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Wave-Dependence of Friction Velocity, Roughness Length, and Drag Coefficient over Coastal and Open Water Surfaces by Using Three Databases

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ABSTRACT

The parameterization of friction velocity, roughness length, and the drag coefficient over coastal zones and open water surfaces enables us to better understand the physical processes of air-water interaction. In context of measurements from the Humidity Exchange over the Sea Main Experiment (HEXMAX), we recently proposed wave-parameter dependent approaches to sea surface friction velocity and the aerodynamic roughness by using the dimensional analysis method. To extend the application of these approaches to a range of natural surface conditions, the present study is to assess this approach by using both coastal shallow (RASEX) and open water surface measurements (Lake Ontario and Grand Banks ERS-1 SAR) where wind speeds were greater than 6.44 m s^{-1}. Friction velocities, the surface aerodynamic roughness, and the neutral drag coefficient estimated by these approaches under moderate wind conditions were compared with the measurements mentioned above. Results showed that the coefficients in these approaches for coastal shallow water surface differ from those for open water surfaces, and that the aerodynamic roughness length in terms of wave age or significant wave height should be treated differently for coastal shallow and open water surfaces.

Key words: sea surface roughness, wave parameter, friction velocity, parameterization

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1. Introduction

Quantitative understanding of the sea surface aerodynamic roughness length is of great importance in the study of air-sea interaction and thus in the study of the global energy and water cycles (Zeng et al., 1998). Since Charnock (1955) proposed the earliest work, there has been increasing interest in the sea surface aerodynamic roughness parameterization by taking into account both wind speed and wave parameters (e.g., Toba, 1972; Toba and Koga, 1986; Smith et al., 1992; Yelland and Taylor, 1996; Taylor and Yelland, 2001; Oost and Oost, 2004; and Drennan et al., 2005). We recently investigated the dependence of sea surface roughness on the wave parameters by using measurements from the Humidity Exchange over the Sea Main Experiment (HEXMAX) (Gao et al., 2006). The new findings include the below relationships

$$u_* = aU_{10\mathrm{N}}^{4/3}/c_p^{1/3} , \tag{1}$$

$$z_0 = 10\exp\left[-\frac{k}{a}(c_p/U_{10\mathrm{N}})^{1/3}\right] , \tag{2}$$

and

$$C_{\mathrm{DN}} = u_*^2/U_{10\mathrm{N}}^2 = a^2(c_p/U_{10\mathrm{N}})^{-2/3} , \tag{3}$$

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where u_* is the friction velocity, $U_{10\mathrm{N}}$ is the neutral 10-m wind speed, c_p is the phase velocity, a is the derived empirical constant, k is the von Karman constant (taken as 0.4), z_0 is the aerodynamic roughness length, and C_{DN} is the neutral drag coefficient. The advantage of these equations is that they enable us to directly parameterize the friction velocity (u_*), the aerodynamic roughness length (z_0), and the neutral drag coefficient (C_{DN}) by using the neutral 10-m wind speed ($U_{10\mathrm{N}}$) and the phase velocity (c_p), unlike previous work where the friction velocity (u_*) was usually necessary in the parameterization of the aerodynamic roughness length (z_0) and the neutral drag coefficient (C_{DN}). Using u_* to parameterize the roughness length will take a lot of computing time when the parameterization formula is used in regional models because the iteration is needed for all grid nodes of the lowest level of the atmospheric model at all time steps, it is especially true for the high resolution simulations over a large region.

The parameterization equations derived by Gao et al. (2006) are only based on the Humidity Exchange over the Sea Main Experiment (HEXMAX) database and therefore further testing is needed. Our purpose here is to assess how these relationships perform in coastal and open water surfaces.

2. The datasets

The data collected during RASEX, Lake Ontario, and the Grand Banks ERS-1 SAR wave spectra validation experiments are used in the present study for the purpose mentioned above. Only brief outlines will be given here.

Database 1. The RASEX database was published by Johnson et al. (1998). The full RASEX instrumentation was described in Barthelmie et al. (1994) and Højstrup et al. (1997). RASEX field campaigns were described in detail by Johnson et al. (1998, 1999), and Taylor and Yelland (2001). The data were collected at a tower in spring and fall campaigns in 1994. This tower was situated at a 48-m open water wind turbine site in Denmark, where the water depth was about 4 m and the upstream fetch was about 15–20 km in a 90-degree sector with upstream water depths of 5–20 m, so the water depth was shallow at this coastal site. The values of u_* were determined by using the sonic data collected by the lowest sonic anemometer (Solent, 3-component research type) mounted 3 m above mean sea level. Data were logged as 30-min time series sampled at 20 Hz.

Database 2. The database of the Lake Ontario experiments was published by Anctil and Donelan (1996). The permanent research tower of the Canadian Centre for Inland Water (CCIW) is positioned in the water where the depth is of about 12 m, 1.1 km offshore at the west end of Lake Ontario, near Hamilton. The data were collected from four meteorological towers in nominal water depths of 2, 4, 8, and 12 m during two wind events.

Database 3. The database of the Grand Banks ERS-1 SAR wave spectra validation experiments (hereinafter ERS-1 SAR for convenience) was published by Dobson et al. (1994). During these experiments, wind, wind stress, and directional wave spectra were measured. This site was in the open ocean in the presence of swell.

The RASEX site represents a coastal shallow zone, the Lake Ontario site represents lake surfaces, and the ERS-1 SAR site represents the open ocean in the presence of swell.

Similar to Gao et al. (2006), we reproduced the variations of friction velocity (u_*), phase velocity (c_p), significant wave height (H_{s}), and the wave age parameter (c_p/u_*) against the neutral wind speed at 10 m ($U_{10\mathrm{N}}$) in Fig. 1. We did not reproduce the variations of the neutral drag coefficient ($C_{\mathrm{DN}} \equiv u_*^2/U_{10\mathrm{N}}$) and wave age parameter ($c_p/U_{10\mathrm{N}}$) against the neutral wind speed at 10 m ($U_{10\mathrm{N}}$), because of a potential spurious correlation in $U_{10\mathrm{N}}$. We only considered the situation that $U_{10\mathrm{N}}$ was higher than 6.44 m s^{-1}, because the minimum value of $U_{10\mathrm{N}}$ at the Lake Ontario site was 6.44 m s^{-1}. Therefore, the present research represents the situation of the moderate to strong wind regime only. To compare to our previous work, we reproduced the HEXMAX data in Fig. 1.

It is obvious that (1) u_* increased with an increasing $U_{10\mathrm{N}}$. The averaged correlation coefficients between u_* and $U_{10\mathrm{N}}$ is 0.98 for all the sites. (2) c_p had no obvious variation with an increasing $U_{10\mathrm{N}}$ for both the RASEX and HEXMAX sites, but increased with an increasing $U_{10\mathrm{N}}$ for the ERS-1 SAR site owing to the presence of swell. More scattered distributions in c_p are found for both the ERS-1 SAR and Lake Ontario sites. We estimated that it was caused by the swells. (3) H_{s} increased with an increasing $U_{10\mathrm{N}}$ for all the sites, and it was especially true for the HEXMAX, Lake Ontario, and ERS-1 SAR sites, all of which were more than 1 km offshore. (4) Wave age scaled by the friction velocity (c_p/u_*) decreased with an increasing $U_{10\mathrm{N}}$ in Fig. 1d.

Figures 1b and 1c show that the phase velocity (c_p) and significant wave height (H_{s}) at the HEXMAX site is significantly higher than those at RASEX when $U_{10\mathrm{N}}$ is determined, although Fig. 1a shows that the variation trends of u_* with $U_{10\mathrm{N}}$ are basically consistent for the four sites, which means that the aerodynamic roughness lengths are identical for the four sites when

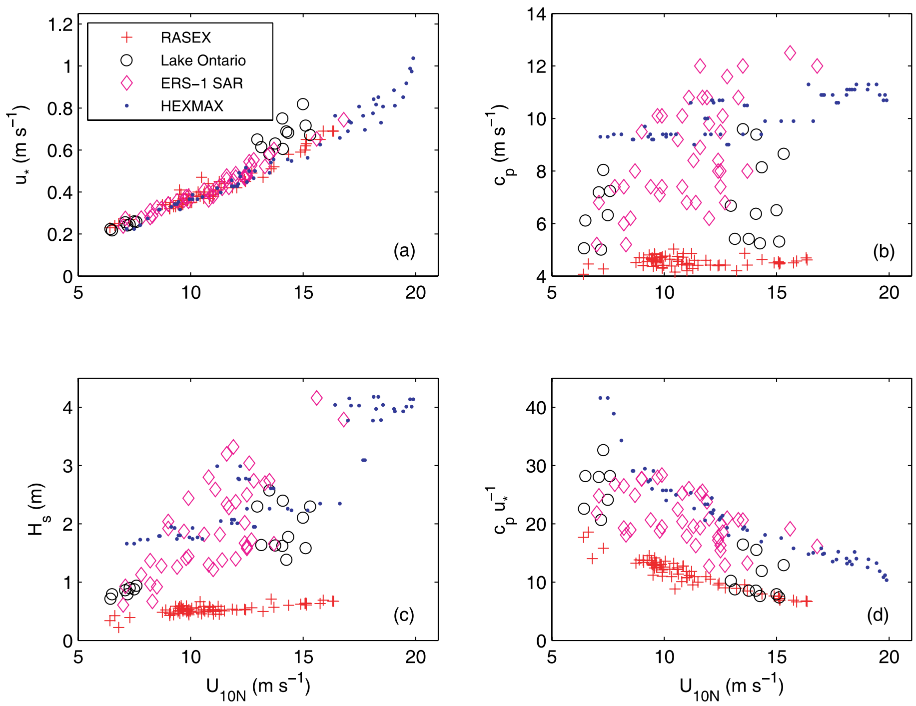

Fig. 1. Data from the experiments: RASEX (Johnson et al., 1998), HEXMAX (Janssen, 1997), Lake Ontario (Anctil and Donelan, 1996), and ERS-1 SAR (Dobson et al., 1994) plotted against the neutral 10-m wind speed, $U_{10\mathrm{N}}$. (a) friction velocity, u_* (m s^{-1}); (b) phase speed at the peak of the wave spectrum, c_p(m s^{-1}); (c) significant wave height H_s (m); and (d) wave age in terms of u_*, c_p/u_*.

$U_{10\mathrm{N}}$ is determined. To make it clearer and curtail possible arguments, we carefully pointed out that the trend lines of the two distributions of u_* for the RASEX and HEXMAX sites intersect. At the point of intersection, $U_{10\mathrm{N}}$ and u_* for the RASEX site are the same as those for the HEXMAX site, respectively. Meanwhile, Eq. (4) implies that an identical $U_{10\mathrm{N}}$ and u_* lead to an identical z_0. Figures 1a, 1b, and 1c show that the properties (H_s and c_p) of the wave field at the coastal RASEX site differ from those at the open water HEXMAX site when the atmospheric condition is determined (i.e., $U_{10\mathrm{N}}$ and u_* are given). Figures 1a and 1d show us a problem: how to obtain identical z_0 using different wave ages collected respectively at the RASEX and HEXMAX sites? Figures 1a and 1d suggest that no single formula of z_0 in terms of only wave age fits both the RASEX and HEXMAX datasets well.

$$u_* = \frac{kU_{10\mathrm{N}}}{\ln(10/z_0)} \,. \tag{4}$$

3. Results and discussion

3.1 *Significant wave height* (H_s) *vs. wave age* (c_p/u_*)

Assuming the linear dispersion relation for wind-wave around the spectral peak, the nondimensional period (T^*) can be directly related to the wave age parameter, c_p/u_*, by the equation $T^* = 2\pi c_p/u_*$. The relationship between the significant wave height (H_s) and the wave age (c_p/u_*), for a steady wind of some duration, satisfies a conspicuous similarity law that can be expressed as

$$H_\mathrm{s} = Bu_*^2(2\pi c_p/u_*)^{3/2}/g \tag{5}$$

where B is an empirical constant (Jones and Toba, 2001).

Gao et al. (2006) tested Eq. (5) by using regression analysis on data collected at the HEXMAX site. The results showed that $B = 0.071$ and the corresponding correlation coefficient: $r = 0.97$. Here, we tested Eq. (5) by using regression analysis on the data collected at the three sites. The results showed that $B = 0.053$, $B = 0.073$, and $B = 0.069$ for the RASEX, Lake Ontario, and ERS-1 SAR databases, respectively, as shown in Fig. 2, with corresponding correlation coefficients: $r = 0.93$, $r = 0.87$, and $r = 0.95$, respectively. These values of B are within the result ($B = 0.062 \pm 20\%$) determined by Toba (1972). Our analyses above show that all of the four databases satisfy the 3/2-power law that was first derived by Toba (1972), who, with his experimental data, eliminated the nondimensional fetch from the complicated empirical formulas for the growth of wind waves given by Wilson (1965).

3.2 *Dimensionless* $u_*(gT_\mathrm{p})^{-1}$ *vs. dimensionless* $U_{10\mathrm{N}}^2(gH_\mathrm{s})^{-1}$

Linear relationships between $u_*(gT_\mathrm{p})^{-1}$ and $U_{10\mathrm{N}}^2(gH_\mathrm{s})^{-1}$ are found by Gao et al. (2006) for the HEXMAX database as follows.

$$u_*(gT_\mathrm{p})^{-1} = a_1 U_{10\mathrm{N}}^2(gH_\mathrm{s})^{-1}, \quad (6)$$

where a_1 is the proportional coefficient, and $a_1 = 1.19 \times 10^{-3}$ is regressed for the HEXMAX site. Here, we plotted the results for the three sites mentioned above in Fig. 3, and we found that $a_1 = 1.11 \times 10^{-3}$, and $a_1 = 1.40 \times 10^{-3}$ for the ERS-1 SAR and Lake Ontario sites, respectively, whereas $a_1 = 5.60 \times 10^{-4}$ for the RASEX site. It is obvious that the distributions for the open water surface sites (HEXMAX, Lake Ontario, and ERS-1 SAR) are close to each other and a_1 ranges from 1.11×10^{-3} to 1.19×10^{-3}, however, the distribution for the shallow and coastal water surface site (RASEX) differs significantly from those open water sites and a_1 is just half of that at the open water sites.

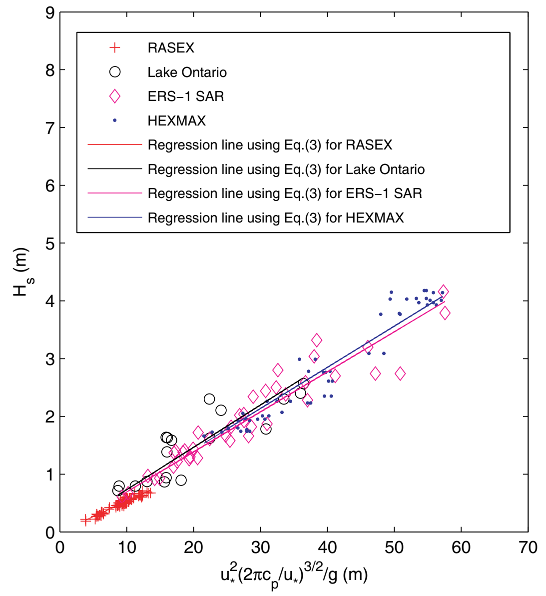

Fig. 2. The 3/2-power law expressed by Eq. (5) for all four databases.

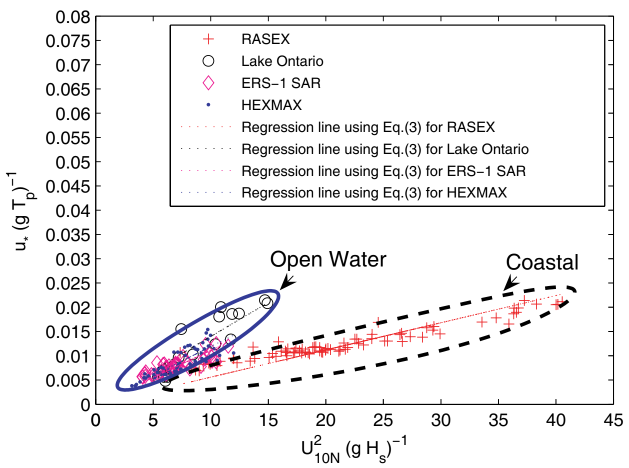

Fig. 3. Dimensionless $u_*(gT_\mathrm{p})^{-1}$ as a function of dimensionless $U_{10\mathrm{N}}^2(gH_\mathrm{s})^{-1}$ for all four databases.

3.3 *Parameterization of* u_**,* z_0*, and* C_{DN} *by using wave age for coastal and open water surfaces*

Let $a = (a_1/\sqrt{2\pi}B)^{2/3}$ where a is a coefficient. Incorporating Eq. (6) into Eq. (5) to eliminate H_s gives Eq. (1). On the other hand, they limited the analysis to an equivalent neutral wind, and the wind profile is as in Eq. (4) following the Monin-Obukhov similarity theory. Combining Eqs. (4) and (1) to eliminate u_* gives Eq. (2). The neutral drag coefficient ($C_{\mathrm{DN}} = u_*^2/U_{10\mathrm{N}}$) can be consequently expressed as Eq. (3) (Gao et al., 2006).

A scatterplot of u_* directly measured at these four sites against $U_{10\mathrm{N}}^{3/4}c_p^{-1/3}$ is given in Fig. 4. It is found that $a = 3.67 \times 10^{-2}$ for the Lake Ontario site and this value is the same as that for HEXMAX, and $a = 3.57 \times 10^{-2}$ for the ERS-1 SAR site, respectively, whereas $a = 2.80 \times 10^{-2}$ for the RASEX site. It is obvious that the distributions for the open water surface sites (HEXMAX, Lake Ontario, and ERS-1 SAR) are close to each other and $a = (3.62 \pm 2\%) \times 10^{-2}$, however, the distribution for the shallow and coastal

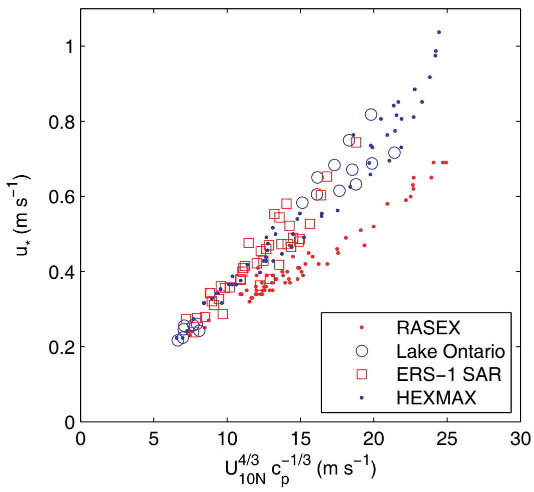

Fig. 4. Friction velocity u_* as a function of $U_{10\mathrm{N}}^{4/3}(c_p)^{-1/3}$ for all four databases.

water surface site (RASEX) differs significantly from those open water sites. We therefore revise Eqs. (1–3) to be

$$\begin{cases} u_* = 0.0362 \times U_{10N}^{4/3}/c_p^{1/3} & \text{(Offshore)}\,, \\ u_* = 0.0280 \times U_{10N}^{4/3}/c_p^{1/3} & \text{(Coastal)}\,, \end{cases} \quad (1')$$

$$\begin{cases} z_0 = 10\exp\left[-\frac{k}{0.0362}(c_p/U_{10N})^{1/3}\right] & \text{(Offshore)} \\ z_0 = 10\exp\left[-\frac{k}{0.0280}(c_p/U_{10N})^{1/3}\right] & \text{(Coastal)}\,, \end{cases} \quad (2')$$

and

$$\begin{cases} C_{DN} = u_*^2/U_{10N}^2 = 1.31 \times 10^{-3}(c_p/U_{10N})^{-2/3} \\ \text{(Offshore)}\,, \\ C_{DN} = u_*^2/U_{10N}^2 = 0.78 \times 10^{-3}(c_p/U_{10N})^{-2/3} \\ \text{(Coastal)}\,. \end{cases} \quad (3')$$

A scatterplot of u_* calculated by using direct regression analyses on Eq. (1) against a direct measurement is given in Fig. 5. The corresponding correlation coefficient is $r = 0.97$.

We consider the values of z_0 derived from $z_0 = 10\exp(-kU_{10N}/u_*)$ as direct measurements where the directly measured U_{10N} and u_* are used. Figure 6 shows the variation of z_0 against c_p/U_{10N} for both the direct measurements and Eq. (2'), respectively and for both the coastal and open water sites. We find that z_0 decreases with an increasing wave age (c_p/U_{10N}). We obtain the variation of C_{DN} with c_p/U_{10N} obtained from Eq. (3') for both the coastal and open water sites as shown in Fig. 7 where the direct measurements are also plotted for comparison. It is found that the distributions of measured data are very scattered in both Figs. 6 and 7. The reasons are mainly (1) that the interaction of sea waves with the atmospheric boundary layer is physically a complicated phenomenon and our approach relationship cannot properly describe every physical process; and (2) that we used three experimental databases for open water analysis, and the difference of the site's nature, such as water depths, creates more complexities and uncertainties.

Meanwhile, combining Eqs. (4) and (1′) to eliminate U_{10N} gives Eq. (2"). The neutral drag coefficient ($C_{DN} \equiv u_*^2/U_{10N}$) can be consequently expressed as

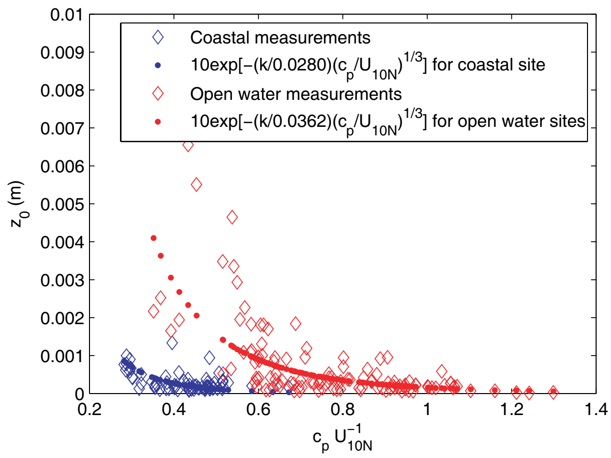

Fig. 6. Variation of the aerodynamic roughness length z_0 against wave age c_p/U_{10N} for both the coastal and open water sites.

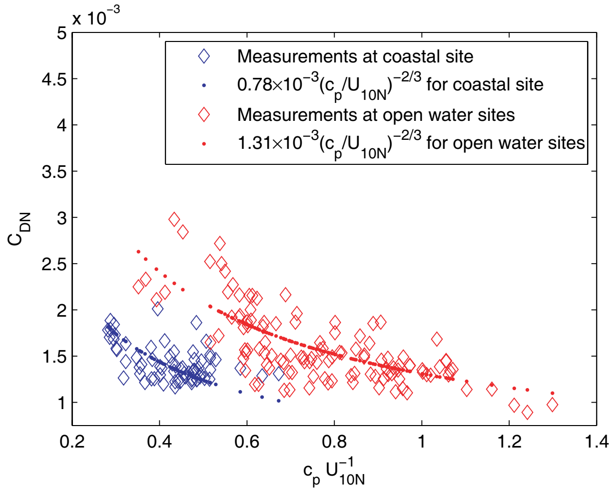

Fig. 7. Variation of the neutral drag coefficient C_{DN} against wave age c_p/U_{10N} for both the coastal and open water sites.

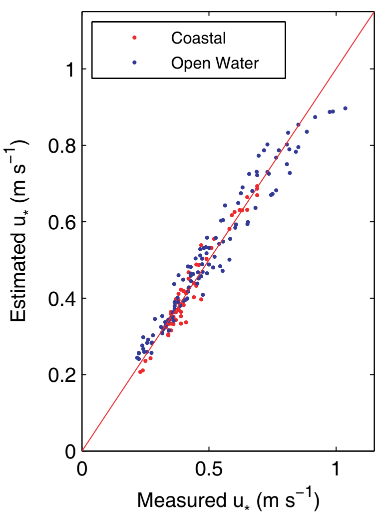

Fig. 5. Scatterplots of u_* estimated by using Eq. (1) against direct measurements for all four databases.

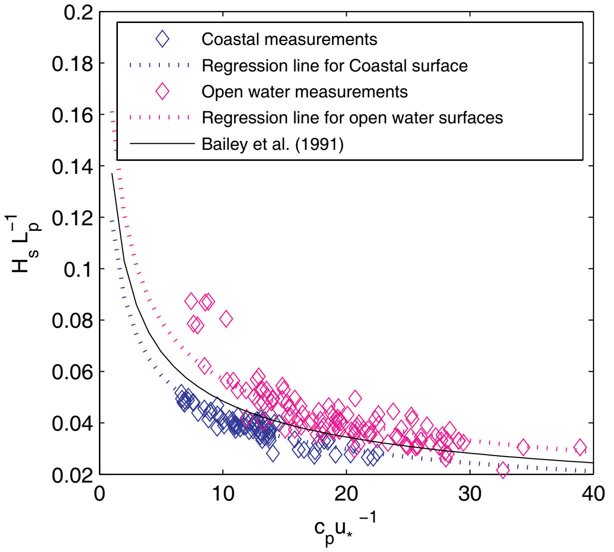

Fig. 8. Steepness of significant wave height as a function of wave age for the coastal zone and open water surfaces.

Eq. (3") for the coastal and open water sites.

$$\begin{cases} z_0 = 10\exp[-\frac{k}{0.0830}(c_p/u_*)^{1/4}] & \text{(Offshore)}\,, \\ z_0 = 10\exp[-\frac{k}{0.0280}(c_p/u_*)^{1/4}] & \text{(Coastal)}\,, \end{cases} \tag{2"}$$

and

$$\begin{cases} C_{\rm DN} = u_*^2/U_{\rm 10N}^2 = 6.90\times10^{-3}(c_p/u_*)^{-1/2} \\ \text{(Offshore)}\,, \\ C_{\rm DN} = u_*^2/U_{\rm 10N}^2 = 4.70\times10^{-3}(c_p/u_*)^{-1/2} \\ \text{(Coastal)}\,. \end{cases} \tag{3"}$$

We do not recommend to use Eqs. (2"–3") in numerical models, because both of them use u_* to parameterize z_0 and $C_{\rm DN}$ so that the iteration process becomes necessary.

3.4 *Parameterization of u_*, z_0, and $C_{\rm DN}$ by using wave steepness for deepwater surfaces*

Using the deep-water dispersion relation: $L_{\rm p} = 2\pi c_p^2/g$ where $L_{\rm p}$ is the wavelength of the waves at the peak of the wave spectrum (Gao et al., 2006), Eq. (5) becomes:

$$H_{\rm s}/L_{\rm p} = (2\pi)^{1/2}B(c_p/u_*)^{-1/2}\,. \tag{7}$$

Eq. (7) suggests that the wave steepness is proportional to the 1/2 power of the inverse wave age (u_*/c_p). The relationship of Eq. (7) is displayed in Fig. 8 in comparison to the coastal and open water measurements. Bailey et al. (1991) gave an alternative relationship indicating that the significant wave steepness is statistically limited, as an equilibrium state of the wind-waves. Their relationship is expressed as

$$\frac{H_{\rm s}}{L_{\rm p}} = (2\pi)^{1/2}B\left(\frac{c_p}{u_*}\right)^{-\frac{1}{2}}\left[1+u_{\rm s}^*\left(\frac{c_p}{u_*}\right)^{-1}\right]^{-2/3}\,, \tag{8}$$

where $u_{\rm s}^* = 0.206$. Equation (8) also suggests that the wave steepness is proportional to the 1/2 power of the inverse wave age (u_*/c_p) because $u_{\rm s}^*(\frac{c_p}{u_*})^{-1} \ll 1$. This relationship is also shown in Fig. 8. It is obvious that the curve of Bailey et al. (1991) is between the coastal and open water distributions. The regression results are given in Eq. (9).

$$\begin{cases} H_{\rm s}/L_{\rm p} = 0.1826(c_p/u_*)^{-1/2} & \text{(Offshore)}\,, \\ H_{\rm s}/L_{\rm p} = 0.1345(c_p/u_*)^{-1/2} & \text{(Coastal)}\,. \end{cases} \tag{9}$$

Combining Eqs. (9) and (2") to eliminate c_p/u_* gives Eq. (10),

$$\begin{cases} z_0 = 10\exp[-5.15k(H_{\rm s}/L_{\rm p})^{-1/2}] & \text{(Offshore)}\,, \\ z_0 = 10\exp[-5.36k(H_{\rm s}/L_{\rm p})^{-1/2}] & \text{(Coastal)}\,. \end{cases} \tag{10}$$

Equation (10) has displayed the two measurements together in Fig. 9. Combining Eqs. (9) and (3") to eliminate c_p/u_* gives Eq. (11),

$$\begin{cases} C_{\rm DN} = u_*^2/U_{\rm 10N}^2 = 3.78\times10^{-2}(H_{\rm s}/L_{\rm p}) & \text{(Offshore)} \\ C_{\rm DN} = u_*^2/U_{\rm 10N}^2 = 3.49\times10^{-2}(H_{\rm s}/L_{\rm p}) & \text{(Coastal)}\,. \end{cases} \tag{11}$$

Equation (11) has displayed the measurements together in Fig. 10.

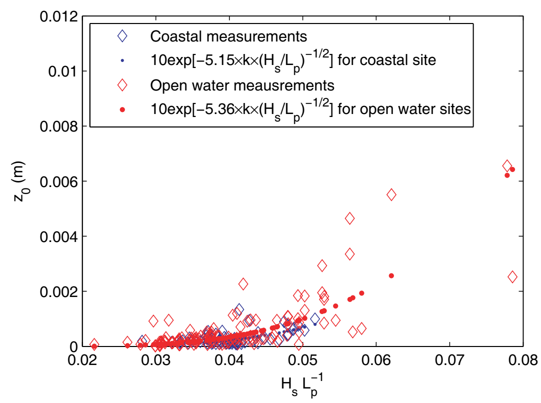

Fig. 9. Variation of the aerodynamic roughness length z_0 against wave steepness $H_{\rm s}/L_{\rm p}$ for both the coastal and open water sites.

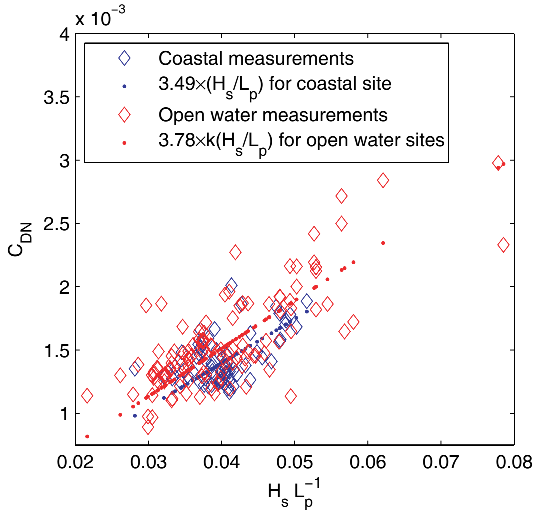

Fig. 10. Variation of the neutral drag coefficient $C_{\rm DN}$ against wave steepness $H_{\rm s}/L_{\rm p}$ for both the coastal and open water sites.

The scattered distributions are found in Figs. 6–7 and 9–10. We think they are caused by the uncertainties in the measurements, and the combination of these uncertainties could make the distributions scattered.

4. Summary and Conclusions

This paper is a growth of the paper by Gao et al. (2006). We have investigated the dependence of sea surface roughness on the wave statues by using the databases of RASEX, HEXMAX, Lake Ontario, and ERS-1 SAR wave spectra validation measurements. Relationships among wave height, friction velocity, and wave age, and between dimensionless variables $u_*(gT_{\rm p})^{-1}$ and $U_{10\rm N}^2(gH_{\rm s})^{-1}$ are re-explored by dimensional analyses for coastal and open water surfaces. When the derived results are combined with the neutral wind profile equation, we obtained the non-linear parameterization relationships between friction velocity (u_*) against the neutral 10-m wind speed ($U_{10\rm N}$) and phase velocity (c_p) for the coastal zone and open water surfaces. The dependences of the roughness length (z_0) on wave age ($c_p/U_{10\rm N}$) and on wave steepness ($H_{\rm s}/L_{\rm p}$) and the dependences of the neutral drag coefficient ($C_{\rm DN}$) on wave age ($c_p/U_{10\rm N}$) and on wave steepness ($H_{\rm s}/L_{\rm p}$) have been generated and identified, for the coastal zone and open water surfaces. These approaches gave realistic estimates and have potential applications within air-sea numerical models.

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