Increased aerodynamic roughness owing to surfzone foam

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Abstract: Drag coefficients ($C_d$) obtained through direct eddy-covariance estimates of the wind stress were observed at four different sandy beaches with dissipative surf zones along the coastline of Monterey Bay, CA, USA. The measured surfzone $C_d$ ($\approx 2x10^{-3}$) is twice as large as open ocean estimates and consistent with recent estimates of $C_d$ over the surf zone and shoaling region. Owing to the heterogeneous nature of the nearshore consisting of non-breaking shoaling waves and breaking surfzone waves, the surfzone wind stress source region is estimated from the footprint probability distribution derived for stable and unstable atmospheric conditions. An empirical model developed for estimating the $C_d$ for open ocean foam coverage dependent on wind speed, is modified for foam coverage owing to depth-limited wave breaking within the surf zone. A modified empirical $C_d$ model for surf zone foam predicts similar values as the measured $C_d$ and provides an alternative mechanism to describe roughness.
1. Introduction

Over land, the geometric surface roughness ($k$) and corresponding aerodynamic roughness ($z_o$) for surface features can be considered temporally constant. Over the open ocean, $z_o$ is a function of both surface texture (associated viscous surface stresses) and the local wave field (associated form drag and flow separation). The associated stresses are dynamically coupled with the wind, can evolve together, and transition from viscous stresses to wave stresses. Non-local wave fields further complicate the dynamical relationship. Numerous, extensive, *open-ocean* field studies have investigated the various stress relationships, resulting in both consistencies and discrepancies (see Edson et al., 2013 for an overview).

Until recently, there have been limited observations of the air-ocean momentum fluxes in the *nearshore* region of the ocean. The nearshore region includes the surface gravity wave shoaling region ($\sim$< 30m depth) and the dissipative surf zone ($\sim$< 2m depth). Unlike the open ocean, surface gravity waves become decoupled from the wind-wave relationship and dependent on water depth ($h$), modifying the dynamical-coupling between the wind and the waves. Furthermore, depth-limited wave breaking occurs within the surf zone reducing the wave height.

Hsu (1970) and Vugts and Cannemeijer (1981) measured elevated drag coefficients, $C_d\sim\mathcal{O}(1\times10^{-3} - 5\times10^{-3}$), related to the surf zone and swash zone. Smith and Bank (1975) recognized that depth-limited wave breaking may have increased their measured $C_d$ owing to their tower being deployed on a sand spit. During Hurricane Ike in 2008, Zachary et al. (2013) and Powell (2008) measured elevated $C_d$ values in the nearshore compared with the open ocean. Anctil and Donelan (1996) found increased $C_d$ values for waves shoaling from
12 m to breaking in 2 m water depth. Shabani et al. (2014, 2016) found that measured $C_d$ for near-neutral, atmospheric stability over the shoaling region and surf zone were $O(2)$ times larger than open-ocean estimates, which they ascribe to the wave celerity ($c$) and shape effects. Similar to Anctil and Donelan (1996), they suggested that as the wave shoals, wave speed slows relative to the wind speed ($U$) increasing $C_d$.

Total aerodynamic roughness, $z_o$, is composed of

$$z_o = z_v + z_w + z_f,$$  \hspace{1cm} (1)

where $z_v$ is the viscous smooth flow roughness, or tangential stress, associated with the sea surface (Charnock, 1955),

$$z_v = \alpha \frac{u_*^2}{g},$$  \hspace{1cm} (2)

where $\alpha \approx 0.011$ (Charnock, 1955; Smith, 1988; Fairall et al., 1996), $g$ is the gravitational acceleration, and $u_*$ is the shear velocity. $z_w$ is the wave aerodynamic roughness, owing to form drag and flow separation due to the presence of waves associated with rough flow (Donelan, 1990; Banner and Pierson, 1998; Reul et al., 2008; Mueller and Veron, 2009). $z_f$ is the aerodynamic roughness due to spray droplets and foam and is often included in $z_w$ or $z_v$. Though $z_o$ can be a linear summation, $C_d$ is not a linear summation (Edson et al., 2013). $z_o$ and $C_d$ at the 10m (subscript 10) for neutral atmospheric stability (subscript N) are related by

$$C_{d10} = \frac{\kappa}{\ln(10/z_o)},$$  \hspace{1cm} (3)
where $\kappa (=0.4)$ is the von Karman constant. Vickers et al. (2013) found that Eq. 2 generally works well for near-neutral stable observations ignoring sea state. Andreas et al. (2012) suggests that the smooth flow formulation ($z_w$) works for $U<8\text{m/s}$ and Donelan (1990) found that the sea becomes fully rough at 7.5m/s. This implies that $z_w$ becomes important for $U>8\text{m/s}$. Andreas et al. (2012) and Edson et al. (2013) found empirical data fits that are a function of $U_{N10}$ using a modified $\alpha$ in Eq. 2. Golbraikh and Shtemler (2016) developed a $z_f$ relationship related strictly to percentage of open-ocean foam coverage and $U$. It is important to recognize that roughness is increased by an order of magnitude by the presence of foam as compared with a non-foam water surface.

Shabani et al. (2014) indirectly posed a fundamental question – if $C_d$ increases within the surf zone, how are the surf zone waves different from the open ocean waves? Here an alternative hypothesis is proposed that the surface roughness of foam ($z_f$) generated by depth-limited wave breaking inside the surfzone also contributes to the increased $C_d$ (Figure 1). Within the surfzone, since surface gravity waves are decaying, the potential influence of the wave form drag ($z_w$) relative to $z_f$ may be reduced, while at the same time $z_f$ is increasing due to increased foam coverage by breaking waves. Using Golbraikh and Shtemler (2016), a modified $C_d$ relationship is developed for surfzone foam coverage.

2. Field Experiment

Co-located sonic anemometers, temperature, and relative humidity sensors were mounted on six, 6-m high towers and deployed simultaneously on four different sandy beaches within the surfzone and near the high-tide line located along 10 km of shoreline in Monterey Bay, CA. Continuous measurements for four weeks in May-June 2016 were divided into 15 minute blocks for analysis. The analysis for computing momentum fluxes
and procedures for quality controlling the data are given in Aubinet et al. (2012), which is similar to that described by Shabani et al. (2014) and Ortiz-Suslow et al. (2014).

A pressure sensor and temperature string was deployed in 10m water seaward of each beach tower. Significant wave height ($H_{\text{sig}}$), average wave period ($T_{\text{avg}}$), and wave set-up were estimated from the pressure observations (Dean and Dalrymple, 1995). The tower position and elevation and beach profile were surveyed with a GPS. The distance between the waterline and tower location including wave set-up was estimated for each stress measurement.

$H_{\text{sig}}$ and $T_{\text{avg}}$ ranged between 0.3-2m and 6-13s associated with local storm-generated events. $U_6$ measured at 6m elevation ranged from 0-10m/s, with maxima in the late afternoon reducing to near zero at night. A diurnal cycle is observed that is occasionally modified by larger meso-scale atmospheric storm events. The beach air temperature ranged between 10-20°C. The water temperature ranged from 12-18°C. The difference of air and water temperatures is predominantly negative implying the atmosphere behaved as an unstable system. Owing to the limitations of empirical formulations used in comparing results, momentum flux data are filtered to limit the range of atmospheric stabilities ($\zeta$) to $-2<\zeta<0.5$, $U_6>3$m/s, and to onshore wind directions that are between ±40° relative to shore-normal. Atmospheric stability is measured as $\zeta= z/L$, where

$$L = \frac{-u'^2T_v}{k_g(w'\theta'_v)},$$

(4)

where $T_v$ is virtual temperature, $w'$ and $\theta'_v$ are the turbulent vertical velocity and turbulent virtual potential temperature perturbations, and $<>$ denotes time average. These limitations
reduced the analyzed data to 3031 onshore records, out of which 630 records are represented by the surf zone (discussed below), representing 21% of the total data acquired.

The Monterey Bay nearshore system is composed of a relatively steep (1:10) foreshore beach flattening out to a low-tide surfzone terrace (1:100) continuing with a 1:30 offshore slope (MacMahan et al., 2010). The offshore distance for which c equals $U_6$, is referred to as the decoupling distance ($x_{dc}$), inside of which the decreasing speed of shoaling waves may increase drag (Antcil and Dolelan, 1996). For the experiment, $x_{dc}$ equals 220m± 80m (1 standard deviation). Considering the surf width is O(100m), the surf zone represents ~30% of the nearshore region for the experimental wind conditions.

2.1 Footprint Analysis

A basic assumption for computing momentum fluxes is that the measurement environment is homogeneous. The nearshore is a heterogeneous environment. The footprint represents the source location where the measured turbulence originates and is estimated by an empirical model that accounts atmospheric stability conditions (Hsieh et al., 2000). It is important to recognize that turbulence measurements obtained on the beach represent turbulence that originates over the ocean that is advected by the wind. The footprint distance ($x$) increases with increasing stability, wind speed, and measurement elevation ($z$) and is represented by a skewed probability density function, $f(x,z)$, as described by

$$f(x,z) = \frac{1}{k^2x^2} Dz^p |L|^{1-p} \exp \left( \frac{1}{k^2x^2} Dz^p |L|^{1-p} \right),$$  \hspace{1cm} (5)
where $D=0.28$, $P=0.59$ for unstable conditions, $D=0.97$, $P=1$ for near neutral conditions, and $D=2.44$, $P=1.33$ for stable conditions (Hsieh et al., 2000). $z_u$ is defined as

$$z_u = z \left( \ln \left( \frac{z}{z_o} \right) - 1 + \frac{z_o}{z} \right).$$ \hfill (6)

Researchers typically use the maximum of the $f(x,z)$ to denote the source location. Here, the relative percentage of contribution for the source region, $R$, is estimated by

$$R = \frac{\int_{x_1}^{x_2} f(x,z) dx}{\int_{0}^{z} f(x,z) dx}.$$

where the particular footprint source region, $f(x,z)$, is defined between two cross-shore locations ($x_1$ and $x_2$). The data were sub-divided into two categories: the surf zone and seaward of the surf zone based on $f(x,z)$. Data for a region are only considered when $R$ is greater than 70% for that region. Filtering the data for $-2<\zeta<0.5$ and $U>3\text{m/s}$, eliminated all dry-beach observations. It is recognized that the footprint analysis approach, particularly for a heterogeneous environment, is not absolute, but is first step in evaluating $C_d$ for the surfzone region.

This also highlights the applicability of these results to other beaches. For the surf zone to be the primary turbulent source region, the nearshore waters need to be warmer than the associated air temperatures setting up an unstable atmospheric scenario allowing for a relatively narrow footprint to develop.

3. Results

The uncertainties in using stability functions based on Monin-Obukuv similarity theory for adjusting to the stability-corrected $C_{dN10}$ are well-recognized, resulting in a wide range of...
\( C_d \), even over homogeneous terrains (Andreas et al., 2012). To avoid these uncertainties, \( C_{d6} \) is estimated first directly at \( z=6m \) by

\[
C_{dz} = \left( \frac{\rho_a (u' w')}{{u_z}} \right)^2 = \left( \frac{u_x}{u_z} \right)^2, \tag{8}
\]

where \( \rho_a \) is the air density, \( u' \) and \( w' \) are the turbulent horizontal and vertical velocity perturbations (as measured herein), and \( <> \) denotes time average. \( C_{d6} \) is \( O(2x10^{-3}) \) for the surf zone (Figure 2a). \( C_{d6} \) seaward of the surf zone is \( O(1.5x10^{-3}) \) (Figure 2a). This suggests that \( C_{d6} \) increases over the surf zone. \( C_{dN10} \) calculated as a function of \( U_{N10} \) using Eq. 8 collapses toward \( O(1.5x10^{-3}) \) (Figure 2b). \( U_{N10} \) for non-neutral conditions is calculated by

\[
U_{N10} = \frac{u_x}{\kappa} \left[ \ln \frac{10}{z_o} - \psi(\zeta) \right], \tag{9}
\]

where \( \Psi(\zeta) \) is the empirical function of the stratification based on stability. Observed open ocean unstable estimates of \( C_{d10} \) are larger than \( C_{dN10} \) (Vickers et al., 2013). Here it is further related to the footprint analysis, where unstable (stable) conditions result in a smaller (longer) and closer (farther) footprint. Applying Monin-Obukhov similarity theory, \( C_{d10}(\zeta) \) [\( C_{d10}(+\zeta) \)] values corrected to \( C_{dN10} \) are reduced [increased]. In practice, the \( C_d \) per source region is dependent upon \( \zeta \), which will collapse to a similar \( C_{dN10} \). For the moment, the similarity of \( C_{dN10} \) (Figure 2b) is suggested as unique and that the different regions (Figure 2a) potentially represent different mechanisms for modifying \( C_d \).

**4. Surfzone foam coverage drag coefficient model**

Golbraikh and Shtemler (2016) developed an empirical model for \( C_d \) as function of \( U \) and foam coverage, \( \delta_f \). \( C_d \) linearly increases with fractional foam coverage owing to
white-capping until saturated foam coverage. Holthuijsen et al. (2012) suggests \( z_o \) of foam is related to the characteristic size of the foam bubbles. The sea foam bubble roughness \( (k) \) is 0.1-2mm (Soloviev and Lukas, 2006) resulting in a surprisingly similar \( z_o \) between 0.1-2mm (Powell et al., 2003). The correlation between aerodynamic and geometric roughness is believed related to the idea that the foam is moving in high wind (Golbraikh and Shtemler, 2016). For the surf zone, the foam is assumed not to be moving, as the foam is generated by a wave roller of a self-similar bore and is left behind as the bore moves forward.

Golbraikh and Shtemler (2016) suggest \( z_o \) averaged over the sea surface, \( S \), is described as

\[
\begin{align*}
z_o &= \frac{S - S_f}{S} z_{ff} + \frac{S_f}{S} z_f = (1 - \delta_f)z_{ff} + \delta_f z_f, \tag{10} \end{align*}
\]

where \( S = S_{ff} + S_f \), where \( S_{ff} \) is the foam-free surface and \( S_f \) is the foam surface, \( z_{ff} \) is the foam-free aerodynamic roughness, \( z_f \) is the foam-covered aerodynamic roughness, and \( \delta_f = S_f/S \) is the fractional foam coverage. For the open ocean, Holthuijsen et al. (2012) developed a \( \delta_f \) approximation as function of a \( U_{10} \). For the surf zone, \( \delta_f \) is approximated for depth-limited wave breaking as given by Sinnett and Feddersen (2016)

\[
\delta_f = \frac{m(\varepsilon_r)}{\rho (gh)^{3/2}}, \tag{11}
\]

where \( m \approx 400 \) and is a fit parameter, \( \langle \varepsilon_r \rangle \) is the wave roller dissipation and \( h \) is the water depth (Battjes, 1975; Feddersen, 2012a,b). The roller dissipation is given by

\[
\langle \varepsilon_r \rangle = \frac{z g E_r s \sin \beta}{c}, \tag{12}
\]
where $E_r$ is the roller energy density and the slope of the roller surface, $\sin \beta = 0.1$ (Deigaard, 1993; Duncan, 2001). $\langle \varepsilon_r \rangle$ is estimated from the one-dimensional wave and roller transformation models (Thornton and Guza, 1983; Ruessink et al., 2001) for normally-incident, narrow-banded waves. The roller energy model is defined as

$$\frac{d}{dx} \left( E C_g + 2E_r C \right) = -\langle \varepsilon_r \rangle,$$  \hfill (13)

where $E$ is the wave energy density, $E = \frac{1}{2} \rho g H_{sig}^2$, $C_g$ is the group velocity, and $x$ is the cross-shore coordinate frame. The Sinnet and Feddersen (2016) surfzone foam coverage model is similar to the breaking wave intensity model as measured by whiteness (as an indication of foam) in video images by Aarninkhof and Ruessink (2004), who also finds the breaking intensity is related to the roller energy dissipation. Examples of the wave height and $\delta_f$ are provided in Figure 3a,b for the experiment conditions.

For Monterey beach, $\delta_f$ averaged over the surfzone from $H_{sig}(max)$ to the beach is estimated for a range of wave heights and wave periods resulting in a $\delta_f$ of 0.35-0.55 (Figure 3a). The foam roughness is defined as

$$z_f \approx \delta_f k \approx \delta_f \frac{k}{3},$$ \hfill (14)

where $k$ is the geometric roughness of foam. Applying constant $z_f = 2 \times 10^{-4}$m (Charnock, 1955) and $z_f = 2 \times 10^{-3}$m (Soloviev and Lukas, 2006), the resulting $C_{dN10}$ is $O(2 \times 10^{-3})$ (Figure 3b). The open-ocean estimate of $z_f$ being similar to $k$ is most likely an over estimate in the surfzone owing to the foam not moving. Reducing $z_f$ by $\sim k/3$ as suggested by land relationships by Neild et al. (2013) results in a $C_{dN10} O(1.5 \times 10^{-3})$ (Figure 3c) similar to the observations (Figure 2b).
The foam-free $z_{ff}$ empirical relationship can be described as a function of wave age, $c/u_*$, in the open ocean to account for wave form (Drennan et al., 2003),

$$z_{ff} = \frac{H_{sig}}{4} 13.4 \left(\frac{u_*}{c}\right)^{3.4}. \quad (15)$$

with the concept that wave age represents a measure of wave height, and therefore roughness, in generation region. Eqs. 2, 10, 14, and 15 are applied across the shoaling region and surf zone to evaluate the relative contributions of $z_o$ and $C_{dN10}$ (Figure 4c,d). $z_{ff}$ (Eq. 15) increases within the surf zone owing to decreasing c, while $H_{sig}$ is decreasing (Figure 4a). It is also suggested that $z_{ff}$ should decrease in the surf zone, as the waves are decreasing in amplitude which should reduce the form drag. For low winds within the surf zone, $z_o$ and $C_{dN10}$ appear to be governed more by foam, Eq. 14 (Figure 4c,d). As the winds increases, $z_{ff}$ (Eq. 15) unrealistically grows (Figure 5a,b), because $c$ remains a depth-limited constant but $u_*$ continues to increase with increasing $U$. This questions the validity of Eq. 15 parameterized using wave age within the surf zone, particularly for faster wind cases. Using Eq. 2 ($Charnock$ formulation) for $z_{ff}$ and $z_f \approx k/3$ in Eq. 10 (black line in Figure 5a,b) results in similar observed surf zone $C_{dN10}$ estimates (black dots in Figure 5a,b). This suggests that summation of Charnock formulation Eq. 2 for $z_{ff}$ and the modified foam model, Eq. 14, in Eq. 10 provides a reasonable estimate of the aerodynamic roughness and corresponding drag coefficient for the surf zone.

Summary & Conclusion

The coupled dynamical relationship between wind and waves in the nearshore region differs from the open ocean. Unlike the open ocean, where surface foam increases as a function of wind speed and concomitant wave height, the wave heights decay while the
foam generation increases within the surf zone. This suggests that aerodynamic roughness, $z_o$, associated with form drag decreases in the surf zone, while surface foam stress increases. Modifying a $z_o$ foam model for the open ocean to a surfzone foam model results in predicted values similar to observed surfzone $C_d$.

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Figure 1. Picture of the 6-m tall, momentum flux tower deployed on the beach in Monterey, CA highlighting the foam surface coverage and texture within the surf zone in the background. Sonic anemometers were collocated with temperature-humidity sensors located on top of the tower, solar panels were located in the middle, and the data acquisition system is located in the white box. Towers were deployed at the high-tide line, where the tower base was approximately 1.2m above mean sea level.

Figure 2. a) $C_{d6}$ as function of $U_6$ and b) $C_{dN10}$ as a function of $U_{N10}$ for $R>70\%$ (Eq. 7) for beyond the surf zone (black squares) and the surf zone (gray triangles). Error bars represent 95% confidence intervals. Colored dots in the center of the symbols represent number of points per bin as described by colorscale to the right.

Figure 3. a) Average surfzone foam coverage, $\delta_f$ (Eq. 11), b) $C_{dN10}$ for $z_f=2x10^{-4}m$ and $z_f=2x10^{-3}m$, and c) $C_{dN10}$ for $z_f=2x10^{-4}m$ and $z_f=(2x10^{-3})/3$ m, as function of wave height and wave period. Colorscales plotted on top for $\delta_f$ and $C_{dN10}$.

Figure 4. The cross-shore distribution of a) wave height, b) fractional foam coverage, c) aerodynamic roughness, and d) drag coefficient using a $H_{sig}=1.4m$, $T_{avg}=8s$, and $u^*=0.2$ ($U~8m/s$), which are representative conditions for the experiment, and a measured beach profile. ff is foam-free (black line, Eq. 15), f is foam (black dashed line, $z_f \sim k/3$, Eq. 14), and o is total (gray line, Eq. 10 using Eq. 2 and Eq. 14).

5. a) Neutral, 10m, drag coefficient, $C_{dN10}$ and b) aerodynamic roughness, z, for Charnock formulation, Eq. 2 (ff, gray line), wave age formulation, Eq. 15 (ff, gray dashed line), surfzone foam formulation, Eq. 14 (f, black dashed line), and the Charnock plus surfzone foam formulation, Eq. 10 (black line), as function of $U_{N10}$. ff is foam-free (Eq 2. or Eq 15), f is foam (Eq. 14), and o is total (Eq. 10). Gray triangles with error bars shown in a) are measured surfzone $C_{dN10}$ estimates.
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