Effect of sea state on the momentum exchange over the sea during neutral conditions

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[1] On the basis of an extensive data set from the air-sea interaction station Östergarnsholm in the Baltic Sea, the dependence of drag on the ocean of wave state parameters has been studied for near-neutral conditions. For developing sea, the drag depends on wave age, \( u^* / c_p \) (\( u^* \) friction velocity and \( c_p \) the phase speed of the dominant waves), in agreement with recent findings over the World Ocean, strongly supporting that the Östergarnsholm station can be relied upon to give results representative of open ocean conditions. For such conditions, it is demonstrated that the logarithmic wind law is indeed valid. For mixed sea/swell the logarithmic wind law is not valid and the drag coefficient, \( C_D \), depends on two parameters representing the wave state: \( E_1 / E_2 \) (where \( E_1 \) is the energy of the relatively long waves (having a phase velocity larger than the wind speed at 10 m) and \( E_2 \) the short wave energy). Thus, plotting \( C_D \) as a function of \( u^* / c_p \) gives a clear ordering of the data in parallel, sloping bands according to the value of \( E_1 / E_2 \). Thus, whereas very young and slow waves affect the atmospheric flow similar to rigid roughness elements, with the occurrence of longer waves, an entirely different mechanism gains successively more importance and dynamical coupling with the atmospheric turbulence occurs. It may be speculated that the often observed kink in the wind profile represents the upper bound of a wave-boundary-layer, which is thus an order of magnitude deeper than predicted and observed during growing sea conditions. INDEX TERMS: 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 3379 Meteorology and Atmospheric Dynamics: Turbulence; 4504 Oceanography: Physical: Air/sea interactions (0312); KEYWORDS: sea state, momentum exchange, neutral wind law and waves, wave age effects


1. Introduction

[2] As reviewed by Komen et al. [1998], correct parameterization of the drag over the ocean has considerable impact not only on a synoptic scale (the development of cyclones) but also on the climate. Although considerable efforts have been spent on the issue, the problem is far from settled, different experiments reported in the literature (see below for details) giving seemingly contradicting results. In particular, the effect of swell on the resulting drag is still far from understood. In this paper several years’ worth of concurrent measurement of turbulent flux, mean atmospheric “profiles,” and wave data are analyzed in order to further understanding of how the state of the sea influences the drag. The data have been gathered at the marine site Östergarnsholm in the Baltic Sea during the years 1995–1999. The general criteria for selection of data have been wind from sector with long undisturbed fetch, near-neutral conditions, and completeness of the data. Overall, 375, 60-min data have been used in the analysis, see section 2.

[3] During neutral atmospheric conditions it is generally assumed that there is a logarithmic wind profile in the lowest 10 m or more. Over a solid surface, this is a well-established fact, supported by innumerable measurements in the laboratory as well as in the atmospheric surface layer. Thus for flow over an aerodynamically rough surface we get (see e.g., Monin and Yaglom [1971], for a derivation):

\[
U = \frac{u^*}{K} \ln(z/z_0),
\]

where \( U \) is mean wind speed at height \( z \), and \( u^* \) is the friction velocity = \( \sqrt{\tau/\rho} \). Here \( \tau \) is the shearing stress, which, above the viscous sublayer can be expressed as \( \tau/\rho = \sqrt{(u'w')^2 + (v'w')^2} \) where \( u'w' \) is the correlation between the longitudinal wind fluctuations and the vertical wind fluctuations, \( v'w' \) is the corresponding correlation between
the transverse (lateral) wind fluctuation and the vertical wind fluctuations, $\rho$ is air density, $\kappa$ is von Karman’s constant $= 0.40$ [Högström, 1996], and $z_0$ is the roughness length. Over a solid surface, $z_0$ is related to the size and geometry of the roughness elements at the surface.

Equation (1) is usually assumed to be valid over the ocean as well during neutral conditions. It is however not self-evident that this is the case over a moving and undulating surface in dynamic interplay with the overlying atmosphere. From the equation of motion it is easy to show that the vertical flux of momentum, $\tau$, in the layers near the surface is approximately height constant. However, in the marine surface layer, $\tau$ can be written as the sum of three components:

$$\tau = \tau_t + \tau_w + \tau_{visc},$$

(2)

where $\tau_t$ is the turbulent flux of momentum, $\tau_w$ is the wave-induced flux, and $\tau_{visc}$ is the viscous (molecular) flux. The logarithmic wind law is thought to be related to the turbulent flux so that $\tau_t = u^* \ln \left[ \frac{z}{z_0} \right]$ [Kitagorodskii, 1973]. However, $\tau_{visc}$ is of importance only in the lowest millimeter, and calculations, for example, Belcher and Hunt [1996], indicate that during wind sea conditions, $\tau_w$ is an important part of $\tau$ only in the lowest meter or so above the surface (the “wave boundary layer”). Then $\tau = \tau_t$, above this height, and we expect the logarithmic law to be valid, with $z_0$ being a measure of the local roughness of the sea. Measurements by Drennan et al. [1999] at 2 m above mean water level indicate that there is no measurable effect from the waves at this height during pure wind sea conditions, supporting the idea that the wave boundary layer is very thin during such conditions.

However, Hare et al. [1997] have made concurrent measurements of fluctuating pressure, wind, and surface waves, and plot the wave-induced pressure field as a function of the nondimensional parameter $kz$, where $k$ is wave number, in bins of the wave-age parameter $uw/c_p$, where $c_p$ is the phase velocity of the dominating waves. For cases with swell, defined as $uw/c_p < 0.04$, they observe significant influence up to $kz = 4$, so that effects of waves with a wavelength of say $30 \text{ m}$ would be felt as high as $30 \text{ m}$. Note, however, that this argument is based on the proposed validity of the similarity arguments presented by Hare et al. [1997], their actual atmospheric measurements being made at 3 m.

Measurements of wind profiles in neutral conditions over the ocean at reliable sites are rare. Most oceanic measurements report in fact only data from one level, usually 10 m and assume that equation (1) is valid. Introducing the drag coefficient

$$C_D = \left( \frac{u^*}{U_{10}} \right)^2,$$

(3)

assuming neutral conditions and that equation (1) is valid, gives

$$C_{DN} = \left( \frac{\kappa}{\ln(10/z_0)} \right)^2,$$

(4)

e.g., a unique relation between the neutral drag coefficient $C_{DN}$ and the roughness length $z_0$. Note, however, that if the wave boundary layer should extend to an appreciable height, as suggested by the results of Hare et al. [1997], the logarithmic law may be invalid, and then a drag coefficient determined from concurrent measurements of $u_w$ and $U_{10}$ is not likely to give physically meaningful values for $z_0$ with the aid of equation (4).

The sonic anemometers have been calibrated in a big wind tunnel, resulting in individual flow distortion correction matrices [Grele and Lindroth, 1994]. Also, the cup anemometers have been individually calibrated in this big wind tunnel. Repeated calibrations of both types of anemometers after about a year of service in the field show very good reproducibility of the calibration results. In the field, turbulence data are recorded at 20 Hz. From the sonic signals the three orthogonal components of the wind and virtual temperature (the measured temperature signal agrees within $0.2\%$ with the virtual temperature) [Dupuis et al., 1997] are obtained. Turbulence statistics, such as variances, covariances, and spectra are calculated as 60-min averages. Profile variables are measured with 1 Hz and averaged over 60-min periods as well. Wave measurements were recorded once an hour. The directional spectrum is calculated from 1600 s vertical, north and west displacement time series on board the buoy following the method presented by Longuet-Higgins et al. [1963]. The spectral variance, mean direction, directional spreading, skewness, and kurtosis calculated at 64 frequency bins cover a frequency range of [0.025, 0.58]. The significant wave height is calculated by trapezoid method from frequencies between 0.05 and 0.58 Hz, and the peak frequency is determined by a parabolic fit to the three frequencies that form the peak of the spectrum.

The meteorological measurements have been running semicontinuously since May 1995. Wave data have
been recorded semicontinuously during the same period but with breaks during wintertime periods with risk for ice damage.

[11] For winds coming from the sector $80^\circ - 220^\circ$, there is undisturbed over water fetch for more than 150 km, and only data with this wind direction have been used here. About 10 km from the peninsula, the depth is 50 m, reaching below 100 m farther out. Smedman et al. [1999] studied in detail the possible influence of limited water depth on the tower measurements. Flux footprint calculations were done, showing that the turbulence instruments “see” areas far upstream of the island. Waves up to 5 s wave period are deep water waves in the footprint of the top level. Longer waves begin to feel the bottom, and their phase speed is reduced. According to Anctil and Donelan [1996], up to rather long wave periods, the only significant effect of steepening of shoaling waves is a change in phase speed. Taking the “footprint weighting function” $F(z)$ from equation (A7) in the appendix of Smedman et al. [1999], it is possible to calculate a weighted mean phase speed

$$\langle c_p \rangle = \int_0^\infty F(x, z)c_p(x)dx. \quad (5)$$

Here the peak wave phase speed $c_p$ was iterated from the dispersion relation

$$c_p = \frac{g}{\omega_0} \tanh \left( \frac{\omega_0 h}{c_p} \right), \quad (6)$$

where $h$ is the water depth, $\omega_0$ is the peak wave frequency, and $g$ is acceleration of gravity. Hereinafter, whenever we use $c$ we will mean the weighted mean $\langle c \rangle$.

[12] The 375 data of hourly means chosen for the analyses are from the years 1995–1999 and have been selected according to the following criteria: (1) wind coming from the sector with long fetch, $80^\circ - 220^\circ$; (2) complete meteorological data and wave data; (3) wave spectra with a single peak; additional analyses with data having multipeak spectra have been done and are especially mentioned in the text; (4) the angle between the dominant waves and the wind $< 15^\circ$; (5) mean wind speed $> 2$ m s$^{-1}$; (6) near-neutral conditions; usually, this criterion is defined in terms of $z/L$, where $L$ is the Monin-Obukhov length

$$L = \frac{-u_T^2 T_0}{gscw/\bar{\theta}_v} \quad (7)$$

and $\bar{w}/\bar{\theta}_v$ is the flux of virtual potential temperature, $T_0$ is mean absolute temperature of the atmospheric surface layer and $g$ is acceleration of gravity. The criterion usually enforced for near-neutrality is that $|z/L| <$ certain small value, less than unity. From Smedman et al. [1999] and Rutgersson et al. [2001] it is, however, known that when swell is present, Monin-Obukhov scaling is found to break down. In these studies it was also shown that $u_T$ tends to be small when there is strong swell. For unstable conditions we adopt in this paper a criterion for near-neutrality based on the magnitude of the heat flux alone: $0 > \bar{w}/\bar{\theta}_v > -0.002$ m s$^{-1}$ K; for stable conditions we require both $0 > \bar{w}/\bar{\theta}_v > -0.002$ m s$^{-1}$ K and $U_{10m} > 6$ m s$^{-1}$. As shown in Appendix A, these criteria imply that remaining stability effects are quite small compared to other effects discussed below. The above criteria apply to most of the analyses presented below, but note that in the particular study restricted to pure wind sea conditions (section 5.1), we have included some slightly nonneutral data and made corrections for the influence of stability with the aid of well-established expressions based on Monin-Obukhov similarity; see section 5.1 for further discussion.

3. Criteria for Characterizing Sea State

[13] On dimensional grounds, Charnock [1955] derived the following expression for the roughness of the sea

$$z_0 = \alpha u_T^2 / g, \quad (8)$$

where $\alpha$ is the so-called Charnock parameter or dimensionless roughness and $g$ is acceleration of gravity. Equation (8) is often used in large-scale synoptic and climatic models with a constant value for $\alpha$, typically in the range 0.01–0.03. For pure wind seas, several investigations have however shown that $\alpha$ is a function of wave age defined as

$$c_p/u_T. \quad (9)$$

That this is indeed the case has convincingly been demonstrated by Komen et al. [1998]. They plot (their Figure 3) $\alpha$ against inverse wave age $u_T/c_p$ and find that field data from Lake Ontario [Donelan, 1990] and from the Humidity Exchange Over the Sea (HEXOS) experiment in the North Sea [Smith et al., 1992] as well as some wave-tank data agree well with predictions from a high-resolution 1-D version of the wave model WAM [Komen et al., 1994]. Thus for very young waves, $u_T/c_p > 0.2$, which are characteristic for the wave-tank data, $\alpha$ increases with decreasing inverse wave age, but for still smaller values of $u_T/c_p$, the dimensionless roughness decreases rapidly, in agreement with the measurements from Lake Ontario and HEXOS. Komen et al. [1998] made the following physical interpretation: “At very short duration (or fetch) few wave modes have been generated, and roughness is low. When more wave modes (of even greater wavelengths) are being excited, the roughness increases, until, at still greater duration the intensity (steepness) of the short wave modes begins to decrease, which leads to reduction of the dimensionless roughness.” In the range 0.03 $< u_T/c_p < 0.2$, the field observations from Lake Ontario and HEXOS give systematic increase of $\alpha$ with $u_T/c_p$, from about 0.01 to 0.1, in agreement with the trend of the WAM simulation. Komen et al. [1998] remark that “much of the scatter in [their] Figure 3 is caused by deviations of the actual spectrum from pure wind sea conditions.”

[14] Drennan et al. [2003] have gathered data from five field experiments with pure wind sea, defined as

$$E(\text{wind sea}) > 5E(\text{swell}), \quad (10)$$

where $E(\text{wind sea})$ is the part of the 2-D wave spectrum identified as pure wind sea, and $E(\text{swell})$ is the correspond-
ing part associated with swell. They also require that \( u^* / c_p > 0.05 \), and that the wave spectra have just one peak. The analysis by Drennan et al. [2003] shows conclusively that \( z_0 / \sigma \) is a function of the wave age alone for \( E_{\text{swell}} / E_{\text{wind sea}} < 0.2 \): \[
\frac{z_0}{\sigma} = 13.3 \left( \frac{u^*}{c_p} \right)^{3.4}.
\] (11)

As shown in section 5, very similar result is obtained for data from this study in pure wind sea conditions.

[15] To parameterize the effect of swell in the simplest possible situation, our selection criteria require that the spectra are single peaked, and the dominant waves have the same direction as the wind. In such a wave field even the directional wave spectrum often does not provide clear and unambiguous means to do the standard partitioning to wind sea and swell that was used by Drennan et al. [2003]. One way to get consistent results with the standard partitioning would be to calculate the spectrum of fully developed waves using the local wind [see, e.g., Smedman et al., 1999, Figure 3] and then composing the spectrum of wind sea from the measured spectrum and calculated spectrum. The method requires a decision as to how the transition from the measured spectrum to the fully developed spectrum is done. The fact that wind input to waves is positive only for waves slower than the wind provides such, but this criteria can also be used directly to make simpler division of the spectra into two parts:

\[
E_1 = \int_{n_1}^{\infty} S(n) dn,
\]

\[
E_2 = \int_{0}^{n_1} S(n) dn,
\]

\[
n_1 = \frac{g}{2 \pi U_{10} \cos \theta}.
\] (12)

[16] Here \( n \) is frequency, \( S(n) \) is the 1-D wave spectrum, and \( n_1 \) is the frequency which corresponds to a phase speed \( c \) equal to the wind speed \( U_{10} \) at 10-m height. One could in principle call \( E_1 \) the swell energy and \( E_2 \) the wind sea energy. However, to avoid any confusion with the standard partitioning and our division, we will hereinafter speak about long-wave spectral part, \( E_1 \), and a short-wave spectral part \( E_2 \).

[17] Figure 1 shows a typical example of spectral analysis of the wave spectra. The four subgraphs show, respectively: Figure 1a, wave direction compared with wind direction, Figure 1b, the logarithm of \( n^4 S(n) \) as a function of \( n \), Figure 1c, the spectrum \( S(n) \) as a function of \( n \), and Figure 1d, comparison of \( U_{10} \) (horizontal line), \( U_c = U_{10} \cos \theta \), where \( \theta = \theta(n) \) is the angle between the wave at frequency \( n \) and the mean wind and the

Figure 1. Example of wave spectral information from one particular hour (2 June 1999, 0700 LST). (a) Wave direction as a function of frequency, \( n \); also shown is the mean wind direction. (b) The logarithm of \( n^4 S(n) \) as a function of \( n \). (c) Spectrum \( S(n) \) as a function of \( n \). (d) Phase velocity, \( c \), mean wind speed at 10 m, \( U_c \), and \( U_c = U_{10} \cos \theta \), where \( \theta = \theta(n) \) is the angle between the wind and the wave, all plotted against \( n \); the vertical line represents the frequency, where \( c = U_c \). This line, which continues up to Figure 1c is the basis for division of the spectrum into two parts: \( E_1 \), representing waves that travel faster than the wind speed at 10 m (long waves) and \( E_2 \), representing slower waves (shorter waves).
Thus $E_1$ is the area to the left of the vertical line in Figure 1c, and $E_2$ is the area to the right of that line.

Figure 2 shows the relation between $U_{10}^2$ and $E_2$ in Figure 2a and $U_{10}^2$ and $E_1$ in Figure 2b. The difference between the two plots is striking; the short-wave part $E_2$ being a strong function of the wind speed (to the fourth power in fact), whereas there is no relation at all between the long-wave part $E_1$ and wind speed.

4. Analysis of the Neutral Wind Profile

During neutral conditions we expect the logarithmic wind law, equation (1) to be valid, implying that, in principle, we would get the same value for the roughness length $z_0$ from measurements of wind speed at “two” levels or more and from measurements of $u^*$ and wind speed at one level. This idea is tested in Figure 3a for the slightly unstable data ($0 < w' T' < 0.01 \text{ m s}^{-1} \text{ K}$) and in Figure 3b for the slightly stable data ($-0.002 < w' T' < 0 \text{ m s}^{-1} \text{ K}$ and $U_{10m} > 6 \text{ m s}^{-1}$), where various estimates of $z_0$ have been plotted against wind speed at 10 m. The stars have been derived with equation (1) from measurements of the friction velocity $u^*$ (with the eddy correlation technique) and the wind speed at the same level, $U_{10m}$, this approach being denoted as the drag method below. The open circles have been derived with the same equation but from measurements of the wind speed at the two lowest levels, 7 and 12 m above the tower base (i.e., at around 8 and 13 m above the water surface), this approach being denoted as the gradient method below. The solid circles have been derived with the Charnock expression, equation (8), the value of the Charnock parameter $\alpha$ being taken as 0.012 and $u^*$ being obtained with the eddy correlation technique. The triangles represent cases with the roughness Reynolds number, $Re = u' z_0 / \nu < 0.11$, for which $z_0$ has been derived with the smooth flow relation: $z_0 = 0.11 \nu / u^*$ where $\nu$ is the kinematic viscosity of air.

Figures 3a and 3b show that there is generally a huge difference between the $z_0$-values obtained with the gradient method (the open circles) and corresponding values obtained with the drag method (stars). This systematic difference, however, decreases markedly for wind speeds above approximately 10 m s$^{-1}$. The gradient symbols (the circles) exhibit a systematically different pattern for the slightly unstable cases, Figure 3a, and for the slightly stable cases in Figure 3b. Thus in Figure 3a most circles are much...
below the values derived with the drag method (stars). The stable data derived with the gradient method, Figure 3b, scatter on both sides of the corresponding data derived with the drag method. This means that the gradient method appears to be extremely sensitive to stability variations very close to neutrality. It is then pertinent to ask the question: Is the result displayed in Figures 3a and 3b perhaps simply as a result of an apparent variation of the parameter $z_0$ caused by the curvature of nonneutral wind profiles in a lin-log representation? This question is addressed in Appendix A. It is shown that with the criteria for near neutrality enforced here, diabatic wind profile formulations found to be universally valid over land produce deviations of $z_0$ from their true values by a factor of less than 5. This should be compared to the observed deviations in Figures 3a and 3b of several orders of magnitude deviation between “drag” and “gradient” estimates of $z_0$.

[21] Figures 4a and 4b show $z_0$ derived with the same four methods and with the same symbols as in Figure 3 but plotted against $E_1/E_2$. It is clear from this graph that for pure wind sea, i.e., $E_1/E_2$ small, there is reasonable agreement between the open circles (the profile data) and the stars (the drag data), but already for as small values of $E_1/E_2$ as 0.05, the circles start to deviate. Note that the spread of the stars relative to the Charnock band of data increases systematically with $E_1/E_2$. The conclusion of Figures 3 and 4 is that the logarithmic wind law over the ocean appears to be valid only for wind speeds above 10 m s$^{-1}$ and for pure wind sea conditions. Note, however, that there is a correlation between high wind speed in general and growing sea. As discussed below, it is likely that the “growing-sea criterion” is the basic one, and so there may be cases when the wind speed is below 10 m s$^{-1}$ and still a logarithmic wind profile is obtained, and that there is likely to be cases with wind speed above this limit with a nonlogarithmic wind profile.

[22] Note in Figures 3 and 4 that the $z_0$-values derived with the gradient method and the drag method for the same case typically differ by many orders of magnitude. This should be compared to corresponding estimates of $z_0$ over uniform land surfaces. There typically the uncertainty of individual estimates based on linear regression of $U$ against log $z$ is less than a factor of 2. Because the roughness length estimate at Östergarnsholm for the analysis displayed in Figures 3a, 3b, 4a, and 4b is obtained from wind measurements at only two levels, the resulting uncertainty in $z_0$ may be slightly larger than that but less than a factor of 10. Note further that more than two levels could not be used here because of the fact that the profiles in lin-log representation were more often than not nonlinear.

[23] With the invalidity of the logarithmic law for cases with $E_1/E_2$ not small enough, $z_0$ derived from a combination of equation (3) and the drag law expression equation (4) loses its usual physical meaning as a measure of the roughness of the sea and should be regarded simply as an integration constant. In the analysis of the variation of the drag with sea state, to be presented in section 5, the approach is taken to explore only the neutral drag coefficient derived with equation (3), i.e., from simultaneous measurements of $u^*$ and $U_{10}$, but sometimes the result is expressed in terms of $z_0$, which is then formally obtained from equation (4).

[24] Figure 5 shows examples of measured wind profiles, based on the wind measurements at five levels on the Östergarnsholm tower, typical for strong to moderate wind conditions with small $E_1/E_2$. The profiles shown in Figure 5a are clearly logarithmic. In Figure 5b are shown the corresponding $u^*$-values (obtained with the eddy correlation technique) along with the 10 m wind speed. In Figure 5c it is shown that $E_1/E_2$ is less than 10$^{-2}$ for all the profiles. Figure 5d shows the $z_0$-values derived for these cases with the gradient method (solid circles) and with the drag method (open circles). In this logarithmic representation the values derived with the two methods appear close (compared to the huge scatter in Figures 3a, 3b, 4a, and 4b). The actual range of the individual values of the ratio $z_0$grad/$z$drag is a factor of 10, the geometric mean, however, being 1.2. A best fit for the eight logarithmic profiles of Figure 5a to Charnock’s relation, equation (8) gives for the Charnock parameter $\alpha = 0.012$, which is in the range typically assumed for $\alpha$. Note, however, that this result is just a rough estimate, which cannot be used to state that $\alpha$ should be independent of wave age. On the contrary, section 5 conclusively shows that such a relation does exist.

[25] Figure 6a shows examples of actual wind profiles in lin-log representation during a particular period of 30 hours with near-neutral (but slightly unstable) conditions and $E_1/E_2$ varying widely with time. It is clear that most profiles are not straight lines, as would have been expected if they were logarithmic. Instead, most profiles appear to be a composite of two lines with different slopes. The intersection of these
lines moves first upward with time, disappears above the highest measuring level during 13–17 hours, descending later again. Figure 6b shows the development of $U_{10}$ (full line) and $c_p$ (full line with circles), and Figure 6c shows $E_1/E_2$ and $c_p/U$, for the same period of time. It is clear that $E_1/E_2$ increases from values originally below 0.1 to more than 10 during the first 17 hours or so, decreasing then again to values around 0.1. There appears thus to be a variation of profile shape with wave age. During the period with large $E_1/E_2$-values, wind speed is almost constant with height. As illustrated in Figure 6d, this gives extremely low apparent $z_0$-values.

The above discussion can be summarized accordingly. A logarithmic wind profile is obtained over the ocean only for growing seas. Then short waves, which move much slower than the wind, dominate. This is “seen” by the wind similarly to a surface with rigid roughness elements, hence the close similarity to results obtained for neutral atmospheric and laboratory conditions with flow over a rough surface. However, as soon as the wave spectrum starts to approach a saturated state, i.e., $E_1/E_2$ increases, waves which move with a speed close to or even larger than that of the wind at 10 m gain increasing importance. Then complex interactions between wave motions and atmospheric motions occur in the atmospheric surface layer at corresponding scales, as observed in the atmosphere by Rieder and Smith [1998], Hare et al. [1997], and others, and expressed in the following words by Donelan et al. [1993]: “The young waves are believed to extract momentum from the wind by mechanisms—flow separation, viscous instability—different from those—instability of the turbulent shear flow in the boundary layer—that drive the longer, older wave component.” The results of the present study show that this leads to a nonlogarithmic wind profile, with a lower portion with less gradient than in the upper portion. This may be interpreted as the occurrence of a wave boundary layer of the order 10 m or more in depth. This view is partly supported by the pressure-velocity correlation measurements made by Hare et al. [1997] over the ocean. In the case of growing seas ($E_1/E_2$ small), the observed validity...
of the logarithmic law indicates that the wave boundary layer is indeed very shallow, as predicted by modeling studies [Belcher and Hunt, 1996; Makin et al., 1995]. For a case of strong swell, Smedman et al. [1999] showed that the long, dominating waves produce wave-induced momentum flux directed from the ocean surface into the atmosphere. It was concluded that the wave boundary layer in this case extended even beyond the highest measuring level, 30 m.

In section 1 it was argued that, during conditions with swell, the depth of the wave boundary layer, i.e., the layer where the wave-induced stress, $\tau_w$, is an appreciable part of the total stress $\tau$, could be on the order 10 m or more. If further, as assumed by Kitaigorodskii [1973], the friction velocity in the logarithmic law, equation (1) equals $\sqrt{\tau_f/\rho}$, where $\tau_f$ is the turbulent part of the stress, then we would expect profiles like those displayed in Figure 6a.

Figure 7 illustrates the situation schematically. In the lowest layer we would expect a profile with relatively small gradient, giving a very low apparent roughness length ($z_{01}$ in Figure 7), as often observed, cf. the open circles of Figures 3 and 4. In the upper parts of the schematic Figure 7, we would expect $\tau = \tau_f$ and a much higher value of the roughness length ($z_{02}$ in Figure 7). Possibly, there is sometimes a transition layer with even larger $z_0$-value ($z_{02}$ in Figure 7), see section 6 for the cases with slightly stable stratification below.

As schematically shown in Figure 8, depending on the actual depth of the wave boundary layer, the shape of the observed wind profiles in the 8–30 m layer covered by the measurements, may look very different. If the wave boundary layer is more than 30 m deep, a profile like 1 of Figure 8 may be observed. This is the situation observed in Figure 6a during the period with large $E_1/E_2$-values. If the depth of the wave boundary layer is less than the lowest measuring level, 8 m, a logarithmic profile is expected to ensue, profile 2 in Figure 8. If the depth of the wave boundary layer is between 8 and 30 m, a profile similar to 3 may appear. Possibly, the transition part shown in that profile may often be absent, like in most of the profiles shown in Figure 6a.

The above discussion seems to be generally applicable to the slightly unstable cases for $E_1/E_2$ larger than some lower limit, cf. section 5.1. As soon as stability becomes even very slightly stable, a different regime appears to ensue. As Figures 3b and 4b indicate, the circles, which represent $z_0$-estimates obtained with the gradient method, may be both above and below corresponding $z_0$-values obtained with the drag method. It does not appear possible to draw any further conclusions for the slightly stable cases.

5. Variation of the Drag With Sea State

5.1. Pure Wind Sea

Drennan et al. [2003], in their study of the effect of wave age on dimensionless roughness, $z_0/\sigma$, employed the criterion expressed by equation (10) for identification of pure wind sea conditions. Accordingly, we introduce a similar criterion: $E_1/E_2 < 0.2$ for pure wind sea conditions (cf. below discussion about this limit). As we expect Monin-Obukhov theory to be approximately valid for pure wind sea conditions, we extend our near-neutral data set to also include some slightly nonneutral cases, which we convert to neutrality (see below), and end up with a group of 299 1-hour data. Figure 9 shows a plot, in lin-log representation, of $z_0/\sigma$ against the inverse wave age parameter $u_*c_p$. Similar to what Drennan et al. [2003] did, the data have been divided into five bins according to the value of $u_*$, see the legend inserted in the figure. Linear regression of $\ln z_0/\sigma$ against $\ln u_*/c_p$ was then done for each $u_*$ bin individually. The resulting regression lines are shown in the figure together with the final result of Drennan et al. [2003], the lower of the two thin curves, and our final regression result. Our regression line has slightly greater slope, in the lin-log representation than the corresponding line of Drennan et al. [2003]. The mean value of our data is about 30% larger than the corresponding value of Drennan et al. [2003]. Nevertheless, it is a gratifying result that our data for this well-defined set of conditions agrees so well with results obtained mainly in open ocean conditions. This also lends credibility to the validity of the results for more complex conditions shown below.
to (for definition, see text). Data have been divided according for data with $E_u$. The correction is, however, so small that essentially identical result is obtained when this correction is not done. When previously discussing Figure 4a, it was mentioned that $z_0$-data derived with the profile method (open circles) are seen to start deviating in a systematic way from the corresponding values derived with the drag method (stars) for as low $E_1/E_2$-value as 0.05. A plot of $z_0/\sigma$ against $u_*/c_p$ for data with $E_1/E_2 < 0.05$ gives a pattern very much the same as that of Figure 9 (not shown here), the total number of data points being reduced from 247 to 168.

The question of self-correlation is always an issue in plots like Figure 9, which include the same parameter on both axes ($z_0$ is derived from equation (1), which contains $u_*$, which is also present in the expression on the abscissa). Making separate analysis for several bins of $u_*$, as done above, is one way to show that self-correlation is unlikely to be the major explanation for the observed ordering of the data. A more complete and systematic analysis of self-correlation is given in Appendix B. The method employed essentially means that the original data set is manipulated in a sequence of five steps, so that in the first step $u_*$ is being randomized, Figure B1b; in the next step both $u_*$ and $U_{10}$ are randomized, Figure B1c, and so on, ending with Figure B1f, where all the parameters $u_*$, $U_{10}$, $w/\theta_v$, $c_p$, and $\sigma$ have been randomized. It is evident from the sequence of figures that the degree of organization in the plot degrades rapidly. As also shown in Appendix B, the root-mean square error (RME) increases rapidly and the correlation coefficient decreases in the course of the randomization process. It seems safe to conclude that Figure 9 basically shows a real physical process.

5.2. Conditions With Mixed Sea/Swell

For the case of the previous subsection characterized by the criterion $E_1/E_2 < 0.2$, it was concluded that $u_*/c_p$ describes the variation of $z_0/\sigma$ in a quite satisfactory way, and that the relation found appears to have universal validity over the ocean. As shown in section 4, this case is also identical to the situation when the logarithmic wind law is found to be valid. At the end of that section, it was discussed that for developing sea, short waves dominate and present a roughness similar to that of a solid, rough surface but that the roughness regime appears to shift gradually as relatively long waves become increasingly important. Komen et al. [1998] express the situation in the following way: “So in general, one may expect the wave spectrum to be quite complex over the full wave number range. Therefore one does not expect, in general a unique relationship between the Charnock parameter, or the drag coefficient, and a single wave parameter, such as the wave age $c_p/u_*$.”

In Figure 10, $C_D$ has been plotted against the wind speed at 10 m, as often done. Five types of symbols differentiate between cases with different $E_1/E_2$-values, as shown in the insert legend. It is clear that this graph contains considerable scatter and that no differentiation according to sea state can be made here. Below, it is shown that two parameters are needed to characterize the sea state influence. The method employed essentially means that the original data set is manipulated in a sequence of five steps, so that in the first step $U_{10}$ is being randomized, Figure B1d; in the next step both $U_{10}$ and $U_{10}$ are randomized, Figure B1c, and so on, ending with Figure B1f, where all the parameters $u_*$, $U_{10}$, $w/\theta_v$, $c_p$, and $\sigma$ have been randomized. It is evident from the sequence of figures that the degree of organization in the plot degrades rapidly. As also shown in Appendix B, the root-mean square error (RME) increases rapidly and the correlation coefficient decreases in the course of the randomization process. It seems safe to conclude that Figure 9 basically shows a real physical process.
to make it dimensionless with the standard deviation of the surface elevation $\sigma$. This is motivated by the fact that, whereas $z_0$ in the case of growing seas is physically related to $\sigma$, in the general case, much of the variation in surface elevation may be due to long waves, the role of which in making up the overall roughness of the surface is very different to that of the short waves. However, plots of $z_0/\sigma$ against $u^*/c_p$ and of $z_0/E_2^{1/2}$ against $u^*/c_p$ (not shown here) show very similar pattern to that displayed in Figure 11.

[37] The data in this graph have been stratified according to $E_1/E_2$. Thus the squares represent $E_1/E_2 < 0.2$ and are the same data set as that used in making Figure 9 less those data that do not fulfill the criterion for near neutrality enforced in section 2. For increasing values of $E_1/E_2$, the data are seen to line up in bands, roughly parallel to those of the squares. The bands move gradually to the left in the figure with increasing $E_1/E_2$. The band farthest to the left is $E_1/E_2 > 4$ and is likely to represent swell conditions. Figure 11 vividly illustrates that the apparent roughness length is a function of two wave state variables, inverted wave age $u^*/c_p$, and the wave spectral ratio $E_1/E_2$. This means that for a certain value of inverted wave age, the apparent roughness length can take on a wide range of values, depending on the value of $E_1/E_2$, i.e., the ratio between the energy of the long and short waves, according to equation (12).

[38] Figure 11 is based on the complete near-neutral data set, i.e., it contains both the slightly unstable and the slightly stable data (cf. section 2). Separate plots (not shown here) of the unstable and the stable data show no systematic differences. This finding is in agreement with the conclusion from inspection of Figures 3a and 3b that the star symbols, which represent computations based on the drag method, have a similar trend in the graph representing unstable conditions, Figure 3a, and the corresponding graph representing stable conditions, Figure 3b.

[39] In Appendix B a self-correlation analysis similar to that performed for the case of young seas, presented above, is given. It shows that the organization of the data, which is evident in Figure 11, disappears when data are being randomized. It is concluded that the result shown in Figure 11 essentially reflects real physics.

[40] Figure 12 is a linear representation of $C_D$ against $u^*/c_p$ for the same data set. The $C_D$ has been obtained with the defining equation, equation (3), from measurements of $u^*$ with the eddy correlation method and $U_{10}$. Like in Figure 11, the data in this graph have been stratified according to $E_1/E_2$. Also, in this graph, the data line up in roughly parallel bands, and a wide range of $C_D$-values ensues for a given value of $u^*/c_p$ according to the value of $E_1/E_2$. A self-correlation analysis again shows that the result is real.

[41] A remarkable feature of Figure 12 is the wide range of $C_D$ values encountered for the data with $E_1/E_2 > 4$ (the diamonds), which are cases likely to represent swell. No systematic analysis has been made at this stage to clarify which factors are responsible for the group of surprisingly high $C_D$ values. Case studies indicate that the history of wave state development and concurrent development of wind direction and speed may be of importance in some cases. Cospectral analysis of the swell cases also reveals a characteristic feature: A distinct high-frequency “ordinary” turbulence part represents a small area in an energy-conserving graph and hence little energy; in addition, there is, however, always present low-frequency spikes, which can be either positive or negative. In cases where there happens to be one or several large negative excursions in the cospctrum, the resulting computed stress derived from integration of the cospctrum then becomes excessively large. However, the physical significance of these low-frequency spikes in the actual stress is not clear.

[42] Figures 11 and 12 show that plotting $C_D$ against $u^*/c_p$ and stratifying the data according to $E_1/E_2$ explains most of the large general variation in observed $C_D$.

6. Discussion and Conclusions

[43] Air/sea interaction field experiments in the past have given seemingly contradictory results concerning the effect

![Figure 11](image1.png)

**Figure 11.** Apparent roughness length derived from inserting measured values of $u^*$ and $U_{10}$ in the logarithmic wind law, plotted against $u^*/c_p$. Data have been divided according to $E_1/E_2$, see insert legend.

![Figure 12](image2.png)

**Figure 12.** The drag coefficient $C_D$ plotted against $u^*/c_p$. Data have been divided according to $E_1/E_2$, see insert legend.
of wave state on the exchange process. Some studies, e.g., Yelland and Taylor [1996], fail to find any influence of wave state. Other studies, notably those of Donelan [1990] and Drennan et al. [2003], show a significant effect of wave age, \( \frac{u^*}{c_p} \), for the case of developing seas. Komen et al. [1998] have simulated this effect with a high-resolution 1-D version of the WAM model, their modeling results showing good agreement with wave-tank data as well as with field data. For the case of developing seas, i.e., for \( E_1/E_2 \to 0 \) (where \( E_1 \) is the energy of the relatively long waves, which was found not to depend on wind speed, and \( E_2 \) is the corresponding energy of short waves, which was found to increase as the fourth power of wind speed), the present study gives a result which is in general agreement with that of Drennan et al. [2003]. This lends credibility to the claim that our site is indeed representative of oceanic conditions and together with the results of Drennan et al. [2003], strongly supports the idea that the relation found has general validity over the ocean for the case of growing seas.

[45] In the case of growing seas, short waves present the dominating roughness elements. As these waves are slow, they are seen by the wind more or less as solid obstacles, and the flow is expected to resemble that over a solid, rough surface. During neutral conditions a logarithmic wind profile is then expected to ensue. This was also demonstrated to be the case here when \( E_1/E_2 \to 0 \).

[46] As relatively long waves start to gain importance, i.e., with increasing \( E_1/E_2 \), it is found that the logarithmic wind law is not valid any more. The observed effects on the wave state. Other studies, notably those of Hare et al. [1990], Rieder [1997], and Hoegstrom [1996] reviewed published data for near-neutral conditions and situations with one-peak wave spectra. Situations with multipeak spectra are common in the open ocean. The present analysis has been carried out for such cases as well, with similar result, although with increased scatter (not shown here).

Table A1. Result of Calculations for the Unstable Cases

<table>
<thead>
<tr>
<th>( \mu^* )</th>
<th>( U_{\text{im}} )</th>
<th>( z_0/\nu^* \alpha_{\text{tuned}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.100</td>
<td>3.21</td>
<td>2.3</td>
</tr>
<tr>
<td>0.150</td>
<td>4.57</td>
<td>4.7</td>
</tr>
<tr>
<td>0.200</td>
<td>5.87</td>
<td>5.5</td>
</tr>
<tr>
<td>0.300</td>
<td>8.36</td>
<td>3.6</td>
</tr>
<tr>
<td>0.500</td>
<td>12.69</td>
<td>1.5</td>
</tr>
<tr>
<td>0.700</td>
<td>16.63</td>
<td>1.2</td>
</tr>
</tbody>
</table>

*Here \( \nu^* = 0.01 \text{ ms}^{-1} \); \( z_0/\nu^* \alpha_{\text{tuned}} \) is the ratio of the assumed value for \( z_0 \) and the corresponding “apparent” value obtained from forcing a logarithmic fit to the calculated wind speed at 8 and 13 m.

\( E_1/E_2 > 4 \) is the swell-dominated case. In between these limits, there is a wide range of wave conditions representing seas in various degree of saturation.

[47] The above findings imply that knowledge of the two wave-state parameters \( \frac{u^*}{c_p} \) and \( E_1/E_2 \) would be needed to give correct estimation of the stress in a numerical model of the flow over the ocean. This in turn is only possible if a wave model (such as WAM) is coupled to the atmospheric model. Even in the relatively simple case of developing seas, information from a wave model is needed.

[48] All results presented in this paper have been derived for near-neutral conditions and situations with one-peak wave spectra. Situations with multipeak spectra are common in the open ocean. The present analysis has been carried out for such cases as well, with similar result, although with increased scatter (not shown here).

Appendix A: Expected Effect of Stability on the Apparent Roughness Length

[49] When the stability, expressed as \( z/L \), is nonzero, the wind profile is expected to be more or less curved in a lin-log representation. If the wind speed at any two heights within a surface layer for which \( z/L \neq 0 \) are taken and the logarithmic law (equation 1) is forced to fit the data, a \( z_0 \)-value is obtained which differs, in general, from the true \( z_0 \)-value for that profile. Below, it is tested to what extent such stability effects may explain the striking difference observed in Figures 3a, 3b, 4a, and 4b between \( z_0 \) values obtained with the drag method and the gradient method.

[50] To enable quantification of stability effects, it is necessary to define functions for the dimensionless wind gradient, \( \phi_m(z/L) \). Hoegstrom [1996] reviewed published data and recommended the following expressions:

For stable conditions: \( \phi_m = 1 + 5.3z/L, \quad z/L > 0. \quad (A1) \)

For unstable conditions: \( \phi_m = (1 - 19z/L)^{-1/4}, \quad z/L < 0. \quad (A2) \)

[51] Integration of equations (A1) and (A2) from \( z = z_0 \) to \( z \) gives, respectively:

\[
U = \frac{\mu^*}{\kappa} \left( \ln \frac{z}{z_0} + 5.3z/L \right), \quad z/L > 0, \quad (A3)
\]

\[
U = \frac{\mu^*}{\kappa} \left( \ln \frac{z}{z_0} - 2 \ln \left( \frac{1 + \phi_m^{-1}}{2} \right) + \ln \left( \frac{1 + \phi_m^{-2}}{2} \right) - 2 \arctg \left( \frac{\phi_m^{-1}}{2} \right) \right), \quad z/L < 0. \quad (A4)
\]
It is now possible, with the aid of equation (A3) or (A4), to determine the wind speed at any height for a certain combination of $u^*$, $L$, and $z_0$, or equivalently, of $u^*$, $w_0 q_0 v$, and $z_0$. If we do that for two heights, $z_1$ and $z_2$, we can insert the corresponding wind speed values $U(z_1)$ and $U(z_2)$ into the expression for the logarithmic law, equation (1), and compute a pair of “apparent” values ($u^*$) and ($z_0$). We can then, finally, compare ($z_0$) with the original $z_0$-value.

The null hypothesis is thus that the variation of $z_0$-values observed in Figures 3a, 3b, 4a, and 4b for the gradient estimates (open circles) is entirely due to the stability effect. It is then assumed that equations (A3) and (A4) are valid representations of the wind profile and that $z_0$ can be obtained from the Charnock expression, equation (8), with $\alpha = 0.012$. The wind speed is calculated for the two heights 8 and 13 m for the combinations of $w_0 q_0 v = /C_0$ and 0.01 m s$^{-1}$ K, and $u^* = 0.100, 0.150, 0.200, 0.300, 0.500,$ and 0.700 m s$^{-1}$. Note that defining $u^*$ also means defining $z_0$ because of the assumed validity of the Charnock expression. The result of the calculations is presented in Table A1 for the unstable case and in Table A2 for the stable case.

For the unstable case it is found that $1 < z_0/(z_0)_a < 5.5$ over the entire wind speed range encountered. Comparing this result with the observed spread of the open circles in Figures 3a and 4a clearly nullifies the hypothesis that the observed spread is due to the stability effect. For the stable case the same conclusion is valid for $U_{8m} > 6$ m s$^{-1}$. This is identical to the criterion enforced on the stable data, therefore it is safe to say that very large scatter of $z_0$-values obtained with the gradient method is not due to the stability effect.

Appendix B: Investigation of Effects of Self-Correlation

In the process of nondimensionalization there is often a risk that the same parameter will occur on both axes of a plot. This is the case with Figures 9, 11, and 12. There is then a potential risk of self-correlation. In order to reveal if this effect is the actual cause of the ordering of the data observed in these graphs, a systematic analysis has been undertaken.

The procedure adopted is best illustrated by looking at Figure B1, which treats the case with young waves. It

![Figure B1](image-url)
contains six subplots of the same parameters, $z_0/\sigma$ against $u^*/c_p$. The first of these, Figure B1a, is identical to Figure 9. Figure B1b is based on the same data set, but the $u^*$-values of the original data set have been randomized. In Figure B1c, $u^*$ as well as $U_{10}$ have been randomized. In Figure B1d, $u^*$, $U_{10}$, and $\overline{u'w'}$ have been randomized. In Figure B1e, all these parameters and, in addition, $c_p$ have been randomized. In Figure B1f, finally, $u^*$, $U_{10}$, $\overline{u'w'}$, $c_p$, and $\sigma$ have all been randomized. It is evident from looking at the sequence of Figures B1a–B1f that the data gradually lose most of their original organization in the randomization process. Correlation analysis of the change $z_0/\sigma$ against log $u^*/c_p$ gives a correlation coefficient that decreases gradually from 0.70 to 0.53. The corresponding RME increases from 0.26 for the original data (Figure B1a) to 1.13. Note that for ease of comparison, all six graphs cover the same ranges on the abscissa and ordinate, respectively, as the original plot, Figure B1a. In the five plots based on more or less randomized data (Figures B1b–B1f), there are, however, data that fall outside the plot range. These are, of course, included in the correlation analysis results given here.

[56] A similar analysis was done for the case of mixed sea/swell. Similar to what was done for the case of young seas discussed above, the parameters involved in the non-dimensionalization were being randomized sequentially. It is clear from the graphs produced from the analysis (not shown here) that the organization of the data in bands according to the value of $E_1/E_2$ is being lost during the randomization process. Correlation analysis was carried out for each $E_1/E_2$ bin individually and for all data taken together. The root-mean-square (RMS) error for the individual bins is in the range 0.10–0.26 in the original data plot and increases gradually to 0.48–1.8 in the last graph.

[57] An exactly analogous analysis was also done for the case of $C_D$ plotted against $u^*/c_p$ (cf. Figure 12). The result (not shown here) is qualitatively similar to that shown in these graphs. The RMS error for the individual bins is in the range 0.04–0.09 in the original data plot and increased to 0.29–0.62 in the last graph. When the data were randomized, the ordering of the data in $E_1/E_2$ bins completely disappeared for the case of $C_D$ plotted against $u^*/c_p$ as well.

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**References**


