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ON THE DEPENDENCE OF SEA SURFACE ROUGHNESS ON WAVE DEVELOPMENT

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MANAGEMENT PERSPECTIVE

Modelling and forecasting of atmospheric and oceanic dynamics, vital in our search to understand Global change, is dependent on an accurate representation of the wind stress on the ocean surface. In this paper the authors show that a published wind stress description is incorrect, and present a correct description.

SOMMAIRE À L'INTENTION DE LA DIRECTION

La modélisation et la prévision des caractéristiques dynamiques de l'atmosphère et des océans, qui sont vitales pour nos recherches visant à mieux comprendre les changements à l'échelle globale, dépendent d'une représentation exacte de la force d'entraînement du vent sur la surface de l'océan. Dans cette publication, les auteurs montrent qu'une description publiée de la force d'entraînement du vent est incorrecte, et présentent une description correcte.

ON THE DEPENDENCE OF SEA SURFACE ROUGHNESS ON WAVE DEVELOPMENT

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ABSTRACT

The aerodynamic roughness of the sea surface, z_o, is investigated using data sets from Lake Ontario, from an offshore platform in the North Sea near the Dutch coast, and from one in the Atlantic Ocean. Scaling the roughness by rms wave height gives consistent results for all three data sets except where the Atlantic Ocean wave heights are dominated by swell, which does not contribute to the roughness. The contribution of waves to the normalized roughness depends strongly on wave age: younger waves (travelling 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. Although this contradicts some recent deductions in the literature, it is shown that the contradiction arises from attempts to describe the roughness in laboratory tanks and in the field with a single parameterization. Here, we demonstrate that laboratory waves are inappropriate for comparisons with field data. Laboratory waves are much smoother than their field equivalents. The requirement that wave height be used to scale the roughness implies that in the open ocean the roughness, and hence the wind stress via the drag coefficient, must be determined from the height of the wind sea, since swell has no measurable effect on it. This in turn implies a need to separate sea from swell in estimating wind stress from wave characteristics.

RÉSUMÉ

La rugosité aérodynamique de la surface de la mer, z_0, est étudiée à l'aide d'ensembles de données provenant du lac Ontario, d'une plate-forme offshore dans la mer du Nord, près de la côte des Pays-Bas, et d'une autre dans l'océan Atlantique. Lorsque la mesure de la rugosité est faite en fonction de la racine quadratique moyenne de la hauteur des vagues, on obtient des résultats constants pour tous les trois ensembles de données, sauf dans l'océan Atlantique, quand les hauteurs des vagues sont dominées par la houle, une condition qui ne contribue pas à la rugosité. La contribution des vagues à la rugosité normalisée dépend fortement de l'âge des vagues. Les vagues les plus jeunes (qui se déplacent plus lentement que le vent) sont plus rugueuses que les vagues plus âgées. Par ailleurs, la rugosité peut être normalisée à l'aide de la vélocité de friction, u_*, de la force d'entraînement du vent. Dans ce cas aussi, les vagues plus jeunes sont plus rugueuses que les vagues plus âgées. Bien que ceci contredise des déductions récentes présentées dans la littérature scientifique, on montre que ces contradictions proviennent de tentatives visant à décrire la rugosité dans des bassins en laboratoire et sur le terrain en utilisant un même ensemble de paramètres. Ici, nous démontrons que les vagues en laboratoire sont inappropriées pour les comparaisons avec des données obtenues sur le terrain. Les vagues de laboratoire sont beaucoup plus douces que les vagues équivalentes observées sur le terrain. L'exigence de l'utilisation de la hauteur des vagues comme base de mesure de la rugosité implique qu'en pleine mer, la rugosité, et par conséquent la force d'entraînement due au vent, dérivée à partir du coefficient de traînée, doit être déterminée à partir de la hauteur de la mer agitée par le vent, étant donné que la houle n'a pas d'effet mesurable sur la rugosité. Ceci implique par ailleurs la nécessité de séparer les caractéristiques de la mer de celles de la houle pour évaluer la force d'entraînement due au vent à partir des caractéristiques des vagues.

INTRODUCTION

Wind stress on the sea surface is a driving force for ocean circulation. Accurate representation of this stress, τ, 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. There has been a gradual evolution of understanding of the roughness and drag coefficient of the sea surface (Donelan, 1992). During the decade of 1965-75 the development of more direct eddy correlation measurements led to reliable values of wind stress at moderate wind speeds. During the next decade (1975-85) it became evident that the drag coefficient increased with wind speed. Over the open ocean the rate of increase was as predicted by the theory of Charnock (1955), who argued on dimensional grounds that for well-developed seas the surface roughness should be proportional to the wind stress (e.g. Smith, 1980). Where younger waves prevail, at shallow or coastal sites, the rate of increase is somewhat greater (e.g. Garratt, 1977; Wu, 1980).

It is obvious that the roughness is due in part to surface waves, but it has been difficult to relate the surface roughness to wave parameters in a quantitative way (Donelan, 1982). Geernaert *et al.* (1987) proposed a dependence of the drag coefficient on wave age C_p/u_* but, lacking wave spectra in their data, they had to deduce certain aspects of the wave field from the wind speed and fetch. (Here C_p is the phase speed of the waves and $u_* = (\tau/\rho)^{1/2}$ is the friction velocity; ρ is air density.) Janssen (1989) used the Miles-Phillips wave growth theory (Miles, 1960) to calculate wind profiles and stresses over growing waves. Nordeng (1991) proposed a "wave-age dependent Charnock constant" based on theoretical development from the ideas of Kitaigorodskii (1973) and of Janssen (1989). Maat *et al.* (1991) extended the Charnock relation to include wave age, based on HEXOS wind stress and wave data at a platform in the North Sea. Blake (1991) empirically fitted measured wind stress 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. Although no single description of the wave age dependence of the roughness emerges, these authors share a common conviction that the roughness decreases with increasing wave age.

Generally the surface roughness z_o is not measured directly, but is calculated from the measured wind speed and friction velocity. The wind profile law for neutral stratification is

$$U(z) = (u_*/\kappa)\ln(z/z_o) \tag{1}$$

and hence

$$z_o = z/\exp(\kappa U/u_*) = z/\exp[\kappa/(C_D)^{1/2}] \tag{2}$$

Toba *et al.* (1990) obtained a wide range of wave ages by combining their open-ocean data from an offshore oil platform with a collection of published coastal, lake and laboratory data. Their own field data tend to show larger roughness for younger waves, but they fitted a power law to the combined data,

$$gz_0/u_*^2 = 0.025\ (u_*/C_p)^{-1} \tag{3}$$

with the opposite dependence on wave age, because the youngest waves of all (laboratory waves) are considerably smoother for a given wave age than the field waves.

It is our contention that the conclusions of Toba *et al* (1990) on the wave age dependence of the sea surface roughness are incorrect and arise entirely through an inappropriate juxtaposition of laboratory data with field data.

In the following we demonstrate the separation of the populations of roughness estimates obtained in the field and in the laboratory. We offer several reasons for the differences, but, 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 necessarily treat the two populations differently.

RELATIONSHIP BETWEEN SURFACE ROUGHNESS AND WAVES

In Figure 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 for younger waves. The regression line

$$z_o/\sigma = 5.5 \times 10^{-4} (U_{10}/C_p)^{2.7} \tag{4}$$

from Donelan agrees quite well with the regression line

$$z_o/\sigma = 5.3 \times 10^{-4} (U_{10}/C_p)^{3.5} \tag{5}$$

fitted to the HEXOS data (Smith *et al.*, 1992) from a platform in 18 m of water 9 km off the Dutch coast in the North Sea, using the average of stresses measured with a sonic anemometer and a pressure anemometer (Oost *et al.*, 1991) and selecting cases with single-peaked wave spectra where the rms wave height is believed to be determined by locally-generated sea.

The idea that the roughness length z_o should be well-correlated with the height of the roughness elements (waves) depends on the concept of aerodynamic roughness. Consequently we restrict our attention - as did Toba *et al* (1990) - to cases where the roughness Reynolds number, $u_* z_o/\upsilon$, exceeds 2.2; here υ is the kinematic viscosity of air.

Donelan's data and the HEXOS data are for pure wind seas and, as such, permit a direct comparison between the roughness length and wave properties. Also shown in Figure 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 lies mainly on or below the lines from Equations 4 and 5, illustrating that for the open ocean the rms wave height is often not determined by local processes and is not an appropriate parameter for scaling the surface roughness. The points for offshore and alongshore winds are more scattered but follow the same pattern. All data sets are for nearly neutrally stratified conditions and are converted to equivalent neutral values. In addition the small correction due to the vertical stress gradient has been applied to recover the surface stresses from those measured near 10m (Donelan, 1990).

The overall regression line through both the HEXOS and Donelan field data sets is indicated in Figure 1 and given by (6) (two of Donelan's data points were excluded from the regression calculation by the "Chauvenet criterion" (*cf* Maat *et al*, 1991): these are circumscribed in the figure):

$$z_o/\sigma = 6.7\times10^{-4}(U_{10}/C_p)^{2.6} \tag{6}$$

The roughness length may be expressed in terms of the wind speed and wave age by application of the empirical relationship between σ and U/C_p from Donelan *et al* (1985)

$$\sigma = 5.5\times10^{-2}(U^2/g)(U/C_p)^{-1.7} \tag{7}$$

so that for aerodynamically rough field conditions

$$z_o = 3.7\times10^{-5}(U^2/g)(U/C_p)^{0.9} \tag{8}$$

This demonstrates that the roughness length for field waves depends on the wind quadratically and approximately inversely as the wave age, C_p/U_{10} [The use of Toba's "3/2 power law" instead of (7) leads to a similar result].

Roughness lengths obtained from laboratory data are also shown on Figure 1. These 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 data set (Donelan, 1990) is also indicated. It is interesting that both field and laboratory data sets show strong positive dependence of the normalized roughness length z_o/σ on the wind forcing parameter U_{10}/C_p (inverse wave age). Various attempts to find a common parameterization of z_o/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 that are smaller than the field results by a factor of 20.

If the field and laboratory data are treated as samples from the same population, the dependence of z_o/σ on U_{10}/C_p is much weaker (roughly linear instead of 2.6) and when equation (7) is applied z_o then shows the opposite dependence on wave age compared to (8).

In Figure 2 the same data are scaled in a different way, which is often used in studies of sea surface roughness. The dimensionless wave height is in the form gz_o/u_*^2 and the 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 HEXOS waves. Allowing for local flow distortion and using averaged wind stress from sonic and pressure anemometers,

$$z_o = 0.48\, u_*^3/gC_p \qquad (9)$$

(solid line in Figure 2), giving the opposite dependence on wave age from Toba *et al.*, 1990) (dashed line).

The separation of field and laboratory data is again apparent in Figure 2. Other choices of non-dimensional 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 (Figure 3) that the dimensionless combination $u_*^2/\upsilon\omega_p$ (where ω_p is the frequency of the wave spectrum peak) is well correlated with the roughness Reynolds number, $u_* z_o / \upsilon$. The line of linear proportionality is equation (3) and does follow the trend of the laboratory data from several sources. The field data show a definitely more rapid (approximately quadratic) dependence of $u_* z_o / \upsilon$ on $u_*^2 / \upsilon \omega_p$.

WHY ARE LABORATORY WAVES LESS ROUGH?

For a recent review of work on the wave growth - water surface roughness relation in both wind-wave flumes and in the field see Donelan (1990). The question of why the waves in laboratory wind-wave flumes should appear smoother to the air above remains unanswered. A number of possibilities come to mind.

First, flumes have side walls and ends. The side walls reflect wave components not travelling directly downwind, focussing them in the centre 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), and any downwind surface drifts set up in the flume must return at the bottom. Thus the air pressure field (the wave induced air pressure, which is proportional to $(U - C)^2$, is affected by upwind travelling waves) and the shear in the water are not correctly modelled. 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 source term balance among wind input, nonlinear interactions and dissipation differs from that found in the field, possibly as a consequence of sidewall reflections and dissipation by breaking less broadly distributed in wavenumber space.

Third, the steepness and enhanced number 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 flume 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 the roughness elements is reduced by the depth of the separation bubble directly upstream. Something of this sort may act to reduce the roughness of laboratory waves.

All of these effects, taken together, make it unlikely that the flume waves model the roughness of the sea surface accurately, and make it difficult to see how the flume results can be lumped together with the field data.

It is interesting to note in Figure 2 that the estimated slope of the very short fetch (16.3m) tank data points of Keller *et al* (1992) is almost orthogonal to the trend of the field data points, whereas the longer fetch (49.8m) tank data of Donelan (1990) has a slightly positive slope and is several times larger than the Keller *et al* data in these coordinates. Perhaps a sufficiently long tank would yield roughnesses that are directly comparable to the field values.

Although the roughness of very young waves ($U_{10}/C > 10$) has been studied extensively in wind-wave flumes it is not known for the open sea. This is partly because the aerodynamic 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, "dominant" waves and so to estimate the contributions of the different wave components to the observed 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 - which drive the longer, older wave components.

DISCUSSION

We have compared aerodynamic roughness with wind speed/wave speed ratio (inverse wave age) from a variety of sources and with a variety of scaling strategies. Our data sets have been carefully selected and laboratory and field results are treated separately. We also use only data that include measured waves and aerodynamic roughness (as opposed to estimates of those parameters inferred by other means).

We find that the roughness/wave age relation for wind flume waves differs 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 that (*cf* Donelan, 1990) 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, ie the closely spaced wind flume waves may shelter each other. In any case we find that the wind flume results, if used, would bias the roughness/wave age relation to lower roughnesses than appropriate for open ocean conditions, and we believe that they should be considered separately.

In contrast Toba *et al.* (1990) choose to compare wind flume results, which are for extremely young waves, with their open ocean results for fully-developed seas to produce a relation which indicates the older waves are rougher. Had they chosen to use only their field results, they would have been led to opposite conclusions.

In the open ocean the wave variance is typically dominated by swell, that is, by wave components that have a negligible affect 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 omit data points from our fits in which the only available measurement is total wave variance and the influence of the swell is unknown (e.g. the Stable Tower data from Smith, 1980), the roughness scaled by the combined rms sea plus swell height lies on or below the regression line from experiments with little or no swell present. Smith found that adding information on rms wave height did not improve on his estimates of u_* from U only. If the wave field directional spectrum is known along with the rms wave height and the wind velocity, then sea can be separated from swell (*cf* Dobson *et al*, 1989) and a more accurate estimate of u_* can be obtained from both wave age and wind speed.

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 the relation between the aerodynamic roughness of the sea surface and the sea state.

2. Open ocean wave heights are usually dominated by swell; directional resolving techniques are required to identify, in the presence of swell, the phase velocity C_p of the peak of the wind sea spectrum and the rms height σ of the sea waves.

3. Young waves are rougher aerodynamically than mature waves. The Toba et al. (1990) contention that old waves are rougher than young waves is inappropriate and misleading. Scaling with u_* is unreliable because significant variations in u_* will produce spurious correlation, masking the sought-after relation between roughness and sea state.

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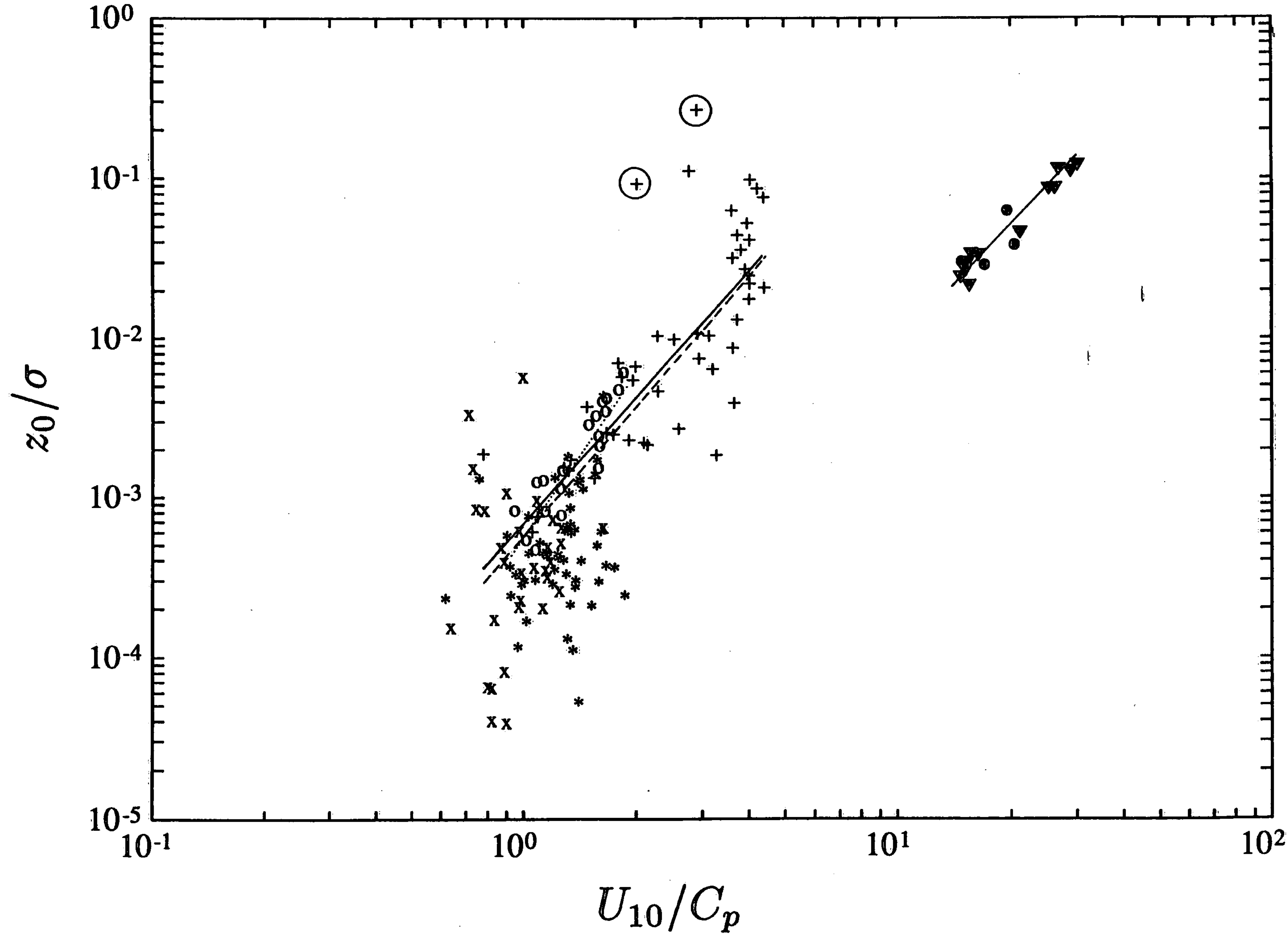
FIGURE CAPTIONS

Figure 1. The ratio of measured roughness length z_o 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 x; Donelan (1990) wave tank ▼, Keller *et al* (1992) wave tank ●. Regression lines: —— Equation 6, overall field data regression; —— Equation 4, Lake Ontario (Donelan, 1990); —— Equation 5, HEXOS (Smith *et al.*, 1992).

Figure 2. Dimensionless roughness gz_o/u_*^2 versus inverse wave age u_*/C_p. Symbols as in Figure 1. Regression lines: —— Equation 9, HEXOS; —— Toba *et al.*, 1990, (our) Equation 3.

Figure 3 (Adapted from Toba & Koga, 1986). $u_* z_o/\upsilon$ vs $u_*^2/\upsilon\omega_p$. Symbols: +, . field data, all others from laboratory waves. Regression lines: —— Equation 3 (slope = 1); —— field data only (slope = 1.9).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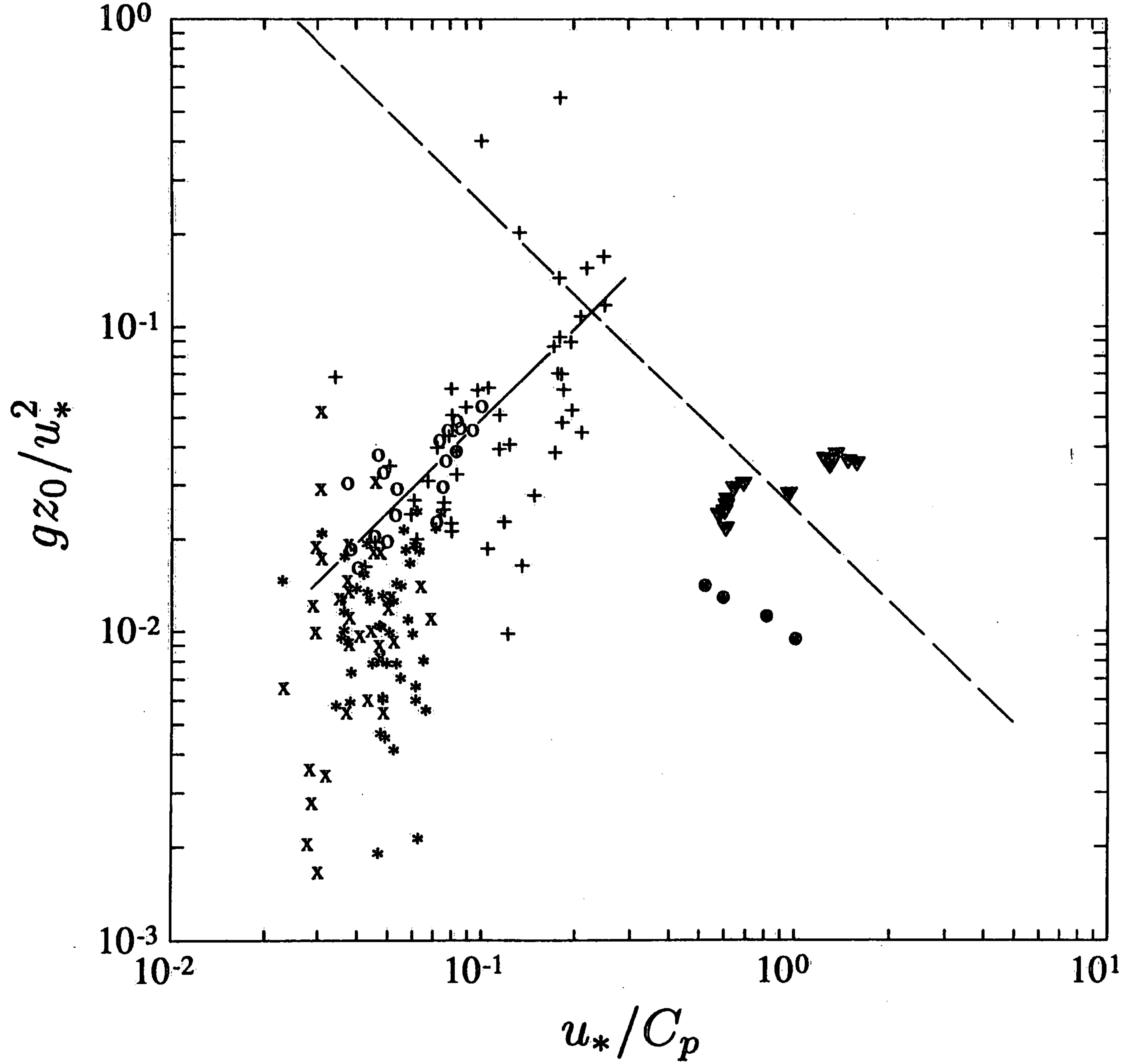

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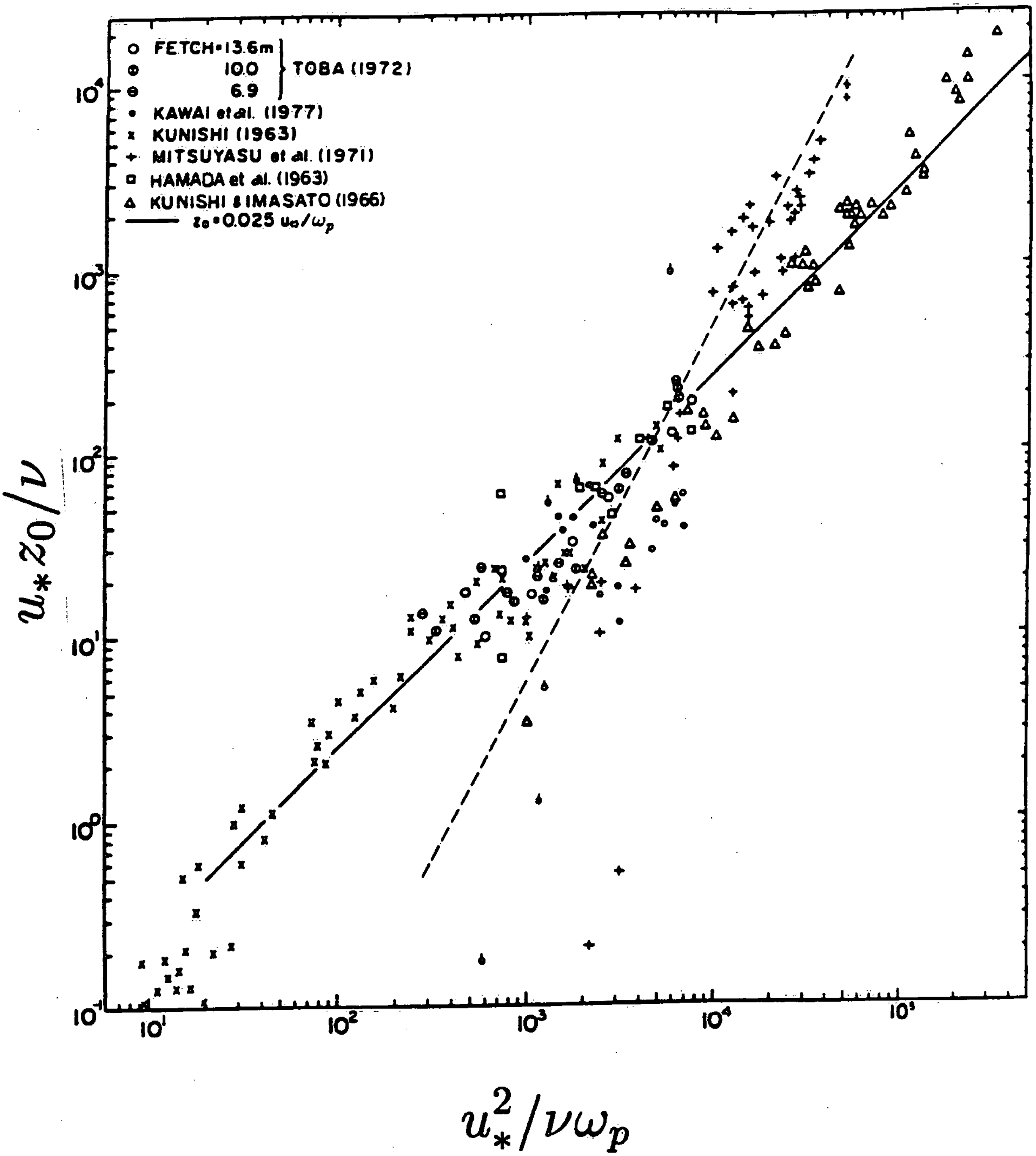

FETCH=13.6m
10.0
6.9
TOBA (1972)
KAWAI et al. (1977)
KUNISHI (1963)
MITSUYASU et al. (1971)
HAMADA et al. (1963)
KUNISHI & IMASATO (1966)
$z_0 = 0.025\, u_0/\omega_p$
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