Fine temporal scale sampling of tides, water masses, and seabirds

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ABSTRACT

The main driver of ecosystem processes in northern coastal ecosystems is tidal current. Previous Pelagic Ecosystems Functions projects have examined relationships of tidal current throughout the channel, but they were not able to document and quantify temporal patterns. My objective was to investigate the fine scale temporal changes of physical and biological factors over a flooding tide through repeated sampling over a short temporal scale. I did this through sampling water masses and seabird abundance. Oceanography results indicated sampling water masses on a fine temporal scale can reveal previously undetected inputs and tidal patterns. Seabird results showed strong temporal patterns in abundance in response to tidal phase in overall abundance and on the species level. These results suggest fine temporal scale sampling can quantify patterns in seabird response to tidal phase that could be used to calibrate coarse scale sampling methods. Based on these results, I suggest fine temporal scale sampling be used in future studies to determine tidal relationships between seabirds and tides.

INTRODUCTION

Effective ecosystem management requires a detailed understanding of the temporal and spatial processes linking physical and biological processes (Embling et al. 2012, Botsford et al. 1997). In the marine environment this is especially challenging since many of the processes involved are concealed from direct observation (Embling et al. 2012, Zamon 2003). Investigating complex interactions between physical drivers, prey, and predators requires the ability to make accurate predictions about the abundance and distribution of animals both in time and space.

The main driver of ecosystem processes in temperate coastal ecosystems is tidal current (Sharples et al. 2007, Zamon 2000, 2002, 2003). Tides affect the food web from primary productivity through the top predators. Tidal currents can aggregate prey and thus predators through interactions with bathymetry (Embling et al 2012, Genin 2004, Zamon 2002). The result of this relationship is a patchy distribution of both predators and prey based on tides. Though this relationship is well established, predicting where and how these patterns of distribution respond to tides has proven difficult due to the complexity of the relationship.

Building on Zamon's work (2003) demonstrating a relationship between tidal current speed and seabirds within south San Juan Channel (Cattle Pass), previous Pelagic Ecosystems Functions projects have examined relationships with tidal current throughout the channel (Navratil 2011, Palmer 2010, Clatterbuck 2009, Jennings 2007), but they did not show consistent temporal patterns.

The relationships may not have been clear because the methods used related samples with long time gaps between them. This type of sampling is not able to distinguish the fine-scale changes taking place in the biological and physical environment (e.g. Ladd et al. 2005, Hunt et al. 1998). Repeated sampling of both physical and biological elements over fine temporal-spatial scale can be used to correlate results to specific tidal phase condition (Embling et al. 2012, Bertrand et al. 2008, Robinson 2007). Using this sampling method it is possible to investigate tide phases, which incorporates both context and speed of the current so what has taken place before and after the time point sampled is considered.

My objective was to investigate the fine scale temporal changes of physical and biological factors over a flooding tide. I designed this study to incorporate repeated sampling over a short temporal scale and relate the results to tide phase. I focused on quantifying two factors: 1) water masses, and 2) overall seabird abundance. I also examined the way taxa with different feeding ecology respond to the flooding tide. This study is the first at this site to use fine-scale temporal sampling to quantify the relationship between seabirds and tide phase.

METHODS

Study Site and Tides:

I conducted this study during 24-29 October 2012 in the south end of San Juan Channel, Washington (Figure 1). This site was chosen because it is tidally active and experiences strong tidal currents during flooding tides. Predicted values for tidal current were obtained from the software program Mr. Tides 3 from the San Juan Channel Pear Point station. I assigned a value to each ½ hour sampling interval that corresponded to a tidal cycle. I divided the tidal cycle into eight tidal phases: slack low (SL), slow flood 1 (SF1), fast flood (FF), slow flood 2 (SF2), slack high (SH), slow ebb 1 (SE1), fast ebb (FE), and slow ebb 2 (SE2) (Figure 2). Categories were assigned based on relative current speed in relation to the predicted slack and max speeds on each day, not according to specific tidal current speeds (i.e. speed on FF varies based on daily max). Consecutive days within a one week period were sampled to minimize the effects of seabird migration and weekly tidal variation (Table 1).

Oceanography:

Changes in surface water masses (top 10-15 meters) over a fine temporal scale were measured through two methods: 1) a SBE 37 Temperature-Salinity (T-S) probe moored at 15 meters from the R/V Centennial held in a stationary position to record temperature and salinity at 5 second intervals, and 2) a Sea Bird Electronics (SBE) Conductivity-Temperature-Depth (CTD) sensor package, SBE 19, equipped with sensors for temperature, salinity (conductivity), and depth (pressure), to profile these variables over a depth of 10 meters at half hour intervals while deployed from a small boat (Figure 3).

For method 1, the moored CTD was deployed 25-October-2012 from the slow ebb to the fast flood. Method 2 was used from slack low tide to the fastest point of the fast flooding tide over three consecutive days. Sampling on two additional days increased coverage to one hour before and after these end points. The CTD was deployed at the south starting point of the strip transect (48° 28' 14.88", 122° 57' 35.28") (Figure 2).

Seabird Abundance:

On one occasion (25-October-2012) a point sampling method was used to determine the changes in abundance at a finer time scale at one location. Surveys were conducted on ten-minute intervals from the slack low to the fast flooding tide. All birds within a 300-meter radius around the boat were counted and identified to species when possible.

Seabird abundance was primarily measured using the strip transects method. Surveys were conducted from small boats running at a constant speed of 10 knots. All birds within 200 meter of the boat on either side were counted and identified to species level. Strip transects ran south (48° 28' 14.88", 122° 57' 35.28") to north (48° 30' 59.40", 122° 57' 55.22").

Surveys were only conducted when the whole transect was clearly visible and free from fog with relatively calm seas (Beaufort Sea State ≤3).

Data analysis:

Stationary T-S measurements

Temperature and salinity were processed with SBE Data Processing software, then graphed in relation to time using Microsoft Excel for the entire moored period. Also, temperature was plotted versus salinity (a T-S plot) to evaluate water mass changes.

CTD Profiles:

Contour plots of both temperature and salinity depth profiles over time were made using SigmaPlot (Version 11.0) to examine variation over the flooding tide at half hour intervals.

Seabird Surveys:

Seabird abundance was measured as density (individuals/km^2) on each individual survey. Mean density was calculated for each half hour transect and each day was analyzed individually. For the four survey dates with consecutive transects covering the entire flooding tide (24-October, 25-October, 26-October, 28-October) I averaged the series of surveys taken between slack low and max. I only analyzed birds within the gull and alcid families. Other birds were in extremely small numbers and the vast majority of these present were traveling through. For these reasons I determined they would not be representative of how the study site was being used by seabirds in response to the tide phase. Densities were calculated for six seabird species: Glaucous-winged Gull (GWGU), Heerman's Gull (HEEG), Mew Gull (MEGU), Bonepartes's Gull (BOGU), Common Murre (COMU), and Rhinoceros

Auklet (RHAU). Marbeled Murrelet (MAMU) and Ancient Murrelets (ANMU), the next two most abundant alcids, were excluded from this analysis due to the fact that the ANMU migration into the San Juan Channel took place around 26-October-2012, directly in the middle of my sampling period. Possible identification error between the two murrelet species led me to also exclude MAMU as well.

RESULTS

Oceanography:

Stationary T-S measurements

The stationary T-S measurements showed a change in water properties from the end of the ebbing tide to the fastest point of the flooding tide. The response was seen in both temperature (Figure 4) and salinity (Figure 5). The degree of spiking in the signal can be used as a proxy for water mixing. The end of the slow ebbing tide showed moderate spiking of both signals, followed by a period of stable readings that coincided with the timing of the slack low tide, implying little to no mixing. Increased spiking, possibly indicating turbulence was observed as the flood tide began. This was followed by a distinct pulse of lower density water (warmer, lower salinity) and then a longer period of higher density water (colder, higher salinity) with significant spiking (turbulence). The T-S plot shows two primary water masses that are mixing along a line, with an intermediate kink in the observed data points indicating influence of other water masses (Figure 6).

CTD Profiles

During the flooding tide surface waters changed in a similar pattern as that observed in the stationary data. The contour plot of surface change over time on 24-October-2012 has little temporal variation in temperature or salinity (Figure 7a and Figure 7b) however, there are two slight pulses of warmer water which move through the channel with the flooding tide (Figure 8a and Figure 8b). The contour plot from 25-October-2012 had patterns similar to those seen in the stationary CTD readings, which were taken on the same day (Figure 9a and Figure 9b). There is a less dense water mass pushed in front of the flooding tide followed by a more dense water mass which corresponds to the start of the fast flood. The 26-October-2012 contour plot shows a pulse of less dense water at the beginning of the flooding tide and another one right before the fast flooding current (Figure 10a and Figure 10b). The contour plot from 29-October-2012 shows a pulse of less dense water at the end of the ebbing tide and another pulse of denser water preceding the increase to fast flood.

Seabirds:

Stationary Count

Seabird abundance changed markedly as the tidal cycle progressed. Numbers were low (<40/km^2) during the end of the ebbing tide and the slack low (Figure 11) but began to increase steadily at the end of the slack low. Density peaked (>160/km^2) just before the start of the fast flood and then decreased to moderate levels during the fast flood.

Small Boat Strip Transects

Comparison of total seabird abundance on all transects over all five days of surveying showed a consistent pattern related to tide phase (Figure 12). Abundance was lowest on slack low and increased with increasing current speed. Abundance was highest on the fast flood tide, though the timing of the highest point varied by 0.5 hour between days. Just after the fast flood when the current speed started to decrease (slow flood 2) abundance remained high for one transect before beginning to drop off. Although based on fewer surveys, the ebbing tide showed a similar pattern with seabird abundance decreasing as the current speed decreased.

This correlation of abundance and tidal phase was observed for all seabirds regardless of their feeding ecology. Mean abundance increased consistently over the flooding tidal phases for both divers (alcids) and surface feeders (gulls) (Figure 13a). The timing of the start of the increase was slightly different between the two feeding groups. Gull numbers began to increase one half hour before alcids began to increase.

The same general pattern was exhibited at the species level but there were detectable differences among the numerically important species (Figure 13b). All four predominant gull species increased in number after the slack , but the increase was less pronounced among the larger gull species (GWGU, MEGU, and HEGU); density at peak was only 2-4 times higher than at the slack low. In contrast, the smallest species the BOGU increased dramatically and was 20 times more abundant at peak at the start of the fast flood phase. Three of the four gull species (all except the GWGU) began to decline in number later in the flooding cycle.

Timing of the response to tide phase also differed between the two large alcid species (Figure 13c). Rhinoceros Auklets were present in moderate densities (>8/km^2) during the slack. Their numbers started to increase early in the flooding cycle and then peaked at 30/km^2 during the fast flooding tide. Common Murres were scarce (<5/km^2) from slack through the first two hours of the flood before rising quickly to peak numbers (25-45/km^2) during fast flood., On the one day of sampling extending after the max flood COMU remained in high numbers (100-110/km^2) after the tidal current began to slow, while RHAU decreased in number by 40%.

Species level analysis of each day surveyed showed patterns consistent with mean densities on four of the five days (Figure 14a-j). On one day, 29-October-2012, BOGU were present in high numbers throughout the slack low and slow flooding tides (65-140/km^2) (Figure 14i), where on all other days BOGU density was low (<40/km^2) during comparable tidal conditions. This increase is not mirrored in any of the other species.

DISCUSSION

Temporal Patterns in Physical Oceanography:

Both the stationary T-S measurements and the CTD depth profiles revealed measurable changes in temperature and salinity over short time periods in association with the tide. These changes, including the influx of warmer fresher water, would have been missed using coarser scale temporal sampling on the scale of a daily sample. I had two hypotheses for how water masses would mix through the flooding tide. The first was that the change happens abruptly. In this hypothesis the flooding tide comes through as a sharp front where a new water mass replaces the old one. My second hypothesis was the change is gradual. In this case the water would mix evenly and slowly together over the course of the flooding tide. My results revealed the water masses during the flooding tide mix in a pattern that does not follow either of my hypotheses, but is instead a combination of both.

The stationary T-S sampling data showed there is a relationship between water mass change, as seen in temperature and salinity variation, and tide phase. Three distinct water masses could be distinguished moving through the study site at the surface level. There was a water mass of intermediate temperature and salinity, followed by a fresher, warmer water pulse of unknown origin preceding an influx of saltier, colder water from the Strait of Juan de Fuca coming in on the flooding tide. This pattern suggests there is a leading edge to the tidal front, delineated by the warmer, fresher water pulse. This feature may travel up the channel over the flooding tide indicating the mixing pattern at the study site has an abrupt edge. After this front travels through, the spiking within the temperature and salinity signals and the linear relationship between these two variables indicates the denser water associated with the flooding tide mixes gradually with the water in the channel. The similarity between the contour plot of the CTD profiles over the flooding tide on 25-October-2012 and the stationary T-S readings taken at one depth confirms that the pulse of warmer, fresher water is not a false reading, since two independent instruments were used.

Similarly, the reappearance of this feature on other days also confirms it as a distinct water mass being pushed in by the flooding tide. Contour plots of all four days showed the water column within the surface layer is extremely well mixed vertically but varied through time and tide phase. There were pulses of fresher, and typically both warmer and fresher, water seen on all four days surface profiles were collected. The data from 24-October-2012 had warmer temperatures that were more consistent throughout the flooding tide than of the other three days. On this day a feature was only barely seen in the salinity below 5 m. The surface CTD profiles taken on 25-October and 26-October-2012 showed similar patterns, both with pulses of warmer, fresher water coming in on the flooding tide followed by colder, saltier waters. On the 25th the warmer, fresher water pulse was only seen once, while on the 26th it occurred twice. This could be due to the water mass swirling back around as it enters the wider north mouth of Cattle Pass, such as in a tidal eddy.

The origin of the warmer, fresher feature in the leading edge of the flooding tide is not certain. We know from other data collected as part of the PEF study that the water mass was not coming from the north, but rather from the south. This warmer, fresher water pulse entering the channel from the south may actually be an influence from the Columbia River plume (Parker MacCready, UW, personal communication 2012). MacCready's numerical model shows that during the fall and winter seasons the Columbia River plume is pushed north along the coast extending up into the Strait of Juan de Fuca (Figure 15). While other Puget Sound river inputs are also possible sources, the Frasier River plume is not.

The fresh water pulse seen on the ebbing tide on 29-October-2012 is likely from Frasier River Plume since it is earlier in the tide phase and coming from the north. Influence from the Frasier River plume is known to extend into the south end of the channel on ebbing tides (Kull 2008).

Previous PEF studies (e.g., Thomas 2011) have shown a strong variation in water masses based on tides in this region, however, this work typically focused on the deeper water observed features at South and other stations (C, B) north of Cattle Pass and was taken on a coarser (i.e. weekly) temporal scale (Thomas 2011, Thomson 1994). The finer temporal scale sampling of water masses used here (i.e. continuous to every 30 min) yielded a fuller picture of how change occurs as the tide moves through. This sampling method can detect short-lived water features that seabirds and other predators may be responding to. The nutrient and prey concentration within the low density (fresher, warmer) feature of the tidal front, as well as within the denser flooding tide waters from outside the channel may reveal more information as regards what predators may respond to. The source of the low density feature, whether Columbia River or Puget Sound rivers, should be further investigated to better understand linkages within regional water masses.

Temporal Patterns in Seabird Abundance:

By measuring change in abundance as a time series over a short time frame it was possible to document and quantify patterns relating to changes in tidal conditions. Because tides are complex and it is problematic to ground-truth predicted tidal conditions for a given site, individual seabird surveys taken on different days are extremely difficult to compare even when at the taken at the same predicted tidal conditions (Spatz 2007). My results showed fine temporal scale sampling can be an effective method for overcoming this difficulty since it captures a temporally based pattern rather then a single snap shot. The sampling method used in this study maintains the temporal relationship between individual transects, making it possible to compare abundance pattern across days and different tidal conditions. This gave a greater level of resolution not possible in pervious studies that only sampled once per day.

My results reveled strong tidal relationships between seabird abundance patterns and tides. This pattern was suggested but not documented clearly with coarser scale sampling (Eisenlord 2011, Palmer 2010, Wang 2008, Spatz 2007). Total seabird abundance varied consistently over flooding tides over all days and both survey methods, showing a strong pattern of increasing abundance as the current increased to max flood. This suggests that birds follow a repeated and predictable pattern in response to the tidal cycle that can be quantified with fine time scale (i.e. hourly) sampling methods. The timing of the increase in abundance seen in the one-day stationary seabird count coincided with increased turbulence and the influx of a colder, saltier water mass seen in the moored CTD temperature and salinity readings. Seabirds are highly mobile animals so aggregations can form and disappear rapidly as prey availability changes (Vleistra 2005, Coyle et al. 1992), making one-location counts a poor measure of abundance. The decrease in seabird abundance observed at the end of the sampling is likely due to the limitations of sampling at one location.

The patterns found in this study are congruent previous studies showing aggregations of seabirds correlate with availability of prey (Vlietstra 2005, Coyle et al. 1992). In tidally complex coastal regions this related to tides increasing access to prey through interactions with bathymetric features (Zamon 2003). In Cattle Pass prey availability is highest during fast moving, flooding tides that force plankton and bait fish into the water column (Zamon 2000). Further, flooding currents have been found to concentrate plankton and bait fish inside Cattle Pass where my study site is located (Zamon 2000). Seabirds are thought to move south out of the pass during fast ebbing tides, probably following the prey during fast ebbing tides (Spatz 2007). Better foraging opportunities elsewhere may account for the low seabird abundance I found during the slack.

Differences in the way different types of seabirds responded to changes in tidal phase were able to give increased resolution important to interpreting overall abundance patterns. The earlier response seen in gulls (surface feeders) compared to alcids (divers) is likely due to their faster response to short lived surface feeding opportunities. Seabirds adjust foraging behavior in response to feeding flocks of other birds (Davoren et al. 2003) and the predictability of prey aggregations (Irons 1998), and differences in these behaviors are based on feeding ecology. Even relatively small differences in timing of response (1/2 – 1 hour) I observed between gulls and alcids birds could have a large impact on assessments of distribution and abundance. This is also important in understanding how predators are responding to prey availability.

Looking at the differences in the response to tidal phase on the species level was able to clarify the cause of the higher numbers of birds seen throughout the slack on the last sampling day. The presence of a large flock of BOGU is driving this divergence from the overall pattern. All other birds remained in low number during the same time. This anomaly is likely due more to behavioral changes in BOGU than a significant change in the physical conditions.

Marked differences between some of the numerically important species were also seen. Between the two alcid species there were pronounced differences in the response to changes in tidal conditions. RHAU showed a pattern of increase that suggests they follow the leading edge of the flooding tide and travel with it up the channel respond to leading edge, while COMU wait for conditions to be optimal to enter the channel and are only present in large number when turbulence is highest. This conclusion is supported by the abundance patterns seen on the two days where I was able to sample seabird abundance directly before and after the flooding tide. RHAU abundance increases and decreases in relation to the tidal current speed, but COMU increased only when the flood was reaching its max, and remain in high numbers after the flooding tide began to slow.

This result is consistent with other studies demonstrating that COMU return to prey hot spots (Davoren et al. 2003) and their foraging behavior correlates with oceanic processes that concentrate prey (Coyle et al. 1992, Parrish and Zador 2003) and higher prey abundance (Vleistra 2005). My results suggest that, as turbulence and prey availability within the study site increased, COMU preferentially relocated from another area to take advantage of the optimal feeding condition presented. RHAU on the other hand have not been shown to select for optimal conditions (Vleistra 2005), which is also consistent with my finding: they seem to travel with the current. These results show that even with species of similar size and feeding ecology there can be behavioral differences in fine temporal scale that could significantly affect survey result.

Conclusions:

In this study I was able to show fine temporal scale sampling (i.e. on half hour intervals) is an effective method to measure changes in water masses and seabird aggregations in relation to changes in tidal conditions. Water mass sampling showed evidence for a frontal edge preceding the period of max turbulence. This lower density fresh water signal may be coming from the Columbia River Plume being pushed through the Strait of Juan de Fuca on the flooding tide in front of a higher density water mass of oceanic water. While modeling results show this influence, this is the first time a possible influence from the Columbia River plume has been reported in the San Juan Channel based on observations. Sampling seabird abundance repeatedly over a fine temporal scale showed a consistent relationship with tidal phase not quantified in previous studies. The specific timing of tidal response differed by species based on feeding ecology, but in all cases abundance varied consistently from slack to max flood tide likely in response to increased feeding opportunities.

Fine temporal scale sampling at other locations and tidal conditions has the potential to help establish mechanistic explanations for seabird abundance. This is interesting ecologically, but may also help provide increased accuracy in conducting population assessments of seabirds. Since seabird abundance can change rapidly, coarser scale temporal sampling may not be representative of actual abundance. By conducting sampling on a fine temporal scale, such as the one used in this study, it may be possible to calibrate coarser scale samples. This may be applied to long term PEF dataset of weekly survey in the San Juan Channel to improve their accuracy in forecasting population trends. This work also has larger implications, as effective management of marine ecosystems, from the top trophic levels down to the lowest, depends on the ability to make predictions. Fine scale sampling is needed to establish coupling between biological and physical factors, which has been identified as a knowledge gap in ecosystem-based fisheries management and studies of trophic ecology (Embling et al. 2012, Botsford et al. 1997). This is especially important in tidally complex coastal ecosystems.

The methods presented here were successful in quantifying temporal changes in water masses and seabird abundance based on the tidal cycle. Further research is needed to establish patterns of fine scale temporal change over the whole tidal cycle and between different tide conditions. I believe fine temporal scale sampling is a powerful tool for studying the how marine prey and predators use their environment and are influenced by it.

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FIGURES AND TABLES

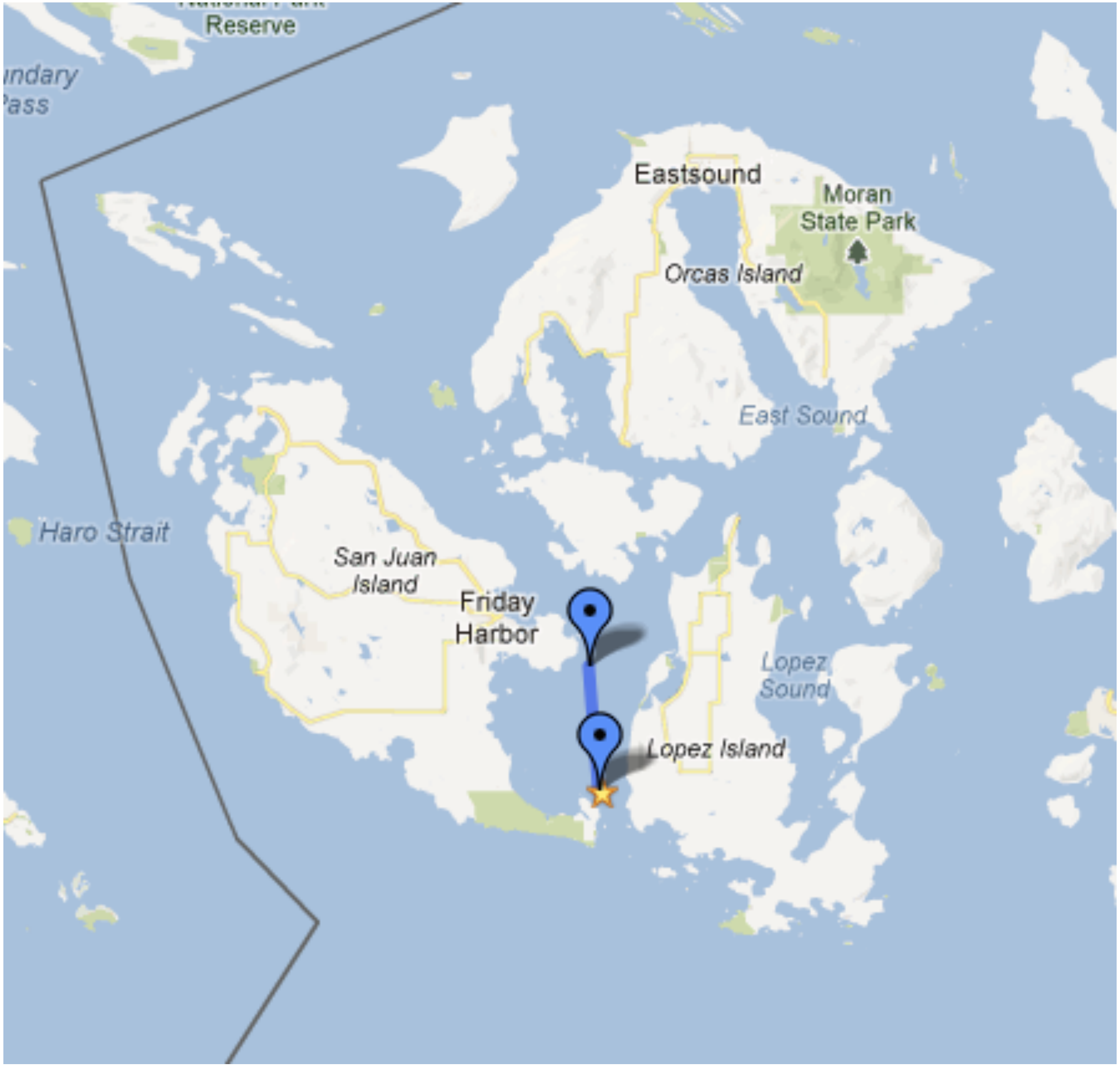


Figure 1: The Study Site was located in the south end of the San Juan Channel, Washington.

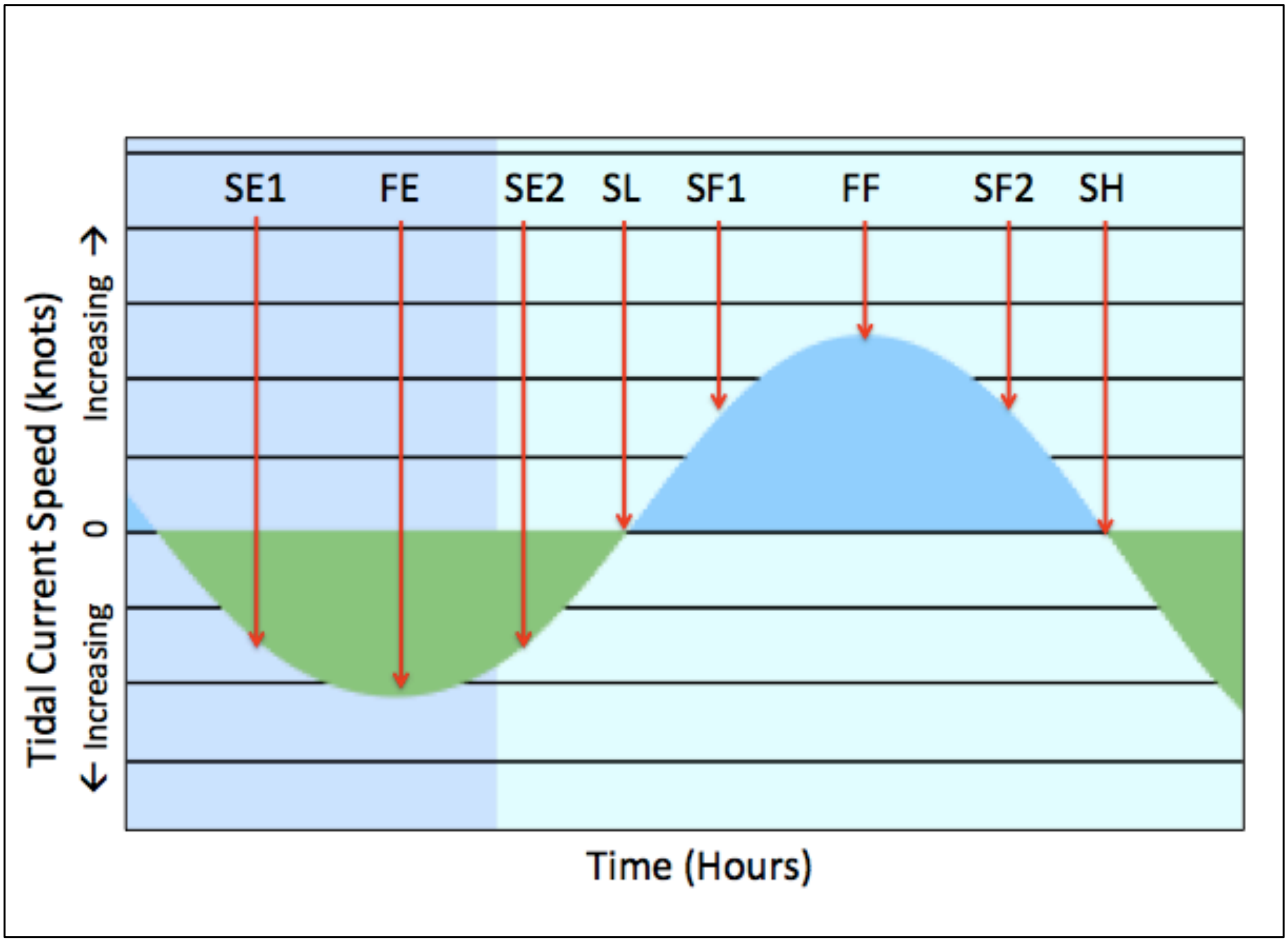


Figure 2: Eight tide phases covering the full tidal cycle. Phases were determined based on the time of slack and max flood on individual each day.

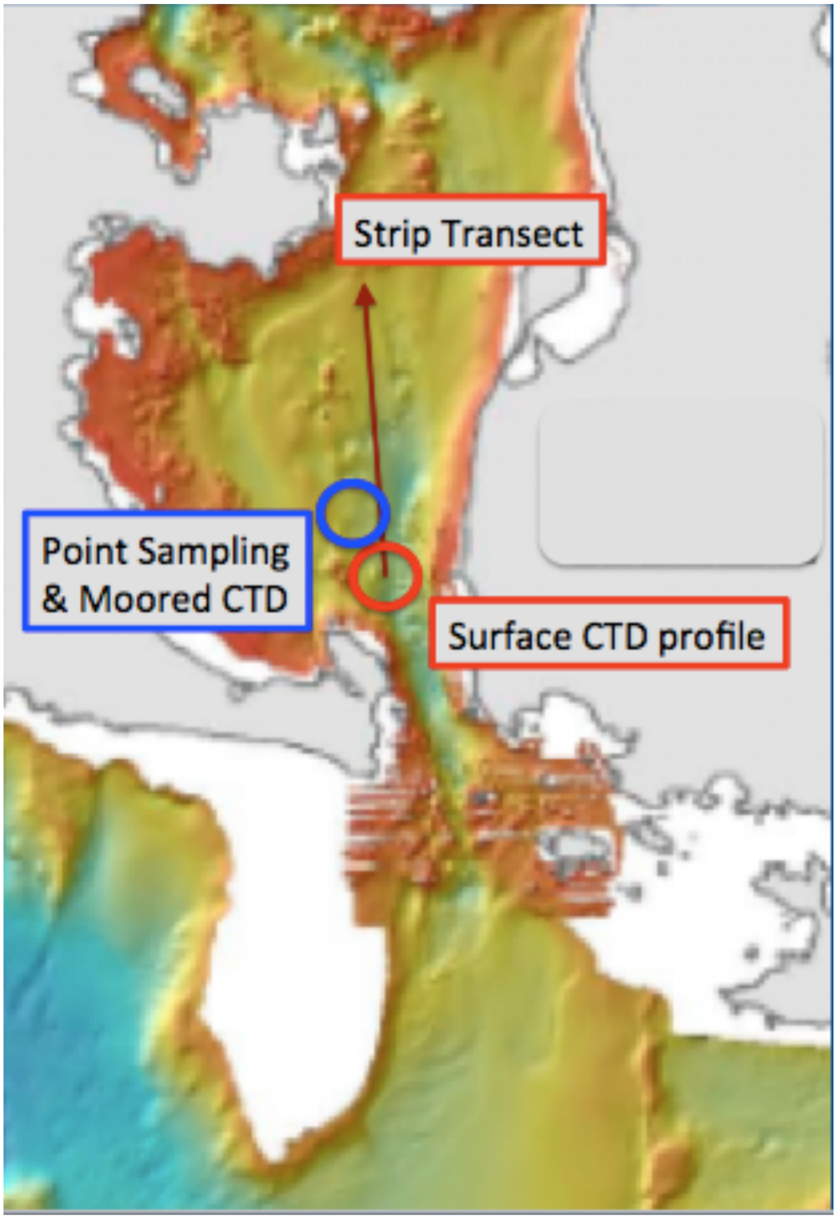


Figure 3: Bathymetric map of study site showing locations of methods used to sample change over a fine temporal scale.

Date	# Transects per day	Tide Phase Covered
24-Oct-12	7	Slack Low – Fast Flood
25-Oct-12	8	Slow Ebb 2 – Fast Flood
26-Oct-12	8	Slow Ebb 2 – Fast Flood
28-Oct-12	10	Slow Ebb 2 – Slow Flood 2
29-Oct-12	8	Slow Ebb 2 – Slow Flood 1

Table 1: Small boat transect dates, number of consecutive transects completed each day, and tide phase covered.

Tide Phase: Slow Ebb 2 → Slack Low → Slow Flood ---------------→ Fast Flood ---→

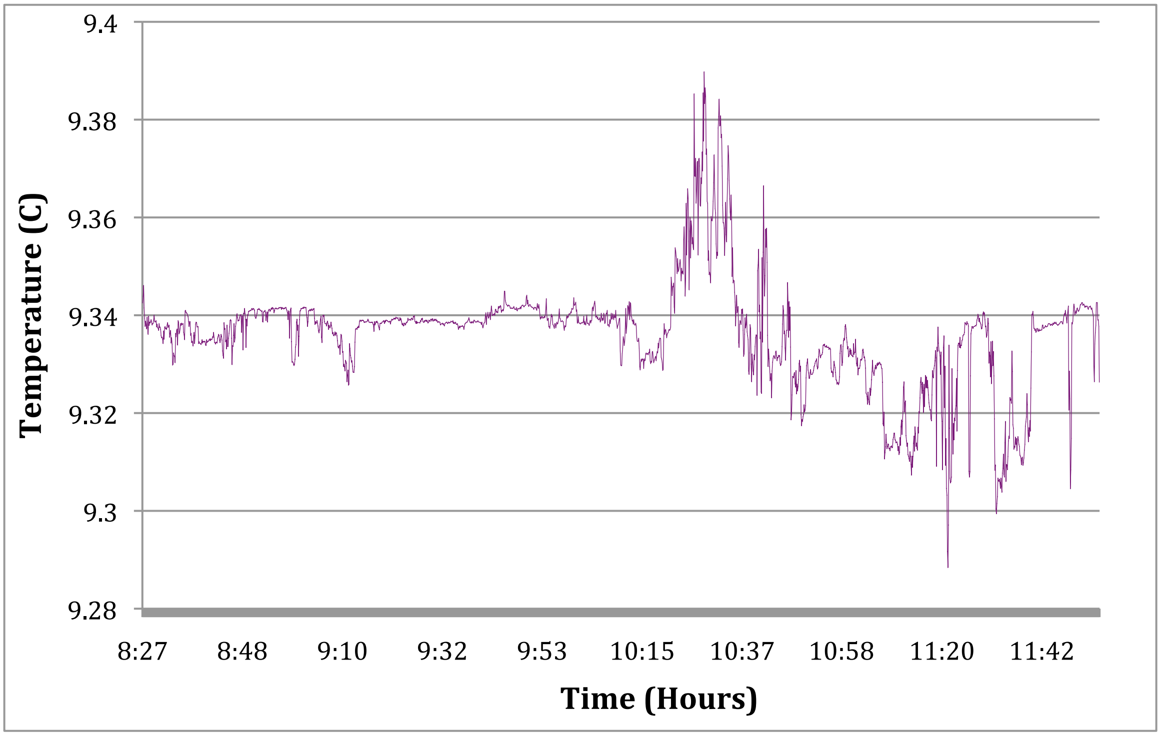


Figure 4: Stationary CTD temperature reading for the tide phases covering slow ebb 2 through fast flood. Tide phase shown at top of graph.

Tide Phase: Slow Ebb 2 → Slack Low → Slow Flood ---------------→ Fast Flood ---→

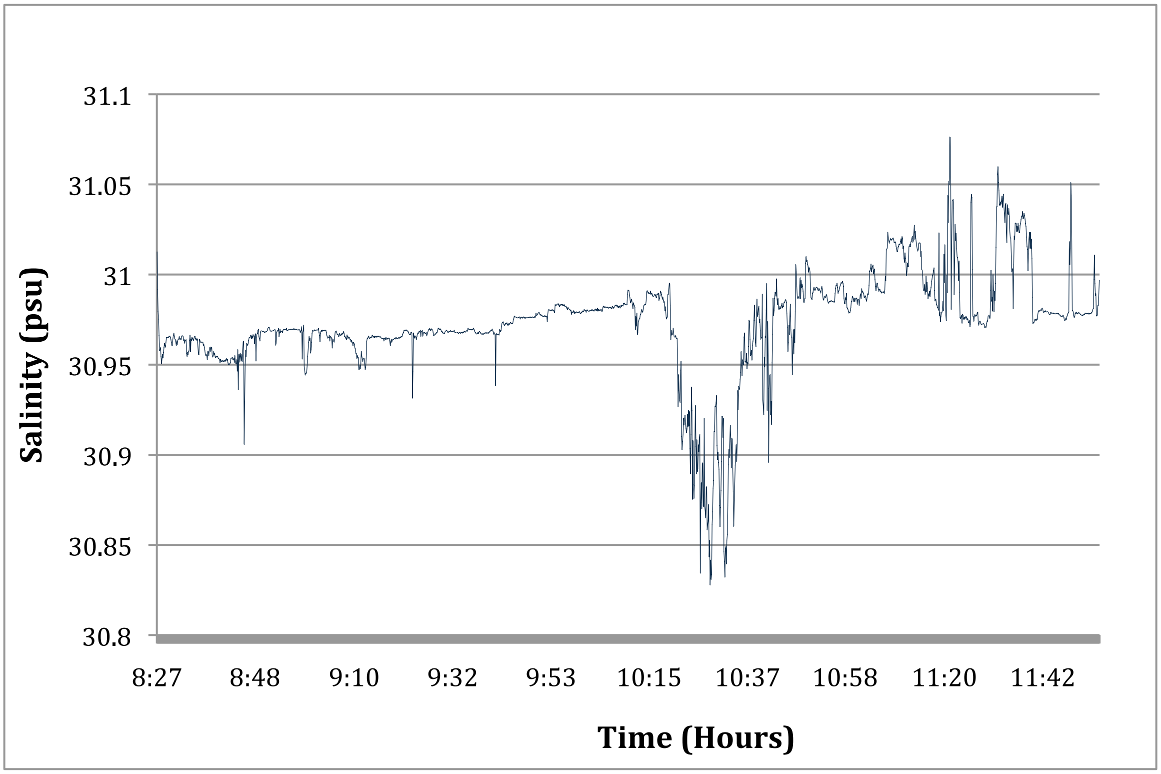


Figure 5: Stationary CTD salinity reading for the tide phases covering slow ebb 2 through fast flood. Tide phase shown at top of graph.

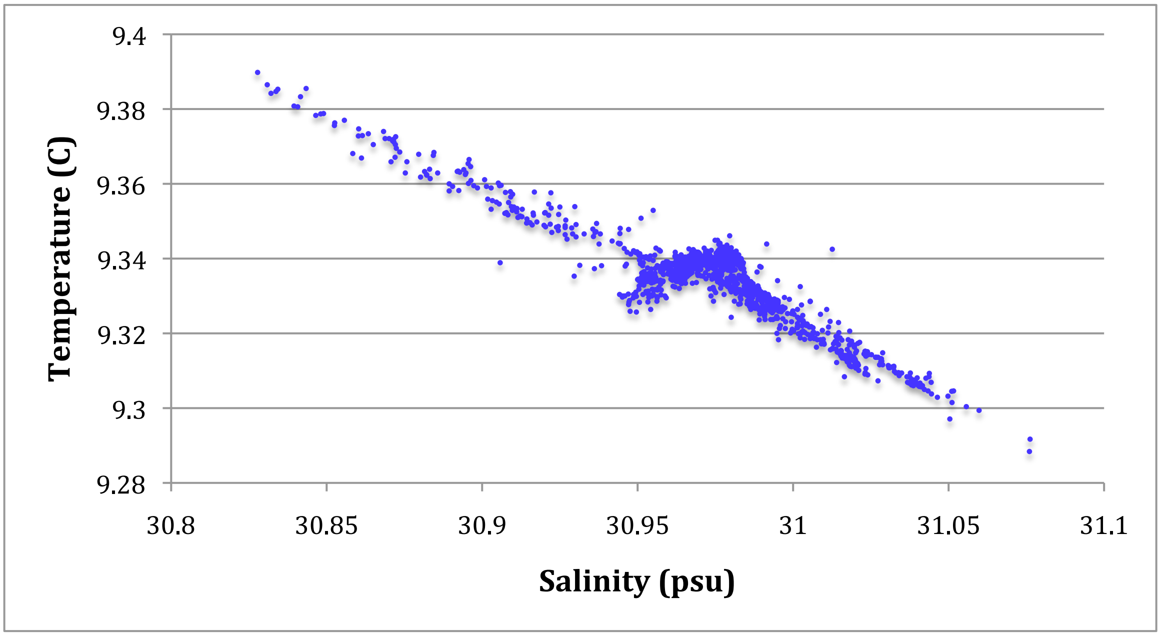


Figure 6: Stationary CTD T-S (temperature and salinity) plot showing water mass change over the flooding tide (slow ebb 2 – fast flood).

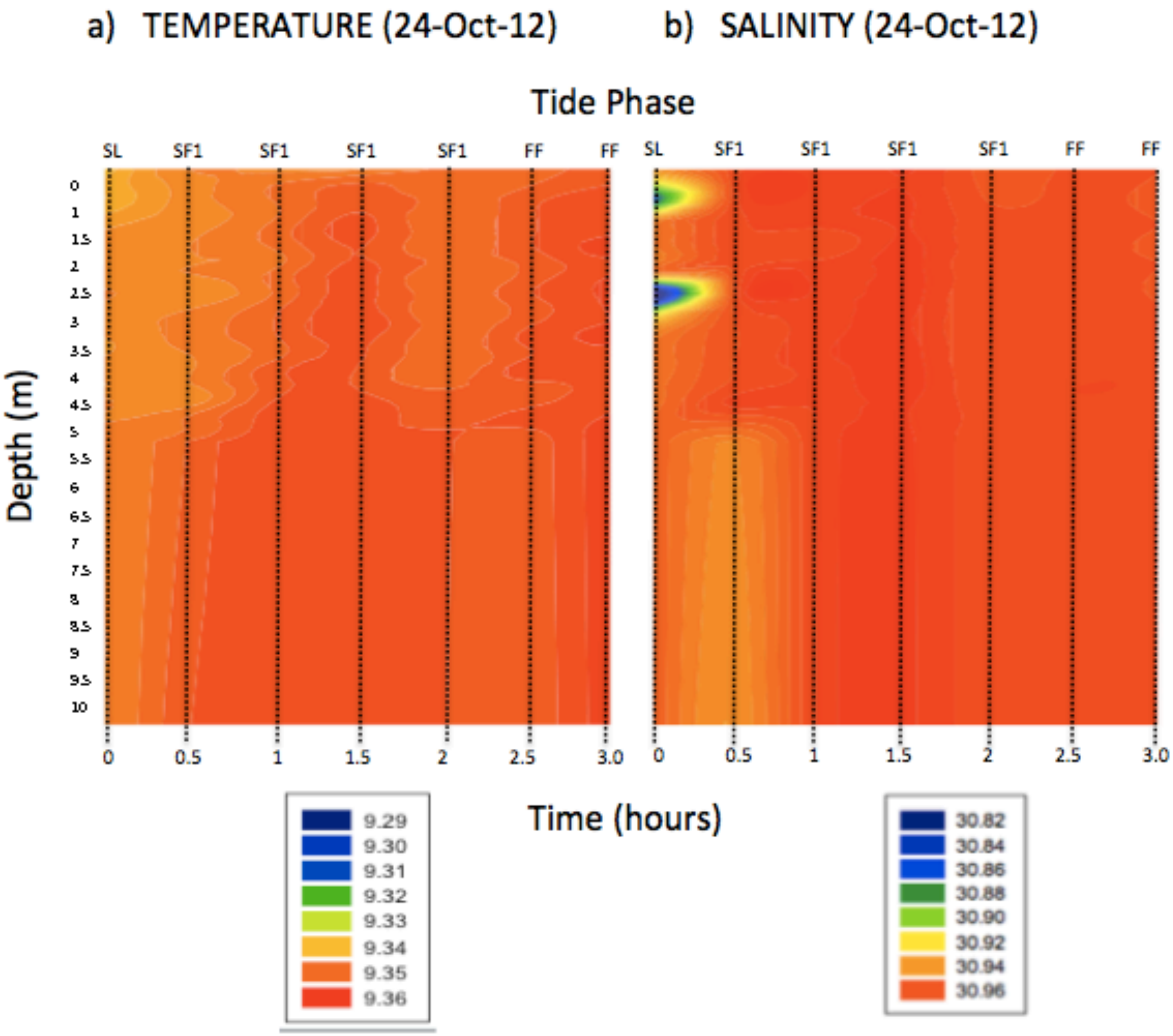


Figure 7. Contour plots of temperature (a) and salinity (b) showing temporal change in the surface water (10-meter depth). Profiles were taken at half hour intervals from the end of slow ebb 2 through fast flood on 24-October2012.

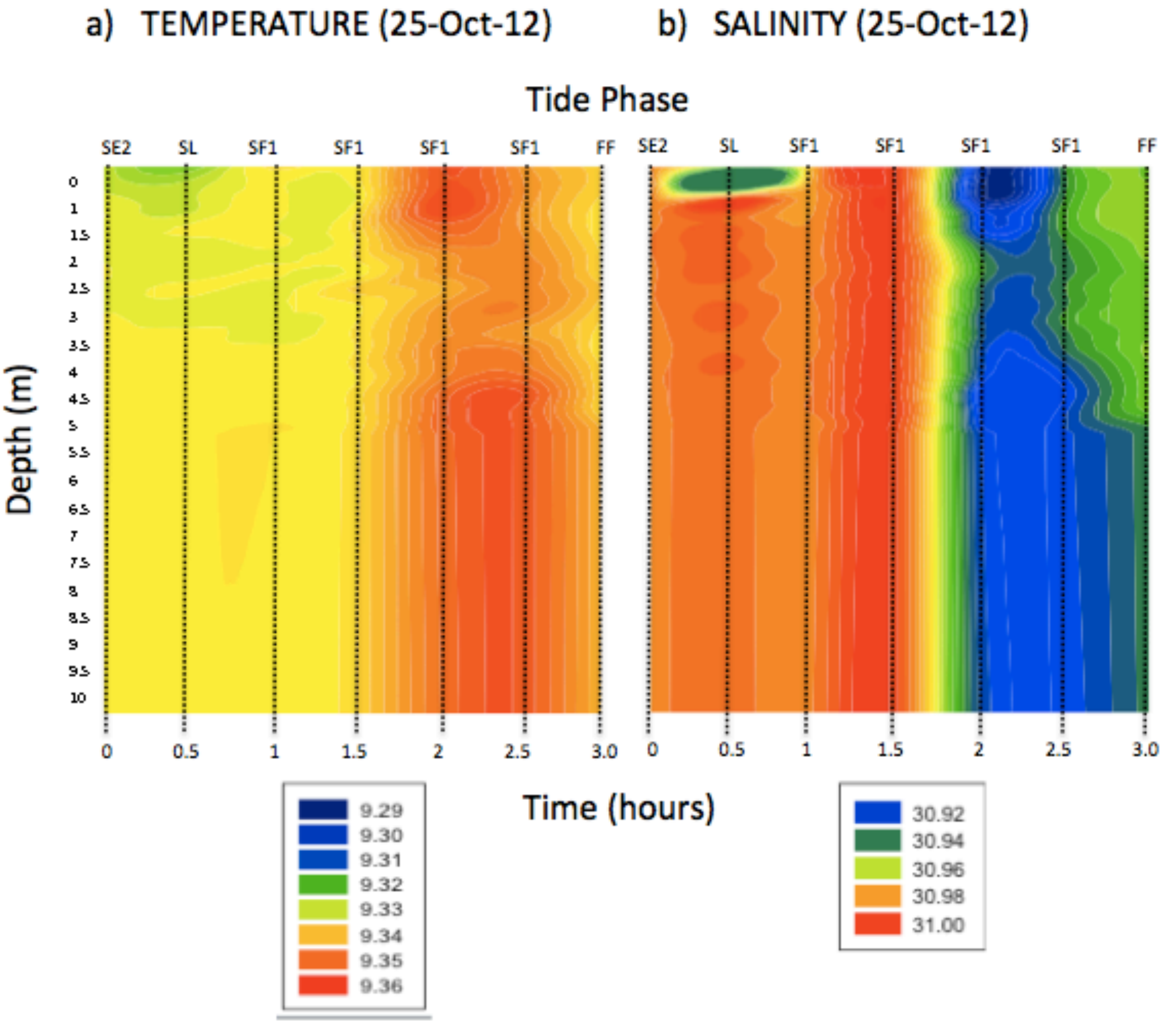


Figure 8. Contour plots of temperature (a) and salinity (b) showing temporal change in the surface water (10-meter depth). Profiles were taken at half hour intervals from the end of slow ebb 2 through fast flood 25-October-2012.

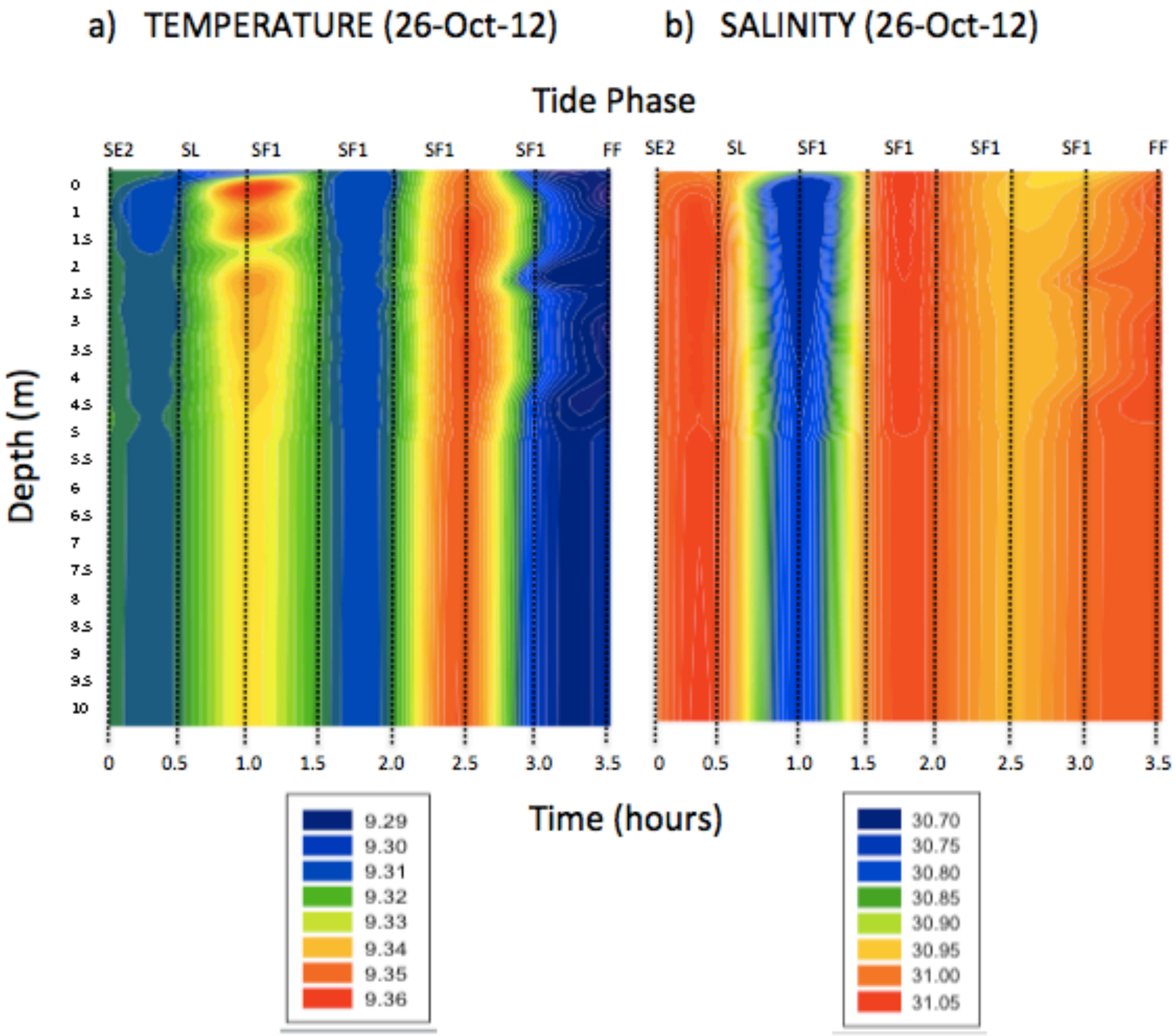


Figure 9. Contour plots of temperature (a) and salinity (b) showing temporal change in the surface water (10-meter depth). Profiles were taken at half hour intervals from the end of slow ebb 2 through fast flood on 26-October-2012.

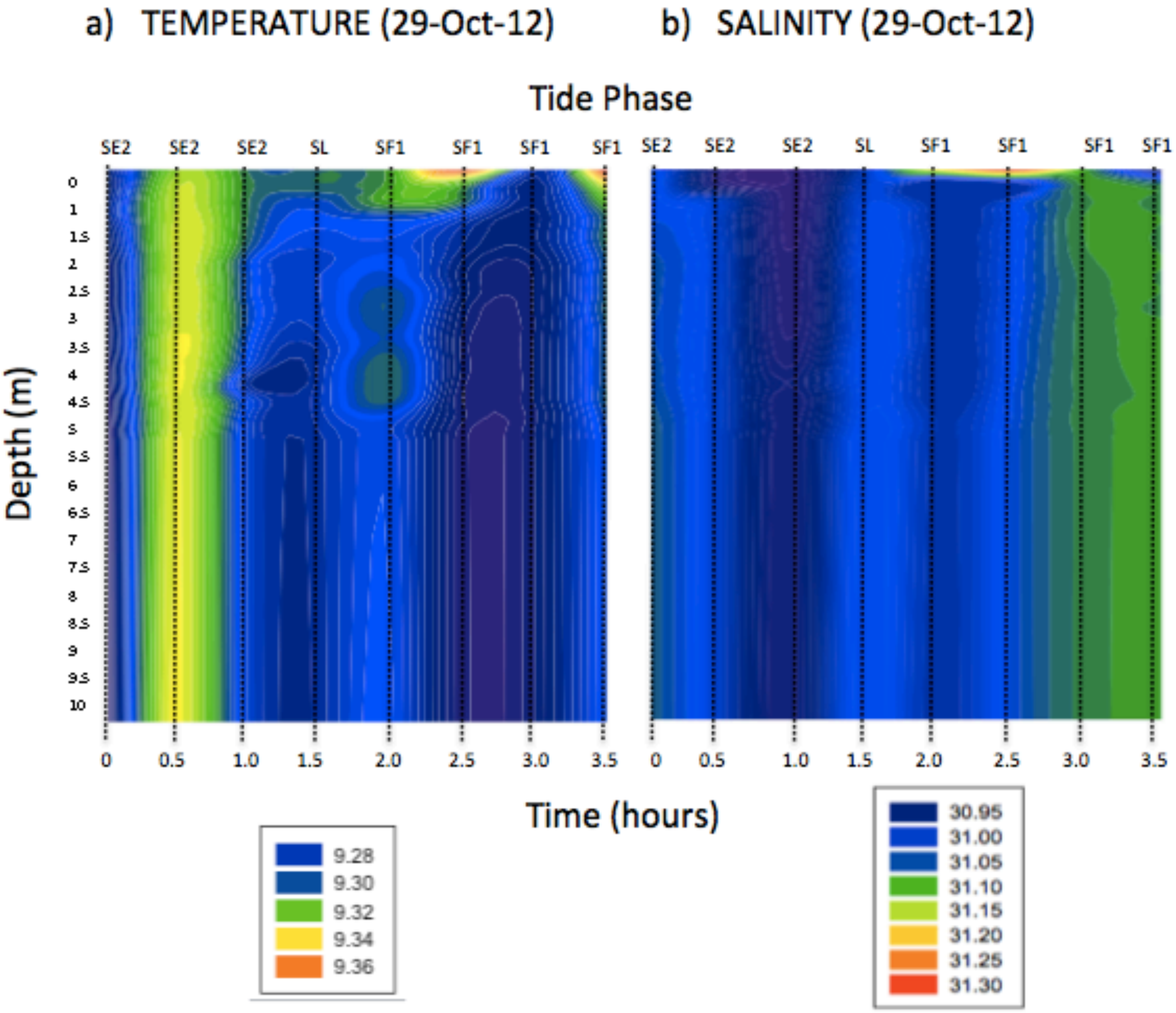


Figure 10. Contour plots of temperature (a) and salinity (b) showing temporal change in the surface water (10-meter depth). Profiles were taken at half hour intervals from the middle of slow ebb 2 until just before the start of fast flood on 29-October-2012.

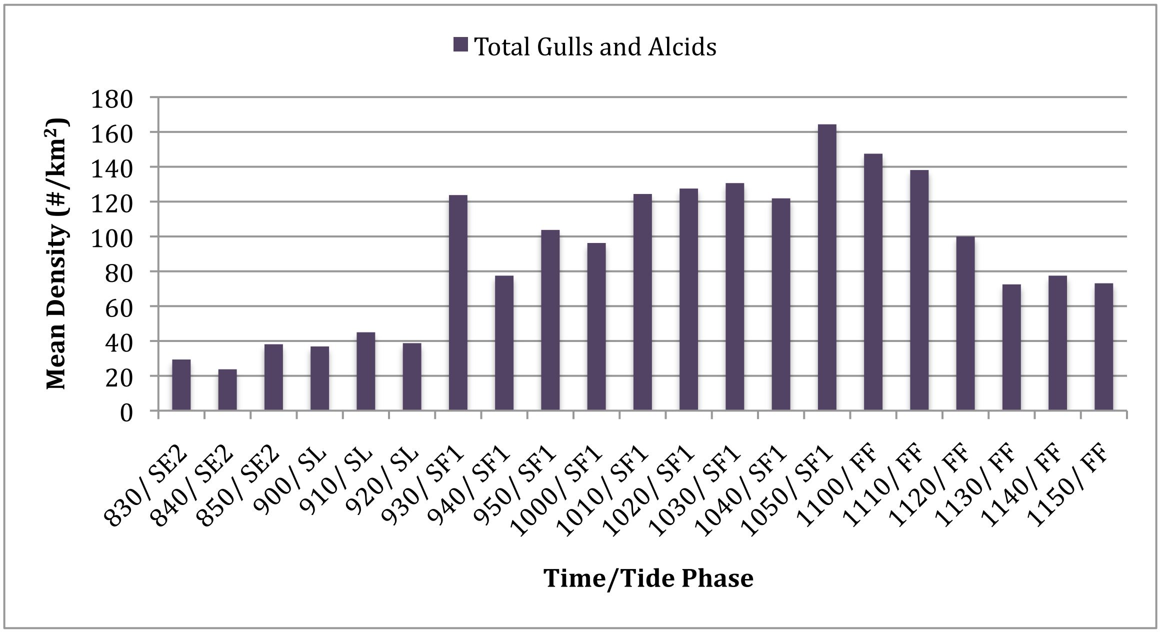


Figure 11: Stationary seabird counts from the R/V Centennial taken on 25-October-2012 from the end of slow ebb through fast flood.

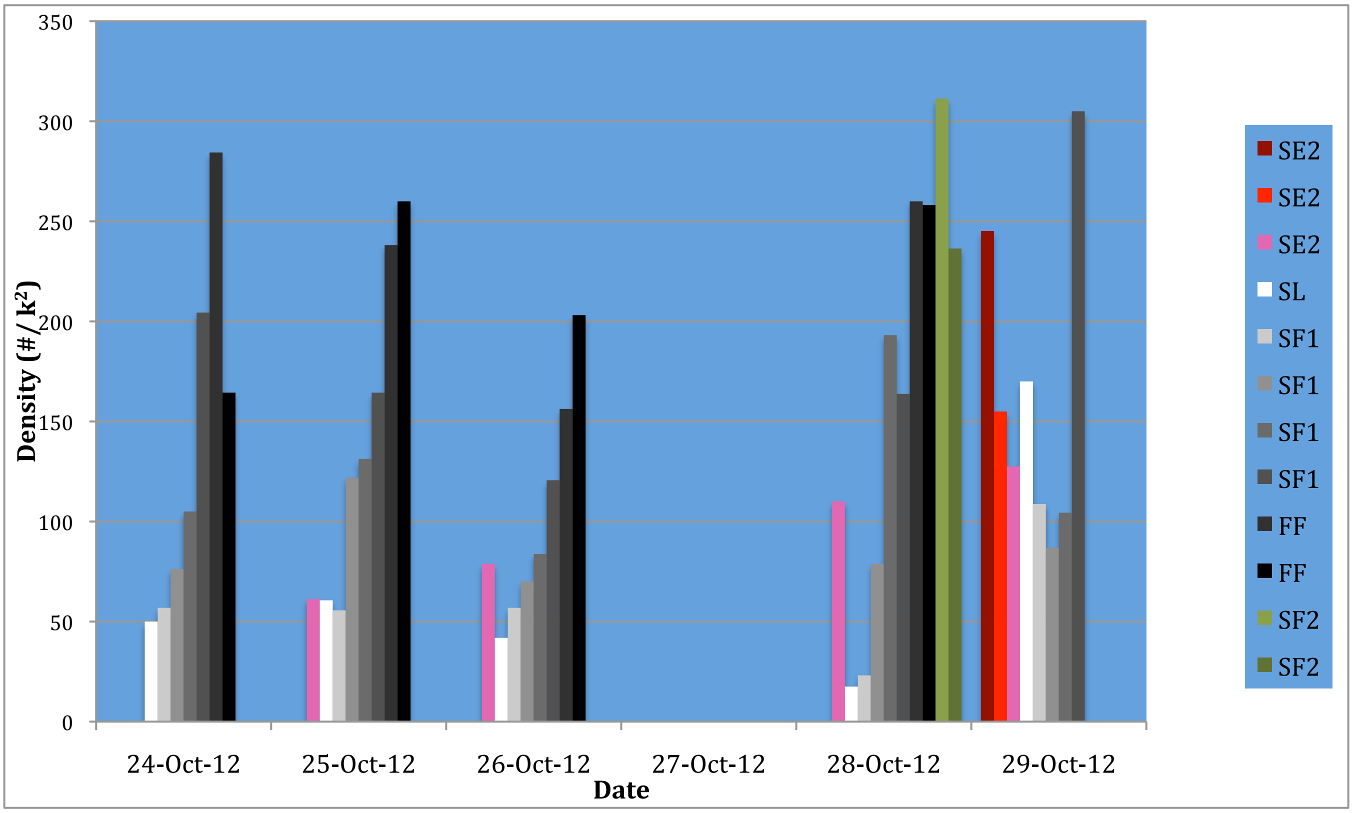
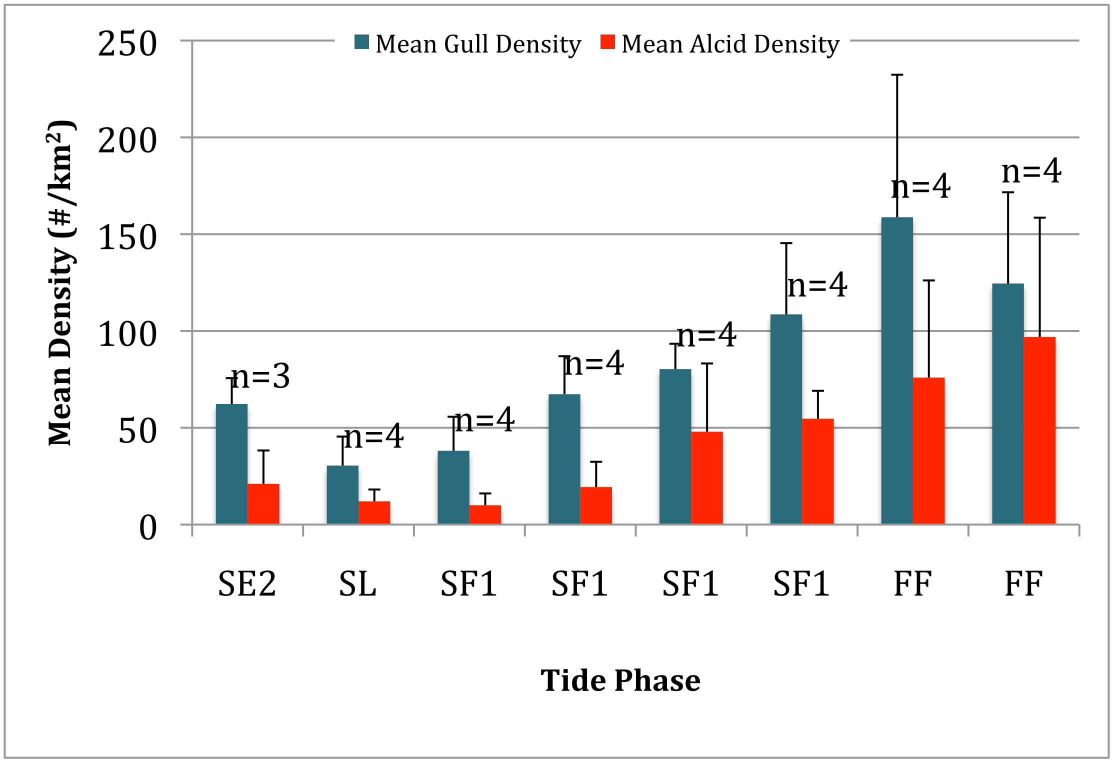
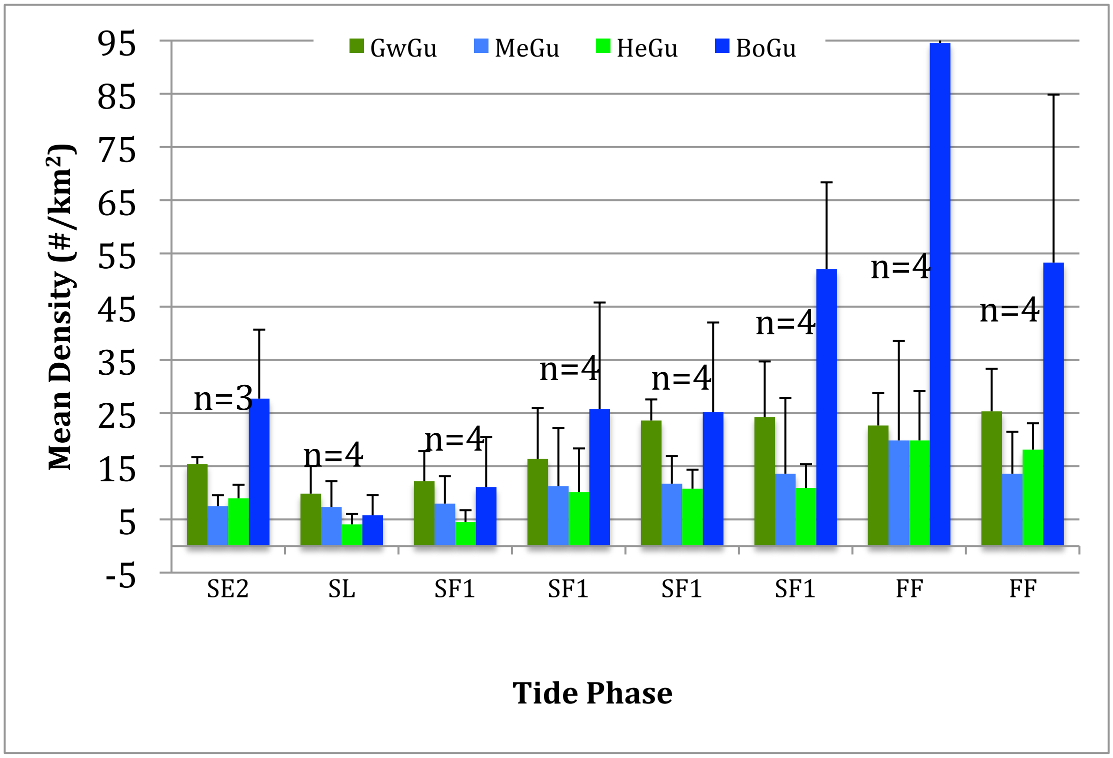


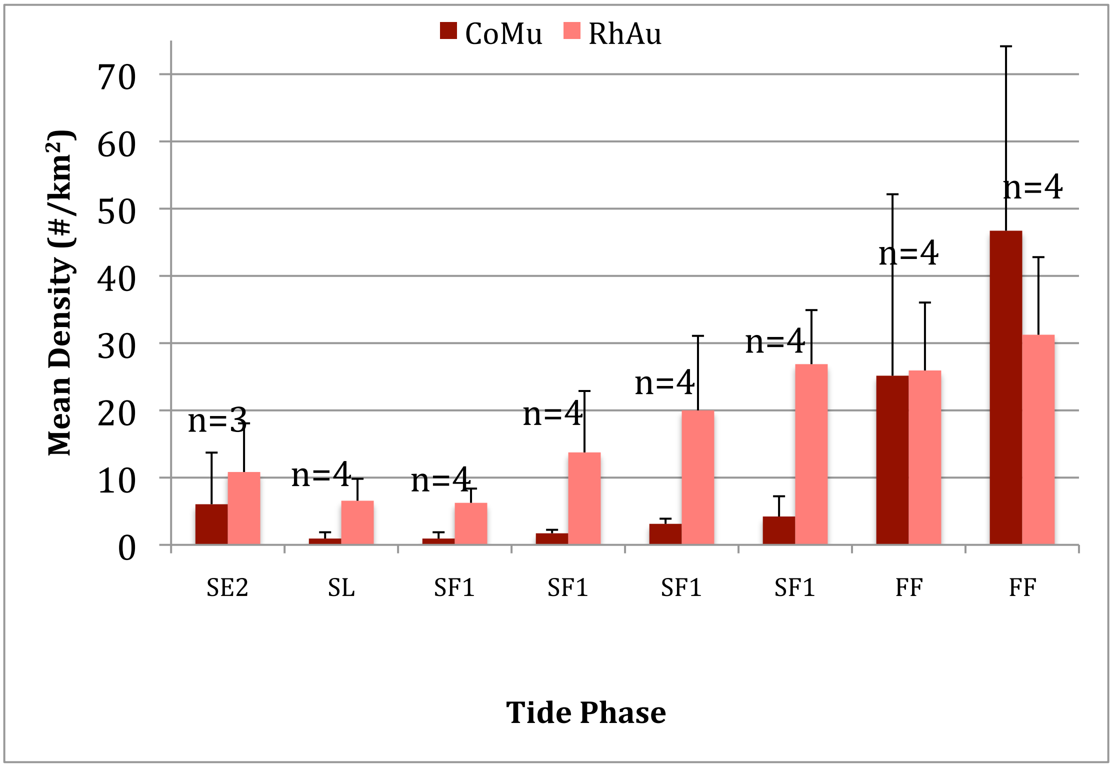
Figure 12. Daily seabird abundance patterns for all gulls and alcids over five survey dates showing total density of gulls and alcids on each individual transect.


Mean Gull Density
Mean Alcid Density
Mean Density (#/km^2)
250
200
150
100
50
0
n=3
n=4
n=4
n=4
n=4
n=4
n=4
n=4
SE2
SL
SF1
SF1
SF1
SF1
FF
FF
Tide Phase

a)

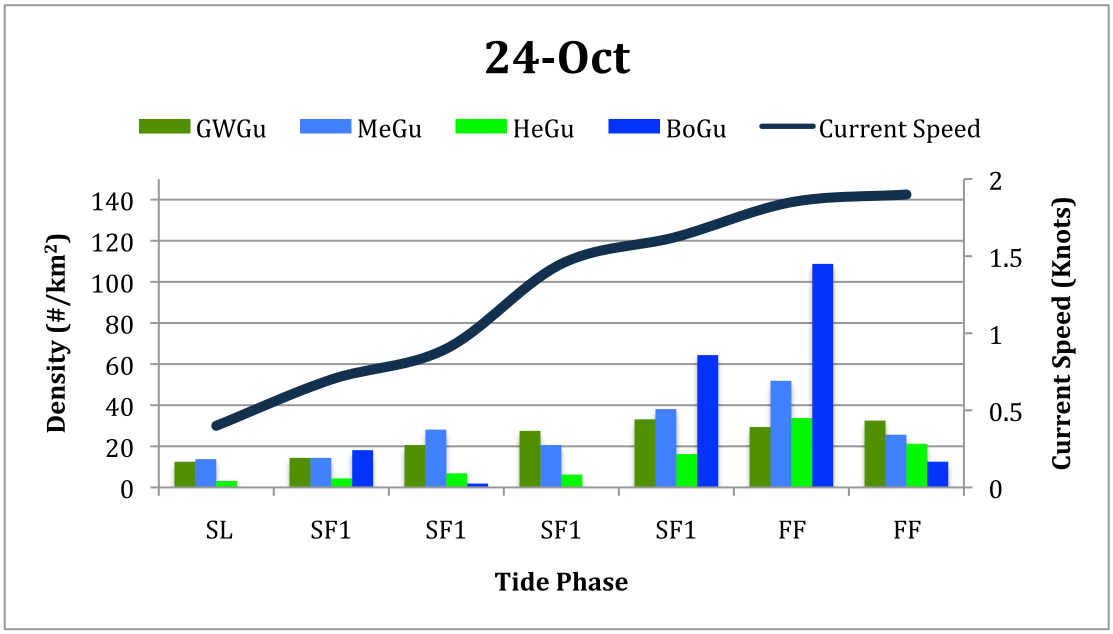

GwGu
MeGu
HeGu
BoGu
Mean Density (#/km^2)
95
85
75
65
55
45
35
25
15
5
-5
n=3
n=4
n=4
n=4
n=4
n=4
n=4
n=4
SE2
SL
SF1
SF1
SF1
SF1
FF
FF
Tide Phase

b)

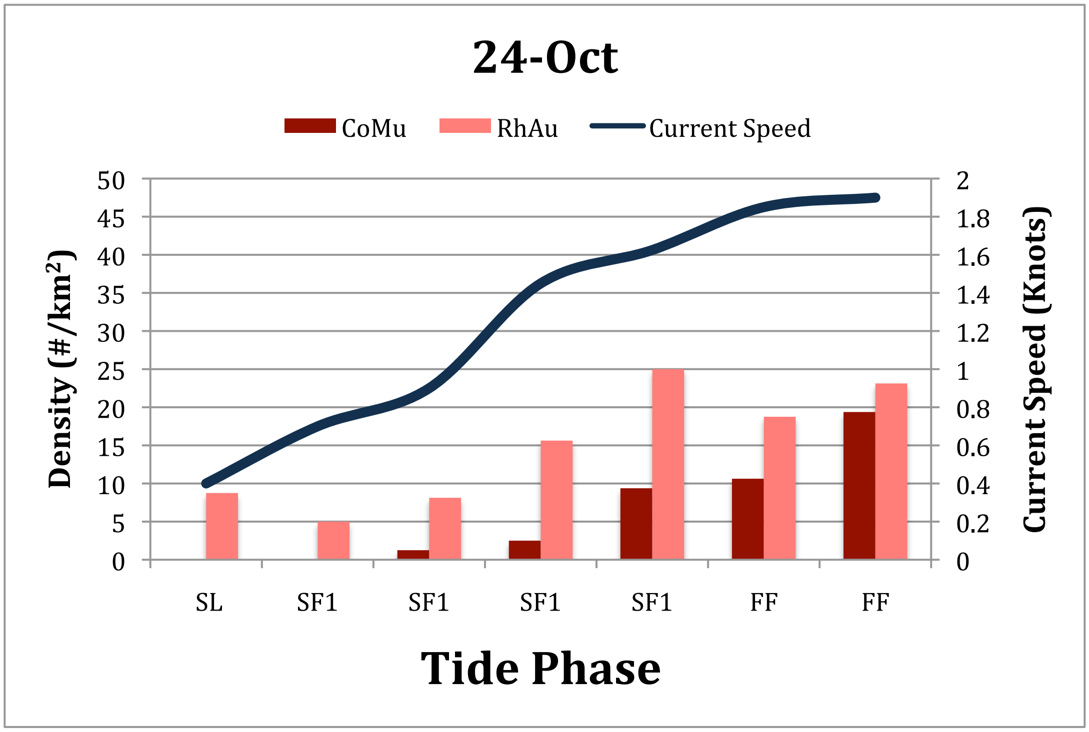


c)

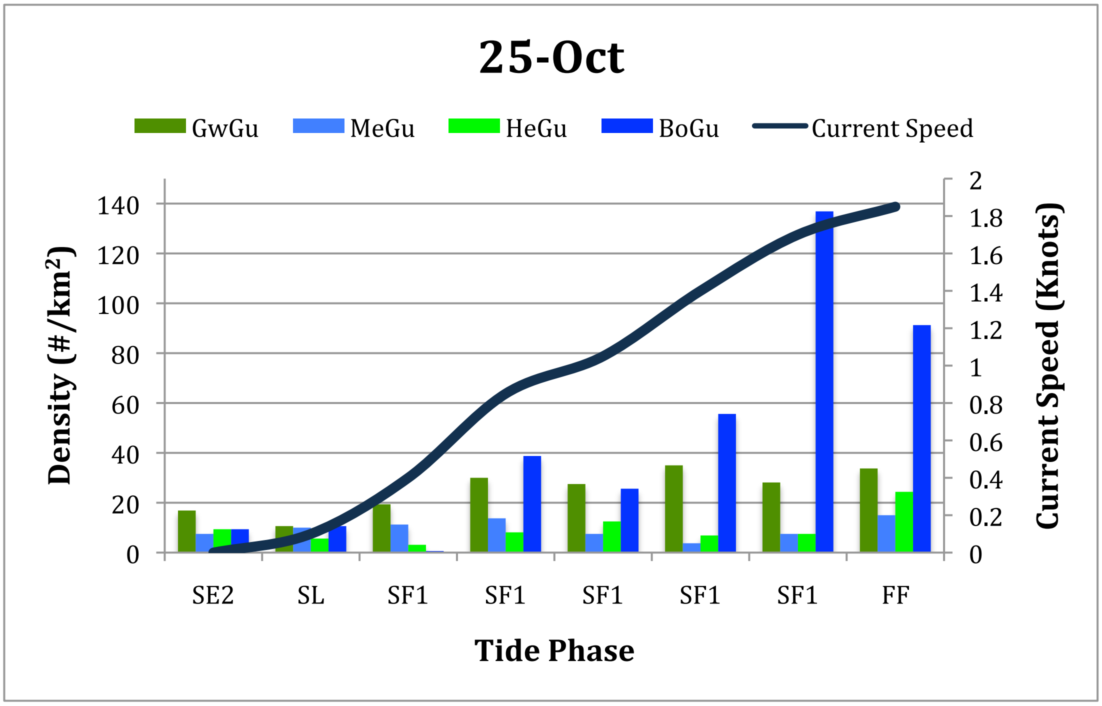
Figure 13. Average seabird abundance from the end of the ebbing tide through the fast flooding tide: a) average abundance of gulls and alcids; b) average abundance of four gull species (GWGU, MEGU, HEGU, and BOGU); c) average abundance of two alcid species (COMU and RHAU).



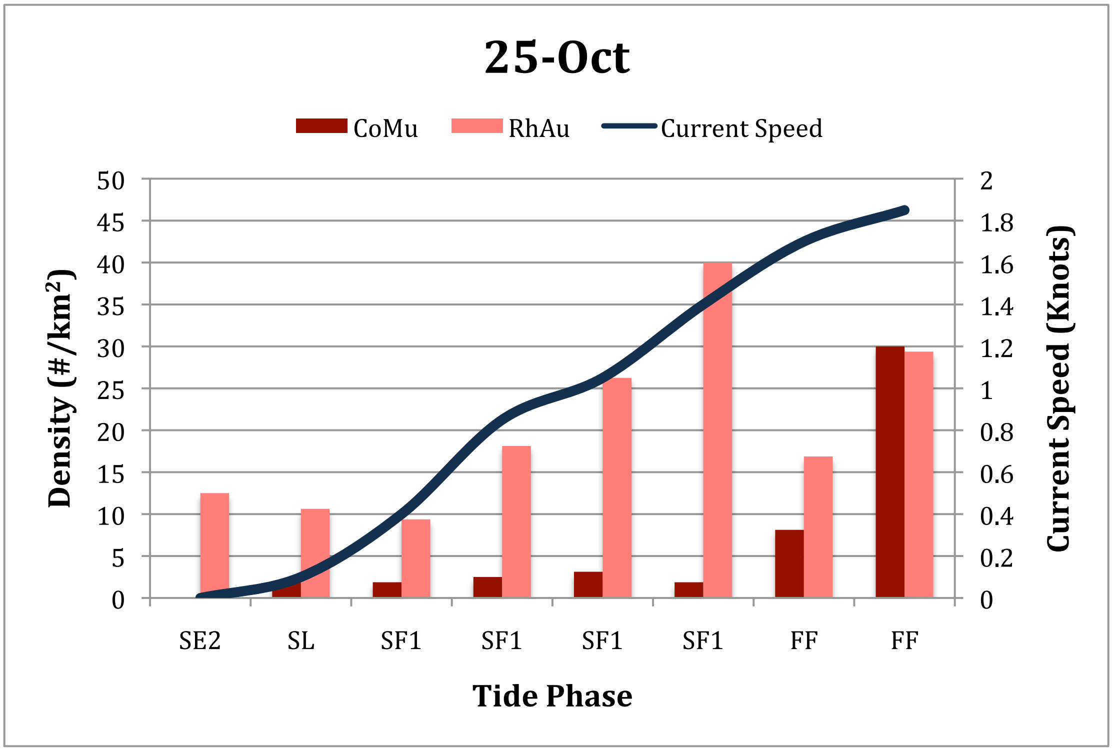
a)


24-Oct
CoMu
RhAu
Current Speed
Density (#/km²)
50
45
40
35
30
25
20
15
10
5
0
Current Speed (Knots)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
SL
SF1
SF1
SF1
SF1
FF
FF
Tide Phase

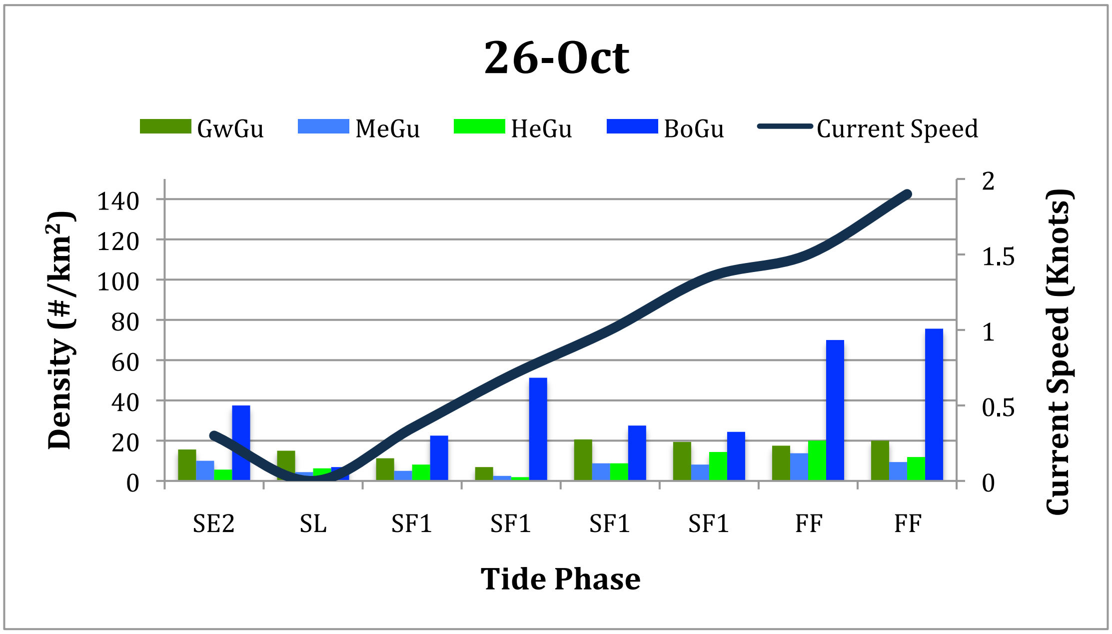
b)


25-Oct
GwGu
MeGu
HeGu
BoGu
Current Speed
Density (#/km²)
140
120
100
80
60
40
20
0
Current Speed (Knots)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
SE2
SL
SF1
SF1
SF1
SF1
SF1
FF
Tide Phase

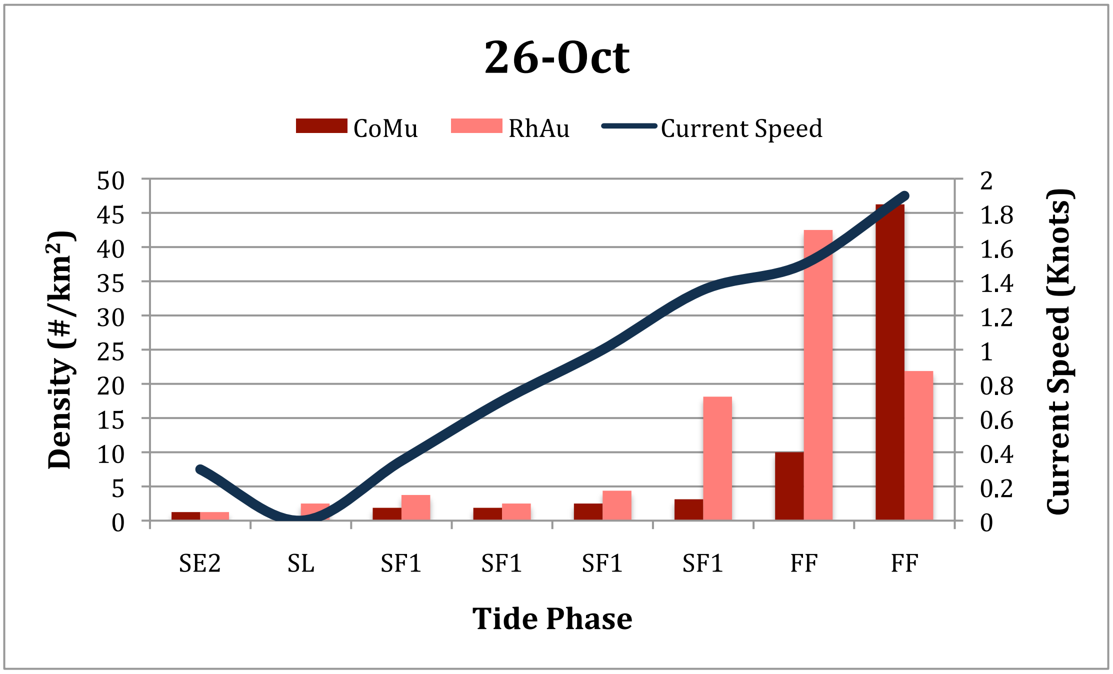
c)


25-Oct
CoMu
RhAu
Current Speed
Density (#/km^2)
50
45
40
35
30
25
20
15
10
5
0
Current Speed (Knots)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
SE2
SL
SF1
SF1
SF1
SF1
FF
FF
Tide Phase

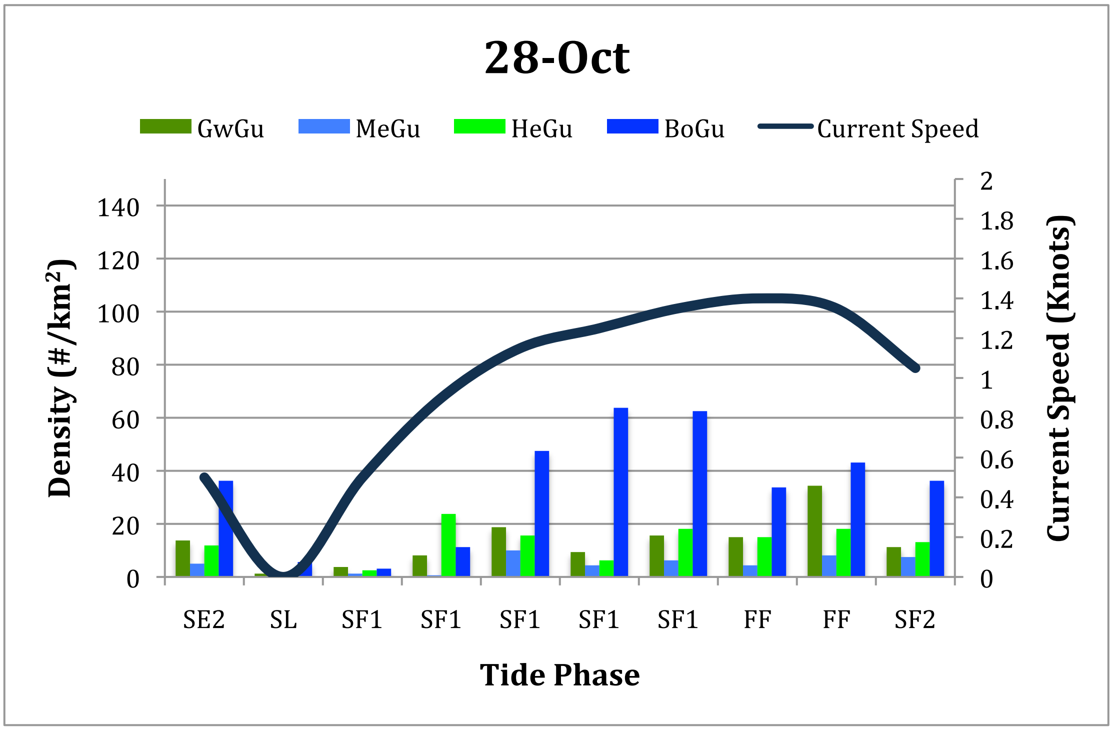
d)


26-Oct
GwGu
MeGu
HeGu
BoGu
Current Speed
Density (#/km^2)
140
120
100
80
60
40
20
0
Current Speed (Knots)
2
1.5
1
0.5
0
SE2
SL
SF1
SF1
SF1
SF1
FF
FF
Tide Phase

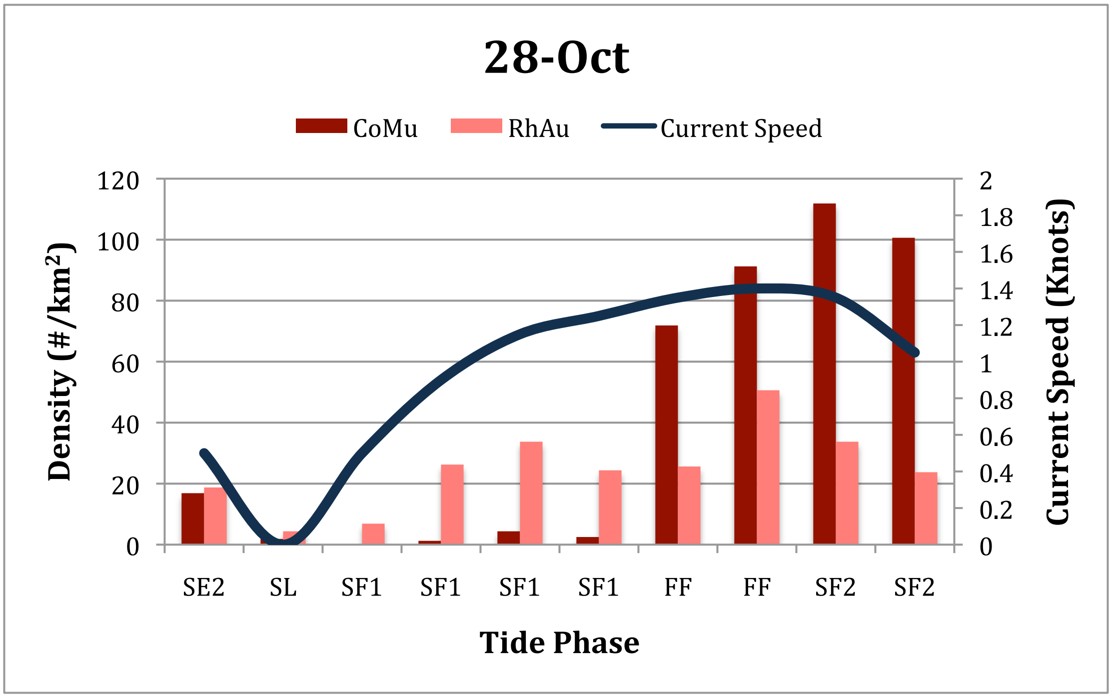
e)


26-Oct
CoMu
RhAu
Current Speed
Density (#/km²)
Current Speed (Knots)
0
5
10
15
20
25
30
35
40
45
50
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
SE2
SL
SF1
SF1
SF1
SF1
FF
FF
Tide Phase

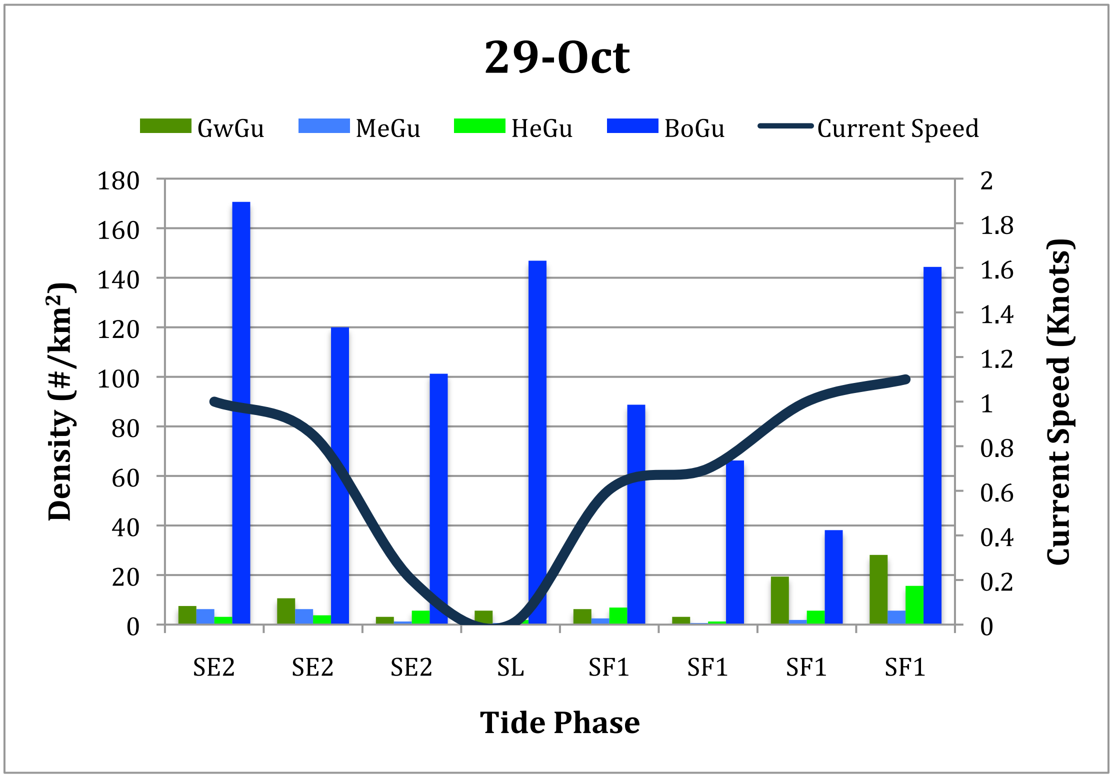
f)


28-Oct
GwGu
MeGu
HeGu
BoGu
Current Speed
Density (#/km²)
Current Speed (Knots)
0
20
40
60
80
100
120
140
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
SE2
SL
SF1
SF1
SF1
SF1
SF1
FF
FF
SF2
Tide Phase

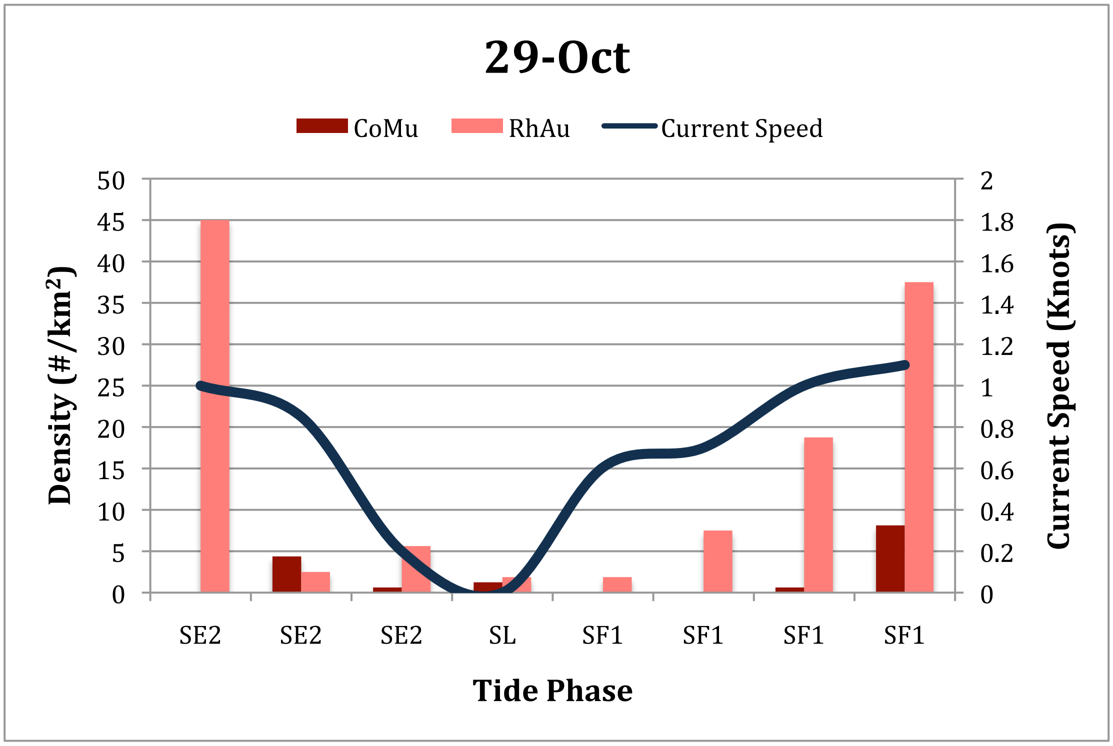
g)


28-Oct
CoMu
RhAu
Current Speed
Density (#/km²)
120
100
80
60
40
20
0
Current Speed (Knots)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
SE2
SL
SF1
SF1
SF1
SF1
FF
FF
SF2
SF2
Tide Phase

h)

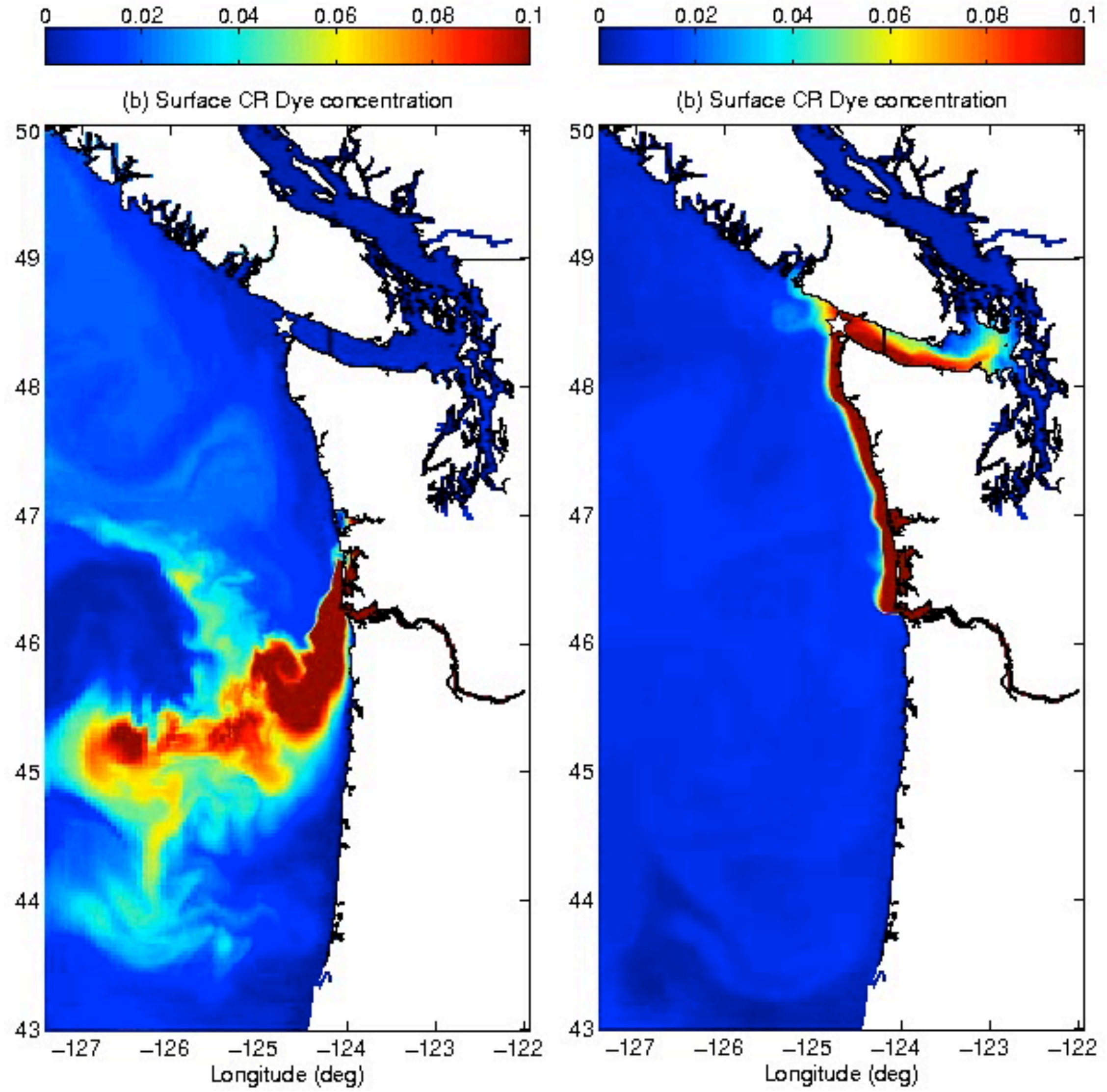

29-Oct
GwGu
MeGu
HeGu
BoGu
Current Speed
Density (#/km²)
180
160
140
120
100
80
60
40
20
0
Current Speed (Knots)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
SE2
SE2
SE2
SL
SF1
SF1
SF1
SF1
Tide Phase

i)



j)

Figure 14.a-j. Seabird abundance by day with the corresponding predicted absolute current speed for each survey. Shows abundance of most abundance gull and alcid species over all transects.



a) b)

Figure 15: Columbia River plume model showing variation between patterns of discharge during the summer and winter. Summer pattern represented by 30-June-2006; winter pattern represented by 21-November 2006 (courtesy of Parker Macready, UW).