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On the nature and origin of water masses in Herald Canyon, Chukchi Sea: Synoptic surveys in summer 2004, 2008, and 2009

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ABSTRACT

Hydrographic and velocity data from three high-resolution shipboard surveys of Herald Canyon in the northwest Chukchi Sea, in 2004, 2008, and 2009, are used to investigate the water masses in the canyon and their possible source regions. Both summer and winter Pacific waters were observed in varying amounts in the different years, although in general the summer waters resided on the eastern side of the canyon while the winter waters were located on the western flank. The predominant summer water was Bering summer water, although some Alaskan coastal water resided in the canyon in the two later years likely due to wind forcing. Both newly ventilated and remnant winter waters were found in the canyon, but the amount lessened in each successive survey. Using mooring data from Bering Strait it is shown that a large amount of Bering summer water in the western channel of the strait follows a relatively direct route into Herald Canyon during the summer months, with an estimated advective speed of 10–20 cm/s. However, while the winter water observed in 2004 was consistent with a Bering Strait source (with a slower advective speed of 5–8 cm/s), the dense water in the canyon during 2008 and 2009 was more in line with a northern source. This is consistent with sections to the west of the canyon and with previously reported measurements implying winter water formation on the East Siberian shelf. Large-scale wind patterns and polynya activity on the shelf are also investigated. It was found that the former appears to impact more strongly the presence of dense water in Herald Canyon.

1. Introduction

Pacific water flowing northward through Bering Strait impacts the ecosystem of the western Arctic Ocean in important ways. In wintertime the cold water provides nutrients that spur the growth of phytoplankton at the base of the food chain (e.g. Hill et al., 2005), which, through vertical export, strongly influences the benthic activity (Grebmeier, 1993). In summertime, the warm water melts pack ice (e.g. Weingartner et al., 2005) and represents an important contribution of freshwater to the Canada Basin (Woodgate et al., 2012). The Pacific water also contributes to the stratification of the water column over large areas of the western Arctic, helping to maintain the upper halocline (e.g. Jones et al., 1998; Anderson et al., 2013).

Seasonally, the temperature and salinity characteristics of the Pacific water vary significantly. There are two types of summer water: warm and fresh Alaskan coastal water, which originates from continental runoff into the Gulf of Alaska and the Bering Sea, and colder, generally saltier Bering summer water. The latter is primarily a mixture of Anadyr water and central Bering shelf water (Coachman et al., 1975). Both of these summer waters are present in the western Arctic Ocean and result in temperature maxima in the upper 100 m of the water column (Steele et al., 2004; Timmermans et al., 2014). During winter and spring, Pacific winter water at/near the freezing point flows through Bering Strait (Woodgate et al., 2005a) and can be further modified during its transit north due to re-freezing polynyas and leads (Weingartner et al., 1998; Itoh et al., 2012; Pacini et al., n.d.). The winter water spans a large range in salinity and ultimately results in a temperature minimum in the deep basin in the depth range of 100–150 m (Steele et al., 2004).

In order to reach the central Arctic Ocean, the Pacific water must first cross the wide and shallow Chukchi Sea. There are three main flow pathways by which this happens, dictated largely by the topography of the shelf (e.g. Woodgate et al., 2005a; Weingartner et al., 2005, see Fig. 1). On the eastern shelf the Alaskan Coastal Current flows northward into Barrow Canyon; on the central shelf a branch flows through the Central Channel; and on the western shelf a pathway extends through Herald Canyon. It is believed that a portion of the western branch is diverted to the east and joins the central pathway (Pickart

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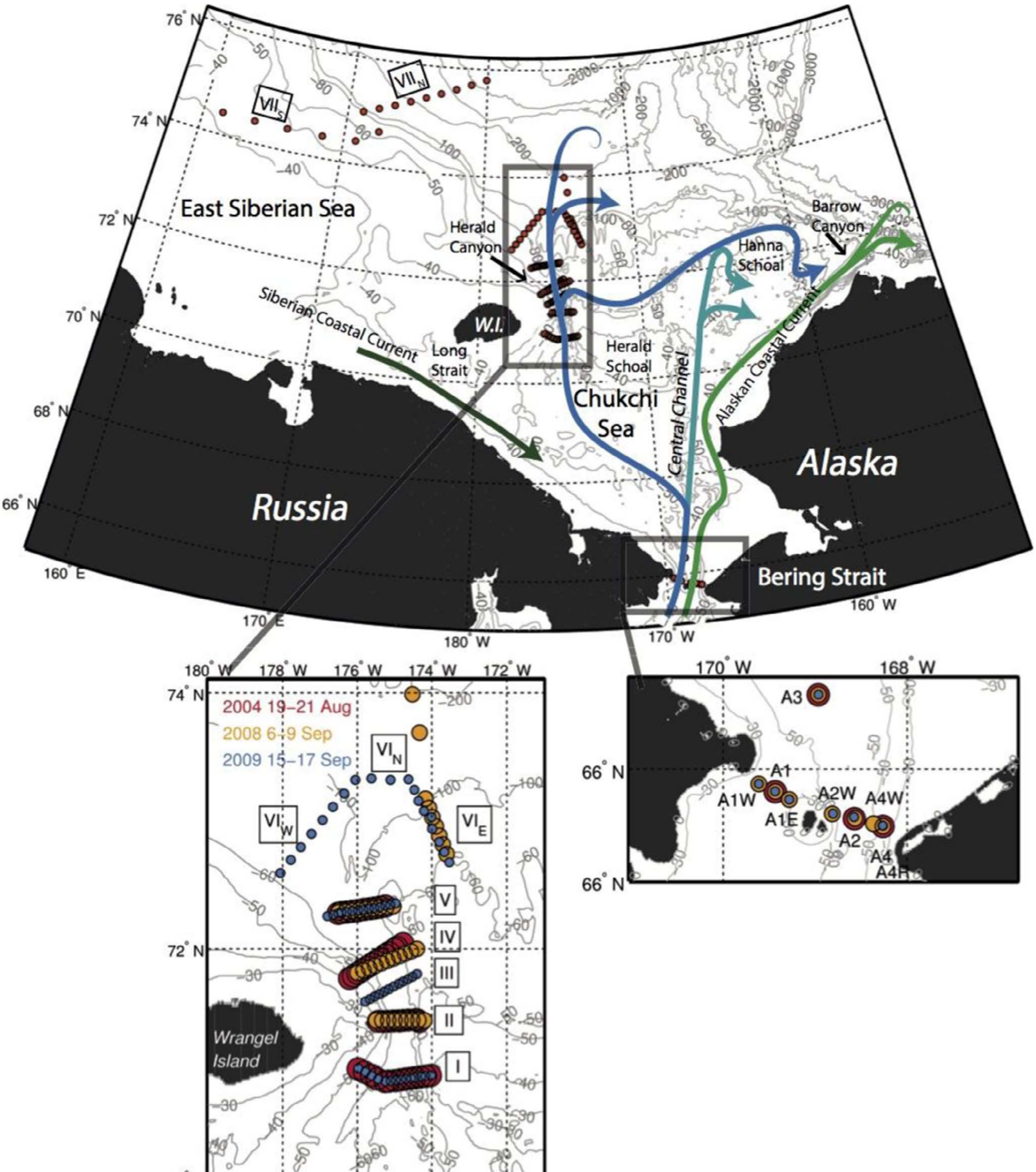

Fig. 1. (a) Map of the Chukchi Sea, including the Herald Canyon hydrographic sections and Bering Strait mooring array. Also shown is the western section VII, situated on the outer-shelf/upper-slope of the East Siberian Sea. A schematic depiction of the circulation of the region is overlain. (b) Detailed map of the Herald Canyon region showing the hydrographic sections used in the study: 2004 (red), 2008 (orange), and 2009 (blue). The dates of the surveys are indicated in the legend. (c) Detailed map of Bering Strait showing the mooring locations, color-coded as in (b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

et al., 2010), and together these waters flow around both sides of Hanna Shoal into Barrow Canyon (Weingartner et al., 2005; Gong and Pickart, 2015; Pickart et al., 2016). There is possibly a fourth pathway through Long Strait into the East Siberian Sea (Weingartner et al., 1999; Woodgate et al., 2005a), although this has not yet been established as a permanent branch. This overall circulation pattern is generally supported by modeling studies (Winsor, 2004; Spall, 2007; Panteleev et al., 2010).

During its transit on the shelf the Pacific water can be modified locally via atmospheric forcing. For example, using data from an extensive set of moorings in the Chukchi Sea during 1990–91, Woodgate et al. (2005a) argued that solar heating during the spring and summer is important for the seasonal variation in temperature, as is cooling via convective overturning during the autumn and winter (see also Weingartner et al., 2005). However, Woodgate et al. (2005a) argued that, overall, the variation of salinity on the shelf is dictated predominantly by advective input from Bering Strait. One major exception to this is the salinization of the water column that occurs in polynyas that form on the shelf. For instance, this happens in the northeast Chukchi Sea polynya (e.g. Itoh et al., 2012; Weingartner et al., 1998, 2005), and is thought to occur in the vicinity of Wrangel Island as well (Pickart et al., 2010). Recently it has been argued that salinization also takes place extensively within small leads and openings throughout the Chukchi shelf (Pacini et al., n.d.).

Transformation of the Pacific water also takes place via mixing along the pathways on the shelf, particularly where the flow is topographically steered during the last part of the shelf transit before entering the deep basin. This has been documented on the northeast shelf where summer and winter waters mix in early summer (Gong and Pickart, 2016). On the northwest shelf, a high-resolution shipboard survey carried out in Herald Canyon in 2004 revealed strong interaction between the northward-flowing summer water on the eastern side of the canyon and the more slowly moving winter water on the western side (Pickart et al., 2010). The winter water was observed to transpose to the eastern flank as it flowed down the canyon, and Pickart et al. (2010) argued that subsequent mixing and bottom boundary layer dynamics resulted in a new intermediate water mass exiting the canyon. Another mechanism for transformation is via upwelling and mixing of Atlantic water on the northern edge of the Chukchi shelf (Woodgate et al., 2005b). Such upwelling is common in Barrow Canyon (Aagaard and Roach, 1990) and may also be occurring in Herald Canyon (Pickart et al., 2010).

Measurements in the vicinity of Herald Canyon on the western Chukchi shelf are relatively sparse compared to the eastern part of the shelf (and Barrow Canyon in particular). As such, fundamental questions exist regarding the role of Herald Canyon in influencing the outflow of Pacific-origin water to the Canada Basin. One basic question is whether processes in and near the canyon promote water mass transformation, or if the canyon is simply an advective pathway through which water from Bering Strait transits relatively unchanged to the open ocean. In this paper we analyze and compare shipboard data from three late-summer surveys in the vicinity of Herald Canyon conducted in 2004, 2008 and 2009. In the latter two years mooring data were also collected in the western channel of Bering Strait. This allows for an assessment of the role of the upstream boundary condition (which was not possible in the analysis of the 2004 Herald Canyon shipboard data carried out by Pickart et al., 2010). The data used in our study are presented in Section 2. In Section 3 the water masses and the along-canyon evolution of the flow are compared for the three surveys. Section 4 focuses on the origins and the nature of the modification of the different water masses in the vicinity of Herald Canyon. Section 5 summarizes our results.

2. Data and methods

As part of the Russian-American Long Term Census of the Arctic (RUSALCA) program and the International Siberian Shelf Study 2008 (ISSS-08), three shipboard surveys of Herald Canyon were carried out during the first decade of the 2000s (Fig. 1). The first survey took place from 19–21 August 2004 (RUSALCA), the second was from 6–9 September 2008 (ISSS-08), and the third was carried out from 15–17 September 2009 (RUSALCA). Based on the velocity data collected during the shipboard surveys (see below), the mean/median northward core speed of the flow is 30 cm/s, which implies that the advection time for a water parcel to transit the length of the canyon (approximately150 km from head to mouth) is 5–6 days for the fastest velocities. Therefore, the surveys can be considered quasi-synoptic. The cross-stream station spacing was approximately 5 km in all years, which is comparable with, or smaller than, the internal radius of deformation calculated from the hydrographic data.

The 2004 expedition was comprised of four sections within Herald Canyon, and in 2008 and 2009 the cruises included three sections inside the canyon (see Fig. 1b). The sections within the canyon are referred to by Roman numerals I–V, progressing northward from the head of the canyon to the mouth. Additional sections were occupied north of the canyon in 2008 and 2009. Section VI was positioned to bracket the inflow/outflow seaward of the canyon (Fig. 1b), and section VII was situated approximately 450 km to the west of the mouth spanning the East Siberian shelf/slope (Fig. 1a). The winds were generally weak during the surveys in 2004 and 2008, but were strongly out of the northeast during the 2009 cruise (see Pisareva et al., 2015).

2.1. Hydrographic data

Hydrographic stations were conducted on all three cruises using an SBE911 + conductivity-temperature-depth (CTD) system. Details on the processing, calibration, and accuracy of the CTD data for the 2004, 2008 and 2009 surveys are given in Pickart et al. (2010), Anderson et al. (2011), and Pisareva et al. (2015), respectively. In 2004 and 2009 the rosette included a lowered acoustic Doppler current profiler (LADCP) system to measure horizontal velocities. This consisted of an upward- and downward-facing 300 kHz RDI Workhorse pair attached to the frame. The procedures used to process and de-tide the LADCP data, including error estimates, are included in the above references for the CTD data.

Vertical sections of properties were constructed for the different transects of the surveys. This was done using a linear interpolator with nearest neighbor at the boundaries, with a typical grid spacing of 2.5 km in the horizontal and 2 m in the vertical. Absolute geostrophic velocities were computed by referencing the thermal wind fields to the cross-transect component of velocity from the LADCP (see Pickart et al. (2010) for details).

2.2. Additional data

The flow through Bering Strait has been measured using moorings since 1990. Here we use a subset of the mooring data from 2004, 2008 and 2009 to help investigate the origin of the water masses in Herald Canyon. The measurements of temperature and salinity were obtained 9 m above the bottom (~45 m depth). For a description of the mooring data see http://psc.apl.washington.edu/HLD/Bstrait/Data/BeringStraitMooringDataArchive.html.

The number of moorings in the Bering Strait array has varied from year to year, but until recently there has been little coverage of the western (Russian) side of the strait. The prevailing notion is that the western flow pathway on the Chukchi shelf, which is steered by the bathymetry into Herald Canon, emanates from the western channel in Bering Strait. Fortunately, the RUSALCA program included year-long mooring deployments on the western side of Bering Strait. Here we consider three locations in the strait: the western channel, the eastern channel, and the central/northern portion of the strait. The latter site corresponds to mooring A3, which is located roughly 60 km to the north of the strait in US waters (Fig. 1c). This is one of the long-term moorings that has been in place for the majority of the deployments over the years. Due to the timing of the various mooring deployments, we are unable use the same set of moorings for each of our study years. For example, in 2004 the western channel moorings were deployed shortly before the hydrographic cruise, hence there is no previous time history for that year. Table 1 lists which moorings were used for the different regions in each year. For simplicity we discuss the mooring results by region – western, central, and eastern strait – not by mooring names.

To assess the polynya activity in the Chukchi Sea during the three survey years we used sea ice concentration data and sea surface

Table 1
Bering Strait mooring data used in the study. See Fig. 1 for the locations of the moorings.

Year	Region of Bering Strait	Mooring name
2004	Western Strait	N/A
2004	Central/Northern Strait	A3
2004	Eastern Strait	A4
2008	Western Strait	A1W
2008	Central/Northern Strait	A3
2008	Eastern Strait	A2
2009	Western Strait	A1W
2009	Central/Northern Strait	A3
2009	Eastern Strait	A2

temperature (SST) data from the Advanced Very High Resolution Radiometer (AVHRR) – Advanced Microwave Scanning Radiometer (AMSR). The horizontal resolution of the ice concentration and SST fields is 0.25°. The atmospheric conditions were investigated using the North American Regional Reanalysis (NARR) which has a temporal resolution of 6 h and spatial resolution of 32 km (Mesinger et al., 2006).

3. Water masses

3.1. Water mass definitions

We consider seven water masses that are found in the study region through the course of the year (Fig. 2). Four of these are Pacific-origin waters. As discussed in the introduction, the two Pacific summer waters are Alaskan coastal water (ACW) and Bering summer water (BSW). Following earlier work (e.g. Brugler et al., 2014; Pisareva et al., 2015; Gong and Pickart, 2015), we define two classes of Pacific winter water: Newly ventilated winter water (NVWW), which was formed via convective overturning in the winter preceding each survey, and remnant winter water (RWW). The latter product is winter water that has been warmed either by solar heating after the pack ice recedes and/or by mixing with summer waters arriving later in the season (Gong and Pickart, 2015). The three remaining water masses are Atlantic water (AW), which resides seaward of the Chukchi shelf beneath the Pacific layer; meltwater/runoff (MWR), which is found near the surface; and Siberian coastal water (SCW), which is advected southeastward in the Siberian coastal current (Fig. 1). The potential temperature–salinity (T-S) boundaries of the seven water masses are shown in Fig. 2. These should be considered approximate boundaries since there are interannual variations in the water masses (e.g. Pisareva et al., 2015). However, they suffice for our purposes and are consistent with previous studies of the region (e.g. Brugler et al., 2014; Gong and Pickart, 2015; Pisareva et al., 2015).

3.2. Water masses inside Herald Canyon

The hydrographic observations inside Herald Canyon show a similar pattern between the years for most sections at depths below 25 m, especially in the eastern part of the channel. In general, there is warm, less saline summer water on the eastern side, associated with strong northward velocities (Figs. 3–5). On the western side there is colder and more saline water, with weaker or even southward velocities. This is most obvious at the head of the canyon, but the pattern remains generally the same farther to the north. The following analysis is based on the above-defined water masses, and in Fig. 6 we use color coding to distinguish the different water types.

3.2.1. Meltwater/runoff

The surface layer of MWR can be defined by the 24 kg m^{-3} isopycnal, which resides at approximately 15 m depth (Fig. 6). In 2004 MWR was present at each of the sections in the canyon, although it was

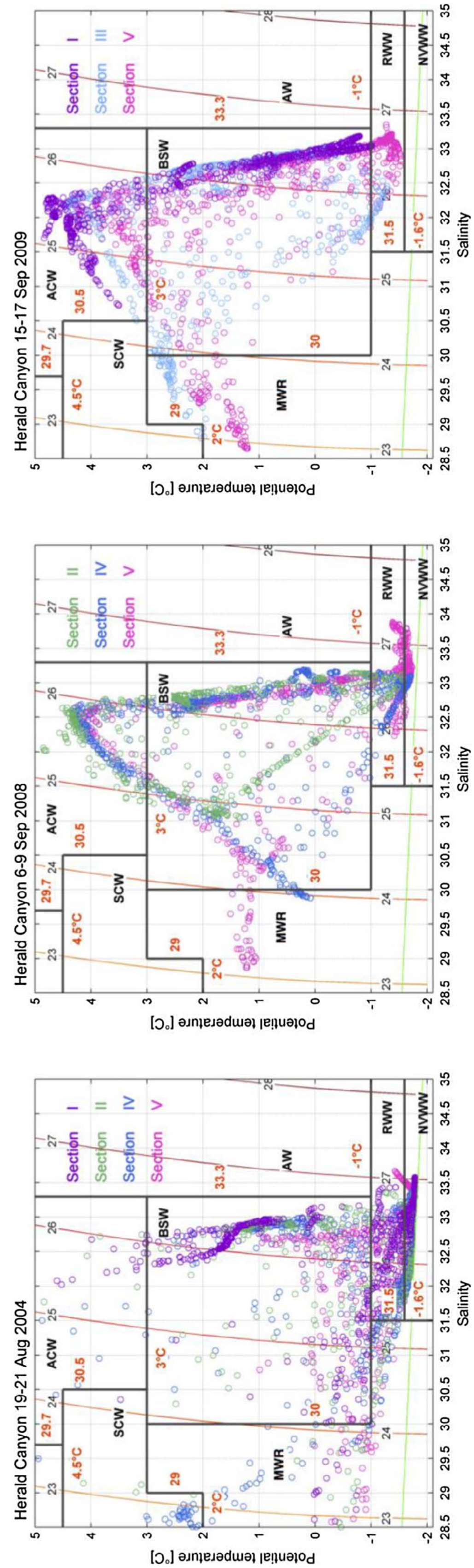

Fig. 2. T-S diagrams for Herald Canyon, color-coded by sections, including water mass definitions. ACW = Alaskan coastal water; BSW = Bering summer water; RWW = remnant Pacific winter water; NVWW = newly ventilated Pacific winter water; SCW = Siberian coastal water; MWR = meltwater/runoff; AW = Atlantic water. (a) Data from 2004, (b) data from 2008, and (c) data from 2009. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

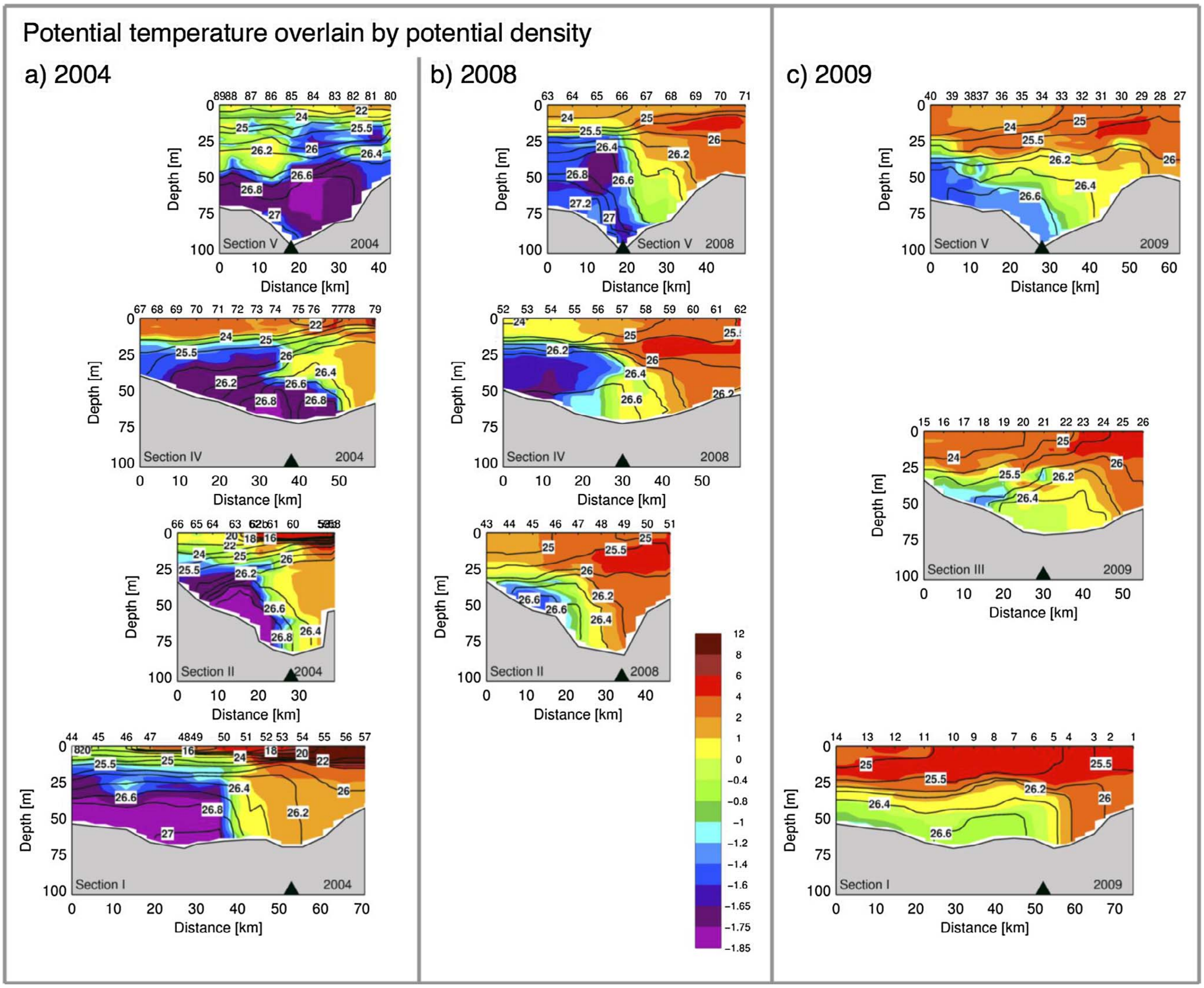

Fig. 3. Potential temperature (°C, color) overlain by potential density (contours, kgm^{-3}) for the sections inside Herald Canyon (I–V). (a) Data from 2004; (b) data from 2008; and (c) data from 2009. For ease of comparison between the years, the sections are positioned vertically in each column in relation to the latitude of the transect and aligned laterally according to the deepest part of the canyon (indicated by the black triangles). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

freshest at the head. This is a reflection of the final ice melt transitioning to open water in the vicinity of Wrangel Island, which, according to satellite imagery (not shown), took place roughly a week before the survey. By contrast, no MWR was present at the head in 2008 and 2009, but appeared farther north in the canyon. This is likely due to the fact that the ice cover melted approximately two weeks earlier in these two years versus 2004. Furthermore, the 2008 and 2009 sections were occupied later in the season, allowing more time for the MWR to be advected elsewhere.

3.2.2. *Summer water*

In all three years, except for the section across the mouth in 2004, there is warm summer water (ACW and BSW) occupying much of the water column on the eastern side of Herald Canyon (Fig. 6). The summer water is associated with a well-defined poleward jet on the eastern flank according to the velocity measurements in 2004 and 2009 (Fig. 5). The northward-directed flow is strongest at the head (40–50 cm s^{-1}) and weakens farther to the north (15–30 cm s^{-1}). Ship drift data during the 2008 survey, when it was extremely calm and thus no significant wind-induced motion of the ship, also indicated strong northward flow along the eastern side of the canyon, most pronounced at the head.

In general, the distribution of summer waters was similar in 2008 and 2009: ACW was present in the upper layer on the eastern flank, diminishing in extent near the mouth, and beneath this resided the BSW. (There was more summer water present in 2009, occupying much of the western flank as well.) The 2004 survey, however, displayed some substantial differences. Firstly, there was very little ACW present in the canyon; this is addressed below in Section 4.1. Secondly, some SCW was observed, particularly at section IV on the western flank of the canyon. While this may seem surprising, Pisareva et al. (2015) observed SCW all around Wrangel Island in 2009, implying that some of this coastal water can get entrained into the anti-cyclonic flow around the island (Pickart et al., 2010). It is therefore quite possible that a small portion could be diverted into Herald Canyon.

The third substantial difference between 2004 and the latter two surveys is that BSW was not present on the eastern flank at the northernmost section in 2004. Instead, winter water occupied most of the eastern side. Pickart et al. (2010) offered two explanations for the disappearance of the BSW in 2004: (1) the summer water was partly mixed due to the cross-channel circulation, and (2) the jet was not fully sampled by observations on the eastern flank. Pickart et al. (2010) noted that the topography north of Herald Shoal should divert some of the summer water to the east. However, in 2008 and 2009 summer

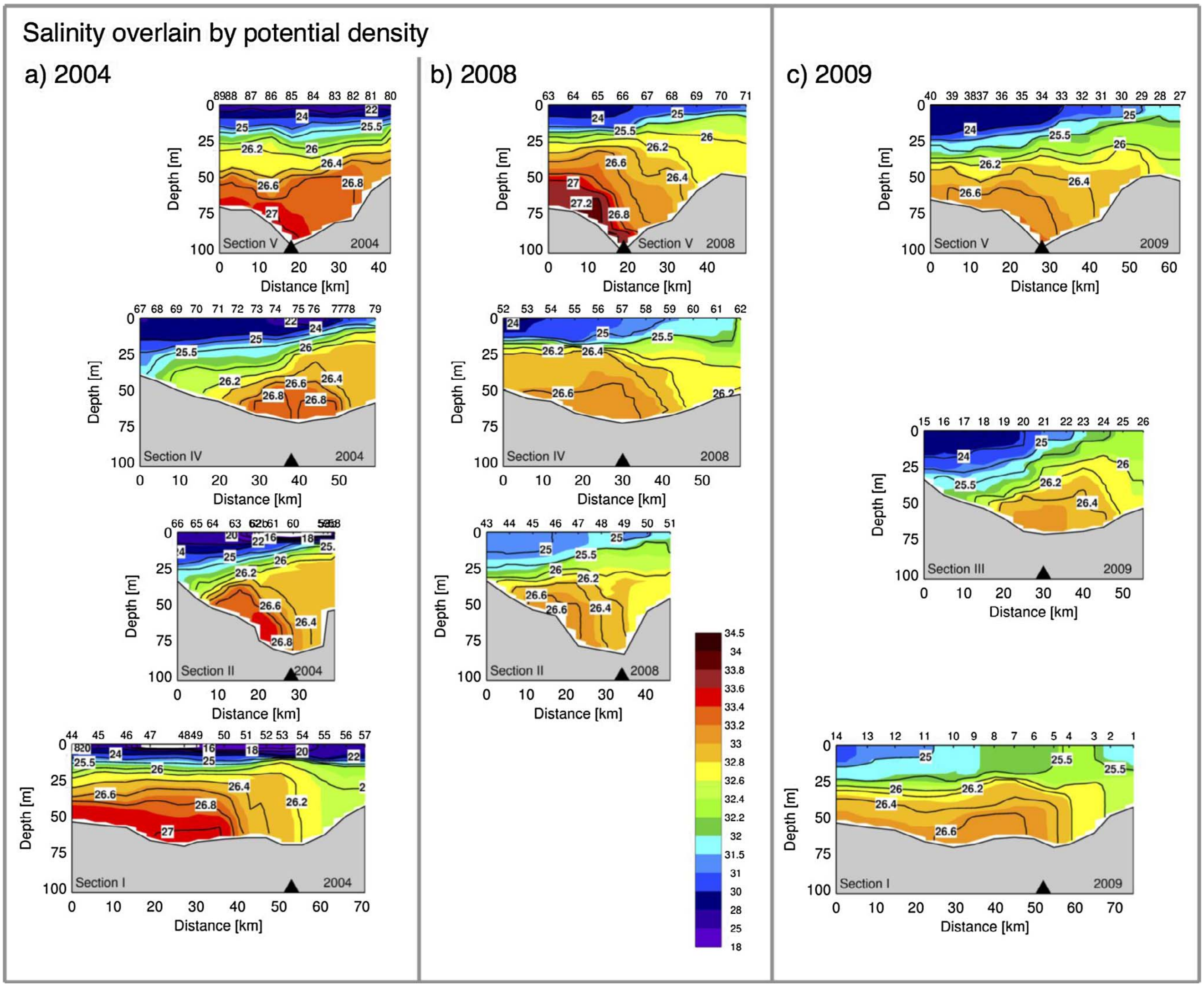

Fig. 4. Same as Fig. 3 except for Salinity (color). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

water was present along the entire eastern flank of the channel, suggesting that the circulation, mixing, and transformation of water that occurs in the canyon can vary substantially from year to year.

3.2.3. Winter water

The coldest water in all of the sections occupied in Herald Canyon was located on the western side, a pattern that is consistent through the three surveys. However, the distribution and properties of the cold water were more variable than for the summer water on the eastern side. The obvious difference is that there was a large amount of winter water in the canyon 2004, significantly less in 2008, and very little (no NVWW at all) in 2009. Interestingly, in 2008 and 2009 the amount of winter water increased from south to north in the canyon, and the temperature of the water decreased, neither of which were true in 2004. This is addressed later in the paper in Section 4.2. Also, the velocities of the winter water in 2009 were rather weak throughout the canyon, and no clear pattern emerged regarding the transport of this water mass, in contrast to 2004 (Pickart et al., 2010).

3.3. Water masses outside Herald canyon

As seen in Fig. 1, several sections were occupied seaward of the mouth of Herald Canyon, crossing the shelfbreak and slope. Section VI bracketed both sides of the canyon and was occupied in 2009 and partly in 2008. This section is subdivided as follows: VI_E for the eastern part, VI_W for the western part, and VI_N for the northern part. Section VII was occupied across the shelf-slope roughly 450 km to the west of Herald Canyon in 2008, and is divided into a southern and northern part: VII_S and VII_N (Fig. 1). The vertical sections of hydrographic properties for these sections are shown in Figs. 7 and 8, and the absolute geostrophic velocity for section VI is displayed in Fig. 9 (no velocity data were obtained on section VII). In Fig. 10 we use the same color coding for distinguishing the different water masses as was applied above for the canyon proper. Although Atlantic water was present in the deepest layers of Sections VI and VII, we do not address this water mass in our study. It is likely that Atlantic water can enter Herald Canyon from the basin during southerly wind events (see Pickart et al., 2010), but in each of our surveys this water resided seaward of the canyon mouth where it is normally found.

3.3.1. Summer water

In both years BSW occupied much of the water column on the shelf and upper slope of VI_E, with a thin layer extending offshore (bottom panel of Fig. 10a and b). The velocities from 2009 indicate that the summer water was progressing to the northeast as a shelfbreak jet (Fig. 9). This is consistent with the northward flow of summer water on the eastern side of the canyon and provides evidence that the Chukchi shelfbreak jet observed farther to the east (Mathis et al., 2007; Corlett

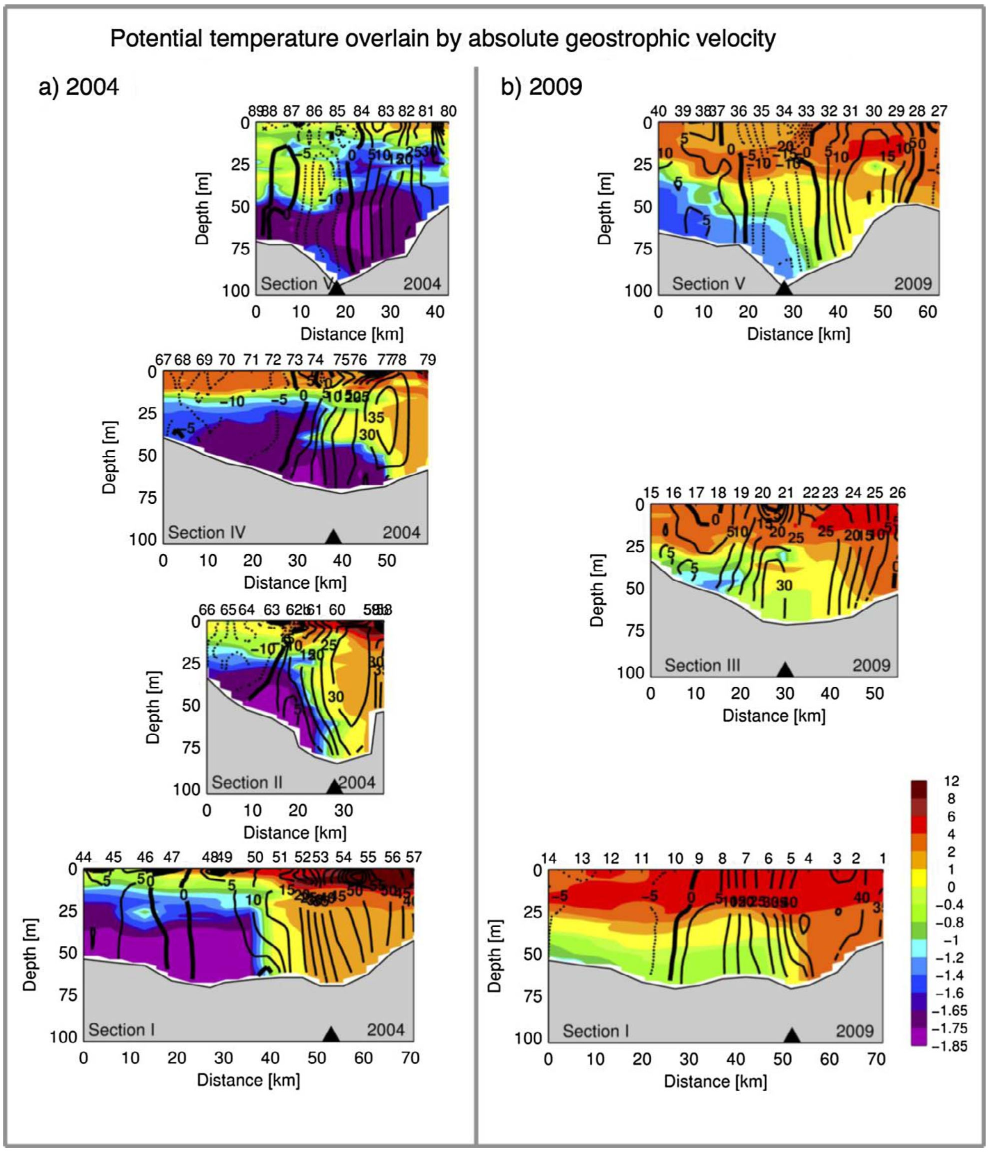

Fig. 5. Potential temperature (°C, color) overlain by absolute geostrophic velocity (contours, cm s^{-1}) for the sections inside Herald Canyon (I–V). (a) Data from 2004, and (b) data from 2009. There were no LADCP data collected in 2008. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and Pickart, 2017) originates from the outflow of Herald Canyon. By contrast, the summer water in section VI_W resided to a greater extent over the mid slope, with very weak velocities. This implies that most of the summer water passing through Herald Canyon in 2009 turned to the right and followed the bathymetry eastward.

In sections VII_S and VII_N one sees that there is little to no Pacific summer water over the shelf and deep part of the slope; BSW is mainly confined to the surface layer over the upper slope (top panel of Fig. 10a). There is a pronounced layer of MWR on the shelf, which becomes progressively fresher and warmer towards the coast as a result of river runoff, ice melt, and solar heating due to the ice free conditions (top panels of Figs. 7a and 8a).

3.3.2. *Winter water*

Both RWW and NVWW were present in 2008 to the west of Herald Canyon at sections VII_S and VII_N, with the layer becoming thicker and deeper towards the north (top panel of Fig. 10a). This corresponded to a pronounced isopycnal tilt across the slope. Such an isopycnal tilt associated with winter water on the continental slope is indicative of a bottom intensified eastward-flowing current. For example, the NVWW that flows eastward in the shelfbreak jet of the Chukchi Sea, as well as the shelfbreak jet of the Beaufort Sea, is associated with such a structure (Corlett and Pickart, 2017; Spall et al., 2008). This implies that, during the 2008 survey, winter water was approaching Herald Canyon from the west, i.e. from the East Siberian Sea. This is discussed later in the paper (Section 4.2). The same general pattern (i.e. presence of winter water with a similar isopycnal tilt) was also seen to the east of Herald Canyon in 2008 at section VI_E (bottom panel of Fig. 10a).

In 2009 there was much less NVWW present in section VI than the previous year, although RWW was found throughout most the section (Fig. 10b). The velocities are northward on the flanks of VI_W and VI_E (Fig. 9), while the deepest part of the section, between stations 47 and 52, shows northward flow on the western side and southward flow on the eastern side (Fig. 8). The reason for this is that the central portion of section VI crossed through an anti-cyclonic eddy of winter water situated just outside of the canyon mouth (note the enhanced presence of winter water at stations 48–50 on section VI_N corresponding to the center of the eddy). This was noted as well by Pisareva et al. (2015) and provides evidence that Pacific winter water is fluxed directly into the basin from Herald Canyon via turbulent processes. The fact that the flow is northward on the flank of section VI_W suggests that winter water can at times flow towards the canyon from the East Siberian Sea

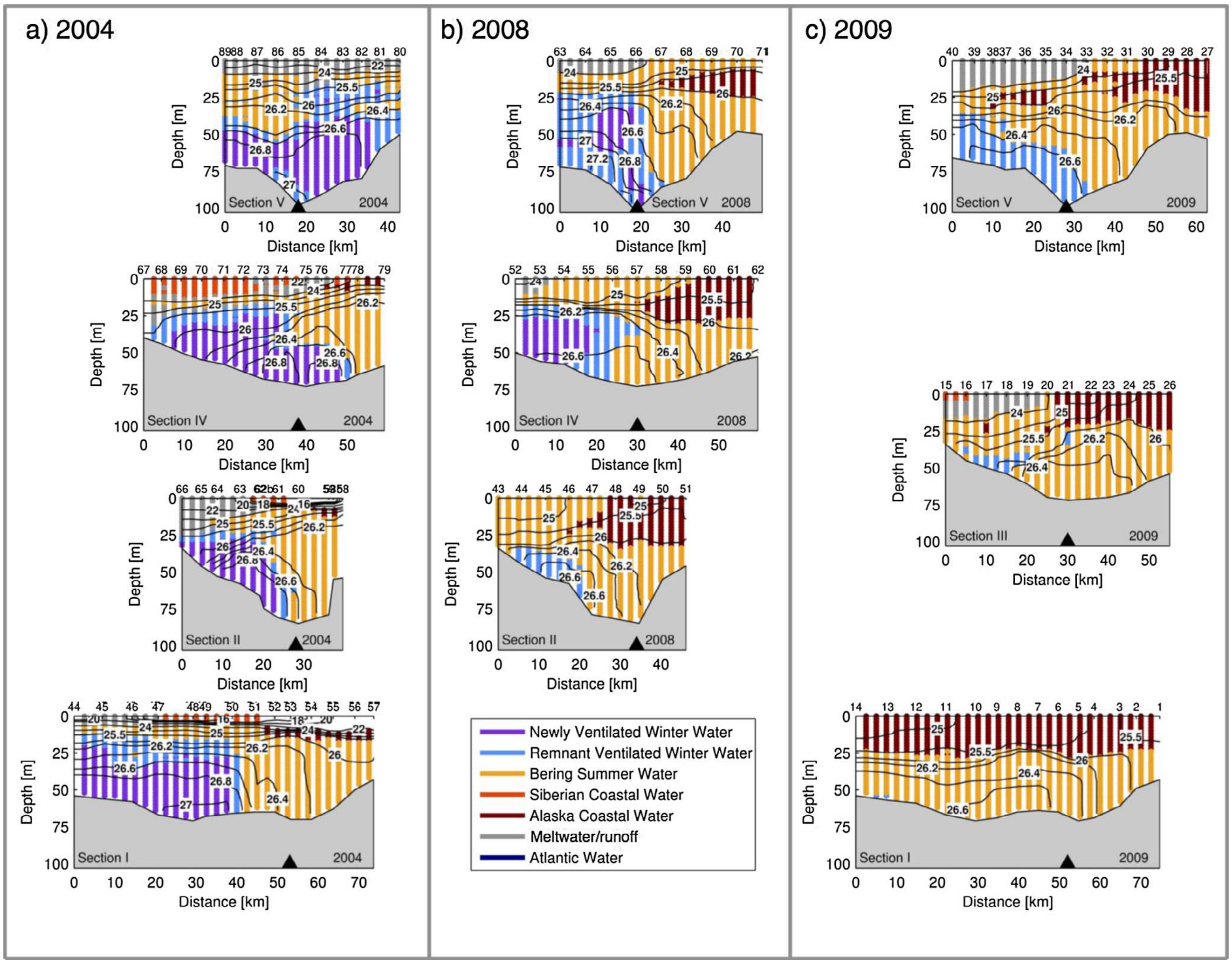

Fig. 6. Vertical sections of the water masses in Herald Canyon, where each water mass is denoted by a different color (see the legend). Overlain on the sections is the potential density (contours, kg m^{-3}). See Fig. 2 for the definitions of the water masses. (a) Data from 2004; (b) data from 2008; and (c) data from 2009. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(consistent with the 2008 hydrographic data), or away from the canyon towards the East Siberian Sea (as seen in 2009). Further work is necessary to understand the factors dictating this variability.

4. Origin of water masses in Herald Canyon

The residence time of Pacific water in the Chukchi Sea is generally less than a year (Woodgate et al., 2005a), indicating that the shelf is an advective system and suggesting that the inflowing water from Bering Strait should have a dominant impact on the T-S properties in the Chukchi Sea (Woodgate et al., 2005a; Spall, 2007). Here we test this notion by comparing the properties of the dominant water masses observed at the southernmost section in Herald Canyon in the three shipboard surveys with the properties of the inflowing water through Bering Strait measured by the moorings.

First, we identify the mode waters present at the head of the canyon in each shipboard survey as follows. Using the gridded potential temperature and salinity data from the vertical sections, we constructed a T-S diagram for each transect with an interval of 0.1 °C and 0.1 in salinity, with a moving window of half the width. If more than 17 data points fall within a given T-S interval, then that interval is considered a mode. A composite water mass mode is then simply the locus of the adjacent intervals that meet this criterion (using a less restrictive threshold meant that the resulting composite modes were less well defined).[1] Fig. 11a shows an example of the two mode waters that were present at the head of the canyon in 2004: a summer mode (consisting of BSW), and a winter mode (comprised of NVWW). Fig. 11b shows where these modes are present in geographical space. The winter mode occupied the western part of the canyon deeper than about 20 m, and the summer mode occupied the eastern half.

4.1. Tracking the summer waters found in Herald Canyon

As discussed in Woodgate et al. (2005c), the inflow through Bering Strait has a large seasonal variation in properties, with the coldest and most saline water entering during February–March, followed by warmer, fresher water during the summer. The northward volume transport also varies seasonally, with a minimum of 0.4 Sv in winter and maximum around 1.2 Sv between May and August. The comparison of the summer mode waters observed at the head of Herald canyon with the properties of the inflowing Pacific water through Bering Strait is shown for the three surveys in Fig. 12. We focus primarily on the BSW, as this is the dominant summer water mass in Herald Canyon (and was measured in all three years). In Fig. 12, the Herald Canyon summer T-S

[1] We invoke the use of modes to simplify the comparison between the mooring data and the shipboard data. The same conclusions would be reached by consideration of the full suite of T/S data.

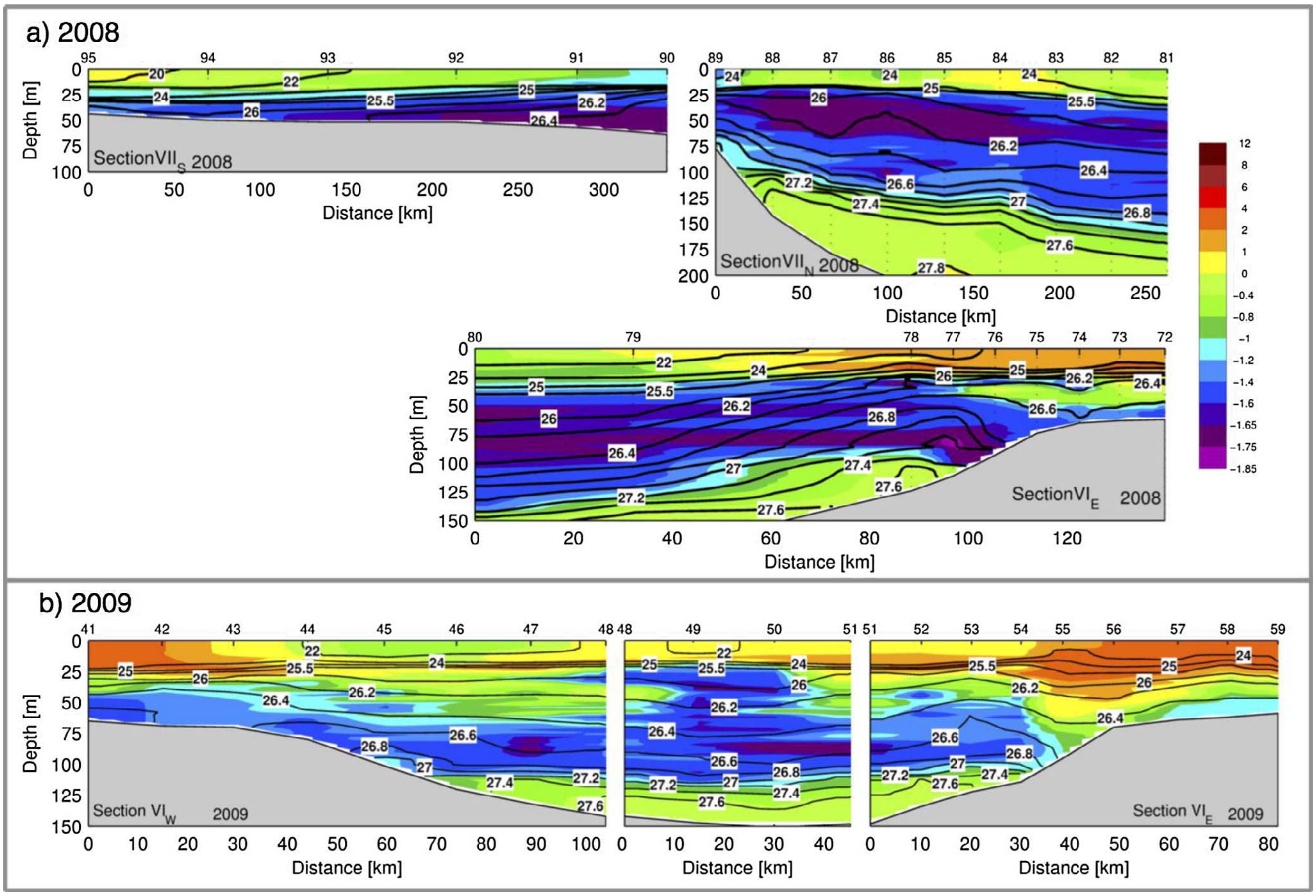

Fig. 7. Potential temperature (°C, color) overlain by potential density (contours, kg m^{-3}) for the sections outside of Herald Canyon in (a) 2008 and (b) 2009. See Fig. 1 for locations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

modes are indicated by the black polygons (the individual Herald Canyon data points are grey dots), and the Bering Strait data are color-coded according to the elapsed time (in months) since parcels passed through the strait prior to the occupation of the Herald Canyon section. Using the estimated distance from the mooring array to the head of the canyon (along the isobaths), we also indicate the implied advective speed for the different values of elapsed time. As such, we can use Fig. 12 to look for connections between the canyon modes and the water entering the Chukchi Sea through Bering Strait.

In 2004 (left hand column of Fig. 12) one sees that, not surprisingly, none of the water measured on the eastern side of Bering Strait ended up in Herald Canyon (Fig. 12a). This would have required significant salinization of the water, which is unlikely, plus the mean flow at this location is northeastward towards Barrow Canyon (Woodgate et al., 2005c). However, the mooring in the central part of the strait did measure water with the proper salinity to be the fresher portion of the canyon mode (Fig. 12b), corresponding to a time lag of 1.3–2 months prior to the occupation of the section (dark and medium blue in the figure legend). This implies an advective speed of roughly 18 cm/s, which seems reasonable. The water appears to be about 0.3 °C warmer in Herald Canyon, and an explanation for this temperature difference is that the Pacific water was heated by solar radiation as it crossed the Chukchi Sea during the summer months. A simple calculation of penetrating solar radiation, based on a representative surface heat flux during the summer and a typical attenuation coefficient for this area (0.08 m^{-1}), gives a temperature increase of 0.35–0.8 °C at 30–40 m depth for two months. This matches the observed difference quite well. Note that the saltier/colder part of the canyon T-S mode is not captured by the observations from either the central or eastern part of Bering Strait, implying that this water originated from the western side (where there were no observations in 2004).

In 2008 (middle column of Fig. 12) there was again one BSW mode in Herald Canyon, and, as was the case in 2004, the water flowing through the eastern side of Bering Strait (Fig. 12c) was too fresh to be associated with this mode. Furthermore, the water passing through the central strait barely overlapped in salinity on the fresh side of the mode (Fig. 12d). Notably, however, the water from the western strait (Fig. 12e) matches the salinity range of this mode for a wide spread of time lags, 0.7–2 months. The longer lag, which equates to roughly 15 cm/s, seems to be more likely. This is because the water in Bering Strait at that time was around 0.6 °C colder, and the analogous calculation as that done above implies that solar heating can account for this magnitude of increase in temperature.

In 2009 (right hand column of Fig. 12) there were two clusters of modes: the warm cluster was similar to the dominant mode in 2008, and the cold cluster was distributed in T-S space between −1 and 0 °C, with a salinity interval of ~0.2. As was the case the previous year, the water in the eastern and central portions of strait could explain little to none of the BSW observed at the canyon head. Again, the best match to the canyon modes was for the water passing through the western strait (Fig. 12b), covering a span of time lags of 0.7–3.6 months. In fact, most of the colder canyon mode matches the western Bering Strait data in both salinity and temperature.

As noted earlier, ACW was present in Herald Canyon in both 2008 and 2009 (Fig. 6). ACW normally flows through the eastern side of Bering Strait, and this was true for these two years as well (not shown). In each case the ACW in the strait was somewhat colder than that observed in the canyon, but in the correct salinity range. Summertime measurements on the northeastern Chukchi shelf suggest that, typically, the ACW flows to the northeast from Bering Strait into Barrow Canyon

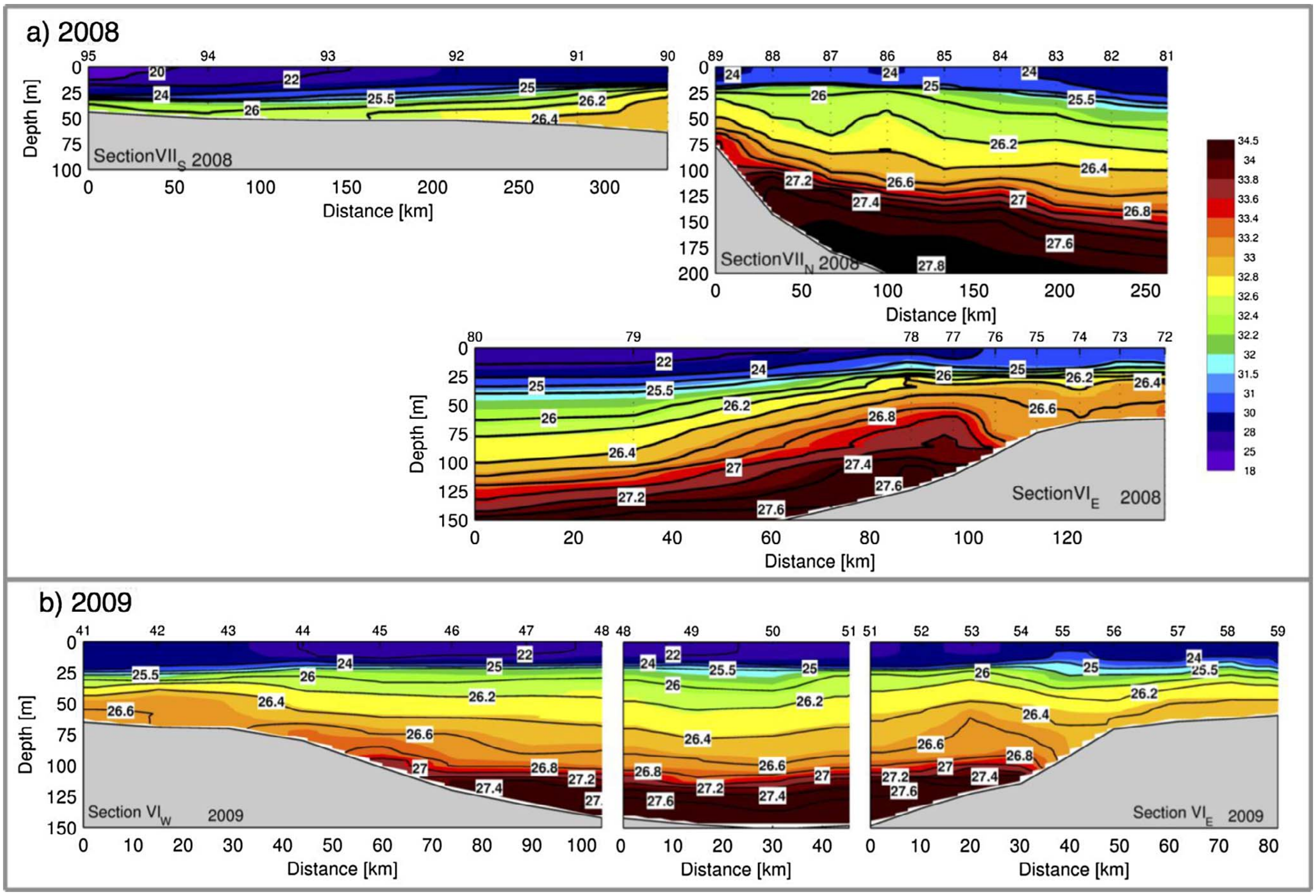

Fig. 8. Same as Fig. 7 except for salinity (color). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(e.g. Gong and Pickart, 2015). However, using the full 2009 RUSALCA shipboard data set, together with a numerical model, Pisareva et al. (2015) showed that enhanced northeasterly winds in late-summer were substantial enough that the Ekman transport in the vicinity of Bering Strait carried the ACW into the western channel. The model indicated that the spin-down process after the wind abated was slow enough that a substantial amount of ACW was transferred from the coastal pathway near Alaska onto the western shelf and into Herald Canyon. Solar heating of the water during this transit would thus account for our measurements of ACW in the canyon in 2009.

The 2008 observations suggest that something similar happened that year. In their study of the 2009 RUSALCA data, Pisareva et al. (2015) considered the time integral of the wind stress over a given wind event, which takes into account both the duration and magnitude of the event. The numerical model allowed them to determine a threshold in this quantity, above which the ACW should transpose to the western channel and get transported towards Herald Canyon. Using Pisareva et al.'s (2015) timeseries of the integral of the wind stress in the region of Bering Strait over the time period 2000–2012, we find that a substantial northerly wind event occurred in mid-August 2008 that exceeded this threshold. By contrast, none of the wind events preceding the 2004 cruise did so (when there was no observation of ACW). This offers an explanation for the varying presence of ACW between the years.

It appears, therefore, that a large amount of the BSW in the western channel of Bering Strait follows a relatively direct route into Herald Canyon during the summer months, with a typical advective speed of 10–20 cm/s. During its transit the water is heated by solar radiation. This result is line with the travel time estimate of 2–3 months based on current meter measurements (Woodgate et al., 2005a) and 1.2 months based on the model results of Spall (2007). Notably, the mooring in the central part of the Bering Strait captures only a small portion of the summer water that enters Herald Canyon.

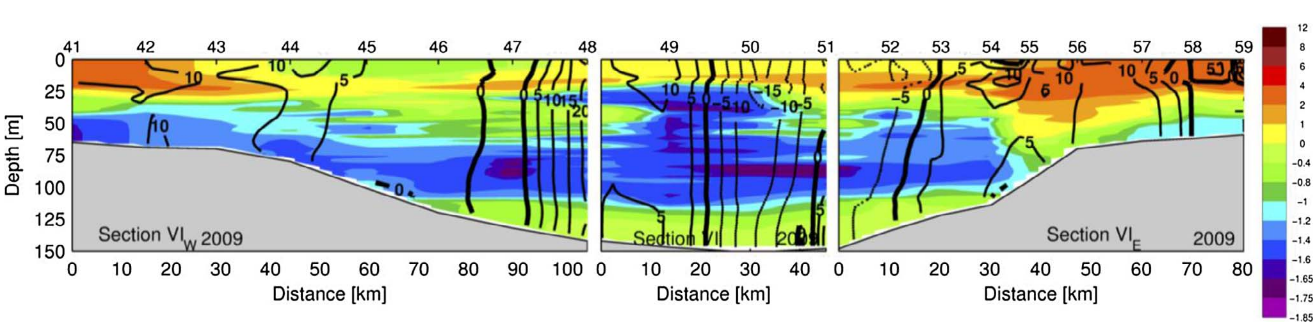

Fig. 9. Potential temperatures (color, °C) overlain by absolute geostrophic velocity (contours, cm s^{-1}) for section VI in 2009. See Fig. 1 for the location of the section. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

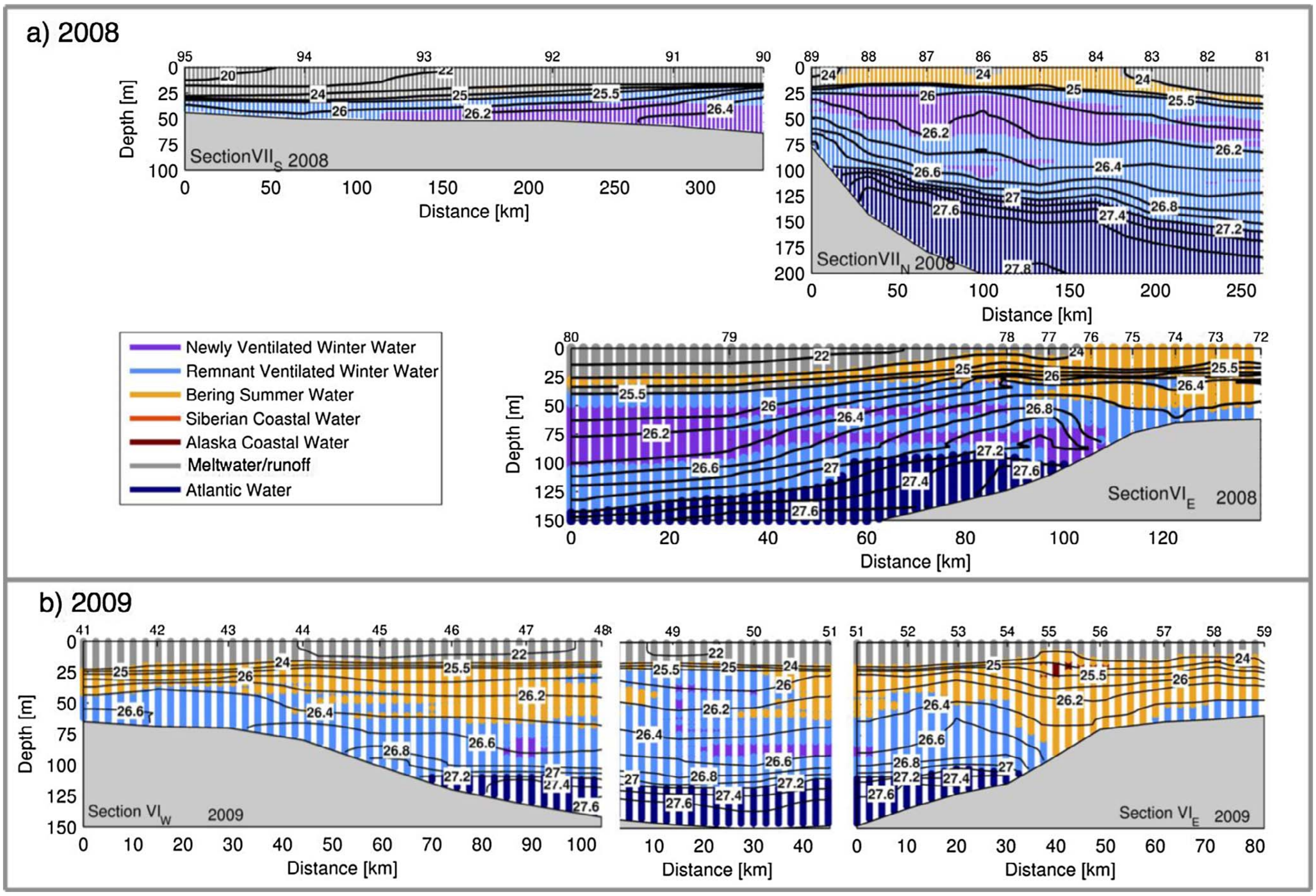

Fig. 10. Same as Fig. 6 except for the sections outside of Herald Canyon in (a) 2008 and (b) 2009. See Fig. 1 for the locations of the sections.

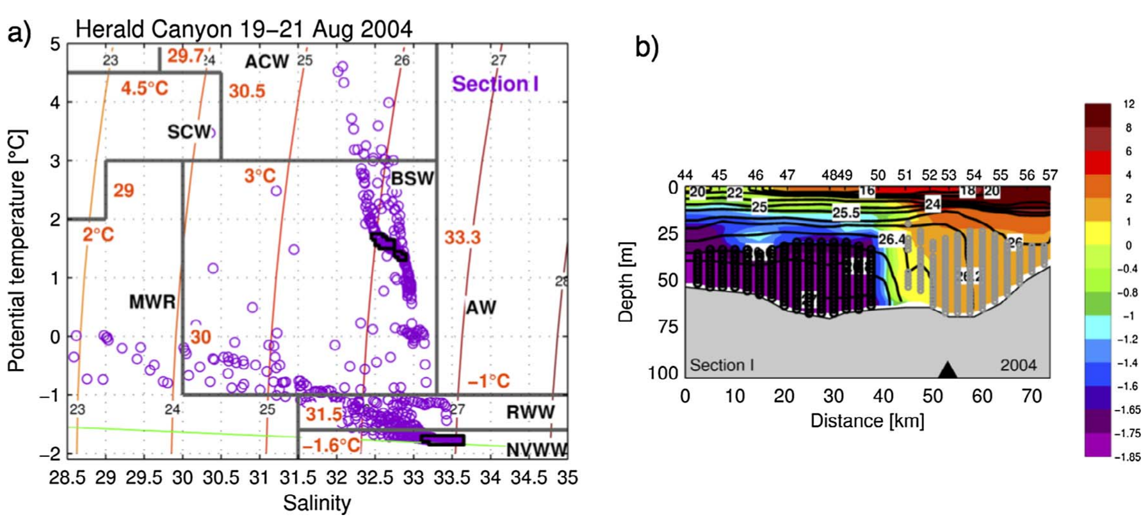

Fig. 11. Example of water mass modes at the head of Herald Canyon. (a) T-S diagram for the water in Herald Canyon section I in 2004. The two water mass modes are delineated by the thick black lines (see text for how the modes were defined). (b) Potential temperature (color, °C) overlain by potential density (contours, kg m^{-3}) for the section in (a). The presence of the two modes is indicated by the grey symbols (the warm mode) and the black symbols (the cold mode). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.2. Tracking the winter waters found in Herald Canyon

4.2.1. Bering Strait influence

We now analyze the winter water using the same approach as was done in the previous section for the summer water. That is, the water masses at the canyon head for each survey are compared to the mooring data from Bering Strait, the latter color-coded by the time lag relative to the date of the Herald Canyon occupations. However, according to our definition of a T-S mode, only the survey in 2004 had a winter water mode at the head of the canyon, and, in 2009, there was virtually no winter water at all at the southern-most section. As such, we do not consider 2009 in this analysis.

In 2004 (left hand column of Fig. 13) a winter water mode was present in the canyon for the salinity range 33.2–33.7. This matches the salinity of the water passing through the central strait 3.5–5.3 months earlier (Fig. 13b), corresponding to an advective speed of 5–8 cm/s. The

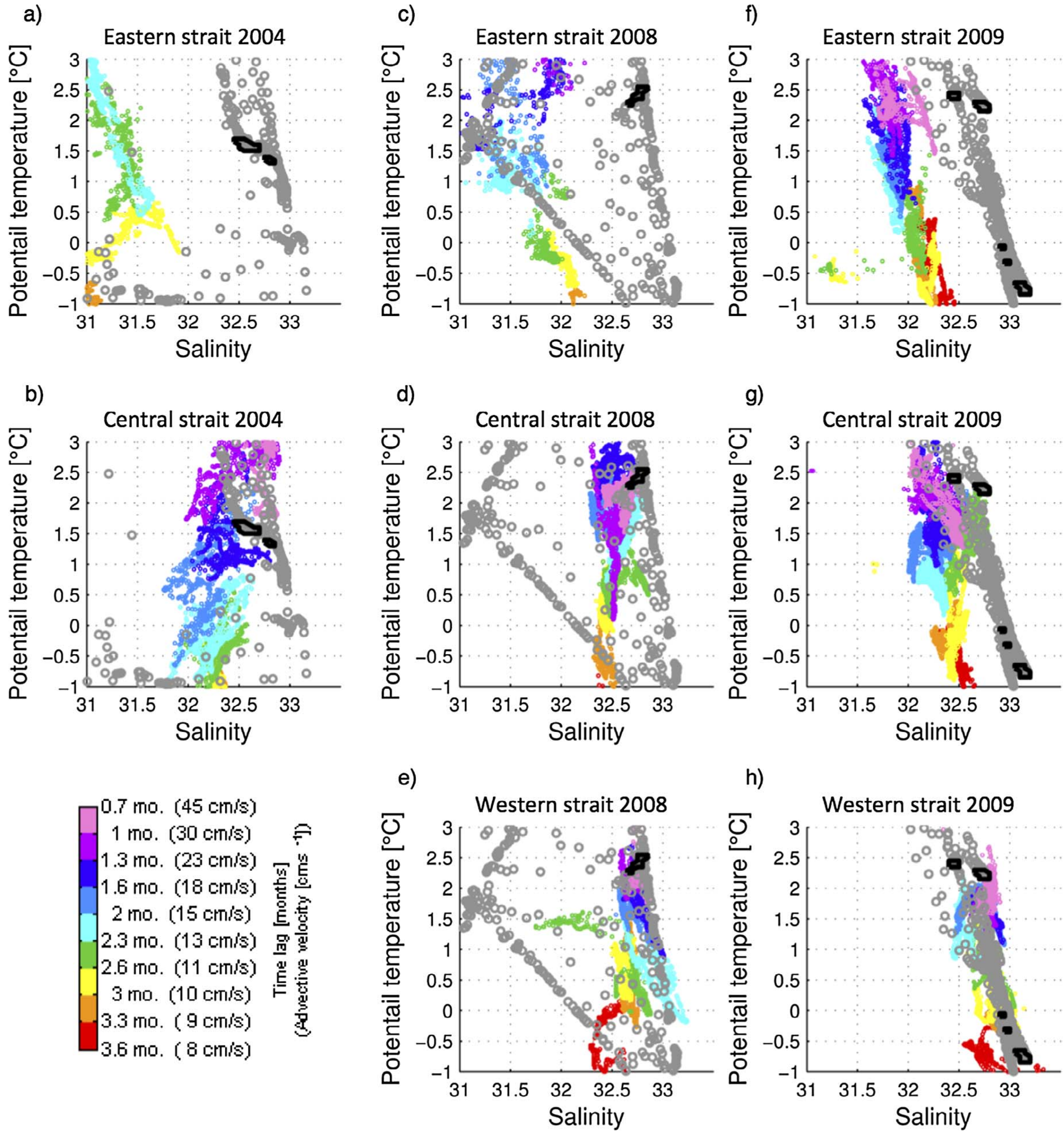

Fig. 12. Comparison of the T-S properties of summer water measured by moorings in Bering Strait versus that measured at the head of Herald Canyon during the shipboard surveys in 2004, 2008 and 2009. The mooring data are color-coded by the time lag between the date of observation in Bering Strait and the date of the occupation of the Herald Canyon section for the given year. The light grey circles are the shipboard data, and the black polygons delimit the water mass modes for each occupation.

Bering Strait water is generally about 0.05 °C colder at the mooring than that measured in Herald Canyon. Based on the same calculation applied earlier, but now with the presence of an ice cover – and noting that the winter water is deeper in the water column – we find it is likely that solar heating resulted in this change. This supports the idea of Bering Strait as a direct origin of the winter water in Herald Canyon in 2004, at least for the southern sections. (There is also the possibility that the winter water in the canyon emanated from the western channel of the strait, but this of course cannot be checked because the western mooring was not in the water then.)

In 2008 (right hand column of Fig. 13) only the warmer RWW and no NVWW was observed at the canyon head (Fig. 6b, section II). Furthermore, the quantity of RWW was not enough to constitute a mode. In contrast to 2004, it is unlikely that any of the winter water at the canyon head in 2008 came from the central strait, due to the large degree of implied warming from the strait to the canyon. In the western strait there is some overlap in both T and S with a time lag of 3.5–3.9 months (approximately 8 cm/s), although the degree of overlap is minimal. This suggests that most of the winter water measured in the 2008 survey did not come directly from Bering Strait.

Overall, the three surveys measured quite different conditions with regard to winter water at the head of the canyon. In 2004 there was predominantly NVWW; in 2008 RWW was present; and in 2009 no winter water was observed. One likely factor contributing to these differences is seasonal variability: the 2004 survey was the earliest (late-August), while the 2008 survey was two weeks later in the season, and the survey in 2009 two weeks later still. Using data from a mooring on the eastern flank of Herald Canyon in 1991, Woodgate et al. (2005a) showed that the temperature increased that year from the beginning of August into September. However, as we now explain, the differences in our three surveys cannot be due simply to measuring a direct supply of winter water from Bering Strait to Herald Canyon at different phases of

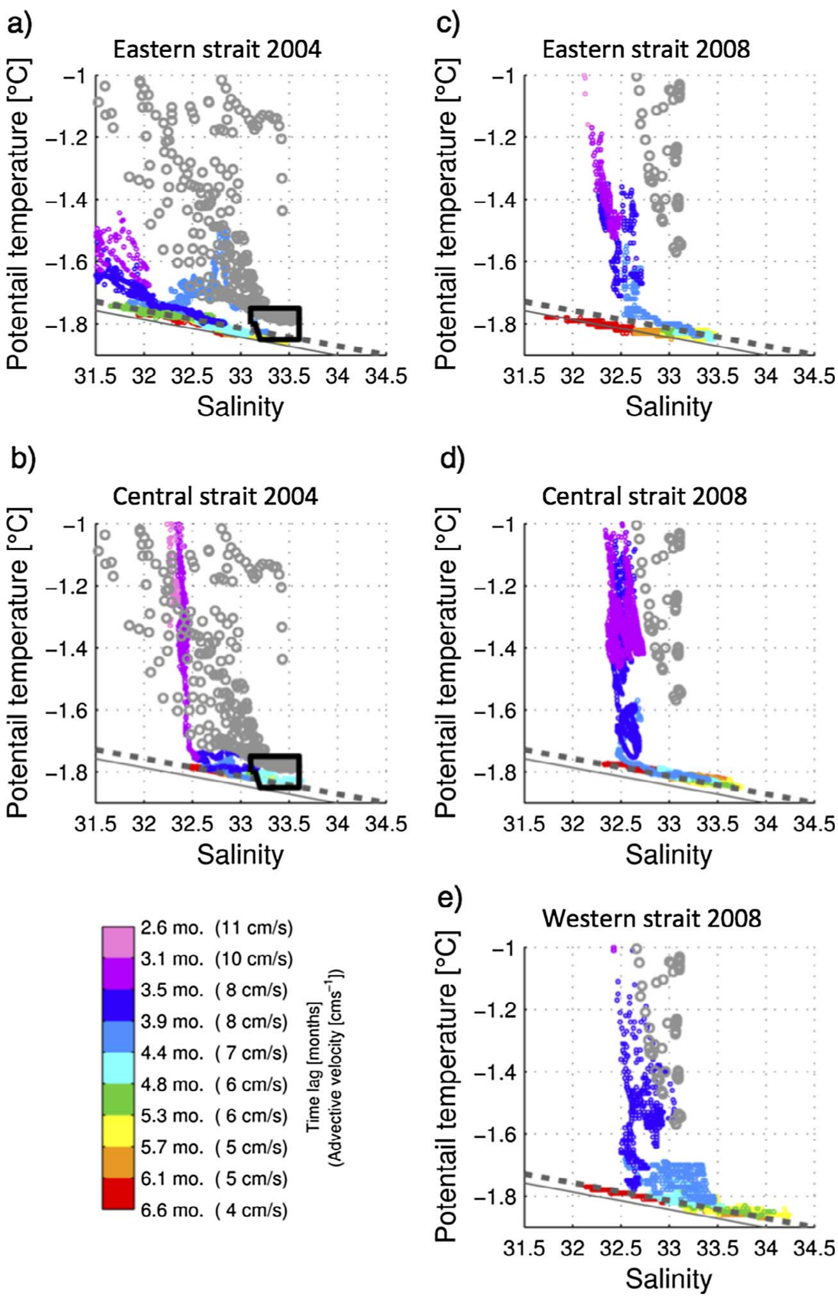

Fig. 13. Same as Fig. 12. except for the winter water observed in Bering Strait and the head of Herald Canyon.

the seasonal cycle.

As seen above, the connection between the Bering Strait mooring data and the shipboard section at the canyon head is tenuous at best for the 2008 winter water. Furthermore, in both 2008 and 2009 the amount of winter water on the western flank increased substantially farther northward in the canyon, and the water became colder as well – suggestive of a southward inflow of winter water from the East Siberian Sea. This, plus the argument presented in Pickart et al. (2010) for polynya-origin water feeding the head of Herald Canyon in 2004, suggests that in order to fully understand the source of the winter water in the canyon we have to consider sources other than Bering Strait.

4.2.2. Northern sources of winter water

Using the 2004 RUSALCA shipboard data, together with ice concentration data and a numerical model, Pickart et al. (2010) argued that the NVWW feeding Herald Canyon at the time of the survey emanated from the Wrangel Island polynya. In particular, it was suggested that dense water from the polynya (on the northwest side of the island) was advected by the prevailing anti-cyclonic circulation around the island, forming a reservoir of NVWW draining into the western side of the canyon head. Progressing northward, the winter water then transposed to the eastern flank of the canyon before exiting the mouth. However, Pickart et al. (2010) also noted that dense winter water was entering the mouth of the canyon on the western side (which presumably re-circulated before progressing very far into the canyon). The source of this NVWW remains unknown, although the additional data available in the present study allows us to shed further light on this.

In 2008, NVWW was found at the two northern sections in Herald Canyon (sections IV and V, Fig. 6b). NVWW was also present that year to the west of the canyon (sections VII_S and VII_N, Fig. 10a), and the geostrophic shear was consistent with NVWW progressing eastward towards the canyon as a bottom-intensified flow. This suggests that part of the dense winter water entering the mouth of the canyon on its western flank in 2008 emanated from a shelfbreak current along the East Siberian Sea. In that case, the origin of the water would likely be the East Siberian shelf. Using data from the same 2008 survey,

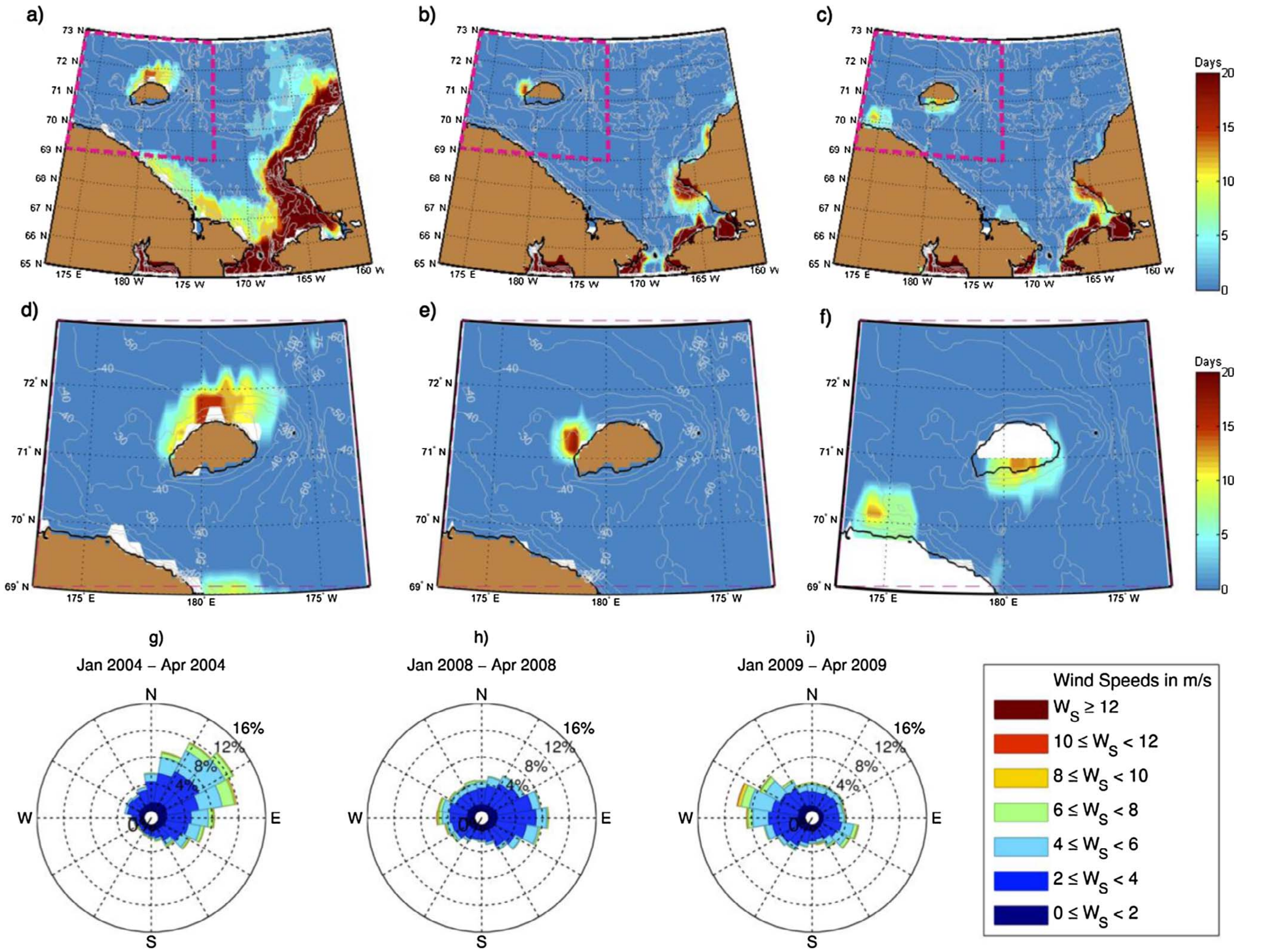

Fig. 14. (a–c) Number of days when the ice concentration was less than 80% during the months of January-April for the years preceding each survey. (d–f) Zoomed-in view of the region near Wrangel Island (indicated by the thick dashed line in (a–c). (g–i) Wind roses showing the average wind speed and direction for the same time periods.

Anderson et al. (2013) argued that ice formation and brine rejection formed winter water on parts of the East Siberian shelf. This dense winter water would subsequently lead to an eastward-flowing buoyancy-driven current at the edge of the shelf (Gawarkiewicz and Chapman, 1995), advecting the water into Herald Canyon. It should be remembered, however, that wind could influence the behavior of such a jet, which is known to be the case for both the Chukchi shelfbreak jet (Corlett and Pickart, 2017) and the Beaufort shelfbreak jet (Pickart et al., 2009). Furthermore, NVWW from the basin could enter the canyon during upwelling favorable conditions (see below).

It thus appears that input from the Bering Sea, formation of dense water on the East Siberian shelf, large-scale wind patterns in the region, as well as polynya activity in the vicinity of the canyon, all might play a role in the presence of winter water in Herald Canyon during summer. We now consider the latter two factors for the three survey years.

4.2.3. Year-to-year differences in polynya activity, ice production, and wind

The Chukchi Sea was more or less fully ice covered at the end of November in the years prior to the 2004 and 2009 surveys, but not until the third week of December prior to the 2008 survey. The late freeze-up that year was a likely response to the record low sea ice extent in summer 2007 (Stroeve et al., 2008). Such a delay in the formation of the ice is a circumstance believed to enhance the formation of winter water on the Chukchi shelf (e.g. Weingartner et al., 2005; Woodgate et al., 2005a), but this effect was not obvious in the Herald Canyon data the following summer. The polynya activity later in winter and spring, with corresponding winter water production, is closer in time to the surveys carried out in Herald Canyon and is therefore of interest to analyze further. We focus mainly on the January–April period, after freeze-up and before melt-back, with air temperatures below the freezing point of sea water. Following Comiso and Gordon (1996), a polynya is defined as an area with < 80% ice concentration surrounded by more highly consolidated ice.

We found no substantial differences in the polynya activity (i.e. the number of days that a polynya was present) in the vicinity of Wrangel Island during the period January–April for the three survey years (Fig. 14a–f). There was, however, notable geographical variation between the years: the polynya was most prevalent north of Wrangel Island in 2004, west of the island in 2008, and south of the island in 2009 (Fig. 14d–f). This generally corresponds to the prevailing winds (Fig. 14g–i, where the wind-driven ice velocity is directed to the right of the wind, Cole et al., 2014). In 2004 the predominant wind direction was from the northeast, in 2008 it was both westerly and easterly, and in 2009 it was northwesterly. Nonetheless, there is no compelling relationship between the polynya characteristics and the interannual variability in winter water presence between the three surveys. We also documented the number of days with < 80% ice concentration and air temperatures below the freezing point for the months of May and June, i.e. after melt-back began in the region. Again, there was no obvious connection to the shipboard observations. These results serve to downplay the importance of the wind-forced Wrangel Island polynya in supplying winter water to Herald Canyon, at least during the late-

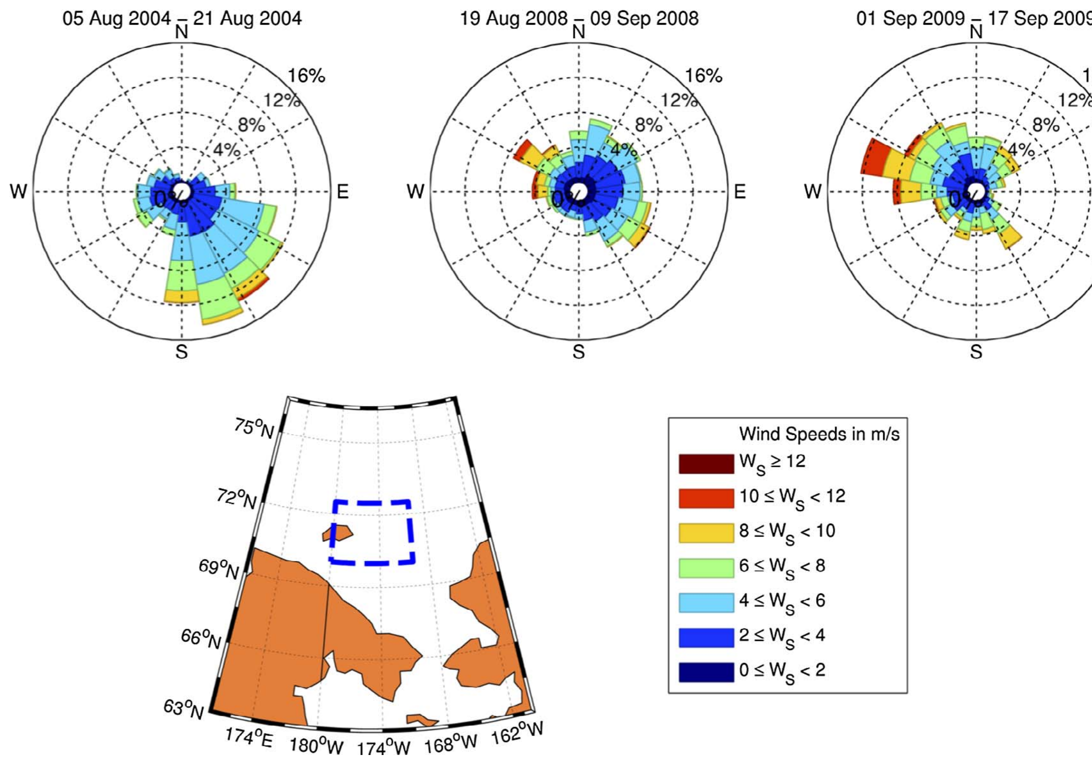

Fig. 15. Wind roses showing the average wind direction and speed for the two weeks prior to the surveys for the area surrounding Herald Canyon (indicated by the blue dashed box). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

summer when the surveys were carried out.

It is still possible that wind forcing could impact the flow of winter water (produced elsewhere) towards the canyon. Strong northerly winds during winter and spring tend to prolong the residence time of winter water on the shelf (e.g. Weingartner et al., 1998; Winsor, 2004) hence delaying the time that the dense water flushes through the canyon. As seen in Fig. 14g–i, the northerly winds during winter/spring were substantially greater in 2004 than in the other two years. This implies that in 2004 it would have been more likely for large amounts of winter water to be present in Herald Canyon in late-summer, as observed. By contrast, in 2008 and 2009 the winter water would not have been retained on the shelf for as long and thus may have largely exited Herald Canyon prior to the time of the surveys.

Finally, the local winds near the time of the surveys could have played a role in the presence of winter water in the canyon. For example, northerly winds have been shown to be associated with flow into the mouth of Herald Canyon (Pickart et al., 2010). The wind patterns during the two weeks before the surveys show differences between the years (Fig. 15). In 2004 the winds were mainly southeasterly, while in 2008 and 2009 they were strongest out of the northwest. This could have contributed to the enhanced presence of winter water at the northern reaches of the canyon in 2008 and 2009.

5. Summary

Observational data from three synoptic surveys carried out in Herald Canyon in 2004, 2008 and 2009 have been analyzed to investigate the interannual variations, water mass composition and transformation in the channel, together with the possible sources of the observed water masses. While there were substantial year-to-year variations in the temperature and salinity of the water in the canyon, a general pattern was present during each of the surveys with warm Bering summer water on the eastern side of the canyon and cold winter water on the western flank. Overall, the water throughout the canyon was warmer in each successive survey. The warming is characterized by higher temperatures of the summer water and significantly less winter water at the southern end of the canyon. While some of this variation is likely due to differences in the timing of the cruises, other factors played a role as well.

Using mooring data from the western, central, and eastern portions of Bering Strait, we were able to assess the upstream influence on the conditions in Herald Canyon. It was determined that, for Bering summer water, there appears to be a direct route from the western channel of the strait into Herald Canyon with a time lag of 1.3–2.3 months, which corresponds to an advective speed of 10–20 cm/s. There are also indications that water from the eastern side of the strait can at times feed the canyon due to wind forcing. For example, Alaskan coastal water was present in 2008 and 2009 but not in 2004, consistent with the different wind regimes in these years.

The connection between Bering Strait and Herald Canyon is less obvious for the winter water. In 2004 the dense water in the canyon likely emanated from Bering Strait. Assuming a reasonable amount of solar heating, it matched the mooring data in the central strait with a time lag of ~4.5 months, corresponding to an advective speed of 5–8 cm/s. However, in 2008 there was no obvious link between the winter water entering the canyon and that observed passing through Bering Strait (there was no winter water at all entering the canyon during the 2009 survey). Instead, the large amounts of winter water at the northern end of the canyon in those years, together with water of similar characteristics observed to the west of the canyon in 2008, suggest a source of winter water on the East Siberian shelf that enters the canyon via a shelfbreak jet. This is consistent with previously reported measurements from the East Siberian Sea. Wind-forced upwelling from the basin could also play a role.

Finally, an investigation of the wind-driven polynya activity on the Chukchi shelf in the winters preceding the three surveys suggests that the Wrangel Island polynya is not a major source of the winter water found in Herald Canyon in the summer. However, the large-scale wind patterns in the region may affect the presence of the dense water in the canyon. During winter/spring 2004 the winds were significantly stronger out of the northeast than for the other two survey years. This in turn would likely have increased the residence time for the winter water on the Chukchi shelf in 2004 such that it was still present at the head of the canyon at time of the survey. On a smaller space/time scale, the winds during the two weeks preceding each cruise were conducive for winter water feeding the head of the canyon in 2004 and feeding the mouth of the canyon in 2008 and 2009, in line with the observations.

Despite the three cruises-worth of data presented here, this region of the Chukchi Sea remains data sparse and presently we are unable to definitively identify all of the sources and variability of the water found in Herald Canyon. In particular, further work is required to fully understand the origin of the winter water that enters the mouth of Herald Canyon and the mechanisms by which this happens, as well as the interplay between this water and the Pacific-origin water supplied to the head of the canyon.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.pocean.2017.09.005.

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