The Dependence of Sea Surface Roughness on the Height and Steepness of the Waves

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ABSTRACT

It is proposed that the sea surface roughness z_o can be predicted from the height and steepness of the waves, $z_o/H_s = A(H_s/L_p)^B$, where H_s and L_p are the significant wave height and peak wavelength for the combined sea and swell spectrum; best estimates for the coefficients are $A = 1200$, $B = 4.5$. The proposed formula is shown to predict well the magnitude and behavior of the drag coefficient as observed in wave tanks, lakes, and the open ocean, thus reconciling observations that previously had appeared disparate. Indeed, the formula suggests that changes in roughness due to limited duration or fetch are of order 10% or less. Thus all deep water, pure windseas, regardless of fetch or duration, extract momentum from the air at a rate similar to that predicted for a fully developed sea. This is confirmed using published field data for a wide range of conditions over lakes and coastal seas. Only for field data corresponding to extremely young waves ($U_{10}/c_p > 3$) were there appreciable differences between the predicted and observed roughness values, the latter being larger on average. Significant changes in roughness may be caused by shoaling or by swell. A large increase in roughness is predicted for shoaling waves if the depth is less than about $0.2L_p$. The presence of swell in the open ocean acts, on average, to significantly decrease the effective wave steepness and hence the mean roughness compared to that for a pure windsea. Thus the predicted open ocean roughness is, at most wind speeds, significantly less than is observed for pure wind waves on lakes. Only at high wind speeds, such that the windsea dominates the swell, do the mean open ocean values reach those for a fully developed sea.

1. Introduction

The momentum transfer between sea and air depends on the surface roughness, but the dependence of the surface roughness on sea state remains a subject of debate. Using a small dataset and dimensional reasoning, Charnock (1955) suggested

$$z_o = z_{\rm Ch} u_*^2/g, \tag{1}$$

where z_o is the roughness length, u_* the friction velocity, and g the acceleration due to gravity. The Charnock parameter, $z_{\rm Ch}$, is, in effect, a nondimensional roughness length that will be used in this paper to characterize the variation of the drag coefficient, C_{D10n}, as a function of wind speed, U_{10n} (where each has been adjusted to 10 m and neutral stability). Because data from lakes and oceans suggest a wide range of $z_{\rm Ch}$ values, many authors have modified (1) by defining $z_{\rm Ch}$in terms of variables representing the sea state. Hsu (1974) suggested that $z_{\rm Ch}$ was a function of the wave slope (H_s/L_p) where H_s is the significant wave height and L_p the wavelength of the waves at the peak of the wave spectrum. However most recent studies (e.g., Smith et al. 1992; Johnson et al. 1998) have sought a relationship between $z_{\rm Ch}$ and the wave age defined either by c_p/u_* or c_p/U_{10n}, where c_p is the phase speed at the peak of the wave spectrum.

HEXMAX was the main experiment in the Humidity Exchange Over the Sea (HEXOS) program. It took place in the North Sea near the Dutch coast. The z_o values implied by the C_{D10n} observations (Smith et al. 1992) were generally larger than typical open ocean values (e.g., Smith 1980; Yelland et al. 1998). Similarly large C_{D10n} values had previously been observed in the North Sea by Geernaert et al. (1986), who had suggested they resulted from the finite water depth. Using a subset of the HEXMAX data chosen to avoid the effects of swell, Maat et al. (1991) and Smith et al. (1992) proposed the ''HEXOS'' relationship:

$$z_{\rm Ch} = \alpha(c_p/u_*)^{-\beta}, \tag{2}$$

with Smith et al. (1992) tentatively suggesting $\alpha = 0.48$ and $\beta = 1.0$. Equation (2) implies that younger waves are rougher than older waves. Despite reservations expressed by Smith et al. (1996), Janssen (1997), and Oost (1998), the HEXOS relationship has been widely used and applied to open ocean situations. For example, Gulev and Hasse (1998) concluded that wind stress would be significantly increased in storm conditions, and Bourassa et al. (1999) included the relationship in their sea-

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state-dependent wind stress parameterization (although they did express doubts as to its general validity).

Other studies have found a stronger wave age dependence of z_{Ch} compared to Smith et al. (1992). Using the HEXMAX data and the Donelan et al. (1985) formulation for the wave spectrum, Monbaliu (1994) proposed $\alpha = 2.87$ and $\beta = 1.69$. Vickers and Mahrt (1997a) concluded that there was a strong dependency on wave age in the data from the Risø Air Sea experiment (RASEX: see section 2c below); for use in (2) they proposed $\alpha = 2.9$ and $\beta = 2.0$ and suggested that these values might vary with the width of the wave spectrum. Johnson et al. (1998) used a combination of RASEX experiment data and the datasets of Donelan et al. (1993) to apparently confirm the functional form of (2) with $\alpha = 1.89$ and $\beta = 1.59$.

Data presented in the review of Geernaert (1990) suggests that roughness lengths in lakes are even higher than those observed in coastal waters. Using data from Lake Ontario, Donelan (1982) suggested a roughness length scaling using the rms height of the shorter waves, η. Using a subset of these data, Donelan (1990) developed the formula

$$\frac{z_o}{\eta} = A\left(\frac{U_{10n}}{c_p}\right)^B, \tag{3}$$

where $A = 5.5 \times 10^{-4}$, $B = 2.7$. Donelan et al. (1993) showed that (3) was also a reasonable representation of the Smith et al. (1992) HEXMAX data. With slightly modified coefficients, Anctil and Donelan (1996) confirmed (3) for strongly shoaling wave conditions. However they found that a relationship between the nondimensional roughness and the rms slope, θ, fitted the data equally well:

$$\frac{z_o}{\eta} = 2.55 \times 10^3\theta^{6.76} \tag{4}$$

and that the best fit was obtained using a combination of wave age and slope:

$$\frac{z_o}{\eta} = 2.26\left(\frac{U_{10n}}{c_p}\right)^{1.82}\theta^{3.83}. \tag{5}$$

Using open ocean data, Juszko et al. (1995) had also found a very strong correlation of u_* with wave parameters such as the mean slope spectral density and the rms wave height. However the wind stress formula that they developed also included a significant wave age dependency.

Despite the apparent progress in understanding the variation of z_o several major problems remain. First, no single formula fits all the datasets well. The HEXOS relationship (2) was recommended in the review of Komen et al. (1998) as fitting the HEXOS and Donelan (1982) data reasonably well; however, it overestimates the RASEX data (Vickers and Mahrt 1997a) and also open ocean wind stress data (Yelland et al. 1998; Yelland and Taylor 1999). Second, a clear wave age dependence has proved hard to detect in open ocean data (Dobson et al. 1994; Rieder 1997; Yelland et al. 1998) and the variations of z_o predicted by wave-aged-based formulas, for example due to sudden or intense storms, have not been observed (Yelland and Taylor 1996; Yelland et al. 1998). Third, variations in open ocean wind stress in the presence of swell have been reported by a number of authors (Donelan et al. 1997; Drennan et al. 1999a; Rieder and Smith 1998), but no clear relationship has emerged. Fourth, while the field data generally suggest that seas with younger wave age have larger z_o than mature seas, laboratory data from wind wave flumes suggest that very young waves are much smoother than would be expected from the results of field measurements (e.g., Donelan et al. 1993).

The purpose of this study is to demonstrate that a modified form of (4) resolves many of these discrepancies. We have used published data from HEXMAX, Lake Ontario, and RASEX (section 2) to determine the required formula (section 3). We show that the formula predicts the different drag coefficient variations observed during those experiments, and also the drag coefficient values observed in other studies, more consistently than a wave-age-based formula (section 4). Our discussion (section 5) will suggest that all deep water pure windseas have a similar C_{D10n} to U_{10n} relationship, whether they be in wave tank, lake, or ocean. However in comparison, typical open ocean C_{D10n} values are lower, apparently due to the effect of swell. We will summarize our conclusions in section 6 and suggest future lines of investigation.

2. The datasets

a. Introduction

This paper will make use of data (published in tabular form) on wind stress and wave conditions from three experiments. The data will be used both to illustrate the problems with wave-age-dependent formulas, and to develop a different formula. The three datasets will be described in this section.

b. HEXMAX

The HEXMAX experiment (Smith et al. 1990; Smith et al. 1996) was centered on the Meetpost Noordwijk Platform (MPN) situated off the Dutch coast in water of about 18-m depth. The instrumentation was exposed to winds from the west implying a fetch of about 175 km or greater. We have used the data subset provided in appendix A of Janssen (1997), which includes wave parameters measured by a Wave Rider buoy and which was selected for cases where a significant swell peak was not present in the spectra. These data are summarized in Fig. 1. Many of the observed C_{D10n} values (Fig. 1a) corresponded to z_{Ch} of around 0.018; however, some

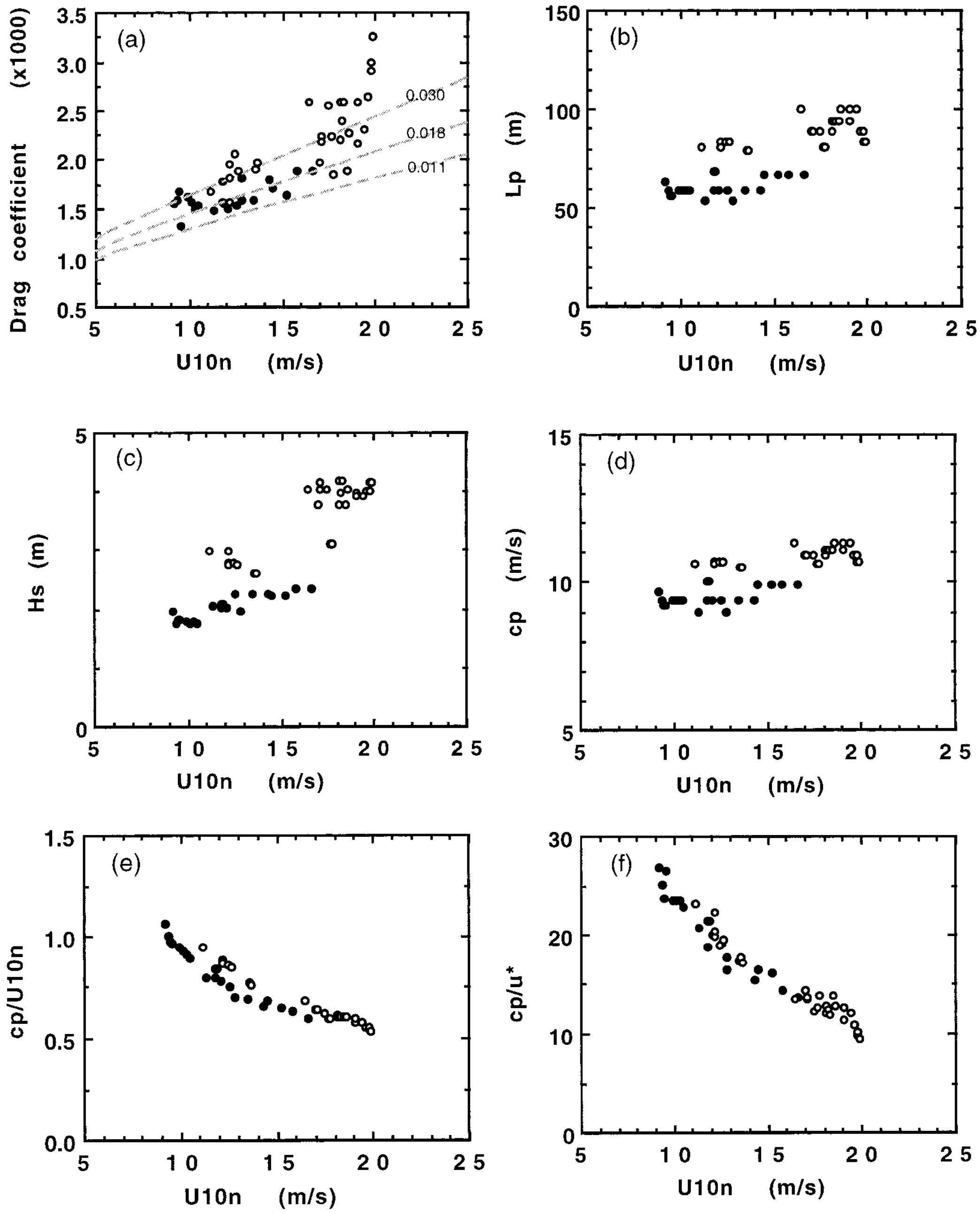

FIG. 1. Data from the HEXMAX experiment (from Janssen 1997) plotted against the 10-m neutral wind speed, U_{10n}; data for which $L_p > 72$ m are shown by open circles: (a) drag coefficient, $C_{D10n} \times 1000$, the dashed lines show z_{Ch} values as indicated; (b) wavelength at peak of the wave spectrum, L_p (m); (c) significant wave height H_s (m); (d) phase speed at peak of the wave spectrum, c_p (m s^{-1}); (e) wave age in terms of U_{10n}, c_p/U_{10n}; (f) wave age in terms of u_*, c_p/u_*.

C_{D10n} values were significantly greater with z_{Ch} around 0.030 or more. As noted by Oost (1998), these higher values were associated with longer wavelength waves; this is illustrated in Fig. 1 by the use of different symbols for data for which L_p was greater than four times the water depth (i.e., >72 m). These longer waves had appreciably greater significant wave height (Fig. 1c) and a greater peak phase velocity (Fig. 1d) compared to the rest of the data.

The limited fetch and depth at the HEXMAX site constrained c_p to between 9 and 11 m s^{-1}. Thus the waves generally became younger at higher wind speeds (Figs. 1e and 1f). It is this overall trend that is represented by the HEXOS relationship [Eq. (2)]. However,

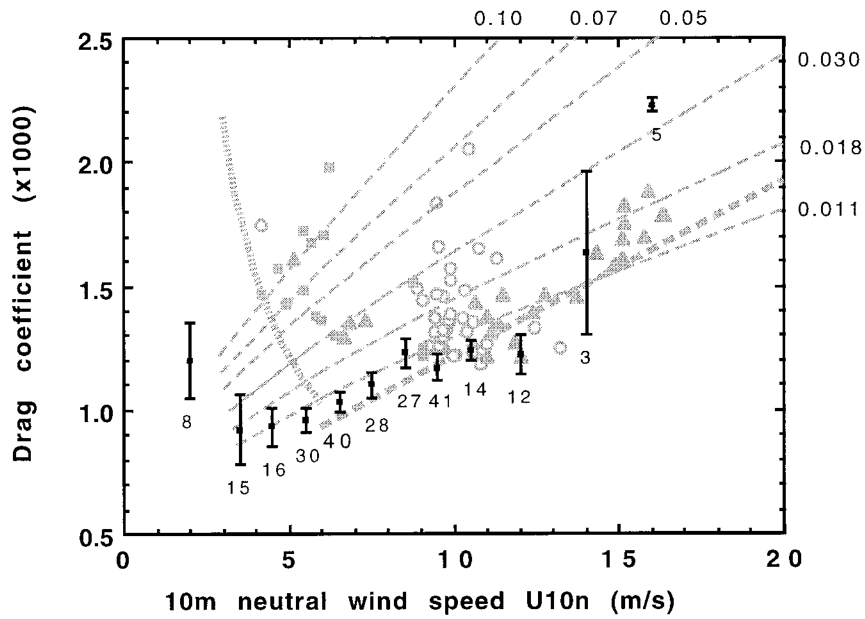

FIG. 2. RASEX data for the case of onshore winds; the drag coefficient C_{D10n} is plotted against the wind speed U_{10n}. The black data points (with the standard error and number of data values averaged) are from Vickers and Mahrt (1997). The gray symbols are data from Johnson et al. (1998) obtained on: 1–10 Oct (mainly 4 and 5 Oct): open circles; 10–20 Oct: filled squares; 30 Oct–5 Nov (mainly 2 Nov): filled triangles. Thin dashed lines represent values for the Charnock parameter z_{Ch} between 0.011 and 0.100 as indicated. The thick dashed line is the Yelland et al. (1998) open ocean relationship and the thick dotted line the Yelland and Taylor (1996) low wind speed formula.

because the longer wavelength waves were associated with greater u_* and greater c_p, their wave age (c_p/u_*) was similar to that of the shorter waves (Fig. 1f), and a wave-age-based formula cannot predict the observed scatter in C_{D10n} (see section 4a). Indeed, if wave age were expressed as c_p/U_{10n}, then for a given wind speed the longer wavelength waves were "older" (Fig. 1e) and would have been expected to be smoother—the opposite of what was observed. While comparison of Figs. 1a–d strongly suggests that the varying wave characteristics caused the observed scatter in C_{D10n}, Figs. 1e and 1f imply that wave age was not the relevant parameter.

c. RASEX

The RASEX experiment took place in the Baltic Sea at a site where the water depth was 3–4 m and the fetch varied between 2 to 5 km for offshore wind flow and 15 to 25 km for onshore flow; thus all these data were fetch limited. Wave data were obtained by an acoustic wave gauge. Various analyses of the RASEX data have been presented by Mahrt et al. (1996), Vickers and Mahrt (1997a, hereafter VM97), Johnson et al. (1998, hereafter JHVL98), and Vickers and Mahrt (1999).

VM97 used subsets of the RASEX data, quality controlled as described in Vickers and Mahrt (1997b), to demonstrate that higher C_{D10n} values were observed in offshore rather than onshore flow. They attributed this effect to the younger wave age for offshore winds. The mean C_{D10n} values for onshore winds from VM97 are shown in Fig. 2. Despite the short fetch and predominantly young waves, typically $5 < c_p/u_* < 15$, most of the C_{D10n} values were similar to open ocean values (e.g., Yelland et al. 1998). The increased roughness shown by a few higher wind speed data was attributed by VM97 to breaking waves possibly caused by shoaling. The increase of the RASEX C_{D10n} values at the lowest wind speeds was discussed by Mahrt et al. (1996). It is believed to be real but ill defined by the data. Apart from the low and high wind speed extremes, the observed C_{D10n} indicated values for the Charnock parameter, z_{Ch}, which were predominantly close to, or slightly less than, the 0.011 value advocated by Smith (1988) for the open ocean. Indeed, VM97 noted that, given the young wave ages, these RASEX C_{D10n} values were much lower than would be predicted by the HEXOS formula. They suggested that this might have been due to the absence of large amplitude swell at the RASEX site. However, the HEXOS formula was developed using cases specifically chosen for the lack of significant swell (Smith et al. 1992). Thus this paper will suggest that, like the HEXOS data, the RASEX data serve to emphasize the limited validity of wave-age-based formulas.

Also shown in Fig. 2 are the data points from JHVL98. The authors used a subset of the RASEX data that had passed several data selection criteria and were chosen for onshore flow. The data were obtained on a small number of days in October and November 1994. First consider the data collected on 2 November during a period when the wind decreased from about 16 m s^{-1} to 11 m s^{-1}. These data indicate a consistent trend of z_{Ch} values increasing from about 0.01 at 11 m s^{-1} to 0.018 at 17 m s^{-1} and generally consistent with the VM97 average values. Now consider the data that were obtained on 4 and 5 October in wind speeds of 9–10 m s^{-1}. For these data the median z_{Ch} value was 0.010, only slightly higher than the VM97 value. However a small number of data points showed unusually high C_{D10n} values resulting in a higher average z_{Ch} of 0.018 for this period. The data from various days between 10 and 20 October, which were obtained in lighter winds, are clearly different from the values obtained by VM97. The z_{Ch} for these data is very high, over 0.100 in some cases, and, since the observed waves were more mature at lower wind speeds, the data appear to indicate that older waves are rougher than younger waves. The explanation offered by JHVL98 for this apparent, unexpected relationship between wave age and roughness length was that it was not significant given the errors in their data. They estimated a $\pm 10\%$ error on their u_* estimates (implying at least $\pm 20\%$ in C_{D10n}) and chose to characterize the whole dataset by using a mean $z_{Ch} \approx 0.030$. Indeed JHVL98 implied that the scatter between individual data points in this (and other) datasets was such that no significant variation of z_o with wave age could be determined from any single dataset.

Since JHVL98 have published the only tabulated data from RASEX, it is that which will be used here (their Table 1), so the accuracy of their RASEX data must be considered. In particular, given that the VM97 and JHVL98 data are all obtained during the same experiment, why should the results at lower wind speeds be so different? VM97 used data from a sonic anemometer at 10 m to calculate both the mean wind speed and wind stress. In contrast, JHVL98 used spectral information from a sonic anemometer on the same mast but at 3 m, and obtained their mean wind speed values from a cup anemometer at 7 m. Vickers and Mahrt (1999) suggested that the 3-m sonic anemometer was subject to potential flow distortion problems and did not use that data in their study of the nondimensional wind profile. We do not know if this significantly affected the JHVL98 data. However the different heights and characteristics of the two anemometers will have caused a degree of mismatch between the u_* and wind speed values. This would have the potential to introduce significant scatter into the calculated drag coefficient (Yelland et al. 1994). Furthermore, noise in the u_* estimates would tend to positively bias the calculated C_{D10n} values at wind speeds below around 10 m s^{-1}. This is because the measured u_* was used in calculating the stability corrections, and the effects of noise are significantly nonlinear at lower wind speeds (Taylor and Yelland 2000).

Because of these uncertainties, in deriving a roughness length formulation this paper will place greater emphasis on the tabulated u_* data from JHVL98 where there was reasonable agreement with the trend of the VM97 values: that is, data for winds greater than 10 m s^{-1}. In evaluating the formula we will compare with both datasets but again place more weight on the VM97 results.

d. Anctil and Donelan (1996)—Lake Ontario

The data used from Lake Ontario were described by Anctil and Donelan (1996—their Tables 2 and 3) and will be henceforth referred to as AD96. Of the various datasets from Lake Ontario, the results from this study were chosen because they were published with concurrent wave information. Although very limited in quantity these data are important because they include cases that are strongly depth limited; indeed the aim of the Anctil and Donelan experiment was to study the effect of shoaling waves. The data were obtained from four meteorological towers in nominal water depths of 2, 4, 8, and 12 m during two wind events. For run 166 the wind speed was about 7 m s^{-1} and the fetch about 8 km. For run 185 the 14 m s^{-1} wind had a fetch of about 300 km. Wave data were measured by wave staffs. These, and other datasets from Lake Ontario will be discussed in more detail below (sections 4b and 5).

3. Development of a roughness length formula

a. Choice of scaling variables

Using the data from HEXOS, RASEX, and AD96, Fig. 3 shows different combinations of nondimensional variables. The often used combination of z_{Ch} and u_*/c_p (Fig. 3a) looks reasonable for AD96 and HEXOS with larger z_{Ch} corresponding to younger waves. However much of the RASEX data appear to be orthogonal to that alignment. Following Donelan (1982), using H_s to scale the roughness (Fig. 3b) appears a better option. However the RASEX data at higher wind speeds still appear to be associated with anomalously young waves. This is also true if wave age is represented by c_p/U_{10n} (Fig. 3c).

Only by using H_s/L_p as a scaling parameter is the higher wind speed RASEX data collapsed onto the HEXOS points (Fig. 3d). Now it is the low wind speed RASEX data ($U_{10n} < 10$ m s^{-1}), those data in which we have less confidence, that appear anomalous. We will therefore adopt this scaling:

$$\frac{z_o}{H_S} = A_1\left(\frac{H_S}{L_p}\right)^{B_1}, \qquad (6)$$

which is similar to Eq. (4) (Anctil and Donelan 1996) except that we have used H_s in place of the rms displacement and H_s/L_p instead of the rms slope. Use of these variables allows us to calculate the roughness

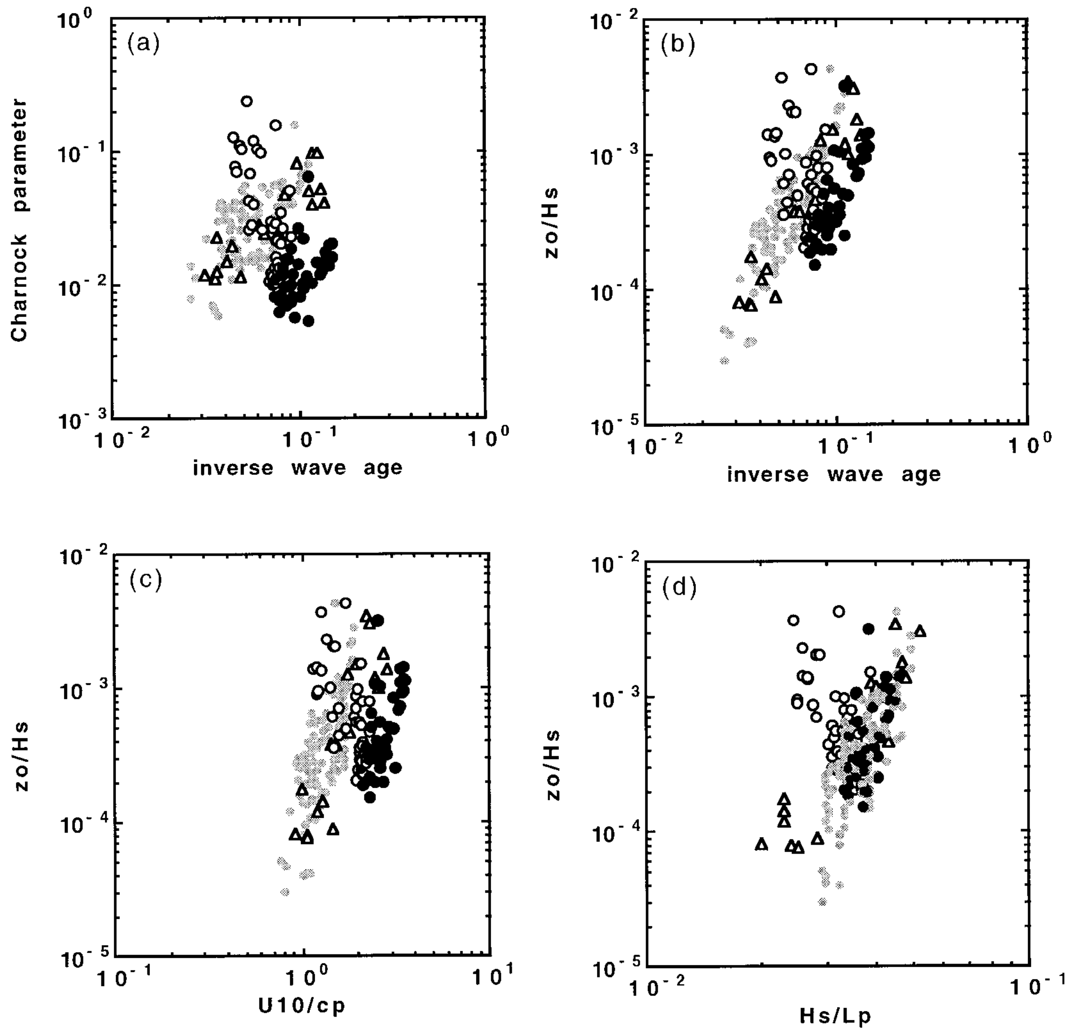

FIG. 3. Nondimensional roughness variables plotted against different scaling variables. Data are from HEXOS (small gray circles), AD96 (open triangles), and RASEX (open circles: $U_{10n} < 10$ m s^{-1}, closed circles: $U_{10n} > 10$ m s^{-1}). Plots are (a) z_{Ch} vs $(c_p/u_*)^{-1}$, (b) z_o/H_s vs $(c_p/u_*)^{-1}$, (c) z_o/H_s vs $(c_p/U_{10n})^{-1}$, and (d) z_o/H_s vs H_s/L_p

without detailed knowledge of the wave spectra but it does introduce the possibility of self-correlation since H_s occurs on both sides of Eq. (6). Noting that with this scaling the lower wind speed data from HEXOS and AD96 diverge, we shall also briefly consider a multiple scaling similar to Eq. (5):

$$\frac{z_o}{H_s} = A_2\left(\frac{H_S}{L_p}\right)^{B_2}\left(\frac{U_{10n}}{c_p}\right)^{C}. \tag{7}$$

b. Choice of coefficients

It is clear from Fig. 3 that the available data are scattered and do not allow the coefficients, A to C in Eqs. (6) and (7), to be precisely determined. Using all the HEXOS and AD96 data, but only RASEX data where $U_{10n} > 10$ m s^{-1}, a one-way regression gave $\ln(A_1) = 6.27$, $B_1 = 4.25$, whereas for a two-way regression: $\ln(A_1) = 15.75$, $B_1 = 7.11$. Since what is ultimately required is a value for the drag coefficient (which has a logarithmic dependence on z_o), we ultimately chose to subjectively tune the values to give a reasonable fit between the set of calculated and observed C_{D10n} values from all three experiments and obtained $A_1 = 1200$ ($\ln(A_1) \approx 7.09$), $B_1 = 4.5$. These coefficients are more similar to the one-way regression, presumably because the scatter is dominated by the error in determining z_o.

Using the wave age and Eq. (7) explained little more of the variance than Eq. (6) ($R^2 = 0.58$ compared to 0.56). Given that Eq. (7) was not significantly better, that it introduces more chance of self-correlation (since U_{10n} is used to determine z_o from the observations), and that the results calculated using (6) explained the observed characteristics of the roughness variation (section

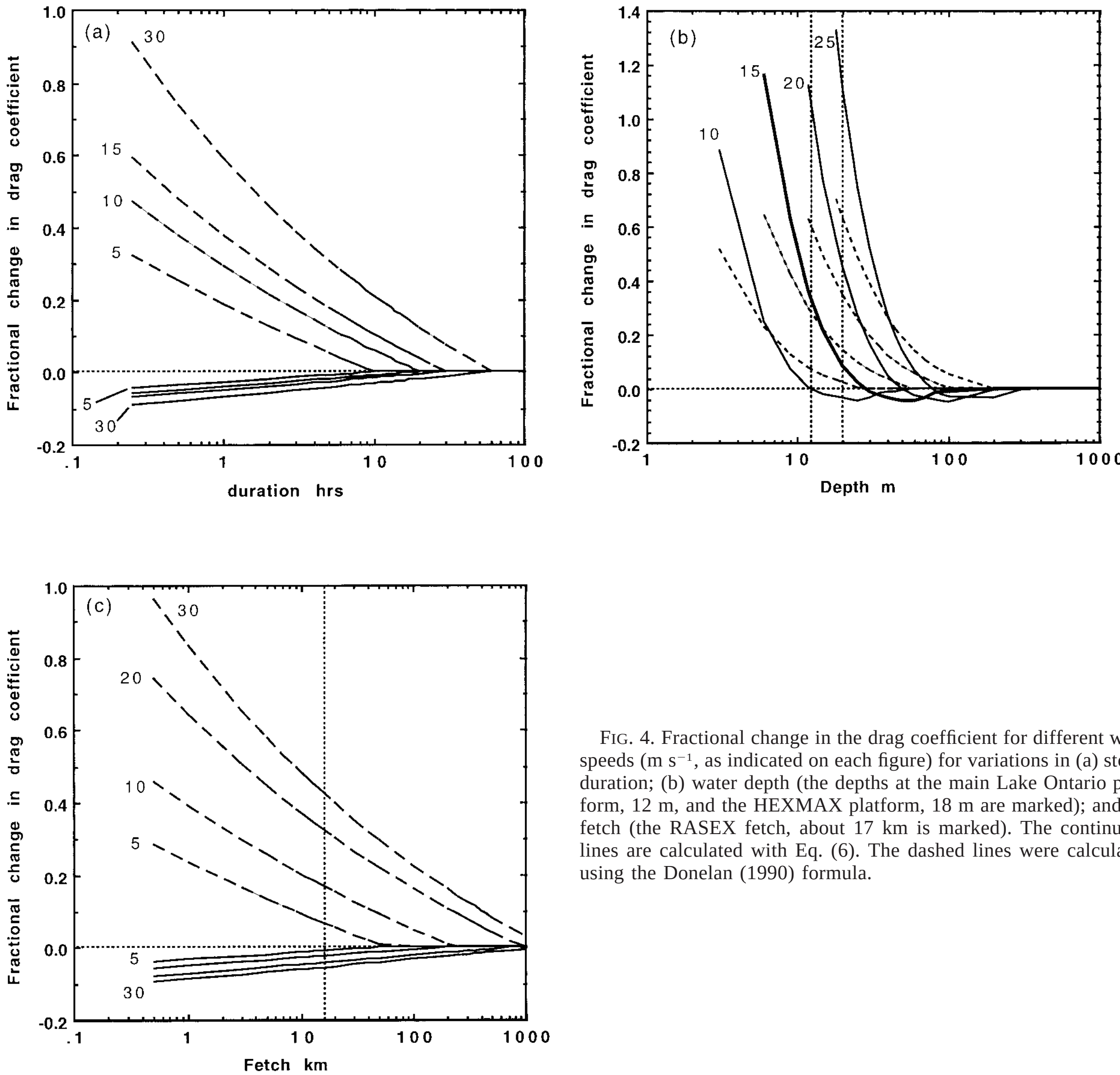

FIG. 4. Fractional change in the drag coefficient for different wind speeds (m s^{-1}, as indicated on each figure) for variations in (a) storm duration; (b) water depth (the depths at the main Lake Ontario platform, 12 m, and the HEXMAX platform, 18 m are marked); and (c) fetch (the RASEX fetch, about 17 km is marked). The continuous lines are calculated with Eq. (6). The dashed lines were calculated using the Donelan (1990) formula.

4), we have not pursued that relationship further. However we will return to this point in the discussion (section 5).

c. Predicted effects of varying duration, fetch, and water depth

In order to use Eq. (6) to predict the variation of the drag coefficient with sea state we need values of H_s and L_p for varying conditions of duration, fetch, and water depth. We have calculated these using formulas developed by Carter (1982) and Tucker (1991); the equations are given in the appendix.

Figure 4 shows our calculations using Eq. (6) for the effect of duration, water depth, and fetch and, for comparison, the change in C_{D10n} that would be expected using the Donelan (1990) formula, Eq. (3) above, which we have chosen because it has the advantage of using c_p/U_{10n} to represent the wave age. The fundamental difference is clear. For short duration and fetch (Figs. 4a and 4c) the waves are young and the Donelan (1990) formula predicts a significantly increased drag coefficient. These younger waves have high values of steepness, H_s/L_p, but this is offset by the low wave height. Thus, rather than predicting an increase, Eq. (6) predicts a slight decrease of C_{D10n} compared to the value for a fully developed sea, normally by less than 10%. Similarly Eq. (6) does not predict high C_{D10n} values for short duration storms.

In contrast the effect of limited water depth as predicted by Eq. (6) is very significant (Fig. 4b). Consider waves propagating into shoaling water of depth h. As the waves begin to be limited by bottom friction c_p, H_s, and L_p all decrease. The waves will become "younger" and the Donelan (1990) formula predicts that C_{D10n} will start to increase. Eq. (6) predicts that at first there is a small decrease of the calculated C_{D10n} values (the 15 m s^{-1} line on Fig. 4b has been emphasized to make this clearer). As the water depth shoals, L_p continues to decrease whereas H_s becomes nearly constant. Thus at about $h = 0.2L_p$ there begins to be a rapid increase of the wave steepness, and of the calculated C_{D10n}. This is well before the very shallow region is reached where H_s noticeably increases and the waves eventually progress to breaking. Thus both Eq. (6) and the Donelan (1990) formula predict significantly enhanced roughness for shoaling conditions.

4. Verification of the calculated C_{D10n} values

a. Simulation of the published datasets

The coefficients in our roughness relationship have been tuned using the observed C_{D10n} values, and in the mean Eq. (6) should give the correct value for the published data from HEXMAX, RASEX, and the AD96 Lake Ontario data. The test is whether it can reproduce the differences in observed C_{D10n} values between the different experiments. In fact, Fig. 5 suggests that the agreement between the calculated and observed C_{D10n} values was remarkably good. For example, for HEXMAX (Fig. 5a) the scatter in the drag coefficient at about 12 m s^{-1} and between 17 and 20 m s^{-1} was similar to that observed. For RASEX data (Fig. 5c) the calculated values were in good agreement with the mean values from VM97 over most of the wind speed range, and with JHVL98 data at wind speeds over (but not those below) 10 m s^{-1}. Importantly, the overall lower C_{D10n} values observed in RASEX compared to HEXMAX were properly predicted. For Lake Ontario (Fig. 5e) the calculated values were similar to those observed, although the greatest C_{D10n} values at the higher wind speeds (corresponding to strongly shoaling waves) were underpredicted.

In contrast the right side of Fig. 5 shows the results for the wave-age-based formula of Donelan (1990). As expected, given the wave observations described in section 2b, this model predicted the overall increase of C_{D10n} with increasing U_{10n} that was observed in HEXMAX but did not predict the scatter about this increase (Fig. 5b). For RASEX, while the model generally predicted much higher C_{D10n} values than were observed, it underpredicted the very high data reported by JHVL98 for winds below 10 m s^{-1}. Only for the higher wind speed Lake Ontario data did this formula perform better than Eq. (6), although again the greatest C_{D10n} values observed were not predicted. While the Donelan (1990) formula was chosen for Fig. 5 because it uses c_p/U_{10n}, the performance of other wave-age-based formulas (such as the HEXOS relationship) was found to be very similar. None were able to correctly reproduce the magnitude and the variation of the observed C_{D10n} values for both the HEXMAX and the RASEX experiments.

b. Simulation of coastal, lake, and wave tank data

In this section Eq. (6) will be used to predict the C_{D10n} to U_{10n} relationship for various published coastal, lake, and wave tank datasets that were not used in developing the model. Where we do not have measured wave data the wave forecasting equations (appendix) will be used to determine the waves that would be possible at the measurement site, given the available fetch and water depth, and assuming a constant wind (infinite duration). Since the predicted C_{D10n} values vary little with duration or fetch (section 3c), these wave estimates should be adequate for the purpose, provided the waves were not depth limited and provided significant swell was not present.

First consider the C_{D10n} data from VM97 for offshore winds (Fig. 6). The waves were limited by the fetch from 2- to 5 km, and therefore in deep water despite the 4-m depth at the observing platform. Since VM97 only give mean wave parameters, and Eq. (6) is nonlinear, the C_{D10n} values have been predicted both using the mean wave observations, and also from wave parameters estimated using the wave prediction formulas (appendix) for both fetch limited and infinite fetch deep water cases. In most cases the results are very similar. Agreement with the observations at the lowest wind speeds would not be expected because Eq. (6) does not consider viscous effects and also because C_{D10n} becomes ill defined at low wind speeds (Mahrt et al. 1996) and may be overestimated (Taylor and Yelland 2000). However the majority of the observations (75%) occurred in the range 4 m s^{-1} $< U_{10n} <$ 9 m s^{-1} where the predicted C_{D10n} and the VM97 data are in reasonable agreement. Above 5 m s^{-1} the predicted values fall within the range $0.018 < z_{\mathrm{Ch}} < 0.030$. In contrast, for onshore flow (Fig. 5c) both the VM97 observations and the predicted values fell in the range $z_{\mathrm{Ch}} \approx 0.011$ to 0.018, significantly lower. Thus Eq. (6) predicts the higher roughness in offshore flow, which VM97 had ascribed to wave age effects. For the relatively few offshore flow data at $U_{10n} >$ 9 m s^{-1}, the observations showed more scatter but tended to be higher than the predictions. Whether this difference is significant will be left to the discussion (section 5).

The second set of observations are those recently published by Ataktürk and Katsaros (1999). Their C_{D10n} data were obtained over Lake Washington for winds between 3 and 9 m s^{-1}, a fetch of 7 km, and in 4-m water depth. This was a similar situation to the RASEX offshore wind case with the waves not affected by the depth, being fetch or duration limited depending on whether the wind had been blowing for more than 3 hours, or less. Hence very similar C_{D10n} values were predicted using Eq. (6), which were again a good fit to the observations (Fig.

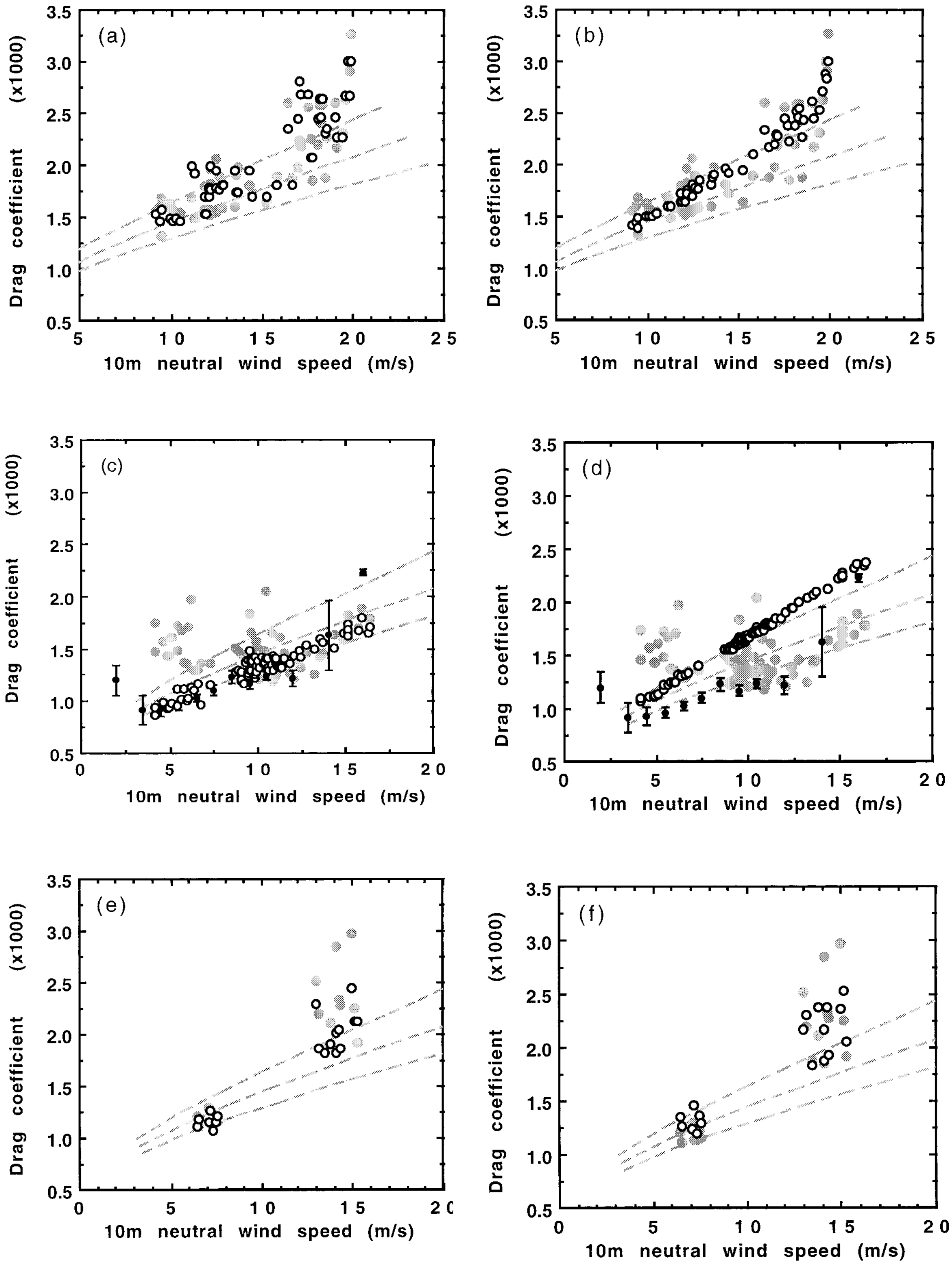

FIG. 5. Observed and calculated values of C_{D10n} for (top to bottom) HEXOS, RASEX, and AD96. Filled gray circles: the observations; open circles: values calculated from Eq. (6) (left plots) and from the Donelan (1990) formula (right plots). On the RASEX plots the gray circles are from JHVL98 and the points with error bars from VM97. The dashed lines show z_{Ch} values of (bottom to top) 0.011, 0.018, and 0.030.

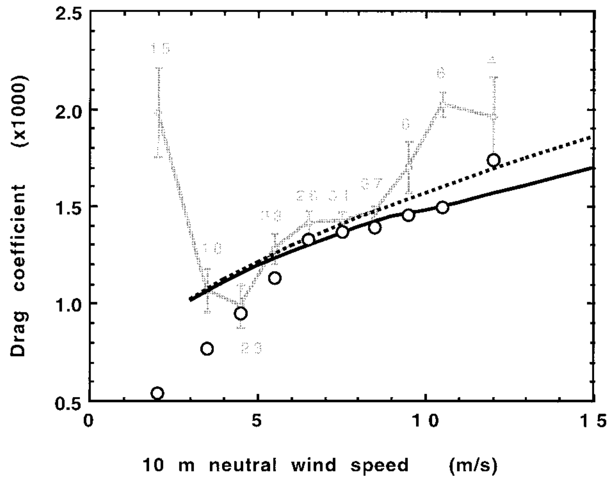

FIG. 6. Observed and predicted C_{D10n} from RASEX for offshore winds. The data points (shown in gray with standard error and number of data averaged) are from Vickers and Mahrt (1997a). The open circles were calculated using Eq. (6) and the mean observed wave parameters. Also shown is the relationship calculated using Eq. (6) with estimated waves with fetch limit (continuous black line) and without fetch limit (dashed black line).

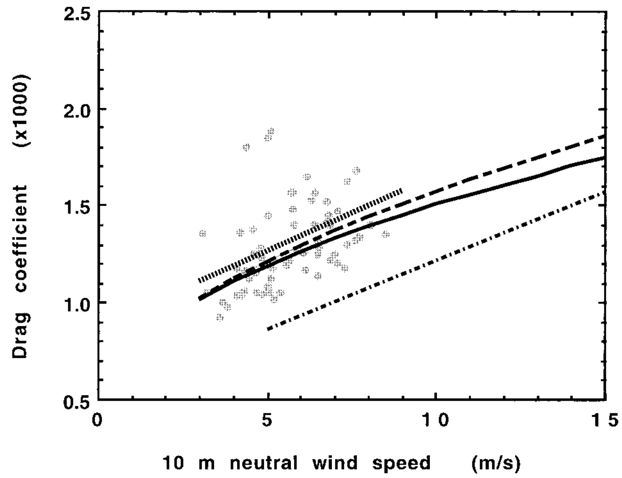

FIG. 7. Observed and predicted C_{D10n} from Lake Washington. The data points were obtained from wave spectra by Ataktürk and Katsaros (1999); the thick dotted line is their regression. Also shown is the relationship calculated using Eq. (6) with estimated waves with fetch limit (continuous black line) and without fetch limit (dashed black line). For comparison, the chain line is the Yelland et al. (1998) open ocean relationship.

7) being very close to the mean relationship obtained by Ataktürk and Katsaros (1999).

Thus for both the offshore RASEX and the Lake Washington case studies most of the observations were close to the C_{D10n} to U_{10n} relationship predicted by Eq. (6) for wave conditions corresponding to a deep water, pure windsea. These C_{D10n} values are significantly higher than is typically observed in the open ocean. This is illustrated in Fig. 7 by the Yelland et al. (1998) open ocean relationship. However it would appear that the pure windsea relationship can be observed on the sea, at least in coastal waters. Thus, for the HEXMAX experiment, Oost (1998) produced a C_{D10n} formula based on a subset of data for which there was no significant swell and L_p was less than 80 m (to ensure that the waves were not significantly affected by the limited depth). This relationship also lies near that predicted for a pure windsea (Fig. 8).

Two sets of wind and wave flume data are also represented in Fig. 8. Cheng and Mitsuyasu (1992) obtained observations at a fetch of 8 m and depth of 0.33 m (their case without mechanically generated waves has been used here), while for Keller et al. (1992) the fetch was 16 m and the depth 0.45. For both these experiments the waves would have been in deep water. The C_{D10n} values predicted by Eq. (6) are essentially the same, in both cases being lower than that predicted for infinite fetch. The Cheng and Mitsuyasu (1992) C_{D10n} data lie close to the prediction. Keller et al. (1992) provided formulas for the observed z_o as a function of u_*. The implied C_{D10n} to U_{10n} relationship is about 10% lower than predicted but, above 5 m s^{-1}, shows a very similar variation with wind speed. This variation actually implies that z_{Ch} decreases with increasing wind speed, an observation that also holds for the data of Cheng and Mitsuyasu (1992), the Oost (1998) HEXMAX subset, and the Ataktürk and Katsaros (1999) data. Again, we will return to this in the discussion (section 5).

Finally in this section we will consider datasets that show characteristics different to those predicted by Eq. (6). The Donelan (1982) data have often been cited as demonstrating the effect of wave age on C_{D10n}. These data were obtained in Lake Ontario on a fixed platform that also has been used in a series of later experiments

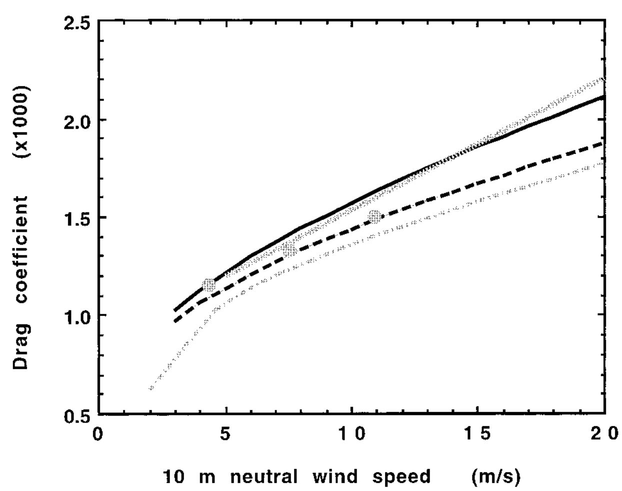

FIG. 8. Further examples of observed and predicted for pure wind seas. The continuous line is the predicted C_{D10n} to U_{10n} relationship for a fully developed pure wind sea. The dotted gray line is the HEXMAX relationship from Oost (1998). The gray circles are wave tank data from Cheng and Mitsuyasu (1992), the gray chain line is the wave tank relationship found by Keller et al. (1992), the dashed line shows the values predicted for the wave tank data using Eq. (6).

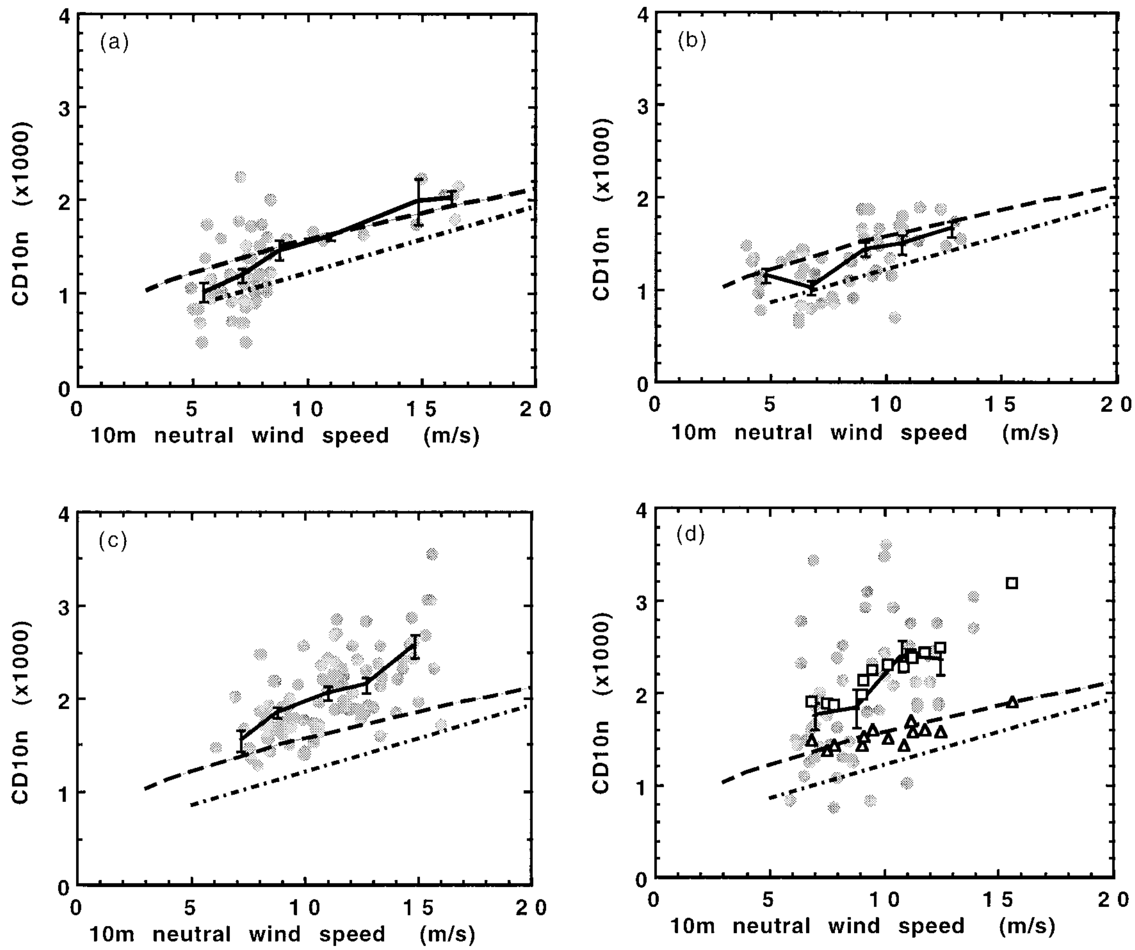

FIG. 9. Values of C_{D10n} from Lake Ontario obtained from eddy correlation measurements (indicated by the gray dots) from (a) Donelan (1982): older wave age ($U_{10n}/c_p < 3$); (b) Colton et al. (1995); longer fetch (>50 km); (c) Donelan (1982): younger wave age ($U_{10n}/c_p >$ 3); and (d) Colton et al. (1995): shorter fetch (<10 km). In each plot the mean of each set is shown (with the standard error of the mean). The pure windsea relationship calculated using Eq. (6) is shown by the dashed line and the Yelland et al. (1998) relationship by the chain line. In (d) the Terray et al. (1996) data points (fetch < 2 km) are marked by open squares and the simulation of these data by the open triangles. The pure wind sea relationship calculated using Eq. (6) is shown by the thick dashed line. The dashed lines show z_{Ch} values of (bottom to top) 0.011, 0.018, 0.030, 0.050.

[including those described by Colton et al. (1995), Anctil and Donelan (1996), Terray et al. (1996), and Drennan et al. (1999b)]. The water depth was 12 m and the possible fetch ranged from 1.1 km to 300 km depending on wind direction. Donelan (1982) stratified his data according to inverse wave age (U_{10n}/c_p). The C_{D10n} values corresponding to more mature waves ($U_{10n}/c_p < 3$) were in the mean similar to, or less than, our pure windsea relationship (Fig. 9a). Similarly data from Colton et al. (1995) for fetches greater than 50 km were generally between the pure windsea relationship and the open ocean relationship of Yelland et al. (1998) (Fig. 9b). For very young waves ($U_{10n}/c_p > 3$) the Donelan (1982) data were more scattered and on average larger than the pure windsea relationship from Eq. (6). Based on the wave age to fetch relationship of Donelan et al. (1985) these larger C_{D10n} values correspond to short fetch conditions (2 km or less). That very high C_{D10n} values occurred at this site for short fetches is confirmed by the Colton et al. (1995) data for fetches less than 10 km (Fig. 9d) and the Terray et al. (1996) data obtained at fetches less than 2 km (also shown in Fig. 9d). Using the values for the observed wave conditions provided by the latter authors, Eq. (6) predicts (as expected) values close to the pure windsea relationship (triangles in Fig. 9d). However, while the Colton et al. (1995) data were very scattered, their mean lay close to the Terray et al. (1996) values, so both these observational datasets have significantly higher C_{D10n} values than would be predicted. We conclude that, for Lake Ontario, Eq. (6) predicts C_{D10n} values similar to or greater than those observed for onshore winds, but it does not predict the high C_{D10n} values observed during offshore winds and very short fetch.

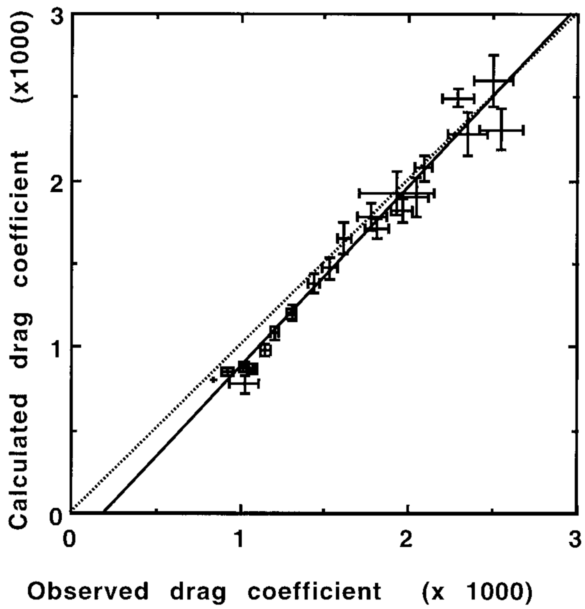

FIG. 10. Calculated values of drag coefficient, C_{D10n}, vs observed values for the SWS-2 experiment; the data have been averaged in intervals of 1 m s^{-1}. Error bars show the standard error of the mean. The regression line shown is $C_{D10n}(\text{calc}) = -0.21 + 1.08C_{D10n}(\text{obs})$ ($R^2 = 0.97$).

c. Simulation of open ocean data

The data used in developing Eq. (6) were from lake or coastal sites, so finally open ocean values for C_{D10n} will be considered for the deep ocean. The data used were from the second Storm Wave Study experiment, SWS-2 (Dobson et al. 1999; Taylor et al. 1999), which took place over the Grand Banks off Newfoundland during October to November 1997. Wind stress data were obtained from a sonic anemometer mounted on a Nomad meteorological buoy. Whereas the wind stress data so far discussed were obtained using the eddy correlation method, the SWS-2 data were obtained using the inertial dissipation method. The buoy was equipped with motion sensors from which the estimates of H_s and L_p (defined by the wavelength at the peak of the energy spectrum) were obtained from spectral analysis. During SWS-2 directional wave spectra were obtained from a Wave Rider buoy but these data are still being analyzed and have not been used here. Thus, like most significant wave height estimates from the open ocean, the wave information represents a mixture of windsea and swell and does not contain directional information.

An initial point by point comparison of the predicted and observed C_{D10n} values was disappointing. Although the range of scatter for the C_{D10n} values calculated using Eq. (6) was similar to that observed, the correlation was poor ($R^2 = 0.44$), worse than using the Yelland et al. (1998) linear relationship between C_{D10n} and U_{10n} ($R^2 = 0.60$). However when mean values were calculated for 1 m s^{-1} increments of U_{10n} the agreement was surprisingly good with $R^2 = 0.97$ (Fig. 10). When the C_{D10n} values were plotted against U_{10n} (Fig. 11), the predicted C_{D10n} values were possibly underestimated at the lower wind speeds but, overall, there was good agreement with the observations. Unlike the results for lake data (e.g., Fig. 7) the predicted values for these open ocean data were similar to the Yelland et al. (1998) open ocean relationship. For most wind speeds these values are significantly less than the relationship predicted by Eq. (6) for a fully developed sea (also shown in Fig. 11). Even details of the mean C_{D10n} variation with wind speed were correctly predicted, for example, the dip in the mean C_{D10n} values at about 22 m s^{-1}. This might previously have been ascribed to noise; however, it was predicted by Eq. (6) because waves during a particular storm had H_s/L_p values less than what was usually observed at those wind speeds.

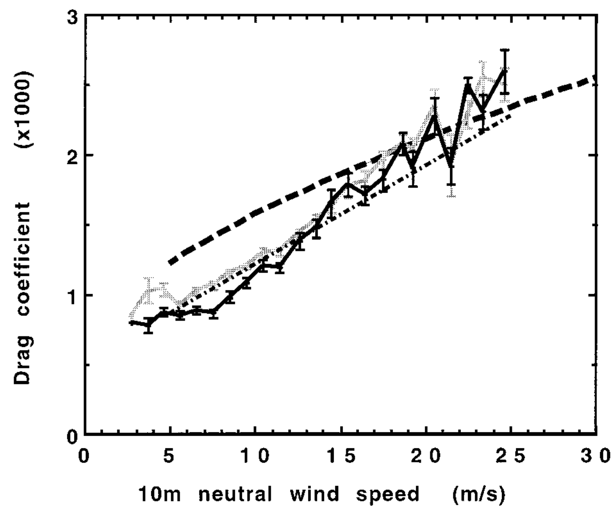

FIG. 11. Mean observed values of the drag coefficient, C_{D10n}, (gray line), and values calculated from Eq. (6) (black line) plotted against the wind speed, U_{10n}, for the SWS-2 data. The data have been averaged in 1 m s^{-1} ranges. Error bars show the standard error of the mean. The thick dashed line was calculated using Eq. (6) for a fully developed sea. The chain line is the Yelland et al. (1998) relationship.

To demonstrate why Eq. (6) predicts relatively small C_{D10n} values for the SWS-2 data compared to a pure windsea, Fig. 12 shows the wave data from the Nomad buoy. Because these data did not differentiate between the contribution to the spectrum of wind-driven sea or remotely generated swell, the values for H_s and L_p at lower wind speeds were greater than might be expected for a fully developed sea (Figs. 12a and 12b). In fact, the mean dominant wavelength varied little, being around 200 m. Because of this long wavelength swell contribution the implied values for the slope, H_s/L_p, were low compared to a fully developed windsea. These low slope values dominated the calculation of roughness length using Eq. (6) and relatively small values of C_{D10n} were obtained. The nearly constant mean L_p also implied little change of c_p with wind speed. As a result the calculated wave age (c_p/u_*) was dominated by the var-

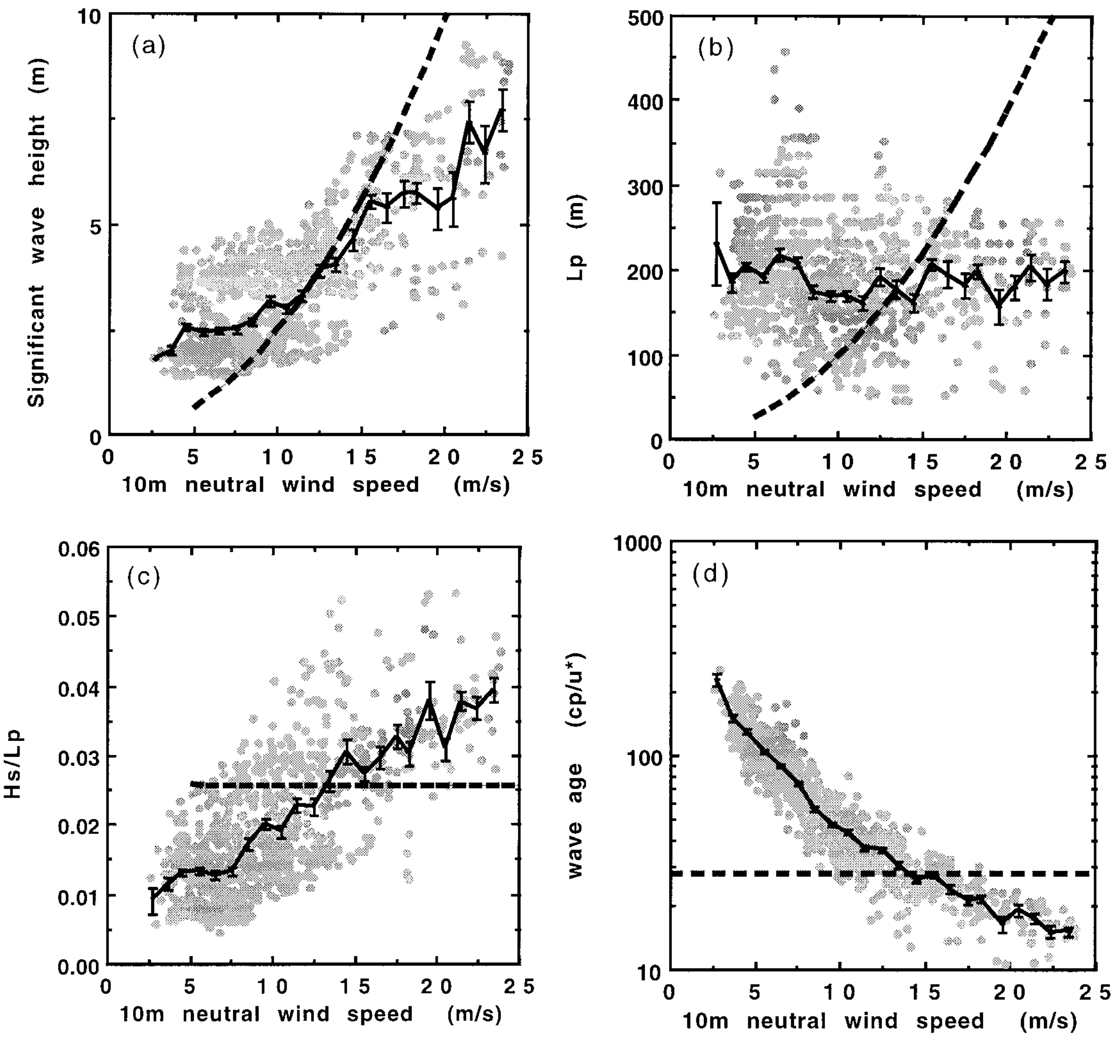

FIG. 12. Wave observations from the SWS-2 experiment. Both individual data point (gray circles) and mean values (in 1 m s^{-1} ranges) are shown. The thick dashed line is the value for a fully developed sea. (a) Significant wave height, H_s, (m); (b) wavelength at the peak of the spectrum, L_p (m); (c) wave slope, H_s/L_p; (d) wave age (c_p/u_*).

iation in u_* (Fig. 12d) resulting in spuriously high values at the lower wind speeds irrespective of the state of development of the windsea.

At wind speeds greater than about 12–15 m s^{-1} the mean values of H_s, L_p, and c_p/u_* became less than those expected for a fully developed sea implying that, on average, the wind sea was dominant over the swell. The predicted and observed C_{D10n} values were close to the pure windsea relation at these higher wind speeds.

5. Discussion

The major difference between the results obtained using the wave steepness formula Eq. (6) and typical wave age formula such as the HEXOS relationship [Eq. (2)] or the Donelan (1990) formula (3) is that the wave age formulas predict that the young waves found at short fetches will result in increased surface roughness and larger C_{D10n} values. In contrast, Eq. (6) predicts that at short fetches the surface roughness and hence C_{D10n} will be similar to, or slightly less than, that observed at long fetch. This is because, although the young waves are relatively steep, the height of the waves is small and the two effects almost cancel. For similar reasons, Eq. (6) does not predict enhanced surface roughness during short duration wind events. Thus for deep water wind waves, in the absence of swell, it is possible to define a C_{D10n} to U_{10n} relationship that, for practical purposes, can be reasonably well approximated by the polynomial:

$$10^3 C_{D10n} = 0.87 + 0.0752 U_{10n} - 0.000661 (U_{10n})^2 \quad (5 \le U_{10n} \le 30 \text{ m s}^{-1}). \tag{8}$$

This deep water wind wave relationship from Eq. (6) has been shown to well represent a number of datasets: the Lake Washington data of Ataktürk and Katsaros

(1999), the longer fetch (>50 km) Lake Ontario data of Colton et al. (1995), the Baltic Sea (RASEX) data for offshore winds between 3 m s^{-1} and 9 m s^{-1} (Vickers and Mahrt 1997), and the North Sea (HEXMAX) relation of Oost (1998). The implied value for z_{Ch} decreases from around 0.030 at 5 m s^{-1} to 0.018 at 20 m s^{-1}. This is in contrast to observed values from the ocean, which imply a low value of z_{Ch} (below 0.01) at lower wind speeds, increasing to 0.018 at 20 to 25 m s^{-1} (Yelland et al. 1998; Hare et al. 1999). Thus Eq. (6) does predict that C_{D10n} values in lakes and sheltered waters will typically be significantly higher than is observed in the open ocean.

Using the observed wave parameters, Eq. (6) also successfully predicted C_{D10n} observations that departed from the expected deep water windsea relationship approximated by Eq. (8). Thus, for HEXMAX, larger C_{D10n} values were associated with waves that were higher, of longer wavelength, and (in terms of c_p/U_{10n}) older than other waves at the same wind speed. Noting that these atypical cases strongly influenced the magnitude of the coefficients in the HEXOS formula [Eq. (2)], Oost (1998) suggested that their higher roughness was caused by shoaling effects. Our own calculations suggest that shoaling can neither explain the observed characteristics of the waves or the magnitude of the roughness enhancement (e.g., Fig. 4b). However regardless of how these waves came to exist at the HEXMAX site, by using the observed H_s and L_p values in Eq. (6), the enhanced roughness was correctly predicted. As a second example, for onshore winds in RASEX, although the fetch was relatively short (from 15 to 25 km), the C_{D10n} values reported by VM97 were relatively small, more typical of what might be observed in the open ocean. Again, using the observed wave characteristics, Eq. (6) correctly predicted the observed C_{D10n}. For these onshore winds, the observed wave characteristics were such that the roughness predicted by Eq. (6) was significantly less than that predicted for the offshore winds. This effect was explained by VM97 using wave-age-based formulas. However, unlike Eq. (6), these wave age formula cannot also successfully predict the characteristics of the C_{D10n} values observed during the HEXMAX experiment.

The roughness length observed in wind–wave flumes is typically much less than would be predicted by wave-age-based formulas given the exceedingly young wave ages. We have shown (Fig. 8) that these low values are also predicted by Eq. (6). The C_{D10n} values are predicted to be less than the case of a fully developed windsea due to the extremely short fetch. This was in good agreement with the observations of Cheng and Mitsuyasu (1992) and Keller et al. (1992). That z_{Ch} would appear to decrease at younger wave ages was also predicted. It occurs because, for measurements at a fixed fetch in the wave flume, older waves occur for lighter winds and vice versa. The largest z_{Ch} ($\approx$0.030) corresponded to the lowest winds and oldest waves, while $z_{Ch} \approx 0.018$ would be a reasonable value for the range of wind speeds between 7 and 15 m s^{-1}. For experiments at very high wind speeds (say over 25 m s^{-1}), implying very young waves, $z_{Ch} \approx 0.010$ would be expected. These values are in reasonable agreement with the collection of wave tank data shown by Toba et al. (1990, their Fig. 14). Obtaining accurate wind stress data in a wind–wave flume is difficult (e.g., see the discussion by Oost 1991) and the results are very scattered. However $z_{Ch} \approx 0.018$ is a reasonable, typical value and, in the mean, the lower z_{Ch} values do correspond to the younger wave ages.

It was a combination of these wave tank data and field estimates that led Toba et al. (1990) to suggest that roughness increases with increasing wave age. That view was disputed by Donelan et al. (1993) who suggested that results from field data and laboratory tanks were essentially different in nature. However, Nordeng (1991) and Komen et al. (1998) have offered explanations of the low z_{Ch} for very young waves, based on the assumed wave age dependence of the shape of the wave spectrum. Indeed Komen et al. (1998) noted that, to obtain the HEXOS relationship (2), one must assume a wave age dependence of the short (decimeter scale) wind waves and that there was no direct evidence for (or against) such a dependency. Here we suggest that the simple scaling represented by Eq. (6) is able to represent the wave tank results while also being compatible with a wider range of field datasets compared to wave-age-based formulas.

The Lake Ontario data of Donelan (1982) has received much attention because it is a field dataset with a very wide range of wave ages. At the experiment site, very young waves corresponded to very short fetches of around 1 to 2 km. Equation (6) failed to predict the large C_{D10n} values observed under these conditions (Figs. 9c,d). In contrast, for onshore flow the observed mean C_{D10n} values were smaller, being close to, or lower than, our predicted pure windsea relationship (Figs. 9a,b). This we might expect since, while swell is less frequent on Lake Ontario compared to the open ocean (Donelan et al. 1985), for onshore flow the drag coefficient tends to be lower compared to pure windsea conditions when swells occur (Drennan et al. 1999b). In addition, for most of the observed wind speed range, shoaling would not have been an important factor.

Possible explanations for the failure of Eq. (6) to predict the short fetch Lake Ontario data are:

1) Waves with inverse wave ages in the approximate range $3 < (U_{10n}/c_p) < 6$ are associated with increased roughness, which is not modeled by Eq. (6). The higher C_{D10n} values of Donelan (1982) are associated with U_{10n}/c_p of at least 2 and mostly > 3. Such young waves were very rarely observed in any of the other field datasets (Table 1). Only the data at the highest wind speeds from RASEX had $U_{10n}/c_p > 3$. Although there were few cases and the data were scattered, the higher wind mean C_{D10n} values were indeed elevated

TABLE 1. Values of fetch and inverse wave age (U_{10n}/c_p) for the different datasets listed, as far as possible, in order of decreasing fetch: (est) indicates that the range of wave ages was determined from the wave forecasting equations.

Site	Reference	Fetch (km)	U_{10n}/c_p
North Atlantic (SWS-2)	Taylor et al. (1999)	Long	<2.2
North Sea (HEXMAX)	Janssen (1997)	>175	<2
Lake Ontario	Colton et al. (1995)	>50	<1.8 (est)
Baltic (RASEX)—onshore	VM97, JHVL98	15–25	1–3.5
Lake Washington	Ataktürk and Katsaros (1999)	7	1–2.6
Baltic (RASEX)—offshore	Vickers and Mahrt (1997a)	2–5	<4 (est)
Lake Ontario	Donelan (1982)	1.1–300	<6
Lake Ontario	Colton et al. (1995)	<10	1.7–5.5 (est)
Lake Ontario	Terray et al. (1996)	<2	3.2–4.2
Wave tank	Keller et al. (1992)	0.016	7–28 (est)
Wave tank	Cheng and Mitsuyasu (1992)	0.008	9–20 (est)

in that experiment too. It might be argued that the success of Eq. (6) in predicting the characteristics of C_{D10n} data from wind–wave flumes (where very young wave ages are present $-U_{10n}/c_p > 7$) contradicts this explanation. However Donelan et al. (1993) have suggested various reasons why waves in flumes should be smoother than those observed in the field, so this argument cannot be considered decisive.

2) Alternatively, the short fetch data on Lake Ontario may be positively biased for some reason. Although photographs (e.g., Terray et al. 1996, Fig. 1) suggest that the instrument platform is somewhat cluttered, the consistency and relatively small scatter for the longer fetch data (Colton et al. 1995) indicates that the exposure of the centrally mounted anemometer is adequate. Komen et al. (1998) suggested that in certain cases the results may have been affected by the upwind roughness over land. The shoreline has single story buildings and trees, some perhaps 10-m height, with electricity pylons spaced at roughly 100–200 m. While the anemometer at 12-m height would be well within the internal boundary layer (IBL) over the lake, Vickers and Mahrt (1999) have suggested that the nondimensional wind shear may be altered in shallow IBL cases. Against these arguments Drennan et al. (1999b) have recently shown that the spectra measured at the Lake Ontario site follow the expected universal scaling laws for both short and long fetch pure windsea conditions. In addition, the C_{D10n} values reported by Terray et al. (1996) were all obtained at very short fetch, between 1 and 2 km, and show little scatter, giving a consistent, high C_{D10n} to U_{10n} relationship (Fig. 9d).

If then the large C_{D10n} values at very young wave ages are indeed real, could they be predicted using a modified form of Eq. (6)—for example, Eq. (7), which includes a wave age dependence? Unfortunately, in the wave age range where Donelan (1982) observed higher roughness ($U_{10n}/c_p > 3$), his data were very scattered and, at any given wind speed, there was no clear wave age dependence. Data points in the youngest wave age category ($4 < U_{10n}/c_p < 6$) ranged between the smaller C_{D10n} values associated with the oldest waves and the highest C_{D10n} values observed. The young wave age data from RASEX were few and also showed large scatter. Thus quantifying any wave age dependency is difficult. Furthermore the addition of any wave age dependency to Eq. (6) degrades the ability to predict the other datasets. In particular, the agreement with the wave tank data is lost. For these reasons we have not attempted to use Eq. (7) to improve the simulation of the Lake Ontario short fetch data.

Finally we must consider the success of Eq. (6) in predicting the observed roughness in the open ocean (Figs. 10 and 11). Between 5 and 15 m s^{-1} the mean C_{D10n} values were correctly predicted to be significantly lower than the pure windsea values observed on lakes. This was due to the use of wave data that included both swell and wind wave contributions. Figure 12 suggests that for wind speeds up to about 7 m s^{-1}, H_s and L_p were always dominated by the existence of swell. Only above about 18 m s^{-1} were H_s and L_p consistently less than would be expected for a fully developed windsea. Indeed, our experience during the experiment was that mixed wind wave and swell conditions were continually present. In those conditions it is clearly an over simplification to use H_s and L_p to characterize a spectrum composed of wind waves and swells of various relative amplitudes and propagation directions. A further problem is the mismatch between the timescale of the individual stress estimates, which were determined from approximately 10-min samples, and the timescale required to significantly change H_s and L_p. It is therefore not surprising that individual predicted and observed data points correlated poorly. That, in the mean, Eq. (6) correctly predicted the observed C_{D10n} values was surprising, particularly since no open ocean data were used in developing the formula.

Why should the effects of swell, in the mean, have acted to decrease the surface roughness? When the directional wave data from SWS-2 are available, it should be possible to investigate this in more detail; for the present we can only speculate. There are observations (e.g., Donelan et al. 1997; Rieder and Smith 1998; Drennan et al. 1999a,b) that swell may significantly influence the surface roughness. Likely mechanisms for this include the modification of the characteristics of the higher frequency windsea by the swell, in addition to direct transfer of momentum (in either direction) between wind and swell. Donelan et al. (1997) show observations of increased wind stress for swells counter to (and in some cases across) the wind direction. Their few cases of following swell had roughness similar to their pure windsea cases; however, this was lower than would be predicted by our pure windsea relationship [Eq. (8)]. Reider and Smith (1998) examined contributions to the stress at periods less than about 16 sec. They found cases where the residual drag (i.e., with wave correlated contribution removed) was greater than the full drag, suggesting that the effect of the longer wavelength swell waves had decreased the stress. Drennan et al. (1999a,b) showed observations where following swells were associated with reduced roughness, as well as cases of counter swells and increased roughness. However the pure windsea relationship of Drennan et al. (1999a) was similar to the Yelland et al. (1998) formula, and therefore, as for Donelan et al. (1997), less than our pure windsea relationship. On the evidence of these papers, our conjecture that the swells on average acted to reduce the surface roughness implies two conditions. First, that there were more occasions when the dominant swell had a major component of motion with the wind direction rather than against (which seems likely). Second, that for cases described as pure windsea, an underlying swell existed. The latter also seems likely. There is evidence from wave flumes (e.g., Donelan, 1987) that even a gentle swell can modify the wind wave spectrum, and our own experience is that swell is rarely absent in the open ocean.

At some higher wind speed, depending on the amount of swell, we would expect the windsea contribution to dominate that from the swell and the C_{D10n} value on average to follow the line for a fully developed sea [Eq. (8)]. This implies lower C_{D10n} values at higher wind speeds than an extrapolation of, for example, the Yelland et al. (1998) relationship. Furthermore, measured z_{Ch} values from the open ocean would be maximum at around 20–25 m s^{-1} and then decrease with increasing wind speeds. Since the waves will become more duration limited, this would appear as a decrease of z_{Ch} with decreasing wave age. However there is little data to test this hypothesis. The high speed wind flume data of Kunishi and Imasato (1966), as reproduced by Kondo (1975), do lie about our predicted pure windsea relationship but with much scatter. However the experimental problems are such that the reliability of these high wind speed flume data must be open to question.

6. Summary

We have suggested that the roughness length scaled by the significant wave height is a function of the wave slope, H_s/L_p, and that this reconciles many of the apparent anomalies caused by seeking relationships between the Charnock parameter and the wave age. An important implication of this scaling is that the predicted roughness length does not vary significantly in cases of short fetch or duration; conditions for which our formula predicts a slight decrease. Thus it is possible to define a C_{D10n} to U_{10n} relationship that should be observed over deep water pure wind waves under most conditions. This relationship is different from that typically observed in the open ocean; it predicts higher C_{D10n} values at lower to moderate wind speeds and a less rapid increase of C_{D10n} with increasing U_{10n}. A number of published field datasets have been shown to exhibit this behavior: offshore winds from the RASEX experiment in the Baltic Sea (up to 9 m s^{-1}), data from Lake Washington, data from the HEXMAX experiment in the North Sea (chosen for lack of swell and other longer wavelength waves), and data from Lake Ontario (for longer fetches). In addition, two sets of wave tank observations have been shown to lie close to this relationship. For these cases the C_{D10n} values were correctly predicted to be slightly less than the pure wind sea values (due to the very short fetches), and the observed variation with wind speed was also well predicted. Thus our formula apparently reconciles the low stress measured in fetch limited laboratory tanks with the open ocean field observations.

Using the observed wave data, our formula correctly predicted that the C_{D10n} values for onshore winds in RASEX were less than those for offshore winds, and also predicted the magnitude and the variation of the C_{D10n} values observed during HEXMAX. Wave-age-based formulas fail to do this. However the formula did not predict the high C_{D10n} values observed over Lake Ontario for short fetches and very young waves ($U_{10n}/c_p > 3$). Such very young waves rarely occur in other datasets; however, a few such observations in RASEX also had, in the mean, high C_{D10n}. These observations suggest that physical processes occur at very young wave ages that are not parameterized by our formula. It also suggests that the success of our predictions for wave tank data may have been spurious. However, these large C_{D10n} values from the field data were very scattered and did not show a clear wave age dependency, so we have not attempted to modify our formula.

In the open ocean the effect of swell changes the effective wave height and steepness. As a result the roughness may be increased or decreased thus introducing scatter into observed C_{D10n} to U_{10n} relationships. Using wave data that had been calculated from the whole spectrum, and not divided into separate windsea and swell contributions, the formula correctly predicted the magnitude of C_{D10n} observed in the open ocean. For most wind speeds (up to 15 m s^{-1} or more) the effect of swell, on average, was to decrease the wave steepness. As a result, significantly lower average values were obtained for C_{D10n} compared to the pure windsea case found for lakes. Thus the results are qualitatively compatible with observations: that swell can significantly change the wind stress, that typical roughness lengths for lakes are greater than for the open ocean, and that variations of stress at a given wind speed do not correlate with wave age.

At higher winds (above around 15 m s^{-1}) where the sea state becomes dominated by the windsea the open ocean C_{D10n} values more nearly conform to the relationship for a fully developed sea. We suggest that in deep water that relationship is effectively an upper limit for the mean C_{D10n}. At very high wind speeds (>25 m s^{-1}) this implies a less rapid increase of C_{D10n} with increasing wind than would be predicted by extrapolation of existing formulas such as Yelland et al. (1998). Since these seas are duration limited, it also implies that wave-age-based formula will increasingly overestimate the stress in high wind conditions.

In summary, a simple parameterization formula based on wave height and steepness has been shown to explain the characteristics of a wide range of datasets. However many questions remain to be answered. The coefficients in Eq. 6 were poorly defined by the data available to us. Other data should now be used to refine the expression, in particular datasets for deep water waves on lakes. It is not obvious why the formula predicts the correct average values for open ocean data with mixed sea and swell. Individual calculated values were poorly correlated with the observations. It is likely that, if the direction difference between the peak waves and the wind direction were taken into account, this scatter in the stress predictions could be significantly decreased. For cases where the wind wave and swell energies are similar, the definition of L_p as the wavelength at the peak of the energy spectrum becomes ambiguous. A different definition of L_p, or a formula based on some other parameter such as the zero crossing period, may be more appropriate. We will investigate these issues when the directional data from SWS-2 can be analyzed. The high drag coefficient values observed in the short fetch, very young wave age data from Lake Ontario also require investigation. Such young wave ages are very rarely observed in the field and the evidence presented in this paper suggests that our proposed formula will predict the observed roughness over lakes on almost all occasions. However, to predict the short fetch Lake Ontario observations some further parameter would need to be incorporated.

Nevertheless, accepting all this, we suggest that the roughness length formulation advocated here will allow further progress, which until now has been continually hindered by the use of wave age formulations.

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APPENDIX

Wave Forecasting Formulas

For deep water and fully developed seas we assume $H_s = 0.0248U_{10n}^2$ and $T_p = 0.729U_{10n}$. Then L_p is determined from the dispersion relationship. Using the JONSWAP spectra Carter (1982) developed the following equations for duration and/or fetch limited seas. For fetch limited seas:

$$H_S = 0.0163X^{0.5}U_{10n} \quad \text{(A1a)}$$

$$T_p = 0.566X^{0.3}U_{10n}^{0.4}, \quad \text{(A1b)}$$

where X is the fetch in kilometers, and for duration limited seas:

$$H_S = 0.0146D^{5/7}U_{10n}^{9/7} \quad \text{(A2a)}$$

$$T_p = 0.540D^{3/7}U_{10n}^{4/7}, \quad \text{(A2b)}$$

where D is the duration in hours. The sea is considered fetch limited if

$$D > 1.167X^{0.7}U_{10n}^{-0.4}, \quad \text{(A3)}$$

which matches H_s, but not L_p between fetch and duration limited seas. Hence small discontinuities in the simulated wave parameters may occur.

Shallow water will be defined as depth h less than $0.5L_p$, although the equations do not predict a large change in wave properties until $h \approx 0.25L_p$. We assume that the deep water values, H_{so}, L_{po}, are those that would occur at that site, if the waves were not affected by the depth, and use the standard equations (Tucker 1991) for the dispersion relationship:

$$\frac{\omega^2}{g} = k \tanh(kh), \quad \text{(A4)}$$

where g is the acceleration due to gravity, k the wavenumber, and ω the angular frequency to obtain L_p and c_p. This was solved by using a fifth-order polynomial to determine the ratio of L_p/L_{po} as a function of h/L_{po}. Following Tucker (1991) the change in H_s is then given by

$$\frac{H_S}{H_{S0}} = [(1 + 2kh/\sinh 2kh) \tanh kh]^{-0.5}. \quad \text{(A5)}$$

REFERENCES

Anctil, F., and M. A. Donelan, 1996: Air–water momentum flux observations over shoaling waves. *J. Phys. Oceanogr.*, **26,** 1344–1353.

Ataktürk, S. S., and K. B. Katsaros, 1999: Wind stress and surface waves observed on Lake Washington. *J. Phys. Oceanogr.,* **29,** 633–650.

Bourassa, M. A., D. G. Vincent, and W. L. Wood, 1999: A flux parameterisation including the effects of capillary waves and sea state. *J. Atmos. Sci.,* **56,** 1123–1139.

Carter, D. J. T., 1982: Prediction of wave height and period for a constant wind velocity using the JONSWAP formulae. *Ocean Eng.,* **9,** 17–33.

Charnock, H., 1955: Wind stress on a water surface. *Quart. J. Roy. Meteor. Soc.,* **81,** 639–640.

Cheng, Z., and H. Mitsuyasu, 1992: Laboratory studies on the surface drift current induced by wind and swell. *J. Fluid Mech.,* **243,** 247–259.

Colton, M. C., W. J. Plant, W. C. Keller, and G. L. Geernaert, 1995: Tower-based measurements of normalized radar cross-section from Lake Ontario: Evidence of wind stress dependence. *J. Geophys. Res.,* **100,** 8791–8813.

Dobson, F. W., S. D. Smith, and R. J. Anderson, 1994: Measuring the relationship between wind stress and sea state in the open ocean in the presence of swell. *Atmos.–Ocean,* **32,** 237–256.

——, R. J. Anderson, P. K. Taylor, and M. J. Yelland, 1999: Storm Wind Study II: Open ocean wind and sea state measurement. *Proc. Symp. on the Wind-Driven Air–Sea Interface: Electromagnetic and Acoustic Sensing, Wave Dynamics and Turbulent Fluxes,* M. L. Banner, Ed., University of New South Wales, 295–296.

Donelan, M. A., 1982: The dependence of the aerodynamic drag coefficient on wave parameters. *First Int. Conf. on Meteorology and Air–Sea Interaction of the Coastal Zone,* The Hague, Netherlands, Amer. Meteor. Soc., 381–387.

——, 1990: Air–sea interaction. *The Sea,* Vol. 9: *Ocean Engineering Science,* B. Le Mehaute and D. M. Hanes, Eds., Wiley, 239–292.

——, J. A. Hamilton, and W. H. Hui, 1985: Directional spectra of wind generated waves. *Philos. Trans. Roy. Soc. London,* **A315,** 509–562.

——, F. W. Dobson, S. D. Smith, and R. J. Anderson, 1993: On the dependence of sea surface roughness on wave development. *J. Phys. Oceanogr.,* **23,** 2143–2149.

——, W. M. Drennan, and K. B. Katsaros, 1997: The air–sea momentum flux in conditions of wind sea and swell. *J. Phys. Oceanogr.,* **27,** 2087–2099.

Drennan, W. M., H. C. Graber, and M. A. Donelan, 1999a: Evidence for the effects of swell and unsteady winds on marine wind stress. *J. Phys. Oceanogr.,* **29,** 1853–1864.

——, K. K. Kahma, and M. A. Donelan, 1999b: On momentum flux and velocity spectra over waves. *Bound.-Layer Meteor.,* **92,** 489–515.

Geernaert, G. L., 1990: Bulk parameterisations for the wind stress and heat fluxes. *Surface Waves and Fluxes.* Vol. 1: *Current Theory,* G. L. Geernaert and W. J. Plant, Eds., Kluwer, 91–172.

——, K. B. Katsaros, and K. Richter, 1986: Variation of the drag coefficient and its dependence on sea state. *J. Geophys. Res.,* **91,** 7667–7679.

Gulev, S. K., and L. Hasse, 1998: North Atlantic wind waves and wind stress fields from voluntary observing ship data. *J. Phys. Oceanogr.,* **28,** 1107–1130.

Hare, J. E., P. O. G. Persson, C. W. Fairall, and J. B. Edson, 1999: Behaviour of Charnock's relationship for high wind conditions. Preprints, *13th Symp. on Boundary Layers and Turbulence,* Dallas, TX, Amer. Meteor. Soc., 252–255.

Hsu, S. A., 1974: A dynamic roughness equation and its application to wind stress determination at the air–sea interface. *J. Phys. Oceanogr.,* **4,** 116–120.

Janssen, J. A. M., 1997: Does wind stress depend on sea-state or not?—A statistical error analysis of HEXMAX data. *Bound.-Layer Meteor.,* **83,** 479–503.

Johnson, H. K., J. Hoejstrup, H. J. Vested, and S. E. Larsen, 1998: Dependence of sea surface roughness on wind waves. *J. Phys. Oceanogr.,* **28,** 1702–1716.

Juszko, B. A., R. F. Marsden, and S. R. Waddell, 1995: Wind stress from wave slopes using Phillips equilibrium theory. *J. Phys. Oceanogr.,* **25,** 185–203.

Keller, M. R., W. C. Keller, and W. J. Plant, 1992: A wave tank study of the dependence of X band cross sections on wind speed and water temperature. *J. Geophys. Res.,* **97,** 5771–5792.

Komen, G., P. A. E. M. Janssen, V. Makin, and W. Oost, 1998: On the sea state dependence of the Charnock parameter. *Global Ocean Atmos. Syst.,* **5,** 367–388.

Kondo, J., 1975: Air–sea bulk transfer coefficients in diabatic conditions. *Bound.-Layer Meteor.,* **9,** 91–112.

Kunishi, H., and N. Imasato, 1966: On the growth of wind waves by high-speed wind flume (in Japanese). *Ann. Disaster Prev. Res. Inst. Kyoto Univ.,* **9,** 667–676.

Maat, N., C. Kraan, and W. A. Oost, 1991: The roughness of wind waves. *Bound.-Layer Meteor.,* **54,** 89–103.

Mahrt, L., D. Vickers, J. Howell, J. Hojstrup, J. M. Wilczak, J. Edson, and J. Hare, 1996: Sea surface drag coefficients in the Risø Air Sea Experiment. *J. Geophys. Res. Oceans,* **101,** 14 327–14 335.

Monbaliu, J., 1994: On the use of the Donelan wave spectral parameter as a measure for the roughness of wind waves. *Bound.-Layer Meteor.,* **67,** 277–291.

Nordeng, T. E., 1991: On the wave age dependent drag coefficient and roughness length at sea. *J. Geophys. Res.,* **96,** 7164–7174.

Oost, W. A., 1991: The wind profile in a wave flume. *J. Wind Eng. Ind. Aerodyn.,* **37,** 113–121.

——, 1998: The KNMI HEXMAX stress data—A reanalysis. *Bound.-Layer Meteor.,* **86,** 447–468.

Rieder, K. F., 1997: Analysis of sea-surface drag parameterizations in open ocean conditions. *Bound.-Layer Meteor.,* **82,** 355–377.

——, and J. A. Smith, 1998: Removing wave effects from the wind stress vector. *J. Geophys. Res.,* **103,** 1363–1374.

Smith, S. D., 1980: Wind stress and heat flux over the ocean in gale force winds. *J. Phys. Oceanogr.,* **10,** 709–726.

——, 1988: Coefficients for sea surface wind stress, heat flux and wind profiles as a function of wind speed and temperature. *J. Geophys. Res.,* **93,** 15 467–15 474.

——, K. B. Katsaros, W. A. Oost, and P. G. Mestayer, 1990: Two major experiments in the Humidity Exchange over the Sea (HEXOS) Program. *Bull. Amer. Meteor. Soc.,* **71,** 161–172.

——, and Coauthors, 1992: Sea surface wind stress and drag coefficients: The HEXOS results. *Bound.-Layer Meteor.,* **60,** 109–142.

——, K. B. Katsaros, W. A. Oost, and P. G. Mestayer, 1996: The impact of the HEXOS programme. *Bound.-Layer Meteor.,* **78,** 121–141.

Taylor, P. K., and M. J. Yelland, 2000: A note on the apparent ''imbalance'' term in the turbulent kinetic energy budget. *J. Atmos. Oceanic Technol.,* **17,** 82–89.

——, ——, F. W. Dobson, and R. J. Anderson, 1999: Storm Wind Study II: Wind stress estimates from buoy and ship. *Proc. Symp. on the Wind-Driven Air–sea Interface: Electromagnetic and Acoustic Sensing, Wave Dynamics and Turbulent Fluxes,* M. L. Banner, Ed., University of New South Wales, 353–354.

Terray, E. A., M. A. Donelan, Y. C. Agrawal, W. M. Drennan, K. K. Kahma, A. J. Williams III, P. A. Hwang, and S. A. Kitaigorodskii, 1996: Estimates of kinetic energy dissipation under breaking waves. *J. Phys. Oceanogr.,* **26,** 792–807.

Toba, Y., H. Iida, H. Kawamura, N. Ebuchi, and I. S. F. Jones, 1990: Wave dependence of sea-surface wind stress. *J. Phys. Oceanogr.,* **20,** 705–721.

Tucker, M. J., 1991: *Waves in Ocean Engineering—Measurement, Analysis, Interpretation.* Ellis Horwood, 431 pp.

Vickers, D., and L. Mahrt, 1997a: Fetch limited drag coefficients. *Bound.-Layer Meteor.,* **85,** 53–79.

——, and ——, 1997b: Quality control and flux sampling problems for tower and aircraft data. *J. Atmos. Oceanic Technol.,* **14,** 512–526.

——, and ——, 1999: Observations of non-dimensional wind shear in the coastal zone. *Quart. J. Roy. Meteor. Soc.,* **125,** 2685–2702.

Yelland, M. J., and P. K. Taylor, 1996: Wind stress measurements from the open ocean. *J. Phys. Oceanogr.,* **26,** 541–558.

——, and ——, 1999: Does the wind stress depend on the sea state? *Wind over Wave Couplings: Perspectives and Prospects,* S. G. Sajjadi, Ed., Oxford University Press, 107–117.

——, ——, I. E. Consterdine, and M. H. Smith, 1994: The use of the inertial dissipation technique for shipboard wind stress determination. *J. Atmos. Oceanic Technol.,* **11,** 1093–1108.

——, B. I. Moat, P. K. Taylor, R. W. Pascal, J. Hutchings, and V. C. Cornell, 1998: Measurements of the open ocean drag coefficient corrected for air flow disturbance by the ship. *J. Phys. Oceanogr.,* **28,** 1511–1526.