The Upper Layer Structure and Variability of an Antarctic Glacio-marine Fjord:

Andvord Bay, Western Antarctic Peninsula

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ABSTRACT

Glacio-marine fjords on the Western Antarctic Peninsula (WAP) are relatively unstudied, rapidly changing systems of high biological productivity. The goal of this research is to characterize the upper layer physical structure and variability of a representative fjord, Andvord Bay, to determine how it changes in time and space in response to external forcing on seasonal and shorter time scales. To analyze the upper layer of Andvord Bay, CTD (Conductivity/Temperature/Depth) profiles and shipboard thermosalinograph data are used from two cruises in the National Science Foundation (NSF) supported project, Fjord ECO. First, the mixed layer depth (MLD) is determined using two different methods: higher order weighting and vertical differences of density above threshold with different commonly used threshold values. The variability of the upper layer salinity, temperature, density, and MLD are analyzed in relation to changes in space, time, and wind forcing. The threshold method using a threshold value of $\Delta\sigma = 0.03$ kg/m^3 is used to define the MLD, with inaccuracies in detection primarily due to the presence of weakly stratified layers at the surface. In the variability analysis, results show that seasonal heat flux is the largest factor impacting the changes in the upper layer of WAP fjords, although wind forcing does play an occasional role. Geographic influences are less prominent and are only relevant between the inside and outside of the fjord. Understanding the upper layer is an important part of understanding the water column dynamics, the chemical characteristics, and the biological diversity of glacio-marine fjords along the WAP.

Keywords: Fjord, Western Antarctic Peninsula, Upper Layer, Physical Oceanography

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CHAPTER 1. INTRODUCTION

High-latitude, glacio-marine fjords of the Western Antarctic Peninsula (WAP) are highly biologically active; however, the specific causes of this activity are not well known due to the relative lack of biological, chemical, and physical data from these systems. The WAP has the largest system of glacio-marine fjords in Antarctica, yet the oceanographic knowledge of these glacio-marine sites is limited. These limitations are caused in part by the inaccessibility of the area during Austral winter months.

Extensive research has been conducted on high-latitude, glacio-marine fjords in the Arctic (Svendsen *et al.* 2002, Boldt *et al.* 2013, Bendtsen *et al.* 2014); however, conclusions inferred from these alternative locations may not be applicable to the Antarctic due to fundamental differences between the fjords in both areas. The fjords in the Arctic exhibit low biological productivity and are highly influenced by meltwater. In contrast, the fjords in Antarctica exhibit high biological activity and appear to be weakly influenced by meltwater (Perkin & Lewis 1978, Svendsen *et al.* 2002, Bendtsen *et al.* 2014). Although many of the variables that contribute to change are the same, there are different degrees of variability and reactions to changes in forcing. The uniqueness of Antarctic fjords signifies that further information is needed to better understand the overall functioning of these systems. Specifically, biological, chemical, and physical oceanographic data are necessary to determine structures and processes of these high-latitude, glacio-marine fjords along the sub-polar WAP.

The Fjord ECO project aims to accomplish the collection of significant data regarding WAP fjords and the characterization of the oceanographic physics, chemistry, and biology. This project aims to deepen the understanding of the effects that these variables have on the upper layer of Andvord Bay. The approach of this project is to characterize the physical properties of the water in the fjord, via observational data and modeling, to develop an understanding of the chemical properties of the water, and to relate these subjects to the biological abundance found in the fjords if possible. The project is a National Science Foundation (NSF) supported, collaborative research effort between the University of Hawaiʻi at Mānoa, Scripps Institution of Oceanography, and the University of Alaska at Fairbanks. During the project cruises, an array of physical, chemical, and biological datasets was gathered from the water column of Andvord Bay, a selected study site that has the general characteristics of many fjords along the peninsula, and this dataset is used to understand the full scope of the processes within WAP fjords. The Fjord ECO project is trying to understand the reasons for the high biological productivity that can be found in the WAP fjords.

Using a portion of the data collected during the Fjord ECO project cruises, this research is specifically focused on the upper layer characteristics and variability of Andvord Bay. The upper layer is important to the chemical and biological processes of fjords, as well as important to the overall structure and variability of the entire water column (Hyatt 2006). My research has two main goals: to understand the basic structure and characteristics of the upper layer in Andvord Bay and to determine how this upper layer changes in time, in space, and in reaction to external forcing, such as wind stress. Seasonal heating is expected to be a large component in how the system changes, but the impacts of shorter time scales, of different geographic locations, and of wind on the upper layer are not entirely well understood.

CHAPTER 2. BACKGROUND

The site chosen for the Fjord ECO project was Andvord Bay. This fjord is located at approximately 65°S, 63°W and is host to a highly active biological system. Throughout the year there is a penguin colony supported at Neko Harbor inside of the fjord and in the summer-autumn months the water column is home to a high population of feeding baleen whales commonly seen in areas of high krill aggregation (Ducklow *et al.* 2007, Nowacek *et al.* 2011). The fjord consists of five sediment basins separated by rocky sills that lead out to Gerlache Strait, to the northeast of the fjord. These basins, in order leading out to the strait, are labeled as inner basin A (IBA), inner basin B (IBB), middle fjord (MF), outer fjord (OF), and the mouth (M) (Figure 1). The basin floors depths are between 450 m to 600 m and the topography surrounding the fjord is mountainous and steep. Due to the elevated topography surrounding the fjord, Andvord Bay is subject to occasional down channel katabatic wind events, meaning that strong winds move down the surrounding high terrain and is directed along the length of the fjord towards Gerlache Strait (Hyatt 2006). The fjord is fed by tidewater glaciers covering 30% – 40% of the shore (Griffith & Anderson 1989); however, it is weakly influenced by meltwater from these glaciers which is similar to many fjords along the Danco/Graham Coast where the climate is cold and dry (Griffith & Anderson 1989). During the winter, Andvord Bay is covered by sea ice and the air temperature is between -18°C and -4°C (King & Harangozo 1998). In spring months, the ice begins to melt and temperatures rise through the summer when air temperatures are often between -1°C and 1.5°C. Warmer temperatures persist until the fall when daylight decreases by approximately 7 minutes per day (King & Harangozo 1998). Andvord Bay was selected because the structure and characteristics are similar to those of other fjords along the sub-polar WAP and it is expected that the information gained from this site will be applicable to other fjords along the Western Antarctic Peninsula.

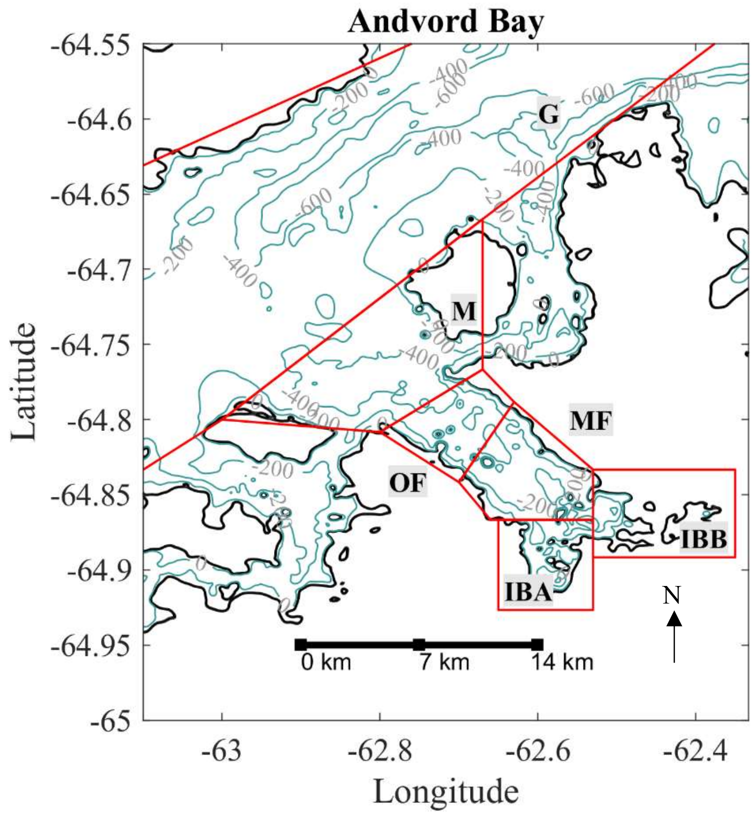

Figure 1: Bathymetric map of Andvord Bay, sectioned off and labeled in polygons showing the 5 basins (IBA, IBB, MF, OF, M), and Gerlache Strait (G).

The Fjord ECO project consisted of three research cruises to Andvord Bay; however, only the first two cruises are addressed in this specific project. The first cruise occurred in November and December of 2015 during Austral summer and the second cruise occurred in April of 2016 during Austral fall. The two cruises were conducted on the United States Antarctic Program (USAP) Research Vessels/Ice Breakers (RVIB): the Laurence M. Gould (LMG) and the Nathaniel B. Palmer (NBP), respectively. During these cruises, there was a wide variety of data collected. To determine the characteristics and structure of the upper layer in Andvord Bay, this project focuses solely on the conductivity, temperature, and depth (CTD) measurements and the shipboard thermosalinograph data collected during the first two cruises. Within the area of study, there are 123 valid CTD casts for the first cruise and 102 valid CTD casts for the second cruise. Some of the CTD casts were invalid due to excessive noise; therefore, they are not analyzed in this project. This research also examines the water temperature, salinity, and wind velocities from the shipboard flowthrough data. The thermosalinograph temperatures and salinities are taken at set depths of 7 m and 10 m for the LMG and NBP, respectively. These depth were determined by finding where the CTD data is best correlated (within 90%) with the shipboard data for the times of each CTD cast. For the shipboard data, there are 22 days of continuous data taken approximately every second for the Austral summer cruise and there are 18 days of continuous data taken approximately every second for the Austral fall cruise.

There are many reasons that studying the WAP fjords is important, including the highly variable seasonality, biological abundance, and chemical significance to the continental shelf. The seasons along the WAP have a profound impact on how the fjords function. The physics of a water column can affect the chemical and biological characteristics and processes (Hyatt 2006, de Boyer Montégut *et al.* 2004). Therefore, in the glacio-marine fjords of the Antarctic, understanding the physics of the system will help in the understanding of the chemistry and biology as well. The upper layer is particularly important because it holds a role in many of the key processes that take place within the fjord. For example, the euphotic zone resides in the upper layer of the water column and is essential to the biological productivity in the area due to its role in photosynthesis and phytoplankton growth (de Boyer Montégut *et al.* 2004). The area has been known to experience large phytoplankton blooms, high krill populations, and baleen whale feeding activity (Ducklow *et al.* 2007, Nowacek *et al.* 2011). The upper layer is also highly influential as it is a key location for interactions between the hydrosphere and atmosphere and, particularly in high-latitudes, between the hydrosphere and cryosphere (Syvitski. 1989, Węsławski *et al.* 2011). Both air-sea and ice-sea interactions play important roles in the chemistry and biology of the system.

Characterizing the structure and variability of the upper layer in glacio-marine fjords along the WAP is the first step in understanding the overall effects the upper layer has on biological and chemical systems in the fjords and how these systems function.

As the globe changes, it is important to recognize how the systems of the Antarctic will change. The Western Antarctic Peninsula is one of the most rapidly changing areas on Earth and the fjords contribute a large amount of the biological productivity along the coast (Meredith & King 2005, Van den Broeke 2000, Marshall *et al.* 2006, Vaughan *et al.* 2003). The regional air temperature at Faraday/Vernadsky Station (65°14′S 64°15′W) increased by 2.94°C from 1951 to 2004 whereas the global average temperature change was approximately 0. 52°C during the same time period (Marshall *et al.* 2006, Meredith & King 2005). Evidence has shown that Antarctica experiences an amplification of the global warming trends. The International Panel on Climate Change (IPCC) estimates that the temperature of the globe will increase between 0.3°C and 0.7°C in the next two decades (IPC 2014). If the trend of amplified warming along the WAP continues into the future, the increased rate of change in temperature may have large effects on the fjords including increased glacial melt, decreased sea ice formation in winter months, and alterations to the fundamental structures of biological communities in the area (Vaughan *et al.* 2003). Any change to the factors that contribute to the fjords could entirely alter how the physics and chemistry behave thereby completely altering the biological activity.

CHAPTER 3. LITERATURE REVIEW

Due to the fundamental differences between the well-studied Arctic glacio-marine fjords and the less researched Antarctic glacio-marine fjords, the processes that are applicable to the former may not be applicable to the latter. Studies suggest that the systems are entirely different based on the varied biological activities, surrounding climate, and general behavior of the waters within the fjords (Syvitski *et al.* 1989, Cowton *et al.* 2015, Farmer & Freeland 1983). The glacio-marine fjords in the Arctic have shown relatively high levels of meltwater inputs whereas the lower temperatures and drier climate in the Antarctic do not allow for the same amount of melting to occur (Griffith & Anderson 1989). This difference in freshwater inputs causes differences in salinity and temperature, altering the density profiles of the water column (Farmer & Freeland 1983). Furthermore, in the Arctic, fjords are often considered poor productivity areas (Syvitski *et al.* 1989), due to high turbidity and influences from meltwater (Cowton *et al.* 2015, Sutherland *et al.* 2014). They rarely have high concentrations of phytoplankton and are considered only as limited refugia for cold water organisms (Syvitski *et al.* 1989). However, data from Antarctica shows evidence of high productivity based on the tendencies of whales to use the areas for feeding, elevated detritus flux to the seafloor, and possible large phytoplankton blooms and krill aggregations (Ware *et al.* 2011, Ducklow *et al.* 2007, Nowacek *et al.* 2011, Griffith & Anderson 1989, Domack & Ishman 1993). This signifies that much of the research on high-latitude fjords cannot be applied to Antarctic fjords due to differences in the structures, processes, and characteristics between the fjords of each area.

There are a number of factors that can affect the mixing of the upper layer in the water column of a fjord. The biggest influences are changes to density by salinity or temperature variations at the surface via ocean-atmosphere interactions (Chu & Fan 2011). Any changes in these variables can destabilize and mix the water column as water of higher density than below forms at the surface (Farmer & Freeland 1983). The densities of the water columns in the fjords of the WAP appear to be driven by salinity (Hyatt 2006). Salinity is affected by meltwater from the glaciers and by ice formation in the fjord (Svendsen *et al.* 2002). With an increase in melt water, there is a decrease in salinity, and with an increase in sea ice formation, there is an increase in salinity (Farmer & Freeland 1983). Although it plays a smaller role in determining density, the water temperature is still significant to the characteristics of the upper layer in the fjord. The upper layer of fjords is often colder and fresher than the layers below which is opposite of what is often seen in warmer oceans (Peralta-Ferriz & Woodgate 2015). This is partially due to the fact that the maximum density of average seawater occurs at 4°C and decreases as the temperature decreases below this value. Therefore, with an increase in temperature from near freezing to higher temperatures, the stratification can be weakened due to increased density at the surface and subduction may occur as the denser water moves downward (Peralta-Ferriz & Woodgate 2015). By decreasing or increasing the salinity, the density is decreased or increased, respectively. Due to the large variability in salinity compared to temperature in many polar systems, the density is largely dependent on salinity. Another important factor in the upper layer mixing is the effect of winds on surface heat flux and horizontal advection. Although the elevated topography surrounding the fjord generally lessens the influence of wind, the area is subject to occasional strong, down-channel, katabatic wind events that can deepen the mixed layer and cause upper layer mixing (Hyatt 2006). The mixed layer may also deepen due to turbulent motions at the base of the layer, typically driven by tidal forcing or wind forced current shears. This research aims to understand what factors contribute to mixing in the upper layer.

The initial step to characterizing the upper layer of the water column is to identify the mixed layer depth (MLD). The mixed layer, defined where the temperature, salinity, and density are relatively constant near the surface, is what defines the upper layer and plays a major role in the biological and chemical characteristics of the water (Chu & Fan 2011, Peralta-Ferriz & Woodgate 2015, Hyatt 2006). A well-mixed layer shows that there is external forcing causing the upper part of the water to homogenize (Lane-Serff & Stansfield 2013, Dong *et al.* 2008). Weakly stratified layers show evidence of less mixing, smaller external forcing, and less mechanical energy input to the system (Hyatt 2006, Lane-Serff & Stansfield 2013, Gordon & Huber 1990). The MLD ends where the homogenized layer reaches the pycnocline, defined as the depth of maximum density change (Peralta-Ferriz & Woodgate 2015). In cases of little to no energy input, the pycnocline may reach to the surface with no mixed layer present. These cases are common in Polar Regions, particularly when there is high ice cover due to limited interaction with the atmosphere (Peralta-Ferriz & Woodgate 2015, Sutherland *et al.* 2014).

The mixing and stratification of the water are essential to the biological processes that occur there. The main driver for life in the ecosystem is in the upper layer is where a majority of the photosynthesis occurs. (Ware *et al.* 2011, Barnes & Conlan 2007, Ducklow *et al.* 2007, Nowacek *et al.*, 2011). The most biologically productive time is estimated to be in the summer season, with decreasing productivity as time progresses to winter (Nowacek *et al.*, 2011). However, due to lack of data, there is no way to definitely know how different characteristics affect the productivity of the system. Based on preliminary data, there are relationships between temperature, salinity, and chlorophyll levels. A goal of this project is to characterize the relationships and trends between physical characteristics and the biological productivity of the fjord.

CHAPTER 4. METHODOLOGY

4.1 Mixed Layer Depth

There are many methods for defining the MLD with a wide range of complexity, application, and accuracy (Thomson & Fine 2003, Peralta-Ferriz & Woodgate 2015, Dong *et al.* 2008). In many situations, the MLD is determined visually by general characteristics of the water column on a case-by-case basis, but this is both inefficient and highly subjective. For this project, I tested two methods using numeric evaluation of cruise CTD cast data against a visual placement of the MLD. For the visual placement, I examined each valid CTD profile and assessed the most plausible depth for a mixed layer based on density (Figure 2). In cases of weak stratification, where no mixed layer was present, I recorded 0 as the MLD. I used these values obtained from visual examination as a base line for the accuracy of my mathematical calculations for MLD. The two methods selected for comparison involve higher order weighting and threshold detection.

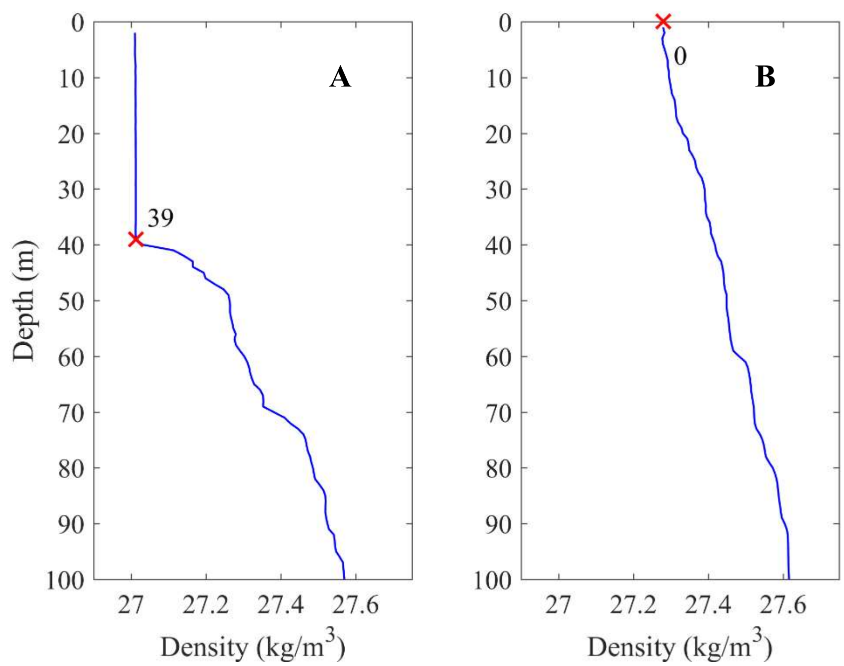

Figure 2: Characteristic plots of visual MLD placement (red X) based on CTD profiles from the Austral fall cruise for A) a well-mixed layer (MLD = 39 m), and B) a stratified layer (MLD = 0 m).

4.1.1 Higher Order Weighting Method

The higher order weighting method makes use of a reference density that is stable in the mixed layer and computes a weighted average of vertical density gradients between a sample depth and the depth of a given reference density (Thomson & Fine 2003). The main objective of this method is to find the depth of maximum change in the density of the water column, where the pycnocline begins and the mixed layer ends (Dong *et al.* 2008). The weighted average is given by:

$$\mathrm{MLD} = \frac{\int_{z}^{z_{ref}} z \left(\frac{\delta\sigma}{\delta z}\right)^{2n}}{\int_{z}^{z_{ref}} \left(\frac{\delta\sigma}{\delta z}\right)^{2n}} \qquad (1)$$

In this equation, z_{ref} is a reference depth for a specific density in the mixed layer, z is a depth, σ is the potential density, and n is a factor to control the power of the monotonically increasing function. The n value can be adjusted to account for noise levels and determines the sensitivity of the function. I use an n value of 3 for the monotonic power to allow enough sensitivity in estimating shallow, weakly stratified mixed layers properly without necessarily being subject to excessive noise in the data. Often, z_{ref} is defined by the location where a certain density occurs in the mixed layer (Price *et al.*, 1986), but due to the high degree of variability in the profiles of Andvord Bay, I used a specific depth of 6 m for z_{ref} even though the densities do vary at this depth. The higher order weighting method is often applied in cases of deep, well-mixed layers, but it is not as common in cases of weak stratification, which the fjord can occasionally exhibit (Thomson & Fine 2003).

4.1.2 Threshold Method

The threshold method defines the MLD as the first depth below the surface that the potential density difference from the surface exceeds a given predetermined numerical threshold. The equation set for the threshold method is:

$$\Delta\sigma = \sigma(z) - \sigma(z_{\min}) \qquad (2)$$

$$\text{MLD} = z \text{ if } \Delta\sigma \geq \text{threshold} \qquad (3)$$

In this case z_{min} is the shallowest depth measured and Δσ is the difference in density between the surface and *z*. There is a range of thresholds used in the literature, with Δσ = 0.1 kg/m^3 being a common choice (Peralta-Ferriz & Woodgate 2015). However, for polar waters, a threshold of Δσ = 0.03 kg/m^3 has been applied (Peralta-Ferriz & Woodgate 2015). A smaller threshold value is, at times, necessary in high latitude waters because there is a smaller range of densities. Ideally, using this method gives the first point at which the difference between the density of a given depth and the minimum depth measured is greater than the threshold. However, it has been found that in profiles with extremely weak stratification or high noise levels, this method is inaccurate and can lead to errors (Peralta-Ferriz & Woodgate 2015). In general, the smaller Δσ values are more subject to noise while the larger Δσ values can miss shallow mixed layers. Determining which threshold to use and when each is applicable is left to the user. For this research, I tested a range of Δσ values, including Δσ = 0.03 kg/m^3 and Δσ = 0.1 kg/m^3, against the visual estimates for the MLD to determine the threshold value that fit best to the measurements in Andvord Bay.

4.2 Variable Trend Observations

To further analyze the upper layer characteristics of Andvord Bay, I examined the temperature, salinity, density, and MLD changes over time, in space, and in relation to surface wind forcing. Using the CTD and underway thermosalinograph shipboard data from the summer and fall cruises, I was able to obtain ample data regarding the upper layer of the water column. To verify the cohesiveness of both data sets with one another, I determined the depth where the ship data was measured for each cruise. I did this by finding the depth where the thermosalinograph data correlated with the CTD data at the time of each cast. The resulting depth was 7 m for the summer cruise and 10 m for the fall cruise with an approximate 0.931 correlation in summer and 0.947 correlation in fall (Figure 3). After verifying that the datasets were well matched, I examined each to find how the upper layer changed based on temporal, spatial, and wind forcing.

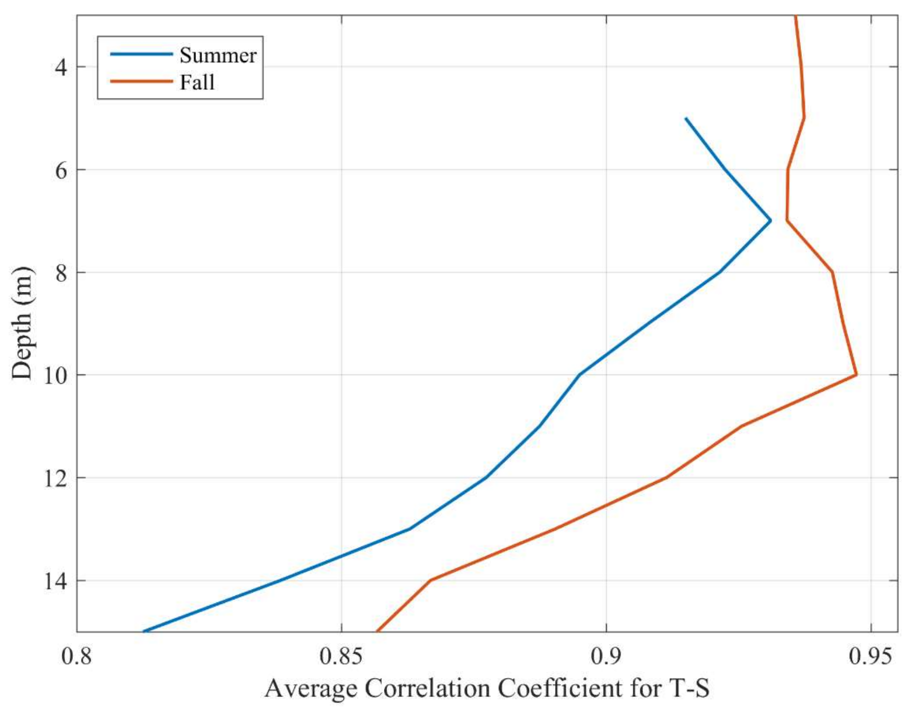

Figure 3: Average temperature and salinity correlation coefficients between shipboard thermosalinograph and CTD datasets for the upper 15 m in summer and fall.

To examine how the characteristics of the upper layer changed spatially, the study area was divided into 6 polygons, 5 of which corresponded to different basins in the fjord (e.g. IBA, IBB, MF, OF, M) and the final polygon corresponded to Gerlache Strait (G) (Figure 1). I compared the differences in the characteristics of the upper layer for each cruise. I also examined the major differences between the upper layers in Gerlache Strait and Andvord Bay.

To determine changes in time, I evaluated the time-series data for both the CTD data and thermosalinograph data from each cruise regarding temperature, salinity, density, and MLD. I then compared the trends found in each cruise with one another to determine variability in seasons. Although I did expect to see the full extent of seasonal change, I quantified changes over the course of each cruise as a measure of seasonal heating and cooling.

Finally, I analyzed the upper layer reaction to wind events. As previously stated, Andvord Bay is subject to occasional down-channel katabatic wind events. During the course of the first cruise (summer), the Fjord ECO project collected CTD and shipboard data for a 24-hour time period in which a large wind event occurred. There were further wind events in the following cruise; however, none were stronger than the one that occurred during the first cruise.

CHAPTER 5. RESULTS

5.1 MLD Determinations

The threshold method appears to be more effective at defining the MLD for the Fjord ECO datasets than the higher order weighting method. Using a range of threshold values, I have determined that using $\Delta\sigma = 0.03$ kg/m^3 is best correlated with the traditional visual approach with a correlation coefficient of approximately 0.700 (Figure 4). Other cases use $\Delta\sigma = 0.1$ kg/m^3 to determine the MLD (Peralta-Ferriz & Woodgate 2015), but, with a correlation coefficient of 0.520, this value was not as well correlated with the visual MLD. The higher order weighting method has a correlation coefficient of 0.480 making it less applicable than the threshold method using either of the most common threshold values. Therefore, between the higher order weighting and threshold methods, the most suitable calculation of MLD for this dataset is the threshold method using $\Delta\sigma = 0.03$ kg/m^3.

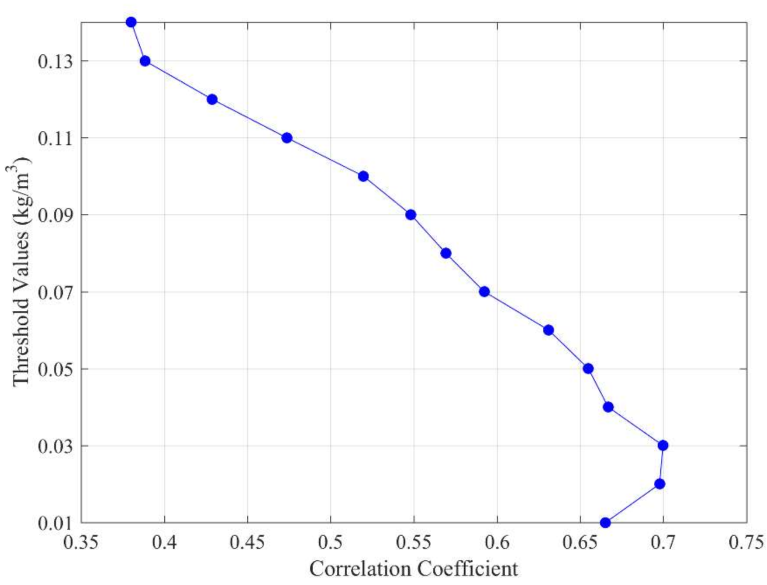

Figure 4: Correlation coefficients between MLD calculations using different threshold values and a visual approach.

However, there were still some discrepancies between the automated threshold and visual inspection approaches. In a well-mixed case (Figure 5, A), the visual and threshold method using $\Delta\sigma = 0.03$ kg/m^3 are well aligned. In a weakly stratified case (Figure 5, B), the pycnocline reaches the surface and there is no true mixed layer present using a visual analysis, but using the threshold method still assigns a value. This type of discrepancy occurs most often in cases with weak stratification and high noise levels where it is difficult for the threshold approach to differentiate between noise and the start of the pycnocline. The density and salinity were relatively similar in shape and MLD for each case. Although the temperature exhibits a similar structure to both the density and the salinity profiles, there is a smaller range of change with more common fluctuations that cause variations in the MLD calculations. Based on this, the major driver of density in this area appears to be salinity.

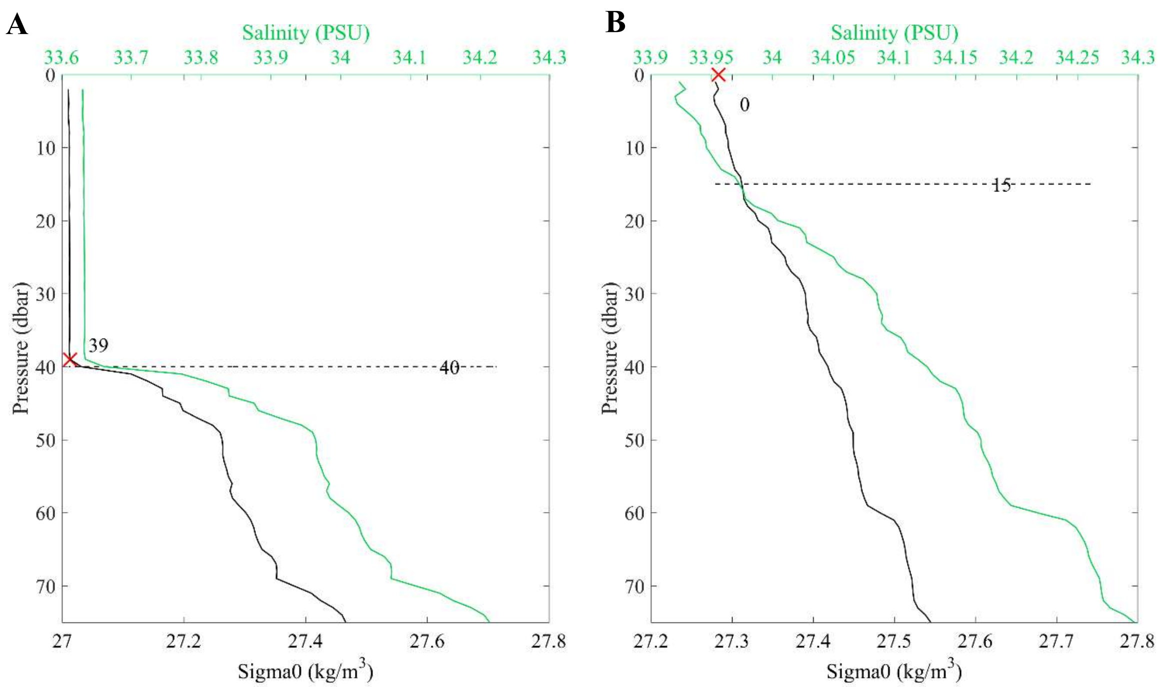

Figure 5: Examples of mixed layer depth estimates based on the threshold method using a threshold value of 0.03 kg/m^3 shown by a dashed line. Each figure shows the effectiveness of the method based on the conditions of the water as compared to the visual approach, denoted by a red x. A) Conditions: well mixed, B) Conditions: weakly stratified.

5.2 Variability Analysis

5.2.1 Variability in Space

There is some spatial impact on the characteristics of the fjord, but it is generally small. The largest spatial difference in the upper layer was between the inside of the fjord and Gerlache Strait (Figure 6). In the strait, the average MLD values appear to be better defined and deeper than inside of Andvord Bay for both the summer and fall cruises. A majority of the well-mixed layers seen in the CTD profiles are from casts taken in the strait. Occasions where the MLD is deeper inside the fjord than outside the fjord had other influences, such as wind.

During the summer cruise, the upper 50 meters of the strait was generally colder and fresher with lower density than the upper 50 meters inside of the fjord (Figure 6a). Below 50 meters, the strait was warmer, but at a similar temperature. During the fall cruise, the average temperature of the upper layer in Gerlache Strait was warmer than inside of Andvord Bay; however, as the cruise progressed the temperatures became more similar (Figure 6b). Above approximately 10 meters, the upper layer of Gerlache Strait is saltier than inside Andvord Bay. Below 10 meters, the temperature and salinity are similar. The difference between the strait and the fjord is more evident during the summer cruise as opposed to the fall cruise. (Figure 6)

There are some differences in the average characteristics of the upper layer between the different basins within Andvord Bay (Figure 7). There was a contrast between IBA and IBB where the average density of the surface layer of IBA is higher than in IBB during the fall cruise. In the summer cruise, the largest variation to the general characteristics of the area is in MF; however, these results are likely skewed due to a katabatic wind event for which hourly sample were taken only in MF. The variability between the different polygons is relatively small when compared to the differences between the strait and fjord and the seasonal variations over time.

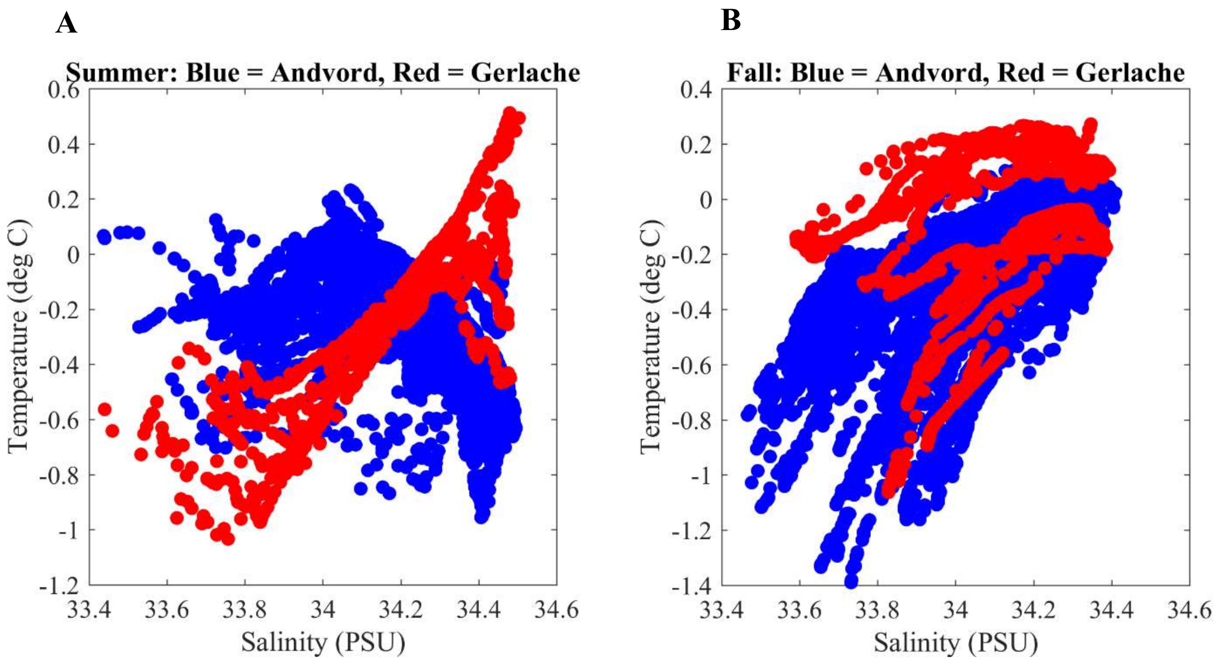

Figure 6: Upper layer (100 m) salinity and temperature for Andvord Bay and Gerlache Strait, denoted in blue and red, respectively. (A) Austral summer, (B) Austral fall.

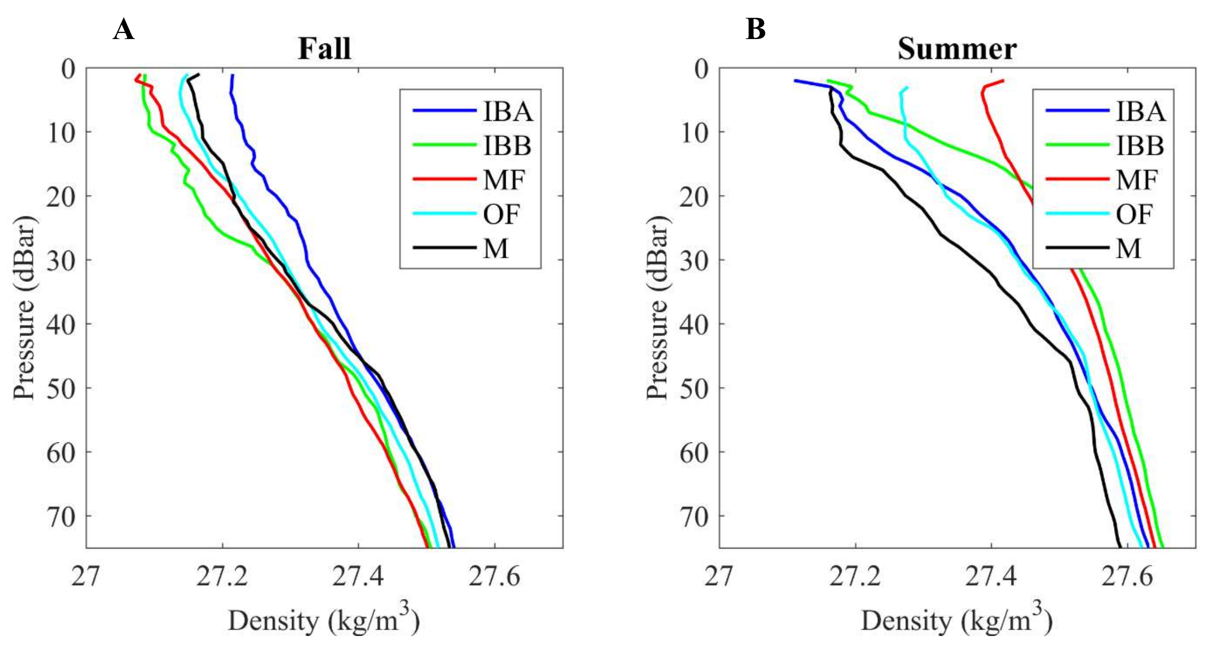

Figure 7: Average upper layer (75 m) profiles for density in each basin of Andvord Bay (IBA, IBB, MF, OF, M). (A) Austral Summer, (B) Austral Fall.

5.2.2 Variability in Time

Overall the largest factor in the variability of the upper layer of the fjord is time. There were variations between the summer and fall cruises, and even within the time period of a cruise there were smaller variations in the characteristics of the upper layer that revealed processes that occur during summer and fall. Between the summer and fall cruises, the temperature of the upper layer decreased significantly, the salinity decreased, and the density decreased as a result (Figure 8). There are clear trends in both the CTD and thermosalinograph data that temperature and salinity are dependent on changes in time (Figure 9). This relationship occurs in all of the basins and in Gerlache Strait. In observing the time-series for temperature and salinity (Figure 10, Figure 11), there are trends that occur within the timespan of a single cruise. The summer cruise shows a slight increase in temperature and a generally constant salinity, suggesting warming of the upper layer without significant meltwater influx. The fall cruise revealed a stronger signal of decreasing temperature and increasing salinity, presumably associated with seasonal cooling and ice formation. During the fall cruise, there is a more evident temporal trend in properties over time. While time does have a large impact on the overall characteristics of the upper layer in Andvord Bay, there is still no obvious temporal trend in MLD (Figure 10, 11).

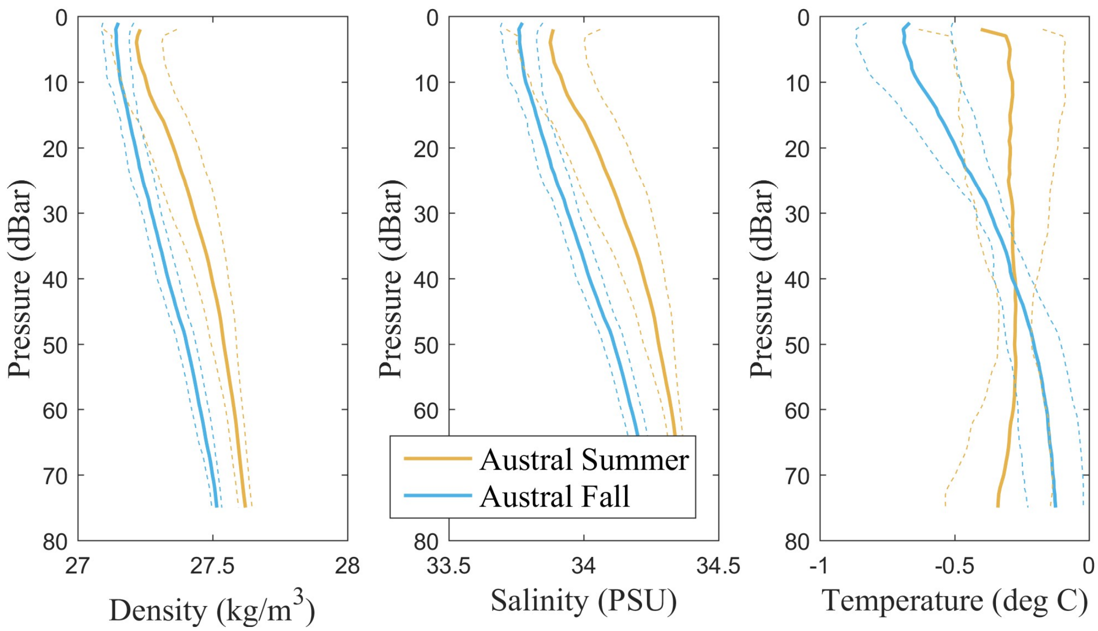

Figure 8: Average upper layer profiles for density, salinity, and temperature for the Austral Summer Season and Austral Fall season CTD casts with ± 1 standard deviation from the mean.

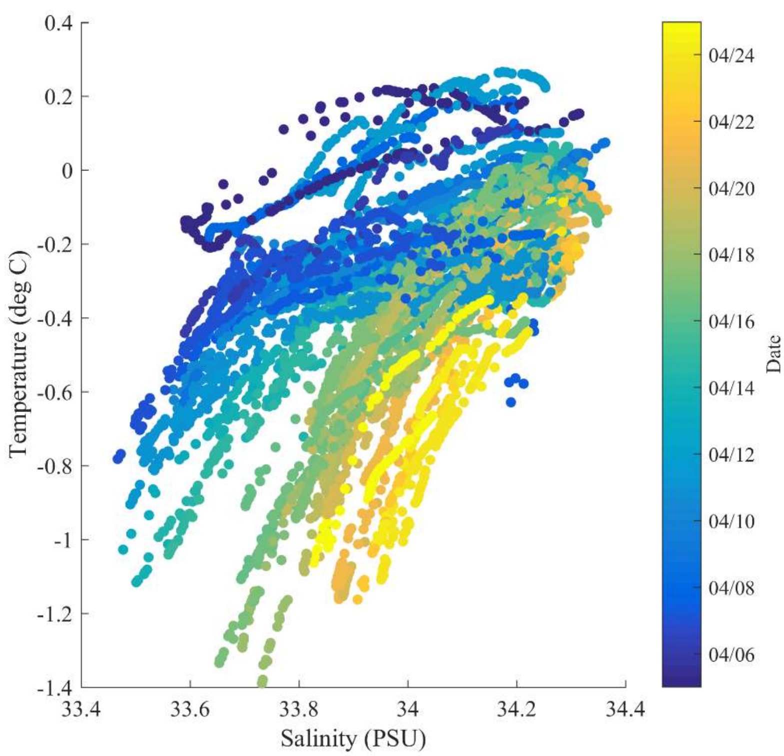

Figure 9: Temperature versus salinity in the top 75 dBar of the water column inside of Andvord Bay for April, falsely colored according to date during the second cruise (Austral fall).

Austral summer

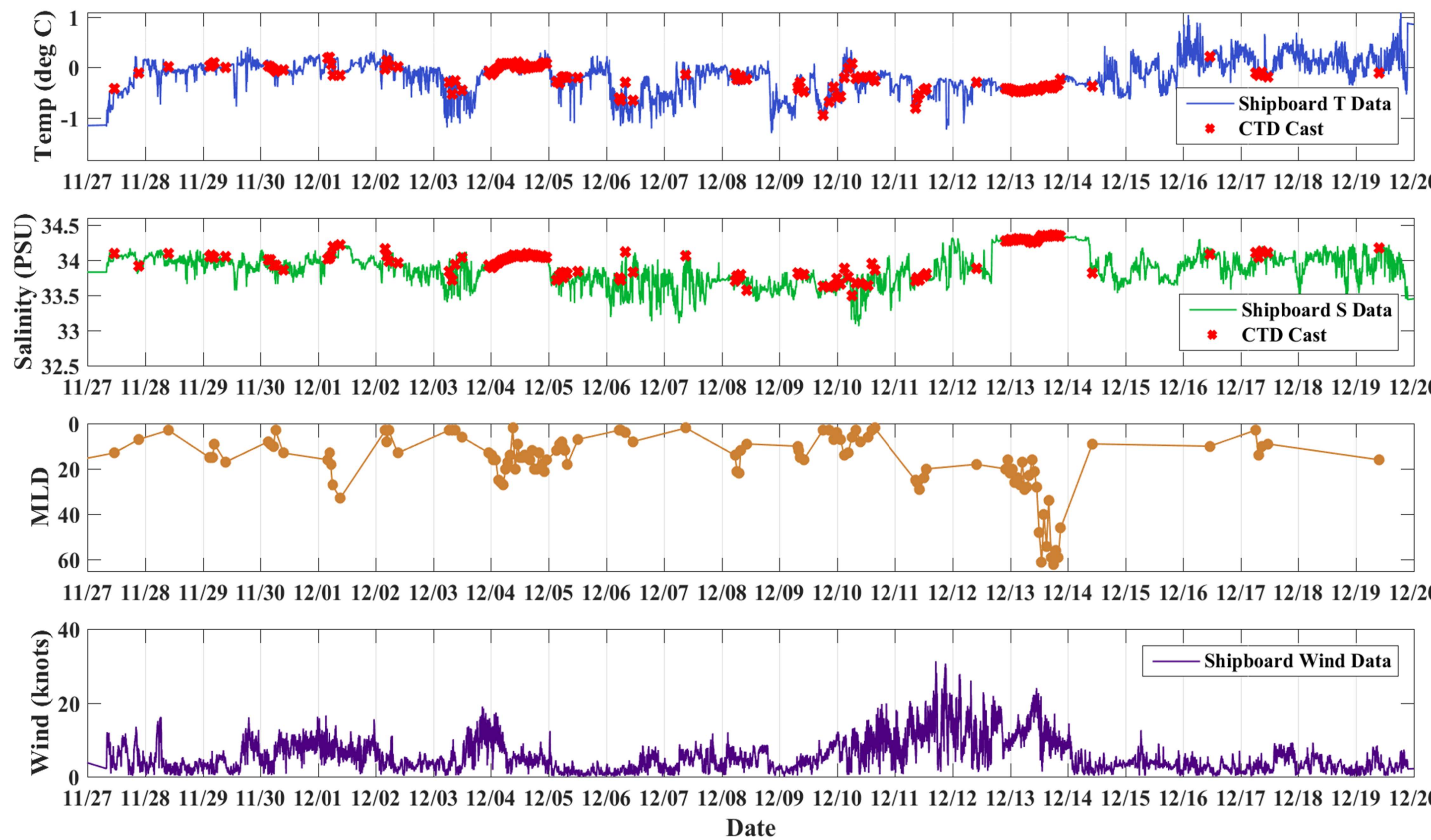

Figure 10: Time series for temperature, salinity, mixed layer depth, and wind velocity from summer 2015 flow-through and CTD data. Red x's mark the CTD data points at the depth of best fit with the ship data, the brown circle in the MLD plot signify the actual data points.

Austral fall

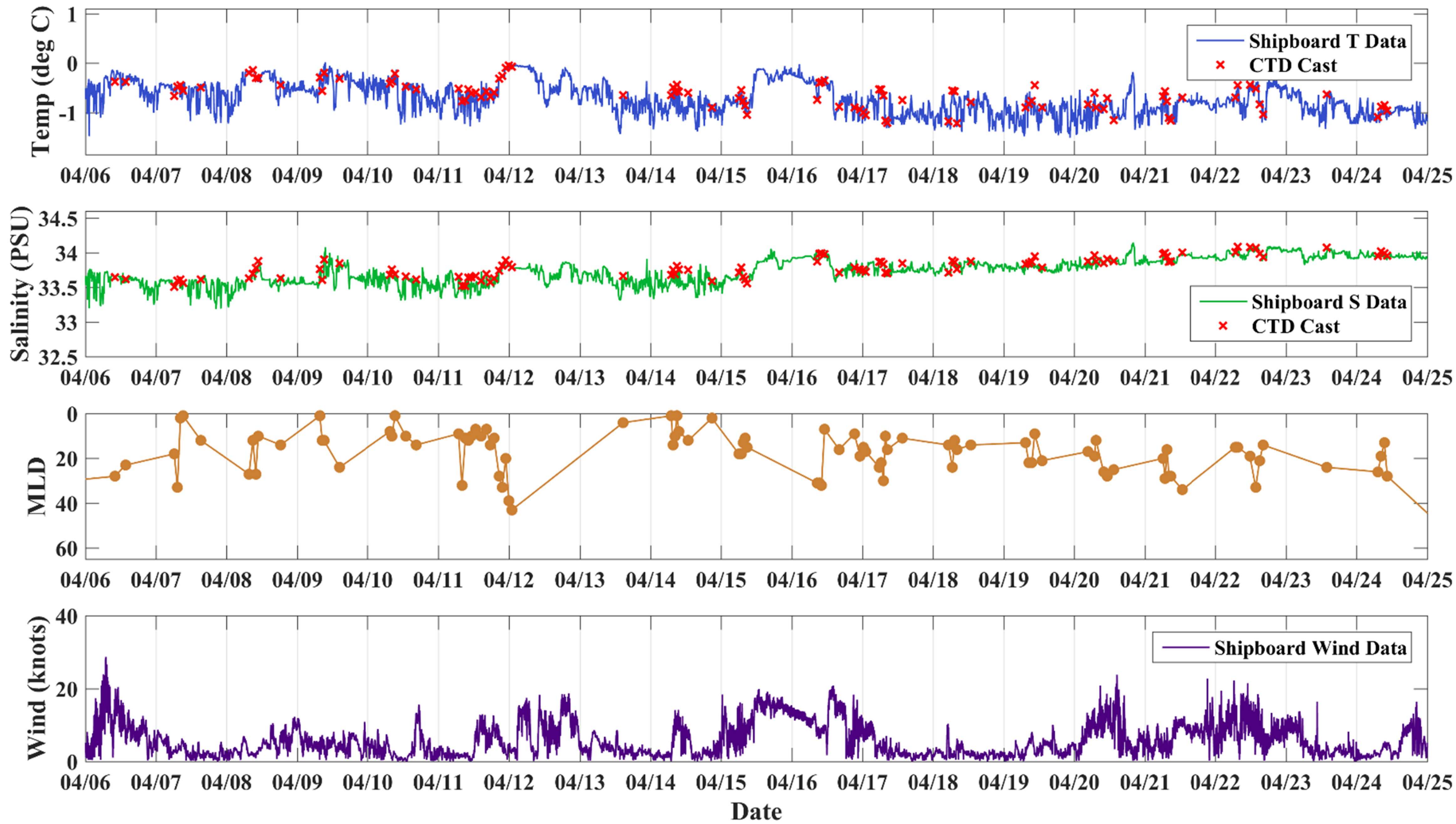

Figure 11: Time series for temperature, salinity, mixed layer depth, and wind velocity from fall 2016 flow-through and CTD data. Red x's mark the CTD data points at the depth of best fit with the ship data, the brown circle in the MLD plot signify the actual data points.

5.2.3 Variability with Wind Forcing

In addition to trends in water properties over the course of each cruise, shorter-term temporal variations occur in response to wind events. In general, the fjord does not experience high wind velocities as it is relatively sheltered by elevated topography and steep walls. However, due to the steep wall topography, there are katabatic wind events that blow down-channel. During the cruises there were a few, apparently katabatic, wind events that occurred, the most prominent of which was during the summer cruise (Figures 10, 11). The dates of the most obvious events for each cruise are April 15-16 for the fall cruise, and December 3-4 as well as December 11-13 for the summer cruise. These events are characterized by a general stabilization of fluctuations in the upper layer as well as an overall increase in salinity and decrease in temperature from the time before the wind event (Figures 10, 11). The system does not immediately react to an increase in wind speed, but the changes lag the start of a wind event by approximately one day (Figure 12). When the changes occur, the MLD deepens significantly. It appears that the upper layer takes on the temperature and salinity qualities of lower levels in the water column, suggesting that the fresh, stratified upper layer is advected out of the fjord and replaced with upwelled waters. The MLD deepening reflects the replacement of the stratified layer by more homogenous deeper water, as well as presumable mixing by wind-driven turbulence in the mixed layer. After the winds weaken, the MLD, temperature and salinity begin to revert to pre-event conditions within 3 days (Figure 12).

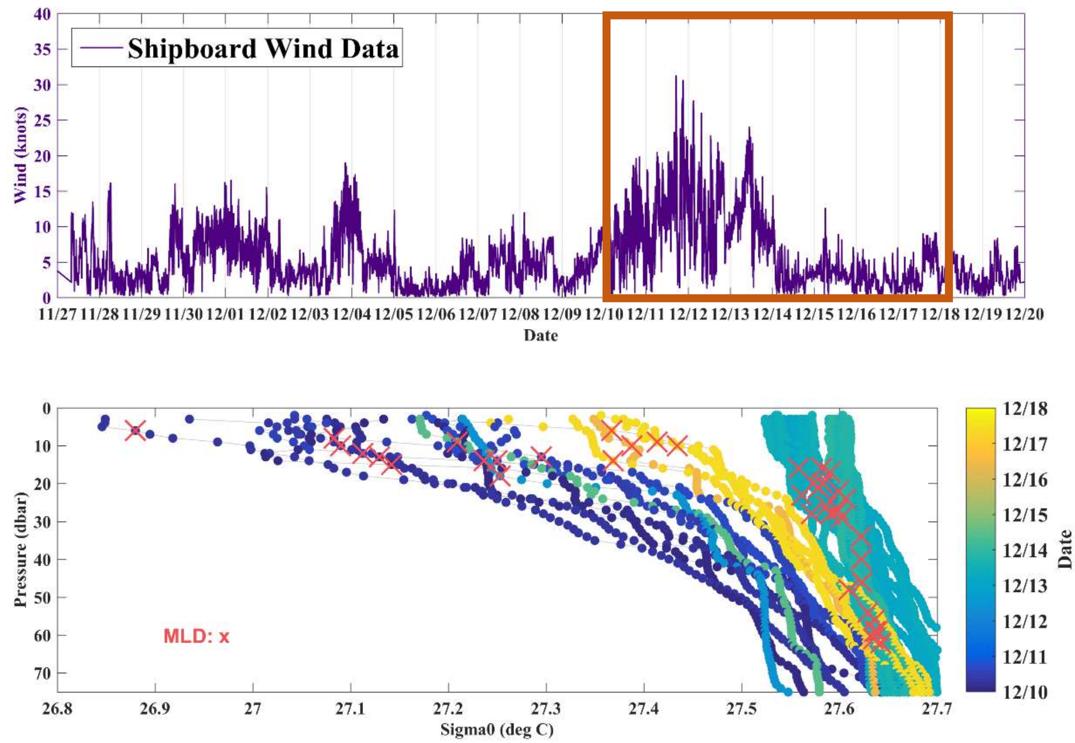

Figure 12:

Top) Ship wind velocity data over time for the first cruise (summer). The orange box highlights a wind event. The box encloses the start of high winds, the subsequent die down, and the eventual return of weak winds.

Bottom) CTD cast data for density in the top 75 dBar marked with the mathematical MLD values of inside the fjord for the times shown in the orange box from above, December 10 – December 18 (before, during, and after the wind event).

CHAPTER 6. DISCUSSION

6.1 MLD Determinations

The MLD calculations were most effective with the threshold method using a threshold value of $\Delta\sigma = 0.03$ kg/m^3. I did expect the use of a lower threshold value to be more accurate than the use of a higher threshold value. Using a lower value is better suited to polar environments because the lower threshold is able to pick up the MLD values that are more subtle. However, I had hypothesized that the higher order weighting method would be the most accurate due to its finer degree of calculations. In reality, the higher order weighting method was not as effective due to the noise and upper layer deviations from a well-mixed layer present in the samples. In general, there remains a wide margin of error between the best mathematic approach, threshold with $\Delta\sigma = 0.03$ kg/m^3, and a visual approach. The main reason for this is because of the occurrence of weakly stratified layers where a visual approach MLD should be 0, but the mathematic approach still assigns a value. This happens because the formula for finding the MLD only looks for the first point where the density moves one threshold away from the surface density regardless of whether or not the pycnocline is started at the surface. One possible solution to gauge the accuracy of the threshold method in future cases is to analyze the slope of the density inside of the mixed layer that the threshold method provides. If the slope is close to vertical, the system is well mixed and the MLD value is likely accurate. If the slope is more slanted, it is possible that the water is weakly stratified and the pycnocline starts at the surface meaning that the mathematic MLD is not accurate.

6.2 Variability Analysis

The most prominent conclusions to draw from the trend analysis portion of this project are that changes in time are the largest factors that impact the variability of the upper layer in WAP fjord, although wind forcing does play an occasional role particularly with MLD and upper layer stratification. Surface flux appears to be a major driver of temperature and salinity in the upper layer. Geographic influences are less prominent and are mostly relevant between the inside and outside of the fjord (Andvord Bay vs. Gerlache Strait).

6.2.1 Variability in Space

The lack of large variation between the different basins was somewhat unexpected. Although I did not expect to see a large difference between the individual basins, I did theorize that the characteristics should approach what is seen in the strait when moving from the inner basins to the mouth of the fjord and into the strait as the water mixed between the two. This effect is not highly prominent and on the surface level it is fairly negligible. The strait is a fast moving, deep column that is not highly sheltered from the normal winds commonly running in a direction parallel to the strait by surrounding topography. Based on the profile from these cruises, the upper layer in the strait is commonly well mixed and relatively deep. The fjord is a lower energy, shallower system that is highly sheltered from winds except in the cases of katabatic wind events. In the fjord, the mixed layer is variable, but it is where the stratified layers occur most often. Because Gerlache Strait and Andvord Bay are different bodies of water that are subject to different forcing, it is clear why the largest spatial difference was between the strait and fjord. Since the fjord and strait are distinct, there are implications that there is a small amount of interaction between the fjord and strait at the surface layer. I hypothesize that there is little interaction particularly in the summer based on the distinct temperature and salinity profiles as well as the MLD calculations; however, it is possible that there is more interaction on the surface layer during the fall (Figure 6). The most unique difference between the fjord basins was between IBA and IBB in the fall cruise. These spatial differences may be accounted for by the inputs into each basin. The density of IBA may be greater than IBB during the fall cruise due to a lower amount of meltwater flux to the surface or a greater amount of ice formation in IBA. This implies that the tidewater glaciers that feed into IBB may be melting at a faster rate. Any differences between individual basins inside of the fjord are greatly overshadowed by the effects of time on the characteristics of the fjord.

6.2.2 Variability in Time

The seasonal variability of the characteristics in the upper layer is the dominant variability. The differences between the summer and fall cruise are due to seasonal heat fluxes that occur between summer and fall. As expected, the temperature decreased between the summer and fall due to the change in season and colder air temperatures. I had predicted that the density and salinity would increase between the two cruises due the start of ice formation. However, I did not see this in the data. I hypothesize that this is because the seasons had not changed enough between the two cruises, thereby not allowing winter sea ice formation to impact the salinity. However, during the fall cruise, evidence of preliminary winter ice formation is present in the general trend of temperature decrease and salinity increase. The sea surface temperature decrease is due to the progression of the season into winter. The colder temperatures allow for ice formation to occur, which causes an increase in salinity from brine rejection as the ice forms. The summer cruise does not show as much of a difference in the salinity because there was considerably less ice at the time of the cruise. There is still an increase in temperature during the summer cruise because the summer season is still progressing onward. The seasonal signals in the fall cruise are more evident than those in the summer cruise because it is during a time of stronger seasonal transition. There are occasional temperature and salinity changes during both cruises that are on a shorter time scale than the seasonal cycle that are likely influenced by local wind stress.

6.2.3 Variability with Wind Forcing

Although Andvord Bay is sheltered from the winds, it is still subject to down-channel katabatic wind events. These wind events have an impact on the upper layer of the system by increasing the momentum flux at the surface. I suspect that the upper layer is advected out of the fjord instead of mixed down during these wind events based on how the upper layer characteristics during wind events appear similar to the waters below (Figure 12). If wind events were mixing the upper layer deeper, I would see a combination of the upper layer and the waters below in Temperature-Salinity plots. Since it appears that the upper layer is advected out of the fjord, the water below the upper layer upwells to the surface. This could be impactful for the chemical and biological fluxes that are key to high productivity in the fjord. Upwelling allows nutrients to be brought to the surface which are essential to the phytoplankton and krill that rely on photosynthesis. The lag between the start of the wind event and the reaction of the water column is to be expected based on the transfer of energy from the surface through the upper layer. Unfortunately, no CTD or shipboard samples were taken in Gerlache Strait during wind events so there is no way to definitively classify how the upper layer of the strait reacts to a different wind direction. A future direction for this work would be to characterize how the upper layer of Gerlache Strait and the area surrounding the fjord reacts to the addition of katabatic wind events.

CHAPTER 7. CONCLUSIONS

A reasonably accurate approach for calculating MLD in Andvord Bay is the threshold method based on density profiles using a threshold value of $\Delta\sigma = 0.03$ kg/m^3. Although there are still discrepancies using this particular method compared to visual detection, it was effective in calculating the MLD in most conditions, particularly when the mixed layer properties are fairly homogeneous. In cases of weak stratification or high noise levels, the threshold method approach is susceptible to errors and a visual analysis of the profiles is recommended. In the future, developing a measure of accuracy utilizing a classification of the mixing and determining which cases are best suited to a numeric approach would aid in finding cases where the threshold approach is less than favorable and would allow for additional criteria in the algorithm, such as weak stratification right to the surface. Finding the MLD was a major part in determining the upper layer structure of Andvord Bay and the first step in understanding the variability of the fjord based on different variables.

As has been previously stated, the largest impact on the changes of the upper layer in Andvord Bay was based on the seasonal heat flux. As the solar radiation decreases and increases in fall and spring, respectively, the relationship between sea ice, salinity, and density becomes a major driver of the characteristics in the upper layer, namely the density. The most predominant changes are likely to occur in the transitional seasons, spring and fall, when winter sea ice is either melting or beginning to form. Because mixed layer densities are largely salinity driven, the seasonal cycle of the area is reflected in the changes of salinity with increasing salinity occurring during decreases in solar radiation and decreasing salinity occurring during increases in solar radiation. Wind velocities contribute smaller time scale variability that may be highly important to the biological and chemical signatures of the fjord. Without the exchange of water between the upper layer and the layers below the pycnocline, nutrients would become more limited and the biological productivity of the fjord would be decreased. The results of this research that focus specifically on the upper layer structure and variability will aid in the continuation of the Fjord ECO project as it develops a deeper understanding of Andvord Bay and other similar WAP fjords.

In furthering this research, examining the dynamics horizontal movement of the upper layer would be beneficial to a deeper understanding of the system. Analyzing how the water moves between basins and between the fjord and strait would help in gaining a larger picture of how the fjord is circulating and how the upper layer contributes to the overall dynamics of the system.

Andvord Bay is very similar to many high-latitude, glacio-marine fjords along the WAP. Using the information gained about the upper layer in union with other projects associated with Fjord ECO, will give a broad idea of the oceanographic physics, chemistry, and biology of other fjords along the WAP. This information may allow for us to predict changes in the system that may occur as the globe changes. Any change in the fjords of this area could have an impact on whale feeding and krill growth. I expect that increases in global temperatures may increase the meltwater flux to the fjords in this area and the systems may begin to behave similarly to Arctic glacio-marine fjords. This means that the turbidity would be increased and the biological abundance may be drastically reduced. If this should happen, there is no definite way to know how the different populations of different species would react. To best predict how the biological hotspots of the WAP fjords will change, a deeper examination using models and observational data of more fjords is necessary.

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