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# Comments on “On the Effect of Ocean Waves on the Kinetic Energy Balance and Consequences for the Inertial Dissipation Technique”

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ABSTRACT

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## 1. Introduction

Open ocean wind stress data obtained from the Southern Ocean (Yelland and Taylor 1996, henceforth YT) were found to be of significantly lower magnitude than collocated stress estimates derived from the operational wave model, WAMcy4, used at the European Centre for Medium-Range Weather Forecasts (ECMWF). Furthermore, the observations did not exhibit the wave age dependence predicted by Janssen (1989) and others (Yelland et al. 1998). Janssen (1999, henceforth J99) suggested that these differences were due to our use of the inertial dissipation (ID) rather than eddy-correlation (EC) method to determine the stress. Janssen argued that the neglect of the pressure fluctuation term in the turbulent kinetic energy budget would cause ID-derived stress data to be biased low for higher wind speeds and suggested a correction factor. In this comment we will argue that 1) the magnitude of our ID stress data is confirmed by EC data from the open ocean, 2) the height dependence of stress estimates predicted by J99 is not observed, and 3) our neglect of the pressure fluctuation term (as calculated by J99) would have enhanced rather than diminished the wave age dependency of our data, had any been present. We conclude that the suggested bias in ID stress estimates is not significant and that J99's criticism of the ID method is not justified. The further implication is that the WAM-derived wind stress estimates were overestimated.

## 2. Comparison of YT, EC, and WAM Charnock parameters

In Fig. 1 we have plotted average values of the Charnock parameter, $z_{Ch}$ (Charnock 1955), from the YT ID data as a function of wind speed. For comparison, we also show $z_{Ch}$ values calculated from the Smith (1980) EC-derived $C_{D10n}$ to $U_{10n}$ formulas. Based on these data, Smith (1988) suggested a constant $z_{Ch}$ (=0.011). The Smith (1980) data [and the similar EC-derived data of Large (1979) and Large and Pond (1981)] were obtained from a well-exposed anemometer on a moored "tower" in the open ocean. Thus, they are preferred to EC data from ships (e.g., Hare et al. 1999) that may be contaminated by flow distortion effects, or from aircraft (e.g., Banner et al. 1999) for which the correction to surface values is a significant source of uncertainty.[1] Figure 1 shows that the YT ID data are similar to or higher than the EC values, not lower as J99 would suggest. Both ID- and EC-derived $z_{Ch}$ values are below 0.015 for wind speeds below 15 m $s^{-1}$. In contrast, the WAM $z_{Ch}$ values are significantly higher, being between 0.020 and 0.030 for all wind speeds.

Further analysis since YT has resulted in the ID results becoming even closer to the EC-derived values and has also removed some previous problems with application of the ID method. For example, following the comparisons of ID and EC data by Large (1979) and Edson et al. (1991), Yelland and Taylor had chosen to use $\alpha' = 0.55$ as the value for the effective Kolmogorov constant. The difference between this "effective" value and the true Kolmogorov constant, $\alpha$, is considered to account for the imbalance between production and dissipation of turbulent kinetic energy (e.g., Deacon 1988; Högström 1996) over the observed range of stability (including neutral conditions). Taylor and Yelland (2000) showed that an additional, stability-dependent imbalance term (YT; Dupuis et al. 1997; Yelland et al. 1998; Edson and Fairall 1998) was not required, thus simplifying the ID method. In addition, while the ID method is less affected by airflow distortion effects than the EC method (Edson et al. 1991), Yelland et al. (1998) used computational fluid dynamics to determine corrections for flow distortion for the YT data. Overall, the difference from the WAM values increased, and the final ID results of Taylor and Yelland (2000) were in close agreement with the Smith (1980) EC-based relationship. Most of the difference between the YT and Taylor and Yelland (2000) results was due to the corrections for airflow distortion (Yelland et al. 1998), which have been verified by comparison with shipboard measurements.

In passing we also note that the use by J99 of $\alpha = 0.50$ is not justified by the review of Högström (1996) quoted by J99. Högström (1996) did indeed suggest $\alpha = 0.52 \pm 0.02$ as the true Kolmogorov value but recommended $\alpha' = 0.59$ for use in the ID method, even higher than the $\alpha'$ value used by YT. By adopting a lower value, J99 increased the YT $z_{Ch}$ values towards better agreement with the WAM data. Thus, in summary, ID results from the open ocean are in very good agreement with EC results, and the adjustments proposed by J99 act to degrade that agreement.

### 3. Height dependency of stress estimates

The correction proposed by J99 is strongly dependent on the height of measurement compared to the wavelengths of the waves (Fig. 2). This suggests a method of experimental verification. During the Storm Wave Study-2 (SWS-2) experiment (Dobson et al. 1999; Taylor et al. 1999) ID wind stress estimates were obtained at two heights: sonic anemometers were mounted at 5.5 m on a Nomad buoy and at 17.5 m on a research ship. Wave spectra were obtained from a Directional Wave Rider (DWR) buoy. We have used the DWR wave data to predict the implied correction factor for the two observation heights using J99's approximate model [his Eq. (20)] with the mean wavenumber $\bar{k} = g/U^2_{10}$ (P. A. E. M. Janssen 1999, personal communication). Hence, we have predicted the expected ratio of the $C_{D10n}$ values from the ship and buoy (Fig. 3). Also shown in Fig. 3 are the observed ratios adjusted for the average variation of stress with height (Donelan 1990). For wind speeds above 10 m $s^{-1}$ the effect of this adjustment was to increase the ratio by a small factor (less than 3%). The ship stress data have also been adjusted for flow distortion, resulting in about a 4% decrease in the ratio. Both these adjustments were small compared to the difference of about 40% between ship and buoy data predicted by the J99 formula at higher wind speeds (Fig. 3). Such a difference was not observed; over much of the wind speed range (including the higher wind cases) the observed data from ship and buoy were in good agreement.

A further test of the J99 formula is to examine the variation of the $C_{D10n}$ values as a function of the nondimensional height, $k_oz$. For the buoy-mounted anemometer at 5.5-m height, the observed $\log_{10}(k_oz)$ values ranged between −0.8 and 10. Much of the data for winds above 10 m $s^{-1}$ had $\log_{10}(k_oz) < -0.1$, implying that, according to J99, significant deficits in the $C_{D10n}$ values should have been observed. To minimize biases due to uneven sampling we have restricted our analysis to the ranges $10 < U_{10n} < 20$ m $s^{-1}$ and $-0.7 < \log_{10}(k_oz) < 0.1$. The latter range corresponds to about a 40% change in the J99 correction factor (Fig. 2). For the observed $C_{D10n}$, and for $C_{D10n}$ values corrected according to J99, we have calculated linear regressions for $C_{D10n}$ on $U_{10n}$ and then calculated $C_{D10n}$ anomalies, these being the difference of each data point from the corresponding regression. The average $C_{D10n}$ anomaly for different ranges of $\log_{10}(k_oz)$ is shown in Fig. 4. The observed data show no significant anomaly even for $\log_{10}(k_oz) \approx -0.6$ ($k_oz \approx 0.25$), where the J99 formulas would predict a $C_{D10n}$ deficit of around 40% (Fig. 2). It follows that application of the J99 correction would result in a significant, spurious $C_{D10n}$ anomaly at low values of $\log_{10}(k_oz)$ of the form shown in Fig. 4.

## 4. Wave age dependency

Janssen (1999) noted that applying the proposed correction to the ID data increased the scatter in the stress values at higher wind speeds and implied that this might be associated with variations of wind stress with wave age, which had otherwise not been detected using the ID method. However, we shall show that the J99 correction has the effect of making mature waves appear rougher relative to younger waves, an opposite effect to that normally expected for wave age dependency (e.g., Komen et al. 1998).

However, first we must note that most datasets (including YT) do show an apparent relationship between wave age and the roughness length, $z_o$, (or the Charnock parameter or nondimensional roughness, $z_{Ch}$). This occurs because both $z_o$ and $z_{Ch}$ are found to increase at higher wind speeds (e.g., Fig. 1) and because, on average, the waves are less mature at higher wind speeds. The more rapid the increase in surface roughness, the stronger this apparent relationship will appear to be. However that alone does not prove that the surface roughness depends on wave age. The increased roughness may be due to the variation with wind speed of some other sea state parameter. The crucial test is whether at a given wind speed the surface roughness is found to vary with wave age (or, equivalently, whether for different wave age ranges the mean $C_{D10n}$ to $U_{10n}$ relationship is systematically different). It is in these important respects that neither the YT nor SWS-2 datasets showed a dependence of the roughness on wave age (YT; Yelland et al. 1998; Taylor et al. 1999).

The calculated correction factors for the SWS-2 wind stress and wave data are shown in Fig. 5 for the two anemometer heights, 17.5 and 5.5 m. Also shown are mean values of the correction factor for different ranges of wave age ($c_p/u_*$). For almost all cases, the maximum corrections at any given wind speed are obtained for a mature wave spectrum. The corrections for younger wave age ranges are progressively smaller. That is because, according to J99, the longest sea waves give rise to the greatest pressure fluctuations at any given observing height. Thus, the proposed correction does not imply that, for a given wind speed, the wind stress has been especially underestimated by YT for young, developing seas (when wave age arguments would suggest that the wind stress should be particularly high). Rather, the implication is that the stress has been underestimated to a greater degree for mature seas.

Thus, by neglecting the correction proposed by J99, YT should have introduced, or enhanced, a wave-age-dependent signal in their dataset, such that, at a given wind speed, young waves would have appeared rougher. Since no such dependency was detected in the original data, application of the J99 correction would result in the opposite, an apparent wave age effect with the more mature waves appearing rougher. This is illustrated in Fig. 6, where we have plotted the mean $C_{D10n}$ anomaly (defined above) for different wave age ranges. For clarity the difference from the value for $0.3 < c_p/U_{10n} < 0.35$ is shown. Without "correction," the observations show a slight increase in $C_{D10n}$ for the more mature waves. Although hardly significant, this increase can be predicted assuming variations in the observed $U_{10n}$ and $u_*$ values that are random and not wave age related. Applying the J99 correction would result in the most mature waves having 30%–40% more drag than younger waves at the same wind speed. Since J99, the approximate model has been tuned by comparison to WAM results (P. A. E. M. Janssen 1999, personal communication), with the result that the magnitude of the constant [in Eq. (20) of J99] has been reduced from 2.66 to 1.9. The adjusted value (also shown on Fig. 6) implies smaller corrections to the ID results but would still introduce an appreciable wave-age-dependent signal of opposite sign to that normally expected.

In the analysis summarized in Fig. 6, it was necessary to represent wave age by $c_p/U_{10n}$ to minimize the effects of spurious correlations. However, similar results are obtained by analysis of the data by calculating anomalies from a regression of $C_{D10n}$ on $u_*$, and then using $c_p/u_*$ to represent wave age. In this case, the original observations show a trend for younger waves to appear slightly rougher. Again, the sign and magnitude of this trend can be predicted on the assumption of purely random variations in the data. Depending on whether the adjusted or original coefficient is used, the J99 correction removes or reverses this trend (so that older waves appear rougher).

We conclude that the lack of an observed wave age dependency of the $C_{D10n}$ values at a given wind speed cannot be explained by the correction proposed by J99 unless the true wave-age dependency is such that more mature waves are rougher than younger waves.

## 5. Summary

The ID wind stress data are in very good agreement with EC data from the open ocean, whereas the WAM wind stress estimates as used by J99 are higher. The correction proposed by J99 is only applicable to ID data and degrades the agreement between ID and EC data. The correction suggests significant differences between wind stress estimates from sensors at different heights. This was not observed. The data do not show a $C_{D10n}$ deficit at low values of the nondimensional height. If it is assumed that young waves are rougher, neglect of the proposed correction should have enhanced any wave-age-dependent signal in the ID wind stress estimates, but no wave-age dependence was found in the YT96 dataset. Thus, the experimental evidence that we have presented supports neither the criticism of the ID method by J99 nor the proposed correction.

*Acknowledgments*

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## Figures

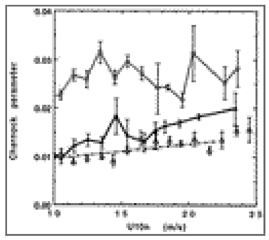

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FIG. 1. Mean values of the Charnock parameter as a function of wind speed for YT (solid line), WAM (dotted line), and the Smith (1980) relationship (chain line). The data points (open triangles) show the YT dataset reprocessed following Yelland et al. (1998) and Taylor and Yelland (2000). Error bars show the standard error of the mean

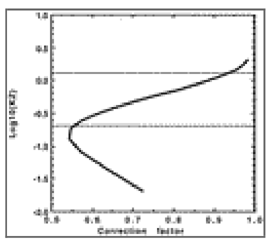

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FIG. 2. The correction factor calculated from the J99 approximate formulas plotted as a function of $\log_{10}(k_o z)$ where $k_o$ is the wavenumber (see J99) and $z$ is the measurement height. The dotted lines mark the range of nondimensional height values ($k_o z$) chosen for analysis of the buoy data (see text)

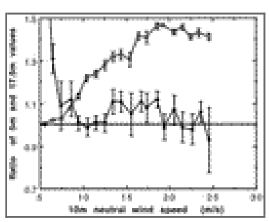

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FIG. 3. Ratio of the SWS-2 wind stress values observed at 17.5 m to those observed at 5.5 m (closed symbols) and the ratio predicted by the J99 correction (open symbols). Error bars show the standard error of the mean

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FIG. 4. The mean $C_{D10n}$ anomaly in the SWS-2 buoy data plotted as a function of $\log_{10}(k_o z)$ where $k_o z$ is the nondimensional height. Shown are the values as observed (closed symbols) and the values after applying the J99 correction (open symbols). Error bars show the standard error of the mean

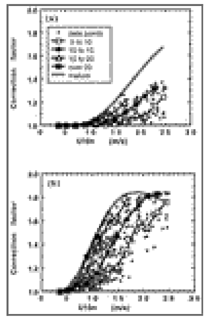

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FIG. 5. Values for the J99 correction factor calculated for the SWS-2 dataset plotted as a function of the 10-m neutral wind speed, $U_{10n}$. Shown are the individual values (gray points) and mean values for different wave age ranges ($c_p/u_*$, see legend). Also indicated is the maximum correction factor corresponding to mature seas (dotted line). (a) Ship data (anemometer height = 17.5 m); (b) buoy data (anemometer height = 5.5 m)

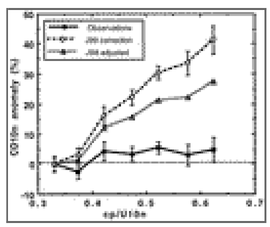

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FIG. 6. The mean $C_{D10n}$ anomaly (%) plotted as a function of wave age ($c_p/U_{10n}$) for the original observations (closed symbols, solid line), after correction following J99 (open symbols, dashed line) and after correction using the adjusted (P. A. E. M. Janssen 1999, personal communication) coefficient (open triangles, dotted line). For clarity, error bars for the adjusted correction have been omitted and the curves show the difference from the anomaly for $0.3 < c_p/U_{10n} < 0.35$

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[1] The Air–Sea Interaction Spar buoy (ASIS; Graber et al. 2000) has recently been developed to provide an open ocean instrument platform of similar or better quality than that used by Smith. At moderate and high winds, $C_{D10n}$ values obtained from ASIS using the EC method are very similar to the Smith (1980) relationship (W. M. Drennan 2000, personal communication).