Nearshore Tracer Exchange by Transient Rip-Currents and Diurnal Surface Heat Flux Forcing.

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Key Points:

• Model runs diagnose the transient rip-current (TRC) and diurnal surface heat flux (SHF) induced cross-shore exchange in the nearshore.

• For Fall Southern CA conditions, SHF induced far weaker exchange than TRC or TRC+SHF, with similar TRC and SHF+TRC induced exchange.

• From exchange velocity definitions, the TRC+SHF exchange to 1000 m offshore is due to TRC-mixing induced mean overturning circulation.

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Abstract
Exchange across the surf-zone and inner-shelf affects coastal water quality and larval recruitment. Surf-zone generated transient rip-currents (TRC) exchange shoreline released tracers onto and across a stratified inner-shelf. Surface heat fluxes (SHF) modify inner-shelf stratification and surf-zone temperature, relative to the inner-shelf, inducing nearshore thermally driven exchange. The coupled effect of TRC and diurnal SHF forcing on cross-shore exchange is evaluated using idealized model surf-zone tracer releases with TRC-only, SHF-only, and combined SHF+TRC forcing. For conditions representing Fall in Southern California, the TRC mechanism dominates cross-shore exchange, relative to SHF, to $12L_{sz}$ offshore ($L_{sz} = 100$ m is the surf-zone width). Tracer and velocity derived estimates of exchange velocity indicate that the TRC cross-inner-shelf exchange mechanism is due to an alongshore mean baroclinic flow set up by TRC vertical mixing of inner-shelf stratification.

Plain Language Summary
Cross-shore transport (also called exchange) of material, e.g., pollutants, larvae, nutrients, plankton, is important in coastal oceanography. Natural surf-zone wave breaking leads to transient rip-currents (TRC), episodic, offshore flows onto the inner-shelf, which vertically mix stratified waters creating a cross-shore exchange pathway. In many regions, such as Southern California, daily surface heating/cooling, or diurnal surface heat-fluxes (SHF), also drive cross-shore exchange, because thermal response varies with water depth. However, the dominant exchange mechanism is not known. Impacts of combined TRC and SHF forcing on exchange and their relative strength are analyzed using idealized numerical model simulations. Cross-shore transport is quantified using an tracer released within the surf-zone. Tracer transport is strongest for simulations including TRCs, relative to SHF forcing alone, and transport induced by TRCs extends well offshore of the surf-zone. Analyses indicate that enhanced TRC driven inner-shelf exchange is associated with the vertical mixing mechanism.

1 Introduction
The cross-shore exchange of tracers (e.g., larvae, pollutants) is a fundamental quantity in coastal oceanography. Various mechanisms contribute to tracer exchange across the nearshore, the region encompassing the inner-shelf (water depths $\lesssim 15$ m) and surf-zone (region of depth limited wave breaking) (e.g., Morgan et al., 2018). Away from rivers (e.g., Rodriguez et al., 2018), nearshore tracer exchange may be driven by surf-zone induced rip-currents (e.g., Castelle & Coco, 2013; Hally-Rosendahl et al., 2014; Suanda & Feddersen, 2015) and surface heat fluxes (e.g., Monismith et al., 2006; Molina et al., 2014), particularly under weak wind forcing (e.g., Lentz, 2001; Lentz & Fewings, 2012). In general, these processes occur simultaneously. Yet, the effect of combined rip-currents
and surface heat flux forcing on inner-shelf cross-shore exchange and their relative importance are not known.

Rip-currents are intrinsic to surf-zones. Finite crest length breaking generates surf-zone horizontal turbulent eddies (e.g., Peregrine, 1998; Clark et al., 2010, 2012), that coalesce to form transient rip-currents (TRCs), episodic offshore directed flows (Johnson & Pattiaratchi, 2006). In alongshore uniform regimes, TRCs exchange tracer from surf-zone to inner-shelf (e.g., Hally-Rosendahl et al., 2014, 2015). In rip-channeled surf-zones, standing and low-frequency varying bathymetric rip-currents dominate surf-zone to inner-shelf exchange (e.g., Reniers et al., 2010; Elgar et al., 2019). As the inner-shelf is often stratified, TRC driven vertical mixing can generate a sub-surface baroclinic exchange pathway, transporting surf-zone released tracer offshore at $\approx 1.5 \, \text{cm s}^{-1}$ in Kumar and Feddersen (2017a, 2017c). However, surface heat flux (SHF) effects, which modulate stratification, were not considered.

Spatially uniform SHF sets up cross-shore thermally driven circulation nearshore owing to a depth dependent thermal response, with shallower regions heating/cooling more rapidly (Farrow & Patterson, 1993). Diurnal (24 h) cycle solar heating/cooling drives diurnal exchange flow, with observed inner-shelf offshore directed flows of $\approx 2 \, \text{cm s}^{-1}$ near the surface for heating response and at depth for cooling (Monismith et al., 2006; Molina et al., 2014). Most short-wave radiation is distributed over vertical length-scale of 1-2 m depending on water properties, increasing near-surface stratification and confining cross-shore thermal gradients to regions onshore of a depth comparable to the absorption length-scale (Lei & Patterson, 2002). In contrast, surface cooling induced convection erodes stratification, developing a surface mixed layer and an offshore gravity current where convection extends to the bottom (Mao, 2019). Regions conducive for diurnal SHF driven exchange may also be exposed to waves (e.g., Molina et al., 2014). During early Fall in Southern California, observed SHF forced surf-zone temperature, relative to the inner-shelf was warm midday (Hally-Rosendahl et al., 2014) and cold early-morning (Grimes et al., 2019), however the SHF driven cross-shore temperature gradient effects on exchange were not examined. Previous thermally driven exchange studies assumed weak wave effects because inner-shelf moorings were well outside the surf-zone and estimated Stokes drift velocities were small compared to observed Eulerian currents (Monismith et al., 2006; Molina et al., 2014). On a wave exposed reef flat, diurnal thermally driven exchange was relatively unaffected by wave height (Molina et al., 2014), but wave range was limited and alongshore variability was strong. These TRC and SHF forced processes have never been jointly observed or modeled.

Herein, idealized surf-zone tracer release simulations are performed to evaluate the relative importance of combined SHF and TRC forcing to inner-shelf cross-shore tracer exchange. Simulations are conducted for SHF and TRC forcing both separately and combined with different model initialization times relative to the surface heat flux cycle and different tracer release times relative to model initialization, allowing for an ensemble
averaging analysis approach (Section 2). The relative strength of SHF and TRC forcing are evaluated from tracer mass distributions (Section 3). Dominant exchange mechanisms and underlying processes are quantified with different exchange velocity definitions (Section 4).

2 Methods

2.1 Model Setup & Forcing

Simulations are performed using the Coupled Ocean Atmosphere Wave and Sediment Transport (COAWST) modeling system (Warner et al., 2010; Kumar et al., 2012) coupling the $\sigma$-coordinate Boussinesq and hydrostatic ROMS circulation model (Shchepetkin & McWilliams, 2005) with the SWAN wave model (Booij et al., 1999). SWAN provides ROMS with bulk wave parameters to estimate Stokes drift velocity $u_S(z)$, breaking-wave turbulence source, and phase-averaged wave forcing. TRCs are generated by adding surf-zone barotropic-rotational body forcing via one-way coupling with wave-resolving model funwaveC (Kumar & Feddersen, 2017b).

The 1 km alongshore ($y$) uniform and periodic domain extends cross-shore ($x$) 5 km (Figure 1a). Alongshore resolution is fixed at $\Delta y = 2$ m. Cross-shore resolution is concentrated nearshore, with constant $\Delta x = 1.25$ m for $-690 < x < 0$ m that increases smoothly offshore to $dx = 200$ m. The Southern California characteristic bathymetry $z = -h(x)$ (black, Figure 1a) matches Kumar and Feddersen (2017b, 2017a) for $x > -800$ m. For $x > -200$ m, $h(x)$ has constant slope of 0.025, transitioning offshore to a smaller 0.004 slope, and $h = 28$ m at the offshore boundary. Fifteen vertical $\sigma$-layers are used (gray, Figure 1a). The extended cross-shore domain, relative to 800 m in Kumar and Feddersen (2017b, 2017a), minimizes offshore boundary conditions influence.

Similar model parameters to Kumar and Feddersen (2017b, 2017a, 2017c) are used including homogeneous quadratic bottom drag coefficient of $C_d = 0.0025$ and Coriolis parameter $f = 7.7 \times 10^{-5}$ s$^{-1}$. The momentum and tracer lateral eddy viscosity $K_H = 0.01$ m$^2$s$^{-1}$ is increased to $K_H = 0.2$ m$^2$s$^{-1}$ within the surf-zone $x > -L_{sz} = -100$ m for simulations with waves, where $L_{sz}$ is the surf-zone width. The $k-\epsilon$ turbulence closure model provides vertical eddy viscosity $K_V$ (Warner et al., 2005); with 15% of wave dissipation supplied as a surface turbulent kinetic energy flux (Feddersen, 2012). The 48 h long simulations are initialized from rest with uniform stratification and $T(z) = 20 + 0.25z$ °C, throughout. The seabed is adiabatic and the offshore boundary temperature is clamped to either the temperature initial condition for runs without SHF or to a 1-D (vertical) $T(z,t)$ evolution for runs that include SHF. The 1-D $T(z,t)$ evolution is estimated via 48 h single-column simulations with offshore boundary depth of 28 m. The $x = 0$ boundary is closed, and the offshore boundary cross-shore Lagrangian velocity $u_L$ (Eulerian + Stokes drift) is zero.
Figure 1. (a) Cross-shore bathymetry $z = -h(x)$ (black) with terrain following $\sigma$-coordinates (gray) showing the full 5 km cross-shore domain. Inset shows form of surf-zone bottom tracer flux $Q_{dye}$ centered on $x = -50$ m (magenta). (b) SWAN model significant wave height for $x > -1200$ m ($H_s$ is roughly constant offshore) with a vertical dashed line at $x = -L_{sz}$ delimiting the surf-zone boundary. (c) Net surface heat flux $Q_{net}$ cycle with red/blue highlighting heating/cooling phases. In (d) solar initialization times $t_i^s$ (green) for $i = \{1, 3\}$ and solar time of the first tracer release $t_{r}^{(1)}$ (red).
Model forcing is representative of Southern California in Fall. Four forcing cases (I-IV) are considered: I) a control case (denoted ø) without external forcing, representing the evolution due to background mixing; II) the wave and rotational-body forced case (denoted TRC), without surface heat fluxes, similar to Kumar and Feddersen (2017c), but with larger cross-shore domain and modified tracer releases (described later); III) a diurnal SHF forcing case (denoted SHF) without any wave forcing; and IV) the novel combination of diurnal SHF with wave and rotational-body forcing (denoted SHF+TRC).

For TRC and SHF+TRC, normally incident waves representing medium sized swell have $10^\circ$ directional spread, peak period of 10 s and significant wave height of $H_s \approx 1$ m at $x = -L_{sz}$, where breaking begins (dashed, Figure 1b).

For SHF and SHF+TRC simulations, incident short-wave radiation, with maximum $Q_{sw} = 750$ W m$^{-2}$, is distributed over the water column following a double-exponential vertical decay for Jerlov water-type I (Paulson & Simpson, 1977, with 58% over 0.35 m and the remainder over 23 m). The short-wave cycle follows $\cos^2(2\pi \tau_s / \tau_{day})$ over solar time $\tau_s \in [6, 18]$ h, with solar day duration $\tau_{day} = 24$ h. Uniform (in space & time) surface longwave outgoing radiation is applied. This results in periodic net surface heat flux $Q_{net}$ (Figure 1c) with midday, $\tau_s = 12$ h, maximum of 565 W m$^{-2}$ and midnight minimum of $-185$ W m$^{-2}$ and zero net daily heat flux. Other surface buoyancy flux sources (e.g., sensible heat flux, MacMahan et al., 2018), the effect of wave heating and surf-zone albedo (Sinnett & Feddersen, 2018), and wind stress effects (e.g., Farrow, 2013, 2016) are not considered.

SHF simulations will have transient evolution varying with the solar forcing phase at model initialization. These are evaluated using a series of four runs, labeled with superscript $i = \{1, 2, 3, 4\}$, that vary the solar time at initialization, denoted $t_s$, at 6 h intervals relative to periodic $Q_{net}$. For the $i$th model run, time relative to the solar day $\tau_{s(i)}$ is given by,

$$\tau_{s(i)} = t + t_s^{(i)},$$

where $t$ is model time and $t_s \in \{0, 6, 12, 18\}$ h. For example, run $i = 1$ is initialized at midnight, $t_s^{(1)} = 0$ h, giving $\tau_{s(1)} = t$ (green dot right of $i = 1$, Figure 1d); whereas in run $i = 3$, the model is initialized midday, $t_s^{(3)} = 12$ h, giving $\tau_{s(3)} = t + 12$ h (green dot right of $i = 3$, Figure 1d). Ensemble averages (described in Section 2.2) are formed with the staggered $t_s^{(i)}$ to remove variability due to solar initialization time.

Tracer $D$ is released over 15 min as a bottom tracer flux $Q_{dye}$ centered on $x = -50$ m (magenta, Figure 1a) with zero momentum. The tracer flux $Q_{dye}$ is normalized such that a homogeneous plume confined to the SZ ($x > -L_{sz}$) would have unit concentration Kumar and Feddersen (2017c), making $D$ a measure of tracer dilution (e.g., $D = 0.02$ indicates a 1/50 decrease in plume concentration). The 48 h simulations are intrinsically transient due to the initial conditions, forcing, and irreversible mixing, making tracer evo
olution dependent on tracer release time relative to model start. To account for model
spin-up effects, four tracer releases occur at 6 h intervals, beginning at model time \( t = 6 \) h. The minimum 6 h spin-up allows surf-zone vorticity to equilibrate (Kumar & Feddersen, 2017b) and inner-shelf circulation to respond to thermal forcing (e.g., Molina et al., 2014; Monismith et al., 1990). Tracer releases are referenced using superscript \( j = \{1, 2, 3, 4\} \), such that \( D^{(i,j)} \) represents tracer from the \( i \)th run and \( j \)th tracer release. The \( j \)th tracer release model time is denoted \( t_{(j)} \). The first release at \( t_{(1)} = 6 \) h is indicated with a red square in Figure 1d for surface heat flux runs \( i = \{1, 3\} \). A tracer release reference time,

\[
\tau_t^{(j)} = t - t_{(j)},
\]

is used in analysis.

### 2.2 Averaging Methods

The alongshore average is denoted with an over-bar, i.e., for generic variable \( c^{(i)} \),

\[
\overline{c}^{(i)} = L_y^{-1} \int_0^{L_y} c^{(i)} \, dy,
\]

where \( c^{(i)} \) is derived from the \( i \)th model run with solar initialization time \( t_s^{(i)} \) and \( L_y = 1 \) km is the alongshore domain length. Alongshore averaged temperature \( \overline{T} \), cross-shore Lagrangian velocity \( \overline{u}_L \), overturning streamfunction \( \overline{\Psi} \), and vertical eddy diffusivity \( \langle K_V \rangle \) are also time averaged over the 24 h diurnal time-scale, i.e.,

\[
\langle c^{(i)} \rangle^{24\ h} = (\tau_{\text{day}})^{-1} \int_{6\ h}^{30\ h} c^{(i)} \, dt,
\]

where \( t \) is model time. Additionally, variables \( \langle c^{(i)} \rangle^{24\ h} \) are ensemble averaged over the \( (i) \)-indices, forming an initialization ensemble averaged \( \langle c \rangle^{24\ h} \), to average over transient effects associated with \( t_s \).

For SHF and SHF+TRC simulations, tracer \( D \) evolution depends on both the solar time \( \tau_s \) of the tracer release (see \( t_{(1)}^{(i)} \) for \( i = \{1, 3\} \) in Figure 1d) and the model spin-up prior to tracer release, i.e., with \( t_{(j)}^{(i)} \). As tracer evolution is secular a 24 h time mean is not used. An initialization and release ensemble averaged alongshore mean tracer field \( \langle \overline{D} \rangle_t^{(i)} \) is formed by aligning the four tracer releases relative to the time since tracer release \( \tau_t^{(j)} \) (2) and then ensemble averaging over solar \( (i) \) and spin-up \( (j) \) times, formally,

\[
\langle \overline{D} \rangle_t^{(i)} (x, z, \tau_t) = \frac{1}{16} \sum_{i=1}^4 \sum_{j=1}^4 \overline{D}^{(i,j)}(x, z, \tau_t^{(j)})
\]

where \( \overline{D}^{(i,j)} \) is the alongshore mean tracer concentration field from the \( i \)th SHF run and \( j \)th tracer release, and \( \tau_t \in (0, 24\ h) \). The ensemble average (5) captures the tracer bulk
3 Results

3.1 Combined Influence of Surface Heat Flux, Wave, and Transient Rip-Current Forcing on Instantaneous Fields

Examples from SHF+TRC forced simulations at solar-times $\tau_s = 0$ h (midnight, Figure 2, left) and $\tau_s = 12$ h (midday, Figure 2, right) illustrate effects of SHF and TRCs on instantaneous $T$ and $D$. Midnight temperature $T^{(3)}$ (Figures 2a and 2c) was extracted from run $i = 3$ at model time $t = 12$ h, giving solar time (1) $\tau_s^{(3)} = t + t_i^{(3)} = 24$ h (Figures 1c-1d). The concurrent tracer $D^{(3,1)}$ (i.e., release $j = 1$, Figure 2e and 2g) has tracer release time (2) $\tau_r^{(1)} = t - t_i^{(1)} = 6$ h. Similarly, midday ($i = 1$) temperature $T^{(1)}$ (Figure 2b and 2d) has model time $t = 12$ h and tracer $D^{(1,1)}$ (Figure 2f and 2h) is at $\tau_r^{(1)} = 6$ h. The surface temperature anomaly $\Delta T^{(i)}$ relative to the $x = -150$ m alongshore average surface temperature is used to enhance horizontal thermal structure (Figure 2a-2b).

The midnight ($\tau_s = 0$ h) $\Delta T^{(3)}$ (Figure 2a) shows consistent cooling toward shore with complex and irregular isotherm structure. Near-surface temperature also decreases toward shore along the $y = 50$ m cross-shore transect (Figure 2c), particularly near $x \approx -500$ m with near-vertical 19.25 °C isotherm from $z = -4$ m to $z = 0$ (thick contour, Figure 2c). For $x < -500$ m, the surface mixed layer is $\approx 3$ m deep, whereas onshore temperature is well mixed to $\approx 5$ m depth or to the bottom. The midnight surface $D^{(3,1)}$ field (Figure 2e) covaries with $\Delta T^{(3)}$, with high $D^{(3,1)}$ corresponding to cold $\Delta T^{(3)}$. As with sub-surface $T^{(3)}$ (Figure 2c), sub-surface $D^{(3,1)}$ is vertically well mixed for $x > -500$ m and $z > -5$ m (Figure 2g), with very sharp vertical front just offshore of $x = -500$ m. Farther offshore, out to $x \approx -600$ m, $D^{(3,1)}$ has a subsurface maximum below the offshore surface mixed layer.

Temperature and tracer structure is notably different midday ($\tau_s = 12$ h). Midday, cold $\Delta T^{(1)}$ (Figure 2b) is isolated to an alongshore band over roughly $-300 < x < -100$ m, with warmer surf-zone and offshore surface temperature. At $x = -150$ m, surface $T$ is $0.31$ °C warmer midday than midnight. Along the $y = 50$ m cross-shore transect, the cooler region is over roughly $-500 < x < -150$ m (Figure 2d). The $z > -5$ m stratification is elevated midday, relative to midnight (compare Figure 2d to Figure 2c). $T^{(1)}$ isotherms also have complex cross-shore structure, e.g., the 19.25 °C isotherm deepens from $(x, z) \approx (-475, -1.5)$ m to $(-250, -4)$ and shoals again to $(-150, -2)$ (thick contour, Figure 2d). Midday, tracer is present in both relatively warm surf-zone and colder inner-shelf (Figure 2b and 2h). Midday $D^{(1,1)}$ and $\Delta T^{(1)}$ covariability at offshore sur-
Figure 2. Instantaneous SHF+TRC forced runs $i = \{3,1\}$ at solar midnight ($\tau_3^{(s)} = 0$ h, left panels) and midday ($\tau_1^{(s)} = 12$ h, right panels) (a)-(b) surface temperature anomaly $\Delta T^{(i)}$; (c)-(d) cross-shore sub-surface temperature $T^{(i)}$; (e)-(f) surface and (g)-(h) cross-shore sub-surface tracer $D^{(i,1)}$. Surface panels (a,b,e,f) are functions of $(x,y)$ and sub-surface panels (c,d,g,h) are functions $(x,z)$ along $y = 50$ m (black dotted line in a,b,e,f). Snap-shots from model time $t = 12$ h, such that solar time (1) is $\tau_s^{(i)} = 12 + t_s^{(i)}$, and in (e)-(f) time relative to tracer release (2) is $\tau_r^{(1)} = t_s^{(1)} - 6$ h. The outer limit of the surf-zone $x = -L_{sz}$ is indicated with a black dashed line and the bottom is gray.
face fronts is similar to midnight. Sub-surface \( D^{(1,1)} \) (Figure 2h) has more structure and is shallower than midnight \( D^{(3,1)} \) (Figure 2g), and cross-shore tracer structure is similar to isotherm variability (Figure 2d and 2h). Offshore of \( x \approx -500 \) m, \( D^{(1,1)} \) also tends toward a sub-surface maximum.

TRC generated eddies create the complex filamentous tracer and temperature patterns onshore of \( x \approx -500 \) m (Figure 2). Midday, eddies in this region heave isotherms and tracer (Figure 2d and 2h) inducing overturns that are mixed via increased \( K_v \) analogously to the surface cooling induced convective mixed-layer deepening (Burchard & Bolding, 2001; Kumar & Feddersen, 2017a). TRC vertical mixing combined with nighttime surface buoyancy loss and depth dependent thermal response strengthen the negative cross-shore surface temperature gradient (Figure 2a), deepening the surface mixed layer relative to \( x < -500 \) m (Figure 2c) and leading to midnight \( x < -500 \) m sub-surface tracer maximum (\( x < -500 \) m, Figure 2g). Although SHF heating should stabilize stratification and develop a positive cross-shore temperature gradient, TRC mixing effects are sufficient to overcome SHF heating, causing the persistent midday inner-shelf cold band (Figures 2b and 2d) and sub-surface tracer maximum (\( x < -500 \) m, Figure 2h).

### 3.2 Average Temperature, Circulation and Tracer Structure

The different effects of SHF and SHF+TRC forcing on temperature and cross-shore circulation are evaluated using alongshore and 24 h time mean \( (3)-(4) \) and initialization ensemble averaged streamfunction \( \langle \tilde{\Psi} \rangle^{24 \, h} \), temperature \( \langle \tilde{T} \rangle^{24 \, h} \), and vertical eddy diffusivity \( \langle K_v \rangle^{24 \, h} \) (Figures 3a-3f). For SHF, the mean overturning stream-function \( \langle \tilde{\Psi} \rangle^{24 \, h} \) is relatively weak and retains the signature of warming response exchange circulation, with near-surface offshore flow \( \langle \tilde{u}_L \rangle^{24 \, h} \approx -1 \times 10^{-3} \text{ m s}^{-1} \) for \( x > -950 \) m (Figure 3a). The SHF \( \langle \tilde{T} \rangle^{24 \, h} \) stratification is decreased above \( z = -4 \) m (Figure 3c) due to diurnal mixed layer development, and offshore of \( x = -500 \) m isotherms are relatively flat.

The SHF+TRC \( \langle \tilde{\Psi} \rangle^{24 \, h} \) and \( \langle \tilde{T} \rangle^{24 \, h} \) are dramatically different (Figures 3b and 3d). The SHF+TRC \( \langle \tilde{\Psi} \rangle^{24 \, h} \) has a prominent inner-shelf circulation cell offshore of \( x \approx -300 \) m, with sub-surface offshore directed flow \( \langle \tilde{u}_L \rangle^{24 \, h} < -3 \times 10^{-3} \text{ m s}^{-1} \) to \( x \approx -600 \) m (Figure 3b). Similar to SHF, the SHF+TRC \( \langle \tilde{T} \rangle^{24 \, h} \) surface diurnal mixed layer is \( \approx 4 \) m thick for \( x \lesssim -1000 \) m (Figure 3d). However, SHF+TRC isotherm structure differs moving toward shore, with the 19.0 °C isotherm sloping downward and the 19.25 °C rising to the surface near \( x = -300 \) m (highest two contours in Figure 3d).

The SHF and SHF+TRC differences in \( \langle \tilde{\Psi} \rangle^{24 \, h} \) and \( \langle \tilde{T} \rangle^{24 \, h} \) are largely due to nearshore TRC vertical mixing. The relatively flat SHF inner-shelf isotherms (Figure 3c) are reflected in the relatively flat \( \langle K_v \rangle^{24 \, h} \) contours, which deepen at \( x \approx -200 \) m, where the \( h \) becomes comparable to the diurnal mixed layer depth (Figure 3e). In contrast, the SHF+TRC \( \langle K_v \rangle^{24 \, h} \) contours progressively deepen onshore for \( x > -1000 \) m (Figure 3f) and SHF+TRC \( \langle K_v \rangle^{24 \, h} \) is 10× that of SHF for \( x > -300 \) m. The shoreward enhanced TRC vertical
Figure 3. SHF (left) and SHF+TRC (right) averaged fields as a function of $(x, z)$. Alongshore and 24 h time mean (3)-(4) and initialization ensemble averaged (a)-(b) velocity overturning stream-function $\langle \bar{\Psi} \rangle_{24h}$ contoured at $2 \times 10^{-3}$ m$^2$s$^{-1}$; (c)-(d) temperature $\langle \bar{T} \rangle_{24h}$ contoured at 0.25 C; and vertical eddy viscosity $\langle \bar{K}_V \rangle_{24h}$ with contours at $\{10^{-5}, 10^{-4}, 10^{-3}\}$ m$^2$s$^{-1}$. In (g)-(h) the alongshore mean and initialization and release ensemble averaged tracer concentration $\langle \bar{D} \rangle_t$, (5) is shown at $\tau_r = 24$ h with overlaid $\langle \bar{T} \rangle_{24h}$ contours from (c)-(d). Shown in (g)-(h) are $x_{50\%}$ (circle) and $x_{90\%}$ (diamond), bounding 50% and 90% of the tracer mass, respectively. For case TRC+SHF (right), $x = -L_{zax}$ is indicated with a vertical dashed line.
mixing maintains the broadened SHF+TRC isotherms that drive the overturning stream-
function.

These SHF and SHF+TRC differences in $\langle \Psi \rangle_{24\,\text{h}}$ and $\langle T \rangle_{24\,\text{h}}$ result in differences in the alongshore, initialization, and release ensemble averaged tracer $\langle D \rangle_{\tau}$ (5) at $\tau = 24\,\text{h}$ (Figure 3g-h). The 24 h SHF $\langle D \rangle_{\tau}$ is nearly all onshore of $x = -500\,\text{m}$, and offshore of $x \approx -200\,\text{m}$, SHF $\langle D \rangle_{\tau}$ has a bimodal vertical structure suggesting tracer exchange occurs incrementally at each phase of diurnal thermal exchange. At $\tau = 24\,\text{h}$, the SHF+TRC $\langle D \rangle_{\tau}$ extends offshore to $x = -1000\,\text{m}$ and the SHF+TRC shoreline $\langle D \rangle_{\tau}$ is 1/3 that of SHF. SHF+TRC $\langle D \rangle_{\tau}$ has a prominent subsurface tracer maximum for $x < -400\,\text{m}$, following the 24 h mean streamlines in Figure 3b, suggesting enhanced exchange is partially due to an alongshore and 24 h time mean exchange flow sustained by TRC vertical mixing (Figure 3f).

### 3.3 Cross-shore Tracer Mass Evolution

Cross-shore tracer exchange is quantified using the integrated tracer mass onshore of $x$,

$$\langle M \rangle_{\tau}(x, \tau_{r}) = L_y \int_{x}^{0} \int_{-h}^{\eta} \langle D \rangle_{\tau}(x', z, \tau_{r}) dz \, dx';$$

(6)

where $\eta$ is the sea-surface. The domain-total tracer mass is denoted $M_{\infty}$, such that the tracer mass fraction onshore of $x$ is $\langle M \rangle_{\tau}/M_{\infty}$ and two locations are highlighted $x_{50\%}$ and $x_{90\%}$ bounding 50% and 90% of the tracer mass, respectively. At $\tau_{r} = 24\,\text{h}$, SHF $x_{50\%} \approx -240\,\text{m}$ and $x_{90\%} \approx -380\,\text{m}$ (circle and diamond, respectively in Figure 3g).

In contrast, at $\tau_{r} = 24\,\text{h}$ the SHF+TRC $x_{50\%} \approx -440\,\text{m}$ and $x_{90\%} \approx -760\,\text{m}$ (circle and diamond, respectively (Figure 3h), quantifying the stronger SHF+TRC exchange.

The time-dependence of SHF & SHF+TRC ensemble averaged tracer mass fraction $\langle M \rangle_{\tau}/M_{\infty}(x, \tau_{r})$ (6) is shown in Figures 4a-4b. At $\tau_{r} = 0\,\text{h}$, $\langle M \rangle_{\tau}/M_{\infty} = 1$ for $x < -100\,\text{m}$, as tracer is released over $x > -100\,\text{m}$. Over time, $\langle M \rangle_{\tau}/M_{\infty}$ contours progress offshore (e.g., $x_{90\%}$ in Figures 4a-4b) indicating cross-shore tracer transport. The $\langle M \rangle_{\tau}/M_{\infty}$ distribution broadening (i.e., increasing separation between $x_{50\%}$ and $x_{90\%}$) indicate either cross-shore advective straining or cross-shore tracer gradient weakening by mixing, or both. For SHF, the early ($\tau_{r} \leq 3\,\text{h}$) cross-shore tracer transport is offshore with $x_{90\%}$ moving at $\approx 2.5\,\text{cm}\,\text{s}^{-1}$ (dotted line, Figure 4a). Shortly thereafter ($3 < \tau_{r} < 8\,\text{h}$), SHF offshore transport slows or even reverses (see $x_{90\%}$ in Figure 4a), likely due to flow reversal during warming-to-cooling transition (and vice-versa). After $\tau_{r} = 12\,\text{h}$, transport is offshore but slow with $x_{90\%}$ moving offshore at $<0.3\,\text{cm}\,\text{s}^{-1}$.

For SHF+TRC, early ($\tau_{r} \leq 3\,\text{h}$) cross-shore tracer transport is more rapid than for SHF, with $x_{90\%}$ moving at $\approx 3.5\,\text{cm}\,\text{s}^{-1}$ (dotted line, Figure 4b). In contrast to the SHF reversal, SHF+TRC $\langle M \rangle_{\tau}/M_{\infty}$ contours continuously progress offshore, although at a progressively slower rate.
Figure 4. Normalized integrated tracer mass $\langle M \rangle_r/M_\infty$ evolution as a function of time since tracer release $\tau_r$ and cross-shore $x$ for (a) SHF and (b) SHF+TRC forced runs, with $x_{50\%}$ (dashed-dotted) and $x_{90\%}$ (dotted) contours indicated. (c) Time evolution of $x_{90\%}$ (colored lines) for each forcing case with $\pm 1$ root-mean-square deviation $\sigma$ from the ensemble average (shading). In (b)-(c) the SZ boundary is indicated by a dashed black line.
The bulk cross-shore tracer transport across all forcing cases is evaluated with the $x_{90\%}$ time evolution (Figure 4c). In the unforced 0 run (brown curve, Figure 4c), background diffusive mixing drives weak exchange, and $x_{90\%} > -110$ m, indicating strong tracer confinement. In contrast, over 24 h, SHF thermally driven exchange draws tracer 3× farther offshore (blue, Figure 4). For TRC and SHF+TRC, tracer mass evolution is statistically indistinct, as evidenced by the overlap in $x_{90\%} \pm \sigma_{x_{90\%}}$ (shading in Figure 4c), where $\sigma_{x_{90\%}}$ is the root-mean-square deviation from the ensemble average, further indicating that the SHF+TRC forced exchange is dominated by TRC effects. After 24 h, the TRC and SHF+TRC $x_{90\%}$ extend twice as far offshore as that for SHF (Figures 3g-3h and 4c), demonstrating that for the wave, stratification, and SHF forcing regime here, the TRC exchange mechanism is stronger than the diurnal SHF exchange mechanism.

4 Discussion and Conclusions

4.1 Quantifying Exchange: Tracer Flux & Velocity Derived Estimates

![Figure 5.](image)

Cross-shore exchange velocity $u_{ex}$ versus cross-shore coordinate $x$ for SHF (blue), TRC (black), and SHF+TRC (red) simulations. Three definitions of $u_{ex}$ are used: $u_{ex}^M$ (solid) derived from tracer mass balances (9), $u_{ex}^\ast$ (dashed) defined using offshore Lagrangian velocities (10) and $\bar{u}_{ex}$ defined using alongshore mean offshore Lagrangian velocities (11). All exchange velocities are 24 h time mean and initialization ensemble averaged, $u_{ex}$ is also ensemble averaged over all releases and is only computed where $\partial \langle M \rangle / \partial x > 10^{-8}$.

Cross-shore tracer transport $T_x$ (e.g., sediment, heat, larvae, or pollutants) is a fundamental quantity of interest in cross-shore exchange studies (e.g., Hally-Rosendahl...
et al., 2015). In the absence of sources/sinks, alongshore averaged tracer transport may be estimated from the evolution of tracer mass \( ⟨M⟩_r \) (6) via (Hally-Rosendahl et al., 2015; Feddersen et al., 2016),

\[
T_x(x, τ_r) = \frac{\partial ⟨M⟩_r}{\partial τ_r}.
\]

(7)

Cross-shore transport potential is often represented with an exchange velocity \( u_{\text{ex}} \), which has various definitions (e.g., MacCready, 2011; Suanda & Feddersen, 2015). Conceptually, transport driven by an idealized exchange flow is parameterized as (e.g., Hally-Rosendahl et al., 2015),

\[
T_x \propto u_{\text{ex}} L_y(\tilde{h} \tilde{D}),
\]

(8)

where \( \tilde{h} = h + \eta \) is the total water depth, and \( \tilde{D} \) the depth average tracer concentration.

Although \( u_{\text{ex}} \) is a useful metric, the assumptions in (8) grossly approximate the tracer conservation equation governing \( T_x \); as such, \( u_{\text{ex}} \) estimates will depend on definition. Here, two unique \( u_{\text{ex}} \) definitions are examined. Leveraging (7) and substituting \( L_y(\tilde{h} \tilde{D}) = \frac{\partial ⟨M⟩_r}{\partial x} \) in (8), yields a tracer-derived exchange velocity,

\[
u_{\text{ex}}^x = \left\langle \frac{\partial ⟨M⟩_r}{\partial τ_r} \left( \frac{\partial ⟨M⟩_r}{\partial x} \right)^{-1} \right\rangle^{24 \text{ h}},
\]

(9)

where the outer average \( \left\langle \right\rangle^{24 \text{ h}} \) is over \( 0 < τ_r \leq 24 \text{ h} \). Although \( u_{\text{ex}}^x \) encapsulates recirculation, tracer presence is required and (9) is only evaluated for \( \frac{\partial ⟨M⟩_r}{\partial x} > 10^{-8} \text{ m}^2 \text{ s}^{-1} \), or \( \tilde{h} \tilde{D} > 10^{-5} \text{ m} \). An alternative exchange velocity \( u_{\text{ex}}^- \) is based on cross-shore flow alone (e.g., MacCready, 2011; Suanda & Feddersen, 2015),

\[
u_{\text{ex}}^- = \left\langle \frac{2}{\tilde{h} + \eta} \int_{-\tilde{h}}^{0} u_L^- dz \right\rangle^{24 \text{ h}},
\]

(10)

where the offshore Lagrangian velocity \( u_L^- \) has onshore values set to zero, and the alongshore average (3), 24 h time average (4) and initialization ensemble average are applied. This \( u_{\text{ex}}^- \) can be estimated over the entire domain. The factor of 2 in (10) recovers (8) for 2-layer exchange flow; and makes (10) analogous to estuarine exchange flow (e.g., Ler-czak et al., 2006; MacCready, 2011).

The SHF \( u_{\text{ex}}^x \) is a factor of 1/3 weaker than that for TRC and SHF+TRC (solid, Figure 5) with TRC and SHF+TRC \( u_{\text{ex}}^x \) differing by \( < 10\% \) for \( x < -200 \text{ m} \), peaking near \( 5\times10^{-3} \text{ m s}^{-1} \). This confirms findings of Section 3.3. Velocity derived \( u_{\text{ex}}^- \) is similarly weaker for SHF than for both TRC and SHF+TRC (dashed curves, Figure 5) and TRC and SHF+TRC \( u_{\text{ex}}^- \) are largely similar. For TRC and SHF+TRC, both \( u_{\text{ex}}^x \) and \( u_{\text{ex}}^- \) are consistent over \( x < -500 \text{ m} \), yet deviate onshore of \( x = -400 \text{ m} \), with \( u_{\text{ex}}^- \) exceeding \( u_{\text{ex}}^x \) by \( 10\times \) at \( x = -L_{sz} \text{ m} \).

For TRC and SHF+TRC, inner-shelf eddy velocities increase toward \( x = -L_{sz} \), and the growing difference between \( u_{\text{ex}}^x \) and \( u_{\text{ex}}^- \) for \( x > -400 \) (Figure 5) is likely due to eddy recirculation that bias high \( u_{\text{ex}}^- \). To account for recirculation in \( u_{\text{ex}}^- \), an exchange

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factor (<1) often is introduced in (10) that depends on \(x\) and hydrodynamics (Lemagie & Lerczak, 2015; Suanda & Feddersen, 2015). Previous estimates of the exchange factor for surf-zone to inner-shelf transport range 0.2-0.3 (Suanda & Feddersen, 2015; Smith & Largier, 1995; Dalrymple et al., 2011), consistent with the differences between \(u_{M}^{x}\) and \(u_{EX}^{-}\) for \(x > -400\) m.

An exchange velocity that removes eddy effects is based on the alongshore mean Lagrangian velocity (e.g., MacCready, 2011; Lerczak et al., 2006),

\[
\bar{u}_{EX}^{-} = \left( \frac{2}{\pi} \int_{-h}^{0} \bar{u}_{L}^{-} dz \right)^{24\ h},
\]

where the alongshore average (3), 24 h and initialization ensemble average (4) are applied. Thus, for non-eddying SHF, estimates of \(u_{EX}^{-}\) and \(\bar{u}_{EX}^{-}\) are indistinguishable (Figure 5). The TRC and SHF+TRC \(\bar{u}_{EX}^{-}\) (dotted curves, Figure 5) are much lower than \(u_{EX}^{-}\) over \(x > -400\) m, converging offshore of \(x = -600\) m, indicating that the transition from eddy dominated to alongshore mean dominated transport regimes occurs at \(x \approx -500\) m (see Figure 2). The similar shape of \(\bar{u}_{EX}^{-}\) and \(u_{EX}^{-}\) for \(x < -200\) m indicates that enhanced 24 h tracer exchange for TRC and SHF+TRC is primarily due to an alongshore mean exchange flow. Horizontal eddies associated with TRCs are inhomogeneous in \(x\), which induces a long-time subdiffusive regime (e.g., Spydell et al., 2019), which may explain why eddy-induced transport is weak. The consistently larger TRC and SHF+TRC \(u_{EX}^{-}\) estimates relative to SHF out to \(x = -1200\) m or \(-12L_{sz}\) (5) confirms that the TRC baroclinic exchange mechanism is dominant for this wave and SHF forcing regime.

### 4.2 Concluding Remarks

For typical early-Fall Southern California conditions, the transient rip-current (TRC) exchange mechanism is stronger than surface heat flux (SHF) induced thermally driven exchange out to at least \(x = -1200\) m or \(-12L_{sz}\), significantly offshore of the 100 m wide surf-zone. Combined SHF forcing with TRCs does not significantly modify the bulk inner-shelf cross-shore tracer exchange induced by TRCs. Inner-shelf TRC vertical mixing with stratification generates an alongshore and time mean inner-shelf overturning circulation with sub-surface offshore directed flow. For quasi-instantaneous surf-zone tracer release, this sub-surface baroclinic pathway is well represented by an exchange velocity derived from the alongshore mean and offshore directed Lagrangian velocity. Including horizontal eddies in exchange velocity estimates over predicted inner-shelf tracer transport, due to recirculation.

The TRC baroclinic cross–inner-shelf exchange flow mechanism critically depends on inner-shelf stratification. Here, the diurnal mixed layer depth does not extend beyond the TRC vertical mixing depth. The baroclinic exchange mechanism may be impacted if enhanced SHF forcing deepens the diurnal mixed layer relative to the TRC mixing depth. Here the diurnal net surface heat flux is zero. A shift toward net-cooling annihilating stratification would reduce transient rip-current exchange. Thus, in Mediterranean cli-
mates the potential for TRC inner-shelf exchange will vary seasonally with wave and stratification changes. For relatively stable diurnal SHF forcing (e.g., tropical climates), episodic incidence of swell, which at times dominate flow and modulate shallow reef thermal response (e.g., Hench et al., 2008; Davis et al., 2011), may diminish TRC exchange relative to persistent diurnal thermally driven exchange. Other mechanisms influencing inner-shelf stratification and hydrodynamics, e.g., wind, internal waves, and tides, are also likely to impact the TRC baroclinic exchange pathway. The ubiquity of coastline with a surf zone and stratified inner-shelf would suggest that TRC exchange is common, motivating further study.

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