11.4 WIND STRESS AND WIND WAVE OBSERVATIONS IN THE PRESENCE OF SWELL

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1. INTRODUCTION

The questions of how wind and ocean waves interact and how this coupling should be parameterized to optimally derive the surface wind stress remain open and central to estimating air-sea coupling at the global and local scales. While much attention has been given to evaluating the effect of the wind-driven waves upon the surface wind stress and air-sea drag coefficient, less emphasis has been given to the more common and more complex mixed sea case. At any given instant, much of the global ocean's wave energy is carried in its swell fields. In fact, the majority of long wave spectra over the seas will exhibit a mixture of locally coupled wind waves and swell that is aligned in some arbitrary fashion with respect to the local wind direction. Recent work (Drennan et al., 1999; Kudryavtsev and Makin, 2004; Larsen et al., 2004; Rutgersson et al., 2001; Smedman et al., 2003) suggests that the swell can and does act to alter the sea drag at light-to-moderate wind conditions. The swell phase speed and direction with respect to the wind vector, the steepness of the swell, and the relative energy of the swell versus the sea are all discussed as factors in this influence. The theoretical work of Kudryavtsev and Makin, (2004) suggests that swell exchanges energy through two mechanisms: the correlation of pressure and wave slope (form drag), and the work of surface turbulent stress against the swell orbital velocity. Observation and theory suggest that it is the case of wind-opposed swell that provides the most substantial increase in the 10 m drag coefficient. An additional point of consideration is the possibility that the wave-induced momentum flux can systematically alter the assumed logarithmic form for the wind profile, perhaps calling into question the use or derivation of a 10 m drag coefficient in some cases.

A goal of the present paper is to provide some additional observations for consideration. In particular, the focus will be upon cases where there is a severe drop in the drag coefficient that occurs in conditions of stable boundary conditions and relatively strong swell fields. Data come from Office of Naval Research's Shoaling Waves Experiment (SHOWEX). The primary measurements to be discussed were obtained using a low-flying aircraft that collected both atmospheric and wave field measurements. Another point of interest is to see when observed variability in the drag and short wave statistics covary. This emphasis is driven by the need to use short-wave remote sensing techniques to derive the wind stress information from satellites.

2. METHODS

Measurements to be discussed were collected over the western Atlantic within 120 km of Duck NC. All flights occurred between 1997 and 1999, with most data collected in the month of November. Data come from 36 separate flights of the NOAA LongEZ covering a variety of wind and wave conditions. A map of the region, aircraft measurement and buoy locations are shown in Fig. 1. For all data presented herein the aircraft flew at an average altitude of 15 m above the surface. This is a unique vantage point that permits high resolution and high fidelity sensing of the sea surface and air above, much as for a fixed experimental platform. Several recent publications discuss the data products, their derivation, and processing (French et al., 2000;Mahrt et al., 2001;Sun et al., 2001;Vandemark et al., 2001). Only limited details are discussed below.

The aircraft data set used here consists of the friction velocity ($u*$), bulk Richardson number (Ri), air and sea temperatures, wind velocity scaled to neutral-stability 10 m using the Toga-Coare bulk flux algorithm (U_{10N}), wind direction, significant wave height (H_s), mean square slope (mss), mean square slope of low frequency waves (mss_l) and mean square slope of high frequency waves (mss_h). The wave data are derived through a combination of laser altimeter and nadir-looking radar scatterometer measurements (Vandemark et al., 2001). Low and high frequency limits pertaining to mss are defined as 0.0 to 0.1 Hz for the low regime and 0.1 to 8 Hz for the high. Slope variance for this low frequency estimate is derived directly from the laser altimeter wave elevation and slope data. Normalized radar cross section data at Ka-band is used to extract mss. The high frequency mss estimate is obtained as mss_h = mss –

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mss_l. The friction velocity is derived using the eddy correlation method on the 50 Hz wind velocity component data (u, v, w) collected by the LongEZ. All variables are discussed and validated in the cited works. The processing of the data for the current study involved computing an average value along each successive 15 km ground track in the data set. Only data segments that lie beyond 15 km offshore in cases of offshore flow, or 5 km offshore for onshore flow, are used. This selection is used to provide data that is representative of open ocean conditions in this region (Vickers et al., 2001).

Buoy data are also used in this study. First is the National Data Buoy Center's directional wave buoy N44014, located about 100 km to the east of Duck NC. This buoy was over flown frequently in 1998. Second are the University of Miami's Air-Sea Interaction System (ASIS) buoys that were located about the SHOWEX site in November of 1999. These buoys were used to validate the wind, wave height and flux data from the LongEZ. For this study we are using them to provide directional long wave information. In particular, the wave phase speed (*c*), direction and rms elevation for both the wind sea and the swell modes observed.

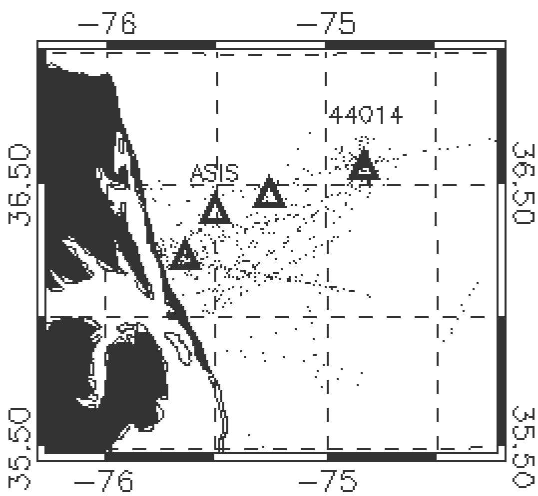

Figure 1 Map of the study region east of North Carolina's outer banks. Large symbols denote the buoy locations. Small symbols show center location of each 15 km aircraft data segment used in the study. Data extend as far as 120 km off shore.

3. RESULTS

Several statements about the general characteristics of the sea drag observed in this open ocean data set can be made. First, the averaged 10 m drag coefficient data, $C_d = u_*^2/U_{10N}^2$, agree quite well with the model of Oost et al. (2002) developed for the North Sea. This is shown in Figure 2. The total size of the data here is 665 samples. The Oost et al. model requires the wind speed, wave height and phase speed of the dominant wave mode and these are provided for each of our observations and averaged versus wind speed bins to create the model line presented. The error bars provide a 95% confidence interval assuming random error in each wind speed bin. As one can see the present observations lie well above the model in the light wind regime but for moderate winds the two results are nearly identical. The model was derived in the North Sea and perhaps similar wave climates and coastal proximity serve to aid this agreement. But the model's incorporation of wave impacts may also be bridging the gap between the two observational data sets to provide a viable model for the drag at moderate winds.

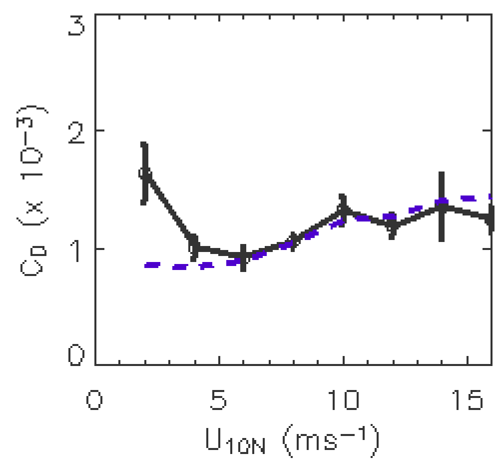

Figure 2 Observed air-sea drag coefficient obtained versus wind speed (averaged across 2 ms^{-1} wind speed bins) for this study with 95% confidence intervals. Dashed line is the model of Oost et al. (2002).

Second, the light wind data in this set should be treated with caution. Knowledge of the vertical structure of the boundary layer can become quite important in this case and most of the data examined here are acquired at only one nominal altitude above the surface, usually 15 m. Profile uncertainties in both deriving the friction velocity and in understanding the actual depths and characteristics of the inner and outer boundary layer regions in this case point our focus towards the moderate wind speed range.

Third, one particularly distinguishing characteristic of the data set is the occurrence of anomalously low C_d values on several of the measurement days where the wind speed at altitude registered a moderate level of 4-7 ms^{-1}. We view these as cases of smooth flow. Upon inspection, these days were typically associated with a relatively stable boundary layer. They are also characterized as cases where the wind and swell directions were within 60 degrees of each other and the swell amplitude exceeds that of the sea by a substantial level.

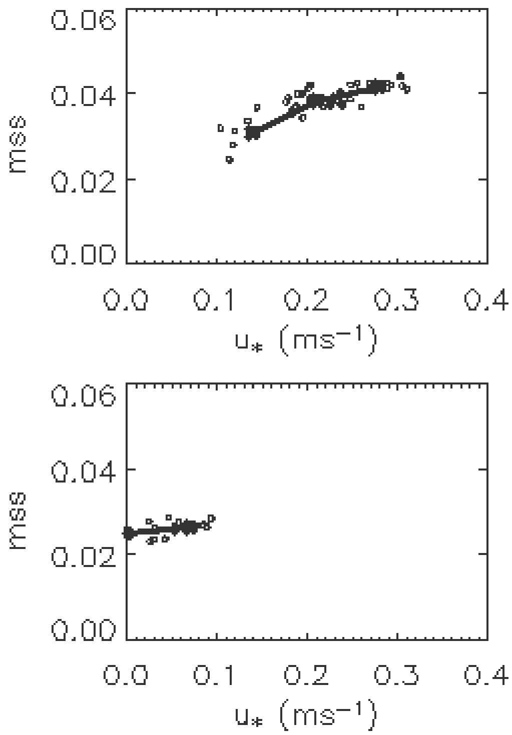

Figure 3 Radar-derived slope variance versus friction velocity for a) upper panel is for Nov. 15, 1998; westerly flow and wind-driven seas. b) Lower panel is for Nov. 16, 1998 where easterly winds prevailed for these measurements.

Another distinguishing feature for these smooth flow cases is seen when one examines the aircraft's wave slope variance and wind data. It is well known that the short waves generally respond well to local wind variations and this fact was well represented in the present data set. As an example, Figure 3a provides aircraft observations of the Ka-band radar derived *mss* versus friction velocity for data from Nov. 15 1998 where the sea state was predominately westerly, wind driven, and the boundary layer near neutral. A much different observation is seen for the smooth flow cases. Fig 3b shows example data from Nov. 16 1998 where the flow reversed to an easterly direction and a low drag coefficient was observed. One can see a clear relationship to the turbulence in the former case and much less in the latter. This lack of correlation is also evident when the data are scattered against the wind speed. Moreover, the level of *mss* does not tend toward zero in Fig 3b as one expects for very low levels of friction velocity. The general lack of correspondance between the wind and mss was a common feature for these cases.

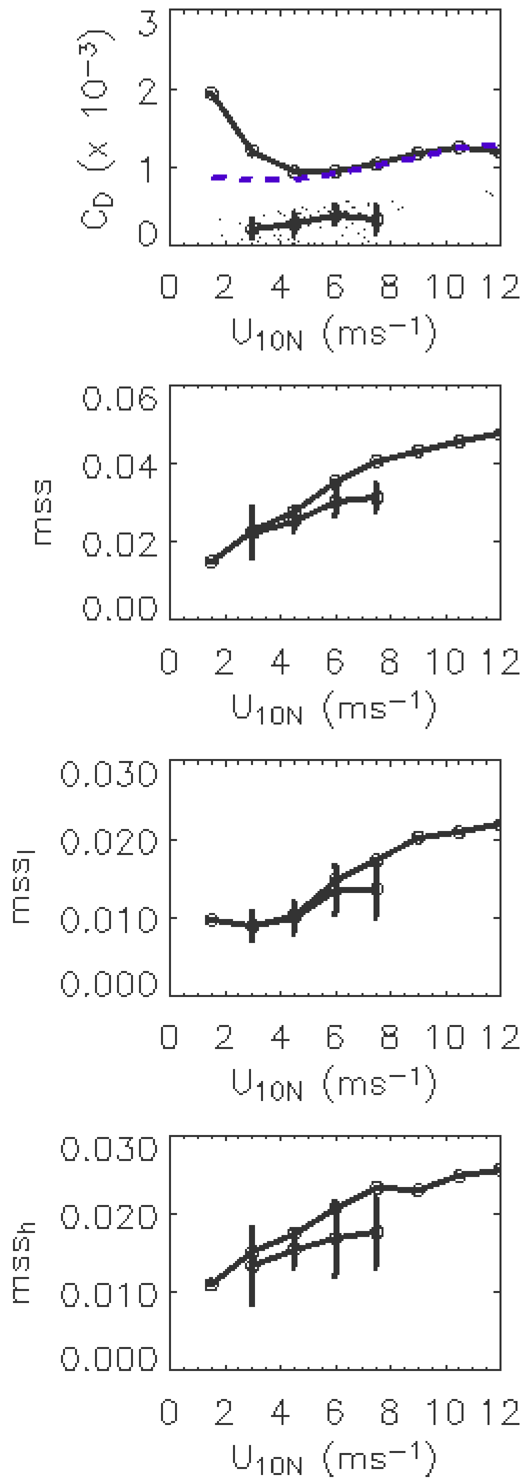

Figure 4 Wind dependence for the 10 m drag coefficient and slope variance estimates. In all cases the upper solid trace is for the overall data set and the lower trace (with error bars) is for the smooth flow cases denoted in Table 1. Dashed line is Oost et al. (2002).

Figure 4 and Table 1 provide further detail for the low drag coefficient events that constitute smooth flow cases in our data set. In Figure 4a we reproduce the sea drag results for the overall experiment (Fig. 2) along with the low level drag observations. It is evident that for these cases the level drops 60-70%. The following 3 panels in the figure provide the overall slope variance relationships for the experiment (upper curves on each panel) as well as the *mss* vs. wind speed relationship for the smooth flow events only. It is apparent the surface wave roughness is lower for the low drag events as the wind speed increases. This is seen for total, low and high frequency *mss* estimates. The relative depression in roughness is largest for the high frequency waves, mss_h, but the relative decrease from the nominal level is not as large as that for C_d . This lack of suppression is consistent with the non-zero levels seen in Fig 3b.

Table 1 Average results for the low Cd cases in the data set. Columns represent the date as yymmdd.

Variable	**981110**	**981116**	**991122**	**991126**
Samples	19	17	9	27
u_*	0.12	0.06	0.10	0.12
Direction				
Wind	113	113	50	156
Sea	85	65.	49	168
Swell	75	122.	120	125
Speed (ms^{-1})				
U_{10N}	6.3	4.4	4.7	5.7
Sea	5.5	6.2	4.9	4.6
Swell	13.1	14.1	14.6	11.4
swell:sea (energy ratio)	7.8	3.3	37.1	16.8
H_s (m)	0.8	0.8	1.6	1.8
Air-sea(degC)	1.6	-0.98	1.5	5.39
Rich. Number	0.02	-0.03	0.02	0.06

While it is known that the drag coefficient, and similarly the roughness length, z_o , can depend on numerous factors, the strong depression of the drag coefficient is not found in any usual parameterization that depends for example upon the atmospheric stability, or the sea state (e.g. via inverse wave age (u*/c) and/or wave height). Each of these factors is, in fact, contained within the model of Oost et al. (2002) and others. Upon consideration of the stable flow regimes and the swell we suggest the cases accord most closely with the condition of ultra-smooth flow (Donelan, 1990). We suggest that the results are akin to that seen in the Baltic (Rutgersson et al., 2001; Smedman et al., 2003) where investigations of swell in stable, neutral and unstable boundary layer conditions have been made. The latter paper examines near neutral data and discusses the fact that in mixed seas the sea drag may need to be examined both as a function of the wave age and of the relative wave spectral energy contributions of the sea and the swell. That paper stratifies the condition of E_{swell}:E_{sea} > 4 to be swell dominated. The data for the cases of Table 1 and for (Smedman et al., 2003) are given in Figure 5. To create these results from Table 1 we adjusted the swell phase velocity by the cosine of the angle with respect to the wind when computing the inverse wage age.

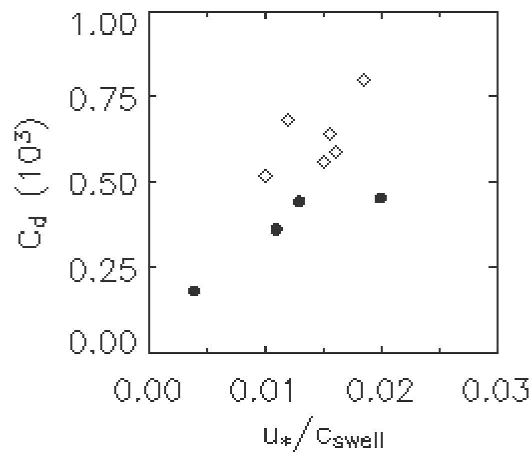

Figure 5 Drag levels (•) for aircraft results of Fig. 4 and Table 1 as given for each of the four days in the Table 1. Diamonds are taken from Fig. 12 of (Smedman et al., 2003) for swell dominated cases with C_d less than 1.e-3.

The present results and those of Smedman et al. in Fig. 5 all represent cases of very old waves. The direction of the swell was not available for that study but there are two estimates in their Fig. 12 at old seas where the drag exceeded 1. e-3 in there work and directionality (e.g. opposing-wind swell) may be an issue. Regardless, the data sets shown here do follow a similar course. Present results off the North Carolina coast suggest that the swell is coupling with the atmosphere with a resulting strong decrease in the drag consistent with that seen in the Baltic.

4. SUMMARY

Field observations are presented that provide some further support for the effects of swell on the 10 m air-sea drag coefficient. The investigation here is preliminary and focused on cases where the drag coefficient dropped to very low levels at moderate wind speeds. Preliminary results indicate the the drag depression is consistent with swell modes traveling in a following-wind (+-70 deg.) direction. The short wave steepness in both the intermediate and cm-scale was reduced for these cases but not with the magnitude seen in the drag.

Some common obstacles to further clarification are being addressed. These include self-correlation, isolation of atmospheric stability effects, and perhaps most importantly understanding the influence of the vertical profile on the observed drag and on the inferences that can be drawn using the single level aircraft data for the cases presented. The recent studies cited (e.g. Kudryavtsev and Makin, 2004; Smedman et al., 2003) indicate that the inner (wave) and outer boundary layer structure may be quite different for the case of swell dominance as opposed to well-couple wind waves. Further examination of the aircraft wind and wave cospectra should aid in this effort.

5. REFERENCES

Donelan, M. A., 1990: Air-sea interaction. *The Sea, Ocean Engineering Science*, B. Le Mehaute and D. M. Hanes, Eds., John Wiley & Sons, Inc., 239-292.

Drennan, W. M., H. C. Graber, and M. A. Donelan, 1999: Evidence for the effects of swell and unsteady winds on marine wind stress. *Journal of Physical Oceanography*, **29,** 1853-1864.

French, J. R., G. H. Crescenti, T. L. Crawford, and E. J. Dumas, 2000: LongEZ (N3R) participation in the 1999 shoaling waves experiment (SHOWEX). Data report OAR ARL-20, 51 pp.

Kudryavtsev, V. N. and V. K. Makin, 2004: Impact of swell on the marine atmospheric boundary layer. *Journal of Physical Oceanography*, **34,** 934-949.

Larsen, X. G., V. K. Makin, and A. S. Smedman, 2004: Impact of waves on the sea drag: measurements in the Baltic sea and a model interpretation. *The Global Atmosphere and Ocean System*, **9,** 97-120.

Mahrt, L., D. Vickers, J. L. Sun, T. L. Crawford, G. Crescenti, and P. Frederickson, 2001: Surface stress in offshore flow and quasi-frictional decoupling. *Journal of Geophysical Research-Atmospheres*, **106,** 20629-20639.

Oost, W. A., G. J. Komen, C. M. J. Jacobs, and C. Van Oort, 2002: New evidence for a relation between wind stress and wave age from measurements during ASGAMAGE. *Boundary-Layer Meteorology*, **103,** 409-438.

Rutgersson, A., A. S. Smedman, and U. Hogstrom, 2001: Use of conventional stability parameters during swell. *Journal of Geophysical Research-Oceans*, **106,** 27117-27134.

Smedman, A. S., X. G. Larsen, U. Hogstrom, K. K. Kahma, and H. Pettersson, 2003: Effect of sea state on the momentum exchange over the sea during neutral conditions. *Journal of Geophysical Research-Oceans*, **108**.

Sun, J. L., D. Vandemark, L. Mahrt, D. Vickers, T. Crawford, and C. Vogel, 2001: Momentum transfer over the coastal zone. *Journal of Geophysical Research-Atmospheres*, **106,** 12437-12448.

Vandemark, D., P. D. Mourad, S. A. Bailey, T. L. Crawford, C. A. Vogel, J. Sun, and B. Chapron, 2001: Measured changes in ocean surface roughness due to atmospheric boundary layer rolls. *Journal of Geophysical Research-Oceans*, **106,** 4639-4654.

Vickers, D., L. Mahrt, J. L. Sun, and T. Crawford, 2001: Structure of offshore flow. *Monthly Weather Review*, **129,** 1251-1258.