

## Modeling surf zone tracer plumes:

### 2. Transport and dispersion

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Received 11 April 2011; revised 26 August 2011; accepted 29 August 2011; published 18 November 2011.

[1] Five surf zone dye tracer releases from the HB06 experiment are simulated with a tracer advection diffusion model coupled to a Boussinesq surf zone model (funwaveC). Model tracer is transported and stirred by currents and eddies and diffused with a breaking wave eddy diffusivity, set equal to the breaking wave eddy viscosity, and a small ( $0.01 \text{ m}^2 \text{ s}^{-1}$ ) background diffusivity. Observed and modeled alongshore parallel tracer plumes, transported by the wave driven alongshore current, have qualitatively similar cross-shore structures. Although the model skill for mean tracer concentration is variable (from negative to 0.73) depending upon release, cross-shore integrated tracer moments (normalized by the cross-shore tracer integral) have consistently high skills ( $\approx 0.9$ ). Modeled and observed bulk surf zone cross-shore diffusivity estimates are also similar, with 0.72 squared correlation and skill of 0.4. Similar to the observations, the model bulk (absolute) cross-shore diffusivity is consistent with a mixing length parameterization based on low-frequency (0.001–0.03 Hz) eddies. The model absolute cross-shore dispersion is dominated by stirring from surf zone eddies and does not depend upon the presence of the breaking wave eddy diffusivity. Given only the bathymetry and incident wave field, the coupled Boussinesq-tracer model qualitatively reproduces the observed cross-shore absolute tracer dispersion, suggesting that the model can be used to study surf zone tracer dispersion mechanisms.

**Citation:** Clark, D. B., F. Feddersen, and R. T. Guza (2011), Modeling surf zone tracer plumes: 2. Transport and dispersion, *J. Geophys. Res.*, 116, C11028, doi:10.1029/2011JC007211.

### 1. Introduction

[2] The rates and mechanisms of surf zone horizontal tracer (e.g., pollution, nutrients, sediment, and larvae) dispersion are understood poorly, and numerical models may be useful for investigating the underlying dispersion processes. However, numerical surf zone tracer models have not been validated, a necessary step before investigating dispersion mechanisms.

[3] Surf zone tracer dispersion has been modeled analytically and numerically. Simple Fickian analytic models were used to estimate bulk surf zone diffusivity from field data [Harris *et al.*, 1963; Inman *et al.*, 1971; Clarke *et al.*, 2007; Clark *et al.*, 2010]. Fickian models may be able to predict bulk surf zone tracer dispersion with the appropriate diffusion coefficient. However, surf zone diffusivity values are poorly known, and diffusivity parameterizations have not been validated over a broad range of conditions. Coupled tracer and (wave-averaged) circulation models have been sparingly used to simulate tracer transport in the nearshore and surf zone [Tao and JianHua, 2006; Issa *et al.*, 2010], but com-

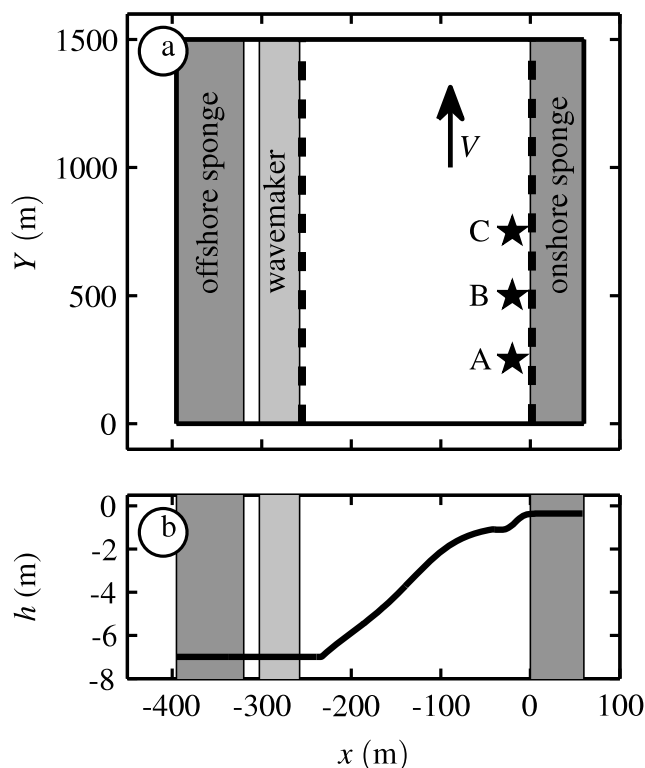
parisons with observations are very limited [Rodriguez *et al.*, 1995].

[4] Scaling arguments [Harris *et al.*, 1963; Inman *et al.*, 1971] and an idealized model [Feddersen, 2007; Henderson, 2007] suggest that the bulk (averaged over many waves) cross-shore tracer diffusivity  $\kappa_{xx}$  from turbulent mixing at the front face of broken waves (bores) scales as  $\kappa_{xx} \propto H_s^2 T_m^{-1}$ , where  $H_s$  and  $T_m$  are the incident significant wave height and mean period, respectively. However, this scaling had marginal correlation ( $r^2 = 0.32$ ) when compared with recently observed bulk cross-shore dye diffusivities [Clark *et al.*, 2010]. Stirring due to low-frequency ( $f < 0.03$  Hz) horizontal surf zone eddies may induce a significant amount of cross-shore tracer dispersion. Higher correlation ( $r^2 = 0.59$ ) was found for a surf zone–eddy mixing length scaling  $\kappa_{xx} \propto \overline{V}_{\text{rot}}^{(IG)} L_x$ , where  $L_x$  is the surf zone width and  $\overline{V}_{\text{rot}}^{(IG)}$  is a surf zone (cross-shore) averaged bulk infragravity (0.004–0.03 Hz) eddy velocity, suggesting that low-frequency eddies may be a primary dispersion mechanism [Clark *et al.*, 2010]. An undertow-induced cross-shore shear dispersion scaling [Pearson *et al.*, 2009] was not found to be applicable [Clark *et al.*, 2010]. Overall, the mechanisms of tracer dispersion and their relative importance are not well understood.

[5] Time-dependent wave-resolving surf zone models (most commonly Boussinesq models), include the broad range of processes, from individual breaking waves to low-frequency eddies and mean currents, required for investigating surf zone tracer dispersion mechanisms. Boussinesq surf

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**Figure 1.** (a) Plan view of a typical model domain (R4 example). The cross-shore distance from the “shoreline” is  $x$ , and  $Y$  is the alongshore coordinate. Gray regions indicate sponge layers and the wave maker. The cross-shore tracer domain (dashed lines) is bounded by the offshore wave maker and the onshore sponge layer. Stars indicate release locations for model tracers A ( $Y_{rl} = 250$  m), B ( $Y_{rl} = 500$  m), and C ( $Y_{rl} = 750$  m), and the arrow indicates the direction of the mean alongshore current  $V$ . (b) Typical model cross-shore bathymetry  $h$  versus  $x$  (R4 example), with a flat region at 7 m depth for the offshore sponge layer and wave maker and a 0.3 m depth flat region for the onshore sponge layer.

zone models, solving an extended version of the nonlinear shallow water equations with weak nonlinearity and dispersion [e.g., *Peregrine*, 1967; *Nwogu*, 1993; *Wei et al.*, 1995], have been used to examine surf zone drifter dispersion in directionally spread random wave fields [*Johnson and Pattiaratchi*, 2006; *Spydell and Feddersen*, 2009; *Geiman et al.*, 2011], but have not been used for surf zone tracer modeling. Finite crest length wave breaking within Boussinesq models provide a (vertical) vorticity source for forcing horizontal eddies [*Peregrine*, 1998] at a range of length scales, which induced surf zone drifter dispersion at scales between 20 and 200 m [*Spydell and Feddersen*, 2009]. Surf zone drifters duck under, and are not dispersed by entrainment in, the front face of breaking waves [e.g., *Schmidt et al.*, 2003, 2005]. By resolving individual wave breaking, Boussinesq models also provide a mechanisms for breaking waves to mix tracer. Thus, a depth-averaged tracer advection diffusion equation coupled to a Boussinesq model contains both stirring by the horizontal eddy field (e.g., vertical vorticity) and the breaking wave mixing mechanisms.

[6] Here, five surf zone tracer releases from the HB06 experiment in Huntington Beach, California [*Clark et al.*,

2010] are simulated with the coupled tracer and Boussinesq model funwaveC. The Boussinesq model is described by *Feddersen et al.* [2011] (hereinafter referred to as Part 1), and compared with Eulerian wave and current observations. The model reproduces the observed significant wave height and (except for one release) alongshore currents. Low-frequency eddies are well modeled in the infragravity frequency ( $f$ ) band ( $0.004 < f < 0.03$  Hz), but are overpredicted by a factor of 2 in the very low frequency (VLF,  $0.001 < f < 0.004$  Hz) band. The HB06 tracer experiments and previous results are summarized in section 2. The tracer model and averaging method are described in section 3.

[7] Mean tracer concentrations are well modeled for 3 out of 5 releases (section 4). For all releases, model skills for cross-shore integrated tracer first and second moments are high, and the model reproduces the observed bulk cross-shore surf zone diffusivity (section 5). The causes of model-data mismatch for mean tracer and alongshore tracer transport are discussed in sections 6.1 and 6.2, respectively. The downstream dilution of the modeled mean plume is consistent with a Fickian analytic solution (section 6.3). The effect of the modeled breaking wave eddy diffusivity on cross-shore tracer dispersion is discussed in section 6.4. Mixing length scalings for modeled bulk cross-shore diffusivity  $\kappa_{xx}$ , using bulk low-frequency eddy velocities, are examined in section 6.5. The results are summarized in section 7.

## 2. HB06 Observations and Dye Releases

[8] The predominant south swell during the HB06 experiment drove strong alongshore currents upcoast (toward the northwest). Waves and currents were measured on a 140 m long cross-shore array of 7 bottom mounted tripods, denoted F1–F7 from near the shoreline to roughly 4 m water depth (Part 1, Figure 1). The observations at F2 were often poor quality, and are not included in the subsequent analysis. Hourly significant wave heights  $H_s$  ranged from 0.41 to 1.02 m during the tracer releases, with mean wave periods  $T_m$  from 9 to 9.9 s, and directional spreads  $\sigma_\theta$  from  $15^\circ$  to  $23^\circ$ . Mean (in time) alongshore currents  $V(x)$  (where  $x$  is the cross-shore distance from the shoreline) were generally maximum near mid surf zone, except for one release with maximum  $V(x)$  near the shoreline. Eulerian wave and current observations are described by *Clark et al.* [2010] and compared with the funwaveC Boussinesq model in Part 1.

[9] Five continuous dye tracer releases (denoted R1, R2, R3, R4, and R6) were performed on different days [*Clark et al.*, 2010]. Dye tracer was injected 0.5 m above the bed in roughly 1 m water depth (4–54 m from the shoreline), at rates between  $1.3$ – $7.1$  mL  $s^{-1}$  ( $263$ – $1489$  ppb  $m^3 s^{-1}$ ). The tracer was advected downstream with the mean alongshore current, forming shore parallel plumes, and measured near the surface for between 40 and 121 min (depending on the release) with a jet ski mounted fluorometer system [*Clark et al.*, 2009].

[10] Visual observation indicated rapid vertical tracer mixing (tracer reaching the surface within several meters of the source), and patchy and highly variable tracer plumes. Dye was sampled on repeated cross-shore transects at 3–9 downstream locations, between 16 and 565 m from the tracer source. With increasing downstream distance  $y$  from the dye source, the mean cross-shore tracer profile  $D(x, y)$  peak

**Table 1.** Model Tracer Release Parameters: Input Tracer Flux  $M_0$  and Cross-Shore Release Location  $x_{r1}$ 

Release	$M_0$ (ppb m <sup>3</sup> s <sup>-1</sup> )	$x_{r1}$ (m)
R1	263	-54
R2	647	-13
R3	1256	-10
R4	1489	-22
R6	485	-12

concentrations decreased and cross-shore widths increased. The cross-shore profiles were often shoreline attached, roughly resembling a half-Gaussian, with a maxima near the shoreline. Bulk cross-shore surf zone diffusivities  $\kappa_{xx}$  were estimated from the downstream evolution of the plume squared cross-shore length scale, and varied between 0.5 and 2.5 m<sup>2</sup> s<sup>-1</sup> [Clark *et al.*, 2010].

### 3. Surf Zone Tracer Modeling and Analysis

#### 3.1. Tracer Model Description

[11] The 5 tracer releases analyzed by Clark *et al.* [2010] are simulated with a time-dependent wave-resolving Boussinesq model (funwaveC, Part 1). The model bathymetry is based on the observed alongshore-averaged survey bathymetry (Figure 1b). Waves matching the observed incident angle, directional spread, and energy spectrum are generated by the model wave maker, and propagate toward the shore where they “break” and dissipate (by the breaking eddy viscosity  $\nu_{br}$ ). Model wave breaking drives alongshore currents and low-frequency ( $f < 0.03$  Hz) surf zone eddies. The observed significant wave height  $H_s(x)$ , mean alongshore current  $V(x)$ , and bulk rotational infragravity (IG) velocities  $\mathcal{V}_{rot}^{(IG)}(x)$  are modeled with high skill. Bulk very low frequency (VLF) rotational velocities were overpredicted by about a factor of 2 (Part 1).

[12] A depth-averaged tracer module, coupled to the time-dependent Boussinesq model funwaveC, allows for three separate noninteracting tracers (denoted A, B, and C) released at different locations. Each tracer samples a different part of the flow field, increasing the degrees of freedom for quantities averaged over the statistics of all three tracers. Model tracer evolves according to an advection-diffusion equation,

$$\frac{\partial[(h + \eta)d]}{\partial t} + \nabla \cdot [(h + \eta)\mathbf{u}d] = \nabla \cdot [(\kappa_{br} + \kappa_0)(h + \eta)\nabla d] + M_0\delta(x - x_{r1})\delta(Y - Y_{r1}) \quad (1)$$

where  $d$  is the tracer concentration (in ppb),  $h$  is the still water depth,  $\eta$  is the free surface elevation,  $\kappa_{br}$  is the breaking wave eddy diffusivity,  $\kappa_0$  is the background diffusivity,  $\nabla$  is the two-dimensional horizontal gradient operator, and  $\mathbf{u}$  is the model horizontal velocity vector, which for small  $kh$  is approximately the depth-averaged velocity. Tracer is injected into the model at ( $x = x_{r1}$ ,  $Y = Y_{r1}$ ) with the input flux  $M_0$  ( $\delta$  is the Kronecker delta function).

[13] In (1),  $\kappa_{br}$  is set equal to the breaking wave eddy viscosity  $\nu_{br}$  (e.g., momentum and tracer are assumed to mix identically), and the background diffusivity  $\kappa_0 = 0.01$  m<sup>2</sup> s<sup>-1</sup>, is two orders of magnitude smaller than the observed bulk  $\kappa_{xx}$ . The  $\kappa_{br}$  is nonzero only on the front face of a breaking wave

(bore), whereas  $\kappa_0$  is applied everywhere. The inclusion of the breaking eddy viscosity allows the breaking wave mixing mechanism discussed by Feddersen [2007] to be examined relative to other tracer dispersion mechanisms.

[14] The vertically integrated Boussinesq and tracer models lack cross-shore dispersion by vertically sheared currents (i.e., undertow). However, this mechanism was not found to be significant in a natural surf zone with directionally spread waves [Clark *et al.*, 2010], and rapid vertical mixing [Feddersen and Trowbridge, 2005; Ruessink, 2010; Feddersen, 2011] implies little vertical tracer structure within the surf zone. However, vertical structure may be important seaward of the surf zone [Kim and Lynett, 2010].

[15] The cross-shore tracer domain (dashed lines, Figure 1a) is embedded in the full Boussinesq model domain. The offshore tracer boundary (set to  $d = 0$  ppb) is located just onshore of the wave maker region between  $x = 232$  and 260 m from the shoreline, depending upon release. The onshore tracer boundary is typically located  $\approx 5$  m onshore of the start of the sponge layer (the depth of the flat region is  $h_0 = 0.2$ – $0.35$  m), where a no-flux boundary condition is applied. In contrast to the  $\eta$  and  $\mathbf{u}$  periodic alongshore boundary conditions, the tracer alongshore boundary conditions (at both ends of the 1500 m alongshore domain) are open, allowing tracer to advect out of the domain (Figure 1a). The alongshore tracer boundary conditions affect tracer concentrations within approximately 25 m of the boundary, and these regions are excluded from the analysis.

[16] The model spins up for 2000 s before starting continuous releases of tracers A, B, and C at alongshore locations  $Y_{r1} = 250, 500,$  and  $750$  m, respectively, from the upstream boundary (Figure 1a). Model and observed cross-shore release locations  $x_{r1}$  and tracer injection rates  $M_0$  are equal (Table 1). Model instantaneous tracer concentrations  $d^{(A,B,C)}$ , sea surface elevation  $\eta$ , cross-shore and alongshore currents ( $u$  and  $v$ ), and breaking wave eddy diffusivity  $\kappa_{br}$  are output every 2 s over the entire domain.

#### 3.2. Model Tracer Analysis: Averaging

[17] The model tracer advects downstream with the mean alongshore current forming a shore-parallel plume that widens with downstream distance. Instantaneous  $d^{(A)}$  model tracer plumes (Figures 2a, 2c, and 2e) are variable and patchy, with eddy-like tracer structure seaward of the surf zone ( $x < -100$  m). The cross-shore structure of modeled low-frequency rotational motions (i.e., eddies) is discussed in Part 1.

[18] The  $D^{(A)}(x, y)$ ,  $D^{(B)}(x, y)$ , and  $D^{(C)}(x, y)$  represent mean modeled tracers A, B, and C, time averaged in a fixed reference frame ( $x = 0$  m at the shoreline and  $y = 0$  m at the release location) between 6000 and 14,000 s after the tracer release started. Time averaging begins once the tracer plume has reached quasi-equilibrium (see Figure 3). The averaging times used for the observed means  $D^{(obs)}$  are limited by instrument and environmental parameters to between 40 and 120 min. The model averages are over 133 min (8000 s) after tracer is equilibrated (Figure 3). Stability of the numerical results is further increased by averaging statistics over tracers A, B, and C. Averages over one 5600 s wave maker recurrence cycle (Part 1) are nearly identical to the 8000 s averages presented here, suggesting the wave maker recurrence does not effect the tracer results significantly. The observed  $D^{(obs)}$



















