Water circulation in Dabob Bay, Washington: Focus on the exchange flows during the diurnal tide transitions

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Non-technical summary

The area of interest is Dabob Bay, Washington. Dabob Bay is one of the closed fjord-like basins in Puget Sound. Water circulation is especially important in distributing nutrients into the Dabob basin. The project focuses on the water inflows and outflows across the entrance at the junction with Hood Canal. The project was conducted using a *RDI Acoustic Doppler Current Profiler (ADCP)* aboard *R/V Clifford A. Barnes* and *Conductivity Temperature Depth (CTD)* to obtain water velocity and density data across the mouth or entrance and along the channel of the basin. Data gathered were analyzed in MATLAB. Water at all depths underwent significant changes in its speed and direction with the tides. The variability was intense on the eastern side of the entrance near northern Hood Canal. Surface outflows were always present on the western side while subsurface waters varied across the basin entrance depending on tide transitions.

Abstract

The project concentrates on the exchange flows across the entrance sill in Dabob Bay, Washington. Dabob Bay is one of the closed fjord-like basins in Puget Sound. Water circulation has received considerable attention since it distributes the nutrients into the basin. Water velocity data were obtained by using a ship-mounted 150 kHz *Acoustic Doppler Current Profiler (ADCP),* and water property data were gathered by *Conductivity Temperature Depth (CTD)* aboard *R/V Clifford A. Barnes* during a complete diurnal tide on March 10th - 12th, 20003. Averaged water velocities at certain waypoints and depths were plotted along two transects: one is along the sill or across the channel, and the other is along the channel in the basin. Currents across the entrance over the sill were the greater and more variable.

Introduction

Dabob Bay is a 185-meter deep and 5-km wide fjord-like basin with a 100-meter sill at its entrance (Ebbesmeyer et al., 1988). It runs north 20 km from its junction with Hood Canal (Figure 1). Since nutrient input from rivers and the atmosphere is negligible, deep water inflow is the only means of entry of dissolved nutrients into the basin over the sill from Hood Canal. No significant influx of any major river or stream is evident in Dabob Bay (Kollmeyer 1965). Because it is responsible for governing hydrography and water flushing, water circulation in such an isolated fjord has received considerable attention. Human contamination, for instance, is of importance to marine ecosystem and coastal communities.

Currents in Puget Sound are predominantly driven by the semidiurnal tide (two highs and two lows a day) that is observed to cause a net outward flow in the upper layer and inward flow in the lower (Downing 1983). Dabob Bay exhibits outflow at the surface and inflow in the subsurface, which is common of an isolated fjord (Figure 2). The sill isolates the water in the deeper basin from that at equal depths outside the basin. Intruding deep water displaces the resident water flowing over the sill in the basin and leads to a general outflow at the surface layer (Kollmeyer 1965).

A hypothesis is that the water circulation is driven by tides and probably by winds. Tidal and non-tidal forces (perhaps winds) are responsible for flushing water in Dabob Bay (Ebbesmeyer 1973). Wind-driven physical processes are not well understood because of wind variability. The general trend is that the prevailing winds are southerly in winter and northerly in summer. The channel of Dabob Bay is oriented north-south; therefore, southerly and northerly winds blow almost directly north towards the head of Dabob Bay during winter and south towards the mouth. The surface water is transported in the direction of the wind along the channel of the basin. Strong southerlies drive the surface water to the north end of Dabob Bay, raising the surface and depressing the isopycnals so that they slope down from mouth to northern end in fall (Kollmeyer 1965).

Kollmeyer (1965) observed that an annual autumn pulse of new water over the sill completely displaces the resident water in the basin. He also concluded that the primary driving force of the general circulation appeared to be the horizontal pressure gradient associated with the continuing influx of water of increasing density over the sill. Ebbesmeyer (1973) observed medium-sized water parcels over the sill, and noted that winds were responsible for flushing in the basin. Northerly (southerly) winds push the surface water out of (into) the basin in summer (winter). No significant oceanographic studies have been conducted in Dabob Bay within the last decade.

This research is limited to a short period of time. It lacks data that could represent the overall circulation in Dabob Bay. Consideration is given to exchange flows across the sill or the mouth, wind effects on the surface, and the postulating of a probable circulation pattern for Dabob Bay.

Methods

To investigate how the tides, winds and sill affect the water circulation in Dabob Bay during a complete diurnal tidal cycle, field measurements were conducted at the two transects and five stations from March 10th – 12th 2003 aboard *R/V Clifford A. Barnes* (Figures 3 & 4). The combined effects of such physical processes were determined by analyzing data gathered from *Acoustic Doppler Current Profiler (ADCP-150kHz), Conductivity Temperature Depth (CTD),* and shipboard anemometer.

Fieldwork

The ADCP runs took place along the two transects with CTD samplings at STN2, 7, 1 and 10 in the order in which they were conducted on the way into Dabob Bay in the afternoon of March 10th when a low tide occurred. Another CTD cast was made at STN4 in the next afternoon. Next, two full ADCP runs were made in the afternoon of March 11th during the transition from high to low tide, and in the morning of March 12th during a high tide (Figures 3 & 4). Samplings were conducted at just five stations out of 11 planned due to the malfunction of CTD during the last two days of the cruise. Additional CTD samplings and ADCP runs have been obtained from the next cruise in Dabob Bay (Table 1).

Post-fieldwork

MATLAB was used for further analysis or interpretation outside fieldwork. Data gathered from both ADCP and CTD were converted to MATLAB format. The ADCP data were divided into five 4-meter bins and were averaged over 400 meters horizontally, then a velocity vector was computed to represent the water speed and direction for each bin (Table 2). Data for the top and bottom 10 meters gathered from ADCP were not available since they were inaccurate (RDI 1996). The missing surface and bottom water velocity data were assumed to be consistent with that just below and above it. Physical properties of water (i.e.

density) at the stations were compared and contrasted in order to determine how the entrance sill affects water flowing over it, and the water behavior at certain bins.

Results

Flood tides

Transect 1 displayed strong inflow and outflow at the surface on the eastern and western sides of the basin entrance. Surface water inflow (blue) from northern Hood Canal appeared to dominate the patterns at all depths during the incoming tide. Some parcels tended to turn towards southern Hood Canal along the sill. Relatively strong subsurface inflow (red) was observed on the eastern side of the entrance. Strong deep water inflow (black) was also seen near northern Hood Canal while others were flowing along the sill (Figure 5). Average flood current velocities were inward and northwesterly across transect 1 near the entrance, and northerly along the transect 2 in the basin. Strong currents were evident around the junction with Hood Canal, but no distinctive currents were seen inside the basin (Figure 6).

Outflow surface currents were still predominant on the western side of the basin entrance during the weak flood tide. However, relatively strong inflow bottom currents (black) reached 0.14 m/s over the sill (Figure 7). No distinctive patterns were seen along transect 2 during the flood tide.

Surface inflow pattern on March 25th was consistent with that on March 10th (Figures 5 & 8). Weaker averaged velocities at mid-level depths were observed. Relatively strong bottom velocities were in westward propagation near the trough (Figure 8).

Ebb tides

Average ebb currents were radially outward almost at all depths across transect 1. Strong outflows were seen at mid-level depths and at the bottom near northern Hood Canal while surface currents were heading Tskutsko Point (Figures 5 & 1). The maximum average velocity at the subsurface (red) near the trough reached 0.16 m/s in the west direction while the other subsurface currents (green) were flowing along the sill in the eastern direction. Easterly surface currents were seen on the eastern side of the junction. Relatively strong northerly strong currents were also evident along transect 2 (Figure 6). It is anomalous in that strong surface inflows were through the center of the entrance during the strong ebb tide while the bottom currents were flowing over the sill on March 31st (Figure 8).

The averaged velocity vectors plotted along transects 1 and 2 showed the significant change in the circulation patterns across the entrance at the junction with Hood Canal when tidal transition reversed (Figures 5 & 6). Average velocities for the flood tide were greatest on the eastern side of the entrance, flowing inward and northwesterly in excess of 0.25 m/s. Outward current velocities on the western side of the entrance were slightly smaller but still relatively strong at about 0.17 m/s (Figure 5). The same pattern of currents at the surface was observed at smaller magnitude of about 0.10 m/s on the western side of the entrance during the ebb tide. Intensification in velocities occurred at middle depths across transect 1 when the transition reversed. The greatest velocity reached 0.16 m/s near northern Hood Canal (Figure 5).

Summary on water velocities

The greatest change in water velocities was seen at all depths on the eastern side of the entrance near northern Hood Canal. Surface outflows were always present on the western side regardless of tide transitions. To sum up, the averaged velocities showed a general current pattern favoring outflow on the western side of the entrance, inflow during the flood tide and outflow during the ebb tide on the eastern side towards northern Hood Canal (Figures 5 & 6).

CTD density observations during the flood tide

Density profiles showed that pycnocline depth was located at about 25 meters at STN1, 2, and 7 during the incoming tide (Figure 9). At STN10, the pycnocline was 10 meters deeper. Surface water density was from STN4, 1, 2, 7 to 10 in the increasing order (Figure 9).

Discussion

Wind effects

Northerly surface currents ranged from 0.09 to 0.21 m/s inside the basin during the transition from high to low tide (Figure 6). It is likely that the surface water was driven by winds. Strong southerly winds were persistent throughout the last two days of the cruise in Dabob Bay in excess of 10 m/s. Since the surface ocean current speeds are about 3% of the 10-m wind speed, 0.3 m/s must be the average speed at the surface in the basin. The two computed and observed values are similar; therefore, the strong southerly wind must have driven low-density surface water to the north end of Dabob Bay on the second day of the cruise (Figures 6 & 9). The primary driving force appears to be the horizontal pressure gradient due to the continuing high-density water inflows in Dabob Bay. The strong southerly winds drive low-density surface water to the northern end of Dabob Bay. It consequently raises the surface height by an unknown amount and depresses the pycnocline to a depth of 40 m so that they slope down from the mouth to the northern end (Kollmeyer 1965) Figure 10 depicts the similar deduced circulation pattern with strong southerly winds. Surface currents in eastward propagation on the eastern side of the entrance appears to be driven by the horizontal pressure gradient associated with the wind-induced high-density of surface water influx into the basin (Figure 5: bottom panel).

Surface water

The plots of water velocity vectors illustrate that, during both tide transitions, the flows are concentrated on the eastern side of the basin entrance. The eastern side of the entrance near northern Hood Canal undergoes dramatic changes in current patterns when the transitions switch. However, the western side exhibits persistent outflows especially at the surface regardless of transitions. Surface currents from northern Hood Canal during an incoming tide tend to pass through the eastern side of the entrance and continue onto the western side. That is, not all of the inflowing surface water makes it into the Dabob basin, but instead flows along the sill and into southern Hood Canal (Figures 5 & 8). It is consistent with Kollmeyer, who stated that approximately 70% of the total incoming water flows into southern Hood Canal while 30% flows into Dabob Bay.

Midlevel-depth and bottom waters

Dramatic changes occur at the midlevel depths and bottom across transect 1 when the transition reverses (Figure 5). When transition shifts from ebb to flood tide, subsurface water increases in its speed and changes its direction. This is consistent with the pattern depicted in Figure 10. Subsurface water flows outward and bottom water flows along the sill eastward during the flood tide instead of westward during the ebb tide. The deeper pycnocline at STN10 appears to be associated with the geostrophic flows (Figure 9). This is consistent with the water influx at all depth levels on the eastern side of the entrance (Figure 5).

Limits

Winds appeared to be crucial in influencing the surface water currents; however, the winds were anomalous due to a storm during the cruise. Wind data are not available for understanding the anomalous northward component of the surface water propogation on March 31st. Long-term data are needed in order to derive the general wind-induced pattern in the Dabob basin. CTD data are available only from 5 stations during a flood tide. It is necessary to have CTD data along transect 1 during an ebb tide to discuss the exact role of the sill in mixing. Water velocity data for the western side of the entrance on March 25th are not available. More ADCP runs have to be made for more accurate data acquisition.

Conclusion

The observed exchange flows during both transitions concentrate on the eastern side of the basin entrance. The major water transport occurs on the eastern side near northern Hood Canal. The primary currents entering the basin are near surface during the flood tide and at midlevel depths during the ebb tide. The incoming surface currents split into the basin and southern Hood Canal at the junction near northern Hood Canal (Figure 11). Outward surface currents are predominant on the western side of the entrance regardless of tidal transitions (Figure 12). Tidal currents are weak within Dabob Bay; therefore, winds appear to play a crucial role in driving the surface currents downwind in the basin. Relatively strong bottom currents are evident parallel to the sill rather than across the sill.

References

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Figures and Tables

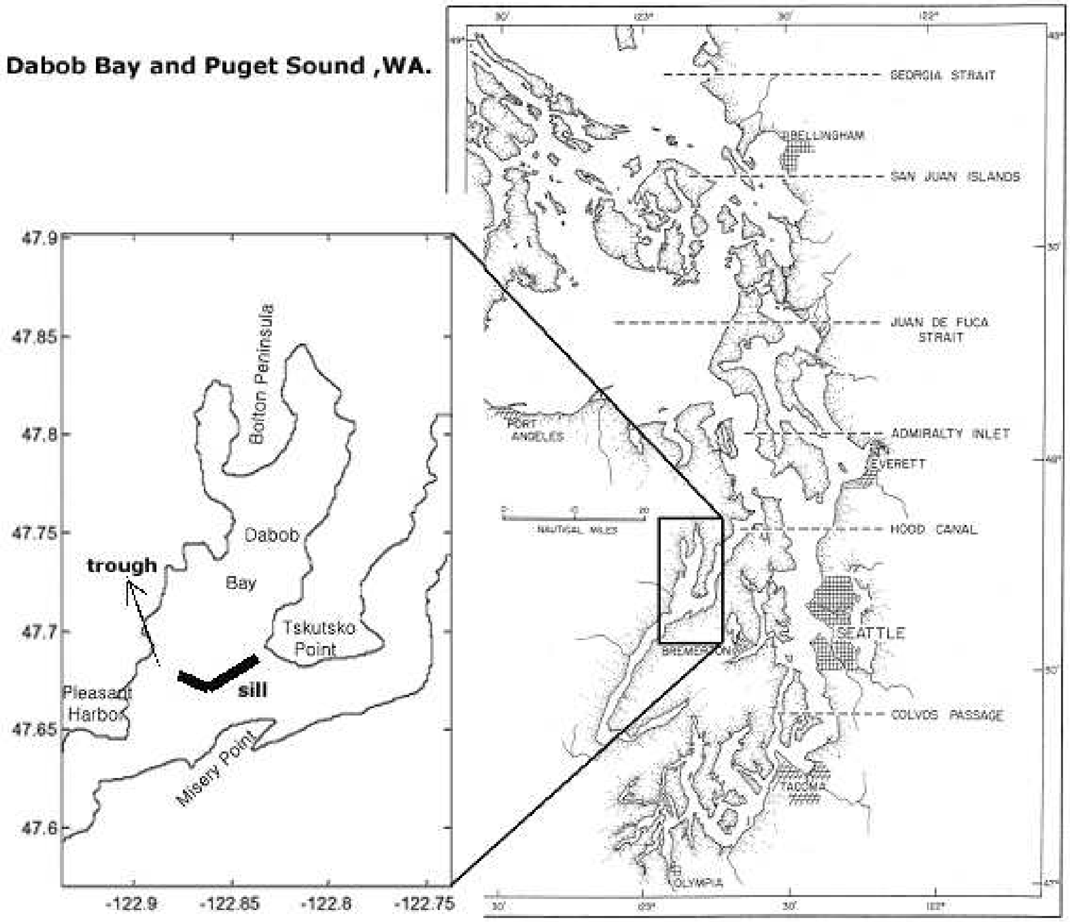


Figure 1. Dabob Bay in Puget Sound, WA.

** The scale bar, which is blurry, indicates from 0 to 20 nautical miles.*

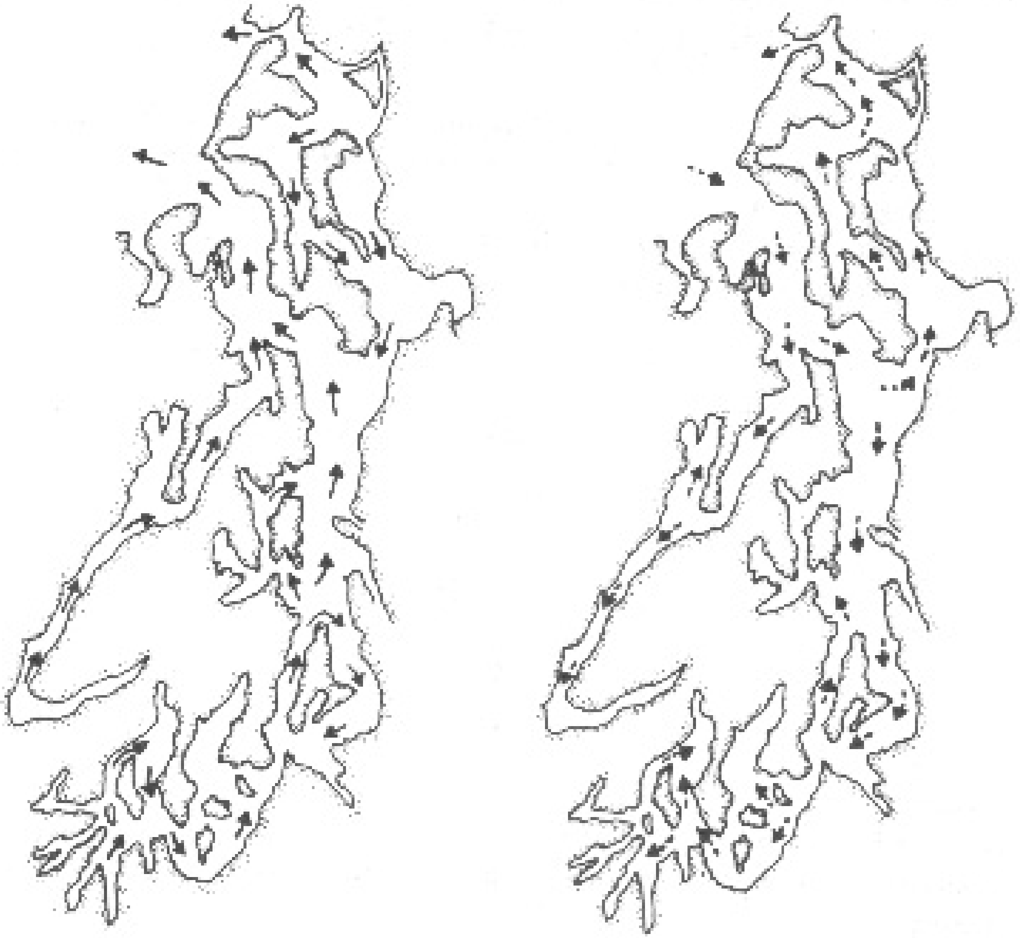


Figure 2. Mean flow pattern in Puget Sound (after Ebbesmeyer et al 1988)
** At left solid arrows indicate flow in the upper layer containing outflow, and at right dashed arrows indicate that in the lower layer containing inflow.*

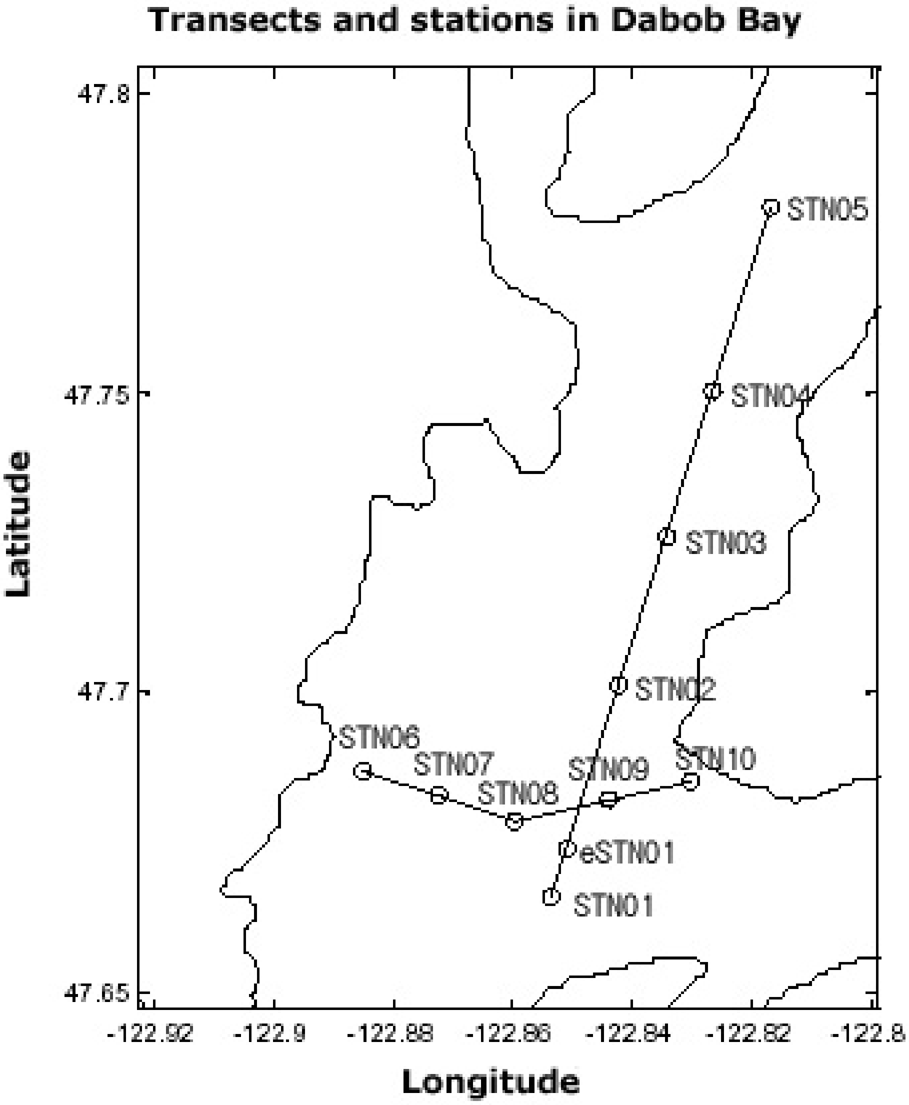


Figure 3. Transects and Stations in Dabob Bay, WA.

** ADCP runs along the transects and CTD casts only at STN1, 2, 4, 7 and 10 were made during a complete diurnal tide.*

** The length of the traverse transect (transect 1, from STN10 to STN06) is approximately 4,000 m.*

** The length of the transect along the channel (transect 2, from STN05 to STN01) is approximately 13,000 m.*

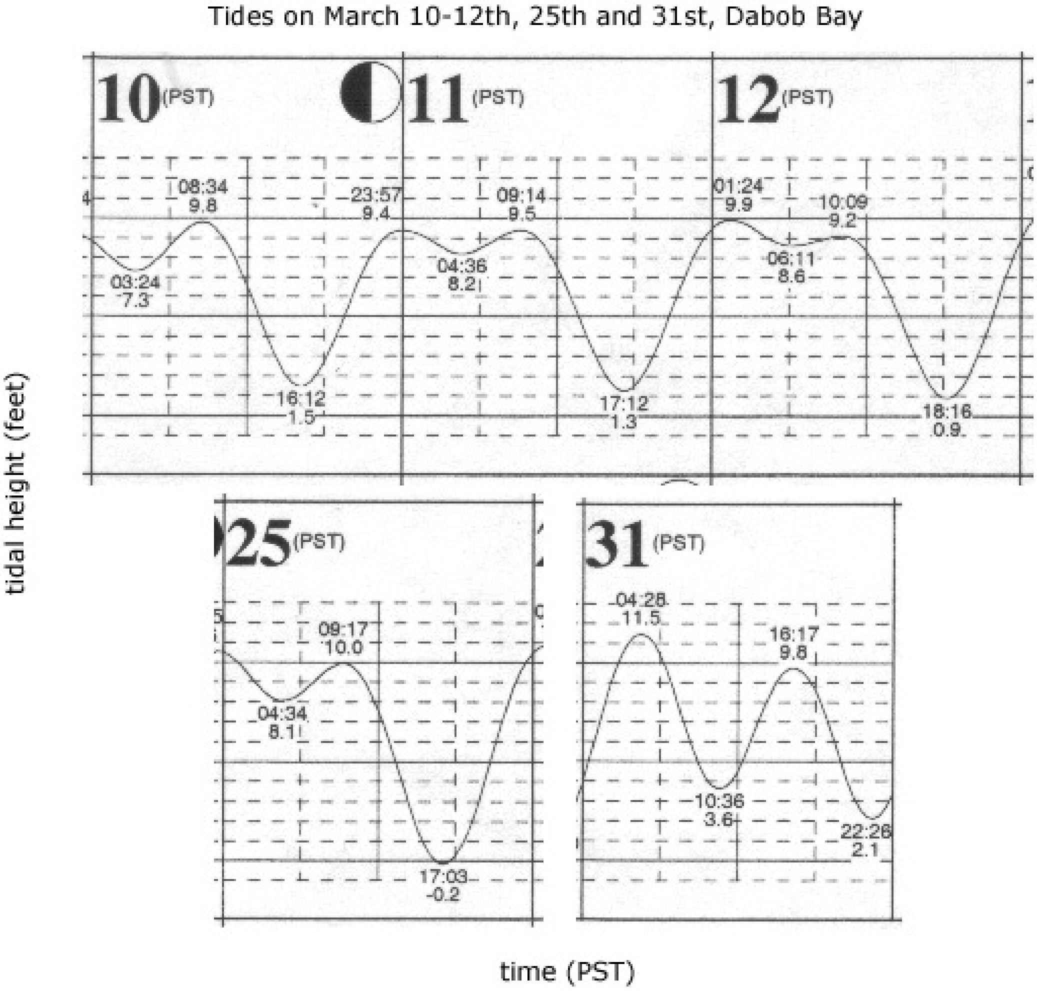
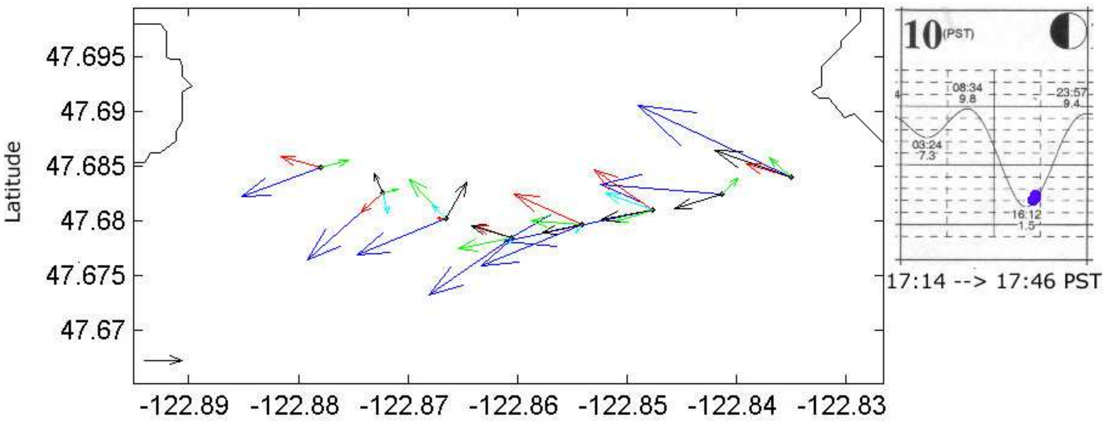


Figure 4. Tides during the cruise (March 10-12th) and next cruise team (March 25th and 31st) in Dabob Bay, WA.

Water velocity vectors during a strong incoming or flood tide (March 10th)



Water velocity vectors during a strong outgoing or ebb tide (March 11th)

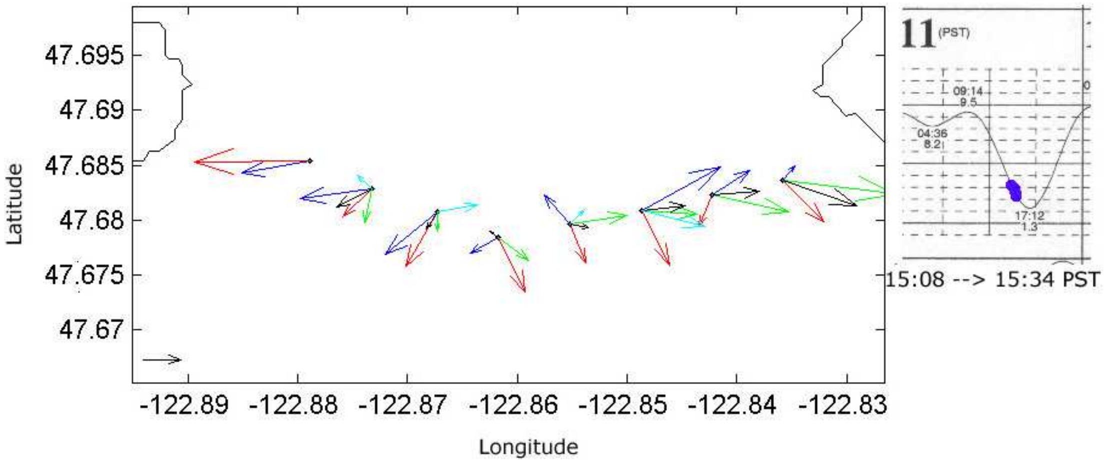


Figure 5. Water velocity vectors plotted at 5 different depth levels along the entrance sill or transect 1

** Top panel: March 10th 17:14 – 17:46 PST during the transition from low to high tide*

** Bottom panel: March 11th 15:08 – 15:34 PST during the transition from high to low tide*

** Unit vector located at the lower left corner indicates 0.05 m/s.*

Water velocity vectors during the strong incoming (left) and outgoing (right) tides

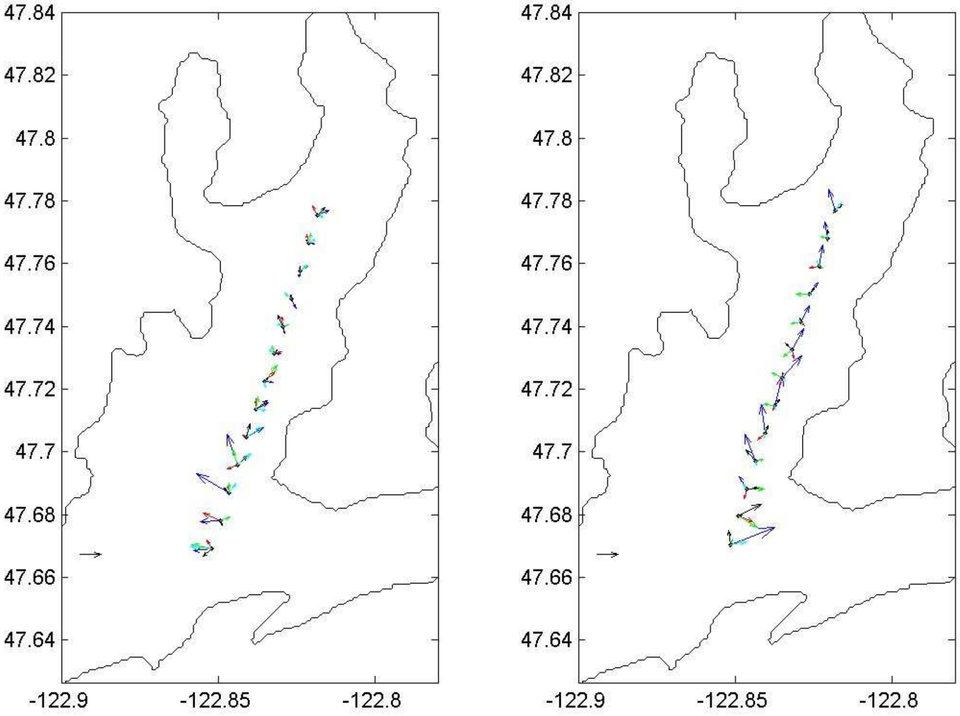


Figure 6. Water velocity vectors plotted at 5 different depth levels along the channel or transect 2

** Left panel: March 10th 18:00 – 19:20 PST during the transition from low to high tide*

** Right panel: March 11th 15:49 – 17:05 PST during the transition from high to low tide*

** Unit vector = 0.05 m/s.*

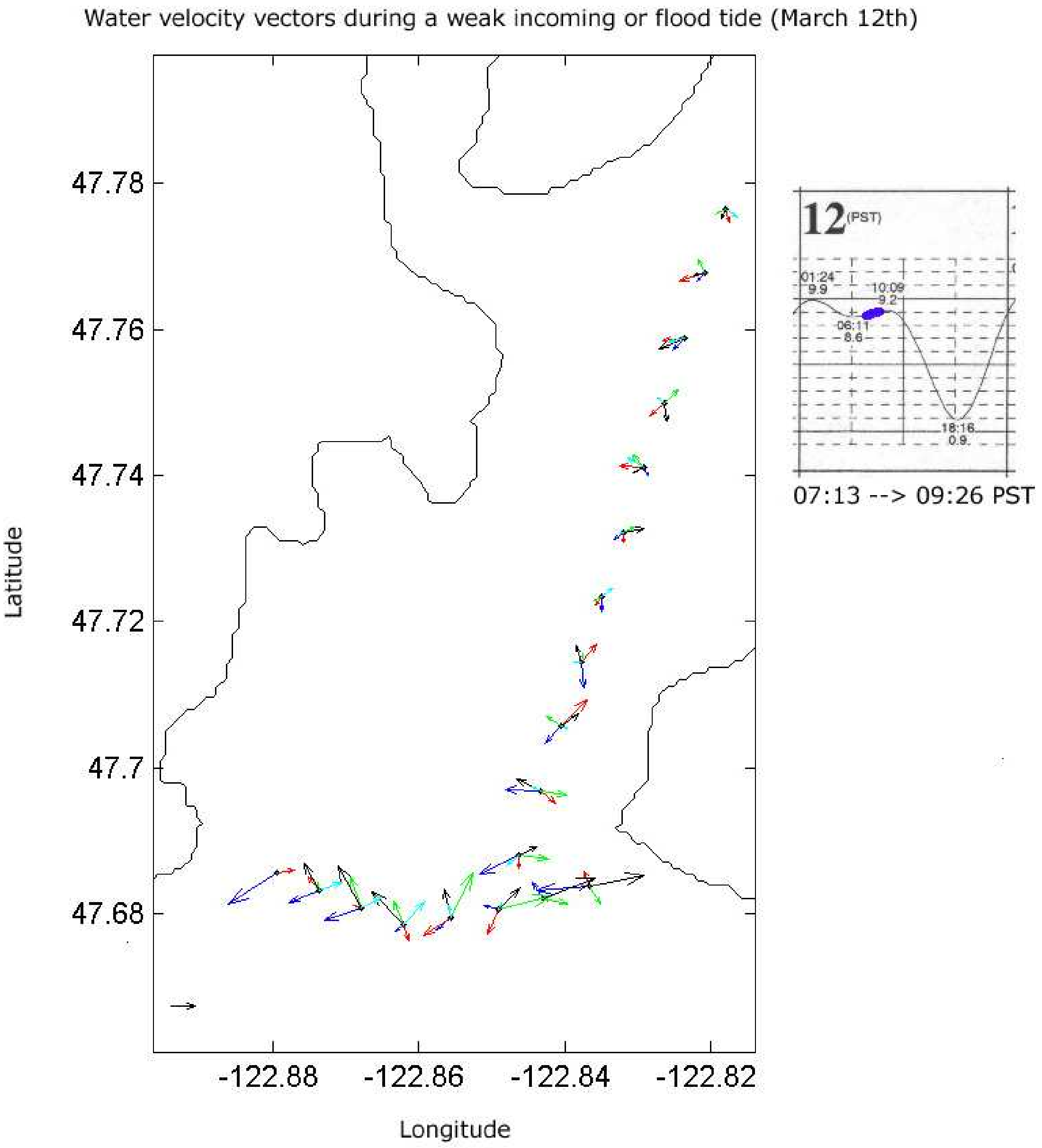
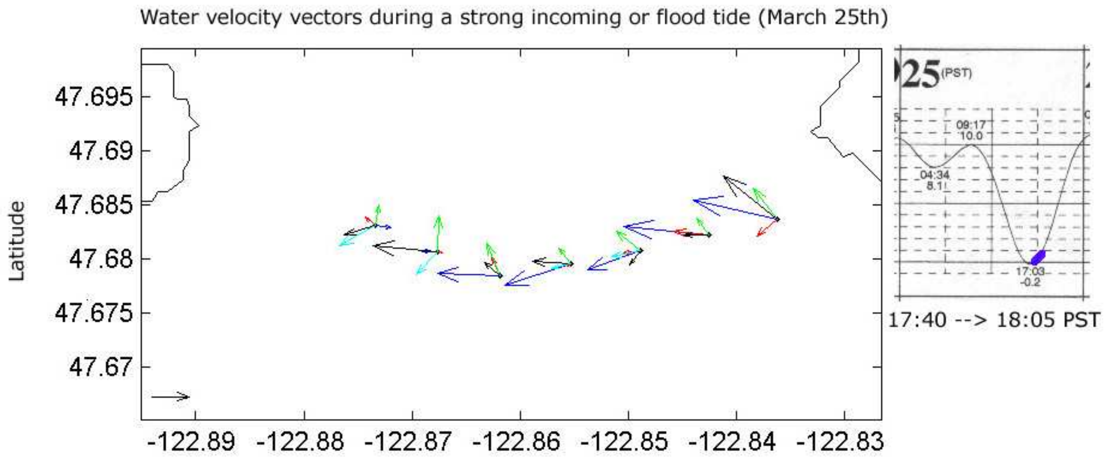


Figure 7. Water velocity vectors plotted at 5 different depth levels along the entrance sill (transect 1) and the channel (transect 2)

** March 12th 07:13 – 09:26 PST during the weak transition from low to high tide*

** Unit vector = 0.05 m/s.*



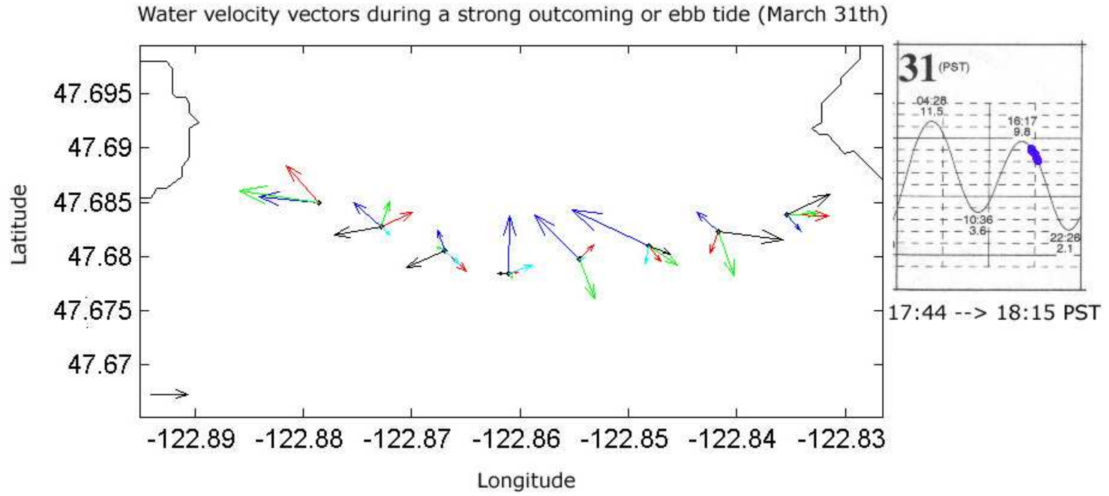


Figure 8. Water velocity vectors plotted at 5 different depth levels along the entrance sill or transect 1

** Top panel: March 25th 17:40 – 18:05 PST during the transition from low to high tide*

** Bottom panel: March 31th 17:44 – 18:15 PST during the transition from high to low tide*

** Unit vector located at the lower left corner indicates 0.05 m/s.*

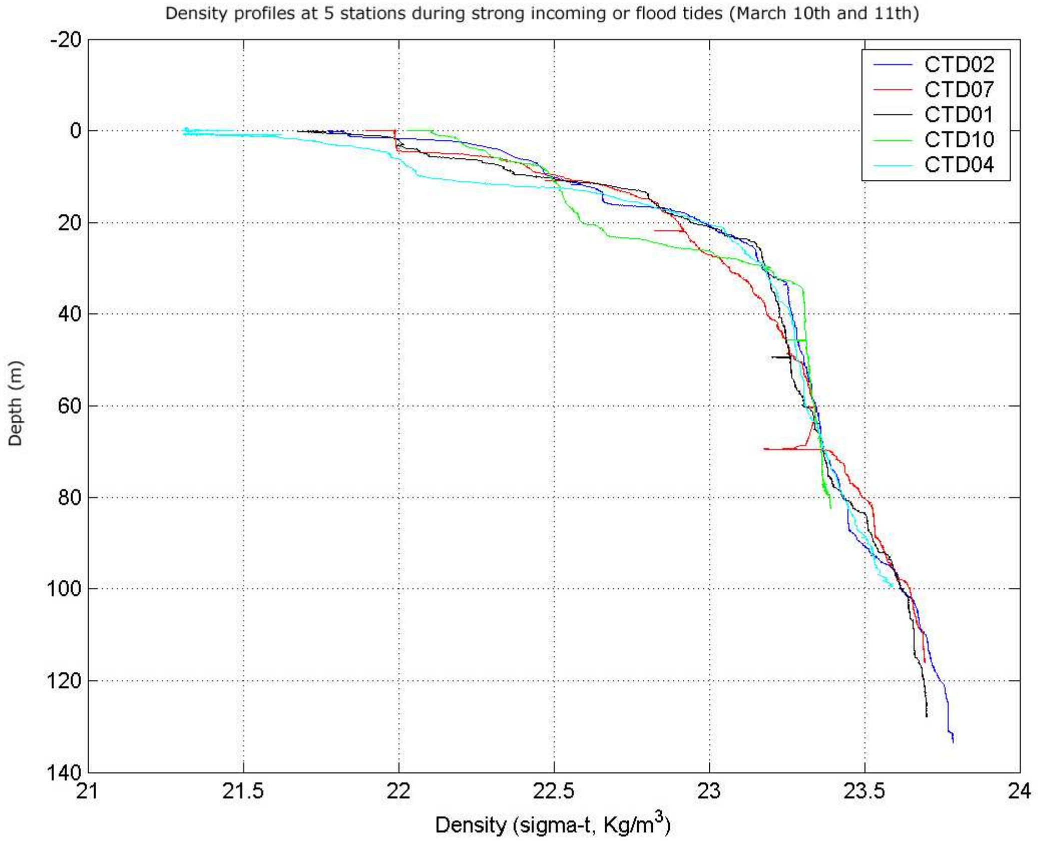


Figure 9. Density profiles at 5 CTD stations 2, 7, 1, 10 and 4.

** All CTD casts were made during the transition from low to high tide.*

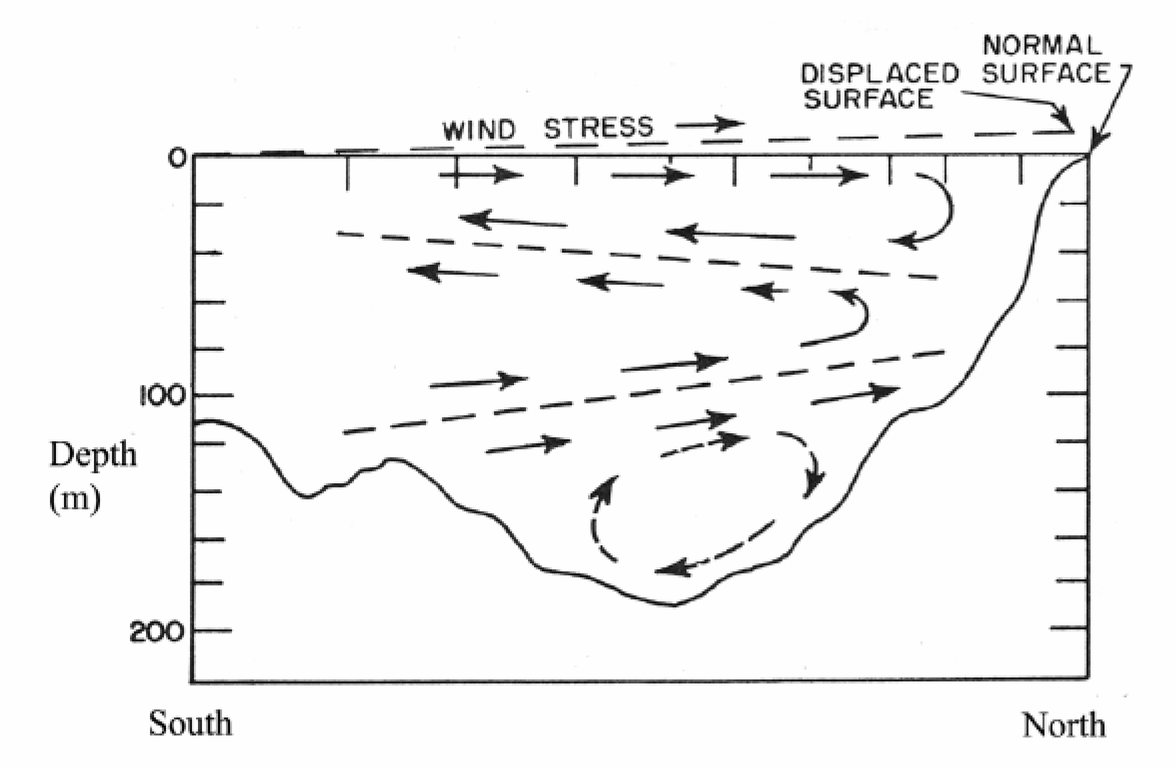


Figure 10. Deduced circulation pattern with strong south wind in Dabob Bay. (After Kollmeyer 1965)

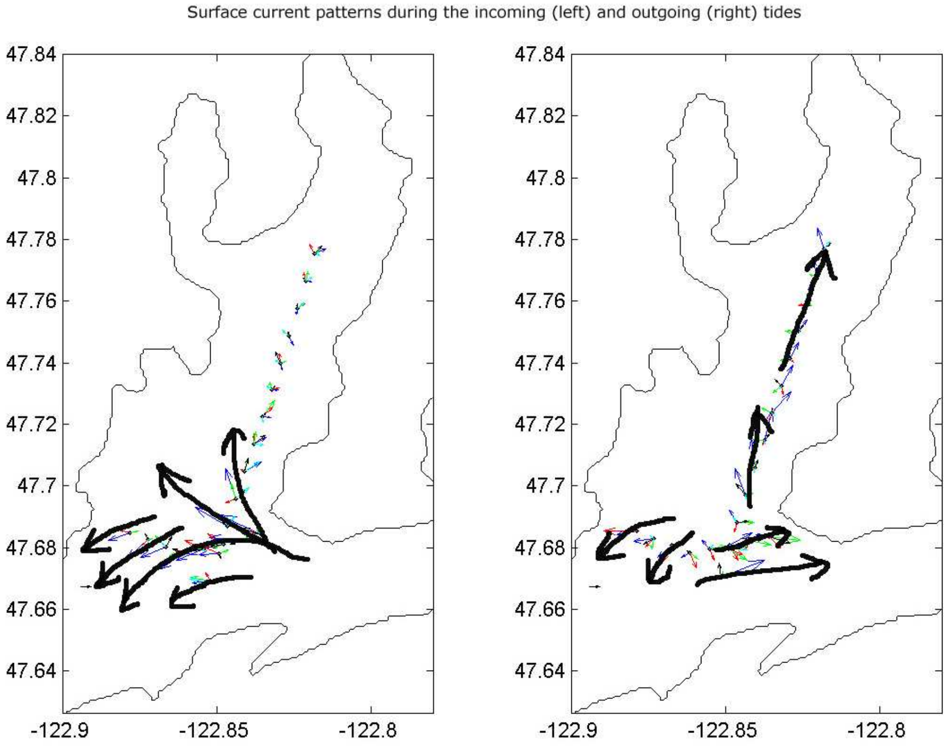


Figure 11. Observed surface current patterns during the incoming and outgoing transitions

** Left panel: conceptual surface currents during the transition from low to high (incoming)*

** Right panel: conceptual surface currents during the transition from high to low (outgoing)*

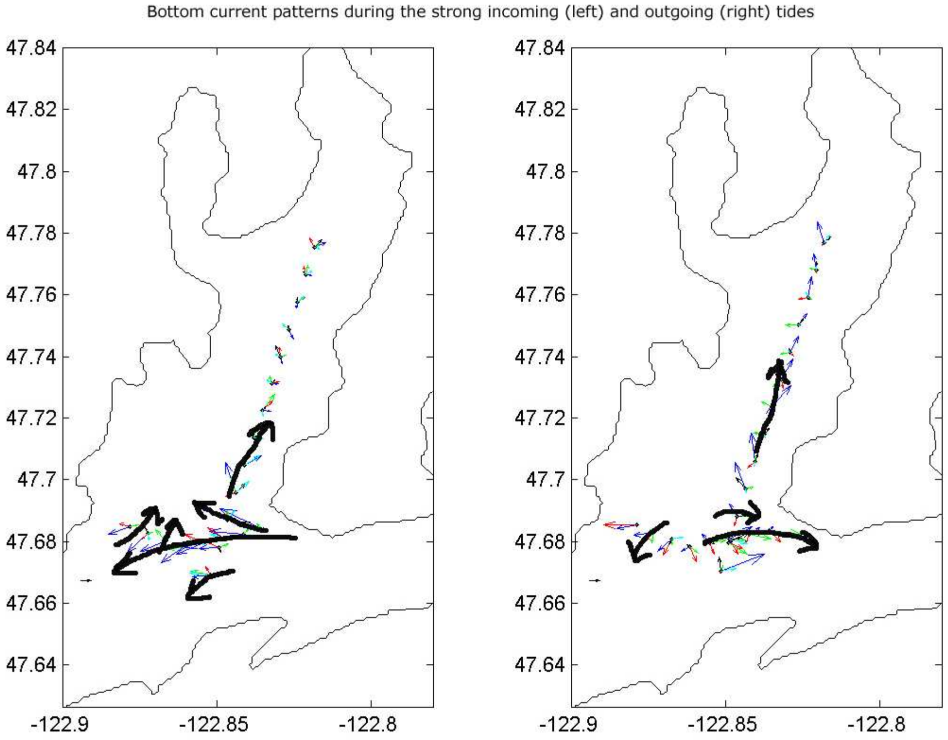


Figure 12. Observed bottom current patterns during the incoming and outgoing transitions

** Left panel: conceptual bottom currents during the transition from low to high (incoming)*

** Right panel: conceptual bottom currents during the transition from high to low (outgoing)*

Ensemble #	**Time elapsed**	**Tidal transition (strength)**
ADCP runs labeled in ensemble numbers		
ADCP traverse		
ADCP066	03/10/2003 17:14 → 17:46 PST	Low to high tide (strong)
ADCP072	03/11/2003 15:08 → 15:34 PST	High to low tide (strong)
ADCP079	03/12/2003 08:59 → 09:26 PST	Low to high tide (weak)
ADCP097	03/25/2003 17:40 → 18:04 PST	Low to high tide (strong)
ADCP102	03/31/2003 17:44 → 18:15 PST	High to low tide (strong)
ADCP along the channel		
ADCP068	03/10/2003 18:00 → 19:20 PST	Low to high tide (strong)
ADCP074	03/11/2003 15:49 → 17:05 PST	High to low tide (strong)
ADCP078	03/12/2003 06:38 → 08:37 PST	Low to high tide (weak)
CTD samplings labeled in station numbers		
CTD02	03/10/2003 15:50 PST	Low to high tide (strong)
CTD07	03/10/2003 16:16 PST	see above
CTD01	03/10/2003 16:42 PST	see above
CTD10	03/10/2003 17:07 PST	see above
CTD04	03/11/2003 19:40 PST	see above

Table 1. Sets of ADCP and CTD data

** All of the data were obtained during the cruise except that the data on 25th and 31st were obtained from the next cruise team in Dabob Bay, WA.*

** The speed of the boat was 6 knots (~=3.1 m/s) on average during each ADCP run.*

	Horizontal ± 200 m along the transect
12 ± 2 m	Average water velocity (color: blue)
30 ± 2 m	Average water velocity (color: red)
48 ± 2 m	Average water velocity (color: green)
68 ± 2 m	Average water velocity (color: black)
88 ± 2 m	Average water velocity (color: cyan)

Table 2. The water velocity data were averaged over 4 meters of depth and 200 meters horizontally at each waypoint.