A cross channel survey of southern Rosario Strait, Puget Sound, Washington during a flood tide using ADCP/CTD methods

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Non-Technical Summary

A series of ADCP (Acoustic Doppler Current Profiler), which measures the strength and direction of the current; and CTD (Conductivity, Temperature, Depth), which measures salinity, temperature, and depth; transects were run along the latitude 48°26’ N across Rosario Strait in order to gain general physical oceanographic knowledge as well as to observe the velocities in the strait. These measurements were made on March 21, 2007. The velocities showed that the water in the strait would move away from the San Juan Islands and into the center of the strait, no matter what the tide. The waters leading up to a flood moved northeastward moving toward the mainland, while after the maximum flood they moved southward. The velocities when coupled with the knowledge that oil tankers pass through the strait everyday to get to the refineries at March Point, help explain in the event of a collision/spill, where the spill might end up. The general oceanographic information provides a baseline study for the further analysis of our environment, and its possible future change. It also showed two intrusions, one of cold freshwater from the Skagit River, and another of warmer saline water from the Strait of Juan de Fuca.

Acknowledgements

I would like to thank everyone who helped me with this project. The professors of the Ocean 443/444 series: Mark Holmes, Rick Kiel, Susan Hautala, Daniel Grunbaum, and as well as the TA Leon Delwiche. From these I would specifically like to thank Susan for her continued help with the beast that is MatLab, her constant reviews of my papers, and helping me narrow down my focus. Some credit also goes to Shane Hollrah for without his questions on MatLab for his project, I would have never asked some of mine. Leon also deserves credit in reviewing my papers, as does Rick for his review of my final draft.

I would also like to thank the wonderful crew of the Thomas G. Thompson who put up with my ridiculous cruise plan (spending 8 hours in one spot is never all that enjoyable) and myself, all the while making sure there was always food available.

I would also like to thank Kathy Krogsland and Aaron Morello at the University of Washington Marine Chemistry Lab who analyzed my nutrient data and got it back to me before I even knew what I was doing with it.

Final thanks go out to my fellow ocean students. Cruises would be an insane bore without you. If I have forgotten anyone, I am truly sorry.

Abstract

On March 21, 2007 a series of transects were run across Rosario Strait at 48°26' N. Five transects were completed, two consisting of 4 CTD drops across the strait centered on a maximum flood tide, and the other 3 using only the shipboard ADCP. From these transects, the sections of the physical properties across the strait were produced. The data showed velocities of 70 cm/s on the west side of the strait, moving northeastward with the flood tide, and southeastward with the ebb tide. For the east side of the strait, velocities were 20 cm/s northeastward on the flood tide, and 30 cm/s with the ebb tide. Using two ADCPs (lowered and shipboard), the velocity in the upper 30 meters of water was examined to predict where a spill of oil might go if a collision of tankers were to occur in the strait. The processed data showed that leading up to a maximum flood the eastern side of the strait would possibly be endangered, while on the ebb tide the sides of the strait had a velocity of about 70 cm/s to propel the possible slick into the Strait of Juan de Fuca where it might disperse. The other physical properties with the change of the tide showed a cold freshwater river plume on the east side, and a warm saline intrusion on the west side. Nutrient samples were collected to further knowledge about the various source water found in Rosario Strait, showing a linear pattern with increased concentrations of silica with the decrease of salinity.

Introduction

Circulation is the 'roadmap' to the world's waters. With knowing the general circulation of the area one not only finds it easier to navigate the waters in order to transport goods or services but can also determine where key components of the water originate. Living on Puget Sound we are confronted with these reminders every day. General circulation in the Sound is typically tidally-dominated (Cannon, 1989). This means that with every flood and ebb of the tide, the circulation changes. During flood tide the waters are colder, denser, and generally more saline. This is due to water entering the Strait of Juan de Fuca, via the Pacific Ocean, which has higher values of these properties compared to river inputs (Cannon, 1989).

Of the waters that enter the Strait of Juan de Fuca roughly 50% goes through Haro Strait, 25% through Admiralty Inlet, 20% through Rosario Strait, and about 5% through Middle Channel (Thomson, 1981). Of these, Rosario Strait and Middle Channel are the least studied. The last complete cross-channel study of Rosario Strait was done by Schumacher and Reynolds in 1974, with other research consisting of various models (Crean et al. 1988; Foreman et al. 1995). This is in stark contrast to the amount of research that is conducted in or near Admiralty Inlet and Haro Strait (Thomson, 1981).

Another motivation to focus on this section of water is the high volume of tanker traffic that makes its way through Rosario Strait in order to get to the March Point refinery area. With this high shipping traffic, it is only a matter of time before a major oil spill occurs in this area. While models (Klinger and Ebbesmeyer 2001; Mearns et al. 2001) have provided an idea of what could happen were such a disaster to occur, field work has been quite sparse. During such events most of the oil stays on the surface, but if dispersed quickly like the current trend in oil removal, the oil droplets sink to the thermocline or pycnocline (Mearns et al. 2001). Ideally, the oil would be advected into the main body of the current and slowly dissolve.

Based on these models (Klinger and Ebbesmeyer 2001; Mearns et al. 2001), the current in the middle of the strait should be approximately 100 cm/s northward during a maximum flood tide (Thomson, 1981). From the Schumacher and Reynolds study (Schumacher and Reynolds, 1975), CTD profiles should show temperatures of about 7-8°C unvarying with depth, salinities on the order of 27-30‰ with the 27‰ appearing more towards Deception Pass and on the surface, and the 30‰ more at depth. The densities will reflect the salinity patterns except on the scale of 22-23 kg/m^3 with the 22 kg/m^3 appearing at Deception Pass on the surface, and the 23 kg/m^3 more at depth and the center of the strait (Schumacher and Reynolds, 1975). These numbers were taken in early February of 1974, so assuming little change; the numbers should remain within this range, with the possibility of seeing decreased numbers in temperature and an increase in salinity from an intrusion of colder, more saline water due to the flood tide.

Another helpful tool useful in deciphering circulation patterns is a chemical tracer. If an area is rich in a certain type of a nutrient, then one can track how strong the circulation patterns are based on that level of nutrient. The Fraser River, located about 100 km north of the transect line, is known to be very rich in silicate with a discharge rate of about 1000 m^3/s (Masson, 2006). This rate is more than twice that of the Skagit River, which averages only 475 m^3/s; though relatively rich in nitrogen and phosphorus (USGS, unpubl., http://waterdata.usgs.gov/wa/nwis; Embrey and Inkpen, 1998). During a tide shift to maximum flood waters are expected to get poorer in silicate and richer in nitrogen and phosphorus, then richer in silicate and poorer in nitrogen and phosphorus as the maximum flood shifts to ebb due to the general circulation patterns in the area.

The main objective of this project is to provide a baseline study for the general physical oceanography in the region, as well to observe the surface currents in order to see their general patterns in the hopes that if any oil spill were to occur, one can more accurately predict where it may end up.

Methods

In order to get a "picture" of the vertical structure of the water column across the southern end of Rosario Strait (Fig. 1), data was collected by means of instrumentation and water sampling surrounding a maximum flood tide taken aboard the R/V Thomas G. Thompson. The cruise took place March 19-23, 2007 with all data being recorded on March 21. All times and weather related information was stored by the ship's DAS (data acquisition system). In order to obtain a velocity profile of the water column, the shipboard 75 kHz ADCP (Acoustic Doppler Current Profiler), manufactured by RD Instruments, was used on a cross channel transect moving at approximately 5-6 kts to determine the current velocities across the strait. The limitations of the shipboard ADCP to depths of 29 meters or more, while other velocities were taken by the LADCP (lowered). A second pass was made across the strait following the same transect line.

Following the ADCP transect a series of CTD profiles were taken along the same transect (Table 1; Fig. 1). The CTD was manufactured by Sea-Bird Electronics, model SBE 911plus, and onboard the CTD/Rosette package was a 300 kHz LADCP. The LADCP was manufactured by RD Instruments, model Workhorse Sentinel. Four CTD/Rosette casts were made to get the physical properties of the water column as well as to collect water samples (duplicates, both at the surface and at depth) for nutrient analysis. This was done by filling a syringe with the water sample, rinsing it out a few times, placing a filter on the end and again filing up the syringe, then finally plunging out the filtered water into a nutrient bottle. This process was repeated for each sample. Water samples were then frozen on board for later nutrient analysis for PO_4, $Si(OH)_4$, NO_3, NO_2, and NH_4 by Kathy Krogsland at the University of Washington Marine Chemistry Lab. After completing the ADCP/CTD transect cycle once, the maximum flood had occurred. The ADCP/CTD transect cycle was than repeated once more in order to see the structure coming up to a maximum flood tide and coming off a maximum flood.

MatLab software was used to analyze the CTD, LADCP, ADCP, and nutrient data. The CTD data was bin-averaged to 1 decibar on the ship using the Seabird processing software. The LADCP data was post-processed by way of separating the files into stations based on time from the DAS. From there the CTD data was used to get the depth at the ADCP, and the coordinates had to be converted beam to earth. Finally the data was averaged into bins. The ADCP data was filtered for bad data points and averaged over 5-minute ensembles by the University of Hawaii Data Acquisition Software (UHDAS).

Results

As expected, the velocity structure of Rosario Strait was highly variable surrounding the maximum flood tide. Leading up to the max, surface velocities were approximately 70 cm/s on the west side of the strait, around 50 cm/s in the center, while only about 20 cm/s on the east side. All surface velocities headed in a northeastward direction. At 29 m, the currents were only slightly smaller, with a range of 50-60 cm/s in the center of the strait and again at about 20 cm/s in the east. These currents headed in a more northward direction. (Fig. 2a) After the maximum flood, the current patterns changed dramatically. The surface current was still on the order of 70 cm/s on west side of the strait; however it was in a southeastward direction. The midwest station had a surface current of about 30 cm/s in a nearly eastward direction. The mid-eastern station had a very weak current, and the far eastern station had a surface velocity of about 30 cm/s in a southern direction.

The currents at 29 m followed much the same pattern as did the surface currents. The midwest station had velocities of about 30-50 cm/s in a northeastward direction The mid-eastern station had velocities of only 10 cm/s in a southward direction, and the far eastern station had velocities of about 40 cm/s in a southward direction. (Fig. 2b)

The physical properties of the water column (Fig.3ab; Fig.4) also changed on either side of the max flood. The change from before the maximum flood to after the maximum flood brought in an increase in salinity of about 0.1-0.2‰ on the west side of the strait below a depth of about 40 m. The east side saw a decrease in salinity in a plume type formation of about 0.1-0.3‰ at a depth of 10-40 m with an increasing change as one gets closer to shore (Fig. 5a). Temperature changed in much the same way. On the west side of the strait the waters increased in temperature by 0.02-0.04°C below a depth of 10 m, while decreasing in temperature by 0.04°C in the upper 10 m. The east side again saw the plume type formation with an intrusion of colder water at 10-40 m depth of about a 0.02-0.06°C decrease in temperature, but no change below this depth (Fig. 5b).

As one would expect, the same changes were seen in the change in sigma-t. On the west side of the strait, the waters increased by 0.05-0.15 kg/m^3 below a depth of 40 m, while decreasing in sigma-t by 0.05 kg/m^3 in the upper 10 m. The east side saw the plume type formation with an intrusion of less dense water at 10-40 m depth of about a 0.05-0.25 decrease in kg/m^3, before seeing a slight increase of 0.05 kg/m^3 at 65 m (Fig. 6).

In order to test silica content of the waters as a tracer of origin the compound $Si(OH)_4$ was plotted against salinity. A simple scatter plot was created and the general trend that is seen is a decreasing salinity value with an increasing $Si(OH)_4$ content (Fig. 7). An extreme value of 56 μM at 29.3‰ was seen at the minimum of the salinity range with the mean values around 53 μM at 29.4‰ at the minimum, and 49.5 μM at 30.2‰ at the maximum.

Discussion

With circulation being the 'roadmap' to the world's waterways, and each originating source being a natural resource, it is important to be able to check on these waterways and make sure they are as expected. To do this a baseline study is needed. This paper provided such a study for southern Rosario Strait, and as such some intriguing data came up.

The physical properties of Rosario Strait were as expected, following Schumacher's 1974 study. The temperatures were on the high side of the 7°C, salinity around 30‰, and the corresponding sigma-t value around 23 kg/m^3 (Schumacher and Reynolds, 1975). However, it was the differences in these values that led to some interesting observations (Fig. 5; Fig. 6). All 3 properties showed a distinct 'plume' at about 10-30 meters coming from the east side of the strait which showed a 0.3‰ decrease in salinity, a 0.06°C decrease in temperature, and a 0.25 kg/m^3 decrease in sigma-t. This occurrence is quite common in all waterways in the spring/summer months when a nearby river is discharging its snow melt (Masson, 2006).

A second plume was observed on the west side of the strait at depth identified by an increase in salinity, temperature, and consequently sigma-t. The change in salinity and sigma-t values can be explained by the intrusion of ocean waters coming from the Strait of Juan de Fuca (Cannon, 1989), while the increase in temperature could be explained by an intrusion of the warm saline water that is occasionally found in shelf or slope waters (Churchill, 1985; Gregg, 1980). This intrusion is similar to another intrusion which was due to near-bottom onshore flow compensating for offshore Ekman transport as hypothesized by Churchill for the nearshore area off of Long Island, New York.

The velocity structure found in the upper 30 meters of the strait also provided some interesting results when looking at the differences with the tide. Leading up to the maximum flood, current velocities were as expected not quite reaching the proposed 100 cm/s by Thomson (Thomson, 1981), but instead reaching only about 70 cm/s. Although surface current velocities were the same, they were moving more northeastward. This could potentially be a problem were a spill to occur on the east side as the slick would most likely move toward Burrows Bay and the islands of Allan and Burrows. With the change of the tide we observe a different scenario. The current velocities now change to a mostly southward direction on either side of the strait which is what was expected (Thomson, 1981). However, in the middle of the strait the current took on almost no N-S direction, which was unexpected and maybe partially explained by the fact that the tide was near slack. If a spill were to occur at this time, it appears that the shoreline would not be affected, but would instead move into the Strait of Juan de Fuca where it would disperse (Mearns et al. 2001).

When studying ocean circulation chemical tracers are an important means of determining a waters source. With Fraser River waters being known to be rich in silicate (Masson, 2006), and the closer Skagit River without any data pertaining to silicate, the data was assumed to mean that lower values of salinity would contain higher concentrations of the silica compound, $Si(OH)_4$. The salinity/ $Si(OH)_4$ graph (Fig. 8) showed this and was interpreted that the Fraser River did influence the chemical make-up of the strait, and therefore at least some of the water from the Fraser River makes its way down through the strait.

<u>Conclusions</u>

Circulation is of utmost importance in understanding the various bodies of water which we live around and use; this is particularly true when looking at Rosario Strait which is a major water way through which oil tanker traffic moves. As such the threat of an oil spill is ever present and if such an event were to occur, understanding how the body of water moves with the changing of the tides helps in predicting which areas are vulnerable.

Since oil does not typically move past the thermocline/ pycnocline (Mearns et al. 2001), it was important to focus on this top layer of the water column when looking at velocities. The results showed that leading up to a maximum flood the nearby eastern shore could easily be affected with surface velocities moving northeastward; however with the starting of the ebb tide either side of the strait had a relatively strong southward flow which would propel the spill into the Strait of Juan de Fuca where it would disperse.

In addition to the velocity data it was also important to collect general data on the physical structure of the strait to establish an updated survey from Schumacher's 1974 study (Schumacher and Reynolds, 1975). However, it was the differences between the tides that led to interesting observations. A cold river plume was found to be entering the strait from the east side, while a warm saline intrusion was found on the west side at depth. The river plume could be explained by the recent snow melt coming from the nearby Skagit River (Masson, 2006); however the warmer saline intrusion would be an interesting area of further study.

The nutrient data also provided an interesting look at the chemical make up of the strait. The data suggested that fresher waters correspond with higher concentrations of silica. This suggests that there is a plume from the Fraser River water that makes its way down through the Strait of Georgia and through Rosario Strait, confirming models such as those presented by Klinger and Ebbesmeyer and Mearns et al (Klinger and Ebbesmeyer 2001; Mearns et al. 2001). It was the data that was not available that could have helped define this study. With a silica concentration from the nearby Skagit River one could more definitively say where these concentrations were coming from.

While this study only looks at a small portion of the strait, it revealed some interesting observations about an area that had not been studied in detail.

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Table 1.

Location of transect lines and station locations.

Sta./WyPt.	Station Location/ Transect End Points Latitude	Longitude	Equipment Used	Station Depth
1	48° 26' N	122° 47' 50" W		
2	48° 26' N	122° 40' 50" W	ADCP	
3	48° 26' N	122° 47' 50" W	ADCP	
(Sta.1)4	48° 26' N	122° 47' 50" W	CTD cast /Nut.Analy	48 m
(Sta.2)5	48° 26' N	122° 46' W	CTD cast /Nut.Analy	67 m
(Sta.3)6	48° 26' N	122° 44' W	CTD cast /Nut.Analy	80 m
(Sta.4)7	48° 26' N	122° 40' 50" W	CTD cast /Nut.Analy	80 m
8	48° 26' N	122° 47' 50" W	ADCP	

Figure Captions

Figure 1. General Location of ADCP/CTD transect in relation to the rest of the Puget Sound

Figure 2. Velocity vectors on map for pre-maximum flood conditions (a) and post-maximum flood conditions (b), with red arrows signifying near surface, and blue arrows signifying 29 m depth.

Figure 3. A contour plot extrapolating the data from each CTD drop across the entire strait in order to get the salinity (a) and temperature (b).

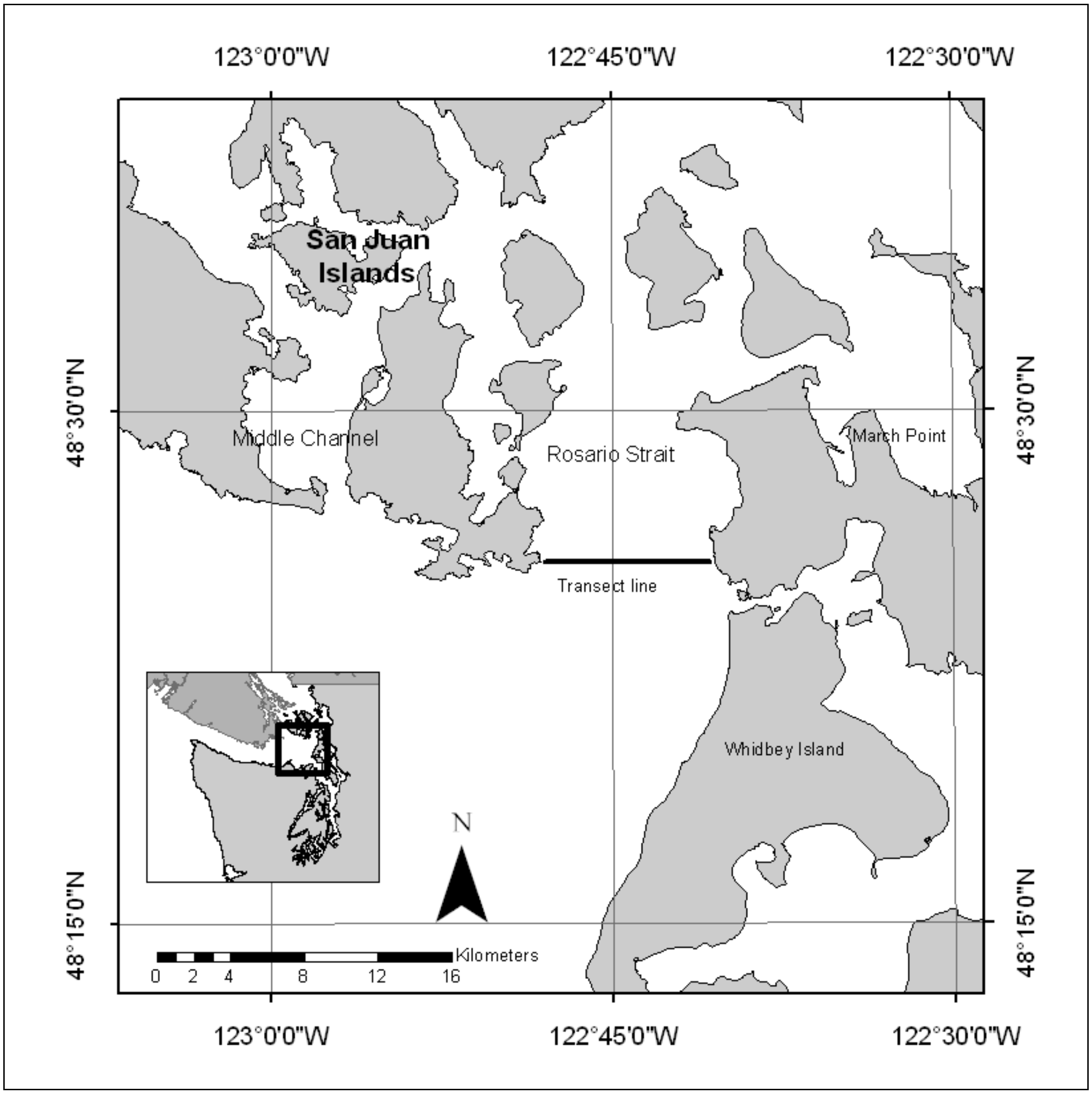
Figure 4. A contour plot extrapolating the data from each CTD drop across the entire strait in order to get the sigma-t.

Figure 5. A contour plot extrapolating the data from each CTD drop across the entire strait in order to get the change in salinity (a) and temperature (b) from after the maximum flood to before.

Figure 6. A contour plot extrapolating the data from each CTD drop across the entire strait in order to get the change in sigma-t from after the maximum flood to before.

Figure 7. A scatter plot of salinity and $Si(OH)_4$ concentration. Units are in for ‰ salinity and µM for $Si(OH)_4$ concentration. A trend line was added to assist in the visual representation.

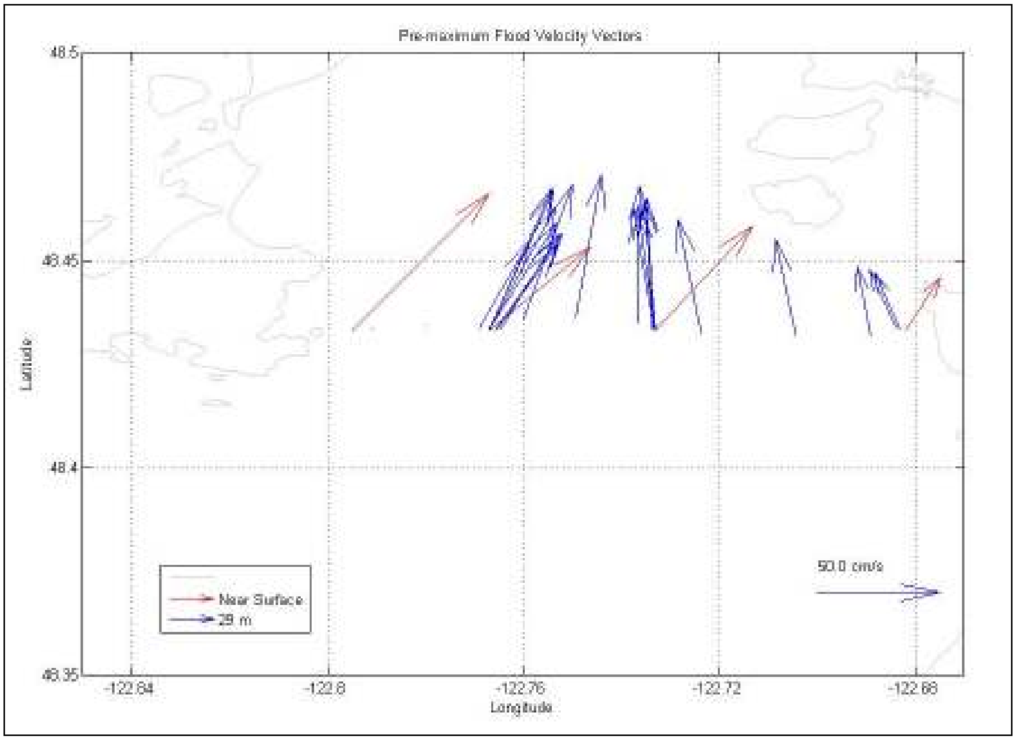
Figure 1.



123°0'0"W
122°45'0"W
122°30'0"W
48°30'0"N
48°15'0"N
San Juan Islands
Middle Channel
Rosario Strait
March Point
Transect line
Whidbey Island
N
Kilometers
0 2 4 8 12 16

Figure 2.

(a)


Pre-maximum Flood Velocity Vectors
48.5
48.45
48.4
48.35
Latitude
-122.84
-122.8
-122.76
-122.72
-122.68
Longitude
Near Surface
29 m
50.0 cm/s

(b)

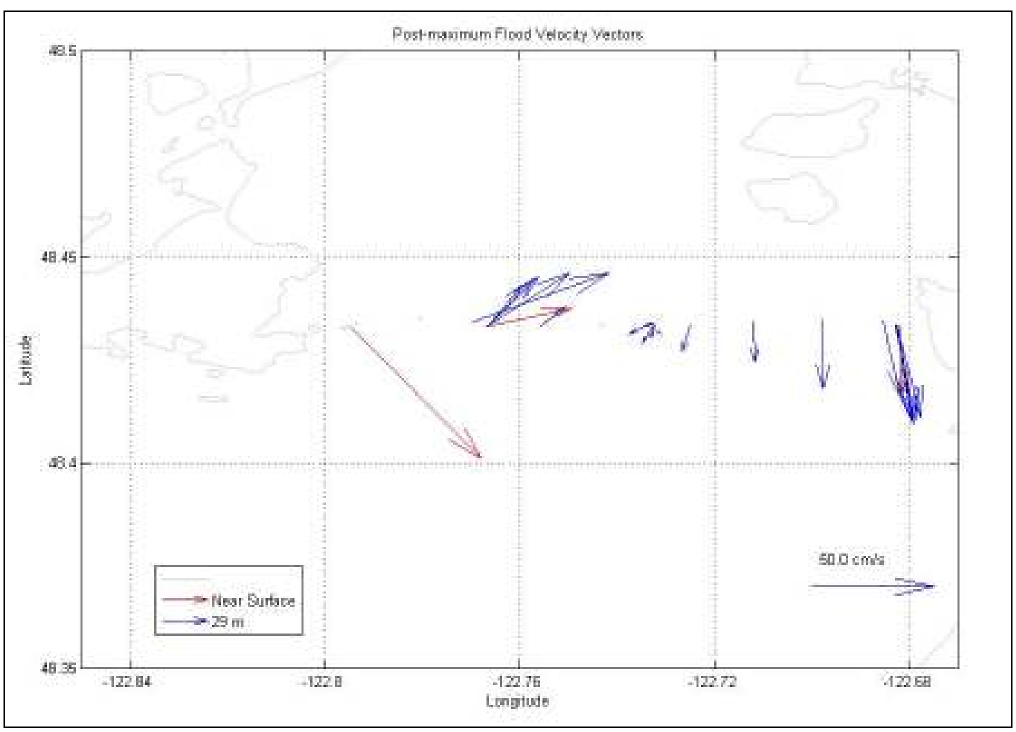
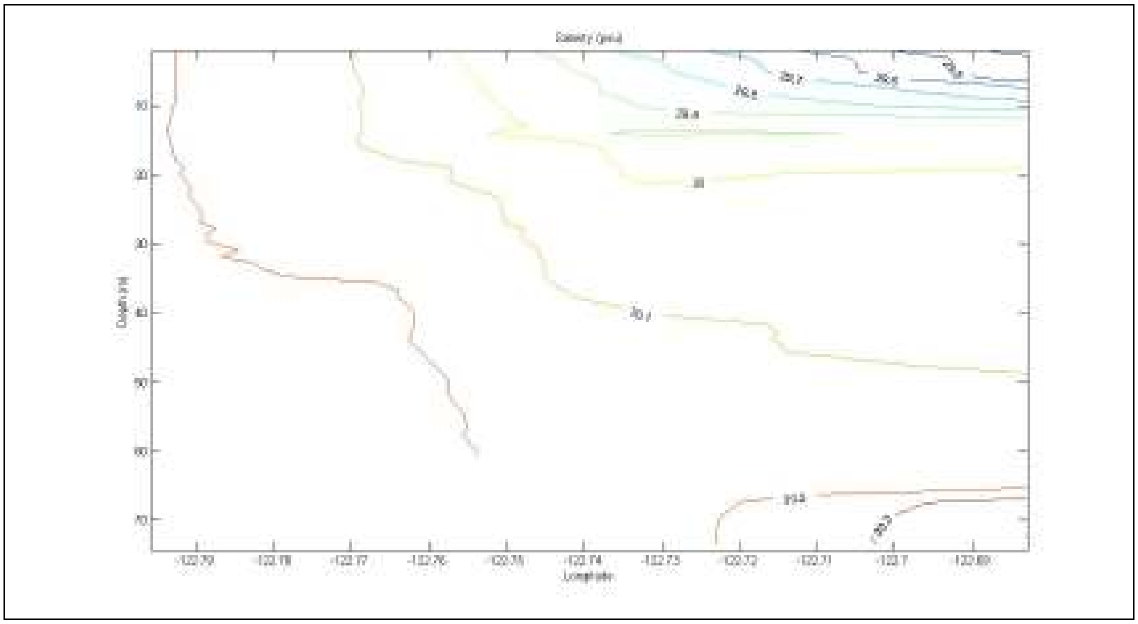

Post-maximum Flood Velocity Vectors
48.5
48.45
48.4
48.35
Latitude
-122.84
-122.8
-122.76
-122.72
-122.68
Longitude
Near Surface
29 m
50.0 cm/s

Figure 3.

(a)


-122.79
-122.78
-122.77
-122.76
-122.75
-122.74
-122.73
-122.72
-122.71
-122.7
-122.69
Longitude

(b)

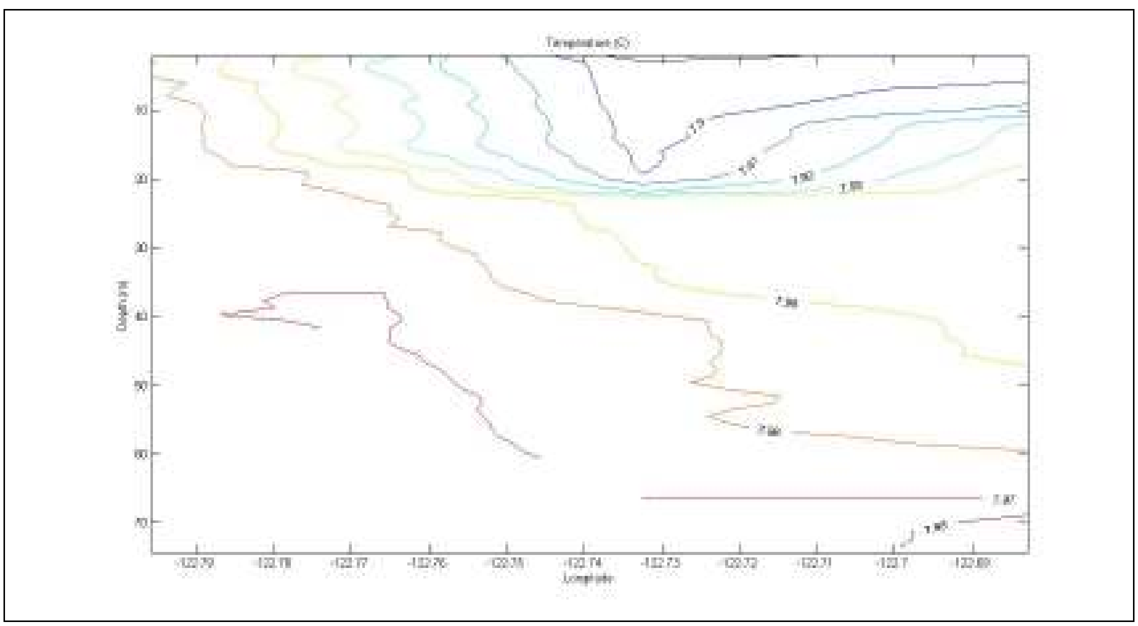
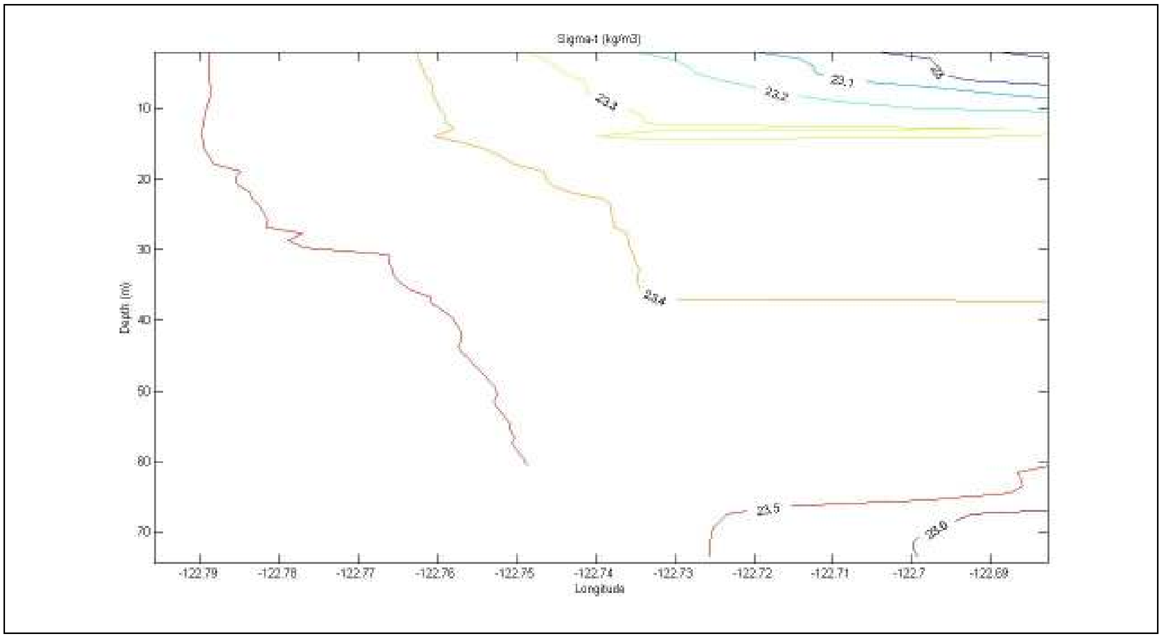

-122.79
-122.78
-122.77
-122.76
-122.75
-122.74
-122.73
-122.72
-122.71
-122.7
-122.69
Longitude

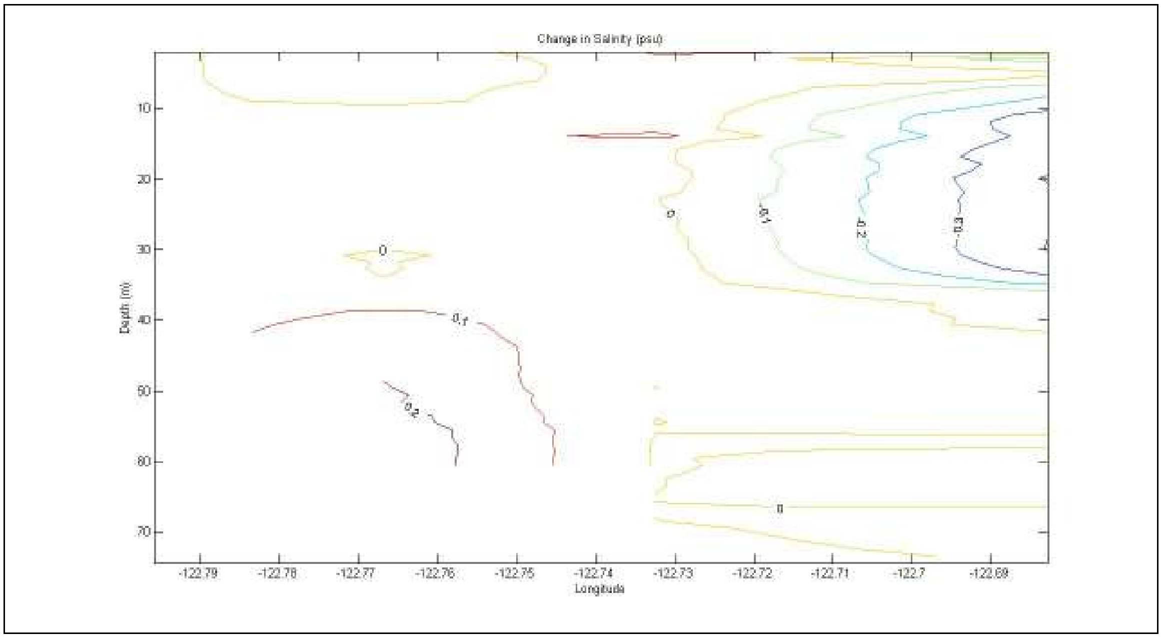
Figure 4.



Sigma-t (kg/m3)
Depth (m)
Longitude
10
20
30
40
50
60
70
-122.79
-122.78
-122.77
-122.76
-122.75
-122.74
-122.73
-122.72
-122.71
-122.7
-122.69
23.1
23.2
23.3
23.4
23.5

Figure 5.

(a)


Change in Salinity (psu)
Depth (m)
Longitude
-122.79
-122.78
-122.77
-122.76
-122.75
-122.74
-122.73
-122.72
-122.71
-122.7
-122.69

(b)

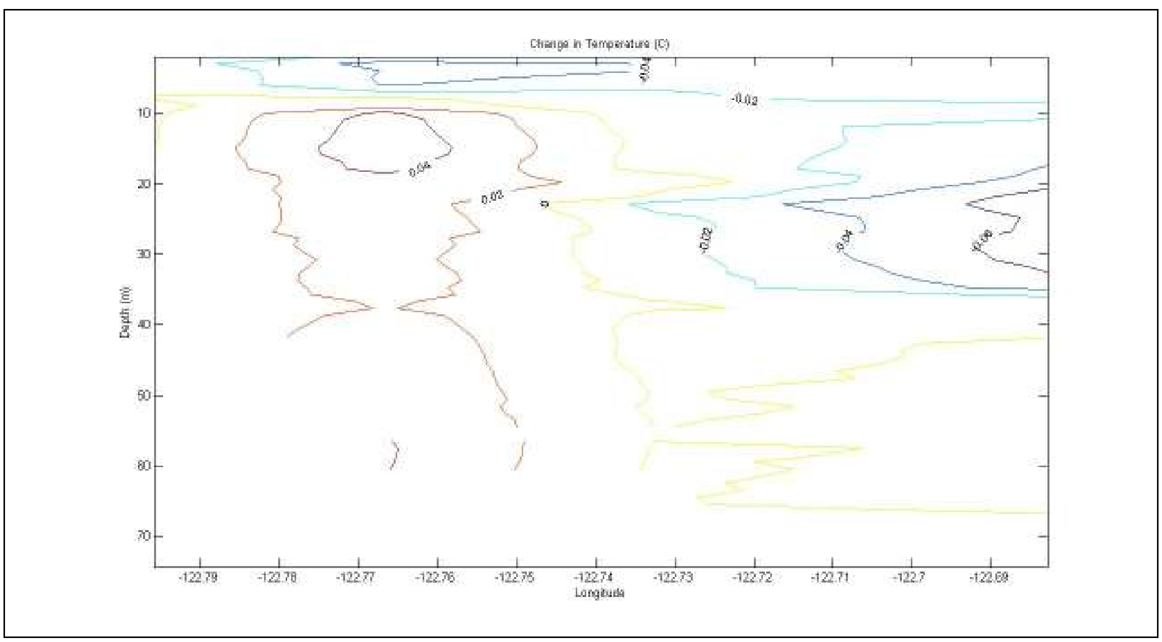

Change in Temperature (C)
Depth (m)
Longitude
-122.79
-122.78
-122.77
-122.76
-122.75
-122.74
-122.73
-122.72
-122.71
-122.7
-122.69

Figure 6.

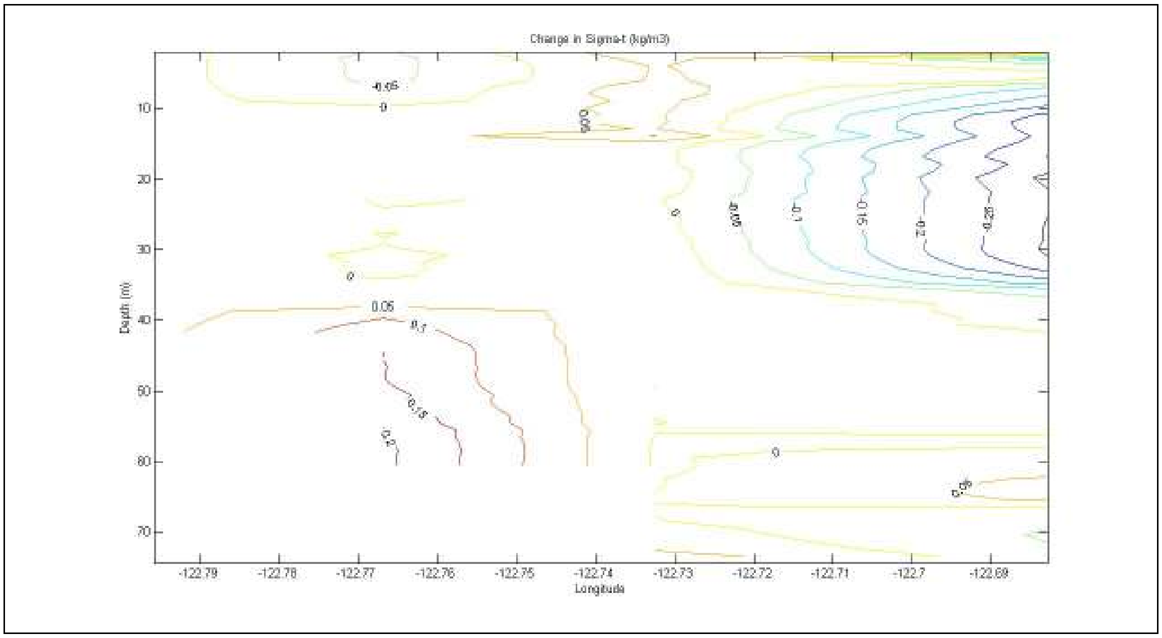
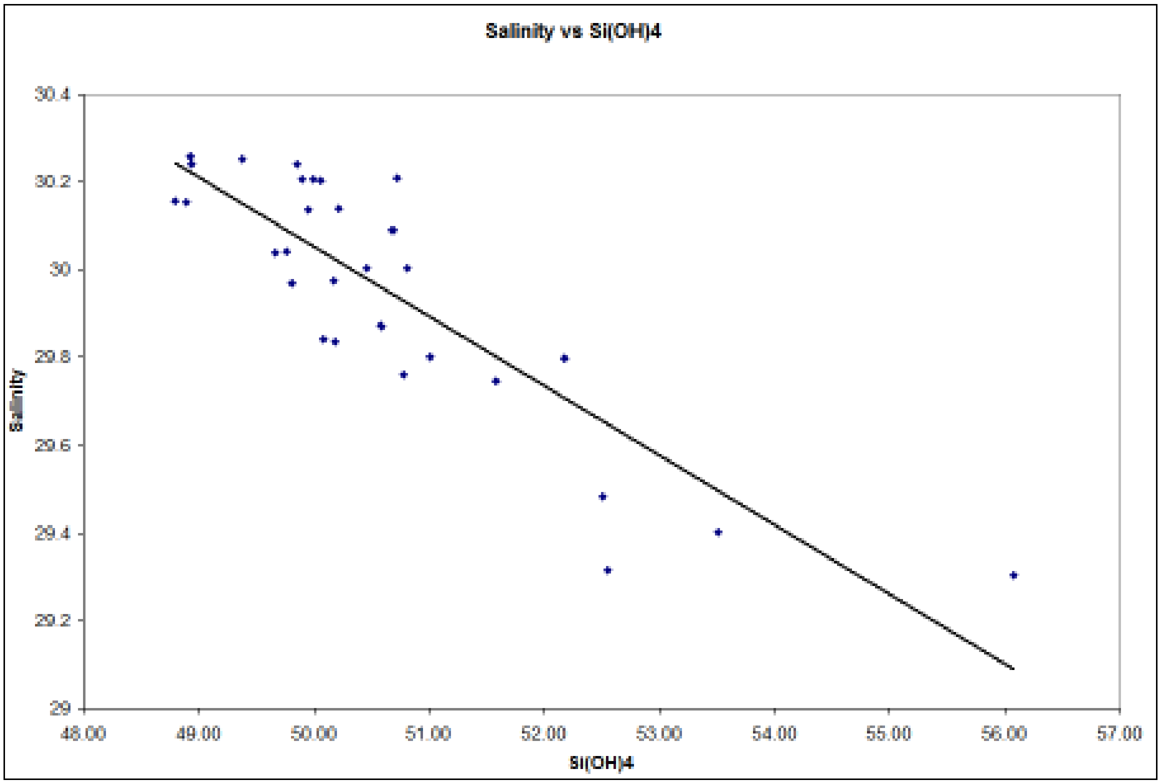


Figure 7.


Salinity vs Si(OH)4
30.4
30.2
30
29.8
29.6
29.4
29.2
29
Salinity
48.00
49.00
50.00
51.00
52.00
53.00
54.00
55.00
56.00
57.00
Si(OH)4