

# Density structure in the outflow region of Colvos Passage:

Observational analysis and model comparison

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## **Abstract**

Puget Sound lies in a densely populated region of the state of Washington with many potential sources of pollution. A better understanding of circulation patterns within Puget Sound, such as the complex intersection of Colvos Passage with Main Basin, is critical to predicting the long-term effects of pollutants. Whether Colvos water is flushed out towards the ocean or recirculated depends on specific details at this intersection. This study compares observations of the outflow from Colvos Passage with the depiction of the same area in LiveOcean, a computer model developed by the UW Coastal Modeling Group. While it appears that Colvos water becomes the surface layer in the outflow area, there is evidence that it settles into an intermediate layer outside of this region. This study finds evidence that a larger portion of water coming out of Colvos Passage is directed seaward in Main Basin than is recirculated through East Passage. The model comparison shows that, while LiveOcean reproduces the general structure of water masses in the area, it does not adequately resolve the interaction between water masses in the outflow area of Colvos Passage.

## **Introduction**

With nearly 5 million people living in the counties bordering Puget Sound (US Bureau of the Census, 2018), this fjord-like estuary is highly susceptible to anthropogenic pollutions. Sewage overflows increase bacteria counts and have long been a concern within Puget Sound (Ebbesmeyer et al., 1984). Combined stormwater and sewer systems continue to see multiple overflows each year (King County, 2018). Stormwater runoff carries substances like pesticides, heavy metals, and petroleum products from streets, industrial facilities, residential and agricultural sources (McCarthy et al., 2008). Excessive buildup of nutrients (eutrophication) can

lead to oxygen depletion and increased mortality of fish populations. Main Basin is flushed frequently, but many of the side basins, such as South Sound, experience eutrophication (Khangaonkar et al., 2011). In order to implement effective mitigation strategies, a better understanding is needed of how substances are moved through the Sound and where they end up.

The effects of pollutants on marine communities depend on how long the pollutants remain in the system. In Puget Sound, these residence times vary between, and often within, sub-basins and depend greatly on circulation patterns. Based on a lengthy historical record, the overall circulation of Puget Sound is well understood (Ebbesmeyer et al., 1984; Babson et al., 2006, Sutherland et al., 2011). However, the record is spatially and temporally uneven. Details are lacking at complex intersections of flow such as that at the north end of Vashon Island.

Estuaries typically exhibit a two-layer flow regime where the surface layer has a net seaward flux and the deep layer has a net landward flux. This is the general pattern of flow within Puget Sound. Fresh water discharged by rivers is more buoyant and lies on top of denser, saltier water drawn in from the ocean. This implies that pollutants contained within surface runoff and wastewater overflows would be quickly transported out towards the ocean. However, there are several major sill zones within the Sound. Sill zones are areas, typically at the junction between basins, that are much shallower than either side and cause turbulent mixing. As surface water mixes in with deep water, it becomes denser and flows back inland with the lower layer. At Admiralty Inlet, a large sill zone near the seaward end of Puget Sound (Fig. 1), as much as 2/3 of the surface water is subducted and refluxed landward (Ebbesmeyer and Barnes, 1980), which suggests that up to 2/3 of pollutants would also be sent back landward.

Vashon Island sits at the southern, landward end of Main Basin and acts as a partition between two channels with flow in opposite directions (Figure 1). With each flood tide, water is

channeled southward through East Passage. At the south end of Vashon Island, some of this water is then upwelled and forced through Tacoma Narrows. The combination of a shallow sill

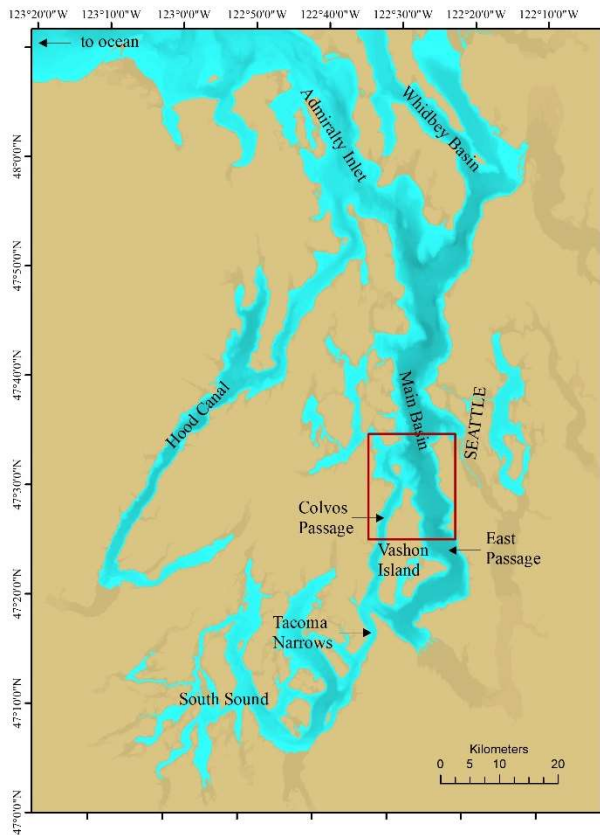


Figure 1. Map of Puget Sound with study area highlighted. (Bathymetry from Finlayson, 2005).

and sharp channel curvature here creates intense mixing of waters on both the flood and the ebb tide (Seim and Gregg, 1997). All water coming into and out of South Sound goes through Tacoma Narrows. On the ebb tide, nearly all of the return flow of water from Tacoma Narrows is channeled through Colvos Passage. In order to satisfy mass balance, the volume of water transported north through Colvos Passage must be equal to the net inflow through East Passage. Colvos Passage, however, is much narrower than East Passage, and thus experiences higher current speeds

(Cokelet et al., 1990). In fact, Colvos Passage sees almost constant northward flow. It experiences maximum speeds during ebb tide and slows down to near zero during flood tide. Occasionally, the incoming flood forces a reversal of direction, but southward velocities are always very small (Ebbesmeyer et al., 1984).

Previous investigators, despite drawing on the same set of historical data, have come to mixed conclusions about the outflow from Colvos Passage. According to Seim and Gregg (1997) water exiting Colvos sinks below river plumes. Cokelet et al. (1990) determined that Colvos Passage always has higher salinity than the surface layer of neighboring water masses, which

implies that water coming out of Colvos would have a higher density and sink below the surface layer when it joins Main Basin/East Passage. However, Cokelet et al. (1990) also say that East Passage has a very shallow surface layer that may not be persistent, leaving one to wonder if there is enough of a surface layer to sink under. Ebbesmeyer et al. (1984) say that much of Main Basin's upper layer transport comes from Colvos Passage. This could be because water from Colvos becomes the surface layer or because it travels with the surface layer as an intermediate layer.

Knowing whether or not water discharged from Colvos Passage gets incorporated into the surface layer is an important clue to understanding how long pollutants might be trapped within Puget Sound. Any pollutants contained within the water column in Colvos Passage will be moved seaward if the discharge moves with the surface layer. If much of the discharge gets mixed into the landward-directed deep layer, pollutants may end up being recirculated around Vashon Island and back through South Sound many times before escaping seaward.

This study aims to address some of these uncertainties. It tests the hypothesis that the well mixed water column coming out of Colvos Passage forms an intermediate layer upon entering the two-layer system of Main Basin. This study also looks for evidence of direction of flow of Colvos water by tracking water properties over two tidal cycles in January 2019.

This study builds on the foundation of a lengthy historical record and decades of analytical and theoretical modeling through classical data collection techniques. One tool being used increasingly in the field of oceanography is computer modeling. In a connection between classical and modern techniques, this study compares the LiveOcean computer model with observations to provide insight into model skill.

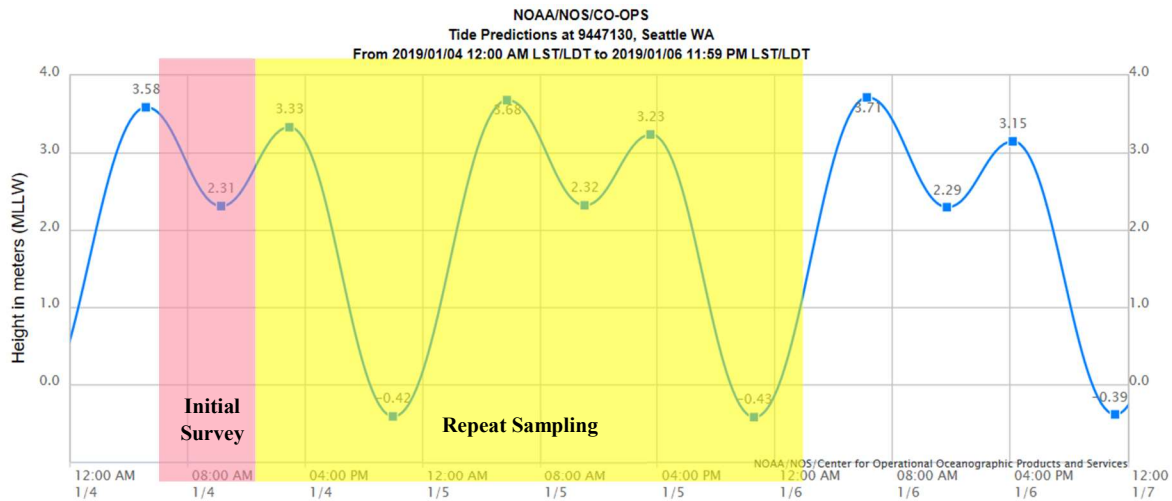


Figure 2. NOAA tide predictions for sampling dates marked with timeframes of data collection.

## Methods

### *Location and Equipment.*

Data collection took place in Puget Sound January 4-6, 2019 aboard the *R/V Rachel Carson* at the north end of Colvos Passage where it intersects with Main Basin (Fig. 1). Seattle experiences a mixed semi-diurnal tide, meaning that most of the time one ebb-flood cycle is significantly larger than the other and referred to as the major phases. Field measurements were repetitive and timed to span two major ebb phases (Fig. 2). This study utilized a Sea-Bird SBE-911 plus Conductivity, Temperature and Depth (CTD), a Teledyne Underway CTD (uCTD), and an RDI Workhorse 300 pole-mounted Acoustic Doppler Current Profiler (ADCP). Locations of transects and CTD stations were chosen based on flow patterns exhibited in the LiveOcean model (model described below), with consideration of multiple ferry routes and local shipping lanes (Fig. 3).

### *Initial Survey.*

The initial survey began around 8 am on Friday, January 4 with three CTD casts at Stations A, B, and C (Fig. 3). These stations represent three focus regions marking one inflow

and two outflow paths. There was enough evidence of layering at these three stations to determine that the station locations would be suitable for the purposes of this study. Additionally, it was determined that the additional sensors available on the CTD package, and not on the uCTD, did not provide enough additional information to warrant the time costs of a stationary CTD cast each time a station was passed. Without stopping for stationary CTD casts, this allowed for approximately three transits of each transect during each tidal phase.

#### *Sampling Procedure.*

The sampling period began around noon on January 4<sup>th</sup>, just before high tide, and ran continuously until weather conditions became unsafe around 2:00 am January 6<sup>th</sup>. The sampling area consisted of a continuous path of transects beginning at Point 1 (Fig. 3) and proceeding in numerical order through Point 7, then back to Point 1. Although, the ADCP ran continuously for the duration of the sampling period, bottom tracking was only effective to 150 m. Along with a mismatch of navigation data formats between the ship and the ADCP software, this meant that velocity data collected in Main Basin could not be reconciled. The uCTD was operated with back-to-back casts through most of the sampling period. However, some technical issues caused gaps in the data. The largest issue was the loss of one uCTD probe, which prevented continuous

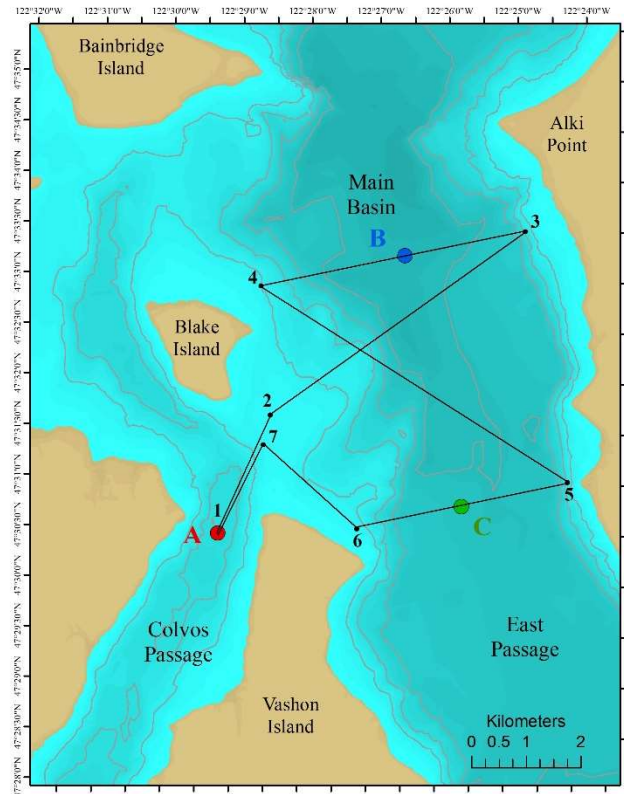


Figure 3. Map of study site. Transects of uCTD casts are marked with black lines and numbered at vertices. Each transect is referred to by the lower number of its two endpoints (Transect 1 includes both segments from 1-2 and 2-3). CTD stations are lettered and marked with colored dots. Contour lines at 50 m intervals.

sampling due to the need to periodically download data. CTD stations were sampled about once per tidal phase at first, but then more often after issues arose with the uCTD.

#### *Data Analysis.*

The CTD and uCTD profiles were used jointly to assess temperature and salinity properties across the study field. The salinity measurements from the uCTD were reduced by 0.01 psu to align with CTD measurements. Temperature-salinity plots were compared at Stations A, B, and C to look for signs that water from Colvos Passage was influencing the properties in Main Basin. Temperature, salinity, and density sections from uCTD casts were created to track movement of water properties similar to those of Colvos Passage across the study field. The first two uCTD casts taken near Station A at the beginning of the major ebb tide on January 4<sup>th</sup> were used to establish the characteristics of water in Colvos Passage. Density sections delineated by the minimum and maximum values of these two casts were examined for evidence of Colvos water being maintained as a cohesive water mass and flowing through the northern and southern boundary transects (Transects 3 and 5). The two uCTD casts taken before and after the beginning of the major ebb tide at Station C were used to identify the density at which the steep pycnocline between surface and deep layers begins. This value was used to delineate the deep layer in the density sections in order to monitor the internal tide. ADCP velocities for Station A, where water depth is less than 150 m and bottom tracking was achieved, were used to calculate tidal excursion and verify the plausibility of observed water mass movement being attributable to water flowing out of Colvos Passage.

Water flows exclusively northward through Colvos Passage, with the exception of a slight, short-lived, southward flow during some flood tides. This does not follow the typical

pattern of ebb and flood, so the standard tidal excursion calculation is inadequate. Instead, the flow coming out of Colvos Passage is modeled as:

$$v = -\frac{V}{2} \cos\left(\frac{2\pi}{T}t\right) + \frac{V}{2}$$

where  $V$  is the maximum northward velocity and  $T$  is the period between the high tides before and after the major phases on January 4th. This results in a tidal excursion of:

$$L_T = -\int_0^{\frac{T}{2}} \frac{V}{2} \cos\left(\frac{2\pi}{T}t\right) + \frac{V}{2} dt = \frac{VT}{4}$$

where only the flow during the ebb tide is considered. After that time, the outflow from Colvos Passage has to compete with the incoming flood tide in Main Basin.

#### *Model Comparison.*

LiveOcean (<http://faculty.washington.edu/pmac/LO/LiveOcean.html>) is a model of the Pacific Northwest coastal ocean, coastal estuaries, and the Salish Sea that utilizes the Regional Ocean Modeling System (ROMS, Shchepetkin and McWilliams, 2005). It is substantially based on the Cascadia model (Giddings et al., 2014; Davis et al., 2014; and Siedlecki et al., 2015). Comparisons of the Cascadia model with observational data show that it has a high skill level (ability to make accurate predictions based on specific metrics) for the vertical structure of velocity, temperature, and salinity and depicts short time-scale and seasonal variation in those parameters well (Giddings et al., 2014, Siedlecki et al., 2015).

LiveOcean takes modeled and real-world data from a variety of sources as boundary conditions (see Appendix) and makes 3-day forecasts of basic water properties including velocity, temperature, and salinity as well as many biogeochemical fields. Simulated moorings were extracted from the LiveOcean model to compare to observations of temperature, salinity, density, and velocity. From these moorings, density sections were created across Transect 1 to

compare to observations. Density bounds of water within Colvos Passage at the top of the major ebb were determined for the model as for observations. Particle tracking experiments for the dates of the study were run to compare with observed water mass movement.

## **Results**

### *Observations*

Temperature and salinity at Colvos Passage (Station A) is remarkably uniform throughout the water column. At high tide prior to the major ebb on January 4<sup>th</sup>, water in Colvos Passage is clearly distinct from water at Main Basin (Station B) and East Passage (Station C) in temperature-salinity (T-S) space (Fig. 4d). As the ebb tide progresses, the lower density tail of Station B curves upward until it overlaps with the higher density tail of Station A (Fig. 4h, l, p). By the time the tide changes direction (Fig. 4p), the measurements at Station B form a nearly linear curve that lines up with the measurements at Station A. The bulk of Station C measurements do not shift in T-S space over this time period. However, the lower density tail of Station C does cool and freshen, a distinct difference from Stations A and B (Fig. 4d, h, l, p).

There is a sharp pycnocline evident in the profiles at Stations B and C delineating the boundary between the surface and deep layers (Fig 4). At times, Station C also shows a smaller, but distinct, pycnocline higher in the water column. At the beginning of the ebb tide, the surface layer of Station B (approx. 0-65 m) displays properties that are distinct from those at Station A. As the tide progresses, both temperature and salinity at Station B gradually become more like those at Station A, until the entire surface layer (now 0-80 m) of Station B is nearly identical to the entire column of Station A (Fig. 4i-k). The properties of Station B then begin to diverge from those of Station A as the flood tide begins (Fig. 4m-o).

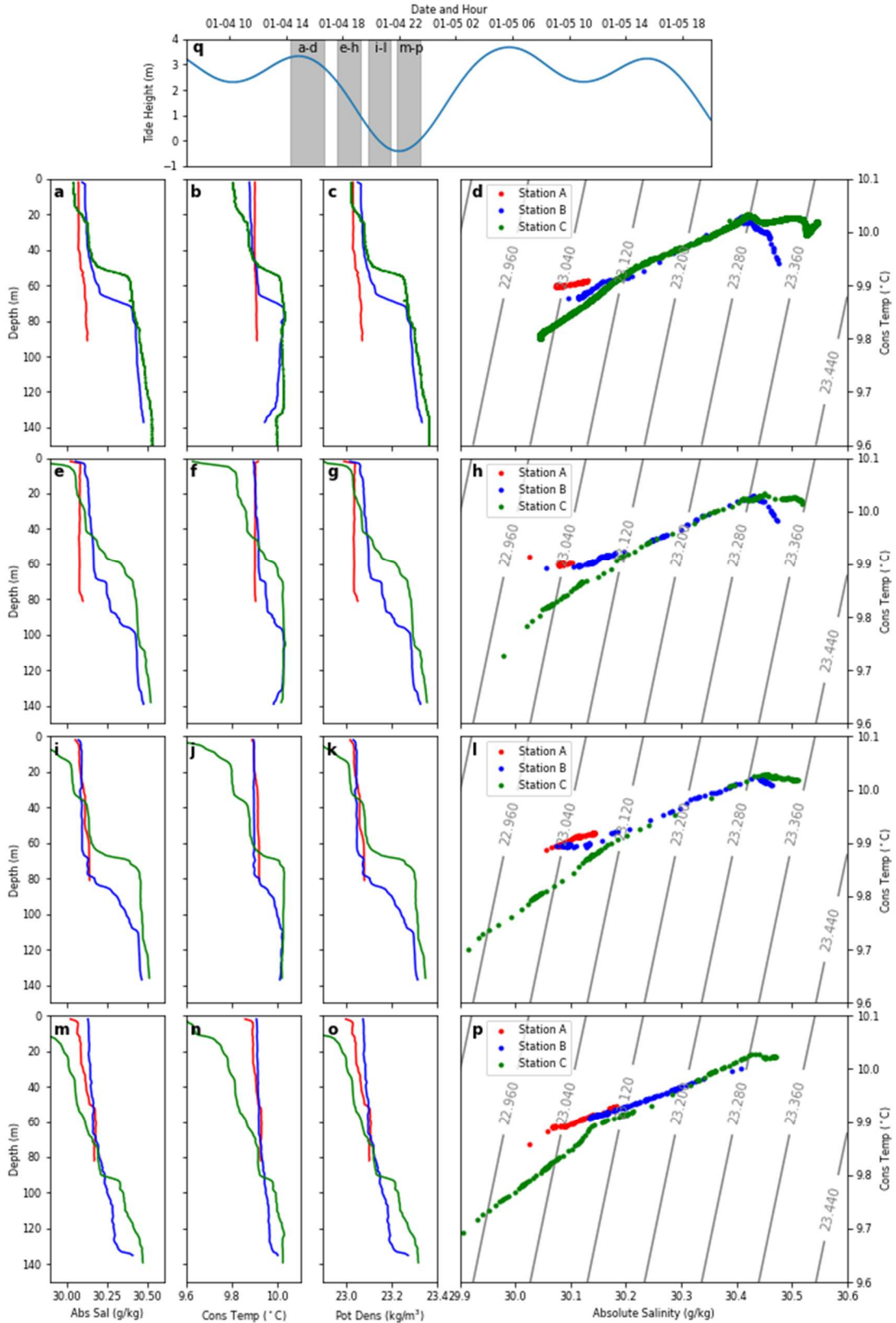


Figure 4 Water properties at Stations A, B, and C over a roughly eight-hour period on January 4, 2019. a-d) High tide just before the major ebb. e-h) Midway through the ebb tide i-l) Bottom of the ebb tide m-p) Low tide at the beginning of the major flood.

The progression of water out of Colvos Passage is visible in density sections over the course of the major ebb tide (Fig. 5). Transect 1 extends northeast from Station A across Main Basin and ends east of Station B (Fig. 3). Colvos water is clearly identifiable as it expands across Transect 1 over the course of the ebb tide (Fig. 5d-f, shown in orange). The maximum northward velocity at Station A was  $.7768 \text{ m s}^{-1}$ . The period between the high tides on either end of the major phases was 14.667 hours, resulting in a tidal excursion of about 10 km.

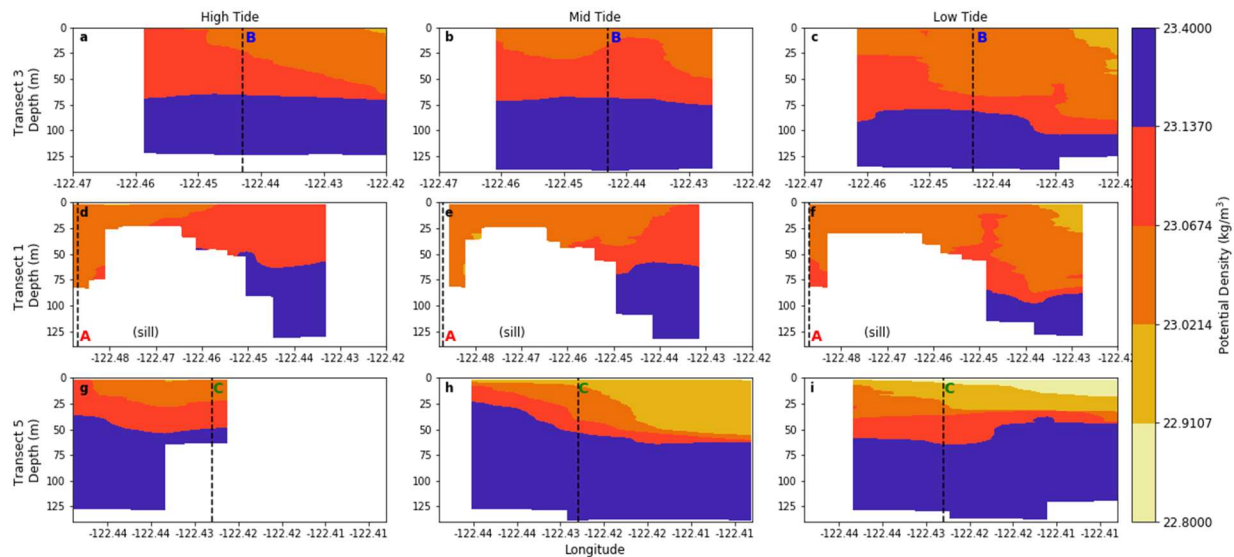


Figure 5. Density sections over the course of the major ebb tide on January 4<sup>th</sup>. Bounds of density near Station A were determined at the top of the ebb tide ( $23.0214\text{-}23.0674 \text{ kg m}^{-3}$ ) and are depicted in orange. Rows depict Transects 3, 1, and 5 (ordered north to south), from top to bottom. Columns show a progression of time from left to right over the duration of the ebb tide. Location of the sill between Colvos Passage and Main Basin is evident and labeled in the region of consistently missing data on the western side of Transect 1. Locations of CTD stations are marked in each section, with Station A in Transect 1 being the exit of Colvos Passage.

Over the same time period, the mass of water within the density bounds of Colvos water ( $23.0214\text{-}23.0674 \text{ kg m}^{-3}$ ) also expands across Transect 3 (Fig. 5a-c), which is the northernmost transect and passes through Station B. Across Transect 5 (southern transect through Station C), there is a thin layer of water within the density bounds of Colvos water that actually decreases in thickness over the ebb tide (Fig. 5g-i). An internal tide is evident in the fall and rise of the deep

layer of water (water below the steep pycnocline, shown in blue, Fig. 5 and 6). The internal tide is particularly pronounced across Transect 1.

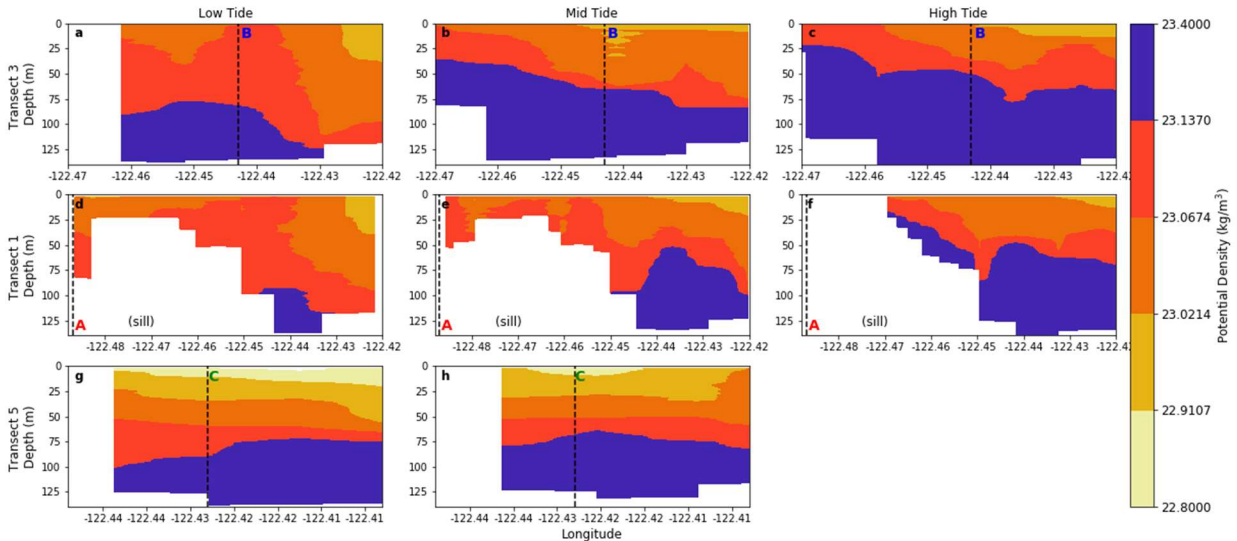


Figure 6. Density sections over the course of the major flood tide on January 4<sup>th</sup>. Bounds of density for Colvos water are the same as those used in Figure 8 and are depicted in orange. Rows depict Transects 3, 1, and 5 (ordered north to south), from top to bottom. Columns show a progression of time from left to right over the duration of the flood tide. Location of the sill between Colvos Passage and Main Basin is evident and labeled in the region of consistently missing data on the western side of Transect 1. Locations of CTD stations are marked in each section, with Station A in Transect 1 being the exit of Colvos Passage.

As the tide turns, the structure of the water column shifts. Over the course of the major flood, the layer of water within the density bounds of Colvos water across Transect 3 is split between east and west sides of Main Basin, recovers across the channel at mid-flood, and then shoals at high tide (Fig. 6a-c). A similar progression is seen across Transect 1 (Fig. 6d-f). Although measurements are not available for the end of the flood tide across Transect 5, the layer of water within the density bounds of Colvos water is significantly thicker during the flood than it was during the ebb tide (Fig. 6g-i).

### *Model*

LiveOcean depicts density in this area with a significantly higher range than that observed, with observations ranging from 22.8-23.4 kg m<sup>-3</sup> and the model ranging from 22.9-

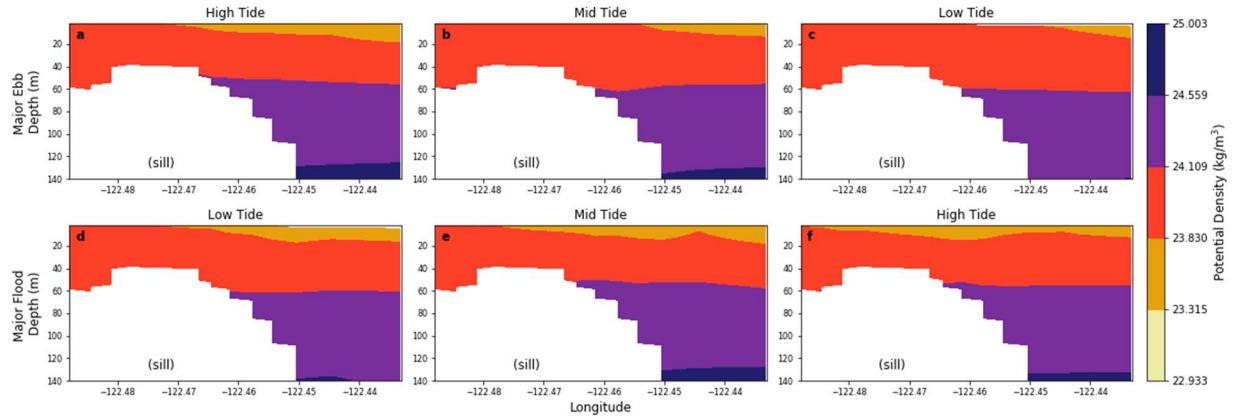


Figure 7. Density sections from simulated moorings across Transect 1 over the duration of the major ebb tide on January 4<sup>th</sup> (row 1) and over the duration of the following major flood tide (row 2).

25.0 kg m<sup>-3</sup>. Therefore, density of Colvos water was determined independently within the model. At the top of the major ebb, the bounds for density of Colvos water in the model is 23.830-24.109 kg m<sup>-3</sup>. Water of this density exists across Transect 1 for the duration of both the ebb and flood tides (Fig. 7). This layer thickens slightly over the duration of the ebb tide.

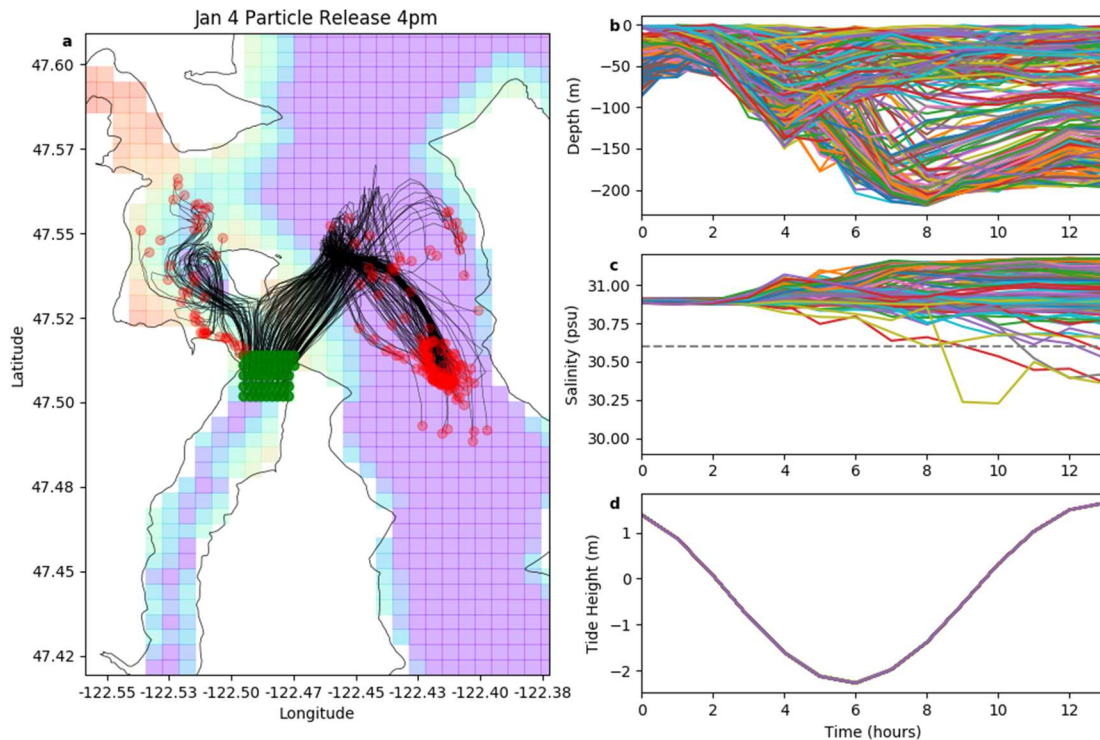


Figure 8. Results of particle tracking experiment for particles released just after high tide on January 4<sup>th</sup> and concluding at the following high tide. a) Start (green) and end (red) positions of particles with tracks shown in black. b) Depth trajectories of particles over time. c) Salinity conditions around each particle over time. Gray dashed line indicates observed salinity at Station A at the top of the ebb tide. d) Sea surface height representing phase of tidal cycle.

The particle tracking experiment run for the starting date of the field study was limited to the duration of the major phases of the tide. On the ebb tide, LiveOcean has most of the particles flowing out of Colvos Passage to the northwest into the center of Main Basin (Fig. 8a). When the tide turns, the particles are diverted southward towards East Passage. Few of the particles make it to the east side of Main Basin, and most of them cross the position of Transect 5 by the end of the flood tide. While many of the particles stay tightly together in the horizontal plane, they are well distributed vertically (Fig 8b). While limited to about 100 m depth range within Colvos Passage, once they've gone over the sill (around 4-6 hours after release) many of them sink to around 200 m while others stay near the surface. There is a discrepancy between the model and observations in salinity similar to that of density (Fig 8c).

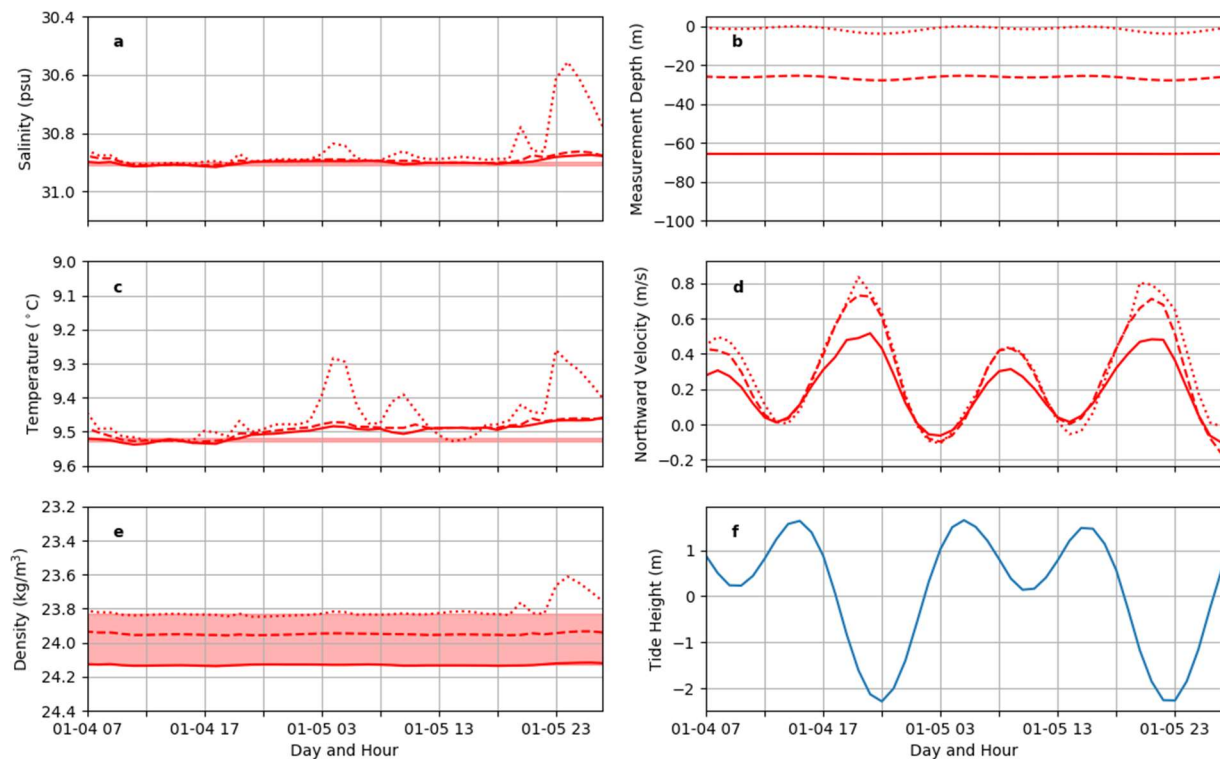


Figure 9. Time series of three depths in a simulated mooring at Station A over the full duration of the study. Pink bars in property time series denote range of that property at high tide before the major ebb. a) Salinity in psu. b) Depth of each measurement level as it varies with tide. c) Temperature. d) Northward velocity. e) Density. f) Sea surface height representing phase of tidal cycle.

A simulated mooring at the location of Station A over the duration of the study establishes properties for Colvos Passage (Fig. 9). The model depicts salinity as nearly constant over the time period and shows only a slight increase in temperature at the end of the second day. Therefore, the density range does not change much over time. Maximum northward velocity for mid-depth matches closely with the observed velocity near Station A.

A simulated mooring at the location of Station B over the duration of the study shows a much larger gradient of each of the properties over depth (Fig. 10). Temperature and salinity at the ~30 m and ~90 m depths approach the temperature and salinity of Station A at the end of each major ebb tide, but the surface layer remains cooler and fresher. Density at the ~30 m depth remains within the density range of Station A the entire time.

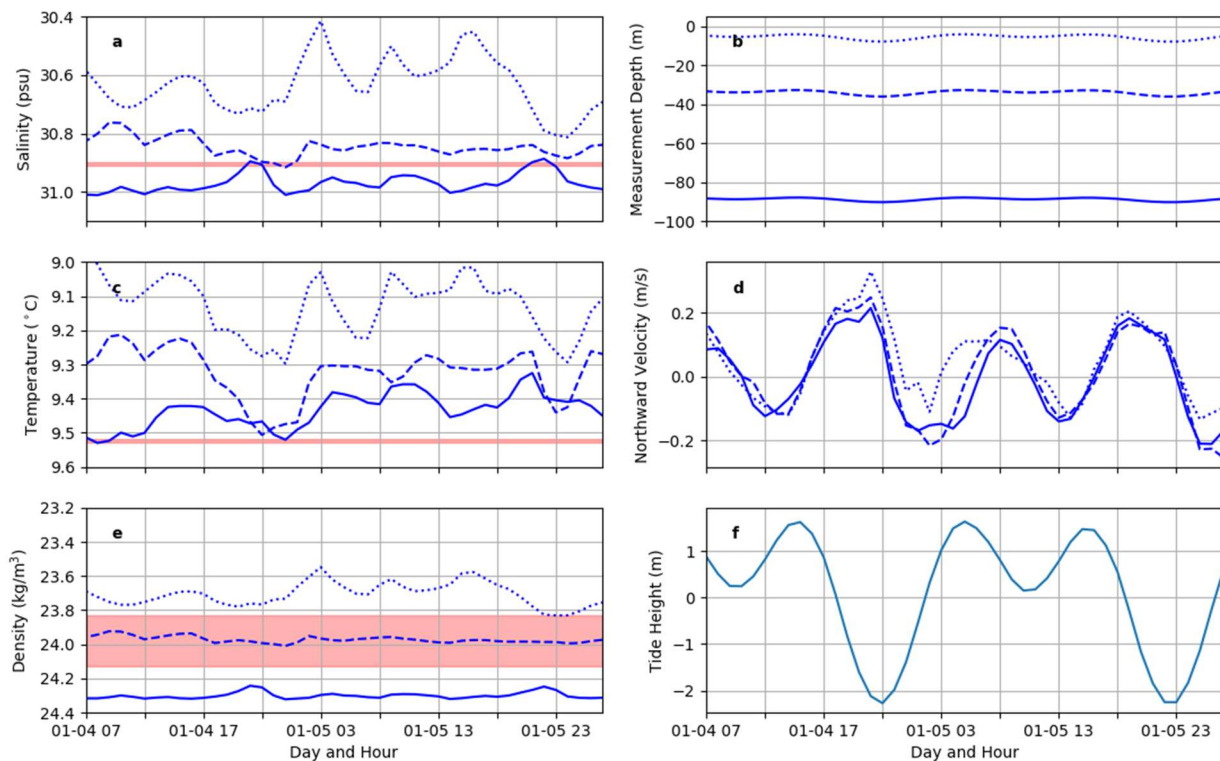


Figure 10. Time series of three depths in a simulated mooring at Station B over the full duration of the study. Pink bars in property time series are the range of that property at Station A (from Fig. 9) at high tide before the major ebb. a) Salinity in psu. b) Depth of each measurement level as it varies with tide. c) Temperature. d) Northward velocity. e) Density. f) Sea surface height representing phase of tidal cycle.

## **Discussion**

### *Observations of Outflow from Colvos Passage*

The water in Colvos Passage is well mixed, creating a single homogenous layer. This shows up in the starkly uniform water properties seen in the CTD profiles at Station A. Cokelet et al. (1990) found that Colvos Passage always had higher salinity than surface waters in neighboring passages. However, this study finds that, while salinity in Colvos Passage is higher than surface salinity in East Passage, it is actually lower than the surface salinity in Main Basin at Station B. This may have been due to recent rainfall or may be particular to this specific area of Main Basin and does not negate the findings of Cokelet et al. It does, however, decrease the likelihood that outflow from Colvos Passage would create an intermediate layer in this area.

From density sections and temperature/salinity profiles, it appears that the outflow from Colvos Passage flows northeastward across Main Basin. As the internal tide lowers the pycnocline between surface and deep layers and the flow out of Colvos Passage increases with the ebb tide, Colvos water appears to displace the surface layer in Main Basin. Colvos water extends eastward across the width of Main Basin and northward past Transect 3. With a tidal excursion calculated from Station A of 10 km and a distance from Station A to the end of Transect 1 of 7.5 km, it is not unreasonable to conclude that the outflow from Colvos Passage can reach the east side of Main Basin, flowing northward of Transect 3, during the major ebb.

On the subsequent flood tide, Colvos water appears to move southward as a thick layer through Transects 3 and 1, but the thick layer doesn't arrive at Transect 5. If the same water is making it all the way south to Transect 5, it is being compressed into a thinner, more horizontal layer during that transit. This could be due to general shoaling of the surface layer as the internal tide rises, or simply because things calm down south of where Colvos Passage continues to

extrude water into Main Basin on the flood tide. If this is the case, a similar situation may be taking place north of the study region as well. Colvos water may be settling into an intermediate layer outside of the chaotic intersection of Colvos outflow with Main Basin.

Seim and Gregg (1997) state that the outflow from Colvos Passage sinks below river plumes. Over the course of the major ebb and major flood during this study, this behavior was not observed in the outflow area. Colvos water was seen from the surface to the pycnocline at the top of the deep layer. During the minor phases of the tide (not shown), more stratification in the outflow area was maintained. Water within the density range identified as Colvos water was seen near the surface, but the outflow from Colvos had a greater density at this time. This higher density water flowing out of Colvos appeared to sink below that surface layer. During the major ebb on January 5<sup>th</sup> (not shown), the sequence of events with this denser water seemed to be similar to that of the major ebb on January 4<sup>th</sup>. However, fewer samples were taken, and patterns were more difficult to decipher.

A shallow layer of relatively fresh water developed across the surface of Transect 5 near the end of the major ebb on January 4<sup>th</sup> that seemed to disappear by the end of the major flood. This may be the transient surface layer that Cokelet et al. (1990) elude to. However, there remained a thicker layer above the pycnocline that consisted of water of the density identified for Colvos Passage in this study and water with a slightly higher density (within the density range of water coming out of Colvos after the major phases). Cokelet et al. state that all water, except the thin surface layer, in East Passage moves landward. Without velocity data, it is impossible to determine which direction the thicker surface layer observed in this study is moving in net.

Ebbesmeyer et al. (1984) state that a large portion of the surface flow in Main Basin comes from Colvos Passage. This study seems to support that. The outflow from Colvos Passage

appears to extend beyond Transect 3 during the major ebb. The volume of water identified as Colvos water across Transect 5 during the flood tide seems to be much smaller than that seen across Transect 3. This implies that a significant portion of Colvos water flows northward upon exiting Colvos Passage. Unfortunately, without velocity data to verify, no definitive conclusion can be drawn.

#### *LiveOcean's depiction of the behavior of the outflow from Colvos Passage*

There is a definite difference between LiveOcean's characterization of water across the study region and the observed properties. LiveOcean depicts lower temperatures, higher salinities, and higher densities than seen in observations. At the scale of this study, the differences are significant, creating little overlap in values between data sources. Since this study evaluated model performance based on its own characterization of Colvos water, a valuable comparison can still be made.

At the beginning of the January 4<sup>th</sup> major ebb, the model shows a range in density values for Colvos water that is about five-fold that of observations, but the model values do not change over time (Fig. 9). Observations show that, while the density range doesn't change much, its value increases over the study period (discussed above). Including all values over the entire study period, the model shows two times greater range in density of Colvos water than observations do.

The model does not show the progression of Colvos water across the density sections that is seen in the observations. The particle tracking experiment clearly shows that this is where the model has Colvos water exiting, but the density across Main Basin remains largely unchanged. The model also shows most of the particles only reaching the center of Main Basin over the ebb tide. On the flood tide, most of these particles make it back across Transect 5. While a significant

portion of Colvos water may, in fact, be transported across Transect 5, the observations show this water as a horizontal layer at about 30-70 m depth (Fig. 6). The model shows these particles at depths from 0-200 m and all clustered on the eastern side (Fig. 8).

There is some agreement between the model and observations at Station B (Fig. 10). At the end of each major ebb, the model shows a definite shift in temperature, salinity, and density values towards those of Colvos water. However, Colvos water never takes over the entire surface layer as seen in the observations. Instead, the model shows maintained stratification across the outflow area throughout each tidal cycle (Fig. 7). While this does not represent the complexity of this intersection, it is quite possibly representative of the overall state of the larger surrounding area and agrees with the suggestion that Colvos water creates an intermediate layer outside of the outflow area.

LiveOcean has a horizontal grid size of about 500 m within Puget Sound. While this resolution is very good for most processes within the Sound, the scale of this study was pushing the model's limits. Most of Colvos Passage is only wide enough for three grid points. It is not surprising that the model is unable to capture much of the detail.

## **Conclusion**

While the complexity of the intersection between Colvos Passage and Main Basin is much greater than previous authors have alluded to, this study agrees with the general assumption that Colvos water creates an intermediate layer within Main Basin. During the major ebb and flood, Colvos water takes over the surface layer within the outflow area. During the less energetic minor phases of the tide, more stratification is maintained, and it appears that an intermediate layer is developing. There is also evidence of Colvos water forming an intermediate

layer in East Passage. At the north end of the study area, there was less evidence of Colvos water as an intermediate layer, but increased stratification may be happening further north.

The observed progression of water masses suggests that much of the water coming out of Colvos Passage is directed northward beyond the northernmost transect in this study, and a smaller portion is recirculated landward. The comparison with LiveOcean shows that the model is able to depict only the general conditions of the region. The model misses much of the detail that is important to this area.

A larger study area would be required to confirm whether or not an intermediate layer is actually forming north of Transect 3. Velocity data would have provided a clearer idea of the proportion of water being recirculated. This area could also benefit from more frequent monitoring to determine whether or not there is seasonal variability.

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## Appendix

LiveOcean takes atmospheric forcing (winds and heating) from the Weather Research and Forecasting Model (WRF) run by the UW Mesoscale Analysis and Forecasting Group ([https://www.atmos.washington.edu/~cliff/cliff.php?in=wrf\\_mm5](https://www.atmos.washington.edu/~cliff/cliff.php?in=wrf_mm5)). Boundary conditions for ocean currents, temperature, and salinity come from HYCOM, a global ocean model operated by the US Navy (<https://www.hycom.org/>). Other ocean properties at the model boundaries are based off of field data collected by NOAA. River input comes from flow gauges maintained by USGS and Environment Canada. Estimates for ungauged rivers are calculated using adjustment factors from WA Department of Ecology. Tidal forcing at model boundaries comes from the TPXO models of ocean tides developed by Oregon State University (<http://volkov.oce.orst.edu/tides/global.html>).

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