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Summertime circulation in the eastern Chukchi Sea

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ABSTRACT

The transport of Pacific-origin water across the eastern Chukchi Sea during summer is studied using shipboard hydrographic and Acoustic Doppler Current Profiler data from multiple surveys. The study identifies two major transport pathways in this region. The well-known Alaskan Coastal Current (ACC) flows poleward along the Alaska coast, while a more recently discovered and slower current flows northward through the Central Channel between Herald and Hanna Shoals. The two currents separate past Point Hope and appear to merge again in Barrow Canyon via previously unresolved pathways flowing west to east across the Chukchi Sea. The collective flow that transports Pacific water from Bering Strait to Barrow Canyon is termed the Bering to Barrow Current System (BBCS). The coastal branch of the BBCS, which encompasses the ACC, is a weakly baroclinic flow with a maximum speed in excess of 80 cm/s inside Barrow Canyon. The Central Channel branch of the BBCS is considerably weaker, with a maximum flow speed under 20 cm/s. A portion of the Pacific water that flows towards Herald Canyon to the west may also contribute to the BBCS, the amount, but the amount is within the margin of error of our data. The difference in the advective time scales of the various branches allows water masses of different seasonal characteristics to be transported simultaneously by the BBCS. Summer water masses occupy most of the southern and central Chukchi Sea while winter water masses occupy Hanna Shoal and shelfbreak regions in the northern Chukchi Sea during summer. The total BBCS volume transport in summer is measured at four different locations in the eastern Chukchi Sea and found to be generally consistent. The overall mean transport is 0.86 Sv, compared to the summer Bering Strait transport of 1.08 Sv. This study suggests that the BBCS is the main transport pathway delivering Pacific water masses into the western Arctic Basin.

1. Introduction

The Chukchi Sea is a shallow (average depth of 50 m) and wide (approximate length of 1000 km) marginal sea just north of Bering Strait (Fig. 1). The mean poleward transport across the shelf, driven by the large-scale Pacific to Arctic sea level gradient (Stigebrandt, 1984; Coachman and Aagaard, 1988), impacts the heat and freshwater budget of the western Arctic Ocean (Coachman et al., 1975). The maximum transport occurs in summer when the fast flowing Alaskan Coastal Current (ACC) advects warm and fresh Alaskan Coastal Water (ACW) into the eastern Chukchi Sea, and the minimum transport occurs in winter when northeasterly winds oppose the poleward flow (Roach et al., 1995; Woodgate et al., 2005b). The penetration of Pacific water through the Chukchi Sea is dictated primarily by the topography of the shelf, which includes canyons and shoals (Overland and Roach, 1987; Winsor and Chapman, 2004; Spall et al., 2008). Three main transport pathways have been identified (Fig. 1): (1) inflow through the western channel of the Bering Strait tends to follow Hope Valley towards Herald Canyon (Coachman et al., 1975; Weingartner et al., 2005; Woodgate and Aagaard, 2005; Pickart et al., 2010); (2) inflow through the eastern channel of the Bering Strait tends to parallel the coast of Alaska into Barrow Canyon (Coachman et al., 1975); and (3) recent observations suggest the existence of a significant transport pathway through Central Channel, between Herald and Hanna Shoals (Weingartner et al., 2005). However, despite a number of studies to date of the circulation and water masses in the Chukchi Sea, a shelf-wide characterization of the structure of the flow is still lacking, and our understanding of the seasonal transition from the ice-covered state to the open water state is incomplete.

A persistent northward flow through Bering Strait was first documented by early explorers in the 18th century (Cook, 1784; von Kotzebue, 1821). Modern assessment of the flow indicates that it has a mean poleward transport of approximately 0.8–1 Sv (Roach et al., 1995; Woodgate et al., 2005a, 2012). However, the transport and physical properties of the Pacific water entering the Chukchi Sea are highly variable over timescales of days to years (Woodgate et al., 2006). Early estimates of the seasonal variability reported maximum northward flow in mid-summer with a transport of 1.1–2.3 Sv, and a minimum northward transport in late-winter of 0.45–

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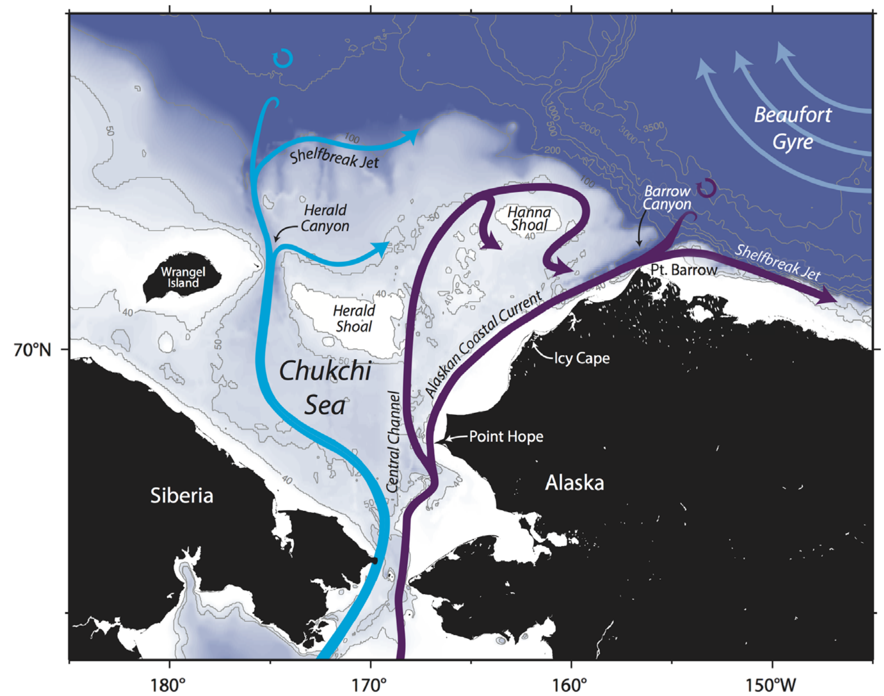

Fig. 1. Bathymetric map of the Chukchi Sea and geographical place names. The prominent topographic features are the narrow Bering Strait, Barrow Canyon to the east, Herald Canyon to the west, and the two shoal regions with Central Channel between them. The purple arrows represent the "Bering to Barrow Current System" (BBCS) in the eastern Chukchi Sea, and the blue arrows denote flow pathways in the western Chukchi Sea. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

0.7 Sv (Fedorova and Yankina, 1964). More recent timeseries measurements indicate a summer transport between 0.7 and 1.3 Sv which consists largely of very warm and fresh ACW along with moderately warm and saltier Bering Sea Water (BSW). In the winter the transport of 0.4–0.7 Sv is predominantly cold and salty Pacific Winter Water (PWW) (Steele et al., 2004; Woodgate et al., 2005b). The poleward transport of ACW and BSW dominates the heat and freshwater flux into the eastern Chukchi Sea during the summer (Steele et al., 2004), which help drive the seasonal melt-back of sea-ice (Paquette and Bourke, 1981; Spall, 2007). These Pacific-origin summer waters are also found throughout the interior Canada Basin (Steele et al., 2004).

Early numerical models of the Chukchi Sea suggested that there were two main flow paths north of Bering Strait (consistent with Coachman et al., 1975), one through Herald Canyon in the west and the other through Barrow Canyon in the east. Overland and Roach (1987) also noted a bifurcation of the northward flow past Point Hope. In particular, during the summer the warm and fresh ACW was found mainly along the Barrow Canyon branch (now known as the ACC) while the cooler and saltier BSW occupied the central portion of the Chukchi shelf (see also Coachman et al., 1975). More recent high-resolution numerical studies, using better bathymetry, resolve the shelf-wide flow structure in greater detail and affirm the two dominant flow pathways, while also revealing the third pathway through Central Channel (Winsor and Chapman, 2004; Spall, 2007). Other more detailed circulation patterns near Central Channel and around Hanna Shoal have been hypothesized based on these model studies, but direct observational evidence has thus far been lacking.

A significant amount of the Pacific water exits the Chukchi shelf through the two canyons – Herald Canyon in the west and Barrow Canyon in the east. Detailed synoptic observational studies in Barrow Canyon during the summer season have revealed that the flow is complex there and highly variable in time (Münchow and Carmack, 1997; Pickart et al., 2005; Weingartner et al., 2005). In the absence of strong winds, the northward flow in the canyon can exceed 70 cm/s, and the PWW is thought to transpose from the western side of the canyon to the eastern side. There is also evidence that the flow in the canyon is baroclinically unstable, which can lead to eddy formation (Pickart et al., 2005). A similar scenario exists in Herald Canyon during summer, where the warm BSW flows swiftly northward on the eastern side of the canyon, while the PWW tends to switch from the western flank to the eastern flank as it flows poleward (Pickart et al., 2010). Model studies to date, as well as observations, indicate that strong northeasterly winds can drive up-canyon flow in both Barrow Canyon (Winsor and Chapman, 2004; Pickart et al., 2005; Weingartner et al., 2005) and Herald Canyon (Pickart et al., 2010). It was found that for large portions of the Chukchi Sea the circulation tends to take on the length scale of the atmospheric circulation (300 km) instead of the length scale of the barotropic Rossby radius (150 km) (Woodgate and Aagaard, 2005).

Seaward of Barrow Canyon, approximately 0.3 Sv of the northward-flowing Pacific water turns east along the edge of the Alaskan Beaufort Sea (Nikolopoulos et al., 2009; von Appen and Pickart, 2012). This current is referred to as the Beaufort shelf-break jet or Pacific-Arctic boundary current. Detailed observations of the current indicate that it has different seasonal configurations, including a surface-intensified state carrying mainly ACW, a bottom-intensified state carrying PWW, and an additional bottom-intensified state advecting a water mass known as Chukchi Summer Water (CSW), which encompasses the BSW previously mentioned (von Appen and Pickart, 2012). Analyses of the energetics of the Beaufort shelf-break jet in its different configurations show that it is both barotropically and baroclinically unstable and that there is a significant offshore flux of Pacific-origin water via eddy formation (Spall et al., 2008; von Appen and Pickart, 2012). It is not presently clear how the Pacific water progressing through the Chukchi Sea transitions into these different shelfbreak current configurations, as well as what drives the transport variability of the different water masses. von Appen and Pickart (2012) noted an intra-seasonal transport pattern of the shelfbreak jet with CSW arriving in early summer, then ACW in mid-summer, followed by a return of CSW in late summer. Understanding this downstream variability requires closer investigation of the structure of the currents and the seasonal timing of the water masses on the Chukchi shelf.

In this paper we examine the summertime transport pathways and hydrographic structure of Pacific-origin waters in the eastern Chukchi Sea using multiple hydrographic and velocity data sets collected over the past decade. We define the locus of pathways that transport Pacific water from Bering Strait to Barrow Canyon as the "Bering to Barrow Current System" (depicted schematically by the purple lines in Fig. 1). This includes the ACC and the Central Channel flow. We examine the two branches of the BBCS to elucidate its cross-stream structure and poleward evolution, providing new insights into its transport and water mass characteristics. We provide additional observational support for the Central Channel branch and identify new circulation features in the region surrounding Hanna Shoal. Because the data used in this study only covers the eastern half of the Chukchi Sea, we cannot directly estimate the transport from Bering Strait to the western Chukchi Sea. Previous studies have deduced that the annual average flow into Herald Canyon is on the order of 0.1–0.3 Sv (Woodgate and Aagaard, 2005). There is hydrographic evidence, supported by modeling results, that some of the Pacific water flowing through Herald Canyon makes its way towards Central Channel and potentially to Barrow Canyon (Weingartner et al., 2005; Winsor and Chapman, 2004). This is addressed indirectly in the present study through a mass budget estimate.

The structure of the paper is as follows. In Section 2 we describe the different data sets, observational methods, and processing techniques used in the study. In Section 3 we characterize the transport pathways in the eastern Chukchi Sea and examine the cross-stream structure of the BBCS. Volume, heat, and freshwater fluxes associated with the BBCS are also presented. In Section 4, the implications of this study for the physical oceanography of the Chukchi Sea are discussed and summarized.

2. Data and methods

The shipboard hydrographic and acoustic Doppler current profiler (ADCP) data used in this study are from three different field programs conducted in the Pacific Arctic during the past decade. The first is the Western Arctic Shelf-Basin Interactions (SBI) program (2002–2004); the second is a component of the Arctic Observing Network (AON) entitled The Western Arctic Boundary Current: Climatic forcing and ecosystem response (2009–2013); and the third is the Impacts of Climate on EcoSystems and Chemistry of the Arctic Pacific Environment (ICESCAPE) project (2010–2011). The geographical domain of our study is the eastern Chukchi Sea and western Beaufort Sea, and the time periods considered are 2003–2004 (SBI) and 2010 (AON and ICESCAPE).

The conductivity–temperature–depth (CTD) instrument used in all three studies was a SeaBird 911+, and the data were calibrated and processed according to standard SeaBird processing procedures to produce 1-db averaged downcast profiles. Details of the data collection and accuracy for the SBI and ICESCAPE programs are found in Pickart et al. (2005) and Arrigo et al. (2014), respectively. The AON CTD data were collected using similar shipboard procedures and calibration methods as in the other two programs, and the resulting accuracies are the same. Potential temperatures and densities were calculated using the TEOS-10 Gibbs seawater equation of state (IOC, 2010). All of the vessel mounted ADCP data used in the study were obtained from the 150 kHz Ocean Surveyor instrument mounted on the USCGC Healy. The ADCP data acquisition, processing, and measurement accuracies are discussed in Brown et al. (2015).

Hourly wind data used in the analysis of Barrow Canyon transports was obtained from the National Climate Data Center (http://www.ncdc.noaa.gov/) for the meteorological station located at Barrow Post-Rogers Airport. The same methodology as Pickart et al. (2013) was used in the processing of the wind data. After obtaining the data from NCDC we converted the wind speed and direction into vector timeseries and subjected them to a detailed manual inspection process through which we removed spikes and obviously contaminated records (e.g. stuck sensor readings). Overall, the data quality was very good and only minimal hand editing was needed or applied, although a number of erroneous zero wind speed readings were removed. To fill in short data gaps that exist in the original dataset or as a result of the de-spiking, the data were linearly interpolated to the beginning of each observation hour. Interpolated records were retained only for those that fell within observational data gaps shorter than 6 h.

Absolute geostrophic velocities were calculated by referencing the thermal wind using the depth-integrated ADCP currents over the common depth of observation for each set of stations. Vertical sections of hydrographic variables and absolute geostrophic velocity were constructed using the 'gridfit' Matlab function (http://www.mathworks.com/matlabcentral/fileexchange/8998-surface-fitting-using-gridfit/). Gridfit is a linear estimator for obtaining an optimal least-squares fit to 2-D surfaces using a gradient/Laplacian regularizer. Repeat transects from different years were projected onto a common axis to facilitate the analysis. The reference salinity for the salt flux calculations is 34.8 (Aagaard and Carmack, 1989), and the reference temperature for the heat flux calculations is 0 °C.

3. Results

3.1. Eastern Chukchi Sea transport pathways

Of the three observational programs considered in this study, the most complete synoptic coverage of the circulation pathways in the eastern Chukchi Sea was obtained during the ICESCAPE survey in June–July 2010 and 2011 (only the 2010 survey is considered here, the 2011 data are analyzed in a separate study. In light of previous observations (Weingartner et al., 1998) and model studies (Winsor and Chapman, 2004; Spall, 2007), the synoptic flow map of ICESCAPE 2010 is deemed representative of the summer seasonal flow pattern. Because of the excellent spatial coverage of ICESCAPE 2010, we use the ADCP survey data to elucidate the circulation pathways in the Chukchi Sea during the summertime. For the sections discussed below, the Central Shelf and Barrow Canyon transects had multi-year shipboard ADCP data available. The quoted velocities for those sections are averages of multiple (3–4) synoptic surveys. Velocities for all the other sections are based on the ICESCAPE 2010 synoptic ADCP survey only.

Sustained wind forcing is known to significantly influence the Chukchi Sea circulation (Weingartner et al., 2005; Winsor and Chapman, 2004). Synoptically, the winds can vary on time scales of hours to days and this can lead to a rapid oceanic response (Woodgate and Aagaard, 2005). However, duration of the ICESCAPE 2010 survey (June 17–July 22, 2010), the wind remained relatively weak and variable with a mean velocity of 2–4 m/s from the northeast (Fig. 2). This is similar to the conditions studied by Weingartner et al. (2005) for summer 1990 and 1991 in which the flow in both Barrow Canyon and the Central Channel was poleward with relative low variability. This suggests that the weak winds during our study period were unlikely to have qualitatively influenced the circulation pattern in the eastern Chukchi Sea. There were, however, quantitative wind effects on the transport in Barrow Canyon, which is addressed in Section 3.5.

The lateral depth-averaged velocity map for ICESCAPE 2010 covering the region east of 169°W from Bering Strait to Barrow Canyon is shown in Fig. 3. The two main branches of the BBCS are evident (indicated by the red lines). The eastern branch,

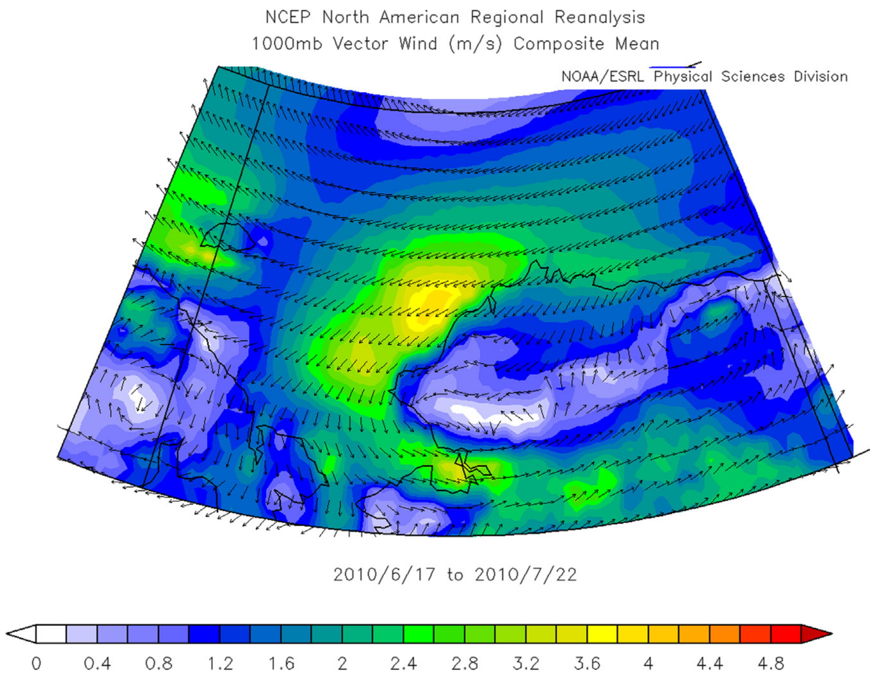

Fig. 2. Vector map of the mean surface wind in the Chukchi Sea during the ICESCAPE 2010 survey period. The color indicates the mean wind speed. The average RMS variability is approximately 3 m/s. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

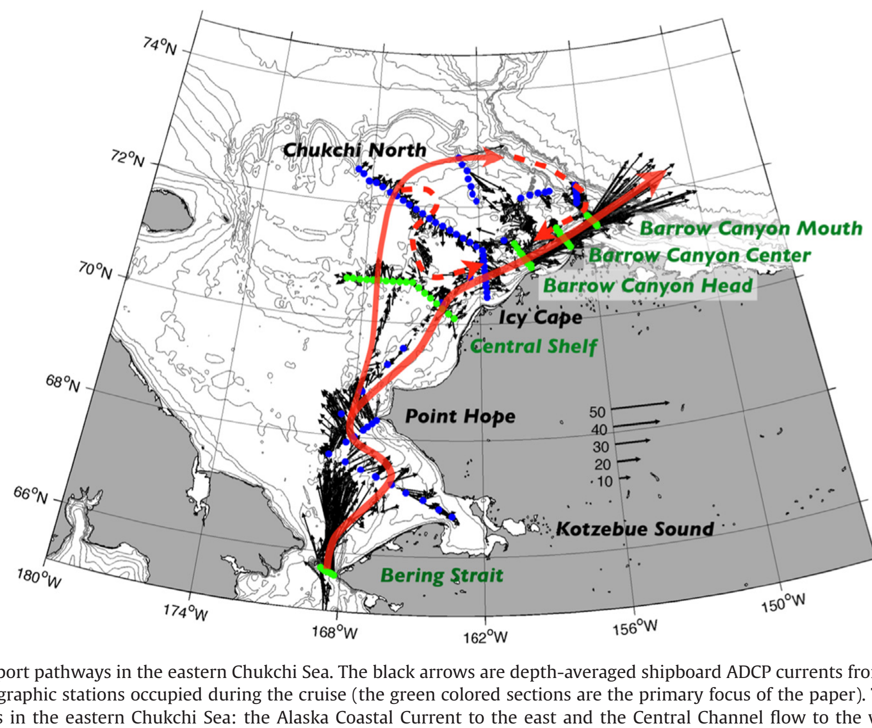

Fig. 3. Map of the major transport pathways in the eastern Chukchi Sea. The black arrows are depth-averaged shipboard ADCP currents from the 2010 ICESCAPE survey. The green and blue dots are hydrographic stations occupied during the cruise (the green colored sections are the primary focus of the paper). The solid red arrows indicate the two major transport pathways in the eastern Chukchi Sea: the Alaska Coastal Current to the east and the Central Channel flow to the west. The dashed red arrows are deduced transport pathways consistent with the synoptic ADCP observations. The unit for current vectors in the the legend is cm/s. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

encompassing the ACC, flows adjacent to the coast of Alaska, while the Central Channel branch flows northward towards the Chukchi shelf-break between Herald and Hanna Shoals. The two branches were difficult to distinguish south of Point Hope, and originate as a composite flow entering the shelf on the eastern side of Bering Strait with a maximum northward velocity exceeding 80 cm/s. In the Kotzebue Sound section just north of the strait, the flow had weakened to approximately 20 cm/s as the shelf widens. Continuing northward towards Point Hope, where the land protrudes westward again, the flow speed increased to 40 cm/s.

Northward of Point Hope, the coastal Alaska and the Central Channel branches of the BBCS diverge. The two branches were observed at the Central Shelf section located 250 km north of Point Hope, where the northward mean flow speed was less than 20 cm/s in each branch. Following the Central Channel branch, the velocity of the current remained under 20 cm/s to the vicinity of the Chukchi shelf-break. Following the coastal Alaska branch, the average flow speed increased again to more than 80 cm/s at Barrow Canyon where the different BBCS branches come together again. The distance from Bering Strait to the Chukchi shelfbreak is approximately 800 km for both the eastern and western pathways. The calculated depth-averaged speeds indicate that the advective time scale was approximately 3 weeks for the coastal Alaska branch and roughly 6–8 weeks for the Central Channel branch. These summer residence time estimates are much shorter than the values quoted by Woodgate and Aagaard (2005) based on year-long mooring measurements. The observed annual mean velocity in central Chukchi Sea is 5 cm/s, which translates to an estimated residence time of 2–4 months.

It is evident from Fig. 3 that topographic features such as canyons and shoals significantly impact the shelf circulation. Based on our summertime survey, there appear to be two retroflections of the flow along the central channel pathway (indicated by the dashed red lines in Fig. 3). The first occurs on the southwestern side of Hanna Shoal near the Chukchi North section (that connects with the Icy Cape section at 162°W, 71.3°N). The second retroflection occurs along the western side of Barrow Canyon, east of Hanna Shoal. The maximum flow speed within the western retroflection was 20 cm/s, while the flow speed of the eastern retroflection was less than 10 cm/s. The western retroflection appears to bend back northward just north of the Central Shelf section and merge with the coastal Alaska branch. Although one needs to be careful about making generalized statements regarding the circulation based on one quasi-synoptic survey, the flow pattern measured here is generally consistent with previous findings (Weingartner et al., 2005). Flow around the isolated topography of Hanna Shoal has been hypothesized as a result of Taylor column (Martin and Drucker, 1997). Notably, such multiple pathways and time-scales of the BBCS flow allow different Pacific water types (e.g. winter waters and summer waters) to reside simultaneously on the shelf.

In addition to the ICESCAPE 2010 survey, the SBI (2002–2004) and the AON (2009–2013) observational programs also provided velocity and hydrographic data on the northeast Chukchi shelf. However, an important difference between the ICESCAPE 2010 survey and the two other programs is the seasonal timing of the measurements. ICESCAPE 2010 was conducted in early summer, while the physical oceanographic SBI surveys and AON cruises occurred in mid- to late-summer. As noted earlier, this seasonal difference does not appear to influence the overall current structure, but it does significantly affect the water masses transported by the currents. We now investigate the different types of water masses, their spatial distribution, as well as the mean summertime structure of the BBCS in the eastern Chukchi Sea along five key transects (highlighted in green in Fig. 3).

3.2. Eastern Chukchi Sea water masses

The combined T/S diagram from the SBI (2003, 2004) and AON (2010) surveys illustrates the typical late-summer (August/September) conditions in the eastern Chukchi Sea and the western Beaufort shelf-break region (Fig. 4). This T–S diagram has been color-coded according to the sample frequency. Water masses of different seasonal and geographical origins were observed. We adopted the various water mass classifications used by previous investigators to the extent that is consistent with our data. However, the precise definition of each water mass should not be considered invariable because the properties can change measurably from year to year, and, to some extent, from season to season.

The warmest water in the eastern Chukchi Sea is the ACW which originates from the Alaska coastal region south of Bering Strait.

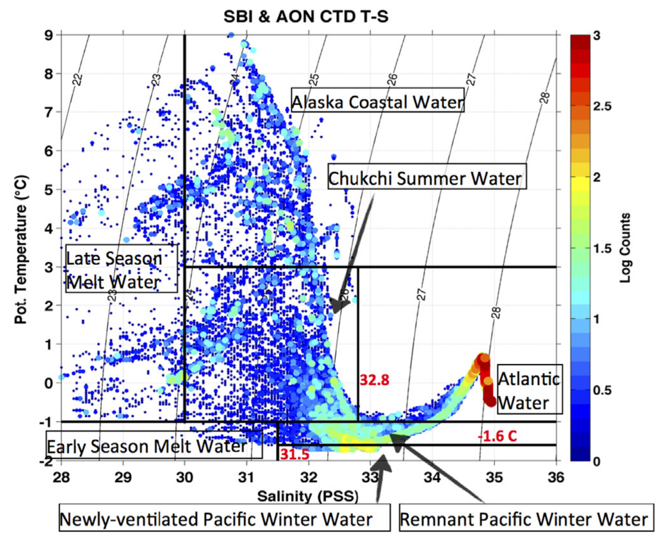

Fig. 4. Temperature–salinity plot of the water masses in the eastern Chukchi Sea and the Beaufort shelfbreak regions. The color and size of the dots both indicate $\log_{10}$ (counts). Potential density contours are overlaid on the T/S diagram. The major water mass classes are labeled. The thick black lines delineate the water mass types. Red numbers indicate the temperature and salinity values separating the different water masses (see text).(For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

ACW enters the Chukchi Sea in mid- to late-summer and is characterized by potential temperatures $T \geq 3$ °C and by salinities $S \geq 30$. The warmest ACW can reach temperatures of 7–10 °C and is typically present in August–September (Coachman et al., 1975; Woodgate et al., 2005a). The ACC is commonly thought of as a seasonal current that carries predominantly ACW. Based on shipboard estimates of the water mass spatial distribution in 2003 and 2010 in mid-summer, approximately one-third of the eastern Chukchi Sea is filled with ACW.

The coldest water in the eastern Chukchi Sea is the PWW (Coachman and Barnes, 1961; Roach et al., 1995; Pickart et al., 2005). It is characterized by temperatures less than -1 °C and salinities greater than 31.5. This water is formed in the northern Bering Sea (e.g. Muench et al., 1988), but can be significantly modified through air–sea interaction in late-fall and winter over the Chukchi Sea. The PWW can be divided into two classes based on its age since formation. The coldest class is referred to as newly ventilated winter water and has temperatures less than -1.6 °C (Fig. 4). It resides near the freezing line in T/S space and is typically observed in spring and early-summer. It largely disappears from the Chukchi Sea in late-summer when the water column warms through solar heating and due to advection of warmer waters from the south. The second class of winter water is termed Remnant Winter Water and is characterized by temperatures between -1.6 °C and -1 °C. It represents winter water that has been warmed by mixing with summer waters and/or by solar heating. Previous studies indicate that the shoal regions of the Chukchi Sea can retain remnant winter water late into the summer (Martin and Drucker, 1997). Using the same ship-based estimation method for water mass distribution as we did for ACW, we find that one-quarter to one-third of eastern Chukchi is filled with PWW (of either the newly ventilated or the remnant class) in mid-summer.

The densest and saltiest water in Fig. 4 is the Atlantic Water (AW). Geographically this was measured over the shelfbreak and near the mouth of Barrow Canyon at depths deeper than 200 m. This water is characterized by salinities $S > 33.6$ and temperatures $T > -1$ °C, although most of the AW in the upper 500 m of the water column is in the range of 34.7–35 and -0.5 to 0.7 °C. AW has little direct impact on the circulation and mixing processes on the central Chukchi shelf. However, upwelling of this water mass occurs along the shelfbreak and in Barrow Canyon, driven by easterly winds (e.g. Pickart et al., 2011) or by the passage of shelf waves (Aagaard and Roach, 1990).

The melt-back of seasonal sea ice results in the formation of a layer of fresh water ($S<31.5$) at the surface in the Chukchi and Beaufort Seas. The northward flow of warm summer waters on the Chukchi shelf advects this surface melt-water towards the shelfbreak. Consequently, melt water is not typically found over the central and southern portion of the Chukchi Sea in mid-summer. Melt water of two different types were observed in our data. Early season melt water has temperatures near the freezing point with $T<-1$ °C and $S<31.5$ (Fig. 4), and late season melt water is warmer ($T>-1$ °C) and fresher ($S<30$). Significant portions of the Chukchi/Beaufort shelfbreak and slope regions are capped with melt water in mid- to late-summer. It is not clear from this dataset what the geographic origin of the melt water is. We suspect that while some of it may have originated from south of Bering Strait, most of it is formed as a result of local ice melt in the Chukchi Sea (see also Paquette and Bourke, 1981).

The final water mass, Chukchi Summer Water (CSW), is found in the intermediate temperature and salinity range from $-1<T<3$ °C and $30<S<33.6$, respectively. While the warmer and fresher ACW is observed in the coastal regions of the eastern Chukchi Sea, the cooler and saltier CSW typically occupies the central shelf. As mentioned above, this water mass is believed to originate from the central/western Bering Sea, and the *T/S* characteristics of the CSW observed during the mid- to late-summer SBI and AON surveys are consistent with this notion (in particular, salinities <32.8, Fig. 4). In contrast, the CSW observed in the early-summer ICESCAPE program appears to have been modified locally on the Chukchi shelf (Gong et al., 2014).

3.3. Spatial distribution of eastern Chukchi Sea water masses

We analyze the lateral distribution of water masses on the Chukchi shelf within two density layers, separated by the $\sigma_\theta=26$ kg m^{-3} isopycnal. This value was chosen because the majority of the PWW is denser than this (Fig. 4). We refer to the two layers as the light layer ($24.5<\sigma_\theta<26$ kg m^{-3} which excludes the near-surface water, see Fig. 6) and the heavy layer ($26<\sigma_\theta<$ 27.5 kg m^{-3}). Within each of the layers, temperature can be considered as a tracer of the different water masses. The spatial pattern of temperature of each density class, based on the summer 2003 SBI survey, is shown in Fig. 5. The colors indicate the mean potential temperature within the density layer, and the size of the colored dots represents the log-thickness of the density layer. One sees that the light layer is composed largely of warm summer waters (ACW and CSW) mainly found on the southern Chukchi shelf, while the heavy layer is composed almost entirely of PWW on the northern shelf. The warm summer waters extend northward along the eastern side of Barrow Canyon (Fig. 5a) suggesting that the ACC transports a significant amount of heat poleward at this time of year. In the region just west of Barrow Canyon and north of Hanna Shoal, remnant PWW is found in the light density layer. This cold water could be ambient upper halocline water that was advected shoreward from the basin, or it could be southern-origin winter water formed the preceding winter that has not completely drained from the Chukchi shelf.

The heavy density layer is composed of a combination of newly ventilated and remnant PWW. For the most part, the water seaward of the shelf edge is older remnant PWW ($T>-1.6$ °C) within the upper halocline, while the water on the northern part of the shelf is more recently formed PWW. Farther to the south, on the mid-shelf, the cold water is again remnant PWW. However, it is likely that this water was only recently warmed (i.e. during the months prior to the survey), whereas the remnant PWW in the Arctic basin is likely more than a year old. Note that only a very small amount of summer water in the heavy density class with temperatures less than 0 °C was observed to the south in the Central Channel region (west of Hanna Shoal, Fig. 5b). No water within the heavy density class was found south of 71°N in mid-summer.

3.4. Mean structure of the BBCS in the eastern Chukchi Sea

To illustrate the hydrographic and kinematic structure of the BBCS in the eastern Chukchi Sea, and its poleward evolution, five composite cross-shelf sections were compiled between Bering Strait and the mouth of Barrow Canyon (see Fig. 3 for the section locations and names). Each composite section of temperature, salinity, and absolute geostrophic velocity contains 3–4 synoptic realizations conducted during the August–September time frame (Figs. 6–8). The mean RMS variability at Barrow Canyon for temperature, salinity, and velocity are 2 °C, 0.5, and 20 cm/s, respectively. The variability at Central Shelf is lower by about 50%.[1] We use a northward speed of 5 cm/s to delineate the branches of the BBCS (see Fig. 3).

The two southern sections (Bering Strait and Central Shelf) are composed mainly of warm and fresh summer waters, whereas the three northern sections across Barrow Canyon contain significant amounts of both cold and salty winter water as well as summer waters. Starting first with the Bering Strait section, the warmest and freshest water is the ACW found on the eastern side of the transect. It is highly stratified with a surface to bottom density difference of more than 3.5 kg m^{-3}. A peak stratification of $N=0.05$ s^{-1} (Brunt Väisälä Frequency) was observed in the upper 15 m of the water column. Seaward of the ACW is the CSW with temperatures from 3 to 5 °C, salinities from 31 to 32.4, and σ_θ between 25 and 25.5 kg m^{-3}. We note that these temperatures are outside of the CSW range defined above. This is because, at this time of year, the CSW entering the strait is at its peak temperature. However, cooling occurs as the water mass is transported northward. Compared to the ACW, the CSW is weakly stratified (which is partly what distinguishes it from the ACW at this southern latitude in late-summer).

Similar to Bering Strait, the central Chukchi shelf section is composed of ACW on its eastern end, and weakly stratified CSW over much of the remainder of the transect (Figs. 6 and 7). The warm temperatures in these two sections indicate that the winter water has been flushed out of the southern Chukchi Sea by late-summer. Note, however, that there remains a thin layer of colder and saltier (and more strongly stratified) CSW within the Central Channel at depth (Figs. 6e and 7e). This observation is consistent with the above analysis of the Chukchi-wide ADCP data, which showed that the Central Channel is a slower pathway of Pacific water than the coastal Alaska branch, and hence the last vestiges of cold water are still present in the channel at this time of year. This is also seen in the composite absolute geostrophic velocity section at the central shelf location (Fig. 8). The ACC is flowing northward adjacent to the Alaskan coast, with weak flow <5 cm/s seaward of the current, separating the coastal branch of the BBCS from the Central Channel branch.

Proceeding northward to Barrow Canyon, where all of the branches of the BBCS have merged, the water mass composition and the structure of the flow change significantly. In the three Barrow Canyon sections, summer and winter water masses are observed in close proximity to one another (Figs. 6a–c, 7a–c, and 8a–c). At the head of the canyon due west of the canyon axis, the water column is strongly stratified ($N=0.036$ s^{-1}), with warm and fresh melt-water near the surface, cooler and saltier summer water in the middle of the water column, and cold and salty winter water in the lower water column. Due east of the canyon axis, very warm and fresh ACW sits atop saltier, cooler CSW, and the stratification is significantly weaker ($N=0.018$ s^{-1}).

As detailed in Section 3.1, different source regions feed the two sides of the canyon. The ACW flows into the eastern side via the ACC in the

[1] There were no direct velocity measurements for the Bering Strait transects, hence there is no composite absolute geostrophic velocity section for that section.

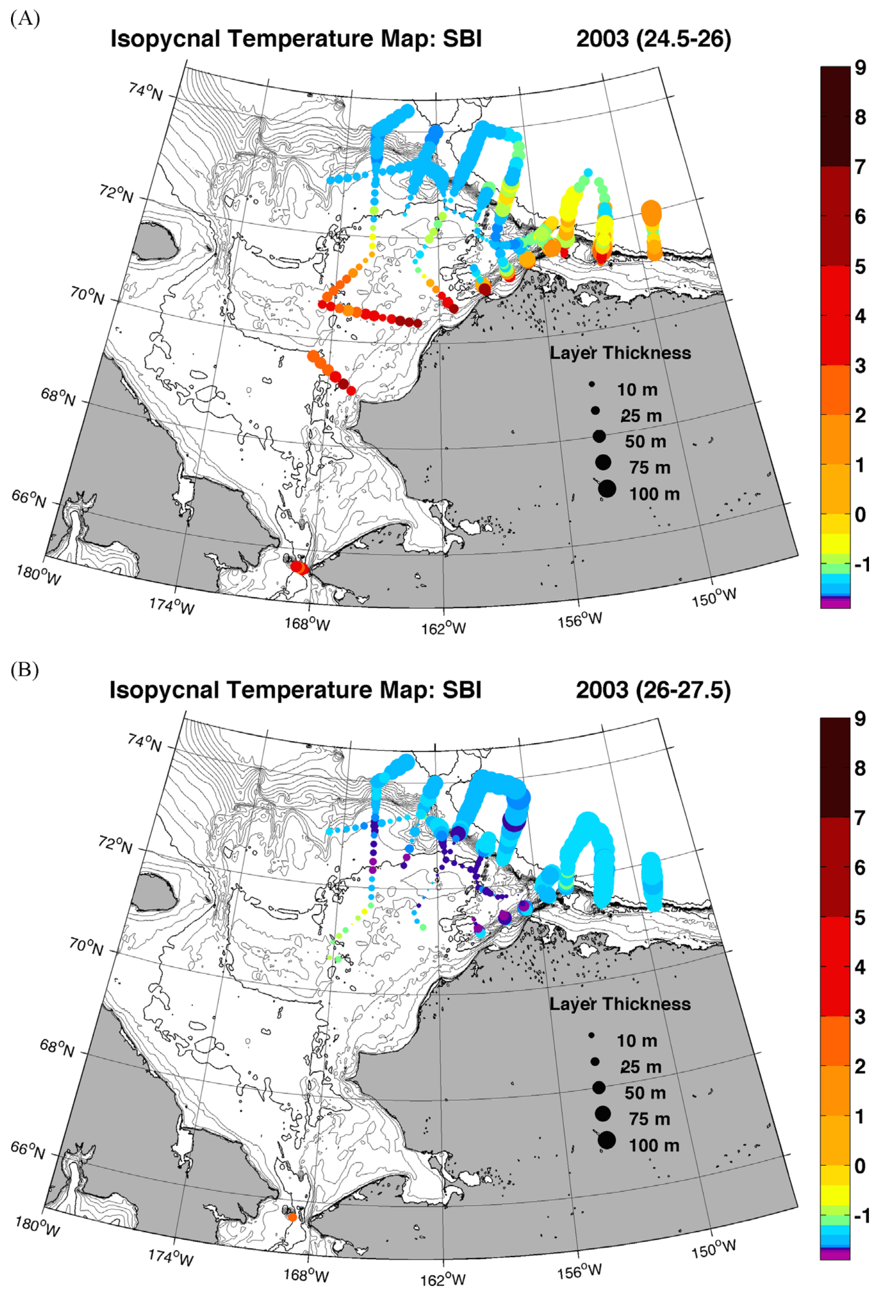

Fig. 5. Maps of average potential temperature for two different density classes: (a) $\sigma_\theta = 24.5–26\ \mathrm{kg\ m^{-3}}$ and (b) $\sigma_\theta = 26–27.5\ \mathrm{kg\ m^{-3}}$. The two density classes represent a light, near-surface layer and a dense, near-bottom layer down to depth of 200 m. The size of the dots indicates the thickness of each layer and color of the dots indicates the mean potential temperature of the layer. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

coastal pathway, while the PWW enters the western side from the Central Channel pathway through the two retroflections on either side of Hanna Shoal (Fig. 3). This notion is consistent with the calculated absolute geostrophic velocities at the head of the canyon which shows a weak southward flow of winter water on the western end of the transect, adjacent to the strong northward flow of the same water mass on the eastern side (Fig. 8a). These results indicate that the supply of PWW in the northeast Chukchi shelf persists from spring to late-summer.

The BBCS is strongest (>80 cm/s) at the eastern end of the transect across the head of the canyon. Note, however, that the current is only weakly baroclinic and extends to the bottom of the canyon where it transports CSW and PWW northward as well. All the water masses present at the head of the canyon are also observed at the next two transects through the canyon center and mouth. The general structure of the water column on the eastern side of the canyon axis remains largely unchanged, although the ACW is warmer at the canyon mouth and the isopycnals are sloped more steeply downward there. On the western side of the canyon one sees that the PWW descends to greater depth as the canyon deepens. Also, the winter water fills more of the canyon to the north and is in contact with the eastern wall at the mouth of the canyon. This is consistent with the findings of Pickart et al. (2005) who investigated the along-canyon structure of the PWW within Barrow Canyon.

The composite velocity sections for the two northern canyon transects indicate that the flow within the canyon is entirely poleward. Velocities remain strong in the upper 40 m of the water column. The width of the composite BBCS current remains about the same as at the head, but the current now extends quite deep, advecting both summer and winter water masses. This is particularly noteworthy from the perspective of heat and freshwater transport

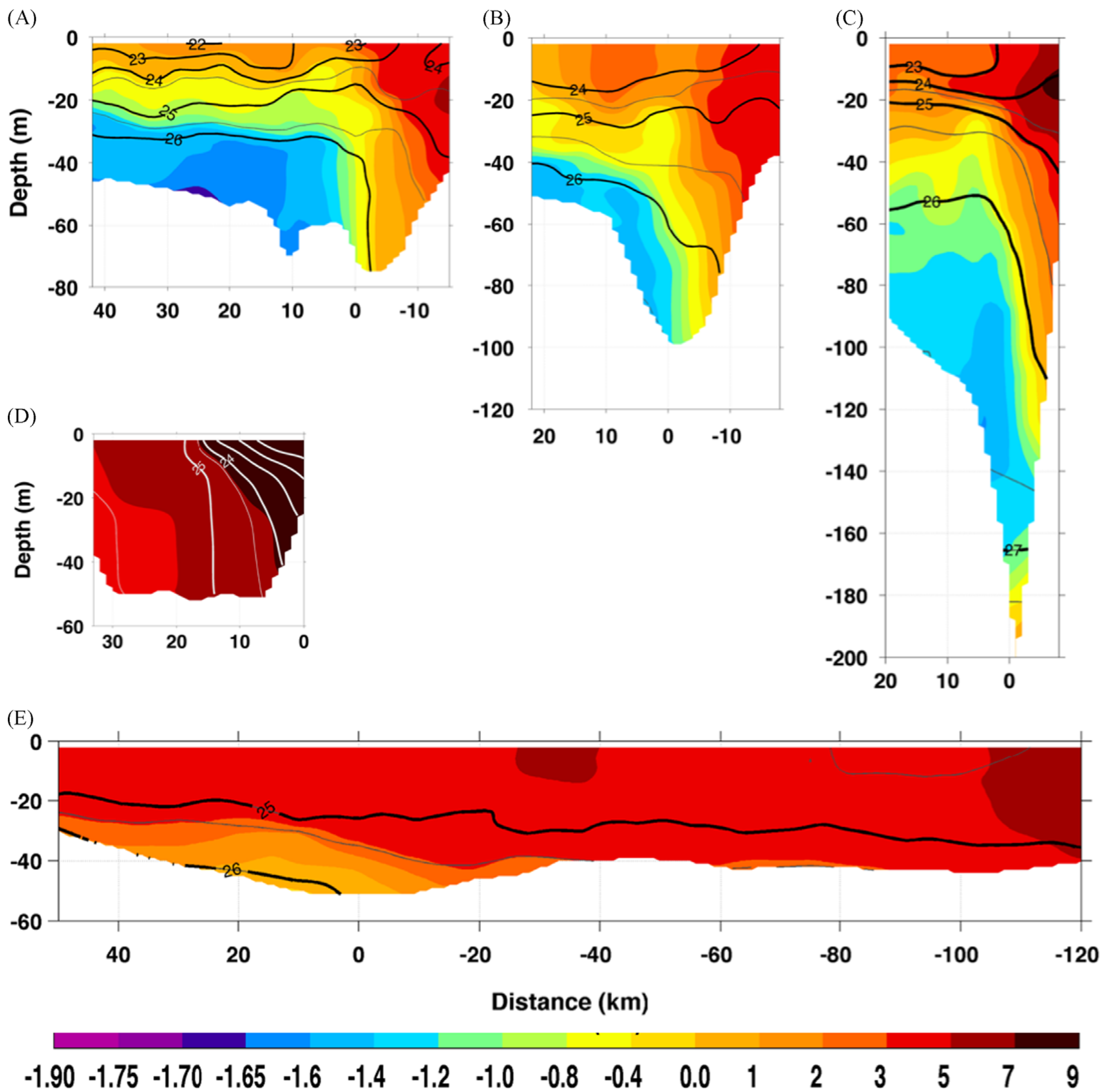

Fig. 6. Composite potential temperature cross-sections in the summer are plotted for (a) Barrow Canyon Head, (b) Barrow Canyon Center, (c) Barrow Canyon Mouth, (d) Bering Strait, and (e) Central Shelf. Each section contains approximately three individual synoptic transects. Potential density anomaly contours are overlaid in each section.

into the western Arctic and the upper ocean heat budget for the interior basin. We now quantify the volume, heat, and freshwater transport associated with the BBCS in our composite sections.

3.5. *Volume transport of the BBCS in the eastern Chukchi Sea*

The long-term annual mean volume transport through Bering Strait is 0.83 Sv (Roach et al., 1995), and the average value for the summertime (July–September) transport is 0.9 ± 0.25 Sv (Woodgate et al., 2005a). However, these estimates do not take into account the inshore part of the ACC, which is located at the eastern end of the strait. Using our composite Bering Strait density section, and assuming a reference level of no motion at the bottom, we compute the missing ACC transport to be 0.18 Sv. We thus estimate a total summertime Bering Strait transport of 1.08 ± 0.25 Sv, although this is likely an underestimate due to our assumption of the reference level.

Using our composite transects to the north we can address the BBCS transport across the Chukchi shelf during summer. There are, however, several factors that can impact the representativeness of such an assessment. Firstly, as noted earlier, the transport through Bering Strait varies over a wide range of time scales (including weeks to months), which will lead to uncertainty in constructing a transport budget. Secondly, local wind events on the shelf can affect the boundary current transport, particularly near Barrow Canyon. Finally, the different surveys comprising our composites do not always fully overlap laterally and the ADCP blanking distance (10–20 m) for each ship is different, leading to observational uncertainties. To produce a robust estimate of the BBCS transport across Chukchi Sea, these issues need to be addressed.

For our composite sections north of Bering Strait, we calculate the standard error of the mean transport ($U_{stddev}/\sqrt{N}$, where N is the number of degrees of freedom). For a sample size of 3 independent crossings, the transport standard error is 0.11 Sv. Next, for each section, only the part of the domain common to all realizations is used in the transport estimate. Unfortunately, one of the Central Shelf occupations is significantly shorter than the other two and misses a significant portion of the coastal branch of the BBCS. To compensate for this sampling deficiency, the calculated composite transport value for the section in question is increased by 30%, an amount directly proportional to the missing cross-sectional area. This gives a composite transport of 0.89 ± 0.2 Sv for the central shelf line. (Transport estimate across the full Central Shelf section using the two complete sections is consistent with the three-section composite). For the three transects in Barrow Canyon, the differences in spatial coverage of the individual transects introduce errors in transport estimated to be 10% of the mean transport.

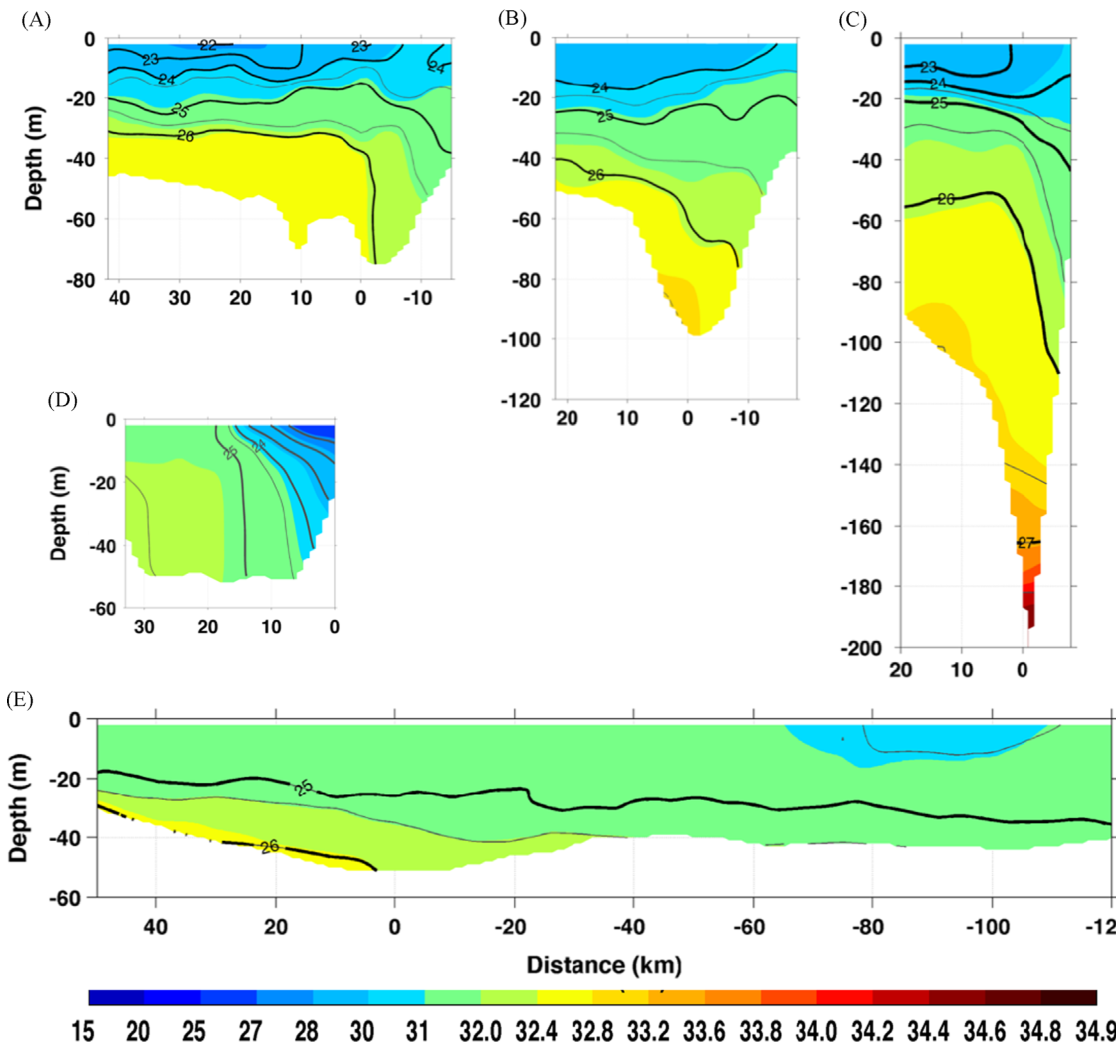

Fig. 7. Same as Fig. 6, for salinity.

While there is no obvious signature of wind-forced variability in our Central Shelf velocity sections, the Barrow Canyon transects are clearly influenced by the wind. This is not surprising since it has been shown that wind forcing strongly impacts the flow through the canyon (Weingartner et al., 1998). To quantify the wind influence on volume transport, the calculated transports for each of the shipboard transects at the three Barrow Canyon locations are plotted versus the along-canyon wind speed during the corresponding sampling periods in Fig. 9. The average along canyon windspeed in the canyon is -1.7 m/s (from the northeast), which is nearly identical to the average wind speed during the occupations of the central shelf section. Using the regression line from Fig. 9, this implies an average transport of 0.83 ± 0.2 Sv in Barrow Canyon. We note that if the transport vs. wind speed is regressed individually for each of the canyon locations (BCH, BCC, and BCM) we obtain a similar result.

Table 1 lists the transport estimates for all five composite sections in the Chukchi Sea, including Bering Strait. It also includes the contribution of both light ($\sigma_\theta < 26$ kg m^{-3}) and dense ($\sigma_\theta >$ 26 kg m^{-3}) water to each section (except for Bering Strait where velocity sections are not available). In light of Fig. 3, both the Central Shelf transect and the Barrow Canyon transects should capture most of the BBCS transport, while the transport at Bering Strait should be larger than this since it includes the flow that feeds Herald Canyon to the west. Our results are consistent with this (0.89 Sv and 0.77–0.89 Sv for the Central Shelf and Barrow Canyon sections, respectively, and 1.08 Sv for Bering Strait). However, none of these values are statistically distinct in light of the error bars. This implies that most of the poleward transport through Bering Strait in the summer can be accounted for by the BBCS in the eastern Chukchi Sea with only a minor contribution from the western Chukchi Sea. This is in contrast to the full-year estimates of Woodgate and Aagaard (2005) who found more of an equipartition of Bering Strait transport along each of the main Chukchi Sea transport branches.

Comparing the volume transport of light and dense water fractions, most of the poleward transport south of Barrow Canyon is associated with light summer water. Although there are no velocity sections for Bering Strait, the composite hydrographic section indicates that nearly all the water present in the mid- to late-summer period is light summer water. This is consistent with the spatial pattern of water masses in Fig. 5 where only warm water is observed in the southern Chukchi Sea. Dense water, mostly composed of remnant PWW, becomes a significant fraction of the transport only at Barrow Canyon.

3.6. Heat and freshwater transport of the BBCS

Using the composite temperature, salinity, and velocity sections presented in Section 3.4, we calculate the corresponding heat and freshwater fluxes as follows:

$$\text{Heat Flux} = uh\rho$$
$$\text{Freshwater Flux} = u(S_0 - S)/S_0,$$

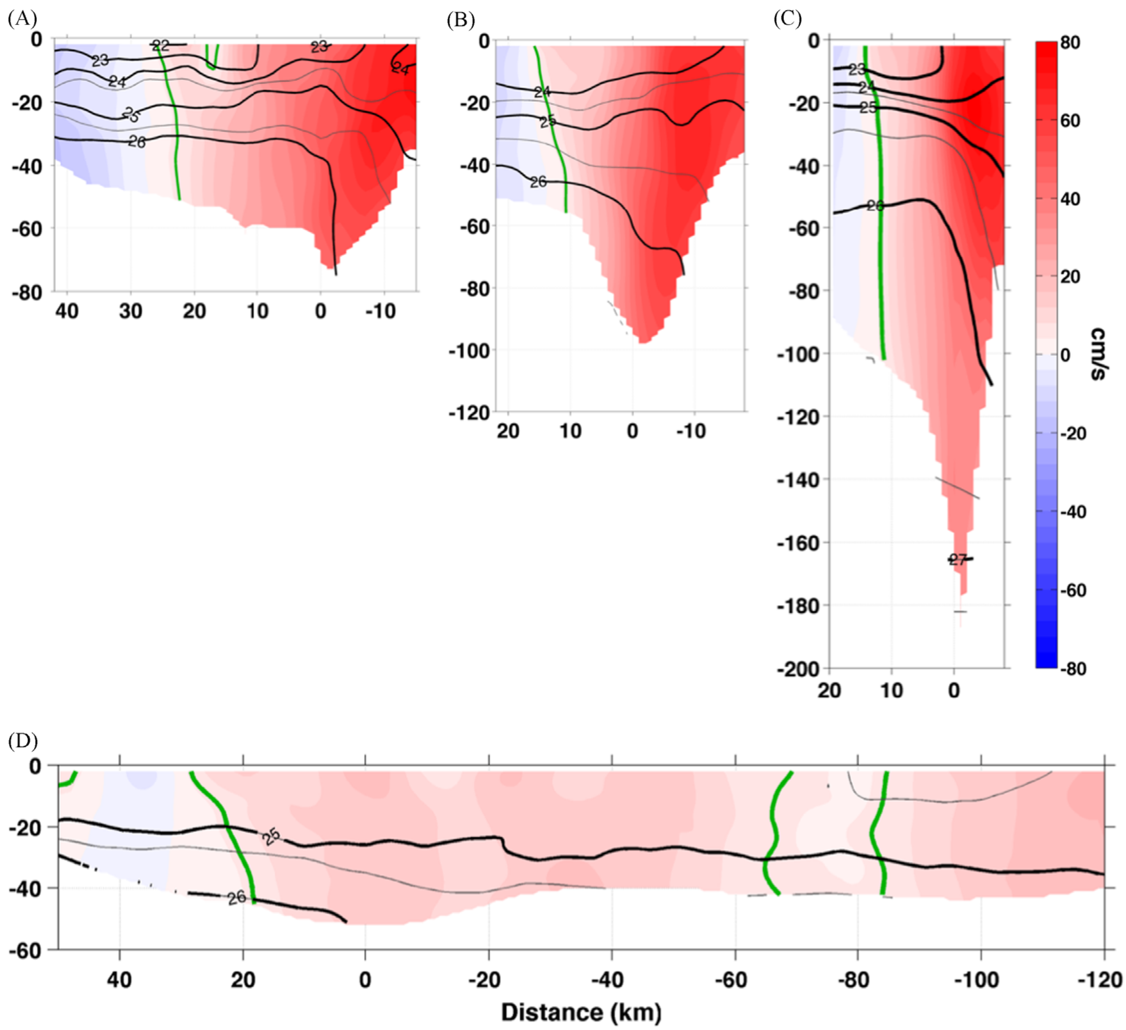

Fig. 8. Same as Fig. 6, for absolute geostrophic velocity. The green lines delineate the branches of the BBCS with poleward speed greater than 5 cm/s. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

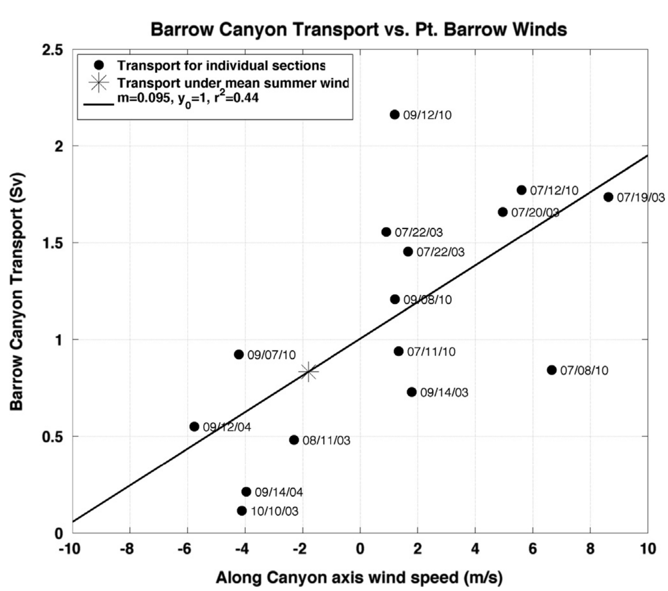

Fig. 9. Volume transport at the three Barrow Canyon sections versus the along-canyon wind-speed during the time of each survey. Positive wind speed is southwesterly. The linear regression line is shown. The canyon transport for the average summertime wind is indicated by the asterisk (0.83 ± 0.12 Sv).

Table 1
Volume transports across eastern Chukchi Sea sections. Units are in Sv unless otherwise noted.

Sections	Transport	Uncertainty	Light water	Heavy water
Bering Strait	1.08	0.25	n/a	n/a
Central Shelf	0.89	0.2	0.79	0.10
Barrow Canyon Composite	0.83	0.12	0.58	0.24
Barrow Canyon Head	0.81	0.2	0.58	0.23
Barrow Canyon Center	0.89	0.2	0.67	0.22
Barrow Canyon Mouth	0.77	0.2	0.50	0.27

where u is the cross-transect velocity, h is the seawater specific enthalpy, ρ is the mean potential density, S is the salinity, and S_0 is the reference salinity. Heat flux has units of W m^{-2} and salt flux has units of m s^{-1}. The vertical sections of heat and freshwater fluxes of the BBCS from Central Shelf to Barrow Canyon Mouth are shown in Figs. 10 and 11. The calculation of specific enthalpy assumes a reference temperature of 0 °C, and the reference salinity S_0 is 34.8, following earlier studies (e.g. Aagaard and Carmack, 1989). Positive heat flux (red) indicates either a poleward transport of water warmer than the reference temperature or an equatorward transport of water cooler than the reference temperature. Similarly, positive freshwater flux (red) indicates either a

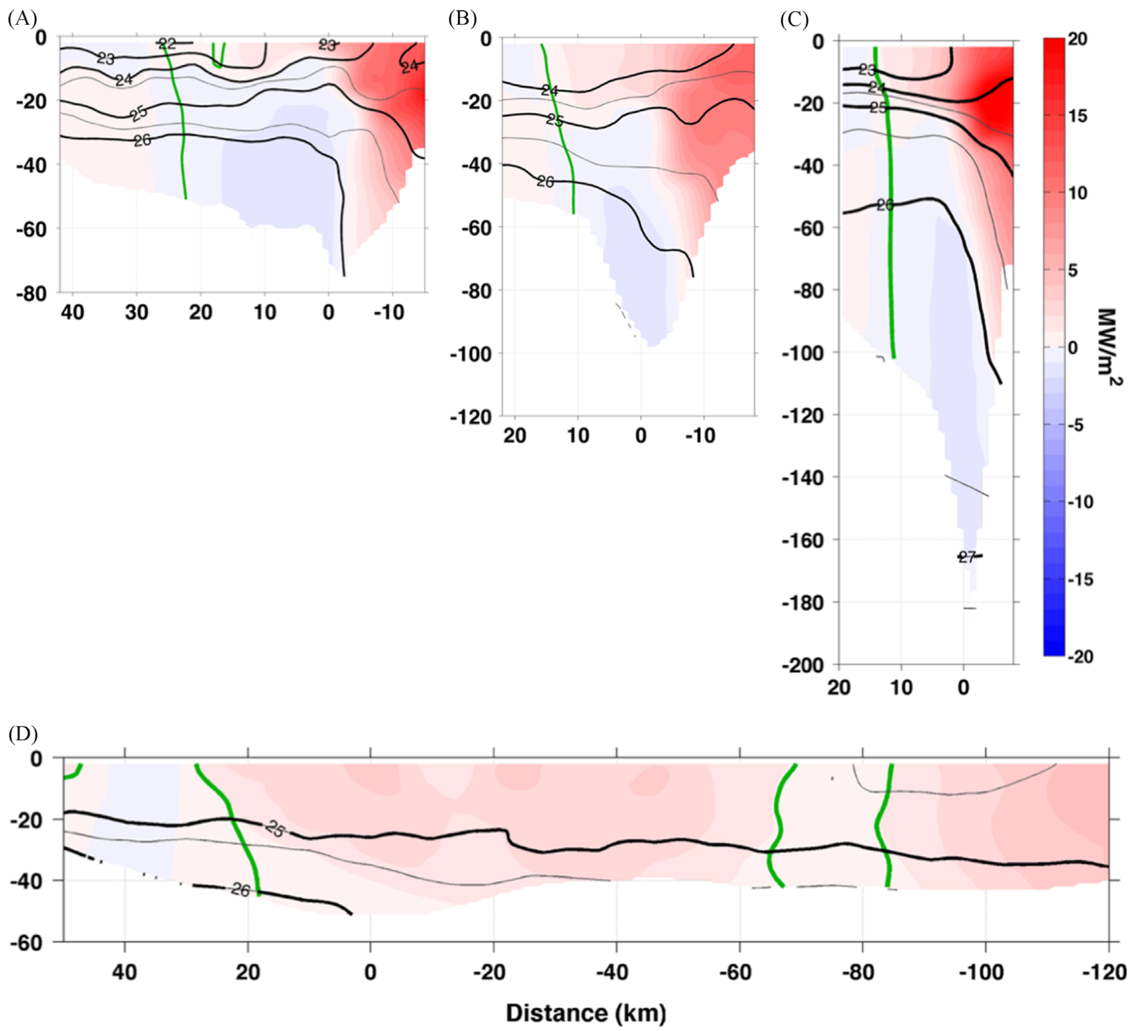

Fig. 10. Composite sections of heat transport for (a) Barrow Canyon Head, (b) Barrow Canyon Center, (c) Barrow Canyon Mouth, and (d) Central Shelf. The red color indicates poleward heat transport, and the blue color indicates equatorward heat transport. The green lines delineate the branches of the BBCS with poleward speed greater than 5 cm/s. Potential density anomaly contours are overlaid in each section. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

poleward transport of water fresher than the reference salinity, or equatorward transport of water saltier than the reference salinity.

Visual inspection of the heat and freshwater flux sections indicates that the BBCS plays an important role in the poleward transport of heat and freshwater during the summer. Most of the heat transport was in the upper portion of the BBCS in Barrow Canyon with $\sigma_\theta < 26\ \mathrm{kg\ m^{-3}}$. At denser levels ($\sigma_\theta > 26\ \mathrm{kg\ m^{-3}}$) the northward flow of cold winter water results in negative poleward heat transport. In contrast, the freshwater flux of the BBCS was positive at all depths resulting in poleward freshwater transport. This is because all of the Pacific water masses in the eastern Chukchi Sea in the summer were fresher than the reference salinity of 34.8, even the relatively salty PWW. However, the largest freshwater flux occurs in the upper portion of the water column in the core of the coastal branch of the BBCS, which encompasses the seasonal ACC.

To compare the impact of individual water masses on the poleward heat and freshwater transports, we tabulated the transports for each of the composite sections in Fig. 12 (again excluding Bering Strait). While the volume transports near Barrow Canyon were corrected for along-canyon winds, the wind correction was not applied to heat and freshwater sections. This is because wind forcing can lead to non-trivial changes in the current's hydrographic structure and we do not have the means to quantify this. Nevertheless, given the influence of winds on the volume transport, we expect the corresponding heat and freshwater transports in Barrow Canyon to be 10–30% less than the plotted values in Fig. 12. The overall mean heat transport for Central Shelf and the three Barrow Canyon sections is 7.7 ± 3 TW. The overall mean freshwater transport for the same sections is 77 ± 5 mSv.

There are clear alongstream trends in both heat and freshwater transport along the BBCS. The heat transport associated with light water is significantly less in the Barrow Canyon sections, and the presence of cold winter water in Barrow Canyon contributes to a decrease in the net poleward heat flux. In contrast, the magnitudes of the freshwater transport are comparable for all the sections. However there is a clear increase in contribution to freshwater transport from the dense and cold winter water at the Barrow Canyon sections. Recall that the most likely source of the winter water in Barrow Canyon is from the slow Central Channel pathway circulating back towards the head of Barrow Canyon through the cross-shelf transport pathways suggested in the synoptic current map of Fig. 3.

4. Discussion and summary

Using shipboard data from several field programs, we have quantified the volume, heat, and freshwater transport of Pacific water across the eastern Chukchi Sea during the summer. In addition to the well-known Alaskan Coastal Current (ACC) and the more recently identified Central Channel pathway (Weingartner et al.,

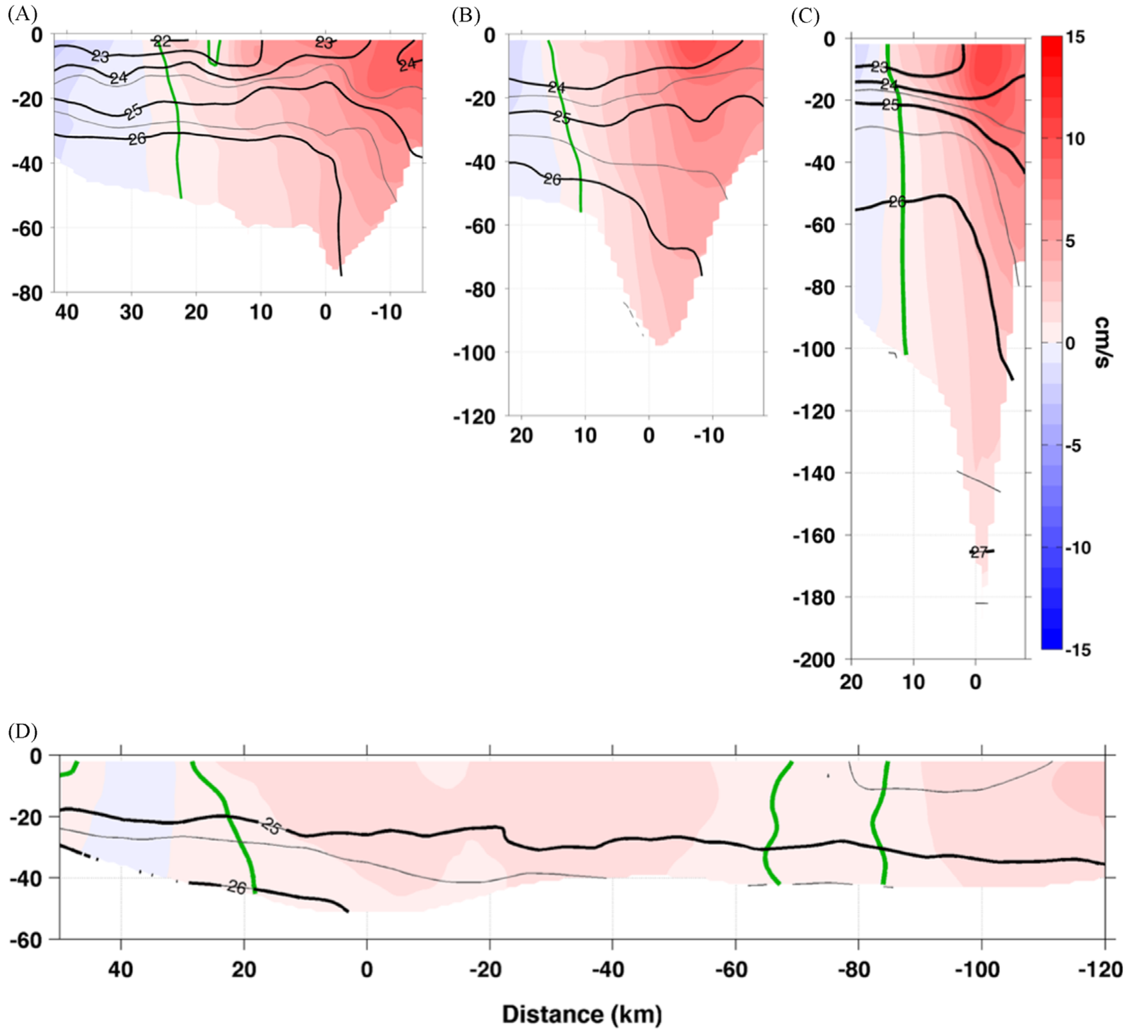

Fig. 11. Same as Fig. 10, for freshwater transport. (For interpretation of the references to color in this figure, the reader is referred to the web version of this paper.)

2005), we have found observational evidence of pathways connecting the Central Channel flow with the ACC in the vicinity of Hanna Shoal and Barrow Canyon. Using a collection of composite hydrographic transects, including one on the central shelf and three in Barrow Canyon, we have determined that the volume transport from Bering Strait to the mouth of Barrow Canyon across eastern Chukchi Sea is nearly constant during the summer. This is only possible if the poleward flow, which splits near Point Hope, merges again at the head of the canyon. We call this network of currents in the eastern Chukchi Sea the Bering to Barrow Current System (BBCS).

The shipboard ADCP data have revealed that the BBCS has a significant barotropic component, even for the coastal branch which encompasses the ACC. Our estimates of the BBCS transport indicate that it is only slightly less than that through Bering Strait during the summer months. Most of the flow exiting Barrow Canyon is expected to turn eastward and join the Beaufort shelf-break boundary current or jet. However, a detailed mooring based study downstream of Barrow Canyon on the Beaufort shelf-break has shown that, on average, only about 0.3 Sv of the expected 0.8–1 Sv Pacific water transport ends up in the shelf-break boundary current (Nikolopoulos et al., 2009). This surprising finding implies that the majority of the Pacific water exiting Barrow Canyon is fluxed directly into the Arctic basin, possibly through eddies as evidenced by the modeling studies of Spall et al. (2008). Based on these findings, we conclude that Barrow Canyon is the dominant gateway for the transport of Pacific water into the interior Arctic basin during the summer. At first glance, this counters the traditional view that the transport through the canyon only accounts for 30–40% of the Bering Strait transport (e.g. Woodgate and Aagaard, 2005; Weingartner et al., 2005). The apparent discrepancy between the studies may be attributed to the fact that the prior estimates are based on mooring observations for the entire year, while our estimates are based on shipboard observations for the summer season only. The significant seasonality in wind forcing, water column structure, and Bering Strait inflow can all lead to large seasonal differences in the transport pattern in Chukchi Sea.

Our results also suggest that a small fraction of Pacific water ($\sim$0.1–0.2 Sv) flows westward towards Herald Canyon from Bering Strait during the summer. A detailed hydrographic survey of Herald Canyon suggested that a portion of the summer Pacific water is diverted eastward on the shelf north of Herald Shoal (Pickart et al., 2010), which is depicted schematically in Fig. 1. However, the constancy of transport between the Central Shelf section and the Barrow Canyon transects presented here implies that most of this water exits the Chukchi shelf before reaching Hanna Shoal. One reason for the significant difference in the summertime circulation pattern compared to the annual mean circulation is that the summertime winds over much of Chukchi Sea tend to be weak and variable, whereas frequent easterly winds occur during the other seasons (Pickart et al., 2013). As demonstrated in Winsor and Chapman (2004), easterly winds over the Chukchi Sea drive the Pacific water towards the western portion of the shelf.

The positive poleward heat transport by light summer waters ($\sigma_\theta < 26\ \mathrm{kg\ m^{-3}}$) in the southern Chukchi Sea was found to be

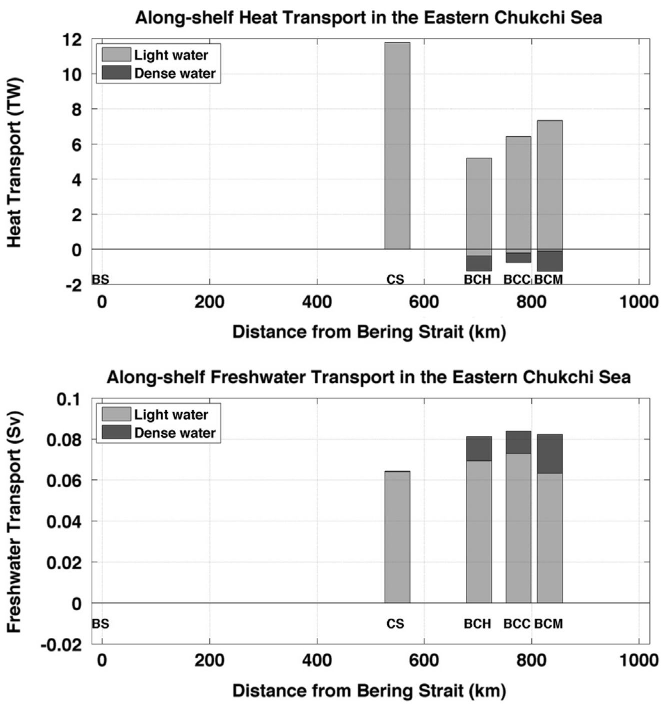

Fig. 12. Plot of heat (upper) and freshwater (lower) transport at the Central Shelf and Barrow Canyon sections, divided into the two density classes.

significantly larger than the corresponding values at Barrow Canyon. This could be the result of mixing and exchange of heat with colder ambient shelf water, enhanced solar heating to the south, or due to the timing of the seasonal water masses along the coastal branch of the BBCS – i.e. the warmest ACW had not yet appeared in Barrow Canyon. There was also negative heat transport associated with the northward flow of cold ($<0\,^{\circ}$C) and dense ($\sigma_\theta > 26\ \mathrm{kg\ m^{-3}}$) winter water in the three Barrow Canyon sections. There are different possible explanations for this. One possibility is that some of the warm summer water transported in the Central Channel branch is exchanged and/or mixed with either cold halocline water across the Chukchi shelf-break or with stagnant remnant winter water over Hanna Shoal (Martin and Drucker, 1997). A second possibility is that winter water was still being flushed from the northeast Chukchi Sea via the slower central channel pathway, joining the warm water from the (faster) coastal pathway at the head of Barrow Canyon. A key remaining unknown is the time that it takes for PWW to completely drain from the Chukchi shelf, and if/how this varies from year to year.

Given that the halocline of the Arctic Ocean controls the upper ocean density structure and heat transfer, it is important to know the time scale of its variability. Below roughly 100 m depth the water column of the western Arctic is ventilated mainly via lateral advective processes at the boundary of the basin, with very little atmospheric influence in the deep basin (Cavalieri and Martin, 1994; Pickart et al., 2005). The inflow of Pacific water across the Chukchi and Beaufort shelfbreaks into the basin plays an important role in halocline ventilation. Our results demonstrate that the BBCS can simultaneously transport multiple water masses of different origins and characteristics (i.e. ACW, PWW, CSW) into the interior halocline. Assuming a halocline volume of 160,000 $\mathrm{km^3}$, the summertime mean transport rate of 0.3 Sv determined here for the dense water ($\sigma_\theta > 26\ \mathrm{kg\ m^{-3}}$) through Barrow Canyon suggests that the BBCS can ventilate the entire western Arctic halocline in approximately 15–20 years if the wintertime transport of dense water is comparable to the summertime transport, and in shorter time if more dense water is transported by the BBCS in the winter. Future observational and modeling studies are needed to determine the transport and structure of the BBCS in other seasons of the year.

Acknowledgments

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