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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<div align="center">**Abstract**</div>

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 varies 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., submitted). 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 et al., 2010), and together these waters flow around both sides of Hanna Shoal into Barrow Canyon (Weingartner et al., 2005; 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 and Chapman, 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, 2005). However, Woodgate et al. (2005a) argued that, overall, the variation of salinity on the shelf is dictated predominantly by
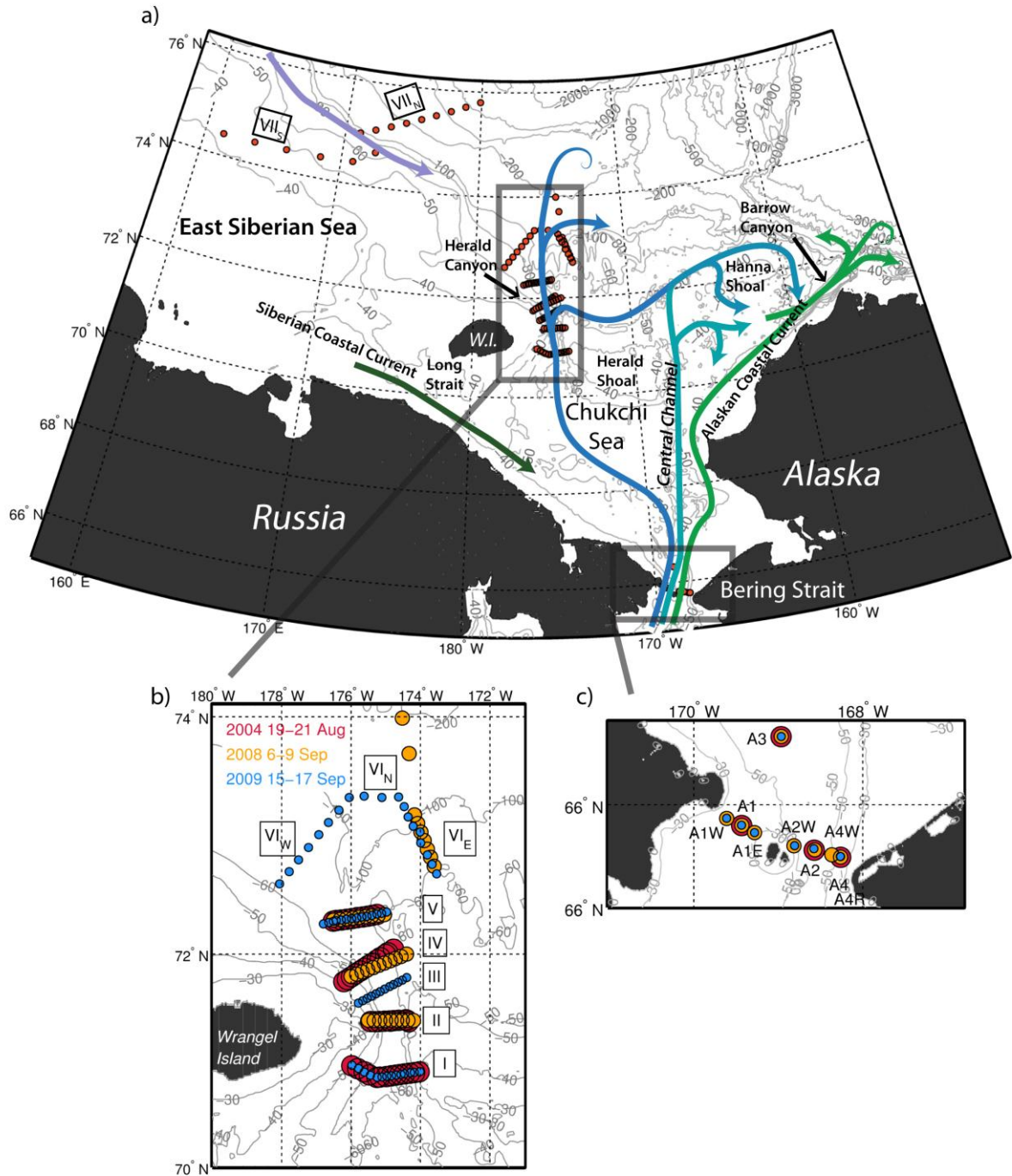
Figure 1: (a) Map of the Chukchi Sea, including the Herald Canyon hydrographic sections and Bering Strait mooring array. Also shown is the western section VII, situated on the outer-shelf / upper-slope of the East Siberian Sea. A schematic depiction of the circulation of the region is overlain (after Corlett and Pickart, 2017). (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).

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; Weingartner et al., 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., submitted).

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. 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

107 the origins and the nature of the modification of the different water masses in the vicinity of

108 Herald Canyon. Section 5 summarizes our results.

109

110 **2. Data and Methods**

111 As part of the Russian-American Long Term Census of the Arctic (RUSALCA) program

112 and the International Siberian Shelf Study 2008 (ISSS-08), three shipboard surveys of Herald

113 Canyon were carried out during the first decade of the 2000s (Fig. 1). The first survey took

114 place from 19–21 August 2004 (RUSALCA), the second was from 6–9 September 2008

115 (ISSS-08), and the third was carried out from 15–17 September 2009 (RUSALCA). Based on

116 the velocity data collected during the surveys, the advection time for a water parcel to transit

117 the length of the canyon is 5-6 days for the fastest velocities; therefore, the surveys can be

118 considered quasi-synoptic. The cross-stream station spacing was approximately 5 km in all

119 years, which is comparable with, or smaller than, the internal radius of deformation

120 calculated from the hydrographic data.

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122 The 2004 expedition was comprised of four sections within Herald Canyon, and in 2008

123 and 2009 the cruises included three sections inside the canyon (see Fig. 1b). The sections

124 within the canyon are referred to by Roman numerals I–V, progressing northward from the

125 head of the canyon to the mouth (a distance of approximately 150 km). Additional sections

126 were occupied north of the canyon in 2008 and 2009. Section VI was positioned to bracket

127 the inflow/outflow seaward of the canyon (Fig. 1b), and section VII was situated

128 approximately 450 km to the west of the mouth spanning the East Siberian shelf/slope

129 (Fig.1a). The winds were generally weak during the surveys in 2004 and 2008, but were

130 strongly out of the northeast during the 2009 cruise (see Pisareva et al., 2015).

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132 **2.1 Hydrographic data**

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134 Hydrographic stations were conducted on all three cruises using an SBE911+

135 conductivity-temperature-depth (CTD) system. Details on the processing, calibration, and

136 accuracy of the CTD data for the 2004, 2008 and 2009 surveys are given in Pickart et al.

137 (2010), Anderson et al. (2011), and Pisareva et al. (2015), respectively. In 2004 and 2009 the

138 rosette also included a lowered acoustic Doppler current profiler (LADCP) system to measure

139 horizontal velocities. This consisted of an upward- and downward-facing 300 KHz RDI

140 Workhorse pair attached to the frame. The procedures used to process and de-tide the

141 LADCP data, including error estimates, are included in the above references for the CTD

142 data.

143

144   Vertical sections of properties were constructed for the different transects of the surveys.

145 This was done using a linear interpolator with nearest neighbor at the boundaries, with a

146 typical grid spacing of 2.5 km in the horizontal and 2 m in the vertical. Absolute geostrophic

147 velocities were computed by referencing the thermal wind fields to the cross-transect

148 component of velocity from the LADCP (see Pickart et al., 2010 for details).

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151 **2.2 Additional data**

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153   The flow through Bering Strait has been measured using moorings since 1990. Here we

154 use a subset of the mooring data from 2004, 2008 and 2009 to help investigate the origin of

155 the water masses in Herald Canyon. The measurements of temperature and salinity were

156 obtained 9 m above the bottom (~45 m depth). For a description of the mooring data see

157 http://psc.apl.washington.edu/HLD/Bstrait/Data/BeringStraitMooringDataArchive.html.

158 Table 1 lists the moorings considered here for the three different years. To assess the polynya

159 activity in the Chukchi Sea during the three survey years we used sea ice concentration data

160 and sea surface temperature (SST) data from the Advanced Very High Resolution

161 Radiometer (AVHRR) – Advanced Microwave Scanning Radiometer (AMSR). The

162 horizontal resolution of the ice concentration and SST fields is 0.25^{o}. The atmospheric

163 conditions were investigated using the North American Regional Reanalysis (NARR) which

164 has a temporal resolution of 6 hours and spatial resolution of 32 km (Mesinger et al., 2006).

165 **3. Water masses**

166

167 **3.1 Water mass definitions**

168   We consider seven primary water masses that are found in the study region through the

169 course of the year (Fig. 2). Four of these are Pacific-origin waters. As discussed in the

170 introduction, the two Pacific summer waters are Alaskan coastal water (ACW) and Bering

171 summer water (BSW). Following earlier work, we define two classes of Pacific winter water:

172 Newly ventilated winter water (NVWW), which was formed via convective overturning in

173 the winter preceding each survey, and remnant winter water (RWW). The latter product is

174 winter water that has been warmed either by solar heating after the pack ice recedes and/or by

175 mixing with summer waters arriving later in the season (Gong and Pickart, 2016). The three

176 remaining water masses are Atlantic water (AW), which resides seaward of the Chukchi shelf

177 beneath the Pacific layer; meltwater/runoff (MWR), which is found near the surface; and

178 Siberian coastal water (SCW), which is advected southeastward in the Siberian coastal

179 current (Fig. 1). The potential temperature–salinity (T-S) boundaries of the seven water

180 masses are shown in Fig. 2. These should be considered approximate boundaries since there

181 are interannual variations in the water masses (e.g. Pisareva et al., 2015). However, they

182 suffice for our purposes and are consistent with previous studies of the region (e.g. Brugler et

183 al., 2014; Gong and Pickart, 2015; Pisareva et al., 2015).

184 **3.2 Water masses inside Herald Canyon**

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186 The hydrographic observations inside Herald Canyon show a similar pattern between the

187 years for most sections at depths below 25 m, especially in the eastern part of the channel. In

188 general, there is warm, less saline summer water on the eastern side, associated with strong

189 northward velocities (Figs. 3-5). On the western side there is colder and more saline water,

190 with weaker or even southward velocities. This is most obvious at the head of the canyon, but

191 the pattern remains nearly the same farther to the north. The following analysis is based on

192 the above-defined water masses, and in Fig. 6 we use color coding to distinguish the different

193 water types.

194 *Meltwater/runoff*

195

196 The surface layer of MWR can be defined by the 24 kg m^{-3} isopycnal, which resides at

197 approximately 15 m depth (Fig. 6). In 2004 MWR was present at each of the sections in the

198 canyon, although it was freshest at the head. This is a reflection of the final ice melt

199 transitioning to open water in the vicinity of Wrangel Island, which, according to satellite

200 imagery (not shown), took place roughly a week before the survey. By contrast, no MWR
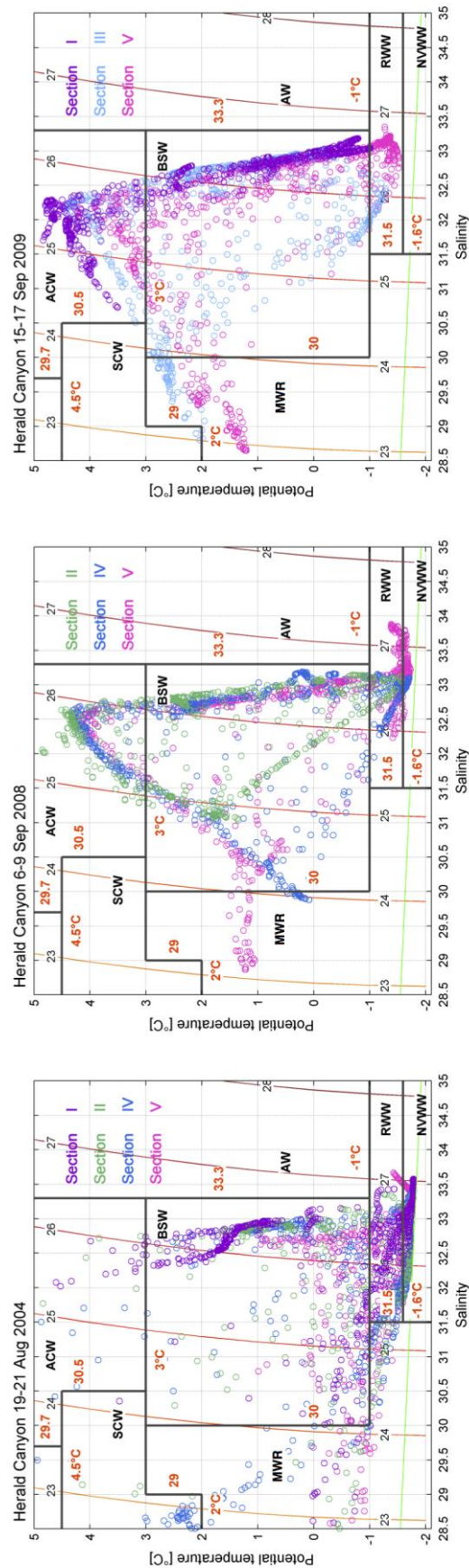
201

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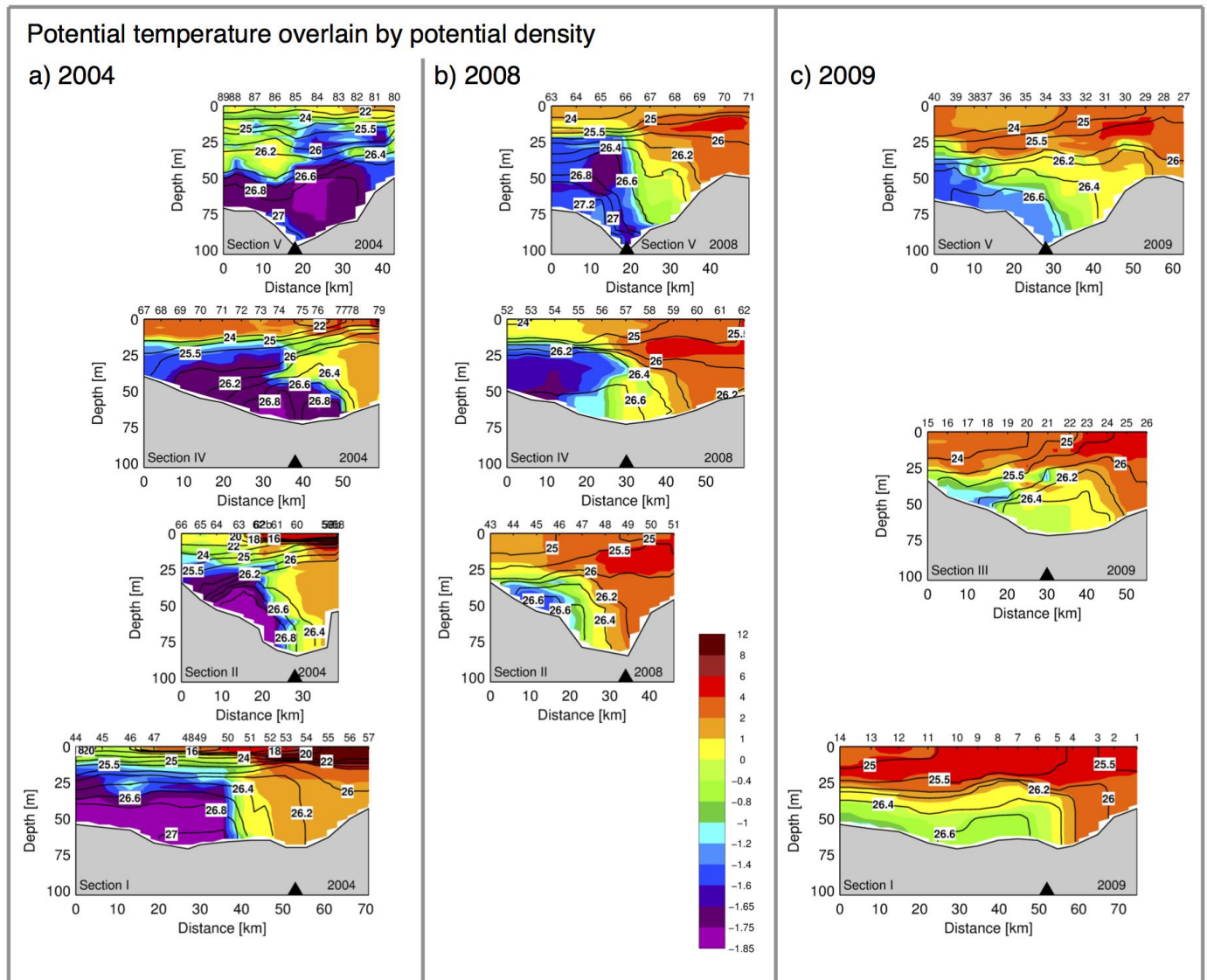
Figure 3: Potential temperature (°C, color) overlain by potential density (contours, kgm^{-3}) for the sections
inside Herald Canyon (I–V). (a) Data from 2004; (b) data from 2008; and (c) data from 2009. For ease of
comparison between the years, the sections are positioned vertically in each column in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

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
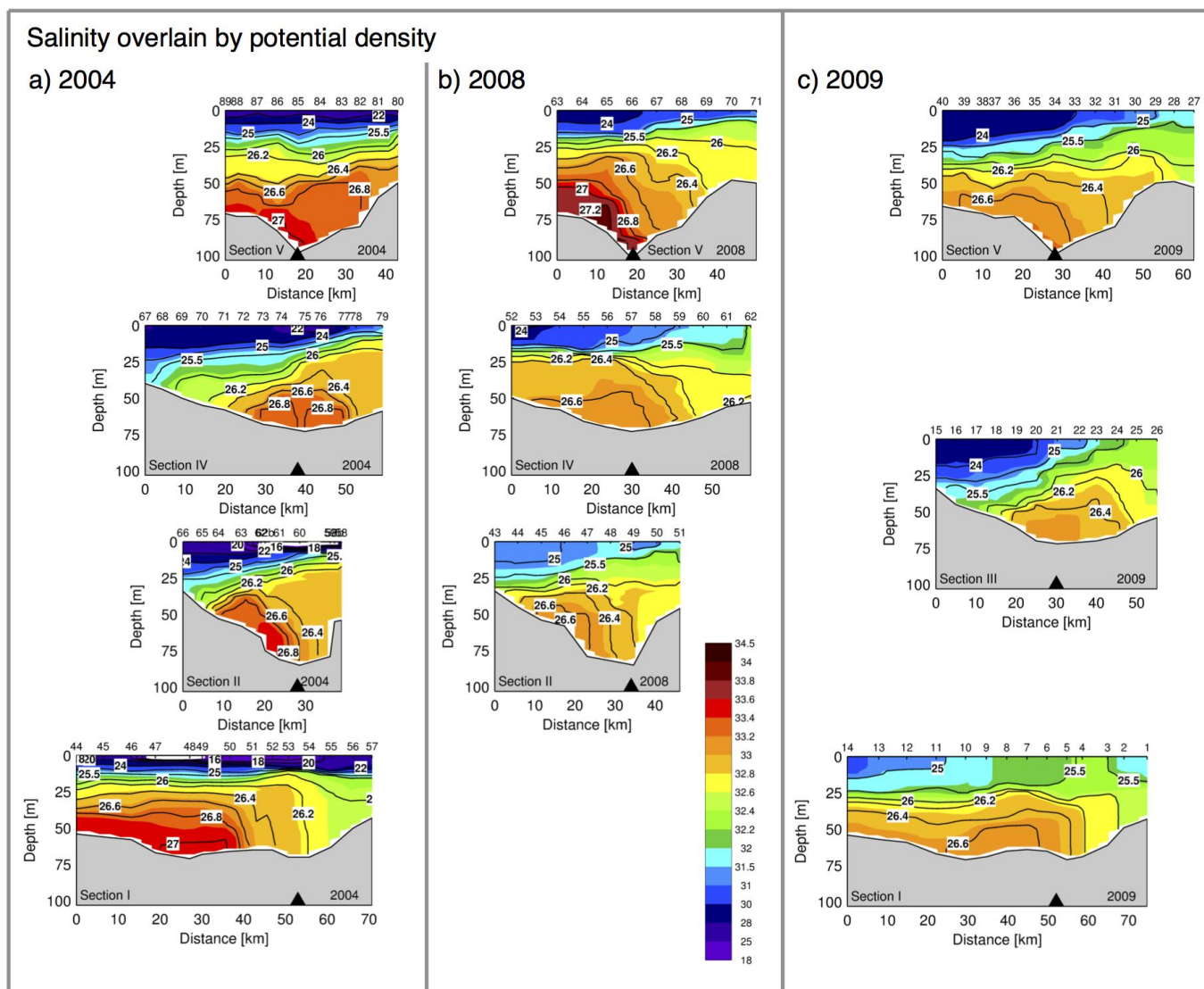season, allowing more time for the MWR to be advected elsewhere.

Figure 4: Same as Figure 3 except for Salinity (color).

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 cms^{-1}). Ship drift data during the 2008 survey, when it was extremely calm and thus no significant wind-induced motion of
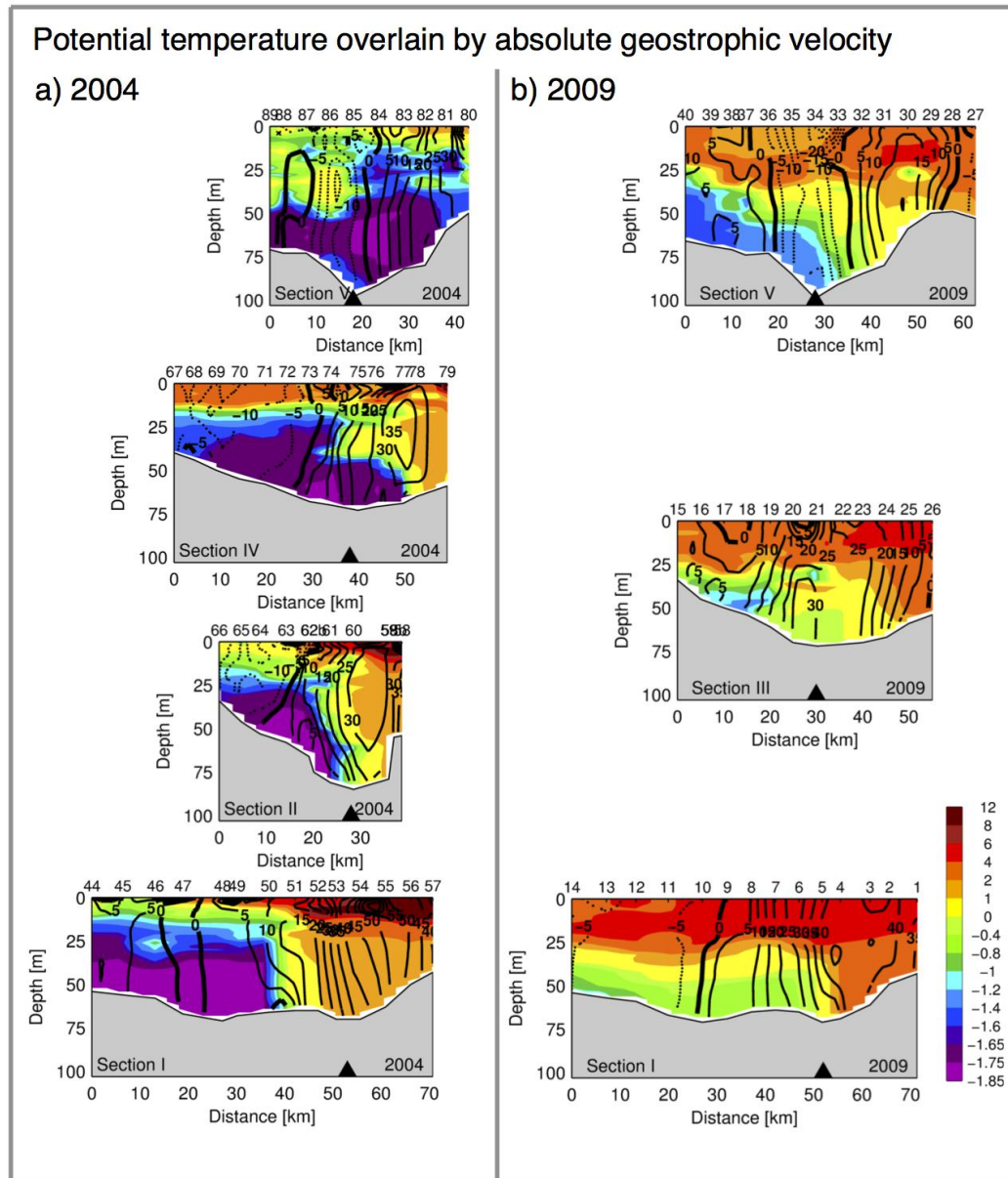
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Figure 5: Potential temperature ($^{\circ}$C, color) overlain by absolute geostrophic velocity (contours, cms^{-1}) for the sections inside Herald Canyon (I–V). (a) Data from 2004, and (b) data from 2009. There were no LADCP data collected in 2008.

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

242   differences. Firstly, there was very little ACW present in the canyon; this is addressed below
243   in section 4.1. Secondly, some SCW was observed, particularly at section IV on the western
244   flank of the canyon. While this may seem surprising, Pisareva et al. (2015) observed SCW all
245   around Wrangel Island in 2009, implying that some of this coastal water can get entrained
246   into the anti-cyclonic flow around the island (Pickart et al., 2010). It is therefore quite
247   possible that a small portion could be diverted into Herald Canyon.
248
249   The third substantial difference between 2004 and the latter two surveys is that BSW
250   was not present on the eastern flank at the northernmost section in 2004. Instead, winter
251   water occupied most of the eastern side. Pickart et al. (2010) offered two explanations for the
252   disappearance of the BSW in 2004: (1) the summer water was partly mixed due to the cross-
253   channel circulation, and (2) the jet was not fully sampled by observations on the eastern
254   flank. Pickart et al. (2010) noted that the topography north of Herald Shoal should divert
255   some of the summer water to the east. However, in 2008 and 2009 summer water was present
256   along the entire eastern flank of the channel, suggesting that the circulation, mixing, and
257   transformation of water that occurs in the canyon can vary substantially from year to year.
258
259   *Winter water*
260
261   The coldest water in all of the sections occupied in Herald Canyon was located on the
262   western side, a pattern that is consistent through the three surveys. However, the distribution
263   and properties of the cold water were more variable than for the summer water on the eastern
264   side. The obvious difference is that there was a large amount of winter water in the canyon
265   2004, significantly less in 2008, and very little (no NVWW at all) in 2009. Interestingly, in
266   2008 and 2009 the amount of winter water increased from south to north in the canyon, and
267   the temperature of the water decreased, neither of which were true in 2004. This is addressed
268   later in the paper in section 4.2. Also, the velocities of the winter water in 2009 were rather
269   weak throughout the canyon, and no clear pattern emerged regarding the transport of this
270   water mass, in contrast to 2004 (Pickart et al., 2010).
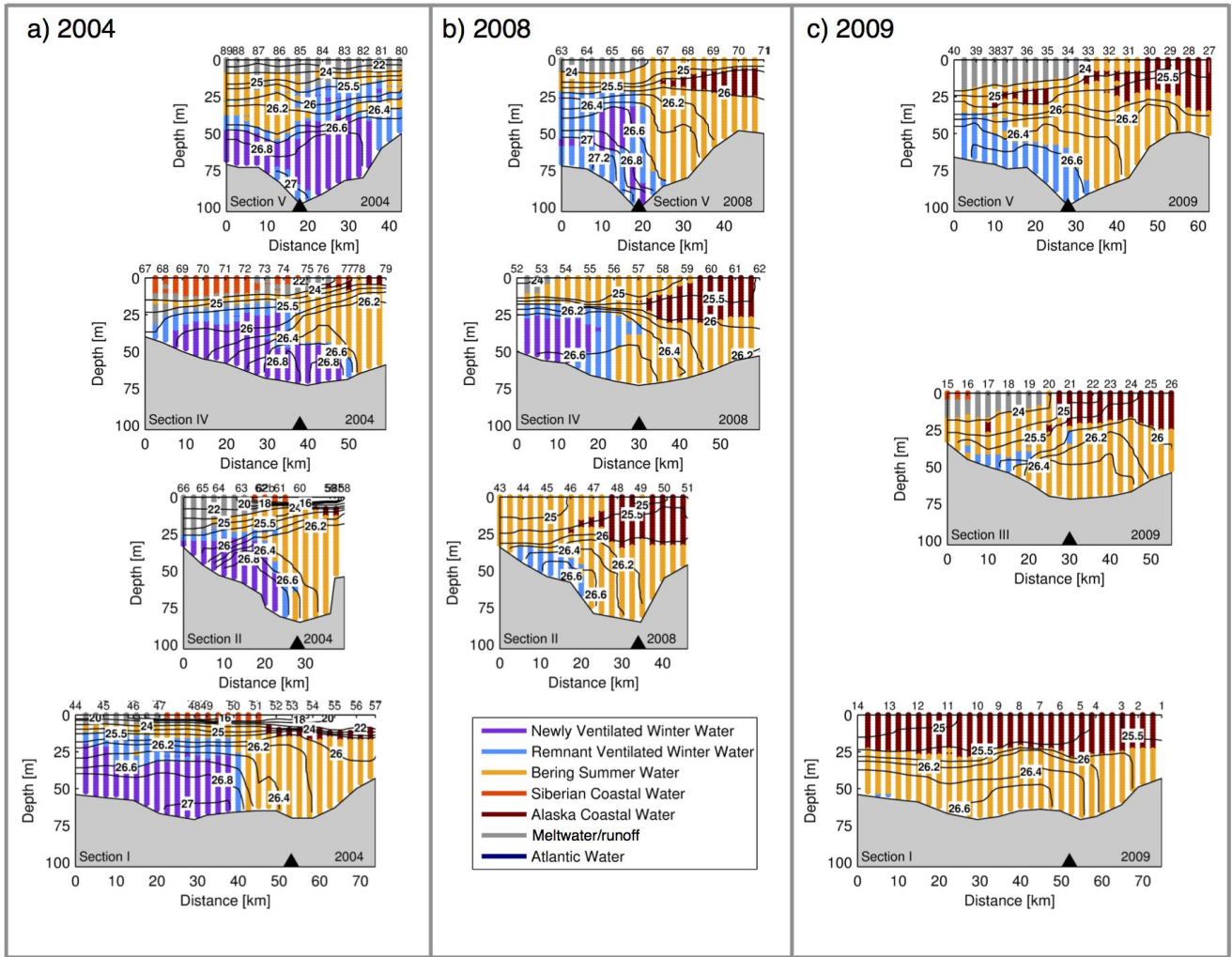271

Figure 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, kgm^{-3}). See Figure 2 for the definitions of the water masses. (a) Data from 2004; (b) data from 2008; and (c) data from 2009.

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.
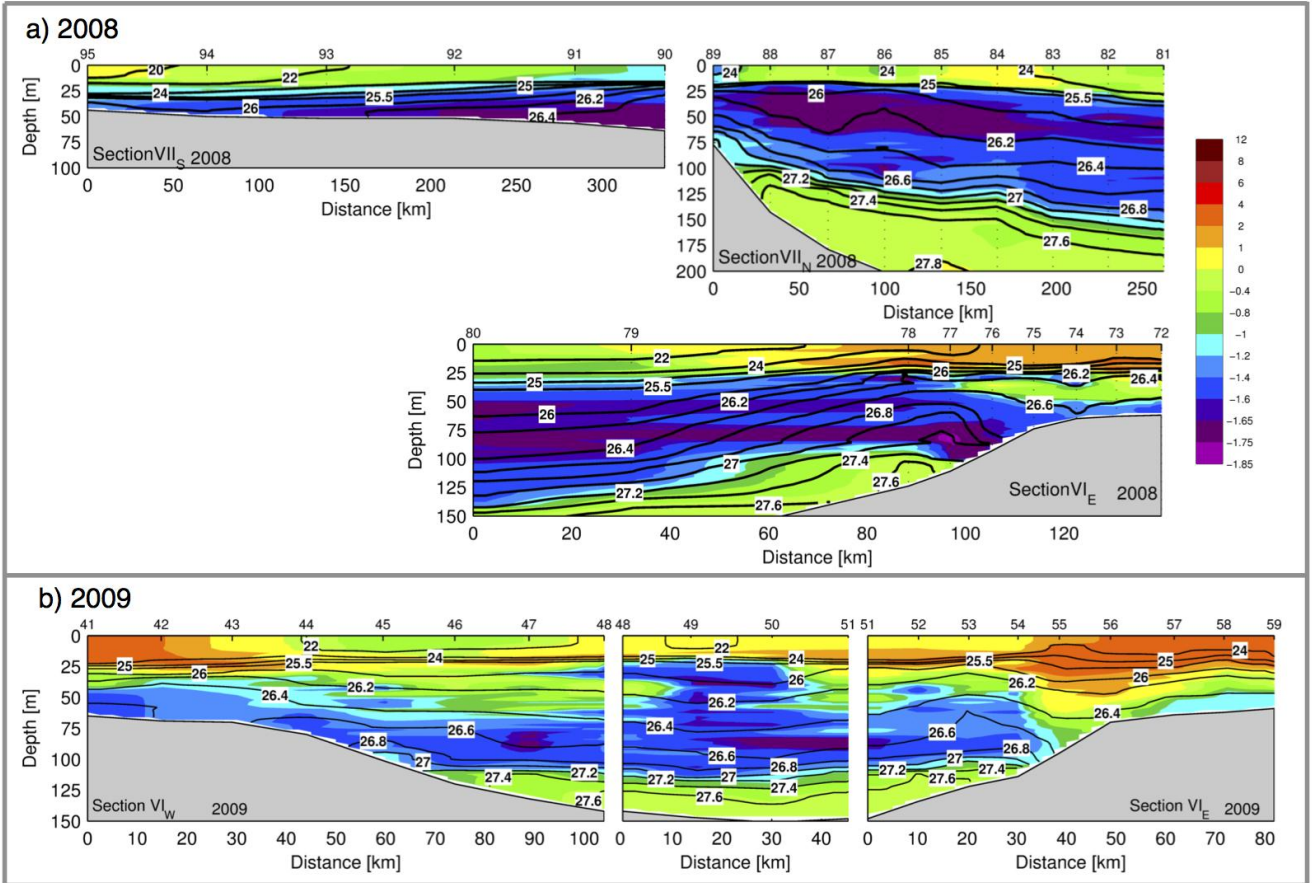
Figure 7: Potential temperature (°C, color) overlain by potential density (contours, kg m⁻³) for the sections

outside of Herald Canyon in (a) 2008 and (b) 2009. See Fig. 1 for locations.

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 Fig. 10b). 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 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

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passing through Herald Canyon in 2009 turned to the right and followed the bathymetry
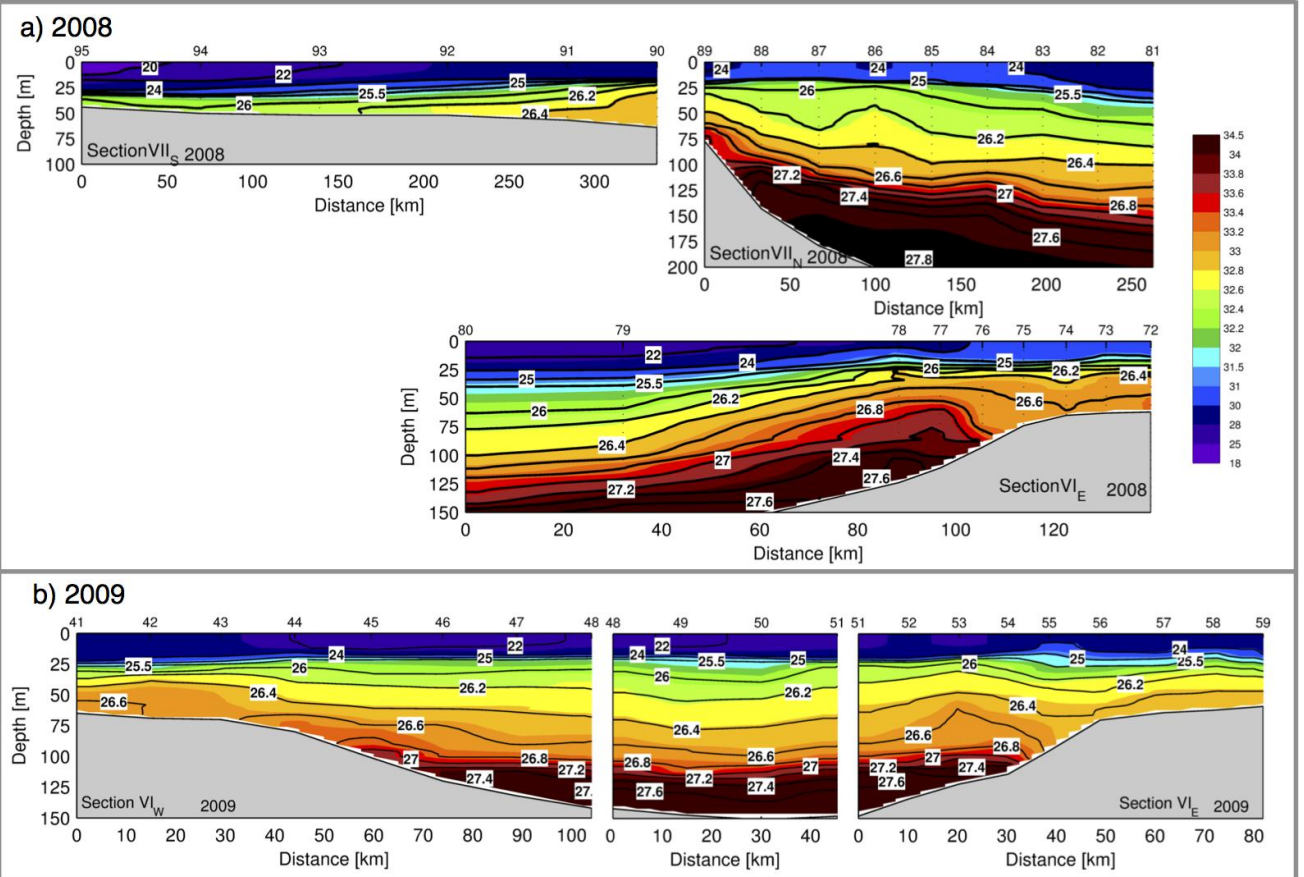
eastward.

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303

Figure 8: Same as Figure 7 except for salinity (color).

306

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).

312

Winter water

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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

318 isopycnal tilt associated with winter water on the continental slope is indicative of a bottom

319 intensified eastward-flowing current. For example, the NVWW that flows eastward in the

320 shelfbreak jet of the Chukchi Sea, as well as the shelfbreak jet of the Beaufort Sea, is

321 associated with such a structure (Corlett and Pickart, 2017; Spall et al., 2008) . This implies

322 that, during the 2008 survey, winter water was approaching Herald Canyon from the west, i.e.

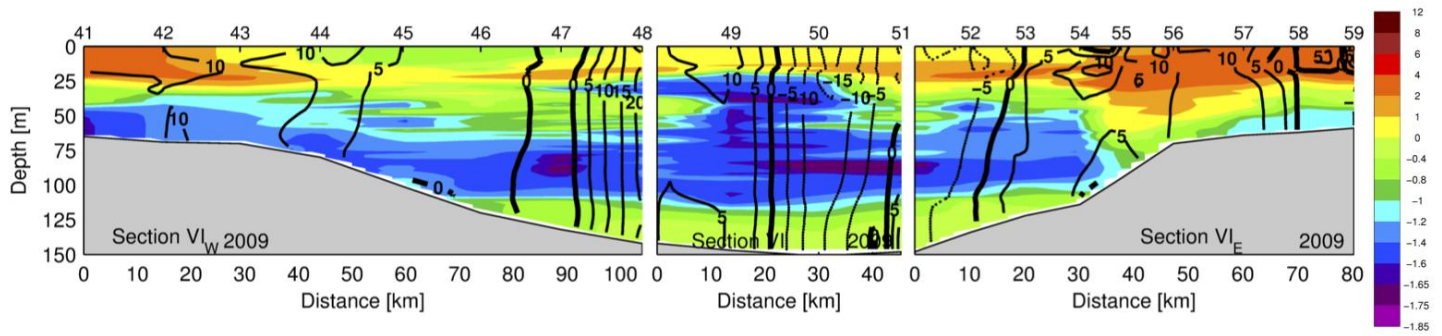323 from the East Siberian Sea. This is discussed later in the paper (Section 4.2). The same

325 **Figure 9:** Potential temperatures (color, $^{\circ}$C) overlain by absolute geostrophic velocity (contours, cms^{-1}) for

326 section VI in 2009. See Figure 1 for the location of the section.

327

328 general pattern (i.e. presence of winter water with a similar isopycnal tilt) was also seen to the

329 east of Herald Canyon in 2008 at section VI$_E$ (bottom panel of Fig. 10a).

330

331　　In 2009 there was much less NVWW present in section VI than the previous year,

332 although RWW was found throughout most the section (Fig. 10b). The velocities are

333 northward on the flanks of VI$_W$ and VI$_E$ (Fig. 9), while the deepest part of the section,

334 between stations 47-52, shows northward flow on the western side and southward flow on the

335 eastern side (Fig. 8). The reason for this is that the central portion of section VI crossed

336 through an anti-cyclonic eddy of winter water situated just outside of the canyon mouth (note

337 the enhanced presence of winter water at stations 48-50 on section VI$_N$ corresponding to the

338 center of the eddy). This was noted as well by Pisareva et al. (2015) and provides evidence

339 that Pacific winter water is fluxed directly into the basin from Herald Canyon via turbulent

340 processes. The fact that the flow is northward on the flank of section VI$_W$ suggests that winter

341 water can at times flow towards the canyon from the East Siberian Sea (consistent with the

342 2008 hydrographic data), or away from the canyon towards the East Siberian Sea (as seen in

343 2009). Further work is necessary to understand the factors dictating this variability.

344

4. Origin of water masses in Herald Canyon

The residence time of Pacific water in the Chukchi Sea is generally less than a year, 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
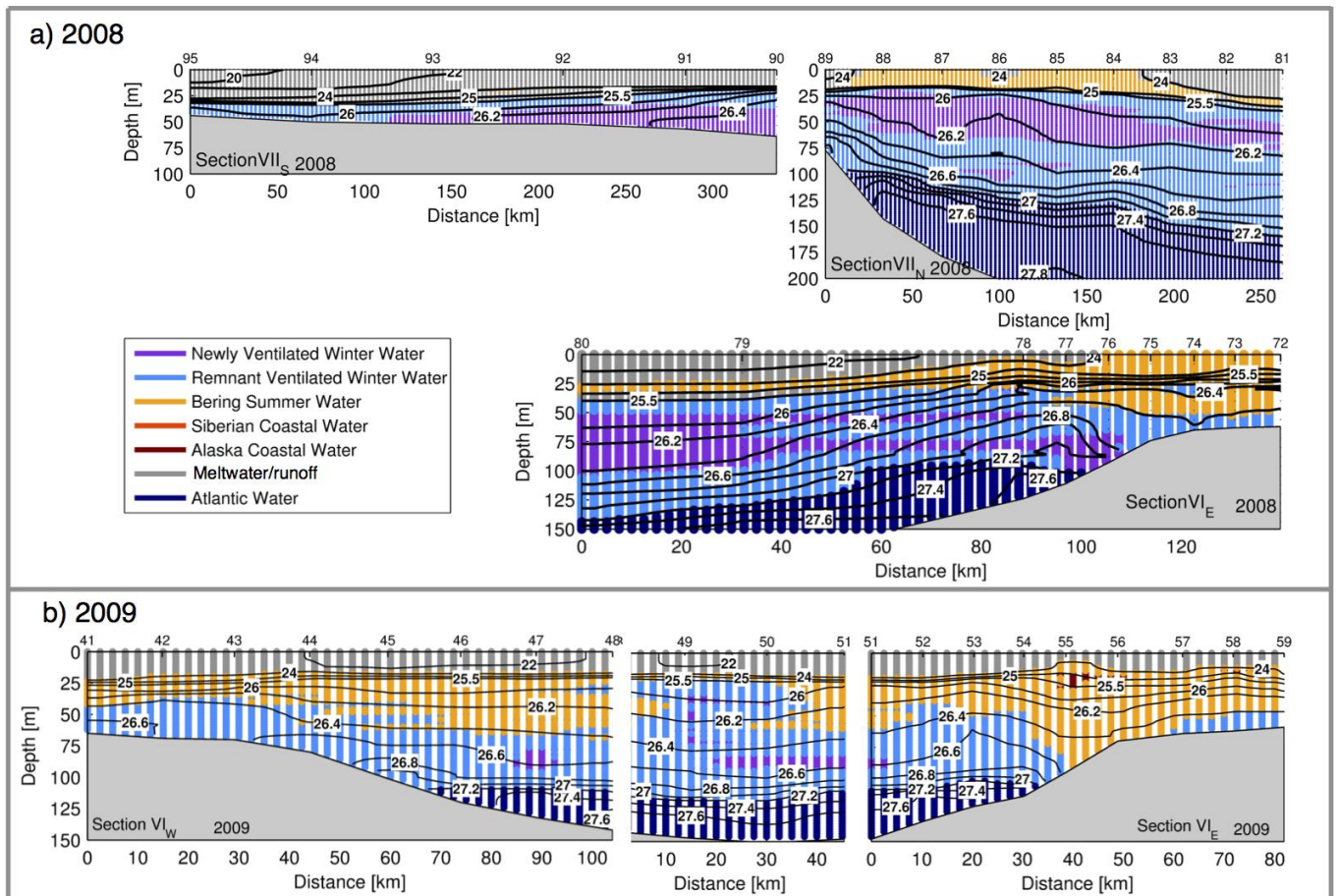

Figure 10: Same as Figure 6 except for the sections outside of Herald Canyon in (a) 2008 and (b) 2009. See Figure 1 for the locations of the sections.

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

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362   salinity, with a moving window of half the width. If more than 17 data points fall within a

363   given T-S interval, then that interval is considered a mode. A composite water mass mode is

364   then simply the locus of the adjacent intervals that meet this criterion. Fig. 11a shows an

365   example of the two mode waters that were present at the head of the canyon in 2004: a

366   summer mode (consisting of BSW), and a winter mode (comprised of NVWW). Fig. 11b

367   shows where these modes are present in geographical space. The winter mode occupied the

368   western part of the canyon deeper than about 20 m, and the summer mode occupied the

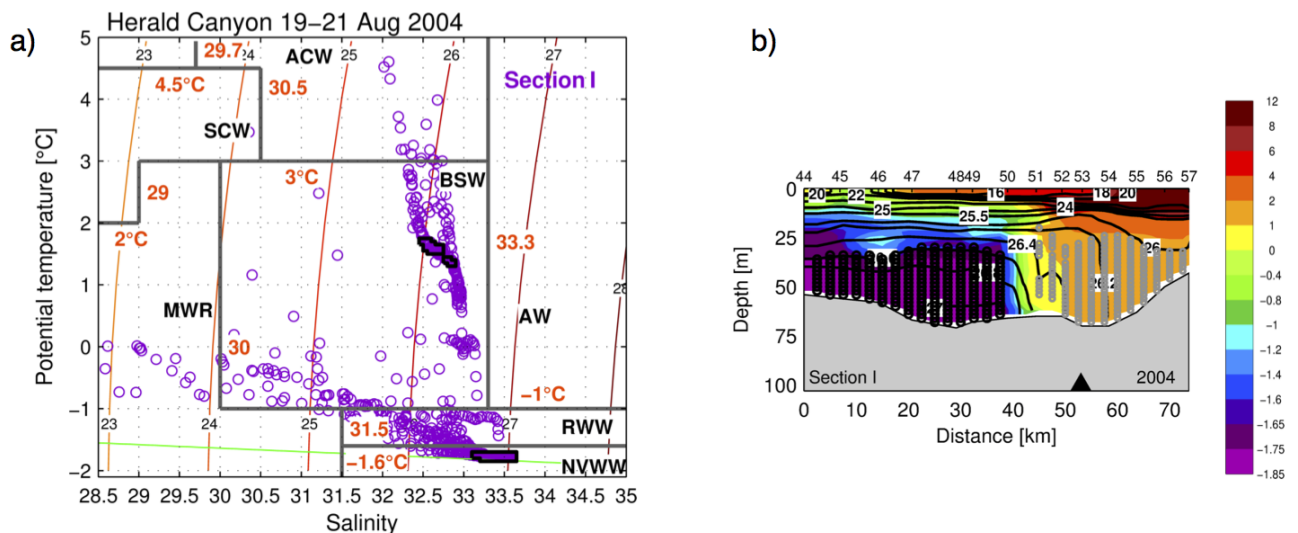369   eastern half.

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371

372 **Figure 11:** Example of water mass modes at the head of Herald Canyon. (a) T-S diagram for the water in Herald

373 Canyon section I in 2004. The two water mass modes are delineated by the thick black lines (see text for how

374 the modes were defined). (b) Potential temperature (color, °C) overlain by potential density (contours, kgm^{-3})

375 for the section in (a). The presence of the two modes is indicated by the gray symbols (the warm mode) and

376 the black symbols (the cold mode).

377

378   The number of moorings in the Bering Strait array has varied from year to year, but

379   until recently there has been little coverage of the western (Russian) side of the strait. The

380   prevailing notion is that the western flow pathway on the Chukchi shelf, which is steered by

381   the bathymetry into Herald Canon, emanates from the western channel in Bering Strait.

382   Fortunately, the RUSALCA program included year-long mooring deployments on the

383   western side of Bering Strait. Here we consider three locations in the strait: the western

384   channel, the eastern channel, and the central/northern portion of the strait. The latter site

385   corresponds to mooring A3, which is located roughly 60 km to the north of the strait in US

386   waters (Fig. 1c). This is one of the long-term moorings that has been in place for the majority

387   of the deployments over the years. Due to the timing of the various mooring deployments, we

388   are unable use the same set of moorings for each of our study years. For example, in 2004 the

389   western channel moorings were deployed shortly before the hydrographic cruise, hence there

390   is no previous time history for that year. Table 1 lists which moorings were used for the

391   different regions in each year. From hereon we discuss the mooring results by region –

392   western, central, and eastern strait – not by mooring names.

393

394   **4.1 Tracking the Summer waters found in Herald Canyon**

395

396   As discussed in Woodgate et al. (2005c), the inflow through Bering Strait has a large

397   seasonal variation in properties, with the coldest and most saline water entering during

398   February-March, followed by warmer, fresher water during the summer. The northward

399   volume transport also varies seasonally, with a minimum of 0.4 Sv in winter and maximum

400   around 1.2 Sv between May and August. The comparison of the summer mode waters

401   observed at the head of Herald canyon with the properties of the inflowing Pacific water

402   through Bering Strait is shown for the three surveys in Fig. 12. We focus primarily on the

403   BSW, as this is the dominant summer water mass in Herald Canyon (and was measured in all

404   three years). In Fig. 12, the Herald Canyon summer T-S modes are indicated by the black

405   polygons (the individual Herald Canyon data points are grey dots), and the Bering Strait data

406   are color-coded according to the elapsed time (in months) since parcels passed through the

407   strait prior to the occupation of the Herald Canyon section. Using the estimated distance from

408   the mooring array to the head of the canyon (along the isobaths), we also indicate the implied

409   advective speed for the different values of elapsed time. As such, we can use Fig. 12 to look

410   for connections between the canyon modes and the water entering the Chukchi Sea through

411   Bering Strait.

412

413   In 2004 (left hand column of Fig. 12) one sees that, not surprisingly, none of the water

414   measured on the eastern side of Bering Strait ended up in Herald Canyon (Fig. 12a). This

415   would have required significant salinization of the water, which is unlikely, plus the mean

416   flow at this location is northeastward towards Barrow Canyon (Woodgate et al., 2005b).

417   However, the mooring in the central part of the strait did measure water with the proper

418   salinity to be the fresher portion of the canyon mode (Fig. 12b), corresponding to a time lag

419   of 1.3–2 months prior to the occupation of the section (dark and medium blue in the figure

420   legend). This implies an advective speed of roughly 18 cm/s, which seems reasonable. The

421   water appears to be about 0.3 °C warmer in Herald Canyon, and an explanation for this

422   temperature difference is that the Pacific water was heated by solar radiation as it crossed the

423   Chukchi Sea during the summer months. A simple calculation of penetrating solar radiation,

424   based on a representative surface heat flux during the summer and a typical attenuation

425   coefficient for this area (0.08 m^{-1}), gives a temperature increase of 0.35–0.8 °C at 30–40 m

426   depth for 2 months. This matches the observed difference quite well. Note that the

427   saltier/colder part of the canyon T-S mode is not captured by the observations from either the

428   central or eastern part of Bering Strait, implying that this water originated from the western

429   side (where there were no observations in 2004).

430

431   In 2008 (middle column of Fig. 12) there was again one BSW mode in Herald Canyon,

432   and, as was the case in 2004, the water flowing through the eastern side of Bering Strait (Fig.

433   12c) was too fresh to be associated with this mode. Furthermore, the water passing through

434   the central strait barely overlapped in salinity on the fresh side of the mode (Fig. 12d).

435   Notably, however, the water from the western strait (Fig. 12e) matches the salinity range of

436   this mode for a wide spread of time lags, 0.7–2 months. The longer lag, which equates to

437   roughly 15 cm/s, seems to be more likely. This is because the water in Bering Strait at that

438   time was around 0.6 °C colder, and the analogous calculation as that done above implies that

439   solar heating can account for this magnitude of increase in temperature.

440

441   In 2009 (right hand column of Fig. 12) there were two clusters of modes: the warm

442   cluster was similar to the dominant mode in 2008, and the cold cluster was distributed in T-S

443   space between -1 and 0 °C, with a salinity interval of ~0.2. As was the case the previous year,

444   the water in the eastern and central portions of strait could explain little to none of the BSW

445   observed at the canyon head. Again, the best match to the canyon modes was for the water

446   passing through the western strait (Fig. 12b), covering a span of time lags of 0.7–3.6 months.

447   In fact, most of the colder canyon mode matches the western Bering Strait data in both

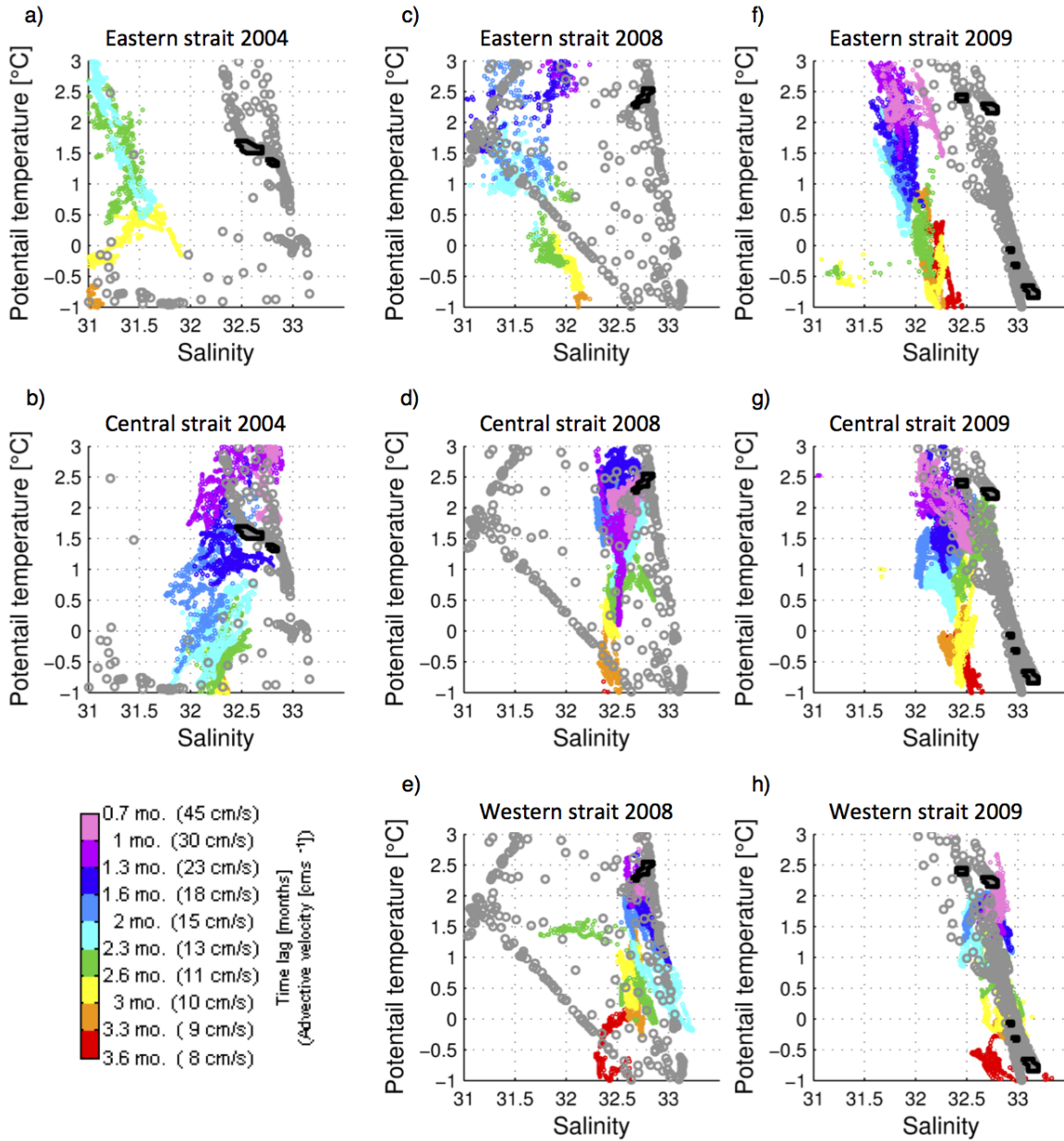448   salinity and temperature.

449

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Figure 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.

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

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464 Bering Strait into Barrow Canyon (e.g. Gong and Pickart, 2015). However, using the full

465 2009 RUSALCA shipboard data set, together with a numerical model, Pisareva et al. (2015)

466 showed that enhanced northeasterly winds in late-summer were substantial enough that the

467 Ekman transport in the vicinity of Bering Strait carried the ACW into the western channel.

468 The model indicated that the spin-down process after the wind abated was slow enough that a

469 substantial amount of ACW was transferred from the coastal pathway near Alaska onto the

470 western shelf and into Herald Canyon. Solar heating of the water during this transit would

471 thus account for our measurements of ACW in the canyon in 2009.

472

473   The 2008 observations suggest that something similar happened that year. In their study

474 of the 2009 RUSALCA data, Pisareva et al. (2015) considered the time integral of the wind

475 stress over a given wind event, which takes into account both the duration and magnitude of

476 the event. The numerical model allowed them to determine a threshold in this quantity, above

477 which the ACW should transpose to the western channel and get transported towards Herald

478 Canyon. Using Pisareva et al.'s (2015) timeseries of the integral of the wind stress in the

479 region of Bering Strait over the time period 2000-2012, we find that a substantial northerly

480 wind event occurred in mid-August 2008 that exceeded this threshold. By contrast, none of

481 the wind events preceding the 2004 cruise did so (when there was no observation of ACW).

482 This offers an explanation for the varying presence of ACW between the years.

483

484   It appears, therefore, that a large amount of the BSW in the western channel of Bering

485 Strait follows a relatively direct route into Herald Canyon during the summer months, with a

486 typical advective speed of 10-20 cm/s. During its transit the water is heated by solar

487 radiation. This result is line with the travel time estimate of 2–3 months based on current

488 meter measurements (Woodgate et al., 2005a) and 1.2 months based on the model results of

489 Spall (2007). Notably, the mooring in the central part of the Bering Strait captures only a

490 small portion of the summer water that enters Herald Canyon.

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4.2 Tracking the Winter waters found in Herald Canyon

Bering Strait Influence

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

507

508   In 2004 (left hand column of Fig. 13) a winter water mode was present in the canyon for the
509   salinity range 33.2–33.7. This matches the salinity of the water passing through the central
510   strait 3.5–5.3 months earlier (Fig.13b), corresponding to an advective speed of 5-8 cm/s. The
511   Bering Strait water is generally about 0.05 °C colder at the mooring than that measured in
512   Herald Canyon. Based on the same calculation applied earlier, but now with the presence of
513   an ice cover – and noting that the winter water is deeper in the water column – we find it is
514   likely that solar heating resulted in this change. This supports the idea of Bering Strait as a
515   direct origin of the winter water in Herald Canyon in 2004, at least for the southern sections.
516   (There is also the possibility that the winter water in the canyon emanated from the western
517   channel of the strait, but this of course cannot be checked because the western mooring was
518   not in the water then.)

519

520   In 2008 (right hand column of Fig. 13) only the warmer RWW and no NVWW was
521   observed at the canyon head (Fig. 6b, section II). Furthermore, the quantity of RWW was not
522   enough to constitute a mode. In contrast to 2004, it is unlikely that any of the winter water at
523   the canyon head in 2008 came from the central strait, due to the large degree of implied
524   warming from the strait to the canyon. In the western strait there is some overlap in both T
525   and S with a time lag of 3.5-3.9 months (approximately 8 cm/s), although the degree of
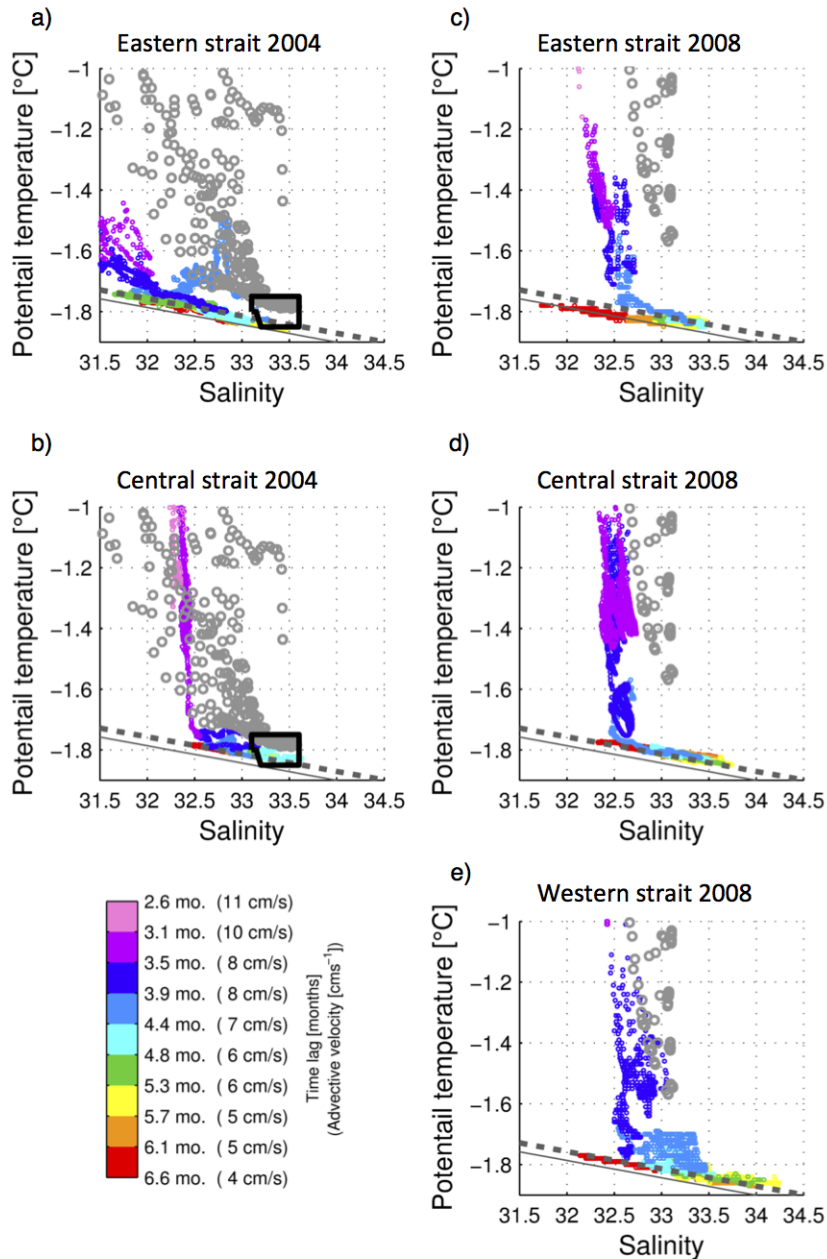526

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

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

538   the 2008 survey was two weeks later in the season, and the survey in 2009 two weeks later

539   still. Using data from a mooring on the eastern flank of Herald Canyon in 1991, Woodgate et

540   al. (2005a) showed that the temperature increased that year from the beginning of August into

541   September. However, the differences in our three surveys cannot be due simply to measuring

542   a direct supply of winter water from Bering Strait to Herald Canyon at different phases of the

543   seasonal cycle.

544

545   As seen above, the connection between the Bering Strait mooring data and the shipboard

546   section at the canyon head is tenuous at best for the 2008 winter water. Furthermore, in both

547   2008 and 2009 the amount of winter water on the western flank increased substantially

548   farther northward in the canyon, and the water became colder as well – suggestive of a

549   southward inflow of winter water from the East Siberian Sea. This, plus the argument

550   presented in Pickart et al. (2010) for polynya-origin water feeding the head of Herald Canyon

551   in 2004, suggests that in order to fully understand the source of the winter water in the

552   canyon we have to consider sources other than Bering Strait.

553

554   *Northern sources of winter water*

555   Using the 2004 RUSALCA shipboard data, together with ice concentration data and a

556   numerical model, Pickart et al. (2010) argued that the winter water feeding Herald Canyon at

557   the time of the survey emanated from the Wrangel Island polynya. In particular, it was

558   suggested that dense water from the polynya (on the northwest side of the island) was

559   advected by the prevailing anti-cyclonic circulation around the island, forming a reservoir of

560   winter water draining into the western side of the canyon head. Progressing northward, the

561   winter water then transposed to the eastern flank of the canyon before exiting the mouth.

562   However, Pickart et al. (2010) also noted that dense winter water was entering the mouth of

563   the canyon on the western side (which presumably recirculated before progressing very far

564   into the canyon). The source of this water remains unknown, although the additional data

565   available in the present study allows us to shed further light on this.

566

25

567   In 2008, NVWW was found at the two northern sections in Herald Canyon (sections IV

568   and V, Fig. 6b). NVWW was also present that year to the west of the canyon (sections VII$_S$

569   and VII$_N$, Fig. 10a), and the geostrophic shear was consistent with NVWW progressing

570   eastward towards the canyon as a bottom-intensified flow. This suggests that part of the

571   dense winter water entering the mouth of the canyon on its western flank in 2008 emanated

572   from a shelfbreak current along the East Siberian Sea. In that case, the source of the water

573   would likely be the East Siberian shelf. Using data from the same 2008 survey, Anderson et

574   al. (2013) argued that ice formation and brine rejection formed winter water on parts of the

575   East Siberian shelf. This dense winter water would subsequently lead to an eastward-flowing

576   buoyancy-driven current at the edge of the shelf (Gawarkiewicz and Chapman, 1995),

577   advecting the water into Herald Canyon. It should be remembered, however, that wind could

578   influence the behavior of such a jet, which is known to be the case for both the Chukchi

579   shelfbreak jet (Corlett and Pickart, 2017) and the Beaufort shelfbreak jet (Pickart et al.,

580   2009).

581

582   It thus appears that input from the Bering Sea, formation of dense water on the East

583   Siberian shelf, large-scale wind patterns in the region, as well as polynya activity in the

584   vicinity of the canyon, all might play a role in the presence of winter water in Herald Canyon

585   during summer. We now consider the latter two factors for the three survey years.

586

587   *Year-to-year differences in polynya activity, ice production, and wind*

588   The Chukchi Sea was more or less fully ice covered at the end of November in the years

589   prior to the 2004 and 2009 surveys, but not until the third week of December prior to the

590   2008 survey. The late freeze-up that year was a likely response to the record low sea ice

591   extent in summer 2007 (Stroeve et al., 2008). Such a delay in the formation of the ice is a

592   circumstance believed to enhance the formation of winter water on the Chukchi shelf (e.g.

593   Weingartner et al., 2005; Woodgate et al. 2005a), but this effect was not obvious in the

594   Herald Canyon data the following summer. The polynya activity later in winter and spring,

595   with corresponding winter water production, is closer in time to the surveys carried out in

596   Herald Canyon and is therefore of interest to analyze further. We focus mainly on the

597   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-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, 1998; Winsor and Chapman, 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.
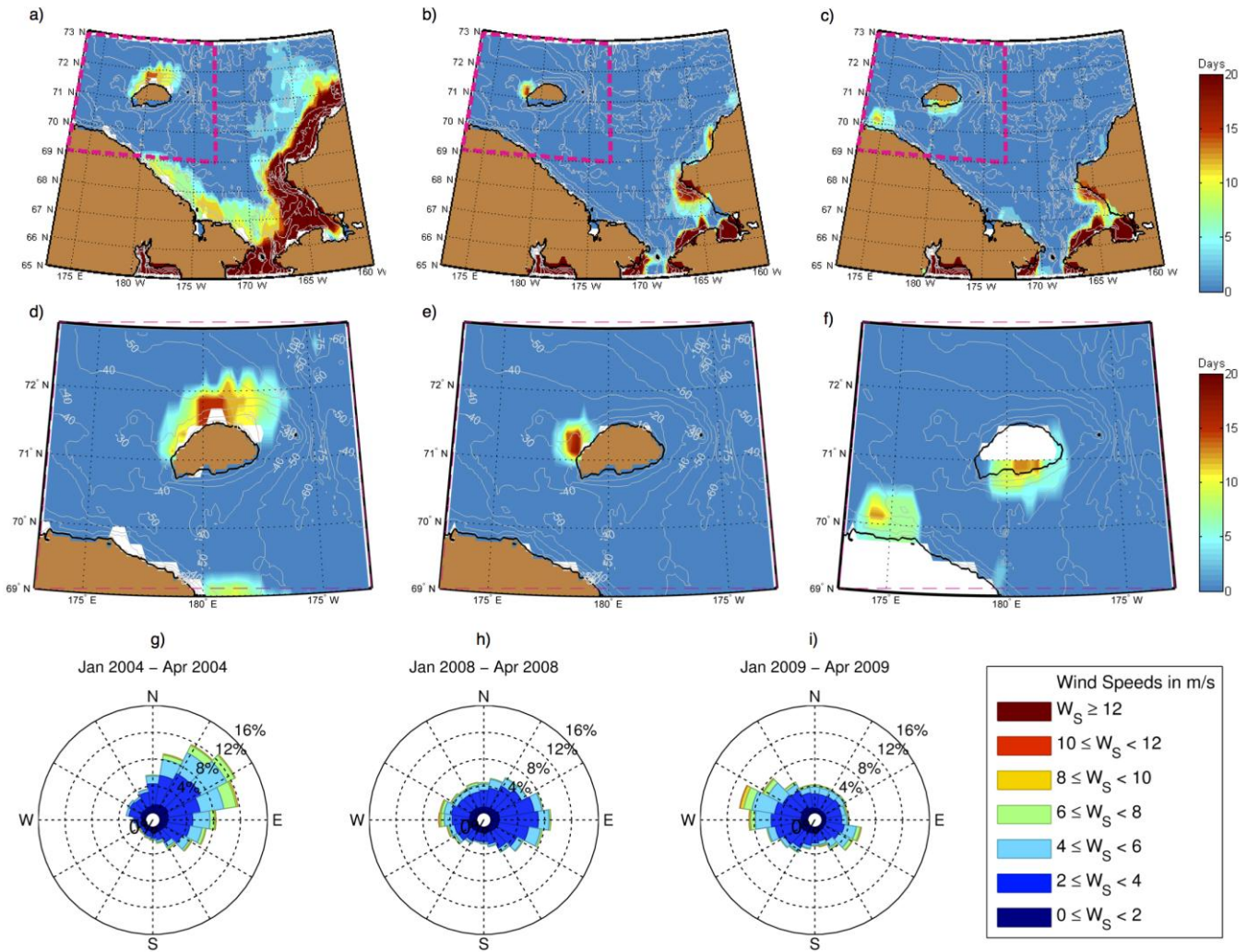
Figure 14: (a-c) Number of days when the ice concentration was less than 80% during the months of January-April for the years preceding each survey. (d-f) Zoomed-in view of the region near Wrangel Island (indicated by the thick dashed line in (a-c)). (g-i) Wind roses showing the average wind speed and direction for the same time periods.

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.
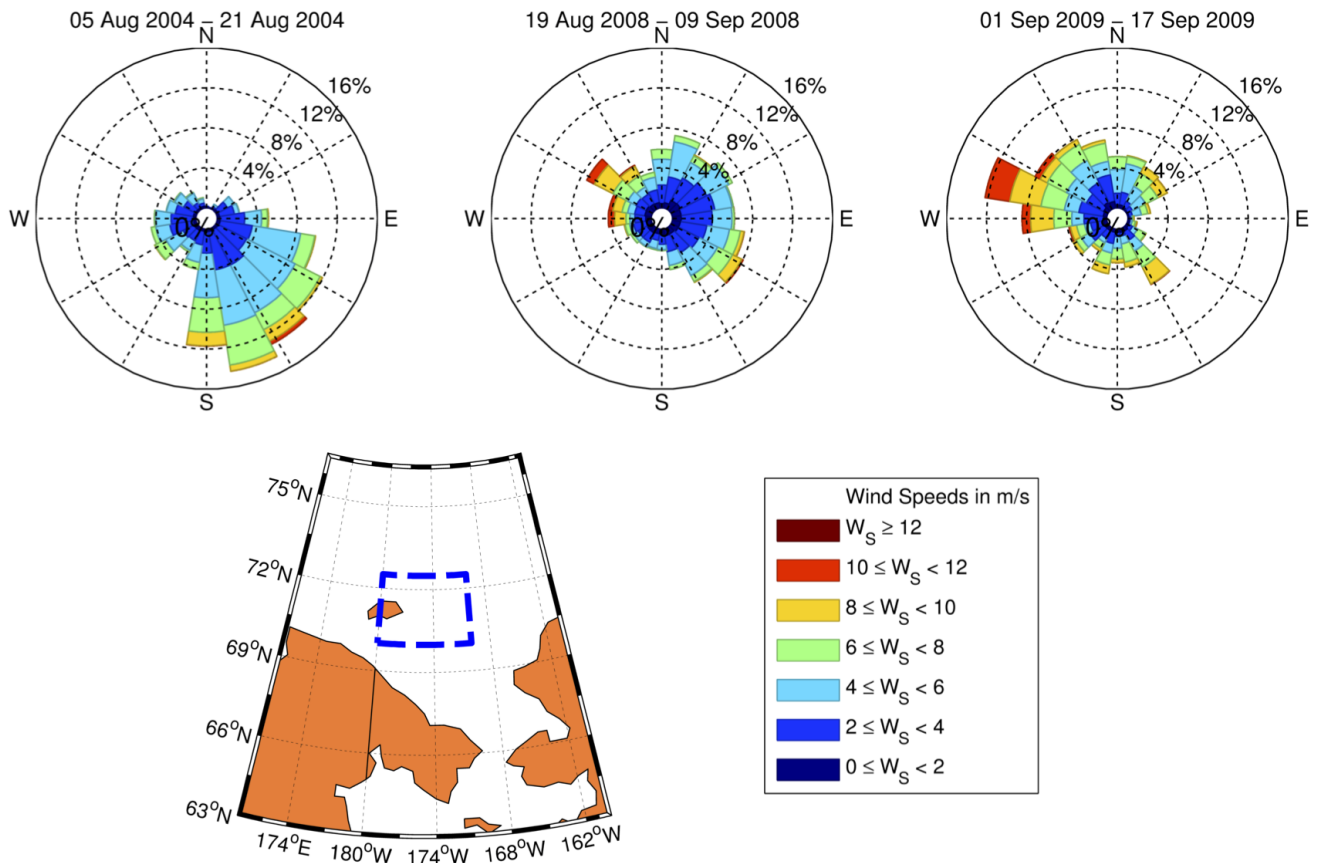
Figure 15: Wind roses showing the average wind direction and speed for the two weeks prior to the surveys for the area surrounding Herald Canyon (indicated by the blue dashed box).

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 in 2009). 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 – consistent with previously reported measurements from the East Siberian Sea.

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. Further work is required to understand the origin of the 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.

Table 1

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

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

References

Aagaard, K., Roach, A.T., 1990. Arctic ocean-shelf exchange: Measurements in Barrow Canyon. J. Geophys. Res. 95, 18,118-163,175.

Brugler, E.T., Pickart, R.S., Moore, G.W.K., Roberts, S., Weingartner, T.J., Statscewich, H., 2014. Seasonal to interannual variability of the Pacific water boundary current in the Beaufort Sea. Prog. Oceanogr. 127, 1–20. doi:10.1016/j.pocean.2014.05.002

713   Coachman, L.K., Aagaard, K., Tripp, R.B., 1975. Bearing {S}trait: {T}he regional physical
714   oceanography. University of Washington Press.

715   Cole, S.T., Timmermans, M.-L., Toole, J.M., Krishfield, R.A., Thwaites, F.T., 2014. Ekman
716   Veering, Internal Waves, and Turbulence Observed under Arctic Sea Ice. J. Phys.
717   Oceanogr. 44, 1306–1328. doi:10.1175/JPO-D-12-0191.1

718   Comiso, J.C., Gordon, A.L., 1996. Cosmonaut polynya in the Southern Ocean: Structure and
719   variability. J. Geophys. Res. 101, 18297–18313. doi:10.1029/96JC01500

720   Corlett, W.B., Pickart, R.S., 2017. The Chukchi Slope Current. Prog. Oceanogr. 153, 50–65.

721   Gawarkiewicz, G., Chapman, D.C., 1995. A numerical study of dense water formation and
722   transport on a shallow, sloping continental shelf. J. Geophys. Res. 100, 4489.
723   doi:10.1029/94JC01742

724   Gong, D., Pickart, R.S., 2016. Early Summer Water Mass Transformation in the Eastern
725   Chukchi Sea. Deep. Res. Part II 130, 43–55. doi:10.1016/j.dsr2.2016.04.015

726   Gong, D., Pickart, R.S., 2015. Summertime circulation in the eastern Chukchi Sea. Deep.
727   Res. Part II Top. Stud. Oceanogr. 118, 18–31. doi:10.1016/j.dsr2.2015.02.006

728   Grebmeier, J.M., 1993. Studies of pelagic-benthic coupling extended onto the Soviet
729   continental shelf in the northern Bering and Chukchi seas. Cont. Shelf Res. 13, 653–668.
730   doi:10.1016/0278-4343(93)90098-I

731   Hill, V., Cota, G., Stockwell, D., 2005. Spring and summer phytoplankton communities in
732   the {C}hukchi and Eastern {B}eaufort {S}eas. Deep Sea Res. II 52, 3369–3385.

733   Itoh, M., Shimada, K., Kamoshida, T., McLaughlin, F., Carmack, E., Nishino, S., 2012.
734   Interannual variability of Pacific Winter Water inflow through Barrow Canyon from
735   2000 to 2006. J. Oceanogr. 68, 575–592. doi:10.1007/s10872-012-0120-1

736   Mathis, J.T., Pickart, R.S., Hansell, D.A., Kadko, D., Bates, N.R., 2007. Eddy transport of

737   organic carbon and nutrients from the {C}hukchi shelf into the deep {A}rctic basin. J.

738   Geophys. Res. 112, 10.1029/2006JC00389.

739   Pacini, A., Pickart, R.S., Moore, G.W.K., Bahr, F., Vage, K., Arrigo, K.R., n.d.

740   Characteristics and transformation of Pacific winter water on the Chukchi Sea shelf in

741   late-spring. Deep Sea Res. II. http://rpickart.whoi.edu/wp-

742   content/uploads/sites/53/2017/03/DSR2_2017_17_Original_V0.pdf

743   Panteleev, G., Nechaev, D.A., Proshutinsky, A., Woodgate, R., Zhang, J., 2010.

744   Reconstruction and analysis of the Chukchi Sea circulation in 1990-1991. J. Geophys.

745   Res. Ocean. 115, 1–22. doi:10.1029/2009JC005453

746   Pickart, R.S., Moore, G.W.K., Mao, C., Bahr, F., Nobre, C., Weingartner, T.J., 2016.

747   Circulation of winter water on the Chukchi shelf in early Summer. Deep. Res. Part II

748   Top. Stud. Oceanogr. 130, 56–75. doi:10.1016/j.dsr2.2016.05.001

749   Pickart, R.S., Moore, G.W.K., Torres, D.J., Fratantoni, P.S., Goldsmith, R.A., Yang, J., 2009.

750   Upwelling on the continental slope of the {A}laskan {B}eaufort {S}ea: {S}torms, ice,

751   and oceanographic response. J. Geophys. Res. 114, C00A13,

752   doi:10.1029/2208JC005009. doi:10.1029/2208JC005009

753   Pickart, R.S., Pratt, L.J., Torres, D.J., Whitledge, T.E., Proshutinsky, A.Y., Aagaard, K.,

754   Agnew, T.A., Moore, G.W.K., Dail, H.J., 2010. Evolution and dynamics of the flow

755   through {H}erald {C}anyon in the Western {C}hukchi {S}ea. Deep Sea Res. II 57, 5–

756   26.

757   Pisareva, M.N., Pickart, R.S., Spall, M.A., Nobre, C., Torres, D.J., Moore, G.W.K.,

758   Whitledge, T.E., 2015. Flow of pacific water in the western Chukchi Sea: Results from

759   the 2009 RUSALCA expedition. Deep. Res. Part I Oceanogr. Res. Pap. 105, 53–73.

760   doi:10.1016/j.dsr.2015.08.011

761   Spall, M.A., 2007. Circulation and water mass transformation in a model of the Chukchi Sea.
762   J. Geophys. Res. Ocean. 112, 1–18. doi:10.1029/2005JC003364

763   Spall, M.A., Pickart, R.S., Fratantoni, P.S., Plueddemann, A.J., 2008. Western Arctic
764   Shelfbreak Eddies: Formation and transport. J. Phys. Oceanogr. 38, 1644–1668.

765   Steele, M., Morison, J., Ermold, W., Rigor, I., Ortmeyer, M., 2004. Circulation of summer
766   Pacific halocline water in the Arctic Ocean. J. Geophys. Res. 109, 1–18.
767   doi:10.1029/2003JC002009

768   Timmermans, M.L., Proshutinsky, A., Golubeva, E., Jackson, J.M., Krishfield, R., McCall,
769   M., Platov, G., Toole, J., Williams, W., Kikuchi, T., Nishino, S., 2014. Mechanisms of
770   Pacific Summer Water variability in the Arctic's Central Canada Basin. J. Geophys. Res.
771   C Ocean. 119, 7523–7548. doi:10.1002/2014JC010273

772   Weingartner, T., Aagaard, K., Woodgate, R., Danielson, S., Sasaki, Y., Cavalieri, D., 2005.
773   Circulation on the north central Chukchi Sea shelf. Deep. Res. II 52, 3150–3174.
774   doi:10.1016/j.dsr2.2005.10.015

775   Weingartner, T.J., Cavalieri, D.J., Aagaard, K., Sasaki, Y., 1998. Circulation, dense water
776   formation, and outflow on the northeast Chukchi shelf. J. Geophys. Res. 103, 7647–
777   7661.

778   Weingartner, T.J., Danielson, S., Sasaki, Y., Pavlov, V., Kulakov, M., 1999. The Siberian
779   Coastal Current: A wind- and buoyancy-forced Arctic coastal current. J. Geophys. Res.
780   104, 29697. doi:10.1029/1999JC900161

781   Winsor, P., 2004. Pathways of Pacific water across the Chukchi Sea: A numerical model
782   study. J. Geophys. Res. 109, 1–16. doi:10.1029/2003JC001962

783   Woodgate, R.A., Aagaard, K., Swift, J.H., Falkner, K.K., W. M. Smethie, J., 2005a. Pacific
784   ventilation of the {A}rctic {O}cean's lower halocline by upwelling and diapycnal

785   mixing over the continental margin. Geophys. Res. Lett. 32, L18609,

786   doi:10.1029/2005GL023999.

787   Woodgate, R.A., Aagaard, K., Weingartner, T.J., 2005b. A year in the physical oceanography

788   of the {C}hukchi {S}ea: {M}oored measurements from autumn 1990-1991. Deep Sea

789   Res. II 52, 3116–3149.

790   Woodgate, R.A., Aagaard, K., Weingartner, T.J., 2005. A year in the physical oceanography

791   of the Chukchi Sea: Moored measurements from autumn 1990-1991. Deep. Res. Part II

792   Top. Stud. Oceanogr. 52, 3116–3149. doi:10.1016/j.dsr2.2005.10.016

793   Woodgate, R.A., Aagaard, K., Weingartner, T.J., 2005c. Monthly temperature, salinity, and

794   transport variability of the {B}ering {S}trait throughflow. Geophys. Res. Lett. 32,

795   L04601, doi:10.1029/2004GL021880.

796   Woodgate, R.A., Weingartner, T.J., Lindsay, R., 2012. Observed increases in Bering Strait

797   oceanic fluxes from the Pacific to the Arctic from 2001 to 2011 and their impacts on the

798   Arctic Ocean water column. Geophys. Res. Lett. 39, 2–7. doi:10.1029/2012GL054092

799