Title
Scaling surf zone turbulence

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Scaling surf zone turbulence

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[1] Turbulence in the surf zone, the shallow region adjacent to the shoreline, has a key role in beach erosion, fertilization, dispersal, and larval settlement of marine invertebrates, and microbial contamination dilution in beach waters. Breaking-wave generated (the dominant source) surf zone turbulence is understood poorly. A new surf zone turbulent dissipation rate ϵ scaling is derived, that collapses new field surf zone ϵ observations with relatively high skill compared to other scalings. The vertically-uniform length-scale is 1/6 the water depth, and 15% of the wave-energy flux gradient is dissipated below the mean surface. Field and laboratory surf zone turbulence observations are shown to be consistent using the scaling. The non-dimensional surf zone diffusivity and suspended sediment profile can be applied to sediment transport and a range of biological processes including microbial pathogen contamination of beach waters. **Citation:** Feddersen, F. (2012), Scaling surf zone turbulence, *Geophys. Res. Lett.*, *39*, L18613, doi:10.1029/2012GL052970.

1. Introduction

[2] Turbulence in the surf zone, the shallow region (typically depth $h < 4$ m) adjacent to the shoreline, mixes vertically, thereby setting the vertical distribution of currents [*Feddersen and Trowbridge*, 2005], sediment [*Ogston and Sternberg*, 2002], fecal indicator bacteria, larvae, or other tracers. Surf zone turbulence is directly linked to tracer dispersion [*Feddersen*, 2007; *Clark et al.*, 2010], successful fertilization [*Serrao et al.*, 1996], spore dispersal [*Gaylord et al.*, 2002], and larval settlement [*Denny and Shibata*, 1989; *Crimaldi et al.*, 2002], and dilution of fecal indicator bacteria [*Grant et al.*, 2005; *Rippy et al.*, 2012]. However, field observations of surf zone turbulence are sparse [*George et al.*, 1994; *Bryan et al.*, 2003; *Ruessink*, 2010; *Feddersen*, 2012] and breaking-wave generated turbulence is understood poorly.

[3] For depth-limited wave breaking and weak mean alongshore current, the surf zone turbulent kinetic energy (TKE) balance is between downward vertical turbulent diffusion from a near-surface breaking-wave turbulent source and dissipation ϵ,

$$\frac{\mathrm{d}}{\mathrm{d}z}\left(K\frac{\mathrm{d}k}{\mathrm{d}z}\right) = \epsilon, \qquad (1)$$

where z is the elevation above the bed, k is the TKE, and K is the TKE eddy diffusivity. Surf zone breaking waves inject turbulence at a rate related to the cross-shore gradient of wave energy flux $\mathrm{d}F/\mathrm{d}x$ [*Battjes*, 1975], where x is the cross-shore coordinate.

[4] For deep water white-capping wave-breaking, turbulence is enhanced [*Agrawal et al.*, 1992], the mean turbulence energetics follow (1), and the near-surface ϵ scales [*Terray et al.*, 1996] as

$$\frac{\epsilon H_s}{G} \propto \left(\frac{z'}{H_s}\right)^{-2}, \qquad (2)$$

where z' is the distance below the mean surface and H_s is the significant wave height, and G is the white-capping induced surface TKE flux parameterized to depend upon the wind stress and the wave growth rates [*Craig and Banner*, 1994; *Terray et al.*, 1996]. Evidence for the -2 power-law exponent has been found in deep water [*Terray et al.*, 1996; *Drennan et al.*, 1996], in intermediate depths of 12 m [*Gerbi et al.*, 2009], and in the mid-to-upper water column in depths as shallow as 4 m [*Feddersen et al.*, 2007; *Jones and Monismith*, 2008a, 2008b]. Implicit in this scaling, is that the turbulent lengthscale l increases with distance below the surface [*Craig and Banner*, 1994].

[5] A surf zone-modified Terray scaling that uses the observed wave energy flux gradient $\mathrm{d}F/\mathrm{d}x$ in place of parameterized white-capping TKE flux had no skill across surf zone locations [*Feddersen*, 2012]. Although this scaling had some skill at individual inner-surf zone locations in the mid-water column, the best-fit power law exponent and other scaling constants varied in the cross-shore [*Feddersen*, 2012], indicating it was not generally applicable to surf zone environments.

[6] Here, a new surf zone turbulence scaling is derived assuming a vertically uniform turbulent length scale that is a constant fraction of the depth (Section 2). Using new observations from the IB09 field experiment (Section 3), this scaling collapses the surf zone ϵ observations when the mean currents are not strong and yields an estimate of the fraction of wave energy-flux gradient dissipated below the mean surface (Section 4). Using the scaling, field and laboratory surf zone ϵ observations are shown to be consistent. The turbulence scaling is used to derive the surf zone eddy diffusivity and the suspended sediment concentration profile (Section 5). The results are summarized in Section 6.

2. Surf Zone Turbulence Scaling

[7] In simple turbulence models (e.g., k-ϵ model), the balance between vertical turbulent diffusion and dissipation (1) is written [*Rodi*, 1987] in terms of k and turbulent lengthscale l,

$$\frac{\mathrm{d}\left(C_\mu l k^{1/2}\mathrm{d}k/\mathrm{d}z\right)}{\mathrm{d}z} = C_\mu^3\frac{k^{3/2}}{l}, \qquad (3)$$

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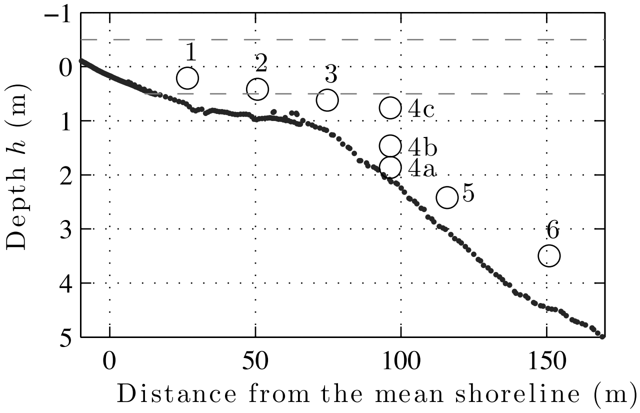

Figure 1. Depth h versus cross-shore coordinate x. The instrument frame locations (circles) are numbered 1–6. Frame 4 had 3 locations in the vertical. The horizontal dashed lines show the tide range standard deviation. Surf zone locations were limited to frame 5 and onshore.

where $K = C_\mu l k^{1/2}$, the RHS of (3) is ϵ, and $C_\mu = 0.57$ [*Rodi*, 1987].

[8] Although the observed Terray scaling (2) is not directly derivable from the TKE energetics (3), with an ad-hoc choice of the surface length-scale and other model constants, two-equation turbulence models (e.g., k-ϵ and k-ω), with length-scale $l \propto z'$, can reproduce the deep-water white-capping z'^{-2} power law dependence (2) [*Burchard*, 2001; *Umlauf et al.*, 2003; *Jones and Monismith*, 2008a, 2008b]. In seaward of the surf zone [*Feddersen et al.*, 2007] or estuarine [*Jones and Monismith*, 2008a, 2008b] white-capping wave breaking, the shallow depths preclude $l \propto z'$ over the entire water column, resulting in poor fits of observed ϵ to the Terray scaling (2) in the lower water column. This also may have led to the poor fits of ϵ to the surf zone modified Terray scaling in the even shallower depths of the surf zone [*Feddersen*, 2012].

[9] Here, a vertically-uniform length-scale equal to a fraction (δ) of the mean water depth (h) $l = \delta h$ is adopted for the development of a new surf zone scaling. Choice of $l = \delta h$ leads to an analytic solution for k from the 2nd order ODE (3). With the surface boundary condition of TKE flux equal to the wave energy flux gradient, i.e., $K\mathrm{d}k/\mathrm{d}z = \mathrm{d}F/\mathrm{d}x$, the analytic solution of (3), once re-written for ϵ, results in a new non-dimensional ϵ scaling,

$$\frac{\epsilon h}{\mathrm{d}F/\mathrm{d}x} = A \exp(\alpha\zeta), \tag{4}$$

where $\zeta = z/h$ is the non-dimensional height above the bed, the vertical decay-scale $\alpha = (3/2)^{1/2} C_\mu/\delta$, and the non-dimensional ϵ magnitude $A = \alpha/\exp(\alpha)$ is linked to the vertical ϵ decay scale. The only unknown is δ (or α). Near the bed ($\zeta < \delta$), l must decrease as the wave boundary layer becomes important, and (4) is not appropriate.

[10] For a surf zone with turbulent energetics described by (1), the constant $l = \delta h$ solution (4) is also a solution of the coupled k-ϵ equations with dissipation Schmidt number $\sigma_\epsilon \approx 1$. The ϵ equation [*Rodi*, 1987] corresponding to (1) is

$$\frac{\mathrm{d}}{\mathrm{d}z}\left(\frac{K}{\sigma_\epsilon}\frac{\mathrm{d}\epsilon}{\mathrm{d}z}\right) = c_{2\epsilon}\frac{\epsilon^2}{k}, \tag{5}$$

where $c_{2\epsilon} = 1.92$ is a well-established k-ϵ constant [*Rodi*, 1987] based on the observed decay of homogeneous turbulence, and σ_ϵ is the dissipation Schmidt number. For classic logarithmic boundary layers [*Rodi*, 1987; *Umlauf and Burchard*, 2003], $\sigma_\epsilon = 1.1$. To reproduce the z'^{-2} deep water ϵ scaling power-law exponent [*Terray et al.*, 1996], an unphysical $\sigma_\epsilon = 2.4$ is required [*Burchard*, 2001; *Umlauf and Burchard*, 2003]. In contrast, the constant $l = \delta h$ solution in (5) yields $\sigma_\epsilon = 2/c_{2\epsilon} = 1.04$, very close to one (equal TKE and ϵ diffusivity), similar to the value for a logarithmic boundary layer.

3. Surf Zone Observations

[11] The new dissipation scaling (4) is tested with recent field surf zone dissipation observations from the IB09 field experiment (Fall 2009 at Imperial Beach CA). Six instrumented tripod frames were deployed spanning the surf zone on a cross-shore transect from near the shoreline to 4.5 m mean water depth (Figure 1). The tripod frames were oriented to minimize flow obstacles from cross-shore propagating waves and the alongshore current. At each frame, the vertical coordinate z is positive upward with $z = 0$ m at the bed. Each instrumented frame had a buried pressure sensor and downward looking 5 MHz Sontek Ocean Acoustic Doppler Velocimeter (ADV), both sampling at 8 Hz. Data was collected for 935 hours starting 14 September 2009, with similar processing and quality control procedure as previously used [*Feddersen*, 2012]. The total water depth h, ADV sensing volume height above the bed z, wave energy flux F, and gradients $\mathrm{d}F/\mathrm{d}x$ are estimated at each frame. The wave energy flux F is calculated from co-located pressure and ADV data over the sea-swell frequency band, as described in *Feddersen* [2010]. Wave energy flux gradients $\mathrm{d}F/\mathrm{d}x$ at frame i are estimated by differencing F at frames $i + 1$ and $i - 1$, except at frame 1 where shoreline $F = 0$ was assumed, analogous to *Feddersen* [2010]. Frames are considered "within" the surf zone when located onshore of the wave-energy-flux estimated surf zone boundary. This corresponds to the self-similar surf zone region where waves have already "broken" and propagate as bores. The hourly turbulent dissipation rate ϵ is estimated and quality controlled from the high frequency ADV vertical velocity spectra [*Feddersen*, 2010]. The quality control methodology often rejects data runs in the upper water column $\zeta > 0.7$) with intense wave breaking due to elevated ADV noise or inconsistency with an inertial subrange [*Feddersen*, 2010].

[12] The incident significant wave height H_s varied between 0.5 and 1.7 m. The surf zone mean alongshore current (V) magnitude was typically (80% of the time) <0.3 m s^{-1}, indicating the bottom boundary layer generated turbulence, neglected here, was not significant [*Feddersen*, 2012]. Surf zone ϵ, measured below trough-level (generally $\zeta < 0.6$), varied between 10^{-4} and 2×10^{-3} m^{2}s^{-3}. To avoid significant bottom boundary layer generated turbulence, the subsequent analysis is restricted to times when $|V| < 0.3$ m s^{-1}. The majority (80%) data points fall below $z/h < 0.4$.

4. Results

[13] The observed non-dimensionalized $\epsilon h/(\mathrm{d}F/\mathrm{d}x)$ at all surf zone locations with $|V| < 0.3$ m s^{-1} are consistent with the new scaling (4) with skill $r^2 = 0.44$ (Figure 2). The

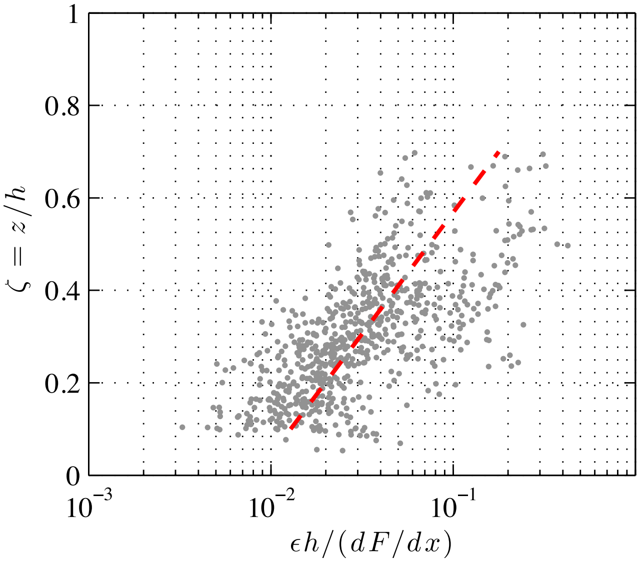

Figure 2. Non-dimensional $\epsilon h/(\mathrm{d}F/\mathrm{d}x)$ versus $\zeta = z/h$ for surf zone observations (N = 688, r^2 = 0.44) for $|V| < 0.3$ m s^{-1}. The fit to $\epsilon h/(\mathrm{d}F/\mathrm{d}x) = A\exp[\alpha\zeta]$ (red dashed line) results in best-fit $\alpha = 4.38(\pm 0.19)$ and $A = 0.0083(\pm 0.0005)$. The best-fit α (using $C_\mu = 0.57$) implies $\delta = 0.16$ and theoretical $\tilde{A} = 0.0548$. The ratio $A/\tilde{A} = 0.15$ implies that only 15% of dF/dx is dissipated below trough level, consistent with laboratory observations.

parameters α and A are fit independently to the data even though the scaling has them linked (i.e., $A = \exp(\alpha)/\alpha$). The best-fit $\alpha = 4.38(\pm 0.19)$ implies that $\delta = 0.16$ and the theoretical $\tilde{A} = \exp(\alpha)/\alpha = 0.0548$. The best-fit $A = 0.0083(\pm 0.0005)$ and the ratio between the best-fit and the theoretical value $A/\tilde{A} = 0.15$ implies that only 15% of the energy lost by the wave field (dF/dx) is dissipated below the water column ($\zeta < 1$).

[14] The new scaling skill is a dramatic improvement over a surf zone Terray ϵ scaling (analogous to equation (2)) that had essentially no skill across surf zone locations from the HB06 experiment [*Feddersen*, 2012]. The new scaling is also superior to the surf zone Terray scaling when applied to the IB09 data set. For the IB09 surf zone locations, the surf zone Terray scaling (Figure 3) has some skill $r^2 = 0.27$ with best-fit power-law exponent of -1.7, near the canonical -2 value. However, the surf zone Terray scaling skill is significantly lower than the new scaling skill ($r^2 = 0.44$). Furthermore, the deviation of the observations from the surf zone Terray scaling best-fit curve (dashed in Figure 3) is skewed at all z'/H_s, indicating that a power-law fit (in a least-squares sense) is not appropriate. This is consistent with the limitations on turbulent length-scale in the surf zone, particularly as the majority of ϵ observations are in the lower-part of the water column.

[15] Significant data scatter remains about the best-fit line (dashed line in Figure 2) that the new scaling (4) does not explain. At $z/h > 0.45$, frame 1 data gives rise to the data cloud > the best-fit line, which likely results from differences in dF/dx estimation method. The general scatter may result from cross-shore variation in the ratio of downward surface TKE flux into the water column and dF/dx, potentially resulting in cross-shore variation in the best-fit A. This was observed in a laboratory inner-surf zone [*Huang et al.*, 2009] where the ratio of depth-integrated ϵ to dF/dx varied a factor of 2 in the cross-shore.

[16] With this new non-dimensional ϵ scaling (4), the field and laboratory ϵ observations are shown to be consistent. Laboratory studies found non-dimensional $\epsilon/(g^3h)^{1/2} \propto \exp[\tilde{\alpha}\zeta]$ with $\tilde{\alpha} = 4.5$ [*Govender et al.*, 2004], $\tilde{\alpha} = 3.68$ [*Huang et al.*, 2009], and $\tilde{\alpha} \approx 3$ [*Yoon and Cox*, 2010], similar to the best-fit field $\alpha = 4.38$ (Figure 2). The vertically-uniform l with inferred $\delta = 0.16$ is consistent with inferred vertically uniform laboratory surf zone length-scales with $l/h \approx 0.1$–0.2, over a similar ζ range ($0.2 < \zeta < 0.7$) [*Govender et al.*, 2004]. In the surf zone $H_s/h \approx 0.4$ [*Raubenheimber et al.*, 1996], implying that $l \approx 0.4\,H_s$, similar to the surface length-scale boundary condition required for deeper-water white-capping wave breaking [*Burchard*, 2001]. In a surf zone with typical depth ranging from 1–2 m, the inferred length-scale of 0.16–0.32 m is consistent with the surf zone 0.2 m surface length scale boundary condition used by *Feddersen and Trowbridge* [2005]. The inferred 15% of dF/dx is dissipated below $\zeta = 1$ is consistent with the 10% level inferred in detailed laboratory surf zone $\epsilon(z)$ observations [*Govender et al.*, 2004; *Huang et al.*, 2009].

5. Discussion

[17] From the new non-dimensional ϵ scaling (4), the non-dimensional eddy diffusivity K is

$$\frac{K(z)}{h(dF/dx)^{1/3}} = \delta^{4/3}A^{1/3}\exp\left(\frac{\alpha}{3}\frac{z}{h}\right), \tag{6}$$

a different vertical structure than the commonly assumed constant [*Faria et al.*, 2000] or log-profile [*Beach and Sternberg*, 1988; *Denny and Shibata*, 1989] based $\approx u_*\kappa z$ (where u_* is the bed friction velocity). The dimensional K depends on wave breaking (dF/dx) analogous to earlier dimensional analysis [*Battjes*, 1975].

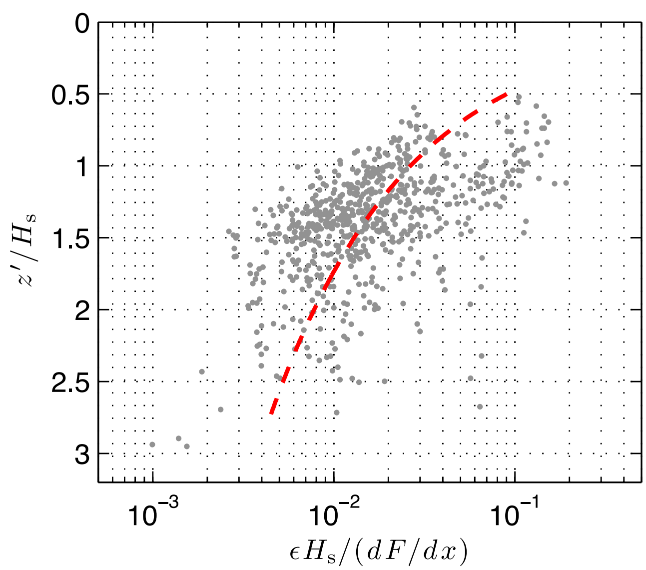

Figure 3. Terray scaled $\epsilon H_s/(\mathrm{d}F/\mathrm{d}x)$ against z'/H_s for surf zone observations (N = 688) for $|V| < 0.3$ m s^{-1}. The best fit power-law scaling $\epsilon Hs/(\mathrm{d}F/\mathrm{d}x) \propto (z'/Hs)^\gamma$ (red-dashed) has best-fit $\gamma = -1.70$ with skill $r^2 = 0.27$.

[18] The vertical distribution of the mean sediment concentration $C(z)$, is set by K, where the falling (with velocity $|w_f|$) sediment flux is balanced by upward diffusion [*Grant and Madsen*, 1986] (i.e., $-|w_f|C = K(z)\mathrm{d}C/\mathrm{d}z$). With (6), the non-dimensional sediment profile solution is $C(z)/C_0 = \exp[-\beta(z/h)(1 - \alpha z/(6h))$, where $\beta = |w_f|[A\delta^4(dF/dx)]^{-1/3}$ is the vertical decay rate of the mean sediment profile and C_0 is the near-bed concentration. The concentration fall-off is weaker than exponential similar to field observations [*Ogston and Sternberg*, 2002]. The vertical sediment decay rate β depends strongly on the wave-breaking energy flux. With coupled observations of $C(z)$ and $\mathrm{d}F/\mathrm{d}x$, this suspended sediment concentration scaling can be tested. Together with the offshore-directed cross-shore flow, also derivable [*Faria et al.*, 2000] analogously using K, the mean suspended sediment flux, which dominates during offshore sandbar migration events [*Gallagher et al.*, 1998; *Hoefel and Elgar*, 2003], can be estimated.

[19] In addition, surf zone diffusivity K is directly linked to biological processes such as the rate of successful external fertilization [*Denny and Shibata*, 1989; *Serrao et al.*, 1996] and larval settlement [*Denny and Shibata*, 1989; *Crimaldi et al.*, 2002] of marine invertebrates, and mass transfer of dissolved species to reef corals [*Falter et al.*, 2007]. The diffusivity is critical to the vertical distribution of macro-algae spores and their dispersal distance [*Gaylord et al.*, 2002] in the wave dominated nearshore including the surf zone. Microbial contamination in beach recreational waters is linked to significant health risk [*Haile et al.*, 1999] and estimated [*Ralston et al.*, 2011] to cause in the US 5 million infections at a cost of \$300 million annually. This breaking-wave surf zone diffusivity has direct application to improve predictions [*Zhu et al.*, 2011; Rippy et al., submitted manuscript, 2012] of microbial water quality in beach waters.

6. Summary

[20] Here a new surf zone turbulence scaling assuming weak mean currents and a vertically uniform length-scale that is a constant fraction of the water depth $l = \delta$. A constant l is consistent with the k-ϵ equation with realistic dissipation Schmidt number near one. The scaling gives an exponential vertical structure of TKE, dissipation ϵ, and diffusivity that all depend upon the breaking wave energy flux gradient. The scaling collapses new field surf zone dissipation observations with relatively high skill ($r^2 = 0.44$) compared to previous scalings. The best-fit to the scaling reveals that surf zone turbulent length-scale is approximately 1/6 the water depth and that 15% of the lost wave energy is dissipated below mean-sea level. Field and laboratory surf zone turbulence observations are shown to be consistent through the scaling. The scaling also allows estimation of the diffusivity, which has application to mean suspended sediment concentration and a range of biological processes.

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