Circulation Changes in the Arctic Ocean and Subarctic Seas and Their Connections to the Global Ocean and Climate

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CIRCULATION CHANGES IN THE ARCTIC OCEAN AND SUBARCTIC SEAS AND THEIR CONNECTIONS TO THE GLOBAL OCEAN AND CLIMATE

by

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Bachelor of Science
University of South Carolina, 2018

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ABSTRACT

Salinity and freshwater fluxes are important tools for monitoring the amount of freshwater entering and exiting the Arctic Ocean. Satellite-derived salinity provides a way to study surface advective freshwater fluxes; however, sea ice contamination, among others, remains an obstacle in the accuracy and reliability of these measurements. In this study, salinity and surface freshwater fluxes are calculated using NASA’s Soil Moisture Active Passive (SMAP) and the ESA’s Soil Moisture Ocean Salinity (SMOS), Argo, and the European Centre for Medium-Range Weather Forecast’s Ocean Reanalysis version 4 (ORAS4). ORAS4 compares well to Argo in the subarctic seas and is used for comparison to the satellites in the Bering Strait and Barents Sea Opening (BSO). There is agreement between satellites and ORAS4 on average and variability of freshwater fluxes in the Bering Strait, demonstrating the potential satellites have to study these fluxes in lower latitude subarctic regions with high freshwater variability. In the BSO, however, the satellites were not able to capture similar fluxes as ORAS4, indicating the need to improve satellite-derived salinity in polar regions.

This finding is increasingly important as the Arctic changes and more accurate, widespread data are needed. Satellites and models are used to examine decadal changes in the Arctic Ocean and subarctic seas. Salinity has undergone one of the most significant changes, as there is a juxtaposition of trends, with the Canada Basin freshening, and many other seas undergoing salinification. This is caused by decreasing sea ice, and a shift toward an anticyclonic atmospheric circulation regime over the Arctic, which alters riverine flow,
freshwater output, and Beaufort Gyre strength. Increasing ocean temperatures across the Arctic Ocean and most significantly, the subarctic Atlantic region, are also found. This likely contributed to thermal expansion which, in addition to ice sheet loss, has caused increasing sea level anomalies across the Arctic and subarctic regions. The warming and salinification in the subarctic Atlantic and Barents Sea may be due to an increased proportion of Atlantic waters in the region, owing to the shift to a more anticyclonic circulation regime in the late 1990s.
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CHAPTER 1

INTRODUCTION

A. Arctic Environment

Salinity plays a large role in the Arctic Ocean as it is the dominant factor impacting stratification and density. However, salinity varies due to seasonal melting and formation of sea ice, high riverine input, and shifts in precipitation patterns. There is also input into the Arctic Ocean of Pacific water through the Bering Strait and Atlantic Water through the Fram Strait and Barents Sea Opening. The Atlantic Ocean water is typically warmer and has a much higher salinity than both Pacific and Arctic water. It circulates through the Arctic Ocean, freshening as it mixes with Pacific and Arctic water and then exits through the Fram Strait, Canadian Arctic Archipelago, or Davis Strait. The typical patterns of upper ocean currents can be seen in Figure 1.1. As shown in this figure, Atlantic water is associated with an upward heat flux, particularly in the Barents Sea and Eurasian Basin.

Dense water formation, contributing to thermohaline circulation occurs in the Arctic and subarctic regions. There has been some debate as to whether a freshening in the Arctic Ocean and Arctic output to the Atlantic can impact the strength of this overturning circulation. Some studies suggest that even a small freshwater addition of 0.1 Sv or less could affect the AMOC [e.g. Hawkins et al., 2011], while other argue that the AMOC is not as sensitive to changes in freshwater [e.g. Jungclaus et al., 2006]. The changes in
salinity in the Arctic Ocean and variability of freshwater fluxes to the subarctic Atlantic are crucially important to understand as the strength of the overturning circulation can impact global climate.

Unfortunately, due to the remoteness of the region and year-round sea ice coverage, measurements of salinity in the Arctic have been scarce. Most Argo floats do not work under sea ice and the amount of data from ships, buoys, and transects is limited, both spatially and temporally. For this region, satellite-derived sea surface salinity (SSS) could potentially help this problem, at least in the ice-free Arctic and subarctic regions. However, there are many problems associated with satellite-derived salinity at the high latitudes due to the cold-water in the polar regions, high winds and strong waves, and sea ice and land contamination. As previously stated, there is a lack of in-situ measurements for validation [Garcia-Eidell et al., 2017; Tang et al., 2014; 2017], as Argo floats do not work under sea ice, and there are few ships and surveys.

B. Oceanic and Atmospheric Changes

Increasing measurements in this region is particularly important as the Arctic environment has been experiencing drastic changes in the past century, with a particularly noticeable increase within the past few decades. It has been warming at a higher rate than the global average, known as Arctic Amplification. These rises in temperature are also associated with a loss of sea ice, in volume, age, and extent [e.g. Stroeve and Notz, 2018]. In addition to the rising air and sea temperatures, freshwater, both in quantity and distribution, have been changing and can have serious implications, hence the need to improve satellite-derived salinity measurements in the Arctic Ocean and subarctic seas.
Several indices help to identify whether circulation changes may be driving salinity variation in Arctic and subarctic regions; these include the Arctic Ocean Oscillation (AOO), Arctic Oscillation (AO), and North Atlantic Oscillation (NAO). Other indices that may have teleconnections in the Arctic Ocean, like El Nino Southern Oscillation or the Pacific Decadal Oscillation, but the AOO, AO, and NAO capture most of the variability.

The AOO is used to describe the cyclonicity of the Arctic atmosphere. This can have major impacts on Arctic circulation. The AO can also be used to define the atmospheric circulation of the Arctic environment. However, within the past decade, while the circulation has been consistently anticyclonic, the AO was variable and did not represent this change. The AO and AOO are typically inversely related. The circulation patterns of the Arctic Ocean are shown during the two phases of AO in Figure 1.2. Low or negative AO (typically positive AOO), referred to as the anticyclonic mode, is characterized by Eurasian runoff exciting through the Fram Strait directly, and strengthening of the anticyclonic Beaufort High and Beaufort Gyre. The positive or high AO (typically negative AOO), referred to as the cyclonic mode or circulation regime, is characterized by increased Eurasian runoff into the Canada Basin, though a weakening or reversal of the anticyclonic Beaufort High and Beaufort Gyre. These modes typically vary every 5 to 7 years. While salinity in the Arctic Ocean changes seasonally due to ice melt in summer and formation in winter, much of the interannual and seasonal variability of salinity is due to changes in circulation. During the anticyclonic mode or circulation regime, freshwater builds up in the Canada Basin.
C. Enhancing Understanding of the Arctic Environment

This thesis explores the current state of knowledge and gaps in understanding of the Arctic Ocean and its connection with subarctic seas. This helps to advance our understanding of the relationship between changes in the Arctic Ocean and global ocean circulation and climate. Chapter two examines salinity and surface advective freshwater fluxes in Arctic pathways, comparing these results to in-situ data and a reanalysis product. There are disagreements between previous estimates and different models as to the strength of these freshwater fluxes, so improvements are necessary. This research provides a new method to calculate these fluxes, while examining areas of improvement, as there is still uncertainty and error in satellite-derived salinity in the Arctic region. The third chapter examines decadal variability in salinity, temperature, wind speed, sea ice extent, and sea level anomalies in the Arctic Ocean and subarctic seas. As these regions are changing so drastically and can impact global climate, their decadal variability has garnered much research attention. However, due to a sparsity of in situ observations, there are still gaps in our knowledge of these changes. Chapter three examines basin-wide changes as well as regionally specific changes, and how they compare to previous literature. This chapter also examines the connection between variability in these parameters and different climate indices. The fourth and final chapter summarizes the findings of this research, and how it has contributed to a better understanding of the changing Arctic landscape, as well as using different methods to study freshwater processes. This chapter also explores the prevailing gaps in our understanding of Beaufort Gyre and the potential for new research. The Beaufort Gyre is important for Arctic circulation and freshwater storage. Chapter four
presents preliminary results on the variability of salinity and freshwater content in this gyre and how it is connected to atmospheric circulation.
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CHAPTER 2

ESTIMATION OF SURFACE FRESHWATER FLUXES IN THE ARCTIC OCEAN

USING SATELLITE-DERIVED SALINITY


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ABSTRACT

The temporal and spatial distribution of sea surface salinity (SSS) is not well known in the Arctic region, and only recent satellite-derived measurements and models have allowed for potential enhancement, though their accuracy remains uncertain. We use NASA’s Soil Moisture Active Passive (SMAP) and the European Space Agency’s Soil Moisture Ocean Salinity (SMOS) to investigate the variability of SSS in the Arctic from 2015 to 2017, as well as to calculate surface advective freshwater fluxes. These data sets are compared with Argo and ECMWF’s Ocean Reanalysis version 4 (ORAS) to assess the ability of satellites in detecting freshwater fluxes. Salinity and surface freshwater fluxes are estimated for the Bering Strait and Barents Sea Opening. In this study, we have compared the Jet Propulsion Laboratory’s (JPL) SMAP salinity to the Remote Sensing System’s (RSS) SMAP salinity product, as well as the CATDS SMOS salinity product. There is disagreement between the reanalysis product and satellites on the mean and variability of surface freshwater fluxes in the BSO; however, the meridional fluxes of the satellites and reanalysis product were significantly correlated within the Bering Strait. This shows the capability of using satellites to measure surface freshwater fluxes in this pathway. However, the discrepancies between satellite derived SSS and fluxes in other regions of the Arctic Ocean emphasizes the need to increase in situ monitoring to help validate satellites in the higher latitudes.
2.1 INTRODUCTION

The Arctic Ocean plays a very important role in the Earth’s freshwater cycle, essential to both the oceanic and atmospheric components in the Northern Hemisphere. The Arctic Ocean acts as a gateway connecting the North Pacific waters to the North Atlantic and is a key region in the deep-water formation of the meridional overturning circulation. High salinity water from the Atlantic cools as it enters the Arctic, causing overturning circulation. Some studies suggest an addition of freshwater into the Arctic could have an effect on this overturning \[ \text{e.g. Rahmstorf et al., 1995; Hawkins et al., 2011} \]. Monitoring freshwater fluxes in the Arctic is therefore crucial to see the effects of freshwater input on circulation and climate. However, Arctic Ocean processes are difficult to study due to perennial ice and the remoteness of the region. Freshwater fluxes and content can be affected by circulation \[ \text{e.g. Haine et al., 2015} \] and salinity, which are in turn impacted by precipitation, evaporation, rivers, and ice \[ \text{Bintania and Selten, 2014} \]. Changes in circulation can impact the strength of the freshwater fluxes as well as where the freshwater is stored or released. The seasonal release of brine and freshwater from ice melting and formation drives changes in near-ice salinity \[ \text{Ricker et al., 2017} \].

In order to determine the surface advective freshwater fluxes into the Arctic Ocean we analyze two major Arctic pathways, the Bering Strait and Barents Sea Opening (BSO), as shown in Figure 2.1. The Bering Strait transports low salinity water from the Pacific Ocean into the Arctic. The BSO is a region of inflow of salty Atlantic water to the Arctic region between Svalbard and Norway. There have been many previous studies estimating freshwater fluxes in the Arctic Ocean \[ \text{e.g. Haine et al., 2015; Bamber et al., 2012; Serreze et al., 2006} \]; however, none have estimated these fluxes using satellite derived SSS. There
is disagreement between different models as to the strength of freshwater fluxes from different regions [Armitage et al., 2016], emphasizing the need to improve estimates using remote sensing techniques. Previous literature has found Bering Strait freshwater contributions to the Arctic have increased since the 1990s [Bamber et al., 2012; Haine et al., 2015]. Most studies do not specifically look at the BSO, but instead include it in “miscellaneous” categories combined with other regions, due to the uncertainty, again emphasizing the need to improve estimates.

Comparisons between satellite-derived SSS, reanalysis products, and in-situ observations will help assess the capability of using satellites to study surface freshwater processes in the Arctic region. SSS in the polar regions is difficult to monitor from satellites due to the cold-water reducing the sensitivity of L-band instruments to SSS [Klein et al., 1977; Lang et al., 2016], high winds and strong waves affecting surface roughness and the accuracy of SSS [Brucker et al., 2014a; 2014b], and the lack of in-situ measurements for validation [Garcia-Eidell et al., 2017; Tang et al., 2014; 2017]. Nevertheless, NASA’s Jet Propulsion Laboratory’s Soil Moisture Active Passive (JPL SMAP) salinity data version 4 utilizes a new correction strategy in the Arctic region to account for the large uncertainties and errors near land and sea ice. It was found to have a root mean square difference less than ~1 psu and a correlation coefficient of ~0.82 psu with in-situ data north of 50° N [Tang et al., 2018]. The Remote Sensing System’s SMAP (RSS SMAP) salinity data version 3 product also provides SSS measurements in the Arctic Ocean, however more data is removed using their algorithm due to ice bias and land contamination, as shown by the extent of the product into the Arctic and along coasts (Figure 2.3). This removes bias associated with the SSS measurements near ice or land; however, important measurements
along the sea ice edge are removed. The LOCEAN CATDS SMOS version 3 product also improved high latitudinal biases in SSS as well as land-sea biases close to coasts. With these uncertainties in mind, we examine the Arctic region using a variety of remote sensing datasets, JPL SMAP, RSS SMAP, and SMOS salinity, as well as surface salinity from the ECMWF’s Ocean Reanalysis version 4 (ORAS).

2.2 MATERIALS AND METHODS

A. Observational data

SMAP was launched on January 31, 2015, with data availability beginning in April 2015. JPL SMAP version 4 level 3 monthly product (DOI: 10.5067/SMP40-3TMCS) [Fore et al., 2016] is used to analyze SSS and derive surface freshwater fluxes within the Arctic. The SMAP product has a 60 km feature resolution and provides sea surface salinity at 0.25° x 0.25° gridded spatial resolution. We also use RSS SMAP version 3 level 3 monthly product (DOI: 10.5067/SMP3A-3SPCS) [Meissner and Wentz, 2016; Meissner et al., 2018]. The feature resolution of this product is 70 km and it is provided in 0.25° x 0.25° gridded spatial resolution. We also use version 3 of debiased Soil Moisture Ocean Salinity (SMOS) level 3 18-day product generated by LOCEAN CATDS [Boutin et al., 2018a; 2018b]. This product is available from January 2010 through December 2017.

In order to calculate the surface freshwater fluxes, meridional and zonal geostrophic currents from Copernicus Marine Environment Monitoring Service (CMEMS) sea surface height (SSH) level 4 products are used for the components of velocity. The product identifier for the SSH from Copernicus is SEALEVEL_GLO_PHY_L4_REP_OBSERVATIONS_008_047 (reprocessed product). These near real-time and reprocessed products allow for quality control checks and cross-
calibration processes to remove residual orbit error. This dataset runs from January 1993 to present in 0.25° x 0.25° resolution.

We also use the Global Ocean Argo gridded data set (version 2018), generated by China Argo Real-time Data Center using the Barnes objective analysis [Lu et al., 2018], in order to validate the satellite derived SSS and reanalysis SSS. It covers the global ocean from 79.5° S-79.5° N from 2004 to 2017 in 1° x 1° spatial resolution. It has 58 vertical levels; however, we will be using the first layer at 0 dbar, or sea surface. When comparing the satellite products to Argo, we regridded the satellites to 1° x 1° spatial resolution.

B. Reanalysis Product

To compare to satellite-derived freshwater fluxes and Argo salinity, we use ECMWF’s ORAS (version 4) [Balmesda et al., 2013; Mogensen et al., 2012]. The product is in 1° x 1° horizontal resolution from 1959 to present and uses the Nucleus for European Modelling of the Ocean (NEMO) v3.0 ocean model with direct surface forcing from ERA40 and ERA-Interim as well as observational data from OIv2 SST, EN3 in-situ, and AVISO SLA.

C. Surface Advective Freshwater fluxes

The surface advective freshwater flux (hereby referred to as freshwater flux) is an important component in salinity variability and the movement of freshwater across the different Arctic regions. First, we estimate the freshwater anomaly ($S_{fw}$) from salinity [Mazloff et al., 2010]:

$$S_{fw} = (S_R - S_{SS})/S_R$$

(1)

$S_R$ is the reference salinity, 34.8 psu. This is approximately the mean salinity of the Arctic region and used in previous studies [Lique et al., 2009; Haine et al., 2015; Serreze et al.,...
2006; Dickson et al., 2007; Aagaard and Carmack, 1989]. SSS are the salinity values. Freshwater fluxes \((FW)\), in units of \(m^2 s^{-1}\), are estimated as:

\[
FW_{\text{zonal}} = U \cdot S_{fw} \cdot \text{lat}_{\text{dist}} \tag{2}
\]

\[
FW_{\text{meridional}} = V \cdot S_{fw} \cdot \text{lon}_{\text{dist}} \tag{3}
\]

\(U\) and \(V\) are the zonal and meridional geostrophic current components respectively \((m s^{-1})\), \(S_{fw}\) is the standardized (unitless) freshwater anomaly value from equation (1), and \(\text{lon}_{\text{dist}}\) and \(\text{lat}_{\text{dist}}\) are the horizontal expanse of the grid cell (m). This is a similar process to [Münchow et al., 2006], however we are only calculating surface fluxes. The relationships between the fluxes are compared through Pearson’s correlation coefficient. The correlations are tested with an alpha of 0.05, resulting in values of 95% confidence level.

\(D.\) Arctic Pathways

The Arctic Pathways considered throughout the analysis are the Bering Strait and BSO. The Bering Strait is important as freshwater is transported through this opening from the Pacific to the Arctic. The BSO is important as water moves between the Atlantic and Arctic in this region. The pathways are defined as:

Bering Strait: 60° N - 68° N and 160° W-170° E

BSO: 71° N-77° N and 17° E-29° E

The projections of the two pathways can be seen in Figure 2.1 overlaid on RSS SMAP SSS for September 2015 and are similar coordinates to Tang et al. (2018).

2.3 Results and Discussion

\(A.\) Comparison of SSS Products

In order to assess the capability of satellites in calculating freshwater fluxes in the Arctic and subarctic, we compare the SSS values of the various products to Argo. ORAS
shows low differences to Argo in both the Pacific and Atlantic (Figure 2.2). The satellites, JPL SMAP particularly, show higher salinity in the Pacific basin. SMOS has a lower SSS in much of the Atlantic whereas JPL SMAP is higher in most of the Atlantic as well. All satellites show higher deviation to Argo along the coasts and in the Greenland and Norwegian Seas. ORAS shows very low deviation from Argo across most of the subarctic. While Argo does not measure SSS in the regions of this study, we see agreement between ORAS and Argo in the regions just outside of the Bering Strait and BSO, suggesting this product can capture SSS well in the pathways defined by our study and may be used as a comparison for the satellites.

The greater similarities between Argo and ORAS may be due in part to sampling depth. The reanalysis product and Argo provide data at approximately 5 meters whereas satellite-derived salinity is measured in the top millimeters of the water column. The reanalysis product is also likely more similar to Argo because it incorporates in-situ observations in the creation of their datasets.

B. Salinity Variability

JPL SMAP, RSS SMAP, SMOS, and ORAS display similar SSS patterns in the subarctic, with high salinity in the Atlantic, lower salinity in the Pacific, and very low salinity in the Arctic (Figure 2.3). This is due to higher precipitation in the North Pacific than the North Atlantic and moisture transport from the Atlantic across Central America to the Pacific [Schmitt, 2008; Widell et al., 2006]. This causes the Pacific Ocean to act as a freshwater input to the Arctic, while the Atlantic input increases the SSS of the Arctic. ORAS covers the entire Arctic region, including below the sea ice, whereas the sea ice contaminated measurements are removed from the satellites. However, JPL SMAP and
SMOS algorithms retrieve and retain SSS measurements at higher latitudes in the Arctic than RSS SMAP. All the satellites, especially JPL SMAP, exhibit higher variability along coasts and the sea ice edge. ORAS shows much lower variability than the satellites in the central Pacific and Atlantic but show similar patterns of increased variability in many other regions. The variability in the satellite SSS for these products may be due to seasonal and interannual changes in SSS as well as residual ice and land contamination. It is important in the future to separate the effects of natural variability and sea ice contamination in order to improve satellite-derived salinity.

The SSS along the two pathways for JPL SMAP, RSS SMAP, SMOS, and ORAS are shown in Figure 2.4. JPL SMAP shows higher variability of SSS during this time period. This high variability occurs mainly during winter months when sea ice is greater in these regions, thus leading to more sea ice contamination. From December 2015 to April 2016 RSS SMAP has no measurements in this region because they were removed likely due to ice contamination, whereas JPL SMAP shows significantly lower SSS. In the Bering Strait the mean and 95% confidence interval are 31.99 ± 0.2090 psu for RSS SMAP, 30.73 ± 0.5469 psu for JPL SMAP, and 32.50 ± 0.0561 psu for SMOS. In the BSO the mean and 95% confidence interval are 34.76 ± 0.1450 psu for RSS SMAP, 34.71 ± 0.2829 psu for JPL SMAP, and 34.76 ± 0.0707 psu for SMOS. These SSS values are similar to previous studies for these regions [e.g. Tang et al., 2018; Schauer et al., 2002; Aagaard et al., 2006; Woodgate and Aagaard, 2005]. JPL SMAP has a lower salinity in the Bering Strait than RSS SMAP or SMOS due to significantly lower salinity during the winter months. BSO has higher SSS than the Bering Strait because most of the water in this region is from the
Atlantic, which has a higher SSS overall compared to the Pacific and the Arctic Oceans [Schmitt et al., 1989].

The variations between the SMAP products are due to the screening for sea ice and land contamination. However, the differences between the SMAP and SMOS products also come from differences in the satellite’s measurements. Sea ice can have a large impact on satellite sensors. More areas were removed from the RSS SMAP product due to sea ice contamination compared to the JPL SMAP. While this removes measurements close to the ice edge, which is an area of importance for freshwater flux measurements, it allows for less bias or error. This is why the Bering Strait and BSO were focused on in this study. Compared with other gateways in the Arctic, like the Davis Strait or Fram Strait, the BSO and Bering Strait have less error due to lower sea ice concentrations, higher water temperatures, and a greater distance from the land.

C. Surface Advective Freshwater Fluxes

These surface advective freshwater fluxes are calculated using geostrophic currents from blended altimetry. The zonal and meridional geostrophic currents are shown in Figure 2.5. These figures show the direction and strength of the currents used to calculate the fluxes. The red (blue) currents represent northward/eastward (southward/westward) propagation. As expected, we can see water entering the Arctic through the Bering Strait as well as the BSO. We can also see that the deviation of these currents within the Bering Strait and BSO range from near 0 up to approximately 0.08 m s\(^{-1}\). This variability from being due to changes in the flow of the water which can be impacted by many factors, most notably wind.
The circulation and strength of surface advective freshwater fluxes between the Arctic and subarctic seas can be seen in Figures 2.6 and 2.7, along with the standard deviation of these fluxes. Red represents freshwater moving northward (eastward) for the meridional (zonal) fluxes. The high standard deviations depict the large seasonal and interannual variability in the freshwater fluxes, as well as error associated with the measurements. The North Atlantic fluxes show lower deviations except along Greenland, however the central Atlantic shows greater variability. Along Greenland, especially in the Fram Strait and Davis Strait, there is a high seasonal cycle of salinity due to the melting and formation of ice. In the central Atlantic, the high variability may be due to variation in the strength and location of the North Atlantic Drift. The fluxes have standard deviations that are as large or higher than the mean fluxes in localized regions. These figures show the regions where freshwater is moving into the Arctic, like the Bering Strait, and regions where freshwater is leaving the Arctic, like much of the subarctic Atlantic. The direction of these fluxes is what we would expect to see based on surface currents in these regions. For example, in most of the subarctic Pacific the fluxes are northward propagating because Pacific waters move into the Arctic. However, in the subarctic Atlantic the freshwater fluxes are generally southward propagating as there is high freshwater export out of the Arctic.

The satellite-derived zonal and meridional surface advective freshwater fluxes are compared to ORAS in the Bering Strait and BSO (Figures 2.8 and 2.9). Some satellite products were able to detect similar mean flux and variability to ORAS in the Bering Strait, however in the BSO they were very different (Table 2.1). ORAS can also be used as an external reference for the satellites, as it covers the same time period and shows similar
SSS to Argo in the subarctic. However, there were no significant correlation between the zonal freshwater fluxes of ORAS and any of the satellites. For meridional fluxes, ORAS was significantly correlated to JPL SMAP (0.4017), SMOS (0.5358), and RSS SMAP (0.4560) in the Bering Strait. While SMOS meridional freshwater flux had the highest correlation to ORAS in the Bering Strait, JPL SMAP was most similar in mean flux to ORAS (1642.40 ± 996.72 m² s⁻¹ for JPL SMAP and 1501.4 ± 1324.5 m² s⁻¹ for ORAS). The only significant correlations with satellite products and ORAS in the BSO were negative, indicating the satellites do not capture an accurate representation of the fluxes in this region. The Bering Strait is at a lower latitude than the BSO which could decrease errors associated with SSS retrieval in the higher latitudes. The means and standard deviations for each product freshwater fluxes are shown in Table 2.1. These values show very different means and standard deviations in the BSO. In the Bering Strait, the meridional flux values are more similar, hence why we see significant correlations between meridional fluxes in this region.

These results indicate these satellites may be capable of measuring the variability of surface freshwater fluxes in the Bering Strait. The BSO, due to its higher latitude and proximity to many land masses, does not show the same capability of satellites in measuring surface freshwater fluxes. The Bering Strait has a much larger amplitude than BSO (Figures 2.8-2.9) which is able to be captured by the satellites and ORAS. This large variability is due to changes in local winds [e.g. Coachman and Aagaard, 1981] and substantial interannual salinity variability [Woodgate and Aagaard, 2005].

Variability in the surface freshwater fluxes are driven by multiple different factors, including SSS and geostrophic currents. These surface advective freshwater fluxes are
estimated as the freshwater anomaly compared to SSS of 34.8 psu. Larger freshwater fluxes indicate SSS values lower than this reference. The long-term trends of surface freshwater fluxes are not calculated as we were calculating fluxes during the SMAP time period and investigating the ability of satellites in measuring surface freshwater fluxes. However, a longer SSS trend will prove the utmost importance in monitoring the Arctic climate. The freshwater fluxes from all these datasets are calculated with geostrophic currents from altimetry based on SSH. While this is not an overall measure of the currents, there is a lack of full coverage currents in the Arctic region. This is a very difficult region to get accurate, year-round measurements due to the sea ice and harsh winter conditions. Error associated with geostrophic currents may also affect the freshwater flux calculations.

2.4 CONCLUSIONS

Satellite-derived SSS can capture overall patterns, like a higher SSS in the Atlantic, a low SSS in the Pacific, and a lower SSS in the Arctic. The satellites and ORAS are similar to Argo SSS in the subarctic seas. However, these satellites have more difficulty accounting for surface freshwater fluxes in smaller regions close to land and sea, like the Arctic gateways. The satellites can detect fluxes in similar magnitude and variability to ORAS in the Bering Strait; however, they have more difficulty in the BSO.

There is large variability, both from seasonal variability and product bias, in the SSS and resulting horizontal advective freshwater fluxes in the Arctic. The lack of consistency between products in these regions emphasizes the need to improve satellite derived measurements and uncertainties in the Arctic. This can be done by increasing in-situ observations on consistent, broad scales in order to validate the satellite data. As sea ice declines, impacting freshwater distribution in the Arctic, it is important to continue and
improve in-situ and satellite monitoring of this area because we do not yet fully know the broader impacts from climate change. While this study focuses on the surface region, it is also important to study potential changes with depth, which is why the accuracy of models and reanalysis products is crucial as well.

This work provides a way to study horizontal advective freshwater fluxes using satellite derived SSS in the Arctic region. As far as we are aware, there has not been work on surface advective freshwater fluxes derived from remote sensing SSS in the Arctic region due to previous data gaps and high latitude satellite uncertainties. The JPL SMAP product provides SSS measurements closer to the coasts and sea ice than previous sensors, which allows for better coverage of processes, but possesses large uncertainties in these regions. RSS SMAP and SMOS therefore have less uncertainty in the high latitudes due to sea ice contamination but miss critical processes along the sea ice in the Arctic. Satellite-derived salinity may also prove to better account for surface freshwater than ocean or ocean-atmosphere coupled models and can be used to improve future model simulations by assimilating these satellite derived salinity products.
**Table 2.1:** Zonal and meridional horizontal advective freshwater flux estimates (m$^2$ s$^{-1}$) from April 2015 to December 2017 in the Bering Strait and BSO for JPL SMAP, RSS SMAP, SMOS, and ORAS.

<table>
<thead>
<tr>
<th></th>
<th>Product</th>
<th>Zonal Mean</th>
<th>Standard Deviation</th>
<th>Meridional Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bering (m$^2$ s$^{-1}$)</td>
<td>JPL SMAP</td>
<td>1563.7</td>
<td>3954.8</td>
<td>1642.4</td>
<td>996.72</td>
</tr>
<tr>
<td></td>
<td>RSS SMAP</td>
<td>222.23</td>
<td>854.25</td>
<td>788.49</td>
<td>436.02</td>
</tr>
<tr>
<td></td>
<td>SMOS</td>
<td>-154.12</td>
<td>1388.5</td>
<td>963.23</td>
<td>503.48</td>
</tr>
<tr>
<td></td>
<td>ORAS</td>
<td>530.11</td>
<td>2799</td>
<td>1501.4</td>
<td>1324.5</td>
</tr>
<tr>
<td>BSO (m$^2$ s$^{-1}$)</td>
<td>JPL SMAP</td>
<td>-381.17</td>
<td>282.74</td>
<td>7.75</td>
<td>95.84</td>
</tr>
<tr>
<td></td>
<td>RSS SMAP</td>
<td>-71.72</td>
<td>329.97</td>
<td>-8.25</td>
<td>26.15</td>
</tr>
<tr>
<td></td>
<td>SMOS</td>
<td>9.15</td>
<td>60.38</td>
<td>4.15</td>
<td>16.3</td>
</tr>
<tr>
<td></td>
<td>ORAS</td>
<td>-41.1</td>
<td>67.39</td>
<td>-11.16</td>
<td>6.79</td>
</tr>
</tbody>
</table>
Figure 2.1: Projection of Arctic Pathways on RSS SMAP SSS for September 2015. Red box represents the Bering Strait and the black the Barents Sea Opening.
Figure 2.2: Mean (a-d) and standard deviations (e-h) of the JPL SMAP (a, e), RSS SMAP (b, f), and SMOS (c, g), and ORAS (d, h) salinity (psu) minus Argo salinity during April 2015 to December 2017.
Figure 2.3: Mean (a-d) SSS (psu) and standard deviation (e-h) from April 2015 to December 2017 for JPL SMAP (a, e), RSS SMAP (b, f), CATDS SMOS (c, g), and ORAS (d, h).
Figure 2.4: SSS (psu) timeseries, with standard error bars, in the Bering Strait and BSO from April 2015 to December 2017 using JPL SMAP (blue), RSS SMAP (orange), SMOS (purple), and ORAS (green).
Figure 2.5: Mean (a-b) and standard deviation (c-d) of the zonal (a, c) and meridional (b, d) geostrophic currents (m s\(^{-1}\)) from April 2015 to December 2017.
Figure 2.6: Mean (a-d) and standard deviation (e-h) of the zonal freshwater fluxes (m\textsuperscript{2} s\textsuperscript{-1}) from April 2015 to December 2017 for JPL SMAP (a, e), RSS SMAP (b, f), SMOS (c, g), and ORAS (d, h).
Figure 2.7: Mean (a-d) and standard deviation (e-h) of the meridional freshwater fluxes (m² s⁻¹) from April 2015 to December 2017 for JPL SMAP (a, e), RSS SMAP (b, f), SMOS (c, g), and ORAS (d, h).
Figure 2.8: Zonal freshwater flux timeseries, with standard error bars, using JPL SMAP (blue), RSS SMAP (orange), SMOS (purple), and ORAS (green) for the Bering Strait and Barents Sea Opening (BSO) from January 2015 to December 2017.
Figure 2.9: Meridional freshwater flux timeseries, with standard error bars, using JPL SMAP (blue), RSS SMAP (orange), SMOS (purple), and ORAS (green) for the Bering Strait and Barents Sea Opening (BSO) from January 2015 to December 2017.
CHAPTER 3

RECENT VARIABILITY IN THE ARCTIC OCEAN AND SUBARCTIC SEAS

ABSTRACT

The Arctic Ocean and subarctic seas have been undergoing significant changes, particularly evident throughout the past few decades. In this paper we examine the declining sea ice extent in the Arctic (-0.0639 million km$^2$ yr$^{-1}$), the increasing sea surface temperature (approximately 0.014 °C yr$^{-1}$ in the Arctic Ocean to 0.03 °C yr$^{-1}$ in the subarctic Atlantic) and sea surface height (2.2 mm yr$^{-1}$ in the Arctic Ocean to 2.4 mm yr$^{-1}$ in the subarctic Atlantic) and changing patterns of sea surface salinity using a variety of reanalysis and observational data products from 1990 to 2017. The Amerasian Basin, particularly the Beaufort Gyre, has been freshening, concurrent with a salinification of the Laptev, Barents, and Greenland Seas, both of which are due to a shift towards a more anticyclonic circulation regime, shift in freshwater storage, and ice melt. Even as this regime began to weaken in the past decade, the freshening in the Beaufort Gyre has continued. When comparing these different variables to climate indices we found an important connection between the Arctic Ocean Oscillation (AOO), sea surface height, sea surface temperatures, and ocean heat content in the subarctic Atlantic region, indicating more widespread impacts of atmospheric circulation changes in the Arctic region. The connection between AOO, sea level, and ocean heat content shows that changes in the cyclonicity of the Arctic Ocean can impact output to the subarctic Atlantic region, which affects the heat and sea level of the region. Salinification and warming in the subarctic Atlantic Ocean and Eurasian Basin indicate an increase in the amount of Atlantic Water in these basins.
3.1 Introduction

The Arctic has been changing at a much higher rate than the global average, a process known as Arctic Amplification [Screen and Simmonds, 2010]. Among the most notable of changes is the loss of sea ice which has been documented extensively [e.g. Stroeve and Notz, 2018; Ricker et al., 2017; Kwok, 2018]. This can have profound impacts on many aspects of the Arctic environment including freshwater content, ocean circulation, and albedo. This loss of sea ice has been caused by rising air and sea temperatures within the Arctic and subarctic regions [e.g. Polyakov et al., 2017; Timmermans, 2015]. Some variability in the Arctic and subarctic regions can be attributed to variations in atmospheric circulation, which can be represented in climate indices, like the Arctic Ocean Oscillation (AOO) and North Atlantic Oscillation (NAO) [e.g. Nagato and Tanaka, 2012; Rigor et al., 2002; Robson et al., 2018; Häkkinen and Proshutinsky, 2004].

There have been many studies examining changes within the Arctic Ocean and subarctic seas, examining the decrease in sea ice [e.g. Kwok and Rothrock, 2009], changes in the freshwater cycle [e.g. Peterson et al., 2006], warming air temperature and Arctic amplification [e.g. Chylek et al., 2009], among others. Most have examined changes in one variable focusing less on the connection between different oceanic and atmospheric parameters. In this paper we examine the decadal trends in sea level, ocean heat content (OHC), temperature, salinity, and sea ice extent (SIE) focusing on the time period since 1990. Sea ice cover can be affected by rising temperatures and affect salinity. The sea level can also be affected by rising temperatures through ice sheet melt and thermal expansion, as shown by increasing OHC. These properties are all interconnected making the study of their trends, but also their connections, integral. We also examine the connections between
AOO and NAO and these variables. These climate indices can describe the state of the atmosphere through time, be it sea level pressure or wind-driven circulation. Many of these parameters have not been examined over long time scales or large spatial areas. We examine surface temperature and salinity, but also examine these changes with depth. This study helps to broaden our current understanding of climatic changes of the Arctic and subarctic regions. We examine broad basin-wide trends, but also look at how and why these trends can change in different regions.

3.2 Data and Methods

A. Observational Data

The AOO index was originally defined by Proshutinsky and Johnson (1997) and is calculated based on an analysis of wind-driven simulated sea surface height (SSH) in the Arctic to describe the cyclonicity of the Arctic and strength of the BG [Proshutinsky and Johnson, 1997; Proshutinsky et al., 2015]. The index is provided by the Woods Hole Oceanographic Institution’s Beaufort Gyre Exploration Project. It provides an annual manually derived AOO index from 1948 to 2015. We also examine the role of the NAO in these regions. The indices are based on sea level pressure differences between the poles and mid-latitudes. These monthly indices are provided by the National Oceanic and Atmospheric Administration’s (NOAA) Climate Prediction Center from 1950 to present. They calculate the NAO index based on the Rotated Principle Component Analysis of the standardized 500-mb height anomalies poleward of 20°N [Barnston and Livezey, 1987].

The Copernicus Marine Environment Monitoring Service provides sea level anomalies (SLA) data from 1993 to present, referenced to the 1993 to 2012 monthly mean SSH. This dataset is in 0.25° spatial resolution. This product as well is a blend from
multiple satellites. However, SLA is not available over sea ice. SIE data are available by NOAA’s National Snow and Ice Data Center Sea Ice Index version 3 [Fetterer et al., 2017]. These data are available monthly from October 1978 to present and provides SIE from 30.98° N to 90° N. The data have a 25 km x 25 km spatial resolution. It uses a variety of sensors from different platforms. OHC data is from NOAA’s National Center for Environmental Information. It is available yearly from 1955 to present in 1° spatial resolution for the 0-700 meters layer.

The Met Office Hadley Center “EN” series version 4 dataset (EN4) [Good et al., 2013] provides monthly salinity and temperature data from 1900 to present. EN4 compiles data from a variety of in-situ observations. The dataset is provided in 1° spatial resolution for 42 vertical layers from 5.0216 m to 5350.3 m.

B. Anomalies, trends, and correlations

The sea surface temperature (SST), sea surface salinity (SSS), and SIE anomalies are calculated based on the 1993-2012 monthly climatological means, as this is the period for which the SLA were calculated. OHC anomalies (OHCA) are calculated based on the 1955 to 2006 reference, as this is how the data is provided. Trends are calculated for the annually averaged anomalies using a robust regression [Huber, 1981; Holland and Welsch, 1977]. This method uses iteratively reweighted least squares with a bisquare weighting function:

\[ w = |r < 1| \times (1 - r^2)^2 \]

Since these variables are not statistically independent, we determine the lag-1 autocorrelation of the detrended variables. This can be used to calculate the effective sample size, the standard error, and the significance of these trends [Santer et al., 2000].
Trends are found to be significant below the 0.05 significance level. In Figures 3.1-3.3, trends are displayed if statistically significant to limit noise in the figure. From 1990 to 2016 sea ice decreased over much of the Arctic and subarctic. Therefore, we mask trends of SLA where no data were provided for any month of any year. This ensures trends are calculated for the entire time period from 1990 (or 1993 for SLA) to 2016, with no seasonal or interannual bias.

The Arctic region is defined as poleward of 66° N. The subarctic Pacific region is defined as 45° N to 66° N and 120° E to 120° W. The subarctic Atlantic region is defined as 45° N to 66° N and 100° W to 35° E. For certain variables we also examine anomalies and trends within the BG using the traditional static box (70.5° N to 80.5° N and 190° E to 230° E) [Proshutinsky et al., 2009]. When examining the correlations between the different variables and climate indices, we compare the detrended, de-seasonalized monthly anomalies to remove the bias of the trends and seasonality. For the time series (Figure 3.4) and correlations we calculate the variables based on the boxes defined above. For SLA, the amount of data available changes, as the sea ice extent decreases.

3.3 Results

A. Sea Level

We found significant increases in SLA from 1993 to 2017 across most of the subarctic and Arctic (Figure 3.1; Table 3.2). In the northeast Pacific and central Atlantic, however, the trends are statistically insignificant in some areas, likely due to changes in ocean currents. The North Atlantic Current and Alaskan Coastal Current can vary in strength and location over time [Gawarkiewicz et al., 2012], which can impact sea level. We see much higher anomalies in the BG region in the 2010s, of up to 10 cm (Figure 3.1c),
as compared with the 1990s, with anomalies of approximately -10 cm (Figure 3.1a). While we could not calculate trends in this region due to sea ice, it is likely that this region has seen high increases in SLA across the ice-free periods. This is due to a spin-up, or convergence, of the BG [Giles et al., 2012]. The trends found in the Pacific and Atlantic are similar to those found in previous studies (1.54 or 2.22 mm yr$^{-1}$ from September 1991 or 1996 to September 2018; Rose et al., 2019). Both ice melt from ice sheets [Alley et al., 2005] and thermal expansion [Wigley and Raper, 1987] can contribute to sea level rise. 

B. Temperature

EN4 shows increasing SST anomalies and trends over much of the Arctic and subarctic (Figure 3.2; Table 3.2), especially in the western subarctic Atlantic and Eurasian Basin. This, and the increasing OHC, points to thermal expansion as the cause of much of the sea level rise exhibited in Figure 3.1. In the central Atlantic, however, there is no significant trend (or a decreasing trend), indicating variability in the North Atlantic Current, which provides a poleward transport of warm ocean water from lower latitudes. The positive trends in the Arctic Ocean and subarctic Pacific Ocean are weaker and less widespread. We see the highest temperature trends in the Atlantic south of Greenland. The oceanic temperature in the central Arctic Ocean has not changed drastically as we still have year-round ice in this region and therefore relatively stable surface temperatures.

We see that these changes in temperature weaken throughout the water column but remain relatively consistent with spatial patterns from the surface layer (Figure 3.5). Trends in the Arctic Ocean and subarctic Pacific Ocean remain significant until water depths of approximately 750 m, while trends in the Atlantic remain significant until water depths of approximately 500 m. This shows that much of the water column is warming which also
implies thermal expansion is occurring. We see the most significant temperature trends in the subarctic Atlantic, specifically in the Labrador and Greenland Seas, similar to the trends in SST. This would indicate a warming of North Atlantic Water in these regions. This water mass can change depth seasonally, interannually, and locally, however it can typically be found around 200 m in the Northern Barents Sea [Lind and Ingvaldsen, 2012]. As these are keys regions of deep-water formation for meridional overturning, there are potential consequences of the warming of these waters on global circulation. Changes in temperature can also impact ice melt and ice formation, which in turn can impact SSS seasonally through the release of freshwater and brine [e.g. Aagaard and Carmack, 1989; Aagaard and Woodgate, 2001], which may explain why we see a significant, albeit weak, relationship between SST in the Arctic and Atlantic and SIE (Table 3.1). This is also apparent because we found the strongest trend in temperature in the summer in the subarctic Pacific and Atlantic regions (Figure 3.6). This would mean rising temperatures during the melt season, resulting in more melting. We also found significantly increasing temperature trends in the subarctic Atlantic in the fall (Figure 3.6) which may prevent ice formation. These increasing temperature trends are also apparent in the spring and winter, however at a lower rate.

C. Salinity

EN4 SSS show weak, though significant, trends in much of the subarctic Pacific and Atlantic basins, as well as higher trends in the Arctic Ocean (Figure 3.3; Table 3.2). There is significant freshening in the Canada Basin, specifically the BG (-0.0735 ± 0.0030 psu yr\(^{-1}\)), however, there is significant salinification in the Laptev, Barents, and Greenland Seas causing low overall trends in the Arctic. This juxtaposition of trends in the Arctic is
likely due to circulation changes. Freshwater has accumulated in the Canada Basin due to a more anticyclonic oceanic and atmospheric circulation change in the Arctic Ocean since the late 1990s [e.g. Proshutinsky et al., 2015; Wang et al., 2019; Morison et al., 2012]. There is also significant salinification south of Greenland, in the Bering Sea and Chukchi Sea, and Gulf of Alaska.

Unlike temperature, the salinity trends only extend to approximately 250 m as opposed to over 500 m (Figure 3.7). This may be because the strongest salinity trends are in the Arctic Ocean and are mainly due to upper ocean processes, like ice melt [Wang et al., 2018], Bering Strait inflow [Woodgate et al., 2012], and a redistribution of riverine runoff [Morison et al., 2012]. The Arctic Ocean has a strong halocline and pycnocline which does not allow for much mixing to deeper layers [Aargaard et al., 1981]. However, the strongest temperature trends are in the subarctic Atlantic region where there is more mixing, upwelling in the subpolar gyre region, and meridional overturning which can contribute to deeper changes.

There is significant freshening in the Amerasian Basin and significant salinification in the Laptev, Barents, and Greenland Seas that extend into the deeper layers. This again is due to the redistribution of freshwater in the Arctic Ocean [e.g. Proshutinsky et al., 2015; Wang et al., 2019; Morison et al., 2012]. There is also significant salinification east of Greenland (Figure 3.3). The salinification may be due to an increased proportion of high salinity Atlantic water in this region, as opposed to fresher Arctic outflow from the Fram Strait. During a positive AOO, more freshwater is accumulated in the BG, whereas during a negative AOO, this freshwater is released through the Fram Strait, east of Greenland [Proshutinsky et al., 2002]. The transition in the late 1990s to a more anticyclonic regime
in the Arctic may explain the increased salinity in the Greenland Seas, as there was less freshwater output.

We also see a salinification in the Gulf of Alaska (Figure 3.3). A previous study found an increasing salinity from 1970 to 2005 from 100 to 250 m depth, but a freshening during this same period in the upper layers [Royer and Grosch, 2006]. They suggest these changes are due to a westward shift of isotherms and an increased cross-shelf estuarine-type flow [Royer and Grosch, 2006; Tully and Barber, 1960]. Our results show a similar sub-surface salinification, however not this freshening in the surface layers. This indicates that this salinity trend may have changed in the mid 2000s as this is when we begin to see the increasing salinity anomalies in the surface layers of this region (Figure 3.3b-c).

D. Monthly Anomalies

The monthly anomalies of SST, SSS, SLA, and SIE are shown in Figure 3.4. As shown in Figure 3.2, SST increases across all the basins (Figure 3.4a-c). Whereas, SSS decreases in the Arctic (Figure 3.4d), increases in the Pacific (Figure 3.4e), and shows small overall changes in the Atlantic (Figure 3.4f). Overall the SLA has been increasing, showing similar trends between basins (Figure 3.4j-l). SIE in the Northern Hemisphere has been decreasing (Figure 3.4m).

When comparing the detrended, de-seasonalized variables we find some important connections (Table 3.1). While many of these correlations were significant, most were still very weak. We did however find strong correlations between SLA and SST in the Pacific and Atlantic, as well as SLA and OHC in these regions. As ocean temperatures increase, there is a rise in SLA, owing to thermal heat expansion. There is also a significant, negative relationship between SSS and SLA in the Pacific. SLA can also increase due to ice sheet
or glacier melt, while this decreases salinity. Many other correlations that are expected to be strong, for example SIE and SSS, were weak or insignificant. Some of this may be contributed to a lag between the variables. For example, the highest correlation coefficient of SLA and SST in the Arctic Ocean was a 4-month lag of SLA to SST. This shows that many of these variables may be connected just with a delay associated with them.

E. Climate Indices

We found a strong correlation between the AOO and SST and OHC in the Atlantic. During a negative AOO, or cyclonic regime, there is a greater output of cool Arctic water into the Atlantic, resulting in a positive relationship between AOO and SST in the Atlantic. The AOO index is also significantly, positively correlated to SLA in the Atlantic, which may be due to thermal expansion. A connection between AOO and SLA in the Atlantic Ocean has not been previously examined. As we see an increase in SST in the subarctic Atlantic during positive AOO, perhaps this results in higher thermal expansion during positive AOO, resulting in increased SLA. Some previous studies have found correlations between AOO and SSS [e.g. Rabe et al., 2014]. We did not find this same relationship which may be due to the opposing salinity trends across this basin (Figure 3.3d). If we examined the relationship in specific seas or regions of the Arctic Ocean (e.g. BG), there may be a higher correlation.

Again, when looking at the lag-correlations, we did find higher correlations between many of the climate indices and variables at different lag times. In many cases it will take some time before changes in the atmosphere and ocean impact one another. This can be due to circulation and mixing which can affect the timing of different effects in different regions. While this did not significantly change any of the correlations it is
something to consider when examining the connection between atmospheric and oceanic parameters.

### 3.4 Discussion and Conclusions

While the Arctic has been freshening overall (Figure 3.4a), its distribution is uneven (Figure 3.3d) [e.g. Rabe et al., 2011; Rabe et al., 2014; Haine et al., 2015]. We find a salinification of the Eurasian Basin and a freshening within the Amerasian Basin, similar to previous studies [e.g. Morison et al., 2012; McPhee et al., 2009; Wang et al., 2019]. This is important as the freshening of the Arctic Ocean may impact meridional overturning. However, it seems the increased freshwater is being contained, at least thus far, to the BG region. This freshening is mainly due to increase in Pacific freshwater flux [Woodgate et al., 2012] and redistribution of Eurasian riverine runoff into the Amerasian Basin, specifically into the BG [Morison et al., 2012]. In the late 1990s the Arctic shifted to a more anticyclonic regime which began to switch back to a more neutral regime (lower AOO) in the early 2010s [e.g. Proshutinsky et al., 2012; Wang et al., 2018]. This shift in the wind regime caused convergence of freshwater in the BG due to Ekman transport [Proshutinsky et al., 2002]. This, in addition to the decreasing salinity in the Amerasian Basin mentioned earlier, contributed to the buildup of freshwater in the Beaufort Gyre and the concurrent salinification of many other regions in the Arctic Ocean. Previous studies found that contributions to this included decreasing wind stress curl [Giles et al., 2012], eddy memory [Manucharyan et al., 2017], and loss sea ice [Rabe et al., 2014]. While the Arctic is still in an anticyclonic circulation regime, over the past decade the AOO has been decreasing. In spite of this decrease, the salinity anomalies in the 2010s were still much lower than the 2000s (Figure 3.3), so the freshwater in the Arctic appears to still be
accumulating. When examining the time series of SSS anomalies in the Arctic (Figure 3.4a) it does initially increase in the early 2010s, but then decreases again in the rest of the time period, so it appears the overall trend has not changed substantially.

This anticyclonic circulation is also associated with increased SLA [e.g. Giles et al., 2012], which explains the heightened SLA within the BG (Figure 3.1c). Whereas the increasing SLA over the rest of the subarctic (Figure 3.1d) may be due to typical factors like thermal heat expansion, based on the increasing OHC, and Greenland ice melt, which may also explain the significant relationship between the SST and SLA in the Pacific and Atlantic.

While the temperature increased in most of the Arctic and subarctic, the greatest rise was in the eastern Eurasian Basin and subarctic Atlantic (Figure 3.2d, Figure 3.5). This is likely due to the recent “Atlantification” of this basin. The Eurasian Basin has been warming due to increased strength and warming of Atlantic inflow [e.g. Årthun et al., 2012; Stroeve and Notz, 2018]. Due to the anticyclonic regime for much of this time period, Atlantic water dominated in the Eurasian Basin. The warming, which began in the Fram Strait, advanced through the Eurasian Basin [Polyakov et al., 2017]. This is shown in the salinity trends as well (Figure 3.3d, Figure 3.7). We see significant salinification of the water around Greenland and through the Fram Strait because more Atlantic Water is dominating in this region, which is higher in salinity than Arctic water. This warming and salinification are both indicators of an increase in warm Atlantic water in this region. These results provide a broader temporal and spatial representation of previous findings [Polyakov et al., 2017], as well as how this change can be shown through salinity.

This study enhances our knowledge of the changes occurring in the Arctic and
subarctic, as well as their connections to the different climate indices. We found similar basin wide trends to previous literature; however, we found some new connections and changes. The impact of the AOO on the North Atlantic has not been examined, with the exception of cyclone activity and could be explored in more depth in future papers. While changes in salinity in the Arctic have been explored previously, we were able to find some new interesting trends of salinification in the Gulf of Alaska and Greenland Sea areas. It is important to continue studying these changes in the Arctic and subarctic as the strength or trajectory of trends can change over time. These regions have a large impact on the rest of the world’s oceans and climate, so the understanding of these changes and what impacts them is critical.
Table 3.1: Correlation coefficients between climate indices (NAO and AOO), detrended SST, SSS, OHC, SLA, and SIE anomalies in the Arctic region (Arc), subarctic Pacific region (Pac), and subarctic Atlantic region (Atl). Statistically significant correlation coefficients at 95% confidence are indicated in red.

<table>
<thead>
<tr>
<th></th>
<th>NAO (yearly)</th>
<th>AOO</th>
<th>SLA</th>
<th>SIE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Arc</td>
<td>Pac</td>
<td>Atl</td>
<td>Arc</td>
</tr>
<tr>
<td>EN4 SST</td>
<td>0.028</td>
<td>0.305</td>
<td>-0.115</td>
<td>-0.139</td>
</tr>
<tr>
<td></td>
<td>-0.006</td>
<td>-0.103</td>
<td>0.171</td>
<td>0.409</td>
</tr>
<tr>
<td></td>
<td>-0.137</td>
<td>0.610</td>
<td>0.103</td>
<td>-0.233</td>
</tr>
<tr>
<td>EN4 SSS</td>
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<td>-0.262</td>
<td>-0.110</td>
<td>0.101</td>
</tr>
<tr>
<td></td>
<td>-0.025</td>
<td>0.301</td>
<td>-0.027</td>
<td>-0.335</td>
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<tr>
<td></td>
<td>0.097</td>
<td>0.291</td>
<td>0.159</td>
<td>-0.036</td>
</tr>
<tr>
<td>OHC</td>
<td>0.396</td>
<td>0.188</td>
<td>0.047</td>
<td>-0.231</td>
</tr>
<tr>
<td></td>
<td>0.149</td>
<td>-0.249</td>
<td>0.135</td>
<td>0.909</td>
</tr>
<tr>
<td></td>
<td>-0.420</td>
<td>0.696</td>
<td>0.138</td>
<td>-0.573</td>
</tr>
<tr>
<td>SLA</td>
<td>0.134</td>
<td>0.054</td>
<td>1.000</td>
<td>0.380</td>
</tr>
<tr>
<td></td>
<td>0.147</td>
<td>-0.372</td>
<td>0.380</td>
<td>1.000</td>
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<tr>
<td></td>
<td>0.164</td>
<td>0.539</td>
<td>0.501</td>
<td>0.244</td>
</tr>
<tr>
<td>SIE</td>
<td>0.028</td>
<td>-0.055</td>
<td>-0.053</td>
<td>0.035</td>
</tr>
</tbody>
</table>
**Table 3.2:** Mean trends for different parameters in the Arctic region and subarctic Pacific and Atlantic regions. SLA trends from 1993 to 2017, and SSTA, SSSA, OHCA, and SIE anomalies trends from 1990 to 2016.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Arctic</th>
<th>Subarctic Pacific</th>
<th>Subarctic Atlantic</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSTA (°C yr⁻¹)</td>
<td>0.014</td>
<td>0.014</td>
<td>0.030</td>
</tr>
<tr>
<td>SSSA (psu yr⁻¹)</td>
<td>-0.016</td>
<td>0.004</td>
<td>0.002</td>
</tr>
<tr>
<td>OHCA (10⁴ joules yr⁻¹)</td>
<td>0.852</td>
<td>2.998</td>
<td>5.469</td>
</tr>
<tr>
<td>SLA (mm yr⁻¹)</td>
<td>2.160</td>
<td>2.342</td>
<td>2.358</td>
</tr>
<tr>
<td>Ice (million km² yr⁻¹)</td>
<td>-0.064</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 3.1: Mean anomalies of altimetrically derived SLA from (a) 1993 to 1999, (b) 2000 to 2009, and (c) 2010 to 2017. (d) The trend (mm yr$^{-1}$) of annual sea level anomalies from 1993 to 2017. Only trends which are significant at the 95% confidence level ($p<0.05$) are shown. Anomalies are calculated based on the 1993 to 2012 monthly climatological means.
Figure 3.2: Mean anomalies of EN4 SST anomalies (SSTA) at 5 meters depth from (a) 1990 to 1999, (b) 2000 to 2009, and (c) 2010 to 2017. (d) The trend (°C yr⁻¹) of annual sea surface temperature anomalies from 1990 to 2017. Only trends which are significant at the 95% confidence level (p<0.05) are shown. Anomalies are calculated based on the 1993 to 2012 monthly climatological means.
Figure 3.3: Same as in Figure 3.2 for EN4 SSS anomalies (SSSA).
Figure 3.4: (a-c) SST A (°C), (d-f) SSSA (psu), (g-i) OHC anomalies (OHCA) (10^8 joules), (j-l) SLA (cm), and (m) SIE anomalies (million km^2) and trends for the Arctic, Subarctic Pacific, and Subarctic Atlantic, respectively, with 95% confidence intervals shaded.
Figure 3.5: EN4 temperature trends (°C yr\(^{-1}\)) from 1990 to 2017 for (a) 5 to 50 m, (b) 50 to 100 m, (c) 100 to 250 m, and (d) 250 to 500 m depth.
Figure 3.6: Trends of EN4 SST for (a) Spring (March-May), (b) Summer (June-August), (c) Fall (September-November), and (d) Winter (December-February) from 1990-2017. Only trends which are significant at the 95% (p<0.05) confidence level are shown, statistically insignificant trends are removed.
Figure 3.7: EN4 salinity trends (psu yr\(^{-1}\)) from 1990 to 2017 for (a) 5 to 50 m, (b) 50 to 100 m, (c) 100 to 250 m, and (d) 250 to 500 m depth.
CHAPTER 4

CONCLUSIONS AND FUTURE WORK

4.1 CONCLUSIONS

Changes in the Arctic region have a major impact on global interests. Melting ice sheets and glaciers cause sea level rise [Alley et al., 2005], melting sea ice opens up shipping routes and potential oil fields, rising temperatures or freshening of the region may have an impact on global overturning circulation, and melting sea ice decreases Earth’s albedo leading to even more accelerated changes globally. These things make the study of the Arctic region even more important. However, due to reasons previously examined, there are a lack of in-situ observations in the Arctic Ocean, which can lead to inaccurate models with little to no validation. This is why the use of satellites can potentially enhance measurements in the ice-free Arctic and subarctic. While there are also many factors that affect the accuracy of these satellites, there is the potential to fix these problems once addressed. The biggest problem remains the error due to land and especially sea ice contamination. The second chapter of the thesis examines how satellite-derived salinity can be used to measure surface advective freshwater fluxes. This was the first study that utilized satellites to measure freshwater fluxes in different pathways of the Arctic Ocean. There was agreement between SSS of the reanalysis product and Argo data in the subarctic seas, which gives some confidence to using the reanalysis as a comparison for the satellite-derived freshwater fluxes in Arctic Pathways. There were similarities between the satellites and reanalysis on the mean and variability in the Bering Strait, however not in the BSO,
which provides confidence that satellite-derived salinity may be used to measure freshwater fluxes in lower latitude subarctic regions that have high freshwater flux variability and are less impacted by sea ice contamination. The third chapter utilizes a combination of satellite and reanalysis data to study variability in the Arctic and subarctic regions. Overall, this research helps expand our knowledge of the Arctic Ocean, its processes, and the different factors that impact it.

This research has several novel findings. The second chapter offers a potential new way to study surface advective freshwater fluxes using satellite-derived salinity. Most Argo floats do not work properly under sea ice, so they cannot be deployed in higher latitudes. Satellites offer a way to measure salinity in ice-free regions of the Arctic. They also have higher resolution than the Argo floats, cover more area than transects and buoys, and can measure areas continuously than ships. While there is some error in satellite measurements, as we showed in our research, there is the potential to use this data for calculations when more improvements are made. We found these satellites capable of measuring similar surface freshwater input to the Arctic Ocean through the Bering Strait, both in mean flux, but also the seasonal and interannual variability, when compared with ORAS4 reanalysis. With better improvements in minimizing land and ice bias on the satellite-derived salinity, this method may eventually be used to measure freshwater output through the Fram and Davis Straits, both major regions of freshwater export from the Arctic. This may provide a method for comparing and validating models.

As previously stated, interest in how the Arctic Ocean responds to climate change is high, as the Arctic impacts global climate and ocean circulation. The results of the third chapter showed consistency with previous literature, particularly a freshening of the
Canada Basin, a warming of the subarctic Atlantic, and a rise in sea level. This freshening of the Canada Basin and decrease in surface salinity in the Arctic is associated with a switch to a more anticyclonic atmospheric circulation regime. The rise in sea level is associated with thermal expansion and melting of ice sheets. The warming of the subarctic Atlantic, Barents Sea, and part of the Eurasian Basin is associated with an increase in Atlantic water into these basins, and also a warming of that water, known as “Atlantification”. There were also some novel findings from this chapter. There is a strong correlation between changes in the AOO, or cyclonicity of the Arctic Ocean, and sea level and surface temperature of the subarctic Atlantic. This is likely because the AOO impacts export through the Fram Strait, which can impact temperature and sea level. This is important as it emphasizes the impact that changes in the Arctic Ocean can have on other basins. We also found a salinification east of Greenland and in the Fram Strait, which further shows the “Atlantification” of these Arctic regions. The Arctic region is changing at a very accelerated rate, as shown by Chapter 2. Even examining a few parameters since just the 1990’s can still show major changes in a relatively short time.

4.2 Future Work

The Beaufort Gyre plays a key role in the Arctic Ocean. As discussed in Chapter 3, freshwater in the gyre has been increasing in recent decades due to an increasingly anticyclonic atmospheric and oceanic circulation [Proshutinsky et al., 2012]. This causes an accumulation of freshwater in the Beaufort Gyre, due to a decrease in the salinity and an increase in the sea surface height of the gyre. The gyre’s freshwater content changes on longer time scales, as the atmospheric circulation changes, and seasonally, due to ice melting and formation. As this gyre is such an important feature in the Arctic in terms of
oceanic circulation and freshwater storage, lots of research has focused on the changes occurring to the gyre. The Woods Hole Oceanographic Institution (WHOI) Beaufort Gyre Exploration Project (BGEP) provides data in the gyre from hydrographic surveys, buoys, and moorings. This provides in-situ data of the gyre from August 2003 onward. However, for longer analyses, models are required. By comparing different models to the BGEP data, we can determine the feasibility of using models to study the changes in the Beaufort Gyre over longer time periods. BGEP also only provides freshwater content within the static gyre region (70.5-80.5° N and 190-230° E). Models can provide data in surrounding regions, which is equally important as the gyre is thought be moving in recent years [Regan et al., 2019].

Recent papers have examined the Beaufort Gyre in regard to its liquid freshwater content (FWC), calculated as:

$$\text{FWC} = \int_{z2}^{z1} \frac{\text{Sref} - S(z)}{\text{Sref}} \, dz$$

The reference salinity (Sref) is 34.8, following previous studies. S(z) is the salinity at depth z. We will be calculating the FWC for the entire water column, so z1 is depth = 0 and z2 is the depth of where S(z) = Sref (the 34.8 isohaline). This freshwater content and the sea surface height are the two metrics which provide the best estimations for the gyre size, center, location, and radius.

We found a rise in ocean temperature in the BG region, concurrent with a decrease in salinity and decrease in sea ice concentration (Figure 4.1). The strongest temperature increase has been seen below the mixed layer depth (MLD), while the strongest freshening has occurred above the MLD. The past decade has seen the greatest rise in temperature and decline in salinity compared to the 1990 to 2009 mean. When comparing the FWC of EN4
to the WHOI BGEP in situ data, we found very strong agreement (R = 0.9489), which indicates that EN4 reanalysis may be used to study the BG on a longer time scale (Figure 4.2). We can also see in Figure 4.2 that from 2003 to 2017 the FWC has been increasing in the BG region, however, there was a hiatus in this growth from approximately 2008 to 2012 and a decline in FWC from 2012 to 2013. Therefore, when examining the FWC trends for each decade since 1980, we see the greatest increase in FWC in the BG region from 2000 to 2009. There is no significant change in FWC in the 1980s and only a decrease in FWC in the more northern part of the BG in the 1990s. In the 2010s, there is a significant increase in FWC in the more northern part of the basin, likely owing to the initial decrease in FWC in the BG at the start of the decade. The FWC trend is due in part to a decrease in salinity from ice melt [Wang et al., 2018] and an increase in sea surface height due to a shift toward a more anticyclonic circulation regime in the late 1990s that has lasted until present, though the AOO has begun to decrease in the past decade.

This future research will include examining different variables impacting the decrease in salinity and increase in freshwater content including sea surface height, riverine output, and sea ice melt. We will also examine the shift in the gyre on a longer time scale to see if the northwest shift from 2003 to 2014 [Regan et al., 2019] is just natural variability or a longer-term trend. The BG and its properties are an important area of study as the BG has the largest freshwater storage in the Arctic and is influenced by atmospheric circulation and potentially by the changing global climate.
Figure 4.1: NSIDC sea ice concentration, EN4 reanalysis salinity and temperature anomalies with depth in Beaufort Gyre region (70.5-80.5°N and 190-230°E) compared to the 1990 to 2009 monthly mean. The black line represents the mixed layer depth.
Figure 4.2: Yearly mean of freshwater content (FWC), relative to a salinity of 34.8 psu, from 2003 to 2017 for (a) WHOI BGEP and (b) EN4 reanalysis. Error bars represent variability of FWC across the Beaufort Gyre region.
Figure 4.3: Trend of freshwater content (m yr\(^{-1}\)), relative to a salinity 34.8 psu, for (a) 1980 to 1989, (b) 1990 to 1999, (c) 2000 to 2009, and (d) 2010 to 2017 using EN4.
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APPENDIX A

PERMISSION TO REPRINT

A.1 CHAPTER TWO COPYRIGHT PERMISSIONS

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Rachel Nichols