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Outflow of Pacific water from the Chukchi Sea to the Arctic Ocean

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Abstract Pacific water exits the Chukchi Sea shelf through Barrow Canyon in the east and Herald Canyon in the west, forming an eastward-directed shelfbreak boundary current that flows into the Beaufort Sea. Here we summarize the transformation that the Pacific water undergoes in the two canyons, and describe the characteristics and variability of the resulting shelfbreak jet, using recently collected summertime hydrographic data and a year-long mooring data set. In both canyons the northward-flowing Pacific winter water switches from the western to the eastern flank of the canyon, interacting with the northward-flowing summer water. In Barrow canyon the vorticity structure of the current is altered, while in Herald canyon a new water mass mode is created. In both instances hydraulic effects are believed to be partly responsible for the observed changes. The shelfbreak jet that forms from the canyon outflows has distinct seasonal configurations, from a bottom-intensified flow carrying cold, dense Pacific water in spring, to a surface-intensified current advecting warm, buoyant water in summer. The current also varies significantly on short timescales, from less than a day to a week. In fall and winter much of this mesoscale variability is driven by storm events, whose easterly winds reverse the current and cause upwelling. Different types of eddies are spawned from the current, which are characterized here using hydrographic and satellite data.

Key words Chukchi Sea, Arctic Ocean, outflow of Pacific water.

1 Introduction

Pacific Water crosses the wide and shallow Chukchi Sea as it flows northward from Bering Strait towards the Arctic interior. Numerical models and observations suggest that the flow occurs in distinct branches, steered to a large degree by the topography of the shelf (Fig 1)[1-3]. Much of the outflow to the Arctic occurs through the two canyons that cut into the edge of the shelf: Barrow Canyon in the east, and Herald Canyon in the west. Recent observations have revealed that the Pacific water undergoes substantial changes within the two canyons, directly impacting the properties and ultimate fate of the water as it enters the Arctic Ocean[4-6].

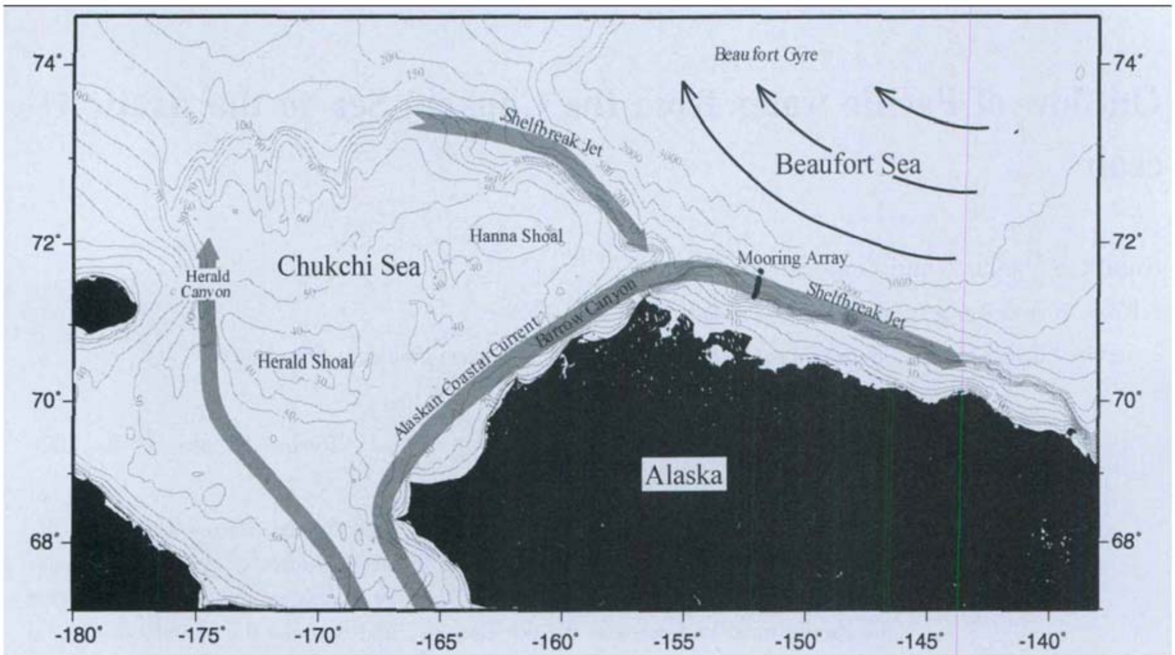

Fig. 1 Schematic circulation of the Chukchi and Beaufort Seas (after Spall *et al.* 2008[7]). Included is the location of the mooring array that measured the shelfbreak current north of Alaska. On average the boundary current flows to the east, but under easterly, upwelling winds the flow reverses to the west.

Numerical models imply that, upon exiting Herald and Barrow canyons, the majority of the Pacific water turns eastward as a boundary current following topographic contours, provided that the wind forcing is weak[3,8]. Indeed, observations show the existence of such an eastward-flowing boundary current, under light winds, situated near the shelfbreak of the Chukchi and Beaufort Seas[9-11]. However, the boundary current is highly variable: it changes seasonally in response to the outflowing currents and water masses from the Chukchi Sea; it is sensitive to local and remote winds[11,12]; and it is baroclinically unstable, readily forming eddies that propagate into the interior Canada Basin[7].

In this note we compare the structure and dynamics of the flow through the two Chukchi Sea canyons, focusing on the ramifications for the establishment of the shelfbreak jet along the boundary of the Chukchi and Beaufort Seas. The nature of the shelfbreak jet downstream (to the east) of Barrow Canyon is then discussed, highlighting its variable nature. Finally, the different classes of Pacific water eddies spawned from the shelfbreak current are summarized.

2 Observations

Two synoptic hydrographic/velocity surveys were recently carried out to investigate the outflow of Pacific water from Barrow and Herald canyons, respectively. In August 2002, as part of the Western Arctic Shelf-Basin Interactions (SBI) program, two high-resolution vertical sections were occupied by the USGCG *Polar Star*; one at the head of the canyon, and a second near the mouth (Fig 2a). In August 2004, as part of the Russian-American Long Term Census of the Arctic (RUSALCA) program, four vertical sections were occupied by the R/V *Khromov* across Herald Canyon (Fig 3a). In both surveys the lateral station spacing of the conductivity/temperature/depth (CTD) casts was on the order of 5 km, which is less than the Rossby radius of deformation at these latitudes (8-10 km). Hence, the dynamical features of interest were resolved in both cases. Furthermore, direct velocity measurements enabled the computation of absolute geostrophic velocity sections. For a detailed description of these two surveys, including measurement accuracies, the reader is referred to Pickart *et al.* (2005) and Pickart *et al.* (2009)[5,6]. Here we compare and contrast the basic features of the two canyon outflows.

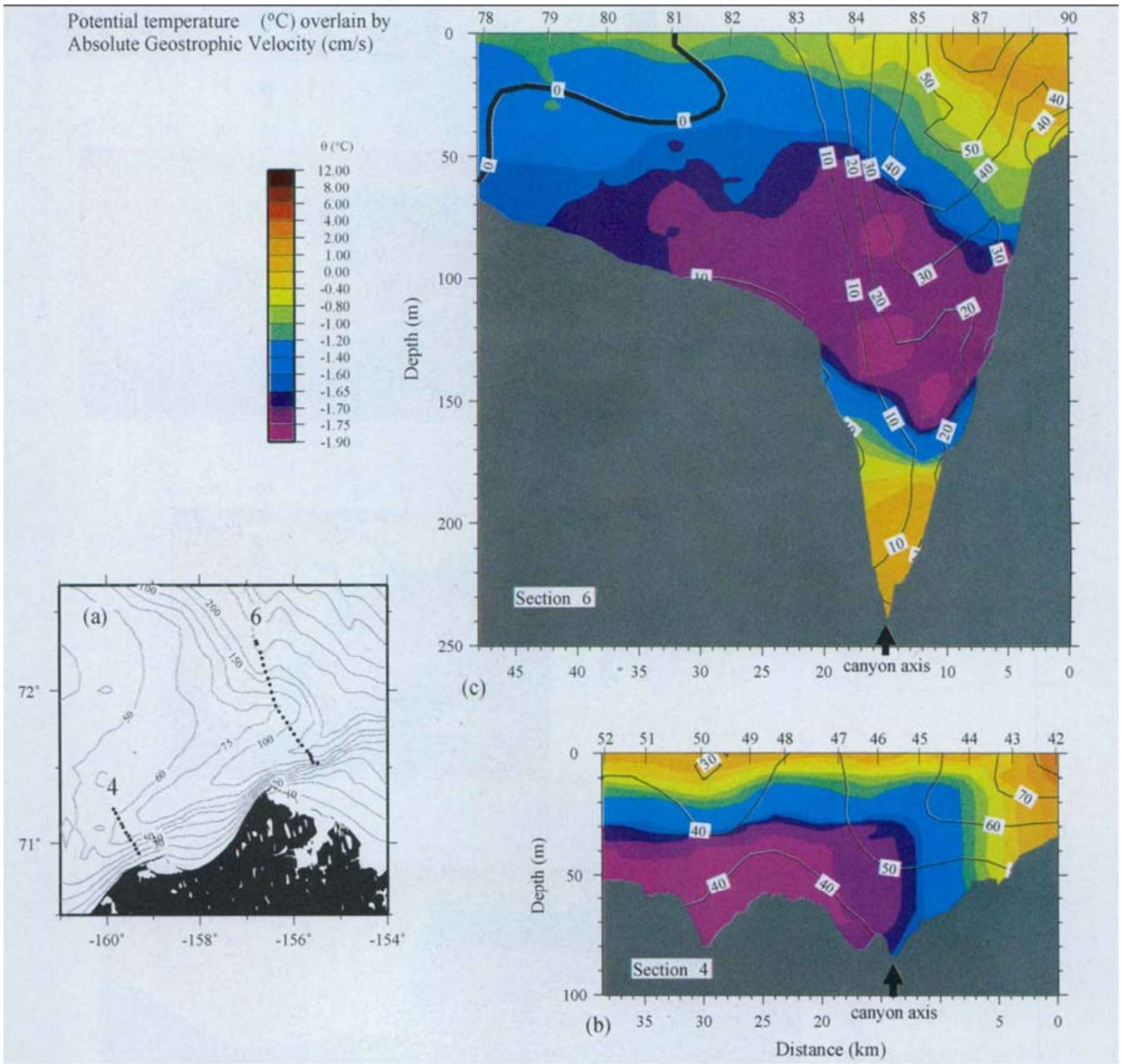

Fig. 2 Evolution of the water masses and flow field from south to north in Barrow Canyon, after Pickart *et al.* (2005)[5]. The vertical sections are oriented such that the viewer is looking northeast, and the sections are positioned so that the center of the canyon is aligned (as indicated by the arrows). (a) Locations of the two transects. (b)-(c) Potential temperature (color, ℃) overlain by absolute geostrophic velocity (contours, cm/s, where positive denotes northeastward flow). Station numbers are indicated along the top.

As part of the SBI program, a two-year mooring array was maintained across the shelfbreak current approximately 150 km east of Barrow Canyon (Fig 1). This location was chosen in order to measure the combined outflow from Herald and Barrow canyons. The array

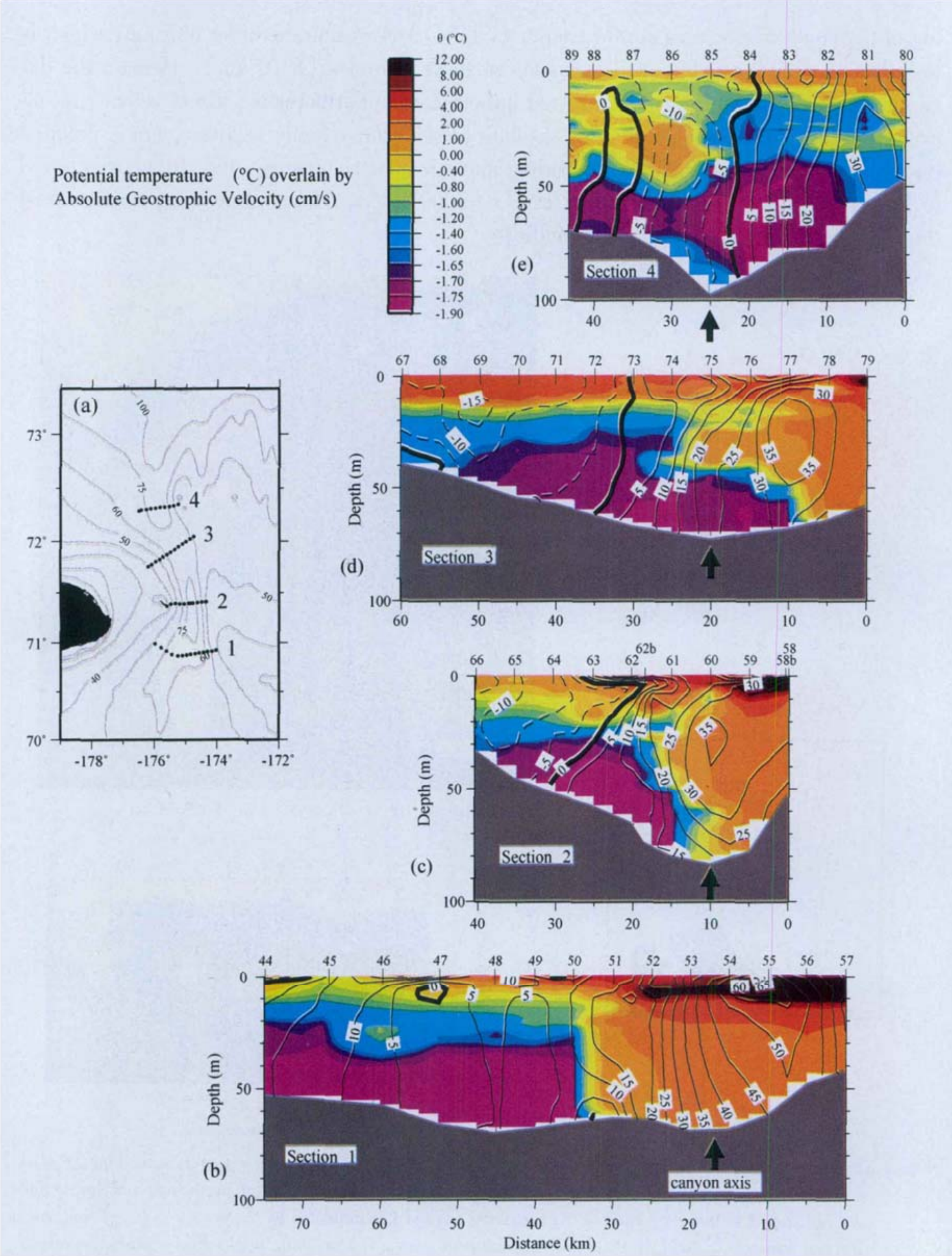

Fig. 3 Evolution of the water masses and flow field from south to north in Herald Canyon, from Pickart *et al.* (2009). The vertical sections are oriented such that the viewer is looking north, and the sections are positioned so that the center of the canyon is aligned (as indicated by the arrows). (a) Locations of the four transects. (b)-(e) Potential temperature (color, ℃) overlain by absolute geostrophic velocity (contours, cm/s, where positive denotes northward flow). Station numbers are indicated along the top.

contained 8 moorings between the outer shelf (50 m isobath) and the base of the continental slope (1400 m isobath). The subset of moorings bracketing the Pacific water boundary current contained moored CTD profilers (sampling from 50 m depth to the bottom) and upward-facing acoustic Doppler current profilers (ADCPs) at the bases of the moorings. This configuration of instruments provided multiple CTD and velocity vertical sections per day. Details of the array and results from the first-year's deployment are presented in Spall *et al.* (2008) and Nikolopoulos *et al.* (2009) [7,11]. Here we summarize the basic features of the boundary current, highlighting its different seasonal and synoptic states. The SBI program also included numerous shelf-slope CTD sections across the edge of Chukchi and Beaufort seas. Some of these sections are used to characterize the Pacific water eddies spawned from the boundary current.

3 Canyon Outflows

3.1 Barrow Canyon

In late-summer/early-fall the flow of Pacific Water entering Barrow Canyon from the south often consists of the warm, buoyant Alaskan Coastal Current on the eastern flank of the canyon, alongside northward flow of cold, dense winter water (formed during the previous winter) on the western flank. This was the case during the summer 2002 hydrographic survey (Fig 2b). As the dense layer flowed from the head of the canyon to its mouth, it switched sides of the canyon, sank, decelerated, and stretched (Fig 2c). As discussed by Pickart *et al.* (2005)[5], strong cyclonic relative vorticity was generated on the seaward side of the jet which compensated for the stretching. This adjustment was incomplete, however, in that it did not extend across the entire current, possibly because of internal mixing due to shear instabilities. There is evidence that hydraulic control was active in the canyon, based on an analysis of the dynamical modes of the water column in the canyon. The resulting vorticity structure of the dense water outflow at the canyon mouth was conducive for baroclinic instability and eddy formation, which has ramifications for the flux of winter water into the Arctic interior. For further details of the dynamics of the flow through Barrow Canyon based on the summer 2002 hydrographic survey, the reader is referred to Pickart *et al.* (2005)[5].

3.2 Herald Canyon

The characteristics of the flow through Herald Canyon in the summer of 2004 were similar in some respects to those observed in Barrow Canyon two years earlier. On the eastern flank of the canyon a jet of warm Chukchi Summer Water (Coachman *et al.* 1975) [13] flowed northward, alongside a weaker poleward flow of winter water on the western flank. As the dense water progressed northward it too switched to the eastern side of the canyon before reaching the mouth, interacting with the summer water jet (Fig 3). As was true in Barrow Canyon, there is evidence that hydraulic control was active in Herald Canyon at the time of the survey. Possibly because of this, significant mixing took place near the canyon mouth, creating a new water mass mode exiting the canyon. There was also evidence of bottom boundary layer detachment associated with the summer water jet, likely pumping warm water towards the western side of the canyon. This may also have played a role in the mixing. Pickart *et al.* (2009)[6] present a detailed examination of the summer 2004 Herald Canyon hydrographic/velocity survey.

3. 3 Ramifications for outflow to the Arctic

One of the main conclusions from the two canyon surveys is that the draining of winter water from the Chukchi shelf in summer involves the interaction of the dense layer with the northward flow of warm water emanating from Bering Strait. Furthermore, evidence suggests that hydraulic control is active in both canyons, impacting the path and mixing of the water as it reaches the shelf edge. There are numerous ramifications associated with this. For example, hydraulic control may dictate the direction that the outflowing water travels after leaving the shelf (eastward versus westward), it may constrain the volume transport of the water exiting the shelf through the two passages, and it may also impact the vorticity structure of the outflow. This in turn would influence the behavior of the shelfbreak jet that forms downstream of the canyons. These results imply that numerical models need to depict accurately the dynamics of the flow in the vicinity of these two topographic features.

4 Shelfbreak Current

4. 1 Seasonal means

The SBI mooring array revealed that there is indeed a mean current trapped to the Beaufort shelfbreak, transporting Pacific water eastward. (Synoptic hydrographic and velocity sections occupied during SBI suggest that a similar current also exists along the edge of theChukchi Sea; e. g. Mathis *et al.* 2007)[10]. The jet has distinct seasonal configurations in its velocity and water mass structure (Nikolopoulos *et al.* 2009; see also Fig 4)[11]. During spring of the first mooring deployment year, the current primarily advected Pacific winter water (which emanated from the Chukchi shelf) as a bottom-intensified current (Fig 4 top panel). By contrast, in summer and early fall the current was surface-intensified, yet still trapped to the shelfbreak (Fig 4 middle panel). During this time of year the current advected predominantly Alaska Coastal Water (originating from the eastern Chukchi Sea via Barrow canyon). However, in the second deployment year a significant quantity of Chukchi Summer Water (Coachman *et al.* 1975)[13] was found in the current, presumably originating from the western Chukchi Sea via Herald Canyon (see Fig 3 and the middle panel of Fig 5). In late-fall and winter the eastward flow of the shelfbreak jet was again bottom-intensified (Fig 4 bottom panel), although there were significant differences between this state and the springtime configuration of the current (Nikolopoulos *et al.* 2009)[11]. In winter the surface layer was flowing to the west, the result of frequent wind-driven flow reversals (see the discussion below). Furthermore, a deep tail of eastward flow was present during the late-fall and winter season, also the result of storm events (see Spall and Pickart, 2009)[14].

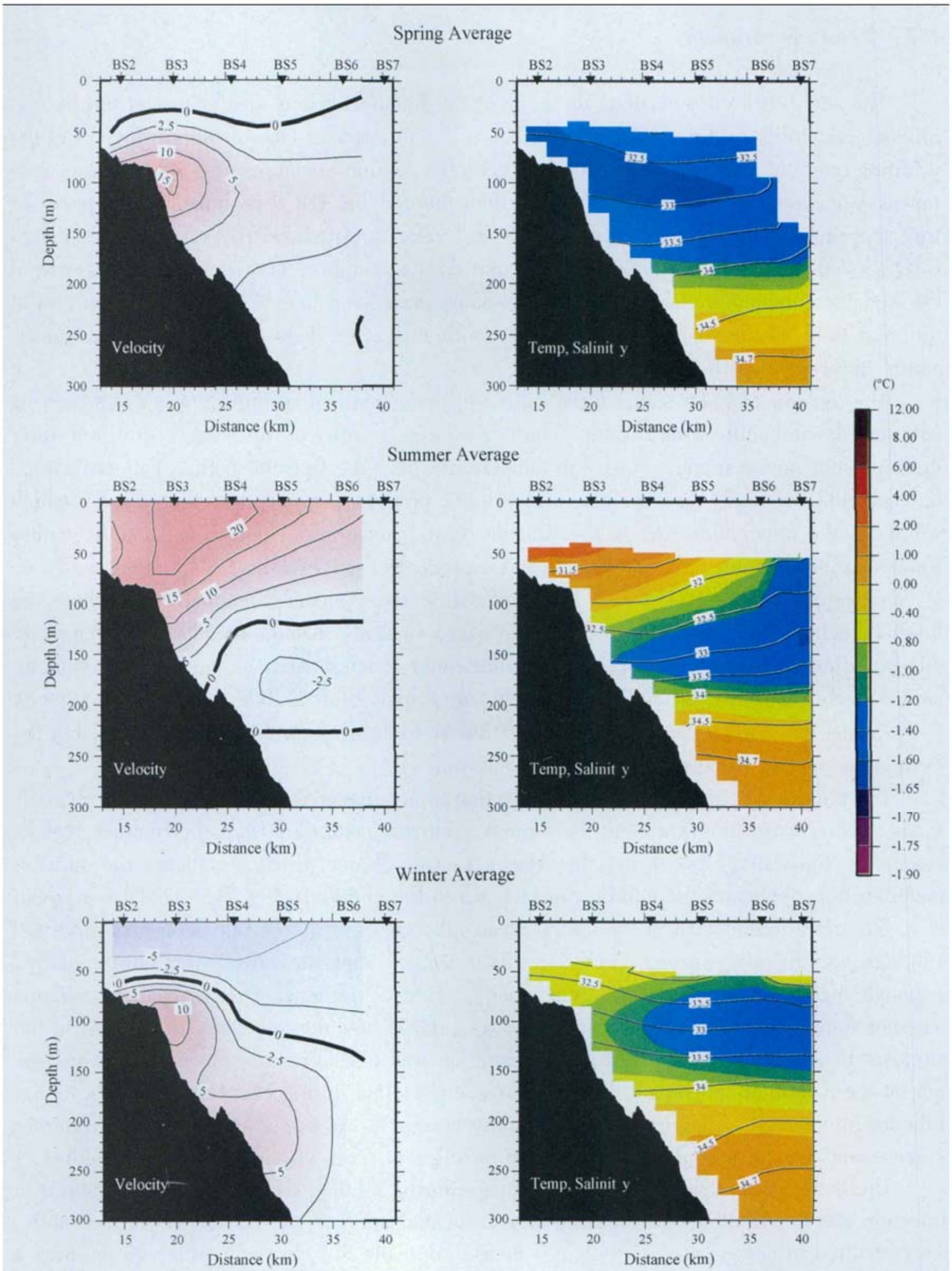

Fig. 4 Seasonal configurations of the shelfbreak jet of the Beaufort Sea near 151° W, from Nikolopoulos *et al.* (2009). The viewer is looking west. The left-hand panel shows the alongstream velocity (cm/s), where positive is eastward. The mooring locations are indicated along the top. The right-hand panel shows potential temperature (color, ℃) overlain by salinity (contours). Top row: Springtime average (Mar-Jun 2003). Middle row: Summertime average (Aug-Sep 2002 and Jul 2003). Bottom row: Wintertime average (Oct 2002-Feb 2003).

4.2 *Mesoscale variability*

The shelfbreak current along the edge of the Beaufort Sea is also characterized by significant variability on timescales of less than a day to a week. One of the advantages of the profiling mooring array was that each hydrographic section encompassing the boundary current was occupied in under an hour (less than this for the ADCP sections). This provided true snapshots of the current's water mass and velocity structure. By contrast, shipboard CTD sections in ice-covered waters often take days to occupy, and therefore alias some of the higher frequency fluctuations. Figure 5 shows three snapshots of the boundary current at different times of the year. As seen, the synoptic character of the current was often significantly different than the seasonal means.

The top row of Fig 5 shows a realization of the current in spring when it was advecting cold and dense Pacific winter water. There is a large quantity of this weakly stratified water mass present in the section, with the temperature near the freezing point. This realization has both the dominant Chukchi Sea winter water product (salinity less than 33.5) which ventilates the upper halocline of the Canada basin, and the "hypersaline" Pacific winter water (salinity greater than 33.5) which is a product of polynyas on the Chukchi shelf (e.g. Weingartner *et al.* 1998)[1]. The hypersaline water is dense enough to ventilate the lower halocline. The evidence to date, however, suggests that the Beaufort Sea boundary current primarily advects the upper halocline winter water during the spring/early-summer season (see Fig 4, as well as Pickart (2004) and Spall *et al.* (2008))[7,9]. The velocity field during this realization was similar in structure to the springtime seasonal mean, but the current was nearly three times stronger (>40 cm/s).

The middle row of Fig 5 shows a realization from summer when the winter water had already advected past the array and the boundary current contained Chukchi Summer Water. Note that this water mass is not the Alaska Coastal Water which dominated the summer mean section (compare the middle row of Fig 5 to the middle row of Fig 4). This snapshot is in fact more reminiscent of the spring mean: the water in the current is weakly stratified (though significantly warmer than the winter water) and the flow is bottom-intensified (though higher up on the continental slope). Hence, although this realization contains summer water, it should still be considered as a dense boundary current, in contrast to the summertime mean of Fig 4. Such a configuration was not commonly observed during year one of the mooring deployment; however, it was prevalent during year two (attesting to significant interannual variability of the boundary current). As discussed below, the different current configurations lead to the formation of different types of boundary current eddies.

The bottom row of Fig 5 shows a snapshot during a fall upwelling event. The storm in question was an Aleutian low pressure system located approximately 2000 km to the south. This resulted in persistent easterly winds measured at the Pt. Barrow weather station over a three-day period. (The weather station is roughly 150 km to the west of the array site.) The realization shown here was near the height of the storm. One sees that there is no signature of the eastward-flowing boundary current; instead the flow is surface-intensified and strongly to the west at nearly 1 m/s. Such flow reversals are common during these types of storms[11]. In response to the storm, warm and salty Atlantic water was upwelled onto the

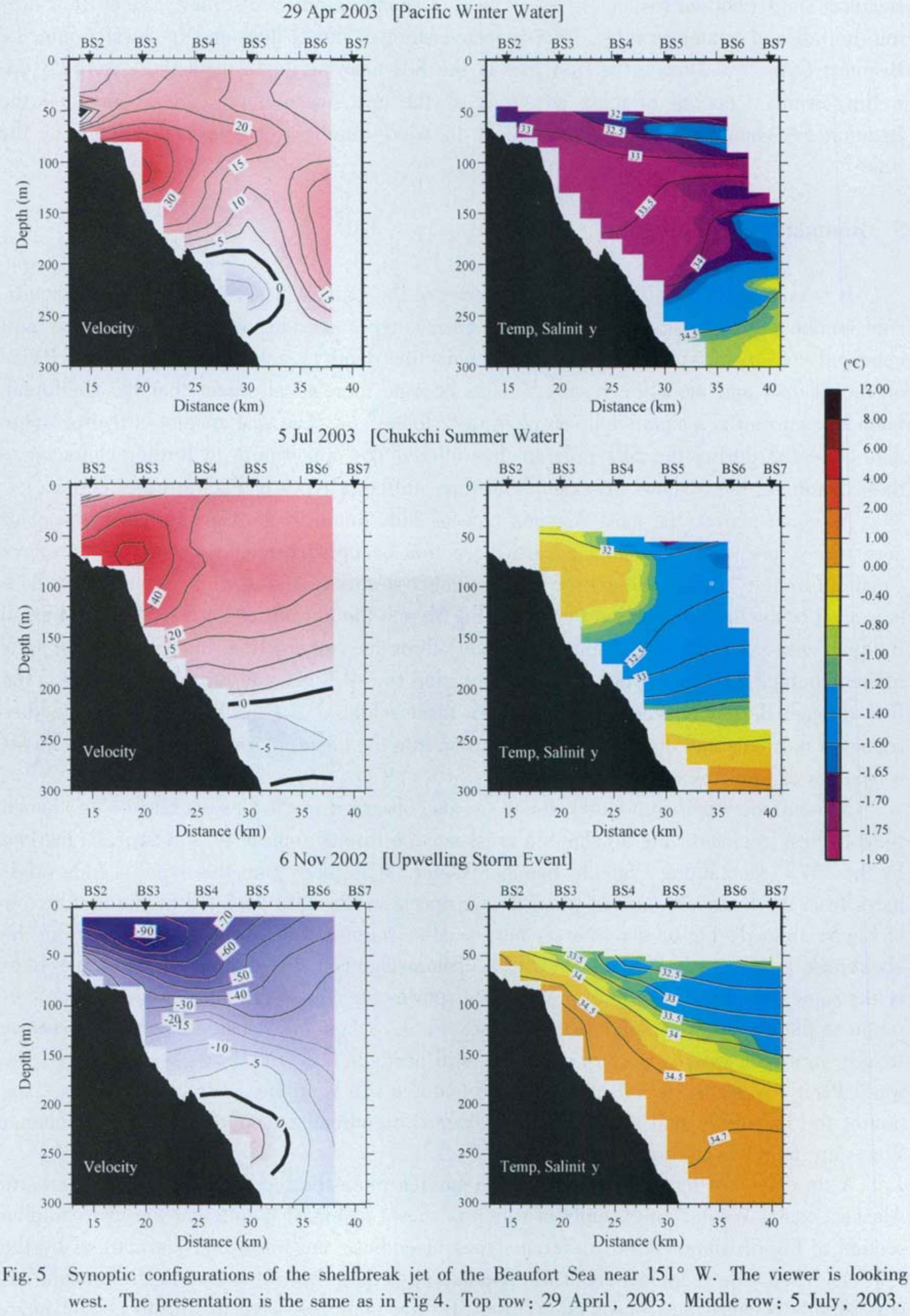

Fig. 5 Synoptic configurations of the shelfbreak jet of the Beaufort Sea near 151° W. The viewer is looking west. The presentation is the same as in Fig 4. Top row: 29 April, 2003. Middle row: 5 July, 2003. Bottom row: 6 November, 2002.

Beaufort shelf (bottom row of Fig 5). The corresponding offshore surface Ekman flow during the fall and winter months, from repeated storms, fluxes heat and freshwater into the Beaufort Gyre[15]. During the first year of the SBI mooring deployment there were 28 upwelling events (not all of them as strong as the one shown here), indicating that the Beaufort Sea boundary current is subject to wind forcing a significant fraction of the time[6].

5 Boundary current eddies

It is now well established that the interior of the Canada basin is populated by significant numbers of small scale eddies[16,17]. Various types of eddies are present, but the most commonly observed type is a sub-surface (halocline depth), cold-core anticyclone. Based on recent data and modeling results, it has become increasingly clear that the shelfbreak boundary current is a significant source of the eddies[5,7]. The vast amount of hydrographic data collected during the SBI program has offered the opportunity to further characterize these features. Fig 6 shows an example of three different types of Pacific water eddies.

As noted above, the most common type of eddy found in the Canada basin is a cold-core anticyclone. Fig 6b shows a vertical section occupied through one of these features (marked by the "C"). The eddy contains weakly stratified Pacific winter water at the density level of the upper halocline (compare Fig 6b and the top row of Fig 5). As investigated by Spall *et al.* (2008)[7], such eddies likely form due to baroclinic instability of the springtime configuration of the boundary current (top row of Fig 4 and top row of Fig 5). The flow through Barrow canyon may also spawn these eddies[5,18,19]. These cold-core eddies transport nutrients and dissolved organic carbon into the basin interior[10], as well as Pacific species of zooplankton[20].

Sub-surface warm-core anticyclones are also observed in the Canada basin[16], though they are less common. Fig 6c shows a cross-section through one of these features (marked by the "W") containing Chukchi Summer Water. It is likely that this type of eddy originates from the boundary current when the current is in the state depicted by the middle row of Fig 5. Indeed, Fig 6c shows a second, smaller warm-core eddy being pinched from the shelfbreak jet (between stations 269-272). The mechanism of formation in this case is likely the same baroclinic instability process that spawns the cold-core eddies since the configuration of the current is similar in both cases (i. e. a bottom-intensified current advecting weakly stratified water)[7]. However, this still needs to be verified. As seen in Fig 6, the warm Pacific water fluxed offshore by these features will ventilate a slightly less-dense portion of the halocline than the cold winter water. Significant amounts of Chukchi Summer Water are found in the interior Canada basin[21].

A third type of Pacific water eddy is a surface-intensified anticyclone containing warm Alaska Coastal Water, an example of which is shown in Fig 6b (note that the hydrographic section of Fig 6b sampled two different types of eddies; the warm eddy is marked by the "W"). Very little is known about the population of these warm features in the Canada basin, largely because past observations from drifting platforms were unable to collect near-surface measurements. However, shipboard hydrographic data suggest that there is a substantial offshore flux of this water[21,22]. Whether or not the flux is predominantly the result

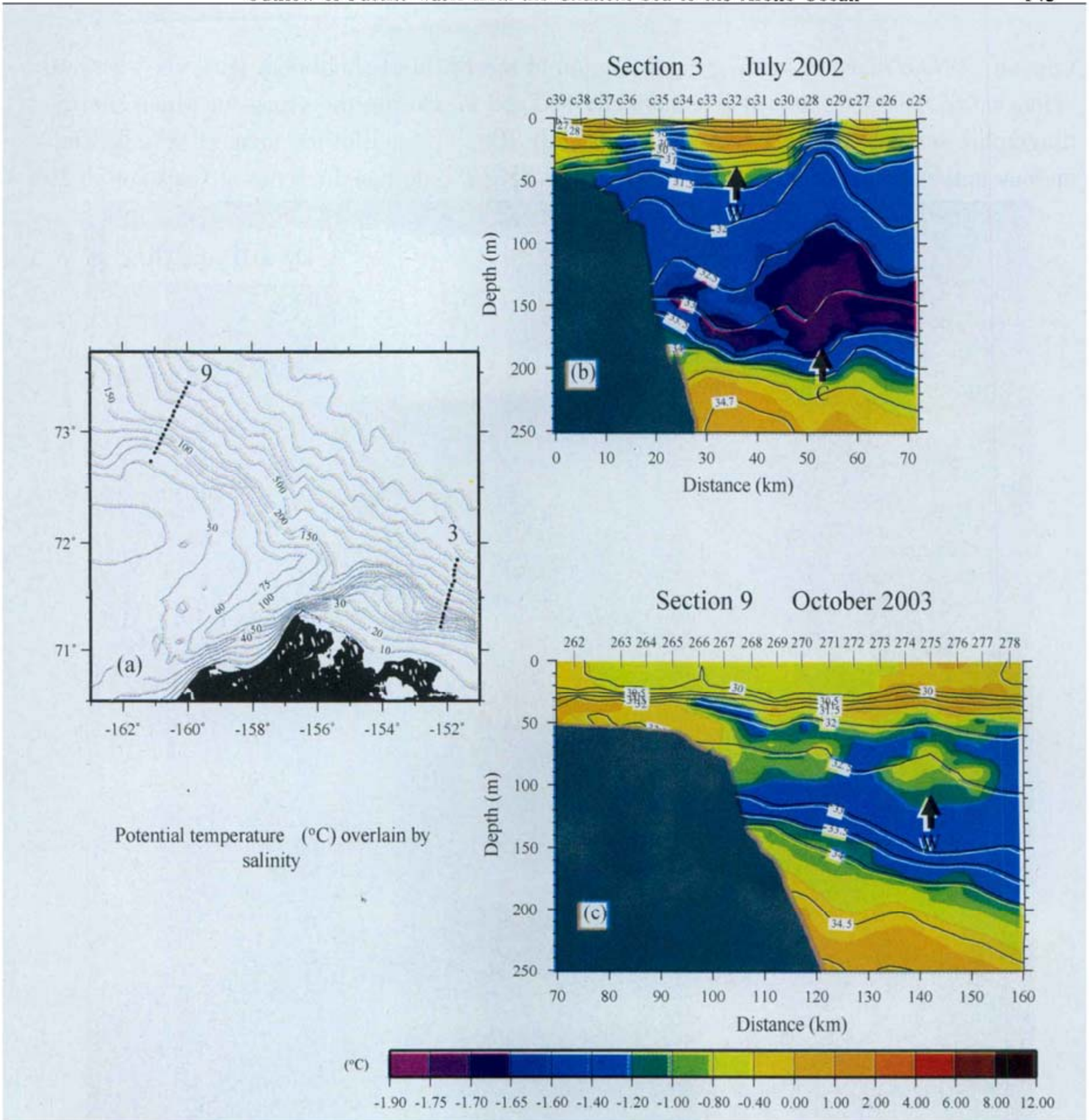

Fig. 6 Hydrographic sections occupied during the SBI program showing three types of Pacific water eddies. (a) Locations of the sections. Section 3, across the Beaufort shelfbreak, was occupied in July 2002; Section 9, across the Chukchi shelfbreak, was occupied in October 2003. (b) Potential temperature (℃, color) overlain by salinity (contours) for section 3. The "C" marks the location of the sub-surface, cold-core eddy; the "W" marks the location of the near-surface, warm-core eddy. The CTD stations are marked along the top. (c) Same as (b) for section 9, where the "W" marks the location of the sub-surface, warm-core eddy.

of discrete eddies of the type shown in Fig 6b is yet to be determined. However, the linear stability analysis of Hunkins (1974) and Manley and Hunkins (1985) suggest that baroclinic instability of the summer configuration of the shelfbreak current (middle row of Fig 4) can form these features[16,23]. Such buoyant shelfbreak eddies are common in other areas of the world ocean (e.g. Garvine *et al.* 1988)[24].

There is in fact compelling evidence that the warm-core, surface-intensified anticyclone of Fig 6b was spawned by the Alaskan Coastal Current (ACC) emanating from Barrow

Canyon. (Note that the summer configuration of the Beaufort shelfbreak jet is the eastward extension of the ACC, shown schematically in Fig 1). During the cruise in which the hydrographic section of Fig 6b was occupied (July 2002), satellite ice imagery revealed numerous anticyclones spinning off from the ACC. Fig 7 (top panel) shows a snapshot on 19

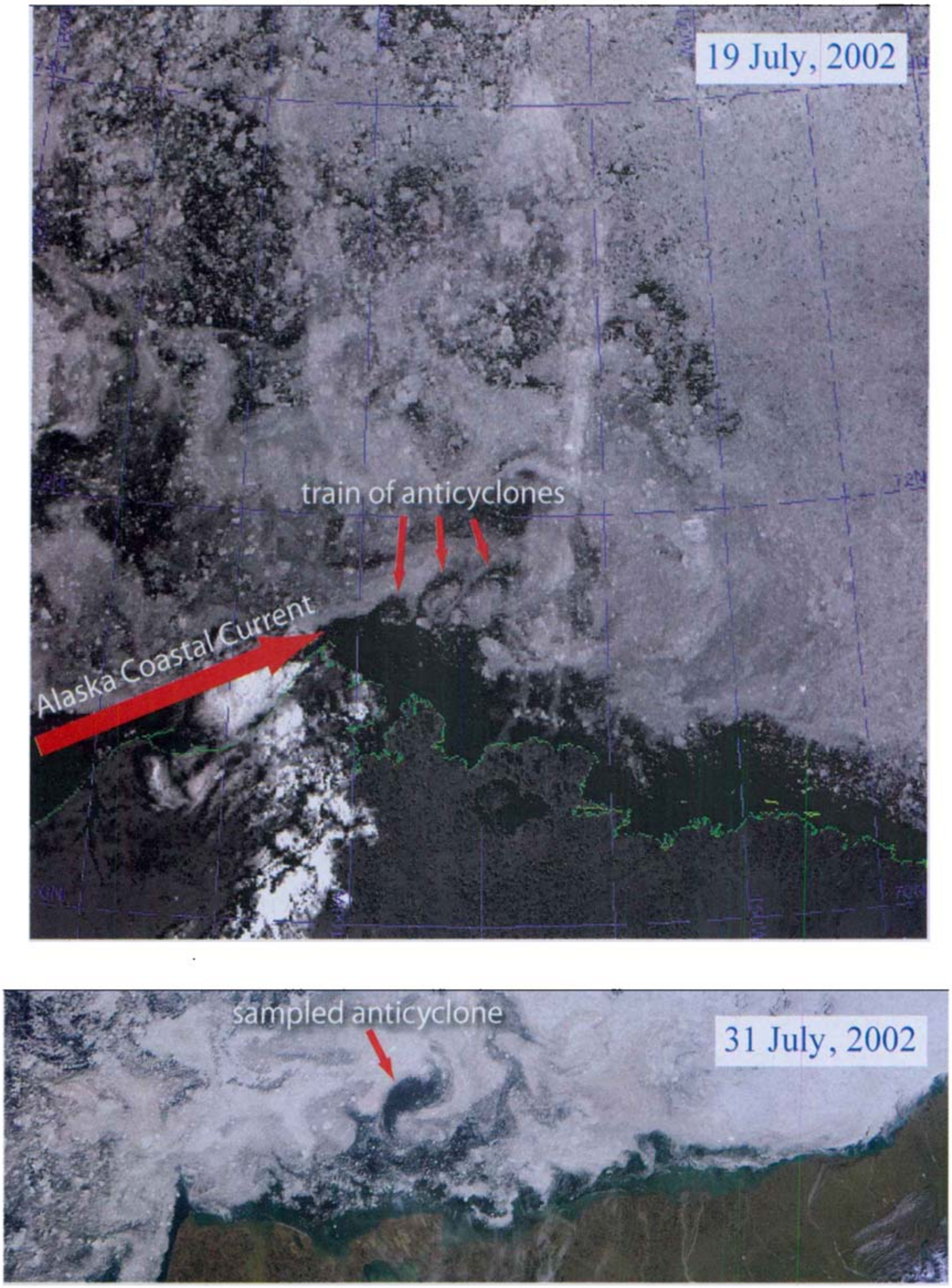

Fig. 7 Visible channel ice images. Top panel: 19 July, 2002. Bottom panel: 31 July, 2002. Pt. Barrow, Alaska is evident in each image.

July, 2002 where a train of three such eddies was being formed downstream of Barrow Canyon. An animation produced by a series of these images clearly reveals the circular motion of the ice being advected by the developing anticyclones. The bottom panel of Fig 7 shows an (ice-free) anticyclone 12 days later. This is the precise eddy that was sampled by the ship: the hydrographic section of Fig 6b crossed directly through this feature. The shipboard data hence "ground-truth" these ice maps for the time period of the cruise, verifying that the swirling features are the surface-manifestation of Alaska Coastal Water eddies. (We note that cloud cover prohibited us from tracking the warm eddy of Fig 6b in the days immediately prior to the occupation of the section.)

It is important to emphasize that all three types of Pacific water eddies shown here have small lateral length scales. Furthermore, they were all presumably spawned from the shelfbreak current via baroclinic instability. Hence, for numerical models to simulate correctly the turbulent flux of Pacific Water from the shelf to the basin, they need to capture faithfully the dynamics of the narrow shelfbreak jet along the Chukchi and Beaufort Seas.

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