Parameterizing the Sea Surface Roughness

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ABSTRACT

The concept of an "equivalent surface roughness" over the ocean is useful in understanding the relation between wind speed (at some height) and the net momentum flux from air to sea. The relative performance of different physics-motivated scalings for this roughness can provide valuable guidance as to which mechanisms are important under various conditions. Recently, two quite different roughness length scalings have been proposed. Taylor and Yelland presented a simple formula based on wave steepness, defined as the ratio of significant wave height to peak wavelength, to predict the surface roughness. A consequence of this formula is that roughness changes due to fetch or duration limitations are small, an order of 10%. The wave steepness formula was proposed as an alternative to the classical wave-age scaling first suggested by Kitaigorodskii and Volkov. Wave-age scaling, in contrast to steepness scaling, predicts order-of-magnitude changes in roughness associated with fetch or duration. The existence of two scalings, with different roughness predictions in certain conditions, has led to considerable confusion among certain groups. At several recent meetings, including the 2001 World Climate Research Program/Scientific Committee on Oceanic Research (WCRP/SCOR) workshop on the intercomparison and validation of ocean-atmosphere flux fields, proponents of the two scalings met with the goal of understanding the merits and limitations of each scaling. Here the results of these efforts are presented. The two sea-state scalings are tested using a composite of eight datasets representing a wide range of conditions. In conditions with a dominant wind-sea component, both scalings were found to yield improved estimates when compared with a standard bulk formulation. In general mixed sea conditions, the steepness formulation was preferred over both bulk and wave-age scalings, while for underdeveloped "young" wind sea, the wave-age formulation yields the best results. Neither sea-state model was seen to perform well in swell-dominated conditions where the steepness was small, but the steepness model did better than the wave-age model for swell-dominated conditions where the steepness exceeded a certain threshold.

1. Introduction

The earliest roughness parameterization was that of Charnock (1955) who, on dimensional grounds, proposed that

$$z_{\rho}g/u_{*}^{2} = \alpha, \tag{1}$$

where z_o is the roughness, u_* is the friction velocity, and g is the gravitational constant; α , now known as the Charnock parameter, was assumed initially to be constant. However, it has long been recognized that (1)

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with a constant α does not adequately describe many datasets. In particular, it was speculated that α was a function of some parameter related to the sea state. Kitaigorodskii and Volkov (1965) proposed that α should depend on the fetch or duration of the wind event. This "wave age" dependence with α as a function of wave age, expressed as either c_p/u_* or c_p/U_{10N} , found qualitative support in the data of Donelan (1982). Here c_p is the wave phase speed at the peak of the spectrum, and U_{10N} is the 10-m neutral wind speed.

Hsu (1974) proposed instead that the Charnock constant be proportional to the steepness of the dominant waves H_s/L , where H_s is the significant wave height and L is the wavelength of the dominant waves. Using (1), the roughness can then be expressed in the dimensionless form

$$z_o/H_s = A(u_*/c_p)^2,$$
 (2)

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TABLE 1. Summary of the eight experiments showing, from top to bottom, which data were used in the development of the wave-age (A) and steepness (S) models (S* refers to the use of a data subset), instrument platform (MPN is the Meetpost Noordwijk platform, and NWRI is the National Water Research Institute tower), experiment location, water depth, the flux measurement method (EC is eddy correlation and ID is inertial dissipation), whether 1D or 2D wave spectra were used, fetch range, anemometer type, anemometer height, sampling period, and number of data.

	AGILE	AWE	FETCH	HEXOS	RASEX	SWADE	SWS2	WAVES
Parameterization	А	_	А	A, S	S	А	_	A, S*
Platform	15-m ship	ASIS buoy	ASIS buoy	MPN tower	Lattice tower	20-m ship	NOMAD buoy	NWRI tower
Location	Lake Ontario	Atlantic coast	Gulf of Lion	North Sea	Baltic coast	Atlantic shelf	North Atlantic	Lake Ontario
Depth (m)	5-50	20	100	18	4	12-2600	81	12
Method	EC	EC	EC	EC	EC	EC	ID	EC
Wave spectra	2D	2D	2D	2D	1D	2D	2D	2D
Fetch (km)	2-20+	2–long	>50	Long	10-20	Long	Long	1-200
Anemometer	Sonic	Sonic	Sonic	Sonic + pressure	Sonic + cup	K-Gill propeller	Sonic	Bivane
Height	7.8 m	6.5 m	7 m	6 + 6 m	3 + 7 m	12 m	5.7 m	12 m
Sampling period	20-25 min	30 min	28.5 min	20 min	30 min	17 min	1 min	30 min
No. of data	101	565	853	50	80	126	1383	238

where the wave phase speed $c = (gL/2\pi)^{1/2}$, which is valid for deep water. Here we take the "dominant" wave properties to be represented by those at the peak of the amplitude spectrum, denoted with subscript *p*. Donelan (1990) sought a more general wave-age dependence,

$$z_{\rho}/H_{s} = A_{1}(u_{*}/c_{\rho})^{B_{1}}.$$
(3)

Although wave-age scalings were introduced over 30 years ago, their usefulness has been questioned by several authors. No universally accepted form of the scaling has appeared, and it often seems that there are as many wave-age relations as there are datasets with a wave-age dependence. Part of the problem relates to the commonly used Charnock form of wave-age dependence (1), $\alpha = z_o g/u_*^2 = f(u_*/c_p)$, where both the dimensionless roughness α and the wave age depend on u_* . This leads to a potential spurious correlation among the variables, one made worse by the fact that for most experiments, variability in u_*/c_p is dominated by variability in u_* (see, e.g., Smith et al. 1992). Lange et al. (2004) showed that the effect of spurious correlation dominated any wave-age signal in the data they examined. In contrast, Drennan et al. (2003; hereinafter DGHQ) sought to reduce this problem by combining data from many field experiments representing a variety of conditions, and grouping the data by u_* , so that the variability in wave age would arise primarily from variations in c_p . Their resultant relation,

$$z_o/H_s = 3.35(u_*/c_p)^{3.4},$$
 (4)

was found to fit their pure wind-sea, rough-flow, deepwater dataset quite well.

Taylor and Yelland (2001; hereinafter TY2001) proposed an alternative scaling for dimensionless roughness, one based on wave steepness. Using three datasets representing sea-state conditions ranging from strongly forced to shoaling, they found

$$z_o/H_s = 1200(H_s/L_p)^{4.5},$$
 (5)

where L_p represents the wavelength at the peak of the wave spectrum. The formula was found to well describe a variety of datasets, both field and laboratory, with the notable exception of very short fetch (or young wave age) field data. This scaling does not suffer from spurious correlation in u_* .

The two scalings yield rather different estimates of roughness in certain conditions, and our purpose here is to assess how each scaling performs in a range of sea states. To this end, we have assembled eight datasets of momentum flux and wave data. These data were collected from buoys (three datasets), towers (three), and ships (two), in environments ranging from the nearshore to the North Atlantic Ocean. In the following section, we will introduce the various datasets and discuss how the data are analyzed. In section 3, we will test the two models on each individual dataset, and on the data as a whole, with the goal of quantifying where each model does and does not predict the data. In the last section we discuss the successes and limitations of current sea-state parameterization efforts and indicate where planned experimental efforts might yield some exciting results.

2. Datasets

Each of the datasets used here includes measurements of wind stress and wave information. The characteristics of the datasets are summarized in Table 1. In seven of the datasets, wind stress is calculated using the "direct" or eddy-correlation (EC) method; in the eighth set, the inertial dissipation (ID) method is used. When the EC measurements are carried out from nonstationary platforms (ships or buoys), all degrees of motion of the platform are measured and used to correct the measured velocity time series. For the ID data, corrections are applied for anemometer response. None of the datasets have been corrected for possible flow distortion effects (Yelland et al. 1998), although these effects are not expected to be significant for these data. The datasets are described briefly below. Further details, including the motion correction and analysis procedures, are provided in the cited references.

For each dataset, the roughness z_o is calculated from u_* and neutral wind speed at a height of z m, U_{zN} , after assuming logarithmic profile shapes:

$$\frac{1}{\kappa} \log \frac{z}{z_o} = \frac{(U_{zN} - U_o)}{u_*}.$$
 (6)

Here, $u_* = (|\hat{\tau}|/\rho)^{1/2}$, where $\hat{\tau} = -\rho(\overline{u'w'\hat{i}} + \overline{v'w'\hat{j}})$ is the wind stress. We note here that while z_o is a scalar, $\hat{\tau}$ is a vector. The implications of this are discussed below. The stress $\hat{\tau}$ is calculated from the detrended turbulent velocity fluctuations, u', v', and w', respectively the horizontal inline with the wind, horizontal cross wind, and vertical components. The overbar represents an average over time periods of 17–30 min; ρ is the air density, and $\kappa = 0.4$ is the von Kármán constant. The surface drift speed, U_o , is typically small and is taken here to be zero. Neutral wind speeds are calculated from

$$U_{zN} = U_z + (u_*/\kappa)\psi_u(z/L) \tag{7}$$

using flux profile relations, ψ_{μ} , from Donelan (1990); L, the Obukhov length, is given by

$$L = -u_*^3 \Theta_{\nu} (\kappa g \overline{\theta_{\nu}' w'})^{-1}, \tag{8}$$

where Θ_v and θ'_v represent, respectively, the mean and turbulent components of virtual potential temperature. For the EC data used here, the buoyancy flux $\overline{\theta'_v w'}$ is estimated using a bulk parameterization with constant Dalton and Stanton numbers equal to 0.0012 (Smith, 1989). The algorithm for *L* is iterative, and nonconvergent points are removed from the dataset. Also, EC data for which $-\overline{u'w'} < 0$, representing upward momentum flux, are removed from the dataset, because *L* is not well defined in these cases (Drennan et al. 1999). For the ID data, *L* was calculated using a bulk formula approach to avoid the possibility of bias at low wind speeds (Taylor and Yelland 2000).

Unless stated otherwise, the wave information is in the form of directional wave spectra, calculated from surface elevation time series collected with an array of wave gauges, or (for the SWS2 experiment) from buoy accelerations. The spectra are used to determine the relevant wave parameters: H_s , L_p , c_p and the peak propagation direction. In addition, the directional spectra are partitioned into the components—wind sea and/ or swells—making up the wave field. Wind sea is defined as the component of the wave spectrum meeting the criteria $|\theta_d| < 45^\circ$, where θ_d is the angle between the mean wind-sea direction and that of the wind, and $U_{10N}\cos\theta_d > 0.83c_p$ (Donelan et al. 1985). At most, one wind sea can exist at any one time. All other wave components are classified as swell. Contrary to several other studies (including DGHO), we have, where possible, avoided the application of a roughness Reynolds number criterion. Lange et al. (2004) have recently shown that such a criterion can result in roughness lengths (and drag coefficients) that are biased high. The reason is that roughness length data taken under rough flow conditions, but which are biased low because of noise, may be falsely identified as smooth flow stress values and eliminated from the dataset. Conversely, data that have little noise or that are biased high are retained, thus causing a high bias in the mean estimate. In their analysis of the RASEX (see below) data, Johnson et al. (1998) applied a roughness Reynolds criterion; therefore, the RASEX roughness data at lower wind speeds are biased high (see below).

In the following analysis, we distinguish between two broad classes of sea state: wind sea-dominant (WSD) and swell-dominant (SD), depending on whether the majority of the wave energy is in the wind sea or swell. Drennan et al. (2003) considered a subclass of WSD cases, those where the wind-sea energy is much greater than the total swell energy. These very conservative criteria for "pure wind sea" (PWS) were chosen so as to avoid any possible influence of swell on the wave-age relationship. The datasets are described below and are summarized in Table 1.

a. Agile

For several months in each of the autumns of 1994 and 1995, an air-sea interaction experiment was conducted in the western basin of Lake Ontario (Donelan and Drennan 1995). The 15-m research vessel *Agile* was equipped to measure waves and turbulence on both sides of the air-water interface. Of interest here are stress measurements made using a Gill R2A three-axis sonic anemometer mounted on a bow mast at 7.8 m above mean water level (MWL). Wave data were collected from a bow-mounted wave staff array. The fetch for these data, collected while the vessel steered into the wind, varied from 2 to over 20 km.

The Agile dataset includes 101 runs of 20–25 min length. These data represent a wide range of wave ages and steepnesses. Eighty of the Agile runs met the WSD criteria, and many of these were strongly underdeveloped (fetch limited). In most of the SD runs the wind was light, and the wind sea was much less than the swell.

b. AWE

The Adverse Weather Experiment (AWE) was held off the coast of Fort Lauderdale, Florida, during April– May 2000. The goal of the experiment was to investigate the impact of a cold front on mixing, air–sea interaction, and sediment transport in the shallow-water column. The data considered here are from an Air–Sea Interaction Spar (ASIS; Graber et al. 2000) buoy moored several kilometers off the coast in 20 m of water. Wind stress is calculated using measurements from a Gill R2A sonic anemometer mounted on a mast 6.5 m above MWL. An array of wave staffs mounted around the buoy provided directional wave information.

The AWE data used here consists of 565 30-min runs. Most of the AWE data were collected in lightmoderate onshore winds, in either swell-dominated or mixed sea conditions. During most of the 335 WSD runs, waves were near full development.

c. FETCH

The FETCH (Flux, État de la Mer et Télédétection en Condition de Fetch Variable, or flux, sea state, and remote sensing in conditions of variable fetch) experiment took place in the Gulf of Lion in the Mediterranean Sea during March and April 1998. The data considered here are from an ASIS buoy moored 50 km offshore along the 100-m isobath. Estimates of wind stress were made using a Gill R2A sonic anemometer mounted on a mast 7 m above MWL (Drennan et al. 2003).

The FETCH dataset includes a wide variety of seastate conditions, ranging from strongly forced mistral events to light wind, swell-dominated seas. The dataset consists of 853 28.5-min runs, of which 323 are classified as WSD. (FETCH data were available on the ALBATROS or FETCH databases online at http:// dataserv.cetp.ipsl.fr.)

d. HEXOS

The Humidity Exchange over the Sea (HEXOS) experiment was carried out in 1986 from a tower in the North Sea, at 18-m depth. Here we use the HEXOS data published by Janssen (1997), averaging the stress and mean wind values from the pressure and sonic anemometers. These data, 50 runs, were selected by Janssen for pure wind sea.

e. RASEX

The Risø Air–Sea Exchange (RASEX) field campaign took place in 1994 at a shallow-water site (4-m depth) off Denmark. We use the RASEX dataset published by Johnson et al. (1998). Wind stress data were collected using a three-axis sonic anemometer mounted on a tower, 3 m above MWL. The mean wind data accompanying the stress data are not from the sonic anemometer, but from a cup anemometer located at 7 m. The tabulated data (80 runs) were selected by Johnson et al. to represent pure wind-sea conditions. However, since only one-dimensional wave spectra are available, the selection criteria are based on spectral width instead of the 2D directional properties used for the other datasets.

f. SWADE

The Surface Wave Dynamics Experiment (SWADE) took place in 1990/91 off the coast of Virginia. During SWADE, air-sea fluxes, wave spectra, and other parameters were measured from a 20-m swath ship (Donelan et al. 1997). Stress data were obtained from a K-Gill anemometer mounted on a bow tower at 12-m height; wave data were collected from a bow-mounted array. The SWADE dataset consists of 121 17-min runs. The sea state was mostly mixed, often with a strong swell component. The 43 wind sea–dominant runs are either at, or near, full development with a large variation in atmospheric stability.

g. SWS2

The Storm Wave Study second experiment (SWS2) took place in autumn 1997 off the coast of Newfoundland (Dobson et al. 1999). Wind measurements were made using a sonic anemometer at 5.75 m on a 6-m Nomad buoy. The friction velocity was calculated from the anemometer data using the inertial dissipation method with correction for anemometer response (Henjes et al. 1999) and bulk stability calculation (Taylor and Yelland 2000). The dataset consists of 1383 runs of 52-s duration, which have been quality controlled for buoy orientation and the spectral slope within the inertial subrange. The buoy was equipped with motion sensors, and these were used to estimate H_s and L_n . With H_s reaching 9 m, the SWS data include much higher seas than the other studies used here. The sea state during SWS2 was mixed, with wind sea and swell(s) of similar magnitudes. Such conditions are typical of the open ocean at high latitudes. Using wave data from a nearby Directional Wave Rider buoy, only 198 of the SWS2 runs are classified as wind sea-dominant.

h. WAVES

The Water–Air Vertical Exchange Study (WAVES) experiment was conducted over 3 yr, 1985–87, in the western basin of Lake Ontario (Donelan et al. 1999). The principal platform was a research tower located 1.1 km offshore, at 12-m depth. Wind stress measurements were made from a bivane anemometer on a mast at 12 m above MWL. Here we use the wind stress dataset from the 1987 WAVES field season (Drennan et al. 1999). The WAVES dataset used here includes 238 30-min runs, covering a wide range of sea states, from strongly forced, and fetch-limited, to swell dominated; 156 of the runs are classified as wind sea–dominated.

3. Tale of two models

The dimensionless roughness z_o/H_s of the 3391 data points are plotted in Fig. 1a against inverse wave age, u_*/c_p . The data are grouped into eight wave-age classes and averaged logarithmically in both roughness and in-



FIG. 1. Dimensionless roughness z_o/H_s vs (a) inverse wave age u_*/c_p and (b) significant steepness H_s/L_p for the combined dataset of 3391 points. In each panel, the data (excluding 25 points with $z_o/H_s < 10^{-9}$) are bin-averaged, with the bin means (logarithmic) indicated by circles. The error bars represent two standard errors about the mean. Also shown (solid lines) are the curves of Drennan et al. (2003) and Taylor and Yelland (2001) in (a) and (b), respectively.

verse wave age, with the group means and error bars showing two standard errors indicated on the plot. The DGHQ curve (4) is seen to describe well the younger sea states ($u_*/c_p > 0.05$). On the contrary, it is clear that the wave-age scaling will give very poor results with swell-dominated data (low u_*/c_p).

For comparison, we show in Fig. 1b the same data plotted using the wave steepness scaling: z_o/H_s versus H_s/L_p . The curve (5) proposed by TY2001 (solid line in Fig. 1b) predicts the mean behavior of the steeper waves but the data with lower steepness are poorly described. These latter data are mostly collected in the swell-dominated regime. Thus neither scaling is expected to give useful predictions in the swell-dominated regime.

We now restrict our dataset to WSD conditions (Fig. 2), using the criteria described above. Using the waveage scaling, the curve of DGHQ is seen to follow the data (1265 points) over most of the wave-age range (Fig. 2a). Also shown are the data averaged (logarithmically) in eight wave-age groups, showing two standard errors in both axes. Sixteen points with $z_o/H_s <$ 10^{-6} are considered as outliers, and omitted from the averages. There is no significant difference between the pure wind-sea data (darker dots, 659 points) and those where there is additional nondominant swell. Hence we conclude that the DGHQ wave-age relation applies equally well for WSD as for PWS cases. Although the performance of the wave-age model decreases somewhat for fully developed waves $(0.025 \le u_*/c_n \le 0.05)$, it has improved in comparison with the results shown by DGHQ. This is due to the inclusion of the smooth

flow data in the present analysis. If these data are excluded, as by DGHQ and others, the roughness in fully developed conditions is biased high.

In Fig. 2b, the same WSD data are plotted using the wave steepness scaling. The TY2001 curve (5) fits the averages well for most of the steepness range, although it is evident that z_o/H_s is significantly underestimated when $H_s/L_p < 0.02$. We therefore propose this as a threshold below which the steepness formulation should not be applied. This is discussed further below.

Comparing either Figs. 1a with 1b or Figs. 2a with 2b, it appears that z_o/H_s correlates better with wave age, u_*/c_p , than with significant steepness, H_s/L_p . However, this difference in part reflects the different effects of self correlation for the two scalings. For wave-age scaling, any spurious variations in u_* effect both dimensionless variables in a similar sense, improving the apparent correlation (see Lange et al. 2004). For steepness scaling, spurious variations of H_s have inverse effects on the dimensionless variables, degrading the correlation.

Although plots of dimensionless roughness are instructive, perhaps the more useful test of a roughness scaling is how it predicts the drag coefficient,

$$C_{10N} = |\hat{\tau}| / [\rho (U_{10N} - U_0)^2] = [u_* / (U_{10N} - U_0)]^2.$$
(9)

The drag coefficient is related to the roughness through (6). A comparison between measured and predicted C_{10N} has been made for each WSD dataset, with both scalings. The results are shown in Figs. 3 and 4. Here the PWS data are distinguished by black points. When



FIG. 2. Dimensionless roughness z_o/H_s vs (a) inverse wave age u_*/c_p and (b) significant steepness H_s/L_p for the combined WSD dataset (1265 points). The 659 darker points represent pure wind-sea conditions. In each panel, the data (excluding 16 points with $z_o/H_s < 10^{-6}$) are bin-averaged, with the bin means (logarithmic) indicated by circles. The error bars represent two standard errors about the mean. Also shown (solid lines) are the curves of Drennan et al. (2003) and Taylor and Yelland (2001) in (a) and (b), respectively, and the curve $H_s/L_p = 0.02$ (dashed).

applying the wave-age scaling, an iterative routine was used, starting from H_s , c_p , and the wind speed. In Fig. 5, the same comparison is made with C_{10N} calculated from the Smith (1980) bulk relation, $C_{10N} \times 1000 = 0.61 +$

 $0.063U_{10N}$. This provides a baseline against which to compare the two sea-state dependent models.

In Tables 2–5, we provide the number of samples, mean error, correlation coefficient, linear regression



FIG. 3. Measured 10-m neutral drag coefficients (\times 1000) vs those predicted using the Drennan et al. (2003) wave-age scaling (using wind-sea peak parameters) for dominant wind-sea conditions with eight datasets. The black points represent pure wind-sea conditions. The thick (thin) solid lines show the best linear fit (1:1 agreement). Dashed lines represent 90% confidence limits based on the sampling variability of each dataset.



FIG. 4. Measured 10-m neutral drag coefficients (\times 1000) vs those predicted using the Taylor and Yelland (2001) significant steepness scaling for dominant wind-sea conditions with eight datasets. The black points represent pure wind-sea conditions. The thick (thin) solid lines show the best linear fit (1:1 agreement). Dashed lines represent 90% confidence limits based on the sampling variability of each dataset.

coefficients (maximum likelihood, assuming equal uncertainty in the measured and predicted C_{10N} s), and the percentage of points falling within the expected range based on sampling variability. Model assessment is based on three statistics: a *t* test on the hypothesis (H1)

that the mean difference between predicted and measured C_{10N} is zero, a test (H2) that the regression line between measured and predicted values is near unity, and a test (H3) that the observed variability can be explained by the sampling variability. To carry out this



FIG. 5. Measured 10-m neutral drag coefficients (\times 1000) vs those predicted using the Smith (1980) bulk relation for dominant wind-sea conditions with eight datasets. The black points represent pure wind-sea conditions. The thick (thin) solid lines show the best linear fit (1:1 agreement). Dashed lines represent 90% confidence limits based on the sampling variability of each dataset.

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TABLE 2. Measured drag coefficients C_{10N} of WSD data compared with estimates from the wave-age model (Drennan et al. 2003). Error indicates two standard errors about the mean; P_{90} indicates actual percent of points within 90% confidence bands.

				1 1		
Data	Ν	Mean error	γ^2	Slope	Intercept	P_{90}
AGILE	80	-0.01 ± 0.06	0.65	0.81 ± 0.05	0.21 ± 0.09	0.88
AWE	335	-0.10 ± 0.02	0.28	0.33 ± 0.01	0.63 ± 0.01	0.87
FETCH	323	0.10 ± 0.03	0.56	1.08 ± 0.03	-0.03 ± 0.04	0.81
HEXOS	50	-0.13 ± 0.03	0.91	1.05 ± 0.03	-0.36 ± 0.05	0.90
RASEX	80	0.18 ± 0.09	0.29	10.08 ± 0.42	-12.94 ± 0.61	0.57
SWADE	43	-0.08 ± 0.10	0.14	0.08 ± 0.03	1.06 ± 0.05	0.93
SWS2	198	0.01 ± 0.03	0.68	0.89 ± 0.03	0.18 ± 0.07	0.93
WAVES	156	0.00 ± 0.06	0.39	0.72 ± 0.06	0.33 ± 0.12	0.77
All	1265	0.01 ± 0.02	0.63	1.01 ± 0.02	-0.06 ± 0.03	0.83

last test, we calculate confidence regions for the scatterplots and determine whether the fraction of points falling outside the region is consistent with the value expected based on sampling variability. Most data predictions show more variability than is predicted by H3. This is likely due to our underestimation of the variability in the model prediction. We consider H3 to be met if 80% or more of the points fall within the 90% confidence limits.

The 90% confidence regions for the EC datasets are calculated following Krogstad et al. (1999) where the sampling errors, ε , have been calculated for each experiment following Donelan (1990). Here,

$$\varepsilon = 9.2z^{1/2}(U\Upsilon)^{-1/2},\tag{10}$$

where Υ is the sampling time (s); *U* is taken as the mean wind speed for an experiment. The coefficient 9.2 in (10) takes into account the variability in -u'w' and U_{10N} . The variability in -u'w' was estimated from the AWE data during a 7-day period of exceptional stationarity. The resultant coefficient (7.7), 30% larger than that of Donelan (1990), was then multiplied by 1.2 to take into account the additional variability in C_{10N} due to wind speed. We assume similar errors for the predicted as for the measured C_{10N} s. The sampling errors in C_{10N} range from 12% for RASEX (z = 3 m, $\Upsilon = 1800$ s) to 33% for SWADE (12 m, 1020 s), with a mean of 21%. For the SWS2 data, calculated by ID, we assume an error equal to the mean sampling error for the EC data (21%). In Figs. 3–6, the 90% confidence regions appear as the areas between the dashed lines.

We first consider the u_*/c_p scaling (Fig. 3, Table 2). This scaling was developed using PWS subsets of the data from AGILE, FETCH, HEXOS, SWADE, and WAVES. Qualitatively, the scaling is seen to work well for the AGILE, FETCH, and SWS2 datasets and fairly well for HEXOS and WAVES. The RASEX data are poorly modeled by u_*/c_p scaling, with much higher variability predicted than was observed. This will be discussed below. Of the eight WSD datasets, H1 (mean difference) is met with AGILE, SWADE, SWS2, and WAVES, and also with the combined WSD dataset; H2 is met, with 90% confidence levels counting both the slope and intercept, for AGILE, FETCH, SWS2, WAVES, and the full WSD dataset; H3 is met at the 90% level with HEXOS, SWADE, and SWS2, and at the 80% level also with AGILE, AWE, FETCH, and the full WSD dataset.

For the most part there is little difference between the pure wind-sea data (black points) and those with additional (nondominant) swell (gray points). The only significant differences arise with the WAVES dataset: H3 is met at the 80% level for PWS data, but not WSD.

It should be emphasized that wind-sea peak parameters were used when applying the u_*/c_p model. For most WSD data above, these wind-sea parameters were also the overall peak parameters. However, for SWS2, this was frequently not the case. During SWS2, the sea state consisted of wind sea and swell of similar magni-

TABLE 3. Same as in Table 2, but compared with estimates from the wave steepness model (Taylor and Yelland 2001).

Data	Ν	Mean error	γ^2	Slope	Intercept	P_{90}
AGILE	80	-0.13 ± 0.07	0.51	0.24 ± 0.01	0.89 ± 0.02	0.74
AWE	335	0.01 ± 0.03	0.12	0.30 ± 0.02	0.78 ± 0.02	0.90
FETCH	323	0.30 ± 0.04	0.44	0.96 ± 0.03	0.33 ± 0.04	0.63
HEXOS	50	0.01 ± 0.03	0.93	0.88 ± 0.02	0.24 ± 0.03	1.00
RASEX	80	-0.09 ± 0.04	0.16	0.61 ± 0.04	0.42 ± 0.05	0.78
SWADE	43	0.24 ± 0.14	-0.16	-0.16 ± 0.06	1.80 ± 0.09	0.86
SWS2	198	0.12 ± 0.05	0.52	1.18 ± 0.06	-0.20 ± 0.12	0.81
WAVES	156	-0.02 ± 0.06	0.32	0.24 ± 0.03	1.08 ± 0.05	0.78
All	1265	0.09 ± 0.02	0.53	0.90 ± 0.02	0.18 ± 0.03	0.78

TABLE 4. Measured drag coefficients C_{10N} of data with $H_s/L_p > 0.02$ compared with estimates from the wave steepness model (Taylor and Yelland 2001). Error indicates two standard errors about the mean; P_{90} indicates actual percent of points within 90% confidence bands.

Data	Ν	Mean error	γ^2	Slope	Intercept	P_{90}
AGILE	84	-0.15 ± 0.07	0.46	0.22 ± 0.02	0.91 ± 0.03	0.71
AWE	329	0.06 ± 0.03	0.17	0.26 ± 0.01	0.87 ± 0.02	0.91
FETCH	544	0.35 ± 0.04	0.44	0.79 ± 0.02	0.56 ± 0.03	0.59
HEXOS	50	0.01 ± 0.03	0.93	0.88 ± 0.02	0.24 ± 0.03	1.00
RASEX	80	-0.09 ± 0.04	0.16	0.61 ± 0.04	0.42 ± 0.05	0.78
SWADE	77	0.11 ± 0.10	-0.18	-0.20 ± 0.04	1.83 ± 0.06	0.94
SWS2	539	0.21 ± 0.03	0.60	0.82 ± 0.02	0.51 ± 0.04	0.78
WAVES	190	0.13 ± 0.10	0.34	0.20 ± 0.02	1.13 ± 0.03	0.75
All	1893	0.18 ± 0.02	0.53	0.76 ± 0.01	0.47 ± 0.02	0.76

tudes. Given that swell fields tend to be more narrow (in frequency and direction) than wind seas, it was often observed that $E_{\text{swell}} < E_{\text{ws}}$ but $f_p = f_{p-\text{swell}}$. If the u_*/c_p scaling is applied with f_p instead of $f_{p-\text{windsea}}$, the model is seen to significantly underpredict C_{10N} (Fig. 6a).

We next apply the steepness scaling to the WSD datasets (Fig. 4, Table 3). This scaling was developed using the HEXOS and RASEX data together with data from Anctil and Donelan (1996), a subset of the WAVES database. Qualitatively, the steepness model is seen to perform well for the HEXOS and SWS2 data, and fairly well for AWE, FETCH, and RASEX. Quantitatively, H1 is met with the AWE, HEXOS, and WAVES datasets; H2 is met with HEXOS, SWS2, and with the full WSD dataset; H3 is met at 90% for two datasets (AWE and HEXOS), and at 80% also for SWADE and SWS2.

The H_s/L_p scaling was developed using the peak parameters—not necessarily those of the wind sea. In the case of the bimodal SWS2 data, use of the wind-sea parameters in the scaling results in a significant overprediction of C_{10N} (Fig. 6b). Since the steepness scaling does not rely on wind-sea parameters, there is no a priori need to restrict the scaling to WSD. In Figs. 1b and 2b, the H_s/L_p scaling is seen to perform best for $H_s/L_p \ge 0.02$. Such a simple criterion is more easily applied than the spectrally derived WSD. The H_s/L_p scaling predictions for each dataset with $H_s/L_p \ge 0.02$ are given in Table 4. For four of the datasets, essentially the same data are selected by the WSD and $H_s/L_p \ge$

0.02 criteria. However for FETCH, SWADE, and especially SWS2 the latter criterion has the advantage of selecting a significantly larger number of points than the former. The steepness scaling predictions of this new SWS2 data subset are shown in Fig. 6c. Although the mean errors are somewhat higher with the steepness cutoff criterion, the correlation coefficients, slopes and P_{90} statistics remain similar for most datasets. Hence the steepness model can be applied in both WSD and the more general "mixed sea" conditions. For the most part seas with $H_s/L_p < 0.02$ are dominated by swells (although 6% of the WSD cases fell below the threshold).

Last, we compare the two sea-state formulas with the simple bulk relation of Smith (1980). The results for the WSD data are shown in Fig. 5, and Table 5. Qualitatively, the bulk relation is seem to perform reasonably well for the RASEX data. However, typical for bulk relations, much less variability is predicted than is present in the data. This is not unexpected, as the sampling variability of mean wind speed (on which bulk estimates are based) is much less than that of momentum flux. Hypothesis H1 is met with two datasets (AWE and SWADE), and nearly met with FETCH. Test H2 (slope) is met only with RASEX. Test H3 is met at the 90% level with AWE and SWADE and at the 80% level with FETCH, SWS2, and the full WSD dataset. The results of the bulk formulation applied to the data with $H_s/L_p \ge 0.02$ are similar, and not shown here.

TABLE 5. Measured drag coefficients C_{10N} of WSD data compared with estimates from the Smith (1980) bulk model. Error indicates two standard errors about the mean; P_{90} indicates actual percent of points within 90% confidence bands.

Data	Ν	Mean error	γ^2	Slope	Intercept	P_{90}
AGILE	80	-0.19 ± 0.05	0.69	0.26 ± 0.01	0.79 ± 0.01	0.76
AWE	335	-0.01 ± 0.02	0.54	0.19 ± 0.00	0.89 ± 0.00	0.96
FETCH	323	0.05 ± 0.03	0.60	0.40 ± 0.01	0.79 ± 0.01	0.85
HEXOS	50	-0.22 ± 0.03	0.87	0.40 ± 0.01	0.71 ± 0.01	0.70
RASEX	80	-0.13 ± 0.04	0.14	0.67 ± 0.04	0.27 ± 0.06	0.69
SWADE	43	-0.07 ± 0.09	0.60	0.14 ± 0.01	0.99 ± 0.01	0.93
SWS2	198	-0.11 ± 0.03	0.73	0.43 ± 0.01	0.80 ± 0.02	0.87
WAVES	156	-0.22 ± 0.05	0.10	0.03 ± 0.01	1.09 ± 0.01	0.58
All	1265	-0.06 ± 0.01	0.59	0.35 ± 0.00	0.76 ± 0.01	0.83



FIG. 6. Measured vs predicted 10-m neutral drag coefficients (×1000) for the SWS2 WSD dataset. (a) Prediction is via the Drennan et al. (2003) wave-age formulation using the peak frequency (not the peak wind-sea frequency). (b) Prediction is via the Taylor and Yelland (2001) significant steepness scaling using the peak wind-sea frequency (not the peak frequency). These two panels demonstrate the importance of using the correct peak parameters in applying the models. (c) Steepness formulation is again used, this time with the data selected using the criterion $H_s/L_p > 0.02$, instead of the spectral WSD.

Among the wind-sea datasets, RASEX is particularly poorly modeled by the wave-age scaling. Also, the low wind RASEX data are not predicted by steepness scaling. The RASEX data of Johnson et al. (1998) have been the subject of some controversy for several reasons. One relates to the fluxes and mean winds having been measured at different elevations. TY2001 exclude all RASEX data for wind speeds below 10 m s⁻¹ because of the possibility of noise contamination, and also because only the higher wind data agree with the results of Vickers and Mahrt (1997) using data from a different anemometer during the same experiment. Recently Lange et al. (2004) have suggested that the use of the roughness Reynolds number criterion caused a spurious trend in the Johnson et al. (1998) data. Thus for wind speeds above about 10 m s^{-1} the Vickers and Mahrt (1997) mean values were at or above the Reynolds number cutoff, but for lower wind speeds data around their mean values would have been eliminated by Johnson et al. Thus the Johnson et al. data below 10 m s^{-1} are biased significantly high. These data points are those appearing below the scatter limits in the RASEX plots of Figs. 3-5. Excluding these data the steepness scaling adequately describes the RASEX data. In contrast fully 90% of the high-wind RASEX data fall outside the 90% confidence range of the waveage scaling: the u_*/c_p scaling predicts much higher values of C_{10N} than were measured. Unfortunately, no directional wave spectra are available for these data, and the classification of wind sea was made using a wave spectral bandwidth parameter (a second point of controversy). Johnson et al. (1998) point out the relatively high wave spectral width in the RASEX data, and also that clear two-peaked behavior was seen in some cases. It is not clear that the criteria used by Johnson et al. to select the data were sufficient to exclude swell contaminated (or dominated) cases. Whether swell, and effects of shallow water, could significantly alter the roughness from the expected wind-sea values remains a point of debate among the present authors.

We next consider the swell-dominated data (Fig. 7). Here we do not distinguish between the various datasets, because the results are similar for all six (RASEX and HEXOS have no swell data). As could be predicted from Fig. 1, both the wave-age and steepness formulations significantly underpredict the roughness (and C_{10N}) in swell-dominated conditions where $H_s/L_p < 0.02$. The bulk formulation, on the other hand, predicts the mean C_{10N} for these data quite well, although the bias noted above is very evident: high/low measured C_{10N} are under/over estimated. The mean behavior of the data is fairly well recovered, but the variability is missed.

For swell-dominated conditions where $H_s/L_p > 0.02$, the steepness formulation does well in comparison with the other two (Fig. 7, gray points). Indeed the distinction between swell and wind sea is less relevant with the steepness formulation than the cutoff based on steepness alone.

4. Discussion and conclusions

We have tested the wave-age model of Drennan et al. (2003) and the wave steepness model of Taylor and Yelland (2001) against eight datasets collected in a variety of conditions. To summarize, no formulation is able to model all WSD datasets. However, both seastate parameterizations were seen to do significantly better than the Smith (or other) bulk formula for most WSD datasets. Comparing the two sea-state parameterizations, the wave-age formula performed better with the more strongly forced field data (AGILE, FETCH, and to a lesser degree, WAVES). This is also evident in



FIG. 7. Measured 10-m neutral drag coefficients (×1000) vs those predicted for swell-dominated conditions. The models used are (a) wave age, (b) steepness, and (c) the Smith (1980) bulk relation. The dark points represent the subset of points with $H_s/L_p < 0.02$. Note that many of the lighter points lie behind the dark ones.

Fig. 2: roughness estimated using the u_*/c_p formula agree well with the data for the youngest waves ($u_*/c_p > 0.05$), whereas roughness predicted by the steepness formula is below the median value for the steepest waves.

On the other hand, the steepness formula better predicts the RASEX and HEXOS data, and also the near fully developed AWE data. In addition, the steepness formula was seen to be well suited to mixed sea conditions, with dominant swell ($H_s/L_p > 0.02$). It should be noted that both sea-state parameterizations perform better on the datasets that were used in their development (AGILE, FETCH, HEXOS, SWADE, and WAVES for the wave-age formula and HEXOS and RASEX for the steepness formula). Presently, we do not fully understand why the performance of the different formula varies in cases such as AGILE, RASEX, and HEXOS. Hence the user should be aware that significant errors in roughness length estimation are possible in limited fetch conditions.

Up to this point, we have evaluated the roughness parameterizations on their ability to predict individual data points. Often, however, one is more interested in the average momentum flux over time scales of weeks or months. Hence, we investigate the ability of the parameterizations to predict the mean observed C_{10N} versus wind speed relation for each experiment. In Fig. 8, the mean curves are shown for WSD. For the SWS2 panel alone, the steepness criterion ($H_s/L_p > 0.02$) is used to select the data for all but the wave-age curve.

Using this method of comparison the Smith (1980) formula generally appears better than in the previous results. In addition to AWE, the data for FETCH follow the Smith relationship for most wind speeds above 8 m s⁻¹. If it is accepted that the RASEX data below 10 m s⁻¹ are biased, then the Smith relationship holds for this experiment too (as confirmed by the Vickers and Mahrt 1997 analysis). Much of the SWADE ($U_{10} < 10$

m s⁻¹) and SWS2 data ($U_{10} < 12$ m s⁻¹) also follow the Smith relationship. However it remains the case that, for several datasets [AGILE, HEXOS, RASEX, SWS2 ($U_{10} > 12$ m s⁻¹), and WAVES] the Smith relationship significantly under predicts the observed roughness.

Based on this method, the two sea-state-based formulas perform with similar success for AWE and WAVES. The wave-age formula also performs well for AGILE, FETCH, SWADE, and SWS2. The two failures for this scaling are HEXOS, for which the roughness at the lower wind speeds is underpredicted, and RASEX, where much higher roughness is predicted than that observed. In these two experiments very different roughness values occurred at similar wave ages. It is a strength of the steepness formula that it can predict the roughness variations found during both RASEX and HEXOS. However, this formula overpredicts the roughness observed during FETCH, SWADE, and SWS2 (for $U_{10} < 15 \text{ m s}^{-1}$) and under-predicts the AGILE data. The poor performance for SWS2 contrasts with the apparently good predictions shown by Taylor and Yelland (2001). The difference is caused by the application of the $H_s/L_p > 0.02$ criterion in the present study.

In Fig. 9, all data are combined. To test the scalings on the same data, Fig. 9a shows WSD data with H_s/L_p > 0.02; Fig. 9b shows swell-dominant data with H_s/L_p < 0.02. For WSD data, the two sea-state models give similar mean curves for most of the wind speed range, except for $U < 8 \text{ ms}^{-1}$, where the steepness model is closer to the data. Either sea-state model is preferred to Smith for WSD data. For the swell-dominated data, neither sea-state model does well, and Smith (1980) provides the best fit to the mean C_{10N} curve.

The poor performance of both scalings on swell data would indicate that sea-state parameters (steepness or wave age) based on swell components do not offer use-



FIG. 8. Mean 10-m neutral drag coefficients vs wind speed for dominant wind-sea conditions with eight datasets. The curves represent data (dotted) and predictions using Drennan et al. (2003) wave-age formula (thick), Taylor and Yelland (2001) wave steepness formula (dashed), and Smith (1980) (thin).

ful first-order information on air-sea fluxes. The largescale swells may dominate the sea surface, but to firstorder it is the smaller-scale wind-driven waves which determine the air-sea fluxes. That said, swell waves have been observed to significantly modify the air-sea transfers (e.g., Volkov 1970). Donelan et al. (1997) reported a doubling of $C_{\rm DN}$ over pure wind-sea values with strong swells running against the wind, while Drennan et al. (1999), Grachev and Fairall (2001) and others have observed a similarly strong reduction of $C_{\rm DN}$ in strong following swells. Clearly any extension of the sea-state models to include swell must account for not only the magnitude, but also the direction of the swell waves.



FIG. 9. Mean 10-m neutral drag coefficients (×1000) vs wind speed for (a) WSD conditions with $H_s/L_p > 0.02$ and (b) swell dominant with $H_s/L_p < 0.02$. The curves represent data (dotted) and predictions using Drennan et al. (2003) wave-age formula (thick), Taylor and Yelland (2001) wave steepness formula (dashed), and Smith (1980) (thin). Error bars show two standard errors.

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As pointed out above, the wind stress is a vector quantity. It is generally assumed that the wind stress vector is aligned with the mean wind, in which case $-\overline{v'w'} \approx 0$. This is the case over land, but stress measurements over the sea sometimes indicate departures from this. Zemba and Friehe (1987) and Geernaert et al. (1993) associated their findings of noncolinear stress and wind with the presence of a coastal jet and swell waves, respectively. Grachev et al. (2003) found the stress vector to lie between the wind and swell directions. Their assumption that the wind stress vector lies in the mean wind direction for pure wind sea is consistent with the findings of Drennan et al. (1999).

In addition to steering the stress direction, dominant swell has also been reported to modify the logarithmic wind profile shape (Donelan 1990). This would invalidate our use of profile functions (6) and (7) in calculating the roughness in these conditions. In contrast, Edson and Fairall (1998) found support for the logarithmic profiles in typical mixed sea conditions. Hence our approach should be valid in pure wind-sea and mixed sea conditions where it is claimed to apply.

As existing results on swell effects on stress are largely qualitative, it is not yet possible to account for them in roughness models such as those described here. Recently there has been a renewed interest in quantifying for the effects of swell on drag coefficient parameterizations. Several new experimental campaigns with these goals in mind are underway. Although we cannot yet claim complete success in efforts to model roughness over the sea, much progress has been made in recent years. It is hoped that the coming experiments will yield sufficient data to address the outstanding issues.

A further point of investigation should be to extend the study of flow distortion effects on flux measurements. These have been quantified for flux data obtained using the ID method on ships (Yelland et al. 1998, 2002; Dupuis et al. 2003), and Oost et al. (1994) quantified the effects of the flow around the instrumented boom on the EC fluxes obtained during HEXOS. In contrast, the effect of turbulent flow distortion around ships or other sizable platforms on EC fluxes has not been quantified.

In the meantime, what formula would we recommend? Much depends on what wave data are available. If no wave data are available, then one is forced to use a bulk formula such as Smith (1980), but one should be aware that the roughness is likely to be underestimated under strongly forced conditions. In passing, we note that this underestimation would be worse for the relationship proposed by Smith (1988), and hence we favor the earlier paper. If spectral wave data are available then the wave-age-based formula was both developed from and better fitted a larger number of the datasets. But this success is dependent on having knowledge of wind-sea parameters (or otherwise that the sea state is wind sea-dominated). If only bulk sea-state properties are available (such as H_s and L_p) then the steepness formula was more robust for cases of mixed wind sea and swell, and for swell dominant conditions with H_s/L_p > 0.02. However, where the swell is dominant (with $H_s/L_p < 0.02$) then the Smith (1980) formula should be used.

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