/C_p. Symbols as in Fig. 1. Regression lines: —— Eq. (11), HEXOS; – – – Toba et al. (1990), (our) Eq. (5).

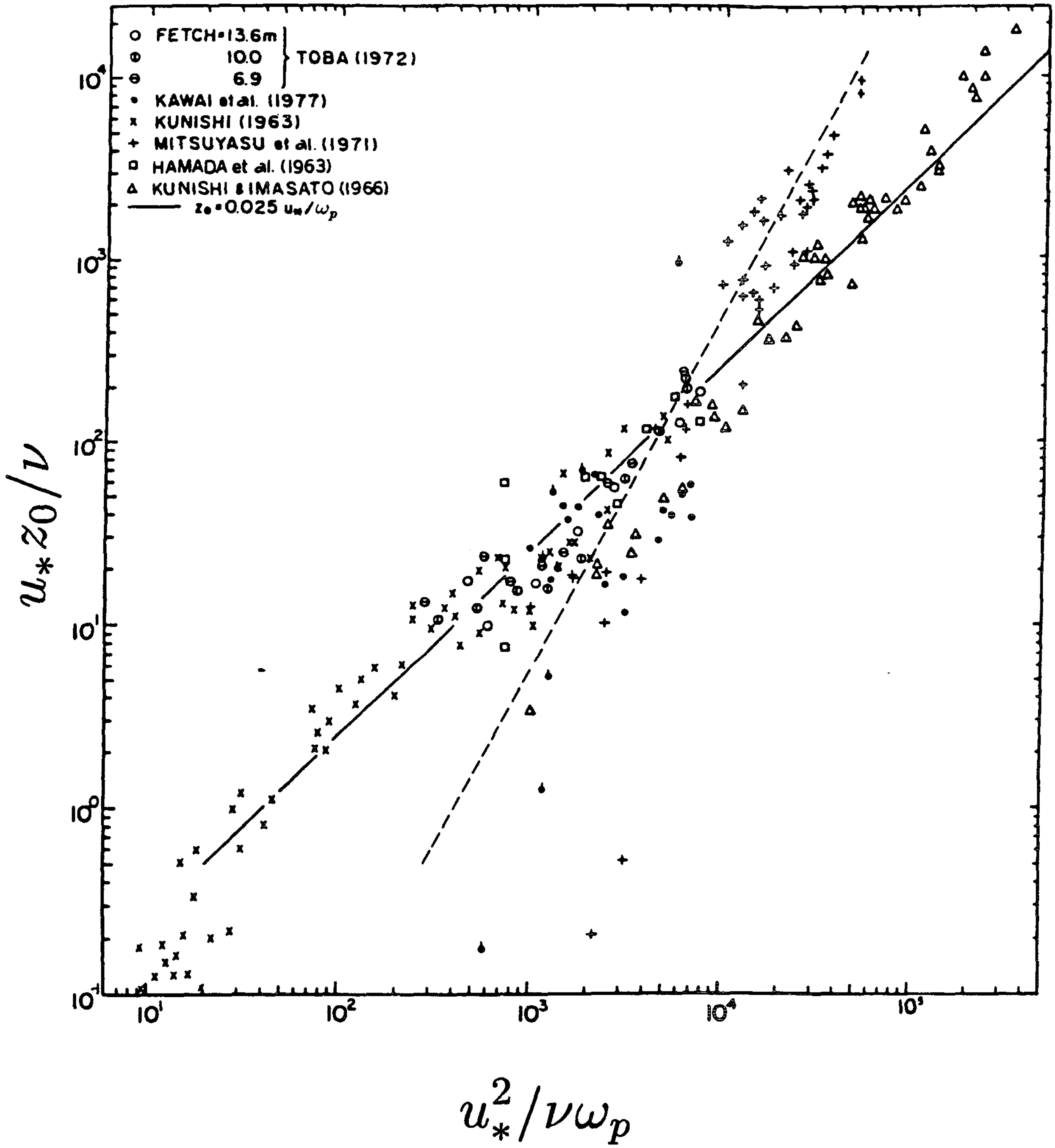

FIG. 3. (Adapted from Fig. 6 of Toba and Koga 1986.) u_*z_0/ν vs $u_*^2/\nu\omega_p$. Symbols: +, ● field data; all others from laboratory waves. Regression lines: —— $z_0 = 0.025u_*/\omega_p$ (slope = 1); – – – line fitted to field data only (slope = 1.9).

3. Why are laboratory waves less rough?

In a recent review of work on the relation between wind stress and wave characteristics (Donelan 1990), data from both wind-wave flumes and the field are discussed. However, the question of why the waves in laboratory wind-wave flumes should appear less rough remains open. A number of possibilities comes to mind. First, flumes have side walls and ends. The side walls reflect wave components not traveling directly downwind, focusing them in the center of the flume (Longuet-Higgins 1990). The ends reflect a small fraction of the waves generated along the fetch, typically about 5% (Papadimitrakis et al. 1986). The wave-induced air pressure, which is proportional to $(U - C)^2$, is strongly affected by upwind traveling waves. Any downwind surface drifts set up in the flume must return at the bottom. Thus, the air pressure field and the shear in the water are not correctly modeled. Both could affect the action density and the rate of transfer of momentum to the waves—hence the stress.

Second, the wave variance in flumes is more concentrated in the dominant wavenumber bands than in nature, that is, flume spectra have sharper peaks. This can be interpreted as a sign that the balance among wind input, nonlinear interactions, and dissipation differs from that found in the field, possibly as a consequence of sidewall reflections, and by dissipation by breaking waves being less broadly distributed in wavenumber space.

Third, the steepness and enhanced wavenumber density of the flume waves may cause them to shelter each other, reducing the effectiveness of flow separation as a growth mechanism for the very young waves. Chang et al. (1971) have shown that the average streamlines over steep laboratory waves show strong separation and the presence of a "stationary eddy" behind the wave crests. The apparent roughness due to steep individual elements increases at first with increasing packing density, and then decreases when the separation distances are comparable to the length of the separation bubbles (Schlichting 1968). In essence, the effective height of closely spaced roughness elements is reduced by the depth of the separation bubbles directly upstream. This may cause the roughness to peak at a wave age between values observed for field and laboratory waves. We do not have direct evidence to support this speculation, but it is interesting to note in Fig. 2 that the estimated very short fetch (16.3 m) tank data points of Keller et al. (1992) have a slope almost orthogonal to the trend of the field data points, whereas the longer fetch (49.8 m) tank data of Donelan (1990) have a slightly positive slope and are several times larger than the Keller et al. data in these coordinates. Perhaps a sufficiently long tank could yield roughnesses that are directly comparable to field values.

All of these effects, taken together, suggest that flume results cannot be directly lumped together with the field data using simple formulas such as we have tested. Presumably if the correct physical law can be found, taking all effects into account, it will be possible to tie tank waves to ocean waves in a consistent manner.

Although the roughness of very young waves ($U_{10}/C_p \approx 10$) has been studied extensively in wind-wave flumes it is not known for the open sea. This is partly because the roughness of a given sea is difficult to measure, but more because it has proven extremely difficult to estimate the amplitude spectra of the very young waves in the presence of the longer, much larger "dominant" waves, and to estimate the contributions of the different wave components to the roughness. The young waves are believed to extract momentum from the wind field by mechanisms—flow separation, viscous instability—different from those—instability of the turbulent shear flow in the air boundary layer—that drive the longer, older wave components.

4. Discussion

We have compared roughness with inverse wave age (wind speed/wave speed ratio) from a variety of sources and with a variety of scaling strategies. Our datasets are carefully selected to include measurements of both waves and wind stress, as opposed to estimates of those parameters inferred by other means.

We find that roughness/wave age relations for wind-flume waves differ substantially from the open ocean relationship. For reasons we can only speculate upon, wind-flume waves of a given age are smoother than their open-sea equivalents. Our speculation centers on the hypothesis (cf. Donelan 1990) that the number density of the wind flume waves is larger than open-sea waves, and at high wavenumbers, where flow separation may be a major contributor to wave growth and hence to wind stress, the separation bubbles may merge and create a surface, which acts smoother than one with lower wave number densities; that is, closely spaced flume waves may shelter each other. In contrast Toba et al. (1990) compared wind-flume results, which are for extremely young waves, with their field results to produce a relation that indicates the older waves are rougher.

In the open ocean the wave height variance is typically dominated by swell, that is, by wave components that are believed to have a negligible direct effect on the wind stress. We find that the presence of significant swell variance precludes an accurate estimation of the roughness/wave age relation. The evidence for this comes from our own data. First, we can only achieve a tight wave age/roughness relation if we carefully exclude from our data all wave fields where more than one peak occurs in the wave spectrum. Second, if we plot data points in which the only available measurement is total wave variance and the influence of the swell is unknown (e.g., the data from Smith 1980), the roughness scaled by the combined sea and swell height lies on or below the regression line from experiments with little or no swell present. Smith (1980) found that adding information on rms wave height did not improve on his estimates of u_* from U only.

5. Conclusions

1) Very young laboratory waves are not as rough as their field equivalents. The two types of waves cannot be used together to determine a simple relation between the roughness of the sea surface and the wave age. We can speculate on possible reasons why this may be so. A complete formula for wave roughness should be able to describe both field and laboratory data, but more

work and new insights will be needed before this is achieved.

2) Young ocean waves are rougher than mature waves. The Toba et al. (1990) contention that old waves are rougher than young waves is based on an inappropriate combination of field and laboratory data.

3) If z_0 is scaled with u_*, variations in u_* can produce spurious correlation with dimensionless wave age, masking the sought-after relation between roughness and sea state. Scaling z_0 with σ is preferable if it can be determined that the rms wave height is due only to locally generated sea.

4) More work will be needed to sort out the relationship between wind stress and sea state in the presence of swell, which is usually present in the ocean.

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