Mechanisms of mid-to-outer shelf transport of shoreline released tracers

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ABSTRACT

Transport of shoreline released tracer from the surfzone across the shelf can be affected by a variety of physical processes from wind-driven to submesoscale, with implications for shoreline contaminant dilution and larval dispersion. Here, a high-resolution wave-current coupled model that resolves the surfzone and receives realistic oceanic and atmospheric forcing is used to simulate dye representing shoreline released untreated wastewater in the San Diego, Tijuana region. Surfzone and shelf alongshore dye transport are primarily driven by obliquely incident wave breaking and alongshore pressure gradients. A mid-(MS) to outer-(OS) shelf boundary (25 m depth) is defined as a mean streamline. At the MS/OS boundary, along-boundary density gradients are persistent, dye is surface enhanced and time- and alongshelf patchy. Using baroclinic and along-boundary perturbation dye transports, two cross-shore dye exchange velocities are estimated and related to physical processes. Barotropic and baroclinic tides cannot explain cross-shore transport. The baroclinic exchange velocity is consistent with the wind-driven Ekman transport. The perturbation exchange velocity is elevated for alongshore dye and cross-shore velocity length-scales < 1 km (within the submesoscale) and stronger alongshore density gradient \( \partial \rho / \partial y \) variability, indicating that along-front geostrophic flows induce offshore transport. This elevated \( \partial \rho / \partial y \) is linked to convergent northward surface along-shelf currents (likely due to regional bathymetry), suggesting deformation frontogenesis. Both surfzone and shelf processes influence offshore transport of shoreline released tracers with key parameters of surfzone and shelf along-coast currents and alongshelf winds.
1. Introduction

Shoreline released wastewater or runoff enters the surfzone (SZ, region of depth-limited wave breaking) delivering pathogens and contaminants to coastal regions, in turn degrading water quality and threatening the health and sustainability of coastal ecosystems (e.g., Ahn et al. 2005; Steele et al. 2018). For example, in the San Diego Bight, within the Southern California Bight (SCB), 35 million gallons per day (mgd) of untreated wastewater is released 10 km south of the US/Mexico border at Pt. Bandera MX (e.g., Orozco-Borbón et al. 2006). Shoreline tracer dilution needed for safe bathing occurs through exchange across the surfzone, inner-shelf, and farther offshore. Similarly, the coastal connectivity of intertidal invertebrates (e.g., Becker et al. 2007; Shanks et al. 2010) also requires cross-shelf exchange. A fraction of shoreline released runoff or small river input is transported alongshore in the SZ, dependent on the flow rate and wave conditions (Wong et al. 2013; Rodriguez et al. 2018). Breaking of obliquely incident waves vertically mixes tracers (e.g., Feddersen 2012) and drives SZ alongshore currents (Longuet-Higgins 1970; Feddersen et al. 1998), transporting SZ tracer alongcoast up to 10 km (Grant et al. 2005; Feddersen et al. 2016; Rodriguez et al. 2018). SZ tracers are cross-shore transported (exchanged) to the inner-shelf due to transient rip currents (Hally-Rosendahl et al. 2014, 2015; Suanda and Feddersen 2015) or bathymetric inhomogeneities (e.g., Castelle and Coco 2013; Brown et al. 2015). Inner-shelf tracer dilution occurs through transport to the mid-shelf and outer-shelf. Thus, understanding cross-shore transport pathways and their associated physical processes has implications for any shoreline released tracer (e.g., heat, larvae, sediment, pollutants).

A variety of processes across a range of time scales can induce cross-shelf tracer transport. On subtidal (> 33 h) timescales, winds, waves, bathymetric variability, or regional-scale (10–100 km) alongshelf pressure gradients (APG) can drive offshore tracer transport. For an alongshelf uniform shelf, alongshelf wind driven Ekman layers induce cross-shore tracer transport that decreases towards the shoreline for both stratified and unstratified conditions (e.g., Austin and Lentz 2002; Lentz and Fewings 2012). As the water depth becomes shallower than the Ekman depth, Ekman transport shuts down. Cross-shore winds also induce transport albeit weaker than alongshore winds (e.g., Fewings et al. 2008; Horwitz and Lentz 2016; Wu et al. 2018). Bathymetric variations such as headlands, capes, and shoals can steer mean flow at a variety of length-scales (e.g., Gan and Allen 2002; Castelao and Barth 2006; Radermacher et al. 2017), inducing cross-shore transport.
A barotropic APG driven flow induces a bottom Ekman transport with a compensating interior cross-shore geostrophic current (Lentz 2008; Marchesiello and Estrade 2010), yielding cross-shore exchange. The vertical mismatch between onshore wave-driven Stokes drift and offshore Eulerian current can also induce long-term exchange (e.g., Lentz et al. 2008).

Semidiurnal and diurnal barotropic (BT, surface) and baroclinic (BC, internal) tides also play an important role in cross-shelf exchange (e.g., Pineda 1994; Walter et al. 2014). Cross-shore dye transport is induced by nonzero covariance between the cross-shore velocity and dye over a tidal cycle, analogous to tidal pumping inducing estuary-ocean exchange (e.g., Lerczak et al. 2006; Geyer and MacCready 2014). On the inner-shelf, strong BT tides can induce residual flow via tidal rectification (e.g., Ganju et al. 2011). In the SCB, semidiurnal (e.g., Lerczak et al. 2003; Buijsman et al. 2012; Kumar et al. 2016; Sinnett et al. 2018) and diurnal BC tides are ubiquitous (Lerczak et al. 2001; Nam and Send 2013; Kumar et al. 2015) even though the diurnal frequency is subcritical at SCB latitudes. The semidiurnal BC tide can drive an onshore cold-water transport through tidal pumping (e.g., Walter and Phelan 2016), and can cross-shore export heat from the nearshore (Sinnett and Feddersen 2019). BC tides enhance model simulated horizontal and vertical tracer dispersion in 30–50 m water depth (Suanda et al. 2018), and enhance mixing, reducing stratification (Suanda et al. 2017) and inducing residual cross-shelf flow. The diurnal internal tide is primarily responsible for the diurnal offshore and onshore advection for a SCB beach-released dye (Grimes et al. 2020).

Submesoscale flows have $O(1)$ km length-scales, are often seen as fronts and filaments, and have $O(1)$ or greater Rossby number $Ro = \zeta / f$ where $\zeta$ is the vertical relative vorticity and $f$ is the local planetary vorticity (e.g., McWilliams 2016). Fronts and filaments can be a primary driver for offshore tracer transport 100’s of km from shore (e.g., Nagai et al. 2015), and may be important in cross-shelf transport within 5 km of shore (e.g., Romero et al. 2016). Submesoscale flow variability is ubiquitous in coastal drifter observations (e.g., Ohlmann et al. 2017) and high resolution coastal models (e.g., Dauhajre et al. 2017). Generation mechanisms of open ocean submesoscale variability include mixed layer instability (e.g., Boccaletti et al. 2007), turbulent thermal wind balance (e.g., McWilliams et al. 2015), and deformation flow induced frontogenesis (e.g., Hoskins 1982). Classic frontogenesis within a non-divergent strain field has an along-front current in thermal wind balance with a cross-front density gradient that is enhanced by an ageostrophic convergent secondary circulation (e.g., Hoskins 1982; McWilliams et al. 2009). However, fronto-
genesis processes in shallow (relative to horizontal scales) and frictional coastal waters are less
clear and under-studied. In coastal environments, bathymetric variations (e.g., Pringle 2002) or
wind forcing (e.g., Tilburg and Garvine 2003) can drive surface deformation flow that may induce
frontogenesis.

As the effects of the Pt. Bandera shoreline released untreated wastewater is unknown, we seek
to understand the offshore transport pathways in the San Diego Bight using a realistic model that
includes the surfzone. Regional studies include examination of San Diego Bay (SDB) tidal
outflow (e.g., Chadwick and Largier 1999), Pt. Loma upwelling (Roughan et al. 2005), episodic
small river plumes (e.g., Warrick et al. 2007), and the evolution of shoreline released dye (Hally-
variability on length-scales of \( \approx 10 \) km with \( O(1) \) Rossby number (Kim 2010). However, the HF
radar cannot resolve length scales < 5 km. Dye observations within 1 km of shore in this region
reveal spatial variability from 0.01–1 km (Hally-Rosendahl et al. 2015; Grimes et al. 2020). Thus,
within 10 km of shore, significant submesoscale flow variability is likely present.

Dye and drifters in realistic shelf models have been extensively used to study Lagrangian trans-
port and dispersion processes (e.g., Uchiyama et al. 2014; Romero et al. 2013; Giddings et al. 2014;
Romero et al. 2016; Dauhajre and McWilliams 2019), with varying grid resolutions. Shoreline lar-
val dispersion patterns for the San Diego Bight were simulated with a realistic model at 600 m
grid resolution (Rasmussen et al. 2009), but without a surfzone. A Lagrangian transport model
forced with HF radar currents was used to estimate Pt. Bandera exposure kernels (Kim et al. 2009).
However, currents were unknown within 1–2 km of shore, surface trapped tracking, and objective
mapping velocity smoothing lead to significant exposure uncertainty (Kim et al. 2010). Coupled
wave and circulation models allow both the surfzone and shelf to be resolved (Kumar et al. 2012),
which is crucial as shoreline released tracer often is surfzone alongshore transported (Feddersen

Here, shoreline-released tracer is simulated from the SZ to the outer-shelf in the San Diego
Bight using a high-resolution wave-current coupled model with realistic forcing. The specific
goal is to elucidate the principal mechanism(s) responsible for offshore tracer transport in the mid
to outer shelf region using relatively simple metrics. The mechanisms considered include Ekman,
barotropic and baroclinic tidal, and submesoscale velocities. Analysis focuses on a three month
(mid-summer to fall) period characterized by weak to moderate winds, prevalent southerly inci-
dent surface gravity waves, strong alongshore pressure gradients, and active internal waves. The model configuration and methods are given in section 2. The spatio-temporal tracer variability and transport are presented in section 3. Alongshore transport mechanisms are examined in section 4. Mechanisms for cross-shore transport across a mid- to outer-shelf boundary are diagnosed in section 5. The relationships between key parameters governing dye transport and the role of other processes are discussed in section 6. Section 7 provides a summary.

2. Method

a. Model configuration

Surfzone and shelf circulation is simulated using the Coupled Ocean-Atmosphere-Wave-Sediment-Transport (COAWST) model system (Warner et al. 2010; Kumar et al. 2012). Three one-way nested parent models (from LV1 to LV2 to LV3) and one high resolution child run (LV4, see Fig. 1a for the four grids) are run from mid summer to early winter 2015 spanning a seasonal transition from summertime mostly southerly incident surface waves to wintertime mostly northerly incident waves. The LV1–LV3 runs employ the Regional Ocean Modeling System (ROMS, Shchepetkin and McWilliams 2005), a three-dimensional, hydrostatic model using a stretched terrain-following vertical coordinate (Shchepetkin and McWilliams 2005). The LV4 run includes surface gravity waves by coupling ROMS with the Simulating W Aves Nearshore model (SWAN, Booij et al. 1999), a phase-averaged wave model that solves the wave action balance equation. NOAA/NAM surface flux fields (wind stress, heat and precipitation) are used for all grids. Over the 5-month simulation period, the 21 days of NAM data gaps are filled with the Coupled Ocean-Atmosphere Mesoscale System (COAMPS) fields. The vertical viscosity and diffusivity are estimated using a $k - \epsilon$ scheme (Umlauf and Burchard 2003). A logarithmic bottom drag scheme is used with a bottom roughness $z_0 = 0.1$ cm, following Kumar et al. (2015). The horizontal eddy viscosity and diffusivity are constant at $0.5 \text{ m}^2\text{s}^{-1}$. For the LV4 model, SWAN and ROMS are two-way coupled at 10 min intervals allowing current effects on waves and wave effects on currents through surfzone wave breaking and vortex force.
1) **Parent Run Grids and Setup**

The model grids of the three parent runs downscale from 2 km horizontal resolution for the SCB (LV1 with $253 \times 390$ horizontal grid cells), to 600 m resolution resolving the southern SCB (LV2 with $266 \times 398$ grid cells), and to 200 m resolution for the greater San Diego shelf region (LV3 with $251 \times 413$ grid cells) (see Fig. 1a). All three domains have 40 terrain-following vertical ($\sigma$) levels with enhanced resolution near the surface and bottom (ROMS vertical coordinate parameters: $V_{\text{transform}} = 2$, $V_{\text{stretching}} = 4$, $\theta_s = 8$ and $\theta_b = 3$). Grid bathymetry is derived from the 3 arc-second NOAA/NGDC coastal relief dataset.

The outermost LV1 domain inherits the boundary and initial conditions from the California State Estimate (CASE) solution, an implementation of the $z$-level, primitive equation MIT general circulation model (MITgcm) (Marshall et al. 1997). CASE assimilates a variety of remote and in situ observations, including satellite altimetry data, satellite measured sea surface temperature, temperature and salinity profiles from Argo and Spray glider, expendable Bathythermograph (XBT) temperature transects, Autonomous Pinniped bathythermograph (APB) temperature profiles, and shipboard CTD profiles (Zaba et al. 2018). Daily averaged CASE solutions are linearly interpolated from $z$- to $\sigma$- level coordinates, and then horizontally interpolated onto the LV1 model grid and open boundaries. CASE does not include tides. Barotropic tidal elevation and velocities of 10 tidal constituents ($M_2$, $S_2$, $N_2$, $K_2$, $O_1$, $P_1$, $Q_1$, $K_1$, $M_4$ and $M_6$) are prescribed on the LV1 open boundaries with the amplitudes and phases from the ADCIRC tidal database (Westerink et al. 1993), allowing generation and propagation of internal waves within the model domain (e.g., Kumar et al. 2015; Suanda et al. 2017; Kumar et al. 2019).

The LV1 solutions provide initial and boundary conditions for LV2. Subsequently, the LV2 solutions are used for LV3, and the LV3 solutions are used for LV4. Chapman and Flather radiation boundary conditions are used for the sea level and the barotropic (depth-independent) velocity (Flather 1976; Chapman 1985). For the baroclinic (depth dependent) flow and tracers, the Oranski radiation condition is used together with nudging to constrain the interior solution to the parent (Marchesiello et al. 2001). In LV1-LV3 domains, the nudging time scale for outgoing baroclinic flow and tracers along open boundaries is $365 \, \text{d}^{-1}$, and the nudging time scale for the incoming baroclinic flow and tracers is $6 \, \text{h}^{-1}$. All solutions are saved at 1-hour intervals. The LV1 model was initialized on 1 July 2015 12:00, and the LV2 and LV3 models were initialized on 4 July 12:00.
and 7 July 12:00, respectively allowing 3-4 days of spinup in each parent grid.

2) LV4 Run Grid and Setup

The LV4 grid (with $486 \times 1142$ grid cells, area $15 \times 36$ km$^2$) spans the outer-shelf to surfzone in the southern San Diego Bight (Fig. 1b), which includes the San Diego Bay (SDB) and the headland Pt. Loma to the north. Southward of the SDB entrance, the shoreline first curves and then straightens, passing the Tijuana River Estuary (TJRE), the US/Mexico border and Punta Bandera (PB) within Mexico. South of the curvature, the bathymetry is largely alongshore uniform, except for a broad shoal seaward of TJRE that extends offshore (Fig. 1b). The LV4 grid cross-shore resolution increases from 110 m at the western open boundary to 8 m along the coastline, and alongshore resolution varies from 110 m at the southern and northern open boundaries to 8 m near the TJRE mouth. The stretched vertical domain has 15 levels (with $\theta_s = 4.5$ and $\theta_b = 3$) and the NOAA 1/3 arc-second coastal digital elevation is used for bathymetry.

The LV4 SWAN model has 25 frequencies between 0.04 and 0.29 Hz and 42 directional bands spanning from $145^\circ$ to $355^\circ$ (wave direction in Nautical convention), covering all potential incidence angles. The shoreline normal direction south of 32.6N is approximately $265^\circ$. CDIP wave model frequency-directional wave spectra are used for open boundary conditions (O’Reilly et al. 2016). The wave-breaking parameter $\gamma = 0.5$ is used following Kumar et al. (2015). Wind-wave generation is also included. Note that because SWAN is a wave-averaged model, the LV4 simulation has bathymetric rip currents but does not have transient rip currents which require a wave-resolving model (Feddersen 2014).

The LV4 ROMS component receives freshwater inputs from PB, TJRE and the Sweetwater River within SDB (see Fig. 1b). The parent grids do not receive freshwater input. At PB, freshwater, representing untreated wastewater, is released onto the beach at a constant discharge rate $Q_r = 1.53$ m$^3$/s$^{-1}$ (35 mgd). TJRE freshwater discharge is given by in-situ measurements at International Boundary and Water Commission (IBWC) gauging station and discharge primarily occurs during rainfall events (Fig. 2a). Additional coastal runoff emanating from the Sweetwater River within SDB is also incorporated in LV4. The Sweetwater River discharge rate is approximately estimated by multiplying the observed flow rate at a nearby river (San Diego River) by the ratio of the drainage area (Archfield and Vogel 2010). As PB and Sweetwater River inflow temperatures
are unknown, a 30-day low-pass filtered in-situ Tijuana River (Oneonta Slough) temperature measurement is applied for all three sources to remove weekly and higher frequency variations that could be variable among sites. Passive tracer (dye) of constant concentration $D = 1$, representing untreated wastewater, is added to the PB freshwater discharge. The off-diagonal radiation stress tensor term $S_{xy}$ (Longuet-Higgins 1970; Feddersen et al. 1998) is estimated as,

$$S_{xy} = -\frac{1}{16} \rho_0 g H_s^2 \frac{c_g}{c} \sin(\theta_w) \cos(\theta_w),$$

where $\theta_w$ denotes the mean wave angle relative to the shoreline normal, $H_s$ denotes the significant wave height, $\rho_0 = 1025$ kg m$^{-3}$ denotes a reference density, $c_g$ and $c$ denote the group and phase speeds. A positive $S_{xy}$ corresponds to southerly incident waves, which drives northward along-shore surfzone currents. Subtidal filtering is performed with the PL64 filter (Limeburner et al. 1985) with 33 h cutoff.

The LV4 coupled model was initialized on 12 July 2015, allowing 5 days of parent LV3 model spinup, and integrated to 25 December 2015. Relevant time-series are shown in Fig. 2. Modeled barotropic tidal amplitudes (Fig. 2b) and phases of $M_2$, $S_2$ and $K_1$ compare well with in-situ measurements (not shown here). NAM winds (Fig. 2c) are consistent with nearby buoy winds (not shown) and are frequently southward directed with low ($|U_w| < 5$ m s$^{-1}$) to moderate 5—8 m s$^{-1}$ speeds. Wave and alongshelf velocities are given at a 30-m depth central location denoted SB (Fig. 1b). At SB, $H_s$ varies between 0.5—1.5 m (Fig. 2d). The LV4 simulation has multiple periods of southerly incident waves ($i.e.$, $S_{xy} > 0$, yellow shading in Fig. 2e). These wave statistics compare well with local buoy observations, consistent with previous Southern California results (O’Reilly et al. 2016). At SB, the subtidal depth-averaged alongshore flow $V_{SB}$ ranges from $-0.1$ m s$^{-1}$ to $0.3$ m s$^{-1}$ and is mostly northward (positive) (Fig. 2f). The modeled dye concentration and dye transport are analyzed during the analysis period from 22 July to 18 October 2015 (dashed line in Fig. 2). This allows a 10-day period of LV4 dye spin up (22 days from LV1 initialization) at which point LV4 domain averaged enstrophy has equilibrated. After 18 October, occurrences of southerly incident incoming waves end northward transport of PB dye.

**b. Analysis methods**

To facilitate the cross- and alongshore dye transport analysis, two regions are defined (Fig. 1b). The first region is the *nearshore* (NS) spanning from the shoreline with a cross-shore width of
\[ L_x^{(NS)} = 500 \text{ m}. \] The NS reaches 10 m water depth and includes both the SZ and the shallow portion of the inner-shelf. The NS southern boundary is located 4.5 km north of PB allowing dye to adjust upon release and the alongshore length is \( L_y^{(NS)} = 18 \text{ km}. \) The northern extent is set to avoid the rapidly curving isobath further north. The second region is the mid-shelf (MS) to outer-shelf (OS) boundary (Fig. 1b) with mean depth of 25 m and alongshore length of \( L_y^{(MS,OS)} = 15.3 \text{ km}. \) The MS/OS boundary curves offshore such that southern and northern ends are approximately 3.1 and 6.3 km from the shoreline, respectively (white dashed lines in Fig. 1b). As offshore transport can be bathymetrically induced, the MS/OS boundary was chosen such that the depth-averaged and time-averaged (over the analysis period) flow across all parts of the the MS/OS boundary is zero (MS/OS boundary is a mean streamline). Note, at any time-step, the depth-averaged and along-boundary averaged cross-boundary flow is not necessarily zero. Analysis of cross-shore dye transport will be performed on the MS/OS boundary. To facilitate alongshore analysis, a MS/OS transition zone is defined centered at the MS/OS boundary with a width of \( L_x^{(MS/OS)} = 1 \text{ km} \) (dashed magenta, Fig. 1b).

Hereafter, the cross-shore \( (x, \text{ positive onshore}) \) and alongshore \( (y, \text{ positive northward}) \) directions are locally defined as the normal to and parallel to the MS/OS boundary. Time-averages (over the analysis period) are denoted with \( \{\cdot\} \). Standard deviations are represented by \( \text{std}(\cdot) \). Because dye is positive definite and does not have a Gaussian distribution, the time-averaged dye \( \langle D \rangle \) is based on a logarithmic average such that \( \langle D \rangle = 10^{(\log_{10} D)} \) (e.g., Hally-Rosendahl et al. 2014). Temporal mean plus (minus) standard deviation of dye are defined as \( \langle (D)_+, (D)_- \rangle = \langle 10^{(\log_{10} D) + \text{std}(\log_{10} D)}, 10^{(\log_{10} D) - \text{std}(\log_{10} D)} \rangle \). Within NS the dye is volume averaged \( \bar{D}^{(NS)} \).

Averaging operators are defined for analysis along the MS/OS boundary. For a variable \( \psi \), an along-MS/OS boundary average is defined as

\[
\bar{\psi}^y = \frac{1}{L_y^{(MS,OS)}} \int_0^{L_y^{(MS,OS)}} \psi \, dy, \tag{2}
\]

where the integral is over the the MS/OS boundary length denoted by \( y \). An MS/OS boundary depth average \( \bar{\psi}^z \) is defined as

\[
\bar{\psi}^z = \frac{1}{\bar{h}^{(MS,OS)}} \int_{-h}^{\eta} \psi \, dz, \tag{3}
\]

with average MS/OS boundary depth \( \bar{h}^{(MS,OS)} = 25.0 \text{ m} \). An along-boundary and depth-average \( \bar{\psi}^{yz} \) is

\[
\bar{\psi}^{yz} = (\bar{\psi}^y)^z. \tag{4}
\]
The cross MS/OS boundary velocity \( u \) is decomposed into three components

\[
u(y, z, t) = \bar{u}(t) + \tilde{u}(z, t) + u'(y, z, t), \tag{5}\]

representing the depth- and along-boundary averaged transport (\( \bar{u} \)), the along-boundary averaged baroclinic (vertically-varying) velocity \( \tilde{u} \), and the along-boundary perturbation velocity \( u' \). These are defined as

\[
\bar{u}(t) = \frac{u^{\text{MS,OS}}_L \cdot n}{L_{\text{MS,OS}}} \tag{6a} \\
\tilde{u}(z, t) = \left( \frac{u^{\text{MS,OS}}_L \cdot n}{L_{\text{MS,OS}}} \right)^y - \bar{u} \tag{6b} \\
u'(y, z, t) = \frac{u^{\text{MS,OS}}_L \cdot n - \bar{u}(t) - \tilde{u}(z, t)}{L_{\text{MS,OS}}} \tag{6c}
\]

where \( u_L \) is the model Lagrangian horizontal velocity (Eulerian plus Stokes drift derived from the wave model) and \( n \) is the normal to the MS/OS boundary. The time-average of the first component \( \langle \bar{u} \rangle = 0 \) by definition as the MS/OS boundary is a streamline of the depth- and time-averaged velocity. Overall, \( \bar{u} \) fluctuates between \(-0.01\) and \(0.02\) m s\(^{-1}\) (Fig. 2g), attributed to bathymetric induced transport due to the significant inverse correlation \((r = -0.4)\) between \( \bar{u} \) and \( V_{SB} \), consistent with mass conservation. The along-boundary averaged baroclinic velocity \( \tilde{u} \) (6b) has by definition \( \tilde{u}^z = 0 \). The third component \( u' \) (6c) is associated with short-scale (relative to \( L_{\text{MS,OS}} \)) variability and by definition \( u'^y = 0 \). This MS/OS boundary decomposition is also applied to the dye and density,

\[
D(y, z, t) = \bar{D}(t) + \tilde{D}(z, t) + D'(y, z, t) \tag{7a} \\
\rho(y, z, t) = \bar{\rho}(t) + \tilde{\rho}(z, t) + \rho'(y, z, t) \tag{7b}
\]

At the MS/OS boundary, the total cross-shore dye transport \( Q_x \) is

\[
Q_x(t) = \int_{0}^{L_{\text{MS,OS}}} \int_{-h}^{\eta} D(y, z, t) \, dz \, dy = L_{\text{MS,OS}} \bar{D}(y) \left( \frac{u^{\text{MS,OS}}_L \cdot n}{L_{\text{MS,OS}}} \right)^y, \tag{8}\]

which is comprised of 3 components \( Q_x = \bar{Q}_x + \tilde{Q}_x + Q'_x \) defined as

\[
\bar{Q}_x(t) = \bar{u}(t) \bar{D}(t) L_{\text{MS,OS}} \bar{h}^{\text{MS,OS}} \tag{9a} \\
\tilde{Q}_x(t) = \tilde{u}(z, t) \bar{D}(z, t) \bar{h}^{\text{MS,OS}} L_{\text{MS,OS}} \tag{9b} \\
Q'_x(t) = u'(y, z, t) D'(y, z, t) L_{\text{MS,OS}} \bar{h}^{\text{MS,OS}}. \tag{9c}\]
For the baroclinic and along-boundary fluctuating dye transports, corresponding MS/OS boundary exchange velocities are defined as

\[
\tilde{U}_{\text{ex}}(t) = \frac{\tilde{Q}_x(t)}{\bar{D}(t) L_y^{(\text{MS,OS})} h^{(\text{MS,OS})}}
\]

(10a)

\[
U'_{\text{ex}}(t) = \frac{Q'_x(t)}{\bar{D}(t) L_y^{(\text{MS,OS})} h^{(\text{MS,OS})}}
\]

(10b)

The \(\tilde{U}_{\text{ex}}\) is ascribed to baroclinic flow developed over a regional (>10 km) scale, while \(U'_{\text{ex}}\) is attributed to shorter scale processes with significant \(u'\) and \(D'\). Both \(\tilde{U}_{\text{ex}}\) and \(U'_{\text{ex}}\) are only estimated when dye is present at the MS/OS boundary \((\bar{D} > 10^{-6})\), which removes 7% of the data. Note, the \(\bar{Q}_x\) exchange velocity is similarly defined but just equals \(\bar{u}(t)\).

Within NS and the MS/OS transition zone, an along-region averaged along-region dye transport velocity is similarly defined as

\[
V^*(r)(y,t) = \frac{1}{L_y^{(r)}} \int_0^{L_y^{(r)}} \left[ \int_{x_1}^{x_2} \int_{-h}^{\eta} v_L D \, dz \, dx \right] \, dy
\]

(11)

where \((r)\) represents NS or MS/OS, \(x_1\) and \(x_2\) represent the offshore and onshore region locations \((e.g., \text{for NS}, (x_1, x_2) = (-L_x^{(\text{NS})}, 0))\), and for MS/OS, \(x_1\) and \(x_2\) represent the dashed lines bounding 500 m on either side of the MS/OS boundary in Fig. 1b), and the Lagrangian alongshore velocity is \(v_L\). We note that dye mass balances within control volumes close, confirming the dye and dye transport estimates. To average over the tidal and higher frequency variability, the quantities \(\bar{D}, \bar{Q}_x, V^*, \tilde{U}_{\text{ex}}\) and \(U'_{\text{ex}}\) are subtidally filtered.

### 3. Results: Spatio-temporal dye variability

**a. Example of an offshore dye transport event**

Upon Pt. Bandera shoreline release at concentration \(D = 1\), dye is advected at a range of spatio-temporal scales spanning surfzone and shelf. An 18-h realization of dye \(D\), density perturbation \(\sigma'_t\) and currents is presented to show the spatio-temporal evolution of an offshore dye transport event (Fig. 3). Density perturbation \(\sigma'_t\) has the spatial mean removed and \(\sigma_t = \rho - 1000 \, \text{kg m}^{-3}\). Event winds and wind stresses were weak (Fig. 2c) with average wind onshore at \(2 \, \text{m s}^{-1}\) and a \(\pm 1 \, \text{m s}^{-1}\) diurnal rotating seabreeze. At the event start, southerly incident waves (red shading
in Fig. 2e) have just arrived driving northward NS dye transport (Figs. 3a1–4). Dye concentration is low \( (D < 10^{-4}) \) on the northern shelf and within SDB (Figs. 3a1–4). An alongshore density gradient is present and the shelf surface currents are primarily northward (Figs. 3b1–4).

At the first time step (7 Aug 14:00, Fig. 3a1), surface \( D \) is advected northward. A high concentration \( (D > 10^{-4}) \) and meandering dye patch extends seaward and obliquely crosses the MS/OS boundary with width (where \( D > 10^{-4} \)) of 3.8 km and peak \( D = 2.7 \times 10^{-3} \). At the dye offshore leading edge, the offshore current is 0.1 m s\(^{-1}\). The surface density perturbation has additional small scale variability (Fig. 3b1). Along the cross-shore transect (green line in Fig. 3a1), dye is concentrated within upper 5-m layer above the thermocline \( T = 19^\circ C \) (Fig. 3c1). The cross-shore current is relatively weak (magnitude < 0.05 m s\(^{-1}\), Fig. 3d1). Six hours later (7 Aug 20:00, Fig. 3a2), the surface dye patch has been advected farther northward and elongated into a filament with MS/OS boundary width of 580 m at high peak concentration \( D = 2.4 \times 10^{-4} \). At the dye offshore leading edge, the offshore current is 0.07 m s\(^{-1}\). The elongation is due to a positive \( \partial u / \partial x \) associated with a negative \( \partial v / \partial y \) (not shown), which also enhances the alongshore density gradient at the MS/OS boundary (Fig. 3b2). At the cross-shore transect, the surface layer onshore current strengthens (reaching 0.2 m s\(^{-1}\), Fig. 3d2), leading to near-surface onshore dye transport. As a result, south of the filament, surface \( D \) is completely contained within the NS (Fig. 3a2). Subsurface, the \( T = 19^\circ C \) isotherm and dye layer deepen to \( z = -14 \) m within 1 km from shore mostly within the NS (see the vertical dye contour \( D = 10^{-4} \) in Fig. 3c2).

Twelve hours later (8 Aug 02:00, Fig. 3a3), the dye filament has been advected farther north orienting more cross-shore. Seaward of the MS/OS boundary, the filament is advected offshore by the surface currents at 0.2 m s\(^{-1}\) (Fig. 3b3). At the MS/OS boundary, the dye filament has a width of 1.3 km with max \( D = 1.4 \times 10^{-4} \). South of the filament, surface dye is almost completely contained within the NS (Fig. 3a3). At the cross-shore transect, the onshore (offshore) current within the surface (bottom) layer is well developed (reaching 0.1 m s\(^{-1}\) at surface, Fig. 3d3). Both the 20 \( ^\circ C \) isotherm (Fig. 3c3) and 23.6 kg m\(^{-3}\) isopycnal (Fig. 3d3) are tilted down toward shore, and the near-bed dye is advected offshore to \( z = -18 \) m, but remains within 1.75 km of shore. Eighteen hours later (8 Aug 08:00), the dye filament decays (Figs. 3a4,b4). Onshore of the MS/OS boundary and south of the strong alongshore density gradient, surface dye is advected offshore extending the \( D = 10^{-4} \) contour onto the MS/OS boundary, as surface and bottom cross-shore currents reverse (Figs. 3c4,d4). Sub-surface, the isotherms and isopycnals flatten and the near
bottom dye is advected back onshore. The short alongshore scales of this offshore dye transport event suggest that submesoscale flows are responsible for the offshore dye transport, although event winds were weak.

\[ \text{Fig. 4} \]

\[ \text{Fig. 5} \]

\[ \text{Fig. 6} \]

\[ b. \text{ } Dye \text{ and density statistics} \]

The spatial variability of temperature $T$, salinity $S$, density anomaly $\sigma_t$ and dye statistics is investigated next (Fig. 4). For depth $< 25$ m, the time-mean temperature $\langle T \rangle$ is elevated on the northern shelf and SDB by $\approx 0.5^\circ$C relative to the southern shelf near PB (Fig. 4a1). This alongshore $\langle T \rangle$ signal is also seen in the parent LV3 results (not shown here), indicating that it is not due to the temperature of the LV4 freshwater discharge. The largest temperature standard deviation $\text{std}(T)$ ($> 1.4^\circ$C) occurs in the nearshore ($h < 10$ m, Fig. 4b1), due to stronger diurnal warming and cooling in shallow water, without a clear alongshore gradient. Relatively low $\text{std}(S)$ and high $\text{std}(\sigma_t)$ occur near the three freshwater sources (Fig. 4a2, b2). The shelf $\langle S \rangle$ also has a north-south gradient, fresher to the north (Fig. 4a2), resulting in an alongshelf gradient of $\langle \sigma_t \rangle$ (Fig. 4a3) with northern $\langle \sigma_t \rangle$ lower by $0.2 \text{ kg m}^{-3}$. The $\text{std}(\sigma_t)$ ($> 0.3 \text{ kg m}^3$) is elevated near freshwater sources and in the nearshore ($h < 10$ m), implying combined contributions from $S$ and $T$. Along the MS/OS boundary, the $\langle \sigma_t \rangle$ gradient is $5.8 \times 10^{-6} \text{ kg m}^{-4}$ but the $\text{std}(\sigma_t)$ is largely alongshore uniform. The surface dye statistics $\langle D \rangle_-$ and $\langle D \rangle_+$ (defined in Section 2b, Fig. 4a4, b4) highlight the upper and lower ranges of typical dye, varying from $10^{-2}$ to $10^{-5}$. Both show northward dye transport and dilution away from PB, resembling a diffusive plume, with higher concentrations onshore, implying net offshore dye transport (Fig. 4b4). Onshore of the MS/OS boundary, $\langle D \rangle_+$ is about $100 \times$ that of $\langle D \rangle_-$.

Large values of the surface density horizontal gradient magnitude $|\nabla_H \rho|$ and $\text{rms}(\zeta/f) > 1$ indicate fronts and filaments and high Rossby numbers. Elevated values of both quantities are seen in the NS (Fig. 4a5, b5), attributed to surface wave breaking, bathymetric irregularities, freshwater inputs and surface heat fluxes. Within the NS $\text{rms}(\zeta/f) > 3$ suggesting an active submesoscale (Fig. 4b5). Both statistics are also elevated near the SDB mouth. Onshore of the MS/OS boundary, the TJRE shoal has elevated $\text{rms}(\nabla_H \rho)$ and $\text{rms}(\zeta/f)$, while for the rest of the domain, the distribution of both is largely alongshore uniform. At the MS/OS boundary, $\text{rms}(\nabla_H \rho) = 1.3(\pm 0.2) \times 10^{-4} \text{ kg m}^{-4}$ and $\text{rms}(\zeta/f) = 0.8(\pm 0.1)$ consistent with those of other
high resolution coastal simulations (e.g., Dauhajre et al. 2017; Dauhajre and McWilliams 2019), and indicates that submesoscale dynamics may be important in this region. Although the PB (1.5 m$^3$s$^{-1}$) and TJRE (Fig. 2a) freshwater input rates are typically small, salinity gradients contribute an average $\approx 30\%$ to the $\text{rms}(|\nabla_H \rho|)$, and are elevated during time of TJRE freshwater input (Fig. 2a).

The temporal and alongshore variability of surface density perturbation $\sigma'_t$ and dye $D$ on the MS/OS boundary are examined in Fig. 5. Density perturbation $\sigma'_t$ has the along-boundary mean removed at each time-step. The $\sigma'_t$ has a persistent negative south to north gradient (Fig. 5a), consistent with Fig. 4a3. Significant variability is present with times of alongshore uniform (e.g., 6–10 Oct, Fig. 5a) or step-function like $\sigma'_t$ (9 Aug, near 32.56N). Surface dye on the MS/OS boundary also has very strong variability (Fig. 5b). The northern end almost always has $D > 10^{-5}$, consistent with the mean dye fields (Figs. 4a4 and b4). The temporal $D$ variability is largely diurnal to subtidal. The along-boundary $D$ variability is often patchy with a few km or less length-scales, consistent with this offshore dye ejection event (Fig. 3). Dye can be present along much of the boundary (26 July), only in a limited region (9 Aug), or nearly absent ($D < 10^{-5}$, 10 Sept).

The logarithmic scale in Fig. 5b obscures the strong along-boundary dye gradients, and the dye patchiness suggests that the MS/OS boundary dye has relatively short alongshore length-scales. A MS/OS boundary alongshore surface dye length scale ($L_D^{(\text{MS,OS})}$) is defined as

$$L_D^{(\text{MS,OS})}(t) = \left[ \frac{(D(y,t) - \bar{D}(t))^2}{\left(\frac{\partial D(y,t)}{\partial y}\right)^2} \right]^{1/2} ,$$

which is evaluated at each time step when MS/OS boundary averaged dye is $> 10^{-6}$, and also subtidally filtered (Fig. 5c). The $L_D^{(\text{MS,OS})}$ varies from 0.3–4 km confirming that the MS/OS boundary $D$ is patchy, and is also consistent with the example event 0.58–3.8 km $D$ length-scales (Fig. 3). The subtidal $L_D^{(\text{MS,OS})}$ varies from 0.4 to 3 km. Length-scales for density $\rho$ and cross-boundary velocity $u$ are similarly estimated along the MS/OS boundary ($L_\rho$ and $L_u$) which also vary between 0.4–4 km, jointly suggesting the importance of submesoscale dynamics (e.g., McWilliams 2016).

The vertical structure of the time mean and std of $\bar{\rho}$, $\bar{D}$ and $\bar{u}$, and the square root of time-alongshore mean of squared $\rho'$, $D'$ and $u'$ are examined at the MS/OS boundary (Fig. 6). During the summer and early fall, the MS/OS boundary is strongly stratified (Fig. 6a1) with time-mean $\partial(\bar{\rho})/\partial z \approx 0.03$ kg m$^{-4}$ (or $N \approx 0.02$ s$^{-1}$) that is two orders of magnitude or larger than the along-
boundary stratification $\text{rms}(|\nabla H| \rho)$ (Fig. 4a5). Associated with the vertical stratification, time mean baroclinic dye $\langle \tilde{D} \rangle$ is surface intensified and decays exponentially downward with 6.3 m decay-scale (Fig. 6a2). The temporal std of $\tilde{\rho}$ and $\tilde{D}$ is elevated at the surface and reaches a minima at 10 m water depth (Figs. 6a1 and a2). The time-mean cross-boundary baroclinic velocity $\langle \tilde{u} \rangle$ has magnitude usually $< 0.01 \text{ m s}^{-1}$ and a three-layer profile with offshore directed flow at surface and bottom, and onshore flow in between (Fig. 6a3). The temporal std of the subtidally averaged $\tilde{u}$ varies between $0.01$ to $0.03 \text{ m s}^{-1}$, is elevated at surface (Fig. 6a3), and has a variability minimum near $z = -10$ m. The $\tilde{u}$ profile statistics are consistent with a combined Ekman and mode-1 baroclinic process. Note, the subtidal filter removes baroclinic tidal velocities, which will be discussed in Section 5a.

In addition, significant temporal and alongshore variability is evident in $\rho'$, $D'$, and $u'$ (Fig. 6b1–b3) through their time- and alongshore standard deviation (i.e., $\langle \rho'^2 \rangle^{1/2}$). The $\langle \rho'^2 \rangle^{1/2}$ is elevated in the upper 10 m near $0.07 \text{ kg m}^{-3}$ (Fig. 6b1), about 10% of the top to bottom $\langle \tilde{\rho} \rangle$ difference (Fig. 6a1), but is comparable to the $\tilde{\rho}$ temporal std suggesting significant alongshore density fluctuations, consistent with Fig. 5a. Similarly, $\langle \tilde{D}'^2 \rangle^{1/2}$ is near-surface elevated, decaying with a $\approx 10$ m vertical scale. The $\langle \tilde{D}'^2 \rangle^{1/2}$ is comparable to the $\tilde{D}$ std, consistent with Fig. 5b, and the $O(1)$ km inferred $L_{D}^{(\text{MS,OS})}$ (Fig. 5c). The $\langle \tilde{u}'^2 \rangle^{1/2}$ increases from $0.02 \text{ m s}^{-1}$ near-bed to $0.04 \text{ m s}^{-1}$ near-surface (Fig. 6b3), slightly larger than the temporal std of $\tilde{u}$ (Fig. 6a3). This decomposition makes clear that MS/OS boundary offshore dye transport can occur due to both alongshore-uniform baroclinic processes or alongshore variable processes.

c. Dye and dye transport temporal evolution

During the analysis period, seven individual south swell events (i.e., $S_{xy} > 0$, Fig. 2e) occur (yellow shading in Fig. 7 and Fig. 2e) each with distinct subtidal NS-averaged dye $\bar{D}^{(\text{NS})}$ peaks mostly $> 10^{-3}$ (Fig. 7a). In between south swell events, $\bar{D}^{(\text{NS})}$ drops by a factor of 10–100. The MS/OS boundary mean $\bar{D}$ (Eq. 7a) is significantly weaker ($\approx 10\%$) than $\bar{D}^{(\text{NS})}$ (Fig. 7a). The $\bar{D}$ peaks are qualitatively lagged relative to $\bar{D}^{(\text{NS})}$ peaks, indicating a transport pathway. The depth std of $\bar{D}$ ($\bar{D}^2$) $^{1/2}$ largely follows and is usually slightly above $\bar{D}$ (Fig. 7a), as dye is surface intensified. During peaks in offshore $\bar{D}$, the alongshore-depth std of $D'$ ($\bar{D}'^2$) $^{1/2}$ usually is just larger than both $\bar{D}$ and ($\bar{D}^2$) $^{1/2}$ indicating along-boundary dye patchiness. The 9/10–9/12 time period (cyan
rectangle in Fig. 7a) is notable because $\bar{D}^{(\text{NS})}$ is strongly elevated ($>10^{-3}$) for an extended duration yet the MS/OS boundary $\bar{D}$, $(\bar{D}^2)^{1/2}$, and $(\bar{D}^{(\text{NS})}^2)^{1/2}$ are all weak (mostly $<10^{-6}$), and will be discussed in more detail in Section 6c.

The depth- and along boundary mean cross MS/OS boundary dye transport $\bar{Q}_x$ (9a) switches sign frequently (Fig. 7b), has a time-mean of $-0.05$ dye m$^3$s$^{-1}$ (representing 19% of total transport) and std of 0.12 dye m$^3$s$^{-1}$, and is attributed to bathymetrically driven flows. The baroclinic dye transport $\tilde{Q}_x$ (9b) is the largest of the three dye transports and is primarily offshore (i.e., negative, Fig. 7b) with time-mean of $-0.15$ dye m$^3$s$^{-1}$ (57% of total transport) and std of 0.33 dye m$^3$s$^{-1}$ over a number of quasi intermittent events. The along-boundary perturbation transport $Q'_x$ (9c) is intermittent and fluctuates with a std of 0.17 dye m$^3$s$^{-1}$ relatively large relative to the time-mean of $-0.06$ dye m$^3$s$^{-1}$ (24% of total transport). Overall $Q'_x$ is the second largest term although occasionally it is bigger than $\tilde{Q}_x$ (e.g., 10 August, Fig. 7b). Nearly all of the net (time-averaged) offshore $Q_x$ occurs prior to 1 September, and for this period time-mean $\langle Q'_x \rangle = 0.11$ dye m$^3$s$^{-1}$ and $\langle \tilde{Q}_x \rangle = 0.13$ dye m$^3$s$^{-1}$ are similar. For the post 1 September time-period, $\langle Q'_x \rangle$ is negligible but $\langle \tilde{Q}_x \rangle$ is the same.

The baroclinic ($\tilde{U}_{ex}$) and alongshore perturbation ($U'_{ex}$) cross-shore dye exchange velocities (10) are largely negative (seaward directed, Fig. 7c), varying between 0.02 m s$^{-1}$ and $-0.07$ m s$^{-1}$. The time-mean $\langle \tilde{U}_{ex} \rangle$ and $\langle U'_{ex} \rangle$ both are $-0.01$ m s$^{-1}$ with std$\langle \tilde{U}_{ex} \rangle = 0.013$ m s$^{-1}$ slightly larger than std$\langle U'_{ex} \rangle = 0.010$ m s$^{-1}$. Thus, for the time-period when $\tilde{U}_{ex}$ and $U'_{ex}$ could be calculated (when $D > 10^{-6}$), both baroclinic processes and alongshore-perturbation processes have similar transport potential. Next, we explore the mechanisms driving alongshore and cross MS/OS boundary dye transports.

4. Alongshore dye transport mechanisms

The 500-m wide nearshore (NS) region (Fig. 1b) typically has a 100-m wide surfzone for the incident wave heights (Fig. 2d). Surfzone alongshore currents are driven by the breaking of obliquely incident waves (e.g., Longuet-Higgins 1970; Feddersen et al. 1998). The nearshore subtidal alongshore dye transport velocity $V_{\text{a}}(\text{NS})$ (Eq. 11) varies between $-0.1$ m s$^{-1}$ and 0.1 m s$^{-1}$ (Fig. 8) corresponding to 9–17 km per day. Consistent with surfzone-dominated transport, the subtidal $V_{\text{a}}(\text{NS})$ is largely positive (northward directed) during southerly wave events (yellow shading
in Fig. 8a) and is highly correlated with $S_{xy}/\rho_0$ with squared correlation of $r^2 = 0.63$ ($p < 0.05$), best fit slope of $\approx 1$, and near-zero intercept. This best fit slope is factor of two consistent with a simple surfzone alongshore wave forcing and linear bottom friction balance assuming a 100 m surfzone width and linear drag coefficient of $3 \times 10^{-3}$ m s$^{-1}$ (e.g., Lentz et al. 1999). In contrast, $V_{*}^{(NS)}$ was only weakly related ($r^2 = 0.14$, $p > 0.05$) to the alongshore wind stress. This demonstrates the primary role of obliquely incident surface gravity waves in driving alongshore NS dye transport over long (10’s of km) distances consistent with previously observations and modeling (Grant et al. 2005; Hally-Rosendahl et al. 2015; Hally-Rosendahl and Feddersen 2016; Feddersen et al. 2016). Other mechanisms such as wind driven currents in the outer NS, tidal currents, and shear dispersion can play a secondary role.

The 1-km wide MS/OS transition zone has a subtidal alongshore dye transport velocity $V_{*}^{(MS/OS)}$ (Eq. 11) that is significantly stronger than within the nearshore $V_{*}^{(NS)}$ (Fig. 8a). The subtidal $V_{*}^{(MS/OS)}$ is strongly correlated to the subtidal depth-averaged SB alongshelf velocity $V_{SB}$ (Fig. 2f) with $r^2 = 0.92$ ($p < 0.05$) and at 75% the magnitude of $V_{SB}$ (Fig. 8a), attributed to a reduced current (i.e., current shear) onshore of SB. Note, alongshore transport is larger than cross-shore transport as $V_{*}^{(MS,OS)}$ is larger than the three $U_{ex}$. The analysis period is characterized by weak to moderate alongshore wind forcing (Fig. 2c). Subtidal alongshore wind stress is uncorrelated ($r^2 = 0.05$, $p > 0.05$) with $V_{SB}$ and has magnitude $4\times$ too weak (using a linear friction of $3 \times 10^{-4}$ m s$^{-1}$ Lentz and Winant 1986) to explain $V_{SB}$, suggesting that other dynamics are driving the alongshelf current. Previous SCB studies (e.g., Hickey et al. 2003) have shown that during fall the barotropic APG is a significant driver of alongshelf flow even in 15 m depth (Lentz and Winant 1986). The subtidal barotropic APG is estimated from north-to-south in 15 m depth within the LV4 domain (S1 and S2 in Fig. 1b). The resulting barotropic APG largely varies between $\pm 2 \times 10^{-6}$ m s$^{-2}$, is mostly northward directed as the alongshelf flow and largely varies on fortnightly time-scales (Fig. 8b). The barotropic APG is reasonably correlated with $V_{SB}$ ($r^2 = 0.49$, $p < 0.05$) and has the correct magnitude for a frictionally balanced flow (using 15 m depth and linear friction of $3 \times 10^{-4}$ m s$^{-1}$). Thus the regional alongshore current which drives mid-shelf alongshore dye transport is primarily driven by the barotropic APG.
5. Cross-shore dye transport mechanisms at the MS/OS boundary

As baroclinic $\tilde{Q}_x$ (Eq. 9b) and the along-boundary perturbation $Q'_x$ (Eq. 9c) were the largest transport terms, here, we separately examine potential mechanisms for $\tilde{Q}_x$ and $Q'_x$, including BT and BC tides, wind-driven Ekman transport, barotropic alongshore pressure gradients, and submesoscale flows. Recall that $\tilde{Q}_x$ can be due to alongshore uniform but baroclinic flows such as Ekman transport or BC tides, while $Q'_x$ can be induced by alongshore variable flows over the 15-km long MS/OS boundary. To elucidate the hydrodynamic processes, we compare the dye exchange velocity components $\tilde{U}_{ex}$ (10a) and $U'_{ex}$ (10b) with relatively simple derived hydrodynamic velocities for each process.

a. Barotropic and baroclinic tidal cross-shore transport

One potential mechanism for the cross-shore dye transport across the MS/OS boundary could be barotropic (BT) and baroclinic (BC) tides. In the example offshore dye transport event (Fig. 3), the diurnal BC tide advects surface dye onshore and offshore and vertically, similar to the observed evolution of shoreline released dye near 32.59N during the analysis period (Grimes et al. 2020). If BT and BC tidal exchange mechanisms (see Section 1) were a primary driver of the cross-shore exchange, then the subtidal BC exchange velocity $\tilde{U}_{ex}$ would be less than and correlated with the slowing varying tidal velocity amplitude. Here, in both the semi-diurnal (SD) and diurnal (DU) bands, alongshore mean (and std) MS/OS tidal surface velocity amplitudes are estimated for BT ($\hat{U}_{SD}, \hat{U}_{DU}$) and BC ($\hat{u}_{SD}^{(1)}, \hat{u}_{DU}^{(1)}$) tides (Appendix). Both BC and BT tidal variability are largely along-boundary coherent (Fig. A1b,c), thus the tidal velocity amplitudes are then compared to the MS/OS boundary baroclinic ($\tilde{U}_{ex}$) exchange velocity. However, as some BT and BC tide alongshore phase variation is present, tidal velocity amplitudes are also compared to the alongshore perturbation ($U'_{ex}$) exchange velocity.

The relationship of barotropic tidal velocity amplitudes and $\tilde{U}_{ex}$ and $U'_{ex}$ are examined first (Fig. 9c). The alongshore averaged $\hat{U}_{SD}$ fluctuates fortnightly between 0.01–0.02 m s$^{-1}$ with very small std along the boundary, indicating that the single BT velocity amplitude is representative. However, $\hat{U}_{SD}$ is much weaker than and uncorrelated ($r^2 = 0.005$, $p > 0.05$, see Table 1) with $\tilde{U}_{ex}$ (Figs. 9 a,c). The alongshore mean $\hat{U}_{DU}$ is generally $< 0.01$ m s$^{-1}$ and poorly correlated ($r^2 = 0.02$, $p < 0.05$) with $\tilde{U}_{ex}$. Similarly, $U'_{ex}$ is uncorrelated with $\hat{U}_{SD}$, and not significantly
correlated with \( \hat{U}_{DU} \) \( (r^2 = 0.18, \ p > 0.05) \), albeit \( \hat{U}_{DU} \) is half the magnitude of \( U^t_{ex} \). Thus, BT tides cannot be the main driver of the \( \hat{Q}_x \) or \( Q^t_x \) cross- MS/OS boundary dye transports. For BC tides, the surface DU BC tidal amplitude \( \hat{u}^{(i)}_{DU} \) is generally larger than the surface SD amplitude \( \hat{u}^{(i)}_{SD} \) (Fig. 9d), similar to previous observations (e.g., Kim et al. 2011; Johnston and Rudnick 2015) and modeling (e.g., Kumar et al. 2015) in the SCB. The \( \hat{u}^{(i)}_{SD} \) is smaller than and uncorrelated \( (r^2 = 0.03, \ p > 0.05) \) with \( \hat{U}_{ex} \) (Fig. 9a,d). The alongshore averaged \( \hat{u}^{(i)}_{DU} \) is comparable in magnitude (reaches 0.15 m s\(^{-1}\)) to \( \hat{U}_{ex} \) (Fig. 9a,d), but is uncorrelated \( (r^2 = 0.007, \ p > 0.05) \). Similarly, the alongshore perturbation \( \hat{U}^t_{ex} \) is uncorrelated with \( \hat{u}^{(i)}_{SD} \) and \( \hat{u}^{(i)}_{DU} \) (see Table 1). Thus, BC tides also cannot be the main driver of the \( \hat{Q}_x \) or \( Q^t_x \) cross- MS/OS boundary dye transports.

### b. Wind-driven Ekman cross-shore transport

Wind-driven Ekman transport is a potential mechanism for offshore dye transport. Here, wind-driven Ekman surface velocity at the MS/OS boundary is estimated following Ekman (1905) and compared with the dye exchange velocity \( \hat{U}_{ex} \). Conceptually, Ekman transport is considered an alongshore uniform and baroclinic process. Thus, if the offshore dye transport \( \hat{Q}_x \) were due to Ekman transport, surface Ekman velocities should be of similar magnitude and correlated to \( \hat{U}_{ex} \).

For a steady, alongshore-uniform shelf with no alongshelf pressure gradients, the shelf velocity has Ekman component (balancing friction) and geostrophic component balancing the cross-shelf pressure gradient required to make the depth-averaged cross-shore velocity zero (Ekman 1905).

For constant depth \( h \), steady conditions, a no slip seafloor boundary condition, no stratification, and a constant eddy viscosity \( A_v \), Ekman’s analytic solution is used to estimate the (cross and along mean MS/OS boundary) velocity \((U_{ek}(z), V_{ek}(z))\) (following Estrade et al. 2008)

\[
U_{ek}(z) + iV_{ek}(z) = (1 - i)\frac{\tau_x + i\tau_y}{\rho_0\sqrt{2fA_v}} \frac{\sinh(m[z + h])}{\cosh(mh)} - \frac{iV_g \cosh(mz)}{\cosh(mh)} \tag{13}
\]

where \( i = \sqrt{-1}, (\tau_x, \tau_y) \) are the (subtidal) wind stress components (estimated from SB), \( m = (1 + i)(f/2A_v)^{1/2} \), and \( V_g \) is the alongshelf geostrophic component obtained from the condition that the depth integrated cross-shore transport is zero. A constant \( A_v = 2.5 \times 10^{-3} \text{ m}^2\text{s}^{-1} \) is used based on the depth- and time-averaged modeled eddy viscosity at SB, a value consistent with Suanda et al. (2017). The Ekman depth \((2 \times A_v/f)^{1/2} = 8 \text{ m} \) is consistent with the \( z \approx 10 \text{ m} \) location of minimum \( \hat{u} \) and \( \hat{D} \) variability (Fig. 6a2,a3). Neglected transient effects in the Ekman velocity (13) are weak as subtidal winds vary on synoptic time-scales. With the predominant southward
wind (Fig. 2c), surface $U_{ek}$ is primarily negative (Fig. 9b). A least squares fit between $U_{ek}$ and $\bar{U}_{ex}$ yields a slope of 0.72 with significant $r^2 = 0.36$ ($p < 0.05$). The correlation is maximum at zero time lag between $U_{ek}$ and $\bar{U}_{ex}$. This indicates that Ekman transport is a principal driver for the baroclinic cross-MS/OS-boundary transport $\tilde{Q}_x$. Note, as expected $U_{ek}$ is uncorrelated with the $U'_{ex}$ ($r^2 = 0.01$, $p > 0.05$).

The time-mean $\langle \tilde{u}(z) \rangle$ has a three-layer profile (Fig 6a3), however $U_{ek}$ (13) has a two-layer profile. This difference together with the moderate $r^2$ between $U_{ek}$ and $\tilde{U}_{ex}$ may result from the assumptions built into (13) or from other processes (e.g., advection). We note that the barotropic APG is mostly northward directed (Fig. 8b) which would induce near-bed offshore Ekman transport and onshore return flow in the remaining water column (e.g., Lentz 2008). Thus, APG driven near-surface flow is of the opposite sign to $\tilde{U}_{ex}$ and cannot drive near-surface offshore tracer transport here.

c. Submesoscale-flow induced cross-shore transport

The simulation snapshots (Fig. 3) show offshore propagating cross-shore elongated dye structures with a width of 0.6 km to 3.8 km. In general, the MS/OS boundary dye is patchy with subtidal dye alongshelf length-scales $L_{D}^{(MS, OS)}$ varying from 0.5 km to 3 km (Fig. 5b,c), scales consistent with the coastal submesoscale (e.g., Dauhajre et al. 2017). Alongshelf surface density gradients are also consistently present at a variety of scales (Fig. 5a). The along-boundary perturbation dye transport $Q'_x$ is a significant component of the total dye transport (Fig. 7b), particularly prior to 1 Sept. Here, we examine the role of submesoscale flows in driving along-boundary perturbation $Q'_x$ via relationships between $U'_{ex}$ (10b), the surface alongshelf dye length-scale $L_D$ (12) and the MS/OS boundary rms surface alongshelf density gradient $\text{rms}(\frac{\partial \rho}{\partial y})^{(MS, OS)}$.

The subtidal exchange velocity $U'_{ex}$ is more negative for smaller $L_{D}^{(MS, OS)}$ (Fig. 10) with binned-mean squared correlation of $r^2 = 0.32$ ($p < 0.05$). On average $U'_{ex}$ is 2× larger for $L_{D}^{(MS, OS)} < 0.9$ km than for $L_{D}^{(MS, OS)} > 1.2$ km. The subtidal cross-boundary velocity length-scale $L_u^{(MS, OS)}$ varies between 0.4–2 km and $U'_{ex}$ is more negative for smaller $L_u^{(MS, OS)}$ (not shown). Overall, the stronger offshore $U'_{ex}$ linked to smaller $L_{D}^{(MS, OS)}$ and $L_u^{(MS, OS)}$ suggests that the perturbation offshore dye transport $Q'_x$ is largely due to relatively short (< 2 km) length-scales associated with submesoscale flows.
An along-boundary density gradient could induce a cross MS/OS boundary (i.e., along-front) flow, and thus $U'_{ex}$, through geostrophic adjustment. As the density is time-dependent (Fig. 5a), such cross MS/OS boundary flow must adjust and $U'_{ex}$ would be elevated and time-lagged for stronger $\text{rms}(\partial \rho / \partial y)^{\text{(MS,OS)}}$. The time-lagged squared correlation $r^2$ between $\text{rms}(\partial \rho / \partial y)^{\text{(MS,OS)}}$ (Fig. 11a) has a maximum $r^2 = 0.19 \ (p > 0.05)$ when $\text{rms}(\partial \rho / \partial y)^{\text{(MS,OS)}}$ leads $U'_{ex}$ by 0.22 inertial periods (5 h). After adjusting for this time lag, $U'_{ex}$ is consistently more negative for larger $\text{rms}(\partial \rho / \partial y)^{\text{(MS,OS)}}$ (Fig. 11b), with binned mean $r^2 = 0.51 \ (p < 0.05)$, particularly for $\text{rms}(\partial \rho / \partial y)^{\text{(MS,OS)}} > 0.5 \times 10^{-4} \ \text{kg m}^{-4}$. Using a scaled-thermal wind relationship and assuming depth-uniform along-boundary density gradients (e.g., McWilliams 2016), a rms geostrophic cross-boundary velocity $\text{rms}(U_g)$ can be written as

$$\text{rms}(U_g)^{\text{(MS,OS)}} = \left( \frac{gh}{\rho_0 f} \right) \text{rms}(\frac{\partial \rho}{\partial y})^{\text{(MS,OS)}}.$$  

Here, the $\langle \rho' \rho'' \rangle^{1/2}$ statistics vary quasi-linearly with $z$ (Fig. 6b1) setting an equivalent depth of $h/2$ in (14) where the MS/OS boundary mean depth is $h = 25.0 \ \text{m}$. With this, a subtidal $\text{rms}(\partial \rho / \partial y)^{\text{(MS,OS)}} = 0.5 \times 10^{-4} \ \text{kg m}^{-4}$ yields a $\text{rms}(U_g)^{\text{(MS,OS)}} = 0.07 \ \text{m s}^{-1}$ a factor 7× larger than $U'_{ex}$, consistent with this process driving exchange. This indicates that when strong density gradients associated with $O(1 \ \text{km})$ length-scales are oriented alongshelf, cross-shore flows are induced with a time-lag that transport dye offshore at these submesoscale lengths (Fig. 10). A model that does not adequately resolve these submesoscale flows will underestimate offshore tracer transport.

6. Discussion

a. Potential mechanism for $\text{rms}$ alongshore density gradient generation

Several mechanisms have been posited for the generation of open-ocean submesoscale variability such as mixed layer instability (e.g., Boccaletti et al. 2007), turbulent thermal wind balance (e.g., McWilliams et al. 2015), and deformation flow induced frontogenesis (e.g., Hoskins 1982). The presence of a shoreline boundary and shallow depths adds additional complexity. Here, we examine the role of an alongshore surface deformation flow in enhancing the existing mean alongshore density gradient potentially leading to the enhanced $\text{rms}(\partial \rho / \partial y)^{\text{(MS,OS)}}$. Detailed diagnosis
of the submesoscale variability and dynamics will occur elsewhere.

Density and alongshelf current statistics are time-averaged and cross-shore averaged within the MS/OS transition zone. The time-averaged and cross-shore averaged surface density, $\bar{\rho}$, has a quasi linear time-mean alongshelf density gradient (Fig. 12a), consistent with the mean density distribution (Fig. 4a3). The average alongshelf density gradient $\partial (\bar{\rho})/\partial y = -6 \times 10^{-6}$ kg m$^{-4}$ is weaker by a factor 5-30× than $\text{rms}(\partial \rho/\partial y)$ (MS,OS) (Fig. 11b). During the analysis period, the subtidal $V_{SB}$ is mostly northward (Fig. 2f). The surface alongshelf velocity is first cross-shore averaged within MS/OS transition zone and then time-averaged when $V_{SB} > 0$ yielding $\bar{v}(>0)(y)$, which has a consistent negative alongshelf gradient (Fig. 12b), indicating alongshelf convergence, likely due to the regional bathymetry. A linear best-fit yields $\partial (\bar{v}(>0))/\partial y = -3.8 \times 10^{-6}$ s$^{-1}$, 2-5× larger than the normal strain rate of mesoscale eddies (e.g., Chaigneau et al. 2008). If this northward convergent flow was responsible for strengthening $\text{rms}(\partial \rho/\partial y)$ (MS,OS), then a stronger $\text{rms}(\partial \rho/\partial y)$ (MS,OS) with increasing $V_{SB}$ would be expected. Indeed, the subtidal $\text{rms}(\partial \rho/\partial y)$ (MS,OS) is consistently enhanced for stronger northward $V_{SB}$ (Fig. 13) with $r^2 = 0.49 \ (p < 0.05)$ and binned-mean $r^2 = 0.88 \ (p < 0.05)$. This fit does not change if only times when $U_{ex}'$ could be calculated (dashed line in Fig. 7a) are used in the fit. This indicates a linkage between the two processes and supports the concept that an alongshelf convergent flow is promoting generation of $\text{rms}$ alongshelf density gradients.

b. Role of other mechanisms in offshore dye transport

Although wind-driven Ekman transport and along-front submesoscale flows were diagnosed as principal drivers of MS/OS boundary offshore tracer transport, the region is complex and other mechanisms may play a role. The stratification and circulation on subtidal time-scales can be modified by BT (e.g., Ganju et al. 2011) and BC (Suanda et al. 2017) tides. Shelf BC tides enhanced 3D and 2D horizontal dispersion relative to simulations without BC tides (Suanda et al. 2018). Although DU BC tides did not principally drive subtidal offshore dye transport through a tidal exchange mechanism, BC tides could be similarly enhancing offshore transport relative to a no BC tide simulation (not performed). The TJRE shoal and large-scale bathymetry (coastline curvature, SDB entrance, and Pt. Loma) could also have a secondary effect on the MS/OS offshore dye transport. For example, enhanced $\text{rms}(\zeta/f)$ (well above 1) and $|\nabla_H \rho|$ variability at both the SDB
entrance and the TJRE shoal (Fig. 4a5,b5) suggests strong local vorticity and buoyancy gradient generation. The surfzone also has strongly elevated vorticity and $|\nabla H \rho|$ variability relative to the MS/OS transition zone (Fig. 4). Although bathymetric rip currents are present here, transient rip current (TRC) forcing is not included in this model. However, TRCs also drive further enhanced vorticity (Johnson and Pattiaratchi 2006; Suanda and Feddersen 2015) and buoyancy gradient (Kumar and Feddersen 2017a,b) variability on alongshore length-scales of 50–500 m (Hally-Rosendahl et al. 2014, 2015; Kumar and Feddersen 2017b). As the NS and regions farther offshore are material transport linked (as evidenced by dye), offshore transport of NS or TJRE shoal vorticity and $|\nabla H \rho|$ may seed submesoscale variability on the inner-shelf and farther offshore, although of course neither is a conserved passive tracer. Although relatively weak, the fresh water sources at TJRE, Pt. Bandera, and within SDB could be an additional density gradient source.

Lastly, we examine the role of horizontal mixing in potentially inhibiting submesoscale variability generation. A horizontal eddy viscosity of $\nu_h = 0.5 \text{ m}^2 \text{s}^{-1}$, 1 km length-scale, and 0.1 m s$^{-1}$ velocity scale give a horizontal Reynolds number of 200, indicating apriori weak horizontal mixing. Surface momentum balance terms calculated at the MS/OS boundary have rms horizontal mixing at $\approx 17 \times$ and $\approx 23 \times$ weaker than the vertical mixing and nonlinear advective terms, respectively. Thus, the horizontal mixing has a minor effect on submesoscale variability. A similar conclusion was drawn for turbulent-thermal wind filament frontogenesis from simulations with a similar grid resolution (12.5 m versus a mean of 20-30 m within the MS/OS transition zone) using both $\nu_h = 0.5 \text{ m}^2 \text{s}^{-1}$ and $\nu_h = 0 \text{ m}^2 \text{s}^{-1}$ (McWilliams et al. 2015).

c. Relative roles of transport terms and key parameters with implications for coastal water quality

For cross-MS/OS boundary dye transport to be non-zero, PB shoreline released dye had to be present at the MS/OS boundary, requiring first northward NS transport driven by moderate waves incident from the south ($S_{xy} > 0$, Fig. 2e). The baroclinic cross-MS/OS boundary transport $\tilde{Q}_x$ is clearly linked to the wind-driven Ekman transport. Although the Ekman velocities were relatively small (Fig. 6a3), they were sustained with surface enhanced dye resulting in significant MS/OS-boundary dye transport with exchange velocity $\tilde{U}_{ex}$ magnitude similar to the Ekman velocity. The along-boundary perturbation transport $Q'_x$ (9c) is linked to increased boundary $\text{rms} (\partial \rho / \partial y)^{\text{MS,OS}}$ through along-front geostrophic flow. Although the submesoscale velocities (Fig. 6a2) are as large...
as the $\bar{u}$ velocities, because the $u'$ flows fluctuate onshore and offshore, significant recirculation is likely present and the resulting MS/OS-boundary $U'_{ex}$ is substantially weaker than the rms velocities (Eq. 14 and Fig. 11b). For the regional geography south of Pt. Loma, the $\text{rms}(\partial \rho/\partial y)_{(MS,OS)}$ is enhanced during northward convergent mean flow, primarily APG driven (Fig. 8), allowing diagnosis of $\text{rms}(\partial \rho/\partial y)_{(MS,OS)}$ from $V_{SB}$ or the APG. Thus, for a shoreline released tracer, the key parameters influencing cross MS/OS boundary transport are $S_{xy}$, alongshelf winds, and $V_{SB}$ (or APG). Other headland bounded regions may be similar.

During the analysis period, $S_{xy}/\rho_0$ is mostly positive (Fig. 2e) and $V_{SB}$ is largely northward with only a few short times of southward flow (Fig. 2f). The winds are mostly upwelling favorable, with only a few cases of sustained downwelling favorable conditions (9/10-9/12 and 10/4-10/6, Fig. 2c). The 10/4–10/6 downwelling winds occur during negative to weak positive $S_{xy}$, and thus relatively little dye is present in both the NS and at the MS/OS boundary (Fig. 7a). The 9/10–9/12 downwelling wind conditions are interesting because $S_{xy}$ was strongly positive leading to strongly elevated $\bar{D}^{(NS)} > 10^{-3}$ (Fig. 7a) and shelf flow was also strongly northward ($V_{SB} > 0.2 \text{ m s}^{-1}$, Fig. 2f). Yet, this time had the weakest MS/OS boundary dye, mostly $< 10^{-6}$ (Fig. 7a), and exchange velocities could not be calculated.

Here, we examine this 9/10–9/12 event with two dye and velocity snapshots spanning 57 h (Fig. 14). At the event-start (9/10 01:00), the shoreline released dye streams north remaining mostly within the 500-m wide NS, before the flow separates near 32.63N, bends around Pt. Loma, and continues north (Fig. 14a). Toward the end of the event (9/12 10:00), dye is still concentrated in the 500-m wide NS, but there are $\approx 1$ km alongshore scale plume structures extending 1–3 km offshore, and, farther north, the dye plume wraps around Pt. Loma (Fig. 14b). In both cases, the $D = 10^{-4}$ contour is always at $> 2$ km from the MS/OS boundary. For the entire event duration, MS/OS boundary never had $D \geq 10^{-5}$ (Fig. 5b, cyan rectangle).

During this time period, winds were only moderately northward (Fig. 2c), yet the MS/OS-boundary surface $\bar{u} \approx 0.05 \text{ m s}^{-1}$ onshore over many days, the strongest of the analysis period (not shown). Although APG driven cross-shelf flows did not induce offshore transport, one possibility is that very strong northward flows, drove sustained onshore surface flows balancing bottom Ekman offshore transport. In conclusion, both SZ and shelf processes influence shoreline concentrations for shoreline released tracers. Simultaneously occurring northward surfzone currents, downwelling winds, and northward forcing APG, as for 9/10–9/12 is the worst-case scenario for regional beach...
water quality, as very little tracer is transported offshore of the NS, and shoreline concentrations are not diluted.

7. Summary

Here, we investigate the processes transporting a shoreline released dye representing untreated wastewater in the San Diego, Tijuana region that has a curving shoreline, an estuary, a bay, and a headland. A high resolution wave-current coupled model is used resolving the surfzone and receiving realistic air-sea forcing, tides, waves, and offshore boundary conditions inherited from a larger-scale data assimilated model. Model dye is shoreline released 10 km south of the US/Mexico border representing untreated wastewater and analyzed from summer to mid fall with largely southerly incident waves, mostly northward alongshelf flow, strong shelf stratification, and moderate wind forcing. Analysis focuses primarily on the tracer transport across the mid-(MS) to outer-shelf (OS) boundary (≈ 25 m depth) chosen as a streamline of the time-mean and depth-averaged velocity.

Within 500 m of the shoreline, alongshore tracer transport is primarily driven by obliquely incident wave breaking. At the MS/OS boundary, alongshore density gradients are persistent and dye is surface enhanced and time- and alongshore patchy with length-scales from 0.3–4 km. Significant vertical (baroclinic) and along-boundary density and velocity variability is present. The cross-MS/OS boundary dye transport has significant baroclinic and along-boundary perturbation components from which baroclinic and along-boundary perturbation dye exchange velocities are estimated. Barotropic tides and semidiurnal baroclinic tides cannot explain these two exchange velocity components. The baroclinic exchange velocity is significantly correlated and has similar magnitude to a simply Ekman transport velocity, indicating Ekman transport is driving the baroclinic cross-MS/OS boundary tracer transport. The perturbation exchange velocity is elevated for smaller (< 1 km) alongshore dye length-scales and stronger root-mean-square (rms) alongshore density gradients $\partial \rho / \partial y$, indicating geostrophic along-frontal submesoscale flows induce the along-MS/OS boundary perturbation transport. During periods of northward flows, the surface alongshore current is convergent with a relatively strong mean deformation rate. Stronger northward flows are linked to elevated $\text{rms}(\partial \rho / \partial y)^{(\text{MS,OS})}$, potentially generated by deformation frontogenesis. A model that does not adequately resolve these submesoscale flows will underesti-
mate offshore tracer transport. Both surfzone and shelf processes influence offshore transport for shoreline released tracers, and the key parameters governing cross MS/OS boundary dye transport are the incident $S_{xy}$, the alongshelf winds, and the APG-driven alongshelf current. When the co-occurrence of these parameters strongly inhibits offshore transport, shoreline concentrations are not effectively diluted leading to poor water quality.

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APPENDIX A Barotropic and baroclinic tide surface velocity amplitude estimation

Here, the MS/OS boundary barotropic and surface baroclinic tidal velocities estimation method is described. The cross-shore velocity is first decomposed into barotropic (BT, depth-averaged) and baroclinic (BC) components along the boundary. These two components are then band-pass filtered to obtain the semidiurnal (SD, $16^{-1}$ to $10^{-1}$ cph) and diurnal (DU, $33^{-1}$ to $16^{-1}$ cph) band components. Here, the SD-band analysis is described. First, we calculate the bulk BT SD tidal velocity amplitude (envelope) ($U_{SD}$), assumed narrow-banded with form

$$U_{SD}(t, y) = \hat{U}_{SD}(\epsilon t, y) \cos(2\pi \omega_{SD} t + \theta_{SD}),$$

(A1)
where $\omega_{SD}$ is the SD frequency, $\hat{U}_{SD}$ is the SD velocity amplitude that varies on longer time-scale (denoted as $\epsilon t$), and $\theta_{SD}$ is a phase that will only vary slightly over the MS/OS boundary. As the BT tidal velocity is narrow-banded, the amplitude $\hat{U}_{SD}$ is estimated via Hilbert transform at each alongshore location. The alongshore mean and std are presented in Fig. 9c.

BC velocities vary with depth and have much shorter length-scales than the BT tidal velocities, leading to additional analysis. At each location $y_i$ along the MS/OS boundary, the SD baroclinic cross-shore current $u_{SD}(y_i, z, t)$ is decomposed into a vertical EOF such that

$$u_{SD}(y_i, z, t) = \sum_{n=1}^{N} I_{SD}(y_i, t) \Phi_{SD}(y_i, z), \quad (A2)$$

where $I_{SD}(t)$ and $\Phi_{SD}(z)$ are the EOF amplitude and vertical structure at $y_i$, and $N = 15$ is the total number of vertical levels. At all MS/OS boundary locations, the first ($n = 1$) EOF accounts for > 78% of the SD-band variance (> 92% of the DU-band variance). For both bands, the first vertical EOF ($\Phi_{SD}(z)$ and $\Phi_{DU}(z)$) is consistent with a first-mode baroclinic motions with mid-water column sign change and is nearly alongshore uniform on the MS/OS boundary (Fig. A1a). Thus, surface BC tidal cross-shore velocities can be reconstructed with a single EOF at all alongshore locations, i.e., for the SD-band surface velocity

$$u_{SD}^{(1)}(y, \eta, t) = I_{SD}^{(1)}(y, t) \Phi_{SD}^{(1)}(y, \eta).$$

The alongshore coherent variability of reconstructed surface SD cross-shore velocity $u_{SD}^{(1)}(y, \eta, t)$ (and also DU $u_{DU}^{(1)}(y, \eta, t)$) is further examined with a Hilbert EOF (CEOF) (e.g., Horel 1984; Merrifield and Guza 1990). A complex time series is generated according to

$$u_{SD}^{(1)}(y, t) = u_{SD}^{(1)}(y, t) + i\tilde{u}_{SD}^{(1)}(y, t) \quad (A3)$$

where $\tilde{u}_{SD}$ is the Hilbert transform of $u_{SD}$ and $i = \sqrt{-1}$. The variability of $u_{SD}^{(1)}(y, t)$ is then CEOF decomposed into

$$u_{SD}^{(1)}(y, t) = \sum_{n=1}^{M} B_{SD}^{(n)}(t) H_{SD}^{(n)}(y) \quad (A4)$$

where $M$ is the total number of MS/OS boundary grid points, $H_{SD}^{(n)}(y)$ is the complex eigenvector, and $B_{SD}^{(n)}(t)$ is the complex amplitude.

The alongshore first CEOF of the SD and DU band explains 56% and 95% of the alongshore variability, respectively. The magnitude of the SD $|H_{SD}^{(1)}(y)|$ is maximum near the center of the
OS/MS boundary, and is reduced about 50% at the northern and southern ends (Fig. A1b). The
DU $|H_{SD}^{(1)}(y)|$ is largely alongshore uniform (Fig. A1b). The SD along boundary phase is estimated as,

$$\theta_{SD}^{(1)}(y) = \text{atan} \left( \frac{\mathcal{I}(H_{SD}^{(1)}(y))}{\mathfrak{R}(H_{SD}^{(1)}(y))} \right), \quad \text{(A5)}$$

where $\mathcal{I}$ and $\mathfrak{R}$ are the imaginary and real operators, respectively. For the SD band, the phase
$\theta_{SD}^{(1)}(y)$ varies quasi-linearly by $\pi/2$ ($90^\circ$) along the 15-km boundary (Fig. A1c), suggesting southward propagation of the SD BC tide. For the DU band, the phase is near-zero for the southern half of the boundary, and varies $\pi/6$ ($30^\circ$) over the northern half (Fig. A1c), also indicating mostly southward propagation, consistent with the regional observations of southward DU-band propagation in 12–15 m depth (Grimes et al. 2020). Overall, the phase variations indicate that the SD and DU BC tides alongshelf scale is substantially larger than the 15 km length of the MS/OS boundary. The amplitude of the first EOF reconstructed SD and DU surface velocities are estimated as for the BT tidal velocity at each $y$ location resulting in surface $\hat{u}_{SD}^{(1)}(y, et)$ and $\hat{u}_{DU}^{(1)}(y, et)$. The alongshore mean and std are shown in Fig. 9d and described in Section 5a.
REFERENCES


Lerczak, J. A., M. Hendershoot, and C. Winant, 2001: Observations and modeling of coastal in-


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http://opg1.ucsd.edu/jklymak/WorkTools.html
Table 1. Squared correlation $r^2$ between the dye exchange velocity components and BT and BC semidiurnal and diurnal tidal velocity amplitudes as well as surface Ekman velocity $U_{ek}$. The values above 95% confidence level are highlighted in bold.

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Figure Captions

Fig. 1. (a) Bathymetry (color shading) of LV1 grid with outlines of the LV2 (yellow), LV3 (black) and LV4 (red) grids; (b) LV4 grid bathymetry and the delineation of the nearshore (NS), mid-shelf (MS) to outer-shelf (OS) boundary (solid magenta lines); (c) NS to OS bathymetry that is alongshore averaged following the NS domain. In panel b, the dashed magenta lines denote the 1-km wide MS/OS transition zone centered at the MS/OS boundary. The red dots denote freshwater sources Punta Bandera (PB), Tijuana River estuary (TJRE) and Sweetwater River within San Diego Bay (SDB). The yellow dots denote the South Bay Ocean outfall (SB) mooring site in 30-m depth and two selected sites (S1, S2) for current dynamics analysis (see text for details). The US/MX border and the headland Pt. Loma are also labeled.

Fig. 2. Time series of (a) freshwater discharge rate, \( Q_r \), at TJRE, (b) sea surface elevation \( \eta \) at SB, (c) wind velocity vectors \( U_w \) at SB, (d) significant wave height \( H_s \) at SB, (e) subtidally averaged off-diagonal radiation stress tensor \( S_{xy}/\rho_0 \) (positive is southerly incident waves) at SB, (f) subtidal depth-averaged alongshore current at SB \( V_{SB} \), and (g) subtidal depth- and along MS/OS-boundary averaged cross-boundary velocity \( \bar{u}(t) \) (6a). In panel e, the yellow shading indicates times of southerly incident waves. In all panels, the two vertical blue dashed lines delineate the analysis period. The small magenta rectangle corresponds to the time period shown in Fig. 3 and the cyan rectangle indicates the time-period shown in Fig. 14.

Fig. 3. Snapshots of an 18-h offshore dye transport event at (left to right) four times at 6 h interval: Surface distribution of (a) dye concentration \( D \) (color shading), (b) density perturbation \( \sigma'_t \) (color shading) and surface current velocity (vectors). Cross-shore and vertical profile of (c) \( D \) (color shading) and isotherms (line contour), (d) density anomaly \( \sigma_t \) (color shading and black contour) and cross-shore current velocity (vectors) along a chosen transect. The magenta curve outlines the NS and MS/OS boundary regions. The green line in panels a and b shows the transect location. The thick black contour in panels a and b and the cyan contour in panel c correspond to \( D = 10^{-4} \).

Fig. 4. Horizontal distribution of (left to right) temporal mean (top) and standard deviation (bottom) of surface \( T(\degree C) \) (a1 and b1), \( S \) (a2 and b2) and density anomaly \( \sigma_t(\text{kg m}^{-3}) \) (a3 and b3), typical high and low surface dye concentrations \( \langle D \rangle_+ \) and \( \langle D \rangle_- \) (a4 and b4), root-mean-square (rms) of horizontal surface density gradient \( \nabla_H \rho \text{kg m}^{-4} \) (a5) and normalized rms surface relative vorticity \( \text{rms}(\zeta)/f \) (b5). Black contours denote the isobaths \( h = [10 25 45] \text{ m} \). The magenta line outlines the NS to MS/OS boundary. The red dot denotes the PB source.
FIG. 5. Hovmöller diagram (time and alongshore distance) of surface (a) density anomaly perturbation (i.e., after removing the alongshore mean density at each time step) and (b) dye along the MS/OS boundary. In panels a and b, the black contour denotes $D = 10^{-4}$. (c) Time series of alongshore dye length scale $L_D$ along MS/OS boundary both hourly (black) and subtidally-filtered (blue). Gaps are when MS/OS boundary-averaged $D < 10^{-6}$. The small magenta rectangle indicates the time period shown in Fig. 3 and the cyan rectangle indicates the time-period shown in Fig. 14.

FIG. 6. MS/OS boundary statistics as a function of the vertical $z$: (top) Time mean (circles) and standard deviation (horizontal bars) of subtidally filtered baroclinic (a1) $\tilde{\rho}$, (a2) $\tilde{D}$, and (a3) $\tilde{u}$; (bottom) root- time-alongshore mean of squared along-boundary perturbation quantities (b1) $\langle \tilde{\rho}^2 \rangle^{1/2}$, (b2) $\langle \tilde{D}^2 \rangle^{1/2}$ and (b3) $\langle \tilde{u}^2 \rangle^{1/2}$.

FIG. 7. Time series of (a) NS volume-averaged dye ($\tilde{D}^{(NS)}$), Depth and along MS/OS-boundary averaged dye $\tilde{D}$ (7a), depth std of $\tilde{D}$ ($\langle \tilde{D}^2 \rangle^{1/2}$), and along-boundary and depth std of $D'$ ($\langle D'^2 \rangle^{1/2}$), (b) MS/OS boundary dye transport components $\bar{Q}_x$, $\tilde{Q}_x$ and $\tilde{Q}_x'$ (9), and (c) MS/OS boundary averaged cross-shore velocity $\bar{u}$, and baroclinic and along-boundary perturbation exchange velocities $\tilde{U}_ex$ and $U'_ex$ (10). The small magenta rectangle indicates the time period shown in Fig. 3 and the cyan rectangle indicates the time-period shown in Fig. 14.

FIG. 8. Time series of subtidal (a) alongshore dye transport velocity within NS ($V^{(NS)}_s$) and the MS/OS transition zone ($V^{(MS/OS)}_s$), as well as the depth-averaged alongshore current velocity at SB ($V^ SB$). (b) Time series of subtidal barotropic alongshore pressure gradient (normalized by density) between sites S1 and S2 (see Fig. 1b for locations). The yellow shading in panel a represents periods of positive $S_{xy}$.

FIG. 9. Time series of MS/OS boundary (a) baroclinic ($\tilde{U}_ex$) and along-boundary perturbation ($U'_ex$) cross-shore dye exchange velocities. (b) barotropic cross-shore velocity amplitude (Eq. A1) in the semidiurnal ($\tilde{U}^{(1)}_{SD}$) and diurnal ($\tilde{U}^{(1)}_{DU}$) band, and (c) surface baroclinic cross-shore velocity amplitude in the semidiurnal ($\tilde{U}^{(1)}_{SD}$) and diurnal ($\tilde{U}^{(1)}_{DU}$) band. (d) estimated surface Ekman transport velocity $U_{ek}$. In panels b and c, the shading represents the alongshore std.

FIG. 10. Scatterplot (gray) with binned-means (red) of MS/OS boundary exchange velocity component $U'_ex$ versus along-boundary dye length-scale $L_D^{(MS,OS)}$. Both values are subtidally filtered, gray points are shown only every 8 h for visual clarity, and the binned means have 120 h points each. The subtidal (and binned-mean) squared correlation is $r^2 = 0.06$ ($r^2 = 0.32$, $p < 0.05$).
FIG. 11. (a) Lagged correlation between $U'_{\text{ex}}$ and the alongshore rms alongshore density gradient $\text{rms}(\partial \rho / \partial y)^{(\text{MS,OS})}$ versus inertial-period normalized time-lag $\Delta t/(2\pi/f)$. Maximum correlation occurs when $\text{rms}(\partial \rho / \partial y)^{(\text{MS,OS})}$ leads $U'_{\text{ex}}^{(\text{MS,OS})}$ by 0.22 inertial periods (red circle) (b) Scatterplot (gray) with binned-means (red) of maximum $r^2$ time-lag adjusted $U'_{\text{ex}}$ versus $\text{rms}(\partial \rho / \partial y)^{(\text{MS,OS})}$. The subtidal (and binned-mean) square correlation is $r^2 = 0.19\ (r^2 = 0.51, p < 0.05)$. The dashed line in (b) denotes the MS/OS transition zone time-mean alongshore density gradient of $6 \times 10^{-6}$ kg m$^{-4}$.

FIG. 12. (a) The temporal mean (black curve) and std (shading) of surface density anomaly $(\overline{\sigma_x^2})$ cross-shore averaged within the MS/OS transition zone, (b) the temporal mean and std of surface alongshelf subtidal current velocity for when $V_{SB} > 0$ $(\overline{\bar{v}_x^2})$.

FIG. 13. The MS/OS boundary rms alongshore density gradient $\text{rms}(\partial \rho / \partial y)^{(\text{MS,OS})}$ versus the depth-averaged subtidal alongshore velocity at SB ($V_{SB}$). All values are subtidally filtered, gray points are shown only every 8 h, and the binned-means have 120 h points each. The subtidal (and binned-mean) squared correlations are $r^2 = 0.49\ (r^2 = 0.88)$. The horizontal dashed line is the MS/OS transition zone time-mean density gradient of $6 \times 10^{-6}$ kg m$^{-4}$.

FIG. 14. Two surface dye (color) and surface current velocity (arrows) snapshots during strong northward wave-driven flow and downwelling winds spanning 58 h: (a) 10-Sept 01:00 and (b) 12-Sept 10:00. Thin lines show bathymetry contours at $h = [10, 25, 45]$ m. The magenta curves outline the NS and MS/OS boundaries. The thick black line represents the $D = 10^{-4}$ contour. The red dot denotes the PB source.

FIG. A1. (a) Vertical profile of the first EOF of the SD and DU band cross-shore current velocity. The alongshelf variation on the MS/OS boundary of the (b) amplitude $(|H^{(1)}_{SD}|, |H^{(1)}_{DU}|)$ and (c) phase $(\theta^{(1)}_{SD}, \theta^{(1)}_{SD})$ of the first cEOF of $\hat{u}^{(1)}_{SD}$ and $\hat{u}^{(1)}_{DU}$, respectively.
FIG. 1. (a) Bathymetry (color shading) of LV1 grid with outlines of the LV2 (yellow), LV3 (black) and LV4 (red) grids; (b) LV4 grid bathymetry and the delineation of the nearshore (NS), mid-shelf (MS) to outer-shelf (OS) boundary (solid magenta lines); (c) NS to OS bathymetry that is alongshore averaged following the NS domain. In panel b, the dashed magenta lines denote the 1-km wide MS/OS transition zone centered at the MS/OS boundary. The red dots denote freshwater sources Punta Bandera (PB), Tijuana River estuary (TJRE) and Sweetwater River within San Diego Bay (SDB). The yellow dots denote the South Bay Ocean outfall (SB) mooring site in 30-m depth and two selected sites (S1, S2) for current dynamics analysis (see text for details). The US/MX border and the headland Pt. Loma are also labeled.
Fig. 2. Time series of (a) freshwater discharge rate, $Q_r$, at TJRE, (b) sea surface elevation $\eta$ at SB, (c) wind velocity vectors $U_w$ at SB, (d) significant wave height $H_s$ at SB, (e) subtidally averaged off-diagonal radiation stress tensor $S_{xy}/\rho_0$ (positive is southerly incident waves) at SB, (f) subtidal depth-averaged alongshore current at SB $V_{SB}$, and (g) subtidal depth- and along MS/OS-boundary averaged cross-boundary velocity $\bar{u}(t)$ (6a). In panel e, the yellow shading indicates times of southerly incident waves. In all panels, the two vertical blue dashed lines delineate the analysis period. The small magenta rectangle corresponds to the time period shown in Fig. 3 and the cyan rectangle indicates the time-period shown in Fig. 14.
Fig. 3. Snapshots of an 18-h offshore dye transport event at (left to right) four times at 6 h interval: Surface distribution of (a) dye concentration $D$ (color shading), (b) density perturbation $\sigma'_t$ (color shading) and surface current velocity (vectors). Cross-shore and vertical profile of (c) $D$ (color shading) and isotherms (line contour), (d) density anomaly $\sigma_t$ (color shading and black contour) and cross-shore current velocity (vectors) along a chosen transect. The magenta curve outlines the NS and MS/OS boundary regions. The green line in panels a and b shows the transect location. The thick black contour in panels a and b and the cyan contour in panel c correspond to $D = 10^{-4}$. 
Fig. 4. Horizontal distribution of (left to right) temporal mean (top) and standard deviation (bottom) of surface $T$ ($^\circ$C) (a1 and b1), $S$ (a2 and b2) and density anomaly $\sigma_i$ (kg m$^{-3}$) (a3 and b3), typical high and low surface dye concentrations $\langle D \rangle_-$ and $\langle D \rangle_+$ (a4 and b4), root-mean-square (rms) of horizontal surface density gradient $\nabla_H \rho$ kg m$^{-4}$ (a5) and normalized rms surface relative vorticity $\text{rms}(\zeta)/f$ (b5). Black contours denote the isobaths $h = [10~25~45]$ m. The magenta line outlines the NS to MS/OS boundary. The red dot denotes the PB source.
Fig. 5. Hovmöller diagram (time and alongshore distance) of surface (a) density anomaly perturbation (i.e., after removing the alongshore mean density at each time step) and (b) dye along the MS/OS boundary. In panels a and b, the black contour denotes $D = 10^{-4}$. (c) Time series of alongshore dye length scale $L_D$ along MS/OS boundary both hourly (black) and subtidally-filtered (blue). Gaps are when MS/OS boundary-averaged $D < 10^{-6}$. The small magenta rectangle indicates the time period shown in Fig. 3 and the cyan rectangle indicates the time-period shown in Fig. 14.
FIG. 6. MS/OS boundary statistics as a function of the vertical $z$: (top) Time mean (circles) and standard deviation (horizontal bars) of subtidally filtered baroclinic (a1) $\bar{\rho}$, (a2) $\bar{D}$, and (a3) $\bar{u}$; (bottom) root-time-longshore mean of squared along-boundary perturbation quantities (b1) $\langle (\rho')^2 \rangle^{1/2}$, (b2) $\langle (D')^2 \rangle^{1/2}$ and (b3) $\langle (u')^2 \rangle^{1/2}$.
FIG. 7. Time series of (a) NS volume-averaged dye ($\bar{D}^{(NS)}$), depth and along MS/OS-boundary averaged dye $\bar{D}$ (7a), depth std of $\bar{D}$ ($\langle \bar{D}^2 \rangle^{1/2}$), and along-boundary and depth std of $D'$ ($\langle D'^2 \rangle^{1/2}$), (b) MS/OS boundary dye transport components $\bar{Q}_x$, $\bar{Q}_x$, and $Q'_x$ (9), and (c) MS/OS boundary averaged cross-shore velocity $\bar{u}$, and baroclinic and along-boundary perturbation exchange velocities $\bar{U}_ex$ and $U'_ex$ (10). The small magenta rectangle indicates the time period shown in Fig. 3 and the cyan rectangle indicates the time-period shown in Fig. 14.
Fig. 8. Time series of subtidal (a) alongshore dye transport velocity within NS ($V_{(NS)}$) and the MS/OS transition zone ($V_{(MS/OS)}$), as well as the depth-averaged alongshore current velocity at SB ($V_{SB}$). (b) Time series of subtidal barotropic alongshore pressure gradient (normalized by density) between sites S1 and S2 (see Fig. 1b for locations). The yellow shading in panel a represents periods of positive $S_{xy}$. 
Fig. 9. Time series of MS/OS boundary (a) baroclinic ($\bar{U}_{ex}$) and along-boundary perturbation ($U'_{ex}$) cross-shore dye exchange velocities. (b) barotropic cross-shore velocity amplitude (Eq. A1) in the semidiurnal ($\hat{U}_{SD}^{(1)}$) and diurnal ($\hat{U}_{DU}^{(1)}$) band, and (c) surface baroclinic cross-shore velocity amplitude in the semidiurnal ($\hat{U}_{SD}^{(1)}$) and diurnal ($\hat{U}_{DU}^{(1)}$) band. (d) estimated surface Ekman transport velocity $U_{ek}$. In panels b and c, the shading represents the alongshore std.
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Fig. 11. (a) Lagged correlation between $U'_{ex}$ and the alongshore rms alongshore density gradient $\text{rms}(\partial \rho / \partial y)^{(MS,OS)}$ versus inertial-period normalized time-lag $\Delta t/(2\pi/f)$. Maximum correlation occurs when $\text{rms}(\partial \rho / \partial y)^{(MS,OS)}$ leads $U'_{ex}$ by 0.22 inertial periods (red circle) (b) Scatterplot (gray) with binned-means (red) of maximum $r^2$ time-lag adjusted $U'_{ex}$ versus $\text{rms}(\partial \rho / \partial y)^{(MS,OS)}$. The subtidal (and binned-mean) square correlation is $r^2 = 0.19$ ($r^2 = 0.51$, $p < 0.05$). The dashed line in (b) denotes the MS/OS transition zone time-mean alongshore density gradient of $6 \times 10^{-6}$ kg m$^{-4}$.
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Fig. 13. The MS/OS boundary rms alongshore density gradient $\text{rms}(\partial \rho / \partial y)_{\text{MS,OS}}$ versus the depth-averaged subtidal alongshore velocity at SB ($V_{SB}$). All values are subtidally filtered, gray points are shown only every 8 h, and the binned-means have 120 h points each. The subtidal (and binned-mean) squared correlations are $r^2 = 0.49$ ($r^2 = 0.88$). The horizontal dashed line is the MS/OS transition zone time-mean density gradient of $6 \times 10^{-6}$ kg m$^{-4}$. 
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