Dispersion in the Surfzone: Tracer Dispersion Studies

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LONG-TERM GOALS

Terrestrial runoff and river input dominates urban pollutant loading rates degrading nearshore and surfzone water quality (e.g., Boehm et al., 2002). Surfzone mixing processes disperse and dilute such (and other types of) pollution. On smaller length-scales (smaller than the water depth), breaking-waves and bed-generated turbulence mix tracer. However, field surfzone observations of turbulence previously have been extremely scarce, and much about surfzone small-scale turbulence is not known. On larger scales (10–100 m), horizontal dispersion is driven by surfzone eddies and meanders associated with shear waves (Oltman-Shay et al., 1989) or finite breaking crest length (Peregrine, 1998). Understanding the small and large length-scale mixing processes important to predicting the fate (transport, dispersal, and dilution) of surfzone tracers whether pollution, bacteria, larvae, or nutrients.

OBJECTIVES

The scientific objective is to improve understanding and modeling of dispersion of tracers (pollution, fecal indicator bacteria, fine sediments) within the nearshore (a few 100 m of the shoreline) and the surfzone. In this report, the focus is on three research components built upon observations from the HB06 experiment (PIs: Feddersen and Guza). First, modeling the HB06 surfzone cross-shore dye tracer dispersion (Clark et al., 2010b) and comparing it to the observed surfzone tracer dispersion (Clark et al., 2010a). Second, a theoretical analysis of alongshore shear dispersion in the presence of turbulent eddies (Spydell and Feddersen, 2010), a situation that regularly occurs within the surfzone. And third, studying the small-scale turbulence in the surfzone due to breaking waves and bottom boundary layer processes (Feddersen, 2010). Other HB06 efforts not described here include studying phytoplankton patchiness (Omand et al., 2010a) and nearshore nutrient fluxes (Omand et al., 2010b). In addition, IB09 experiment (performed in collaboration with R. T. Guza) analysis is ongoing and is not described here.

APPROACH

HB06 Dye Dispersion Modeling
Here, a Boussinesq wave-current model funwaveC has been coupled with a tracer evolution model. The model reproduces the observed wave and current conditions on the 5 days of HB06 dye releases. Dye tracer is released in the model, and the model dye tracer transport and dispersion is analyzed analogous to the observations (e.g., Clark et al., 2010a).

Shear Dispersion with Finite Lagrangian Time-Scale Eddies

Taylor (1953) showed that for along-pipe flow (which can be generalized to the alongshore current for surfzone flows) the shear-induced asymptotic diffusivity (or shear diffusivity) \( D_T \sim V^2 L^2 / \kappa \) where \( V \) is the along-pipe flow (alongshore current), \( L \) is the pipe width (surfzone width), and \( \kappa \) is the cross-pipe (cross-shore) diffusivity. This result holds for times longer than the cross-pipe (cross-shore) diffusion time \( \tau_D = L^2 / \kappa \). Taylor’s and all subsequent theoretical analyses require that the cross-pipe dispersion be Brownian, implying that all particle displacements are independent or that the Lagrangian time-scale \( \tau_L \) is zero (the time-lag Lagrangian velocity covariance is a delta function). This assumption is clearly not valid in many geophysical settings (e.g., the surfzone Spydell et al., 2007) where turbulent eddies have relatively large length- and time-scales. Analytic shear-dispersion expressions consistently under-predict the observed along-pipe (alongshore) dispersion (e.g., Spydell et al., 2009). The approach here, developed by Project Scientist Matt Spydell, is to extend the body of shear-dispersion theoretical work to include the effect of finite Lagrangian time-scale.

Small-scale Surfzone Turbulence

The vertical structure of turbulence in the surfzone is of interest. Both breaking waves and near-sea-bed shear are possible sources of turbulence. Here a key turbulence statistic, the turbulent dissipation rate \( \epsilon \) is estimated from Acoustic Doppler Velocimeters observations following Feddersen et al. (2007) and Feddersen (2010). The effect of both wave-breaking and bottom boundary layer processes (BBL) upon \( \epsilon \) are examined.

WORK COMPLETED

- Omand et al. (2009) and Clark et al. (2009a) have both been published. These manuscripts dealt with the technical details of making Chlorophyll and Rhodamine WT dye observations in the surfzone.
- A manuscript (Clark et al., 2010a) of the HB06 dye dispersion studies is in press to JGR Oceans.
- A manuscript (Feddersen, 2010) is in press to J. Atmospheric and Oceanic Tech.. This manuscript deals with the methods of analyzing Acoustic Doppler Velocimenter data for estimating the turbulent dissipation rate in the surfzone and air-sea boundary regions
- A manuscript (Omand et al., 2010a), reporting on the evolution and dynamics of a nearshore red tide observed during HB06, is revised to Limnology and Oceanography.
• A manuscript (Feddersen, 2010), on surfzone turbulence dynamics from HB06 observations is in preparation to JPO.

• A manuscript (Spydell and Feddersen, 2010), on a theoretical analysis of finite-Lagrangian time-scale on shear dispersion is in preparation to JFM, which is important in being able to explain alongshore drifter dispersion.

• The IB09 (Imperial Beach CA in Sept-Oct 2009) experiment was performed (PIs: Guza and Feddersen) and analysis is currently under way.

RESULTS

Background: HB06 Experiment

Observations were collected from 15 September to 17 October 2006 (800 hours) at Huntington Beach CA, a site with chronic water quality problems. A cross-shore transect of co-located pressure sensors and acoustic Doppler Velocimeters was deployed spanning 160 m out to 4 m mean water depth. The tide range was nominally $\pm 1$ m. The data was sampled at 8 Hz. The ADVs sampled between 0.5-1.0 m above the bed. The cross- and alongshore coordinate are $x$ and $y$, respectively. The mean water depth is given by $h$. At each of the frames, hourly estimates of significant wave height $H_{\text{sig}}$, mean alongshore current $\overline{v}$, and turbulent dissipation rate $\epsilon$ were estimated.

HB06 Dye Dispersion Modeling

Dye tracer, observed during the HB06 experiment, released relatively close to the shoreline, was transported alongshore by the alongshore current and dispersed in the cross-shore in a manner resembling a wall-bounded turbulent plume, analogous to a smokestack plume, with axis parallel to the shoreline (Clark et al., 2010a). An example (release 6) of the observed cross-shore mean tracer profiles $D(x, y_j)$, averaged over stirring and meandering, is shown for different downstream positions $y_j$ in Fig 1, top. The initially narrow $D(x, y_j)$ profiles disperse across the surfzone and peak concentrations decrease with downstream distance (increasing $y$) from the source (Fig 1, top). The observed $D(x, y_j)$ profiles are shoreline attached with maxima at or near the shoreline (Fig 1, top).

The modeled cross-shore mean tracer profiles as a function the same $y_j$ are shown in Fig. 1, bottom. The model $\overline{D}(x, y_j)$ also is maximum near the shoreline and disperses in the cross-shore with increasing downstream distance. The relatively good agreement between the observed and model $D(x, y_j)$, indicates that the model is reproducing the surfzone mixing mechanisms that induce the dispersion.

The cross-shore tracer dispersion is quantified by examining the time evolution of the 2nd tracer moment (or squared half-width) $\sigma^2_{\text{surf}}$ defined as

$$\sigma^2_{\text{surf}}(y_j) = \int x^2 D(x, y_j)dx,$$

(1)
where the integral is over the surfzone width. Together with an alongshore-advection pseudo-time \( t_p \) (defined as \( t_p = y/V \), where \( V \) is the surfzone-averaged mean alongshore current), the cross-shore surfzone diffusivity is defined \( \kappa_{xx} = (1/2)d\sigma_{surf}^2/dt_p \).

The release 6 observed \( \sigma_{surf}^2 \) grows linearly with time for \( t_p < 2000 \) s, indicating Brownian diffusion within the surfzone (Fig. 2, top) with a observed surfzone cross-shore diffusivity \( \kappa_{xx} = 0.5 \) \( \text{m}^2 \text{s}^{-1} \). After saturating the surfzone the \( \sigma_{surf}^2 \) remains constant as it is advected downstream (\( t_p > 2000 \) s, Fig. 2, top). The model \( \sigma_{surf}^2 \) also grow linearly with time similar to the observations and result in a model \( \kappa_{xx} = 0.55 \) \( \text{m}^2 \text{s}^{-1} \), very close to the observed. At longer \( t_p \), the modeled \( \sigma_{surf}^2 \) also remains constant indicating surfzone saturation of tracer. The agreement between modeled and observed \( \kappa_{xx} \), as well as \( \sigma_{surf}^2 \), demonstrates that the model \textit{funwaveC} is reproducing the observed dispersion and that the dominant mixing mechanisms are contained within the model. Model-data comparison with other dye tracer releases is nearing completion (Clark et al., 2010b).
Shear Dispersion with Finite Lagrangian Time-Scale Eddies

The details of the theoretical analyses are skipped over here. For full details refer to Spydell and Feddersen (2010). The primary result is that for finite-Lagrangian time-scale, the asymptotic shear diffusivity $D_s^\infty$ is enhanced over the Taylor (1953) diffusivity $D_T$ which assumes zero Lagrangian time-scale. The ratio $D_s^\infty / D_T$ is always $\geq 1$ and is a function of $\tau_L / \tau_D$ (Fig. 3). The effect of non-zero $\tau_L$ can be quite significant. At $\tau_L / \tau_D = 0.1$, the asymptotic shear dispersion is enhanced a factor of 3 over Taylor dispersion (i.e., $D_s^\infty / D_T = 3$, Fig. 3) and for $\tau_L / \tau_D = 1$, the effect is large and $D_s^\infty / D_T = 10$. Thus, coherent turbulent eddies with non-negligible time-scales relative to cross-pipe diffusion can significantly modify, in some cases significantly, the asymptotic along-pipe (alongshore) dispersion. In the surfzone, typically $\tau_D = O(1000) \text{ s}$ and $\tau_L = O(200) \text{ s}$ (Spydell et al., 2009). Thus, the effect may be significant and can explain the factor 3-4 underprediction by the classic Taylor shear diffusivity (Spydell et al., 2009).

Small-scale Surfzone Turbulence: Importance of Bottom Boundary Layer Processes?

During the HB06 experiment, the turbulent dissipation rate $\epsilon$ typically was significantly larger (by a factor of 10) within the surfzone relative to seaward of the surfzone, suggesting the impor-
Figure 3: The ratio of the asymptotic shear diffusivity to the Taylor diffusivity $D_S^\infty/D_T$ versus $\tau_{L,y}/\tau_{D,y}$, the ratio of the Lagrangian to diffusive time-scale to the diffusive time scale. The "exact" (numerically integrated) formula is thin solid black line, the small Lagrangian time-scale approximation is the thick solid gray line, the large Lagrangian time-scale asymptotic solution is the thick dashed gray line, and the leading term of this solution is the thin dashed black line.

tance of wave breaking to surfzone turbulence. However, bottom boundary layer processes (BBL) may also be important as alongshore currents $\tau$ were stronger within the surfzone. In typical BBL situations, the dissipation rate scales as $\epsilon = u_*^2/(\kappa z)$ where $u_*$ is the bottom friction velocity and $\kappa$ is Von Karman’s constant, and $z$ is the height above the bed. To examine the relative importance of BBL processes within and seaward of the surfzone, a non-dimensional dissipation $\epsilon\kappa z/u_*^3$ is examined (Fig. 4).

For both surfzone and seaward of the surfzone locations, $\epsilon\kappa z/u_*^3 > 1$, but approaches for larger $\tau$. For surfzone locations with $|\tau| > 0.4$ m/s, $\epsilon\kappa z/u_*^3$ is roughly constant at $\approx 3$, indicating that BBL processes can be important within the surfzone. At $|\tau| < 0.4$ ms$^{-1}$, the ratio $\epsilon\kappa z/u_*^3$ is larger within the surfzone relative to seaward of the surfzone, indicating the effect of breaking-wave generated turbulence. This analysis is one aspect of a detailed examination of the dynamics and scalings of the surfzone turbulent dissipation rate (Feddersen, 2010).

**IMPACT/APPLICATIONS**

Potential impacts include improving surfzone and nearshore mixing parameterizations based upon bulk factors such as wave height, wave period, bathymetry, and currents.

**RELATED PROJECTS**

The Tidal-Inlets/River-Mouths DRI project is building upon the dye tracer and drifter results here, but with expanded geographical scope to include a tidal inlet.
Figure 4: Binned-mean and standard-deviation of $\epsilon \kappa z / u^3$ versus mean alongshore current magnitude $|\vec{v}|$ at (a) locations seaward (blue, diamonds) and within (red, circles) the surfzone. The horizontal dash-dot line represents $\epsilon \kappa z / u^3 = 1$.

References


Feddersen, F., Quality Controlling Surfzone Acoustic Doppler Velocimeter Observations to Estimate the Turbulent Dissipation Rate, J. Atmospheric Oceanic Tech., in press, 2010.


**PUBLICATIONS**

Recent publications acknowledging ONR support during this support period can be downloaded at [http://iod.ucsd.edu/~falk/papers.html](http://iod.ucsd.edu/~falk/papers.html) and inude.


