Journal of Physical Oceanography (IF:3.179)

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

Peter K. Taylor and Margaret J. Yelland
Southampton Oceanography Centre, Southampton, United Kingdom

Reporter: Cao Zhengda

Contents

- Introduction
- Objective
- The datasets
- Development of a roughness length formula
- Verification of the calculated $C_{D10\mathrm{n}}$ values
- Discussion
- Summary

Introduction

- The variation of the roughness length z_o with wind speed for rough flow over the sea is first described by Charnock (1955)

$$z_o = z_{Ch} u_*^2 / g \qquad (1)$$

where u_* is the friction velocity, g the acceleration due to gravity, and z_{Ch} the Charnock parameter used to characterize the variation of the drag coefficient C_{D10n} with wind speed U_{10n} at 10m.

- Hsu (1974) suggested that z_{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 peak of the wave spectrum.
- Using a subset of the HEXMAX data chosen to avoid the effects of swell, Matt et al. (1991) and Smith et al. (1992) proposed the "HEXOS" relationship

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

where c_p / u_* is defined as the wave age, and c_p the phase speed at the peak of the wave spectrum. Eq. (2) implies younger waves are rougher than older waves.

Introduction

- Using data from Lake Ontario, Donelan (1990) developed a wave-age-based formula

$$\frac{z_o}{\eta} = 5.5\times10^{-4}(\frac{U_{10n}}{c_p})^{2.7} \quad (3)$$

Anctil and Donelan (1996) found the slope-based formula fitted the data equally well:

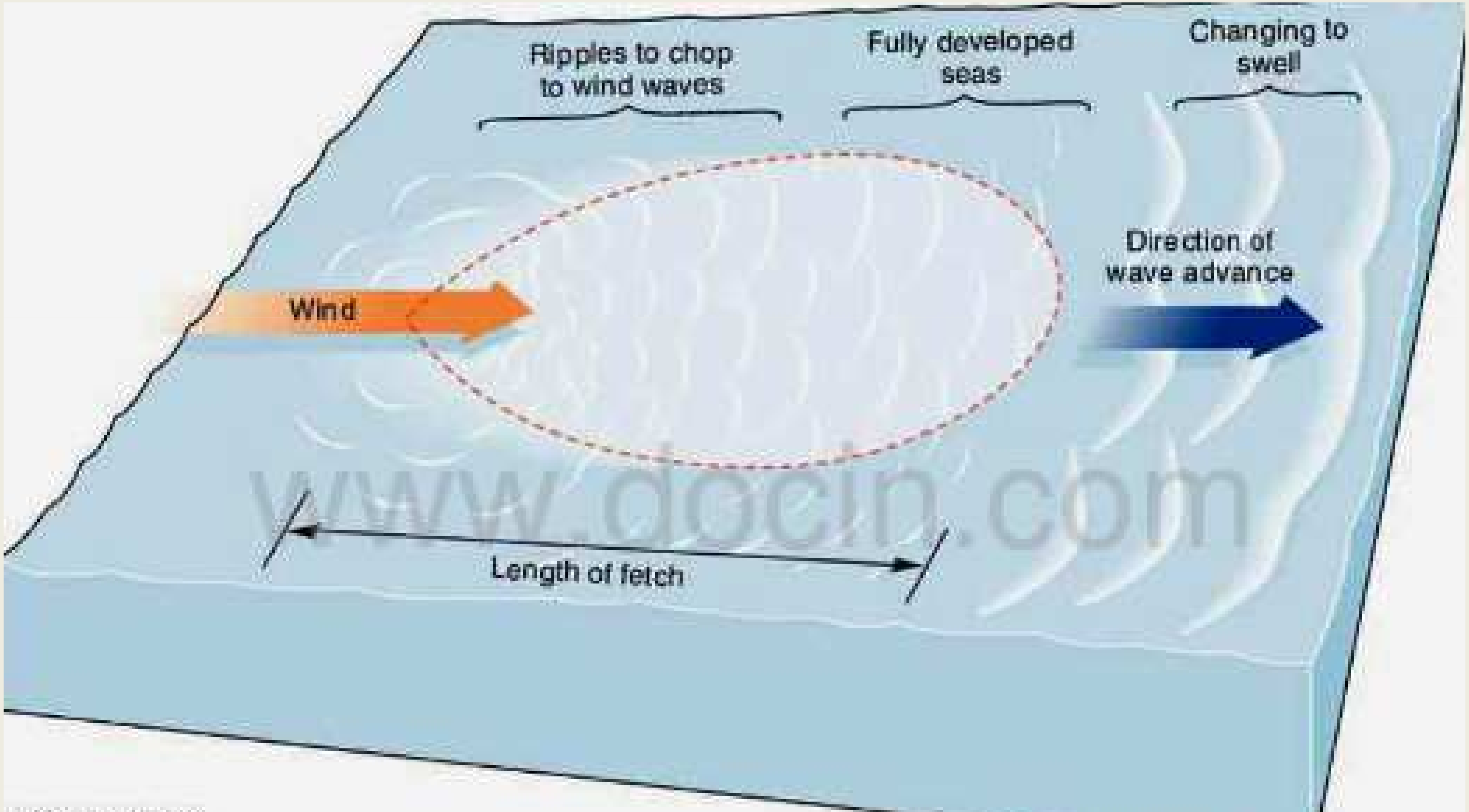
$$\frac{z_o}{\eta} = 2.55\times10^{3}\theta^{6.76} \quad (4)$$

where θ is the rms slope.

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

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

Development of waves



Relationship between C_{D10n} and z_o

$$U_{10n} = \frac{u_*}{\kappa} \ln \frac{10}{z_o}$$

$$C_{D10n} = \left(\frac{u_*}{U_{10n}}\right)^2$$

$$C_{D10n} = \kappa^2 / [\ln(10 / z_o)]^2$$

Objective

By using a modified form of Eq. (4) resolve several major discrepancies caused by seeking relationships between the roughness and the wave age.

The datasets

- HEXMAX

  Fetch: >= 175 km

  No swell

  For a given wind speed the longer wavelength waves were older and would have been excepted to be smoother—the opposite of the observation.

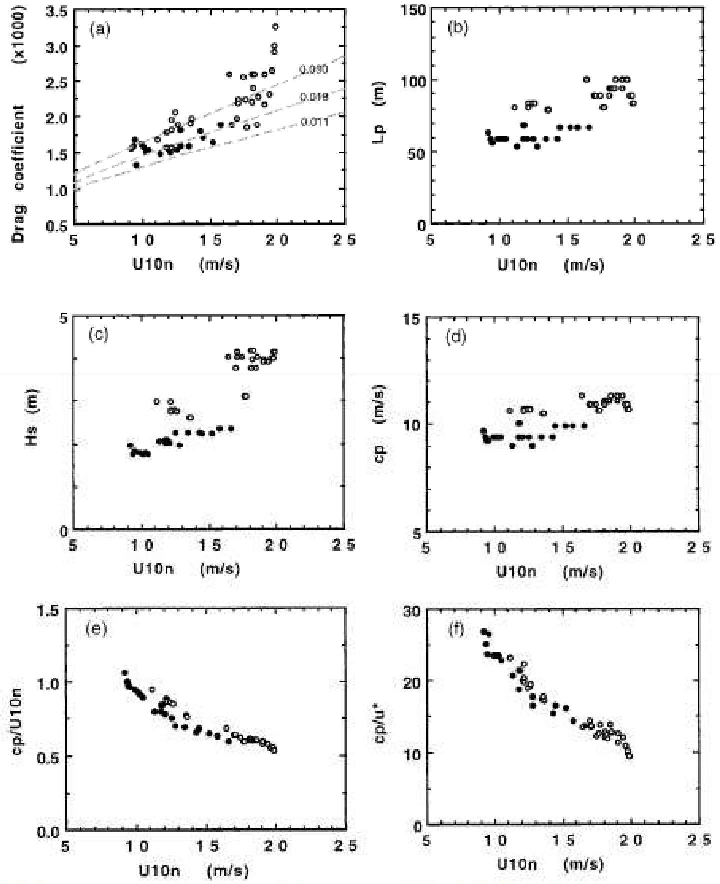


FIG. 1. Data from the HEXMAX experiment (from Janssen 1997) plotted against the 10-m neutral wind speed, U_{10n}; data for which $L_p > 72$ m are shown by open circles: (a) drag coefficient, $C_{D10n} \times 1000$, the dashed lines show z_{Ch} values as indicated; (b) wavelength at peak of the wave spectrum, 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_*.

The datasets

- RASEX

  Fetch limited:

  2-5 km for offshore wind flow

  15-25 km for onshore wind flow

  Higher C_{D10n} values were observed in offshore rather than onshore flow.

  The RASEX C_{D10n} values for on-shore winds were much lower than would be predicted by Eq. (2).

  —Vickers and Mahrt (1997a, hereafter VM97)

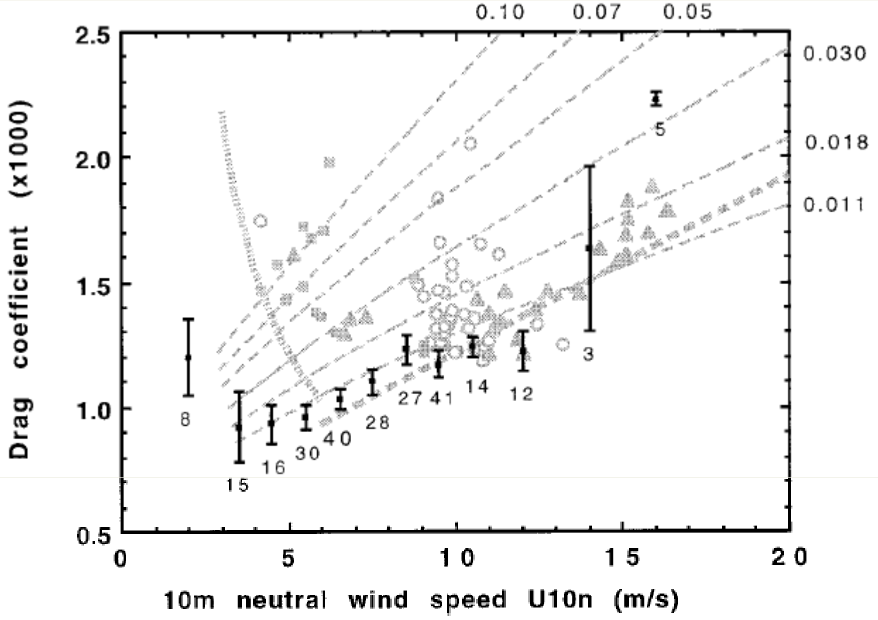


FIG. 2. RASEX data for the case of onshore winds; the drag coefficient C_{D10n} is plotted against the wind speed U_{10n}. The black data points (with the standard error and number of data values averaged) are from Vickers and Mahrt (1997). The gray symbols are data from Johnson et al. (1998) obtained 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.

The datasets

- Anctil and Donelan (1996)-Lake Ontario

  Depth: 2, 4, 8, 12 m

  For run 166 wind speed: 7 m/s fetch: 8 km

  For run 185 wind speed: 14 m/s fetch: 300 km

The results from this study were chosen for they were published with consistent wave information.

The purpose of this experiment was to study the effect of shoaling waves.

Development of a roughness length formula

- Choice of scaling variables

Using H_s to scale the roughness appears a better option.

Only by using (H_s / L_p) as a scaling parameter is the higher wind speed RASEX collapsed onto the HEXOS points.

Therefore adopt this scaling:

$$z_o / H_s = A_1 (H_s / L_p)^{B_1} \quad (6)$$

Noting that with this scaling the lower wind speed data from HEXOS and AD96diverge, a multiple scaling similar to Eq. (5) is considered:

$$z_o / H_s = A_2 (H_s / L_p)^{B_2} \left(\frac{U_{10n}}{c_p}\right)^{c} \quad (7)$$

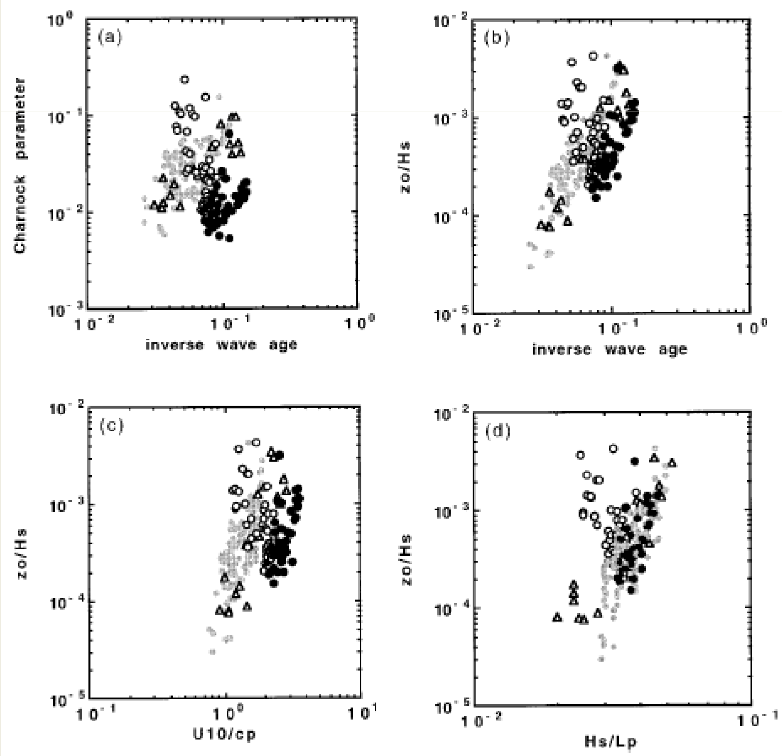


FIG. 3. Nondimensional roughness variables plotted against different scaling variables. Data are from HEXOS (small gray circles), AD96 (open triangles), and RASEX (open circles: $U_{10n} < 10$ m s^{-1}, closed circles: $U_{10n} > 10$ m s^{-1}). Plots are (a) z_{Ch} vs $(c_p/u_*)^{-1}$, (b) z_o/H_s vs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

Development of a roughness length formula

- Choice of coefficients

Using the wave age and Eq. (7) can explain little more of the variance than Eq. (6) ($R^2 = 0.58$ compared to 0.56), and maybe introduce more chance of self-correlation, then Eq. (6) could be better.

Obtain $\ln(A_1) = 7.09, B_1 = 4.5$ for a two-way regression, which are more similar to the one-way regression, presumably because the scatter is dominated by the error in determining z_o .

Development of a roughness length formula

- Predicted effects of varying duration, fetch, and water depth

Eq.(6) predicts a slight decrease of compared to the value for a fully developed sea, normally by less than 10%.

At about $h_s = 0.2L_p$ the effect of shoaling occurs.

Both Eq. (6) and the Donelan (1990) predict enhanced roughness for shoaling conditions.

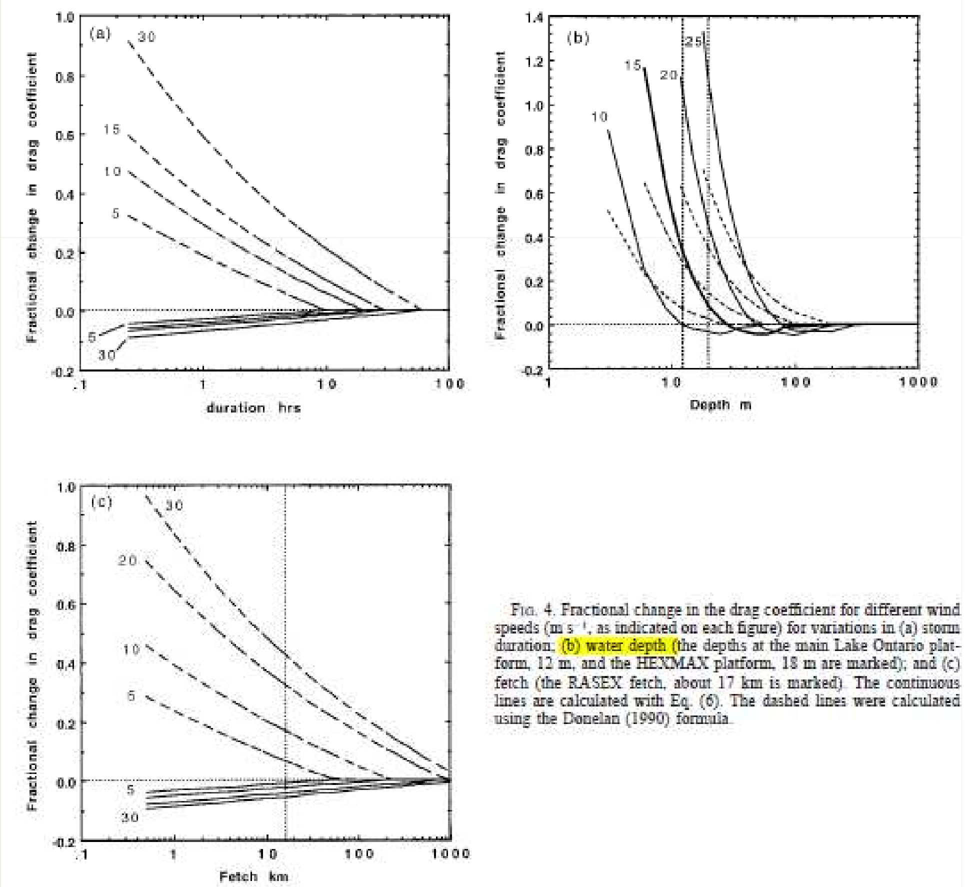


FIG. 4. Fractional change in the drag coefficient for different wind speeds ($m\ s^{-1}$, as indicated on each figure) for variations in (a) storm duration; (b) water depth (the depths at the main Lake Ontario platform, 12 m, and the HEXMAX platform, 18 m are marked); and (c) fetch (the RASEX fetch,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

Verification of the calculated C_{D10n} values

- Simulation of the published datasets

The agreement between the calculated (Eq(6)) and observed C_{D10n} values was good, except the underprediction at higher wind speeds for AD96 (strongly shoaling waves).

The results for the wave-aged-based Eq. (3) show more disagreement compared to that of Eq(6).

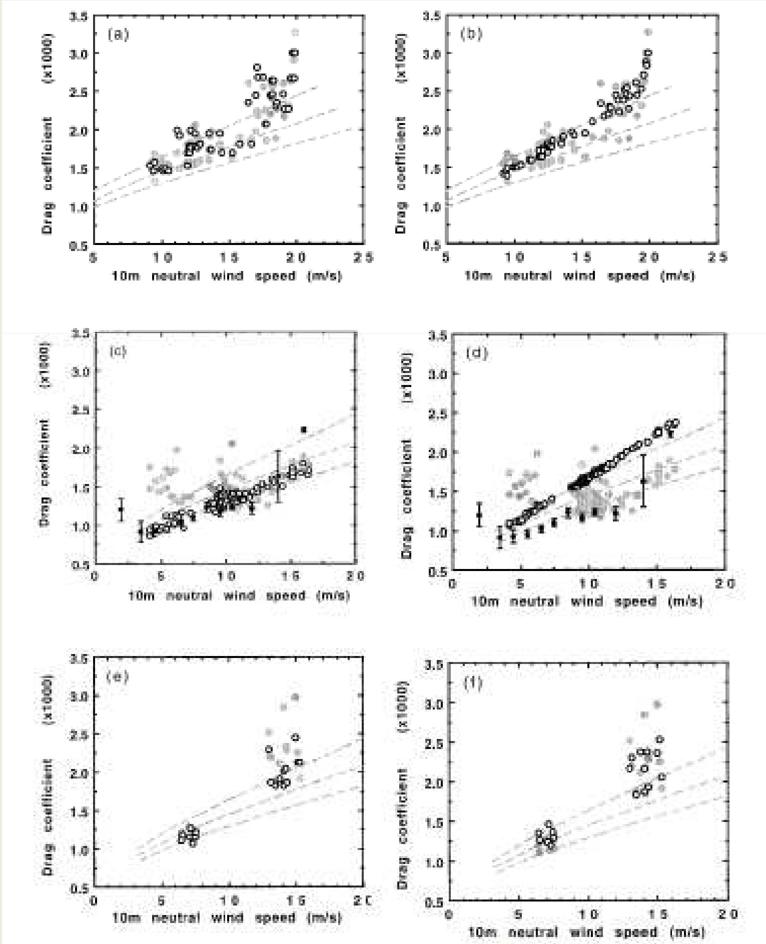


FIG. 5. Observed and calculated values of C_{D10n} for (top to bottom) HEXOS, RASEX, and AD96. Filled gray circles: the observations; open circles: values calculated from Eq. (6) (left plots) and from the Donelan (1990) formula (right plots). On the RASEX plots the gray circles are from JHVL98 and the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

Verification of the calculated C_{D10n} values

- Simulation of coastal, lake, and wave tank data

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.

Since the predicted C_{D10n} values vary little with duration or retch, these wave estimates should be adequate for the purpose, provided the waves were not depth limited and significant swell was not present.

Verification of the calculated C_{D10n} values

(1) VM97 data for offshore winds

The majority of the observations (75%) occurred in the range 4 m/s < U_{10n} < 9m/s where the predicted C_{D10n} and the VM97 data are in reasonable agreement.

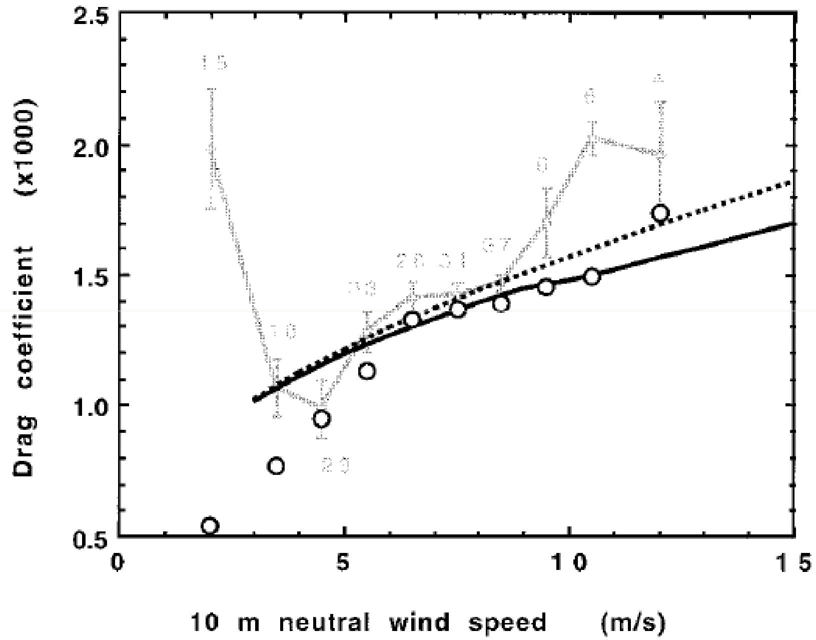


FIG. 6. Observed and predicted C_{D10n} from RASEX for offshore winds. The data points (shown in gray with standard error and number of data averaged) are from Vickers and Mahrt (1997a). The open circles were calculated using Eq. (6) and the mean observed wave parameters. Also shown is the relationship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

Verification of the calculated C_{D10n} values

(2) Atakturk and Katsaros (1999) — Lake Washington

Very similar C_{D10n} were predicted using Eq. (6) compared to the RASEX offshore wind since both have the similar situation.

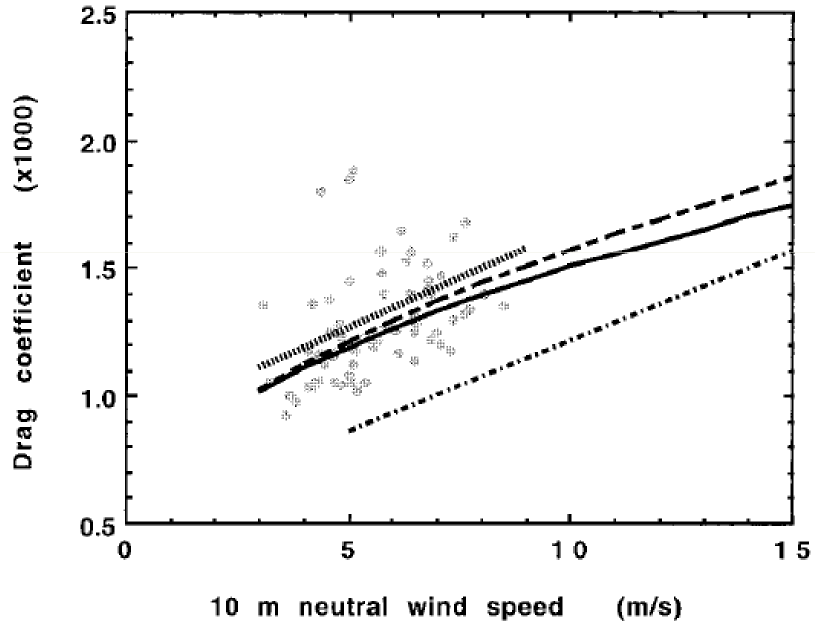


FIG. 7. Observed and predicted C_{D10n} from Lake Washington. The data points were obtained from wave spectra by Ataktürk and Katsaros (1999); the thick dotted line is their regression. Also shown is the relationship calculated using Eq. (6) with estimated waves with fetch limit (continuous black line)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

Verification of the calculated C_{D10n} values

(3) Wave tank

For both these experiments the waves would have been in deep water.

The C_{D10n} values predicted by Eq. (6) are in both cases being lower than that

The implied C_{D10n} to U_{10n} relationship is about 10% lower than predicted but, above 5m/s, shows a very similar variation with wind speed.

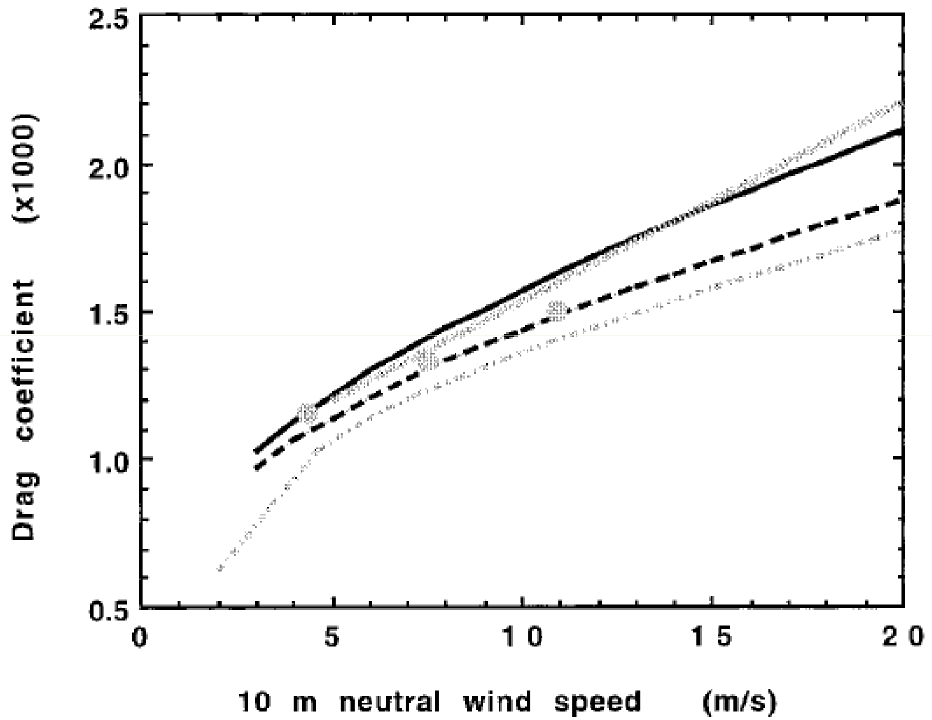


FIG. 8. Further examples of observed and predicted for pure wind seas. The continuous line is the predicted C_{D10n} to U_{10n} relationship for a fully developed pure wind sea. The dotted gray line is the HEXMAX relationship from Oost (1998). The gray circles are wave tank data from Cheng and Mitsuyasu (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).

Verification of the calculated C_{D10n} values

(4) The Donelan (1982) data

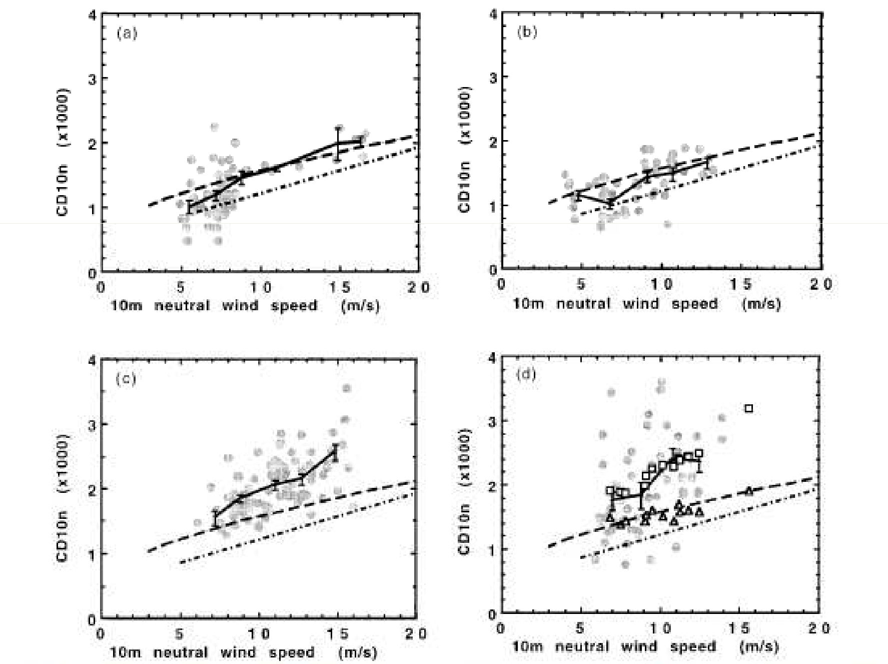


FIG. 9. Values of C_{D10n} from Lake Ontario obtained from eddy correlation measurements (indicated by the gray dots) from (a) Donelan (1982): older wave age ($U_{10n}/c_p < 3$); (b) Colton et al. (1995); longer fetch (>50 km); (c) Donelan (1982): younger wave age ($U_{10n}/c_p >$ 3); and (d) Colton 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.

For Lake Ontario, Eq. (6) predicts C_{D10n} values similar to or greater than those observed for onshore winds (older wave age or longer fetch),but it does not predict the high C_{D10n} values observed during offshore winds and very short fetch

Verification of the calculated C_{D10n} values

- Simulation of open ocean data

The data used in developing Eq. (6) are from lake or coastal sites, so finally open ocean values for C_{D10n} will be considered for the deep ocean.

The wave information(from SWS-2) represents a mixture of windsea and swell and does not contain directional information.

The initial point by point comparison of the predicted and observed C_{D10n} was disappointing with poor correlation (R^2=0.44).

Verification of the calculated C_{D10n} values

- Simulation of open ocean data

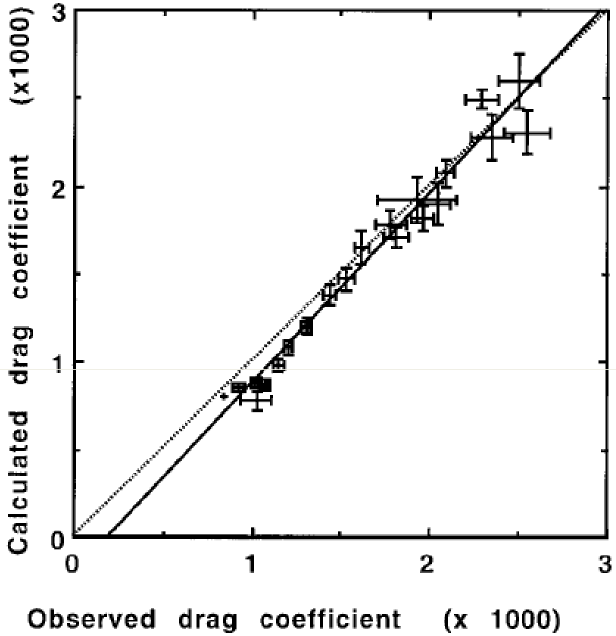


FIG. 10. Calculated values of drag coefficient, C_{D10n}, vs observed values for the SWS-2 experiment; the data have been averaged in intervals of 1 m s^{-1}. Error bars show the standard error of the mean. The regression line shown is C_{D10n}(calc) = −0.21 + 1.08C_{D10n}(obs) (R^2 = 0.97).

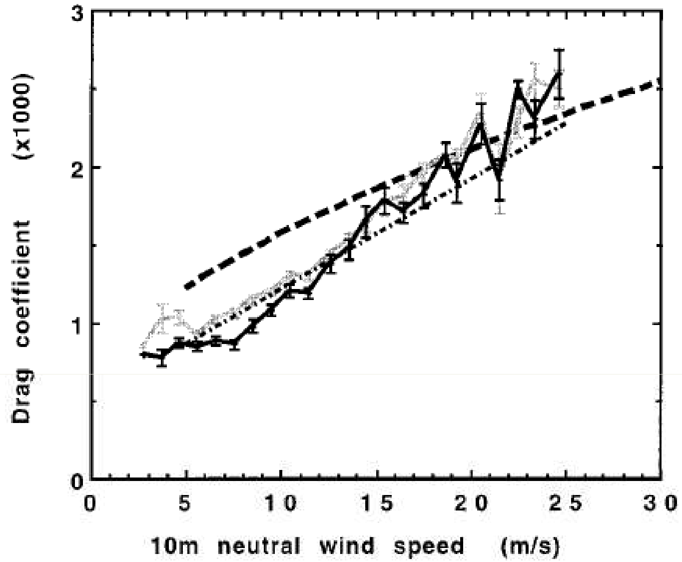


FIG. 11. Mean observed values of the drag coefficient, C_{D10n}, (gray line), and values calculated from Eq. (6) (black line) plotted against the wind speed, U_{10n}, for the SWS-2 data. The data have been averaged in 1 m s^{-1} ranges. Error bars show the standard error of the mean. The thick dashed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

Mean values were calculated for 1m/s increments of U_{10n} the agreement was good with R^2=0.97(Fig. 10).

Verification of the calculated C_{D10n} values

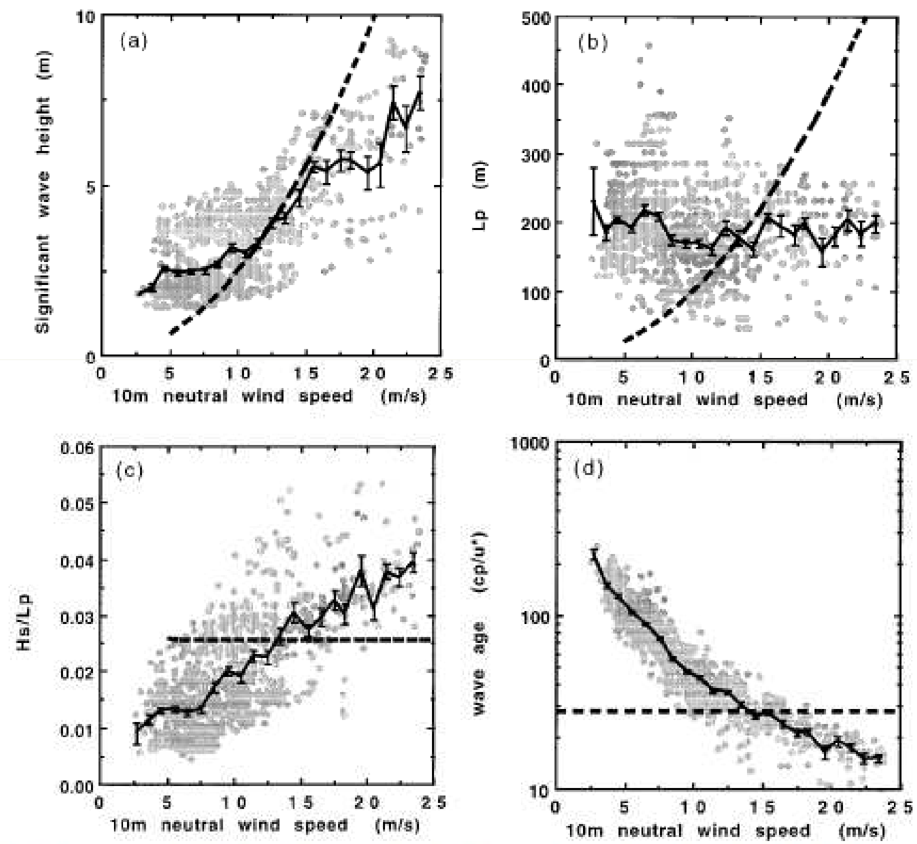


FIG. 12. Wave observations from the SWS-2 experiment. Both individual data point (gray circles) and mean values (in 1 m s^{-1} ranges) are shown. The thick dashed line is the value for a fully developed sea. (a) Significant wave height, H_s (m); (b) wavelength at the peak of the spectrum, L_p (m); (c)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

Because of the dominant long wavelength swell contribution, the values for the slope, H_s / L_p, were low compared to a fully developed sea at lower wind speeds.

At wind speeds greater than about 12-15 m/s, the wind sea was dominant over the swell.

Discussion

- Since the effect of the steepness of young waves is cancelled by the small height, Eq. (6) falsely predicts the roughness of waves at short fetch.
- For deep water wind waves, in the absence of swell, for practical purpose, a relationship is defined

$$10^3 C_{D10n} = 0.87 + 0.0752U_{10n} - 0.000661(U_{10n})^2 \qquad (8)$$

$$(5 \le U_{10n} \le 30m/s)$$

  Which well represents a number of datasets.
- Using the observed wave parameters, Eq. (6) successfully predicted $C_{D10\text{n}}$ observations that departed from the expected deep water windsea relationship approximated by Eq. (8).
- The possible explanations for the failure of Eq. (6) to predict the short fetch Lake Ontario data are the difficult-observed young waves and the data bias for some reason.

Discussion

- It is surprising that Eq. (6) correctly predicts the observed $C_{D10\text{n}}$ values of open ocean since no open ocean data are used in developing the formula.

Summary

- The function of the wave slope, $z_o / H_s = A(H_s / L_p)^B$, is proposed to predict the roughness length, which reconciles many anomalies caused by studying relationships between the Charnock parameter and the wave age.
- The formula correctly predicts the behavior of a number of published field datasets, that is, higher C_{D10n} values is predicted at lower to moderate wind speeds and a less rapid increase of C_{D10n} with increasing U_{10n} compared to the open ocean.
- The formula predicts well the magnitude of C_{D10n} in the open ocean which includes the effect of swell changing the effective wave height and steepness.
- The roughness length formulation advocated here will allow further progress since until now it has been continually hindered by the use of wave age formulation.

Thank you