Spatial and Temporal Variation in San Juan Channel during Fall 2013

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Pelagic Ecosystem Function in the San Juan Archipelago Research Apprenticeship

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Abstract

The San Juan Channel links the Strait of Georgia and the Strait of Juan de Fuca, and is dominated by an estuarine flow regime. For fall 2013, Pelagic Ecosystem Function Research Apprenticeship sampled a 5-station transect along the San Juan Channel. A CTD was deployed and temperature, salinity, and density data were collected. From these data, channel structure could be deduced, and contour plots were created to help extrapolate out the trends. Water and air temperature decreased throughout autumn. Short-term channel salinity and density structure was modulated by tides and winds. Density stratification was highest at South Station and North Station stratification was greatest when the freshwater signal was strongest. The depth of the pycnocline at South Station was not correlated to tidal height. However, when data points were separated by tidal cycle, there was a correlation between neap tide's pycnocline depth and tidal height. Also, finer temporal resolution analysis of the northern channel salinity structure revealed that there is extensive within channel variation, and that salinity is regulated by tidal phase and cycle, as well as winds. The temperature, salinity and density structure patterns presented within this study, strengthens our understanding of their physical drivers within the San Juan Channel.

Introduction

The San Juan Channel, along with the Haro Strait to the west and the Rosario Strait to the east, is one thoroughfare that connects the Juan de Fuca Strait with the Strait of Georgia (Herlinveaux and Tully 1961).The channel is dominated by an estuarine flow regime with oceanic input from the Juan de Fuca Strait in the south and brackish water from the northern-bordering Strait of Georgia. In accordance with a classic estuarine flow regime, brackish waters enter via the Strait of Georgia at surface and exits in the southern channel through the Juan de Fuca Strait. Conversely, oceanic waters enter at depth from the Juan de Fuca Strait and continue northward into the Strait of Georgia. Estuarine circulation is dominant year round, but most pronounced in the summer months. In the winter, transient flow regimes can overtake estuarine flow regimes. The switch from predominantly estuarine to transient flow occurs as a result of shifts in wind direction from northeast to southwest. In the winter, southwesterlies, which blow from the southwest towards northeast, dominate and the brackish water originating from the Strait of Georgia is driven north and away from the San Juan Channel. By inhibiting the delivery of brackish water to the San Juan Channel, estuarine flow cannot occur and the resulting regime is transient (Thomson 2007). Overlaid on this estuarine-transient flow regime are mixed semidiurnal tides. A biweekly oscillation between spring (high exchange) tides and neap (low exchange) tides effect the physical water properties of the San Juan Channel.

Various features of the San Juan Channel –including bathymetry, channel width and estuarine flow regime –effect the expression of the mixed semidiurnal tides within the channel and makes it an area of high exchange. Sills are a major bathymetric feature that can promote mixing and the exchange of water between basins. The Victoria Sill, located near Victoria, Vancouver Island, and a sill located at Cattle Pass, near the southern entrance of the San Juan Channel, destabilize the water column and promote within channel mixing (Thomson 2007, Herlinveaux and Tully 1961). The sills also act as a catchment for deep waters –preventing their backward movement at depth and allow flood tides to propagate the oceanic waters at depth through the San Juan Channel to the Strait of Georgia. This process is often referred to as a "tidal pump", in which flooding tides ease deep, oceanic waters over the sill and pile up on the north-side of the sill. Ebbing tides push surface brackish waters out of the channel and create instability in the upper part of the water column, but do not exert enough force to cause a retreat in deep water intrusion back over the sill. Flooding tidal phases continue to push deep water through the channel until they are eventually delivered to the Strait of Georgia. Thus, the San Juan Channel is an important delivery system of saline waters to the Strait of Georgia (Herlinveaux and Tully 1961).

The San Juan Channel constricts incoming currents, causing current speeds to increase, leading to greater instability and channel homogeneity (Herlinveaux and Tully). At its narrowest point, the San Juan Channel is less than a mile wide, and at it widest point barely exceeds two miles (University of Washington, *Topography*). Herlinveaux (1957) explored the effect of tidal speed on sea surface temperature within the San Juan Channel and discovered that surface salinity increased with tidal speed, and that in the winter sea surface temperature increased with tidal speed and in the summer sea surface temperature decreased with increased tidal speed. This result is indicative of the fact that increased tidal speed promotes mixing of deep and surface waters. Thus, narrower channels experience greater exchange between deep and surface waters and the San Juan Channel is vital to the resurfacing of cold, oxygen poor and nutrient rich waters (Herlinveaux and Tully 1961).

The San Juan Channel's estuarine flow regime is regulated by tidal cycle. During spring tides, a greater hydrologic barrier caused by greater tidal exchange is expressed in the mixing region and obstructs surface waters from exiting the channel. On the other hand, neap tides have a decreased hydraulic barrier in the mixing region and surface water can exit the channel (Thomson 2007). This trend is due to the intense tidal mixing associated with spring tides that is not seen with neap tides.

The purpose of this study was to characterize the physical water properties within the San Juan Channel to understand temporal variation in the freshwater signal in the north and the oceanic signal in the south, and how tides and wind affect the expression of these signals within the San Juan Channel by addressing the following questions:

1) How does the Pelagic Ecosystem Research Apprenticeship's cruise transect vary from south to north?

2) How do tides affect within channel estuarine flow regime?

3) How are seasonal changes within the channel expressed?

4) How does tidal stage affect salinity in the north end of the transect?

Methods

Study Site and Sampling Methods

The Pelagic Ecosystem Function Research Apprenticeship (PEF) oceanographic data for fall 2013 was collected on September 26th through November 13th for a total of 7 cruises aboard the RV Centennial. Cruises took place on September 26th, October 9th, October 15th, October 22nd, October 29th, November 5th and November 7th. For all cruises, except cruise four (October 22nd), a SB/SC SBE 19 CTD was deployed at 5 stations and a total of six times. The CTD measured conductivity (salinity), temperature, pressure, depth, descent rate, fluorescence, and oxygen. SeaTerm and SeaSave were used on the boat to convert and save the files as HEX.

Cruises were conducted in the following order: North Station (48° 35.00'N, 123° 02.500' W), South Station (48 25.200' N, 122° 56.600' W), Station C (48° 28.991' N, 122° 57.470' W), Station B (48° 31.398' N, 122° 56.704' W), Station A (48° 32.709' N, 122 °58.746' W), and North Station (48° 35.000' N, 123° 02.500' W) (figure 1). The first sampling at North Station is referred to as North One. The Second sampling at North is referred to as North Two. The cruise portion from South Station back to North Station is referred to as a transect. Water collection occurred at South Station and North One –firing two niskins at near bottom depths, 50m, 20m, 10m, and surface. Due to heavy fog on October 22nd, cruise four proceeded: North Station, Station A, Station B, Station C, and South Station. The CTD was deployed 5 times and water collection occurred at Stations South and North, respectively. Since transects were analyzed from South to North in respect to time and direction and no North Two was sampled, cruise four is not included in this study.

Data Processing and Analysis

Transect Contour Plot Construction

Using SBE Inc. SeaSave software, CTD data were converted from HEX files to COM and then imported into Excel. CTD density, temperature, salinity and depth data were transferred to a SigmaPlot.11 workbook and contour plots of temperature, salinity and density were constructed with depth as the Y axis, stations on the x-axis, and the respective water property on the z-axis. Bathymetry was overlaid referencing the max depth of each station and overlaying black boxes corresponding to the respective station depth via PowerPoint©. The black boxes extended from one station to the midpoint between the next station.

For every cruise, contour plots of the transect were constructed for salinity, temperature and density throughout the channel with respect to location and time. Contour plot's were constructed for each variable using both the full range of the data and a consistent range covering the variation of all cruises.

Pycnocline and Stratification Assessment

The standard deviation of density values was used to determine station stratification. A higher standard deviation corresponds to greater stratification. Consistent with Thomas 2012, the pycnocline depth at South Station was defined as a change between three consecutive 0.5m bins greater than 0.02 kg/m^3. When multiple pycnoclines were indicated, the pycnocline with greatest change was chosen. If multiple pycnoclines were separated by one value less than 0.02 kg/m^3, then the pycnoclines were combined. Pycnocline upper limits were established by the shallowest depth of the pycnocline. Pycnocline lower limits were defined as the meter below the last change greater than 0.02 kg/m^3 because the bins accounted for a change of three consecutive 0.5m bins. Pycnocline width was defined as the difference between the upper and lower limits. Pycnocline depth was defined as the mid-point between upper and lower limits. Data were organized by tidal cycle and then pycnocline depth was plotted against NOAA NOS water height and a linear regression was run to determine correlation coefficients.

Winds Analysis

Data were obtained from the Friday Harbor Weather Station at Cantilever Point. Wind direction and magnitude data were imported into SigmaPlot.11 and polar plots were constructed for the daily wind for each cruise date and the preceding two days. Wind direction data for the months of September, October and November were used to establish monthly wind patterns.

Salinity and Tidal Data Analysis at North

Salinity values from the underwater verified Friday Harbor Weather Station data were imported into Excel© and used to construct graphs of temporal changes in salinity at Cantilever Point. Water height data were accessed from the NANOOS Data Explorer (URL), for the NOAA NOS station at Friday Harbor. The NOS data were saved as an Excel© CNV file, imported into Excel© and plotted against date. To assess the relationship between tidal phase and salinity at Cantilever Point, NOS water height data were reduced to only values on every 24th minute of every hour to allow for comparison between Salinity values (which existed for every 25th minute of every hour from September 27, 2013 to October 27, 2013). Salinity at Cantilever Point was plotted against date and overlaid on the graph with water height against date. This allowed for a direct comparison of water height to salinity.

Plots of surface salinity at Cantilever Point were created for September 26th, October 9th, October 15th, October 26th and November 13th to compare with surface values from North One and North Two. The Friday Harbor Weather Station performed maintenance on the underwater sensor at the beginning of November, so salinity data at Cantilever Point on November 5th, cruise six, was not available and is not included in the analysis of the northern channel.

For each cruise a profile of salinity, temperature and density at North One versus North Two were created using Excel© by importing their respective salinity, temperature and density values and graphing them together against depth. The NOS data for water height was used to construct tidal curves for each cruise. These tidal curves were used to assign North One and North Two specific tidal phases ranging from slack high, ebb, slack low to flood.

Results

Fall Wind Regime and Air Temperature

Throughout the course of PEF, the air temperature decreased (figure 2). Starting September 23rd, the air temperature decreased from an average of 11.956°C to 7.571°C on November 17th. For the months of September through November, there was no consistent wind regime. Instead, September and November were dominated by strong southwesterlies and October was dominated by northeasterlies (figure 3). The wind regime for cruises one, three, four, five and six had a strong northeasterly component (figure 4). Cruises two and seven occurred on days that had dominant southwesterlies (figure 5).

Tide Cycle and Tidal Phase

Cruises 1, 2 and 6 were spring tides and cruises 3,5 and 7 were neap tides. For cruises 1 and two, North one was sampled during the middle of a medium flood and the transect sampling occurred from slack high to slack low of the following ebb (figure 6). Cruises 3,5 and 7 were sampled on similar tidal phases. North One sampling occurred at slack low, and the transect sampling occurred on the proceeding flood with North Two sampled at slack high (figure 7).

Within Season Variation in Temperature and Salinity

During fall 2013, water temperature decreased consistently over the course of the season (figure 8). For all stations, surface water temperature were relatively warm (about 11C) early in the season. Later in the fall during cruises six and seven, temperatures were much colder (about 8C). Additionally, water temperature throughout the water column and the transect gradually became more uniform as the season progressed. From cruise one to cruise seven, transect temperature variation decreased from 3.3574C to a gradient of 1.2073C. These patterns were consistent with seasonal changes in atmospheric air temperatures (figure 2).

Progressively over fall, the brackish water signal in the northern end of the San Juan Channel dissipated. Both trends in salinity and density revealed a consistent surface freshwater signal at North Station for cruises one through five (ranging between 21 and 22kg/m^3) that is not apparent in cruises six or seven (figure 9, figure 10). The largest intrusion of surface freshwater across the transect occurs on cruises three and five. Cruise three exhibits two distinct freshwater signals. The first is apparent within the top five meters of South Station and the second is seen expanding across the top 20 meters of North Station. The average density of the freshwater plume at South Station was 22.95kg/m^3 and for the same depth (5.5m) at North Station 22.71kg/m^3. The density contour plot for cruise six displays a small fresh water signal at North Station that is not exhibited in the cruise seven plot. The slow disappearance of the freshwater signal can be used as a proxy of estuarine versus transient flow, which occurs due to changes in wind direction.

Within Season Variation in Density

Cruises three, five and seven exhibit distinct patterns at depth, which can be explained by tidal phase. Transect sampling for cruises three, five and seven occurred with South Station sampling at slack low and North Station sampling at slack high. The effect of the flooding event that occurred during transect sampling can be seen in the intrusion of high density water at depth. This intrusion traces the progression of the flooding event. This oceanic signal characteristic of a flooding event can even be seen in the following ebbing event. For example, cruise one transect sampling follows a large flooding event. The remnants of this flood is seen at depth in figure 10, where high density water intrudes at depth beyond South Station.

Cruises one, two and six have more defined density gradients at South Station indicative of instability and more uniform water masses. Cruises two and six major contour lines at depth at South Station have a distinct vertical component, confining the oceanic signal to South Station. These trends are represented in channel stratification as well (figure 11).

Over the course of the study, salinity and density structure throughout the channel closely resembled each other. However, while contour plots of transect temperature for cruise one closely resembles the density and salinity contour plots for cruise one, as the cruises progressed temperature became more uniform, colder and less similar to the corresponding plots of salinity and density.

Tides and Pycnocline Depth at South Station

This year, no correlation between Pycnocline depth at South Station and tide height was found. When standard deviation was plotted against tidal height and linear regression was runand R^2 value of 0.0067 was obtained. When pycnocline depth values were separated by tidal cycle, R^2 equaled 0.0682 for spring tides, showing no correlation for spring tides and pycnocline depth. On the other hand, neap tide pycnocline depth showed a direct correlation with tidal height with an R^2 value of 0.9962.

Tides and Salinity in the Northern Channel

This study looked at general trends in Cantilever Point salinity and at daily salinity values in order to assess the change occurring at North Station in regards to the greater channel. Friday Harbor Cantilever Point Weather Station data were used to assess long term patterns of salinity in the northern San Juan Channel (figure 12). When salinity values at Cantilever Point were plotted against time, distinct patterns emerged. A fortnightly pattern between lowest salinity patterns was apparent and a seasonal pattern of an increased gradient between salinity high and low values during the summer, and an overall decrease in salinity variation during the winter. A decreased variation of salinity gradients throughout the study was exhibited in the North One versus North Two profiles; this finding correlates with what was observed in the Cantilever Point data.

“Zoomed in” profiles of salinity at Cantilever Point were created for each cruise day and compared to corresponding North One versus North Two profiles (figure 13). Cruise one and two’s North One, and North Two salinity profiles were not in agreement with the corresponding Cantilever Point salinity values. For cruise one, North One salinity value at 6ft is 26.6psu; for North Two, the salinity value at 6ft is 28.3psu. For the corresponding times, Cantilever Point salinity values were 30.7psu and 28.8psu, respectively. The magnitude of change in salinity value at Cantilever Point relative to North Station is similar –approximately a 1.9psu change was exhibited at Cantilever Point, while 1.7psu change was shown at North Station. Although there is relative agreement in the magnitude of change between North Station and Cantilever Point salinity values, the direction of change oppose each other. According to the values at Cantilever Point, one would expect to see higher salinity values for North One than North Two; however, the opposite is true. For cruise two, salinity values of North One and North Two at six feet were as follows: 29.4psu and 29.9; corresponding Cantilever Point salinity values were 30.4psu and 29.9psu. Again, the magnitude of change exhibited within the northern channel was the same, but the direction was opposite.

Cruises three, five and seven demonstrated a different trend then cruises one and two. For these cruises, North Two had greater surface salinity than North One and the same trend was present in the salinity data for Cantilever Point. For cruise three, surface salinity was 29psu for North One and 29.6psu for North Two. At the time of North One’s sampling, the salinity value at Cantilever Point was 29.7 and at the time of North Two’s sampling, salinity at Cantilever Point was 30.1psu. For cruise five, salinity at the surface of North One and North Two were as follows: 28.6psu and 28.7psu. This same trend of increasing salinity over time is shown at Cantilever Point as well, with corresponding North One and North Two salinity values of 28.8psu and 29.1psu, respectively. Cruise seven's North One and North Two surface salinity values and the corresponding Cantilever Point salinity values were as follows: 30.5psu, 30.6psu, 30.6psu and 30.7psu. For cruises three, five, and seven, the relative magnitude and direction of change in surface salinity values are the same.

Therefore, the Pelagic Ecosystem Function North Station data does not always agree with measured changes in surface salinity at Cantilever Point, but the data does agree with broader, seasonal patterns observed at the Friday Harbor Weather Station.

Discussion

Seasonal and Tidal Effects on Transect Water Properties

Tidal cycle and phase, along with seasonal wind direction shifts and cooling and warming patterns all effect the physical water properties of water. These are all powerful drivers of ocean circulation, and the effect of each driver can be seen in the patterns exhibited by the transect contour plots.

The relationship between spring-neap tidal cycle and the movement of freshwater through the transect is exhibited clearly in the structure of transect density over the course of the study. For example, cruises three, five, and seven all occurred during the neap tidal cycle. Cruises three and five exhibited the greatest intrusion of freshwater at the surface. This aligns with Thomson's observation that neap tide cycles have a decreased hydrologic barrier that facilitates the outflow of freshwater from the channel. However, tidal cycle alone is not enough to explain the trends presented figure 10 –cruise seven does not have a freshwater signal exhibited in the transect. This anomaly for a neap tide can be explained by patterns in wind direction. As previously stated, southwesterlies are associated with suppressed freshwater signals and northeasterlies promote the expression of the freshwater signal in the northern San Juan Channel. Thus, the contour plot of density for cruise seven exhibits no fresh water signal because of persistent southwesterly winds that occurred during the cruise (figure 10b). Consequently, the freshwater is apparent and extensive for cruises three and five is most likely attributed to the combined effect of strong northeasterly winds and the depressed hydrological barrier characteristic of a neap tidal cycle.

Cruises one, two and six are characterized by spring tidal cycles and exhibit different patterns than cruises three, five and seven (figure 10a). The wind regime during cruise one fluctuated between southwesterlies and northeasterlies. During cruise two, the wind was mainly blowing towards the northeast. However, both of the contour plots for density structure on these days exhibit freshwater signal at North Station. At first this result was surprising considering the combined effect of tidal cycle and wind regime on the suppression of the freshwater signal at North Station. However, the only apparent explanation for the observed trends is tidal phase. For cruises one and two, South Station was sampled mid-flood and North Station was sampled during the following ebb. During ebbing events, northern characteristics are more expressed within the channel –most evident of this fact is the presence of a freshwater signal at North Station despite tide cycle and wind regime. This effect can also be seen when comparing cruise one transect density structure with cruise two transect density structure. For cruise one, North Station data were collected earlier in the ebbing event than during cruise two. The freshwater signal exhibited in figure 10a is more confined and the water column at North Station is more stratified than the signal exhibited in the cruise two contour plots of transect density. These factors suggest that the observed freshwater signal is remnant of the previous exchange, a large ebb that preceded the medium flood that South Station was sampled during. For cruise two, the freshwater signal expands across the channel from North Station almost to Station B. This is indicative of further progression of the ebbing event. In fact, the tidal phase for cruise two is further along than for cruise one and the freshwater signal exhibited throughout the transect on October 9th can be viewed as the progression of the signal exhibited on September 26th. Cruise six transect sampling occurred between two slack highs, with South Station sampled at the first slack high and North Station sampled at the next slack high. The flood and ebb event in between the slack highs resulted in a tidal exchange of about one foot, consequently the presence of a freshwater signal at North Station may be surprising. However, the signal can be explained by northeasterly winds that dominated November 5th.

The first important characteristic of figure 11 is that South Station tends to be the most stratified. This is indicative of estuarine flow, in which the dissimilar water masses create greater layering at South Station where oceanic input occurs. Secondly, the importance of estuarine flow is exhibited in the high stratification values of North Station for cruises one and five, in which low surface density values at North Station differed most from the density values at depth. Next, the inner channel, stations C, B and A, have generally low stratification values. This is related to the relative mixing that occurs within the channel. As Thomas (2011) discussed, mid-channel stations have high levels of mixing caused by Bathymetric shoaling in the mid-channel and the sill at Cattle Pass between South Station and Station C. The combined effect of shoaling and the sill cause the depressed stratification values for the inner channel. Lastly, the gradient between the inner channel becomes depressed over the season. This is result of the switch to transient flow, in which water masses within the channel are more similar because of the lack of freshwater input. When water masses are more similar, they mix together more easily and the result is decreased stratification.

Relationship between Pycnocline Depth and Tide Height

Bernard (2010) and Thomas (2011) established relationships between pycnocline depth and tide height that were not apparent for 2013 (fig 14). This could be attributed to a smaller data set for 2013 than used in the past. Thomas (2011) analyzed monthly data for the entire year of 2011. Bernard (2010) assessed a data set comprised of PEF data from years 2006, 2008, 2009 and 2010. For this study, only data from the seven cruises was used to assess the relationship between pycnocline depth and tide height. Even with the limitation of our data set, there was a correlation between neap tide pycnocline depth and tide height. This relationship should be further explored in future studies and should be analyzed in context of the entire PEF data set for the past 10 years.

Friday Harbor Weather Station and North One versus North Two Profiles

This study focuses on many components underlying overall trends in measured surface salinity at Cantilever Point, including: long term seasonal effects, which has already been discussed, and forces driving salinity variability. To further explore Herlinveaux and Tully's (1961) established relationship between surface salinity values and tidal current speed, this study explored the relationship between tidal height and surface salinity values at Cantilever Point. When tidal height over time was overlaid on surface salinity values at Cantilever Point over time, a distinct relationship was found (figure 15). Figure 15 clearly demonstrates that tidal height highs correspond with highest surface salinity values, and that the lowest tidal height corresponds with the lowest salinity values. The two profiles do not overlay exactly, but this is to be expected as this study has already demonstrated that salinity values are controlled by more than just one factor. However, the tidal drive of trends in salinity should not be ignored.

This study further explored this relationship between salinity values and tidal height by exploring the relationship between tidal phase, indicative of tidal height, and changes in the profile of North Station at North One versus North Two. Sampling of North One and North Two occurred at similar times in the tidal phase for cruises one and two. During cruise one, preceding a large ebb North One was sampled mid-flood during and North Two was sampled on the ebbing side of slack low. At surface, the salinity profile of North One is fresher than that of North Two. This is most likely due to initially low surface salinity values at North Station due to the large ebb that preceded the sampling of North One. The full effect of the tidal phase is not exhibited by North One's salinity profile. This argument stems from the initial low surface salinity values and the relative isohaline structure of the profile at depth –oceanic waters are distinctly more saline than channel water and would be indicated by a jutting out of the profile at depth. The effect of the flood can be seen in the salinity profile of North Two, which has higher surface salinity values and whose profile juts out at depth, indicating a second water mass.

North One versus North Two salinity profiles for cruise one clearly indicate the effect of tidal phase; however, these characteristics are not as pronounced for the North Station profiles for cruise two. Figure 11 demonstrates that stratification for cruise one was much greater than stratification for cruise two. Depressed stratification is indicative of increased mixing, and a decrease in apparent change between North One and North Two profiles reflect the homogeneity of the channel on October 9th.

Cruises three, five and seven all occurred during a flooding event, and North One and North two were sampled at similar times in the tidal phase for each cruise. The North One versus North Two salinity profiles for cruise three clearly exhibit the expected tidal phase effect on salinity values. North One was sampled at slack low and North Two was sampled at slack high. At the surface, North One is less saline than North Two, this is a residual effect of the preceding ebb event. At depth, North One is more saline than North Two. This high salinity signal at depth of North One is indicative of the previous large flood event whose signal was not decreased by the following small ebb that preceded the sampling of North One. This is because ebbs have a greater effect on the surface of the water column, while floods have a greater influence at depth. Furthermore, North One and North Two profiles for cruises three and seven have less pronounced change than cruise five. Similar to the variation between cruises one and two, cruise three and seven North Station is less stratified than for cruise five. This decreased stratification is representative of increased mixing and explains the relatively isohaline structure of North Station.

Conclusion

This study only focused on the trends exhibited in the Pelagic Ecosystem Function Research Apprenticeship 2013 data set. From this data, trends in temperature, salinity and density structure were assessed and were in agreement with the broad patterns assessed by earlier Pelagic Ecosystem Function apprentices. However, this year the relationship between pycnocline depth and tide height was not expressed for all South Station values, but it was expressed for neap tide cycles. This relationship should be further explored in future studies and should be analyzed in context of the entire PEF data set for the past 10 years. Along with the relationship between tidal height and pycnocline depth, more extensive research should be performed looking at salinity structure in the northern part of the channel. The Friday Harbor Weather Station provides continuous surface salinity values that could be used to track the freshwater signal over a longer time scale. A comprehensive interannual look at salinity structure at Cantilever Point and North Station may provide a better understanding of the estuarine structure of the channel and the importance of water exchange between the Strait of Georgia and the Juan de Fuca Strait. This would build upon our understanding of the drivers discussed in this study –winds and tides –and help to illuminate greater questions relating to circulation.

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References

Bernard GA. 2010. Effects of tides and remote forcing on oceanographic properties within the San Juan Channel during early fall. University of Washington, Friday Harbor Labs: 1-22.

Herlinveaux RH, Tully JP. 1961. Some oceanographic features of Juan de Fuca Strait. Journal of the Fisheries Research Board of Canada 18(6):1027-1071.

Herlinveaux RH. Tidal currents in Juan de Fuca Strait. Pacific Naval Laboratory and Pacific Oceanographic Group: 799-815.

Masson D. 2002. Deep water renewal in the Strait of Georgia. Estuarine, Coastal, and Shelf Science 54:115-126.

Redfield AC. 1950. Notes on the circulation of a deep estuary. Proceedings of the Colloquium on the Flushing of Estuaries. Woods Hole Oceanographic Institution.

"The Geology of the San Juan Islands (Topography)." The Geology of the San Juan Islands (Topography). University of Washington, n.d. Web. 22 Nov. 2013.

Thomas KA. 2011. Seasonal and tidal effects on water density gradients in the San Juan Channel. University of Washington, Friday Harbor Labs: 1-44.

Thomson RE. 1994. Physical oceanography of the Strait of Georgia-Puget Sound-Juan de Fuca Strait System. Canadian Technical Report of Fisheries and Aquatic Sciences No. 1948.

Thomson RE. 2007. Estuarine versus transient flow regimes in Juan de Fuca Strait. Journal of Geophysical Research, Vol. 112.

Tully JP, Dodimead AJ. 1957. Properties of the water in the Strait of Georgia, British Columbia, and influencing factors. Journal of the Fisheries Research Board of Canada 14(3):241-319.

Waldichuk M. 1957. Physical oceanography of the Strait of Georgia, British Columbia. Journal of the Fisheries Research Board of Canada 14(3):321-486.

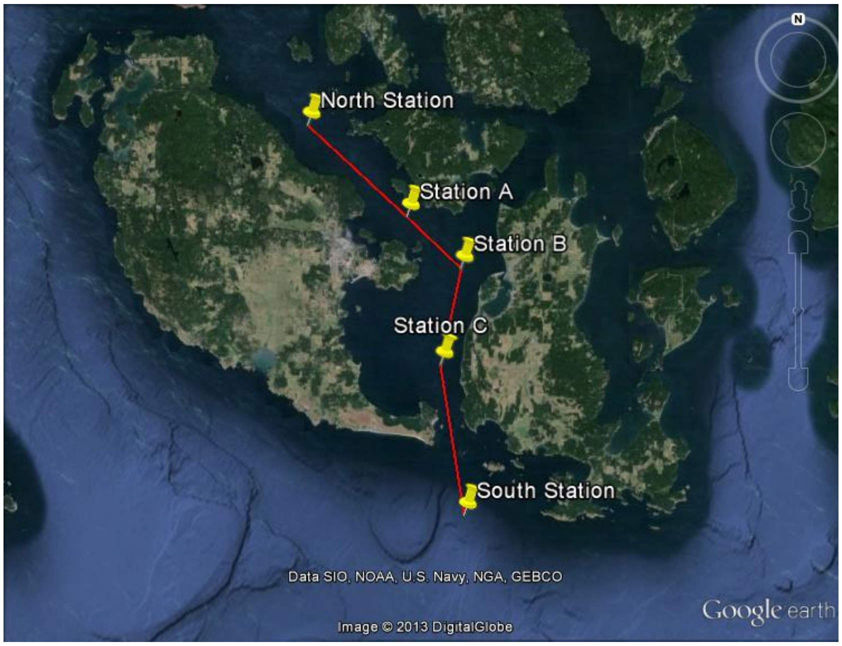


Figure 1: Cruise Transect is indicated with pins. In order, transect sampling occurs South Station, Station C, Station B, Station A and last North Station.

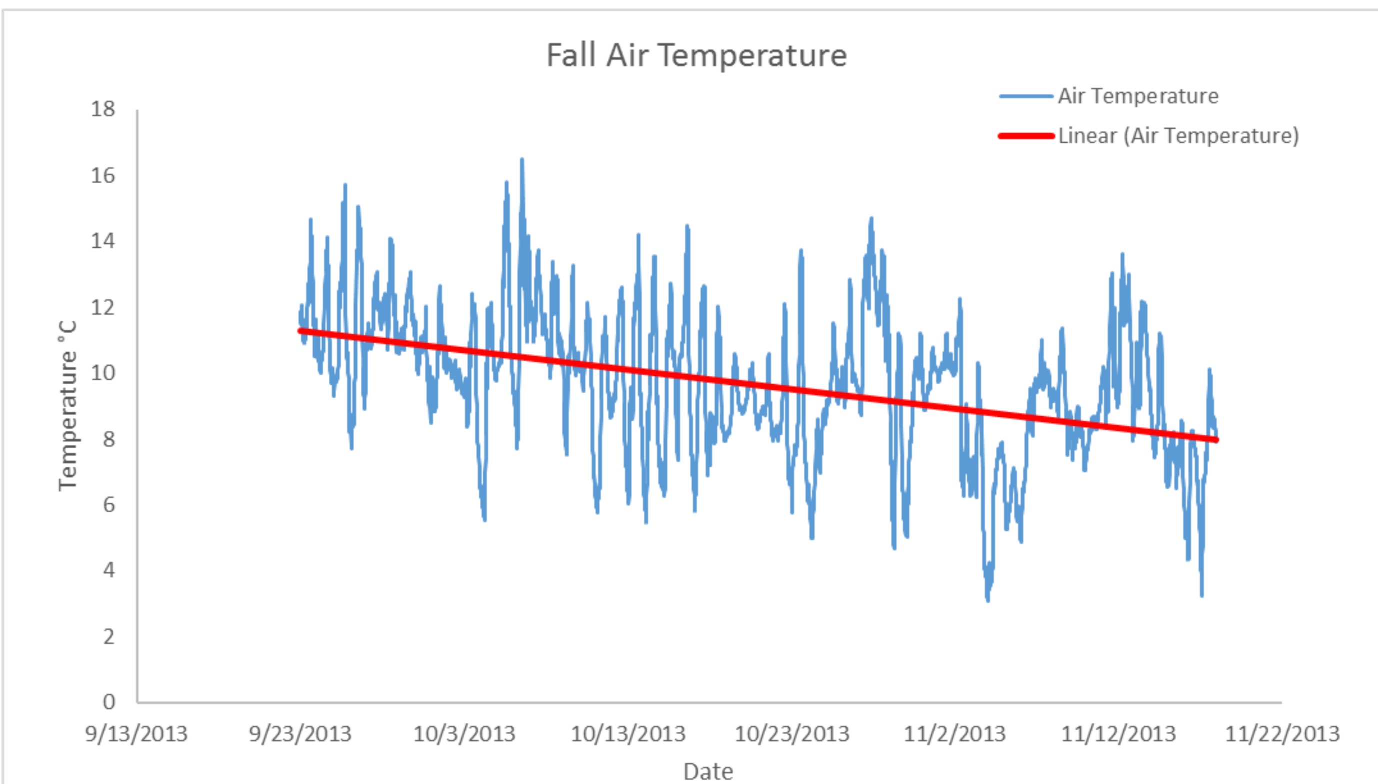


Figure 2: Fall air temperature over the course of the study. There is a clear trend in a decrease in air temperature over the course of the study. Data provided by Friday Harbor Weather Station.

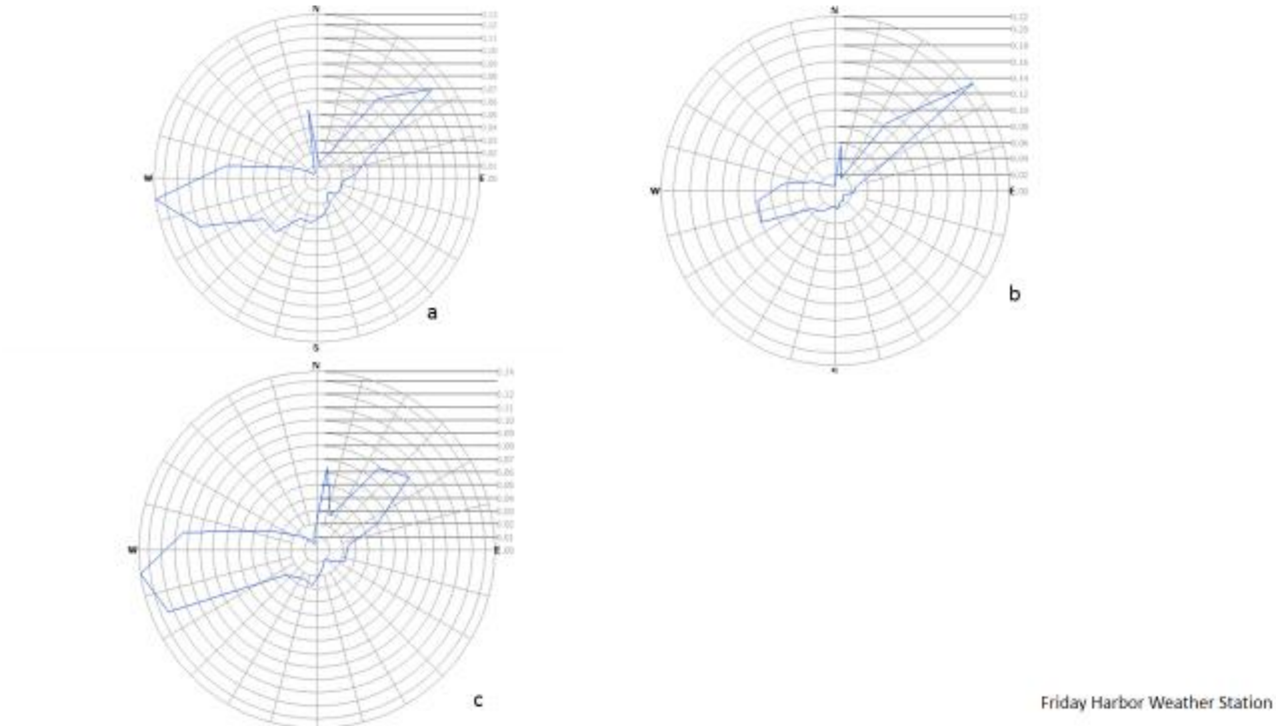


Figure 3: Wind roses depicting wind direction during fall 2013 provided by the Friday Harbor Weather Station. a) Strong southwesterly component in winds for September. b) Northeasterly winds dominated October's wind regime. c) Wind direction for the month of November is again dominated by southwesterlies.

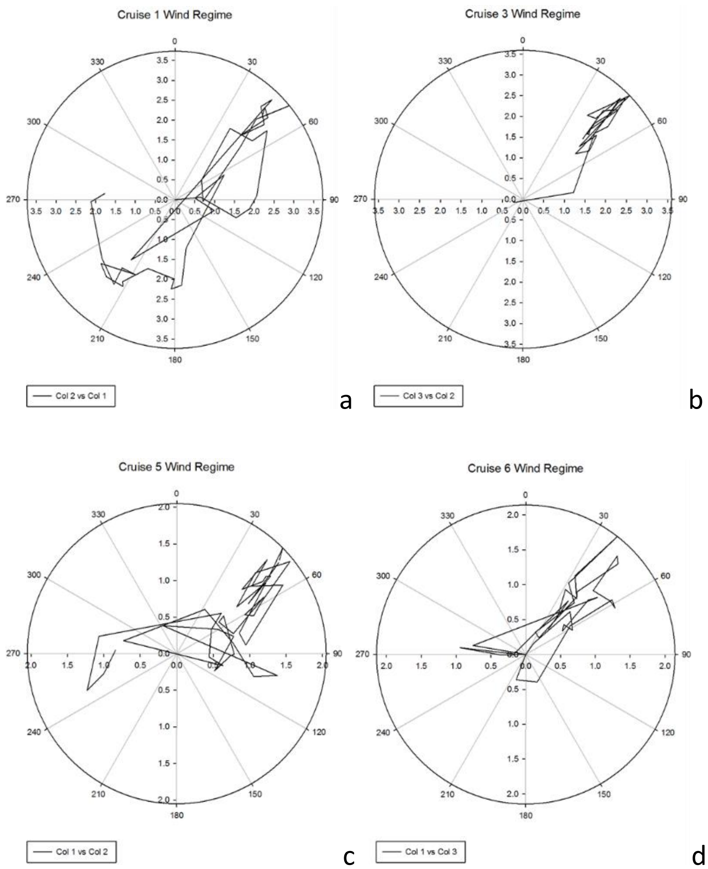


Figure 4: Cruises 1(a), 3(b), 5(c) and 6(d) had predominately northeasterly winds.

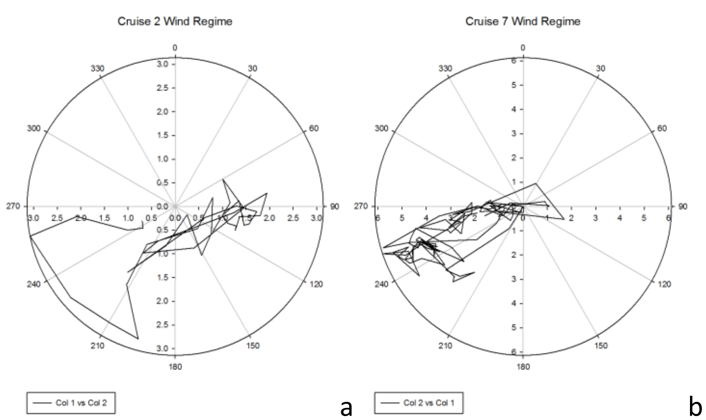
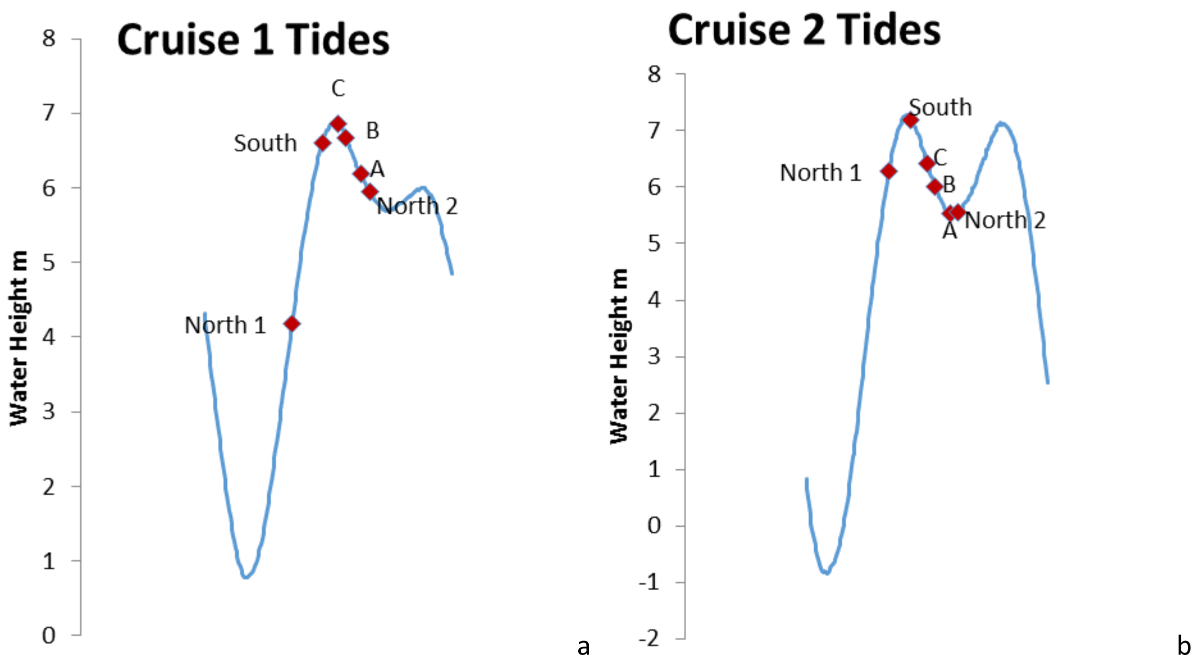
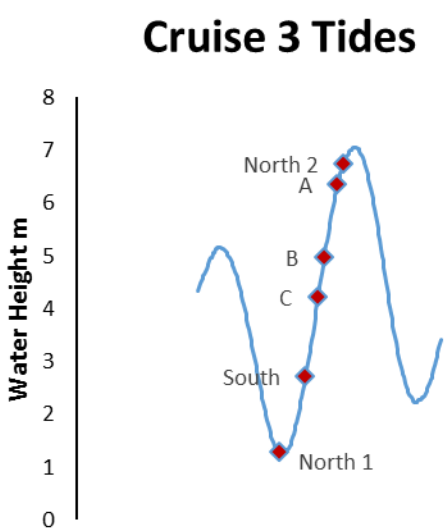


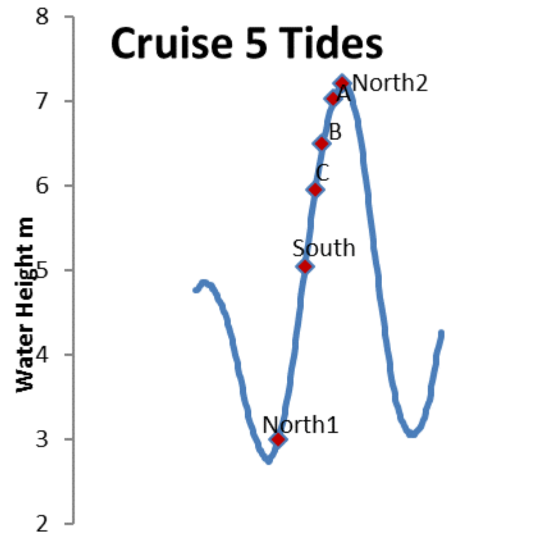
Figure 5: Cruises 2(a) and 7(b) had predominately southwesterly winds.



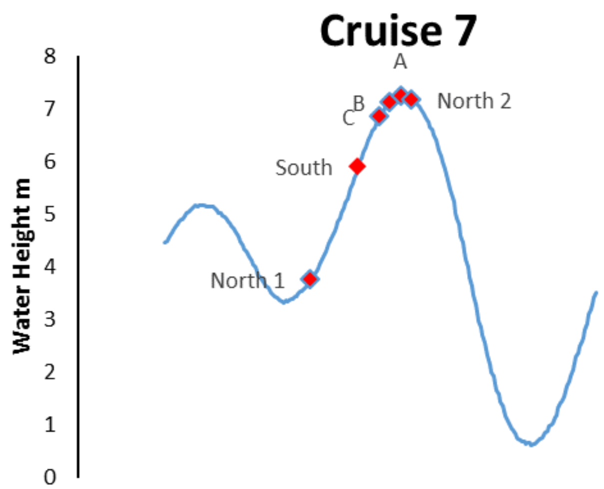
Firgure 6: Cruises 1(a) and 2(b) occur during similar tidal phases: slack high to slack low.



a



b



c

Figure 7: Cruises 3 (a), 5 (b) and 7 (c) were sampled at similar points during tidal phase: slack low to slack high.

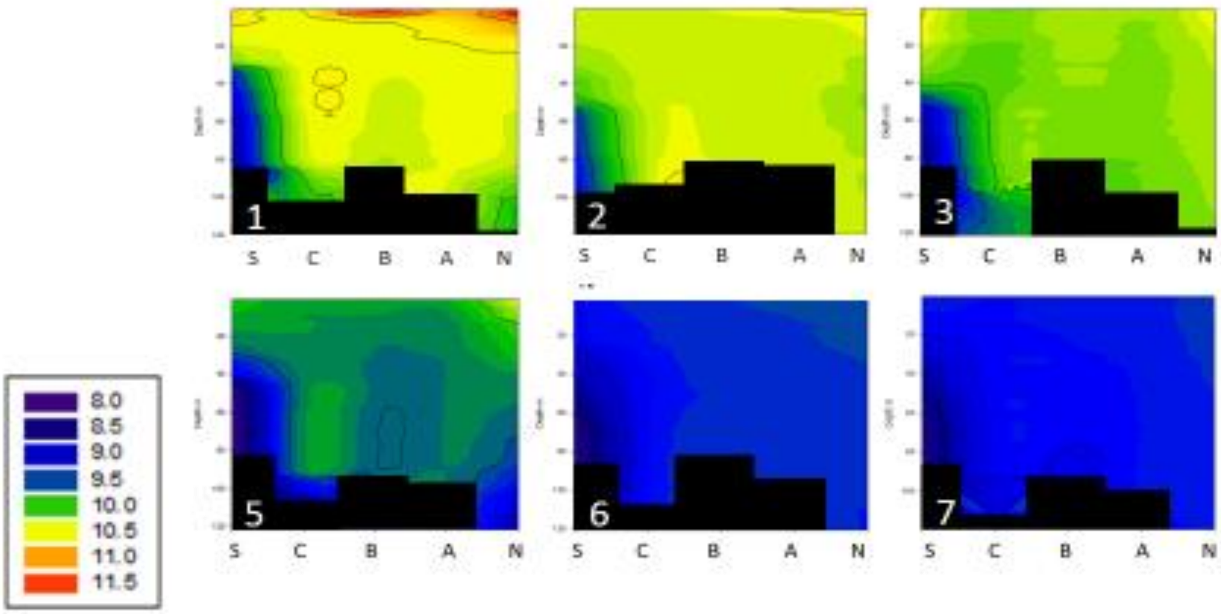


Figure 8: The contour plots are on uniform scale with warm colors corresponding to warm temperature and cold colors to cold temperatures. Cruise number is indicated in the bottom left-hand corner of each plot and it is apparent that from cruise one to cruise seven, temperature decreases and becomes more uniform.

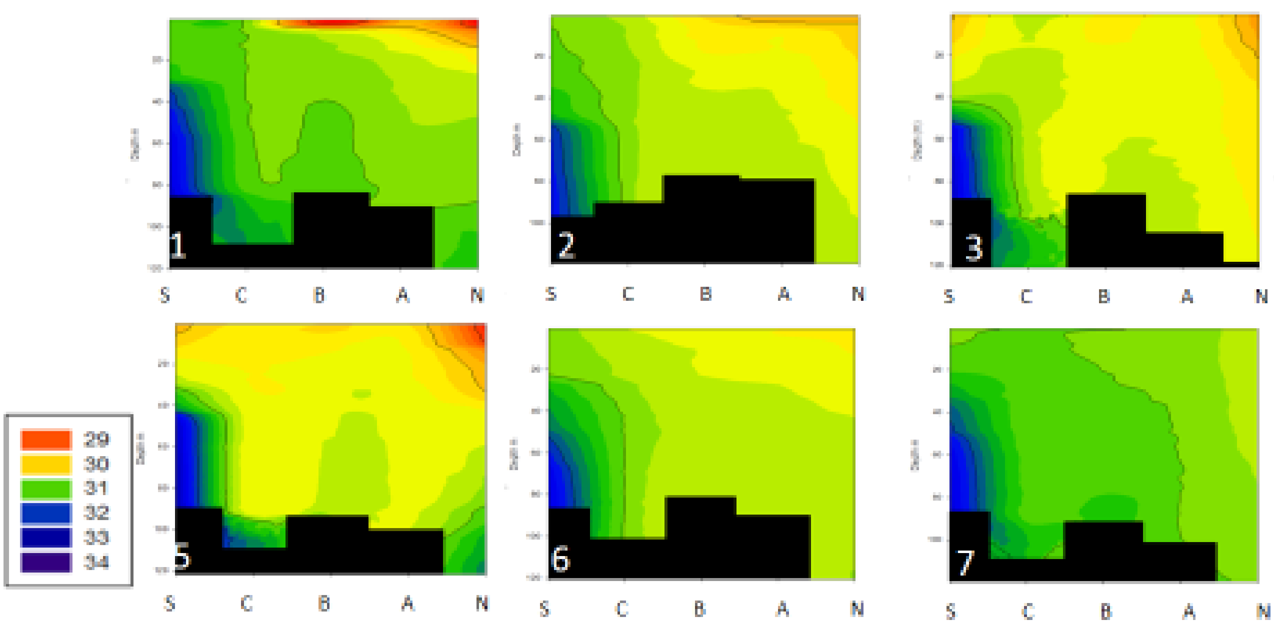


Figure 9: The contour plots are on uniform scale with warm colors corresponding to low salinity and cool colors corresponding to high salinity Cruise number is indicated in the bottom left-hand corner of each plot and one can see that over the course of fall the low-saline signal in the northern channel disappears. Also, the channel becomes more uniform over the course of the study.

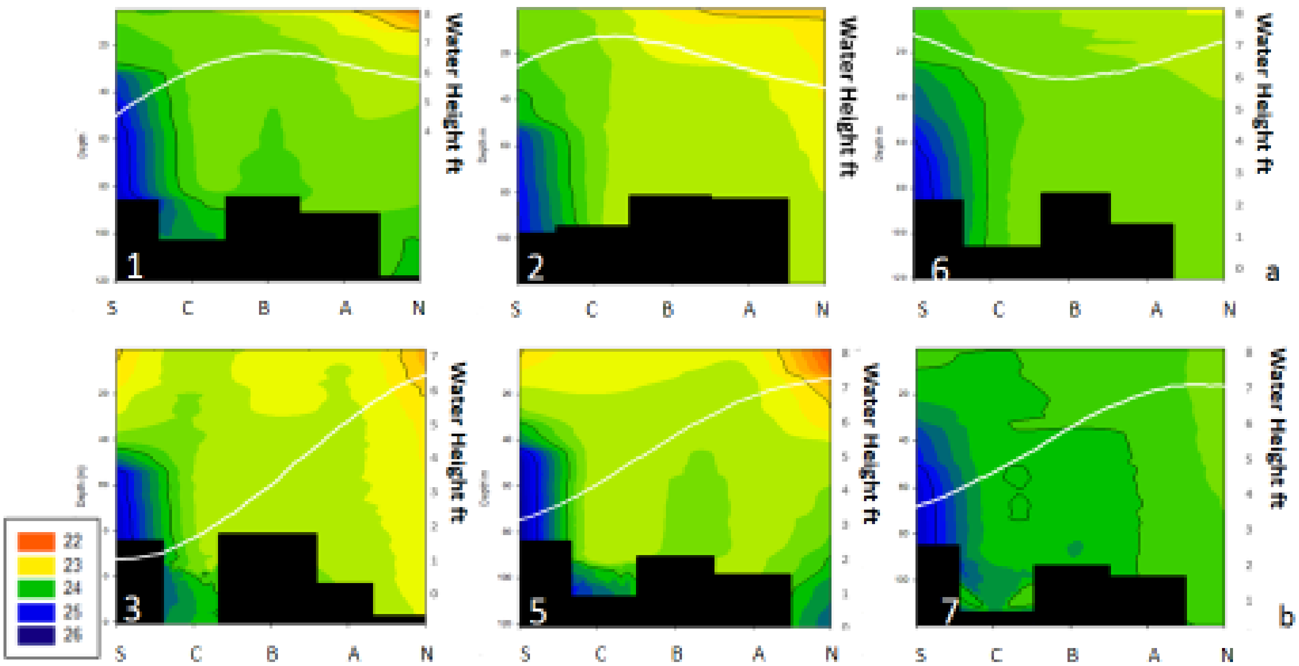


Figure 10: Contour plots of transect density are displayed on uniform scales with water height overlaid to represent the tidal curve. Low density is represented by warm colors and high density by cool colors and cruise number is indicated in the bottom left-hand corner. The first thing to notice is the disappearance of the low density signal in the northern channel. Second is the relationship between tidal curve progression and deep water intrusion –when South Station is sampled at slack low or on a flooding event (cruises one, two, three, five and seven), high density water is seen extending northward at depth. Conversely, cruise six, which was sampled between two slack highs, shows a restriction of deep, high density water to the southern channel. A) Spring tide cycle cruises. B) Neap tide cycle cruises; surface, low density signal is extensive, and apparent throughout the channel.

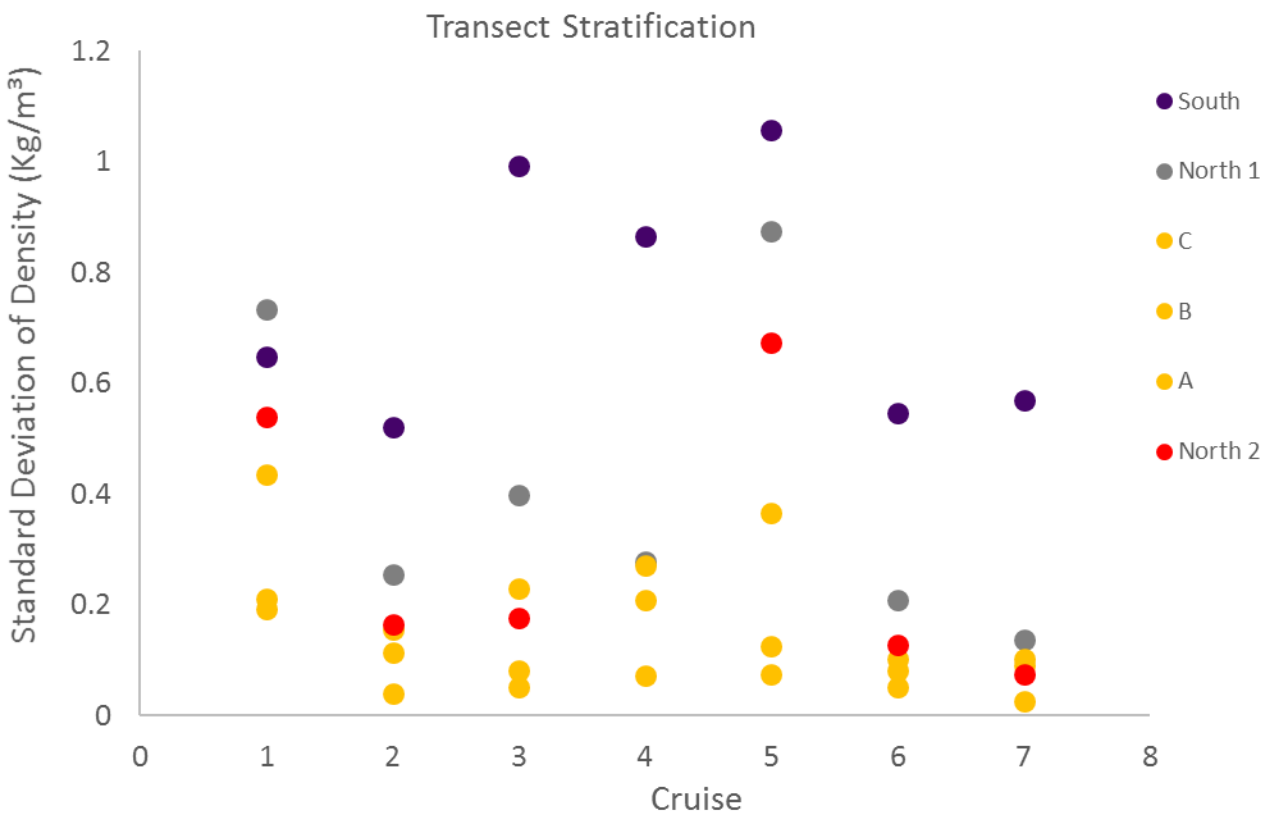


Figure 11: Transect Stratification is represented by standard deviation of density of each station for each cruise. North Station is represented twice, grey dots correspond to North One and red dots correspond to North Two. South Station is represented by purple dots, and the inner channel, stations C, B and A, are represented by yellow dots. Estuarine flow is evident in the high stratification values for South Station and the unusually high stratification values for North Station on cruises one and five. Inner channel stratification tends to be relatively close in value and there is a decreased gradient in stratification values after cruise five.

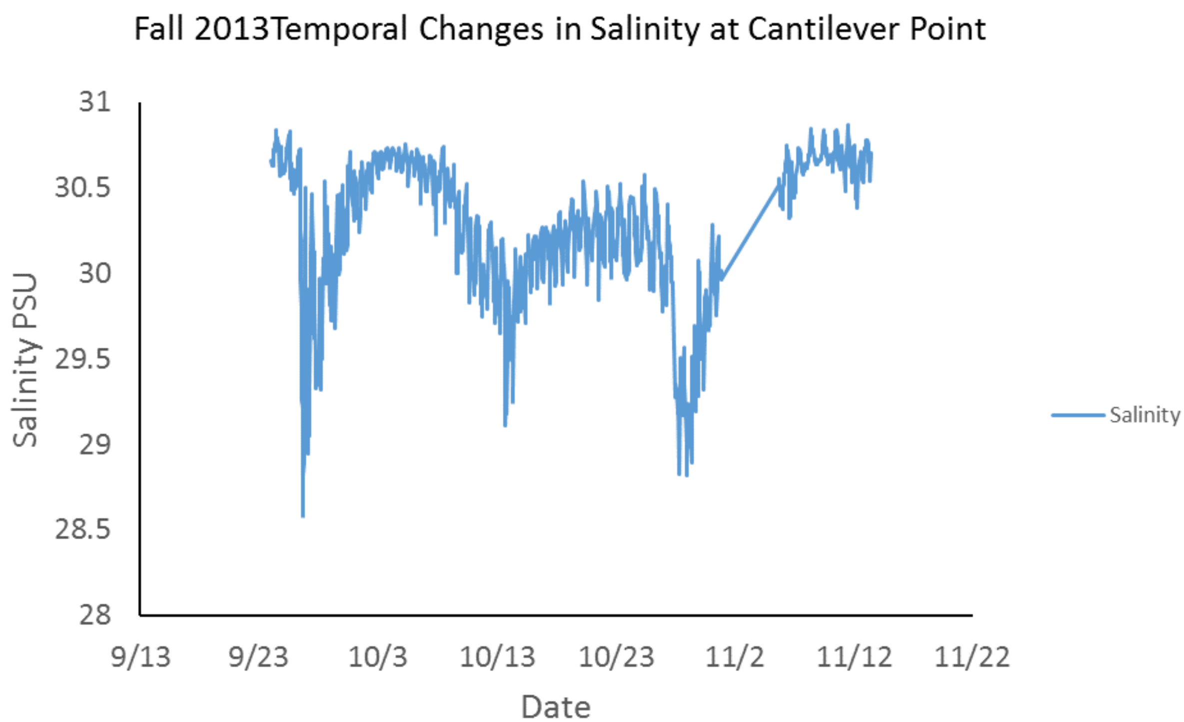


Figure 12: Provided by the Friday Harbor weather station, this graph shows salinity throughout fall 2013. There are three defining characteristics of this lot: 1) high frequency noise 2) fortnightly dips in salinity values and 3) changes in the peak salinity values.

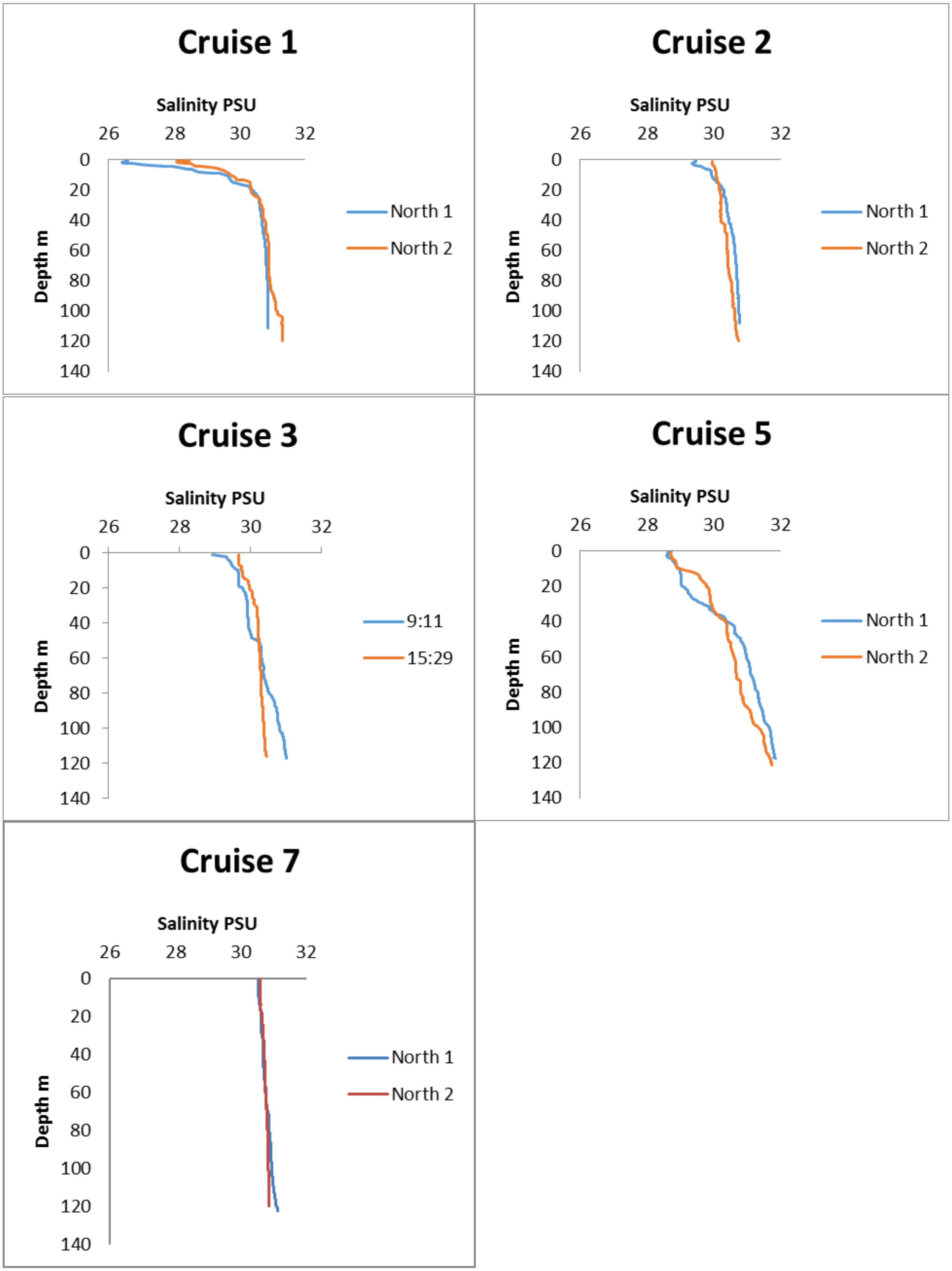


Figure 12: Salinity profiles of North One and North Two for cruise one through seven.

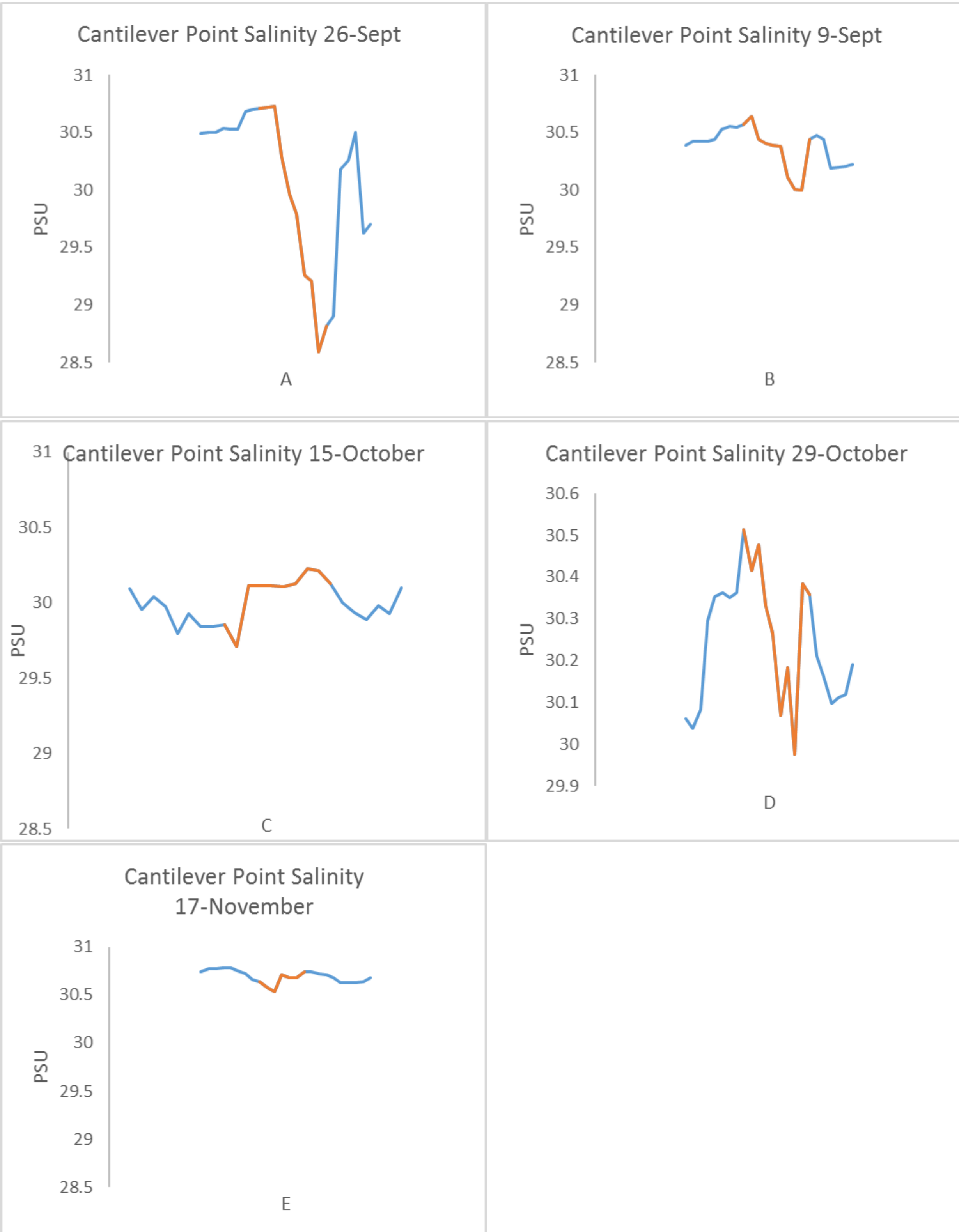
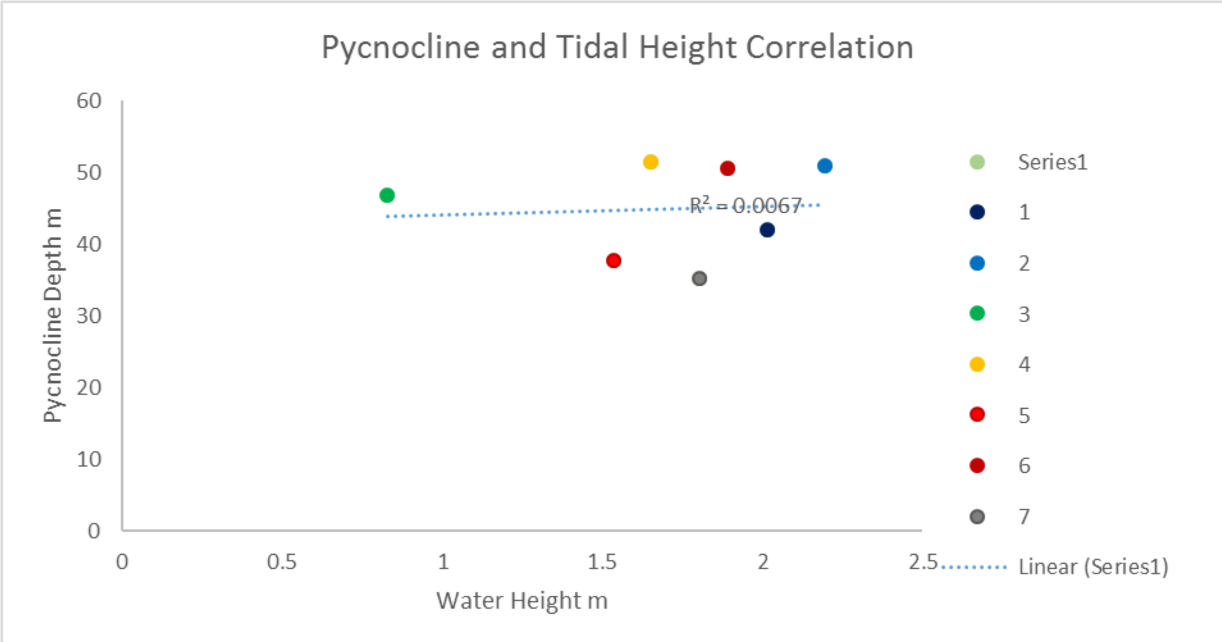
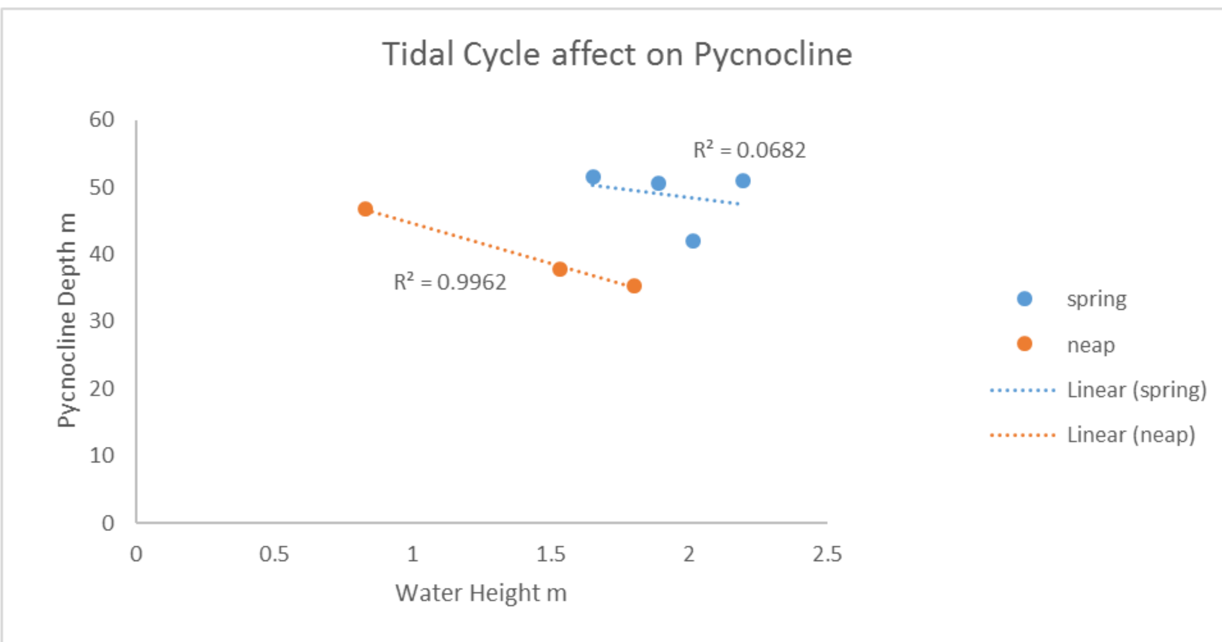


Figure 13: "Zoomed in" graph of surface salinity at Cantilever Point for the corresponding cruise day. The time between North One and North Two sampling is highlighted in red.

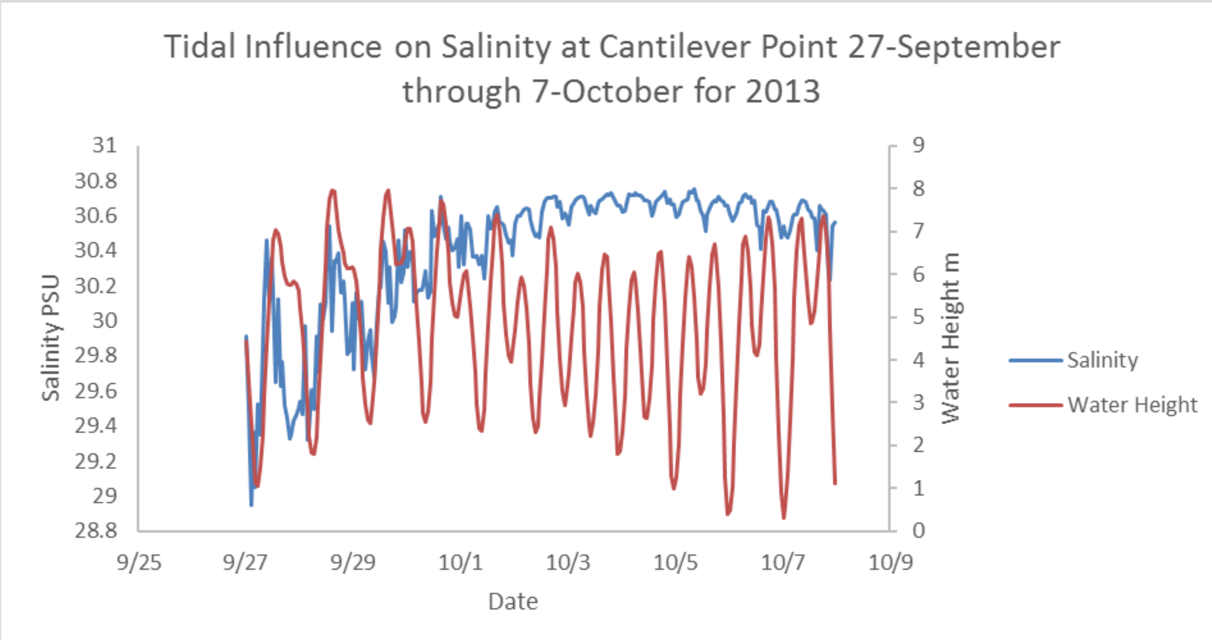


a



b

Figure 14: a) Tidal height and pycnocline depth showed no correlation this year. Cruise number is represented in the legened and the R^2 value corresponds to the relationship between all cruises and tide height, represented by series 1. b) When the cruises were grouped by tidal cycle (spring is blue and red represents neap), a correlation between neap tide's pycnocline depth and tidal height was found.



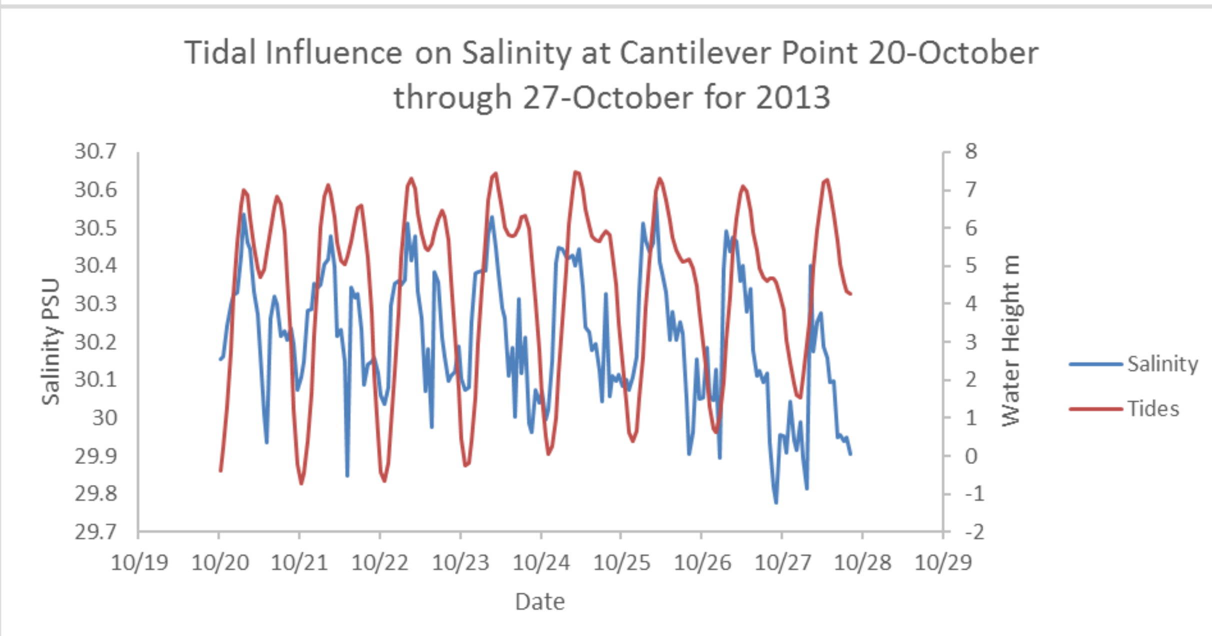


Figure 15: Tidal height over time was overlaid on surface salinity values at Cantilever Point over time revealing that tidal height highs corresponded with high salinity values and visa versus for tidal height lows.