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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 California 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 1,000 m offshore is due to TRC-mixing induced mean overturning circulation

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Tracer Exchange Across the Stratified Inner-Shelf Driven by Transient Rip-Currents and Diurnal Surface Heat Fluxes

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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 setup by TRC vertical mixing of inner-shelf stratification.

Plain Language Summary Cross-shore transport (also called exchange) of material, for example, pollutants, larvae, nutrients, and plankton, is important in coastal oceanography. Natural surf-zone wave breaking leads to transient rip-currents (TRCs), 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 a 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 and pollutants) affects marine population connectivity (e.g., Pineda et al., 2007) and coastal water quality (e.g., Boehm et al., 2017). Various mechanisms contribute to tracer exchange across the nearshore, the region encompassing the inner-shelf (water depths ≤ 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) and under weak wind forcing (e.g., Lentz, 2001; Lentz & Fewings, 2012), nearshore tracer exchange may be driven by surface heat fluxes (e.g., Monismith et al., 2006; Molina et al., 2014) and surf-zone induced rip-currents (e.g., Castelle & Coco, 2013; Hally-Rosendahl et al., 2014; Suanda & Feddersen, 2015). Under natural conditions, these two processes occur simultaneously. Yet the combined effect of rip-currents and surface heat flux forcing on inner-shelf cross-shore exchange and their relative importance are not known.

Thermally driven cross-shore flows are an important and ubiquitous inner-shelf exchange mechanism (e.g., Herdman et al., 2015; Monismith et al., 2006; Molina et al., 2014; Ulloa et al., 2018), particularly as Ekman transport is shut-down on the shallow inner-shelf (e.g., Lentz & Fewings, 2012). Spatially uniform surface heat-flux (SHF) sets up cross-shore thermally driven inner-shelf circulation owing to depth-dependent thermal response, with shallower regions heating/cooling more rapidly (e.g., Farrow & Patterson, 1993).

Diurnal (24 hr) cycle solar heating/cooling drives diurnal exchange flow, with observed inner-shelf offshore directed flows of $\approx 2 \, cm \, s^{-1}$ near the surface for heating response and at depth for cooling (Monismith et al., 2006; Molina et al., 2014). The heating/cooling cycle also strongly affects stratification. During daytime, most short-wave radiation is distributed within the upper 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, nighttime 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, but the impact of surf-zone processes on thermally driven exchange is not clear (e.g., Molina et al., 2014). Previous thermally driven exchange studies within 1 km of the coast 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.

Transient rip-currents (TRCs) are strong, episodic offshore directed flows commonly generated within natural surf-zones (e.g., Johnson & Pattiaratchi, 2006) that dominate tracer exchange between the surf-zone and inner-shelf (e.g., Clark et al., 2011; Hally-Rosendahl et al., 2014, 2010, 2015; Reniers et al., 2010). Recently, based on idealized simulations, TRC-induced mixing on the stratified inner-shelf generated a subsurface baroclinic exchange pathway that transported surf-zone released tracer across the inner-shelf at ≈ 1.5 cm s⁻¹ (Kumar & Feddersen, 2017a, 2017c). This exchange mechanism depends critically on the inner-shelf stratification. However, surface heat flux (SHF) effects, that modulate stratification, were neglected in these simulations. Separate surf-zone tracer release experiments conducted in early Fall in Southern California observed SHF forced thermal gradients, where surf-zone temperature, relative to the inner-shelf, was warm midday (Hally-Rosendahl et al., 2014) and cold early-morning (Grimes et al., 2020). However, SHF effects on exchange were not examined. Whether the TRC-driven inner-shelf baroclinic exchange mechanism is maintained with diurnal SHF-forced stratification and circulation effects is unknown, nor is how the magnitude of these exchange mechanisms compare.

Herein, idealized surf-zone tracer release simulations are performed to evaluate exchange across the inner-shelf induced by combined SHF and TRC forcing. Because both SHF- and TRC-induced exchange rely on baroclinic pressure gradients and vertical mixing, 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-induced exchange mechanisms 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 and Forcing

Simulations are performed using the Coupled Ocean Atmosphere Wave and Sediment Transport (COAWST) modeling system (Kumar et al., 2012; Warner et al., 2010) coupling the σ -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, as developed and validated by Kumar and 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 $\Delta x = 200$ m. The Southern California characteristic bathymetry z = -h(x) (black, Figure 1a) matches (Kumar & Feddersen, 2017a, 2017b) 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 σ -layers are used (gray, Figure 1a). The extended cross-shore domain, relative to 800 m in Kumar and Feddersen (2017a, 2017b), minimizes offshore boundary conditions influence.





Figure 1. (a) Cross-shore bathymetry z = -h(x) (black) with terrain following σ -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 > -1, 200 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) are solar initialization times $t_s^{(i)}$ (green) for $i = \{1, 3\}$ and solar time of the first tracer release $t_r^{(1)}$ (red).

Similar model parameters to Kumar and Feddersen (2017a, 2017b, 2017c) are used including homogeneous quadratic bottom drag coefficient of $C_d = 0.0025$ and Coriolis parameter $f = 7.7 \times 10^{-5} \,\mathrm{s}^{-1}$. To account for the increased lateral diffusivity associated with surf-zone bores (Feddersen, 2007), the momentum and tracer lateral eddy viscosities $K_H = 0.01 \,\mathrm{m}^2 \,\mathrm{s}^{-1}$ are increased to $K_H = 0.2 \,\mathrm{m}^2 \,\mathrm{s}^{-1}$ within the surf-zone $x > -L_{\rm sz} = -100 \,\mathrm{m}$ for simulations with waves, where $L_{\rm sz}$ is the surf-zone width. This background surf-zone eddy viscosity is 5× smaller than tracer/drifter derived eddy diffusivity estimates for similar wave height and beach slope as surf-zone eddies dominate lateral mixing (Clark et al., 2010, 2011) and are resolved in these simulations. The vertical eddy viscosity K_V is given by the $k-\epsilon$ turbulence closure model (Warner et al., 2005) where (as commonly practiced, e.g., Kumar et al., 2012; Rodriguez et al., 2018) 15% of the wave dissipation is supplied as a surface turbulent kinetic energy flux, consistent with surf-zone turbulence observations (e.g., Feddersen, 2012). The remaining energy dissipation occurs in the surface roller (e.g., Feddersen & Trowbridge, 2005).

The 48 hr 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 a 1-D (vertical) T(z, t) evolution for runs that include SHF. The 1-D T(z, t) evolution is estimated via 48 hr 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.

Model forcing is representative of Southern California in Fall. Four forcing cases (I–IV) are considered: (I) a control case (denoted \emptyset) without external forcing and represents the evolution due to background mixing, that is, as determined by K_H and K_V ; (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) is 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° 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 $Q_{sw} = 750 \text{ W m}^{-2}$, is distributed over the water column following a double-exponential vertical decay for Jerlov water-type I (with 58% over 0.35 m and the remainder over 23 m, Paulson & Simpson, 1977). The short-wave cycle follows $\cos^2(2\pi\tau_s/\tau_{day})$ over solar time $\tau_s \in [6, 18 \text{ hr}]$, with solar day duration $\tau_{day} = 24 \text{ hr}$. Uniform (in space and time) surface long-wave outgoing radiation is applied. This results in periodic net surface heat flux Q_{net} (Figure 1c) with midday, $\tau_s = 12 \text{ hr}$, 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.

The transient evolution of SHF simulations will vary with the solar forcing phase at model initialization. This transient evolution is evaluated through four independent runs, referenced using superscript $i = \{1, 2, 3, 4\}$, which vary the solar time at initialization, $t_s = \{0, 6, 12, 18 \text{ hr}\}$ relative to periodic Q_{net} . In so doing, time relative to the solar day $\tau_s^{(i)}$ is given by

$$\frac{t_{s}^{(i)}}{t_{s}} = t + t_{s}^{(i)},$$
 (1)

where *t* is model time. This is illustrated in Figures 1c and 1d. Run *i* = 1 is initialized at midnight, $t_s^{(1)} = 0$ hr, giving solar time $\tau_s^{(1)} = t$ (green dot right of *i* = 1, Figure 1d), whereas run *i* = 3 is initialized midday, $t_s^{(3)} = 12$ hr, giving solar time $\tau_s^{(3)} = t + 12$ hr (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 from the bed with flux Q_{dye} centered on x = -50 m (magenta, Figure 1a). The tracer flux Q_{dye} is normalized such that a homogeneous plume confined to the SZ ($x > -L_{sz}$) has unit concentration (Kumar & Feddersen, 2017c), making *D* a measure of tracer dilution (e.g., D = 0.02 indicates a 1/50 decrease in plume concentration). The 48 hr simulations are intrinsically transient due to the initial conditions, forcing, and irreversible mixing. Thus, tracer evolution depends upon tracer release time. To account for this, four separate tracer releases are performed at 6 hr intervals following an initial 6 hr adjustment period for 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*, such that $D^{(i,j)}$ represents tracer from the *i*th SHF run and *j*th tracer release. The model time of the release is denoted $t_r^{(j)}$, and in Figure 1d the first release, at $t_r^{(1)} = 6$ hr, is indicated with a red square for SHF runs $i = \{1, 3\}$. The elapsed time since tracer release is

$$\tau_{\rm r}^{(j)} = t - t_{\rm r}^{(j)}.$$
 (2)

Both solar time $\tau_{s}^{(i)}$ and time since tracer release $\tau_{r}^{(j)}$ are used in the analysis.

2.2. Averaging Methods

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

$$\bar{c}^{(i)} = L_y^{-1} \int_0^{L_y} c^{(i)} \, \mathrm{d}y, \tag{3}$$

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 \bar{T} , cross-shore Lagrangian velocity \bar{u}_L , overturning streamfunction $\bar{\Psi}$, and vertical eddy diffusivity $\langle K_V \rangle$ are also time averaged over the 24 hr diurnal time-scale, that is,

$$\langle c^{(i)} \rangle^{24 \text{ hr}} = (\tau_{\text{day}})^{-1} \int_{6 \text{ hr}}^{30 \text{ hr}} c^{(i)} \, \mathrm{d}t,$$
 (4)

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

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

$$\langle \bar{D} \rangle_{\rm r}(x,z,\tau_{\rm r}) = \frac{1}{16} \sum_{i=1}^{4} \sum_{j=1}^{4} \bar{D}^{(i,j)}(x,z,\tau_{\rm r}^{(j)}), \tag{5}$$

where $\bar{D}^{(i,j)}$ is the alongshore mean tracer concentration field from the *i*th SHF run and *j*th tracer release, and $\tau_r \in (0, 24 \text{ hr}]$. The ensemble average (5) captures the tracer bulk time evolution by averaging over successively longer model spin-up times, for example, $t_r^{(1)} = 6$ hr versus $t_r^{(4)} = 24$ hr, and solar cycle timing, for example, $i = \{1, 3\}$ and j = 1 in Figure 1d. For ø and TRC simulations (i.e., no SHF) the release ensemble average is only over (*j*) and also denoted $\langle \bar{D} \rangle_r$.

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 $\tau_s = 0$ hr (midnight, Figure 2, left) and $\tau_s = 12$ hr (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 hr, giving solar time (1) $\tau_s^{(3)} = t + t_s^{(3)} = 24$ hr (Figures 1c and 1d). The concurrent tracer $D^{(3,1)}$ (i.e., release j = 1, Figures 2e and 2g) has tracer release time (2) $\tau_r^{(1)} = t - t_r^{(1)} = 6$ hr. Similarly, midday (i = 1) temperature $T^{(1)}$ (Figures 2b and 2d) has model time t = 12 hr, and tracer $D^{(1,1)}$ (Figures 2f and 2h) is at $\tau_r^{(1)} = 6$ hr. The surface temperature anomaly $\Delta T^{(i)}$ relative to the x = -150 m alongshore average surface temperature is used to enhance horizontal thermal structure (Figures 2a and 2b).

The midnight ($\tau_s = 0$ hr) $\Delta T^{(3)}$ (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 ≈ 3 m deep, whereas onshore temperature is well mixed to ≈ 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 subsurface $T^{(3)}$ (Figure 2c), subsurface $D^{(3,1)}$ 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 ($\tau_s = 12 \text{ hr}$). 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 \bar{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 (cf. Figure 2d to Figure 2c). $T^{(1)}$ isotherms also have complex cross-shore structure, for example, the 19.25 °C isotherm deepens from (x, z) $\approx (-475 \text{ m}, -1.5 \text{ m})$ 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 (Figures 2b and 2h). Midday $D^{(1,1)}$ and $\Delta T^{(1)}$ covariability at offshore surface fronts is similar to midnight. Subsurface $D^{(1,1)}$ (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 (Figures 2d and 2h). Offshore of $x \approx -500 \text{ m}$, $D^{(1,1)}$ also tends toward a subsurface maximum.

TRC generated eddies create the complex filamentous tracer and temperature patterns onshore of $x \approx -500 \text{ m}$ (Figure 2). Midday, eddies in this region heave isotherms and tracer (Figures 2d and 2h) inducing overturns that are mixed via increased $K_{\rm V}$ 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 subsurface tracer maximum (x < -500 m, Figure 2g).



Figure 2. Instantaneous SHF+TRC forced runs at solar midnight ($\tau_s^{(3)} = 0$ hr, left panels) and midday ($\tau_s^{(1)} = 12$ hr, right panels) (a,b) surface temperature anomaly $\Delta T^{(i)}$; (c,d) cross-shore subsurface temperature $T^{(i)}$; (e,f) surface; and (g,h) cross-shore subsurface tracer $D^{(i,1)}$. Surface panels (a,b,e,f) are functions of (*x*, *y*), and subsurface panels (c,d,g,h) are functions of (*x*, *z*) along *y* = 50 m (black dotted line in a,b,e,f). Snap-shots from model time t = 12 hr, such that solar time (1) is $\tau_s^{(i)} = 12 + t_s^{(i)}$ where $i = \{3, 1\}$, and in (e) and (f) time relative to tracer release (2) is $\tau_r = 12 - t_r^{(1)} = 6$ hr. The outer limit of the surf-zone $x = -L_{sz}$ is indicated with a black dashed line and the bottom is gray.



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Figure 3. SHF (left) and SHF+TRC (right) averaged fields as a function of (x, z). Alongshore and 24 hr time mean (3) and (4) and initialization ensemble averaged (a,b) velocity overturning streamfunction $\langle \bar{\Psi} \rangle^{24}$ hr contoured at $2 \times 10^{-3} m^2 s^{-1}$; (c,d) temperature $\langle \bar{T} \rangle^{24}$ hr contoured at 0.25*C*; and vertical eddy viscosity $\langle \bar{K}_V \rangle^{24}$ hr with contours at $\{10^{-5}, 10^{-4}, 10^{-3}\}m^2s^{-1}$. In (g) and (h) the alongshore mean and initialization and release ensemble averaged tracer concentration $\langle \bar{D} \rangle_r$ (5) is shown at $\tau_r = 24$ hr with overlaid $\langle \bar{T} \rangle^{24}$ hr contours from (c) and (d). Shown in (g) and (h) are $x_{50\%}$ (circle) and $x_{90\%}$ (diamond), bounding 50% and 90% of the tracer mass, respectively. For case TRC+SHF (right), $x = -L_{sz}$ is indicated with a vertical dashed line.

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 subsurface 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 hr time mean (3) and (4) and initialization ensemble averaged streamfunction $\langle \bar{\Psi} \rangle^{24 \text{ hr}}$, temperature $\langle \bar{T} \rangle^{24 \text{ hr}}$, and vertical eddy diffusivity $\langle K_V \rangle^{24 \text{ hr}}$ (Figures 3a–3f). For SHF, the mean overturning streamfunction $\langle \bar{\Psi} \rangle^{24 \text{ hr}}$ is relatively weak and retains the signature of warming response exchange circulation, with near-surface offshore flow $\langle \bar{u}_L \rangle^{24 \text{ hr}} \approx -1 \times 10^{-3} \text{ m s}^{-1}$ for x > -950 m (Figure 3a). The SHF $\langle \bar{T} \rangle^{24 \text{ hr}}$ 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 $\langle \bar{\Psi} \rangle^{24 \text{ hr}}$ is markedly different owing to TRC-driven modification of $\langle \bar{T} \rangle^{24 \text{ hr}}$ (Figures 3b and 3d). The SHF+TRC $\langle \bar{\Psi} \rangle^{24 \text{ hr}}$ has a prominent inner-shelf circulation cell offshore of $x \approx -300 \text{ m}$, with subsurface offshore directed flow $\langle \bar{u}_L \rangle^{24 \text{ hr}} < -3 \times 10^{-3} \text{ m s}^{-1}$ to $x \approx -600 \text{ m}$ (Figure 3d). Similar to SHF, the SHF+TRC $\langle \bar{T} \rangle^{24 \text{ hr}}$ surface diurnal mixed layer is $\approx 4 \text{ m}$ thick for $x \lesssim -1,000 \text{ m}$ (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 $\langle \bar{\Psi} \rangle^{24}$ hr and $\langle \bar{T} \rangle^{24}$ hr are largely due to inner-shelf TRC vertical mixing. The relatively flat SHF inner-shelf isotherms (Figure 3c) are reflected in the relatively flat $\langle K_V \rangle^{24}$ hr contours, which deepen at $x \approx -200$ m, where the hr becomes comparable to the diurnal mixed layer depth (Figure 3e). In contrast, the SHF+TRC $\langle K_V \rangle^{24}$ hr contours progressively deepen onshore for x > -1,000 m (Figure 3f) and SHF+TRC $\langle K_V \rangle^{24}$ hr is 10× that of SHF for x > -300 m. The shoreward enhanced vertical mixing is due to TRC effects. In TRC-only runs (not shown), K_V increases > 1 order of magnitude onshore of x = -400 m, consistent with Kumar and Feddersen (2017a, Figure 8b). Additionally, the shoreward broadened SHF+TRC isotherms that drive the inner-shelf overturning streamfunction are similar to the TRC-only case (cf. Figure 5 in Kumar & Feddersen, 2017c).

These SHF and SHF+TRC differences in $\langle \bar{\Psi} \rangle^{24}$ hr and $\langle \bar{T} \rangle^{24}$ hr result in differences in the alongshore, initialization, and release ensemble averaged tracer $\langle \bar{D} \rangle_r$ (5) at $\tau_r = 24$ hr (Figures 3g and 3h). The 24 hr SHF $\langle \bar{D} \rangle_r$ is nearly all onshore of x = -500 m, and offshore of $x \approx -200$ m, SHF $\langle D \rangle_r$ has a bimodal vertical structure suggesting tracer exchange occurs incrementally at each phase of diurnal thermal exchange. At $\tau_r = 24$ hr, the SHF+TRC $\langle \bar{D} \rangle_r$ extends offshore to x = -1,000 m and the SHF+TRC shoreline $\langle \bar{D} \rangle_r$ is 1/3 that of SHF. SHF+TRC $\langle \bar{D} \rangle_r$ has a prominent subsurface tracer maximum for x < -400 m, following the 24 hr mean streamlines in Figure 3b. In TRC-only runs (not shown), the subsurface tracer maximum is more pronounced (cf. Kumar & Feddersen, 2017c, Figure 2b), relative to SHF+TRC, because SHF-induced surface mixing slightly weakens vertical tracer gradients above z = -4 m in Figure 3h. Thus, enhanced SHF+TRC exchange relative to SHF+only is likely due to the alongshore and 24 hr 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,

$$\langle M \rangle_{\rm r}(x,\tau_{\rm r}) = L_y \int_x^0 \int_{-h}^{\eta} \langle \bar{D} \rangle_{\rm r}(x',z,\tau_{\rm r}) \,\mathrm{d}z \,\mathrm{d}x', \tag{6}$$

where η is the sea-surface. The domain-total tracer mass is denoted M_{∞} , such that the tracer mass fraction onshore of x is $\langle M \rangle_r / M_{\infty}$ and two locations are highlighted $x_{50\%}$ and $x_{90\%}$ bounding 50% and 90% of the tracer mass, respectively. At $\tau_r = 24$ hr, SHF $x_{50\%} \approx -240$ m and $x_{90\%} \approx -380$ m (circle and diamond, respectively, in Figure 3g). In contrast, at $\tau_r = 24$ hr the SHF+TRC $x_{50\%} \approx -440$ m and $x_{90\%} \approx -760$ m (circle and diamond, respectively, Figure 3h), quantifying the stronger SHF+TRC exchange.

The time dependence of SHF and SHF+TRC ensemble averaged tracer mass fraction $\langle M \rangle_r / M_{\infty}(x, \tau_r)$ (6) is shown in Figures 4a and 4b. At $\tau_r = 0$ hr, $\langle M \rangle_r / M_{\infty} = 1$ for x < -100 m, as tracer is released over x > -100 m. Over time, $\langle M \rangle_r / M_{\infty}$ contours progress offshore (e.g., $x_{90\%}$ in Figures 4a and 4b) indicating cross-shore tracer transport. The $\langle M \rangle_r / M_{\infty}$ 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 ($\tau_r \leq 3$ hr) cross-shore tracer transport is offshore with $x_{90\%}$ moving at ≈ 2.5 cm s⁻¹ (dotted line, Figure 4a). Shortly thereafter ($3 < \tau_r < 8$ hr), SHF offshore transport slows or even reverses (see $x_{50\%}$ in Figure 4a), likely due to flow reversal during warming-to-cooling transition (and vice versa). After $\tau_r = 12$ hr, transport is offshore but slow with $x_{50\%}$ and $x_{90\%}$ moving offshore at <0.3 cm s⁻¹. For SHF+TRC, early ($\tau_r \leq 3$ hr) cross-shore tracer transport is SHF, with $x_{90\%}$ moving at ≈ 3.5 cm s⁻¹ (dotted line, Figure 4b). In contrast to the SHF reversal, SHF+TRC $\langle M \rangle_r / M_{\infty}$ contours continuously progress offshore, although at a progressively slower rate.

The bulk cross-shore tracer transport across all forcing cases is evaluated with the $x_{90\%}$ time evolution (Figure 4c). In the unforced ø run (brown curve, Figure 4c), background diffusive mixing induces weak exchange, and $x_{90\%} > -110$ m, indicating strong tracer confinement. In contrast, over 24 hr, 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 hr, 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.



Figure 4. Normalized integrated tracer mass $\langle M \rangle_r / M_{\infty}$ evolution as a function of time since tracer release τ_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 ±1 root-mean-square deviation σ from the ensemble average (shading). In (b) and (c) the SZ boundary is indicated by a dashed black line.

4. Discussion and Conclusions

4.1. Quantifying Exchange: Tracer Flux and Velocity Derived Estimates

Cross-shore tracer transport \mathcal{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 $\langle M \rangle_r$ (6) via (Hally-Rosendahl et al., 2015; Feddersen et al., 2016)

$$\mathcal{T}_{x}(x,\tau_{\mathrm{r}}) = \frac{\partial \langle M \rangle_{\mathrm{r}}}{\partial \tau_{\mathrm{r}}}.$$
(7)

Cross-shore transport potential is often represented with an exchange velocity u_{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),

$$\zeta_x \propto u_{\rm EX} L_{\nu}(\tilde{h}\tilde{D}),$$
(8)

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

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Although u_{EX} is a useful metric, the assumptions in (8) grossly approximate the tracer conservation equation governing T_x ; as such, u_{EX} estimates will depend on definition. Here, two unique u_{EX} definitions are



Figure 5. 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}^L (dashed) defined using offshore Lagrangian velocities (10), and \bar{u}_{EX}^L defined using alongshore mean offshore Lagrangian velocities are 24 hr time mean and initialization ensemble averaged; u_{EX} is also ensemble averaged over all releases and is only computed where $\partial \langle M \rangle_r / \partial x > 10^{-8}$.

examined. Leveraging (7) and substituting $L_y(\tilde{h}\tilde{D}) = \partial \langle M \rangle_r / \partial x$ in (8) yields a tracer-derived exchange velocity,

$$u_{\rm EX}^{M} = \left\langle \frac{\partial \langle M \rangle_{\rm r}}{\partial \tau_{\rm r}} \left(\frac{\partial \langle M \rangle_{\rm r}}{\partial x} \right)^{-1} \right\rangle^{24 \, \rm hr},\tag{9}$$

where the outer average $\langle \rangle^{24}$ hr is over $0 < \tau_r \leq 24$ hr. Although u_{EX}^M encapsulates recirculation, tracer presence is required, and (9) is only evaluated for $\partial \langle M \rangle_r / \partial x > 10^{-8} m^2$, or $\tilde{h}\tilde{D} > 10^{-5}$ m. As an alternative, a Lagrangian velocity derived exchange u_{EX}^L is based on cross-shore flow alone (e.g., MacCready, 2011; Suanda & Feddersen, 2015),

$$u_{\rm EX}^L = \langle \frac{2}{h+\eta} \int_{-h}^{\eta} u_{\rm L} dz \rangle^{24 \rm hr}, \qquad (10)$$

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

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

For TRC and SHF+TRC, inner-shelf eddy velocities increase toward $x = -L_{sz}$, and the growing difference between u_{EX}^M and u_{EX}^L for x > -400 (Figure 5) is likely due to eddy recirculation that bias high u_{EX}^L . To account for recirculation in u_{EX}^L , an exchange 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 (Dalrymple et al., 2011; Suanda & Feddersen, 2015; Smith & Largier, 1995), consistent with the differences between u_{EX}^M and u_{EX}^L for x > -400 m.

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

$$u_{\rm EX}^{L} = \langle \frac{2}{h + \bar{\eta}} \int_{-h}^{\bar{\eta}} \bar{u}_{\rm L} \, d\bar{z} \rangle^{24 \, \rm hr}, \tag{11}$$

where the alongshore average (3), 24 hr and initialization ensemble average (4) are applied. Thus, for non-eddying SHF, estimates of u_{EX}^L and $u_{EX}^L b$ are indistinguishable (Figure 5). The TRC and SHF+TRC $u_{EX}^L b$

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(dotted curves, Figure 5) are much lower than u_{EX}^L 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 $u_{EX}^L b$ and u_{EX}^M for x < -200 m indicates that enhanced 24 hr 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 = -1, 200 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 = -1, 200 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 subsurface offshore directed flow. For quasi-instantaneous surf-zone tracer release, this subsurface 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 climates 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., Davis et al., 2011; Hench et al., 2008), may diminish TRC exchange relative to persistent diurnal thermally driven exchange. Other mechanisms influencing inner-shelf stratification and hydrodynamics, for example, 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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