Changes in the Character of the Pacific Water in the Central Canada Basin from 2004-2012

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1. Abstract

Water from the Pacific Ocean that flows northward through Bering Strait has an important relationship to the sea-ice cover of the Arctic Ocean, acting as a source both of heat and of low-salinity water. Given the role of this relatively fresh water in insulating the ice cover from warmer water beneath, understanding the character of the Pacific Water will provide valuable insight into a critical feature of the Arctic Ocean. The Pacific Water is comprised of several distinct water masses, which are defined in terms of their salinity: the Alaskan Coastal Water (ACW) has traditionally been defined as having salinity $31 < S < 32$, the summer Bering Sea Water (sBSW) has salinity $32 < S < 33$, and the winter Bering Sea Water (wBSW) has a salinity of about $S = 33.1$. To investigate the nature and the variability of the Pacific Water, data from Ice-Tethered Profilers (ITPs) were analyzed in the Central Canada Basin for the years 2004-2012. Our analysis shows that the traditional salinity ranges no longer accurately characterize the water masses, with the sBSW having a narrower range than presumed and the ACW requiring a range closer to $29 < S < 32.3$ to account for freshening in recent years. Knowledge of these water masses' interannual variability in temperature and spatial extent was another outcome of this investigation. In sum, the results of this study will prove useful in future studies of the Pacific Water: the reexamination of its salinity ranges is important for the accurate identification of its constituent water masses, and a knowledge of its interannual variability will prove valuable in tracking changes in the character of the Pacific Water over time.

2. Introduction

The inflow of water from the Pacific Ocean through Bering Strait, which is the only oceanic link between the Pacific and Arctic Oceans [*Woodgate et al.*, 2009], is the most significant source of low-salinity water to the Arctic Ocean [*Aagaard and Coachman*, 1975]. Roughly 1.4 million cubic meters of water flow northward through Bering Strait in summer, with the wintertime flow rate being three to four times lower [*Coachman and Barnes*, 1961]. The relatively fresh near-surface layer resulting from this inflow is vital for the maintenance of the

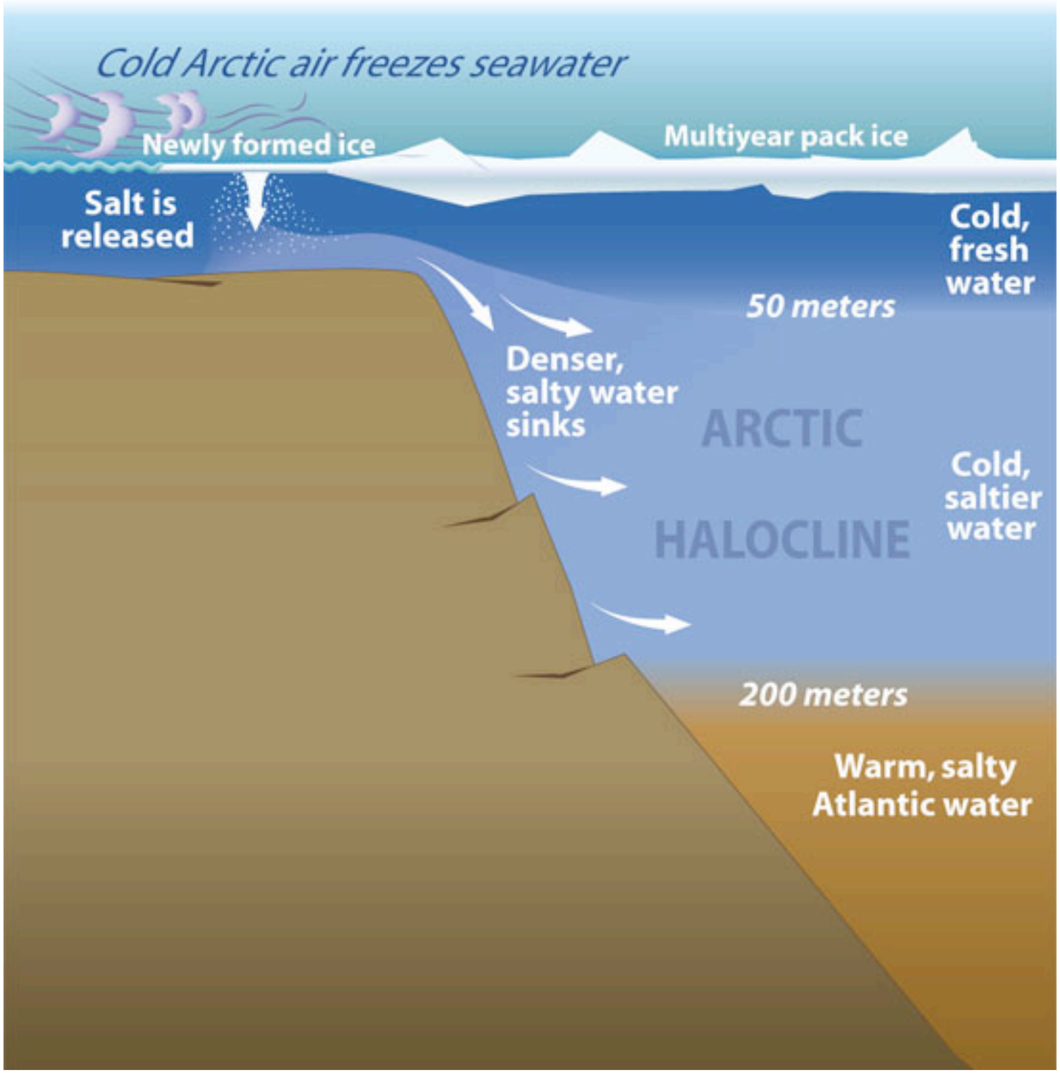


Figure 1. Schematic of the Arctic Ocean vertical stratification. (Jayne Doucette, WHOI)

Arctic sea ice cover, for at a depth of about 300 meters lies a layer of warm water originating in the Atlantic that extends throughout much of the Arctic Ocean. Were a low-salinity surface layer not overlying the Atlantic water, this much warmer water mass could easily penetrate to the surface and melt vast amounts of sea ice [*Knauss*, 1978]. The vertical stratification of the Arctic Ocean is represented in Figure 1. However, the Pacific Water itself also acts as a heat source to the ice cover and has an decisive role in summer ice melt. The fact that it extends over roughly half of the Arctic Ocean [*Woodgate et al.*, 2010] further emphasizes the significance of this water mass. *Woodgate et al.* [2010] put it succinctly: "the Bering Strait inflow influences sea-ice by providing a trigger for the onset of solar-driven melt, a conduit for oceanic heat into the Arctic, and (due to long transit times) a subsurface heat source within the Arctic in winter."

Given the importance of the inflow of Pacific Water to the state of the Arctic sea ice cover and the importance of the sea ice cover to the global climate system, understanding the character of the Pacific Water is critical. Particularly vital will be monitoring any changes in the Pacific Water and determining the nature of its interannual variability to pin down its role in the melting of sea ice. Understanding changes to the Pacific Water in the Central Canada Basin will provide a good idea of its overall variability in the region of the Beaufort Gyre. (The Beaufort Gyre—the large-scale anticyclonic atmosphere, ice, and ocean flow important for its role in storing fresh water in the Arctic—is approximately centered over the Central Canada Basin, with some interannual variation in location due to shifts in the large-scale anticyclonic atmospheric circulation. (M.-L. Timmermans, personal communication, 4 April 2012, *Proshutinsky*, 2011) We will be investigating the nature of the Pacific Water using new data collected by Ice-Tethered Profilers (ITPs, www.whoi.edu/itp) from 2004 through 2012.

The thesis is organized as follows. In the upcoming section, we define the Pacific Water and distinguish between its three constituent water masses (the Alaskan Coastal Water, the summer Bering Sea Water, and the winter Bering Sea Water). In Section 4, we describe the ITP systems and observations; we then explain our data analysis methods in Section 5. We then delve into the results of our study, starting in Section 6 with a reassessment of the salinity range of the summer Bering Sea Water (sBSW). Likewise, Section 7 contains a critical analysis the salinity range of the Alaskan Coastal Water (ACW). We change directions somewhat in Section 8, turning to an assessment of the interannual variability of Pacific Water temperature. Section 9 provides an overview of certain hypotheses concerning the pathways taken by the Pacific Water from Bering Strait to the Canada Basin, followed by a discussion of the difficulties of analyzing seasonality. Finally, in Section 10, we use data from the entire Canada Basin to assess interannual variability in the extent of the ACW.

3. Pacific Water Characterization

Water from the Pacific Ocean that flows through Bering Strait into the Chukchi Sea, and from there eventually into the Canada Basin, is called either Pacific Summer Water (PSW) or Pacific Winter Water (PWW), depending on the season in which it enters the Arctic Ocean. (A map of the relevant region is shown in Figure 2.) In their 2009 paper, *Jackson et al.* cite *Coachman and Barnes*' 1961 definition of PSW as Pacific origin water that is modified in the Chukchi Sea during the summer, with PWW being that which is modified in the Chukchi Sea in winter. The temperature of the Pacific Water varies seasonally such that PWW provides a cold,

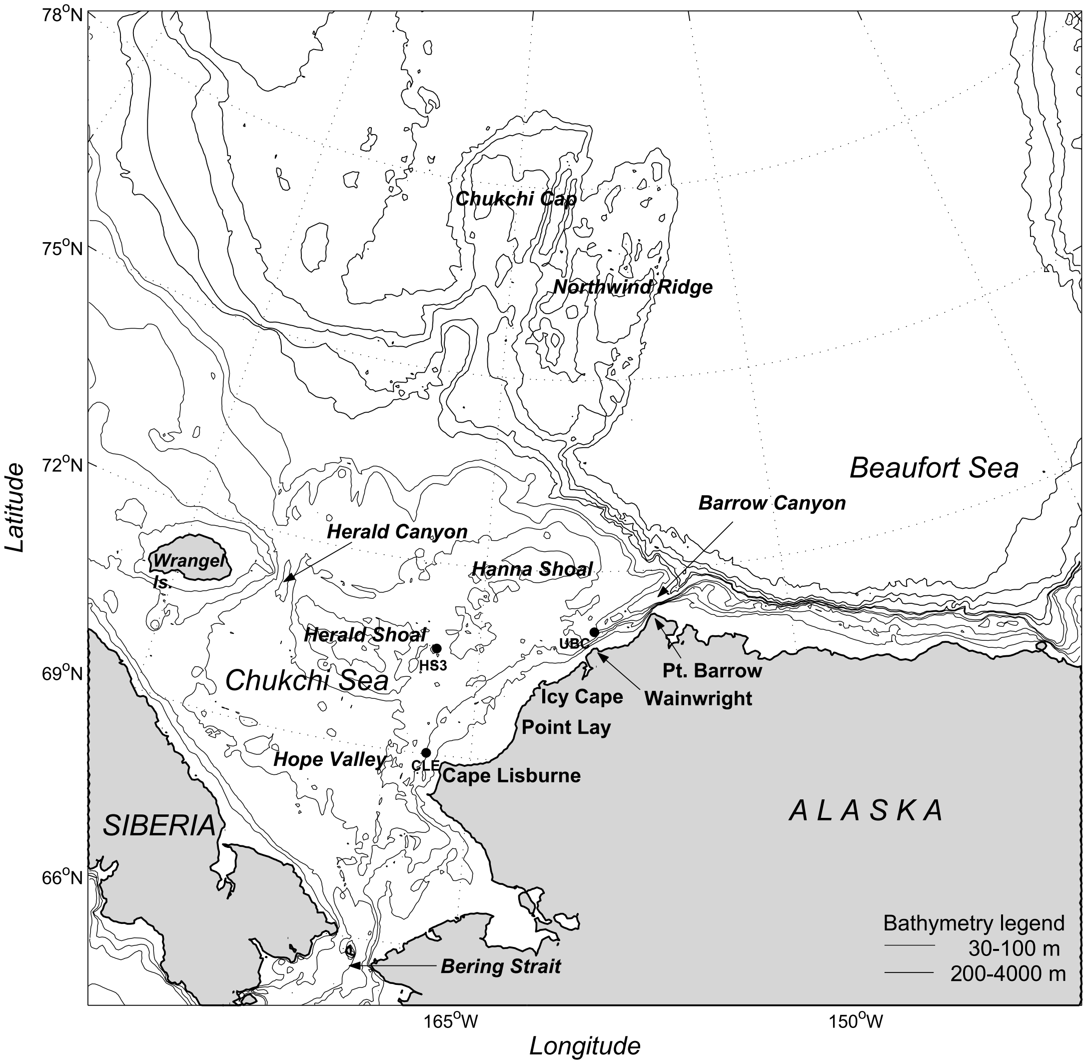


Figure 2. A bathymetric map depicting the region of interest. The Central Canada Basin is found to the northeast of the Northwind Ridge in the Beaufort Sea. (Winsor and Chapman, p. 2)

fresh insulating layer that protects the sea ice from warmer water beneath, yet PSW is a heat source to the sea-ice cover and the atmosphere in the Canada Basin (Woodgate, 2004). (PSW is an important factor in summer sea-ice melting: in the region near the Northwind Ridge, it contains stored heat calculated in 1998 to be about 140 MJm^2, enough to melt 50 centimeters of sea ice [*Shimada et al.*, 2001].) The temperature profile of the PSW (a shallow temperature maximum in the halocline) shows it to be fairly shallow, usually less than 100 meters deep (Woodgate, 2004). While the thrust of this study concerns the heat advected by Pacific Water into the Arctic Ocean, it is important to note that the heat content of this water mass is also determined by vertical processes such as mixing and diffusion [*Jackson et al.*, 2010].

The northward advection through Bering Strait is driven by local wind effects [*Woodgate et al.*, 16 Feb. 2005] as well as by the salinity difference between the fresher North Pacific and the saltier Arctic Ocean, which causes a steric height different on the order of 0.5 meters. The inflow is greater during the summer, when winds tend to be weak, and lesser in winter due to frequent northerly winds. Upon passing through Bering Strait, the Pacific Water enters the Chukchi Sea, with its different components typically spending between 6 and 30 months in transit on their way to the Beaufort Gyre [*Winsor and Chapman*, 2004]. In traversing the shallow Chukchi Sea, the Pacific Water cools significantly, but its salinity does not change dramatically. Thus, in terms of long-term trends, the salinity of the Pacific Water in Bering Strait is a good indicator of the salinity it will have upon outflow into the Arctic Ocean many months later [*Woodgate et al.*, 29 Nov. 2005]. (However, the state of the water masses at the Strait does not neatly and predictably translate to their state in the Chukchi Sea and beyond; see Section 9 for a further exploration of the complicated link between water properties at Bering Strait and in the Canada Basin.)

Although the exact pathways taken by the Pacific Water through the Chukchi and into the Arctic Ocean remain uncertain, another topic which receives a much more thorough treatment in Section 9, the northward flow is thought to travel in three principal branches, steered by topography: the easternmost branch hugs the Alaskan coast, passing through Barrow Canyon; the central branch flows between Herald Shoal and Hanna Shoal, and the westernmost branch passes through Herald Canyon. In such a shallow sea, bathymetry can be expected to play an important role in the steering of currents, along with wind forcing [*Winsor and Chapman*, 2004]. All relevant topography can be seen in the map in Figure 2.

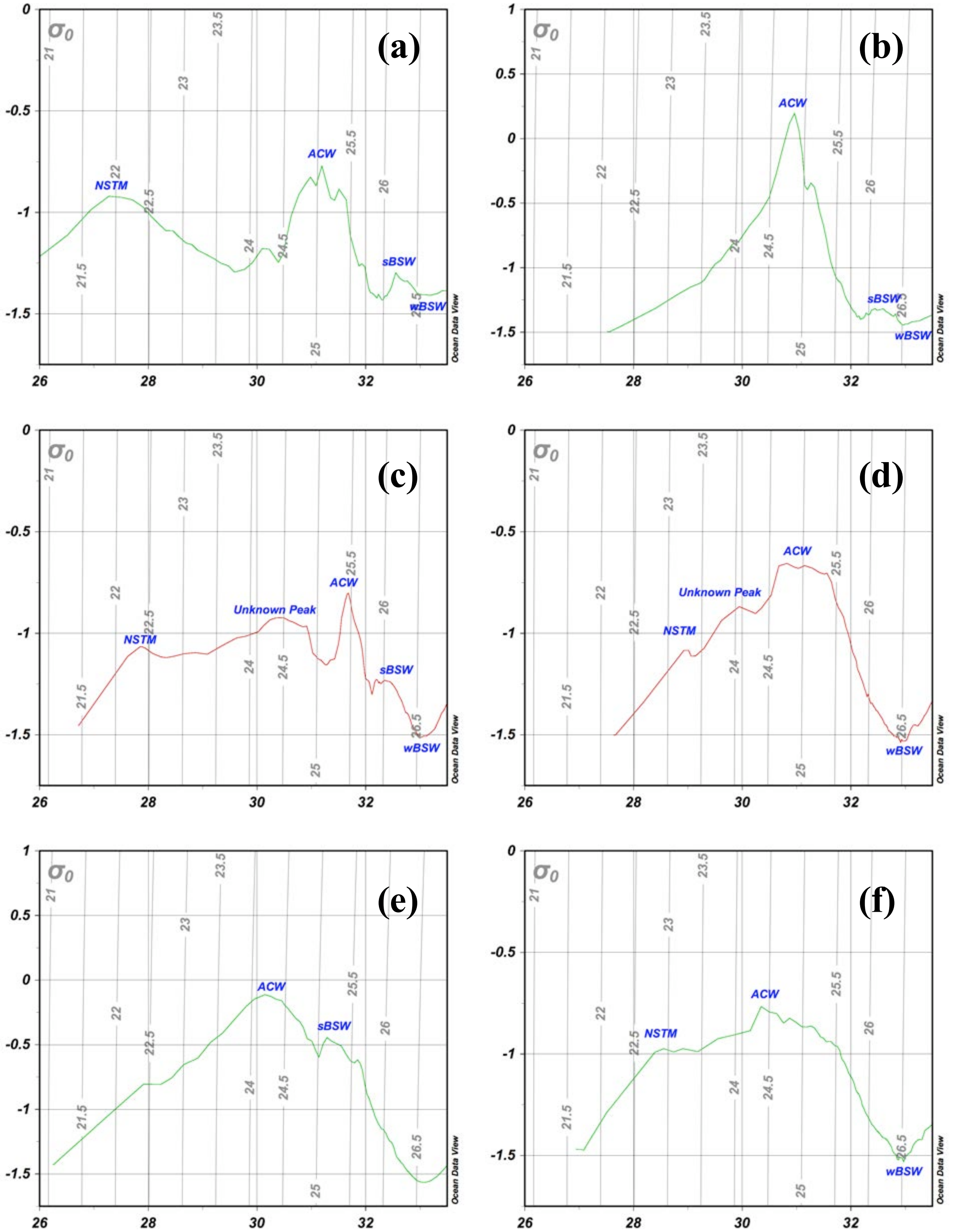
These three components of the Pacific Water have distinct properties even in Bering Strait, with the easternmost referred to as the Alaskan Coastal water, the central as Bering Shelf water, and the westernmost as Anadyr water. In the Chukchi Sea, Bering Shelf water and Anadyr water merge to form the Bering Sea Water [*Woodgate et al.*, 29 Nov. 2005]. The distinction between these water masses is not entirely clear-cut, though: transport through Barrow Canyon is not simply comprised of water flowing along the Alaskan Coast directly from Bering Strait, but also includes flow from the Central Channel and Herald Canyon [*Spall*, 2007].

Traditionally, the aforementioned water masses can be distinguished from each other and from the near-surface temperature maximum (the NSTM: a warm, relatively fresh layer immediately beneath the surface layer, whose heat content is derived from incoming summer solar radiation [*Jackson et al.*, 2010]) by their salinities. The salinity of PSW is given to be $31.0 < S < 32.0$ by *Shimada et al.* [2001], 31.9 by Woodgate (2004), and $31.6 < S < 32.4$ by *Coachman and Barnes* [1961]. (In this paper, all salinities are given in practical salinity units, or psu.) *Steele et al.* [2004] cite three types of Pacific Water: Alaskan Coastal Water (ACW), summer Bering Sea Water (sBSW), and winter Bering Sea Water (wBSW). Together, ACW and sBSW are referred to as “summer Pacific halocline waters,” though ACW is fresher and warmer than sBSW. The salinity of ACW is $31 < S < 32$, whereas that of sBSW is $32 < S < 33$. The salinity of wBSW is given as ~33 by *Shimada et al.* [2001], 33 by Woodgate (2004), and 33.1 by *Steele et al.* [2004]. As the authors are all in fairly good agreement, these were the starting values for salinity that were used in this analysis. ACW, sBSW, and wBSW are also the three subcategories of Pacific Water we identify and work with, though other papers sometimes call them by other names or take them in conjunction. (PSW encompasses both ACW and sBSW, for example, as in the paper cited in the next paragraph.)

Bourgain and Gascard define the PSW somewhat more stringently in their 2012 paper “The Atlantic and Summer Pacific waters variability in the Arctic Ocean from 1997 to 2008.” They require that the temperature maximum that defines the PSW be 1) deeper than 40 db to ensure that it is not confused with the NSTM, and shallower than the top of the thermocline, which is usually located around 180-200 dbar in the Canada Basin; 2) the temperature maximum must be associated with a layer of minimum thickness 5 db to avoid temperature spikes; 3) the PSW temperature range is 31 < S < 33; and 4) the PSW temperature maximum is at least 0.16ºC above the freezing temperature. Our definition of the PSW satisfies their third criterion. It was also verified that criteria #1 and #4, though not included in our initial data analysis, held true for the data in the region of interest. We did not methodologically account for their second criterion, because temperature spikes, which tend to be caused by instrument noise or fouling, were not a significant issue in the ITP data analyzed here (M.L. Timmermans, personal communication, 7 March 2012). Therefore, our general method of data analysis was consistent with the requirements put forth by *Bourgain and Gascard*; as will be explained, though, stringently adhering to this definition became more of a hindrance than a help.

Distinguishing between these water masses is useful in order to be able to analyze changes in each component of the Pacific Water rather than just in the Pacific Water as a whole, and to take the NSTM out of the picture. Because they are defined by their salinity, plots of potential temperature (θ) versus salinity are used to discriminate between the water masses; Figures 3a and 3b provide "standard" θ-S profiles of the Pacific Water for reference. However, defining these water masses has recently become a more complicated proposition. Relying on the standard salinity ranges in our data analysis ultimately proved inadequate: the ACW and sBSW no longer fit neatly into these salinity ranges, prompting us to conduct year-by-year analyses to more accurately characterize the water masses.

Figure 3. (**next page**) A representative hodgepodge of many different Pacific Water θ-S diagrams, grouped together to give an idea of the sheer amount of variability within this water mass. Plotted in the background are isopycnals. (**a**) "Normal" profile evidencing NSTM as well as ACW, sBSW, and wBSW, from 11/28/07. (**b**) "Normal" profile not evidencing NSTM, from 4/12/07. (**c**) Profile from 2006 (11/14/06) demonstrating unknown peak between NSTM and ACW. (**d**) Profile from 10/30/09 demonstrating an intriguing double peak that was not explored in this paper, as it occurs mostly outside the CCB, but appears in 2009. (**e**) Profile from 12/16/10 showing an instance of a fresh ACW (S = 30.15) associated with what seems to be a very fresh sBSW (S = 31.29). (**f**) Profile from 11/15/09 evidencing particularly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Ocean Data View
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Ocean Data View
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4. Measurements

In recent years, ITPs have contributed vastly to the collection of data about the Arctic Ocean. Their ability to take samples of the ocean beneath the sea ice is especially valuable for collecting data during the winter months. ITPs are affixed to individual ice floes and sample the properties of the underlying ice-covered ocean for periods of up to three years. On top of the ice rests a surface buoy with a tether extending beneath it through the ice and down 500-800 meters into the ocean. An instrument cycles vertically up and down this tether, collecting data with oceanographic sensors and transmitting it to shore in near-real time. The entire apparatus, depicted in Figure 4, drifts with the ice floe [*Krishfield et al.*, 2008].

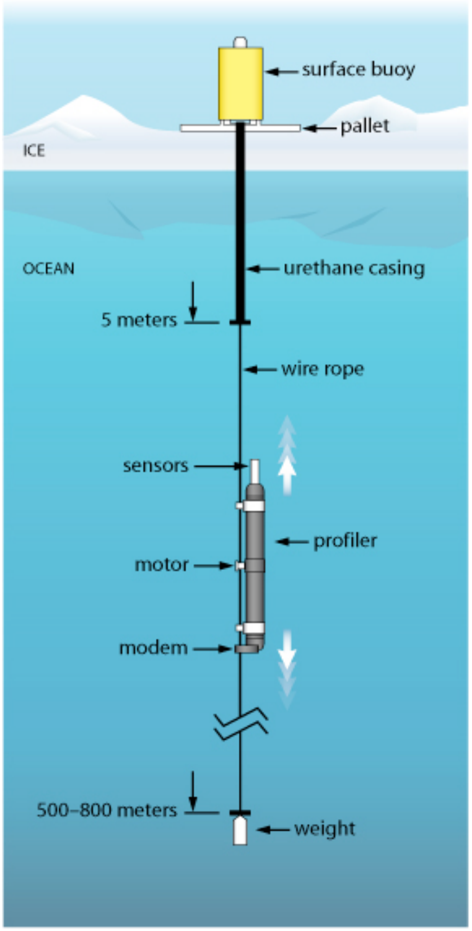


Figure 4. Schematic depicting the setup of an Ice-Tethered Profiler (ITP). (Woods Hole Oceanographic Institution (WHOI) website)

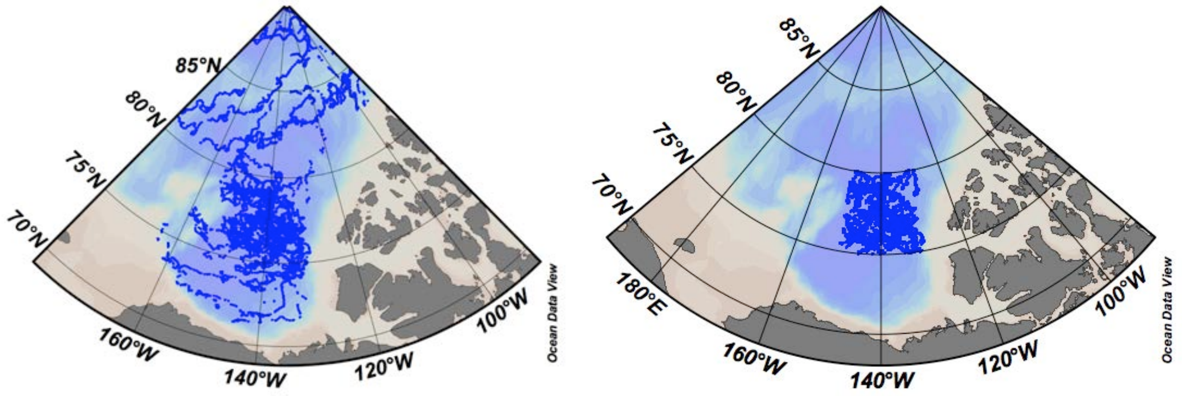
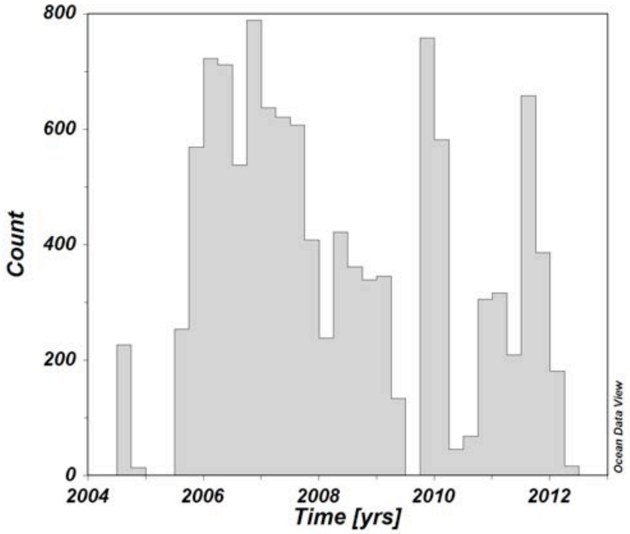


Figure 5. (**left**) Map depicting the drift tracks of all ITPs analyzed in this study. Each dot represents a vertical profile of the water column collected by the ITP. (**right**) ITP data from the Central Canada Basin (defined as the region within 80°N, 210°W, 75°N, and 250°E).

Data from 46 ITPs (ITP numbers 1 through 55 with the exception of 20, 30-1, 39, 40, 44-6, and 50) were analyzed and cover the entire area of study shown in Figure 5. The region that was the focus of our study, which had the densest data collection, is the Central Canada Basin (CCB; see Figure 5). This area is defined as the region within 80ºN, 210ºW, 75ºN, and 250ºE. The ITPs relevant to the Central Canada Basin are the following: 1-6, 8, 11, 13, 18, 21-2, 32-5, 41-3, and 52-5. The CCB was the focus of our study both because it had the densest data collection from which the most reliable trends could be gleaned and because its characteristics provide a good approximation of the basin as a whole. However, even in the CCB, data are sparser in some years than in others: Figure 6 shows histograms of the number of ITP profiles collected over time in both the CCB and the Canada Basin as a whole.

5. Methods

After deciding on the appropriate salinity ranges to use to define the ACW and the sBSW, the program MATLAB was used to determine whether or not there was a potential temperature maximum within each salinity range that would indicate the presence of the water mass at a given location. For instance, to determine whether or not the ACW appears in a certain profile, the maximum θ in the salinity range $31.0 < S < 32.0$ is sought. To ensure that this θ_{max} is a true maximum and not simply an apparent maximum at the edge of the salinity range resulting from a



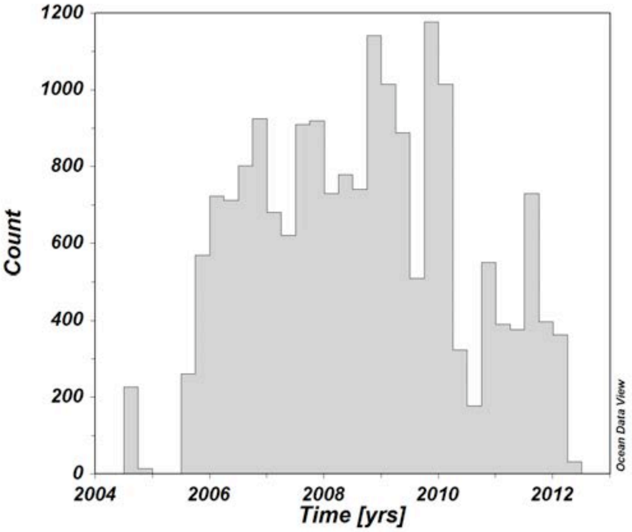


Figure 6. Histogram of the number of profiles taken over time in the Central Canada Basin (**top**) and in the region as a whole (**bottom**).

monotonic increase or decrease, the θ_{max} is compared to the potential temperatures of the five points on either side of the salinity range.

To determine the presence and potential temperature of the wBSW, a θ minimum was sought in the salinity range $32.6 < S < 33.6$. (This range was chosen in order to encompass points where the salinity of the wBSW deviates slightly from $S = 33.1$ but where it is still represented by a distinct θ minimum. Our priority in this study being the ACW and the sBSW, merely ensuring that we captured the wBSW was adequate for our purposes.) The pressure and salinity associated with the θ maxima of the ACW and sBSW and the θ minima of the wBSW were then identified by our MATLAB routine for further analysis with the program Ocean Data View (http://odv.awi.de/). Ocean Data View was also employed later in the investigation to prepare θ-S dot plots using all of the data from the ITPs in the Central Canada Basin rather than just the θ_{max}.

Results and Discussion

6. sBSW Salinity Range Revision

The Alaskan Coastal Water (ACW) and summer Bering Sea Water (sBSW) are conventionally defined in terms of their salinity: *Steele et al.* [2004] give the salinity of ACW to be $31 < S < 32$, and that of sBSW to be $32 < S < 33$. (As explained in the overview of the Pacific Water in Section 3, other definitions of the ACW and the sBSW stray little from these salinity ranges.) Upon investigating the data concerning these water masses between 2004 and 2012, though, it becomes apparent that the usual definitions of sBSW and ACW are not entirely appropriate. In particular, the sBSW has a narrower, more well-defined salinity range than its conventional definition would indicate.

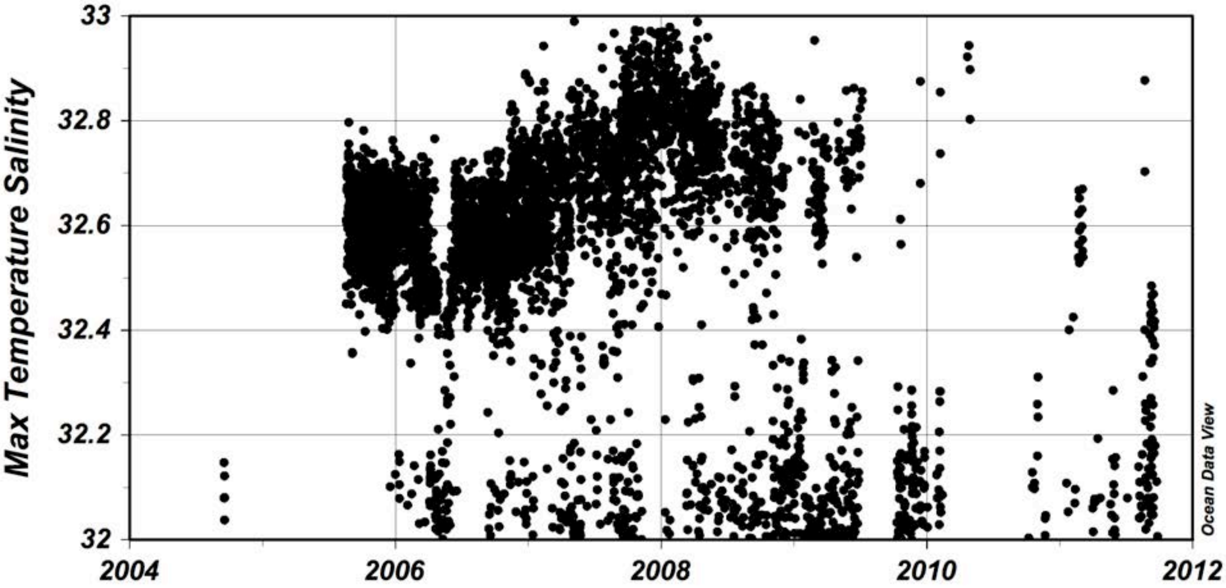
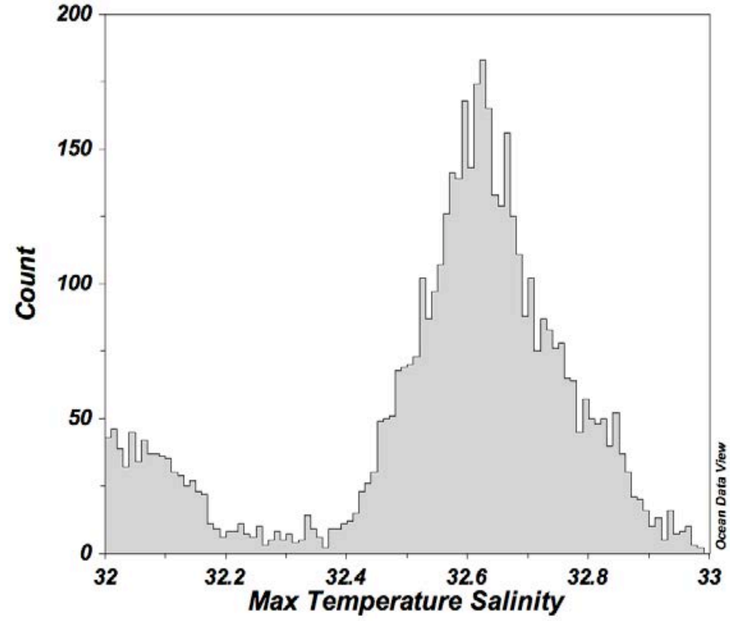


Figure 7a. Timeseries of the salinity of the sBSW that initially aroused suspicions, as the points clustered close to S = 32 do not seem to belong to the sBSW.



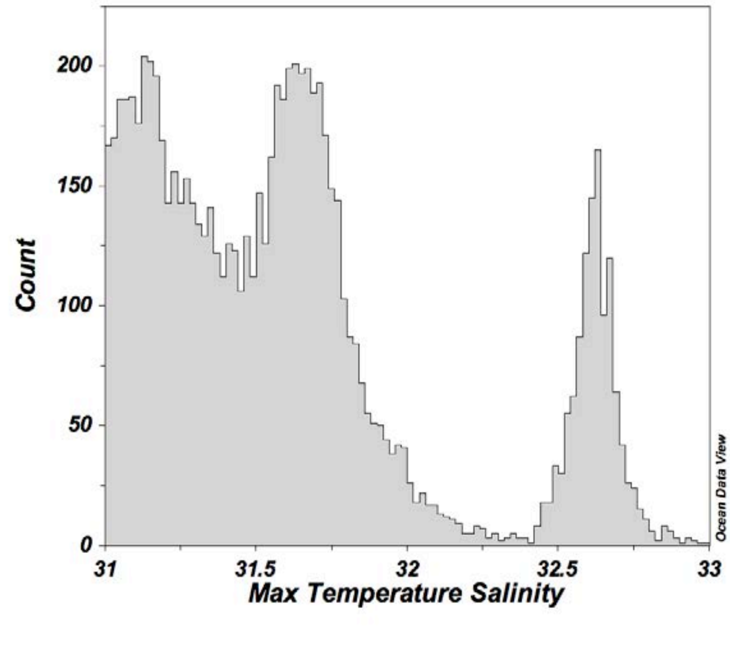


Figure 7b. (**Top**) Histogram of the salinity of the θ_{max} of the sBSW in the Central Canada Basin, made with traditional salinity range definitions. (**Bottom**) Histogram of the salinity of the θ_{max} of the Pacific Water in the Central Canada Basin, made with traditional salinity range definitions.

The first indication that prompted a closer look into the character of the sBSW was the fact that, in a timeseries of the salinity of the θ_{max} associated with the sBSW in the Central Canada Basin, it appeared distinctly bimodal over most of its range; one clump of data lay between $S = 32.4$ and $S = 32.8$, and the other was concentrated around $S = 32.1$ (see Figure 7a). A histogram of the salinity of the sBSW (Figure 7b) made this bimodality explicit: the sBSW formed a peak clearly centered around $32.6 < S < 32.7$, with the points on the lower end of its salinity range appearing to be part of a separate water mass.

A histogram of the salinity of the θ_{max} of the summer Pacific Water (see Figure 7b), which contains both ACW and sBSW, confirmed that the points clustered at the lower end of the sBSW salinity range belong to the foothills of the ACW: the second peak of the sBSW around $S = 32$ is just ACW with a higher salinity than is accounted for in its conventional definition. The separation between the ACW and the sBSW, as well as the narrower effective salinity range of the sBSW, is dramatic and clearly demonstrates the encroachment of the ACW into the salinity range conventionally reserved for the sBSW.

In light of this interpretation of the data, it makes sense to redefine the salinity ranges of the sBSW and ACW such that they better represent the actual water masses, and to use this new definition alongside the conventional one. We have therefore chosen to take a value of $S = 32.3$ as our cutoff. A range of $31 < S < 32.3$ thus fits the ACW, and $32.3 \leq S < 33$ makes more sense for the sBSW. However, it is important to remember that the definitions of these water masses are continually evolving, as will be explored in more detail in the next section. These salinity ranges are appropriate for the years addressed by our study but are not intended to act as new, permanent definitions. Indeed, the idea of a “permanent definition” of these constantly changing water masses may be idealistic in and of itself, as is described in the next paragraph and in Section 7.

It is worth noting that this revised salinity range, while broadly representative of the sBSW from 2004-2012, still fails to account for certain outlying features. In particular, upon examining certain θ-S profiles from 2010 and 2011, it appears that the sBSW tends to jump outside its salinity range when it is associated with a particularly fresh ACW peak (see Figure

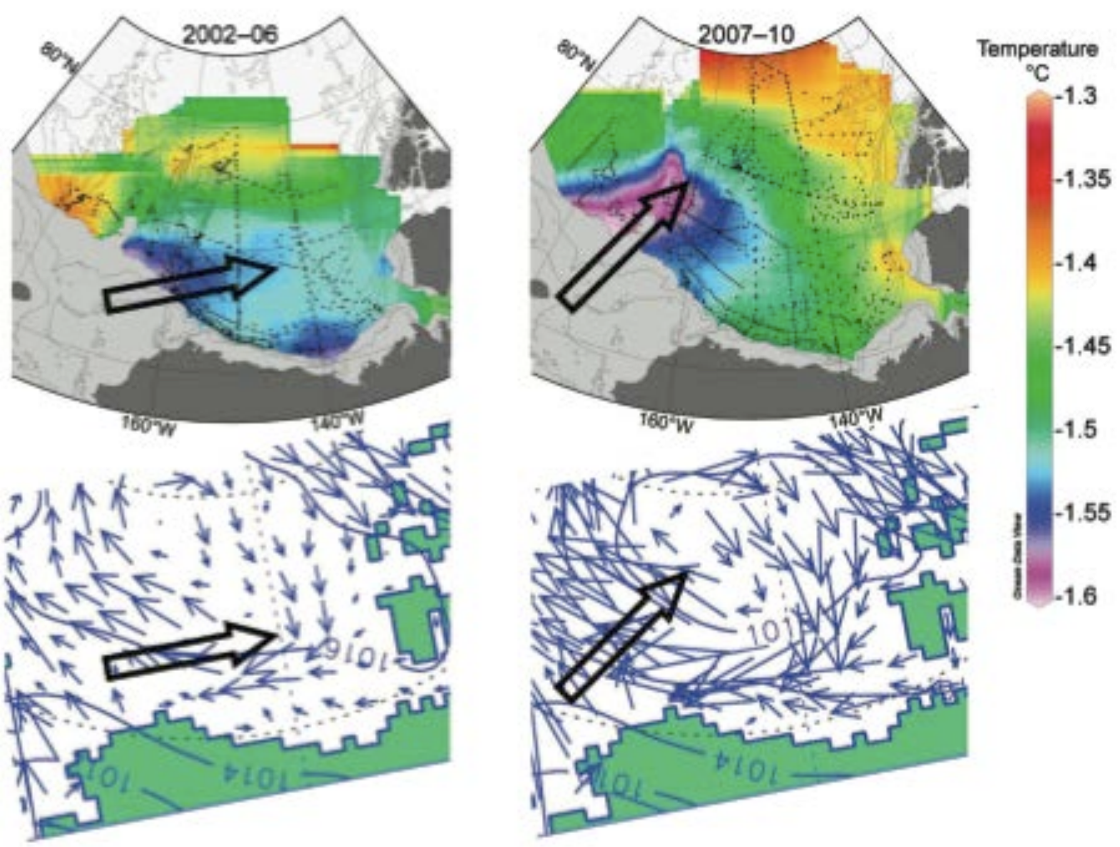


Figure 8. Map from BAMS Report "State of the Climate in 2010", p. S148. Caption in the report: "Top panels: potential temperature (ºC) in the Canada Basin at the S = 33.1 isohaline. Bottom panels: sea level atmospheric pressure (hPa) and simulated wind-driven component of ice drift. Left and right panels: 2002-06 and 2007-10, respectively. Large arrows show suggested spreading of Pacific winter waters."

3e). When the salinity of the ACW peak approaches S = 30, the salinity of the sBSW commonly drops to S = 31.7 and sometimes as far as S = 31.2. (Additionally, sometimes there seems to be no sBSW at all associated with a very warm and fresh ACW peak, but this apparent lack could simply be a consequence of our newfound lack of certainty of where to look for the sBSW.)

Potential explanations for these phenomena are several: variations in the salinity of the source water from Bering Strait could explain the deviation. Another possibility is a change in source-water pathways, which would alter the mixing and water-mass modification as the sBSW travels to the CCB. Much variability in pathways is created by the huge amount of interannual variability in the winds affecting the Arctic Ocean. (The importance of the prevailing winds with respect to the direction taken by the Pacific Water as it enters the Arctic is illustrated by a map in the 2010 BAMS State of the Climate Report, shown in Figure 8.)

While these occurrences of fresh sBSW deviate significantly from the redefined salinity range, the bulk of the sBSW in our data set appears to fall within the bounds $32.3 \leq S < 33$, which remained our working definition for this study. However, careful attention to particularly fresh sBSW will certainly be merited in the future, especially in association with the potential freshening of the ACW temperature maximum.

7. Apparent ACW Freshening Trend

In a paper detailing recent changes to the near-surface waters of the Canada Basin, *Jackson et al.* [2011] explore an "apparent freshening of the PSW temperature maximum" between 1993 and 2009. Drawing on CTD data and on data from ITP #8, they state that between 2004 and 2008, the salinity of the PSW in the Canada Basin was 28-32, which stands in contrast to the 31.6-32.4 range of *Coachman et al.* [1961] and the 31-32 range defined by *Shimada et al*. [2001] and *Steele et al*. [2004]. In their abstract, *Jackson et al.* also state that the salinity range of the PSW dropped from 30-32 in 1993 to 28-32 in 2008.

Jackson et al. proffer several hypotheses to explain the PSW freshening they observe between 1993 and 2008. A freshening of the source water in Bering Strait is a possibility that they discount, but not without noting that direct relationships between source water and water in the Gyre are hard to establish. Other potential causes are changes to the pathway and velocity of the PSW, but these are not well-supported by evidence. Thus, the authors find diffusion of heat and salt between the NSTM, PSW, and rWML (remnant of the mixed layer from the previous winter) to be the most plausible explanation, with freshening of the rWML causing the observed PSW freshening. However, as they acknowledge, the simple 1-D diffusion model employed does not account for lateral advection, wind mixing, the freeze-melt cycle, or diffusion changes caused by stratification, and therefore their conclusions remain speculative.

Taken year by year, our data do not seem to support the assertion made by *Jackson et al.* that the salinity of the PSW temperature maximum was between 28 and 32 from 2004 to 2008; this statement does not hold true, at least, in the Central Canada Basin. To come to this

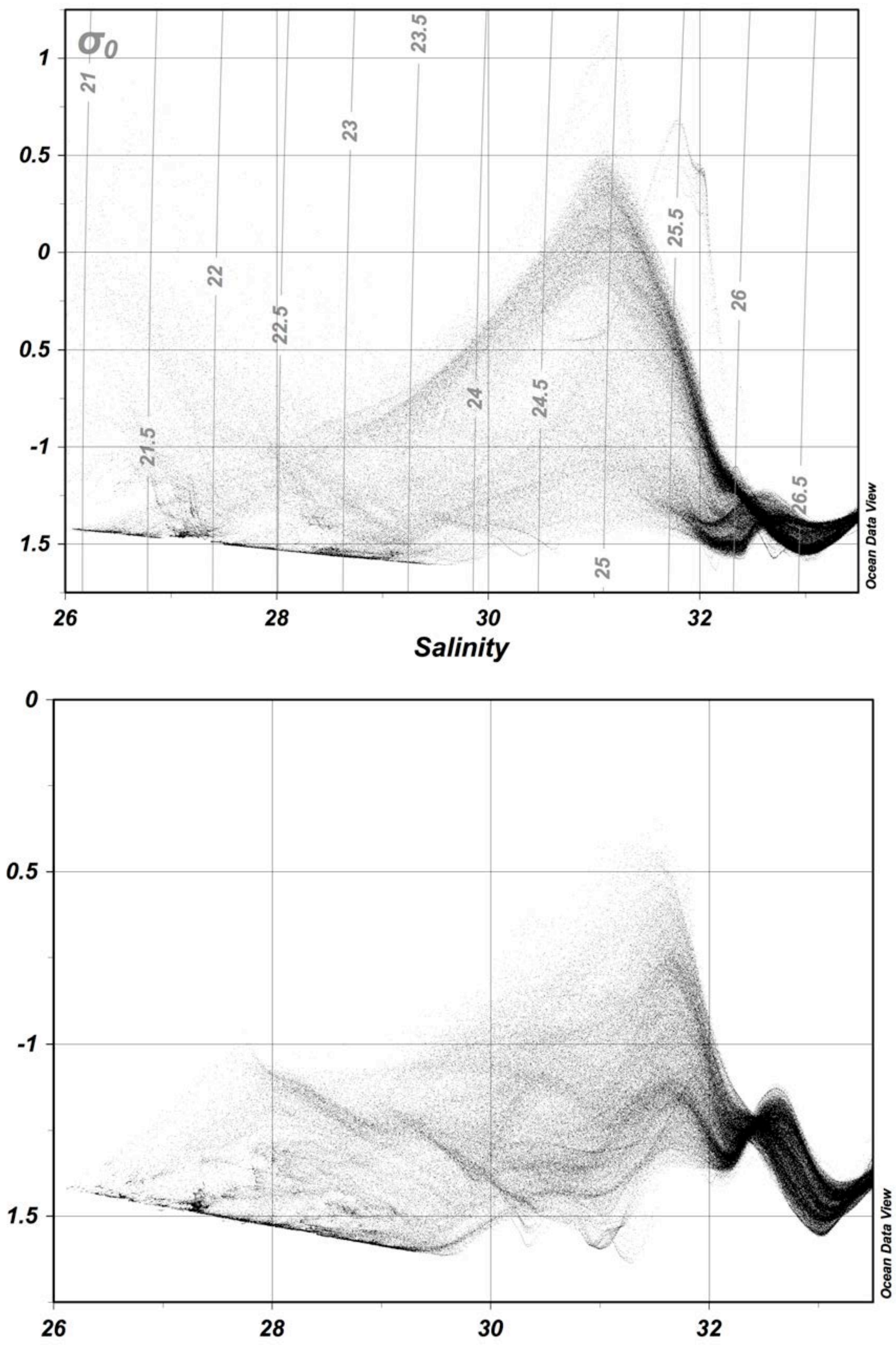


Figure 9. θ-S dot plot for all profiles in the CCB for 2007 (**top**). T-S dot plot for all profiles in the CCB for 2006 (**bottom**); complicating double peak apparent around S = 29.8.

conclusion, we separated all ITP data in the CCB by year; we then amalgamated plots of potential temperature versus salinity for all profiles in each year, as shown in Figure 9. The ACW potential temperature peak was then visually identified for each year. (We focused on the ACW in making this comparison with *Jackson et al.* because they are studying PSW; although PSW comprises both ACW and sBSW, the place to look for overall freshening of the PSW would be in the ACW, which is fresher of the two water masses.)

In contrast to *Jackson et al.*'s assertion of PSW freshening in 2004-2008, the ACW shown on our yearly θ-S plots for this time period is firmly within its expected salinity range of 31-32. The ACW shown in our plots dominates the higher end of the salinity range between 2004 and 2008: the ACW salinity, as determined by the salinity of the temperature peak shown on the θ-S dot plots, was around S = 31.5 in 2004, S = 31.6 in 2005, S = 31.6 in 2006, S = 31.2 in 2007, and S = 31.5 in 2008. (These peaks are also apparent on histograms of salinity for each year.) The only year from 2004-2008 in which the salinity of the ACW seems to approach S = 28 is 2006, where a second peak around S = 29.8 is weakly apparent alongside the peak at S = 31.6. This phenomenon could indicate, among other possibilities, the presence of two instances of ACW that took different pathways to the Central Canada Basin and acquired different θ-S profiles along the way. *Jackson et al.* [2011] attribute this double peak to an intrusion of cold water on the temperature maximum in 2006. In any case, our data from 2004-2008 seem to indicate that extending the lower bound of the ACW range to S = 29.5 or 30 would be appropriate in order to include ACW temperature peaks that fall on either side of the overall maximum. To extend it to S = 28, though, was not a conclusion supported by our data, even after accounting for the 2006 double peak.

Although the ACW does not appear unusually fresh from 2004-2008 in the Central Canada Basin, an examination of the data in the CCB does reveal a distinct freshening of the ACW temperature maximum from 2009-2012. As with the data from 2004-2008, we identified the ACW (PSW) on θ-S dot plots. The most prominent temperature maximum in 2009 occurs at about S = 30.9.[1] 2010 evidences an ACW potential temperature peak early in the year at S = 30.8, and a peak late in the year closer to S = 30.1. In a logical continuation from the 2010 data,

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[1] A complicating, even fresher temperature maximum unique to 2009 will not be discussed in this paper, as it is mostly in evidence outside the CCB, but is represented in Figure 3d.

the ACW peak early in 2011 is about S = 30.2, becoming somewhat more saline later in the year, with a peak around S = 30.6. The salinity of the peak for the limited amount of 2012 data is near S = 30.8.

In light of this four-year run of fresher-than-average ACW, seeking it in the conventional salinity ranges may no longer always prove fruitful. To accommodate this new state of affairs, we adjusted our MATLAB code to search for an ACW peak in the salinity range $29 < S < 32.3$. Dropping the lower bound of salinity to 29 does run the risk of overlapping with the salinity range of the NSTM; however, analyzing our data year by year allowed us to verify that the potential temperature maximum of the ACW exceeded that of the NSTM when the latter fell above S = 29, allaying any worries that a warm NSTM would mask the true ACW.

It is unclear if the decreasing salinity of the ACW is part of a longer-term freshening trend or not; it cannot be said from this study whether $31 < S < 32$ is still a generally appropriate range for the ACW that happened not to characterize 2009-2012. Rather, what becomes clear from this part of the study is the necessity of critically assessing a data set to ensure that it fits the standard formulae. As in the case of the sBSW, being alert to the true range of the ACW in future studies will be critical.

8. Interannual Variability of the ACW Temperature

One of the most striking results of this study was the revelation that while certain components of the Pacific Water remained relatively constant in temperature over the time period of the study, others fluctuated wildly. This phenomenon is clearly represented in Figure 10. Namely, despite the fact that the temperature of the wBSW demonstrated no long-term trend or even notable interannual variability, the maximum temperature of the ACW varied significantly from year to year. (The maximum temperature of the sBSW fluctuates slightly along with the ACW, warming when the latter is warm and vice versa, but the amplitude of variation in the sBSW is significantly less than that of the ACW.) Though discerning a long-term trend in the ACW is difficult given the limited time range of the data and the multitude of variables that

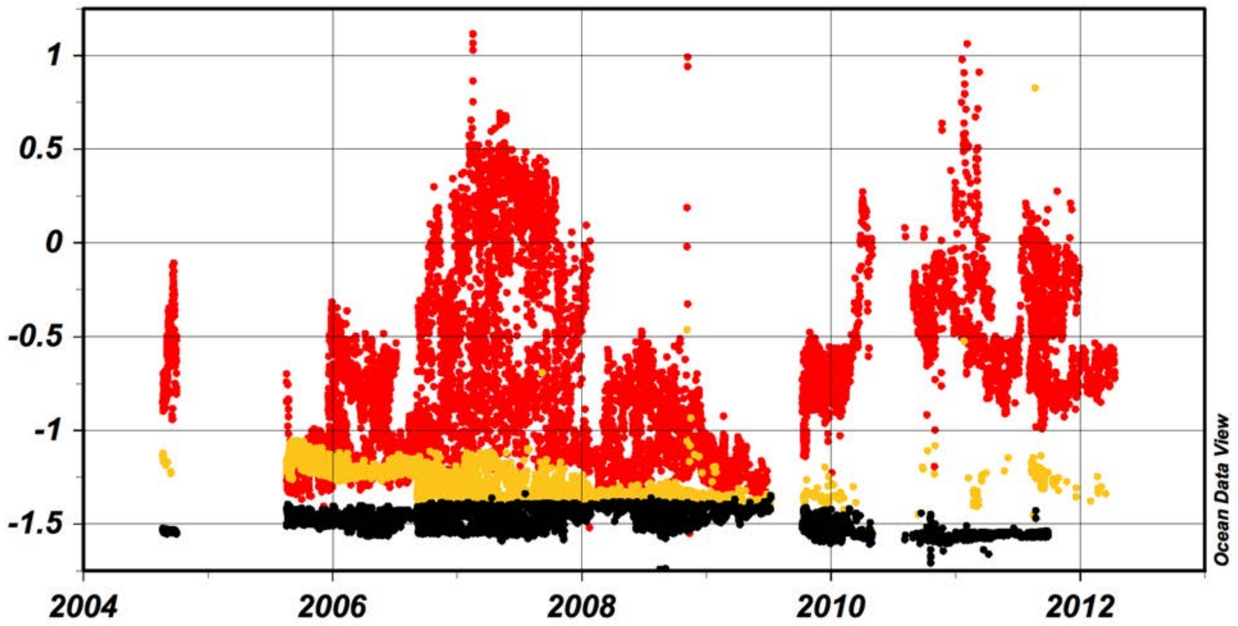

Figure 10. A timeseries of the maximum potential temperature (°C) of the ACW (red), sBSW (yellow), and wBSW (black) in the Central Canada Basin, made with updated salinity ranges (ACW: $29 < S < 32.3$; sBSW: $32.3 \leq S < 33$).

impact this water mass, these results help demonstrate the range of interannual variability possible in the ACW.

The ACW was at its warmest in the Central Canada Basin in 2007, with temperatures dropping off afterwards before peaking at a slightly cooler temperature in 2011. While *Bourgain and Gascard* [2012] observe "a warming trend since the early 2000s" in their study of the Canada Basin, we can less readily draw this conclusion from our study: whereas they analyzed data through 2008, near when the ACW temperature peaked, examining temperatures through 2012 highlights the interannual variability of the temperature rather than a discernible global trend. More precisely, the temperature of the ACW dips in 2008 and remains cooler for a few years before rising again in 2011.

Variations in the temperature of the ACW show some degree of correlation with variations in its salinity, as can be seen in Figure 11: especially for the second half of the time period analyzed, as both temperature and salinity rise, warm years tend to be fresh years, and cool years tend to be saltier. This variability is potentially significant because, of the three water masses under study, the ACW is the most buoyant and the closest to the sea ice cover. As fresher, warmer water tends to lie closer to the surface, the ACW would likely approach the ice cover

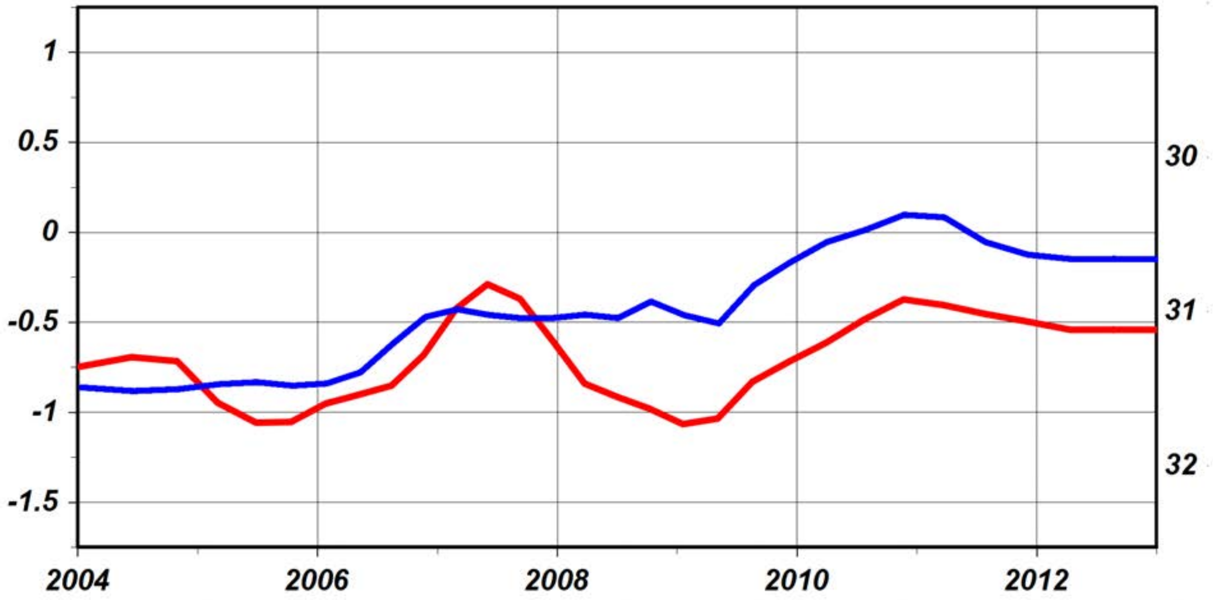

Figure 11. A timeseries of the maximum potential temperature (°C) (red, left axis) and the salinity of this temperature maximum (blue, right axis, no grid) of the ACW in the Central Canada Basin.

precisely when it is carrying the most heat, making these interannual variations particularly noteworthy in terms of ice melt. However, freshening results in enhanced vertical stratification, which in turn limits the flux of vertical heat by increasing the energy needed to mix Pacific Water heat to the surface. Thus, the effect of changing ACW temperatures on ice melt is not entirely straightforward.

9. Seasonality and Pathways of the Pacific Water

In addition to investigating interannual variability, we hoped to get a sense of the seasonal variability of the Pacific Water. Helpful in determining seasonality is having an understanding of the pathways taken by the Pacific Water from Bering Strait to the Central Canada Basin, as pathways influence the mixing properties and timescales for heat and salt diffusion from the resident Pacific Water. While the literature does not provide a definitive answer on this point, (due to data limitations in a highly variable wind- and buoyancy-driven system) taking several different studies in conjunction proves helpful in making sense of our data.

The behavior of the Pacific Water exiting the Chukchi Sea seems to vary significantly by season, with *Watanabe and Hasumi* [2009] proposing that it is carried by eddies into the Canada Basin in summer, but is transported toward the western side of the shelf and the Northwind Ridge by easterly winds in winter. *Watanabe and Hasumi* argue that mesoscale eddies are the main method of Pacific Water inflow into the Canada Basin. According to the authors, these eddies are the result of the instability of the shelf-break jet flowing through Barrow Canyon, with most eddy activity during late summer and early fall. (The peak of the shelf-to-basin transfer would occur simultaneously with maximal eddy activity, reaching 0.3 Sv. Reduced sea ice concentration is suggested to accelerate the flow through Barrow Canyon, increasing instability and thus generating more Basin-bound eddies in summertime.) The eddies are baroclinic, have a vertical scale of 200-300 meters [*Jackson et al.*, 2011], and have a lifetime of several months; they grow by merging with one another from August to September before shrinking in early winter. *Watanabe and Hasumi* demonstrate that in the winter no Pacific Water is transported into the Canada Basin along the route taken by the eddies during the summer.

The authors determine that the presence or absence of ice cover on Barrow Canyon does not appreciably affect the jet strength or the density profile of the Pacific Water in the canyon, for the contribution of the horizontal temperature gradient to the density gradient counterbalances the effect of the salinity gradient [*Watanabe and Hasumi*, 2009]. *Shimada et al.* [2006], though, note that ice along the Alaskan Coast hampers the retroflexion (westward turning) of the Pacific Water toward the Northwind Ridge. However, when the ice cover does not hug the coast, or when its formation is delayed, there is enhanced westward turning of the Pacific Water just as the warmest pulse of PSW arrives on the Beaufort Slope in October or November. The ultimate effect of this westward turning is the observation of the warmest PSW during winter over the Northwind Ridge [*Shimada et al.*, 2006].

The Northwind Ridge, represented by *Shimada et al.* [2006] as the area within 73° to 77°N and 150° to 165°W, is thought to be an important point on the pathway of the Pacific Water into the Canada Basin. There is a hotspot over the Northwind Ridge that, according to the authors, indicates that the typical annual advective pathway of the ACW lies along the Chukchi

Plateau and the Northwind Ridge. Moreover, the expected baroclinic flow carrying the ACW northward alongside the Ridge is essentially parallel to the seafloor topography [*Shimada et al.*, 2006]. A 2004 study by *Winsor and Chapman* substantiates the idea of the westward turning of the Pacific Water due to easterly winds, demonstrating with a model that it is only an easterly wind that prevents the outflow from the Chukchi Sea from simply hugging the Alaskan Coast [*Shimada et al.*, 2001]. They also confirm that the observed flow of the Pacific Water seems to be barotropic and steered by bathymetry. [*Winsor and Chapman*, 2004] The 2011 paper by *Jackson et al.* further corroborates the idea that the Pacific Water follows a path from the Northwind Ridge to the Canada Basin: temperatures at a downstream station in the Beaufort Gyre were always cooler than those at an upstream station near the Northwind Ridge.[2] Our data lend support to this proposed pathway: as seen in Figure 12, the warmest water in the Basin appears to originate at the Northwind Ridge before cooling as it progresses into the Basin.

Jackson et al. [2011] indicate that during the period of their study, 1993-2009, pathways and mixing between Bering Strait and the Northwind Ridge apparently remained constant; as support they cite the lack of variation in the relationship between water at a mooring in eastern Bering Strait and that at a station near the Northwind Ridge. They were able to use this result to draw tentative conclusions regarding the time lag of the path of the Pacific Water from Bering Strait to the eastern Northwind Ridge, noting that 2002 temperature and salinity data from Bering Strait were well-correlated with 2004 data on the Northwind Ridge.[3]

On the whole, though, it seems that variability in Pacific Water properties in the Central Canada Basin is equally likely to be explained by variability in and along pathways to the CCB as it is to be due to variability in source water. A 2007 paper by Michael Spall reinforces this idea: remote forcing (from Bering Strait) of seasonal cycles in temperature and salinity only explains some of their variability, for the role of advective and in situ processes must be taken in

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[2] The authors go on to note that the water mass properties at the second station were similar to those observed at the first station a year earlier [*Jackson et al.*, 2011].

[3] Unfortunately, we were unable to test their hypothesis due to a paucity of data in the area of interest near the Northwind Ridge (though this direction could be promising for a future investigation. Likewise, their finding that water properties at this location near the Northwind Ridge were similar to those and near 140°W, 73°N (continuing around the Beaufort Gyre) one year later proved difficult to corroborate with our data.

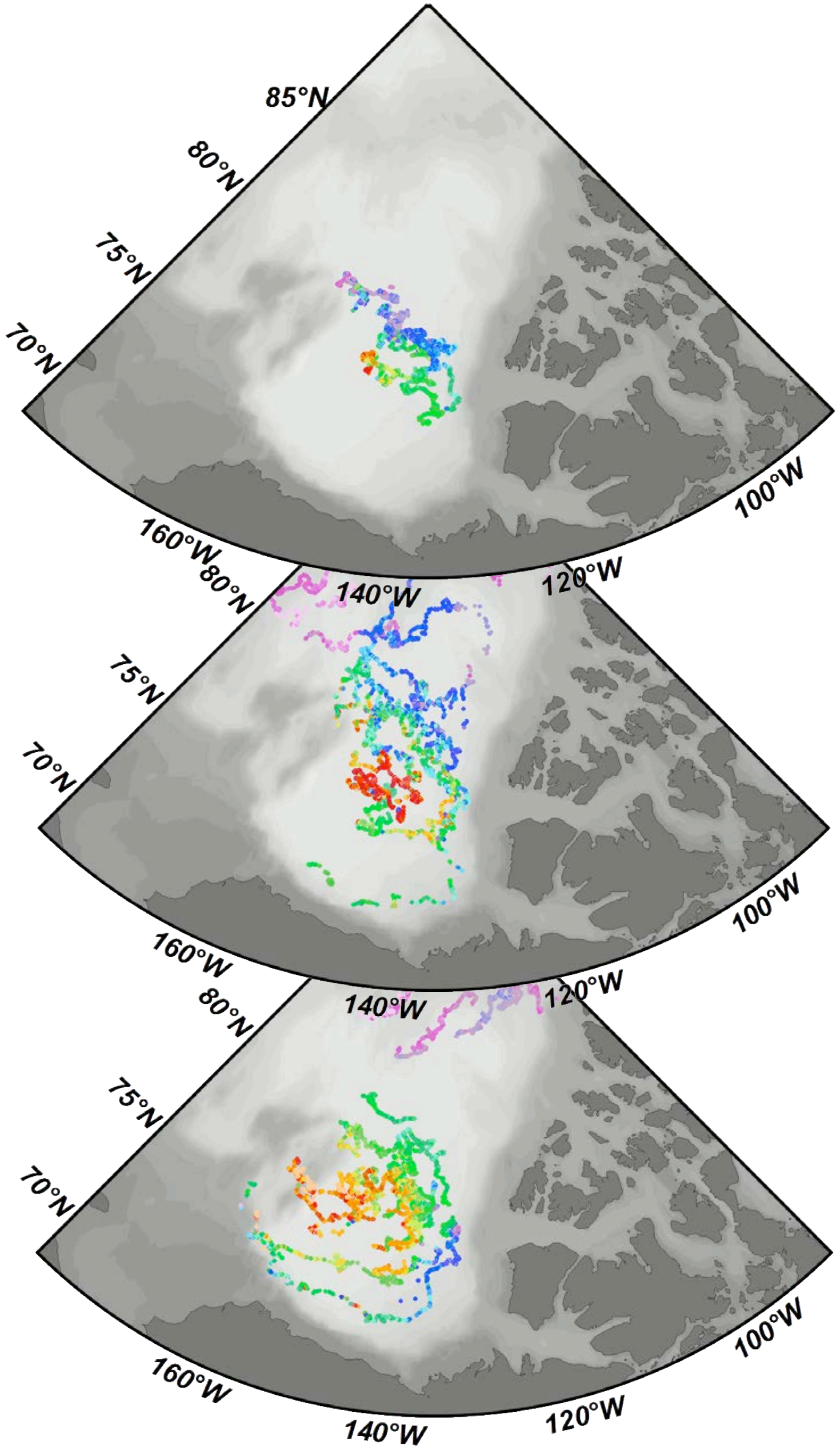


Figure 12. Maps demonstrating the proximity of the warmest water to the Northwind Ridge and the apparent path of the water from the Northwind Ridge to the Canada Basin. The first map contains data from 2004-2006, the second from 2007-2008, and the third from 2009-2012.

conjunction. In particular, while the salinity of water in much of the southern Chukchi Sea is driven by the seasonal cycle of salinity at Bering Strait, variability in temperature in the Chukchi cannot be explained by Bering Strait transport. Furthermore, whereas long-term variability in salinity is directly tied to the Bering Strait inflow, variability on seasonal timescales near the region where the Pacific Water enters the Canada Basin cannot be explained by the salinity of the inflow [*Spall*, 2007].

In light of these various working conclusions concerning the pathways of the Pacific Water from Bering Strait into the Canada Basin, the difficulty of analyzing seasonality becomes apparent. Spall concludes that water properties in Bering Strait, which clearly demonstrate seasonal variation in both temperature and salinity (Woodgate, 2004), are not a dependable proxy for water properties in the Canada Basin. Furthermore, given the data backing the idea that the Pacific Water is transported to different parts of the Canada Basin in different seasons, we did not expect the temperature profile of the Pacific Water at one particular location to evidence a recognizable seasonal cycle. Whereas eddies appear to transport Pacific Water directly into the Canada Basin in late summer and early fall, none is transported along this same route in the wintertime, indicating that water from different seasons is spatially separated [*Watanabe and Hasumi*, 2009]. *Shimada et al.* [2006] note that the October/November pulse of the warmest Pacific Water is directly followed by a shift in the current velocity from eastward to westward, which carries the warm water toward the Northwind Ridge. Furthermore, in a 2001 paper *Shimada et al.* states that while this upstream warm event has a pulselike character, lasting only two months, there is no corresponding pulselike downstream event; rather, the warm water persists at the Northwind Ridge, again defying a standard assessment of seasonality. Finally, *Jackson et al.* [2009] note no apparent seasonal cycle in the amount of heat stored in the Pacific Water at the ITPs. They explain this lack of seasonality as heat perennially trapped beneath the summer halocline, though they do suggest that heat content is affected by advective as well as vertical processes.

Given these obstacles, therefore, it is hardly surprising that our data turned up very little in terms of seasonality. Whereas the ACW does not show any apparent seasonal variability in

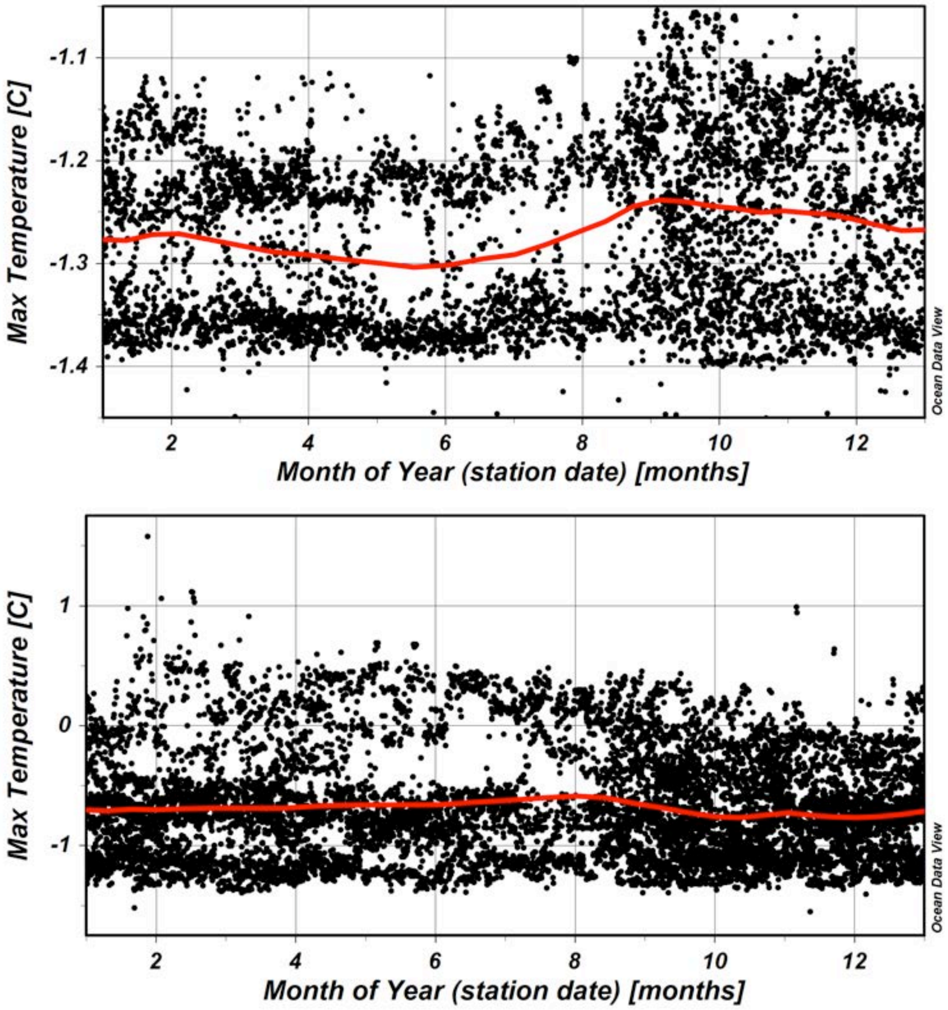


Figure 13a. Month-by-month plot of sBSW temperatures (**top**) and ACW temperatures (**bottom**) in the Central Canada Basin for 2004-2012 as part of an analysis of seasonality.

temperature when all CCB data from the study period were plotted together, the sBSW demonstrates a somewhat more appreciable seasonality in the CCB (both shown in Figure 13a). The temperature of the sBSW reaches a distinct minimum between late winter and late spring before peaking near the end of the summer and remaining fairly high throughout the winter. Salinity-wise, though, the sBSW appears not to vary significantly throughout the year in the CCB (see Figure 13b). The ACW, on the other hand, evidences a very slight peak in salinity in early summer. Overall, if anything is to be made of these weak variations in temperature and salinity, a fuller understanding of Pacific Water pathways would be decisively helpful.

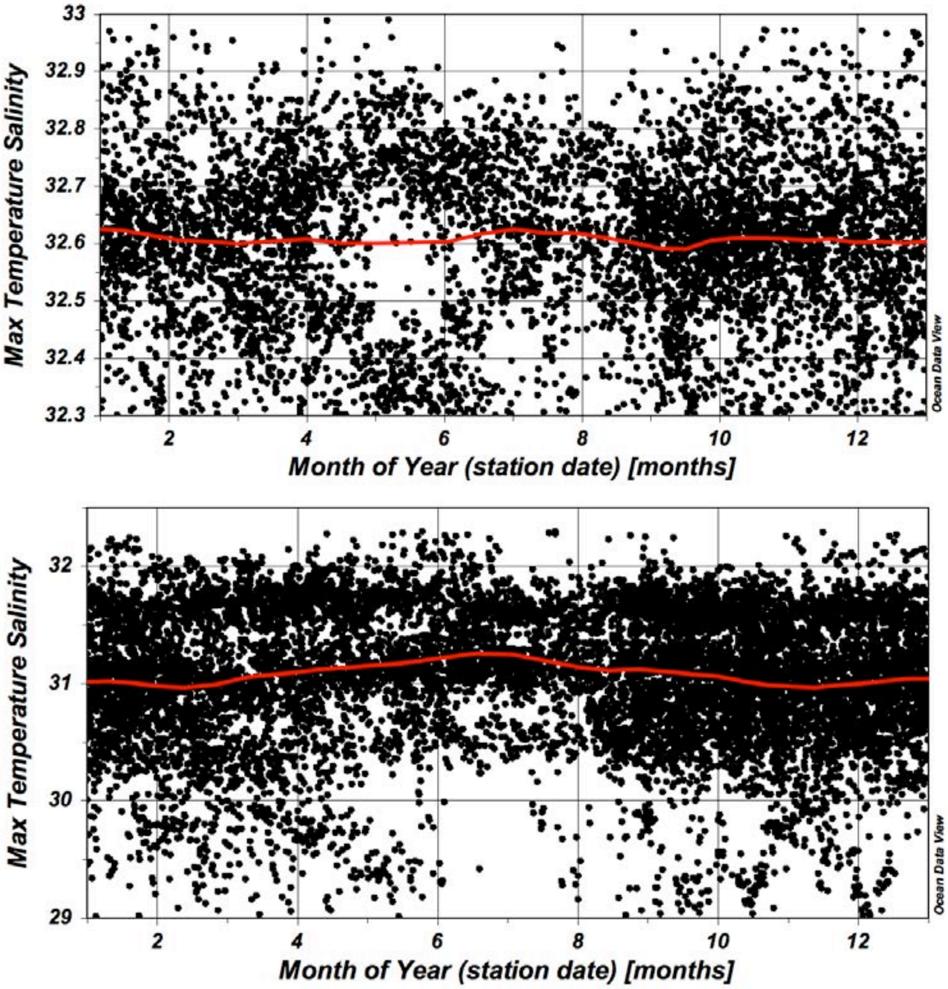


Figure 13b. Month-by-month plot of sBSW salinity (**top**) and ACW salinity (**bottom**) in the Central Canada Basin for 2004-2012 as part of an analysis of seasonality.

10. Interannual Variability of Water Mass Extent

Venturing outside the Central Canada Basin, we were also interested in analyzing temperature fronts associated with the Pacific Water; in particular, we hoped to determine if the spatial distribution of the water masses in question had changed since the 2004 analysis by *Steele et al*. of their extent in 1996-1997 and 1999-2000 (see Figure 14b). In order to identify the fronts apparent for the ACW and the sBSW in our data, all available ITP data were grouped into three sets of years (2004-2006, 2007-2008, and 2009-2012), and Ocean Data View was used to place automatic contours in the areas of the sharpest temperature gradients. (These groupings of years

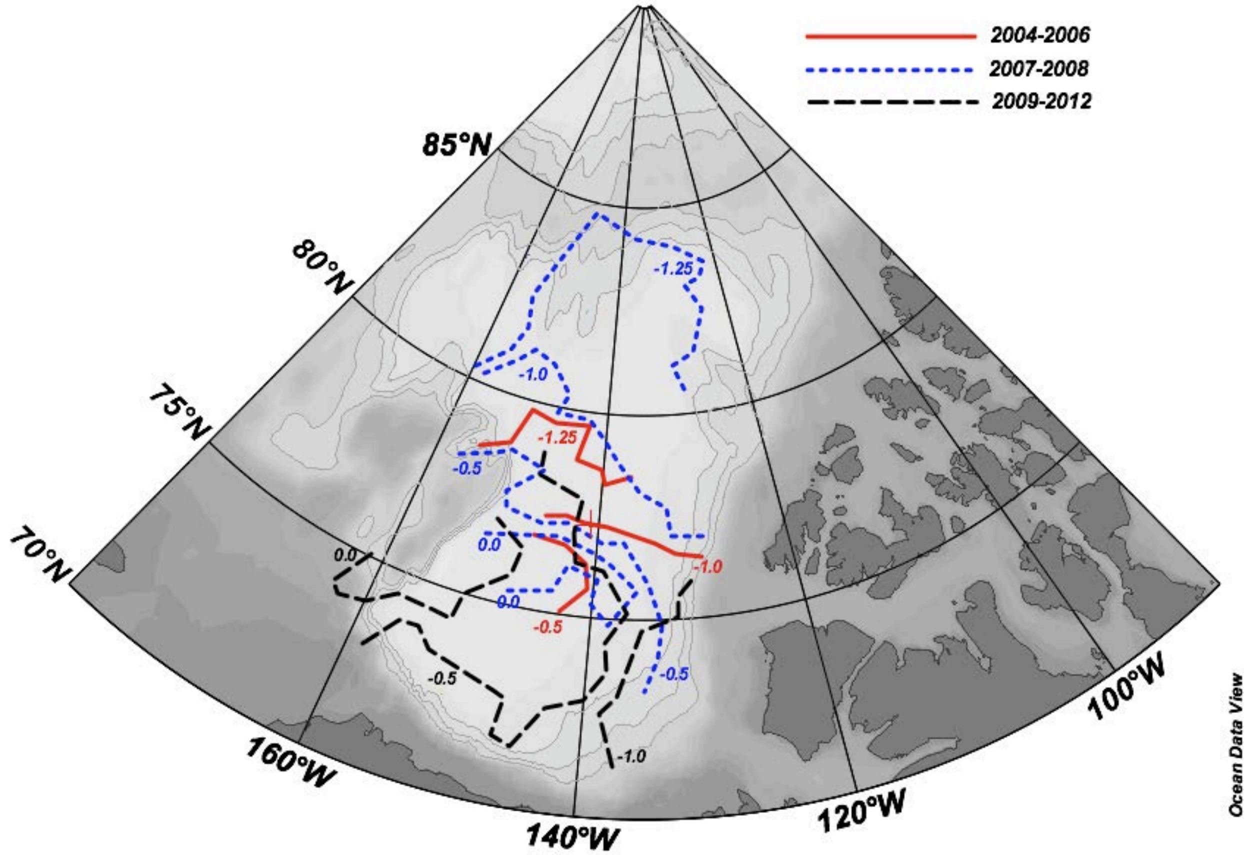
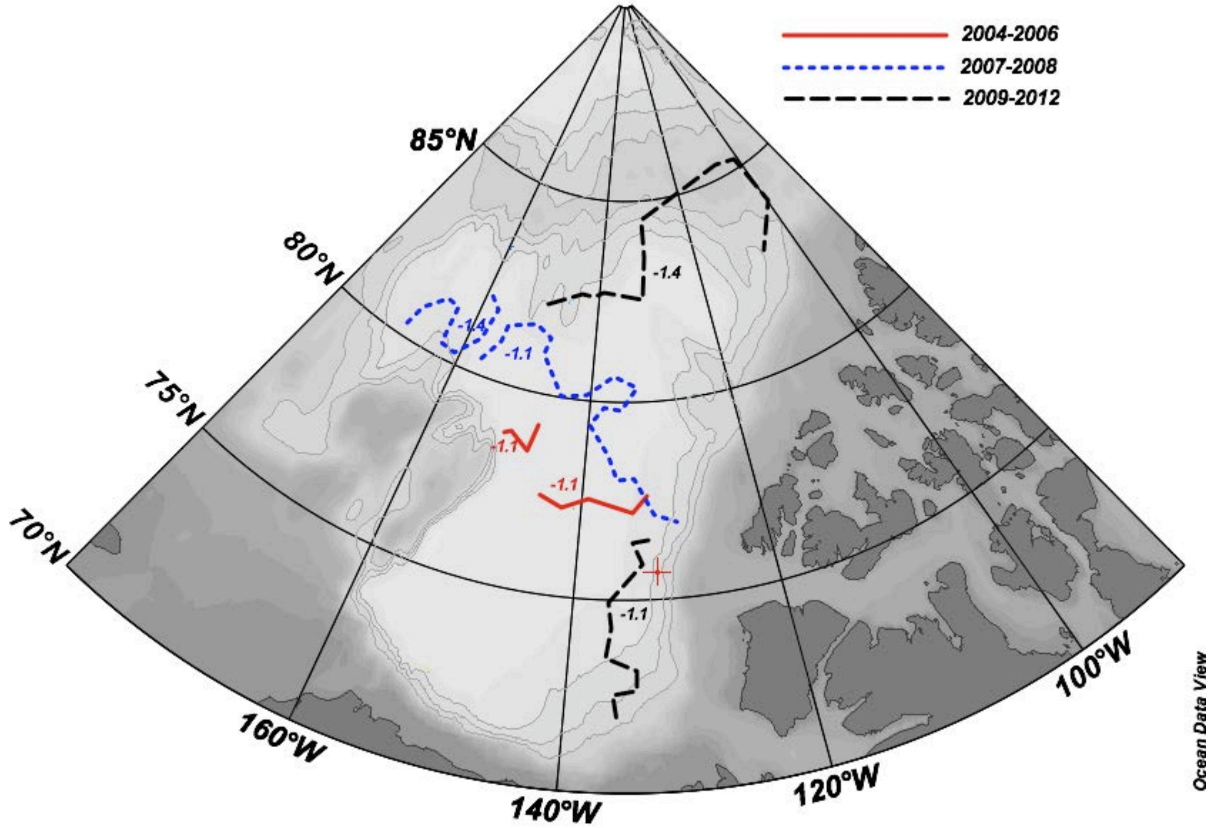
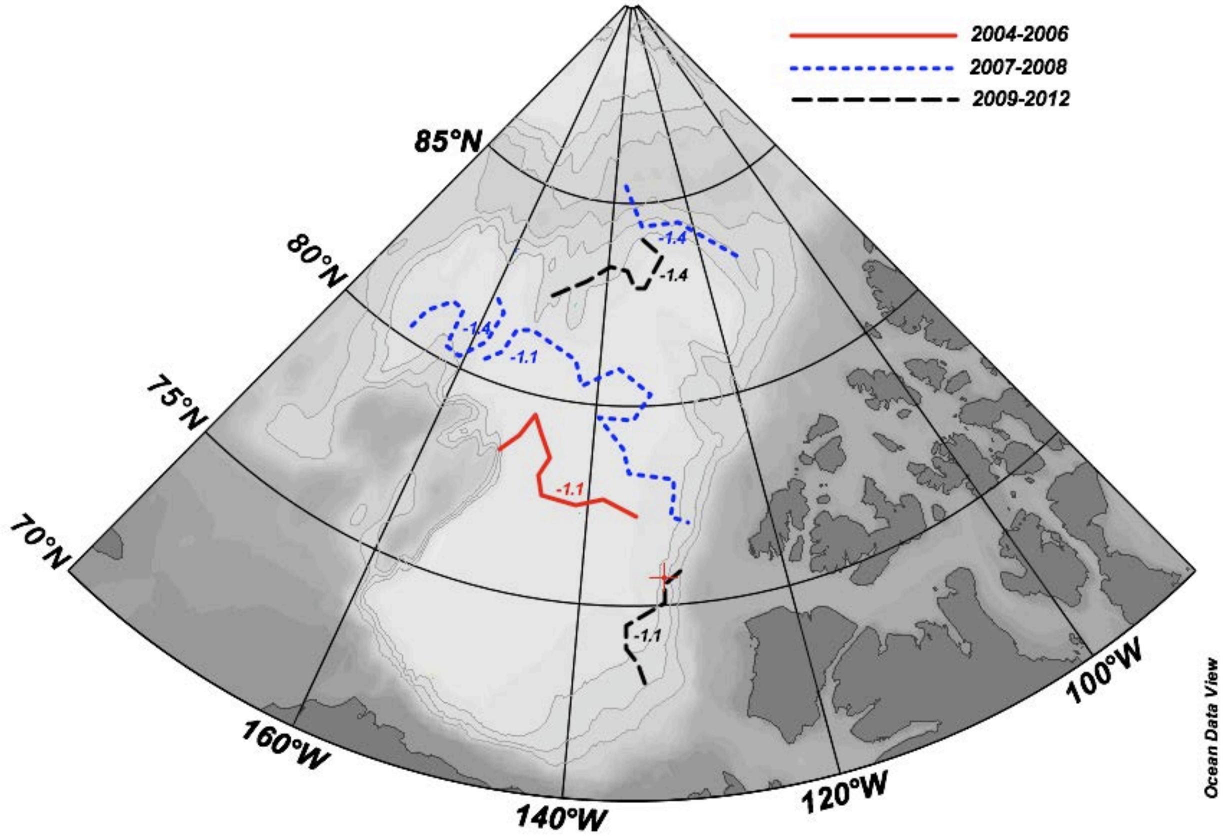


Figure 14a. Maps of the Canada Basin marked with contours apparent in our data (first figure) and with contours used by *Steele et al.* (second and third figures, next page). The second figure was made with the original ACW salinity range, 31 < S < 32, and the the third figure was made with the revised ACW salinity range, 29 < S < 32.

were chosen because they each contain comparable numbers of data points for the ACW θ_{max}: the first group contains 4239 data points, the second contains 3630, and the third 4007.) The sBSW did not lend itself to frontal analysis: the only apparent fronts were created by apparently anomalous points. The ACW, on the other hand, displayed several sharp temperature gradients; the fronts we designated for the ACW can be seen in the map in Figure 14a. Next, to compare the data with the analysis of *Steele et al.*, we created a separate map and used ODV to place automatic contours at -1.1ºC and -1.4ºC, which were the fronts defined by the authors.

The fronts in Figure 14a were made using ACW peaks found within the revised salinity range 29 < S < 32.3. The contours chosen—0.0°C, -0.5°C, -1.0°C, and -1.25°C—were traced over automatic contours generated by Ocean Data View, and were selected for several reasons. First and foremost, these contours are representative of the sharpest temperature gradients for


2004-2006
2007-2008
2009-2012
85°N
80°N
75°N
70°N
-1.4
-1.4
-1.1
-1.1
-1.1
-1.1
160°W
140°W
120°W
100°W
Ocean Data View


2004-2006
2007-2008
2009-2012
85°N
80°N
75°N
70°N
-1.4
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-1.1
-1.1
-1.1
160°W
140°W
120°W
100°W
Ocean Data View

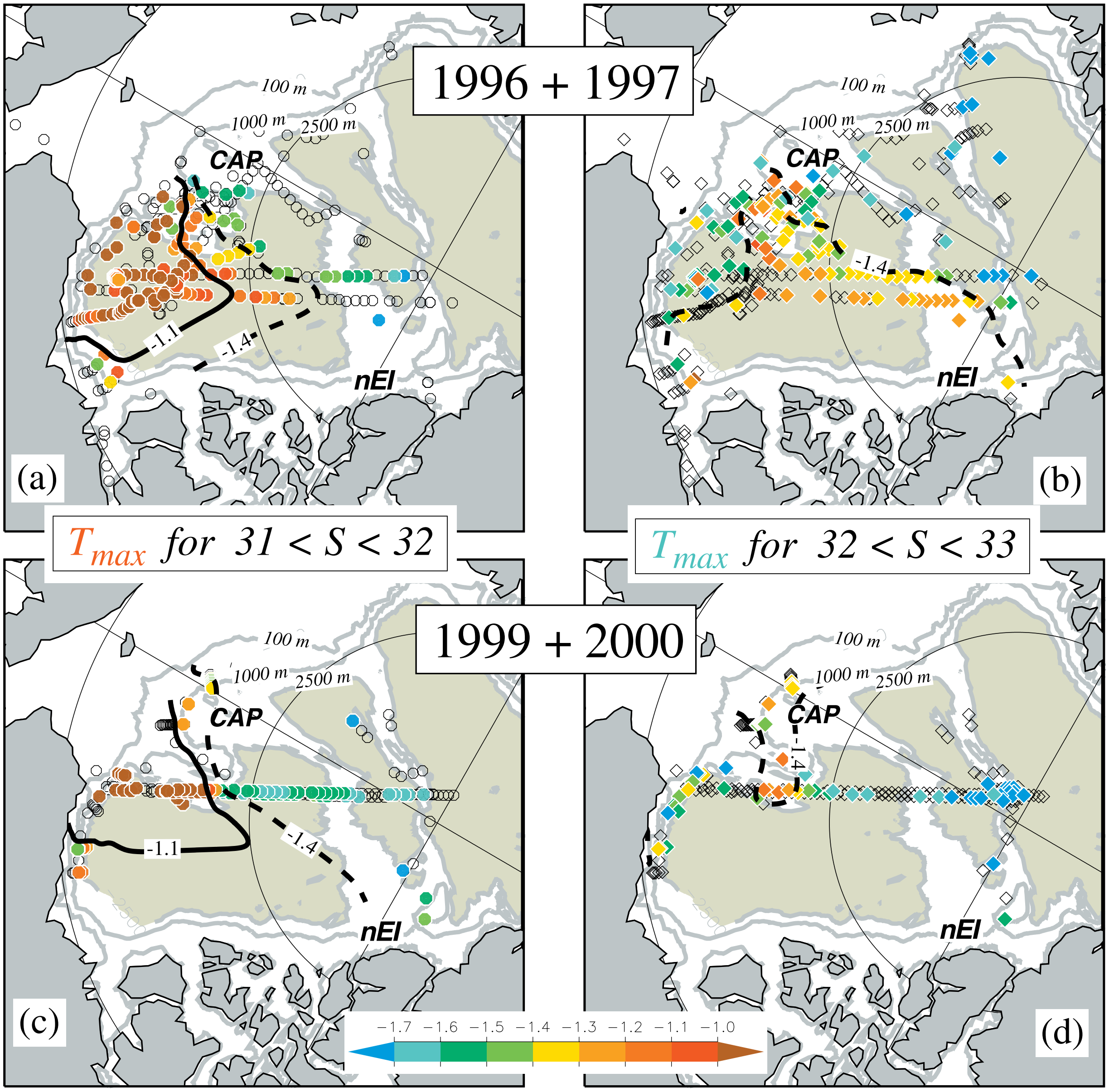
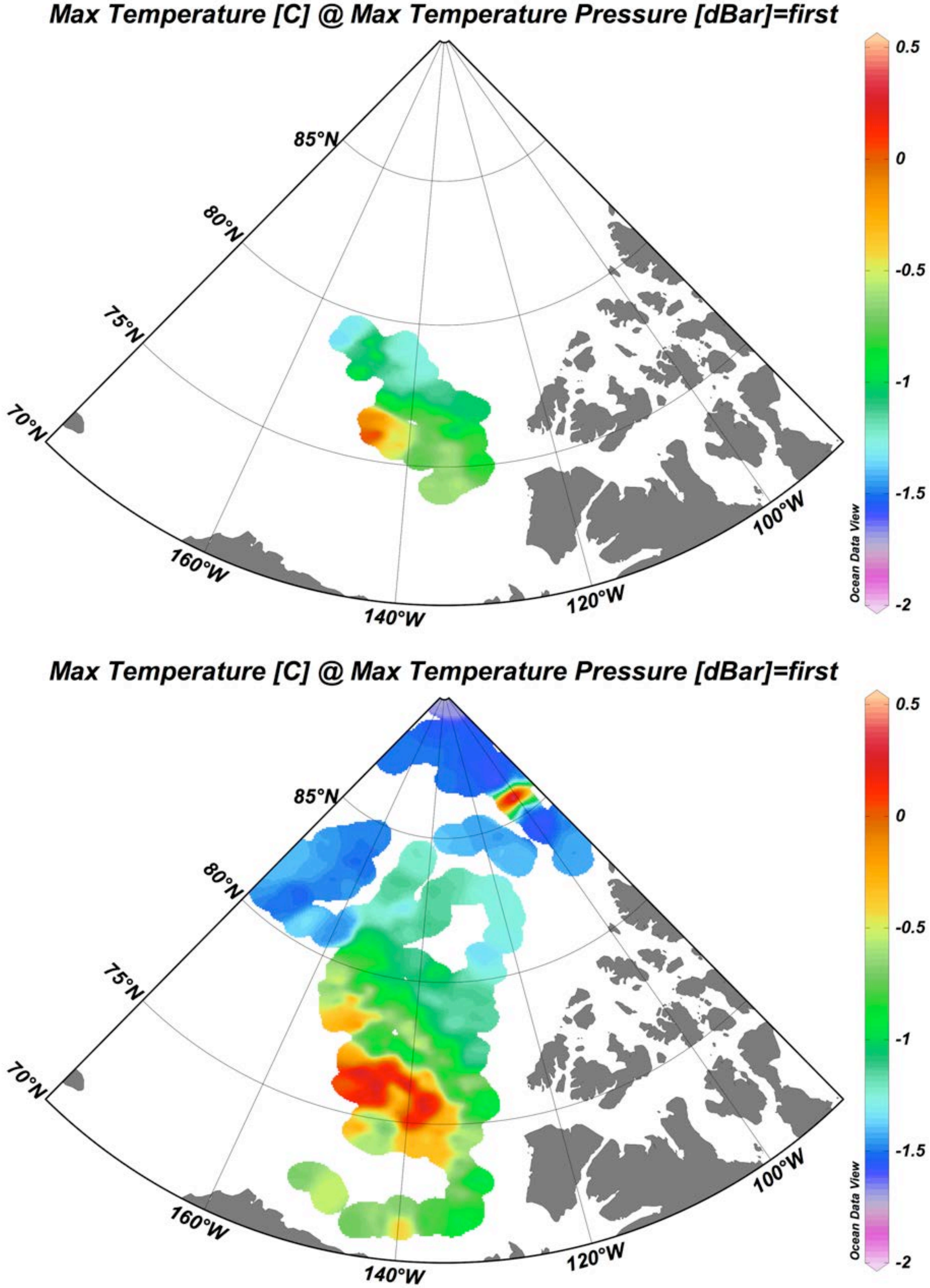
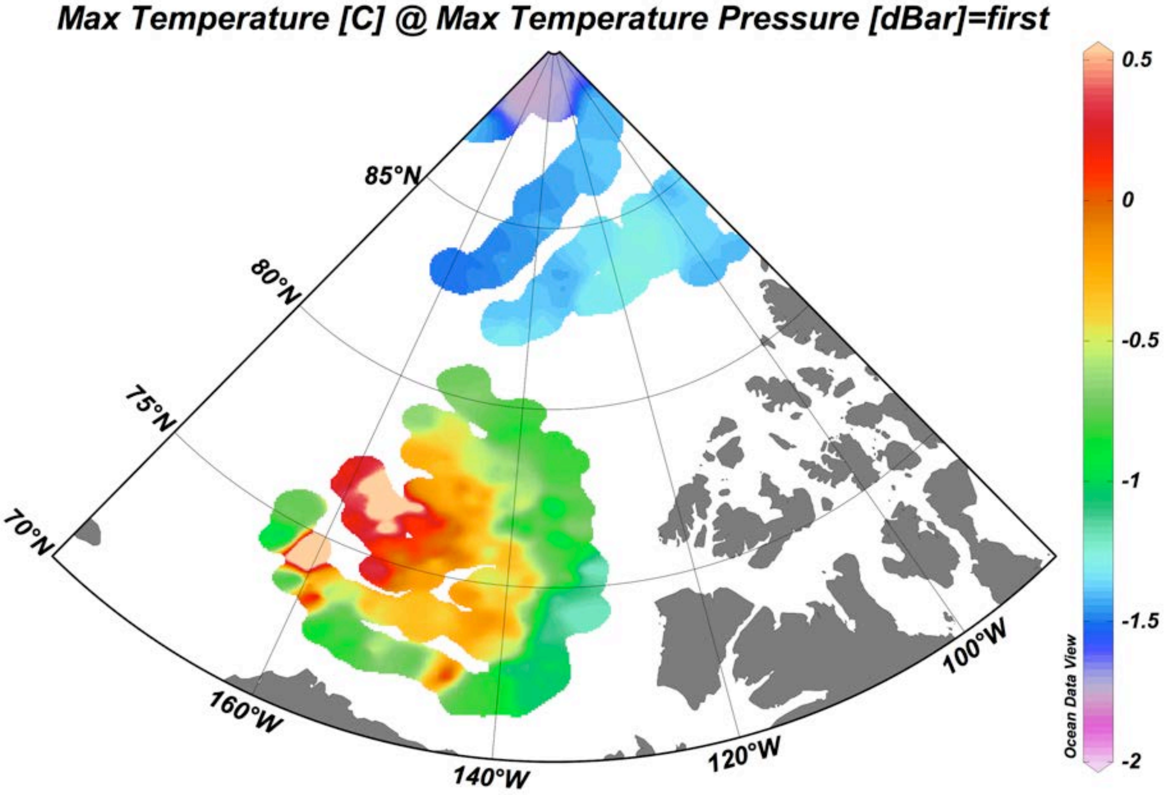


Figure 14b. Frontal maps from Steele et al.; ACW fronts from 1996-1997 and 1999-2000 are represented by the two leftmost panels. (From Steele et al., "Circulation of summer Pacific halocline water in the Arctic Ocean," 2004.)

Figure 14c. Temperature maps for 2004-2006 (**top**), 2007-2008 (**middle**), and 2009-2012 (**bottom, next page**) to accompany the map of fronts in 14a; intended to demonstrate the actual temperatures and temperature gradients associated with the fronts.





each set of years—they actually delineate temperature fronts—a fact that can be visually verified in the temperature maps of Figure 14c. Second, these temperatures are representative of all sets of years; for example, although the particularly warm data from 2007-2008 would also logically include a contour at 0.5°C, neither of the other clumps of years have sharp gradients at this high of a temperature, and thus adding a contour at 0.5°C would not contribute to an interannual comparison. Finally, choosing evenly spaced temperature contours (separated by 0.5°C, with the exception of -1.25°C) allows for an intuitive appreciation of the extent of the Pacific Water both over time and within a single set of years.

Overall, the results of the frontal analysis conducted with our own contours were inconclusive. Examining our own frontal contours, we find that there are certain fronts that seem to progress neatly northward and outward from the Northwind Ridge for each subsequent set of years: the front at -1.0ºC, for example, follows this pattern well. Likewise, the -1.25ºC front moves distinctly from about 79ºN to 84ºN between 2004-2006 and 2009-2012. However, there are certain fronts that do not conveniently and concentrically nest in one another (such as the contour at -0.5ºC), which complicates the interpretation of the progression of the fronts from year to year. Because 2007-2008 was an exceptionally warm set of years, and because data from each set of years cover different parts of the Canada Basin, drawing firm conclusions about the extent and progression of the Pacific Water is difficult. However, this frontal analysis ties in neatly with the previous discussion of Pacific Water pathways: the ACW fronts correspond well with the image of the warmest ACW cooling as it spreads outward from the Northwind Ridge, as seen in Figure 12. This result is consistent with the expected destination of the warmest Pacific Water, as predicted by *Shimada et al.* [2006].

However, this observed spreading does not correspond well with the apparent spreading pattern of the Pacific Water as shown by *Steele et al.* [2004]: rather, their diagrams seem to show the Pacific Water spreading more directly from Bering Strait, with temperature fronts progressing northward instead of northward and away from the Northwind Ridge (see Figure 14b). The 2010 State of the Climate Report (Figure 8) again offers an explanation for this difference, showing that variability in the prevailing winds leads to variability in the direction taken by the wBSW (and, presumably, other components of the Pacific Water) when entering the Canada Basin. Nevertheless, it seems that the -1.1ºC front has tended to progress farther north since the years of Steele's observations: in 1996-1997 the -1.1ºC front was just below 80ºN, extended to 80ºN in 1999-2000, and apparently reached its northernmost limit (81-82ºN) in 2007-2008. This front apparently was at its easternmost extent, at the edge of the Canada Basin, from 2009-2012. The -1.4ºC front also appears to broaden its range over time, extending farther west in the Canada Basin in 2007-2008 than it did in 1999-2000.

11. Conclusions and Directions for Further Research

The centrality of the role of the Pacific Water in the Canada Basin has long been apparent to oceanographers, and thus an understanding of its character and its variability has long been sought. The results of this study help shed light on the capricious nature of this water mass and will hopefully prove useful in future investigations of the Pacific Water. The results can be divided into two basic categories: a reassessment of the definition of the water mass itself (including an appreciation of the fundamentally evolving nature of this definition) and an investigation of the interannual variability thereof.

Because the ACW, the sBSW, and the wBSW are essentially defined by their salinities, ensuring that these water masses actually lie within their prescribed salinity ranges is indispensable for any study of the Pacific Water. Especially because dealing with large amounts of data necessitates the use of a data analysis program rather than a visual assessment, it is especially important to be alert to the possibility that changes in the Pacific Water may quietly render the data analysis routines inaccurate. In this study, had we not conducted a visual, year-by-year study of the Central Canada Basin, we would have presumed that the Pacific Water was simply sparser in the years 2009-2012 rather than unexpectedly fresh. Redefining the salinity range of the ACW to $29 < S < 32.3$ was an important result of our study; however, these limits were derived specifically for the years 2004-2012 and should not be used blindly in future analyses of the ACW. Likewise, though we determined that the sBSW seems to fall neatly in a certain salinity range, the possibility that it, too, is freshening indicates that the limits $32.3 \leq S < 33$ should be not be adopted on faith. Rather, salinity ranges should be chosen that best represent the actual nature of the ACW and the sBSW for the years in question.

Furthering our understanding of the interannual variability of the aforementioned water masses was the other principal result of this study. This analysis is where the value of our decision to analyze the ACW and the sBSW separately, rather than taking the PSW as a whole, becomes apparent: as shown in Figure 10, the different components of the Pacific Water behave very differently. Whereas the sBSW demonstrates a certain amount of interannual variability in temperature, warming somewhat in 2007 and 2011, the ACW steals the show: its yearly temperature fluctuations are much more drastic. Though a nine-year data set does not lend itself to an understanding of long-term trends, gaining an idea of the range of the interannual variability of the ACW was a useful result of this study; the ACW being shallower and containing much more heat than the sBSW, knowing that its temperature varies the most dramatically is significant in terms of sea-ice melt. Future studies might try to pin down the reasons behind the ACW temperature variation and the degree of its impact on the ice cover.

The other aspect of our study that dealt with interannual variability was the assessment of Pacific Water fronts: *Steele et al.* [2004] put forth a map of the fronts of the ACW in 1996-1997 and 1999-2000, and we hoped to build upon this knowledge of the location of the Pacific Water with our own data. Ultimately, we only came to an inexact appreciation of the northward spreading of the Pacific Water between 1996 and 2012 as represented by the -1.1°C and -1.4°C temperature fronts; because both *Steele et al.*'s data and our own data were confined to certain regions of the Canada Basin at certain times, it was difficult to draw solid conclusions about the progression of the fronts. This analysis did, though, provide an interesting window into interannual variability in the pathways taken by the Pacific Water from Bering Strait to the Canada Basin: while our data show Pacific Water apparently spreading from the Northwind Ridge, those of *Steele et al.* seem to demonstrate a more direct pathway from Bering Strait. Interannual variability in pathways, thus, was an intriguing suggestion resulting from this comparison of the two studies.

The pathways of the Pacific Water, while cursorily summarized in our study, certainly merit further investigation. The complex issue of pathways plays into the overall theme of variability apparent in our study, be it variability in the temperature of one water mass versus another, interannual variability in salinity, or the appearance of unanticipated temperature peaks in Pacific Water profiles. A lack of solid knowledge about the routes taken by the water masses hampered the analysis of seasonality we had hoped to conduct, and likewise precludes a full understanding of the impact of the Pacific Water in the Canada Basin. Further study of pathways, therefore, would be an invaluable contribution to our knowledge of this water mass. Despite this gap in our understanding, though, we have managed to put forth several ideas which we think will be useful in future investigations of the Pacific Water in the Arctic Ocean.

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References

Aagaard, K., and L. Coachman. “Toward an Ice-Free Arctic Ocean.” *Eos Trans*. AGU 1975: 484-86.

Blunden, J., D. S. Arndt, and M. O. Baringer, Eds. *State of the Climate in 2010: Special Supplement to the* Bulletin of the American Meteorological Society. Rep. 6th ed. Vol. 92.

Bourgain, Pascaline, and Jean Claude Gascard. “The Atlantic and summer Pacific waters variability in the Arctic Ocean from 1997 to 2008.” *Geophysical Research Letters* 39 (2012): 1-6. doi:10.1029/2012GL051045.

Coachman, L. K., and C. A. Barnes. “The Contribution of Bering Sea Water to the Arctic Ocean.” *Arctic*. 14.3 (1961), 147-161.

Jackson, J. M, E. C. Carmack, F. A. McLaughlin, S. E. Allen, and R. G. Ingram. “Identification, characterization, and change of the near-surface temperature maximum in the Canada Basin, 1993-2008.” *Journal of Geophysical Research* 115 (2010): 1-16. doi:10.1029/2009JC005265.

Jackson, J. M, S. E. Allen, F. A. McLaughlin, R. A. Woodgate, and E. C. Carmack. “Changes to the near-surface waters in the Canada Basin, Arctic Ocean from 1993–2009: A basin in transition.” *Journal of Geophysical Research* 116 (2011): 1-21. doi:10.1029/2011JC007069.

Knauss, John A. *Introduction to Physical Oceanography*. Englewood Cliffs, NJ: Prentice-Hall, 1978. Print.

Krishfield, R., J. Toole, A. Proshutinsky & M.-L. Timmermans, 2008. “Automated Ice-Tethered Profilers for seawater observations under pack ice in all seasons.” *J. Atmos. Ocean. Tech.*, 25, 2091-2095.

Münchow, Andreas, and Eddy C. Carmack. “Synoptic Flow and Density Observations near an Arctic Shelf Break.” *Journal of Physical Oceanography* 27 (1997): 1402-1419.

Proshutinsky, Andrey. "Background." *Beaufort Gyre Exploration Project*. Woods Hole Oceanographic Institution, 24 June 2011. Web. <http://www.whoi.edu/page.do?pid=66316>.

Roach, A. T., K. Aagaard, C. H. Pease, S. A. Salo, T. Weingartner, V. Pavlov, and M. Kulakov. “Direct measurements of transport and water properties through the Bering Strait.” *Journal of Geophysical Research* 100 (1995): 443-457.

Shimada, Koji, Eddy C. Carmack, Kiyoshi Hatakeyama, and Takatoshi Takizawa. “Varieties of Shallow Temperature Maximum Waters in the Western Canadian Basin of the Arctic Ocean.” *Geophysical Research Letters* 28.18 (2001), 3441-3444.

Shimada, Koji, Takashi Kamoshida, Motoyo Itoh, Shigeto Nishino, Eddy Carmack, Fiona McLaughlin, Sarah Zimmermann, and Andrey Proshutinsky. “Pacific Ocean inflow: Influence on catastrophic reduction of sea ice cover in the Arctic Ocean.” *Geophysical Research Letters* 33 (2006): 1-4. doi:10.1029/2005GL025624.

Spall, Michael A. “Circulation and water mass transformation in a model of the Chukchi Sea.” *Journal of Geophysical Research* 112 (2007): 1-18. doi:10.1029/2005JC003364.

Steele, Michael, James Morison, Wendy Ermold, Ignatius Rigor, Mark Ortmeyer, and Koji Shimada. “Circulation of summer Pacific halocline water in the Arctic Ocean.” *Journal of Geophysical Research*, 109 (2004): 1-18. doi:10.1029/2003JC002009.

Watanabe, Eiji and Hiroyasu Hasumi. “Pacific Water Transport in the Western Arctic Ocean Simulated by an Eddy-Resolving Coupled Sea Ice–Ocean Model.” *Journal of Physical Oceanography* 39 (2009): 2194-2211.

Weingartner, Tom. "Chukchi Sea Circulation." University of Alaska Fairbanks, School of Fisheries and Ocean Science, Institute of Marine Science, 24 Apr. 2001. Web. <http://www.ims.uaf.edu/chukchi/>.

Winsor, Peter, and David C. Chapman. “Pathways of Pacific water across the Chukchi Sea: A numerical model study.” *Journal of Geophysical Research* 109 (2004): 1-16. doi: 10.1029/2003JC001962.

Woodgate, Rebecca A., Knut Aagaard, Tom Weingartner, Igor Lavrenov. “Bering Strait: Pacific Gateway to the Arctic.” Polar Science Center, University of Washington, 2004. <http://psc.apl.washington.edu/HLD/Bstrait/bstrait.html>.

Woodgate, Rebecca A., Knut Aagaard, and Thomas J. Weingartner. “A Year in the Physical Oceanography of the Chukchi Sea: Moored measurements from Autumn 1990-1991.” *Deep Sea Research Part II: Topical Studies in Oceanography* 52 (29 Nov. 2005): 3116–3149.

Woodgate, Rebecca A., Knut Aagaard, and Thomas J. Weingartner. “Monthly temperature, salinity, and transport variability of the Bering Strait through flow.” *Geophysical Research Letters* 32 (16 Feb. 2005): 1-4. doi:10.1029/2004GL021880.