P3.5 SEA SURFACE ROUGHNESS: HIGH WINDS AND SHORT FETCHES

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1. INTRODUCTION

Despite many years of field measurements there are very few direct observations of the aerodynamic roughness length (z_0) of the sea surface for 10m, averaged wind speeds greater than 25 m/s. Knowledge of z_0 (or equivalently the drag coefficient, C_{D10n}) under these conditions is needed, for example, for hurricane research and forecasting. Unfortunately it is at these high wind speeds that the available parameterisations diverge significantly. For example, the latest version of the TOGA COARE algorithm, (presently version 2.6bfw but to be renamed Version3; Fairall et al. 2003) includes the option to define z_0 in terms of the sea state. Present choices include a formula based on wave age (Oost et al. 2002) or one based on the significant height and slope of the waves (Taylor and Yelland, 2001: TY2001 hereafter). We shall show (Section 2) that the latter formula predicts significantly lower roughness at high wind speeds compared to Oost et al. (2002) or other wave age based formulas (e.g. Drennan et al. 2002).

Given the paucity of field observations, we shall examine (Section 3) results from a number of wind-wave flume studies. These typically report C_{D10n} values which, despite the very short fetch and exceedingly young waves, are similar in magnitude to those observed in the open ocean. Thus the proponents of wave age formulas have argued that laboratory and field waves are fundamentally dissimilar (Donelan et al. 1993). However the TY2001 formula will be shown to successfully predict various characteristics of the observed roughness data. In section 4 we will briefly consider the performance of the different formulas in predicting the roughness observed in field experiments, before presenting a summary in Section 5.

2. THE ROUGHNESS LENGTH FORMULAS

In this section we will define the different formulas and contrast the predicted drag coefficients for varying wave conditions. We shall use the Oost et al. (2002) formula as defined in the COARE algorithm:

$$\frac{z_0}{L_p} = \frac{50}{2\pi}\left(\frac{u_*}{c_p}\right)^{4.5} \tag{1}$$

where L_p and c_p are the wavelength and phase speed of waves at the peak of the spectrum and u_* is the friction velocity. An alternative wave age formula is that of Drennan et al. (2002) for pure wind driven seas:

$$\frac{z_0}{H_S} = 3.35\left(\frac{u_*}{c_p}\right)^{3.4} \tag{2}$$

Since (u_* / c_p) is the inverse wave age, (1) and (2), like other wave age formula, imply that younger waves have increased roughness. The TY2001 formula is:

$$\frac{z_0}{H_s} = 1200\left(\frac{H_s}{L_p}\right)^{4.5} \tag{3}$$

where (H_s / L_p) represents the significant wave slope. Finally, to aid comparison between different figures, we will use the linear C_{D10n} to U_{10n} relationship of Smith (1980):

$$C_{D10n} = 0.61 + 0.063U_{10n} \tag{4}$$

which has been found to be a good, mean representation of open ocean data (Yelland et al. 1998; Taylor & Yelland 2000).

Figure 1(a) shows the C_{D10n} values predicted by (1) to (4) for fully developed wave conditions (as defined by the default values in the COARE 2.6bfw algorithm). The Oost et al. (2002) and TY2001 predictions are similar to Smith (1980); the Drennan et al. (2002) prediction is much lower. Indeed the latter authors noted that their wave age formula performed poorly for fully developed seas, possibly because the roughness would not be expected to scale with wave age in those conditions.

For winds above say 15m/s, it is unlikely that the waves would be fully developed (e.g. TY2001, Fig. 12). Using values for the sea state development typical of ocean conditions (Fairall 2002, pers. comm.) and which, at higher wind speeds might be typical of those observed in hurricanes, the C_{D10n} relationships predicted by the vaarious formulas are significantly different (Figure 1b). For these wave conditions, the strong wave age dependence of the Oost et al (2002)

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formula (1) results in very high C_{D10n} predictions values for wind speeds above 15 to 20 m/s. The Drennan et al. (2002) formula (2) gives values similar to observational data sets up to about 25 m/s (e.g. TY2001, Figure 11), but predicts high roughness in the 30 to 40 m/s range. In contrast, at those very high wind speeds the TY2001 formula (3) predicts much lower C_{D10n} values, in fact slightly less than would be obtained by extrapolation of the Smith (1980) relationship (4). For comparison, the compilation of C_{D10n} values by Wu (1982) uses studies of hurricane momentum budgets to suggest $10^{-3}C_{D10n}$ values of 3.4 and 4.1 at 40 m/s and 50 m/s respectively, very similar to Smith (1980).

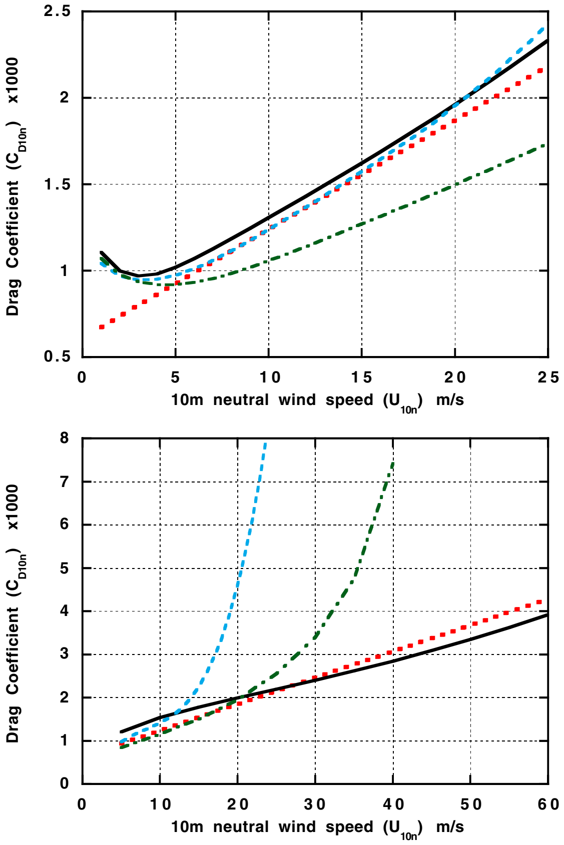

Figure 1. Comparison of the 10m neutral drag coefficient (C_{D10n}) predicted by the formulas of Oost et al. (2002) - blue dashed line, Drennan et al. (2002) - green chain line, Taylor and Yelland (2001) - black line, Smith (1980) - red dotted line.

(a - top) for fully developed waves as defined in the COARE 2.6bfw algorithm.

(b - bottom) for the under-developed wave fields typically observed in the open ocean.

The comparison shown in Figure 1 demonstrates that, although wave age based formula may be based on a range of data sets, they fail to predict the roughness over all wave conditions. The TY2001 formula generally predicts less variation in roughness compared to the wave age formula, and has drag coefficients similar in magnitude to those of Smith (1980) for many wave conditions.

3. EVIDENCE FROM LABORATORY STUDIES

The above comparison was based on hypothetical (though believed realistic) wave conditions. Given the lack of observational field data at very high wind speeds, in this section we shall consider a sample of laboratory studies extending to high values of the equivalent 10m wind speed. A problem for wind-wave flume experiments is that momentum will be lost to the ceiling of the flume as well as to the water (e.g. Oost 1991). We shall therefore select experiments in which the stress at the water surface was estimated either from well defined logarithmic wind profiles or by other techniques such as the wind induced slope of the water surface in the tank. Flume experiments are also different from the open ocean because of the narrow band width of the directional wave spectra (e.g. Donelan et al. (1993). We shall therefore consider some experiments in which the wave state in the flume was varied by some artificial means. This is a continuing study, here we will present some preliminary results.

In an early laboratory study, Francis (1951) used a narrow (7.6cm) 6m flume with a fan and, as a wave generator at the upwind end, a circular 1.2m circumference tank above which paddles rotated at 1300 rpm (equivalent to about 25 m/s). The wind stress was determined by the setup of the water surface. Wind, wind stress, and wave data were presented for a range of wind speeds, with and without the use of the wave generator, and for the upwind and downwind halves of the flume. Whereas Francis extrapolated his wind measurements, obtained using a pitot tube 10 cm above the water, to 10m height, the results presented here are recalculated using the observed roughness lengths and Monin-Obukhov scaling.

The observed C_{D10n} values (Figure 2) are typical of many flume experiments in being similar in magnitude to the open ocean values of Smith (1980). Indeed, at the downwind end of the flume the results lie along the Smith(1980) line irrespective of whether the wave generator was in use (Figures 2c,d). At the upwind end of the flume with the wave generator off, the roughness was slightly less than the Smith (1980). relationship (Figure 2a). For each of these cases the observed C_{D10n} to U_{10n} relationship was well predicted

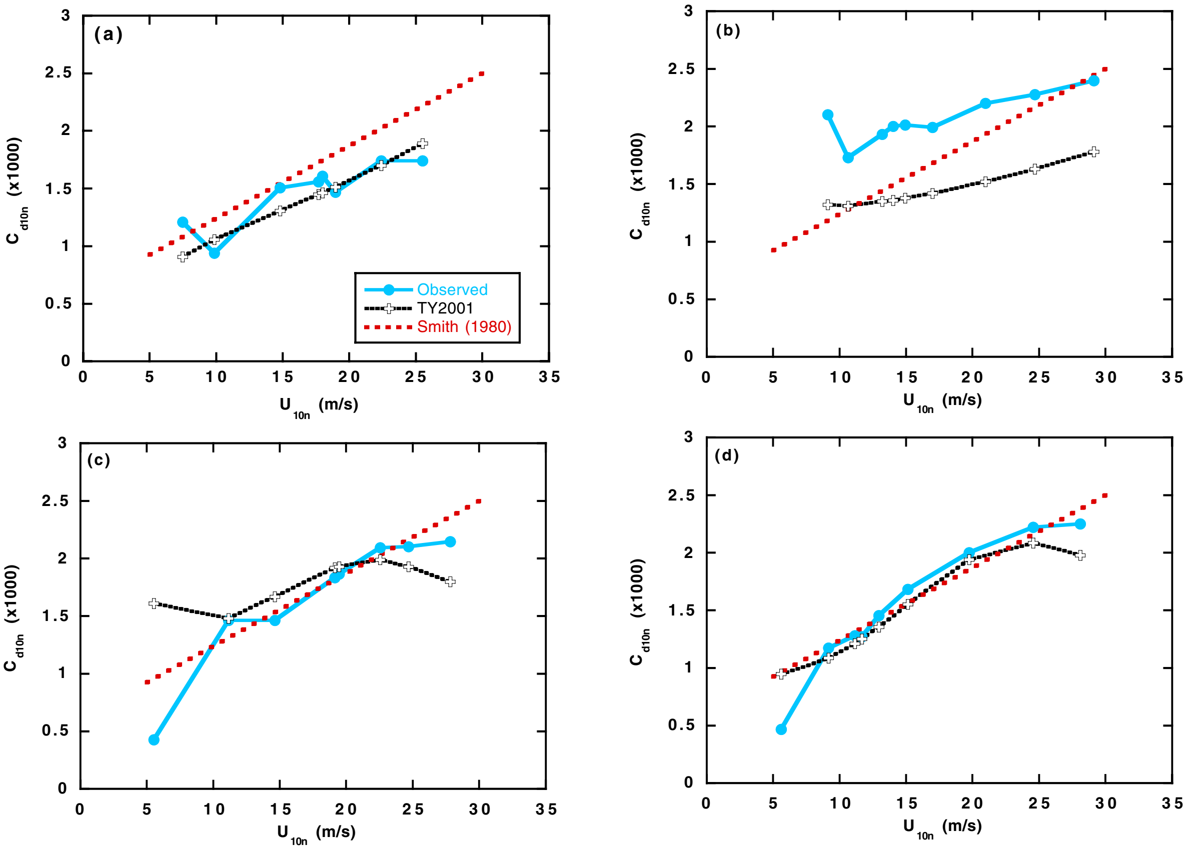

Figure 2. C_{D10n} to U_{10n} results from Francis (1951) (blue circles) and the values predicted by the Taylor and Yelland (2001) formula from the observed wave conditions. The Smith (1980) relationship (red dotted line) is shown to aid comparison. The top row of plots are at the upwind end of the flume, the lower plots at the downwind end; the left plots are for fan only, the right hand plots are for fan plus wave generator.

Table 1. Characteristics of the wave flume studies used in this paper. The columns give total length of the flume, fetch to the measurement site, the wind range studied, how the wind stress was determined, and whether a mechanical wave generator was used for some of the runs.

Study	Flume Length (m)	Fetch (m)	10m wind range (m/s)	Stress method	Wave generator
Francis (1951)	6	3m,5m	5 - 30	setup	yes
Kunishi & Imasato (1966)	40	10 - 20m	15 - 60	profile	no
Lai & Shemdin (1974)	46	24m	19 - 27	profile	yes
Keller et al. (1992)	30.5	16m	0 - 28	profile	not used

by the TY2001 formula using the observed wave characteristics. Only for the upwind case with the wave generator on (Figure 2b) were the observed C_{D10n} values not predicted. One might argue that for this case the artificially generated waves had not adjusted to the flume wind speed, a process which had been completed at the downwind end of the flume (Figure 2d).

In Figure 3 we plot the results from Francis (1951) along with C_{D10n} from the experiments listed in Table 1. The results from Kunishi & Imasato (1966), as quoted by Kondo (1972), were very scattered and we show averages for wind speed ranges together with the standard error of the mean. Lai and Shemdin (1974) is the only data set containing measurements over salt water but these do not appear significantly different from the fresh water values. For Keller et al. (1992) we show their averaged relationship over the wind speed range observed. Despite the very short fetches and very young waves, all these wind flume data lie close to the Smith (1980) relationship. This is as predicted by the TY2001 relationship, whereas wave age based formula would predict much greater roughness for all these cases.

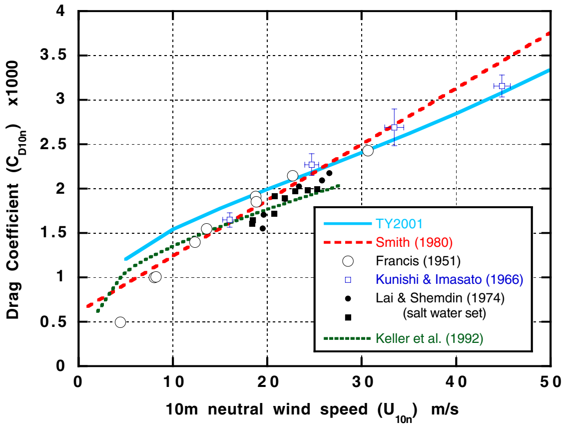

Figure 3. The C_{D10n} to U_{10n} relationship observed in the flume experiments listed in Table 1. Also shown is the result of applying the TY2001 formula to high wind wave conditions (Figure 1b) and, for reference, the Smith 1980 relationship.

4. COMPARISON WITH FIELD EXPERIMENTS

A paper describing a detailed comparison of the performance of formulas (2) and (3) for a wide range of field experiment data sets is in preparation (Drennan, Taylor and Yelland, 2002), so in this note we will only make some general remarks.

Each of the formulas (1) to (3) has been developed and tested using a selection of field data. Oost et al. (2002) used data from the ASGAMAGE experiment in the North Sea to develop the formula represented by (1). The Drennan et al. (2002) formula was developed principally using data from the FETCH experiment in the Mediterranean Sea, but also using data from the WAVES and AGILE experiments on Lake Ontario, the SWADE experiment off the coast of Virginia, and the North Sea HEXOS experiment (Janssen, 1997). TY2001 based their formula on an examination of the same data from HEXOS, the Baltic Sea RASEX experiment (Vickers and Mahrt, 1997; Johnson et al. 1998) and a small data set from Lake Ontario (Anctil and Donelan, 1996).

Perhaps unsurprisingly, each formula was claimed to well represent the data on which it was based. TY2001 also tested their formula against other data, the SWS-2 experiment off Nova Scotia and further published data from Lake Ontario. While the SWS-2 results, and longer fetch data from Lake Ontario, were well modelled by (3), data for very young waves on Lake Ontario showed greater roughness than was predicted. TY2001 argued against including a wave age dependent term in their formula because such a term would remove the good agreement found with the RASEX and HEXOS experiments. In contrast, the wave age based formula (3) predicts the high roughness observed with very young waves on Lake Ontario but fails to predict the low roughness observed at short fetches during RASEX.

Evaluation of roughness length scalings using field data is fraught with pitfalls. The TY2001 formula was developed because, despite having amassed a very large data set of open ocean measurements, we were unable to detect any variation of roughness with wave age at a given wind speed (Yelland and Taylor, 1996; Yelland et al., 1998). The qualification with regard to wind speed is important. Since surface roughness (C_{D10n} or z_0) increases with wind speed (Figures 1 to 3) and since the waves at higher wind speeds tend to be younger (since a longer period or fetch is needed to produce an equilibrium sea state), there is bound to be an apparent relationship between roughness length and wave age. Thus Figure 4 shows the roughness lengths predicted by the TY2001 formula (3) for the SWS-2 experiment data plotted using the wave-age scaling of the Drennan et al. (2002) formula (2). Although TY2001 is not a wave-age based formula, the fitted line explains 78% of the variance and is equivalent to:

$$\frac{z_0}{H_s} = 2.3\left(\frac{u_*}{c_p}\right)^3 \qquad (5)$$

which is not dissimilar to formula (2). The vital question is whether this apparent relationship actually reflects physical causality. If such causality exists then the scatter in C_{D10n} values at a given wind speed should show such a relationship, but we have failed to detect it in the SWS-2 data or in other data sets.

A particular example is the HEXOS data set. This is arguably the most reliable existing data set since it represents the results of a number of different research groups each with different instrumentation. Furthermore, it has been the object of a number of studies (e.g. Smith et al. 1992, Janssen 1997, Oost, 1998). Careful examination of the HEXOS data set shows that, at a given wind speed, it was the older

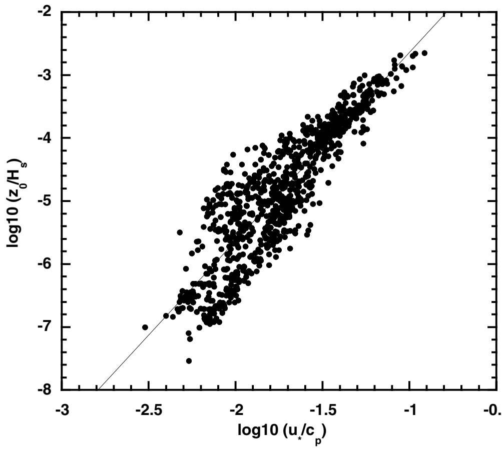

Figure 4 The roughness length predictions using the TY2001 formula for the SWS-2 experiment plotted using wave age scaling to show that the results from this non-wave age formula do show an apparent wave age relationship (see text).

waves that had higher c_p and greater roughness (TY2001). These waves occurred when the wind direction resulted in a longer fetch permitting greaterwave development. Thus, despite being directly based on the self same HEXOS data set, the wave age formula of Smith (1992) can only predict the mean trend of the data (Figure 5). Using the observed wave characteristics, the TY2001 formula predicts this enhanced roughness far better.

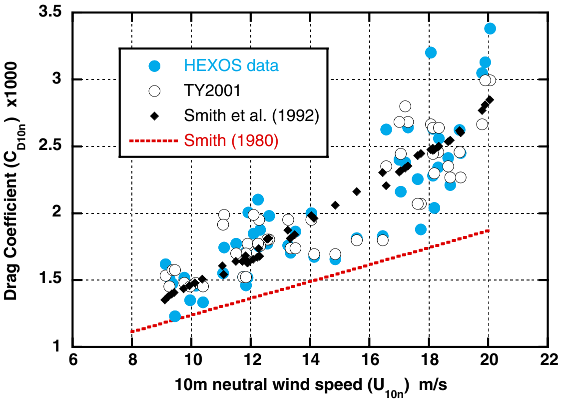

Figure 5. Observations of C_{D10n} and U_{10n} from the HEXOS experiment and the corresponding values predicted by the TY2001 formula and by the Smith (1992) wave age formula. The latter was based on the HEXOS data shown. Also shown for comparison is the Smith (1980) relationship.

5. SUMMARY

We have discussed two sets of conditions when the surface roughness is less than would be predicted using a wave age based formula. That is, at very high wind speeds, and at very short fetches in a wind wave flume (with low or high winds). This behaviour was successfully predicted by the TY2001 formula. The latter formula suggests that, under a wide range of conditions, the drag coefficient is similar to the Smith (1980) relationship. Nevertheless it is able to predict well a case like HEXOS where the roughness was significantly greater than Smith (1980). Indeed for HEXOS it does better than the Smith (1992) wave age based formula which was based on the HEXOS data (and better also than other wave age formulas). Taken together, these results would seem to suggest similarity of the surface roughness over a wide range of wind speeds and sea states. However this similarity does not appear to hold for observations under young wave conditions on Lake Ontario, since the TY2001 formula under predicted the roughness for those data sets. A study comparing the performances of TY2001 and a wave age formula (Drennan et al. 2002) is in progress. For now we will only claim that the TY2001 formula appears applicable over most conditions observed in the field, and succeeds at high winds and very short fetches in wind-wave flumes, when wave age formulas fail.

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