Joint effects of boundary currents and thermohaline intrusions on the warming of Atlantic water in the Canada Basin, 1993-2007

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Abstract

The 1990-91 influx of Atlantic water, both anomalously warm and in greater volume than in the past, enveloped the Chukchi Borderland in the western Canada Basin by 2002 and spread across the southeastern Canada Basin by 2007. Warmer, younger (more ventilated) and less dense Fram Strait Branch waters have replaced colder, older and denser waters, increasing the temperature of the Fram Strait Branch core from a fifty-year or more mean of ~0.45 ^{o}C to ~0.7 ^{o}C. Physical and geochemical data collected from 1993-2007 show that the two main transport mechanisms are the boundary current and thermohaline intrusions, established by large thermal gradients. The boundary current operates in a cyclonic direction whereas the thermohaline intrusions operate in an anticyclonic direction due to the influence of the Beaufort Gyre. This shows the Beaufort Gyre's effect on ocean circulation extends into the Fram Strait Branch of the Atlantic layer. The boundary current, a fully-pan Arctic structure, is much slower in the Canada Basin than in basins upstream, with an effective speed of ~ 0.5 cm/s. The effective spreading rate of the thermohaline intrusions, relative to the core, is 0.2 cm/s. Thermohaline intrusions show signs of dissipation near the Northwind Ridge in 2007

suggesting that, as temperature gradients between inflowing and resident waters decrease, they will disappear from the Canada Basin.

1. Introduction

The subsurface temperature maximum of Atlantic water has long been used to investigate the circulation of the Arctic Ocean, beginning with Nansen who observed that it followed the continental slope in a well-defined current and in a cyclonic direction [Nansen 1902; Helland-Hansen and Nansen 1912; Nansen 1915]. Worthington [1953; 1959] proposed that the ocean-wide circulation must be more complex because his observations downstream in the Canada Basin indicated that Atlantic water circulation was anticyclonic. Both Timofeyev [1957] and Coachman and Barnes [1963] produced maps of the circulation of Atlantic water in the Arctic Ocean, the latter by tracing the percent retention of the Atlantic water's temperature maximum with data collected over 60 years. Their maps showed Atlantic water circulation was generally cyclonic but in the southwestern Canada Basin, near the Northwind Ridge, the direction was anticyclonic. Newton and Coachman [1974], applying the same method to data collected 1950-1972 in the Canada Basin, confirmed that circulation was primarily anticyclonic in the deep basin but that Atlantic water was also transported along the slope south of the Chukchi Plateau toward the southeast in a narrow band. Aagaard [1989], using sparse current meter data, suggested that the boundary current was stronger in the Eurasian Basin than in the Canadian Basin. During the 1990s, basin-wide hydrographic surveys showed that the boundary current, carrying Atlantic water, was closely associated with topography, both along the margin and along the Lomonosov Ridge [Anderson et al., 1989; Anderson et

al., 1994; Rudels et al., 1994; Rudels et al., 1999; Swift et al., 1997]. Atlantic water was also observed to be comprised of warm, saline Fram Strait branch (FSB) and colder, fresher Barents Sea branch (BSB) waters [Schauer et al., 1997; Schauer et al., 2002].

Although analysis of archival data indicated that warming events have occurred on multi-decadal time scales during the twentieth century [Polyakov et al., 2004; Swift et al., 2005], the first reported evidence occurred in 1990 when the temperature maximum of FSB water in the Nansen Basin was observed to be ~1 ^{o}C higher than the climatological record [Quadfasel, 1991; Quadfasel et al., 1993]. The downstream appearance of this 1990-91 warm temperature anomaly (hereafter referred to as WTA) has been used since to elucidate Arctic Ocean circulation on large and regional scales: in the Amundsen Basin [Woodgate et al., 2001; Schauer et al., 2002]; Makarov Basin and Mendeleyev Ridge [Carmack et al., 1995; Swift et al., 1997]; and the western Canada Basin [Shimada et al., 2004; McLaughlin et al., 2005; Woodgate et al., 2007). Both observational and model data indicate that the WTA was due to an increase in both volume and temperature of the inflowing Atlantic water [Karcher et al., 2003; Schauer et al., 2004]. This event was also associated with periods of stronger cyclonic atmospheric circulation [Proshutinsky and Johnson, 1997; Dickson et al., 2000]. Inflows of anomalously warm Atlantic waters have been subsequently recorded in the Greenland Sea [Walczowski et al., 2007] and Eurasian Basin [Dmitrenko et al., 2008] but, as noted below, there is no evidence that these recent signals have yet reached the Canada Basin and thus our analysis is confined to the WTA.

Although the boundary current transports heat and other properties around the Arctic Basin margin, lateral spreading along near-isopycnal surfaces by thermohaline

intrusions also advect properties into the basin interior. Thermohaline intrusions, consisting of interleaving layers of warm/salty and cold/fresh waters, have been observed in the Atlantic Layer in the Eurasian Basin [Perkin and Lewis, 1984; Rudels et al., 1994; Rudels et al., 1999], but only after 1993 in the Canadian Basin [Carmack et al., 1995; McLaughlin et al., 2004; Woodgate et al., 2007]. Perkin and Lewis [1984] suggested that intrusions were caused by cross-flow interaction between older basin water and new Atlantic water entering through Fram Strait. Using data from the 1994 Arctic Ocean Section, Carmack et al. [1997] showed that intrusions are: double diffusive structures in potential temperature (θ) and salinity (S); aligned or nested in θ-S space across the Makarov, Amundsen and Nansen basins, a distance of over 2000 km, and also aligned in θ-S space with those observed by Perkin and Lewis [1984]. They found intrusive layers to be 40-50 m thick and their density increased as they spread laterally into the basin interior. Because of their apparent robustness over such distance and time, Carmack et al. [1998] suggested that the layers may be self-organized and self-propelled by the conversion of potential to kinetic energy by salt-flux convergence, contraction on mixing or both. The presence of such features - which we call thermohaline intrusions to distinguish them from the more commonly recognized thermohaline fine structure [Federov, 1979] - is likely due to the weak ambient turbulence in the ice-covered Arctic Ocean [Padman, 1995].

All available data obtained prior to 1993, including high resolution CTD data [cf. Carmack et al., 1995], reveal no evidence of anomalously warm (i.e. >0.5^{o}C) Atlantic water or intrusions in the Canadian Basin. Intrusions were first observed together with the arrival of the WTA in the boundary current above the Mendeleyev Ridge in the Canadian

Basin in 1993 [Carmack et al., 1995], and subsequently in the Canada Basin over the

Chukchi Abyssal Plain slope in 1994 [Swift et al., 1997], north of the Chukchi Plateau in

1998 [McLaughlin et al., 2004] and downstream as far as the northern Northwind Ridge

in 2002 [Woodgate et al., 2007]. Woodgate et al. [2007] used the shape of intrusions to

identify the core of the boundary current and delineate FSB and BSB circulation

pathways in 2002 across and around the Chukchi Borderland, a complex topographic

region that includes the Chukchi Plateau and Gap, Northwind Abyssal Plain and

Northwind Ridge.

This paper is about warming: what happened, how it happened and what it means.

We use time-series (1993-2007) temperature maximum and heat content data from the

Canada Basin to trace the arrival and spreading of the WTA and delineate circulation

pathways. We use the shape of θ-S to investigate how the signal is transported around

and across the basin by boundary currents and thermohaline intrusions, respectively, and

use geochemical tracers to identify other properties of WTA waters. Profiles of θ, S and

density from selected locations, both in the boundary current and basin interior, are used

to investigate changes over time and estimate rates.

2. Data collection and methods

Data were collected from the *CCGS Louis S. St-Laurent* by researchers from

Fisheries and Oceans Canada (DFO), the Japan Agency for Marine-Earth Science and

Technology (JAMSTEC), the National Oceanic and Atmospheric Administration (2002)

and Woods Hole Oceanographic Institution (2003-2007). In 2002 the program combined

a hydrographic and biology survey from the Northwind Abyssal Plain, across the

Northwind Ridge to the southeastern Canada Basin. From 2003 onward, the hydrographic and mooring program included an investigation of the effect of wind forcing on the storage and release of freshwater in the Beaufort Gyre [cf. Proshutinsky et al., 2002]. Surveys consisted of four interlocking sections, two north-south sections, along 140 ^{o}W and 150 ^{o}W, and two oblique east-west sections from ~78 ^{o}N to ~75 ^{o}N and ~76°N to ~73 ^{o}N from ~165 ^{o}W to 130°W (Figure 1). The distance between stations in regions crossing topographical gradients (e.g. Northwind Ridge and Beaufort slope) was ~ 20 km and in low-energy areas of the basin interior, away from the boundary current, the distance was 60-100 km. Each year the same stations were occupied, as close to the same location as ice conditions allowed, and sixteen stations were re-occupied four or more times. Data from cruise # 2002-23 are available at http://www-sci.pac.dfo-mpo.gc.ca/oasp/ data/ default.html and 2003-2007 data are available at http://www.whoi.edu/beaufortgyre/data_hydro.html.

Water samples were collected using a 24-bottle rosette with a Seabird CTD (SBE 911 plus) equipped with oxygen (SBE-43), fluorescence and transmission sensors. Temperature sensors were calibrated yearly and conductivity and oxygen sensor data were calibrated with bottle data following methods reported in McLaughlin et al. [2008]. Silicate, oxygen and salinity samples were analyzed onboard ship and CFC samples were analyzed onboard in 2002, 2005 and 2006. Silicate samples were analyzed on an AutoAnalyzer using standard methods [Barwell-Clarke and Whitney, 1996]; oxygen samples were analyzed using an automated Winkler system; salinity samples were analyzed on an AutoSal calibrated daily with IAPSO standard seawater; and CFC samples were analyzed with an automated purge and trap chromatographic system and

data are reported on the SIO-98 scale. Expendable probes (XCTDs) were deployed to increase spatial resolution. Precision for the 2002-2007 data are: CTD S = 0.003; CTD temperature = 0.001 $^{\circ}$C; oxygen sensor $\leq$ 0.06 ml/l; XCTD temperature = 0.02 $^{\circ}$C; bottle S $\leq$ 0.007; bottle oxygen $\leq$ 0.04 ml/l; CFC-12 $\leq$ 0.06 nmol/m^3; CFC-11 $\leq$ 0.11 nmol/m^3.

These data were combined with CTD data from a joint DFO/JAMSTEC Beaufort slope survey on the *CCGS Sir Wilfrid Laurier* in 2001, hydrographic data from the JAMSTEC program *RV Mirai* in 2002 and 2004, XCTD data from SCICEX 1993-2000, hydrographic data from SHEBA/JOIS 1997-98 and hydrographic data from the Chukchi Borderland CBL-2002 data to improve spatial coverage in the Canada Basin and provide information about upstream conditions. Sampling methods and precision for these data are reported in Shimada et al. [2005]; Shimada et al. [2008]; McLaughlin et al. [2004]; and Woodgate et al. [2007]. Only temperature from the SCICEX dataset is used because salinity is of low accuracy.

3. Results and discussion

Since 1951, and probably earlier, the core properties of FSB water (i.e. at θ_{max}) in the Canada Basin have been constant: θ_{max} = 0.4-0.5 $^{\circ}$C at S = 34.85-34.87 at a depth 450-500 m [cf. Worthington, 1953; Coachman and Barnes, 1963; Newton and Coachman, 1974; Kinney, 1979; McLaughlin et al., 1996]. In 1998 the WTA (>0.7 $^{\circ}$C) had reached the Chukchi region and was observed to be tightly associated with topography: in the south through the Chukchi Gap; and to the north around the Chukchi Plateau and Northwind Ridge at ~77N [McLaughlin et al., 2004]. Shimada et al. [2004] examined 1990-2003 southern Canada Basin data and showed that advection of FSB

waters was well-correlated with bottom topography in the Chukchi region, but that the boundary current debouched at the northern tip of the Northwind Ridge and spread eastward into the Canada Basin interior, confirming Swift et al.'s [1997] description that the Chukchi-Mendeleyev boundary region was an injection site for the interior of the Canada Basin. This newly discovered pathway explained earlier observations of Atlantic water being more ventilated in the northern Canada Basin than in the south [Smith et al., 1999, Smethie et al., 2000]. Shimada et al. [2004] noted that the complicated Chukchi/Northwind Ridge topography both modulated and slowed the spreading and advancement of the WTA. They reported that although FSB temperatures decreased rapidly along the Beaufort Slope, the depth-integrated heat content remained near constant, suggesting enhanced vertical mixing through the Atlantic Layer. Using 2002 data collected from the Mendeleyev Ridge to the Chukchi Borderland, Woodgate et al. [2007] showed the circulation was strongly steered by topography along the margin of the Chukchi Abyssal Plain and around the Chukchi Plateau and Northwind Ridge and that the boundary current was 50 km wide, positioned between the 1500 and 2500 m isobaths. In the following we use both core temperature and heat content of the Atlantic Layer to examine the progression of WTA water into and across the Canada Basin.

3.1 Following the temperature maximum 1993-2007

We examine temporal and spatial distributions of θ_{max}, both historical and new data, and because the warming signal is carried by boundary currents and thermohaline intrusions, our discussion will focus first on the continental margin and then on the basin interior. Warming was first evident in 1993 in the boundary current along the slope of the

Chukchi Abyssal Plain where θ_{max} was 0.9 ^{o}C (Figure 2), the same year θ_{max} was 1.4 ^{o}C, upstream over the Mendeleyev Ridge [cf. Carmack et al., 1995]. At this time θ_{max} elsewhere in the southern Canada Basin was ~0.45-0.5 ^{o}C. By 1995 the FSB θ_{max} had increased to 1 ^{o}C in the boundary current over the western flank of the Chukchi Plateau and ~0.7 ^{o}C downstream along the northeast tip of the Northwind Ridge near 78 ^{o}N, indicating arrival of the core and leading edge of the WTA, respectively. The distribution of waters warmer than 0.7 ^{o}C in 1997 identified a northern route around the Chukchi Plateau and a southern route through the Chukchi Gap, the latter corroborating observations by Newton and Coachman [1974]. The 1997 data also suggest that WTA water spread eastward into the basin interior, and this spreading will be discussed in greater detail below. In 1998 waters warmer than 0.7 ^{o}C identify a narrow boundary current, carrying the leading edge of the WTA southward along the eastern flank of the Northwind Ridge. Temperatures continued to increase and, in 2000, θ_{max} was higher than 1 ^{o}C to the northeast of the Chukchi Plateau. Here high temperatures are evident over an area more than 125 km wide, suggesting that the boundary current may debouch and spread into the basin interior from the eastern flank of the Chukchi Plateau. By 2002 waters across the northern Chukchi Borderland were all warmer than 1 ^{o}C. Waters warmer than 1 ^{o}C were also observed as far south as 74 ^{o}N but these waters likely arrived via a southern route. Temperature variability indicates that two or more spreading pathways transport FSB waters across the Chukchi Borderland, as noted by both Shimada et al. [2004] and Woodgate et al. [2007].

Interpretation of the WTA arrival along the Beaufort slope is confounded by circulation and multiple pathways of water transiting the highly irregular topography of

the Chukchi Borderland. For example, assuming a rate of 2 cm s^{-1} [Woodgate et al., 2001; cf. Woodgate et al., 2007], this time would only be 1-3 years, depending on the specific pathway. This is far shorter than the observed 8-10 year transit time, suggesting that the boundary current progressively weakens along its pathway in the Canadian Basin, resulting in a slower mean speed. In 1997 θ_{max} along the Chukchi/Beaufort slope was 0.6 ^{o}C as far as ~160 ^{o}W, and by 1999 (not shown) was more than 0.9 ^{o}C. By 2002 WTA waters near 1 ^{o}C were found as far south as 74 ^{o}N at 160 ^{o}W, but in 2003 θ_{max} in this region cooled by 0.1-0.2 ^{o}C, suggesting variability in the flow or arrival via a different pathway. Between 2004 and 2006 θ_{max} increased to 0.8 ^{o}C in the southwestern corner of the Canada Basin. These observations suggest that the volumes transported via these various pathways are not equal; for example, the volume transport through the southern Chukchi Gap route may be smaller than that through the northern routes. The fact that θ_{max} along the southeastern Beaufort slope was not higher than 0.7 ^{o}C by 2007 suggest that θ_{max} alone cannot be used identify progress of the WTA in the boundary current in this region [c.f. Shimada et al., 2004] and thus changes in heat content will be investigated below.

The distribution of θ_{max} also shows the importance of lateral spreading by thermohaline intrusions because the temperature of the 'warmest' intrusion is also θ_{max}. In 1997 θ_{max} values near 0.7 ^{o}C were observed about 150 km away from the boundary current, north and east of the Northwind Ridge. In 2002, waters warmer than 0.8 ^{o}C were also found 150 km east of the boundary current. From 2003 onward, data were collected over a larger area of the basin and WTA waters with θ_{max} greater than 0.8 ^{o}C were evident in the basin interior, as far east as 140 ^{o}W at 77 ^{o}N and over 300 km east of the

Northwind Ridge. From 2003 to 2007 WTA waters progressed southward in the basin interior: in 2003 0.8 ^{o}C water was found further south on the western side, by 2005 it was found across the basin at 75 ^{o}N and then in 2007 it was found further south on the eastern side. In 2005 WTA waters spread both northward from the boundary current along the Beaufort slope at 150 ^{o}W as well as southward from the basin interior. In 2007 WTA waters with θ_{max} >0.7 ^{o}C were present over two-thirds of the Canada Basin and FSB waters with a θ_{max} of 0.5 ^{o}C or less, typical of the 1990s and earlier, were present only along the eastern slope and north of Banks Island. Thus the spreading front progressed outward from the boundary current and in an anticyclonic direction in the basin interior.

3.2 Heat content anomaly

To investigate boundary current transport and mixing along the southern margin of the Canada Basin the heat content anomaly of FSB waters was determined with CTD data, using conditions in 1993 – prior to the arrival of the WTA – as a reference. Density was used to define the upper and lower boundaries of the FSB instead of depth [cf. Shimada et al., 2004] to incorporate temporal and spatial variability. The density range was determined by plotting θ versus density to select the two boundaries: σ_θ= 27.65, at the intersection of the lower halocline and the sharp increase in the thermocline; and σ_θ=27.98, the boundary between FSB and underlying BSB waters. The thickness of the FSB, so defined, remains relatively constant (~ 500 m) from 1993 to 2007. The heat content in the Canada Basin in 1993, relative to 0 ^{o}C, was calculated at 21 basin stations and averaged to obtain the reference heat content Q_R = 4.3 x 10^8 J/m^2 (one standard

deviation of Q_R= 0.5 x 10^8 J/m^2). The heat content anomaly, relative to 1993, was

calculated at each station for each successive year using the following equation:

$$Q_{A93} = [Cp \times \rho \times \sum_{z=\sigma\theta27.65}^{z=\sigma\theta27.98} (\theta)\Delta z] - Q_R$$

where Cp = 3985 J/(kgK) and ρ = 1027.0 kg/m^3.

Maps of the heat content anomaly (Figure 3) indicate warming of FSB waters due

to the transport of the WTA's leading edge along the Beaufort Sea slope in 2001 by the

boundary current. By 2002 the heat content anomaly was 9-10 x 10^8 J/m^2 over the

Chukchi-Northwind Ridge region and in the southwestern basin, indicating arrival of the

WTA core via the northern route. By 2005 an increase of 6 x 10^8 J/m^2 was evident north

of 75 °N across the basin as far east as 140 °W. In 2007 the heat content anomaly was 6 x

10^8 J/m^2 or more over half of the basin and over 2 x 10^8 J/m^2 in the southeastern part of

the basin. These maps clearly show that lateral spreading into the basin interior by

thermohaline intrusions is as important as the boundary current in transporting heat and

other properties. A comparison of the heat content anomaly and temperature maximum

maps indicates that some process occurs along the southern margin of the Canada Basin

whereby the temperature maximum is no longer an effective tracer of the WTA. Shimada

et al. [2004] suggested enhanced vertical mixing in Barrow Canyon and along the

southern margin was responsible. Another possibility is that enhanced mixing (lateral

shear dispersion) occurs as the cyclonic boundary current encounters the counter-flowing

(anticyclonic) Beaufort Gyre along the Beaufort slope where the boundary current is not

as tightly constrained by topography as along the Northwind Ridge.

Some outliers are also evident in the general pattern of θ_{max} and heat content

anomaly as discussed above. One type of outlier is due to the presence of cold Atlantic-

core eddies in 2002, 2004 and 2007 [cf. Zimmermann et al., 2006] and another due to the

presence of a warm Atlantic-core eddy in 2007. These eddies appear to originate in the

southwest corner of the Canada Basin where the topography changes from the steep slope

along the Northwind Ridge to the broad Chukchi/Beaufort shelf. Another type of outlier

is located near 75 $^{\circ}$N and 150 $^{\circ}$W, where the temperature of θ_{max} was ~0.9 $^{\circ}$C in 2005,

decreased to ~0.7 $^{\circ}$C in 2006 and then increased again in 2007. One explanation for this

temporal variability is that significant lateral gradients in temperature are established due

to multiple spreading pathways into the interior. Here, for example, WTA waters spread

both eastward from the boundary current located along the Northwind Ridge and also

southward in the basin interior.

3.3 Physical and geochemical properties of the WTA

Arrival of the WTA is evident at Station A, located near 72.5 $^{\circ}$N and 145 $^{\circ}$W and

away from the slope at a depth of ~3500 m. The station was occupied frequently from

1990-2007 and, while exact locations varied owing to ice conditions, all data were

collected within a 50 km radius. Up to 1997 profiles of θ, S and the θ- S plot were

smooth, with no evidence of thermohaline intrusions (Figure 4). Small changes in FSB

core properties were evident, beginning in 1993 when the salinity (and density)

associated with the θ_{max} decreased from 34.87 to 34.83 [cf. McLaughlin et al., 2002]. In

2002 the first evidence of thermohaline intrusions appeared at Station A, first as small

steps in temperature and salinity profiles and small zigzags in θ-S plots indicating arrival

of the leading edge of the WTA. By 2007, when the temperature gradient increased due

to the southward advance of the WTA, the small zigzags evolved into large zigzags, suggesting thermohaline intrusions are formed locally in the Canada Basin.

In addition to heat, WTA waters also carry higher concentrations of oxygen and CFC-11 (Figure 5). These higher concentrations (increased ventilation) show that the WTA waters are younger than ambient basin waters. For example, in 2005 the plots of θ-S data, colored by latitude show that the highest temperatures are found in the north (see also Figure 2). Maps of oxygen and CFC-11 concentrations on density=27.92, corresponding to the density at θ_{max}, indicate that concentrations are higher in the north than in the south.

Potential temperature and density on a south to north section along 140 ^{o}W are plotted yearly 2003-2007 to illustrate the spreading of the WTA by thermohaline intrusions relative to the core (Figure 6). The leading edge forms a well-defined, density-compensating front with large horizontal gradients such that even small shifts in position can yield large changes in scalar properties at a specific location. In 2003 the first signs of warming (θ_{max} >0.6^{o}C) are evident north of 75 ^{o}N, and the subsequent advance of WTA waters southward is clear in the year-to-year comparison. From these data, which clearly show the difference between the leading edge and the core properties of WTA waters, an effective spreading speed of the thermohaline intrusions, relative to the core (0.1 cm/s), is 0.2 cm/s. These data also show that the depth of the WTA core deepens as it advances southward from ~360 m in 2004 to ~ 420 m in 2007.

3.4 Thermohaline structures

It is clear that the arrival of the FSB WTA in the Canada Basin coincides with the spreading of thermohaline intrusions. We now use the shape of individual θ-S plots to investigate transport by the boundary current and by thermohaline intrusions, recognizing that the 1993-2007 θ-S plots from the Canada Basin, east of the Northwind Ridge, belong in one of the following four θ-S groups:

1) smooth θ-S shape (i.e. no intrusion) and only θ indicates whether waters are ambient "old" water (~0.45 ^{o}C) or if they have experienced processes that erase the θ-S intrusion.

2) small zigzag shape that indicates interleaving between waters whose temperature difference is small.

3) large zigzag shape that indicates interleaving between waters whose temperature difference is large, for example the intersection of WTA in the boundary current waters and colder ambient basin waters.

4) point and bump (P&B) shape that Woodgate et al. [2007] attributed to a combination of double diffusive and mechanical mixing processes.

We have used the same terminology as Woodgate et al. [2007] to simplify comparison between the two regions. The major difference between their 2002 Chukchi Borderland study and this Canada Basin study is that WTA water had already arrived in the Chukchi Borderland in 2002 whereas we investigate its arrival and subsequent spreading into the basin, and the θ-S curve changes from a smooth shape to one with large zigzags in over a decade and a half.

To illustrate the distribution of these four θ-S structure types, both CTD and XCTD data were coded (squares = smooth (no intrusion), diamond= small zigzag, triangle= large zigzag and circle= P&B) and mapped using color to indicate θ_{max} temperature (Figure 7). Large and small symbols represent CTD and XCTD data, respectively. In 1997 there were no intrusions in the southeastern Canada Basin, however large zigzags, P&Bs as well as smooth θ-S shapes and temperatures near 1.0 ^{o}C (i.e no intrusion) were evident over the Chukchi Borderland. By 2003 large zigzags were evident eastward to 135 ^{o}W and southward to 75 ^{o}N, with temperatures ranging from 0.5 - 1 ^{o}C. There were no intrusions along the southern or eastern margins and only small zigzags were present between the margins and 75 ^{o}N. Large zigzags were found further south each year, replacing small zigzags which in turn moved southward. In 2007 the predominant θ-S structure in the Canada Basin was the large zigzag and the only remaining vestige of 1990's Canada Basin FSB water was located along the eastern slope north of Banks Island. Both large and small zigzags were found in the basin interior (with the exception of locations where deep eddies were observed) whereas P&B were only observed along the basin margin, indicative of the boundary current. Clearly thermohaline intrusions are a major mechanism in the propagation of signals across the southern Canada Basin interior.

3.5 Investigating an intrusion: over time and geography

Having established the regional distinction between transport via boundary current versus via thermohaline intrusions, we now look at the evolution of the θ-S structures at specific locations, both within the boundary current and within the basin

interior, acknowledging that flow is not fixed but meanders over time. The first set of

stations is located near 75.5 ^{o}N and 156 ^{o}W, along the steep slope along the Northwind

Ridge. Data are from 1993, 2002, 2003, 2005-2007 and station depths range from 1000 -

2500 m. Several stations from each year are included in this set to show the variability of

θ-S shapes that occur over a small distance; 50 km in the north-south direction and 15 km

east-west. Profiles of θ and density illustrate the step-like nature of the intrusions and

interleaving between warmer and less dense water with colder and denser ambient

Canada Basin waters (Figure 8a). Thus a single intrusion consists of a salt finger

component (warm, salty over cold, fresh) and a diffusive (cold over warm) component.

The time sequence of θ-S plots shows the evolution from a small zigzag in 1993 with θ_{max}

= 0.49 ^{o}C to mainly large zigzags with θ_{max} >0.8 ^{o}C in the 2000s. In 1993 intrusions

(small zigzags) were evident along the Northwind Ridge, at 75.5, 76 and 77 ^{o}N,

indicating the first signs of the leading edge of the WTA. The θ_{max} was highest in 2002

(1.15 ^{o}C), signaling arrival of the WTA core, and subsequently decreased, however the θ-

S structure maintained a large zigzag shape. The persistence of the large zigzag shape,

once formed, indicates the robustness of this θ-S structure, and the decrease in θ_{max}

between 2002 and 2007 likely reflects the continuing loss of heat by driving intrusions

into the basin interior. It could also be due to arrival of colder water [cf. Woodgate et al.,

2007]. The P&B shapes are observed within the core of the boundary current, over depths

of 1800-2000 m, similar to observations over the Chukchi Borderland (1500-2500 m) by

Woodgate et al. [2007]. The average thickness of the main intrusive feature, generally

containing θ_{max}, is ~70 m, and in a large zigzag, most of this depth is occupied by the salt

finger component. In the P&B however, the salt finger and diffusive components are

about the same thickness and this is likely due to turbulent mixing in the faster moving part of the boundary current as Woodgate et al. [2007] suggested. This mixing is evident by comparing the S and θ gradients through the salt finger step in the large zigzag to that in the P&B; S and θ clearly decrease with depth in the large zigzag and decrease slightly in the P&B. In the diffusive portion temperature is near constant in the large zigzag and decreases in the P&B. Thus mixing decreases the stratification within the P&B intrusion as would be expected in three component mixing. The 200-800 m θ profile (Figure 8a) illustrates the sweeping change in the FSB Atlantic water due to arrival of the WTA, with an increase in both in temperature, (Δ θ_{max} =0.7 ^{o}C) and volume (ΔV= 160 m).

It is important to note that θ-S shapes change over time and therefore can only be used as a qualitative indicator of the boundary current. For example all four θ-S shapes are evident at stations from 2002-2007 in the boundary current at the northernmost tip of the Northwind Ridge (Figure 8b). These stations are located within a 40 km radius and the topography ranges from 1000-2500 m. All the θ_{max} are above 0.9 ^{o}C and thus indicate the arrival of WTA waters. Between 2002 and 2005 θ-S shapes were large zigzags or P&Bs; in 2006 and 2007 the shapes were small zigzags, P&B and smooth curves. This evolution occurs because the temperature difference between the WTA and the cold ambient waters initially is large but, as more WTA arrives, it mixes with similarly warm waters and then, once there is no thermal gradient, the thermohaline intrusions begin to dissipate due to turbulence in the boundary current.

Downstream in the boundary current region along the Beaufort slope, θ-S shapes are either small zigzags or smooth and this holds along the slope from 150 to 131 ^{o}W (Figure 8c). The θ_{max} was highest in 2006 east of Barrow Canyon near 150 ^{o}W, about 600

km downstream of the data from the Northwind Ridge, discussed above; and assuming this reflects arrival of the WTA core via the northern route, the effective boundary current speed in the southern Canada Basin is ~0.5 cm/s. Comparison of the 200-1000 m θ profile with the one upstream along the Northwind Ridge supports the assumption that the WTA arrived here by 2006, as do the heat content maps.

Further downstream near 140 ^{o}W, θ_{max} is 0.62 ^{o}C in 2007 and the first signs of small zigzags are evident. (As θ_{max} alone is not a good indicator of boundary current transport along the Beaufort slope because of mixing, we use the appearance of the small zigzag θ-S structure and temperature instead). If we assume the leading edge of the WTA had arrived in 1993 along the Northwind Ridge, as indicated by small zigzags, we calculate a boundary current speed of 0.25 cm/s (1100 km traveled in 14 years). Current measurements indicated boundary current speeds in the Eurasian Basin are 5 cm/s and in the Makarov Basin are 2 cm/s [Woodgate et al., 2002]. Further downstream the arrival of WTA waters along the Northwind Ridge flank in 2002 suggested an apparent speed of ~0.34 cm/s [McLaughlin et al., 2005]. Our data support this trend of reduced boundary current speed in the Canada Basin, as first proposed by Aagaard [1989]. This decrease in speed is to be expected because much of the water delivered upstream, near the Lomonosov Ridge, supplies water to reservoirs and drive intrusions *enroute* to the Beaufort Shelf.

Focus now turns to stations in the basin interior and we can observe how the water column is modified by the arrival of the leading edge of the WTA. We start in the southeast at Station 23, located near 72.7 ^{o}N and 138 ^{o}W, depth ~2700 m, data were collected in 2002, 2003, 2005 and 2007; stations in successive years are less than 35 km

apart (Figure 9a). The steps in temperature are small in 2002 and 2003, where the difference between the top and bottom of the salt finger component of the intrusion is 0.02 $^{\circ}$C, and increases markedly in 2007 to $\Delta\theta$=0.10°C. As a result the θ-S structure evolves from a small to a large zigzag in 2007.

Northward at Station 18, located near 75 $^{\circ}$N and 140 $^{\circ}$W and depth of 3700 m, data were collected in 1997, 2003-2007 (distance between stations is less than 20 km). The leading edge of the WTA is already present in 2003, indicated by the large zigzag θ-S shape (Figure 9b). In 2005 θ_{max} had increased to 0.81 $^{\circ}$C, S increased by 0.01 and the θ difference between the top and bottom of the salt finger component was the largest of all the years at $\Delta\theta$=0.14 $^{\circ}$C. In 2006 and 2007 θ_{max} increased slightly and the difference in θ and S salt finger component diminished. These data suggest the core of the WTA arrived here in 2006. Note that within the main intrusion, the single temperature step evident in 2005 evolved into a double temperature step within the salt finger component of the same intrusion in 2006 and 2007.

The last interior basin location to be examined is Station 11, located near 79 $^{\circ}$N and 150 $^{\circ}$W, depth 3900 m, and data were collected in 1993 and 2003-2007 (stations are less than 40 km apart). Here, northeast of the Northwind Ridge, all stations show large zigzags in θ-S and θ_{max} was already 0.85 $^{\circ}$C by 2003 when the difference between the top and bottom of the salt finger component of the intrusion is $\Delta\theta$=0.21 $^{\circ}$C and $\Delta S = 0.020$ (Figure 9c). In 2004 θ_{max} increased to 1.08 $^{\circ}$C, signaling the arrival of the WTA core. Although the large zigzag shape persisted, the temperature of θ_{max} decreased each year and by 2007 was 0.93 $^{\circ}$C. The density profile indicates that FSB waters are less dense in

2007 than they were in 1993 and thus the incoming (lighter) WTA has displaced older (heavier) ambient Canada Basin waters.

3.6 Time dependent tracers and mixing scales

In 2005 salinity, oxygen and time dependent tracer samples (CFCs and ^{129}I) were collected in ~10 m intervals through the main intrusion (350-550 m) at Stations 4 and 15 to investigate the properties of the two interleaving layers of the main (θ_{max}) thermohaline intrusion, estimate relative age differences and mixing scales. Profiles of θ, S (sensor and bottle) illustrate the level of sampling through the θ_{max} intrusion and the agreement between bottle and sensor data at both stations. The O_2 (sensor and bottle) and CFC-12 (Figure 10) data show the new WTA waters have higher concentrations of oxygen and CFC-12 than the Canada Basin waters they are displacing. The difference in apparent age between the top and bottom of the salt finger component of the main intrusion is ~ 2 years. Assuming speed of the thermohaline intrusions is 0.2 cm/s, the effective lateral mixing scale length is 120 km, similar to the 50-100 km length estimated by Walsh and Carmack [2003].

Conclusion

The temperature of FSB waters in the Canada Basin increased by ~0.25 ^{o}C from 1993 to 2007 and clearly demonstrates the WTA, first observed in the Nansen Basin in 1990, finally arrived across most of the Canada Basin almost two decades later. This signal was transported jointly, in a cyclonic direction by the boundary current, and in an anticyclonic direction by thermohaline intrusions and the influence of the Beaufort Gyre.

Indeed, the co-occurrence of the boundary current and Beaufort Gyre was first noted by Newton and Coachman [1974].

Tracing the WTA arrival through increases in temperature provided a means to deduce FSB circulation and pathways in the Canada Basin, illustrated in Figure 11. WTA water is delivered by the boundary current to the Chukchi Abyssal Plain. On reaching the Chukchi Borderland, the boundary current bifurcates, with one branch flowing northward along the flank of the Chukchi Plateau, and one branch flowing through the Chukchi Gap [McLaughlin et al., 2004]. On reaching the northern Chukchi Plateau the northern branch bifurcates once more, with one branch flowing eastward across the Canada Basin [cf. Swift et al., 1997; Shimada et al., 2004] and one branch bending southward along the eastern flank of the Northwind Ridge [McLaughlin et al., 2004; Woodgate et al., 2007]. This later branch continues southward to merge with the branch that flows through the Chukchi Gap and then continues eastward (cyclonic) along the Beaufort Shelf. This suite of boundary currents carried new WTA water into a background of older, colder water, thus establishing the necessary conditions (temperature gradient) to form thermohaline intrusions, which subsequently propagate the WTA into the basin interior [see Walsh and Carmack, 2003]. In turn these thermohaline intrusions spread into a basin dominated by the Beaufort Gyre and were therefore driven in an anticyclonic direction. Dynamic height calculations with respect to 1000 m (not shown) indicate there is weak anticyclonic flow at 400 m and corroborate Newton and Coachman's [1974] findings that the influence of the Beaufort Gyre extends into the FSB of the Atlantic layer. Velocities associated with these three transport mechanisms are 0.1-0.5 cm/sec at the core depth of the θ_{max} [cf. Newton and Coachman, 1974]. The

combination of cyclonic boundary current and anticyclonic Beaufort Gyre also explains the reverse "S" isotherm pattern associated with the spread of thermohaline intrusions that develops between 2004 and 2007 (Figure 2).

To increase the temperature of the FSB by 0.25 ^{o}C over an area of $3.5 \ 10^5$ km^2 and 500 m thick in the southern Canada Basin required an amount of heat $\Delta H = 1.5 \ 10^{20}$ J, using specific heat of $Cp = 4 \times 10^3$ J/(kgK) and density $= 10^3$ kg/m^3. If this heat was provided by additional oceanic heat advection over a five year period, an increase of ~1 TW is required. Schauer et al. [2004] estimated that $\Delta H = 5 \ 10^{20}$ J was required to increase Eurasian Basin waters 0.5 ^{o}C as a result of the early 1990 warming event, and concluded that this heat remained within the basin for several years and was not released to the atmosphere or ice. Our data shows that heat input to the Canada Basin (~30% of the Eurasian Basin input) via boundary currents and thermohaline intrusions remains in the basin on decadal time scales and, further, when this water eventually exits the Arctic Ocean back into the North Atlantic it will warm the Atlantic layer of the East Greenland current.

Will the thermohaline intrusions persist? Their presence depends on forcing by lateral temperature gradients. In the absence of such gradients, they must ultimately dissipate and the water column will revert to a new, warmer state with smooth profiles of temperature. Should new pulses of either warmer or colder water arrive, however, horizontal gradients would be re-established and thermohaline intrusions would result again. Indeed observations in the upstream Nansen Basin of increased flow and temperature of Atlantic water [Schauer et al., 2005; Polyakov et al., 2004; Dmitrenko et al., 2007] suggest that future warming events are likely *en route* to the Canada Basin.

This of course assumes that the interior of the "future" Arctic Ocean will remain sufficiently "quiet" to allow the thermohaline structure to persist and not be removed by increased turbulence associated with the removal of ice cover.

Acknowledgements

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Figures

Figure 1. a) Map of the Arctic Ocean showing location of the major topographic features. Atlantic inflow and circulation are indicated by the grey arrows. The study area is identified by the area outlined in black. The expanded inset (b) shows the major topographical features of the southern Canada Basin and stations occupied in 2007. Stations referred to in the text are identified by station number.

Figure 2. Maps of the Fram Strait Branch potential temperature maximum 1993-2007. The potential temperature maximum (^{o}C), determined from CTD and XCTD data, is indicated by the color of the dot, referenced to the color bar shown at the bottom of the figure. Bathymetry is from IABCO and depths are shown in 500, 1000, 1500, 2000, 3000 m intervals. Temperatures greater than 0.7 ^{o}C, due to the arrival of the 1990 WTA, are evident across most of the Canada Basin in 2007 and transport by the boundary current along the southern margin appears weak.

Figure 3. Maps of the Fram Strait Branch heat content anomaly. The mean heat content was determined for 1993 and the heat content anomaly, with respect to 1993, was calculated at each station from 1995-2007 (see text for details). The color of the dot indicates the heat content anomaly value in J/m^2 x 10^8, referenced to the color bar shown at the bottom of the figure. The maps show transport of the WTA by the boundary current along the margins and by thermohaline intrusions in the basin interior.

Figure 4. Physical properties at Station A: 1990-2007. a) Potential temperature-salinity plot; b) potential temperature profile; c) potential temperature profile, expanded scale; d) salinity profile, expanded scale to illustrate step structure. Note the smooth potential temperature-salinity structure prior to 2002. The appearance of small zigzag structures and steps in temperature and salinity from 2002-2007 indicate arrival of the leading edge of the WTA via thermohaline intrusions.

Figure 5. CTD data from 2006 a) Potential temperature-salinity plot, colored by latitude and referenced to the scale on the right, illustrates the distribution of thermohaline intrusions in the Canada Basin: large zigzags are found in the north, small zigzags in the central and smooth curves (i.e. no intrusions) in the south. b) CTD oxygen sensor data on density surface = 27.92, the density of the potential temperature maximum. c) CFC-11 data mapped on density surface 27.92. Color of the dots indicates the concentration, referenced to the color bars on the right. Together these data show that the WTA signal carries waters that are younger, or more ventilated, than in the past.

Figure 6. Potential temperature data from a section along 140 $^{\circ}$W: 2003-2007. These data show the southward spreading of the WTA by thermohaline intrusions. Color contours of potential temperature (scale on the right) are overlain with line contours of sigma-theta at 0.02 kg/m^3 intervals. Contours begin at 0.45 $^{\circ}$C and 27.84 kg/m^3 respectively. Station locations are shown by dotted vertical lines and red triangles, the top scale is latitude and the bottom is distance. Contours were made with data gridded to a field 10 km by 10 m, using an inverse distance to a power method.

Figure 7. Distribution of the four potential temperature-salinity structures in the southern Canada Basin. a) CTD and XCTD data are mapped, coded by symbol according to θ-S structure: a circle identifies the point and bump θ-S shape that Woodgate et al., 2007 attributed to a combination of double diffusive and mechanical mixing processes; a triangle identifies the large zigzag θ-S shape that indicates interleaving between waters whose temperature difference is large; a diamond identifies the small zigzag θ-S shape that indicates interleaving between waters whose temperature difference is small; and a square identifies a smooth θ-S shape (i.e. no intrusion) where only θ indicates whether waters are ambient "old" water (~0.45 °C) or if they have experienced processes that erase the θ-S intrusion. The symbols are colored by temperature in °C, referenced to the color bar shown at the bottom of the figure. b) Potential temperature-salinity plots and potential temperature profiles representative of each of the four potential temperature-salinity structures.

Figure 8a. Potential temperature-salinity plots, potential temperature and density profiles at selected locations in the boundary current. a) Northwind Ridge Profiles of θ and density illustrate the step-like nature of the intrusions and interleaving between warmer and less dense water with colder and denser ambient Canada Basin waters. Changes in θ-S shape occur because the temperature difference between the WTA and cold ambient waters is initially large but, as more WTA arrives, the thermal gradient decreases and the thermohaline intrusions begin to dissipate due to turbulence in the boundary current.

Figure 8b. Potential temperature-salinity plots, potential temperature and density profiles at selected locations in the boundary current. b) northern tip of the Northwind Ridge

Figure 8c. Potential temperature-salinity plots, potential temperature and density profiles at selected locations in the boundary current. c) east of Barrow Canyon along the Beaufort slope.

Figure 9a. Potential temperature- salinity plots, temperature and density profiles at selected locations in the Canada Basin interior. a) Station 23

Figure 9b. Potential temperature- salinity plots, temperature and density profiles at selected locations in the Canada Basin interior. b) Station 18

Figure 9c. Potential temperature- salinity plots, temperature and density profiles at selected locations in the Canada Basin interior. c) Station 11.

Figure 10. Distribution of physical and geochemical properties in a thermohaline intrusion at stations 4 and 15. a) potential temperature (in red) and salinity (in blue) profiles from CTD (solid line) and bottle (filled triangles) data. b) Oxygen sensor (solid line) and bottle (filled triangles) and CFC-12 bottle data profiles. Bottle and sensor data illustrate that bottle samples were collected intensively through the main thermohaline intrusion. The CFC-12 and oxygen data show that concentrations at the top of the salt-finger component of the intrusions are higher than at the bottom. The relative difference

between the top and bottom in apparent age is ~ 2 years and this is used to calculate an effective lateral mixing length scale of 120 km.

Figure 11 Schematic of circulation in the Southern Canada Basin. The boundary current, shown by a thick black line, carries WTA in a cyclonic direction into the southern Canada Basin along the basin margin. One branch of the boundary current debouches east of the Chukchi Plateau and enters the central basin. Thermohaline intrusions spread laterally into the basin from the boundary current and circulate in an anticyclonic direction due to the influence of Beaufort Gyre, represented by the dashed line circles and located using 2003-2007 dynamic height calculations at 400 m with a reference depth of 1000 m.

Potential temperature (°C)

Heat content anomaly (J/m^2 ×10^8)

(a)

(b)

(c)

1997

2003

2005

2007

Potential temperature (°C)
0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2

● point and bump (P&B)
▲ large zigzag
◆ small zigzag
■ no intrusion

(a) Station 4, Station 15

Potential temperature (°C)

(b) Station 4, Station 15

Oxygen (mmol/m^3)