

1 **Separation of an upwelling current bounding the Juan
2 de Fuca Eddy**

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9 **Key Points:**

- 10 • The shelf break current along Vancouver Island separates downstream of a submarine
11 bank.
- 12 • Offshore water is drawn onto the shelf and forms a sharp semi-persistent front with
13 the Juan de Fuca Eddy.
- 14 • The Eddy shows evidence of long residence times, and little evidence of deep-water
15 origin.

16 **Abstract**

17 Observations of temperature, salinity, and oxygen on the southern Vancouver Island
 18 shelf show a large-scale exchange of shelf water with offshore water, just offshore of a semi-
 19 permanent recirculation. ~~The semi-permanent cyclonic recirculation (, often termed the~~
 20 Juan de Fuca Eddy). ~~The Eddy~~ occupies a region where the shelf widens abruptly in the
 21 lee of a bank. The water in this Eddy is a mixture of offshore water and water from a buoyant
 22 coastal current. This water is well-mixed along a mixing line in temperature-salinity space,
 23 though it retains stratification, and is either rapidly mixed or has a long residence time.
 24 There is a ~~sharp less than 1-km wide~~ temperature-salinity front on the offshore side of this
 25 well-mixed water ~~, no more than 1-km wide, and that~~ has no sign of instabilities. The
 26 clearest evidence of cross-front transport is found during a ~~short~~ tidally resolved survey over
 27 a bank, ~~and was~~. ~~The transport is~~ due to flows in the cross-bank direction ~~driving large~~
 28 ~~mixing in that also drive~~ 50-m tall hydraulic jumps. Upstream of the ~~recirculation~~ ~~Eddy~~
 29 there is an along-shelf current flowing equatorward. However the whole current separates
 30 from the shelf before reaching the ~~recirculation~~ ~~Eddy~~, in the lee of a bank, and is replaced by
 31 water from offshore. The separation event was also seen in sea-surface temperatures from
 32 satellite images as a tongue of cool coastal water that is ejected offshore.

33 **Plain Language Summary**

34 The southern Vancouver Island continental shelf is biologically productive due to high
 35 nutrient input from the Strait of Juan de Fuca and Salish Sea estuarine system and sub-
 36 stantial cross-shelf transport due to the complicated topography. Here we present intensive
 37 sampling of the Juan de Fuca Eddy region. The observations show that below the surface
 38 mixed layer, the water in the Eddy is low in oxygen, and has undergone substantial vertical
 39 and lateral mixing. In contrast to previous literature we find that the low oxygen in the
 40 ~~eddy~~ ~~Eddy~~ is likely because of respiration rather than being pulled from low-oxygen water
 41 in the California Undercurrent.

42 The observations also show a remarkable flow separation of the equatorward shelf
 43 current. The current is seen to detach and is pushed offshore. Such events are readily seen
 44 in satellite imagery, but our observations indicate that the separation extends the depth of
 45 the water column on the shelf, and that this separation may be partially driven by the local
 46 bathymetry. The separation is a very strong cross-shelf exchange event, and transports
 47 substantial nutrient-rich coastal water offshore to drive productivity in the deeper ocean
 48 adjacent to the continental slope.

49 **1 Introduction**

50 Cross-shelf exchange is important to the health and productivity of continental shelf
 51 regions, allowing for offshore oxygenated water to be exchanged with nutrient-rich, but
 52 oxygen-depleted, nearshore water. Cross-shelf transport usually requires ageostrophic flow,
 53 since geostrophically balanced flow will tend to follow topographic contours, often providing
 54 a barrier to lateral exchange (Brink, 2016). Mechanisms of cross-shelf exchange include
 55 internal waves and instabilities in shelf-break fronts. However, these mechanisms can be
 56 smaller in magnitude compared to intermittent three-dimensional exchange, driven by ed-
 57 dying, often catalyzed by topographic irregularity (Barth et al., 2000).

58 Here we present detailed *in-situ* observations from the southern Vancouver Island shelf,
 59 collected in summer 2013, and sampled by a rapid profiling vehicle equipped with a CTD
 60 and oxygen sensor, supplemented by traditional hydrographic surveys bracketing the high
 61 resolution observations by a month. The shelf has complicated bathymetry (Fig. 1), with
 62 a relatively simple 50-km wide shelf poleward of our study site ~~–~~that widens to over 75
 63 km wide equatorward of La Perouse Bank. The South Vancouver Island Shelf is this wide

shelf region, characterized by a number of banks, and finally is incised on the poleward equatorward side by the Juan de Fuca eanyonCanyon. Water from the Strait of Juan de Fuca flows poleward as a buoyant current that hugs the coast (Thomson et al., 1989; Hickey et al., 1991), while shelf water flows equatorward in the summer both forced by local winds and via teleconnections with the long, homogenous shelves equatorward off Washington and Oregon (Hickey et al., 1991; Thomson & Krassovski, 2015; Engida et al., 2016). Trapped between these two currents is a region of relatively homogenous water that has been termed the Juan de Fuca Eddy (Freeland & Denman, 1982; Freeland & McIntosh, 1989; Foreman et al., 2008; MacFadyen & Hickey, 2010), denoted “EDDY” below.

A goal of our study was to understand how the EDDY persists and how it exchanges water properties with offshore water. We focus on water deeper than 50m, below the summer mixed layer, because this water is trackable with water mass properties, even though the EDDY is often studied from the point of view of the surface circulation (MacFadyen & Hickey, 2010). Past studies have found low oxygen concentrations in the EDDY, and inferred that water is upwelled from the California Undercurrent from as deep as 400 m (Freeland & Denman, 1982; Dewey & Crawford, 1988). This inference was based on the assumption that oxygen is eonservativea conservative tracer, and hence water in the EDDY had to come from the oxygen minimum zone found further offshore (Mackas et al., 1987). ~~This lead to hypotheses that perhaps It was hypothesized that~~ the EDDY was fed by waters being drawn up a spur canyon (called the Spur Canyon) via ageostrophic transport from offshore to onshore due to low pressure in the EDDY center (Weaver & Hsieh, 1987). Below, we will argue that there is no evidence of such transport and that oxygen is likely low because of local consumption due to respiration.

A second goal of our study was to better understand cross-shore exchange between shelf and offshore water. Gross-shore For a two-dimensional topography with wind forcing, cross-shore transport is supplied by Ekman layersin simple geometries under wind forcing. However, in many locations there is also evidence of eddies, meanders and filaments driving wholesale separation of shelf currents into the deep ocean. These have been well-studied off California (Strub et al., 1991) where satellite and *in-situ* observations show large meanders of coastal upwelling currents leading to coastal water injected into the offshore domain. Along the Vancouver Island shelf, large filaments or instabilities of the coastal current have also been inferred using satellite images (Ikeda & Emery, 1984; Thomson & Gower, 1998). Direct observations of such filaments have been made further to the south off Cape Blanco (Barth et al., 2000), and off other coasts (Relvas & Barton, 2005). Net cross-shore transport of nutrients and chlorophyll have been found in hydrographic surveys off Vancouver Island (Mackas & Yelland, 1999), and associated with mesoscale features in geostrophic velocities and in satellite observations. The mechanisms driving such separations are poorly understood, but hypotheses include coastal hydraulics leading to along-shore trapping of coastal waves (Dale & Barth, 2001), wind stress curl variations (Castelao & Barth, 2007), induced relative vorticity due to stretching of parcels that overshoot their initial isobaths due to a sudden change in downstream bathymetry (D’Asaro, 1988), and, at this location, non-linear breaking of large-scale meanders due to baroclinic instability between the wind-driven current and the California Undercurrent (Ikeda et al., 1984; Batteen, 1997).

In this paper we present observations of water masses on the Southern Vancouver Island Shelf collected in 2013 (section 2), presenting the data in a number of ways to highlight the important processes, with a. We focus on the offshore side of the EDDY region (section 3) where we consider the age of the EDDY, the steadiness of the front separating the EDDY and the offshore water, properties along the spur-canyon Spur Canyon that was believed to feed the EDDY, and a large offshore tongue of the shelf-break current and its intrusion into the interior. We discuss conclude by discussing the origin of the EDDY and the implications of the separating jet (section 4).

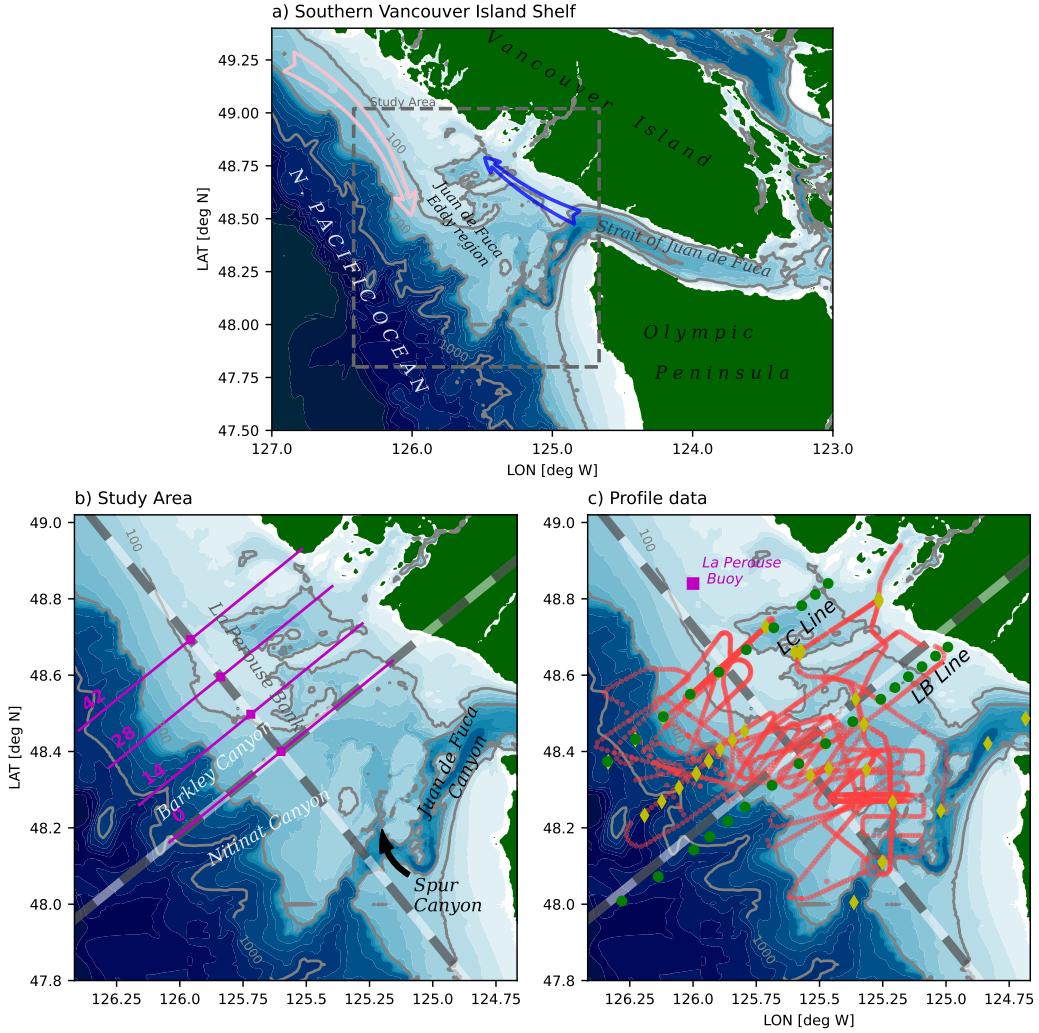


Figure 1. a) Study site on the Vancouver Island Shelf. The blue arrow indicates the direction of the Vancouver Island Coastal Current, and the pink arrow indicates southward flow of the coastal upwelling current. The dashed box indicates the approximate limits of the study area. b) The study area with major bathymetric features labelled. The coordinate system used for this paper is shown with alternating grey and white bands at 10-km intervals in the along- and cross-shore directions. c) sample locations with hydrographic casts from the La Perouse cruises along the LB and LC Lines (green dots), hydrographic casts during the Falkor cruise (yellow diamonds), and finescale Moving Vessel Profiler casts (red dots). The coordinate system used for this paper Magenta square is shown with alternating grey and white bands at 10-km intervals in the along- and cross-shore directions La Perouse wind buoy.

115 **2 Site and Methods**

116 The study site was the southern portion of the Vancouver Island Shelf (Fig. 1a), a
 117 particularly complicated region due to the bathymetry and varied forcing. At the south end
 118 of the study site is the Juan de Fuca ~~canyon~~Canyon, which feeds dense water into Juan de
 119 Fuca Strait. This dense water is mixed with fresh water from the Fraser River at the sills and
 120 archipelagos further inland and fluxes out the Strait again, where it turns poleward along
 121 Vancouver Island to form the Vancouver Island Coastal Current. The Juan de Fuca Canyon
 122 has a notable spur canyon (Spur Canyon) ~~–~~ that incises the shelf towards the north into the
 123 study site (Fig. 1b). The rest of the shelf is punctuated by a series of banks and shallow
 124 basins. La Perouse ~~bank~~Bank separates the outer shelf from a deeper inner basin and forms
 125 the poleward boundary off where the shelf widens abruptly south of 48.5 N. Equatorward,
 126 the shelf widens further, and the shelf break has a series of submarine canyons, in particular
 127 Nitnat Canyon and Barkley Canyon.

128 We ~~present observations~~use an along/across-shelf co-ordinate system with an origin
 129 at 48.4°N and 125.6°W, with the across-shelf *x* oriented 39 degrees north of East (Fig. 1b,
 130 grey/white alternating lines). The projection is Cartesian with a central latitude at 48.4°N,
 131 which is fine for the limited geographic extents discussed here.

132 Observations from La Perouse hydrographic surveys along the LB and LC lines, col-
 133 lected aboard the *CCGS Tully* from 2013-05-30 to 2013-05-31 (“May”), and 2013-09-07
 134 to 2013-09-09 (“September”) are used to put finescale observations in context of routine
 135 hydrographic work in the study region. These lines span the 50 m isobath to deep offshore,
 136 with casts every 7.5 km across shelf. The data comes from a lowered Seabird 9-11 CTD,
 137 with an SBE 43 oxygen sensor. Oxygen data have been corrected against bottle casts, and
 138 the CTD corrected for sensor offsets and thermal lags.

139 ~~We focus~~The focus in this paper is on finescale surveys carried out between these
 140 hydrographic surveys, from 2013-08-21 to 2013-08-30. Data were collected from the *R/V*
 141 *Falkor* with an AML Oceanographic Moving Vessel Profiler (MVP). Data was collected
 142 analogously to data collected during similar field campaigns (Klymak et al., 2015, 2016;
 143 D’Asaro et al., 2018). The MVP was equipped with an AML Oceanographic CTD, and
 144 a Rinko Oxygen sensor with a 7-s response time foil. The MVP profiled to depths of 200
 145 m or to within 5 m of the seafloor, whichever was shallower, and dropped at a speed of
 146 approximately 3 m s^{-1} . Data collection took place while the ship cruised at speeds between
 147 5 and 8 kts, usually at around 6 kts, to enable fine horizontal spacing of the casts, with
 148 typical spacing of 800 m in deep water, and less in water shallower than 200 m. Data is
 149 reported for the downcast, which mostly follows a vertical path. The rapid speed of the
 150 profiling makes the oxygen measurements somewhat coarse, and probably biased due to the
 151 phase lag of the sensor, so we treat these qualitatively in this paper.

152 Unfortunately, neither vessel had an operational acoustic Doppler profiler during the
 153 cruises with which to make water velocity measurements.

154 Winds during the cruises were typical for the west coast of Vancouver Island, with
 155 equatorward upwelling-favorable winds during July and early August (Fig. 2). During the
 156 finescale survey, and for the week previous, the winds were intermittently downwelling fa-
 157 vorable. Note that this locale is strongly affected by coastally trapped waves from further
 158 south, so doming of near-bottom isopycnals often persists despite local wind forcing, and
 159 takes a finite amount of time to spin down (Thomson & Krassovski, 2015; Engida et al.,
 160 2016).

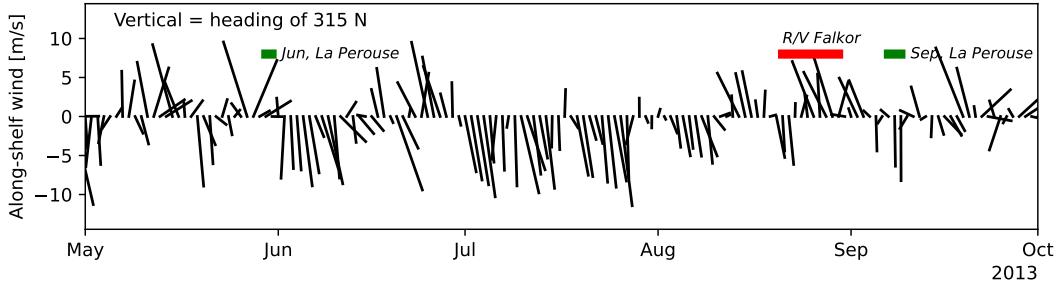


Figure 2. Wind from the La Perouse buoy at 48.84 N, 126 W (DFO, 2022). The vertical direction is along-shelf (chosen as a heading of 315 N), so vectors pointing straight down represent upwelling winds. The wind components have been low-pass filtered to one-day averages. The timing of the surveys discussed in the paper are shown as colored bands.

3 Observations

3.1 Early and late summer hydrographic surveys

Hydrographic sections along the LB and LC hydrographic lines highlight summer conditions on the Southern Vancouver Island Shelf and indicate some of the features we are focusing on in this paper presented to give context to the more detailed survey carried out on the R/V Falkor (Figure 3). During both surveys, and along both lines, there is clear evidence of upwelling, with the 26.4 kg m^{-3} isopycnal reaching from 130 m depth offshore to shallower than 85 m over the shelf. This upwelled water tends to be low in oxygen and cool. Further onshore, the Vancouver Island Coastal Current hugs the coast, where isopycnals tilt down towards the shore, and water is warmer than offshore.

The Juan de Fuca Eddy region is observed along the LB Line (Fig. 3, bottom three rows), mostly inshore of 0 km. This water is cooler and lower in oxygen than along the same isopycnal further offshore. Near the surface, the isopycnals are domed, and the low-oxygen anomaly extends as high as the thin surface mixed layer.

The water upstream of the EDDY region, along the LC line, is less mixed than the EDDY water (Fig. 3, top three rows). It does not show as much drawdown of oxygen, and is warmer, at least offshore of La Perouse bank ($X \approx 5 \text{ km}$) and has higher oxygen. Based on these properties, offshore water does not appear to make it over La Perouse bank into the onshore basin, or if it does, it does so intermittently and with substantial mixing. Note that the water along the 26.4 kg m^{-3} isopycnal (Fig. 3, magenta contours) becomes cooler and lower in oxygen where it intersects the shelf, consistent with both enhanced mixing near the shelf and with drawdown of oxygen by respiration.

The contrast in onshore and offshore waters can be clearly traced in temperature-salinity ($\theta-S$) anomalies along isopycnals (Fig. 4a). Denser than 26.6 kg m^{-3} , the deep water masses found offshore are largely homogenous. In the lighter water masses, there are distinct differences between warm and salty offshore water compared to water on the shelf at the same densities.

We use a spice anomaly defined as relative to a straight line in $\theta-S$ space (Fig. 4) representing an approximate mixing line for water in the EDDY, and passing through the points 7.75°C , 30 psu and 6.6°C , 35 psu. Spice anomaly for a given water sample at density σ_θ is given by $\gamma = \alpha(T - T_0(\sigma_\theta)) + \beta(S - S_0(\sigma_\theta))$ where $T_0(\sigma_\theta)$, $S_0(\sigma_\theta)$ are the temperature and salinity along the mixing line at the same density as the water sample.

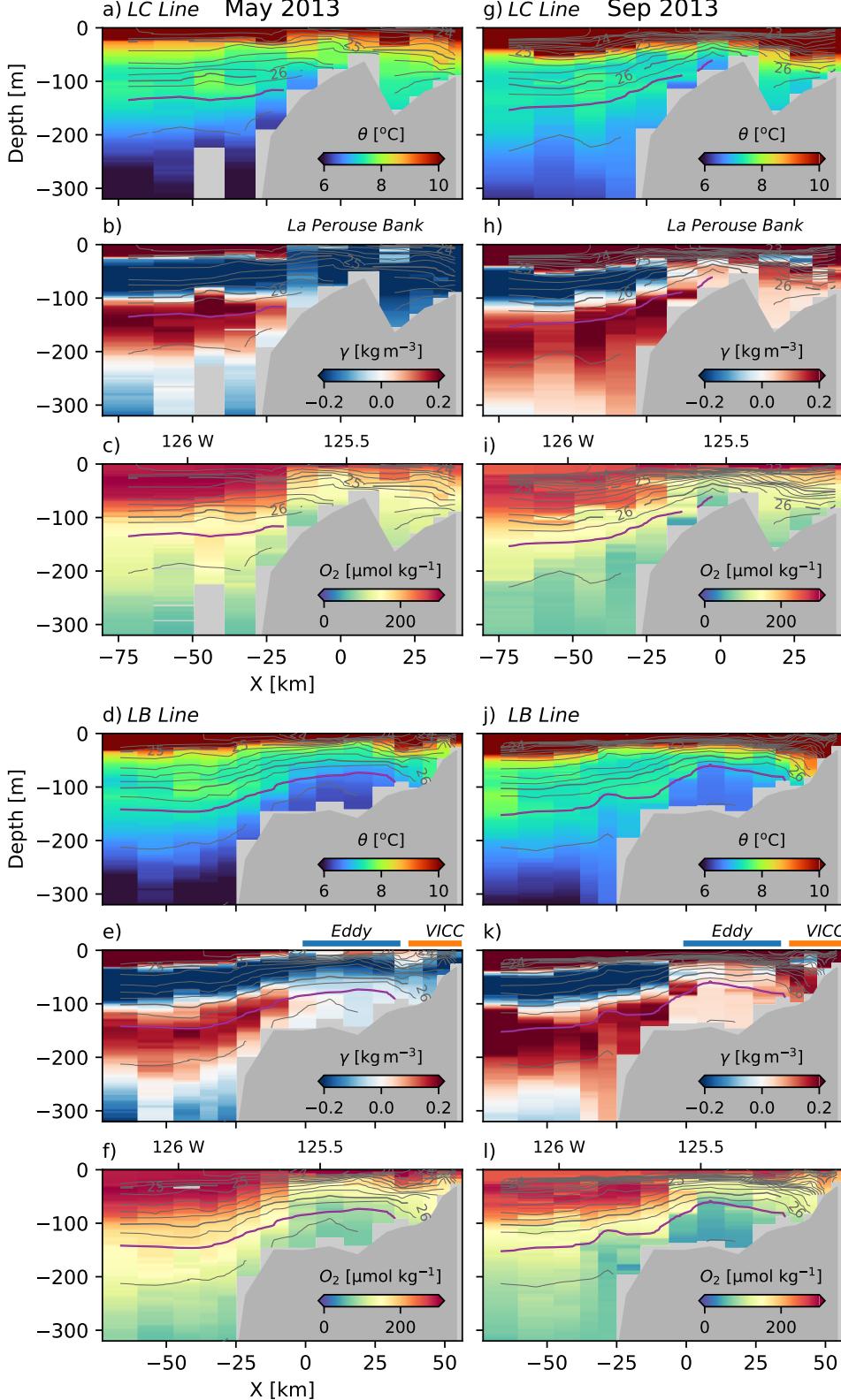


Figure 3. Observations along LC Line in May (a–c) and Sep (g–i) and LB lines in May (d–f) and Sep (j–l). X is across-shelf distance in the coordinate system shown in Fig. 1. Potential density is contoured every 0.2 kg m⁻³, with the 26.4 kg m⁻³ colored magenta. Potential temperature, θ , splice anomaly, γ and oxygen concentration, O_2 , are colored for each section.

193 The sign convention is that a positive anomaly is warmer and saltier than data along the
 194 mixing line.

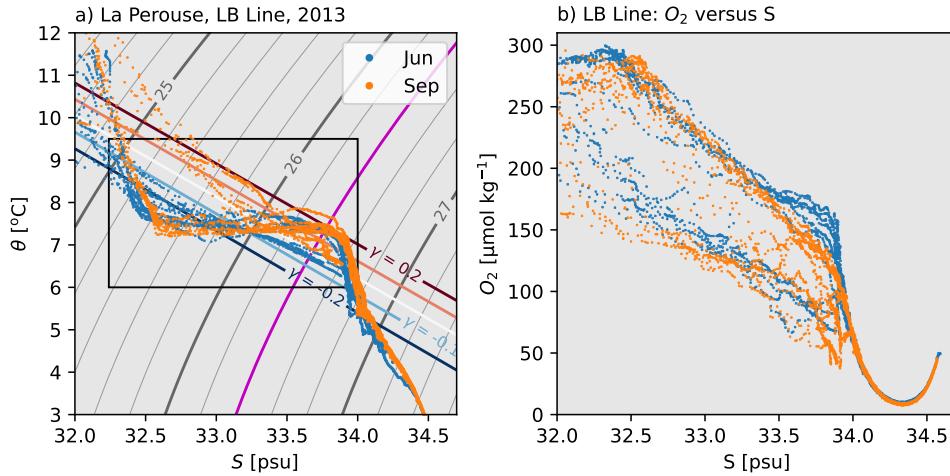


Figure 4. a) Potential temperature, θ , versus salinity, S , for the La Perouse data shown in Fig. 3; potential density is contoured every 0.2 kg m^{-3} , with the 26.4 kg m^{-3} colored magenta. A definition of spice anomaly is shown in this plot, and discussed in the text. The rectangle is the $\theta - S$ range used in Fig. 5 below. b) The same data with oxygen concentration versus salinity.

195 Using this metric of spice anomaly, offshore water tends to have high absolute values
 196 (Fig. 3, middle rows), with a positive-anomaly layer ($\text{red } \gamma \approx 0.2 \text{ kg m}^{-3}$, red colors) centered
 197 at 26.4 kg m^{-3} sandwiched between negative-anomaly layers above and below. On the shelf
 198 ($-10 \text{ km} < X < 30 \text{ km}$), the distinct $\theta - S$ masses are attenuated and much closer to the
 199 defined mixing line than the offshore water ($\text{closer to white in color in } \gamma \approx 0 \text{ kg m}^{-3}$, almost
 200 white Fig. 3).

201 There are temporal changes over the summer. Away from the surface, water has
 202 upwelled from deeper depths by September, but the offshore water maintains the same water
 203 mass characteristics through the summer. Hugging the coast ($X > 30 \text{ km}$), the Vancouver
 204 Island Coastal Current warms during the summer, and the spice anomaly goes from negative
 205 to positive. In the EDDY, the water stays near the mixing line, but is cooler in the spring
 206 (Fig. 3, LB Line, left-hand column: slightly negative spice anomaly) and warms during the
 207 summer (Fig. 3, LB Line, right-hand column: slightly positive spice anomaly).

208 Oxygen concentration in both surveys has a similar dichotomy between the EDDY and
 209 off-shelf water. Water found in the EDDY has oxygen concentrations $100 \mu\text{mol kg}^{-1}$ lower
 210 on the shelf than off-shelf (Fig. 3, Fig. 4b). The very deepest water ($S \approx 33.9 \text{ psu}$) on the
 211 shelf shows a further $50 \mu\text{mol kg}^{-1}$ decrease in concentration between May and September
 212 along the LB line.

213 3.2 Finescale surveys

214 3.2.1 Overview

215 The finescale surveys covered most of the EDDY region, with an emphasis on the
 216 offshore edge near the shelfbreak front (Fig. 1). For water denser than 26 kg m^{-3} , there
 217 are three distinct water masses sampled on the shelf (Fig. 5). The first is offshore water,
 218 which tends to be warmer, and hence has a positive spice anomaly ($\gamma \approx 0.2 \text{ kg m}^{-3}$ along

$\sigma_\theta = 26.4 \text{ kg m}^{-3}$). The second is water in the EDDY, which during this survey was found along the straight mixing line in $\theta - S$ space (Fig. 5, $\gamma \approx 0 \text{ kg m}^{-3}$ along $\sigma_\theta = 26.4 \text{ kg m}^{-3}$). Between these two water masses, there is a less populous mass (Fig. 5, $\gamma \approx 0.1 \text{ kg m}^{-3}$ along $\sigma_\theta = 26.4 \text{ kg m}^{-3}$) that we demonstrate below is found on the shelf poleward of the EDDY.

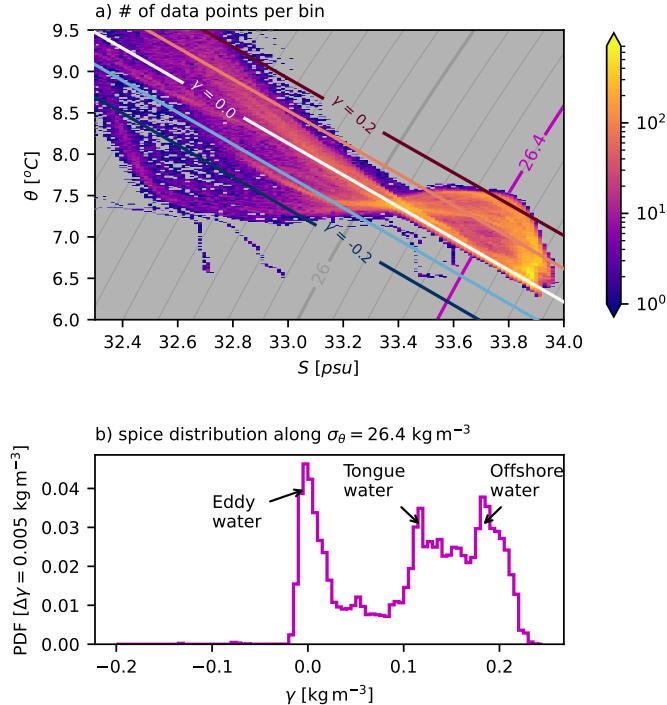


Figure 5. a) Binned sample density of salinity and potential temperature from the cruise, with a logarithmic color scale. Grey contours are potential density relative to the surface at intervals of 0.1 kg m^{-3} ; the magenta contour is the 26.4 kg m^{-3} isopycnal. Colored contours are spice anomaly, γ , relative to the white line labeled $\gamma = 0.0$. b) Distribution of spice, γ along the 26.4 kg m^{-3} isopycnal.

In synthetic cross sections of spice anomaly, the EDDY is clearly identifiable as having low spice anomaly ($\gamma \approx 0 \text{ kg m}^{-3}$, Fig. 6c, d). This signature of well-mixed These lines are made with a two-dimensional interpolation where MVP casts at a given depth have a Gaussian weight $w = e^{-(r/r_0)^2}$, where r is the distance from the line and $r_0 = 1.5 \text{ km}$. Note that the section at The low-spice anomaly water extends from the seafloor to approximately 30 m depth, onshore of $X \approx 0 \text{ km}$. Despite lying along a mixing line, the EDDY water is still stratified. The high-spice water ($\gamma \approx 0.2 \text{ kg m}^{-3}$) is found offshore of the EDDY water, on the other side of a sharp $\theta - S$ compensated front. This front is even sharper in individual sections than in these composite sections (see section 3.2.3).

In contrast, the third population of partially mixed water between the EDDY and offshore water (Fig. 5) is all found poleward of the EDDY region (Fig. 6a, b) as water with a weaker spice anomaly ($\gamma \approx 0.1 \text{ kg m}^{-3}$, pink colors). This water is not as warm as offshore water, indicating some mixing with offshore water has taken place. Of note is that this intermediate water mass appears completely absent in the sections further equatorward

(Fig. 6c, d), indicating that it is either mixed away or that it is advected elsewhere; we argue below that it is advected offshore in a large-scale tongue.

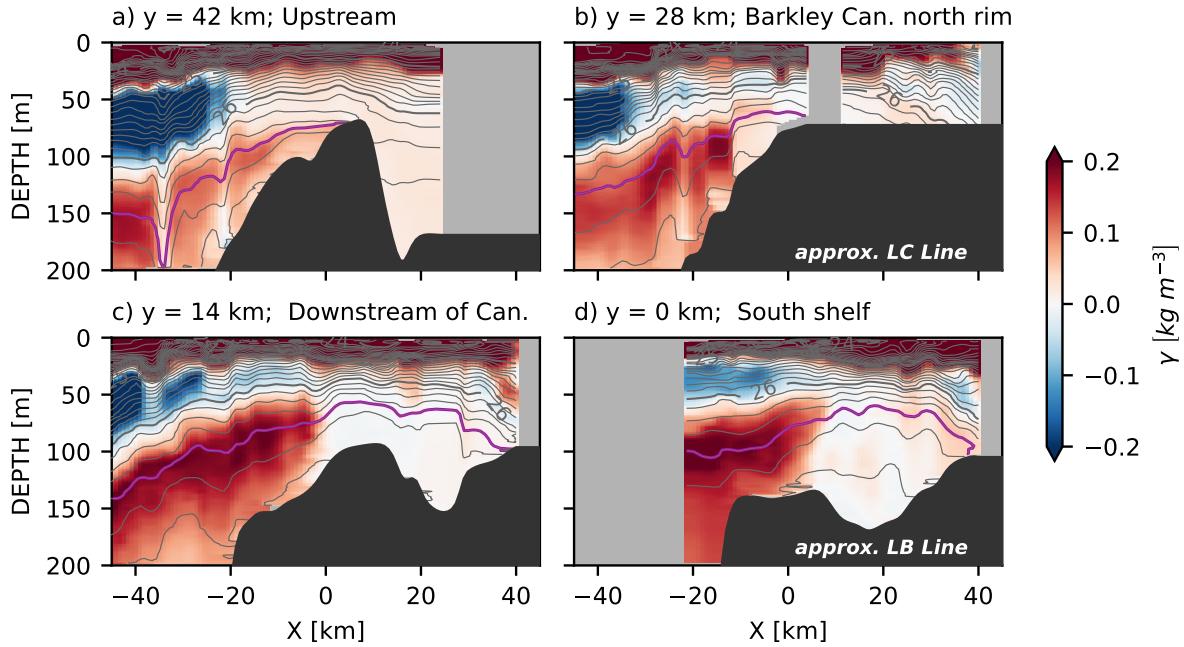


Figure 6. Synthetic sections of spice anomaly from the MVP data, projected along four lines from poleward (upstream of coastal current) a) to equatorward (downstream); the lines are shown in Fig. 1b^a). Isopycnals are contoured every $\sigma_\theta = 0.2 \text{ kg m}^{-3}$, with the $\sigma_\theta = 26.4 \text{ kg m}^{-3}$ isopycnal highlighted in magenta. Colors are spice anomaly as defined in Fig. 5. "BC" in panel (c) refers to Barkley Canyon. Note that b) is along LC line (Fig. 3a–c,g–i), and d) is along the LB line (Fig. 3d–f,j–l).

Oxygen saturation sections show that the deep water in the EDDY has very low oxygen saturation (Fig. 7c, d) compared to surrounding water (though again, we caution against the quality of these saturation values from such a fast profiling instrument with a slow response time). More oxygenated water is found offshore, and the oxygen deficit is not as strong in the poleward sections (Fig. 7a, b). The T/S compensated front also shows an abrupt transition from the EDDY water and the offshore. Note the excellent correlation between oxygen saturation and spice anomaly in Fig. 6.

The spatial patterns are very clear when considering a map view of properties along the $\sigma_\theta = 26.4 \text{ kg m}^{-3}$ isopycnal (Fig. 8). There is a region onshore of the south tip of La Perouse Bank (approximately 44.5°N, 125.75°W), that consists of water that is found along the mixing line (spice anomaly $\gamma \approx 0 \text{ kg m}^{-3}$) that also has low oxygen saturation. Offshore of this region is water that is very warm and salty in comparison ($\gamma > 0.15 \text{ kg m}^{-3}$), and relatively high in oxygen (saturation of approximately 60%). The region transition between these two water masses is very abrupt, and stretches from La Perouse Bank to a shallow bank just above the Juan de Fuca canyon (48.3°N and 125.4°W).

Poleward of La Perouse bank and Barkley Canyon, the water along the shelf has the weaker spice anomaly characteristic of the third water mass ($\gamma \approx 0.1 \text{ kg m}^{-3}$, light pink colors). This water is also somewhat lower in oxygen than water from offshore, though not as depleted as the water in the EDDY. This water appears to be pushed offshore just

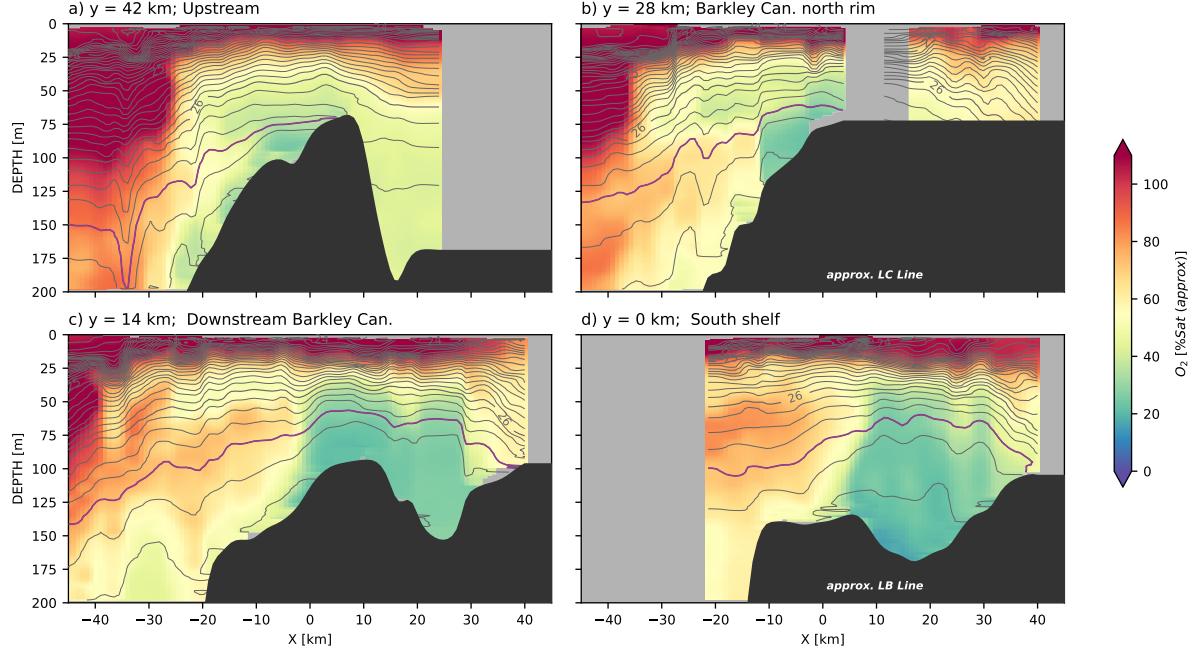


Figure 7. As in Fig. 6, for oxygen approximate saturation.

upstream of Barkley Canyon and replaced on the shelf by the warmer (high spice) offshore water.

The correspondence between low oxygen water and water on the mixing line that defines $\gamma \approx 0 \text{ kg m}^{-3}$ is quite strong (Fig. 8c). Eddy water is onshore (more red colors), low in oxygen, and along the mixing line. Offshore water is high in oxygen and has a high spice anomaly. Water that is found poleward on the shelf is still relatively high oxygen, but of intermediate spice $\gamma \approx 0.125 \text{ kg m}^{-3}$.

3.2.2 Spur Canyon

The Spur Canyon leading from the Strait of Juan de Fuca has been implicated in allowing dense water to be upwelled into the EDDY (Mackas et al., 1987; Weaver & Hsieh, 1987). The sea surface is low in the middle of the EDDY, so it has been hypothesized that water moves up the Spur Canyon due to ageostrophic motion (Weaver & Hsieh, 1987; Freeland & Denman, 1982). This It is difficult to infer flow up the Spur Canyon from the observations collected here. Three transects up the canyon indicate that deep isopycnals slope up into the canyon (Fig. 9, to approximately 30 km). Continuing across the EDDY, isopycnals are largely flat until they intersect the Vancouver Island Coastal Current ($80 \text{ km} X_{\text{canyon}} = 80 \text{ km}$). The deeper isopycnals are not found in the deeper basin northeast of La Perouse bank Bank (70 km), thus the bank is a natural poleward boundary of the EDDY.

Spice anomaly along the canyon indicates a transition from offshore water to EDDY water. Oxygen saturation behaves in a similar manner, though some of the incoming water has slightly lower oxygen than water inside the EDDY (not shown). Based on these sections, it is difficult to infer water motion up the canyon.

Much of the modified water in the Spur Canyon appears to come from the shelf to the west, but heavily modified by tidal mixing. A repeat tidal survey over the bank on the west side of the canyon shows a strong hydraulic response during onshore flow (17:58–21:00,

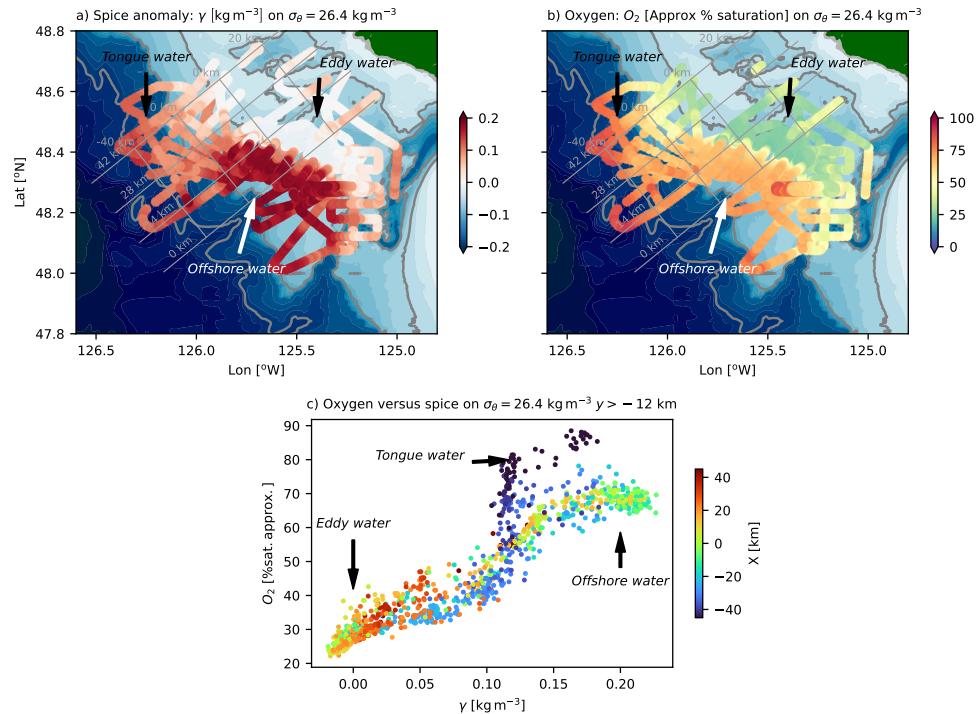


Figure 8. Spatial overview of a) the spice anomaly, and b) oxygen saturation on the $\sigma_\theta = 26.4 \text{ kg m}^{-3}$ isopycnal. Grey cross-slope lines are cross sections indicated in Fig. 6. Along-slope grey lines are every 20 km in the cross-slope direction, with $X = 0 \text{ km}$ near the 100-m isobath at the north end of the observation area. c) distribution of oxygen as a function of spice anomaly and $\sigma_\theta = 26.4 \text{ kg m}^{-3}$, colored by x-coordinate. Data from the Juan de Fuca Canyon region ($y < -12 \text{ km}$) is not shown.

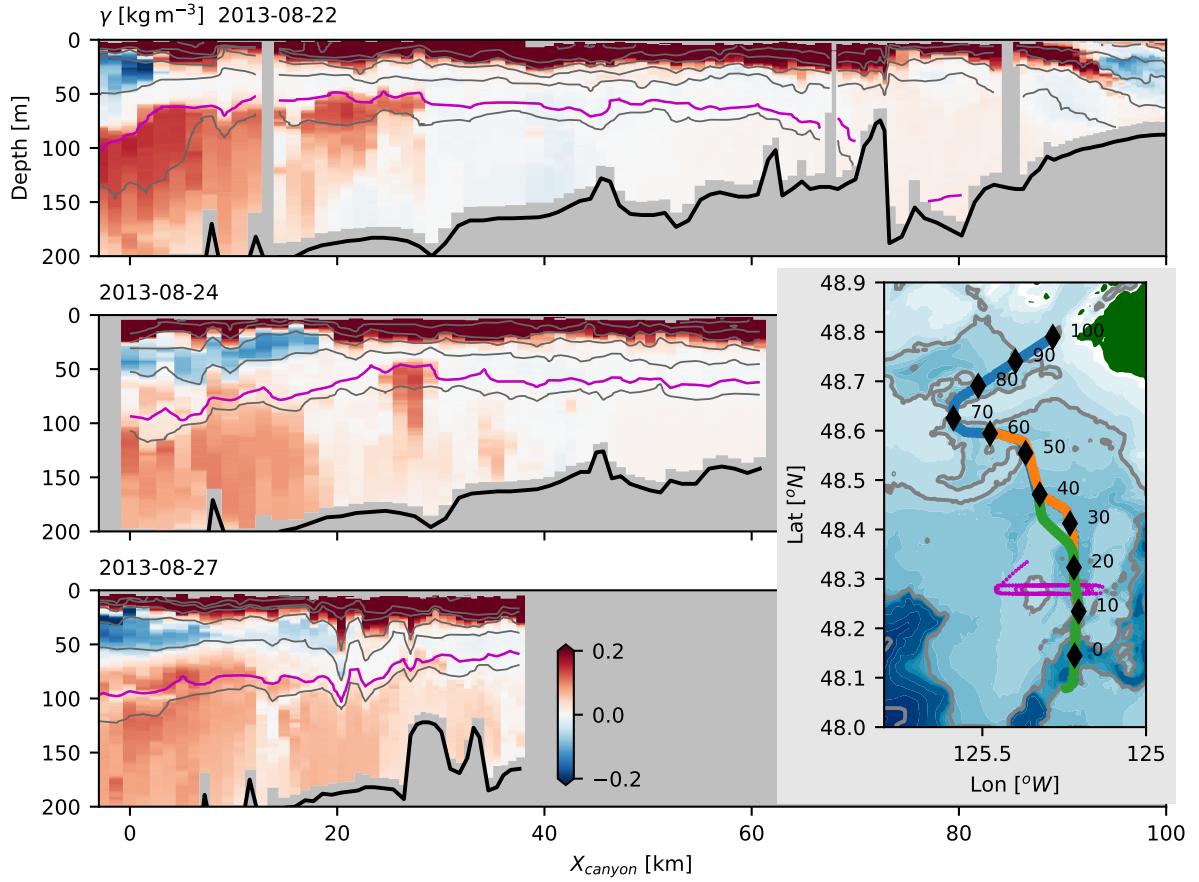


Figure 9. Spice anomaly surveys up the Spur Canyon, where $\underline{X}-\underline{X}_{canyon}$ is along-canyon as defined in the map. Grey isopycnals are contoured every 0.5 kg m^{-3} , and the 26.4 kg m^{-3} isopycnal is shown in magenta. The seafloor is indicated with the thick black line. Map (lower right) shows the path taken during each survey in chronological order (blue, orange, and green). Magenta line is path taken during a cross-canyon survey (Fig. 10).

283 Fig. 10). Dense water passes from the offshore side into the canyon, and plunges down
 284 the side wall before rebounding downstream. Note that the tide here is largely diurnal, so
 285 this onslope flow only occurs once a day. Given the stratification of $N \approx 6 \times 10^{-3} \text{ rad s}^{-1}$
 286 and an overturning scale of 50 m, we might expect dissipation rates reaching $\epsilon \sim L^2 N^3 \approx$
 287 $5 \times 10^{-4} \text{ m}^2 \text{s}^{-3}$, which is three orders of magnitude higher than dissipation observed on
 288 the shelf west of this location by Dewey and Crawford (1988). This estimate of turbulence
 289 dissipation rate implies a diapycnal diffusivity of $\kappa = \gamma \epsilon / N^2 \approx 1 \text{ m}^2 \text{s}^{-1}$ $\kappa = \gamma \epsilon / N^2 \approx 0.5 -$
 290 $5 \text{ m}^2 \text{s}^{-1}$, assuming a mixing efficiency of $\gamma = 0.2$. Water spills over from the offshore front
 291 into the canyon during the onshore tide. This water is rapidly mixed with surrounding water
 292 such that its strong offshore spice values are attenuated.

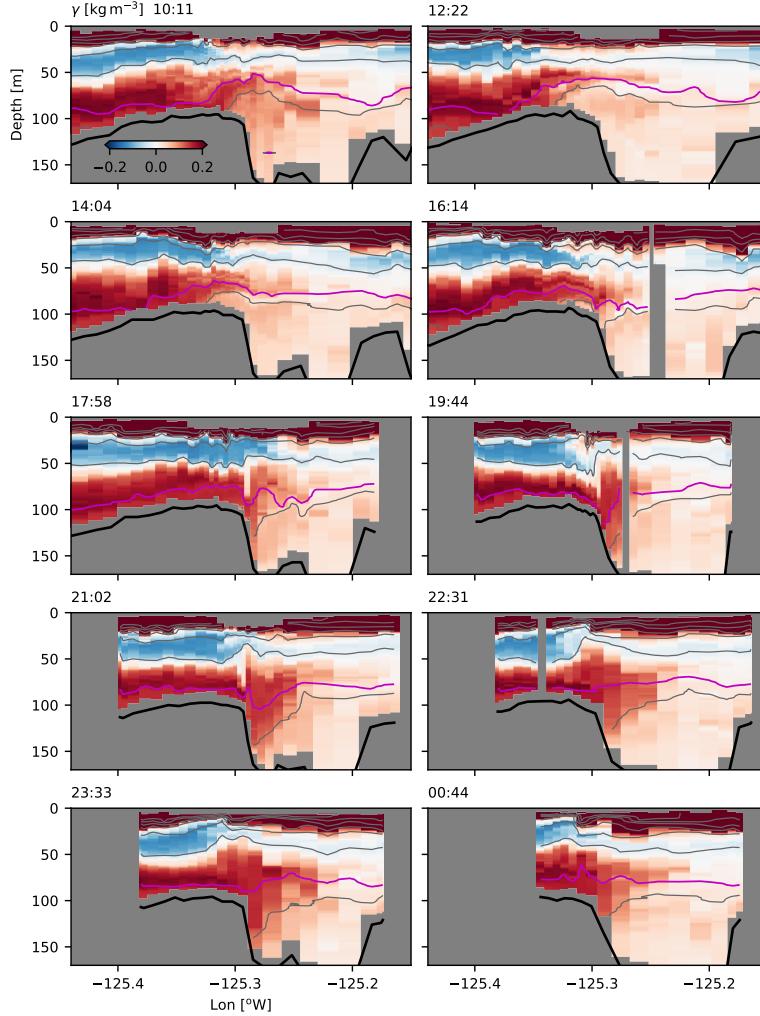


Figure 10. Spice anomaly observed in repeated, tide-resolving survey across the Spur Canyon, time is indicated in the upper left of each plot (29 August, 2013). Location of survey shown in Fig. 9 as a magenta line.

293 The turbulence found on the canyon rim makes it ambiguous if there is water moving
 294 up the canyon or not. There is a general tendency along the canyon for higher spice water
 295 to be found offshore (Fig. 9) but it seems likely that the source of the higher spice water
 296 is from over the bank rather than water being advected up the canyon. ~~This~~ ~~The~~ tidally

297 driven flow over the bank is the most significant source of high-spice offshore water into the
 298 ~~eddy~~EDDY region identified during our surveys.

299 3.2.3 *Frontal survey*

300 A systematic survey through the front between the offshore water and the EDDY water
 301 demonstrates the sharpness and persistence of this front (Fig. 11), suggesting that it has
 302 limited exchange with the offshore region.

303 The survey started close to shore, and passed through the Vancouver Island Coastal
 304 Current (along-track 0-10 km). The coastal current forms a buoyant ~~front~~current, and is
 305 fresher and colder than water at the same density. ~~This front~~The front with the coastal
 306 water is relatively thick, greater than 20 km wide, and has entrained partially mixed water
 307 down from the surface to the foot of the front ($\gamma \approx 0.1$).

308 Offshore of this coastal current, measurements were collected crossing the front be-
 309 tween the offshore water and the EDDY water 10 times, showing its evolution following the
 310 along-shore equatorward flow. First, as noted in the composite sections, isopycnals slope
 311 up from offshore onto the shelf. In the first crossing, the front is very sharp, (along-track
 312 distance 50 km) though two small tendrils of higher spice water can be seen separating from
 313 the front on the inshore side. Similar tendrils are found on the second crossing, perhaps a
 314 bit more separated from the front (≈ 80 km), and on the third crossing (≈ 95 km). These
 315 tendrils are made of up partially mixed water. The subsequent passes have more of this
 316 partially mixed water, such that the partially mixed front is up to 5-km wide by the fifth
 317 pass (≈ 150 km). However, the deeper isopycnals retain a sharp front, and indeed the front
 318 appears sharp again by the seventh pass at all depths (≈ 200 km).

319 There is evidence of some warmer water swirling into ~~Eddy~~EDDY, particularly along
 320 isopycnals deeper than 26.4 kg m^{-3} . Regions of warmer (and more oxygenated) water are
 321 found in tendrils at these depths (e.g. $\approx 170 \text{ km}$ $\approx 170 \text{ km}$ and ≈ 185 km). The overall
 322 effect is similar to what was seen in the Gulf Stream with similar observations (Klymak et
 323 al., 2016); there are two quite distinct water masses, the ~~Eddy~~EDDY water and the offshore
 324 water, as seen in the θ - S plot (Fig. 11c) with only a small population of samples between
 325 these two. ~~This distribution of~~These distinct θ - S properties ~~is~~are indicative of substantial
 326 isopycnal and vertical mixing, but even these populations are relatively cut off from the main
 327 water masses, indicating that they are well-mixed on their own, in short episodic events.
 328 Regardless, this front is very sharp given that it has no density signature, indicating that
 329 there is not strong advection from offshore into the EDDY region.

330 3.3 Separation of coastal water

331 Upstream of the the sharp front between the low-spice EDDY and the high-spice off-
 332 shore water is a substantial mass of intermediate-spice water along the shelf (compare Fig. 6a
 333 and c). This intermediate spice water is moving equatorward along the shelf upstream of
 334 the EDDY, but is pushed offshore just upstream of Barkley Canyon (Fig. 12d). There is a
 335 tongue of intermediate-spice water (γ ~~is~~ $\approx 0.1 \text{ kg m}^{-3}$ pink along 26.4 kg m^{-3}) that sep-
 336 arates from the shelf just west of 126°W . The surveys do not cross the full extent of the
 337 tongue, but it is at least 30 km wide. It also appears to end at approximately 48.2°N . This
 338 intermediate-spice water reaches from relatively shallow isopycnals to at least 26.6 kg m^{-3}
 339 26.55 kg m^{-3} (Fig. 12, left panelh). Unfortunately, we cannot track the fate of this wa-
 340 ter mass because isopycnals tilt down offshore, below the depth limit of the MVP. The
 341 25.5 kg m^{-3} 25.8 kg m^{-3} isopycnal appears to have the tongue (Fig. 12a), but closer to the
 342 shelf than at 26.4 kg m^{-3} , indicating strong three-dimensionality to this feature.

343 This separating tongue is embedded in the larger scale isopycnal tilt caused by the
 344 upwelling (Fig. 12, ~~right panels~~c,f, and j), so it is difficult to see dynamically what is driving
 345 this offshore push. If the offshore motion were geostrophically balanced, we would expect the

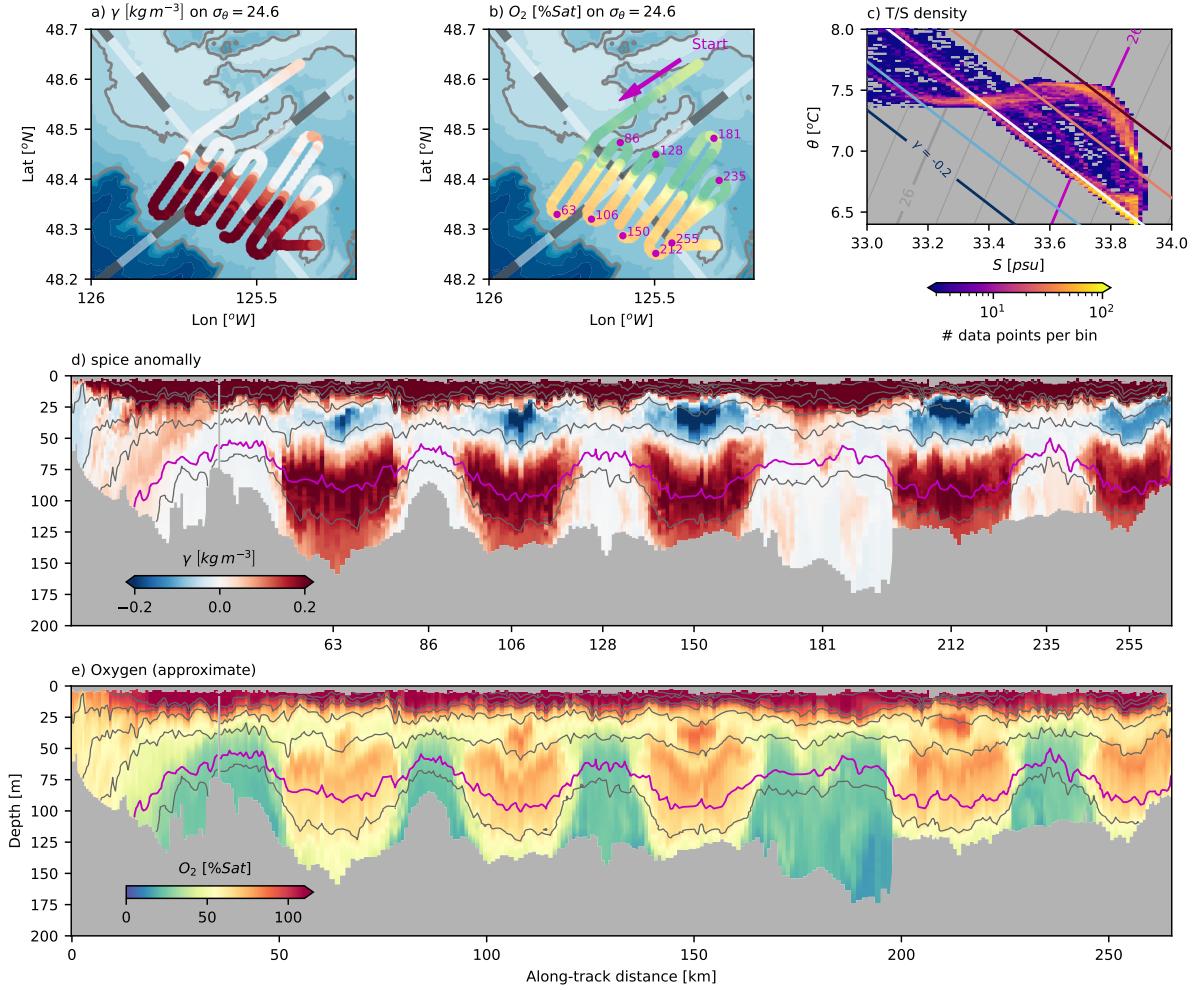


Figure 11. Data from the [frontal-offshore front](#) survey a) spice anomaly along 26.4 kg m^{-3} . Grey-white alternating lines are the coordinate system, with 10-km alternating shades. b) oxygen saturation along 26.4 kg m^{-3} ; magenta dots correspond to [turn locations as](#) distance along-track. c) density of data points (logscale) in this section of data. d) cross-section of spice anomaly along track. Grey isopycnals are contoured every 0.5 kg m^{-3} , and the 26.4 kg m^{-3} isopycnal is shown in magenta. [Ticks are turn locations](#) e) cross-section of oxygen saturation.

346 isopycnals to dome upwards from poleward towards Barkley Canyon, but if such doming is
 347 happening, it is weaker than variability from internal tides and synoptic unsteadiness. One
 348 possibility is that it is simple flow separation caused by the water not being able to make
 349 the sharp turn around La Perouse Bank, which would be an ageostrophic effect. Whatever
 350 causes it, downstream of the separation, the water is replaced by offshore water with much
 351 higher spice values.

352 There is a clear surface expression of the separating tongue in satellite imagery (Fig. 13).
 353 Water flowing equatorward along the shelf tends to be cooler than offshore water, likely due
 354 to mixing with the colder coming out of the Strait of Juan de Fuca. On August 25, there is a
 355 cold tongue of water separating from La Perouse ~~bank~~Bank, crossing isobaths and pointing
 356 south at 125.8°W. There is a cooler tendril streaming west at 48 N off the south end of
 357 this tongue. This feature is not as well-developed in the previous image (Aug. 21) perhaps
 358 indicating that it is an evolving feature. By 31 August, there is no surface expression of
 359 the feature, though small tendrils of cooler water can be seen separating from La Perouse
 360 Bank. By 5 September, the water has significantly warmed, and the offshore anomaly does
 361 not appear to have a surface signature.

362 Satellite-based surface chlorophyll estimates show the same feature (Fig. 14) ~~demonstrating~~
 363 suggesting the advection of high chlorophyll to the west side of the EDDY. They also show
 364 a relatively high-chlorophyll tendril to the west, again exiting the study region at approxi-
 365 mately 48 degrees N. The feature is relatively long-lived, on the order of one month. Inspec-
 366 tion of images before August 5 were too obscured by clouds or did not show this feature.
 367 By September 6, we see the feature fading from the satellite image. Note that this feature is
 368 centered 0.2 degrees of latitude south of tongue that we observe deeper in the water column,
 369 again indicating that there is depth-dependent structure in the feature.

370 4 Summary and Discussion

371 The intensive sampling discussed here has demonstrated a few important features of
 372 the South Vancouver Island Shelf. The Juan de Fuca Eddy water is readily identified as
 373 falling along a mixing line in $\theta - S$ space, compared with offshore water that was warmer and
 374 saltier (high-spice anomaly). There was not strong evidence of the EDDY being supplied by
 375 water moving up the Spur Canyon during our observations, but the Spur Canyon was a site
 376 of hydraulic cross-canyon flows in which we infer significant mixing has occurred. There is a
 377 sharp and persistent temperature-salinity compensated front between offshore water and the
 378 partially mixed EDDY water. Finally, upstream of the EDDY, water in the equatorward shelf
 379 current has intermediate spice anomaly, and is seen to separate from the shelf at the point
 380 of an abrupt bend in an underwater bank. The water mass crosses isobaths and is ejected
 381 into the interior. This separation event can also be observed from satellite measurements
 382 of sea surface temperature and chlorophyll. Thus the water that is offshore of the EDDY
 383 appears to have been brought onto the shelf in exchange for the offshore ejection of shelf
 384 water via this tongue.

385 4.1 Age and source of the EDDY water

386 The source of water and formation mechanism of the Juan de Fuca Eddy has received
 387 substantial attention, however, the observations of EDDY waters being found along a tight
 388 mixing line in $\theta - S$ space has not previously been noted. The deepest water in the EDDY
 389 could originate along the $\theta - S$ line from approximately 5.5°C to 7.5°C (Fig. 4a), which in
 390 the open ocean spans depths from 420 m to 70 m. Mackas et al. (1987) attempted to
 391 determine the origin of the water by including oxygen as a third variable to resolve the
 392 ambiguous $\theta - S$ relation. However, as Fig. 4b makes clear, oxygen does not appear to be
 393 a conserved property in the EDDY, with concentrations up to 150 $\mu\text{mol kg}^{-1}$ lower in the
 394 EDDY than the water found offshore, and in a way that definitely cannot be the result of
 395 conservative mixing. As a best guess, if the water in the deepest part of the EDDY came

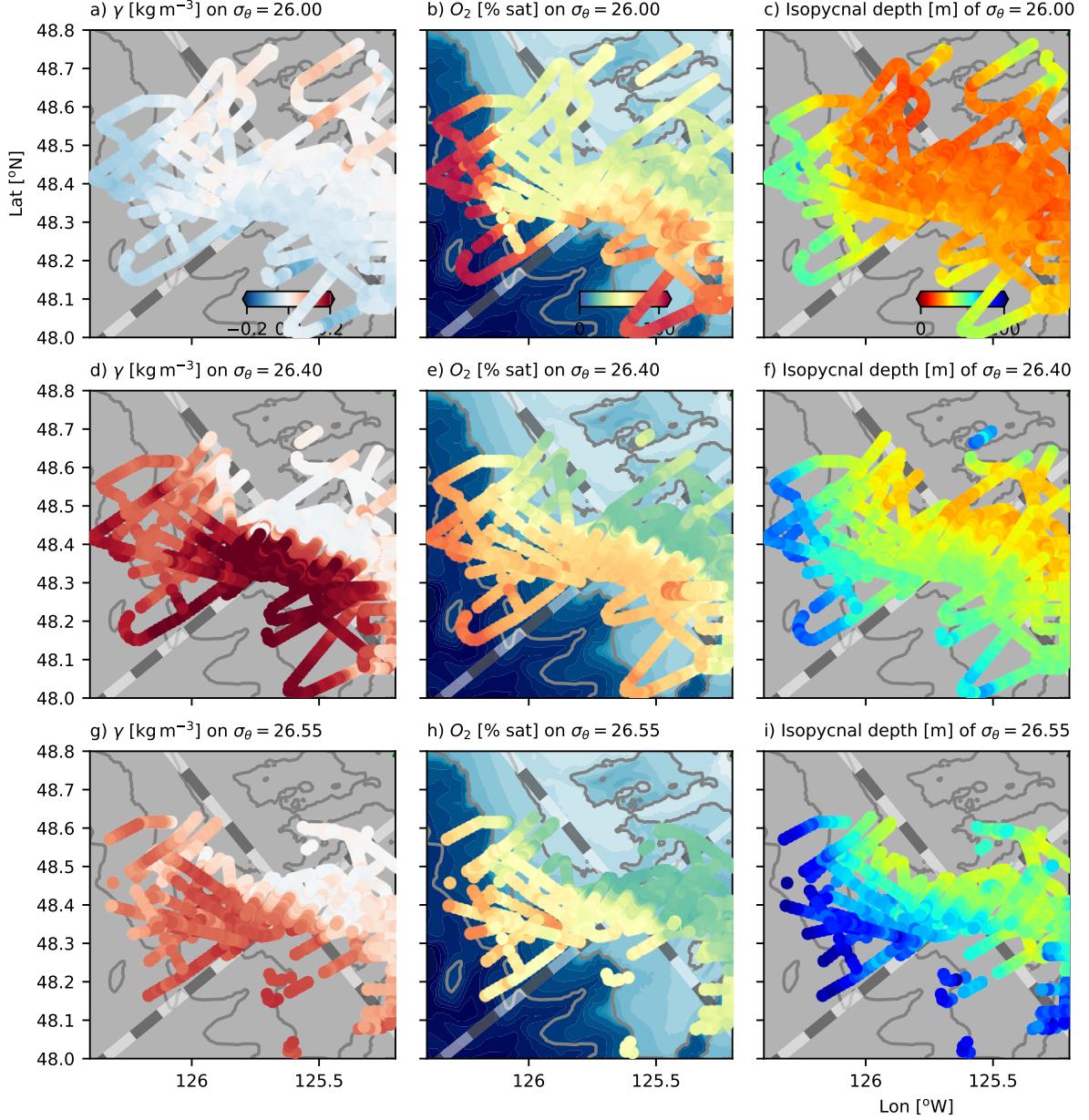


Figure 12. Isopycnal slices [through-of the MVP data](#) showing the vertical structure of the water separating from the shelf, with the first row along 25.5 kg m^{-3} , second along 26.4 kg m^{-3} , and the third at 26.6 kg m^{-3} . First column is the spice anomaly, second is oxygen saturation, and the last column is depth of each isopycnal.

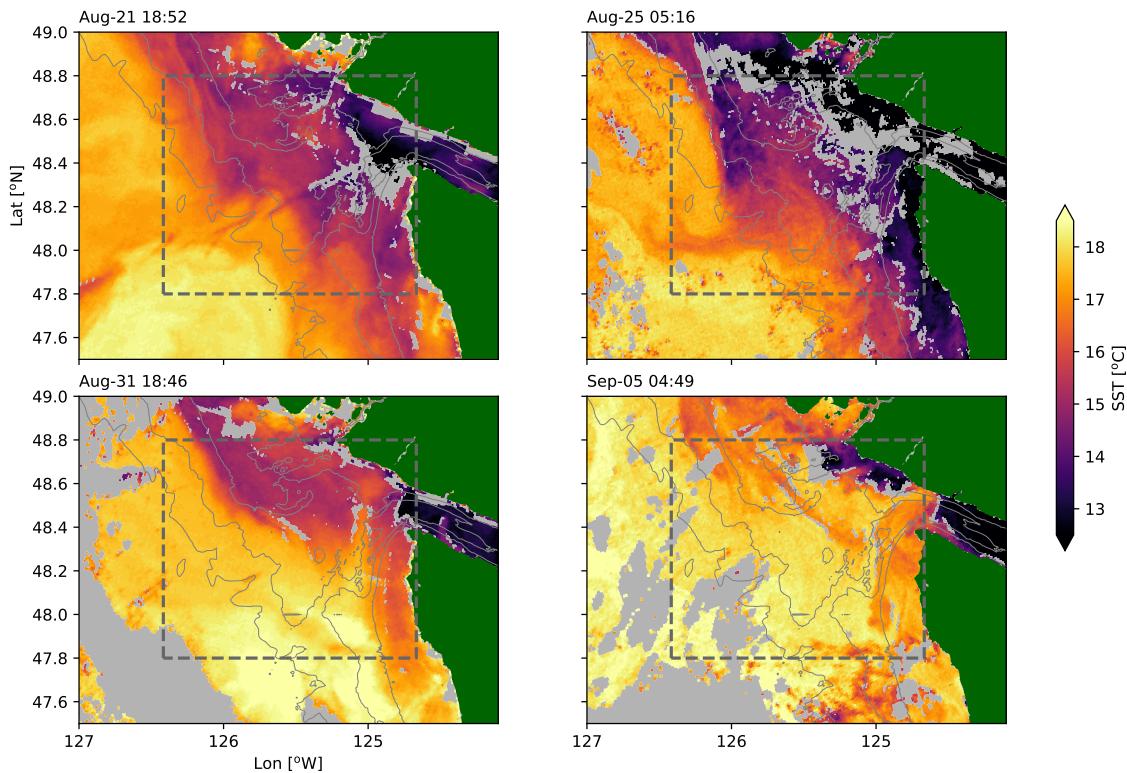


Figure 13. Sea surface temperature snapshots from the observation period. Grey areas are clouds; dashed gray line is the study area. Depths are contoured in thin gray lines at 200, 150 and 100 m. (OSI SAF, 2015)

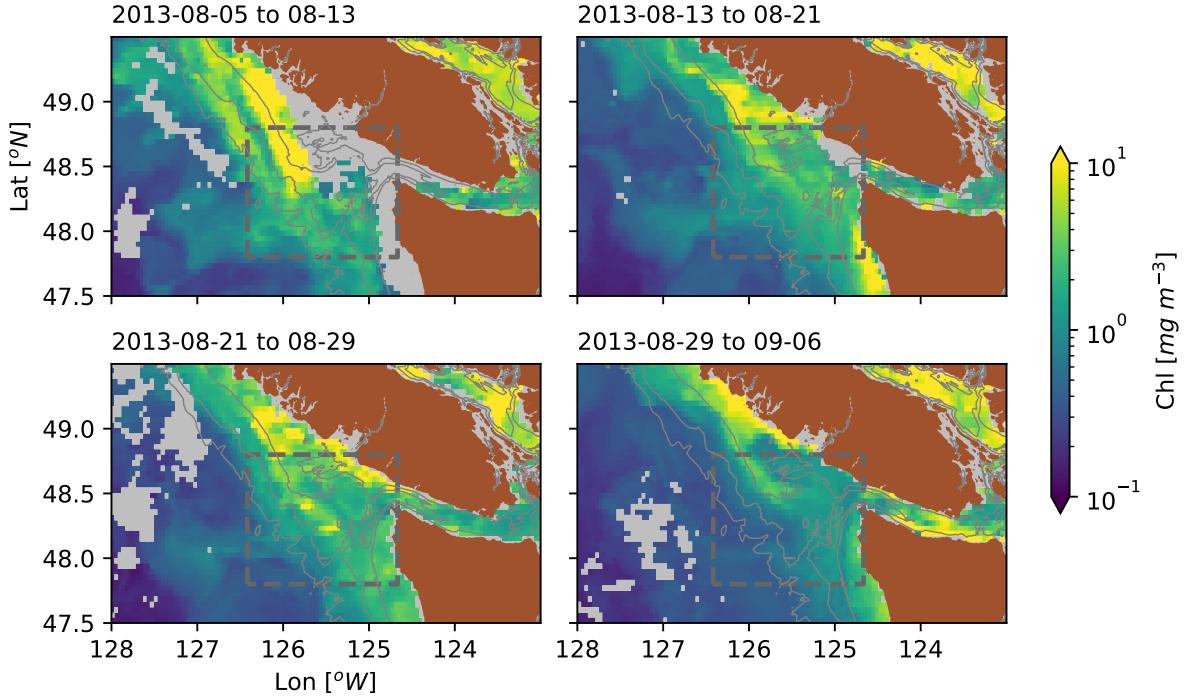


Figure 14. Surface chlorophyll density estimated from ocean color (Hu et al., 2012; NASA Ocean Biology Processing Group, 2017) over 8-day windows in 4-km bins. Gray regions had too many clouds to compute averages.

from a vertical mixture of the water at 26.5 kg m^{-3} and an equal distance down in density space of 26.7 kg m^{-3} , then the deepest water in the EDDY may be coming from a depth of 250 m. This is a typical upwelling depth for coastal flows, and may not require extra input up the Spur Canyon as posited by Freeland and Denman (1982).

We found little evidence of flow up the Spur Canyon or, if there is, then the mixing in the canyon is intense enough to remove the θ - S signature of offshore water within 20 km of the canyon mouth (Fig. 9). We did find substantial evidence of mixing in the canyon, but the primary pathway of high-salinity water into the canyon appears to be due to tidal flow over the banks on the west side (Fig. 10), rather than flow up the canyon. However, it is worthy of note that upwelling winds had ceased at the point of these observations (Fig. 2), so the offshore surface pressure gradient may be reduced, leading to reduced ageostrophic upwelling in the canyon. Whether the cessation of winds would also lead to a reduction of the low sea level height in the center of the EDDY that may drive up-canyon flow is an open question.

There is evidence of aging of the water in the EDDY between late spring and late summer (Fig. 3), with a reduction of oxygen in the EDDY over this time span. If we posited that the reduction was all in the same water, then the oxygen consumption rate over the time between the late-May and early September cruises would be on the order of $0.5 \mu\text{mol kg}^{-1}\text{d}^{-1}$. This is on the low side of estimates of apparent oxygen utilization rates in continental upwelling systems, which are between 1 and $5 \mu\text{mol kg}^{-1}\text{d}^{-1}$ (Dortch et al., 1994) (Dortch et al., 1994; Connolly et al., 2010). So it seems ~~possible likely~~ that the EDDY ~~had enough has~~ exchange with the surrounding water ~~for the residence time to have been less than the full time period from late May to September~~. Note that during the May cruise, the water in the EDDY is slightly cooler than the mixing line, and

420 during the September cruise is slightly warmer than the mixing line, ~~so further evidence~~
 421 ~~that~~ the water in the EDDY is evolving seasonally, ~~, and probably affected by the water~~
 422 ~~temperature in the Vancouver Island Coastal Current and the amount of water getting~~
 423 ~~through the onshore front (Fig. 3e,k)~~. This is consistent with findings on the Oregon shelf
 424 where physical processes are thought to account for 55–70% of changes in dissolved oxygen
 425 concentrations (Adams et al., 2013). Definitively identifying the exchange mechanisms into
 426 the EDDY is challenging from this data set. The offshore front does not appear to have much
 427 exchange, however as noted above there does appear to be strong tidal flows and mixing over
 428 the submarine banks that can transport more oxygenated water into the EDDY. Further,
 429 the Vancouver Island coastal current is oxygen rich, and has a much less sharp front than
 430 the offshore front (Fig. 11).

431 The water is mixed enough in the EDDY that it falls along a mixing line, though it
 432 remains vertically stratified. The amount of homogenization is such that either the mixing is
 433 very strong, or the water is retained in the EDDY for a long time. The amount of turbulence
 434 required to homogenize 100 m of water over 90 days is $\kappa \approx 10^{-3} \text{ m}^2 \text{s}^{-1}$. Given that the diffu-
 435 sivity implied in the cross-channel surveys was on the order of $\kappa_p = 10 \text{ m}^2 \text{s}^{-1}$ $\kappa_p = 0.5\text{--}5 \text{ m}^2 \text{s}^{-1}$,
 436 this number is not outrageous if we think that such high dissipation is found in 10^{-4}
 437 ~~0.2–0.02%~~ of the water column. We can more carefully quantify this by considering a
 438 synthetic profile of temperature and salinity based on an offshore profile, extrapolated from
 439 the bottom of the 200-m cast to 250 m, assuming that the temperature and salinity at 250
 440 m are 6.2 [°C] and 34 psu respectively (Fig. 15). Water at the offshore station was warmer
 441 than onshore, so the profile was also linearly interpolated to a surface value of (12 °C,
 442 31.6 psu). The profile was then linearly compressed into a depth range of 150 m representa-
 443 tive of the shelf depth in the dense pool, and subjected to mixing with a constant diffusivity
 444 of $\kappa = 10^{-3} \text{ m}^2 \text{s}^{-1}$, with the surface and bottom values pinned under the assumption that
 445 the near-bottom source and surface waters are replenished from a large reservoir. ~~Similar to~~
 446 ~~the naive scaling~~ In this calculation, the T-S relationship does not approach a straight line
 447 until after approximately 60–100 days, or until the mixing affects a vertical length scale of
 448 $\lambda = (\tau \kappa)^{1/2}$ that is greater than $\approx 70 \text{ m}$ $\lambda = (\tau \kappa)^{1/2} \gtrsim 70 \text{ m}$.

449 Combined with the oxygen observations, the implication is that the water in the EDDY
 450 likely experiences exchange with the outside water, but at a very modest rate. In terms of a
 451 volume flux, we might estimate the EDDY area as 900 km^2 , over 100 m depth, so that 100-d
 452 residence time corresponds to a transport of $10^4 \text{ m}^3 \text{s}^{-1}$, which is remarkably weak for the
 453 transport in and out of such a large area.

454 The sharpness of the front with the EDDY and the offshore water is intriguing. It was
 455 persistent for the duration of our detailed survey (Fig. 8), and, so far as we can tell with
 456 the limited resolution of the hydrographic surveys, was present during the bracketing La
 457 Perouse cruises. There is not any substantial bathymetry blocking the onshore incursion of
 458 water at this location, so there must be a dynamic barrier.

459 Numerical simulations of this region reported by (Sahu et al., 2022) using a NEMO
 460 36th-degree regional model contained relatively rapid exchange between the deep EDDY
 461 water and the rest of the coastal ocean. The region where the EDDY resides has velocities
 462 equal or greater than other parts of the shelf, and water has an approximate residence time
 463 of less than 20 days. The EDDY water in the model does develop a distinct θ - S signature,
 464 but not along a sharp mixing line as observed. It also has a front with the offshore water,
 465 but the front is substantially wider than that observed here. ~~Overall it seems that the~~
 466 ~~model sees stronger cross-shelf advection than are apparent in these observations, though~~
 467 ~~the reason for this will require further study.~~

468 Overall, it would be an improvement to our understanding of the EDDY if we could
 469 sample the shelf more persistently. The EDDY was already well-formed by the May La
 470 Perouse cruise, and seems to evolve slowly during that time. Capturing its formation,

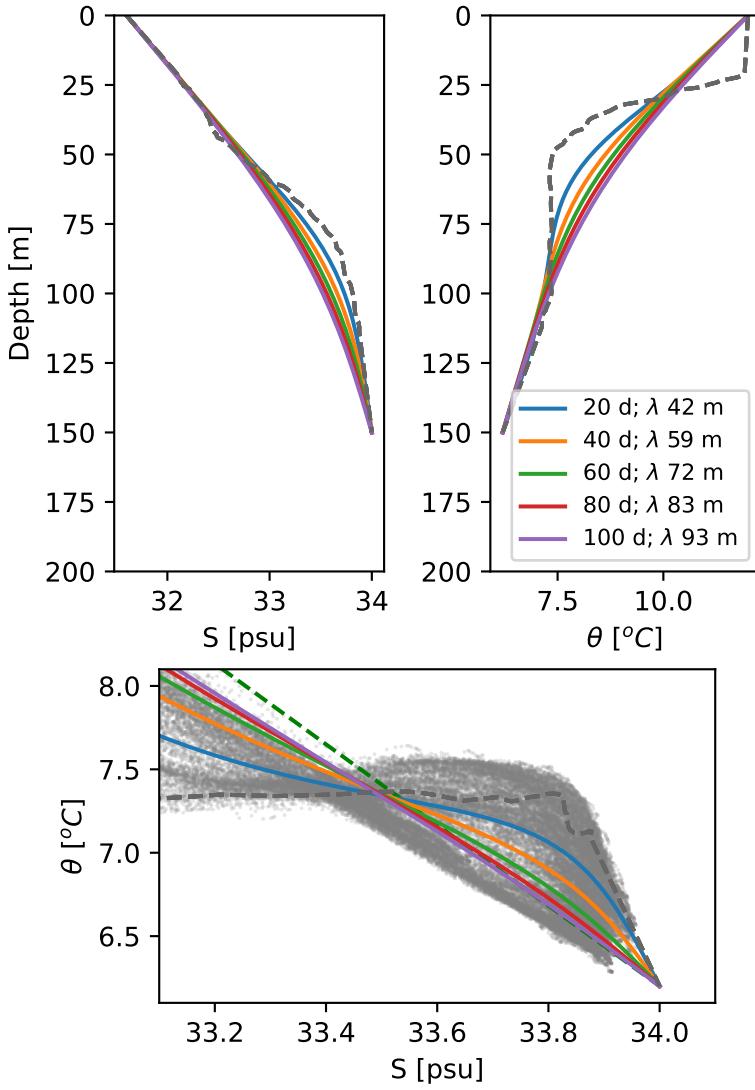


Figure 15. Mixing model assuming constant eddy diffusivity of $\kappa = 10^{-3} \text{ m}^2 \text{s}^{-1}$ acting on an offshore temperature and salinity profiles compressed from 250 thick to 150 m thick (grey dashed lines). Profiles are pinned to the deep $\theta - S$ value at (34 psu, 6.2 °C), and a shallow one at (31.6 psu, 12 °C). The green dashed line is the mixing line defined in the text.

471 presumably earlier in the spring, as well as its evolution through the year, would be valuable
 472 in understanding retention and exchange on this productive part of the shelf.

473 4.2 Offshore exchange of shelf water

474 The displacement of shelf water from La Perouse Bank is a dramatic departure from
 475 geostrophically balanced isobath-following flow. Eddies have been known to separate from
 476 irregular coastal topography, both at the surface (Barth et al., 2000) and deeper in the
 477 water column (Pelland et al., 2013). It has been recognized that instabilities lead to exchange
 478 between the open ocean and the shelf at this location (Ikeda & Emery, 1984, 1984). However,
 479 observations of the wholesale replacement of shelf water by a new water mass from offshore
 480 are [relatively](#) rare. In the observations presented here, it is clear that water from as deep as
 481 150 m is separating from the shelf and moving offshore (Fig. 8, Fig. 12).

482 Satellite imagery shows that there is often exchange between coastal and deep waters
 483 along the Vancouver Island shelf (Fig. 16). Most years there are three of four large filaments
 484 from the shelf into the open ocean, many of them over 100 km long. This length scale is
 485 longer than the 60 km inferred for this region by Ikeda et al. (1984) using a four-layer
 486 instability analysis. It is possible that there is spatial locking of these features, with a
 487 persistent separation at the north tip of Vancouver Island, and a strong tendency for one
 488 at 49.5 N. There is also evidence of separation events in most of the years, with 2011
 489 being the only clear exception. General baroclinic instability of the upwelling front is a
 490 possible mechanism to drive offshore exchange (Ikeda et al., 1984; Durski & Allen, 2005),
 491 but this tends to be shallow, with smaller-scale instabilities that will not extend as far into
 492 the interior ocean as observed here. Rather it seems likely that the topographic change
 493 engendered by the sudden turn to the east of La Perouse ~~bank~~[Bank](#) catalyses a larger scale
 494 instability at this location. [In California, most of the cold filaments observed appear to be](#)
 495 [catalyzed by headlands and underwater topography \(Strub et al., 1991\), though modelling](#)
 496 [studies find instabilities are possible even in two-dimensional flows \(Pierce et al., 1991\).](#)
 497 Durski and Allen (2005), when modelling the Oregon shelf, found that including realistic
 498 shelf bathymetry catalyzed intermittent large-scale instabilities[similar to the feature here](#),
 499 a finding that is deemed likely to apply at other coastal locations (Battieen, 1997).

500 Large-scale mixing between the shelf and open ocean has been evident since the satellite
 501 era. Here we demonstrate that in the Vancouver Island shelf the flow is originating on the
 502 shelf and separating from the bathymetry and being injected into the interior. A similar
 503 observation was made by Barth et al. (2000) downstream of Cape Blanco, Oregon, where
 504 the coastal current was observed to detach from the shelf in the lee of the cape and flow into
 505 the interior. They hypothesized that as the current moved offshore, it deepened, stretching
 506 isopycnals and creating cyclonic relative vorticity that would tend to push the current back
 507 onshelf, but then it was caught in the undercurrent and stalled, being pushed offshore. It is
 508 also possible that coastally trapped waves in the region experience a hydraulic control, and
 509 these separation events are part of the response (Dale & Barth, 2001).

510 Regardless of the dynamics of the separation events, the offshore transport can be
 511 substantial. If we assume the coastal current is approximately 0.1 m s^{-1} over 100 m in
 512 the vertical and 20 km in the horizontal, it represents 0.2 Sv of nutrient- and chlorophyll-
 513 rich shelf water transported offshore. [Sometimes the along-shelf currents are substantially](#)
 514 [larger than this \(Thomson & Krassovski, 2015\) reaching \$0.4 \text{ m s}^{-1}\$.](#) Our observations are
 515 a ~~finer-detailed~~[finer-detailed](#) representation of the kind of cross-shore transports inferred
 516 by Mackas and Yelland (1999) from hydrographic surveys, and definitively show that this
 517 water can originate from the shelf from relatively deep depths and be transported offshore.
 518 We do not have velocity measurements for the water that replaces it, but assuming that
 519 water also flows along-shelf, these separation events are associated with a large replacement
 520 of shelf water with offshore water at this location. This emphasizes the importance of

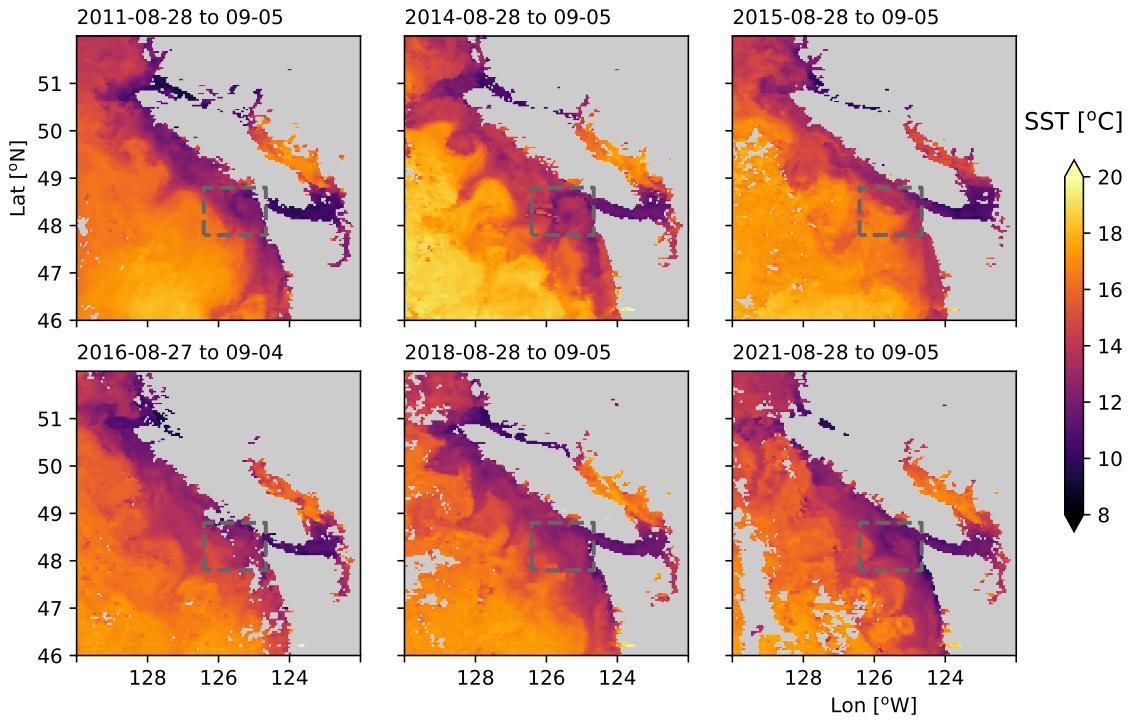


Figure 16. Available late-August sea-surface temperature from 8-day composites, 2011 to 2021 (NASA Ocean Biology Processing Group, 2019); missing years had too much cloud cover or no satellite coverage.

521 three dimensional observations and modeling of cross-shelf dynamics when thinking about
522 physical and biological processes on the shelf.

523 Open Research

524 Derived data files (1-m vertical binned CTD files) and analysis scripts are available at
 525 <https://ocean-physics.seos.uvic.ca/~jklymak/PW13DataAnalysis/>. Raw CTD data
 526 is available on request. Data was processed using a scientific python toolchain as listed at
 527 <https://ocean-physics.seos.uvic.ca/~jklymak/PW13DataAnalysis/environment.yml>;
 528 major components include xarray (Hoyer & Hamman, 2017), numpy (Harris et al., 2020),
 529 and Matplotlib (Caswell et al., 2022), but those all leverage many smaller but vital projects.

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