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Nearshore Tracer Fate: Observations and Modeling of Cross-Shore Exchange Between the Surfzone and Inner-Shelf

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Nearshore Tracer Fate: Observations and Modeling of Cross-Shore Exchange Between the Surfzone and Inner-Shelf

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy in Oceanography by

Kai Hally-Rosendahl

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2015
The dissertation of Kai Hally-Rosendahl is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

University of California, San Diego

2015
DEDICATION

I dedicate this work to my father, John Rosendahl
(1955 – 9/1/2012).
I love and miss you, Dad.
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ABSTRACT OF THE DISSERTATION

Nearshore Tracer Fate: Observations and Modeling of Cross-Shore Exchange Between the Surfzone and Inner-Shelf

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Doctor of Philosophy in Oceanography

University of California, San Diego, 2015

Professor Falk Feddersen, Chair

The nearshore region, consisting of the surfzone (shoreline to seaward boundary of depth-limited wave breaking) and inner-shelf (surfzone boundary to \( \approx 20 \) m water depth), is vitally important to coastal economies, recreation, and human and ecosystem health. Yet, despite the detriments of frequently contaminated coastal water, dynamical complexities of the surfzone/inner-shelf interface have limited our understanding of nearshore transport and dilution.

A shoreline-source contaminant’s fate is ultimately determined by its exchange with the inner-shelf. Here, cross-shore exchange is examined with coupled surfzone/inner-shelf observations of temperature and dye during two continuous releases at alongshore-uniform Imperial Beach, CA. Dye is mixed and alongshore-
transported in the surfzone while being ejected to the inner-shelf by transient rip currents (TRCs). The second release is simulated with a wave-resolving model.

In situ 29 September observations reveal a vertically-mixed surfzone that is warmer than the inner-shelf, where elevated temperature and dye co-occur in alongshore-narrow TRC ejections and are depth-uniform in a warm upper layer. Below, stratification limits vertical dye mixing to magnitudes of ocean interiors, despite proximity to the well-mixed surfzone. A temperature-derived bulk cross-shore exchange velocity \( u^*_T = 0.9 \times 10^{-2} \, \text{m s}^{-1} \) suggests TRCs dominate the exchange.

Observations from 13 October include aerial-based multispectral dye images, enabling novel surfzone/inner-shelf tracer mass budget closure. Over 5 h and 3.25 km downstream, 1/2 the surfzone-released dye is transported offshore to the inner-shelf. Near-shoreline dye follows power-law decay (exponent \(-0.33\)). Observed cross-shore transports are parameterized well using a bulk exchange velocity and mean surfzone/inner-shelf dye difference. The best-fit velocity \( u^* = 1.2 \times 10^{-2} \, \text{m s}^{-1} \) is similar to temperature-derived \( u^*_T \) from 29 September. The \( u^* \) magnitude, inner-shelf dye vertical structure, time- and length-scales indicate TRC dominance again during this release.

The 13 October release is simulated with the wave-resolving, Boussinesq model funwaveC, which generates TRCs but does not resolve inner-shelf vertical variation. The model largely reproduces observed dye cross-shore profiles, alongshore transport, near-shoreline power-law decay, and surfzone/inner-shelf mass budgets for \( 1.2 \times 10^4 \, \text{s} \). Thereafter, inner-shelf (surfzone) dye is somewhat over-predicted (under-predicted), possibly due to funwaveC’s lack of tide or vertical variation. The good overall model–data agreement indicates that nearshore tracer dispersion is realistically simulated, and that the funwaveC TRCs accurately induce cross-shore surfzone/inner-shelf exchange.
Chapter 1

Cross-Shore Tracer Exchange Between the Surfzone and Inner-Shelf

1.1 Abstract

Cross-shore tracer exchange between the surfzone and inner-shelf is examined using temperature and dye measurements at an approximately alongshore-uniform beach. An alongshore-oriented plume is created by releasing dye continuously for 4.5 h in a surfzone alongshore current. The plume is sampled for 13 h from the release point to 700 m downstream, between the shoreline and 250 m offshore (6 m water depth). Within the surfzone ($\leq 2$ m depth), water is relatively warm, and dye is vertically well-mixed. On the inner-shelf (3–6 m depth), alongshore currents are weak, and elevated temperature and dye co-occur in 25–50 m-wide alongshore patches. Within the patches, dye is approximately depth-uniform in the warm upper 3 m where thermal stratification is weak, but decreases rapidly below 3 m with a strong thermocline. Dye and temperature vertical gradients are correlated, and dye is not observed below 18 °C. The observations and a model indicate that, just seaward of the surfzone, thermal stratification inhibits vertical mixing to magnitudes similar to those in the ocean interior. Similar surfzone and
inner-shelf mean alongshore dye dilution rates are consistent with inner-shelf dye properties being determined by local cross-shore advection. The alongshore-patchy and warm inner-shelf dye is ejected from the surfzone by transient rip currents. Estimated Stokes drift driven cross-shore exchange is small. The transient rip current driven depth-normalized heat flux out of the surfzone has magnitude similar to those of larger scale shelf processes. Dye recycling, from the inner-shelf back to the surfzone, is suggested by relatively long surfzone dye residence times.

1.2 Introduction

The surfzone (the region between the shoreline and the seaward boundary of depth-limited wave breaking) and the inner-shelf (extending seaward from the surfzone to nominally 20 m water depth) are widely used for recreation and commerce, and are important habitats for larvae and other marine organisms (e.g., McLachlan and Brown, 2010). Surfzone and inner-shelf water quality is often compromised by contaminants from terrestrial runoff and offshore waste disposal (e.g., Koh and Brooks, 1975; Schiff et al., 2000). Tracers (pollutants, sediment, larvae, etc.) with shoreline sources are first mixed and transported within the surfzone (e.g., Harris et al., 1963; Inman et al., 1971a; Grant et al., 2005; Clark et al., 2010), and ultimately diluted by exchange with the inner-shelf. Conversely, tracers on the inner-shelf can be transported into the surfzone (e.g., Boehm et al., 2002; Noble et al., 2009; Wong et al., 2012). The surfzone and inner-shelf are each dynamically complex, with very different processes driving dispersion. The intersection of, and exchange between, these two regions is not understood.

Dye tracers and Lagrangian surface drifters have been used recently to observe nearshore dispersion. Clark et al. (2010) studied the cross-shore dispersion of a dye tracer continuously released in the surfzone at alongshore-uniform Huntington Beach, California. However, observations were limited to \( \leq 2 \) h and usually < 400 m downstream of the dye source, and analyses were specifically restricted to the surfzone-contained portions of the dye plumes. Spydell et al. (2007, 2009) observed Lagrangian drifter dispersion at alongshore-uniform beaches, but analysis
periods were limited to < 17 min, when drifters were generally surfzone-confined.

Several mechanisms, spanning a range of time and length scales, can drive cross-shore exchange across the inner-shelf and the surfzone. In 12 m water depth with small waves, cross-shelf winds can drive subtidal cross-shore exchange on the inner-shelf (e.g., Fewings et al., 2008). Along-shelf winds are less effective than cross-shelf winds in driving cross-shore inner-shelf exchange at subtidal time scales (e.g., Austin and Lentz, 2002; Kirincich et al., 2009). In Southern California, the site of the present observations, internal tides and higher frequency internal waves can drive cross-shore exchange. Semi-diurnal internal tides in 20 m depth can cause significant cross-shore heat and nitrate fluxes (Lucas et al., 2011). Diurnal and semi-diurnal internal tides can advect cold water from 60 m depth several km onshore to less than 6 m depth (Boehm et al., 2002). Higher frequency internal bores can propagate into shallow depths (5 m) and cause minute-to-hour fluctuations in temperature (Winant, 1974; Pineda, 1991, 1994) and phytoplankton (Omand et al., 2011).

In water depths less than about 15 m when waves are significant, cross-shore flow can be dominated by surface gravity wave forcing, even with no wave breaking (Lentz et al., 2008; Fewings et al., 2008). With weak vertical mixing, the offshore Eulerian flow is roughly equal in magnitude but opposite in direction to the onshore Stokes drift at all depths, resulting in no cross-shore exchange. However, with strong vertical mixing, the mismatch in vertical structures of the onshore Stokes flow and offshore Eulerian flow can induce significant cross-shore exchange (e.g., Lentz et al., 2008; Kirincich et al., 2009). Surface gravity wave conditions often vary over periods of a few days, so this wave-driven exchange mechanism varies on subtidal time scales.

Surfzone wave breaking drives currents and eddies that can lead to rip currents, long-recognized to exchange water between the surfzone and inner-shelf (e.g., Inman et al., 1971a; Talbot and Bate, 1987, among others). Most observational rip current studies have focused on beaches with alongshore inhomogeneous bathymetry, with rips located near channels in sand bars. Bathymetrically controlled rips can vary temporally, often pulsing on infragravity time scales (e.g.,
MacMahan et al., 2004). Smith and Largier (1995) observed re-occuring rip currents near a pier, possibly bathymetrically controlled, and inferred that these rips dominated the exchange between the surfzone and inner-shelf. On beaches with alongshore-uniform bathymetry and no solid structures (e.g., piers or jetties), rip currents are often temporally transient and lack preferred alongshore locations. Transient rips eject seaward the vorticity (eddies) generated in the surfzone by finite crest length wave breaking (Peregrine, 1998; Clark et al., 2012), but their time and length scales are not well understood (Johnson and Pattiaratchi, 2006). Infrared remote sensing of ocean surface temperature (Marmorino et al., 2013) and X-band radar backscatter (Haller et al., 2014) can reveal these ejection events. Surfzone flushing by bathymetrically controlled rip currents has been estimated to occur in a few hours, but most of the flushed water returns to the surfzone (Reniers et al., 2009; MacMahan et al., 2010). Similarly, over a few hours, surfzone-released dye tracer (Clark et al., 2010) and surface drifters (Spydell et al., 2009) at alongshore-uniform beaches are observed to generally remain within two surfzone widths (≈ 100-200 m during these studies) of the shoreline.

Vigorous vertical mixing in the surfzone (Feddersen and Trowbridge, 2005; Ruessink, 2010; Feddersen, 2012a) suggests there will be at most weak vertical structure in surfzone temperature or dye concentration. However, significant inner-shelf stratification (≈ 0.7 °C m⁻¹) has been observed just offshore (≈ 5 m water depth) of Southern California surfzones in late summer and early fall (Winant, 1974; Omand et al., 2011). We show that this stratification can play an important role in surfzone/inner-shelf exchange.

Cross-shore tracer exchange between the surfzone and the inner-shelf was observed during the multi-disciplinary IB09 experiment conducted at alongshore-uniform Imperial Beach, California. Extensive temperature and dye measurements were made with novel and complimentary instrument platforms. Temperature is a dynamical tracer with multiple sources and sinks (e.g., solar heating, air-sea fluxes), whereas dye is a passive tracer with a known and localized source. These unique, coupled observations resolve tracer structure and evolution in both the surfzone and inner-shelf, and in the cross-shore, alongshore, and vertical directions.
The IB09 experiment site, dye release method, instrument platforms, and sampling schemes are described in Section 1.3. Background waves and currents are discussed in Section 1.4.1. In Section 1.4.2, overviews of dye and temperature observations are given, and time periods for subsequent analyses established. The cross-shore and vertical structures of dye and temperature in the surfzone and inner-shelf are described in Sections 1.4.3 and 1.4.4. Alongshore and vertical inner-shelf tracer structure is analyzed in Section 1.4.5. The relationship between dye concentration and temperature in both the surfzone and inner-shelf is examined in Section 1.4.6. Cross- and alongshore dye dilution is examined in Section 1.4.7, and surfzone alongshore dye transport estimates are presented in Section 1.4.8. Results are synthesized in the Discussion (Section 1.5). In particular, inner-shelf vertical tracer mixing (Section 1.5.1), the magnitude and mechanisms of cross-shore surfzone/inner-shelf tracer exchange (Section 1.5.2), and the implications of these observations for surfzone dilution modeling (Section 1.5.3) are discussed. Section 1.6 is a summary.

1.3 IB09 Experiment

1.3.1 Field Site and Coordinate System

IB09 field observations were acquired during fall 2009 at Imperial Beach, California (32.6°N, 117.1°W), a west (269.6°) facing beach with an approximately straight shoreline (Figure 1.1). The case study presented here is 11:00–24:00 h (PDT) on 29 September 2009. In the right-handed coordinate system, cross-shore coordinate $x$ increases negatively seaward ($x = 0$ m at the mean shoreline), along-shore coordinate $y$ increases positively toward the north ($y = 0$ m at the dye release location), and vertical coordinate $z$ increases positively upward ($z = 0$ m at mean sea level, Figure 1.1). Bathymetry surveys from 25 September and 2 October were similar, and are averaged to give a representative bathymetry for 29 September that is approximately alongshore uniform (Figures 1.1a, 1.1b). The 29 September wind, measured at a nearby meteorological station, was light onshore (approximately 4–9 knots, WNW), typical for Southern California.
Figure 1.1: (a) Planview of IB09 bathymetry contours versus cross-shore coordinate \(x\) and alongshore coordinate \(y\). Star indicates dye release location. Diamonds denote the cross-shore array of instrumented frames f1-f7. Vertical, black dashed line through f4 denotes the seaward surfzone boundary \(x_b\), defining the surfzone \((x \geq x_b)\) and the inner-shelf \((x < x_b)\). Vertical, gray dashed line at 2\(x_b\) is an idealized alongshore boat transect. Horizontal, gray dashed lines \((y = 200, 600 \text{ m})\) represent idealized cross-shore transects driven repeatedly by jetskis at various alongshore locations. (b) Depth \(h\) (curve) versus cross-shore coordinate \(x\), with mean sea level at \(z = 0\) m. Diamonds are f1-f7 locations; f4 is instrumented at three vertical locations. The mean cross-shore location of the alongshore-towed vertical array ET1-ET5 (circles) is at 2\(x_b\). Waves, currents, dye, and temperature are measured at f1-f6 (black symbols), whereas only dye and temperature are measured at f7 and ET1-ET5 (gray symbols). (c) A 29 September 2009 aerial photograph with superposed coordinate system \((x, y, z)\), mean alongshore current \(V\), surfzone boundary \(x_b\), mean cross-shore location of inner-shelf alongshore boat transects \((2x_b)\), dye release location (star), and instrument frames (f1-f7). Dye is alongshore-patchy on the inner-shelf.
1.3.2 Dye Release

Rhodamine WT dye ($2.1 \times 10^8$ parts per billion (ppb)) was released continuously into the surfzone near the shoreline at $(x, y) = (-10, 0)$ m at 3.6 mL s$^{-1}$ for approximately 4.5 h (11:10–15:47 h). A peristaltic pump atop a heavy metal cart forced the dye through a small hose and out of a diffuser roughly 20 cm below the surface. Visual observations suggested rapid vertical mixing, and measured surface dye concentrations were reduced from $O(10^8)$ ppb to less than 100 ppb within 10 m of the release. Therefore, the initially concentrated dye (1.2 specific gravity) was quickly diluted to a specific gravity of approximately 1. Rhodamine WT has a photochemical decay e-folding time of approximately 667 hours of sunlight (e.g., Smart and Laidlaw, 1977). Therefore, photochemical decay over the approximately 8 hours of sunlight during this study is negligible.

1.3.3 Surfzone and Inner-Shelf Instrumentation

1.3.3.1 Cross-Shore Array

A 190 m-long cross-shore array of seven fixed, near-bed instrument frames (denoted f1–f7, onshore to offshore) was deployed from near the shoreline to approximately 6 m water depth, 465 m north of the 29 September dye release location (diamonds, Figures 1.1b, 1.1c). Frames f1-f6 held Paros pressure sensors and SonTek acoustic Doppler velocimeters (ADVs) to measure waves and currents, Yellow Springs Instrument Company thermistors to measure temperature $T$, and WET Labs ECO Triplet fluorometers (hereafter ET) to measure dye concentration $D$. One frame (f4), located near the seaward edge of the surfzone (2.1 m water depth), held instrument packages at three locations spanning 1.1 m vertically (0.2, 0.7, and 1.3 m above the bed). Instruments on frames f1–f6 sampled for 51 minutes each hour. The remaining 9 minutes of each hour were used by the ADVs to estimate the bed location. Frame f7 held a thermistor-equipped ET to measure temperature and dye concentration. The ET on f7 sampled from 11:00–17:30 h, whereas f1-f6 instruments sampled throughout the entire day.
1.3.3.2 Surface Dye and Temperature Cross-Shore Transects

Surface $T$ and $D$ were measured with thermistors and fluorometers mounted on two GPS-tracked jetskis (Clark et al., 2009a) that drove repeated cross-shore transects from $x \approx -250$ m to the shoreline (Figures 1.1a, 1.1c) between $y = 0$ m and $y = 600$ m. The alongshore spacing between transects varied from approximately 20 to 200 m. Outbound transects, sometimes corrupted when the jetskis swerved or became airborne jumping over waves, are discarded. Inbound transects, when jetskis were driven immediately in front of bores to minimize turbidity from bubbles and suspended sand, are analyzed during 11:10-16:00 h.

1.3.3.3 Inner-shelf Dye and Temperature Alongshore Transects and CTD+F Casts

Offshore of the surfzone, the alongshore and vertical structure of dye concentration $D(y, z)$ and temperature $T(y, z)$ was measured with a vertical array of five thermistor-equipped ETs towed alongshore behind a small boat. The vertical array sampled from $z = -1$ to $-3$ m at 0.5 m spacing (Figures 1.1b). During approximately 11:00–16:00 h, repeated $\approx 700$ m-long alongshore transects were driven at roughly 0.7 m s$^{-1}$ at a mean cross-shore location nominally twice the surfzone width. The transects were approximately shore-parallel with deviations to avoid large waves (e.g., Figure 1.2a).

The inner-shelf vertical structures of $T$ and $D$ were also measured with small boat CTD+F casts using a Seabird SBE25 CTD and co-located WET Labs Rhodamine WT fluorometer. Casts extended from near the surface to the seabed in approximately 4–6 m water depth. Analyses include 21 casts during 11:49-15:17 h within dye plumes located $-313 \leq x \leq -141$ m, $-338 \leq y \leq 592$ m. CTD salinity varied $< 0.2$ psu, consistent with weak salinity variations observed over the upper water column 30 km to the north (Lucas et al., 2011) and at the SIO pier ($\approx 40$ km to the north, sccoos.org).
Figure 1.2: (a) Dye concentration $D$ at $z = -2$ m versus cross-shore coordinate $x$ and alongshore coordinate $y$ from an alongshore boat transect ($t \approx 12:40–13:00$ h). Magenta star denotes the dye release location, dashed line the surfzone boundary $x_b$, and diamonds the bottom-mounted frames f1-f7. (b) Dye concentration $D$ and (c) temperature $T$ versus alongshore coordinate $y$ and vertical coordinate $z$. Star in (b) denotes the alongshore and vertical location of the shoreline-released dye.
1.3.4 Corrections to Measured Dye Fluorescence

Rhodamine WT fluorescence is temperature-dependent (Smart and Laidlaw, 1977), and measured fluorescence depends on the turbidity (e.g., from sand and bubbles) of the sample (Clark et al., 2009a). All $D$ observations are corrected for temperature (Smart and Laidlaw, 1977), and all $D$ observations except those from the CTD+F casts (where turbidity measurements are not available) are corrected for turbidity (Clark et al., 2009a). Corrected $D$ typically differ from measured $D$ by less than 5%.

1.3.5 Dye and Temperature Averaging

Depending on the situation, temperature and dye concentration are averaged over time, cross-shore direction, alongshore direction, vertical direction, or realizations (jetski transects, boat transects, and CTD+F casts). Throughout, temperature statistics are computed arithmetically. Since dye concentration is a positive semi-definite quantity, dye statistics are at times computed logarithmically, such that mean dye concentration $\overline{D} = \exp [E(\log D)]$, where $E()$ represents the typical averaging operator (expected value). The logarithmically computed dye concentration standard error is defined as $\overline{D} \pm \sigma_D = \exp [E(\log D) \pm \text{std}(\log D)]$, where $\overline{D} \pm \sigma_D$ represents ± a standard deviation from the mean, ensuring that $\overline{D} - \sigma_D \geq 0$ ppb. Figure captions indicate when dye statistics are computed logarithmically.

1.4 Results

1.4.1 Background Waves and Alongshore Currents

The bathymetry is terraced close to shore ($x > -40$ m), and approximately planar (slope $\approx 0.02$) farther offshore (Figure 1.3c). The average (11:00–16:00 h) significant wave height $H_s(x)$ shoals to a maximum of 0.71 m near f4 ($x = -81$ m), and then decreases shoreward after waves break (Figure 1.3a). The incident wave
Figure 1.3: Time-averaged (11:00–16:00 h) (a) significant wave height $H_s$, (b) alongshore current $V$, and (c) vertical locations of f1-f6 versus cross-shore coordinate $x$. Seaward surfzone boundary $x_b$ is the cross-shore location of maximal $H_s$ (f4). In (b), vertical bars indicate standard deviations of 5 min-averaged alongshore velocities. In (c), the black curve gives the bathymetry $h(x)$.

peak period is $T_p = 14$ s. The mean (11:00–16:00 h) alongshore current $V(x)$ is northward (positive) at all locations, with a maximum (0.17 m s$^{-1}$) inside the surfzone near f2 (Figure 1.3b). The 5 min-averaged alongshore current fluctuates at very low frequencies (bars in Figure 1.3b), but is always northward within the surfzone. At f4, the vertical variation of $V$ is weak (compare shaded symbols in Figure 1.3b). Seaward of the surfzone, the mean alongshore current weakens; $V = 0.06$ and 0.02 m s$^{-1}$ at f5 and f6, respectively.

During 11:00–16:00 h, the incident wave field is relatively constant, and the tide varies by only 0.35 m (low tide is at 13:27 h, Figure 1.4a). Hourly cross-shore profiles of $H_s$ and $V$ vary little, and for this time period the seaward surfzone boundary is defined as the f4 cross-shore location, $x_b = -81$ m (mean depth $h_b = 2.1$ m, Figure 1.3c).
1.4.2 Time Variation of Bulk Dye and Temperature

Surfzone bulk temperature \( \langle T \rangle \) and dye concentration \( \langle D \rangle \) are calculated as 30 minute averages, integrated over the surfzone frames f1–f4 (curves in Figures 1.4b, 1.4c). The mean vertical location of f1–f4 is \( z \approx -1 \text{ m} \). Inner-shelf \( \langle T \rangle \) and \( \langle D \rangle \) (nominally at \( 2x_b \)) are calculated at ET1 (\( z = -1 \text{ m} \)), averaged over each alongshore boat transect (dots in Figures 1.4b, 1.4c). Vertical variation is described in Sections 1.4.4 and 1.4.5.

The dye release begins at 11:10 h (magenta bar in Figure 1.4c). Prior to 13:00 h, the surfzone is warmer, and warms more rapidly, than the inner-shelf (Figure 1.4b), due in part to the greater efficacy of solar heating in the shallower surfzone. The surfzone/inner-shelf \( \langle T \rangle \) difference increases from 0.15 °C to 0.33 °C. This differential surfzone and inner-shelf warming is discussed in Section 1.5.2. From 11:10–13:00 h, \( \langle D \rangle \) is not steady, increasing in both the surfzone and inner-shelf (Figure 1.4c). After 13:00 h, a fog bank decreases incident solar radiation significantly, the surfzone cools, and surfzone and inner-shelf \( \langle T \rangle \) equilibrate (Figure 1.4b). Between 13:00–16:00 h, surfzone and inner-shelf bulk dye concentrations are approximately stationary (Figure 1.4c).

The time variation in \( \langle T \rangle \) and \( \langle D \rangle \) motivates defining two separate analysis periods (shaded regions in Figure 1.4). The first time period SC (for secular change) is 11:10–13:00 h, when surfzone and inner-shelf \( \langle T \rangle \) and \( \langle D \rangle \) increase (Figures 1.4b and 1.4c). The second time period EQ (for equilibration) is 14:00–16:00 h, when \( \langle T \rangle \) and \( \langle D \rangle \) are approximately stationary (Figures 1.4b and 1.4c). These two time periods will often be analyzed separately.

1.4.3 Cross-Shore Structure of Dye and Temperature: Surfzone and Inner-Shelf

Surface mean temperature \( \overline{T}(x) \) and dye concentration \( \overline{D}(x) \) for SC and EQ are calculated by time- and alongshore-averaging (\( 0 < y < 600 \text{ m} \)) all jetski transect realizations during each period (Figure 1.5). These jetski surface observations are qualitatively consistent with the \( z \approx -1 \text{ m} \) bulk quantities calculated
Figure 1.4: (a) Time-averaged sea-level $\eta$ (measured at f6) relative to mean sea level (dashed), (b) bulk temperature, and (c) bulk dye concentration versus time. In (b, c) surfzone $\langle \rangle$ (solid) is a cross-shore average of the surfzone frames f1-f4 ($z \approx -1$ m), and inner-shelf $\langle \rangle$ (dots) is an average over each alongshore transect at ET1 ($z = -1$ m). Magenta bar in (c) denotes time when dye is released continuously near the shoreline. Gray shaded regions indicate secular change (SC) and equilibrated (EQ) time periods.
Figure 1.5: Binned means (time- and alongshore-averaged) of jetski-measured surface (a) temperature and (b) dye concentration versus cross-shore coordinate $x$ during SC (blue) and EQ (red). Vertical bars indicate standard deviations about the means (statistics are computed arithmetically for $T$ and logarithmically for $D$). Dashed vertical lines indicate the seaward surfzone boundary ($x_b$) and the mean cross-shore location of inner-shelf alongshore boat transects ($2x_b$).

Using the surfzone frames and inner-shelf alongshore boat transects (Section 3.2).

During SC, surface $T(x)$ has a surfzone maximum ($19.28\, ^\circ\text{C}$ at $x = -30\, \text{m}$) and decreases to a minimum near $2x_b$ on the inner-shelf (Figure 1.5a, blue). The cross-shore surface temperature difference of $T_{\text{max}} - T_{\text{min}} = 0.14\, ^\circ\text{C}$ is similar to the mean SC surfzone to inner-shelf bulk temperature difference $\Delta\langle T\rangle_{\text{SZ-IS}} = 0.25\, ^\circ\text{C}$ (Figure 1.4b). During EQ, surface $T(x)$ is warmer than during SC at all $x$ ($T_{\text{max}} = 19.48\, ^\circ\text{C}$) and is nearly cross-shore uniform (Figure 1.5a, red), consistent with the surfzone and inner-shelf $\langle T \rangle$ equilibration (Figure 1.4b). Surface $T$ increases steadily during SC, so the variance is larger than during EQ (compare blue and red vertical bars in Figure 1.5a).

Although dye is non-stationary during SC, surface $D(x)$ has a similar profile shape during SC and EQ, with a surfzone maximum and monotonic decrease offshore (Figure 1.5b). Consistent with the surfzone and inner-shelf $\langle D \rangle$ (Fig-
Figure 1.6: Means (diamonds) and standard deviations (vertical bars) of (top) temperature and (bottom) dye concentration versus cross-shore coordinate $x$ at the cross-shore frame array. Left (a,b) and right (c,d) columns are for SC and EQ, respectively. Statistics are computed arithmetically for $T$ and logarithmically for $D$. Dashed vertical lines are at $x_b$. Data from f4 are offset laterally for plotting purposes; f4 instruments were located at the same cross-shore coordinate ($x_b$) 0.2, 0.7, and 1.3 m above the bed (Figure 1.3c).

During SC and EQ, time-averaged temperature $\overline{T}(x, z)$ at the cross-shore array ($y = 465$ m) is warm and roughly uniform within and near the surfzone (f1–f5, Figures 1.6a, 1.6c). However, $\overline{T}(x, z)$ decreases significantly at the deeper frames; $\overline{T} \approx 18.5 ^\circ C$ at $(x, z)_f6 = (-135, -3.6)$ m, and $\overline{T} \approx 17.1 ^\circ C$ at $(x, z)_f7 = (-199, -5.7)$ m (Figure 1.6c). In contrast, the jetski-measured surface temperature is relatively constant in the cross-shore during each period, with variations of less than 0.2 $^\circ$C between the shoreline and $x = -230$ m (Figure 1.5a). Vertical temperature stratification with the thermocline generally below $z_{f5} = -2.6$ m significantly reduces $\overline{T}$ at f6 and f7 relative to the shallower f1–f5 (Figures 1.6a, 1.6c).

During SC, time-averaged surfzone (f1–f4) $\overline{D}(x, z) < 5$ ppb (Figure 1.6b), and the variability represents the dye concentration growth early in the release period (Figure 1.4c). During EQ, dye is approximately stationary at the frames,
Figure 1.7: Dye concentration $D$ versus time at the three vertically-separated ETs on f4 (Figure 1.3c), located 0.2, 0.7, and 1.3 m above the bed (mab). Magenta bar shows time when dye is released continuously near the shoreline, 465 m south of the cross-shore array (Figure 1.1). Shaded regions indicate SC and EQ. Gaps in the time-series result from sampling for 51 minutes of each hour.

and $\overline{D}(x, z)$ weakly decreases seaward from f1 to f4 (Figure 1.6d), consistent with the EQ jetski-measured surface $\overline{D}(x)$ averaged over time and $0 < y < 600$ m (Figure 1.5b). Farther offshore at f6 and f7, EQ $\overline{D}(x, z)$ decreases significantly (Figure 1.6d). Although dye spreads offshore and reaches the surface above f6 and f7 (Figure 1.5b, red, $x_{f6} = -135$ m and $x_{f7} = -199$ m), it does not readily spread vertically down to $(x, z)_{f6} = (-135, -3.6)$ m and $(x, z)_{f7} = (-199, -5.7)$ m (Figure 1.6d), where the temperature is colder (Figures 1.6a, 1.6c).

1.4.4 Vertical Structure of Dye in the Surfzone

The vertical structure of dye concentration is measured at frame f4, located at the approximate seaward surfzone boundary $x_b$ in mean water depth $h_b = 2.1$ m (Figure 1.3c). Three ETs span 1.1 m vertically (0.2, 0.7, and 1.3 m above the bed). Dye is approximately vertically uniform, indicating that it is well-mixed over this water depth (Figure 1.7). $D$ is very similar at the lower two ETs, while $D$ at the upper ET is sometimes about 1-2 ppb lower. The first EOF of dye concentration (not shown) is approximately vertically uniform (11% top-to-bottom variation) and represents 99% of the dye concentration variance.
1.4.5 Inner-Shelf Alongshore and Vertical Structure of Dye and Temperature

1.4.5.1 Inner-Shelf Alongshore Transects

A typical inner-shelf alongshore boat transect of dye concentration $D(y, z)$ during SC is alongshore-patchy with approximately 25–50 m-wide bands of elevated $D(y, z)$ (Figure 1.2b), consistent with the aerial photograph of alongshore-patchy dye plumes (Figure 1.1c). $T(y, z)$ varies alongshore with structure similar to $D(y, z)$, and the vertical stripes of elevated $D$ and $T$ co-occur (Figures 1.2b, 1.2c). Within the dye patches, $D(y, z)$ and $T(y, z)$ are approximately vertically uniform from $z = -1$ to $-3$ m.

For subsequent analysis of inner-shelf boat transects, the alongshore-towed vertical ET array measurements are decomposed into an along-transect and vertical average and a perturbation, i.e.,

$$T_i(y, z_k) = \langle T \rangle_i + T'_i(y, z_k), \quad (1.1)$$

where subscript $i$ denotes alongshore transect number (a proxy for the time evolution of $T$ and $D$) and subscript $k$ denotes the vertical ET location. The mean $\langle T \rangle_i$ is defined as an average over $y$ and $z$, i.e.,

$$\langle T \rangle_i = \frac{1}{L_{y_i}L_z} \int_{-3}^{-1} \int_{y_{min}}^{y_{max}} T_i(y, z_k) dydz, \quad (1.2)$$

where $L_z = 2$ m is the vertical span of the ET array, and $L_{y_i} = y_{max} - y_{min}$ is the alongshore span of transect $i$. $D$ is also decomposed according to (1.1) and (1.2). $\langle D \rangle_i$ is similar to the bulk inner-shelf quantity at $z = -1$ m shown in Figures 1.4b and 1.4c, but it is also vertically averaged from $z = -1$ to $-3$ m. This decomposition separates the $T$ and $D$ variability due to secular changes throughout the day (i.e., temporal variability, $\langle D \rangle_i$) and the variability due to horizontal and vertical structure (i.e., $D'_i(y, z_k)$).

Averaging $T'_i(y, z_k)$ and $D'_i(y, z_k)$ over all alongshore locations and all transects ($t = 11:10–16:00$ h) gives the ensemble-averaged vertical structures $\overline{T'}(z_k)$.
Figure 1.8: (a,b) Time- (11:10–16:00 h) and alongshore-averages of inner-shelf perturbation temperature $T'_{i}(y,z_{k})$ and dye concentration $D'_{i}(y,z_{k})$ (Equations (1.1) and (1.2)) versus vertical coordinate $z$ from the alongshore-towed vertical array. Dashed lines indicate standard deviations about the means. (c,d) First EOFs of perturbation $T'_{i}$ and $D'_{i}$ versus vertical coordinate $z$, representing 83% and 92% of the variance, respectively. (e,f) Mean temperature $\overline{T}$ and dye concentration $\overline{D}$ versus vertical coordinate $z$ for 21 dye plume CTD+F casts during 11:49–15:17 h. Dashed lines indicate standard deviations about the means (statistics are computed arithmetically for $T$ and logarithmically for $D$). Note that the vertical axes of panels (e,f) differ from those of (a-d).
and \( \overline{D}(z_k) \) (Figures 1.8a, 1.8b). Consistent with observations from a single inner-shelf alongshore transect (Figure 1.2b), the mean \( \overline{D}(z_k) \) and standard deviation of \( D^\prime_i(y, z_k) \) are approximately vertically uniform (Figure 1.8b). The vertical variation of ensemble-averaged \( \overline{T}(z_k) \) is weak, and variability of \( T^\prime_i(y, z_k) \) is strongest at \( z = -3 \text{ m} \), where the standard deviation is approximately twice as large as at \( z = -1 \text{ m} \) (Figure 1.8a). The mean \( \overline{D}(z_k) \) and dye variability computed for SC and EQ separately are similar to those for the 11:10–16:00 h period (Figure 1.8b). The mean vertical temperature structures \( \overline{T}(z_k) \) during SC and EQ are also similar to the 11:10–16:00 h ensemble average (Figure 1.8a). However, the standard deviation of \( T^\prime_i(y, z_k) \) is approximately twice as large at all \( z_k \) during SC as during EQ.

The inner-shelf \( D^\prime_i \) and \( T^\prime_i \) variability is analyzed with vertical EOFs over 11:10–16:00 h. The first EOF of \( D^\prime_i \) (representing 92% of the variance) is approximately vertically uniform (17% top-to-bottom variation), decreasing slightly with depth (Figure 1.8d). The weak vertical variation of both the mean (Figure 1.8b) and the first EOF (Figure 1.8d) indicates that dye is typically well mixed from \( z = -1 \text{ to } -3 \text{ m} \), consistent with Figure 1.2b. The first EOF of \( T^\prime_i \) (representing 83% of the perturbation variance) increases monotonically with depth, having 72% top-to-bottom variation (Figure 1.8c). The weak vertical variation of the mean (Figure 1.8a), combined with the depth-increasing first EOF (Figure 1.8c), indicates that temperature is often vertically well-mixed from \( z = -1 \text{ to } -3 \text{ m} \) (Figure 1.2c), but that the temperature variability increases from \( z = -1 \text{ to } -3 \text{ m} \).

1.4.5.2 CTD+F Casts

Individual CTD+F casts (not shown) within dye plumes in 4-6 m water depth often reveal significant temperature and dye vertical stratification near or below \( z \approx -3 \text{ m} \). Estimated from 21 CTD+F dye plume-contained casts between 11:49–15:17 h, mean \( \overline{T}(z) \) and \( \overline{D}(z) \) vary weakly over the upper 3 m (Figures 1.8c, 1.8e, 1.8f), consistent with the inner-shelf alongshore transect \( \overline{T}(z_k) \) and \( \overline{D}(z_k) \) (Figures 1.8b, 1.8a). Below \( z = -3 \text{ m} \), \( T(z) \) decreases rapidly and \( D(z) \) is near zero.
Below \( z \approx -4.6 \) m, \( D \approx 0 \) ppb in all casts (Figure 1.8f), and with the exception of a single cast during SC near the release location \((y = 0 \) m), essentially no dye is observed for \( T < 18 \) °C (Figures 1.8e, 1.8f). CTD+F dye variability (dashed, Figure 1.8f) is largest near the surface, where concentrations are highest. In contrast, \( T \) variability is maximum between \( z \approx -3 \) and \(-5 \) m (Figure 1.8e) owing to variations in thermocline depth.

### 1.4.6 Dye-Temperature \((D-T)\) Relationships

The natural temperature tracer has an alongshore-uniform surfzone source during SC (Figures 1.4b, 1.5a), which contrasts with the near-shoreline point source (11:10–15:47 h) of anthropogenic dye tracer. Separate analyses of \( T \) and \( D \) reveal temporal, alongshore, cross-shore, and vertical tracer variability (Figures 1.2, 1.4, 1.5, 1.6, 1.8, and 1.8). To infer mechanisms governing \( D \) and \( T \) transport and mixing, \( D-T \) relationships are examined with the inner-shelf alongshore transects and the cross-shore array (Figure 1.1).

#### 1.4.6.1 Inner-Shelf Alongshore Transect \( D-T \) Relationship

The perturbation dye \( D'_i(y, z_k) \) and temperature \( T'_i(y, z_k) \) relationship is examined on inner-shelf alongshore transects at the upper-most \((z = -1 \) m\) and lower-most \((z = -3 \) m\) vertical locations. During SC, moderately elevated \( D'_i > 15 \) ppb correspond to warm \( T'_i > 0.1 \) °C, and the highest \( D'_i > 30 \) ppb generally correspond to the warmest \( T'_i \geq 0.2 \) °C at both vertical locations (Figures 1.9a, 1.9b). Cold events \((T'_i < -0.25 \) °C\) correspond to low \( D'_i < 10 \) ppb, and at \( z = -3 \) m the coldest water \((T'_i < -0.5 \) °C\) generally has negative \( D'_i \) (Figures 1.9b, 1.9d). Although the variability of \( D'_i \) and \( T'_i \) is reduced during EQ relative to SC (compare right with left columns, Figure 1.9), the same \( D'_i-T'_i \) relationship is observed for both periods: warm water is required for elevated \( D'_i \), and cold water has low \( D'_i \).

The highest inner-shelf \( D'_i > 30 \) ppb, likely surfzone water most recently delivered to the inner-shelf, occur during SC, when the surfzone to inner-shelf temperature difference is largest (Figure 1.4b). The alongshore structures of inner-
Figure 1.9: Perturbation dye concentration $D_i'$ versus perturbation temperature $T_i'$ (Equations (1.1) and (1.2)) for inner-shelf alongshore transects during (a,b) SC and (c,d) EQ at (a,c) $z = -1$ m (ET1) and (b,d) $z = -3$ m (ET5).
Figure 1.10: Perturbation (a1, a2, a3) dye concentration $D'_i$ and (b1, b2, b3) temperature $T'_i$ (Equations (1.1) and (1.2)) at $z = -3$ m (ET5) versus relative alongshore position $y - y_{pk}$ for three case examples (ab1, ab2, ab3) where $D'_i > 30$ ppb during SC. For each case, $y_{pk}$ is the alongshore location of maximal $D'_i$, and an alongshore region ±100 m of $y_{pk}$ is shown. Colored triangles in (a2) and (b2) indicate corresponding extrema.

shelf $D'_i$ and $T'_i$ are examined at $z = -3$ m for the three events when $D'_i > 30$ ppb (Figure 1.10). During these events, $D'_i$ and $T'_i$ are elevated in approximately 25–50 m-wide alongshore bands (Figure 1.10), and are approximately vertically uniform between $z = -1$ to $-3$ m (consistent with Figures 1.8b, 1.8a). The perturbation temperature $T'_i$ typically varies alongshore by 0.5 °C (Figures 1.10b1, 1.10b2, 1.10b3) and co-varies with $D'_i$ (Figures 1.10a1, 1.10a2, 1.10a3), similar to the overall $D'_i$–$T'_i$ relationship (Figure 1.9).

Even at alongshore length scales < 10 m, $D'_i$ and $T'_i$ are frequently related. For example, during the second event (Figures 1.10a2, 1.10b2), the maximum $D'_i = 38$ ppb at $y - y_{pk} = 0$ m (where $y_{pk}$ is the alongshore location of maximal $D'_i$) corresponds to elevated $T'_i = 0.25$ °C (red symbol in Figures 1.10a2, 1.10b2).
At $y - y_{pk} = 9$ m, the local minimum $D'_i = 8$ ppb corresponds to a local minimum $T'_i = -0.15$ °C (green symbol in Figures 1.10a2, 1.10b2). At $y - y_{pk} = 17$ m, secondary maxima of $D'_i = 18$ ppb and $T'_i = 0$ °C coincide (yellow symbol in Figures 1.10a2, 1.10b2). Local $D'_i$ and $T'_i$ minima also coincide another 15 m alongshore at $y - y_{pk} = 32$ m (blue symbol in Figures 1.10a2, 1.10b2). Similar spatial co-variability of $D'_i$ and $T'_i$ occurs in the other examples. However, as in Figure 1.9, this alongshore co-variation is not linear since temperature has an alongshore-uniform surfzone source whereas dye has a surfzone point source and decays in the alongshore direction. The alongshore-patchiness (Figures 1.2, 1.10) and general $D'_i-T'_i$ relationship (Figure 1.9) suggest that inner-shelf lateral mixing is relatively weak.

1.4.6.2 Cross-Shore Array $D$–$T$ Relationships

Here, the variability and co-variability of $D$ and $T$ are examined at the cross-shore array over a 13 h period from the start of the dye release. Prior to 18:00 h (including both SC and EQ), the surfzone (f2) is warm with relatively small $T$ variability (Figure 1.11a, red). On the inner-shelf (f5–f7), mean $T$ decreases and variability increases with distance offshore and depth, with $T$ varying by approximately 1.5 °C and 2 °C at f6 and f7, respectively (Figure 1.11a). The 18 °C isotherm can migrate as much as 3.1 m vertically in approximately 1.25 h (e.g., $T = 18$ °C at f5 ($z = -2.6$ m) at $t \approx 15:45$ h, and $T = 18$ °C at f7 ($z = -5.7$ m) at $t \approx 17:00$ h, Figure 1.11a). At f2, $D > 10$ ppb arrives at $t \approx 12:00$ h, about an hour after the release begins (Figure 1.11b, red). At inner-shelf f5 and f6, significant dye arrives at approximately 12:45 h and 13:30 h, respectively (Figure 1.11b, green and gray). Mean dye concentrations decrease with distance offshore and depth, with comparable $D$ variability among f2, f5, and f6 (Figure 1.11b).

Mean dye concentrations at f2–f6 begin to decrease at approximately 16:00 h (the continuous dye release stops at 15:47 h, Figure 1.11b). Prior to 17:00 h, the temperature at f7 is cold (< 18 °C), and no f7 dye is observed. However, at approximately 17:00 h, f7 $T$ increases above 18 °C (Figure 1.11a, blue), coinciding
Figure 1.11: (a) Temperature $T$ and (b) dye concentration $D$ versus time $t$ at the cross-shore array within (f2) and seaward of (f5, f6, and f7) the surfzone. Magenta bar in (b) denotes time when dye is released near the shoreline, 465 m south of the array (Figure 1.1). Shaded regions indicate SC and EQ, and a post-EQ period of non-zero $D$ at f7. Note that f7 data are unavailable after $t = 17:30$ h. Gaps in the f2, f5, and f6 time-series result from sampling for 51 minutes of each hour.
with a non-zero \( D \) burst at \( f_7 \) (Figure 1.11b, blue). Similarly, when \( f_6 T < 18 \, ^\circ C \), \( f_6 D \) also becomes negligible (Figures 1.11a and 1.11b, gray, \( t \approx 15:00 \) and 16:00 h). Observations at \( f_7 \) end at 17:30 h.

Between 18:00–22:00 h, temperature and dye conditions change substantially. \( T \) at \( f_2, f_5, \) and \( f_6 \) is warm (\( > 19 \, ^\circ C \)) and uniform (Figure 1.11a), indicating a thermocline deepening. Similarly, dye at \( f_2, f_5, \) and \( f_6 \) is well-mixed, particularly from 20:00–22:00 h (Figure 1.11b). Between 22:00–24:00 h, thermal stratification re-appears, influencing the dye field. For example, as \( f_6 T \) becomes \( < 18 \, ^\circ C \) at \( t \approx 22:30 \) h, dye concentration becomes negligible, similar to earlier times when \( T < 18 \, ^\circ C \) at both \( f_6 \) and \( f_7 \) (Figures 1.11a, 1.11b). This lack of dye for water colder than \( 18 \, ^\circ C \) is consistent with CTD+F vertical profiles. With the exception of a single cast during SC near the release location (\( y = 0 \) m), no dye is observed for \( T < 18 \, ^\circ C \) (Figure 1.8).

\( D-T \) relationships vary with frame location (Figure 1.12). During the stationary EQ period, within the surfzone at \( f_2 (z = -0.4 \) m), \( T \) variation is small, dye concentration is always relatively high (\( D > 15 \) ppb), and no clear \( D-T \) relation-

\textbf{Figure 1.12}: Dye concentration \( D \) versus temperature \( T \) at cross-shore array instruments within (\( f_2 \)) and seaward of (\( f_5, f_6, \) and \( f_7 \)) the surfzone during EQ.
ship is evident (Figure 1.12, red). In contrast, on the inner-shelf at f6 ($z = -3.6$ m), $D$ and $T$ are related linearly for $18 \leq T \leq 19.2$ °C, while for $T < 18$ °C, $D \approx 0$ ppb (Figure 1.12, gray). Slightly farther onshore at f5 ($z = -2.6$ m, just seaward of the f4 surfzone boundary), the $D-T$ relationship is a blend of that observed at inner-shelf f6 and surfzone f2 (Figure 1.12, green). At the deepest frame f7 ($z = -5.7$ m), the water is cold ($T < 18$ °C) during EQ, and $D = 0$ ppb throughout this period (Figure 1.12, blue).

1.4.7 Surfzone and Inner-Shelf Alongshore Dye Dilution

During EQ, the mean (time- and alongshore-averaged) cross-shore profiles of surface dye show that $\overline{D}(2x_b) \approx 0.4\overline{D}(x_b)$ (Figure 1.5b, red). Dye at $2x_b$ is consistently observed to be vertically well-mixed down to $z = -3$ m (Figure 1.8b). The inner-shelf ($2x_b$) alongshore-patchiness and $D-T$ relationship that suggest that horizontal mixing on the inner-shelf is weak, and that inner-shelf dye is locally (at the same $y$) advected from the surfzone. Such advection would result in vertical dye spreading seaward of $x_b$ ($h = 2.1$ m) which is accounted for by defining a depth-normalized dye concentration $\hat{D}$, where

$$\hat{D} = \begin{cases} D, & \text{for } x \approx x_b \\ \frac{3}{2T} D, & \text{for } x \approx 2x_b \end{cases}.$$  

(1.3)

Applying this normalization (1.3) results in EQ time- and alongshore-averaged $\overline{D}(2x_b) \approx 0.6\overline{D}(x_b)$. That this ratio is less than but near unity suggests that the assumption of local cross-shore dye advection from the surfzone to $2x_b$ is reasonable. To explore this concept further, the alongshore dilution of dye is examined both within the surfzone and on the inner-shelf.

Mean cross-shore profiles of surface dye concentration $\overline{D}(x,y_j)$ are calculated by averaging the 11:10–16:00 h jetski-measured $D$ over individual transect realizations at designated alongshore locations $y_j$ (not shown). For $y_j \geq 30$ m, the surface $\overline{D}(x,y_j)$ are approximately cross-shore uniform within the surfzone and decay offshore of $x_b$, similar to the EQ mean cross-shore dye profile in Figure 1.5b. However, $\overline{D}(x,y_j)$ decrease in the positive alongshore direction both within the
surfzone and on the inner-shelf.

The alongshore dilutions of $\hat{D}$ at $x_b$ and $2x_b$ are compared during 13:00–16:00 h (instead of during the EQ period, 14:00–16:00 h) to increase sample sizes during approximately stationary dye conditions, excluding only SC when temporal changes in dye concentrations are large (Figures 1.4c). We compute $\hat{D}(x_b, y)$ using the cross-shore jetski transects and $\hat{D}(2x_b, y)$ using ET1 ($z = -1$ m) from the alongshore boat transects. $\hat{D}(x_b, y)$ is averaged over a 20 m cross-shore region ($x_b \pm 10$ m). Boat transects are not perfectly alongshore, and $\hat{D}(2x_b, y)$ is averaged over an 80 m-wide cross-shore region ($2x_b \pm 40$ m). The data are alongshore-binned using the same bins for $\hat{D}(x_b, y)$ and $\hat{D}(2x_b, y)$, with bin widths ranging from $\Delta y = 50$ m (nearest the dye release) to $\Delta y = 240$ m (farthest from the release).

Alongshore dilutions of $\hat{D}(x_b, y)$ and $\hat{D}(2x_b, y)$ are similar (Figure 1.13) and consistent with a power-law in $y$, i.e.,

$$\hat{D} = \hat{D}_0 (y/y_0)^\alpha,$$

where $\hat{D} = \hat{D}_0$ at $y = y_0$, and $y_0 = 1$ m is chosen for simplicity. The best-fit $\hat{D}_0$ at $x_b$ and $2x_b$ are 42 ppb and 30 ppb, respectively, and best-fit power-law exponents at $x_b$ and $2x_b$ are $\alpha = -0.19$ and -0.21, respectively (dashed lines in Figure 1.13). The ratio $\hat{D}_0(2x_b)/\hat{D}_0(x_b) \approx 0.7$, consistent with alongshore-averaged $\bar{D}(2x_b)/\bar{D}(x_b) \approx 0.6$. The downstream dye dilutions can also be fit with exponentials, resulting in alongshore decay scales $L_{eff} \approx 1350$ m, that give approximately linear decay for the observed alongshore region ($y < 700$ m). For $y > 75$ m, the best-fit exponentials have similar but slightly larger root-mean-square (rms) errors than the best-fit power-laws (1.4). However, for $y < 75$ m, the exponential fits significantly under-predict the observed dye concentrations. The dye dilution rates farther downstream ($y > 700$ m) are unknown.

The similar downstream dye dilutions for both the surfzone and inner-shelf, together with the inner-shelf alongshore-patchiness and $D$-$T$ relationship, indicate that inner-shelf dye is locally (at the same $y$) cross-shore advected from the surfzone. The downstream dilution power-law exponents $\alpha \approx -0.2$ are smaller than that observed and modeled for surfzone-contained dye plumes ($\alpha \approx -0.5$ (Clark
et al., 2010)), indicating that once the surfzone is saturated with dye, the dilution rate slows. As the surfzone-contained plume model (Clark et al., 2010) uses a constant cross-shore surfzone diffusivity, the difference between the IB09 and surfzone-contained power-law exponents further indicates that cross-shore diffusivity on the inner-shelf is reduced relative to the surfzone.

1.4.8 Alongshore Dye Transport

The alongshore dye flux observed during 11:10–24:00 h at the cross-shore array 465 m downstream from the release location (Figure 1.1a) is compared with the near-shoreline dye release rate \( Q_R = 717.45 \text{ ppb m}^3 \text{s}^{-1} \) during 11:10–15:47 h, total release amount \( V_R = 1.19 \times 10^7 \text{ ppb m}^3 \). Dye is advected from the release location \((x, y) = (-10, 0)\) m towards the cross-shore array by the northward \((+y)\) alongshore current \( V \). Assuming vertically uniform \( V(x, t) \) and \( D(x, t) \) in the surfzone (between the shoreline and f4), the surfzone alongshore dye transport
$M^y_{SZ}$ is

$$M^y_{SZ}(t) = \int_{x_b}^{0} d(x,t)V(x,t)D(x,t) \, dx,$$

(1.5)

where 30 s averaged total water depth $d = h + \eta$, $V$, and $D$ are used. $D(x,t)$ generally varies between 0–30 ppb (Figure 1.6d), and $V$ is usually northward with maximum 0.25 m s$^{-1}$ (Figure 1.3b). The surfzone alongshore dye transport $M^y_{SZ}$ becomes significant around 13:00 h and varies between approximately 0 – 450 ppb m$^3$ s$^{-1}$, fluctuating at infragravity and very low frequency (VLF) time scales (Figure 1.14a). By 24:00 h, $M^y_{SZ}$ decreases to $\approx 40$ ppb m$^3$ s$^{-1}$ (when, e.g., $f_2 D \approx 4$ ppb, Figure 1.11b, red). The 11:10–24:00 h time-averaged $\overline{M^y_{SZ}} = 124$ ppb m$^3$ s$^{-1}$, and the 13:00–16:00 h average $\overline{M^y_{SZ}} = 208$ ppb m$^3$ s$^{-1}$ (Figure 1.14a), about 17% and 29% of the dye injection rate $Q_R$, respectively.

The ratio of the cumulative (time-integrated) surfzone alongshore dye transport to the total amount of dye released is

$$\Gamma^y_{SZ}(t) = \frac{\int_{t_0}^{t} M^y_{SZ}(\tau) \, d\tau}{Q_R},$$

(1.6)

where $t_0 = 11:10$ h is the dye release start time. $\Gamma^y_{SZ}$ increases approximately linearly between 13:00–18:30 h, increases more slowly until 22:30 h, and roughly equilibrates thereafter (Figure 1.14b). About 20% of the total dye released is surfzone alongshore transported through the cross-shore array ($y_f = 465$ m) between 13:00–16:00 h (dye released 11:10–15:47 h at $y = 0$ m), and another $\approx 25\%$ of the total between 16:00–24:00 h. At $t = 24:00$ h, approximately 8 h after the end of the dye release, 46% of the released dye has been alongshore transported through the surfzone portion of the cross-shore array (Figure 1.14b). Seaward cross-shore dye fluxes across the surfzone boundary are discussed in Section 1.5.3.1.
Figure 1.14: (a) Surfzone ($x_0 = 0$ m to $x_b = -81$ m) alongshore dye transport at the cross-shore array (465 m north of dye release) versus time. Positive transport is northward. Shaded regions denote periods SC and EQ. Magenta bar denotes dye release period. (b) Cumulative (time-integrated) surfzone alongshore dye transport relative to the total amount of released dye ($\Gamma_{SZ}$ is defined in (1.6)) versus time.
1.5 Discussion

1.5.1 Inner-Shelf Vertical Dye Mixing: Vertical $D$ and $T$ Gradients

Within the surfzone, dye is vertically well-mixed (Figure 1.7). On the inner-shelf, $D$ is largely vertically uniform from $z = -1$ to $-3$ m (Figure 1.8b). At f6 and f7, both located below $z = -3$ m, non-zero $D$ is only observed for $T \geq 18^\circ$C (Figure 1.11), even out to $t = 24:00$ h, 13 h after the dye release begins. From CTD+F casts, dye concentrations decrease below $z = -3$ m (Figures 1.8f), non-zero $D$ (> 1 ppb) is not observed below $z \approx -4.6$ m, and with the exception of a single cast during SC near the release, no dye is observed for $T < 18^\circ$C. These observations indicate that as dye moves offshore from the well-mixed surfzone, the presence of inner-shelf thermal stratification slows vertical dye mixing.

The effect of temperature stratification on inner-shelf vertical dye mixing is quantified during EQ using vertical $D$ and $T$ gradients estimated between f5 and f6 ($\Delta z = 1$ m). Their small cross-shore separation $\Delta x = 35$ m is neglected. During EQ, the observed f5–f6 thermal stratification is variable and sometimes strong, with $\Delta T/\Delta z \approx 0–1.5$ $^\circ$C m$^{-1}$ (Figure 1.15), corresponding to Brunt-Väisälä frequencies $N \approx 0–0.05$ Hz. When the thermal stratification is strong (weak), the dye gradients are large (small), and f5–f6 $\Delta D/\Delta z$ and $\Delta T/\Delta z$ are approximately linearly related with a best-fit slope 9.7 ppb $^\circ$C$^{-1}$ (Figure 1.15). For the same f5–f6 depth range ($z = -2.6$ to $-3.6$ m), the CTD+F cast-estimated $\partial D/\partial z$ and $\partial T/\partial z$ (not shown) are similar to the f5–f6 gradients. These observations indicate that thermal stratification can inhibit vertical dye mixing immediately offshore of the turbulent and vertically well-mixed surfzone (f5 and f6 are 19 and 54 m from $x_b$, respectively, Figure 1.1).

The effect of temperature stratification on inner-shelf vertical dye mixing is further examined with a dye diffusion model in isotherm coordinates,

$$\frac{\partial D}{\partial t} = \kappa_{TT} \frac{\partial^2 D}{\partial T^2},$$

where $\kappa_{TT}$ is the isotherm diffusivity. As surfzone and inner-shelf surface dye
Figure 1.15: Vertical dye concentration gradient $\Delta D/\Delta z$ versus vertical temperature gradient $\Delta T/\Delta z$ during EQ. Gradients are between inner-shelf frames f5 and f6 ($z = -2.6$ and $-3.6$ m, respectively). Squared correlation is $r^2 = 0.79$. Best-fit slope is 9.7 ppb $^\circ$C$^{-1}$.

concentrations have similar alongshore dilution rates (Figure 1.13) and inner-shelf alongshore currents are weak (Figure 1.3b), a local (instead of water-following) analysis is acceptable. The temperature domain considered is $T = 16 - 20 \, ^\circ$C. About an hour after arriving at f2, dye arrives at f5 ($t \approx 13:00$ h, Figure 1.11b) with average f5 concentration $D \approx 13$ ppb during EQ (Figure 1.6d) when the f5 temperature is generally $\geq 19 \, ^\circ$C (Figures 1.6c, 1.11a). Thus, at $t = 13:00$ h, a step-function initial condition of $D = 13$ ppb for $T \geq 19 \, ^\circ$C and $D = 0$ ppb for $T < 19 \, ^\circ$C is used. Boundary conditions $D = 13$ ppb at $T = 20 \, ^\circ$C and $D = 0$ ppb at $T = 16 \, ^\circ$C are applied. The top boundary condition simulates a continuous dye source from the warm surfzone.

At 16:00 h, three hours after dye initially arrives ($T > 18 \, ^\circ$C), observed $D$ is still negligible ($< 1$ ppb) at the 18 $^\circ$C isotherm (Figure 1.11). Requiring that after three hours modeled $D$ at $T = 18 \, ^\circ$C is only 5% (0.7 ppb) of the upper layer concentration yields an isotherm diffusivity $\kappa_{TT} = 1.5 \times 10^{-5} \, (^\circ$C$)^2 \, s^{-1}$. This estimated $\kappa_{TT}$ may be biased high, as f6 $D$ is still negligible for $T < 18 \, ^\circ$C even
12 h after the start of the dye release (Figure 1.11). The modeled $D$ versus $T$ profiles yield a $\partial D / \partial T$ gradient that varies between 7.2–9 ppb °C$^{-1}$ during EQ, similar to the f5–f6 observed $(\Delta D / \Delta z)/(\Delta T / \Delta z) = 9.7$ ppb °C$^{-1}$ relationship during the same time period (Figure 1.15). Using the average CTD+F thermal stratification $\partial T / \partial z = 0.7$ °C m$^{-1}$ over $z = -2.6$ to $-3.6$ m (Figure 9a), the vertical (diapycnal) diffusivity for the f5–f6 depth range is estimated as $\kappa_{zz} = \kappa_{TT}(\partial T / \partial z)^{-2} \approx 3 \times 10^{-5}$ m$^2$ s$^{-1}$, which may also be biased high.

This inferred vertical diffusivity $\kappa_{zz}$ is only slightly larger than vertical diffusivities $10^{-5}$ m$^2$ s$^{-1}$ estimated from observations of dye and microstructure in the largely quiescent ocean interior away from ridges (e.g., Ledwell et al., 1993; Polzin et al., 1997; Ledwell et al., 2011). The vertical isotherm displacements (Figure 1.11a), significant inner-shelf stratification (Figure 1.15), and shallow water depths (Figure 1.3c) suggest that the 29 September $\kappa_{zz}$ might be elevated by breaking internal waves (IW). However, the inferred $\kappa_{zz}$ is quite weak, similar to mid-column diffusivities of $(0.5–2) \times 10^{-5}$ m$^2$ s$^{-1}$ observed on the summer stratified New England outer-shelf in 70 m water depth during low IW activity (MacKinnon and Gregg, 2003). During spring restratification at the same New England outer-shelf site, average vertical diffusivities during moderate IW $(3 \times 10^{-4}$ m$^2$ s$^{-1}$) and strong IW $(2 \times 10^{-3}$ m$^2$ s$^{-1}$) events (MacKinnon and Gregg, 2005) were 1–2 orders of magnitude larger than the IB09 vertical diffusivity inferred here. Closer to shore (15 m water depth in the Southern California Bight), Omand et al. (2012) used observations of vertical nitrate fluxes to estimate bottom boundary layer driven and IW driven diffusivities up to $4 \times 10^{-4}$ m$^2$ s$^{-1}$. Further, the inferred IB09 inner-shelf diffusivity $(3 \times 10^{-5}$ m$^2$ s$^{-1}$) is several orders of magnitude smaller than the expected surfzone diffusivities of $10^{-2} – 10^{-1}$ m$^2$ s$^{-1}$ (Feddersen and Trowbridge, 2005; Feddersen, 2012b). For the 29 September observations, immediately seaward of the vertically well-mixed surfzone, thermal stratification inhibits vertical mixing between upper layer surfzone influenced water and cooler water below to the magnitude that occurs in ocean interiors.
1.5.2 Cross-Shore Exchange Velocity

The observations analyzed in Sections 1.4.6.1 and 1.4.7 indicate that rip currents advect warm, dye-rich surfzone water onto the inner-shelf. Here, observations and a two-box temperature model are used to estimate an effective cross-shore exchange velocity $u^*$ between the surfzone and inner-shelf to determine the importance of the transient rip ejections relative to Stokes drift driven advection. The model domain is two-dimensional (assumes alongshore uniformity) and has piecewise linear bathymetry (a triangular surfzone and a trapezoidal inner-shelf). The model has separate surfzone and inner-shelf regions with their own temperature, and a cross-shore heat flux between the two. Solar radiation heats both regions. No heat flux across the seaward inner-shelf boundary, no heat exchange with the seabed, and no air-sea heat fluxes (winds were weak) are assumed. The coupled model equations are (subscripts $SZ$ and $IS$ denote surfzone and inner-shelf quantities, respectively)

$$\frac{1}{2} h_{SZ} |x_{SZ}| \frac{dT_{SZ}}{dt} = |x_{SZ}| \frac{R(t)}{\rho c_p} - h_{SZ} u^* (T_{SZ}(t) - T_{IS}(t)), \quad (1.8a)$$

$$\frac{1}{2} (h_{IS} + h_{SZ}) |x_{IS} - x_{SZ}| \frac{dT_{IS}}{dt} = |x_{IS} - x_{SZ}| \frac{R(t)}{\rho c_p} + h_{SZ} u^* (T_{SZ}(t) - T_{IS}(t)), \quad (1.8b)$$

where $T_{SZ}(t)$ and $T_{IS}(t)$ are the spatially-averaged surfzone and inner-shelf temperatures, $x_{SZ}$ and $x_{IS}$ are the seaward boundaries of the surfzone and inner-shelf (with $x = 0$ m at the mean shoreline), $h_{SZ}$ and $h_{IS}$ are the water depths at $x_{SZ}$ and $x_{IS}$, $\rho = 1025 \text{ kg m}^{-3}$ and $c_p = 4.0 \times 10^3 \text{ J kg}^{-1} \text{ °C}^{-1}$ are the seawater density and specific heat, and $R(t)$ is the incident solar radiation. The depth-integrated temperature flux between the surfzone and inner-shelf is parameterized as $h_{SZ} u^* (T_{SZ} - T_{IS})$, where $u^*$ is an effective cross-shore exchange velocity across the surfzone/inner-shelf boundary $x = x_{SZ}$.

The total incident solar radiation $R(t)$ is inferred from observations of photosynthetically active radiation (PAR, 400–700 nm) measured above the ocean surface at the experiment site (an empirical scaling factor is used to convert from
Figure 1.16: (a) Observed (symbols) and modeled (curves) surfzone and inner-shelf temperature (see legend) versus time. Surfzone $\langle T \rangle$ is 30 min averaged among surfzone-contained frames. Inner-shelf $\langle T \rangle$ is defined in (1.2). Modeled (b) surfzone and (c) inner-shelf temperature time-derivative (gray) versus time, and the contributions from solar heating (magenta) and cross-shore heat flux (cyan). At 13:15 h, fog significantly reduces the incident solar radiation.
PAR to total solar radiation). Under clear skies, $R(t)$ is approximately constant (at $\approx 575 \text{ W m}^{-2}$) from 10:30–13:15 h, after which heavy fog moves in and decreases $R(t)$ by approximately 75%. Choosing $x_{SZ} = x_b$ and $x_{IS} = 2x_b$ (recall $2x_b$ is the mean cross-shore location of inner-shelf alongshore transects) and using observed depths $h_{SZ} = 2.1 \text{ m}$ and $h_{IS} = 4.5 \text{ m}$, the coupled equations (1.8a) and (1.8b) are solved numerically using observations of $T_{SZ}$ and $T_{IS}$ at 10:34 h as initial conditions. The best-fit $u^* = 8.6 \times 10^{-3} \text{ m s}^{-1}$ is found by minimizing the rms model–data error.

The model solutions agree well with observations, reproducing the differential surfzone and inner-shelf warming prior to 13:15 h and the equilibration of surfzone and inner-shelf temperatures after 13:15 h (Figure 1.16a, compare symbols and curves). As the surfzone and inner-shelf regions have the same widths, they receive equal cross-shore integrated solar radiation. Yet, because the surfzone is shallower, prior to 13:15 h the solar radiation (magenta curves in Figures 1.16b, 1.16c) warms the model surfzone faster than the inner-shelf (Figure 1.16a, compare red and blue slopes), consistent with the observations. Both before and after 13:15 h, the cross-shore heat flux has the effect of cooling the warmer surfzone and warming the cooler inner-shelf (cyan curves in Figures 1.16b, 1.16c). When fog decreases incident solar radiation at 13:15 h, the cross-shore heat flux becomes the dominant forcing mechanism for both regions (Figures 1.16b, 1.16c), resulting in surfzone and inner-shelf equilibration (Figure 1.16a).

The inferred cross-shore exchange velocity $u^* = 8.6 \times 10^{-3} \text{ m s}^{-1}$ incorporates all potential surfzone/inner-shelf exchange mechanisms, including both rip currents and Stokes drift driven exchange (onshore near-surface mass flux balanced by undertow at depth). Clark et al. (2010) found the Stokes drift driven exchange mechanism to be negligible in surfzone cross-shore dye dispersion due to the surfzone being vertically well-mixed (assumed in Clark et al. (2010), demonstrated here in Figure 1.7). However, seaward of the surfzone, where dye concentration is not vertically uniform throughout the water column, Stokes drift driven advection could potentially be an important cross-shore exchange mechanism. Here, the $u^*$ magnitude is compared to that expected for Stokes drift driven exchange offshore.
of the surfzone.

For normally incident, narrow-banded, slowly shoaling waves, the Stokes drift velocity $u_S$ is shoreward at all depths, and maximum at the surface:

$$u_S = \frac{1}{2} (ak)^2 C \frac{\cosh (2k(z + h))}{\sinh^2 (kh)},$$

(1.9)

where $a$ is the wave amplitude, $k$ is the wavenumber, $C$ is the phase speed, and $h$ is the still water depth. As the IB09 bathymetry and wave field are approximately alongshore-uniform, the Stokes drift driven exchange is expected to also be alongshore-uniform, with shoreward Stokes drift balanced by a seaward Eulerian return flow $u_E$ such that

$$\int_{-h}^{0} u_S dz = - \int_{-h}^{0} u_E dz.$$  

(1.10)

Within the surfzone, the Eulerian flow $u_E$ has been modeled and observed to have a seaward maximum at depth (e.g., Faria et al., 2000; Reniers et al., 2004). If a depth-intensified flow were to continue offshore of the surfzone, the seaward of surfzone dye would have a maximum at depth. However, the 29 September seaward of surfzone dye observations show that $D$ is approximately vertically uniform in the upper 3 m, and decreases significantly below 3 m (Figures 1.8b, 1.8). Also, just offshore of the surfzone, $u_E$ profiles have been previously modeled and observed to be largely depth-uniform (Putrevu and Svendsen, 1993; Faria et al., 2000; Reniers et al., 2004; Kumar et al., 2012). Therefore, the seaward of surfzone cross-shore Eulerian flow $u_E$ is assumed vertically uniform,

$$u_E = - \frac{1}{h} \int_{-h}^{0} u_S dz = - \frac{1}{2} (ak)^2 \frac{C}{2kh} \frac{\sinh (2kh)}{\sinh^2 (kh)},$$

(1.11)

resulting in net cross-shore Lagrangian flow

$$u_L = u_S + u_E = \frac{1}{2} (ak)^2 \frac{C}{\sinh^2 (kh)} \left[ \cosh (2k(z + h)) - \frac{\sinh (2kh)}{2kh} \right],$$

(1.12)

which is shoreward near the surface and seaward at depth.

The observed waves are assumed normally incident and narrow-banded so $a = H_s/(2\sqrt{2})$. At $f_5$ ($x = -100$ m, the seaward of surfzone frame closest to the surfzone boundary $x_b = -81$ m), the 11:00–16:00 h average incident wave
height $H_s = 0.66$ m, peak period $T_p = 14$ s, and depth $h = 2.9$ m. From (1.12), $u_L$ at $f_5$ is shoreward in the upper water column and seaward only below $z = -1.24$ m. Averaging vertically over the seaward portion of the velocity profile yields $\pi_{L_{sea}} = 8.7 \times 10^{-4}$ m s$^{-1}$, an order of magnitude smaller than the inferred seaward exchange velocity $u^* = 8.6 \times 10^{-3}$ m s$^{-1}$. Similarly at $f_6$ ($x = -135$ m), $\pi_{L_{sea}} = 5.8 \times 10^{-4}$ m s$^{-1}$, and $u_L$ is seaward only below $z = -1.78$ m. Inner-shelf observations at $x \approx 2x_b$ (offshore of f6) show that dye (which has a vertically-mixed surfzone source) is approximately vertically uniform above $z = -3$ m (Figure 1.8b). This requires seaward dye advection in the upper water column, which is inconsistent with the Stokes drift driven exchange mechanism (shoreward in the upper water column and seaward at depth). Furthermore, inner-shelf $D$ and $T$ are distinctively alongshore-patchy (Figures 1.2 and 1.10), but the Stokes drift driven exchange is expected to be approximately alongshore-uniform. These discrepancies in magnitude, vertical structure, and alongshore-patchiness suggest that the observed surfzone/inner-shelf cross-shore tracer exchange is dominated by transient rip ejections on this day with moderate waves. Stokes drift driven exchange may be important farther seaward of $2x_b$ (Lentz et al., 2008). Future analyses of dye releases on days with varying waves, tides, winds, and stratification may reveal the effects of these conditions on cross-shore tracer exchange between the surfzone and inner-shelf.

Here, the inferred surfzone/inner-shelf cross-shore heat flux is compared to other cross-shelf heat flux estimates during similar times of the year (late summer and early fall). During SC, when a surfzone/inner-shelf temperature difference is consistently present, the depth-normalized cross-shore heat flux across the surfzone/inner-shelf boundary ($h_b = 2.1$ m) is $\rho c_p u^* \Delta T \approx 10$ kW m$^{-2}$ in the seaward direction. Farther offshore in 20 m water depth near Mission Beach, California ($\approx 30$ km north of the IB09 experiment site), Lucas et al. (2011) observed a depth-normalized cross-shelf heat flux of $\approx 7$ kW m$^{-2}$ that was shoreward, dominated by the semi-diurnal internal tide. Fewings and Lentz (2011) observed the mean upwelling circulation in 12 m water depth in the Middle Atlantic Bight, where they measured a seaward cross-shelf heat flux of $\approx 15$ kW m$^{-2}$, and concluded that
the mean upwelling circulation was likely driven by a combination of surface gravity waves (Lentz et al., 2008), tidal rectification (Fewings et al., 2008), and an alongshelf pressure gradient (Lentz, 2008). These 29 September IB09 observations suggest that transient rip ejections can drive cross-shore surfzone/inner-shelf heat fluxes with depth-normalized magnitudes comparable to those of much larger scale processes.

1.5.3 Surfzone Tracer Transports and Downstream Dilution

1.5.3.1 Cross-Shore Dye Transport

Here, the surfzone to inner-shelf cross-shore dye transport is estimated following the two-box model for temperature (1.8) and is compared to the dye release rate and the alongshore surfzone dye transport (1.5). The cross-shore dye flux \( F_{SZ}^{x} \) from the surfzone to the inner-shelf is estimated as

\[
F_{SZ}^{x} = h_{b}u^{*}\Delta D, \tag{1.13}
\]

where \( h_{b} \) is the water depth at the surfzone boundary \( x_{b} \), \( u^{*} \) is the best-fit exchange velocity (Section 1.5.2), and \( \Delta D = D_{SZ} - D_{IS} \) is the surfzone and inner-shelf mean dye concentration difference. Using \( D_{IS} = 0.4D_{SZ} = 0.4D_{0sz} (y/y_{0})^{\alpha} \) (Section 1.4.7) in (1.13) yields

\[
F_{SZ}^{x} = 0.6h_{b}u^{*}D_{0sz} (y/y_{0})^{\alpha}, \tag{1.14}
\]

which is valid only during 13:00–16:00 h when the downstream dye dilution has been fit with the power-law (1.4). The surfzone to inner-shelf cross-shore dye transport between the dye release location \( (y = 0 \text{ m}) \) and the cross-shore array \( (y_f = 465 \text{ m}) \) is then

\[
M_{SZ}^{x} = \int_{0}^{y_f} F_{SZ}^{x} dy = \frac{0.6h_{b}u^{*}D_{0sz}}{\alpha + 1} \left( \frac{y_f}{y_{0}} \right)^{\alpha + 1} y_{0}. \tag{1.15}
\]

The best-fit \( D_{0sz} = 42 \text{ ppb} \) and \( \alpha = -0.19 \) (Section 1.4.7) yield \( M_{SZ}^{x} = 81 \text{ ppb m}^{3} \text{ s}^{-1} \), about 11% of the instantaneous dye release rate \( Q_{R} \). The cross-shore dye transport can also be estimated using exponential downstream dilution instead of the
power-law (1.4), with similar results. During 13:00–16:00 h, the cross-shore dye transport $M_{SZ}^x$ between the dye source and $y_f$ is approximately 40% of the mean alongshore surfzone dye transport $\bar{M}_{SZ}^y = 208 \text{ ppb m}^3\text{s}^{-1}$ at $y_f$. Given that non-negligible alongshore surfzone dye transport $M_{SZ}^y$ is observed long after the release ends (Figure 1.14a), it is likely that $M_{SZ}^x$ changes sign (becoming shoreward) as inner-shelf-accumulated dye (which has slow alongshore advection) is recycled back into the surfzone when the last of the surfzone-released dye would have otherwise been alongshore-advected past $y_f = 465$ m.

1.5.3.2 Alongshore Surfzone Dilution Models

Using aerial photographs and in-situ measurements, Inman et al. (1971a) observed surfzone tracer concentrations to decay exponentially with alongshore distance from the source. Using historical fecal indicator bacteria (FIB) data, Boehm (2003) also observed exponential alongshore surfzone decay and developed a differential equation based model, which in steady-state, shows agreement with the discretized Inman et al. (1971a) model. Grant et al. (2005) developed both time-varying and steady-state solutions for a differential equation model similar to that of Boehm (2003). Based on dye and FIB observations, Grant et al. (2005) concluded that, to a good approximation, the steady-state model was valid for the moderate environmental conditions during their field observations.

However, a key assumption of Boehm (2003) and Grant et al. (2005) is that inner-shelf tracer accumulation is negligible, so that no cross-shore tracer recycling from the inner-shelf to the surfzone occurs. This might be a reasonable assumption for FIB when inferred mortality rates are larger seaward of the surfzone (e.g., Rippy et al., 2013a). However, for 29 September IB09 dye tracer, there is significant inner-shelf dye accumulation (Figures 1.4c, 1.5b, 1.13). Further, the prolonged presence of surfzone dye several hours after the end of the dye release (Figures 1.11b, 1.14b) suggests recycling of inner-shelf-accumulated dye back into the surfzone. Thus, in general, inner-shelf tracer accumulation and recycling to the surfzone must be considered for the long-time downstream evolution of surfzone-source tracers.
1.6 Summary

Cross-shore tracer exchange between the surfzone (≤ 2 m water depth) and inner-shelf (≈ 3–6 m water depth) was examined with 29 September IB09 (Imperial Beach, CA 2009) field experiment observations of temperature and Rhodamine WT dye (released continuously near the shoreline in an alongshore current from 11:10–15:47 h). Temperature and dye concentration were measured using a near-bed cross-shore array, repeated cross-shore surface transects at various alongshore locations, inner-shelf CTD+F casts, and a unique, inner-shelf alongshore-towed vertical array.

Prior to 13:00 h, the surfzone and inner-shelf regions both warmed, and the surfzone was consistently warmer than the inner-shelf. Thereafter, heavy fog reduced incident solar radiation significantly, and surfzone and inner-shelf temperatures equilibrated. From 14:00–16:00 h, surfzone and inner-shelf temperature and dye concentration were roughly stationary. Surfzone dye was laterally and vertically well-mixed. Inner-shelf temperature and dye concentration were often alongshore-patchy with coincident warm and dye-rich water. Inner-shelf dye was generally vertically well-mixed in a 3 m-thick upper layer, but dye concentration decreased below 3 m, where thermal stratification was strong. At the cross-shore array, inner-shelf dye and temperature variability was significant (temperature fluctuations up to 2 °C/hr⁻¹), dye concentration and temperature were linearly related, and non-zero dye was not observed for water < 18 °C, even 13 h after the dye release began. The alongshore dilutions of surfzone and inner-shelf dye were similar and followed a power-law relationship with exponents ≈ −0.2, smaller than that previously observed and modeled for surfzone-contained dye plumes (exponent ≈ −0.5). At the cross-shore array, 465 m downstream of the release location, the alongshore dye transport within the surfzone accounted for approximately half of the total dye released.

The vertical mixing of dye below 3 m was inhibited by thermal stratification, where vertical dye and temperature gradients were linearly related. Observations and an isotherm-coordinate dye diffusion model were used to infer a very weak
inner-shelf vertical dye diffusivity of $\approx 3 \times 10^{-5}$ m$^2$ s$^{-1}$, suggesting that, immediately offshore of the well-mixed surfzone, thermal stratification can inhibit vertical mixing to levels similar to those observed in ocean interiors. Observations and a model of surfzone and inner-shelf temperature were used to estimate an effective cross-shore surfzone/inner-shelf exchange velocity $u^* = 8.6 \times 10^{-3}$ m s$^{-1}$.

The inner-shelf dye and temperature alongshore-patchiness and consistent dye-temperature relationship indicate that inner-shelf lateral mixing was relatively weak. Similar surfzone and inner-shelf downstream dye dilution rates indicate that inner-shelf dye and temperature properties were determined by cross-shore advection from the surfzone. Together with magnitude and vertical structure discrepancies between $u^*$ and Stokes drift driven velocities, the inner-shelf tracer alongshore-patchiness indicates that transient rip current ejection events were the dominant cross-shore surfzone/inner-shelf exchange mechanism on 29 September.

The inferred depth-normalized cross-shore heat flux induced by these transient rip ejections is comparable to IW driven and subtidal circulation driven heat fluxes. During the dye release, the cross-shore surfzone to inner-shelf dye transport between the release point and 465 m downstream, estimated with $u^*$ and power-law alongshore dye dilution, was approximately 40% of the alongshore surfzone dye transport measured 465 m downstream of the release. The significant levels of alongshore surfzone dye transport up to 8 h after the end of the release indicate that dye that accumulated on the inner-shelf (where alongshore advection was slow) was recycled back into the surfzone. This is inconsistent with existing surfzone box models that treat the inner-shelf as a tracer sink.

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Chapter 2

Surfzone to Inner-Shelf Exchange Estimated from Dye Tracer Balances

2.1 Abstract

Surfzone and inner-shelf tracer dispersion are observed at an approximately alongshore-uniform beach. Fluorescent Rhodamine WT dye, released near the shoreline continuously for 6.5 h, is advected alongshore by breaking wave- and wind-driven currents, and ejected offshore from the surfzone to the inner-shelf by transient rip currents. Novel aerial-based multispectral dye concentration images and in situ measurements of dye, waves, and currents provide tracer transport and dilution observations spanning about 350 m cross-shore and 3 km alongshore. Downstream dilution of near-shoreline dye follows power law decay with exponent $-0.33$, implying that a 10-fold increase in alongshore distance reduces the concentration about 50%. Coupled surfzone and inner-shelf dye mass balances close, and in 5 h roughly 1/2 of the surfzone-released dye is transported offshore to the inner-shelf. Observed cross-shore transports are parameterized well using a bulk exchange velocity and mean surfzone to inner-shelf dye concentration difference ($r^2 = 0.85$, best fit slope = 0.7). The best fit cross-shore exchange velocity
\( u^* = 1.2 \times 10^{-2} \text{ m s}^{-1} \) is similar to a temperature-derived exchange velocity on another day with similar wave conditions. The \( u^* \) magnitude and observed inner-shelf dye length scales, time scales, and vertical structure indicate the dominance of transient rip currents in surfzone to inner-shelf cross-shore exchange during moderate waves at this alongshore-uniform beach.

\section*{2.2 Introduction}

The nearshore region, consisting of the surfzone (shoreline to \( x_b \), the seaward boundary of depth-limited wave breaking) and the inner-shelf (\( x_b \) to approximately 20 m water depth), is vitally important to coastal economies, recreation, and human and ecosystem health. However, nearshore water quality is often compromised by terrestrial runoff and offshore waste disposal (e.g., Koh and Brooks, 1975; Schiff et al., 2000; Halpern et al., 2008). Globally, microbial pathogen exposure from polluted nearshore water causes an estimated 120 million gastrointestinal illnesses and 50 million severe respiratory illnesses annually (Dorfman and Stoner, 2012) with significant economic impacts. Furthermore, excess nutrients in polluted runoff can spur rapid growth of harmful algal blooms (HABs), damaging ecosystems and causing serious and even life-threatening human illnesses through direct ocean exposure or consumption of algal-contaminated seafood (Dorfman and Haren, 2013).

Pathogens, HABs, and other contaminants are all nearshore tracers; their transport and dilution are governed by surfzone and inner-shelf physical processes. Yet, despite the detriment of contaminated coastal water to our health and economy, understanding of nearshore transport and mixing remains relatively poor. Several field experiments have tracked Lagrangian surface drifters on alongshore-uniform beaches (e.g., Spydell et al., 2007, 2009, 2014) and rip-channeled beaches (e.g., Brown et al., 2009; MacMahan et al., 2010; Brown et al., 2015) to investigate dispersion in the nearshore. Similarly, fluorescent dye (e.g., Harris et al., 1963; Inman et al., 1971a; Grant et al., 2005; Clark et al., 2010) has also been used to explore nearshore mixing. However, many of these observations were limited by sparse sampling or small spatio-temporal domains. A rapid-sampling,
jetski-based dye measurement platform (Clark et al., 2009b) provided improved observation methods. Analyses of dye plume evolution at Huntington Beach, California (HB06) showed that surfzone cross-shore tracer dispersion is dominated by horizontaleddies (Clark et al., 2010; Feddersen et al., 2011; Clark et al., 2011) forced by finite crest length wave breaking (Peregrine, 1998; Spydell and Feddersen, 2009; Clark et al., 2012; Feddersen, 2014). However, HB06 observations were limited to \( \leq 2 \) hours and usually < 400 m downstream of the dye source, and analyses were specifically restricted to surfzone-contained portions of the dye plumes. While shoreline-source tracers are first transported and mixed within the surfzone, their fate is ultimately determined by exchange with the inner-shelf (e.g., Hally-Rosendahl et al., 2014). An improved understanding of long time and distance nearshore tracer dilution requires quantitative estimates of net cross-shore surfzone/inner-shelf exchange.

The surfzone and inner-shelf are governed by drastically different dynamics. The surfzone is dominated by breaking-wave-driven currents (e.g., Thornton and Guza, 1986) and horizontal eddies (e.g., Peregrine, 1998; Clark et al., 2012), whereas the inner-shelf is forced by a combination of wind, tides, buoyancy, and both surface and internal waves (e.g., Lucas et al., 2011; Lentz and Fewings, 2012; Kumar et al., 2014; Sinnett and Feddersen, 2014). The intersection of, and exchange between, these dynamically different regions is particularly complex.

The fall 2009 experiment at Imperial Beach, California (IB09) was designed to observe the dispersion of shoreline-released dye with better resolution, for longer times, and over greater cross- and alongshore distances than preceding studies. Hally-Rosendahl et al. (2014, hereafter HR14) analyzed 29 September in situ observations across the surfzone and inner-shelf, spanning approximately 7 hours and 700 m alongshore. The 29 September mean alongshore current on the inner-shelf was essentially zero. The surfzone was vertically well mixed, while the inner-shelf was strongly stratified immediately offshore of the wave breaking boundary. Horizontal and vertical structure of transient rip current ejection events and the strong stratification limits on inner-shelf vertical mixing were inferred from dye–temperature relationships. Surfzone and inner-shelf alongshore dye dilution
followed similar power law decay over 700 m, indicating that inner-shelf dye was locally cross-shore-advected from the surfzone. The power law decay was weaker than previously observed and modeled for dispersion of surfzone-contained dye over shorter times and downstream distances (Clark et al., 2010). Overall, these observations and analyses suggested that transient rip currents (offshore advection of surfzone eddies) dominated surfzone to inner-shelf cross-shore tracer exchange at alongshore-uniform Imperial Beach (HR14). However, the cross-shore dye transport could not be measured, and observations were limited to 700 m downstream of the release.

Here, a novel aerial-based dye imaging system (Clark et al., 2014) is used to make high spatial resolution maps of inner-shelf dye spanning > 3 km downstream of a 13 October continuous release. Combined aerial and in situ dye observations across the surfzone and inner-shelf are used to investigate far-downstream dye dilution, surfzone and inner-shelf dye mass balances, and cross-shore dye exchange. These are the first quantitative, coupled surfzone and inner-shelf dye mass balances, and in total 88% of the released dye is accounted for. The IB09 experiment site, dye release, instrument platforms, and sampling schemes are described in section 2.3. Wave and alongshore current conditions are presented in section 2.4.1. In section 2.4.2, the aerial dye observations are described, and time periods and spatial regions for subsequent analyses are established. Surfzone cross-shore and vertical dye structure are described in sections 2.4.3 and 2.4.4, respectively. Downstream dye dilution is examined in section 2.4.5, and alongshore dye transports are presented in section 2.4.6. Sections 2.5.1-2.5.3 present total and regional dye mass balances (with estimation methods described in Appendix 2.8). The closure of these balances allows for observational estimates of surfzone to inner-shelf cross-shore dye transports (section 2.5.4) which are compared with parameterized estimates in section 2.6.1. Cross-shore surfzone/inner-shelf exchange mechanisms are discussed in section 2.6.2. Section 2.7 is a summary.
2.3 IB09 Experiment Methods

2.3.1 Field Site and Coordinate System

IB09 field observations were acquired during fall 2009 at Imperial Beach, California (32.6°N, 117.1°W), a west (269.6°) facing beach with an approximately straight shoreline (Figure 2.1). In the right-handed coordinate system, cross-shore coordinate $x$ increases negatively seaward ($x = 0$ m at the mean shoreline), along-shore coordinate $y$ increases positively toward the north ($y = 0$ m at the dye release location), and vertical coordinate $z$ increases positively upward ($z = 0$ at mean sea level). The dye release examined here took place on 13 October 2009. Bathymetry surveys from 9 and 19 October were similar, and each was approximately alongshore-uniform; these are averaged to give a representative bathymetry for 13 October that is approximately alongshore-uniform (Figure 2.1). All times are in PDT.

2.3.2 Dye Release

Fluorescent Rhodamine WT dye ($2.1 \times 10^8$ parts per billion (ppb)) was released continuously at $2.4 \text{ mL s}^{-1}$ near the shoreline at $(x, y) = (-10, 0)$ m for approximately 6.5 h (10:39-17:07 h). Visual observations suggested rapid vertical mixing, and measured dye concentrations were reduced from $O(10^8)$ ppb to $O(10^2)$ ppb within 10 m of the release. Therefore, the dye specific gravity was quickly reduced from 1.2 to $\approx 1$. Rhodamine WT has a photochemical decay $e$-folding time of approximately 667 h of sunlight (e.g., Smart and Laidlaw, 1977); decay over the $\approx 9$ h of sunlight during this study is negligible.

2.3.3 In Situ Instrumentation: Surfzone and Inner-Shelf

2.3.3.1 Cross-Shore Array

A 125 m-long cross-shore array of six fixed, near-bed instrument frames (denoted f1-f6, onshore to offshore) was deployed from near the shoreline to approxi-
Figure 2.1: Planview of IB09 bathymetry contours versus cross-shore coordinate $x$ and alongshore coordinate $y$. Star indicates dye release location. Diamonds denote the cross-shore array of bottom-mounted instrument frames f1-f6 (onshore to offshore). Circles indicate SA1-SA4 fluorometer locations. Vertical dashed line represents an idealized boat alongshore transect driven repeatedly near this cross-shore location. Horizontal dashed line represents an idealized jetski cross-shore surface transect driven repeatedly at various alongshore locations.
mately 4 m water depth (diamonds, Figure 2.1). The frames held Paros pressure sensors, SonTek acoustic Doppler velocimeters (ADVs), Yellow Springs Instrument Company thermistors, and WET Labs ECO Triplet fluorometers (hereafter ET) to measure dye concentration $D$. One frame (f4), located near the seaward edge of the surfzone, held instruments at three different vertical locations (0.2, 0.7, and 1.3 m above the bed). Cross-shore array instruments sampled for 51 min each hour, with the remaining 9 min used by the ADVs to estimate bed location (Feddersen, 2012b; Spydell et al., 2014). On 13 October, the dye release ($y = 0$ m) was 248 m to the south (Figure 2.1); the alongshore location of this f1-f6 array is denoted by $y_t = 248$ m.

2.3.3.2 Surfzone Near-Shoreline Alongshore Array

Four thermistor-equipped ETs were deployed near the shoreline at $y = 82, 546, 1069, 1662$ m (circles, Figure 2.1), referred to as SA1-SA4, respectively. For some analyses, ET data from f2 (at $y_t = 248$ m) are used in conjunction with data from SA1-SA4. The ET on f2 sampled throughout (and after) the dye release, while SA1-SA4 were deployed after the dye release started.

2.3.3.3 Cross-Shore Jetski Transects

Surface dye concentration and temperature were measured with fluorometers and thermistors mounted on two GPS-tracked jetskis (Clark et al., 2009b) that drove repeated cross-shore transects from $x \approx -300$ m to the shoreline (e.g., Figure 2.1) at various designated alongshore locations between $y = 5$ m and $y \approx 2$ km. The alongshore spacing between transects varied from approximately 20 m (near the release) to 300 m (far downstream of the release). Analyses only include shoreward transects, when jetskis were driven immediately in front of bores to minimize turbidity from bubbles and suspended sand. Seaward transects, sometimes corrupted when jetskis swerved or became airborne jumping over waves, are discarded.
2.3.3.4 Inner-Shelf Alongshore Boat Transects

Offshore of the surfzone, the vertical and alongshore structure of dye concentration and temperature were measured with a vertical array of five thermistor-equipped ETs towed alongshore behind a small boat. The vertical array sampled from $z = -1$ to $-3$ m at 0.5 m spacing. During 14:06-17:43 h, repeated $\approx 2$ km-long alongshore transects (e.g., Figure 2.1) were driven at roughly 1 m s$^{-1}$ at a mean cross-shore location nominally twice the surfzone width. The transects were approximately shore-parallel with deviations to avoid large waves.

2.3.4 Inner-Shelf Dye Aerial Remote Sensing

Novel aerial observations of near-surface dye concentration were obtained from a small plane with a multispectral camera system and coupled global positioning and inertial navigation systems (Clark et al., 2014). Two cameras captured images near the peak excitation and emission wavelengths of the fluorescent Rhodamine WT. Dye concentrations were determined by calibrating the ratio of emission to excitation radiances with coincident in situ data. Aerial dye concentration errors range from $\pm 1.5$ ppb near $D = 0$ ppb to $\pm 4.5$ ppb near $D = 20$ ppb. The georeferenced aerial images are combined into mosaics and regridded onto a rectangular grid with 2 m $\times$ 2 m lateral resolution. See Clark et al. (2014) for details.

Between 11:21 and 15:32 h, 23 mosaic images were obtained, each separated by roughly 6 min (with a longer gap from 13:08 to 14:56 h). The dye field was imaged from the shoreline to roughly 350 m offshore and from the release to roughly 3 km downstream. Pixels with excitation image brightness above an empirical threshold (Clark et al., 2014) owing to sun glitter or white foam from breaking waves are discarded. The surfzone is therefore often poorly resolved, and quantitative analyses of aerial images are confined to the inner-shelf.
Figure 2.2: Time-averaged (11:00-16:00 h) (a) significant wave height $H_s$, (b) alongshore current $V$, and (c) vertical locations of f1-f6 versus cross-shore coordinate $x$. In (c), the black curve gives the bathymetry $h(x)$. The mean seaward surfzone boundary $x_b = -81$ m is defined as the location of maximum $H_s$.

2.3.5 Corrections to Measured Dye Fluorescence

All aerial and in situ dye observations are corrected for temperature per Smart and Laidlaw (1977), and all in situ dye observations are corrected for turbidity per Clark et al. (2009b). Corrected $D$ typically differ from measured $D$ by less than 5%.

2.4 Observations

2.4.1 Wave, Wind, and Alongshore Current Conditions

During the dye release, the incident wave field (with peak period $T_p = 13$ s) is relatively constant, and the tide varies less than 0.7 m (low tide at 12:33 h). The release-averaged significant wave height $H_s(x)$ shoals to a maximum of 0.87 m at f4 (break point $x_b = -81$ m, mean breaking depth $h_b = 2.1$ m, Figures 2.2a and 2.2c). The mean alongshore current $V(x)$ is northward (positive) at all f1-f6 locations,
with a near-shoreline maximum of 0.40 m s\(^{-1}\) (Figure 2.2b). Offshore, \(V\) decreases to 0.12 m s\(^{-1}\) at the seaward surfzone boundary \(x_b\) and then increases slightly to 0.17 m s\(^{-1}\) at inner-shelf \(f_6\) (\(x = -135\) m, Figure 2.2b). The mean surfzone (\(f_1\)-\(f_4\)) alongshore current is \(V_{SZ} = 0.22\) m s\(^{-1}\), and the mean inner-shelf (\(f_4\)-\(f_6\)) alongshore current is \(V_{IS} = 0.14\) m s\(^{-1}\). Wind is from the south at 4-7 m s\(^{-1}\).

### 2.4.2 Inner-Shelf Surface Dye Evolution

Aerial images (e.g., Figures 2.3a-2.3f) spanning 0:42-4:53 h after the \(t_0 = 10:39\) h start of the dye release are partitioned into three time periods based on temporal gaps in images and the dye plume evolution: period I (early-release, 11:21-11:53 h), period II (mid-release, 12:08-13:01 h), and period III (late-release, 14:56-15:32 h). Approximately 40 min after the release begins (Figure 2.3a, period I), surfzone dye has advected about 600 m alongshore at \(\approx 0.25\) m s\(^{-1}\), consistent with in situ \(V_{SZ} = 0.22\) m s\(^{-1}\) (Figure 2.2b). Surfzone dye is ejected onto the inner-shelf in narrow (\(\approx 50\) m) alongshore bands (Figure 2.3a), presumably due to transient rip currents (e.g., HR14). As the dye release continues (Figures 2.3b-2.3d, period II), the leading portion of inner-shelf dye is alongshore-patchy with length scales \(\approx 50\) m (as in Figure 2.3a). Behind the leading edge, slower alongshore advection of inner-shelf dye (e.g., the feature at \(y \approx 1250\) m and 1500 m in Figures 2.3e and 2.3f, respectively, period III) is apparent at a speed of \(\approx 0.15\) m s\(^{-1}\), consistent with in situ \(V_{IS} = 0.14\) m s\(^{-1}\) (Figure 2.2b). At these longer times and downstream distances (Figures 2.3e and 2.3f, period III), inner-shelf dye advects alongshore, disperses cross-shore, and moves to larger alongshore length scales. In particular, Figures 2.3e and 2.3f reveal a coherent nearshore eddy feature (at \(y \approx 1250\) m and 1500 m, respectively) with an alongshore length scale \(\approx 300\) m, roughly six times larger than the length scales of inner-shelf dye patches when recently ejected from the surfzone (Figure 2.3; also see Figure 2.14, which is discussed in detail in section 2.6.2).

In addition to the temporal partitioning into periods I, II, and III (defined above), the spatial domain is cross-shore-partitioned into the surfzone (SZ) and inner-shelf (IS) regions (separated by \(x_b = -81\) m, section 2.4.1) and alongshore-
Figure 2.3: Aerial multispectral images of surface dye concentration $D$ (ppb, see colorbar) versus cross-shore coordinate $x$ and alongshore coordinate $y$ for six times (indicated in each panel). The mean shoreline is at $x = 0$ m. Green star indicates location of continuous dye release (starting at $t_0 = 10:39$ h). Yellow diamonds indicate cross-shore array f1-f6 locations, and yellow circles indicate SA1-SA4 locations. Light gray indicates regions outside the imaged area, and black indicates unresolved regions due to foam from wave breaking. Vertical dashed cyan line at $x_b$ divides the surfzone (SZ) and inner-shelf (IS), and horizontal cyan line divides the near- and far-field regions A and B (see panel (a)). Plume leading edge $y_p(t)$ is shown with green triangles at $x \approx -100$ m (for panel (f), $y_p \approx 3250$ m). Panels (a), (b)-(d), and (e)-(f) are in time periods I, II, and III, respectively.
partitioned into near- and far-field regions A and B (separated by the cross-shore frame array at \( y_f = 248 \text{ m} \), Figure 2.3a).

The leading alongshore edge of the dye plume \( y_p(t) \) is defined as the northernmost location where aerial-imaged inner-shelf \( D \) exceeds 3 ppb within 40 m of \( x_b \) (green triangles in Figures 2.3a-2.3e). The plume leading edge \( y_p(t) \) increases roughly linearly during each time period, with the fastest advance during period III (Figure 2.4a). The \( y_p(t) \)-associated alongshore velocity averaged over periods I, II, and III is \( 0.17 \text{ m s}^{-1} \) (Figure 2.4a), and is between the surfzone and inner-shelf means \( V_{SZ} = 0.22 \text{ m s}^{-1} \) and \( V_{IS} = 0.14 \text{ m s}^{-1} \) observed at the f1-f6 array (Figure 2.2b and section 2.4.1).

### 2.4.3 Cross-Surfzone Mean Dye Profiles

Time-averaged surface dye profiles \( \overline{D}(x, y_j) \) from repeated jetski cross-shore transects at designated alongshore locations \( y_j \) are cross- and alongshore-binned corresponding to where near-shoreline dye is released \( (y = 0 \text{ m}) \) and measured (SA1, f2, SA2, SA3, and SA4, Figure 2.1). Near the release \( (y = 14 \text{ m}) \), mean dye concentration is high \( (\approx 80 \text{ ppb}) \) near the shoreline and decays to \( \approx 10 \text{ ppb} \) near \( x_b \) (Figure 2.4b). Immediately downstream \( (y = 87 \text{ m}) \), as dye is dispersed offshore, the mean dye cross-surfzone profile begins to flatten. At each alongshore location, the dye standard deviation is \( \propto \overline{D} \). Thus, for \( y \geq 207 \text{ m} \), dye is well mixed across the surfzone (Figure 2.4b), indicating that surfzone-representative \( D \) can be estimated using near-shoreline measurements. These observations of dye cross-surfzone uniformity for \( y \geq 207 \text{ m} \) are similar to other observational (Clark et al., 2010) and modeling (Clark et al., 2011) results in which the surfzone was well mixed at \( y \gtrsim 200 \text{ m} \) for similar wave and current conditions.

### 2.4.4 Surfzone Dye Vertical Structure

Surfzone dye measured at f4 (Figure 2.2c) is vertically uniform across the three fluorometers (Figure 2.4c), indicating that the surfzone water column is well mixed by breaking waves. This is consistent with a similar result found during
Figure 2.4: (a) Alongshore coordinate of dye plume leading edge $y_p$ versus time. The determination of $y_p(t)$ is described in section 2.4.2. Black bars denote time periods I, II, and III. (b) Time-averaged, cross- and alongshore-binned surfzone $D$ from jetski surface transects versus cross-shore coordinate $x$ (see legend for alongshore locations $y$). The analogous dye standard deviation is $\propto D$ at each $y$, and thus surfzone dye profiles for $y \geq 207$ m are cross-shore uniform. (c) Dye concentration $D$ versus time at three ETs with different vertical elevations (mab is meters above bottom) on f4 at the seaward surfzone boundary $x_b$ (see legend and Figure 2.2c). Gaps in the time series result from sampling for 51 minutes of each hour. Magenta bars in (a) and (c) indicate duration (10:39–17:07 h) of near-shoreline, continuous dye release at $y = 0$ m (star in Figures 2.1 and 2.3).

a 29 September dye release (HR14), and demonstrates that surfzone dye can be assumed vertically uniform for the purposes of estimating surfzone dye mass and alongshore transport.

2.4.5 Near-Shoreline Alongshore Dye Dilution

Here, alongshore dye dilution is examined with near-shoreline in situ data from SA1-SA4 and f2 (yellow circles and diamond, respectively, Figure 2.3). SA1-SA4 were deployed after the dye plume had arrived at their respective locations;
data start times (beginning progressively later with downstream distance) indicate instrument deployment times, not plume arrival times (Figure 2.5). With the exception of SA3 ($y = 1069$ m), SA instruments were recovered shortly after the dye release ended.

When the dye field is roughly stationary, mean near-shoreline dye concentration decays with downstream distance from the release (Figures 2.5 and 2.6) because dye is dispersed cross-shore onto the inner-shelf as it is advected alongshore (Figure 2.3). Near-shoreline dye variability also decreases significantly with $y$ (Figure 2.5 and vertical bars in Figure 2.6). For example, near the release at $y = 248$ m, $D$ varies between 0-80 ppb with a mean of 15 ppb, while at $y = 1662$ m, $D$ varies between 4-12 ppb with a mean of 8 ppb (Figures 2.5b, 2.5e, and 2.6). Furthermore, the time scale of dye variability increases with downstream distance from the release (Figures 2.5a-2.5e); the characteristic time scale $\left(\frac{(dD/dt)^2}{D^2}\right)^{-1/2}$ increases monotonically from 71 s at $y = 82$ m to 584 s at $y = 1662$ m. This increasing time scale suggests that characteristic alongshore surfzone dye length scales ($\approx 16$ m at $y = 82$ m and $\approx 130$ m at $y = 1662$ m using $V_{SZ} = 0.22$ m s$^{-1}$) also increase with $y$. This downstream increase in surfzone length scale is qualitatively consistent with the inner-shelf length scale increase (Figures 2.3a-2.3f). However, quantitative surfzone and inner-shelf length scale comparison is avoided given the uncertainty in how characteristic tracer length scales evolve with distance from a shoreline boundary.

The near-shoreline mean dye dilutes following a power law,

$$\overline{D} = \overline{D}_0 (y/y_0)^\alpha,$$

(2.1)

where $y_0 = 1$ m is chosen for simplicity. The least squares power law fit has high skill ($r^2 = 0.98$) with best fit constants $\overline{D}_0 = 98(\pm 13)$ ppb and $\alpha = -0.33(\pm 0.02)$ (dashed line in Figure 2.6). Note that $\alpha = -0.33$ corresponds to relatively weak decay; a 10-fold increase in $y$ reduces $\overline{D}$ by $\approx 50\%$. Power law dilution was also observed during a 29 September dye release over shorter distances (700 m) with $\alpha = -0.19$ (HR14). The power law exponents $\alpha = -0.33$ (observed here) and $\alpha = -0.19$ (HR14) are both smaller than the $\alpha \approx -0.5$ observed and modeled for short (generally $\leq 200$ m) portions of dye plumes confined to the surfzone
Figure 2.5: Dye concentration $D$ versus time at the near-shoreline $f_2$ and SA1-SA4 (diamond and circles, respectively, Figures 2.1 and 2.3). Alongshore location is indicated in each panel. Magenta bars indicate duration of near-shoreline, continuous dye release at $y = 0$ m (star in Figures 2.1 and 2.3). SA1-SA4 data start times correspond to instrument deployment times, not plume arrival times. Vertical axes differ.
Figure 2.6: Mean (time-averaged) dye concentration $\overline{D}$ versus alongshore coordinate $y$ at the near-shoreline f2 and SA1-SA4 (diamond and circles, respectively, Figures 2.1 and 2.3). Vertical bars are standard deviations about the means. Best fit line (dashed) is $\overline{D} = \overline{D}_0 (y/y_0)^\alpha$, where $y_0 = 1$ m is chosen for simplicity, and best fit constants are $\overline{D}_0 = 98$ ppb and $\alpha = -0.33$.

(Clark et al., 2010, 2011). Note that $\alpha = -0.5$ is only expected for a domain with cross-shore uniform alongshore current and constant eddy diffusivity (i.e., an idealized surfzone, as assumed in Clark et al. (2010)), and when the inner-shelf acts as an idealized tracer sink, not recycling any dye back into the surfzone. Once dye disperses seaward of the surfzone onto the inner-shelf, the $V_{SZ}$ and $V_{IS}$ difference, the potential surfzone and inner-shelf diffusivity difference, and the inner-shelf providing an additional dye source to the surfzone (e.g., HR14) each preclude a simple constant-diffusivity Fickian solution ($\alpha = -0.5$) or other simple analytic solution to compare with the observed $\alpha = (-0.19, -0.33)$. The surfzone to inner-shelf cross-shore dye transports and underlying exchange mechanisms that lead to the downstream decay rates observed here are discussed in section 2.6.

2.4.6 Alongshore Dye Transport

Dye is advected by the northward alongshore current $V$ (Figures 2.2b and 2.3) from the release location $(x, y) = (-10, 0)$ m past the cross-shore array at
$y_t = 248$ m. The alongshore dye transport $T^{y_{A/B}}$ from region A to region B through $y_t$ (Figure 2.3, diamonds) is estimated for the surfzone,

$$T_{SZ}^{y_{A/B}}(t) = \int_{x_b}^{0} d(x,t)V(x,t)D(x,t) \, dx,$$

(2.2)

and the inner-shelf,

$$T_{IS}^{y_{A/B}}(t) = \int_{x_{f6}}^{x_b} d(x,t)V(x,t)D(x,t) \, dx,$$

(2.3)

using in situ, 30 s-averaged total water depth $d = h + \eta$, alongshore current $V$, and $D$ at f1-f6, assuming vertically uniform $V(x,t)$ and $D(x,t)$. For the surfzone, this assumption is a good approximation (Figure 2.4c). However, inner-shelf $D$ is not necessarily vertically uniform, as thermal stratification can significantly inhibit inner-shelf vertical dye mixing, even immediately offshore of the vertically mixed surfzone (not shown here, similar to HR14, Figure 15). Inner-shelf $V$ may also be vertically sheared, likely larger in the upper water column, driven by southerly wind. Lastly, dye at $y_t$ sometimes extends offshore of $f_6$ (e.g., Figure 2.3), but $V$ measurements, and therefore the extent of cross-shore integration for (2.3), are limited to $x_{f6} = -135$ m. For these reasons, $T_{IS}^{y_{A/B}}$ is biased low.

The surfzone and inner-shelf alongshore dye transports $T_{SZ}^{y_{A/B}}$ and $T_{IS}^{y_{A/B}}$ generally vary between approximately 0-1000 ppb m$^3$s$^{-1}$ and 0-400 ppb m$^3$s$^{-1}$, respectively (Figures 2.7a and 2.7b). Averaged over the release period, $\overline{T_{SZ}^{y_{A/B}}} = 320$ ppb m$^3$s$^{-1}$ and $\overline{T_{IS}^{y_{A/B}}} = 76$ ppb m$^3$s$^{-1}$, with roughly four times more alongshore dye transport in the surfzone than between f4 and f6. The cumulative (time-integrated) alongshore dye transports at $y_t$ for the surfzone and inner-shelf are $\int_{t_0}^{t} T_{SZ}^{y_{A/B}}(\tau) \, d\tau$ and $\int_{t_0}^{t} T_{IS}^{y_{A/B}}(\tau) \, d\tau$, respectively, where $t_0 = 10.39$ h is the dye release start time. The cumulative surfzone alongshore transport $\int_{t_0}^{t} T_{SZ}^{y_{A/B}} \, d\tau$ is roughly linear during the dye release (Figure 2.7c) with small steps corresponding to pulses of $T_{SZ}^{y_{A/B}}$ (Figure 2.7a). At $t = 18:00$ h, after the last of the dye is advected past the cross-shore array, 62% of the total dye released has been alongshore-transported between the shoreline and f4, and at least 15% of the total between f4 and f6 (Figure 2.7c). Therefore, at least 77% of the total dye released 248 m south of $y_t$ is alongshore-transported within $|x_{f6}| = 135$ m of the shoreline (recall $T_{IS}^{y_{A/B}}$ is biased low).
Figure 2.7: Time series of alongshore dye transport from region A to B in the (a) surfzone \( T_{SZ}^{A/B} \) defined in (2.2)) and (b) inner-shelf \( T_{IS}^{A/B} \) defined in (2.3)). Vertical axes differ. (c) Time series of cumulative (time-integrated) surfzone and inner-shelf alongshore dye transports (see legend). Magenta bars indicate duration of near-shoreline, continuous dye release (Figure 2.3a, star) 248 m south of the cross-shore array (Figure 2.3a, diamonds) that separates regions A and B. The dye release rate \( Q = 512 \text{ ppb m}^3\text{s}^{-1} \), and the total dye released is \( 1.19 \times 10^7 \text{ ppb m}^3 \). In panel (c) at \( t = 18.00 \text{ h} \), the resulting cumulative dye transports normalized by the total dye released are 0.62 (surfzone) and 0.15 (inner-shelf).
2.5 Dye Mass Balances and Cross-Shore Exchange

In sections 2.5.1-2.5.3, dye mass balances are shown to close in total, for near-field region A and far-field region B, and for the surfzone and inner-shelf. These results are used in section 2.5.4 to infer the surfzone to inner-shelf cross-shore dye tracer exchange.

2.5.1 Mass Balance: Total and Regional

Surfzone and inner-shelf dye masses integrated over the entire alongshore domain (regions A \((0 < y \leq 248 \text{ m})\) and B \((y > 248 \text{ m})\) combined) are

\[
M_{SZ}^{A+B}(t) = \int_{0}^{y_p(t)} \int_{0}^{0} \int_{-h}^{0} D(x, y, z, t) \, dz \, dx \, dy,
\]

and

\[
M_{IS}^{A+B}(t) = \int_{-\infty}^{\infty} \int_{-\infty}^{x_b} \int_{-h}^{0} D(x, y, z, t) \, dz \, dx \, dy,
\]

where \(y_p(t)\) is the alongshore location of the leading edge of the northward-advecting dye plume (green triangles in Figure 2.3). Estimation methods for (2.4) and (2.5) are described in Appendix 2.8. The total dye mass balance for the surfzone and inner-shelf is

\[
M_{SZ}^{A+B}(t) + M_{IS}^{A+B}(t) = \int_{0}^{t} Q \, d\tau,
\]

where \(Q\) is the steady dye release rate, \(t_0 = 10:39 \text{ h}\) is the dye release start time, and \(M_{SZ}^{A+B}(t_0) \equiv M_{IS}^{A+B}(t_0) \equiv 0 \text{ ppb m}^3\).

The total dye mass balance (2.6) closes well over the 11:21-15:32 h time span of aerial images (Figure 2.8a, compare red asterisks with red line). On average, 88% of the released dye tracer is accounted for using these novel aerial and (relatively sparse) in situ measurements. Note, \(M_{SZ}^B\) (and therefore \(M_{SZ}^{A+B}\)) may be biased low because \(y_p(t)\) may be underestimated (Appendix 2.8.1). Analyses are broken into time periods I, II, and III based on temporal gaps in aerial data (e.g., Figure 2.8a) and dye plume evolution (recall section 2.4.2 and Figure 2.3). Early in the release during period I, \(M_{SZ}^{A+B} \approx M_{IS}^{A+B}\) (Figure 2.8a). Starting in period II, as more dye spreads from the surfzone to the inner-shelf, \(M_{IS}^{A+B}\) becomes larger than \(M_{SZ}^{A+B}\).
Figure 2.8: Dye mass $M$ versus time. Black bars denote time periods I, II, and III. (a) Surfzone estimates $M_{SZ}^{A+B}$ (gray) are from in situ observations, and inner-shelf estimates $M_{IS}^{A+B}$ (blue) are from aerial observations. Red asterisks are $M_{SZ}^{A+B} + M_{IS}^{A+B}$. Red line shows the time-integrated dye released since $t_0 = 10:39 \text{ h}$ ($\int_{t_0}^{t} Q \, d\tau$, where $Q$ is the steady dye release rate). (b) Surfzone dye mass $M_{SZ}$ versus time for the near-field region A ($y \leq 248 \text{ m}$, triangles) and the far-field region B ($y > 248 \text{ m}$, squares). Solid gray diamonds are $M_{SZ}^{A+B}$. (c) Inner-shelf dye mass $M_{IS}$ versus time for region A (triangles) and region B (squares). Solid blue circles are $M_{IS}^{A+B}$. Estimation methods for $M_{SZ}$ and $M_{IS}$ are described in Appendix 2.8.1 and 2.8.2, respectively.
In period III, \( M_{IS}^{A+B} \approx 2M_{SZ}^{A+B} \) (Figure 2.8a), indicating significant cross-shore transport of surfzone-released dye to the inner-shelf.

The surfzone and inner-shelf are also decomposed into near-field region A and far-field region B (Figure 2.3a). For the surfzone, \( M_{SZ}^{A} \approx M_{SZ}^{B} \) during period I (Figure 2.8b), when dye has not advected very far downstream (e.g., Figure 2.3a). As the dye plume advects farther alongshore during period II, \( M_{SZ}^{B} \) becomes larger than \( M_{SZ}^{A} \). Though dye concentrations are highest near the release (region A) and decrease downstream, the power law decay is weak (equation (2.1) and Figure 2.6), and the larger alongshore extent of the dye plume in region B than region A results in period II \( M_{SZ}^{B} \approx 2M_{SZ}^{A} \) (Figure 2.8b). During period III, dye has advected far downstream (e.g., Figures 2.3e and 2.3f), and \( M_{SZ}^{B} \approx 4M_{SZ}^{A} \) (Figure 2.8b). Similar trends are observed for the inner-shelf. During period I, \( M_{IS}^{A} \approx M_{IS}^{B} \) (Figure 2.8c). In period II, \( M_{IS}^{B} \) begins to dominate \( M_{IS}^{A} \), and during period III, \( M_{IS}^{B} \approx M_{IS}^{A} \) (Figure 2.8c).

### 2.5.2 Mass Balance: Near-field Region A

In near-field region A, the total released dye mass must balance the surfzone and inner-shelf accumulated dye mass and the time-integrated alongshore transport from region A to B:

\[
M_{SZ}^{A}(t) + M_{IS}^{A}(t) + \int_{t_0}^{t} \left( T_{SZ}^{g,A/B} + T_{IS}^{g,A/B} \right) d\tau = \int_{t_0}^{t} Q d\tau.
\]  

(2.7)

On average, the sum of the observed region A mass and cumulative A to B transports account for 76% of the released dye (Figure 2.9a, compare red asterisks with red line). The largest terms of (2.7) are the cumulative surfzone and inner-shelf alongshore transports, with \( \int_{t_0}^{t} T_{SZ}^{g,A/B} d\tau \approx 0.6 \int_{t_0}^{t} Q d\tau \) and \( \int_{t_0}^{t} T_{IS}^{g,A/B} d\tau \approx 0.2 \int_{t_0}^{t} Q d\tau \) during the aerial data time span (Figure 2.9a, gray and blue curves, respectively). The region A dye masses \( M_{SZ}^{A} \) and \( M_{IS}^{A} \) are relatively small, especially during period III (Figure 2.9a, triangles). The 24% of dye unaccounted for in region A is consistent with the low-bias of \( T_{IS}^{g,A/B} \) (described in section 2.4.6).
Figure 2.9: Dye mass balance terms versus time for (a) near-field region A ($0 < y \leq y_f = 248$ m) and (b) far-field region B ($y > y_f = 248$ m). See legend in each panel, and equations (2.7) and (2.8) for panels (a) and (b), respectively.
2.5.3 Mass Balance: Far-field Region B

Similar to the near-field region A, the far-field region B surfzone and inner-shelf accumulated dye mass must balance the time-integrated alongshore transport from A to B:

\[
M_{SZ}^B(t) + M_{IS}^B(t) = \int_{t_0}^{t} \left( T_{y,A/B}^{y,A/B} + T_{IS}^{y,A/B} \right) d\tau. \quad (2.8)
\]

The observed mass and transport estimates agree well, having 18% relative rms error (Figure 2.9b, compare red circles with red squares), confirming the consistency among aerial and in situ data and the validation of mass and transport estimation methods. On average, the region B accumulated dye mass (red squares, Figure 2.9b) is slightly larger than the time-integrated alongshore transport (red circles, Figure 2.9b), again consistent with the low bias of \( T_{IS}^{y,A/B} \) (section 2.4.6).

2.5.4 Cross-Shore Surfzone/Inner-Shelf Exchange

Because the section 2.5.1-2.5.3 dye mass balances close, cross-shore surfzone to inner-shelf transport estimates for regions A and B (\( T_{SZ/IS}^{x,A} \) and \( T_{SZ/IS}^{x,B} \), respectively) can be inferred from the observations. The region A inner-shelf dye mass must balance cross-shore transport input from the region A surfzone and alongshore transport loss to the region B inner-shelf (Figure 2.10). The region B inner-shelf dye mass must balance cross-shore transport input from the region B surfzone and alongshore transport input from the region A inner-shelf (Figure 2.10). The corresponding equations are

\[
\int_{t_0}^{t} T_{SZ/IS}^{x,A} d\tau = M_{IS}^A(t) + \int_{t_0}^{t} T_{IS}^{y,A/B} d\tau, \quad (2.9a)
\]

\[
\int_{t_0}^{t} T_{SZ/IS}^{x,B} d\tau = M_{IS}^B(t) - \int_{t_0}^{t} T_{IS}^{y,A/B} d\tau. \quad (2.9b)
\]

Adding (2.9a) and (2.9b) yields the expected inner-shelf balance for regions A and B combined:

\[
\int_{t_0}^{t} \left( T_{SZ/IS}^{x,A} + T_{SZ/IS}^{x,B} \right) d\tau = M_{IS}^A(t) + M_{IS}^B(t). \quad (2.10)
\]
Figure 2.10: Planview photograph and superposed schematic of dye mass balances (2.9a), (2.9b), and (2.10). Star denotes location of dye released at steady rate $Q$. 
Figure 2.11: Time series of cumulative (time-integrated) cross-shore dye transports from the surfzone to inner-shelf (circles) inferred from inner-shelf dye mass observations $M_{IS}$ and alongshore transport measurements $T_{y, A/B}$. See (2.9a), (2.9b), and (2.10). Line segments are least squares fits for each time period, and line segment slopes yield inferred cross-shore dye transports $T_{ SZ/IS}$. Thin red line shows the time-integrated dye released since $t_0 = 10.39$ h.

The total (A+B) inner-shelf-accumulated dye mass must balance the time integral of the total cross-shore transport of surfzone-released dye. The time-integrated cross-shore transports (2.9a), (2.9b), and (2.10) are inferred from the observed inner-shelf dye mass and alongshore transport.

The inferred time-integrated cross-shore transports $\int_{t_0}^{t} T_{ SZ/IS} d\tau$ are approximately linear in each time period, and the associated cross-shore transports $T_{ SZ/IS}$ are estimated from the slope of each best fit line (Figure 2.11). The region A cross-shore transport $T_{x,A}^{SZ/IS}$ is similar for periods I and II (137 and 115 ppb m$^3$s$^{-1}$, respectively), consistent with the fixed 248 m alongshore extent of region A, independent of the dye plume advecting farther northward with time. In contrast, the region B cross-shore transport $T_{x,B}^{SZ/IS}$ increases significantly among periods I, II, and III (25, 263, and 495 ppb m$^3$s$^{-1}$, respectively) as $y_p(t)$ moves northward (e.g., Figures 2.3 and 2.4a). As a result, the region A and B combined cross-shore transport $T_{x,A+B}^{SZ/IS}$ also increases with time. During period I, when dye has not advected far downstream (e.g., Figure 2.3a), $T_{x,A+B}^{SZ/IS} = 162$ ppb m$^3$s$^{-1} = 0.32Q$. During period II, when dye has advected farther downstream (e.g., Figures 2.3b-2.3d), $T_{x,A+B}^{SZ/IS} = 378$ ppb m$^3$s$^{-1} = 0.74Q$. During period III, when dye has ad-
vected approximately 3 km downstream (e.g., Figures 2.3e and 2.3f), $T_{SZ/IS}^{x,A+B} = 498$ ppb m$^3$s$^{-1} = 0.97Q$, and most of the cross-shore transport occurs in region B (Figure 2.11, compare red with green best fit slopes). Over the approximate 5 h of aerial observations, roughly 1/2 of the shoreline-released dye is cross-shore transported to the inner-shelf, i.e., $\int_{t_0}^{t} T_{SZ/IS}^{x,A+B} d\tau \approx \frac{1}{2} \int_{t_0}^{t} Q d\tau$ (Figure 2.11, compare blue symbols with thin red line).

2.6 Discussion

2.6.1 Parameterizing Cross-Shore Tracer Exchange

The box-model-based cross-shore tracer flux parameterization used for temperature by HR14 is tested here for dye with the inferred estimates of surfzone to inner-shelf cross-shore dye transport (section 2.5.4). The cross-shore dye flux $\hat{F}_{SZ/IS}^x$ (units ppb m$^2$s$^{-1}$) at the surfzone/inner-shelf boundary $x_b$ is parameterized as

$$\hat{F}_{SZ/IS}^x = h_b u^* \Delta D,$$  \hspace{1cm} (2.11)

where $h_b$ is the water depth at $x_b$, $u^*$ is a bulk cross-shore exchange velocity, and $\Delta D = D_{SZ} - D_{IS}$ is the difference between surfzone and inner-shelf mean dye concentrations. Here, $\Delta D$ is computed separately for region A and region B and for each time period using period-averaged dye mass estimates $\overline{M}_{SZ}^A$, $\overline{M}_{IS}^A$, $\overline{M}_{SZ}^B$, $\overline{M}_{IS}^B$ (section 2.5.1) and approximate volumes $\nu$ of each region (e.g., $D_{SZ}^A = \overline{M}_{SZ}^A/\nu_{SZ}^A$). The surfzone volumes are defined by the integration regions for $\overline{M}_{SZ}^{A,B}$ (see Appendix 2.8.1). The inner-shelf volumes are estimated using $h_{dye}$ (Appendix 2.8.2), cross-shore width $| - 250 \text{ m} - x_b | = 169 \text{ m}$ (e.g., Figure 2.3), and alongshore extents $y_f = 248 \text{ m}$ (region A) and $\overline{y}_p - y_f$ (region B), where $\overline{y}_p$ is the mean of $y_p$ for each time period. The parameterized surfzone to inner-shelf cross-shore dye transports $\hat{T}_{SZ/IS}^x$ (units ppb m$^3$s$^{-1}$) are then

$$\hat{T}_{SZ/IS}^{x,A} = \int_0^{y_f} \hat{F}_{SZ/IS}^{x,A} dy = \int_0^{y_f} h_b u^* \Delta D_A^A dy = h_b u^* \Delta D_A^A y_f,$$ \hspace{1cm} (2.12a)

$$\hat{T}_{SZ/IS}^{x,B} = \int_{y_f}^{\overline{y}_p} \hat{F}_{SZ/IS}^{x,B} dy = \int_{y_f}^{\overline{y}_p} h_b u^* \Delta D_B dy = h_b u^* \Delta D_B (\overline{y}_p - y_f).$$ \hspace{1cm} (2.12b)
Figure 2.12: Parameterized cross-shore dye transport $\hat{T}_{SZ/IS}^x$ versus inferred cross-shore dye transport $T_{SZ/IS}^x$ for regions A, B, and A+B during periods I, II, and III (see legend). The one-to-one line is plotted in gray. The parameterized $\hat{T}_{SZ/IS}^x$ follow (2.12a), (2.12b), and (2.13). The $T_{SZ/IS}^x$ are inferred from aerial and in situ observations (see (2.9a), (2.9b), and (2.10)).

for region A and region B, respectively, and

$$\hat{T}_{SZ/IS}^{x,A+B} = \hat{T}_{SZ/IS}^{x,A} + \hat{T}_{SZ/IS}^{x,B}$$

(2.13)

for regions A and B combined. The parameterized $\hat{T}_{SZ/IS}^{x,A}$, $\hat{T}_{SZ/IS}^{x,B}$, and $\hat{T}_{SZ/IS}^{x,A+B}$ are each computed for periods I, II, and III.

Parameterized $\hat{T}_{SZ/IS}^x$ and inferred $T_{SZ/IS}^x$ are generally similar (Figure 2.12) with squared correlation $r^2 = 0.85$ and best fit slope 0.7. Minimizing the rms error among parameterized $\hat{T}_{SZ/IS}^x$ and inferred $T_{SZ/IS}^x$ transports yields the best fit bulk cross-shore exchange velocity $u^* = 0.012 \pm 0.001$ m s$^{-1}$. This is consistent with the $u^* = 0.009$ m s$^{-1}$ found using temperature observations on another day with similar wave conditions (HR14).

The parameterized $\hat{T}_{SZ/IS}^{x,A}$ during periods I and II are both similar to the
inferred $T_{SZ/IS}^{x,A}$ (Figure 2.12, green circle and square), while the period III parameterized $T_{SZ/IS}^{x,A}$ over-estimates the small inferred $T_{SZ/IS}^{x,A}$ (Figure 2.12, green triangle). The parameterized $T_{SZ/IS}^{x,B}$ increases among periods I, II, and III (Figure 2.12, vertical coordinates of red symbols) as $y_p(t)$ moves farther northward (Figure 2.4a), consistent with the increase of inferred $T_{SZ/IS}^{x,B}$ (Figure 2.12, horizontal coordinates of red symbols). Similarly, parameterized $T_{SZ/IS}^{x,A+B}$ and inferred $T_{SZ/IS}^{x,A+B}$ are comparable, and both increase with time among periods I, II, and III (Figure 2.12, blue symbols).

During period III, the inferred $T_{SZ/IS}^{x,A}$ is small (Figure 2.12, horizontal coordinate of green triangle), suggesting that most of the region A surfzone dye is transported alongshore to the region B surfzone rather than offshore to the inner-shelf. Consistent with this inference, the mean period III surfzone alongshore transport $\bar{T}_{SZ}^{y,A/B} = 507$ ppb m$^3$ s$^{-1}$ is within 1% of the dye release rate $Q = 512$ ppb m$^3$ s$^{-1}$. Combined with the small $M_{IS}^A$ and $\frac{d}{d t} (M_{IS}^A)$ during period III (Figure 2.8c, triangles), this confirms that the period III surfzone to inner-shelf cross-shore transport within region A is small. This is explored further in the next section.

### 2.6.2 Surfzone/Inner-Shelf Exchange Mechanisms

The exchange velocity $u^* = 1.2 \times 10^{-2}$ m s$^{-1}$ represents all potential cross-shore surfzone/inner-shelf exchange mechanisms, including rip currents, Stokes-drift-driven flow, and internal waves. For alongshore-uniform bathymetries, wave-driven cross-shore exchange over the inner-shelf is generally attributed to Stokes-drift-driven flow (e.g., Monismith and Fong, 2004; Lentz et al., 2008; Lentz and Fewings, 2012). Within the vertically well mixed surfzone (e.g., Figure 2.4c), Stokes-drift-driven flow was found to be a negligible cross-shore dye dispersion mechanism relative to surfzone eddies (Clark et al., 2010). However, outside the surfzone on the inner-shelf, vertical dye profiles are not necessarily uniform, and vertically varying Stokes-drift-driven flow could potentially be an important cross-shore dye exchange mechanism. Here, the $u^*$ magnitude and observed inner-shelf vertical dye profiles are compared with an estimated Stokes-drift-driven velocity profile offshore of the wave breaking boundary.
Assuming that the near-surface onshore mass flux due to Stokes drift is balanced by a vertically uniform Eulerian return flow yields an estimated Lagrangian (Stokes plus Eulerian; referred to here as Stokes-drift-driven) velocity profile that is shoreward in the upper water column and seaward at depth. With normally incident, narrow-banded waves (amplitude \( a = H_s/(2\sqrt{2}) \)), the depth-normalized Stokes-drift-driven seaward velocity appropriate for comparison with \( u^* \) is

\[
u_s^* = \left| \frac{(ak)^2 C}{2 (z_0 + h) \sinh^2 (kh)} \int_{-h}^{z_0} \left[ \cosh (2k(z + h)) - \frac{\sinh (2kh)}{2kh} \right] dz \right|,
\]

where \( k \) is the peak wavenumber, \( C \) the phase speed, \( h \) the still water depth, and \( z_0 \) the vertical location at which the velocity profile switches sign. At \( f6 \), the observed \( H_s = 0.76 \text{ m} \) (Figure 2.2a), peak period \( T_p = 13 \text{ s} \), and mean water depth \( h = 4.2 \text{ m} \) (Figure 2.2c) yield \( u_s^* = 5.9 \times 10^{-4} \text{ m s}^{-1} \), which is \( 20 \times \) smaller than the inferred exchange velocity \( u^* = 1.2 \times 10^{-2} \text{ m s}^{-1} \). Note that if the Eulerian return flow is surface-intensified (e.g., Putrevu and Svendsen, 1993; Lentz et al., 2008) instead of depth-uniform, an analogous \( u_s^* \) is even smaller than estimated by (2.14).

The estimated Stokes-drift-driven velocity profile at \( f6 \) is also compared with nearby vertical dye profile observations. Time- and alongshore-averaged in situ measurements near \( 2x_b \) (roughly 25 m offshore of \( f6 \), Figure 2.1) show that the mean inner-shelf dye concentration is surface-intensified and decreases with depth (Figure 2.13). Because inner-shelf dye is delivered from the vertically mixed surfzone (Figure 2.4c), the observed inner-shelf mean vertical profiles require seaward dye transport in the upper water column. This is inconsistent with the \( f6 \)-estimated Stokes-drift-driven velocity profile which is shoreward in the upper water column and seaward only below \( z_0 = -1.8 \text{ m} \).

Moreover, the observed surfzone to inner-shelf dye ejections are episodic and short-lived \((O(1) \text{ min})\) and have small alongshore length scales \((O(10-100) \text{ m})\); Figures 2.3 \((y \leq 1500 \text{ m})\), 2.10, and 2.14), whereas Stokes-drift-driven exchange is expected to be quasi-stationary and essentially uniform in the alongshore. Similarly, other potential exchange mechanisms such as winds (e.g., Fewings et al., 2008), tides (e.g., Lentz and Fewings, 2012), or internal waves (e.g., Sinnett and Feddersen, 2014; Suanda et al., 2014) are expected to generally have much larger
Figure 2.13: Mean (time- and alongshore-averaged) inner-shelf dye concentration $\bar{D}$ versus vertical coordinate $z$ from the alongshore-towed vertical array (section 2.3.3.4) for data within inner-shelf dye patches ($D(x, y, z = -1 \text{ m}, t) \geq 2 \text{ ppb}$). Dashed curves indicate standard deviations about the mean.

The above differences in exchange velocity magnitude, vertical structure, and time and alongshore length scales indicate that on this day with moderate waves, the observed surfzone to inner-shelf cross-shore dye transport is dominated by rip current ejections. Farther offshore of the surfzone, Stokes-drift-driven exchange (e.g., Lentz et al., 2008; Suanda and Feddersen, 2015) or other inner-shelf processes may become important. The alongshore length scales and longer time scales than those observed. Farther offshore of the surfzone, Stokes-drift-driven exchange (e.g., Lentz et al., 2008; Suanda and Feddersen, 2015) or other inner-shelf processes may become important. The above differences in exchange velocity magnitude, vertical structure, and time and alongshore length scales indicate that on this day with moderate waves, the observed surfzone to inner-shelf cross-shore dye transport is dominated by rip current ejections.

Here, an example rip current event is highlighted using two of the aerial images (Figure 2.14). Just offshore of the dye release at $t = 12:22$ h (Figure 2.14a), a rip current ejects concentrated ($\geq 15 \text{ ppb}$) dye out of the surfzone through a 20 m wide neck, terminating in a roughly 50 m wide rip current head 100 m offshore of the surfzone boundary. Gradients between dye-rich and dye-free water are very strong (Figure 2.14a). On a subsequent aerial pass ($t = 12:35$ h, Figure 2.14b), the ejected dye has advected $\approx 150$ m alongshore, dispersed to larger spatial scales, and lost its clear rip current signature. Other dye ejections with similar spatial
scales and evolution are seen throughout the 23 aerial images (e.g., Figure 2.3). The observed ejection events are episodic and brief ($O(1)$ min) and occur at random alongshore locations, indicating that these rips are transient and are not bathymetrically controlled, consistent with the approximately alongshore-uniform bathymetry at Imperial Beach (Figure 2.1). The magnitudes of $u^*$ and $T_{SZ/IS}^x$ are related to the surfzone eddy field and the frequency and intensity of these transient rip current events, which depend on the incident wave field and beach slope (Johnson and Pattiaratchi, 2006; Suanda and Feddersen, 2015).

Note that the small $T_{SZ/IS}^{x,A}$ inferred for region A during period III (Fig-
ure 2.12, green triangle) and the associated lack of significant transient rip ejections (i.e., period III lack of dye in region A inner-shelf, Figures 2.3e and 2.3f) are not surprising, as transient rip currents are sporadic in space and time, and region A is small (< 250 m alongshore) and period III short (< 40 min). Because the cross-shore dye flux (2.11) is a bulk parameterization and does not resolve the spatial or temporal variability of transient rip ejections, (2.12a) overpredicts the small cross-shore transport $T_{x,A}^S$ observed during period III for region A. However, the period III parameterized $T_{x,A+B}^S$ still agrees well with the observed $T_{x,A+B}^S$ for the full alongshore domain (regions A+B; Figure 2.12, blue triangle).

### 2.7 Summary

A continuous 6.5 h, near-shoreline release of fluorescent Rhodamine WT dye tracer was observed on 13 October 2009 at the alongshore-uniform Imperial Beach, California (IB09 experiment). Surfzone and inner-shelf dye concentrations were measured in situ with fixed and mobile (jetski- and boat-mounted) fluorometers, and remotely with a novel aerial-based multispectral camera system. Waves and currents were measured between the shoreline and roughly 4 m water depth. Dye was advected alongshore by breaking wave- and wind-driven currents, forming a several km long plume.

Aerial images showed the plume advecting alongshore at rates consistent with in situ observations while transient rip currents intermittently transported surfzone dye to the inner-shelf via brief ($O(1)$ min) and narrow ($O(10)$ m) seaward ejections at random alongshore locations. Once on the inner-shelf, the ejected dye patches continued to advect (less quickly) alongshore while dispersing to larger cross- and alongshore length scales. At a cross-shore instrument array 248 m downstream of the release location, 77% of the released dye was alongshore-advected through the array within roughly two surfzone widths of the shoreline.

Alongshore dye dilution power law exponents $-0.33$ (observed here over $\approx 2$ km) and $-0.19$ (on 29 September over $\approx 700$ m, HR14) are both smaller than $-0.5$ previously found for surfzone-contained dye plumes over much shorter
downstream distances before dye leaked offshore to the inner-shelf (Clark et al., 2010, 2011). This deviation of the long distance power law exponents ($-0.33, -0.19$) from the short distance, surfzone-only exponent ($-0.5$) highlights the complexity of the coupled surfzone/inner-shelf domain and the governing dynamical processes.

A combination of aerial and in situ measurements were used to calculate the first coupled surfzone and inner-shelf dye mass balances. On average, 88% of the total released dye mass was accounted for across the surfzone and inner-shelf ($\approx 350$ m cross-shore and 3 km alongshore) over a 5 h period during the release. Dye mass and alongshore transport observations for separate near- and far-field regions were also in agreement, and the small discrepancies were consistent with low-biased inner-shelf alongshore transport measurements. The closure of these dye mass balances allowed for quantitative observational estimates of surfzone to inner-shelf cross-shore dye transports, which amounted to roughly 1/2 of the shoreline-released dye during the same 5 h period.

The observed cross-shore dye transports were parameterized well (correlation $r^2 = 0.85$, best fit slope 0.7) using a bulk exchange velocity and surfzone/inner-shelf mean dye concentration difference. The resulting best fit bulk exchange velocity $u^* = 1.2 \times 10^{-2}$ m s$^{-1}$ is consistent with a temperature-derived exchange velocity from another day with similar waves. An estimated Stokes-drift-driven velocity is $20 \times$ smaller than $u^*$ and has a vertical profile that is inconsistent with the observed inner-shelf mean vertical dye structure. Other potential cross-shore exchange mechanisms (e.g., winds, tides, internal waves) are expected to generally have spatio-temporal scales much larger than the alongshore-narrow ($O(10 - 100)$ m) and short-lived ($O(1)$ min) rip current events observed here. These differences suggest that the transient rip current ejections observed at this alongshore-uniform beach dominated the cross-shore surfzone to inner-shelf tracer exchange during moderate wave conditions.
2.8 Appendix: Dye Mass Estimates

2.8.1 Surfzone

The total surfzone dye mass in regions A and B is defined as
\[ M_{SZ}^{A+B} (t) = \int_0^{y_p(t)} \int_{x_b}^{0} \int_{-h}^{0} D(x, y, z, t) \, dz \, dx \, dy, \]  
(2.15)
where \( h \) is the water depth, \( x_b \) is the seaward surfzone boundary, and \( y_p(t) \) is the location of the leading alongshore edge of the northward-advecting dye plume (Figures 2.3 and 2.4a; explicit definition in section 2.4.2). The surfzone dye mass is estimated at times corresponding to the aerial images.

The three \( M_{SZ} \) integrals \((dz, dx, dy)\) are estimated as follows. Dye is vertically well mixed in the surfzone (Figure 2.4c and HR14), and therefore the vertical integral becomes
\[ \int_{-h}^{0} D(x, y, z, t) \, dz = hD(x, y, t). \]  
(2.16)
Cross-shore \( D \) profiles do not exist for all \( y \) and \( t \). However, cross-shore jetski transects were repeated at various \( y \) and are used to compute time-averaged cross-shore dye profiles (see section 2.4.3 and Figure 2.4b) at alongshore locations near f2 and SA1-SA4, where near-shoreline dye was measured continuously. These mean profiles are used to compute a surfzone dye cross-shore uniformity parameter \( \xi(y) \) defined as
\[ \xi(y) = \frac{\int_{x_b}^{0} h(x) \overline{D}(x, y) \, dx}{\overline{h}_{SZ}|x_b| \overline{D}(x \approx -10 \, m, y)}, \]  
(2.17)
where \( \overline{h}_{SZ} \) is the mean surfzone water depth, and \( x \approx -10 \, m \) is the location of the shoreward-most observations. By definition \( 0 < \xi(y) \leq 1 \), with \( \xi \approx 0 \) corresponding to shoreline-released dye being highly shoreline-concentrated and \( \xi = 1 \) corresponding to dye being perfectly cross-shore uniform. Close to the dye release (\( y = 14 \, m \)), the cross-shore uniformity parameter \( \xi \approx 0.5 \). Downstream, as dye mixes across the surfzone, \( \xi \) increases to > 0.9 by \( y = 810 \, m \) (Figure 2.15). The cross-shore integral is estimated as
\[ \int_{x_b}^{0} h(x) \, D(x, y, t) \, dx = \overline{h}_{SZ}|x_b| \xi(y) D_{sl}(y, t), \]  
(2.18)
Figure 2.15: Surfzone dye cross-shore uniformity parameter $\xi$ (2.17) versus along-shore coordinate $y$.

where $D_{sl}(y, t)$ is dye measured near the shoreline. Combining (2.15)-(2.18) yields

$$M_{SZ}^{A+B}(t) = \int_0^{y_p(t)} \tilde{h}_{SZ}|x_b|\xi(y)D_{sl}(y, t) \, dy. \quad (2.19)$$

The integral (2.19) is alongshore-integrated numerically using the trapezoid rule with $D_{sl}(y, t)$ at $y = 1$ m, $y_{SA1}$, $y_{f}$, $y_{SA2}$, $y_{SA3}$, $y_{SA4}$, and $y_p(t)$ (Figure 2.3, yellow symbols and green triangle). Nearest the release, $D_{sl}(y = 1$ m, $t) = 98$ ppb is estimated via the best-fit (2.1) (see Figure 2.6) during times that dye is being released (note that all $M$ estimates are during the release period). Downstream, $D_{sl}(y_p(t), t)$ is also estimated using the best-fit (2.1) (see Figures 2.4a and 2.6).

$M_{SZ}^{A+B}(t)$ are decomposed into $M_{SZ}^{A}(t)$ ($0 \leq y < y_f$) and $M_{SZ}^{B}(t)$ ($y_f \leq y \leq y_p(t)$) using the alongshore boundary $y_f = 248$ m. $M_{SZ}$ estimates are computed for all aerial image times when in situ near-shoreline dye data are available. Note that $M_{SZ}^{B}(t)$ and $M_{SZ}^{A+B}(t)$ may be biased low because $y_p(t)$ (defined as the northernmost location where aerial-imaged inner-shelf $D$ exceeds 3 ppb within 40 m of $x_b$; green triangles in Figures 2.3a-2.3e) may be smaller than the actual extent of the dye plume within the surfzone (where the alongshore current is fastest (Figure 2.2b)) and the transient rips that eject dye from the surfzone to the inner-shelf are sporadic in space and time.
2.8.2 Inner-Shelf

The total inner-shelf dye mass in regions A and B is defined as

\[ M_{IS}^{A+B}(t) = \int_{-\infty}^{\infty} \int_{-\infty}^{x_b} \int_{-h}^{0} D(x, y, z, t) \, dz \, dx \, dy, \] (2.20)

where \( h \) is the still water depth, and \( x_b \) is the surfzone/inner-shelf boundary. Inner-shelf dye mass estimates are calculated using surface dye concentration maps \( D_s(x, y, t) \) from the aerial images (e.g., Figure 2.3) and in situ observations of inner-shelf vertical dye structure (Figure 2.13) from the boat-towed vertical array (section 2.3.3.4). The towed array data resolve inner-shelf \( D \) for \( z = -1 \) to \(-3 \) m, thus requiring assumptions for the vertical structure outside this range. As inner-shelf dye comes from the vertically mixed surfzone (Figure 2.4c and HR14), inner-shelf \( D(x, y, z, t) \) is assumed vertically uniform in the upper 1 m. For \( z < -3 \) m, the best fit of mean \( \overline{D}(z) \) (Figure 2.13) is extrapolated to the depth where it would vanish. This structure is then vertically integrated, and \( h_{dye} \) is computed as the depth that yields an equivalent vertical integral \( h_{dye}D_s(x, y, t) \). The inner-shelf vertical dye integral is thus estimated as

\[ \int_{-h}^{0} D(x, y, z, t) \, dz = h_{dye}D_s(x, y, t), \] (2.21)

where \( D_s(x, y, t) \) is the aerial-measured surface dye concentration, and \( h_{dye} = \min (2.67 \, m, \, h) \). The inner-shelf dye mass estimates are then

\[ M_{IS}^{A+B}(t) = \int_{-\infty}^{\infty} \int_{-\infty}^{x_b} h_{dye}D_s(x, y, t) \, dx \, dy, \] (2.22)

integrated using the trapezoid rule in each lateral direction. \( M_{IS}^{A+B}(t) \) are decomposed into \( M_{IS}^{A}(t) \) (\( 0 \leq y < y_f \)) and \( M_{IS}^{B}(t) \) (\( y_f \leq y < \infty \)) using the alongshore boundary \( y_f = 248 \, m \).

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Chapter 3

Modeling Surfzone to Inner-Shelf Tracer Exchange

3.1 Abstract

A near-shoreline, continuous dye release at an approximately alongshore-uniform beach (IB09 experiment) is simulated with the wave-resolving Boussinesq model funwaveC. The model generates surfzone eddies and transient rip currents but does not resolve inner-shelf vertical variation or stratification. The funwaveC model reproduces well the observed surfzone and inner-shelf dye observations over roughly 350 m cross-shore and 2000 m alongshore. Dye is advected alongshore by wave- and wind-driven currents similarly in the observations and model. Near-shoreline mean dye decays downstream as a power law with similar observed (−0.33) and modeled (−0.38) exponents. Observed and modeled cross-shore mean dye profiles are similar, although modeled inner-shelf dye is elevated somewhat. Observed and modeled alongshore dye transports agree, although with compensating surfzone and inner-shelf errors later in the release. Observed and modeled dye budgets are similar to each other and close to within 10% for times < 3.5 h, before dye begins exiting the domain. Half the released dye is exported to the inner-shelf in both the model and observations. Later in the release, surfzone and inner-shelf dye mass are under- and over-predicted, respectively. Model–data differences may
be due to the model’s lack of vertical variation, stratification, or tide. The good overall model-data agreement indicates that nearshore tracer transport and dispersion are realistically simulated over 5 h and 2000 m alongshore, and that the model transient rip currents accurately induce cross-shore exchange between the surfzone and inner-shelf.

3.2 Introduction

The nearshore region, consisting of the surfzone (shoreline to \(x_b\), the seaward boundary of depth-limited wave breaking) and the inner-shelf (\(x_b\) to approximately 20 m water depth), is of vital economic, ecological, and recreational importance. Maintaining the well being of this region requires understanding the exchange of tracers (e.g., sediment, larvae, nutrients, and pollutants) between the surfzone and inner-shelf, which have dramatically different dynamical regimes. Despite the importance of this region to our economy and health, understanding of nearshore tracer mixing and transport remains relatively poor.

Several field experiments have tracked Lagrangian surface drifters on alongshore uniform beaches (e.g., Spydell et al., 2007, 2009, 2014) and rip-channeled beaches (e.g., Brown et al., 2009; MacMahan et al., 2010; Brown et al., 2015) to explore nearshore transport and dispersion. Similarly, surfzone fluorescent dye release experiments have also been used to investigate tracer mixing and transport (e.g., Harris et al., 1963; Inman et al., 1971b; Grant et al., 2005; Clark et al., 2010). However, these observations were limited by sparse sampling or small sampling regions. Until recently, a quantitative coupled surfzone and inner-shelf tracer mass budget had never been performed, and dye tracer mass balance closure has remained elusive in larger scale oceanographic contexts.

By combining a suite of dye, wave, and velocity observations from a dye release at an approximately alongshore-uniform beach (IB09 experiment), Hally-Rosendahl et al. (2015, hereafter HR15) closed a tracer mass budget and showed that about half of the released dye was exchanged onto the inner-shelf over 5 h and 3.25 km downstream. The primary driver of this cross-shore exchange was transient
rip currents, which occur due to the coalescing of surfzone eddies generated by finite crest length wave breaking (*Peregrine*, 1998; *Clark et al.*, 2012; *Suanda and Feddersen*, 2015).

Wave-resolving models include this surfzone eddy generation mechanism, but wave-averaged models do not (*Feddersen*, 2014). However, wave-resolving models are essentially depth-averaged and thus do not include vertical variation or stratification effects. In *Hally-Rosendahl et al.* (2014, hereafter HR14) and HR15, surfzone dye concentration was vertically uniform. However, inner-shelf dye was surface-intensified due to stratification. As the surfzone and inner-shelf have such different dynamics, it is not clear that a depth-averaged wave-resolving model can accurately reproduce the cross-shore exchange between these two regions.

Here, the wave-resolving Boussinesq model *funwaveC* (e.g., *Spydell and Feddersen*, 2009; *Feddersen et al.*, 2011; *Suanda and Feddersen*, 2015) is used to simulate the dye release described in HR15. The *funwaveC* model has been shown to accurately simulate surfzone dye dispersion in moderate alongshore currents (*Clark et al.*, 2011). However, this study was limited to small cross-shore ($\leq 250$ m) and alongshore ($\leq 600$ m) distances, and to short times when dye was largely contained within the unstratified surfzone. Although the dispersion of shoreline-source tracers is initially within the surfzone, tracer fate is ultimately determined by exchange between the surfzone and inner-shelf (e.g., HR14; HR15) over longer times and larger cross- and alongshore distances than those previously modeled.

Here, we investigate *funwaveC*'s ability to reproduce the dye observations and dye mass budget of HR15. The IB09 dye release experiment and the *funwaveC* model are briefly described in Section 3.3. Qualitative and quantitative comparisons of observed and modeled dye are presented in Section 3.4. A model dye mass budget is performed and compared to the observations of HR15 in Section 3.5. The results are discussed in Section 3.6 and summarized in Section 3.7.
3.3 Methods: Observations and Model

3.3.1 IB09 Observations: 13 October

The 13 October 2009 dye release (HR15) as part of the IB09 field experiment at Imperial Beach, CA (e.g., Feddersen, 2012b; Spydell et al., 2014; Rippy et al., 2013b) is briefly described here. Full details are in HR15. The shoreline and bathymetry are approximately alongshore-uniform (Figure 3.1), with cross-shore coordinate $x = 0$ m at the mean shoreline increasing negatively seaward, and alongshore coordinate $y = 0$ m at the dye release location increasing positively toward the north. The vertical coordinate $z = 0$ m at mean sea level and increases positively upward. Fluorescent Rhodamine WT dye was released continuously at $Q = 512$ ppb m$^3$ s$^{-1}$ near the shoreline at $(x_{rl}, y_{rl}) = (-10, 0)$ m for approximately 6.5 h, with $t = 0$ s defined here as the dye release start time. While dispersing cross-shore, dye was advected alongshore by breaking-wave- and wind-driven currents, forming a several kilometer long, shoreline-attached plume.

Waves, currents, and dye concentration were measured on a 125-m long cross-shore array of six near-bottom frames (denoted f1-f6 onshore to offshore, Figure 3.1, diamonds) located at $y_f = 248$ m. Near-shoreline dye was measured with four thermistor-equipped ECO Triplet fluorometers (ETs) deployed at $y = 82, 546, 1069,$ and $1662$ m after the dye release had started. The f2 instruments (at $y_f = 248$ m) are used in conjunction with these four ETs to make the near-shoreline array SA1-SA5 (Figure 3.1, circles and gray diamond). All frame and SA observations are averaged over 30 s to filter out individual wave effects.

Surface dye concentration was measured using two GPS-tracked jetskis (Clark et al., 2009b) that drove repeated cross-shore transects from $x \approx -400$ m to the shoreline (e.g., Figure 3.1) at various designated alongshore locations between $y = 5$ m and $y \approx 2$ km (HR15). Inner-shelf upper water column dye concentration was measured with a vertical array ($z = -1$ to $-2.5$ m at 0.5 m spacing) of ETs towed alongshore behind a small boat. Repeated $\approx 2$ km alongshore transects (e.g., Figure 3.1) were driven at roughly 1 m s$^{-1}$ at a mean cross-shore location.
Figure 3.1: Planview of Imperial Beach bathymetry contours versus cross-shore coordinate $x$ and alongshore coordinate $y$. Star indicates the 13 October 2009 dye release location. Diamonds denote the cross-shore array of bottom-mounted instrument frames f1–f6 (onshore to offshore). Circles and gray diamond indicate the near-shoreline array SA1-SA5. Vertical dashed line represents an idealized boat alongshore transect driven repeatedly near this cross-shore location. Horizontal dashed line represents an idealized jetski cross-shore surface transect driven repeatedly at various alongshore locations.
nominally two surfzone widths from the shoreline. Near-surface dye concentration was also observed remotely from a small plane using a georeferenced multispectral camera system (Clark et al., 2014). The dye field was imaged from the shoreline to approximately $\approx 350$ m offshore and from the release to $\approx 3.25$ km downstream. Quantitative aerial image analyses are confined to the inner-shelf due to surfzone noise from wave breaking foam (HR15).

### 3.3.2 Wave-Resolving funwaveC Model

#### 3.3.2.1 Model Waves and Currents

A description of the wave-resolving, Boussinesq funwaveC model is provided here, and additional details can be found elsewhere (Spydell and Feddersen, 2009; Feddersen et al., 2011; Suanda et al., 2015). The funwaveC model equations (Nwogu, 1993) are similar to the nonlinear shallow water equations but allow for higher order dispersion. The mass conservation equation is

$$
\frac{\partial \eta}{\partial t} + \nabla \cdot [(h + \eta)\mathbf{u}] + \nabla \cdot \mathbf{M}_d = 0,
$$

where $\eta$ is the instantaneous free surface elevation, $t$ is time, $h$ is the still water depth, $\mathbf{u}$ is the instantaneous horizontal velocity vector at the reference depth $z_r = -0.531h$ (with $z = 0$ m at the still water surface), and $\mathbf{M}_d$ is a dispersive term (Nwogu, 1993). The horizontal gradient operator $\nabla$ acts on the cross-shore ($x$) and alongshore ($y$) directions. The momentum equation is

$$
\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -g \nabla \eta + \mathbf{F}_d + \mathbf{F}_{br} - \frac{\tau_b}{(h + \eta)} + \frac{\tau_w}{(h + \eta)} - \nu_b \nabla^4 \mathbf{u},
$$

where $g$ is gravity and $\mathbf{F}_d$ is a dispersive term (Nwogu, 1993). The breaking term $\mathbf{F}_{br}$ is parameterized as a Newtonian damping (Kennedy et al., 2000; Lynett, 2006) with standard parameters (e.g., Guza and Feddersen, 2012). The instantaneous bottom stress $\tau_b$ is given by a quadratic drag law,

$$
\tau_b = c_d |\mathbf{u}| \mathbf{u},
$$

with non-dimensional drag coefficient $c_d = 2.25 \times 10^{-3}$, consistent with previous momentum balances and Boussinesq modeling studies (e.g., Feddersen et al., 1998;
The applied wind stress $\tau_w$ is alongshore ($+y$) at $8.5 \times 10^{-5} \text{ m}^2 \text{s}^{-2}$ (HR15). The biharmonic friction ($\nabla^4 u$) term damps instabilities with hyperviscosity $\nu_{hi} = 0.5 \text{ m}^4 \text{s}^{-1}$.

The alongshore-uniform model bathymetry is an alongshore average of the observed approximately alongshore-uniform bathymetry at Imperial Beach, with an added offshore $\approx 300 \text{ m}$ region of constant $7 \text{ m}$ depth and a planar sub-aerial beach (slope $\beta = 0.02$) extending $2 \text{ m}$ above mean sea level to allow runup (Figure 3.2). In the constant $7 \text{ m}$ depth region, there is a wavemaker (Wei et al., 1999) and a $100 \text{ m}$ offshore sponge layer to absorb seaward propagating waves. Shoreline runup utilizes the thin layer method (Salmon, 2002) as described in Guza and Feddersen (2012). A small sponge layer at the shoreward boundary of the beach face absorbs any runup wave energy that reaches this location. The model cross-shore and alongshore grid sizes are $1 \text{ m}$ and $1.35 \text{ m}$, respectively. The total cross-shore domain width is $650 \text{ m}$, and the alongshore domain is $2025 \text{ m}$ with alongshore-periodic boundary conditions for $\eta$ and $u$. The model coordinate system is fixed and is the same as in the observations (Section 3.3.1). The wavemaker, forced at 801 random frequencies (Suanda et al., 2015) spanning $0.04 < f < 0.25 \text{ Hz}$, approximately generates the back-refracted, release-averaged wave field observed at $f_6$ (Figure 3.1). The realistic, directionally spread, modeled incident wave field enables surfzone vorticity to be generated at the small length scales of individual short-crested breaking waves (e.g., Peregrine, 1998; Clark et al., 2012) and at the larger length scales of wave groups. The model time step is $6.25 \times 10^{-3} \text{ s}$. Instantaneous sea surface elevation $\eta$, cross-shore ($u$) and alongshore ($v$) velocities are output every $2 \text{ s}$ over the entire spatial domain and every $1 \text{ s}$ for select linear transects. The simulation was run for $36000 \text{ s}$, and model output is analyzed after $3000 \text{ s}$, once mean-square vorticity has equilibrated (e.g., Feddersen et al., 2011).

### 3.3.2.2 Model Tracer

The funwaveC tracer module is used to simulate the observed 13 October dye release (HR15). The model dye tracer $D_m$ evolves according to a depth-
Figure 3.2: (a) Planview of funwaveC model domain. Cross-shore coordinate $x$ is the distance from the mean shoreline ($x = 0$ m, thin dashed line). Alongshore coordinate $y$ is the distance from the dye release location ($y = 0$ m, star). Dark gray regions indicate offshore and onshore sponge layers. Light gray region indicates the wavemaker. The cross-shore tracer domain (heavy dashed lines) is bounded by the wavemaker and the onshore sponge layer. Diamonds denote the cross-shore array of frames f1-f6 (onshore to offshore). Circles and gray diamond indicate the near-shoreline array SA1–SA5. (b) Alongshore-uniform model bathymetry $h$ (curve) versus $x$ with a constant 7 m depth region for the wavemaker and offshore sponge layer, and a planar ($\beta = 0.02$) subaerial beach for runup.
integrated advection-diffusion equation (Clark et al., 2011),
\[
\frac{\partial [(h + \eta) D_m]}{\partial t} + \nabla \cdot [(h + \eta) u D_m] = \nabla \cdot [(\kappa_{br} + \kappa_0)(h + \eta) \nabla D_m] + Q \delta(x-x_{rl})\delta(y-y_{rl}),
\]
(3.4)
where the breaking wave eddy diffusivity $\kappa_{br}$ is non-zero only on the face of breaking waves and is set equal to the breaking wave eddy viscosity $\nu_{br}$ (i.e., the tracer Schmidt number is unity). The background diffusivity $\kappa_0 = 0.075 \, m^2 \, s^{-1}$, applied everywhere, is an order of magnitude smaller than bulk surfzone cross-shore tracer diffusivities observed by Clark et al. (2010) for conditions similar to 13 October at IB09. Model dye is released at the same rate $Q = 512 \, ppb \, m^3 \, s^{-1}$ and the same location $(x_{rl}, y_{rl}) = (-10, 0) \, m$ as in the observations (Section 3.3.1), and $\delta$ is the Kronecker delta function.

The tracer module cross-shore domain (heavy dashed lines, Figure 3.2a) is contained within the larger funwaveC domain (Section 3.3.2.1). A no-flux tracer boundary condition is applied at the top of the beach, and the offshore tracer boundary condition zeros out $D_m$ just onshore of the wavemaker. In contrast to the periodic alongshore boundary conditions for $\eta$ and $u$, the $D_m$ alongshore boundaries are open at both ends, which allows $D_m$ to advect out of the model domain but not recirculate back in. Model dye is released 67.5 m away from the southern boundary (Figure 3.2a, star). The tracer module is turned on after 3000 s of simulation once mean square vorticity has equilibrated. Instantaneous $D_m$ snapshots are output every 2 s over the entire spatial domain and averaged over 30 s to filter out individual wave effects as with the observations. In both the model and the observations, $t = 0 \, s$ is the dye release start time.

### 3.4 Model–Data Comparisons

Model–data comparisons are analyzed first for waves and currents, and then for various tracer quantities. Observed quantities are denoted with $(\_)_o$, and modeled quantities with $(\_)_m$. 
3.4.1 Waves and Currents

During the 13 October IB09 dye release, the observed wave field is dominated by southerly swell with peak period $T_p = 13$ s. Averaged over the release, the maximum observed significant wave height $H_{s_o} = 0.87$ m occurs at f4 (Figure 3.3a, symbols). The modeled wave field, forced with the back-refracted f6-observed spectrum, has maximum $H_{s_m} = 0.89$ m occurring between f5 and f4 (Figure 3.3a, curve). The model–data $H_s$ root mean square error (rmse) is 0.03 m. As in HR15, the surfzone/inner-shelf boundary $x_b = -81$ m is defined as the cross-shore location of f4 (Figure 3.3c), where modeled and observed $H_s$ are maximum. The observed mean alongshore current $V_o(x)$ is northward at all frames with a surfzone maximum of 0.23 m s$^{-1}$ (Figure 3.3b, symbols). Observed $V_o(x)$ decreases to a 0.12 m s$^{-1}$ minimum near the seaward surfzone boundary, and then increases slightly offshore. Modeled $V_m(x)$ has a similar profile with a 0.22 m s$^{-1}$ maximum (Figure 3.3b, curve). The model–data rmse for $V$ is 0.02 m s$^{-1}$; agreement is particularly good for the surfzone where the alongshore currents are strongest.

3.4.2 Surfzone and Inner-Shelf Dye Evolution

The 13 October near-surface dye field was aerially observed over nearly 5 hr after the start of the dye release (Figure 3.4) and described in detail by HR15. Here, for convenience, time is given as hh:mm after the start of the release. All subsequent analyses are in seconds after the start of dye release. The observed dye maps are cross-shore-partitioned into the surfzone (SZ) and inner-shelf (IS) regions (separated by $x_b = -81$ m, Section 3.4.1) and alongshore-partitioned into near- and far-field regions A and B (separated by the cross-shore frame array at $y_f = 248$ m, Figure 3.4a). Note that due to wave-breaking foam, the aerial observations are not able to consistently resolve surfzone dye (regions blacked out in Figure 3.4); aerial image quantitative analyses are therefore restricted to the inner-shelf.

Approximately 40 min after the release begins (Figure 3.4a), surfzone dye has advected about 600 m alongshore at $\approx 0.25$ m s$^{-1}$, consistent with in situ velocity observations (Figure 3.3b). Surfzone dye is ejected onto the inner-shelf in
narrow (≈ 50 m) alongshore bands (Figure 3.4a) by transient rip currents (HR15). As the plume continues advecting northward (Figures 3.4b-3.4d), the leading portion of inner-shelf dye is alongshore-patchy with length scales ≈ 50 m (as in Figure 3.4a). Behind the leading edge, inner-shelf dye features (e.g., at y ≈ 1250 m and 1500 m in Figures 3.4e and 3.4f, respectively) are advected alongshore at ≈ 0.15 m s⁻¹, consistent with in situ f5 and f6 Vo observations (Figure 3.3b). At these longer times and downstream distances (Figures 3.4e and 3.4f), inner-shelf dye has both spread further offshore and dispersed more alongshore than near the release. In particular, the coherent nearshore eddy feature in Figures 3.4e and 3.4f (at y ≈ 1250 m and 1500 m, respectively) has an alongshore length scale ≈ 300 m, roughly six times larger than the alongshore length scales of inner-shelf dye that has been recently ejected from the surfzone (e.g., Figures 3.4c and 3.4f, ejection features at y ≤ 250 m).

The model $D_m$ field has similar concentrations and evolves similarly to the observed $D_o$ field during the ≈ 5 h observation period (Figure 3.5). The

Figure 3.3: Observed (symbols) and modeled (curves) time-averaged (a) significant wave height $H_s$ and (b) alongshore current $V$ (with modeled alongshore standard deviation shaded) versus cross-shore coordinate $x$. (c) Locations of f1–f6, with the black curve giving the bathymetry $h(x)$. 

Figure 3.4: Aerial multispectral images of observed dye concentration $D_o$ (ppb, see colorbar) versus cross-shore coordinate $x$ and alongshore coordinate $y$ for six times (indicated in each panel). The mean shoreline is at $x = 0$ m. Green star indicates location of continuous dye release (starting at $t = 00:00$ h). Yellow diamonds indicate cross-shore array f1–f6 locations, and yellow circles indicate SA1–SA5 locations. Gray indicates regions outside the imaged area, and black indicates unresolved regions due to foam from wave breaking. Vertical cyan line at $x_b$ divides the surfzone (SZ) and inner-shelf (IS), and horizontal cyan line at $y_f$ divides the near- and far-field regions A and B (see panel (a)).
Figure 3.5: Planview of modeled dye concentration $D_m$ (ppb, see colorbar) versus cross-shore coordinate $x$ and alongshore coordinate $y$ for six times (indicated in each panel). The mean shoreline is at $x = 0$ m. Green star indicates location of continuous dye release (starting at $t = 00:00$ h). Yellow diamonds indicate cross-shore array f1-f6 locations, and yellow circles indicate SA1–SA5 locations. Vertical cyan line at $x_b$ divides the surfzone (SZ) and inner-shelf (IS), and horizontal cyan line at $y_f$ divides the near- and far-field regions A and B (see panel (a)).
\(D_m\) surfzone front propagates northward while ejecting narrow bands of dye off-shore to the inner-shelf, consistent with the observations. The modeled inner-shelf dye cross-shore extent and alongshore advection rate are both similar to the observed dye. The inner-shelf \(D_m\) length scales increase with downstream distance (e.g., Figure 3.5f), consistent with the observed trend (e.g., Figure 3.4f). However, inner-shelf modeled \(D_m\) is patchier than observed \(D_o\), with smaller alongshore length scales. The model dye is implicitly vertically-uniform. However, while the observed dye was vertically uniform within the surfzone, it was surface-intensified on the inner-shelf (HR15) consistent with thermal stratification. When seaward rip current driven dye ejections are confined to a stratified inner-shelf upper layer, dye undergoes increased lateral spreading relative to a vertically uniform tracer (e.g., funwaveC modeled dye) entering unstratified inner-shelf water (e.g., Spydell et al., 2015).

### 3.4.3 Alongshore Dye Propagation

Here, the alongshore dye propagation rate is compared between the observations and model. The northward advecting dye plume leading edge is expected to be within the surfzone, where the observed and modeled mean alongshore current \(V\) is strongest (Figure 3.3b). However, the poor surfzone resolution of the aerial images precludes surfzone dye tracking for the observations. Instead (see HR15), the leading alongshore edge of the observed dye plume \(y_{po}(t)\) is defined as the northernmost location where aerial-imaged inner-shelf \(D_o\) exceeds 3 ppb within 40 m of \(x_b\), where inner-shelf dye has been recently ejected from the surfzone (e.g., Figure 3.4). Model \(y_{pm}(t)\) is defined analogously with \(D_m\) (e.g., Figure 3.5).

The observed plume leading edge \(y_{po}(t)\) increases roughly piecewise linearly over the observation period (Figure 3.6, symbols) at an average rate of 0.17 m s\(^{-1}\), consistent with in situ \(V_o\) (Figure 3.3b). When the dye leading edge is within the model alongshore domain \((t < 1.2 \times 10^4 \text{ s})\), modeled \(y_{pm}(t)\) is very similar to the observed \(y_{po}(t)\) (Figure 3.6, compare curve and symbols), consistent with the good agreement between observed and modeled \(V(x)\). For \(t > 1.2 \times 10^4 \text{ s}\), when the model dye plume leading edge has advected beyond the northern boundary
Figure 3.6: Observed (symbols) and modeled (curve) dye plume leading along-shore edge $y_p$ (defined in Section 3.4.4.2) versus time. Magenta bar indicates duration of near-shoreline, continuous dye release at $y = 0$ m (star in Figures 3.1 and 3.2). Horizontal dashed line denotes the model domain northern boundary $y_{\text{max}}$ ($y_{\text{max}} = 1957.5$ m, dashed line in Figure 3.6), observed $y_{p_\text{obs}}(t)$ and modeled $y_{p_{\text{mod}}}(t)$ can no longer be compared. Note the faster propagation of observed $y_{p_\text{obs}}(t)$ during $t > 1.2 \times 10^4$ s; this is discussed in Section 3.6.3.

3.4.4 Near-Shoreline Dye

Near-shoreline array (SA1–SA5) dye observations are discussed in HR15. Here, SA1–SA5 model–data time series are first compared qualitatively, followed by comparison of statistics quantifying downstream dye dilution and dye time scales.

3.4.4.1 Near-Shoreline Dye Time Series

Observed SA1-SA5 data begin at instrument deployment times (after the dye plume has arrived at their respective locations) and end shortly after the dye release stops (Figure 3.7, left column). Model SA1-SA5 observations are available
for all times (Figure 3.7, right column), and the model dye release spanned the simulation (Figure 3.7, magenta bars). Observed and modeled dye time series are qualitatively similar across SA1 to SA5. For example, near the release at $y = 82$ m, observed $D_o$ varies between 0–200 ppb with many intermittent spikes (Figure 3.7ao). At $y = 82$ m, the modeled $D_m$ varies over a similar range and is also highly intermittent (Figure 3.7am), more so than observed. At farther downstream locations, the observed and modeled $D$ range decreases, and the time series are less intermittent and spiked, becoming more smooth. For example, at $y = 1662$ m, observed $D_o$ varies between 4–12 ppb (Figure 3.7eo) less rapidly that at $y = 82$ m. Similarly, modeled $D_m$ at $y = 1662$ m varies over a comparable range (Figure 3.7em) and less rapidly than at smaller $y$.

This similarity between observed and modeled dye (Figure 3.7) motivates further quantitative comparison. Note, in the model $D_m$ at $y = 1662$ m (Figure 3.7em), there is a clear dye ramp up period around $t = 10^4$ s. In addition, the model dye release was not turned off, and there is an indication at $y = 1069$ m and $y = 1662$ m of continued increasing $D_m$ trends at $t > 2.5 \times 10^4$ s (Figures 3.7dm and 3.7em). Given the good $V(x)$ (Figure 3.3b) and $y_p(t)$ (Figure 3.6) model–data agreement, near-shoreline dye tracer statistics are calculated using the same time periods for the model and the observations. Thus, quantitative model–data comparison is performed only over the observed time range at each of the SA1-SA5 (Figure 3.7, shaded regions).

### 3.4.4.2 Near-Shoreline Dye Alongshore Dilution

Here, the observed and modeled alongshore decay rates of near-shoreline mean dye concentration $\overline{D}$ are compared. HR15 found that the observed near-shoreline mean dye diluted downstream following a power law relationship,

$$\overline{D} = \overline{D}_0 (y/y_0)^{\alpha},$$

where $y_0 = 1$ m. The least squares power law fit to the observed $\overline{D}_o$ (black dashed line and symbols, respectively, Figure 3.8a) has high skill ($r_o^2 = 0.98$) with best fit constants $\overline{D}_{o_0} = 98(\pm 13)$ ppb and $\alpha_o = -0.33(\pm 0.02)$. The modeled near-shoreline
Figure 3.7: Observed (left) and modeled (right) dye concentration $D$ versus time at SA1–SA5 (circles and diamond, Figures 3.1 and 3.2). Alongshore location is indicated in each panel. Magenta bars indicate duration of near-shoreline, continuous dye release at $y = 0$ m (star in Figures 3.1 and 3.2).
mean $\overline{D}_m$ dilutes downstream with $y$ in a manner very similar to the observations. The least squares power law fit to modeled $\overline{D}_m$ (colored dashed line and symbols, respectively, Figure 3.8a) also has high skill ($r_m^2 = 0.95$), with best fit constants $\overline{D}_{0,m} = 104(\pm 30)$ ppb and $\alpha_m = -0.38(\pm 0.05)$. The observed ($\alpha_o = -0.33$) and modeled ($\alpha_m = -0.38$) power law exponents are similar (within a standard error of each other), although the model dye dilutes slightly more rapidly. At the farthest downstream location $y_{SA5} = 1662$ m, this results in observed $\overline{D}_o = 8.2$ ppb whereas modeled $\overline{D}_m = 6.4$ ppb (Figure 3.8a).

Both the observed and modeled dye variability at SA1–SA5 also decrease downstream (Figure 3.7). The least squares power law fit to the observed standard deviation $\sigma_{D_o}$ (black dashed line and symbols, respectively, Figure 3.8b) has slope $-0.88$. Similarly, the least squares power law fit to the modeled standard deviation $\sigma_{D_m}$ (colored dashed line and symbols, respectively, Figure 3.8b) has slope $-1.06$. The observed and modeled near-shoreline dye standard deviations are similar across SA1–SA5, although modeled $\sigma_{D_m}$ is larger than the observed $\sigma_{D_o}$ at the nearest location SA1 and slightly smaller than the observed $\sigma_{D_o}$ at the farthest downstream location SA5 (Figure 3.8b).

### 3.4.4.3 Near-Shoreline Dye Time Scales

A near-shoreline dye time scale $\tilde{t}_D$ is defined as

$$\tilde{t}_D = \left[ \frac{(dD'/dt)^2}{D''^2} \right]^{-1/2},$$

where $D' = D - \overline{D}$. For observations, the $\tilde{t}_{D_o}$ are calculated using the full available time series, which span time periods when dye has equilibrated at each of the SA1–SA5 locations (Figure 3.7, left column). Model dye concentration time scales $\tilde{t}_{D_m}$ are calculated over the same times as the observations (Figure 3.7, shaded regions).

The observed $\tilde{t}_{D_o}$ increase from 53 s at SA1 to 127 s at SA5 (Figure 3.9, black symbols). Similarly, the modeled $\tilde{t}_{D_m}$ increase from 62 s at SA1 to 150 s at SA5 (Figure 3.9, colored symbols). The ratio of modeled to observed $\tilde{t}_D$ is
Figure 3.8: (a) Observed (black) and modeled (color) mean (time-averaged) dye concentration $\bar{D}$ (squares) versus alongshore coordinate $y$ at the near-shoreline SA1–SA5 (Figures 3.1 and 3.2). Best fit lines (dashed) are $\bar{D}_o = \bar{D}_{0o} (y/y_0)^{\alpha_o}$ and $\bar{D}_m = \bar{D}_{0m} (y/y_0)^{\alpha_m}$ for the observations and model, respectively, with $y_0 = 1$ m. The best fit observed $\alpha_o = -0.33$ and modeled $\alpha_m = -0.38$. (b) Observed (black) and modeled (color) dye concentration standard deviation $\sigma_D$ (circles) versus along-shore coordinate $y$ at the near-shoreline SA1–SA5. Best fit $\sigma_D$ power law exponents are $-0.88$ and $-1.06$ for the observations and model, respectively.
Figure 3.9: Observed (black) and modeled (color) dye time scale $\tilde{t}_D$ (3.6) versus alongshore coordinate $y$.

about 1.2 across all locations. This downstream increase in both $\tilde{t}_{D_{o}}$ and $\tilde{t}_{D_{m}}$ indicates a transition to larger surfzone alongshore length scales as dye concentration alongshore gradients, initially strong near the release, are reduced downstream (e.g., Figures 3.4 and 3.5) as dye is stirred and mixed by both individual bores (e.g., Feddersen, 2007) and surfzone eddies (e.g., Peregrine, 1998; Clark et al., 2012; Suanda and Feddersen, 2015). The downstream increase in surfzone length scales is also consistent with the downstream increase in inner-shelf length scales seen in the observed and modeled planview images (Figures 3.4 and 3.5). Such transition to longer length scales is common in a variety of turbulent environments such as flow behind a cylinder (e.g., Tennekes and Lumley, 1972).

3.4.4.4 Near-Shoreline Dye Discussion

These similarities between observed and modeled near-shoreline qualitative dye time series and quantitative dye statistics (Figures 3.7, 3.8, and 3.9) suggest that the model is simulating reasonably well the observed near-shoreline dye evolution, although the modeled mean $\overline{D_m}$ is slightly too small and the modeled $D_m$ variability is somewhat too strong relative to the observations. The good model–data comparison of alongshore currents $V(x)$ (Figure 3.3b) and the dye plume front $y_p(t)$ (Figure 3.6) indicate that the alongshore dye advection is well simulated. Together, this suggests that the model is ejecting dye from the surfzone to the inner-shelf realistically as well, consistent with the similarities of the observed
and modeled planview dye maps (Figures 3.4 and 3.5).

### 3.4.5 Cross-shore Dye Profiles

From Huntington Beach 2006 releases, Clark et al. (2011) showed reasonable agreement between observed and funwaveC-modeled cross-shore dye profiles within the surfzone, but no farther than 160 m offshore and no farther than 225 m downstream of the dye source. Here, jetski-observed (surface) and modeled (depth-averaged) mean dye cross-shore profiles are compared up to 350 m offshore and roughly 1700 m downstream. For this comparison, the jetski-observed surface dye $D_o^s(x)$ must be normalized to a depth-average. The observed dye was vertically well mixed in the surfzone (HR15), while inner-shelf dye was surface-intensified with a vertical scale such that the observed depth-averaged dye

$$D_o(x) = \left( \frac{h_{dye}}{h} \right) D_o^s(x),$$

where $h_{dye}(x) = \min[h(x), 2.7 \text{ m}]$ (HR15).

The mean observed $\overline{D}_o(x)$ are calculated by averaging the repeated jetski cross-shore transects at alongshore locations $y_j$ closest to the SA locations, with transects sub-sampled at times during the SA observation time periods (Figure 3.7, left column). The jetskis were driven as far onshore as possible but were unable to sample all the way to the mean shoreline. Modeled cross-shore dye profiles $\overline{D}_m(x)$ at the SA1-SA5 alongshore locations are averaged during the observed time periods (Figure 3.7, shaded), when model dye had equilibrated at each SA location. The $\Delta y$ between jetski transects and SA locations was typically $<2\%$ of the downstream distance $y$, except at SA2 where $\Delta y = 40 \text{ m}$. No model–data comparison is made for SA3 (just north of the Imperial Beach pier), as the jetskis could not operate safely near this location.

At SA1 ($y = 82 \text{ m}$), observed $\overline{D}_o(x)$ has a near-shoreline maximum of 50 ppb and decays across the surfzone (Figure 3.10a, black). At the surfzone/inner-shelf boundary $x_b$ (Figure 3.10a, dashed vertical line), $\overline{D}_o \approx 25 \text{ ppb}$. Roughly 30 m offshore on the inner-shelf, observed dye decays to $\overline{D}_o < 5 \text{ ppb}$. The modeled $\overline{D}_m(x)$ has a similar near-shoreline maximum and decays rapidly offshore (Figure 3.10a,
Figure 3.10: Observed (black) and modeled (color) mean dye concentration $\bar{D}$ versus cross-shore coordinate $x$ at select alongshore locations $y$ (for the model, the SA1–SA5 $y$ locations; for the observations, the jetski transect locations $y_j$ nearest SA1–SA5). Vertical dashed line denotes the surfzone/inner-shelf boundary $x_b$. 
colored). Near $x_b$, the modeled $D_m$ is weaker than observed. However, offshore of $x \approx -120$ m, the modeled $D_m(x)$ and observed $D_o(x)$ are again similar, as near the shoreline. At SA2 ($y = 248$ m), observed $D_o(x)$ has diluted near the shoreline (with a maximum of 30 ppb), and has spread farther offshore onto the inner-shelf (Figure 3.10b, black). The SA2 modeled $D_m(x)$ is similar to the observed, both in the surfzone and inner-shelf regions (Figure 3.10b, colored). Farther downstream at SA4 ($y = 1069$ m), the observed $D_o(x)$ is roughly uniform across the surfzone (as in HR15) and out to $x \approx -120$ m (about $1.5x_b$, Figure 3.10c, black). Offshore of $x \approx -120$ m, observed $D_o(x)$ decreases to $D_o < 1$ ppb at $x < -300$ m, consistent with the planview aerial images (Figure 3.4). Similarly, SA4 modeled $D_m(x)$ is also cross-shore uniform from the shoreline to roughly $1.5x_b$ (Figure 3.10c, colored), with magnitude slightly less than observed. Offshore, modeled dye decays to $D_m < 1$ ppb at $x < -300$ m as in the observations, but the inner-shelf modeled dye decays less rapidly than observed. At the farthest downstream location SA5 ($y = 1662$ m), observed $D_o(x)$ has further slowly diluted at the shoreline, is again cross-shore uniform out to roughly $1.5x_b$ (Figure 3.10d, black), and decays offshore in a manner similar to the SA4 observed cross-shore decay. The SA5 modeled $D_m(x)$ is also well mixed out to $x \approx -120$ m (Figure 3.10d, colored), but as at SA4, the SA5 modeled $D_m(x)$ decays less quickly than observed.

The $D(x)$ model–data agreement close to the release ($y < 250$ m), where dye is largely surfzone-contained (Figures 3.10a and 3.10b), shows that the model accurately reproduces surfzone cross-shore tracer dispersion. The far downstream ($y > 1000$ m) model–data $D(x)$ agreement within $-120 < x < 0$ m demonstrates that the model accurately disperses dye out to roughly 1.5 surfzone widths of the shoreline, but farther offshore, the inner-shelf has somewhat more dye in the model than in the observations (Figures 3.10c and 3.10d). Averaged over the SA locations, the inner-shelf has 26% more cross-shore integrated dye in the model than in the observations, although the modeled and observed $D(x)$ decay scales are similar.
Figure 3.11: Observed (dashed) and modeled (solid) cumulative (time integrated) alongshore dye transports at $y_f = 248$ m versus time. Observed and modeled dye was released near the shoreline at $y = 0$ m (Figures 3.1 and 3.2) throughout this time period (magenta bar). Vertical dashed line separates periods 1 and 2.

3.4.6 Alongshore Dye Transport

Observed and modeled cumulative alongshore dye transports are compared at the cross-shore frame array $y_f = 248$ m during the observed dye release time period. The alongshore transport $T_{y_f}$ from region A to region B (see Figure 3.4a) is defined (HR15) for the surfzone,

$$T_{y_f}^{SZ}(t) = \int_{x_{b}}^{x_f} d(x,t)V(x,t)D(x,t) \, dx,$$  \hspace{1cm} (3.8)

and the inner-shelf,

$$T_{y_f}^{IS}(t) = \int_{x_{f6}}^{x_{b}} d(x,t)V(x,t)D(x,t) \, dx.$$  \hspace{1cm} (3.9)

The surfzone and inner-shelf alongshore transports are estimated using 30 s averaged total water depth $d = h + \eta$, alongshore current $V$, and dye concentration $D$. For the observations, (3.8) and (3.9) are estimated with measurements from the near-bottom frames f1-f6 (Figure 3.3c), where $V_o(x,t)$ and $D_o(x,t)$ are assumed vertically uniform, and cross-shore integration is performed with the trapezoid rule. Model $V_m$ and $D_m$ are available at all $x$ and are vertically uniform throughout the domain.
The observed and modeled alongshore dye transports (3.8) and (3.9) fluctuate significantly (not shown here; see HR15 for observed), consistent with the observed and modeled $D(t)$ fluctuations (e.g., at f2/SA2; Figures 3.7bo and 3.7bm). Here, the cumulative (time-integrated) alongshore transports $\int_0^T \mathcal{T}_f(\tau) \, d\tau$ are compared between the model and observations for the surfzone and inner-shelf regions separately and together. The observed cumulative surfzone alongshore transport increases approximately linearly (Figure 3.11, gray dashed) and at the end of the observed dye release ($t = 2.3 \times 10^4$ s) totals 62% of the released dye. The corresponding release-averaged $\mathcal{T}_{SZ_o} = 320 \text{ ppb m}^3\text{s}^{-1}$. The modeled cumulative surfzone alongshore transport is similar to the observed for $t < 1.2 \times 10^4$ s, and becomes less than the observed for $t > 1.2 \times 10^4$ s (Figure 3.11, compare gray solid and dashed). At the end of the observed release, the modeled cumulative surfzone alongshore transport is roughly three quarters of the observed surfzone transport. For the inner-shelf, the observed cumulative alongshore transport is also approximately linear (Figure 3.11, blue dashed) and at the end of the release reaches 15% of the total released dye. The corresponding release-averaged $\mathcal{T}_{IS_o} = 76 \text{ ppb m}^3\text{s}^{-1}$, roughly one quarter of the observed surfzone mean $\mathcal{T}_{SZ_o}$. The modeled cumulative inner-shelf alongshore transport is similar to the observed transport for $t < 1.2 \times 10^4$ s and becomes greater than observed thereafter (Figure 3.11, compare blue solid and dashed). At the end of the observed dye release, the modeled cumulative inner-shelf alongshore transport is approximately twice that of the observations.

Overall, the total (surfzone + inner-shelf) cumulative alongshore transports are very similar for the observations and the model (Figure 3.11, compare black dashed and solid curves). The smaller modeled surfzone alongshore transport is compensated by a larger modeled inner-shelf alongshore transport. The model–data surfzone alongshore transport difference is consistent with the smaller surfzone $\mathcal{D}$ in the model than in the observations (e.g., Figures 3.8 and 3.10). The model–data alongshore transport difference on the inner-shelf could be due to model–data differences in region A surfzone to inner-shelf ejection rates or to a low-biased estimation of (3.9) for the observations. These differences are further discussed in
Sections 3.6.2 and 3.6.3.

3.5 Dye Mass Balances and Surfzone/Inner-shelf Exchange

In Section 3.4, both qualitative and quantitative model–data dye comparisons are good, motivating examination of dye mass budgets and surfzone/inner-shelf exchange. HR15 closed the first coupled surfzone/inner-shelf dye budget. Over roughly 5 h and 3.25 km downstream, approximately 1/2 of the shoreline-released dye was transported offshore from the surfzone to the inner-shelf (HR15). This transport was parameterized well using a bulk exchange velocity and mean surfzone to inner-shelf dye concentration difference (HR15). Here, a model dye mass budget is examined and compared to the observations.

Surfzone and inner-shelf dye masses over the alongshore model domain are defined for both the observations and the model as

\[ M_{SZ}(t) = \int_{y_{min}}^{y_{max}} \int_{x_{h}}^{0} \int_{-h}^{\eta} D(x, y, z, t) \, dz \, dx \, dy, \]

(3.10)

and

\[ M_{IS}(t) = \int_{y_{min}}^{y_{max}} \int_{x_{off}}^{x_{b}} \int_{-h}^{\eta} D(x, y, z, t) \, dz \, dx \, dy, \]

(3.11)

where \( x_{off} \) is the offshore boundary of the aerial observations (e.g., Figure 3.4) or the offshore model tracer domain boundary (Figure 3.2, heavy dashed line), and the alongshore integration limits \( y_{min} = -67.5 \, m \) and \( y_{max} = 1957.5 \, m \) correspond to the model domain. HR15 developed a methodology for estimating observed \( M_{SZo} \) and \( M_{ISo} \), calculated over the full alongshore extent of the dye plume (> 2 km downstream in the later observations, e.g., Figure 3.6, symbols). Here, the observed surfzone \( M_{SZo} \) and inner-shelf \( M_{ISo} \) are recalculated using the same HR15 methodology, but with alongshore integration limits restricted to the model domain \((y_{min}, y_{max})\). The observed dye mass estimates are available only at the times of the aerial images (e.g., Figure 3.4) spanning roughly \( t = (0.2 - 1.8) \times 10^4 \, s \) (e.g., Figure 3.6, symbols). Modeled dye masses are directly calculated from the vertically averaged, highly resolved \((x, y, t)\) model output (Section 3.3.2.1).
For the purposes of observed and modeled dye mass balance analysis, the time period $t = 0 - 2 \times 10^4$ s is separated into two. Period 1 ($t < 1.2 \times 10^4$ s) is the time prior to the observed and modeled dye plumes reaching the alongshore extent of the model domain (Figure 3.6), and period 2 ($t > 1.2 \times 10^4$ s) is the time after observed and modeled dye begins advecting beyond this region.

3.5.1 Dye Mass Balance: Total, Surfzone, and Inner-shelf

The total dye mass balance for the surfzone and inner-shelf is

$$M_{SZ}(t) + M_{IS}(t) = \int_0^t Q \, d\tau,$$

(3.12)

where $Q = 512$ ppb m$^3$s$^{-1}$ is the steady dye release rate starting at $t = 0$ s, and $M_{SZ} = M_{IS} = 0$ ppb m$^3$ at $t = 0$ s. The observed total dye mass balance (3.12) closes within 10% during period 1 (Figure 3.12a, compare black symbols and magenta line). During period 2 when the dye plume extends beyond $y_{\text{max}}$, the total observed dye mass within $y_{\text{min}} \leq y \leq y_{\text{max}}$ levels off at $\approx 70\%$ of the cumulative released dye mass (Figure 3.12a). The modeled total dye mass balance also closes well during period 1 (Figure 3.12a, compare black curve and magenta line). A small fraction ($<10\%$) of model total dye mass is lost at the upstream (southern) boundary $y_{\text{min}}$ when near-release eddies recirculate dye southward. Similar to the observations, the rate of increasing modeled total dye mass slows during period 2, as dye being released into the domain is offset by dye alongshore-advecting out of the domain through $y_{\text{max}}$.

Early in period 1, the observed $M_{SZ_o} \approx M_{IS_o}$ (Figure 3.12a, gray and blue symbols). Starting later in period 1, as more dye spreads from the surfzone to the inner-shelf, the observed $M_{IS_o}$ becomes larger than $M_{SZ_o}$. During period 2, both $M_{SZ_o}$ and $M_{IS_o}$ level off due to dye propagating beyond $y_{\text{max}}$, with the observed dye mass remaining larger for the inner-shelf than the surfzone (Figure 3.12a, gray and blue symbols). For the model, $M_{SZ_m} > M_{IS_m}$ for roughly the first hour of the release (Figure 3.12a, gray and blue curves, respectively), as expected with a surfzone dye source. For the remainder of period 1, modeled $M_{IS_m} > M_{SZ_m}$, with both inner-shelf and surfzone modeled dye mass magnitudes very similar to
Figure 3.12: Observed (symbols) and modeled (curves) surfzone and inner-shelf dye masses for regions A and B versus time. Magenta line shows the cumulative dye mass released near the shoreline. Vertical dashed line denotes the time when the observed and modeled dye plumes advect beyond the model domain (Figure 3.6), defining periods 1 and 2, noted above panel (a).
the observations (Figure 3.12a, blue and gray curves and symbols during period 1). However, during period 2, the inner-shelf modeled dye mass is larger than observed \( M_{ISm} > M_{ISo} \), Figure 3.12a, blue curve and symbols, respectively), while the surfzone modeled dye mass is smaller than observed \( M_{SZm} < M_{SZo} \), Figure 3.12a, gray curve and symbols, respectively). Overall, the total, surfzone, and inner-shelf dye masses are very similar for the model and the observations during period 1, and less similar during period 2 (Figure 3.12a, compare curves with symbols). The period 2 differences are discussed in Section 3.6.3.

### 3.5.2 Near- and Far-Field Dye Masses

As in HR15, the observed and modeled domains are partitioned alongshore into the near-field region A \((y \leq y_f)\) and the far-field region B \((y > y_f)\), where \(y_f = 248 \text{ m}\). For the observed surfzone dye masses, during the early portion of period 1 when dye has not advected very far downstream (e.g., Figures 3.4a and 3.6), \( M_{SZo}^A \) and \( M_{SZo}^B \) are comparable (Figure 3.12b, symbols). As dye moves farther downstream during period 1 (e.g., Figures 3.4b–3.4d and 3.6), observed \( M_{SZo}^B \) becomes larger than \( M_{SZo}^A \). Though dye concentrations are highest near the release (region A), the observed downstream power law decay (3.5) is relatively weak \((\alpha_o = -0.33)\), and the larger alongshore extent of the dye plume in region B than region A results in \( M_{SZo}^B \approx 2M_{SZo}^A \) (Figure 3.12b, symbols). During period 2 when dye has advected > 2 km downstream (e.g., Figures 3.4e, 3.4f, and 3.6), the observed \( M_{SZo}^B \approx 4M_{SZo}^A \) (Figure 3.12b, symbols). Similar trends are seen in the inner-shelf observations (Figure 3.12c, symbols) but with period 1 and 2 observed inner-shelf \( M_{ISo}^B/M_{ISo}^A \) ratios larger than the observed surfzone \( M_{SZo}^B/M_{SZo}^A \) ratios. Early in period 1, \( M_{ISo}^A \approx M_{ISo}^B \). Later in period 1, \( M_{ISo}^B \) increases while \( M_{ISo}^A \) remains approximately constant. During period 2, observed \( M_{ISo}^B \gg M_{ISo}^A \) (Figure 3.12c, symbols).

For the modeled surfzone dye masses early in period 1, \( M_{SZm}^A > M_{SZm}^B \) (Figure 3.12b, curves), as dye has not yet advected far downstream (e.g., Figures 3.5a and 3.6). As dye moves farther downstream in period 1 (e.g., Figures 3.5b–3.5d and 3.6), modeled \( M_{SZm}^B \approx M_{SZm}^A \), with \( M_{SZm}^A \) greater than observed, and \( M_{SZm}^B \)
less than observed (Figure 3.12b, curves and symbols). During period 2, modeled $M_{SZm}^A$ is similar to observed $M_{SZo}^A$ (Figure 3.12b, dashed curve and triangles), but $M_{SZm}^B < M_{SZo}^B$ (Figure 3.12b, dotted curve and squares), resulting in a period 2 mean model ratio $\overline{M_{SZm}^B/M_{SZm}^A}$ smaller than the corresponding observed ratio $M_{SZo}^B/M_{SZo}^A$ (Figure 3.12b, compare curves and symbols). On the inner-shelf, modeled $M_{ISm}^A$ and $M_{ISm}^B$ are comparable early in period 1, similar to the observations (Figure 3.12c, compare curves and symbols). Later in period 1, modeled $M_{ISm}^B$ increases at a rate consistent with observed $M_{ISo}^B$ (Figure 3.12c, dotted and squares), while $M_{ISm}^A$ remains nearly constant as in the observations (Figure 3.12c, dashed and triangles). During period 2, modeled $M_{ISm}^A$ remains small and comparable to observed $M_{ISo}^A$, while modeled $M_{ISm}^B$ continues increasing, becoming larger than observed $M_{ISo}^B$ (Figure 3.12c), leading to total (A+B) modeled $M_{ISm}$ larger than total observed $M_{ISo}$ (Figure 3.12a, compare blue curve and symbols).

### 3.5.3 Cross-Shore Surfzone/Inner-Shelf Exchange

Because the observed and modeled dye mass budgets close during period 1 (Figure 3.12a and Section 3.5.1), the inner-shelf dye mass can be used to calculate the surfzone to inner-shelf cross-shore transport of shoreline-released dye. At any time, the total inner-shelf dye mass must equal the cumulative (time-integrated) cross-shore transport input from the surfzone and the cumulative inner-shelf alongshore transport loss through $y_{max}$, i.e.,

$$\int_0^t T_{SZ/IS}^x(\tau) \, d\tau = M_{IS}(t) + \int_0^t T_{IS}^{y_{max}}(\tau) \, d\tau.$$

(3.13)

During period 1, before $y_p(t)$ has reached $y_{max}$ (Figure 3.6), the inner-shelf alongshore transport $T_{IS}^{y_{max}}$ is zero. Therefore, the period 1 cross-shore transport $T_{SZ/IS}^x = \frac{d}{dt}(M_{IS})$ and can be estimated via the best fit slope of inner-shelf dye mass $M_{IS}$. In period 1, the observed and modeled inner-shelf total dye masses agree very well (Figure 3.13, compare symbols and curve). The period 1 observed and modeled cross-shore transports $T_{SZ/IS}^x$ are calculated via the least-squares slopes of observed and modeled $M_{IS}$, respectively, during times spanning the inner-shelf dye mass observations ($t = (2.5 - 8.9) \times 10^3$ s, Figure 3.13). The resulting pe-
period 1 observed and modeled cross-shore transports ($\mathcal{T}_{SZ/ISo} = 382$ ppb m$^3$ s$^{-1}$ and $\mathcal{T}_{SZ/ISm} = 349$ ppb m$^3$ s$^{-1}$) agree within 10%. This model–data $\mathcal{T}_{SZ/IS}$ agreement implies that the transient rip currents of funwaveC accurately reproduce cross-shore surfzone to inner-shelf tracer transport for alongshore-uniform bathymetry and the observed wave conditions.

3.6 Discussion

3.6.1 Mechanisms of Surfzone/Inner-Shelf Exchange

For alongshore-uniform bathymetries, potential surfzone/inner-shelf cross-shore tracer exchange mechanisms include transient rip currents (e.g., Hally-Rosendahl et al., 2014; Suanda and Feddersen, 2015), internal waves (e.g., Sinnett and Feddersen, 2014), and Stokes-drift-driven flow (e.g., Lentz et al., 2008). Based on the 13 October observed dye, dye mass budgets, and inferred exchange velocity magnitude, HR15 showed that the observed surfzone/inner-shelf dye exchange on this day with moderate waves was dominated by transient rip currents. The depth-averaged funwaveC model includes this mechanism but does not include internal...
waves or Stokes-drift driven exchange. The good model–data $M_{IS}$ agreement in all regions (Figure 3.12) implies that the model accurately reproduces the observed cross-shore surfzone/inner-shelf exchange $T_{SZ/IS}^x$, confirming that transient rip currents were the dominant exchange mechanism within 3 surfzone widths of the shoreline during the observed 5 h time period. Over longer time scales or farther offshore of the surfzone, internal waves (e.g., Suanda et al., 2014; Walter et al., 2014), Stokes-drift-driven flow (e.g., Lentz et al., 2008), or other inner-shelf processes may become important.

3.6.2 Inner-shelf Stratification and Vertical Variation

HR15 showed that the 13 October dye field was vertically uniform within the surfzone. However, inner-shelf dye was surface-intensified (see Figure 13 in HR15) with a vertical dye scale $h_{dy} = 2.7$ m, potentially due to inner-shelf thermal stratification. The vertically integrated Boussinesq and tracer models lack stratification and vertical dye variation. Although the overall model–data agreement is good, the model’s lack of vertical variation might be important for particular inner-shelf model–data differences.

For example, modeled inner-shelf $D_m$ is patchier than the observed inner-shelf $D_o$ (compare Figures 3.4 and 3.5). Consider a fluid column of dye ejected by a rip current from the surfzone onto the deeper inner-shelf. If the ejection is confined to an upper layer by inner-shelf stratification (e.g., HR14; HR15), it would be expected to undergo greater lateral spreading (resembling elevated lateral mixing) relative to an ejection that is able to stretch vertically over the entire water column as it moves offshore (e.g., funwaveC modeled dye). This stratified upper layer spreading mechanism explains the difference in observed and modeled lateral spreading of drifters leaving a tidal inlet (e.g., Spydell et al., 2015), and may explain the difference in patchiness between the observed and funwaveC modeled inner-shelf dye.

Vertical variation might also be important for the inner-shelf alongshore transport $T_{IS}^{yf}$ model–data difference. Although the total (surfzone + inner-shelf) cumulative alongshore transports are similar for the observations and the model
(Figure 3.11, compare black dashed and solid curves), this is due in part to the opposing differences for the surfzone and the inner-shelf (Figure 3.11, compare dashed and solid gray and blue curves, respectively). The smaller modeled surfzone alongshore transport is consistent with smaller near-shoreline $\overline{D}$ in the model than in the observations (e.g., Figures 3.8 and 3.10). For the inner-shelf, the larger modeled alongshore transport could imply that region A dye is ejected offshore of the surfzone more quickly in the model than in the observations. However, another possibility is that because the $D_o$ and $V_o$ used in (3.9) are near-bottom measurements, the observational estimate $T_{IS_o}$ is biased too low due to inner-shelf $D_o$ vertical dye stratification (see Figure 13 in HR15) or possible inner-shelf vertical shear in the wind-driven $V_o$.

### 3.6.3 Additional Model–Data Comparison Considerations

Overall, the surfzone and inner-shelf dye model–data agreement is quite good. However, specific model and analysis simplifications that might contribute to the model–data differences are discussed here. First, the wind and wave field are stationary in the model, while the observed wind and wave field did evolve somewhat, as did the observed alongshore current $V_o$ (note the faster $y_{pb}(t)$ propagation for $t > 1.2 \times 10^4$ s, Figure 3.6). This might contribute to the larger observed than modeled surfzone alongshore transport during period 2 (Figure 3.11, compare gray dashed and solid curves). However, the general model–data agreement indicates that the stationary wave and wind field in the model is a reasonable approximation, particularly for $t < 1.2 \times 10^4$ s. Second, the model has no tidal variation. The observed low tide occurred at $t = 6.8 \times 10^3$ s (roughly midway through period 1) and rose by $\approx 0.7$ m by the end of period 2. While the surfzone/inner-shelf boundary $x_b$ is fixed and identical in both the model and observations, the true observed surfzone/inner-shelf boundary may have shifted onshore by $\approx 20$ m, potentially biasing the period 2 model–data dye mass comparisons. This could also explain in part the differences between observed and modeled alongshore dye transports (Figure 3.11). If the model had a rising tide with a fixed $x_b$, this could result in larger modeled surfzone transport and weaker modeled inner-shelf transport, more
closely matching the period 2 observations.

3.7 Summary

A near-shoreline, continuous 6.5 h dye release on 13 October 2009 at the approximately alongshore-uniform Imperial Beach, CA (IB09 experiment; see HR15) is simulated with the wave-resolving Boussinesq model funwaveC. The model generates surfzone vorticity and transient rip currents driven by finite crest length wave breaking. However, the depth-averaged model does not resolve stratification or vertical dye variation, which are potentially important on the inner-shelf. Here, we compare the observed and modeled surfzone and inner-shelf dye dispersion and cross-shore exchange.

The funwaveC model is initialized with the alongshore-averaged Imperial Beach bathymetry and the 13 October observed offshore wave spectrum and mean wind. The model reproduces the inner-shelf and surfzone observed significant wave height and alongshore current. Both qualitative and quantitative model–data agreement for dye is good. Observed and modeled surfzone dye advects alongshore at similar rates while being intermittently ejected offshore onto the inner-shelf. The narrow inner-shelf dye features evolve to larger length-scales as they advect downstream, with modeled dye somewhat patchier than observed. Over 1700 m alongshore, near-shoreline mean dye concentration decays downstream following a power law relationship with similar observed (-0.33) and modeled (-0.38) exponents. Observed and modeled near-shoreline dye time scales increase similarly with downstream distance, consistent with the inner-shelf downstream evolution to larger dye length scales. Mean cross-shore dye profiles are similar for the observations and the model, with near-release dye strongest at the shoreline and decaying rapidly offshore. Farther downstream (> 1000 m), observed and modeled profiles widen, with dye cross-shore well mixed out to 1.5 surfzone widths from the shoreline. On the inner-shelf, the depth-normalized observed cross-shore dye profiles decay more quickly than the modeled profiles, but the observed and modeled cross-shore decay scales are similar. Surfzone and inner-shelf alongshore
dye transports are each well modeled early in the release, while they are under-
and over-predicted, respectively, later in the release. The total alongshore dye
transport is well modeled at all times.

Modeled and observed dye mass budgets over the model domain (≈ 2 km
alongshore) are similar to each other for times < 3.5 h, before observed and mod-
eled dye begin advecting out of the domain. During this time, the observed and
modeled dye budgets each close to within 10% and have very similar distribu-
tions of surfzone and inner-shelf dye mass. Cross-shore dye transports for the
observations and the model agree within 10%. Later in the release, after dye be-
gins advecting beyond the model domain, total observed and modeled dye masses
still agree fairly well, while modeled dye mass is under-predicted in the surfzone
and over-predicted on the inner-shelf. Model–data differences may be due to the
model’s lack of inner-shelf stratification and vertical dye variation or the model’s
lack of tide, biasing the location of the surfzone/inner-shelf boundary.

Overall, the good model–data agreement indicates that the wave-resolving,
depth-averaged Boussinesq model funwaveC accurately reproduces nearshore tracer
transport and dispersion over 5 h and 2000 m for approximately alongshore-uniform
bathymetry during moderate wave conditions. This confirms that transient rip cur-
rents are the dominant mechanism of the observed surfzone/inner-shelf cross-shore
tracer exchange, and suggests that funwaveC realistically reproduces the intensity,
frequency, and scales of the observed transient rip currents.
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Chapter 3, in part, is currently being prepared for submission to a peer-reviewed journal. Hally-Rosendahl, Kai; Feddersen, Falk. The dissertation author was the primary investigator and author of this material.
Chapter 4

Bibliography


Lucas, A., P. Franks, and C. Dupont (2011), Horizontal internal-tide fluxes support elevated phytoplankton productivity over the inner continental shelf, *Limnology*


