Near-Neutral Drag Coefficients Over Open-Ocean Waves

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Abstract—Reanalysis of open-ocean eddy-correlation drag coefficients observed at Argus Island Tower near Bermuda indicates that near-neutral drag coefficients decrease with increasing mean horizontal wind velocity when the dominant (spectral peak) ocean wave phase velocity is much greater than the mean wind velocity. Near-neutral drag coefficients attain constant values when the dominant wave phase velocity approaches mean wind velocity, and increase again when mean wind velocity is greater than or equal to dominant wave phase velocity.

I. INTRODUCTION

OPEN-OCEAN drag coefficients appear to depend on sea state for some ranges of mean horizontal wind velocity, particularly in middle latitudes where storm systems result in wind-generated waves and swell [1]. In this paper we show the influence of ocean waves on near-neutral drag coefficients using 7.5-m eddy-correlation data from Argus Island Tower near Bermuda [1], augmented by previously unpublished drag coefficient data at 5.5 and 7.5 m. In addition, we present a one-month sequence of open-ocean wave phase velocities calculated from wave spectral peaks compared to corresponding mean horizontal wind velocities observed every 3 h at the Argus Island Tower. These data show that dominant ocean wave phase velocity, calculated from the wave spectral peak frequency, is greater than the 43-m mean wind velocity for 68 percent of the observations. We suggest that this ubiquitous condition explains the tendency of drag coefficients to decrease with increasing winds at lower wind velocities. Drag coefficients then converge to the constant values reported by many investigators, at intermediate wind velocities, ranging from 10^3C_10 = 1.0 to 10^3C_10 = 1.3. For stronger winds, mean wind velocities are usually greater than or equal to dominant ocean wave phase velocity (spectral peak), and drag coefficients tend to increase again.

The subject is of some immediate concern because wind velocity and wind stress will be estimated on an oceanwide basis with polar orbiting satellites as a direct result of success of the radar scatterometer (SASS) on Seasat. After waves become fully developed, dominant waves associated with the wave spectral peak will travel at phase velocities equal to the wind velocity. As the mean horizontal wind velocity decreases, for example to 80 or 90 percent of its former value, faster moving long-wavelength dominant waves can exert a feedback effect on the wind turbulence structure associated with wind shear over the waves. Hence, in addition to serving as a modulating carrier of capillary and short gravity waves, longer waves may influence the momentum flux from atmosphere to ocean surface. This implies that transfer functions for scatterometer estimates of wind stress, for example, could be improved by inclusion of an ocean surface wave parameter [2]. The total amount of well-documented momentum flux and wave spectra data for the open ocean is severely limited, and there is no convincing evidence which either emphasizes or diminishes the extent of such influence on the momentum flux. In this paper we review and reinterpret some of the available evidence which tends to emphasize such influence in terms of the drag coefficients.

II. DRAG COEFFICIENTS

Fig. 1 illustrates 311 measurements of the near-neutral open-ocean drag coefficient C_7.5, where C_7.5 is defined as follows:

\[ C_{7.5} = -\langle u'w' \rangle / U_{7.5}^2 \]  \hspace{1cm} (1)

and the data are plotted as a function of the mean horizontal wind velocity, U_{7.5}. Also in (1), \langle u'w' \rangle denotes the covariance of the horizontal and vertical wind velocity fluctuations \( u' \) and \( w' \), respectively. Near neutral refers to a gradient Richardson number \( Ri \) in the range

\[ |Ri| \leq 0.034 \]  \hspace{1cm} (2)

which is a less restrictive criterion than the one used by DeLeonibus [1] where neutral stability was given by \( |Ri| \leq 0.01 \). Complete details on the Argus Island experiment, calculation of momentum flux, Richardson numbers, and wave spectra are given in [1].

Fig. 1 illustrates a new analysis of the Argus Island Tower data observed during 1964, 1967, and 1969. This includes data from [1, table 2, p. 6516] plus 80 previously unreported observations of the drag coefficient observed at 5.5 m, (corrected to C_7.5) and 26 previously unreported observations of C_7.5 at wind velocities between 12 and 15 m\cdot s^{-1}.

For the data set of Fig. 1, 10^3C_{7.5} falls into three ranges: 1) a steady decrease of 10^3C_{7.5} from 1.7 to 0.71 as the mean horizontal wind velocity increased from 4 to 7 m\cdot s^{-1}; 2) constant values of 10^3C_{7.5} = 1.34 (corresponding to 10^3C_{10} = 1.22) for the mean wind between 8 and 13 m\cdot s^{-1}; and 3) higher values of 10^3C_{7.5} = 2.2-2.4 at U_{7.5} = 14 and 15 m\cdot s^{-1}.

Fig. 1 applies to wind velocities U_{7.5} \leq 15 m\cdot s^{-1} and can therefore be compared to the field data of Large and Pond [3].
and to the extensive summaries of Garratt [4] and Wu [5] for this wind speed range. Fortunately, wind velocities up to 15 m·s\(^{-1}\) account for a large fraction of middle latitude winds, and this fraction is certainly adequate to illustrate open-ocean wave influence on drag coefficients. Fig. 1 is similar to observations of Large and Pond [3, eq. 3] for wind velocities between 8 and 13 m·s\(^{-1}\), but differs significantly from their observations for \(U_7.5 < 7\) m·s\(^{-1}\) and \(U_7.5 > 13\) m·s\(^{-1}\). In particular, Large and Pond observed the following for \(C_{10'}\):

\[
10^3C_{10'} = \begin{cases} 
2.2, & 4 < U_{10} < 11 \text{ m} \cdot \text{s}^{-1} \\
0.49 + 0.065U_{10}, & 11 \leq U_{10} \leq 25 \text{ m} \cdot \text{s}^{-1} 
\end{cases}
\tag{3}
\]

Fig. 1 also differs significantly from the linearly increasing drag coefficient summaries of Garratt [4] and Wu [5] given by (4) and (5), respectively:

\[
10^3C_{10} = 0.75 + 0.067U_{10}, \quad 4 \leq U_{10} < 21 \text{ m} \cdot \text{s}^{-1} \tag{4}
\]

\[
10^3C_{10} = 0.8 + 0.065U_{10}, \quad U_{10} > 1 \text{ m} \cdot \text{s}^{-1} \tag{5}
\]

Kondo et al. [6] observed near-neutral drag coefficients which decreased when mean wind velocities increased from 3 to 7 m·s\(^{-1}\) before increasing again. Kondo et al. illustrated wave influence on the horizontal wind component but did not specifically relate the drag coefficient to dominant wave phase velocities.

The open-ocean surface is nearly always covered with a composite of shorter wind-generated waves and longer wave-length swell which, in turn, influence surface layer wind turbulence through feedback mechanisms that include wave generation, wave breaking, and wave propagation. Since the shorter waves that control much of the drag are advected and modulated by the long dominant waves, it is physically realistic to interpret near-neutral drag coefficients in terms of the actual roughness regimes experienced over the open ocean. In this paper we assume that dominant longer waves are represented by the phase velocity at the wave spectral peak.

III. WAVE PHASE VELOCITY AND WIND VELOCITY

Fig. 2 illustrates a scatter diagram of dominant open-ocean wave phase velocity \(C_M\) given by

\[
C_M = g / 2\pi f_M
\tag{6}
\]

where \(f_M\) is the wave frequency at the spectral peak, \(g\) is the acceleration of gravity, and \(C_M\) is plotted against \(U_{7.5}\). Fig. 2 illustrates the wind and wave spectra observed during near-neutral and moderate instability conditions (\(Ri = -0.097\)) during the Argus Island Tower momentum flux program (March and May 1964; March and April 1967; January and February 1969). Fig. 2 illustrates that \(C_M\) is greater than \(U_{7.5}\) in most of the observations. There appears to be no difference in the data scatter for either near-neutral or moderately unstable conditions.

Wind and wave observations were obtained also during February 1964 before the beginning of the momentum flux observation program. Fig. 3 illustrates that \(C_M > U_{43}\) for 111 of 161 observations (68 percent) for the period February 5–29, 1964, where mean horizontal winds at 43 m (\(U_{43}\)) and wave spectra were observed continuously at 3-h intervals. These winds and waves were observed during slightly unstable atmospheric conditions, in that the average air and sea temperature differences reported by ships around Argus Island and Bermuda were equal to \(-2.8^\circ\text{C}\). It should be emphasized that both Figs. 2 and 3 include only those data for which wind and wave directions differed by less than 20\(^\circ\). In both Figs. 2 and 3 wave data were averaged over 20-min wave records. Wind velocities in Fig. 2 are 15-min averages and they are hourly averages in Fig. 3. Wave directions were determined from visual observations at the tower, from ship reports, and inferred from 6-h surface weather maps.

Thus, if February 1964 is a representative month, the wintertime middle latitude sea surface is characterized by shorter waves superimposed on longer dominant waves moving faster than surface layer winds more than half the time. This tends to reduce the drag for such winds, and we observe a constant drag coefficient for an intermediate range of wind velocities, i.e., approximately 8–13 m·s\(^{-1}\). Before approaching a constant value, however, the drag coefficient in Fig. 1 decreased from \(10^3C_{7.5} = 1.7\) at 4 m·s\(^{-1}\) to 0.7 at 7 m·s\(^{-1}\).

Fig. 1 also shows higher values of \(10^3C_{7.5} (= 2.2 \text{ and } 2.3)\) at 14 and 15 m·s\(^{-1}\). Such higher values are likely to occur when the open-ocean surface provides a larger drag, i.e., when \(U \geq C_M\) and wave systems are less than or equal to fully developed. This is illustrated in 108 observations of \(C_{7.5}\)
plotted as function of \( gH_{1/3}/U_{7.5}^2 \) in Fig. 4, where \( H_{1/3} \) is significant waveheight. Note that \( C_{7.5} \) reaches a peak value between \( gH_{1/3}/U_{7.5}^2 = 0.13 \) and 0.19. In this range, waves are still growing under the action of the wind as shown by numerous shipborne wave recorder observations summarized by Pierson [7]. Pierson observed that waves continued to grow up to

\[
gH_{1/3}/U_{19.5}^2 \leq 0.21
\]

which corresponds to

\[
gH_{1/3}/U_{7.5}^2 = 0.25.
\]

In his study, Pierson used sea-level synoptic weather maps in conjunction with shipborne wave recorder observations to include only the wave-generating cases up to fully developed, and he excluded all cases where swell also occurred.

All eddy-correlation estimates of momentum flux exhibit large scatter, and Figs. 1 and 4 are no exception. Nevertheless, the general trends are clear. Fig. 4 illustrates that when waves are less than fully developed (with no swell), higher values of drag coefficient can be observed. Fig. 3 suggests this could occur about one-third of the time in winter if February 1969 is typical.

Fig. 5 illustrates higher values of near-neutral \( C_{7.5} \) when waves are close to fully developed. During the interval 1800Z, March 19, to 0200, March 20, 1964, with \( H_{1/3} \) slightly greater than 4 m, \( 10^3C_{7.5} \) was observed to be greater than 2.0 during most of the interval (mean value = 2.4). These high \( C_{7.5} \) values were associated with a mean value of \( gH_{1/3}/U_{7.5}^2 = 0.19 \) and mean wind velocities between 13 and 15 m\( \cdot \)s\(^{-1} \) (mean value = 14.3 m\( \cdot \)s\(^{-1} \)). Hourly wind profiles in Fig. 5 were kinked both downward and upward and did not tend to a logarithmic form over this interval of time.

IV. SUMMARY

Open-ocean tower observations of near-neutral drag coefficients appear to depend on ocean wave background as well as mean horizontal wind velocity. Many investigators have discussed the interaction between atmospheric surface layer winds and surface waves, beginning with Stewart [8]. More recently, Longuet-Higgins and Smith [9] describe oceanic wave data that suggests that air flow separation associated with breaking waves can result in a higher drag coefficient. Most
Fig. 3. Phase velocity of open-ocean wave spectral peak ($C_{w}$) versus mean horizontal wind velocity at 43 m ($U_{43}$) observed at Argus Island Tower every 3 h from February 5, through February 29, 1964.

Fig. 4. Drag coefficient ($C_{d}$) as function of dimensionless waveheight ($gH_{b}/U_{10}$) for near-neutral stability. Number of observations indicated at each point. Standard deviation indicated by vertical bar.
future polar orbiting satellites include simultaneous observations of wave spectra, as well as atmospheric stability and wind data, particularly in view of the recent findings of Keller et al. [2], which illustrate a dependence of the modulation transfer function on long-wave slope for near-neutral stability.

REFERENCES


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