



Physical dynamics controlling variability in nearshore fecal pollution: Fecal indicator bacteria as passive particles

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ABSTRACT

We present results from a 5-h field program (HB06) that took place at California's Huntington State Beach. We assessed the importance of physical dynamics in controlling fecal indicator bacteria (FIB) concentrations during HB06 using an individual based model including alongshore advection and cross-shore variable horizontal diffusion. The model was parameterized with physical (waves and currents) and bacterial (*Escherichia coli* and *Enterococcus*) observations made during HB06. The model captured surfzone FIB dynamics well (average surfzone model skill: 0.84 [*E. coli*] and 0.52 [*Enterococcus*]), but fell short of capturing offshore FIB dynamics. Our analyses support the hypothesis that surfzone FIB variability during HB06 was a consequence of southward advection and diffusion of a patch of FIB originating north of the study area. Offshore FIB may have originated from a different, southern, source. Mortality may account for some of the offshore variability not explained by the physical model.

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1. Introduction

Approximately 90% of California's beach closures are due to elevated levels of fecal indicator bacteria (FIB) (Dufour and Wymer, 2006). FIB are nonpathogenic enteric bacteria, present at high concentrations in human and animal wastes, that are used to track bacterial pathogens in coastal systems (Sinton et al., 1993). FIB are released from contaminated sources – often non-point source run-off or riverine discharge – become suspended in the surfzone (coastal waters shoreward of the breaker line), and are transported to beaches (Boehm et al., 2002, 2005; Grant et al., 2005). The spatial and temporal distribution of FIB sources, and the dynamics of the surfzone through which FIB are transported, play an important role in regulating the extent and intensity of beach bacterial contamination. Furthermore, because FIB survival in the surfzone determines the duration of transport, factors regulating FIB growth and mortality in coastal waters are also central to our understanding of bacterial pollution (Anderson et al., 2005; Boehm, 2003; Boehm et al., 2005).

Beach pollution events are often poorly predicted, and about 40% of contamination postings are erroneous (Kim and Grant, 2004). With over 550 million annual person-visits to California beaches, this inaccuracy impacts both individual beach goers and California's multi-billion dollar coastal tourism industry (Grant et al., 2001). Predictive modeling of bacterial pollution using read-

ily measured (or modeled) physical parameters (wave height/direction, river flow, rainfall, etc.) could be a cost-effective way to improve the accuracy of beach contamination postings. However, to be effective in a range of settings, these models require mechanistic understanding of bacterial sources, transports, and extra-enteric growth or decay. Mechanistic understanding moves beyond correlations, and examines the effects of individual processes structuring beach pollution.

Currently, mechanistic FIB models range in complexity from simple mass balance equations (Boehm, 2003; Boehm et al., 2005; Kim et al., 2004) to 3D hydrodynamic simulations (Sanders et al., 2005; Liu et al., 2006; Thupaki et al., 2010; de Brauwere et al., 2011; Zhu et al., 2011). In conjunction with field observations and laboratory studies, these models have been used to identify processes structuring nearshore FIB contamination such as alongshore currents (Kim et al., 2004; Liu et al., 2006; Thupaki et al., 2010), tides (de Brauwere et al., 2011), internal waves (Wong et al., 2012), rip cells (Boehm, 2003; Boehm et al., 2005), cross-shore diffusion (Thupaki et al., 2010; Zhu et al., 2011), sediment resuspension (Sanders et al., 2005), solar insolation (Boehm et al., 2009; Liu et al., 2006; Thupaki et al., 2010), and temperature (de Brauwere et al., 2011). To date, however, only a handful of studies have used models to look at the relative importance of these processes in the nearshore. Thupaki et al. (2010) used a 3D hydrodynamic model to show that FIB loss in Lake Michigan due to alongshore current reversals and diffusion was over an order of magnitude greater than loss due to mortality. Zhu et al. (2011), however, revealed the opposite pattern in a quiescent Florida embayment. Furthermore, simple mass budget models for Califor-

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nia's Huntington State Beach suggest that multiple processes can interchangeably dominate FIB dynamics (Boehm, 2003; Kim et al., 2004; Boehm et al., 2005; Grant et al., 2005). Taken together, these studies imply that the processes controlling surfzone FIB are likely to vary both in time (at a given beach), and space (beach to beach). Thus far, however, our analyses have been limited to the most nearshore of waters, as the majority of FIB data collected and used to calibrate models come from ankle- to knee-deep samples (Grant et al., 2001; Boehm, 2003; Liu et al., 2006; Thupaki et al., 2010). Recreational beach use, especially in California (where surfing is common), is not limited to the shoreline. This makes it important to evaluate FIB contamination and the processes controlling it over wider recreational domains where physical processes are different, and FIB survivorship may also change (Davies-Colley et al., 1994; Kim et al., 2004).

Here we present results from an along and cross-shore resolved field program with joint physical and bacterial observations designed to identify the dominant mechanisms controlling FIB variability within (and seaward) of the surfzone. By directly measuring currents out to 300 m cross-shore, we both enable the evaluation FIB flow fields over appropriate recreational domains, and avoid estimating current velocity from wave direction or along-shore drift, which has increased uncertainty in other models (Boehm, 2003; Kim et al., 2004). In the present paper we focus on quantifying the contribution of physical processes (advection and diffusion) to observed FIB patterns, and developing a best-fit physical model from this analysis. The contribution of biological processes to nearshore FIB variability is addressed in Rippey et al. (2012).

2. Methods

2.1. Field site description

Southern California's Huntington State Beach is ~3.2 km long, with chronically poor surfzone water quality (Grant et al., 2001; Kim et al., 2004). At its southern end, the beach receives brackish flows from the Talbert Marsh (TM) and the Santa Ana River (SAR), both of which have been implicated as sources of surfzone FIB (Kim et al., 2004). In fall 2006, a multi-institutional field campaign ("HB06") focused on observing nearshore waves, currents, temperature, phytoplankton, and FIB at this beach. The present study concerns the bacterial component of HB06, a 5-h FIB survey with high spatial and temporal resolution conducted on October 16th along transects extending 1 km north of the TM/SAR outlets, and 300 m offshore.

2.2. FIB sampling program

2.2.1. Sample collection and processing

FIB concentrations were measured at 8 stations: 4 in knee-deep water along a 1000 m alongshore transect north of SAR (SAR, TM, FHM, F1; Fig. 1), and 4 along a 300 m cross-shore transect starting at F1 (knee-deep water), and terminating at an offshore Orange County Sanitation District mooring (OM) in ~8 m mean water depth (F1, F3, F5, F7, OM; Fig. 1). Every 20 min, from 0650 h to 1150 h PDT, 100 ml water samples were taken at all stations. Samples were stored on ice and transported to the Orange County Sanitation District (OCS) within 6 h of collection. All samples were analyzed for *Escherichia coli* (IDEXX Colilert) and *Enterococcus* (EPA method 1600) concentrations by OCS personnel.

2.2.2. Spatial and temporal patterns in bacterial decay

Temporal rates of FIB loss were estimated for each station from regressions of log (FIB) versus time. We refer to these FIB loss rates as "decay", where decay includes removal/dilution due to advec-

tion and diffusion as well as biological mortality. In contrast, the term "mortality" will be used to denote the portion of decay that is due to FIB senescence alone, and is *not* caused by the measured physical processes.

At stations where FIB concentrations dropped below minimum sensitivity standards for our bacterial assays (<10 MPN/100 ml for *E. coli* or <2 CFU/100 ml for *Enterococcus*) prior to the end of the study period, decay rates were calculated using only data up until these standards were reached (SI Fig. 1). Decay rates were compared across sampling stations to look for spatial patterns in bacterial loss. Decay rates were also compared across FIB groups (*E. coli* vs. *Enterococcus*) to identify group-specific patterns. Statistical analyses were performed using MATLAB (Mathworks, Natick, MA).

2.2.3. Nearshore instrumentation

Pressure sensors and Acoustic Doppler velocimeters (ADV's) (Sontek, 2004), both sampling at 8 Hz, were placed in the nearshore to monitor the wave and current field during our study. All instruments were mounted on tripod frames fixed on the seafloor at seven locations (F1–F7) along the shoreward-most 150 m of the cross-shore transect shown in (Fig. 1.). Cross-shore resolved estimates of the alongshore current field were determined using 20 min averaged alongshore water velocities from each ADV.

2.3. 2D individual based FIB model

The contribution of physical processes in structuring FIB concentrations during HB06 was quantified using a 2D (x = alongshore, y = cross-shore) individual-based advection–diffusion or "AD" model for FIB (informed by the model of Tanaka and Franks, 2008). Only alongshore advection, assumed to be uniform alongshore, was included in the model. Both cross-shore and alongshore diffusivities were also included. These were assumed to be equal at any point in space, and alongshore uniform. The cross-shore variation of diffusivity was modeled as:

$$\kappa_h = \kappa_0 + \frac{(\kappa_1 - \kappa_0)}{2} \left(1 - \tanh\left(\frac{(y - y_0)}{y_{scale}}\right) \right) \quad (1)$$

Here κ_0 is the background (offshore) diffusivity, κ_1 is the elevated surfzone diffusivity (Reniers et al., 2009; Spydell et al., 2007), y_0 is the observed cross-shore midpoint of the transition between κ_0 and κ_1 (i.e., the offshore edge of the surfzone) and y_{scale} determines the cross-shore transition width. Representative values of κ_1 ($0.5 \text{ m}^2 \text{ s}^{-1}$) and κ_0 ($0.05 \text{ m}^2 \text{ s}^{-1}$) were chosen based on incident wave height and alongshore current measurements (Clark et al., 2010; Spydell et al., 2009). The observed width of the surfzone (i.e., the region of breaking waves) was used to determine y_0 . Significant wave height was maximum at F4 and low at F1 and F2, suggesting that the offshore edge of the surfzone was between F2 and F4 (Fig. 2a); thus $y_0 = 50 \text{ m}$, near F3. To give a rapid cross-shore transition between surfzone (F2) and offshore (F4) diffusivity, y_{scale} was set to 5 m (SI Fig. 2). The AD model was only weakly sensitive to the parameterization of y_{scale} , κ_0 and κ_1 , with sensitivity varying by station (SI Fig. 3). Cross-shore advection was not included in the model, as alongshore samples were taken from the same water depth each time (i.e., following the tidal excursion). Neglecting cross-shore advection (including rips, etc.) will generally lead to conservative estimates of the contribution of physical dilution to FIB decay.

2.3.1. Particle motions

In the AD model, FIB particles are advected alongshore by 20 min average currents (u), that vary in the cross-shore (y). FIB particles diffuse along- and cross-shore by horizontal diffusion (κ_h). For a particle starting at (x_t, y_t) , its position at $(x_{t+\Delta t}, y_{t+\Delta t})$ is:

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