The effect of barotropic and baroclinic tides on coastal dispersion

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The effects of barotropic and baroclinic tides on coastal drifter dispersion are examined with realistic high-resolution Central Californian shelf simulations. For virtual drifters tracked in three-dimensions over 48 h, the horizontal relative dispersion and vertical dispersion are similar between simulations with no tides and with barotropic tides. In contrast, including baroclinic tides induces a factor 2–3 times larger horizontal dispersion and a factor 2 times larger vertical dispersion. Vertical dispersion is enhanced by baroclinic tides through increased vertical velocities and sub-surface model vertical diffusivity. The increase in horizontal dispersion with vertical mixing is qualitatively consistent with weak-mixing shear dispersion and demonstrates the need to include baroclinic tides and three-dimensional tracking for coastal passive tracer dispersion. For surface following drifters, horizontal dispersion is similar in all simulations. However, after 48 h ensemble drifter trajectory differences between simulations with no tides and baroclinic tides are 10 km, suggesting their importance for search-and-rescue or oil-spill response operations.
1. Introduction

Tracer dispersion in the coastal ocean is relevant to pollutant dispersal [e.g., Boehm et al., 2002; Macfadyen et al., 2011; Poje et al., 2014], search-and-rescue operations [e.g., Spaulding et al., 2006], and the connectivity of marine organisms [e.g., Pineda et al., 2007; Cowen and Sponaugle, 2009]. Lagrangian analysis of surface-following drifters [e.g., Davis, 1985; Spydell et al., 2009; Ohlmann et al., 2012], dye releases [e.g., Sundermeyer and Ledwell, 2001; Dale et al., 2006; Clark et al., 2010; Moniz et al., 2014; Hally-Rosendahl et al., 2014], and virtual drifter tracking with high-frequency radar velocities [e.g., Rypina et al., 2016], provide estimates of dispersal patterns and dispersion rates at different space- and time-scales that inform coastal resource management. Due to limited Lagrangian observations, marine connectivity [Mitarai et al., 2009; Petersen et al., 2010; Drake et al., 2011] and pollutant dispersion [e.g., Thyng and Hetland, 2017] are also estimated by virtual drifters advected with realistic numerical models.

The broad range of space- and time-scales from the nearshore ($O(10)$ m and $O(1)$ min) to the outer continental shelf ($O(10)$ km, $O(1)$ day), also present a challenge to coastal numerical modeling. Regional operational models such as those from Integrated Ocean Observing Systems (https://ioos.noaa.gov/) can well-represent wind-driven and mesoscale dynamics [e.g., Veneziani et al., 2009], but typically have relatively coarse horizontal resolution ($O(1 - 3)$ km) and poorly resolve continental shelf circulation from the shoreline to 100-m water depth [e.g., Mitarai et al., 2009; Drake et al., 2011]. Both a U. S. West-Coast wide dispersal study with a 3-km resolution model [Drake et al., 2011] and regional study with a 1-km resolution model [Mitarai et al., 2009], describe the effects of large space-scale ($> 10$ km) and long time-scale ($> 10$ day) dispersion processes. Because $< 1$-km spatial scales within a model can impact
coastal dispersion estimates [e.g., Rasmussen et al., 2009; Bracco et al., 2018], these processes are resolved by further model nesting [e.g., Romero et al., 2013], or parameterized within the Lagrangian submodel [e.g., Lacorata et al., 2014; Rypina et al., 2016]. For oil-spill response applications, or to compare with surface-following drifter observations, some model-based dispersion studies focus on near-surface horizontal (two-dimensional, 2D) dispersion [e.g., Ohlmann and Mitarai, 2010; Romero et al., 2013; Thyng and Hetland, 2017]. However, non-buoyant tracers such as pollutants, nutrients, and larvae are advected by the full three-dimensional (3D) flow field, with a potentially important relationship between horizontal and vertical dispersion.

Many previous U. S. West-Coast model-based dispersion studies have not included tides [e.g., Mitarai et al., 2009; Drake et al., 2011; Kim and Barth, 2011]. Although hindcast [Kurapov et al., 2017] and operational models [Chao et al., 2017] of the region have recently incorporated tides, dispersion studies with realistic models that incorporate tides remain limited [e.g., Romero et al., 2013]. Barotropic (surface) and baroclinic (internal) tides potentially impact dispersion through processes including barotropic tidal rectification [e.g., Ganju et al., 2011], internal wave shear dispersion [Young et al., 1982; Steinbuck et al., 2011; Kunze and Sundermeyer, 2015], and internal wave Stokes’ Drift [Wunsch, 1971]. In realistic coastal models, the importance of including barotropic (BT) and baroclinic (BC) tides relative to coastal processes driven by winds, stratification, and bathymetric variability on tracer dispersion is not well understood.

In a study using a high resolution (250-m grid spacing) coastal model that included BT and BC tides, horizontal dispersion was due to a combination of submesoscale processes and tides [Romero et al., 2013]. However, no distinction between BT and BC tidal effects were made and...
no direct comparison of dispersal rates or drifter trajectories between models that include and neglect tides were provided.

The effect of BT and BC tides on mid- to inner-shelf stratification and vertical mixing were examined using three Central California (U.S. West-Coast) simulations with identical realistic wind and large-scale boundary conditions but with either no-tides, BT-only tides, or both BT and BC tides [Suanda et al., 2017]. Tidal effects were isolated by analysis of a time period with similar volume-averaged heat content and upwelling mean flows in the three simulations. Relative to simulations without BC tides, the onshore-propagating dissipating baroclinic tide increased mid-water column vertical mixing and reduced subtidal stratification with comparable magnitude to the observed natural seasonal cycle [Suanda et al., 2017]. Here, the effects of BT and BC tides on 3D and surface-following (2D) coastal dispersion are examined with a Lagrangian drifter study using the three simulations of Suanda et al. [2017].

The model setup, drifter tracking methods, and Lagrangian statistics are described in Section 2. Horizontal and vertical dispersion statistics in the no-tides, BT-tides, and BC-tides simulations are compared in Section 3. The mechanisms inducing additional vertical and horizontal dispersion with BC tides, the differences between 3D and 2D dispersion, and the trajectory difference between simulations are discussed in Section 4. Results are summarized in Section 5.

2. Model and Methods

2.1. ROMS simulations

Realistic continental shelf hydrodynamics within the Central Californian coastal upwelling system are simulated with ROMS (Regional Ocean Modeling System), a three-dimensional, terrain-following, open source numerical model that solves the Reynolds-averaged
Navier-Stokes equations with hydrostatic and Boussinesq approximations [Shchepetkin and McWilliams, 2005; Haidvogel et al., 2008; Warner et al., 2010]. The ROMS setup is briefly described here with further details in Suanda et al. [2016, 2017]. Three levels of offline nesting (downscaling) transmit large scale variability through open boundary conditions from a U. S. West-Coast-wide ocean simulation to a continental shelf domain [e.g., Marchesiello et al., 2001; Mason et al., 2010; Suanda et al., 2017]. The shelf domain is about 80-km by 25-km wide, with a horizontal grid spacing of 200 m, and 42 vertical levels (Fig. 1). The $k-\epsilon$ turbulence closure model, representing subgrid vertical mixing, gives the time- and space-varying vertical eddy diffusivity $K_V$ [e.g., Umlauf and Burchard, 2005; Warner et al., 2005]. All levels of nesting use the same realistic COAMPS daily-averaged atmospheric forcing with $\approx 9$-km resolution [Hodur et al., 2002]. The model is run for 60 days from 1 June to 31 July 2000.

Three continental shelf simulations are conducted. The first has no barotropic or baroclinic tides (referred to as no-tides, NT). A second simulation includes barotropic tides (local tides, LT) by adding harmonic sea level and barotropic velocity of eight astronomical semidiurnal and diurnal tidal constituents and two overtones from the ADCIRC Tidal Constituent Database for the Eastern North Pacific Ocean [e.g., Mark et al., 2004] to the domain open boundaries (Fig. 1a). The third simulation has both barotropic and baroclinic tides (with-tides, WT), inheriting boundary conditions with the addition of the ADCIRC barotropic tidal forcing applied on the prior level of nesting. Barotropic-to-baroclinic tidal conversion within the larger domain results in a net onshore, remotely-generated, semidiurnal internal tide energy flux of $\approx 100\text{ W m}^{-1}$ on the boundary of the continental shelf domain [Suanda et al., 2017].

2.2. Lagrangian drifter tracking (LTRANS)
In the three simulations (WT, LT, NT), virtual Lagrangian drifters are released and tracked with the offline software package LTRANS [North et al., 2006], utilizing the ROMS model three-dimensional (3D) and time-dependent velocities and diffusivity. In the East-West ($x$) direction drifters are advected by,

$$x_{n+1} = x_n + u \delta t + [2K_H \delta t]^{1/2} R_n,$$

where $x_n$ is the drifter $x$-position at time-step $n$, $u$ is the ROMS $x$-velocity interpolated to drifter position, $K_H = 1 \text{ m}^2 \text{s}^{-1}$ is a constant horizontal diffusivity, the LTRANS time-step $\delta t = 120 \text{ s}$, and $R_n$ is a normally-distributed random number. North-South ($y$) drifter advection is analogous to (2). Vertical ($z$) drifter advection is given by

$$z_{n+1} = z_n + \left( w + \frac{\partial K_V}{\partial z} \right) \delta t + [2K_V \delta t]^{1/2} R_n,$$

where the space- and time-dependent vertical diffusivity $K_V$ from $k-\epsilon$ closure is interpolated to the drifter position. Because $K_V$ varies in $z$, an additional term $\partial K_V / \partial z$ is included to account for Lagrangian advection to regions of high diffusivity [e.g., Davis, 1991; North et al., 2006; Schlag and North, 2012].

### 2.3. Drifter releases

The specific five-day time period of upwelling-favorable conditions and similar heat content across NT, LT, WT [Suanda et al., 2017], was chosen for drifter release experiments. Time-dependent model winds were from the northwest, increasing in intensity from $\approx 5 \text{ m s}^{-1}$ to $\approx 10 \text{ m s}^{-1}$ over the five days (Fig. 1c). Barotropic tides had a 2 m maximum tide range (Fig. 1d), and were very similar in LT and WT [Suanda et al., 2017].
In each simulation, drifters are repeatedly released in two near-surface patches centered on the 30- and 50-m isobaths in regions of relative along-shore uniformity (black dots, Fig. 1 a). Each patch extends 500 m by $\approx 4$ km by 2 m in the cross-, along-isobath, and vertical directions with release spacing of 125 m, 200 m and 1 m respectively (Fig. 1b). A total of twenty one releases separated by $\Delta t = 6$ h were conducted over the 5-day period resulting in 6300 drifters in each patch. After release, drifters are tracked for 48 h. Drifters crossing land, sea-surface, or bottom boundaries are specularly reflected. In 48 h, $\approx 2\%$ of released drifters leave the model domain and are only included in the analysis when within the domain.

2.4. Drifter statistics

Bulk drifter relative dispersion rates are quantified by temporal growth in drifter position variance from the 30- and 50-m isobath releases, respectively. The time-staggered releases are recast into hours after release $t$ [e.g., Davis, 1983]. In the $x$-direction, the patch relative dispersion $D_{xx}^2$ [e.g., LaCasce, 2008; Rypina et al., 2016] is

$$D_{xx}^2(t) = \langle (\Delta x(t) - \overline{\Delta x_i}(t))^2 \rangle,$$

(3)

where $\Delta x(t)$ is a drifter’s East-West displacement from release location, $\overline{\Delta x_i}$ is the mean East-West displacement of all drifters in a release $i$ (center of mass), and the ensemble average $\langle \cdot \rangle$ is over all drifters in a release and all 21 releases. An analogous expression to (3) is defined in the North-South ($y$) direction ($D_{yy}^2(t)$) and also for the cross-dispersion $D_{xy}^2(t)$. These $D^2$ components are used to define principal axes directions ($x', y'$) such that $D_{yy'}^2$ and $D_{x'y'}^2$ are the relative dispersion in the major and minor axis direction, respectively [e.g., Sundermeyer and Ledwell, 2001; Romero et al., 2013; Rypina et al., 2016]. The principal axes dispersion defines
a bulk horizontal relative dispersion ellipse with area (ensemble patch size),

\[ D_E^2(t) = \pi(D_{xx}^2 D_{yy}^2)^{1/2}. \]  

(4)

The horizontal diffusivity \( K_E \) is based on the time-derivative of ellipse area,

\[ K_E(t) = \frac{1}{2} \frac{dD_E^2}{dt}, \]  

(5)

where derivatives are estimated as forward Euler differences. To minimize error in noisy estimates of \( K_E \), a time-smoothing box car filter with linearly increasing span up to 24 h is used before calculating the time derivative.

In the vertical (\( z \)), the relevant statistic is absolute dispersion as the sea-surface is adjacent to the release location [e.g., Clark et al., 2010; Spydell and Feddersen, 2012]. The absolute vertical dispersion \( D_{zz}^2 \) is defined as,

\[ D_{zz}^2(t) = \langle (\Delta z(t))^2 \rangle, \]  

(6)

where \( \Delta z \) is the drifter displacement from its release location. A corresponding vertical diffusivity \( K_z \) is defined analogous to the horizontal diffusivity (5).

3. Results

A snapshot of drifter positions at \( t = 30 \) h for all 30-m isobath releases shows the initial center of mass and dispersal pattern in the NT, LT, and WT simulations (Fig. 2a–c). In all three simulations, the release center of mass (white circles, Fig. 2a–c) has migrated south and offshore of their initial location (white strip, Fig. 2a), consistent with coastal upwelling. Drifters remain onshore of the shelf-break (\( \approx 100 \)-m isobath) and form alongshore-elongated patches, as in previous studies [e.g., Davis, 1985; Dever et al., 1998; Romero et al., 2013]. In
geographic coordinates, the alongshore drifter dispersion in WT (Fig. 2c) is larger than in NT or LT (Fig. 2a,b).

### 3.1. Horizontal relative dispersion

In all three simulations with 30-m isobath releases, the relative dispersion major axis is $3-4 \times$ larger than the minor-axis (Fig. 2d–f) at $t = 30$ h. At this time, the horizontal relative dispersion ellipse area $D_E^2$ (4) is very similar between NT and LT (Fig. 2d, e). In contrast, the WT $D_E^2$ is about twice as large as NT and LT (Fig. 2f). The drifter probability distribution in both $x'$ and $y'$ directions are similar in NT and LT (shaded curves, Fig. 2d, e). The WT simulation probability distributions are significantly wider (Fig. 2f) consistent with the larger $D_E^2$. Results are similar for the 50-m isobath release.

Time series of bulk ellipse area $D_E^2(t)$ (4) and bulk diffusivity $K_E(t)$ (5) further quantify the dispersion differences between WT, NT and LT for 30-m and 50-m isobath releases (Fig. 3). For $t < 10$ h, drifters occupy less than 3 km$^2$ (Fig. 3a–b), with rapidly increasing $K_E$ (Fig. 3c–d) for both 30-m and 50-m isobath releases in all simulations. For longer times ($t > 10$ h), $D_E^2$ and $K_E$ continue increasing but without a clear indication of reaching a diffusive limit of constant $K_E$. Over the 48 h, NT and LT $D_E^2$ and $K_E$ are similar while WT $D_E^2$ and $K_E$ are a factor $2-3 \times$ larger than NT and LT for both 30-m and 50-m releases (Fig. 3). The similarity between LT and NT horizontal dispersion statistics indicates that at this location barotropic tides only induce a weak increase in horizontal dispersion relative to the horizontal stirring in NT. In contrast, baroclinic tides induce a $2-3 \times$ increase in horizontal dispersion statistics.

### 3.2. Vertical drifter dispersion
Increased horizontal dispersion in WT relative to NT and LT is also mirrored in the vertical drifter dispersion. At $t = 24$ h the NT and LT vertical drifter distributions are similar (green and red lines, Fig. 4a) having dispersed from their near-surface release ($-3 \leq z \leq -1$ m) down to about $z = -12$ m, with no drifers below $z = -15$ m. In contrast, the WT simulation has a smaller near-surface drifter fraction relative to NT and LT with substantial drifter fraction below $z = -15$ m (black line, Fig. 4a). After 48 h, drifter dispersion $D_{zz}^2$ is about $50$ m$^2$ in NT and LT, whereas WT $D_{zz}^2$ is 4 times larger than NT and LT (Fig. 4b). For WT, the vertical diffusivity $K_z$ is fairly constant over the 48 h (Fig. 4c), implying diffusive vertical drifter dispersal. The NT and LT $K_z$ are similar, initially increasing and becoming approximately constant for $t > 30$ h (Fig. 4c), suggesting that barotropic tides do not have a large effect on the vertical dispersion of near-surface released drifters. For $t < 24$ h, the WT $K_z$ is factor 5–10× larger than the LT and NT $K_z$. For longer times ($t > 40$ h), the WT $K_z$ is a factor of 2–2.5× larger than LT and NT. Thus, baroclinic tides in this region also significantly increase drifter vertical dispersion.

### 3.3. Eulerian profiles

Root-mean-square (rms) Eulerian profiles of horizontal speed ($V = (u^2 + v^2)^{1/2}$), shear ($S = ((\partial_z u)^2 + (\partial_z v)^2)^{1/2}$), vertical velocity $w$, and model vertical eddy diffusivity $K_V$ (Fig. 5) are examined to understand differences between WT, NT and LT horizontal and vertical drifter dispersion. Here, the rms is taken through both time (5 day period, 01–06 July) and space (20 km following the 30-m isobath) and includes both tidal and subtidal time-scales. The vertical profiles of rms($V$) (Fig. 5a) and rms ($S$) (Fig. 5b) are not significantly affected by the presence of BT or BC tides. This suggests that the increased WT horizontal dispersion is not due to horizontal stirring processes. In all three simulations, model rms($K_V$) are generally similar in
the upper 10-m (Fig. 5c) as wind-driven processes dominate near-surface mixing [e.g., Allen et al., 1995; Austin and Lentz, 2002; Wijesekera et al., 2003], and are not significantly modified by BT or BC tides [Suanda et al., 2017]. This 10-m thick surface layer roughly corresponds to the depth reached by NT and LT drifters after 24 hours (Fig. 4a). Note, that in this upper layer the rms($K_V$) are dominated by the time mean. Below $z = -10$ m, WT rms($K_V$) is larger than NT or LT due to dissipating BC tides [Suanda et al., 2017]. Throughout the water column, WT rms($w$) is significantly (4–5×) larger than in the NT and LT simulations (Fig. 5d). The WT rms($w$) vertical profile has mid-water column maximum, similar to the expected structure of a mode-1 baroclinic tide. The additional vertical stirring provided by WT rms($w$) together with the sub-surface enhanced WT rms($K_V$) induces increased vertical drifter dispersion relative to NT and LT (Fig. 4).

4. Discussion

4.1. Shear dispersion due to coastal baroclinic tides

Horizontal dispersion in the NT and LT simulations is presumably due to horizontal stirring by coastal eddies on length-scales spanning 1–10 km (Fig. 2). As the WT, LT, and NT simulations all have similar rms horizontal velocities (Fig. 5a), the horizontal stirring is likely similar and cannot explain the enhanced $D_H^2$ and $K_E$ in WT. In WT, increased vertical mixing by baroclinic tides potentially induces additional horizontal dispersion through shear dispersion [e.g., Young et al., 1982; Steinbuck et al., 2011]. Classic vertical shear dispersion [e.g., Taylor, 1953], an asymptotic state with vertically-uniform drifter distribution (i.e., strong mixing), has horizontal diffusivity inversely proportional to the vertical diffusivity, contrary to the results here.
However, shear dispersion in an unbounded fluid [Saffman, 1962] or with weak mixing [Young et al., 1982], $K_E$ increases with $K_z$.

For the 30-m isobath release, the near-surface released WT drifters are concentrated in the upper-half of the water column (Fig. 4a) and $D_{zz}^2 < h^2$ over 48 h (Fig. 4b), indicating no influence of the lower boundary. Furthermore, Young et al. [1982] introduce a non-dimensional parameter $k^* = K_z m^2/\omega$ to distinguish strong ($k^* \gg 1$) and weak ($k^* \ll 1$) mixing regimes, where $m$ and $\omega$ are the vertical wavenumber and frequency of oscillatory shear, respectively. Applied to the WT simulation at the 30-m isobath, the $t = 48$ h WT vertical diffusivity is $K_z = 4.7 \times 10^{-4} \text{ m}^2\text{s}^{-1}$ (Section 3.2) and a mode-1 semi-diurnal (12.42 h period) internal tide has $m = \pi/h = 0.1 \text{ rad/m}$ and $\omega = 1.4 \times 10^{-4} \text{ rad/s}$. This yields $k^* = 0.03$, indicating a weak mixing regime where horizontal dispersion increases with vertical dispersion. This is consistent with the larger horizontal and vertical dispersion in the WT simulation relative to NT and LT.

4.2. Horizontal dispersion with 2D surface tracking

Three-dimensional (3D) drifter evolution is not necessarily important for all coastal tracers. For example, planning for search-and-rescue or oil-spill response applications require knowledge of surface-following (2D) horizontal relative dispersion statistics over time. This raises the question of whether including BT and BC tides is similarly important to accurately represent the horizontal dispersion of surface-following material. Here, the $z = -1 \text{ m}$ near-surface released drifters are advected only in the horizontal, thus maintaining a constant $z$-level as a surface drifter. Lagrangian statistics from 2D-advection are denoted $WT_{2D}$, and are not affected by shear dispersion. The full 3D tracking with mixing (Section 3) for $z = -1 \text{ m}$ released drifters is denoted $WT_{3D}$, with a similar distinction for NT and LT simulations.
The horizontal $D_E^2$ and $K_E$ in WT$_{2D}$ is about eight times smaller than the WT$_{3D}$ tracking after 48 h (Fig. 6a). Both NT and LT 2D $K_E$ values are smaller than their 3D counterparts (dashed curves in Fig. 6a compared to solid curves Fig. 3a), reinforcing the connection between vertical motion and increased horizontal drifter dispersion. Furthermore, the $K_E$ for WT$_{2D}$, NT$_{2D}$, and LT$_{2D}$ are similar, indicating that including BT or BC tides does not significantly alter 2D horizontal relative dispersion statistics within realistic coastal simulations. Thus in this region, BC and BT tides can be neglected in operational models used for planning oil-spill plume sizes [e.g., Thyng and Hetland, 2017; Macfadyen et al., 2011] or other applications that require surface-following horizontal relative dispersion statistics.

In practice, specific search-and-rescue or oil-spill response missions require actual drifter trajectories, not relative dispersion statistics. To quantify the difference in individual drifter trajectories between WT$_{2D}$ and NT$_{2D}$, an ensemble separation statistic $\bar{s}^{(WN)}$ is defined as

$$\bar{s}^{(WN)}(t) = \langle [\Delta x^{(WN)}(t)]^2 + [\Delta y^{(WN)}(t)]^2 \rangle^{1/2},$$

where $\Delta x^{(WN)}(t)$ and $\Delta y^{(WN)}(t)$ are the time-dependent East-West and North-South separations from individual release locations between the WT$_{2D}$ and NT$_{2D}$ simulations, respectively, and the ensemble average $\langle \cdot \rangle$ is over all drifter trajectories and releases. The ensemble LT$_{2D}$ and NT$_{2D}$ separation $\bar{s}^{(LN)}$ is similarly defined as in (7).

The WT$_{2D}$ and NT$_{2D}$ ensemble separation $\bar{s}^{(WN)}$ grows with time, with values of $\bar{s}^{(WN)} = 4$ km at $t = 24$ h and $\bar{s}^{(WN)} = 10$ km at $t = 48$ h (Fig. 6b). The magnitude of $\bar{s}^{(WN)}$ is significantly greater than the WT$_{2D}$ relative horizontal dispersion $D_E$ (Fig. 6a). Although the bulk relative dispersion is similar between WT$_{2D}$ and NT$_{2D}$, individual particle trajectories are substantially different and reflect the importance of BC tides. In contrast, the ensemble...
separation $s^{\text{LN}}$ is much smaller than $s^{\text{WN}}$, reaching only $s^{\text{LN}} = 2 \text{ km at } t = 48 \text{ h}$, and is comparable in magnitude to the LT$_{2D}$ relative horizontal dispersion $D_E$ (Fig. 6a). As BT tidal currents are relatively small and predictable on the Central Californian coast [Rosenfeld et al., 2009; Buijsman et al., 2011; Suanda et al., 2017], adding BT tides to models will result in a small decrease in drifter trajectory uncertainty. For a model with BC tides, trajectory uncertainty can increase if the BC tide amplitude and phase is incorrect. This region has strong BC tides from multiple sources [Kumar et al., 2017; Buijsman et al., 2011] with BC tidal phasing that is difficult to predict [Nash et al., 2012] due to background stratification changes and coastal eddies. Thus, BC tides in a model must be well validated to be used for operational missions.

5. Summary

The effects of BT and BC tides on coastal drifter dispersion are examined with realistic high-resolution Central Californian shelf simulations. For 3D tracked drifters over 48 h, the horizontal relative dispersion and vertical dispersion are similar between simulations with no tides and with BT tides. In contrast, BC tides induce a factor 2–3 times larger horizontal dispersion and a factor 2 times larger vertical dispersion through increased vertical velocities and subsurface model vertical diffusivity. The increase in horizontal dispersion with vertical mixing is qualitatively consistent with weak-mixing shear dispersion. For surface-following (2D) drifters, horizontal relative dispersion is similar in the WT, LT, and NT simulations, and much weaker than the horizontal dispersion in WT with 3D-tracking. In contrast, after 48 h drifter trajectory differences between simulations with no tides and BC tides are 10 km, much larger than horizontal relative dispersion estimates from an individual model. This suggests the importance of BC tides for search-and-rescue or oil-spill response operations. However, these results results
apply to the Central Californian continental shelf region and requires accurate BC tide predictions. Other regions have different relative strengths of BC and BT tides, which will affect their relative importance on coastal dispersion with both 3D-tracking and 2D-tracking.

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Figure 1. (a) Continental shelf model domain. Bathymetry is contoured in white curves in 10 m increments with the 100 m isobath highlighted by the black and white curve. Black dots denote release locations of near-surface drifters along the 30- and 50-m isobaths. (b) Schematic of a portion of the drifter release pattern expanded from black square in panel a. The dashed line is the release isobath and each black dot is the release location at three vertical levels ($z = -1, -2, -3$ m). (c) Regional model winds and (d) modeled sea surface elevation versus time. In (c) and (d), vertical line colors indicate drifter release times (separated by 6 hours) between 07/01 (dark blue) to 07/06 (dark red).
Figure 2.  Top (a - c): Snapshot of all ($n = 21$) 30-m isobath drifter releases versus latitude and longitude at $t = 30$ hours after release in the (a) NT, (b) LT, and (c) WT simulations. Colors indicate release times (see Figure 1c, d). Each release center of mass is denoted by white circles. Black curve is the 100 m isobath and drifter release locations are marked by the white strip in panel (a). Bottom (d - f): Snapshot of all 30-m isobath drifter releases in the principal axes coordinate system ($x', y'$) at $t = 30$ hours after release. The white ellipses indicate the horizontal dispersion ellipse with area $D^2_E$ (4). Dark shaded curves are the normalized probability distribution functions along each axes.
Figure 3. Top (a, b): Horizontal relative dispersion ellipse area $D_E^2$ (Eq. 4) and bottom (c, d): horizontal diffusivity $K_E$ (Eq. 5) versus time after release $t$ for the (a, c) 50-m and (b, d) 30-m isobath releases. The WT, LT, NT simulations are indicated in legend (panel a).
Figure 4.  (a) Vertical drifter location probability distribution function at $t = 24$ hours after release from the 30-m isobath. The initial release locations at $z = -1, -2, -3$ m are indicated by dashed cyan lines and reach fractional value of 0.33.  (b) Vertical drifter dispersion $D_z^2$ and (c) one-half its time derivative analogous to Eq. 5, versus time after drifter release. The WT, LT, NT simulation line colors are indicated in legend (panel a).
Figure 5. Vertical profiles of 30-m isobath root-mean-square (rms) Eulerian quantities: (a) rms horizontal velocity \( V = \sqrt{u^2 + v^2} \), (b) rms shear \( S = \sqrt{u_z^2 + v_z^2} \), (c) rms model vertical eddy diffusivity \( K_V \), and (d) rms vertical velocity \( w \). The root-mean-square is calculated in both time between 07/01 - 07/06 and 20 km following the 30-m isobath latitude 34.9° and 35.1°N. The bottom 2 m of the water column is masked due to tidal sea level fluctuations.
Figure 6. (a) Horizontal relative dispersion ellipse area $D_E^2$ versus time after drifter release from the $z = -1$ m, 50-m isobath. Two methods of drifter tracking are from the full 3D velocity field and vertical mixing (WT$_{3D}$, solid black), and the 2D surface horizontal velocity only (WT$_{2D}$, NT$_{2D}$ and LT$_{2D}$, dashed). The WT, LT, NT simulation line colors are indicated in legend. (b) Ensemble separations $s^{(WN)} (7)$ and $s^{(LN)}$ versus time after drifter release from the 50-m isobath for 2D tracking.