PHYSICAL OCEANOGRAPHIC MEASUREMENTS IN THE KLONDIKE AND BURGER SURVEY AREAS OF THE CHUKCHI SEA: 2008 AND 2009

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FINAL REPORT

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Introduction

The Chukchi and Beaufort seas are the northernmost shelves bordering Alaska. Although properly a part of the western Arctic Ocean, both shelves are linked, atmospherically and oceanographically, to the Pacific Ocean. These connections profoundly influence the wind and wave regimes, the seasonal distribution of sea ice, the regional hydrologic cycle, and the water masses and circulation characteristics of the Chukchi shelf (**Figure 1**). The atmospheric connection is primarily via the Aleutian Low, whose time-varying position and strength and interactions with polar air masses affects regional meteorological conditions. The oceanographic link is via the mean northward flow through Bering Strait, which draws water from the Bering Sea shelf and basin, and which is sustained by a large-scale pressure gradient between the Pacific and Atlantic oceans [*Coachman et al.*, 1975; *Aagaard et al.*, 2006].

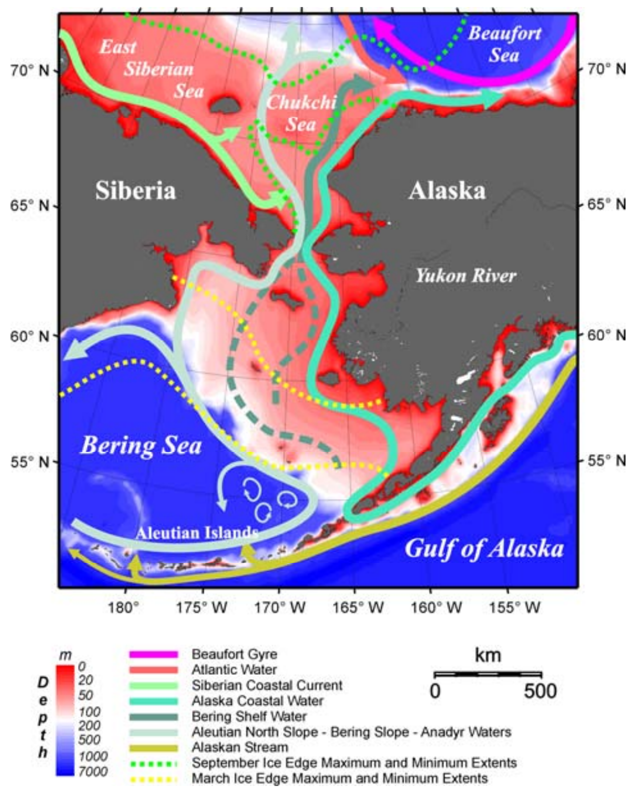

Figure 1. Schematic circulation map of the Bering-Chukchi-Beaufort shelves.

The northward flux of mass, heat, nutrients, carbon, and organisms through the strait bequeath the Chukchi shelf with physical and ecological characteristics that are unique among arctic shelves. For example, the spring retreat of ice occurs earlier and fall ice formation is delayed in comparison to most other arctic shelves because of the northward heat flux through the strait. *Woodgate et al*. [2006] estimate that summer Pacific waters provide a heat source capable of melting nearly the entire (~640,000 km^2) 2-m thick ice cover of the Chukchi Sea and *Shimada et al.* [2006] contend that this flux may be an important source of interannual variability in the ice cover. Similarly, the enormous biological productivity of this shelf [*Walsh et al.*, 1989; *Grebmeier and McRoy*, 1989; *Springer and McRoy*, 1993], including its ability to support large and diverse marine mammal populations, is due to the carbon and nutrient loads carried through Bering Strait.

The water properties of the strait throughflow reflect the time-varying output of physical processes occurring over the Bering shelf and northern North Pacific. These fluxes are a result of the net effects of upwelling from the deep Bering Sea basin and areally integrated heat and freshwater fluxes [*Aagaard et al.,* 2006], including the freezing and melting of sea ice [*Danielson et al.*, 2006], river runoff, atmospheric moisture and heat fluxes, and heat and freshwater contributions from the Gulf of Alaska [*Weingartner et al.,* 2005a], all of which ultimately affect the heat and salt budgets of the Chukchi Sea shelf [*Coachman et al*., 1975; *Woodgate et al.*, 2005b]. The remainder of the introduction summarzies our present understanding of the northeast Chukchi Sea shelf.

Much of our understanding of the Chukchi shelf derives from the early syntheses of the modeling and theoretical work of [*Gawarkiewicz and Chapman*, 1995], and the sea-ice studies of *Muench et al*. [1991], *Liu et al*. [1994], and.

Mean Circulation

The shallow (~50m) Chukchi Sea shelf extends ~800 km northward from Bering Strait to the shelfbreak at about the 200 m isobath. The mean flow over much of the shelf is northward *Weingartner and Proshutinsky* [1998], *Weingartner et al.* [1998], *Weingartner et al*. [2005] due to the Pacific-Arctic pressure gradient and opposes the prevailing winds, which are from the northeast This pressure gradient propels the Bering Strait throughflow along three principal pathways that are associated with distinct bathymetric features (**Figure 2**); Herald Valley, the Central Channel, and Barrow Canyon. Herald Shoal separates Herald Valley from the Central Channel, and Hanna Shoal is between Barrow Canyon and the Central channel. The recent MMS Chukchi Sea lease sales lie on the northeast shelf between the Central Channel and Barrow Canyon and south of Hanna Shoal (**Figure 2**).

As sketched in **Figure 1**, a western branch flows northwestward from the strait and exits the shelf through Herald Valley [*Coachman et al*., 1975; *Walsh et al.*, 1989; *Hansell et al.*, 1993]. While most of this outflow probably descends through Herald Valley, some of it may spread eastward across the central shelf. A second branch flows northward through the Central Channel *Paquette and Bourke* [1974], *Weingartner et al.* [2005b] and then probably splits; with some water continuing eastward toward the Alaskan coast along the south flank of Hanna Shoal while the remainder flows northeastward toward the continental slope [*Johnson* 1989; *Weingartner and Proshutinsky*, 1998; *Münchow and Carmack,* 1997] Some of this water likely rounds the northern flank of Hanna Shoal and then turns southward toward the head of Barrow Canyon *Winsor and Chapman*, 2002; *Spall*, 2007]. The third branch flows northeastward along the Alaskan coast towards Barrow Canyon at the junction of the Chukchi and Beaufort shelves [*Mountain et al.* 1976; *Paquette and Bourke,* 1981; *Ahlnäes and Garrison*, 1984]. In summer this flow includes the northward extension of the Alaskan Coastal Current (ACC) that originates south of Bering Strait [*Aagaard et al.,* [1985], *Aagaard* [1988],*Münchow et al.* 2000]. At the head of Barrow Canyon the ACC is joined by waters flowing eastward from the central shelf *Weingartner et al*. [2005], with the merged flow then continuing downcanyon as a narrow, but strong, coastal jet *Aagaard and Roach* [1990], *Pickart et al.* [2005].

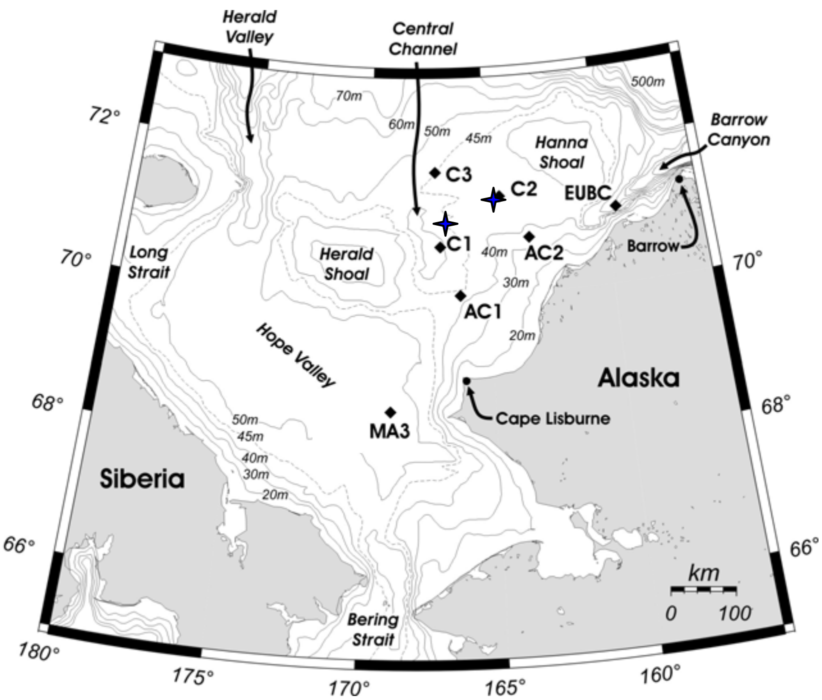

Figure 2. Bathymetric map of the Chukchi Sea shelf showing the Herald Valley, Central Channel, Barrow Canyon and two prominent shoals: Herald and Hanna. Also shown are the locations of current meter moorings deployed from 1994-1995. The blue stars are the approximate locations of the Klondike and Burger leases.

Mean current speeds within the Herald and Barrow canyons are swift (~25 cm s^{-1}), more moderate in the Central Channel (~10 cm s^{-1}), and generally $\leq$5 cm s^{-1} elsewhere (**Figure 3**). Long-term transport estimates for these three pathways are very approximate at best and suggest that the flow through the Central Channel is ~200,000 m^3 s^{-1}, while the branches in both Herald Valley and Barrow Canyon carry ~300,000 m^3 s^{-1} [*Woodgate et al.*, 2005b]. Estimates of transit time from Bering Strait to Barrow Canyon are from 3 – 4 months in summer and longer in winter (*Weingartner et al*., 2005; *Woodgate et al.,* 2005b]. The vectors in **Figure 3** suggest that some of the Barrow Canyon outflow proceeds eastward along the Beaufort continental slope. Water mass analyses and current meter measurements clearly show that this is indeed the case, but apparently not all of the mass transported down the canyon is captured by the slope flow [*Pickart*, 2004, *Steele et al.,* 2004, *Nikoloupolis et al.,* 2009; *Pickart et al*., in press]. Instead some of the outflow is entrained into shelfbreak eddies that drift into the deep basin [*Pickart et al.,* 2005; *Spall et al.,* 2008], some appears to spill over onto the inner Beaufort shelf when winds from the northeast are sufficiently weak [Okkonen, pers. comm.], and some appears to drift northwestward from the canyon's mouth and into the Arctic basin [*Shimada et al*., 2006]. The mean flow outlined from observations is similar to that produced by numerical circulation models of the Chukchi shelf [*Weingartner and Proshutinsky*, 1998; *Winsor and Chapman*, 2004; *Spall* 2007]. Of importance to this study are that some of the model results suggest that waters over Hanna Shoal are trapped by this bank and are only mixed slowly with adjacent shelf waters. The models also predict that flow through the Central Channel continues northeastward around the northern flank of Hanna Shoal, then turns southward at ~72^{o}N (between Hanna Shoal and Barrow Canyon) before turning eastward to enter Barrow Canyon at ~71^{o}N. We are unaware of any observations that confirm the clockwise flow around Hanna Shoal, but it is dynamically consistent with barotropic, geostrophic dynamics. An implication from the models is that materials discharged southwest of Hanna Shoal may be advected around the northern and eastern sides of the shoal and then swept down Barrow Canyon.

The influence of the three main flow pathways is evident, in summer and fall, by the formation of perennial "melt-back embayments" [*Paquette and Bourke*, 1981] that indent the ice edge. The embayments reflect accelerated melting by the warm Bering Sea summer waters that are channeled northward along these pathways. The routes and transit times by which Bering water ultimately enters the Arctic Ocean affects the distribution of hydrographic properties across the Chukchi Sea shelf and gives rise to complex shelf hydrographic structures as discussed next and as found in the measurements reported herein.

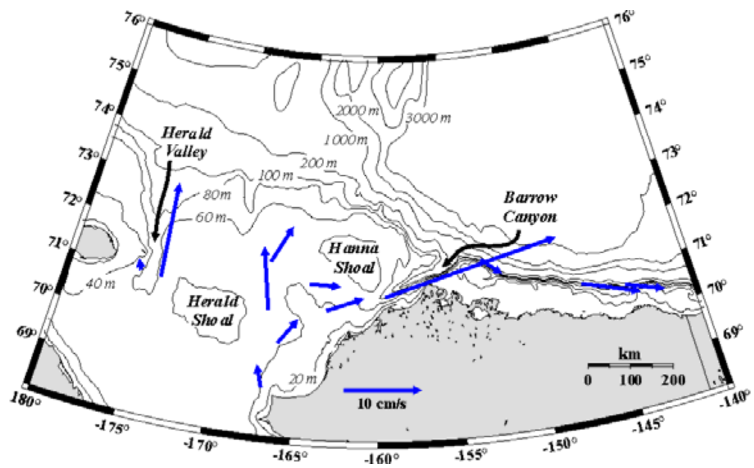

Figure 3. Mean flow vectors (blue arrows) from moorings deployed in the Chukchi Sea and Beaufort slope deployed between 1990-1995 and with record lengths exceeding 9 months.

In general, relatively warm (>2^{o}C), salty (salinity >32.4) and nutrient-rich "summer" water from Bering Strait is found in Herald Valley and the Central Channel [*Coachman et al.,* 1975; *Hansell et al.,* 1993; *Cooper et al.* 1997; *Weingartner et al.;* 2005b; *Münchow et al*., 1999; *Codispoti et al.,* 2005]. Warm, but fresher (salinity <32.2), Alaskan Coastal Water, also of Bering Sea origin, flows along the coast and occupies the eastern wall of the head of Barrow Canyon [*Coachman et al*., 1975; *Weingartner et al.,* 2005b; *Pickart et al.,* 2005]. Ice tends to remain over Herald and Hanna shoals longer than elsewhere [*Drucker and Martin*, 1997] due to topographic obstruction of the flow and so cold, dilute waters, derived from ice melt, often lie within the upper 20 meters atop Herald Shoal, Hanna Shoal, and between the Central Channel and Barrow Canyon [*Drucker and Martin*, 1997; *Weingartner et al.,* 2005b]. The region south of Hanna Shoal, between the Central Channel and Barrow Canyon, is often strongly stratified with the water column having a 2-layer structure [*Weingartner et al.,* 2005b]. The stratification increases from spring through summer and then erodes in fall as strong winds, cooling, and freezing enhance vertical mixing. The bottom half of the water column usually contains relatively cold, salty water remnant from the previous winter, whereas the surface layer consists of ice melt, and/or mixtures of Alaskan Coastal Water or water flowing through the Central Channel. Seasonal changes in stratification may possibly lead to different surface velocity responses to winds. In addition to its spatial complexity, the hydrographic structure can vary considerably on seasonal and storm time scales as well as from year-to-year.

Wind-Forced Variability

The mean circulation is due to the large scale oceanographic pressure field between the Pacific and Arctic oceans and opposes the mean winds, which are from the northeast at ~ 4 m s^{-1} on average. The winds are, however, the principal cause of flow variations [*Weingartner et al.,* 2005b], which can be substantial. Wind forcing varies seasonally with the largest variations being in fall and early winter and the smallest being in summer. Over the northeast Chukchi Sea shelf, current fluctuations are coherent with wind velocity variations over spatial scales of at least 300 km, with currents responding to wind variations in something less than a day [*Weingartner et al.,* 2005b]. These circulation adjustments reflect wind-induced modifications to the shelf pressure field. Although the adjustment envelopes a broad area, the magnitude of the current response varies over the shelf. In particular both the wind-forced (and mean) currents are more vigorous in regions of strong bathymetric gradients (e.g., Central Channel and Barrow Canyon) than in areas of gentler bottom relief. On occasion, and most frequently in fall and winter, strong storm winds from the northeast can reverse the shelf flow field or even re-distribute the flow from one of the main flow pathways to another.

There are, in addition, mesoscale flow variations associated with frontal instabilities, which have not been studied extensively in the Chukchi Sea. In summer and fall there are particularly prominent along ice-edge fronts [*Muench*, 1990; *Liu et al.*, 1994]. In winter, they are likely associated with the cross-shelf spreading of cold, saline water formed in the coastal polynyi along the northwest coast of Alaska [[*Cavalieri and Martin,* 1994; *Gawarkiewicz and Chapman*, 1995; Gawarkiewicz et al., 1998].

The current measurements discussed above were obtained from current meters installed ~10 m above the seabed in depths $\geq$40 m. However, these measurements may not reflect currents in the upper 3 m since near-surface currents are difficult to measure from year-round moorings with present technology. Although there are no direct measurements of surface currents on the Chukchi Sea, ice drift measurements suggest that ice drifts westward (and downwind) over the outer Chukchi shelf [*Muench et al.* [1991]. In addition, several passive acoustic recorders prematurely released in summer 2008 drifted westward out of the lease sale area [C. Rea, pers. comm., 2009]. These few observations suggest that the flow in a “thin” surface layer, which absorbs the bulk of the momentum imparted by the wind to the water column, may differ from the deeper flow measured by current meters. The thickness of this wind-shear layer will likely vary due to wind velocity, ice, bathymetry, and stratification. We note that a joint industry-government program is presently underway to address this issue. That program involves the combined use of shore-based, radars that map the surface currents and upward looking Acoustic Doppler Current Profilers (ADCPs), moored within the radar mask, to measure flow to within ~3 m of the surface.

In the following sections we discuss separately the 2008 and 2009 variations in the winds and sea ice fields during the survey periods and then examine the water property distributions. These presentations are then followed by a brief discussion of the differences between the two years. The water property distributions are based on 1-meter averages of the CTD data collected at the various stations established in each prospect.

Methods

Data were collected with a Seabird, Inc. SBE-19+V2 CTD sampling at 4 Hz. The instrument was lowered throughout the water column at a rate of ~0.5m min^{-1} so that ~480 samples m^{-1} were obtained. Measured variables include pressure, temperature, conductivity, beam attenuation, beam transmission, and fluorescence. Derived variables include depth, salinity, density and speed of sound. Data were processed according to the manufacturer's recommended procedures [provided in the SBE Data Processing manual) and further screened for anomalous spikes, dropouts and density inversions. Data are averaged to 1 decibar (approximately 1 meter) vertical profiles. Post-season calibrations of the temperature and conductivity cells are performed at the manufacturer's calibration facility are inspected for reasonable drift since the pre-season calibration. Typical drift of these sensors is less than or equal to 0.005 °C in temperature and 0.02 in salinity.

Results: 2008 Survey

Winds and Sea Ice.

Figures 7-10 show the weekly averaged wind and sea ice fields over the northeast Chukchi Sea throughout the survey period. The figures are constructed from the QuikSCAT satellite data set (http://www.remss.com/qscat/scatterometer_data_weekly.html) and obtained from Remote Sensing Systems. The weekly wind fields are constructed from twice-daily scatterometer data with a 25 km resolution. In all figures, the black regions are sea ice or grid cells contaminated by adjacent land (see the Bering Strait region for example) and the red circle denotes the location of Barrow. For the week of July 26, 2008, prior to the beginning of the 2008 surveys, winds were from the northeast at 5 – 10 m s^{-1} over the Beaufort Sea and the north over the Chukchi Sea. Although sea ice had retreated over broad areas of both shelves by late July, relatively heavy concentrations remained over Hanna Shoal and in a broad band extending westward over the northern Chukchi shelf. For the week preceding August 2 the mean winds were from the southwest at 7 – 10 m s^{-1}. These winds would have enhanced northeastward flow over the northeast Chukchi Sea and promoted the erosion and retreat of sea ice over Hanna Shoal as evidently occurred upon comparing **Figures 7** and **8**. However, for the week ending August 9 (**Figure 7, bottom panel**), the mean winds had reversed and were from the north and northwest, which would tend to advect ice toward the Alaskan coast. Nevertheless, the seasonal progression of melting continued to reduce ice concentrations. Winds over the next two weeks (**Figure 8, top and middle panels)** were again from the northeast on average with mean speeds of 7 - 10 m s^{-1}. At the resolution of the scatterometer aboard the QuikSCAT satellite the ice appears to have completely dispersed by this time, however visible satellite imagery, with a 2 km resolution, showed extensive bands of ice remaining over the Hanna Shoal region on both August 16 and August 24 (**Figures 10 and 11**). This was likely rotting ice, which probably persisted until the end of the month. It appears that all the ice had melted or retreated by the middle of September, (although there are few clear satellite images available to determine a precise date of complete ice-free waters). The relatively late ice cover that remained over Hanna Shoal in summer 2008 undoubtedly contributed to the considerable amount of meltwater found over much of the Burger prospect through summer and fall (as discussed below). Winds throughout September (**Figure 9**) winds were persistently from the north or northeast at 7 m s^{-1} and somewhat stronger over the southern Chukchi shelf. Similar wind conditions occurred in late September and until the end of the survey period (**Figure 10**); although wind speeds more typically averaged about 10 m s^{-1} during this latter period. We expect that these northerly winds would have retarded northward flow over the Chukchi shelf and/or swept cold, dilute Arctic Ocean surface waters southward onto the northeast Chukchi Sea.

The ice conditions in summer 2008 were quite different from those of summer 2007 as shown in **Figure 12**. The proximal reasons for these differences appear to be the much greater frequency and strength of winds from the south in summer 2007, which would have enhanced the flow of warm water over the Chukchi shelf and blown the ice northward and off Hanna Shoal.

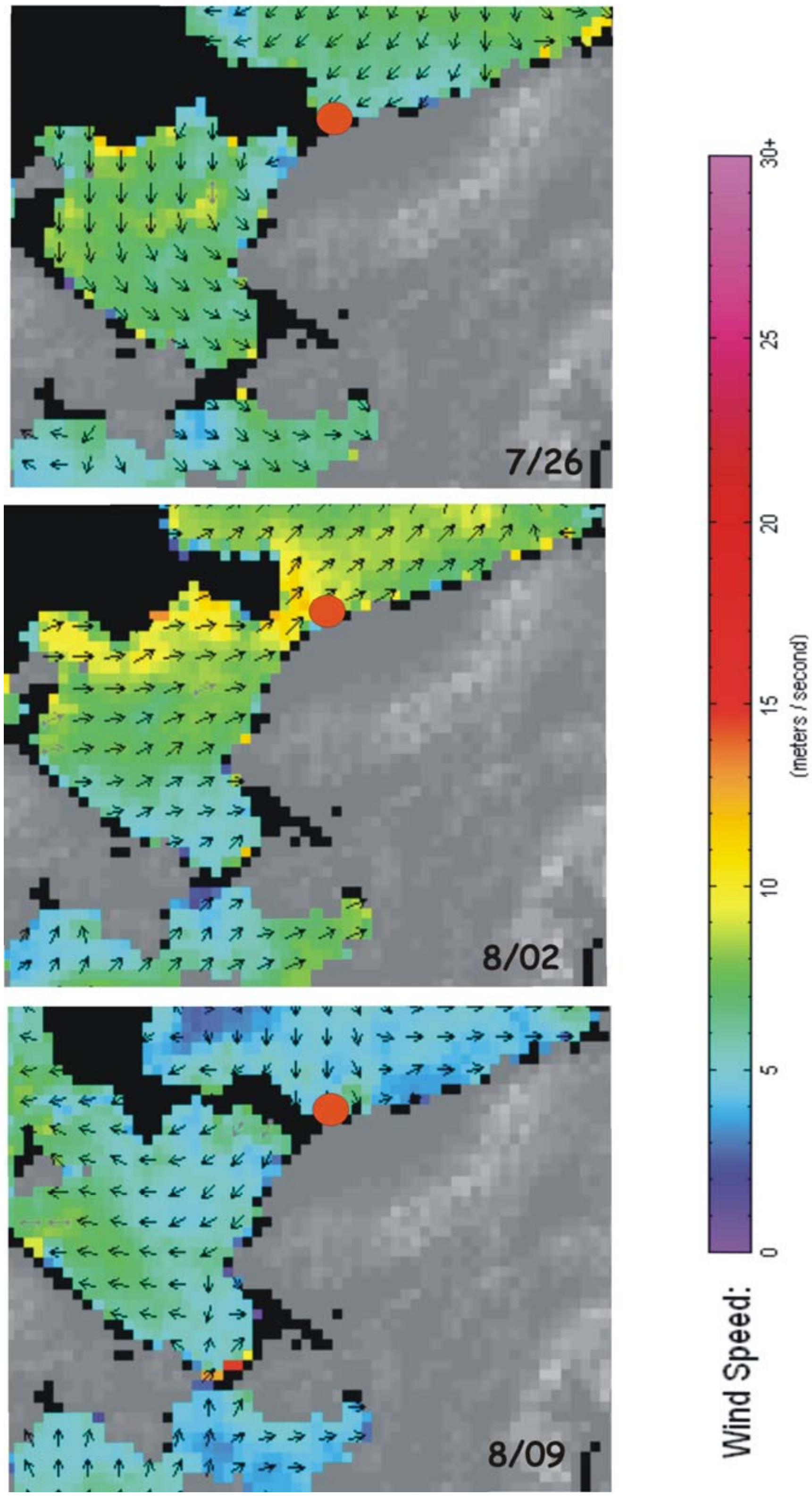

Figure 7. Weekly averaged vector winds and wind speeds over the northeast Chukchi Sea for the week ending July 26, 2008 (top), August 2 (middle) and August 9 (bottom). The red dot indicates the location of Barrow.

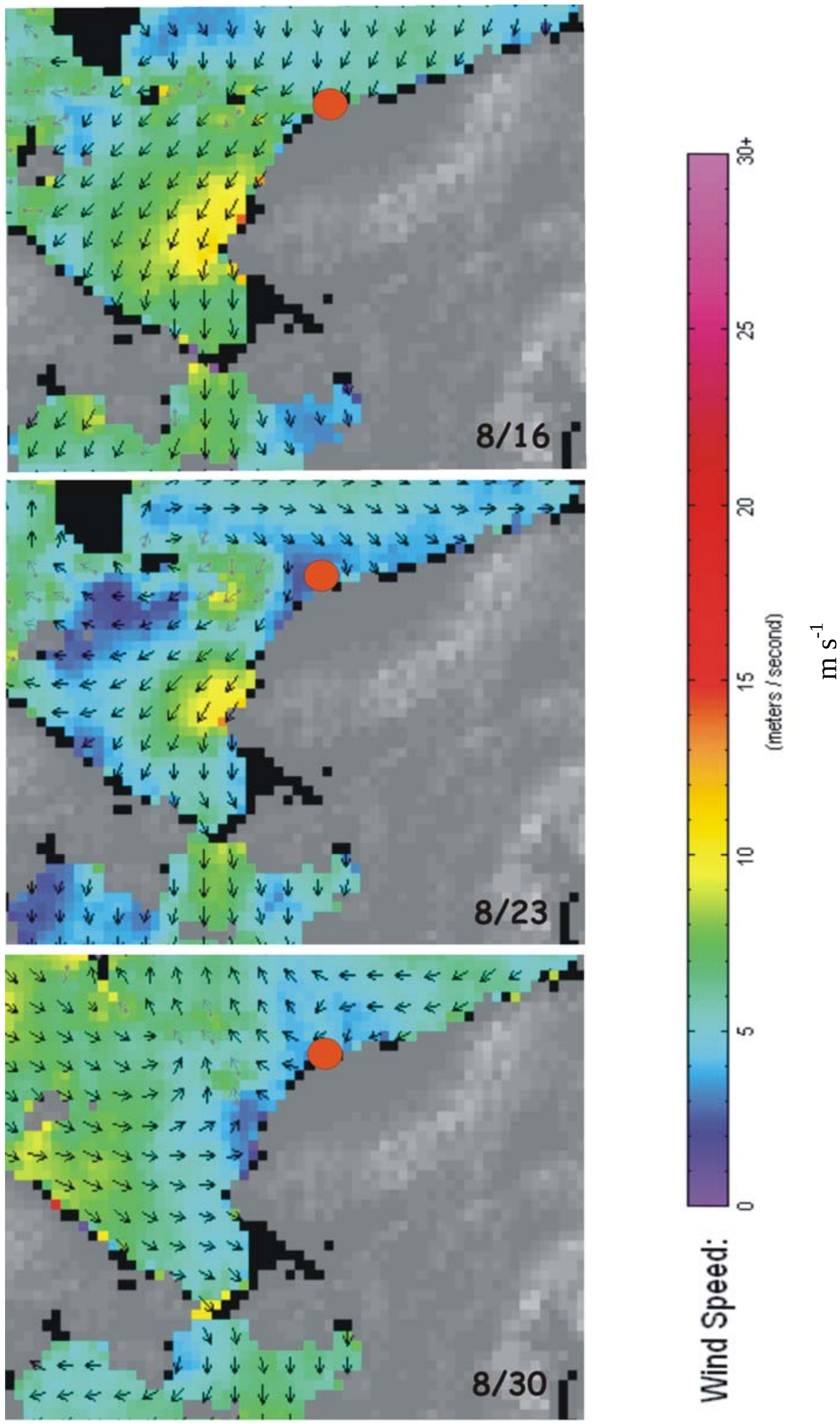

Figure 8. Weekly averaged vector winds and wind speeds over the northeast Chukchi Sea for the week ending August 16, 2008 (top), August 23 (middle) and August 30 (bottom). The red dot indicates the location of Barrow.

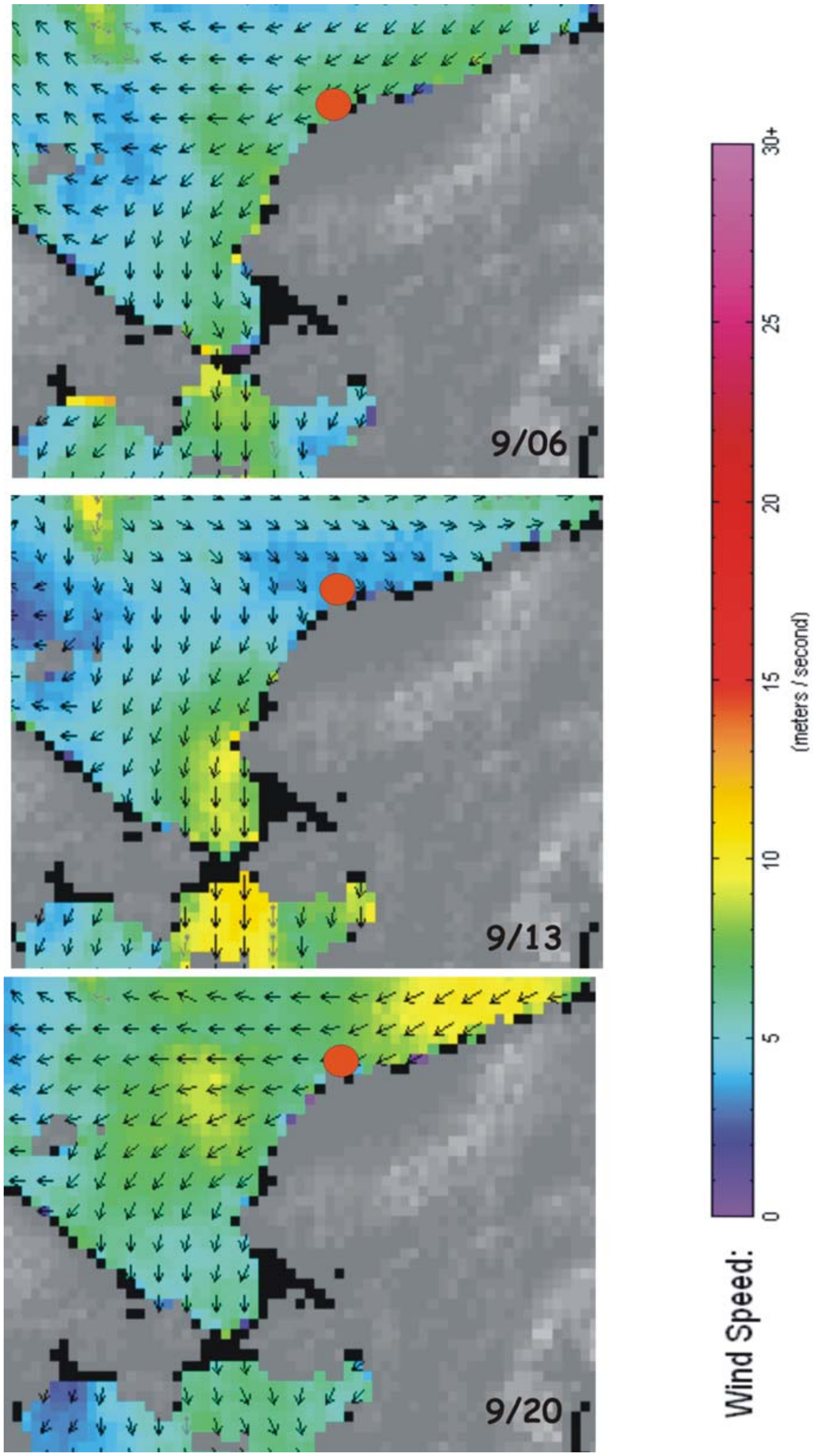

Figure 9. Weekly averaged vector winds and wind speeds over the northeast Chukchi Sea for the week ending September 6, 2008 (top), September 13 (middle) and September 20 (bottom). The red dot indicates the location of Barrow.

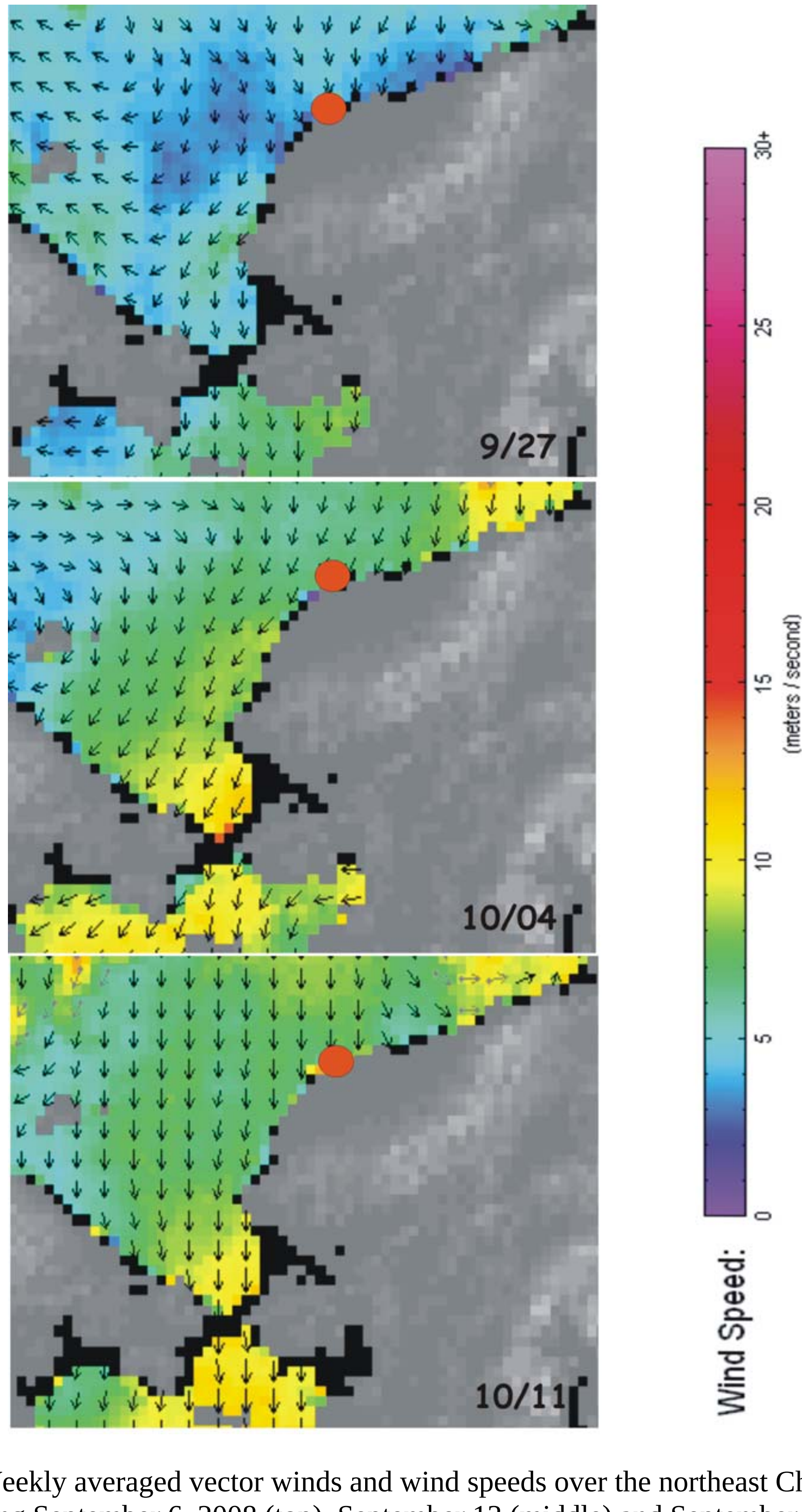

Figure 10. Weekly averaged vector winds and wind speeds over the northeast Chukchi Sea for the week ending September 6, 2008 (top), September 13 (middle) and September 20 (bottom). The red dot indicates the location of Barrow.

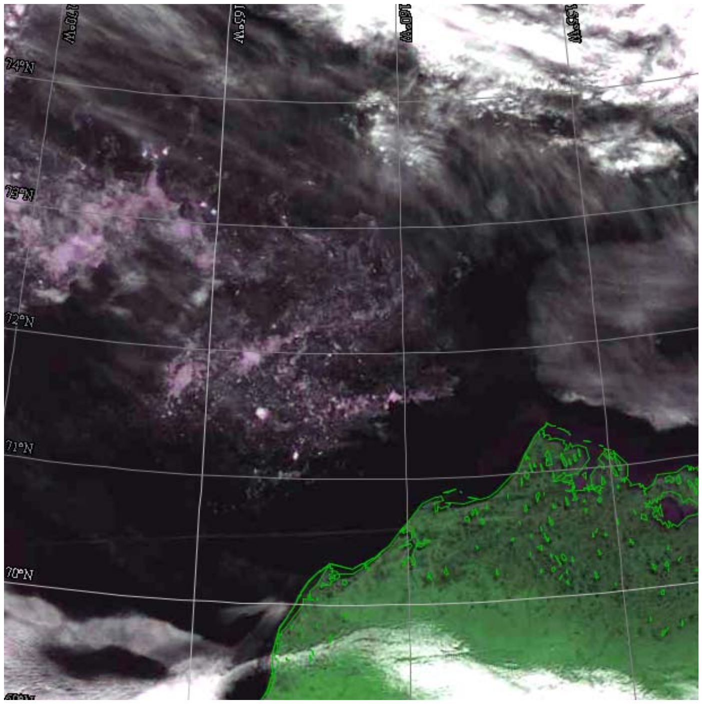

Figure 10. Visible satellite image (August 16, 2008) showing bands of ice over Hanna Shoal and the shelf to the west of the Shoal. The ice extends south of 71°N along about the 164°W meridian.

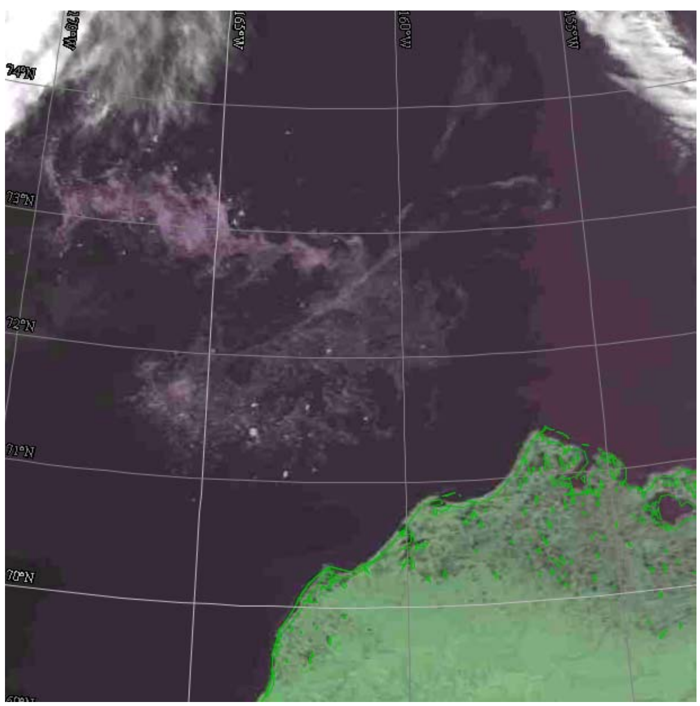

Figure 11. Visible satellite image (August 24, 2008) showing broken ice over Hanna Shoal and the shelf to the west of the Shoal. The ice extends nearly to 71°N along about the 164°W meridian.

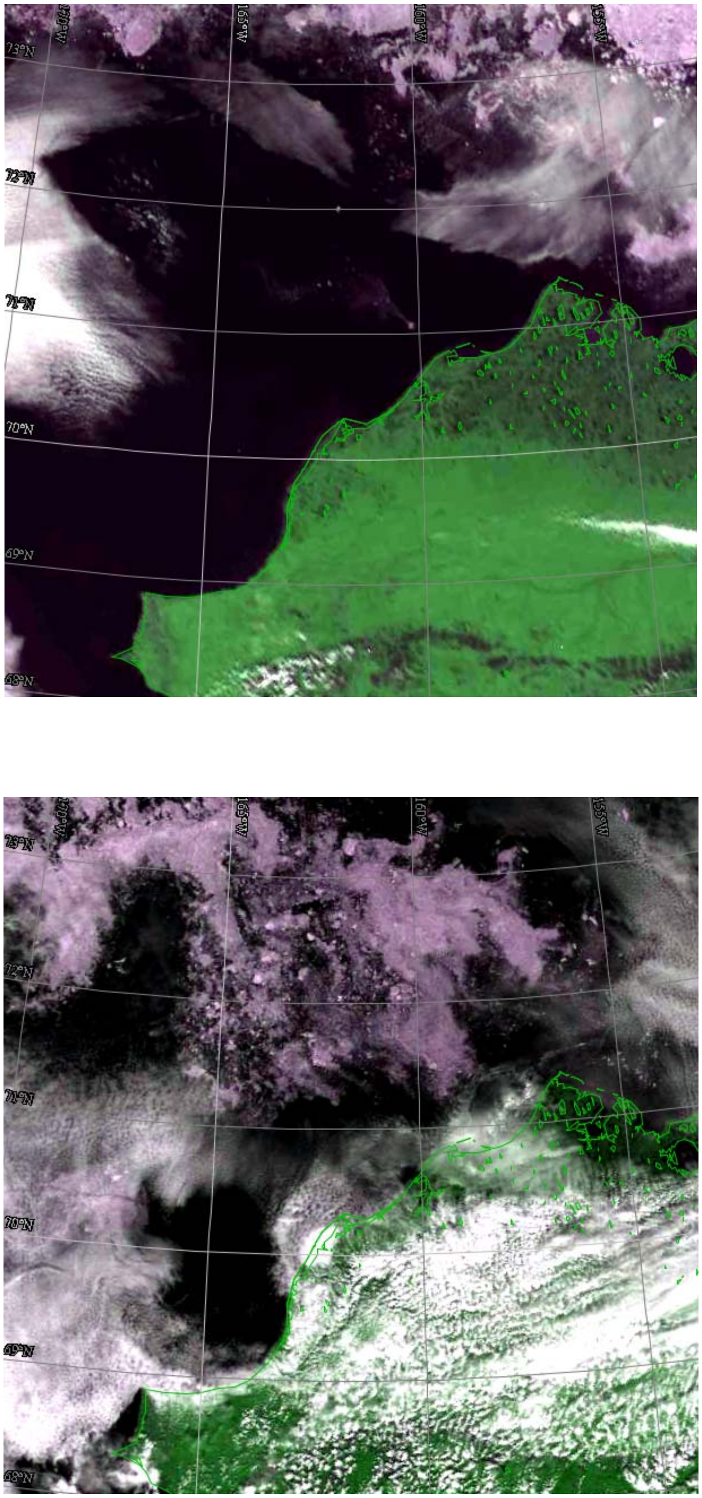

Figure 12. A comparison of ice conditions in the Chukchi Sea on July 23, 2007 (top) and July 23, 2008 (bottom).

Temperature and salinity

Before presenting the spatial distribution of temperature and salinity along the CTD transects we first describe the various water masses observed in both survey areas with the aid of **Figure 13**, which shows the temperature and salinity characteristics at each 1-meter averaged CTD sample from all casts. These data are plotted as scatter plots in temperature-salinity (T/S) space and color-coded red for Burger and blue for Klondike. Separate plots are presented for each cruise, which allows us to examine the seasonal evolution of water properties at each site. The data distribution indicates considerable variability with temperatures ranging from nearly 5.8°C to –1.7°C and salinities ranging from <28 to ~33 over all 2008 surveys. The temperature range is greater at Klondike than Burger while the salinity range is greater at Burger than Klondike. The water types in Burger and Klondike tend to differ from one another for each cruise, with the greatest overlap of water properties occurring on the 8/18 – 9/20 cruise. In general, Klondike waters are saltier and warmer than Burger waters for all water types with salinities <32.5. At higher salinities, the temperatures are at or near the freezing point so that the water properties at each station merge. The coldest and most saline waters were formed the previous winter during freezing and the extrusion of salt during ice formation and are only slowly removed from this sector of the NE Chukchi shelf in summer (*Weingartner et a*l., 2005) by the flow. As shown later, these waters are all found near the bottom and in both the Burger prospect and the northeast portion of the Klondike prospect. However, the winter-formed waters were absent from Klondike during the 20 September- 9 October cruise, although still present in Burger. The relatively cold (<2°C) and fresh (e.g., salinity ~ <30) waters are likely associated with melting ice and primarily occurred at Burger. The warmer and saltier waters are probably recently advected northward onto the Chukchi shelf from Bering Strait and were chiefly found at Klondike.

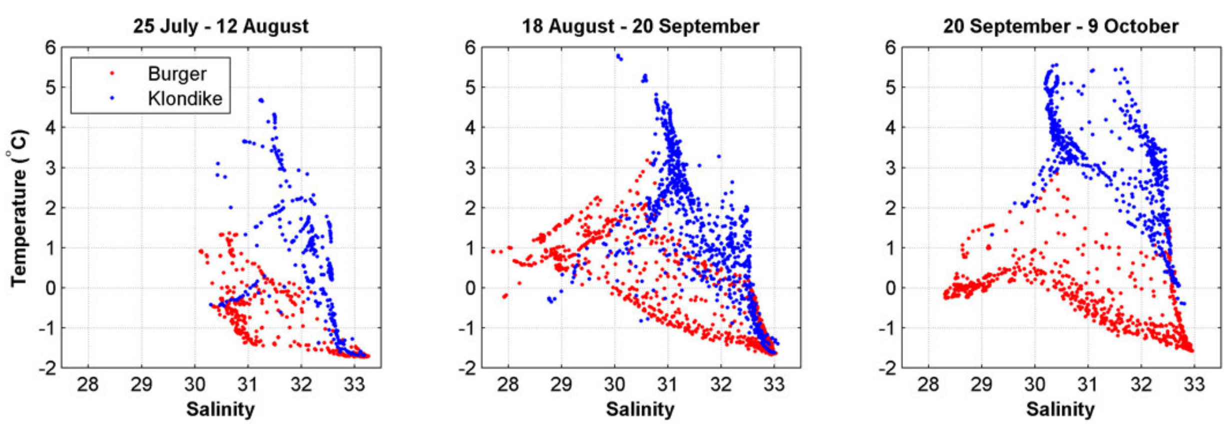

Figure 13. Temperature-salinity diagrams for each survey conducted in 2008.

We next investigate the temperature, salinity, density, and fluorescence distributions as a function of distance and depth (pressure) along a number of transects across both the Klondike and Burger survey areas. For each survey, we constructed transects that extend from west-east, south-north and from southwest-northeast across both survey areas. **Figure 14** shows the transect locations used in these constructions. These transects were contoured since they constitute the broadest possible sections from the survey cruises. Note that the diagonal and south-north transects each include a dogleg.

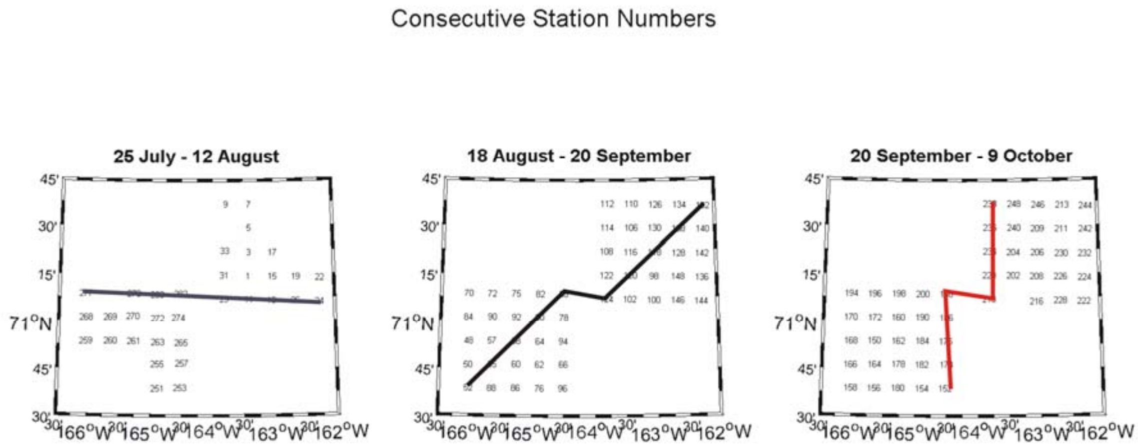

Figure 14. The distribution of stations during each survey in 2008. The black line in the 25 July – 12 August survey shows the stations that were used in constructing the east-west transects. The black line in the 18 August- 20 September survey shows the stations used in constructing the southwest-northeast transects. The red line in the 20 September – 9 October survey shows the stations used in constructing the south-north transect. The west-east, southwest-northeast, and south-north transects were contoured for each survey.

August 3 – 12 2008 Survey

The spatial distributions of water mass properties are shown along several sections constructed from the Klondike and Burger stations. **Figures 15 - 17** are west-east, south-north, and southwest-northeast transects formed from stations occupied in both survey areas (**Figure 14**). For each transect we show four panels; temperature (^{o}C), salinity (unitless), sigma-t (a scaled variable for water density), and fluorescence (volts). The latter is a relative measure of chlorophyll biomass.

The section from the 3-12 August survey (**Figure 15**) indicates a west-east division in water masses. The two westernmost stations are relatively warm (1 to 1.5^{o}C), moderately saline (~32 to 32.5) and weakly stratified in the lower 10 m of the water column. These stations are separated from those to the east by a weak surface temperature and salinity front across which temperatures (salinities) decrease by 1^{o}C (1). We suspect that this front lies along the eastern flank of the Central Channel that carries Bering shelf water northward onto the outer Chukchi shelf. East of the front, the stations have a nearly 20 m thick bottom layer of cold (~-1.5^{o}C), salty (33) water remnant from the previous winter. The bottom layer is separated by a strong halocline (across which salinities increase by about 2 over 10 m), from a relatively fresh (<31) and cold (0 – 1.0^{o}C) 15 m thick surface layer. Fluorescence is maximal at mid-depth and generally within the stratified zone, suggesting that at this depth both light and nutrients are abundant enough to suggest photosynthesis. The southwest to northeast section across Klondike and Burger is shown in **Figure 16** and has many of the same features seen in the west-east section.

T1we 3 - 12 August 2008

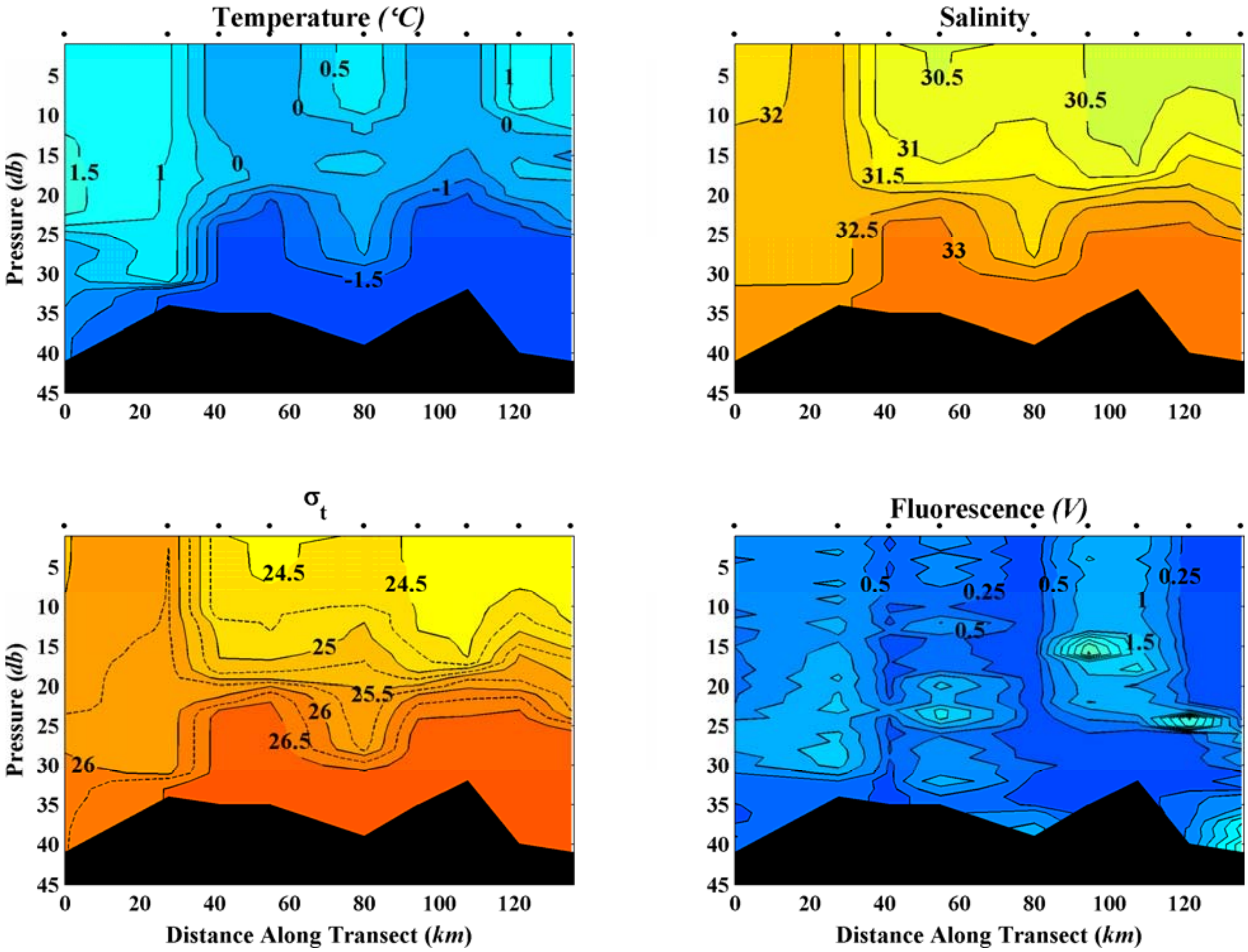

Figure 15. West-east section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 3-12 August survey.

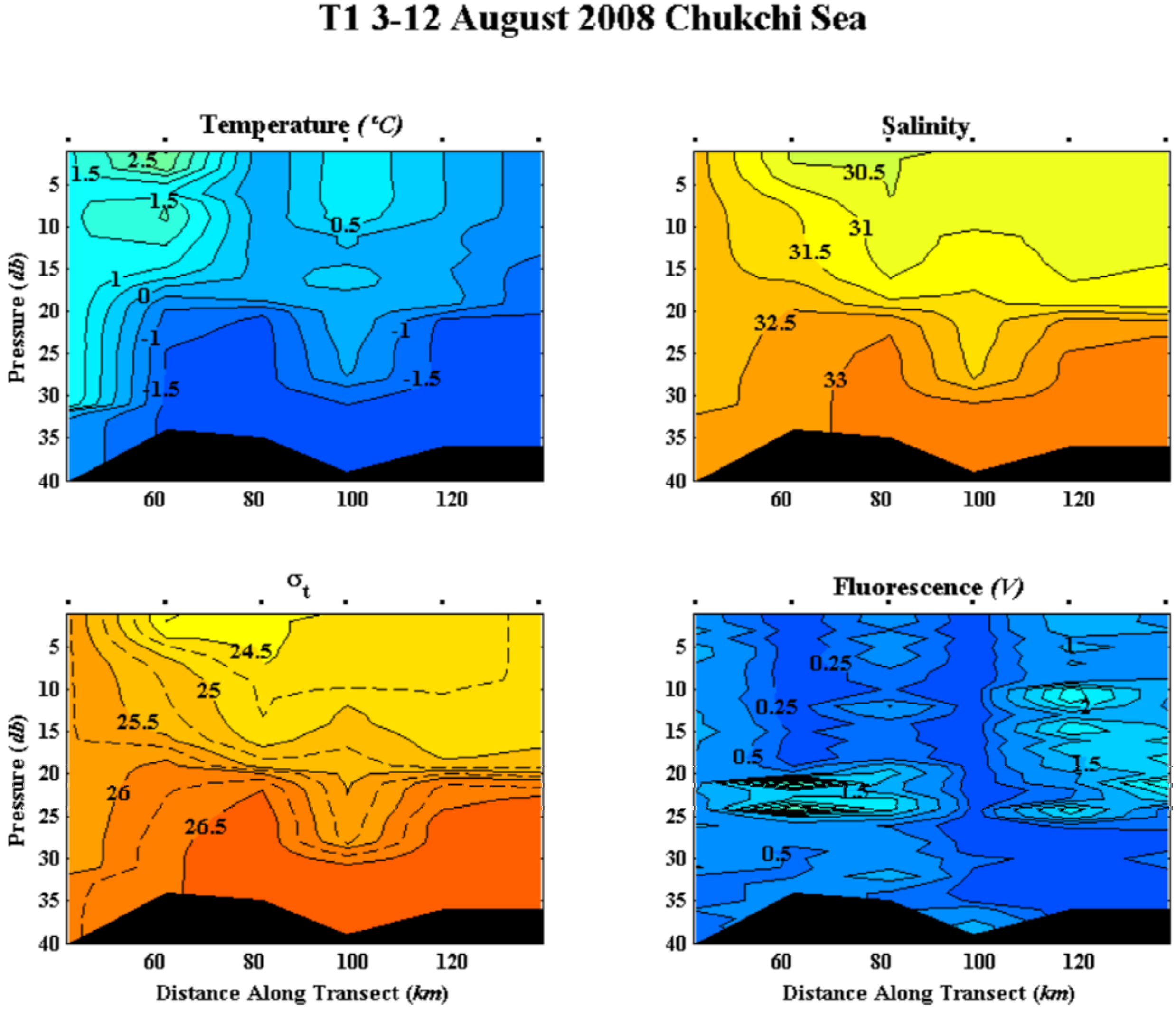

Figure 16. The southwest-northeast section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 3-12 August survey.

The south-north sections (**Figure 17**) from the August 2008 survey further illustrate the spatial variations in water properties. Warm (>4°C) waters are found at the southern end of the transect and are confined to the upper 10 m of the water column. Surface temperatures decrease rapidly north of this warm water (e.g., they decrease by 3°C across a temperature front that spans a distance of 40 km), before more gradually decreasing to about 0°C at the northern end of the transect. Temperatures are, however, relatively cold beneath the surface layer and range from 0°C at the southern end of the section to -1.5°C at the northern end. The surface temperature front slopes downward to the south, indicating that relatively warm surface waters are moving over the colder subsurface water. The salinity structure along this section includes relatively dilute surface waters at the northern end of the section and moderately saline surface waters at the southern end and at mid-depth over the middle of the section. At depths deeper than 20 m the entire section is filled with high salinity water, with the highest salinities at the northern end of the section. Note also that the 31 and 31.5 isohalines bow upward toward the south. The inclination of these isohalines is opposite to that of the isotherms. However, there is no strong frontal structure evident in the isopycnals (sigma-t isopleths), which implies that the density of the fresh, the density of the cold waters along the northern end of the transect is similar to the density of the warm and salty waters penetrating from the south. Hence, neither the thermal or haline front along this section is a dynamic front in across which frontal exchange is inhibited; thus the water masses can easily mix laterally with one another here.

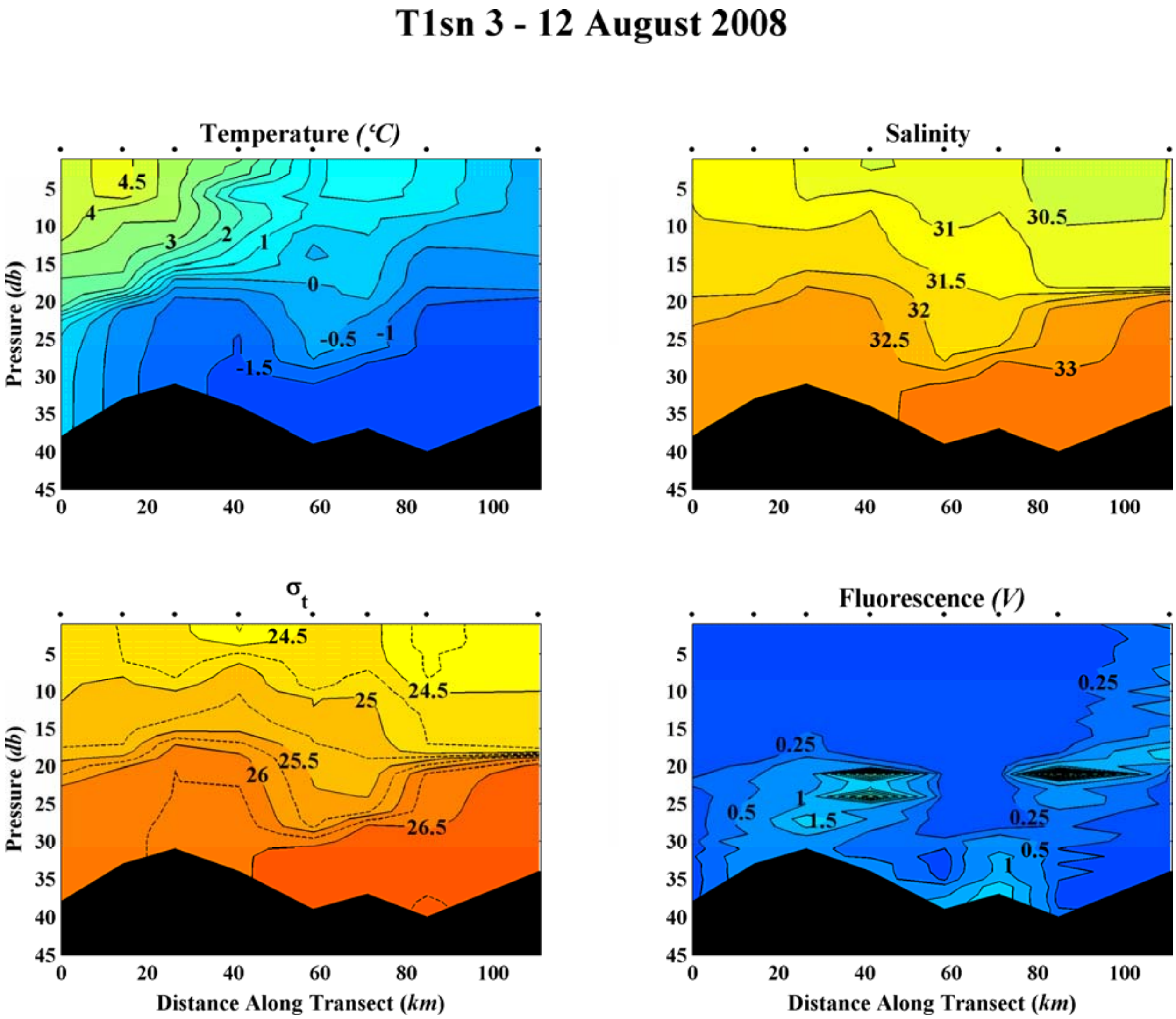

Figure 17. The south-north section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 3-12 August survey.

August 18 – September 20 2008 Survey

The corresponding figures for this survey are shown in **Figure 18** (west-east), **Figure 19** (southwest-northeast) and **Figure 20** (south-north). At this time bottom waters with salinities $\geq$ 33 had been flushed from the region and bottom temperatures had warmed slightly since there were only a few stations with bottom temperatures <-1.5°C. Instead the lower half of the water column, in both Klondike and Burger, has salinities of 32.5 or greater and temperatures <0°C. The surface layer, however, has a more complicated temperature and salinity structure. Along the western end of the section, relatively warm and moderately saline waters are found adjacent to the Central Channel, and the waters here are relatively unstratified compared to the other stations. Elsewhere, but primarily in the northeastern corner of Klondike and within Burger, the surface layer consists of bands of cool (~0°C), low salinity (29) water, very likely associated with ice meltwater, separated by warmer and saltier filaments. These bands are shallow, ~20 m or less, and are most likely associated with shallow eddies and meanders emanating from dynamic instabilities associated with ice edge fronts and/or meltwater presumably trapped over Hanna Shoal.

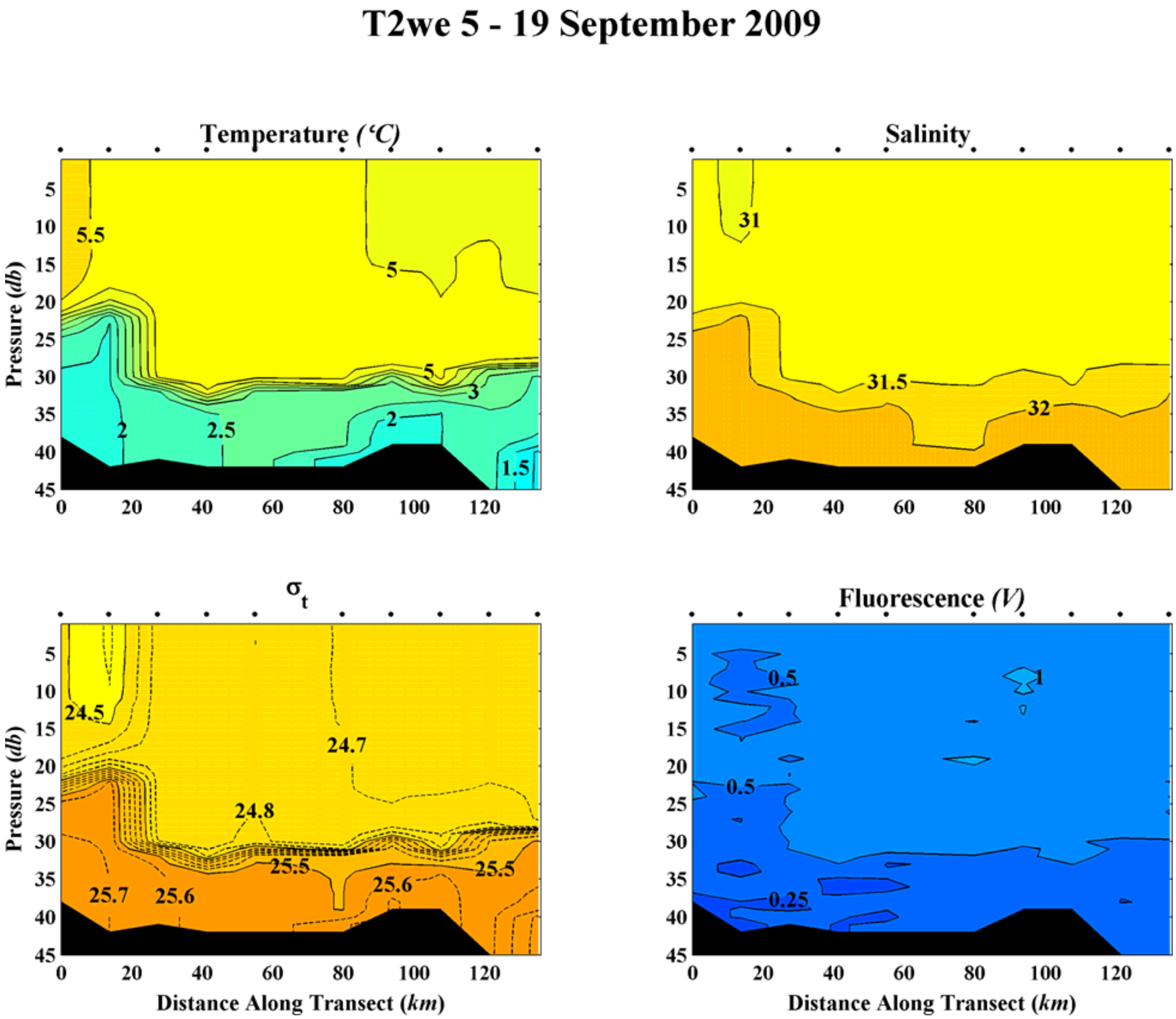

Figure 18. The west-east section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 18 August – 20 September survey.

This was surmised to be the case based on the review of the satellite imagery presented earlier and it is also suggested in both the southwest-northeast (**Figure 19**) and south-north (**Figure 20**) transects, which indicate cold (<2°C), low-salinity (<30) water in the upper right hand panel of each figure.

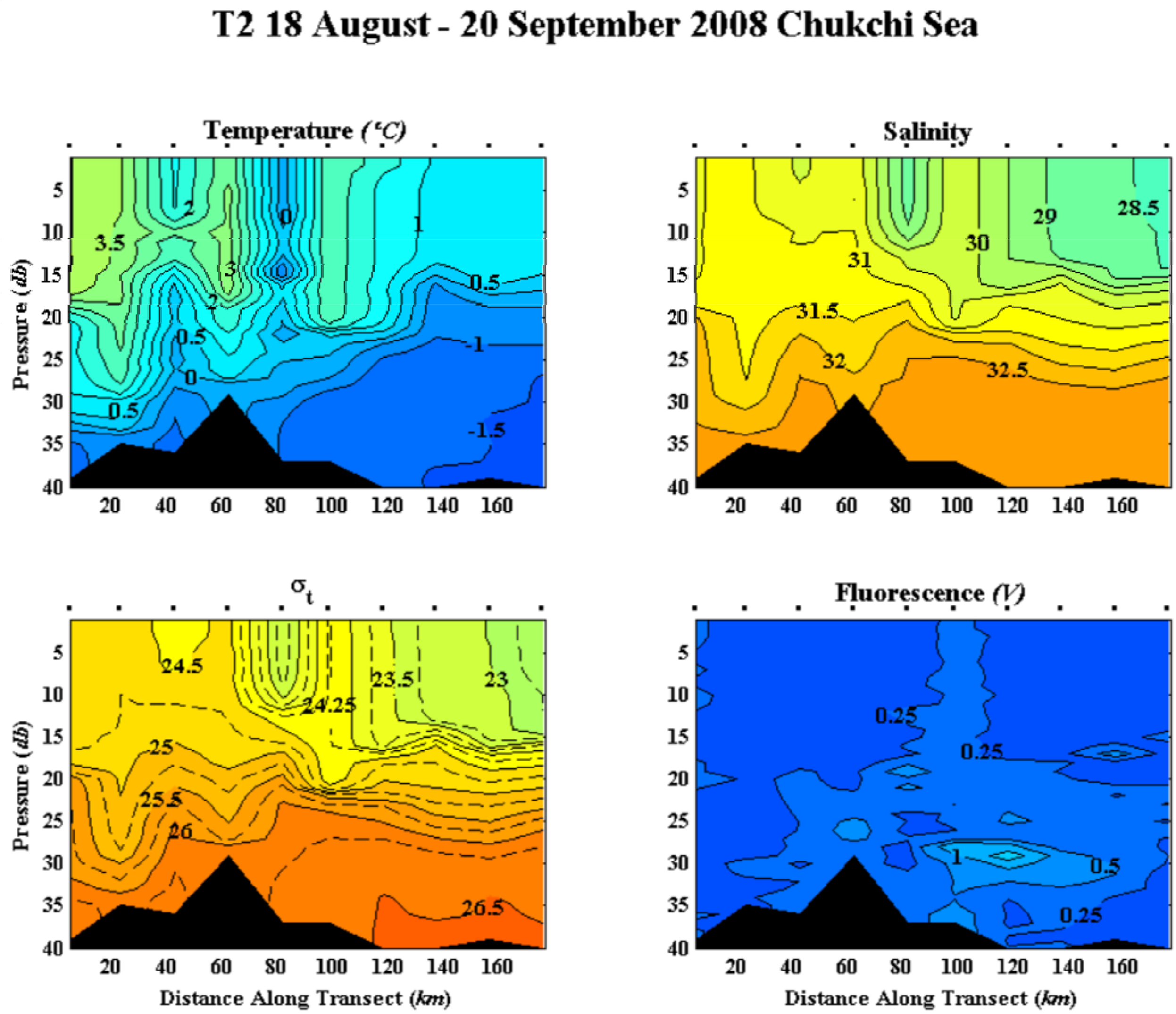

Figure 19. The southwest-northeast section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 18 August – 20 September survey.

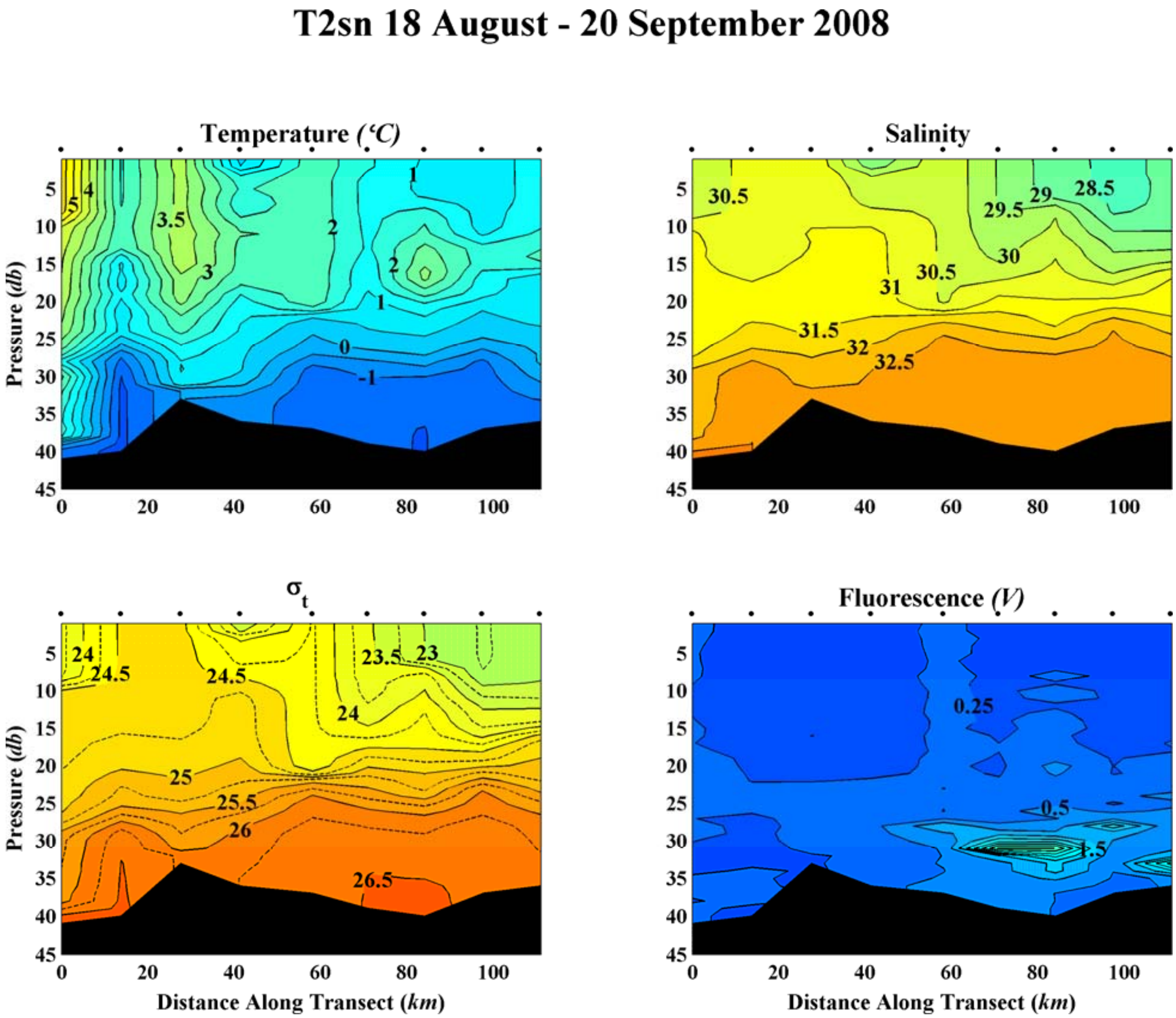

Figure 20. The south-north section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 18 Aug. – 20 Sept. survey.

September 20 – October 9 2008 Survey

Many of the basic features of the hydrography evident during the first two surveys were present by the time of the third survey. For example, relatively warm and moderately saline water is still found in the westernmost stations along the west-east line (**Figure 21**), and cold, saline water occupies the bottom 15 m or so of the water column, while cool, dilute water occupies most of the upper water column. There is a noticeable decrease in the amount of water with salinity of 32.5 found in all sections compared with the second survey. In addition, the bands and filaments inferred on the second survey have largely disappeared. These have been replaced with broad pools of cool, dilute water. Conceivably the filaments inferred from the second survey mixed (both laterally and vertically) through time and thus formed a rather thick upper layer water mass with salinities <30 and temperatures of from 0.0 to 2^{o}C. We note that there is still a considerable amount of warm water entering the southwestern, southern and western flank of the Klondike prospect (**Figures 22 and 23**), although that water has not penetrated much farther north than on the other surveys. This is consistent with the notion that the waters south of Hanna Shoal are only replenished slowly throughout the summer and fall.

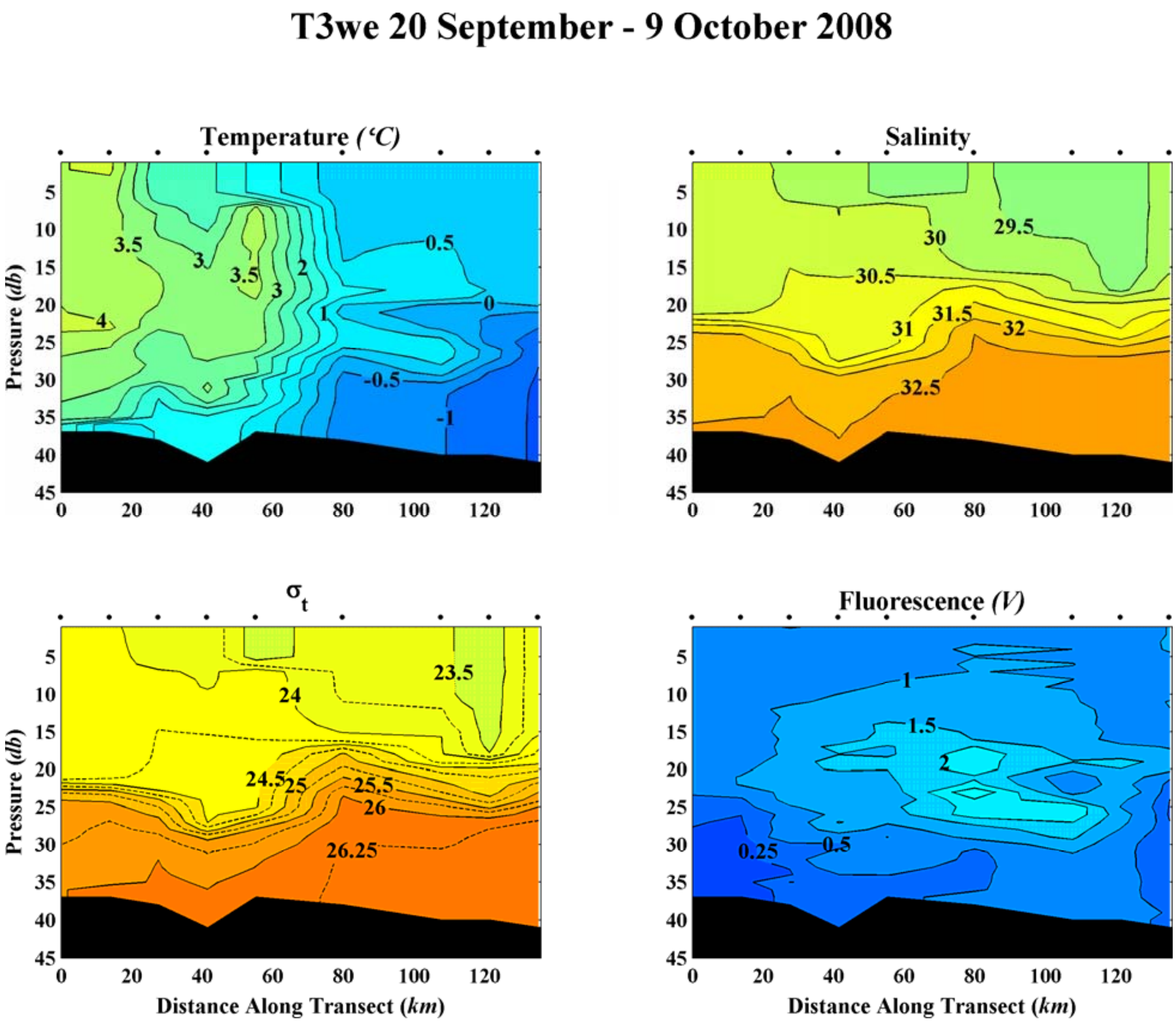

Figure 21. The west-east section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 20 September – 9 October survey.

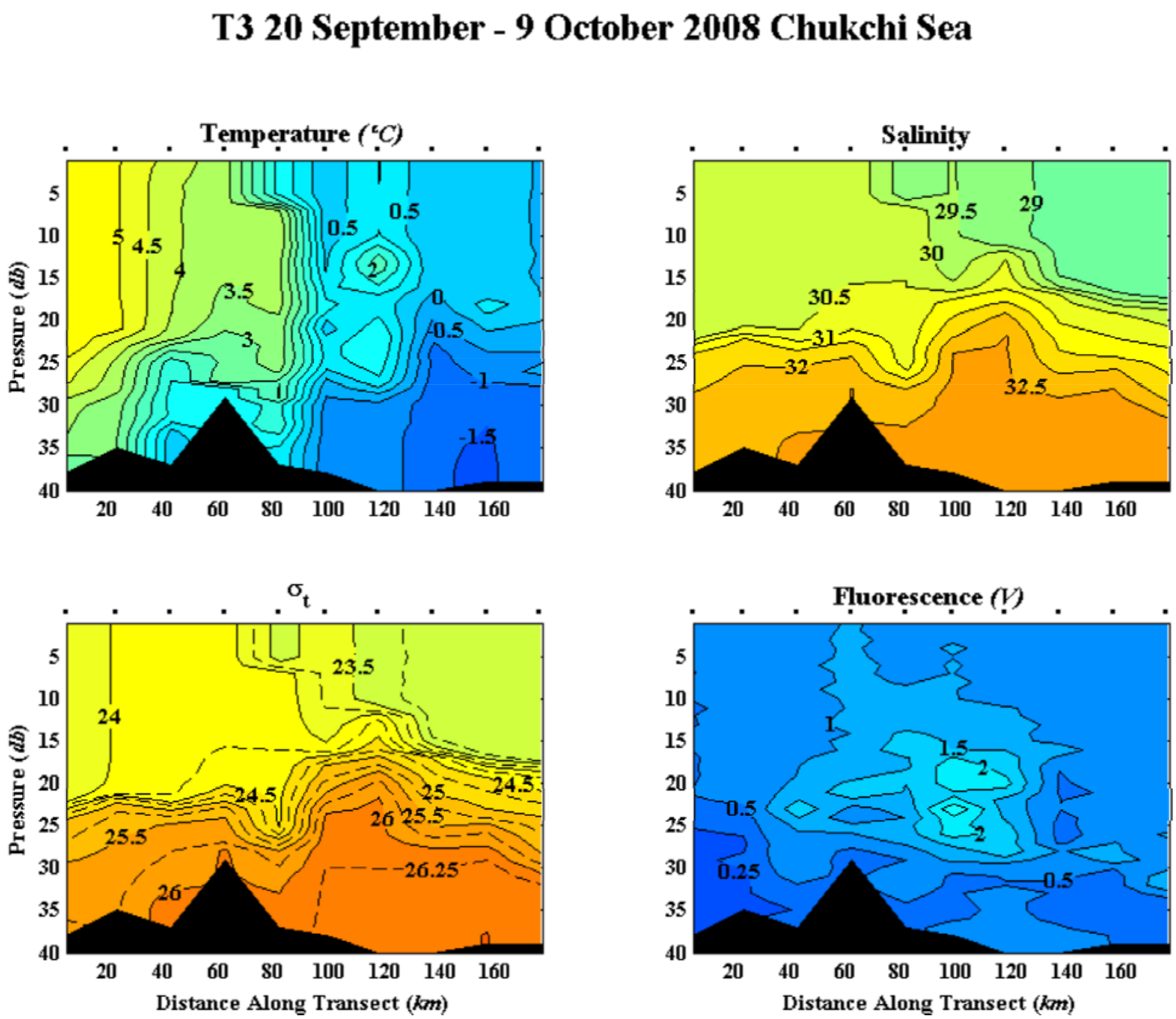

Figure 22. The southwest-northeast section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 20 September – 9 October survey.

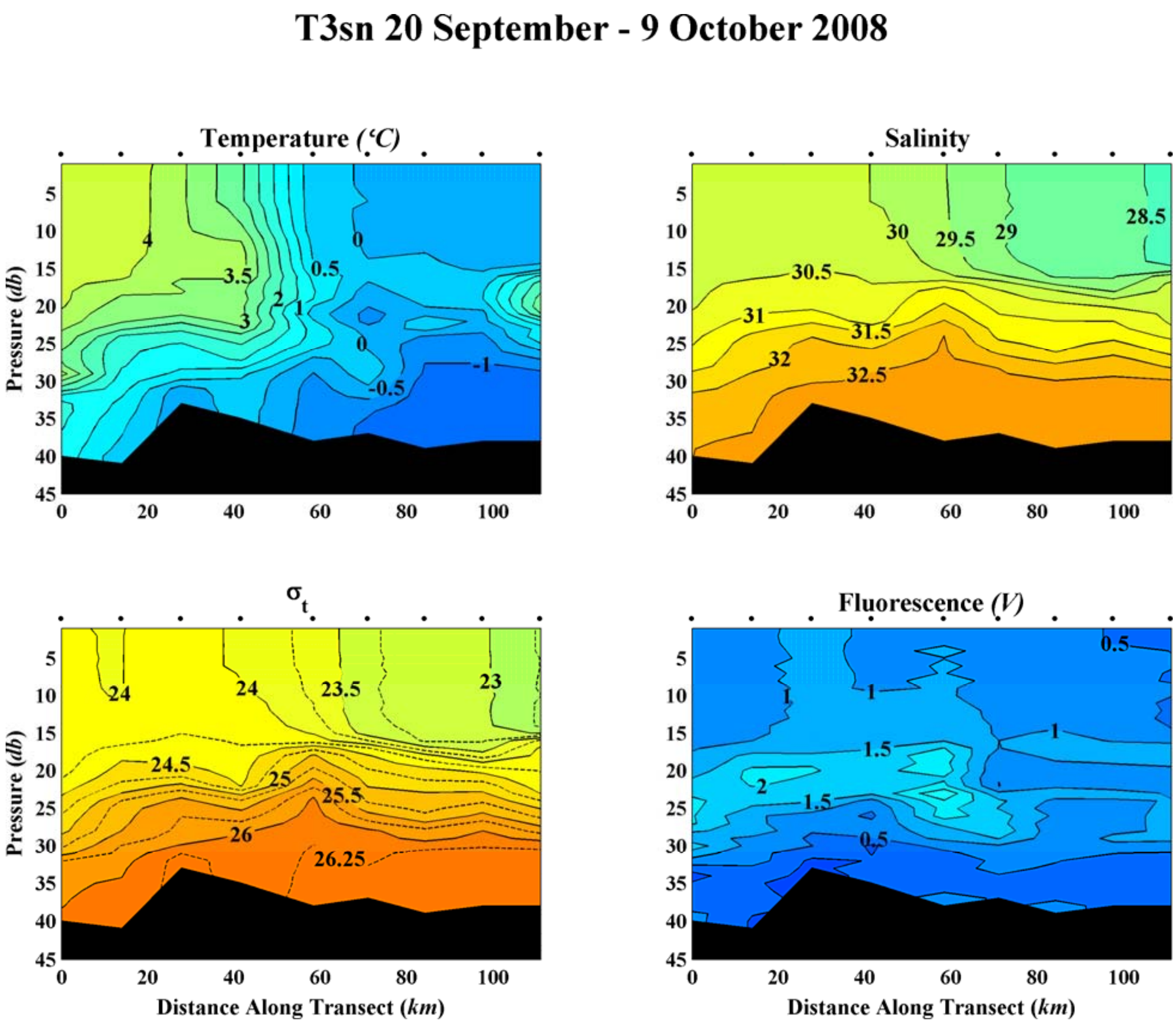

Figure 23. The south-north section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 20 September – 9 October survey.

We close by noting that in all the sections the maximum fluorescence is not found at the surface, but at mid-depth and within the halocline that separates the surface mixed layer from the deeper waters. This suggests that the upper layers were depleted in nutrients by the time of the first survey, but that sufficient light and nutrients were available at mid-depth to maintain primary production throughout the summer and early fall.

Many of the features alluded to above are also evident in vertically-averaged temperature and salinity properties, with the averaging performed over the upper (or lower) 10 m of the water column. For example, **Figures 24 and 25** show these variables for each survey averaged over the upper 10 m and contoured in plan view. **Figure 24** shows that upper ocean temperatures in the Burger prospect changed only slowly through time, whereas, Klondike surface temperatures warmed appreciably between early August and Late September. Moreover, the temperature and salinity (**Figure 25**) pattern also suggest the northward penetration of warmer salty water on the west side of Klondike and the presence of a moderately strong thermal front in Klondike. That front does not appear to have changed position throughout the year, although the strength of the thermal gradient is variable.

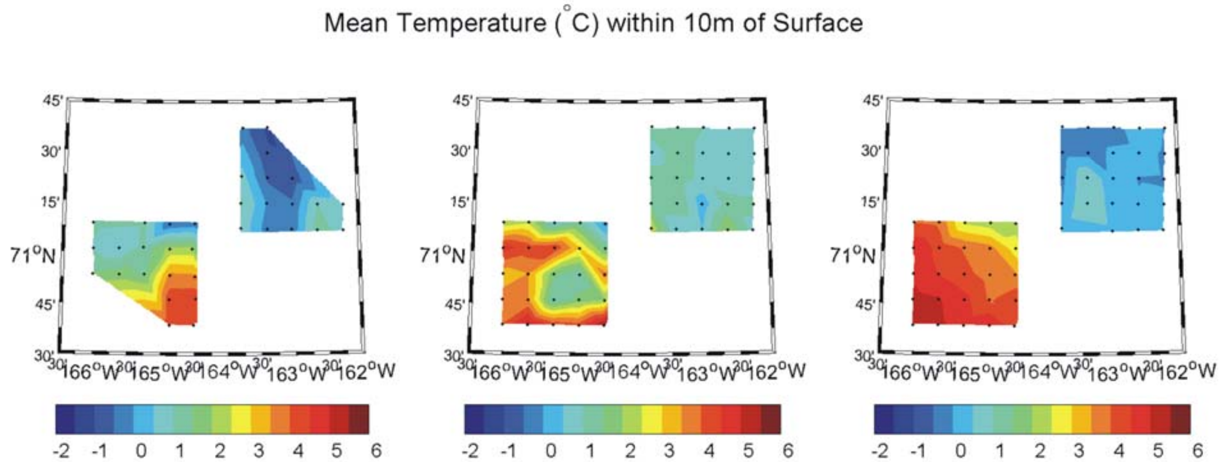

Figure 24. Plan view of mean temperature over the upper 10 m of the water column for the 25 July - 12 August survey (left), the 19 August -29 September survey (middle) and the 20 September – 9 October survey (right).

The front is also evident in satellite imagery, which affords a broader scale perspective (**Figure 26**). The image shows that the warm water spreads northward from Bering Strait, with a tongue protruding northward through the Central Channel (indicated by an arrow in the figure), while to the north and northeast surface temperatures are relatively cold. Note that the sharp color (and thermal) contrast between the warm water from the south and the cold water to the north defines the position of the front. We also not that the warm water does not extend along the northwest coast of Alaska (as is often the case) in this image. Most likely this reflects the winds from the northeast that prevailed in much of August. These winds would have promoted upwelling of cold water along the coast and/or prevented the Alaskan Coastal Current from penetrating northeastward along the coast.

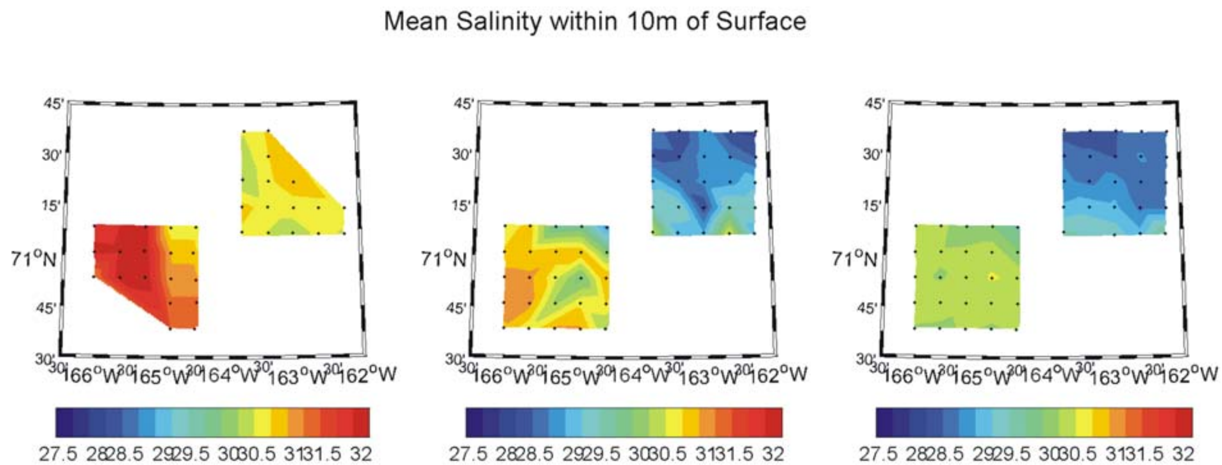

Figure 25. Plan view of mean salinity over the upper 10 m of the water column for the 25 July - 12 August survey (left), the 19 August -29 September survey (middle) and the 20 September – 9 October survey (right).

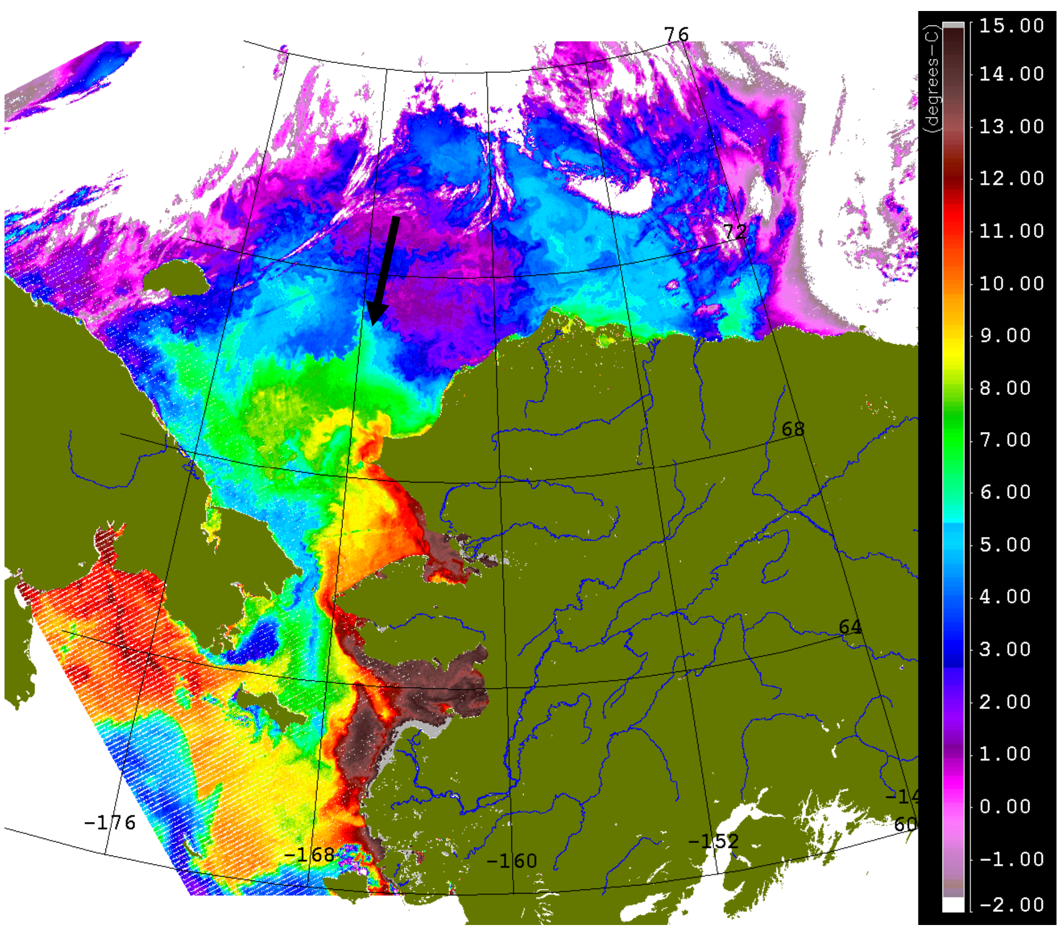

Figure 26 August 22, 2008 MODIS sea surface temperature image of the Chukchi Sea and Bering Strait. (MODIS/Aqua data obtained from Ocean Color Data Processing Archive NASA/Goddard Space Flight Center Greenbelt, MD – USA and available at:

http://mather.sfos.uaf.edu/~mschmidt/ims_chukchi_sea_summary.html. The black arrow indicates the tongue of relatively warm water in the Central Channel.

By contrast, we show a comparable image from August 24, 2007, when winds were more frequently from the south. In 2007, warm waters pervaded the northeast Chukchi shelf, with the warmest waters seen moving along the Alaskan coast, past Barrow and out onto the Beaufort Sea slope.

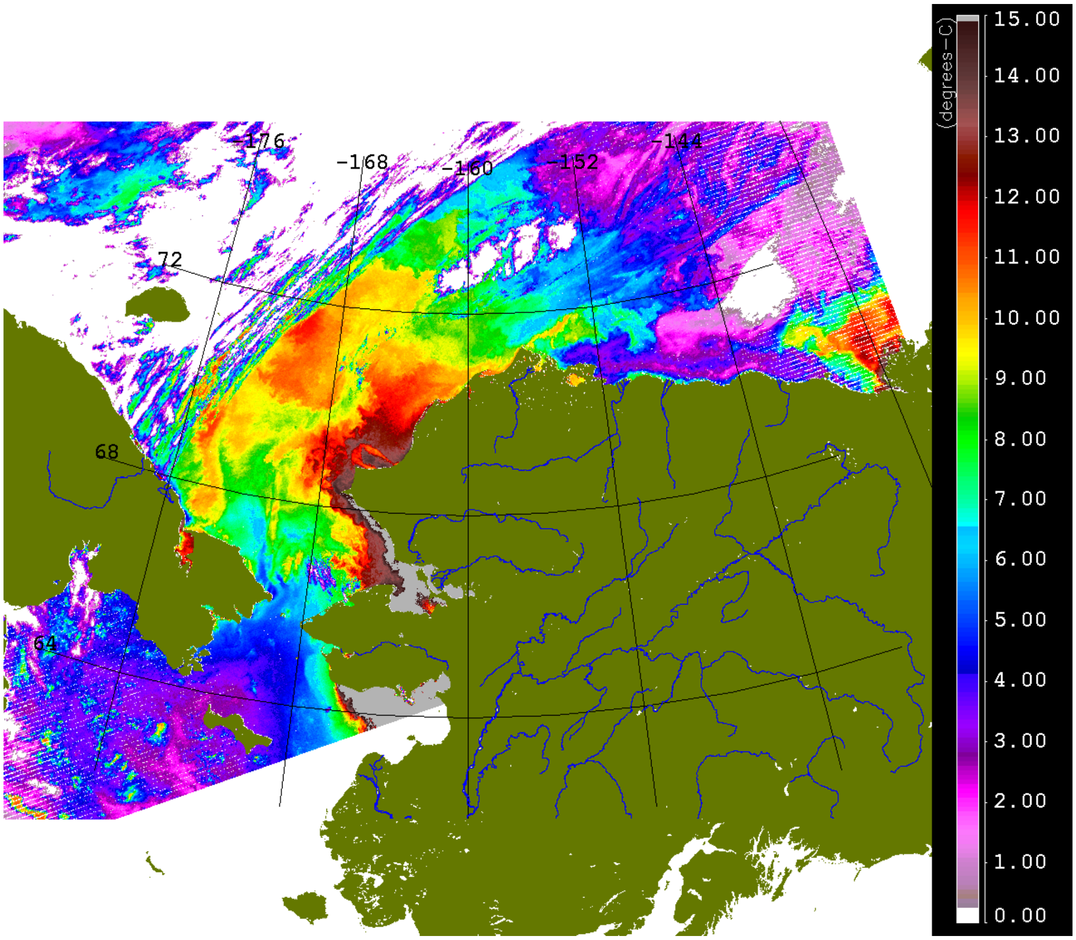

Figure 27 August 24, 2007 MODIS sea surface temperature image of the Chukchi Sea and Bering Strait. (MODIS/Aqua data obtained from Ocean Color Data Processing Archive NASA/Goddard Space Flight Center Greenbelt, MD – USA and available at: http://mather.sfos.uaf.edu/~mschmidt/ims_chukchi_sea_summary.html.

We conclude this section with **Figures 28 and 29**, which show the temperature and salinity averaged over the bottommost 10-m of the water column for each survey. Once again these figures underscore that relatively rapid changes in temperature and salinity occur in Klondike over the season, while nearly constant temperature and salinity conditions occurred at Burger.

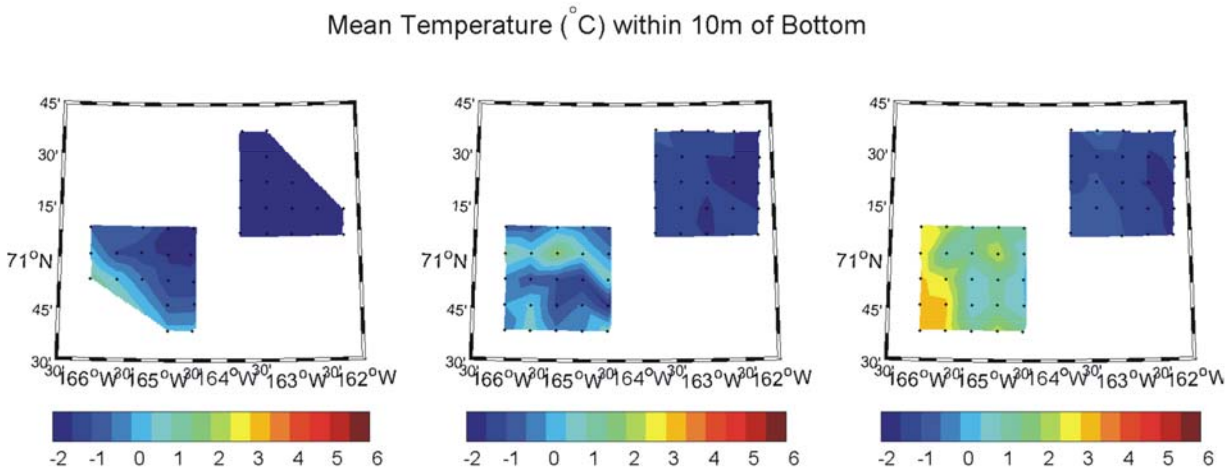

Figure 28. Plan view of mean temperature over the bottom 10 m of the water column for the 25 July - 12 August survey (left), the 19 August -29 September survey (middle) and the 20 September – 9 October survey (right).

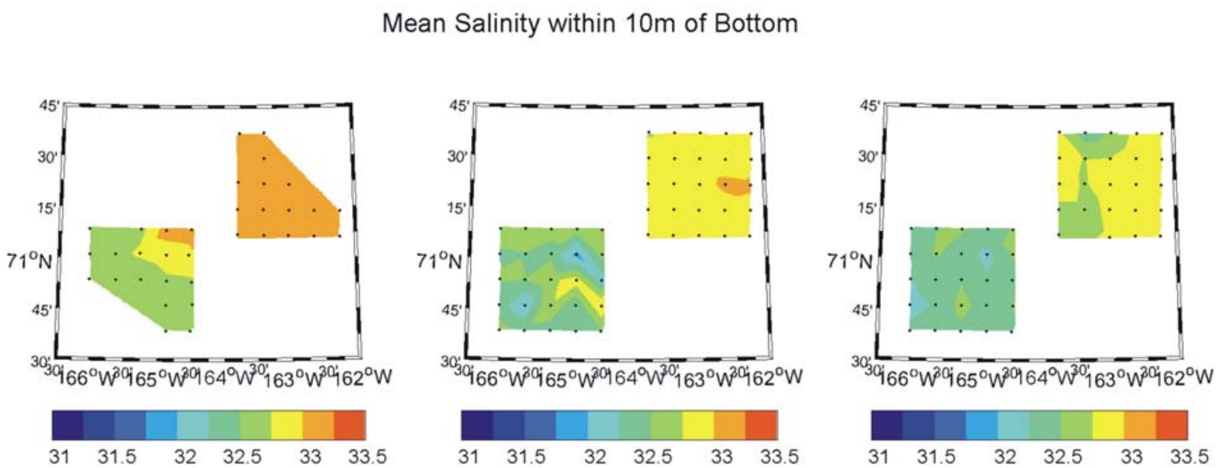

Figure 29. Plan view of mean salinity over the bottom 10 m of the water column for the 25 July - 12 August survey (left), the 19 August -29 September survey (middle) and the 20 September – 9 October survey (right).

Results: 2009 Survey

Winds and Sea Ice.

Figures 30-32 show the QuikSCAT-based weekly averaged wind and sea ice fields over the northeast Chukchi Sea throughout the 2009 survey period and are comparable to **Figures 7-10**. In all figures, the black regions are sea ice or grid cells contaminated by adjacent land (see around Bering Strait for example) and the red circle denotes the location of Barrow. The mean winds for the week ending July 27, 2008 (**Figure 30**) were from the northeast at 5 – 10 m s^{-1} over the Beaufort and Chukchi shelves. As in 2008, sea ice had retreated over broad areas of both shelves by late July but relatively heavy concentrations remained over Hanna Shoal and in a broad band extending westward over the northern Chukchi shelf. For the week preceding August 3 the mean winds were westward at ~5 m s^{-1}. However, there were strong southerly winds during that week that rapidly displaced (or enhanced) melting of the ice over Hanna Shoal. Mean winds for the week prior to August 8, were also southerly and thus enhanced the retreat of ice that began the preceding week. Winds during the next three weeks (**Figure 31**) were either westerly or southerly at speeds of 5 - 10 m s^{-1} and so favorable to northward flow of Bering Sea waters onto the Chukchi Sea shelf and northward retreat of sea ice. Southerly winds continued through the first week of September (**Figure 32**) but thereafter northerly or northeasterly winds developed and persisted through early October (**Figures 31 and 32**).

Although extensive cloud cover precluded obtaining visible satellite imagery in 2009, high-resolution sea ice maps obtained from the Advanced Microwave Scanning Radiometer suggest that ice-free conditions developed over Hanna Shoal by early August 2009. In contrast, ice persisted over Hanna Shoal until late August 2008. One reason for the difference between years appears to be the more persistent northerly winds in July and August of 2008 compared to 2009. However, Barrow air temperatures in July and August of 2008 were ~1^{o}C below normal whereas in 2009 Barrow air temperatures for the same months were 1 – 2^{o}C above normal. This suggests that melting may also have been more rapid in 2009 than in 2008. There may also have been a larger transport of mass (and heat) through Bering Strait in mid-summer 2009 than in 2008 owing to the differences in summer winds. Finally we note, that sea ice began retreating earlier in the southern Chukchi Sea in 2009 than in 2008. An earlier retreat is expected to enhance melting since water has a smaller albedo than sea ice. Hence as open water appears more of the solar radiation is absorbed by the water than the ice. As the water is advected northward it will enhance melting along the ice edge.

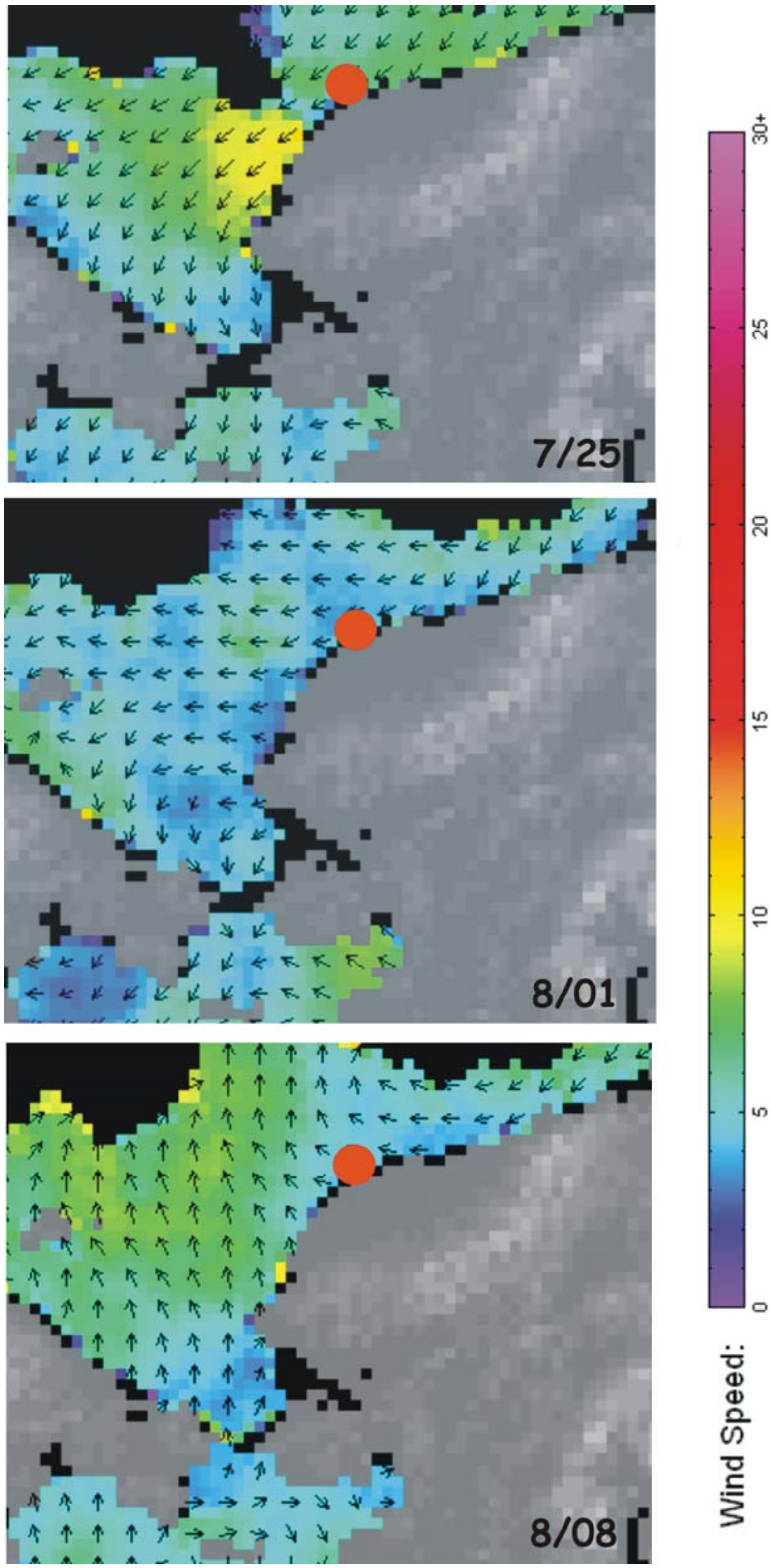

Figure 26. Weekly averaged vector winds and wind speeds over the northeast Chukchi Sea for the week ending July 25, 2009 (top), August 1 (middle) and August 8 (bottom). The red dot indicates the location of Barrow.

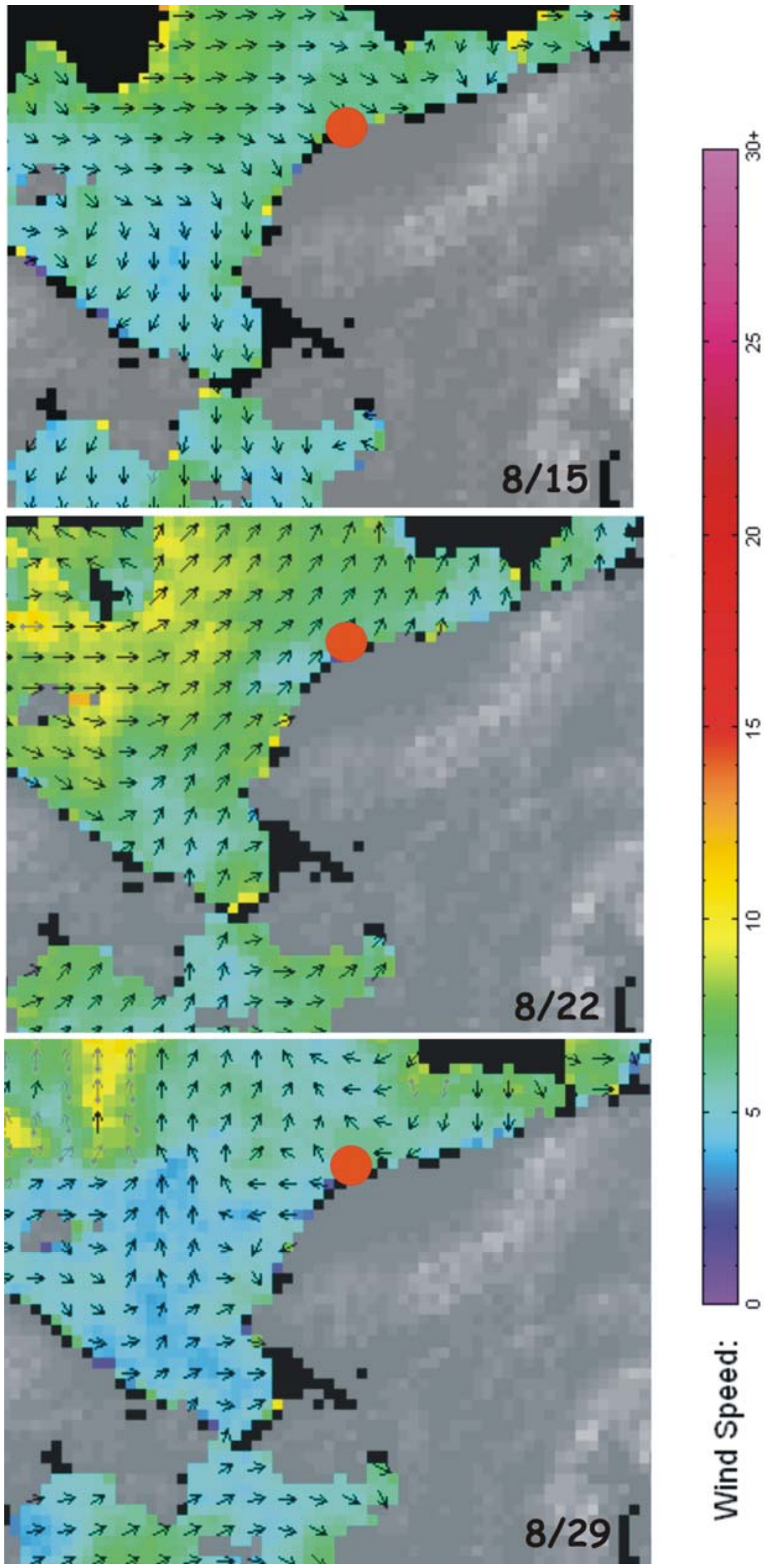

Figure 30. Weekly averaged vector winds and wind speeds over the northeast Chukchi Sea for the week ending August 15, 2009 (top), August 22 (middle) and August 29 (bottom). The red dot indicates the location of Barrow.

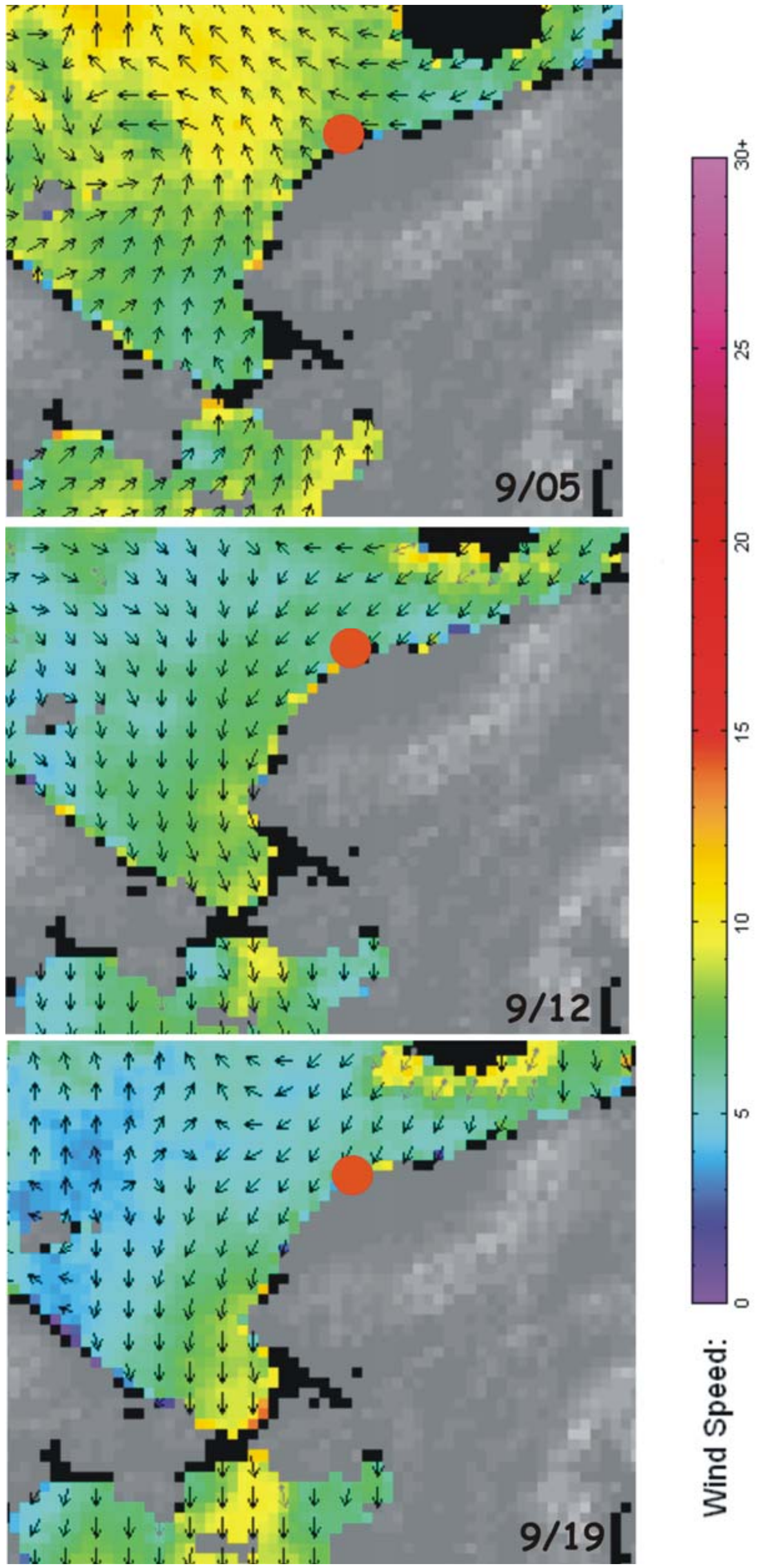

Figure 31. Weekly averaged vector winds and wind speeds over the northeast Chukchi Sea for the week ending September 5, 2009 (top), September 12 (middle) and September 29 (bottom). The red dot indicates the location of Barrow.

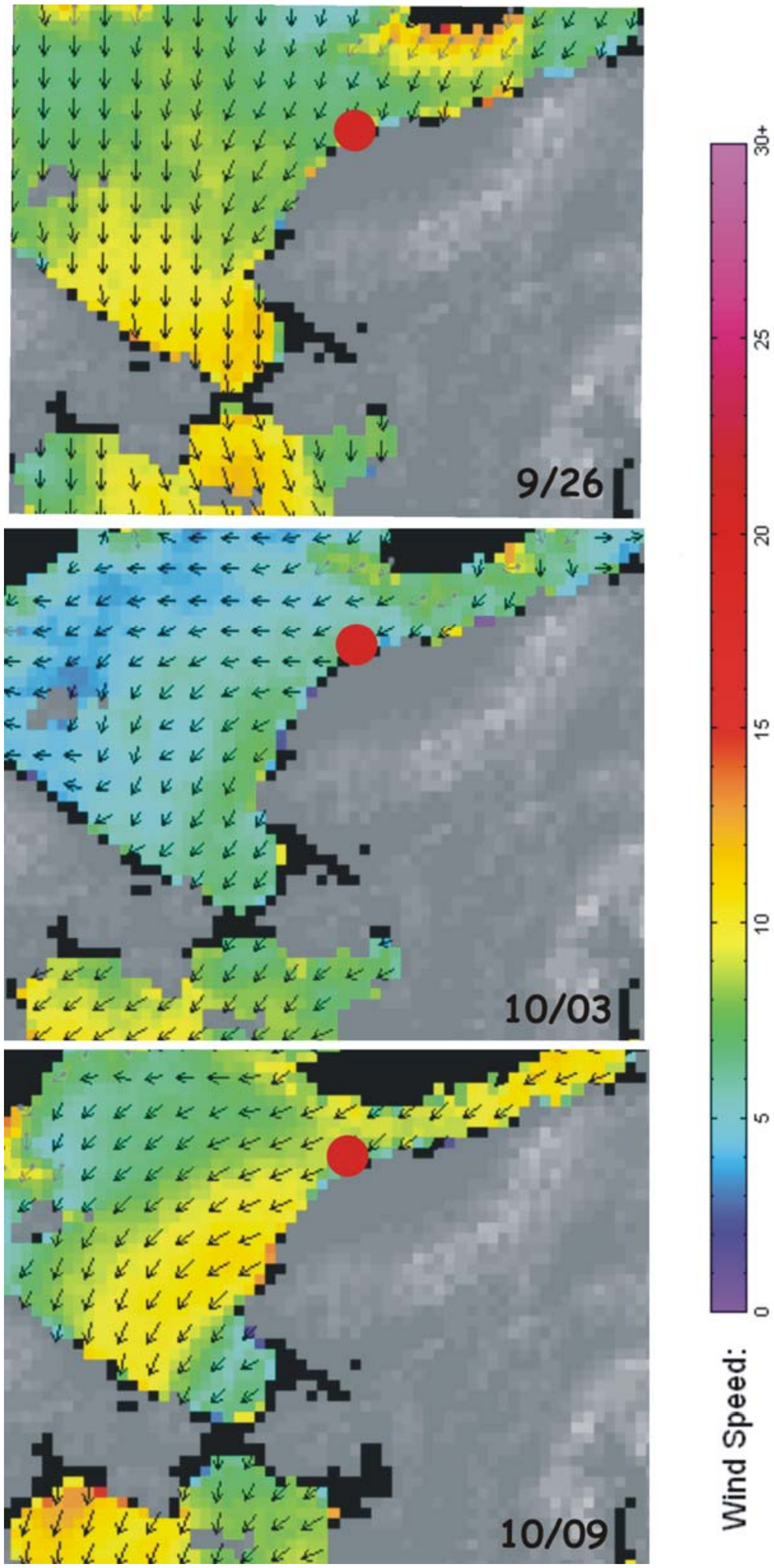

Figure 32. Weekly averaged vector winds and wind speeds over the northeast Chukchi Sea for the week ending September 26, 2009 (top), October 3 (middle) and October 9 (bottom). The red dot indicates the location of Barrow.

Temperature-Salinity

As with the 2008 survey, we begin by reviewing the temperature-salinity (T/S) diagrams for each cruise (**Figure 33**), with red dots signifying data from the Burger prospect and blue dots indicating data from Klondike. Separate plots are presented for each cruise and these may be directly compared with their 2008 counterparts. The data distribution indicates considerable variability with temperatures ranging from nearly 8°C to –1.7°C and salinities ranging from ~28 to ~32.8. As in 2008, the temperature range is greater at Klondike than Burger while the range in salinity is greater at Burger than Klondike. However, for salinities >32, the water properties at each prospect are similar. The broad range in T/S properties at Burger, especially for water types with salinities <~31, reflects warming of ice-melt waters and mixing with adjacent water masses. In general, Klondike waters are saltier and warmer than Burger waters for all water types with a salinity <32.5.

The T/S diagrams for each site and cruise reflect the seasonal transition in water masses. For example, at Klondike the salinity distribution varies very little between cruises, but there is a systematic decrease in temperatures at the high temperature end of the Klondike distribution, which reflects seasonal cooling of the upper ocean. This seasonal temperature decrease is also evident at Burger, particularly between the second and third surveys. There is also a systematic change in the properties of the coldest and saltiest waters at each site between summer and fall, e.g., the coldest and saltiest waters present on the 14 – 29 August cruise are gradually replaced by warmer and fresher waters. The changes in these near-bottom waters reflects the gradual replacement of the coldest and saltiest waters formed the previous winter by slightly warmer and fresher water from the Bering Sea.

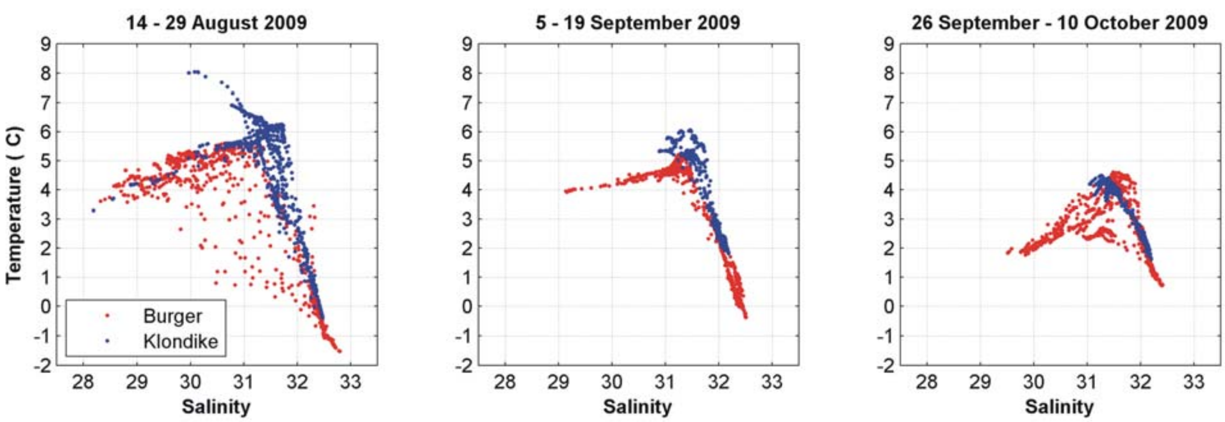

Figure 30. Temperature-salinity diagrams for each of the three surveys conducted in 2009.

Figure 34 shows the distribution of stations occupied in 2009 for the three surveys. As done for the 2008 data we constructed vertical cross-sections of temperature, salinity, density and fluorescence. For each survey we constructed west-east, south-north and southwest-northeast transects that cross both survey areas. The section lines are sketched in **Figure 34**.

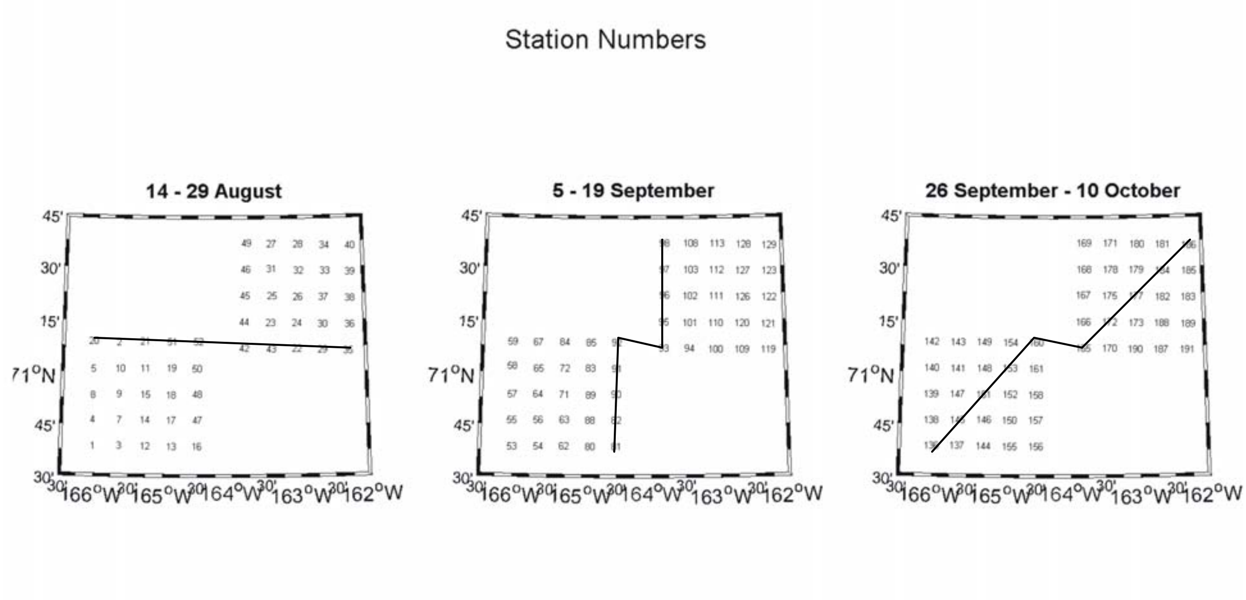

Figure 34. The distribution of stations during each survey. The black line in the 25 July – 12 August survey shows the stations that were used in constructing the west-east transects. The black line in the 18 August- 20 September survey shows the stations used in constructing the southwest-northeast transects. The red line in the 20 September – 9 October survey shows the stations used in constructing the south-north transect. The west-east, southwest-northeast, and south-north transects were contoured for each survey.

August 14 – 29 2009 Survey

Figures 35 - 37 are the west-east, southwest-northeast, and south-north transects formed from stations occupied in both survey areas. The west-east sections from this survey (**Figure 35**) indicate an essentially 2-layer system with temperatures exceeding 4^{o}C and salinities <31.5in the upper 25 m and colder and saltier waters below this depth. Note that the pycnocline separating the two layers is only ~5 m thick, so that the waters in each layer are nearly uniform in the vertical. Temperatures decrease by ~4^{o}C and salinities increase by about 0.5 across the pycnocline. There are however important differences across this section. At the two westernmost stations (near the Central Channel), the upper layer is warmer and saltier than elsewhere suggesting that these waters have recently arrived from the Bering Sea. In contrast the surface waters in the easternmost part of the transect are relatively fresh and may either be vestiges of ice melt waters that have warmed or are filaments of Alaskan Coastal Water extending westward from the coast. The coldest (~-1 C) and saltiest (>32.5) waters, which were formed the previous winter, are also found in the east and along the bottom. Consequently the stratification is stronger in the east than in the west. Fluorescence varies but little throughout the section, although there is a suggestion of a small sub-surface maximum within the pycnocline at some of the stations. The southwest to northeast (**Figure 36**) and the south-north (**Figure 37**) sections across Klondike and Burger have many of the same features seen in the west-east section. Note again that the warmest (> 7^{o}C) water occurs at the surface at the southwestern stations.

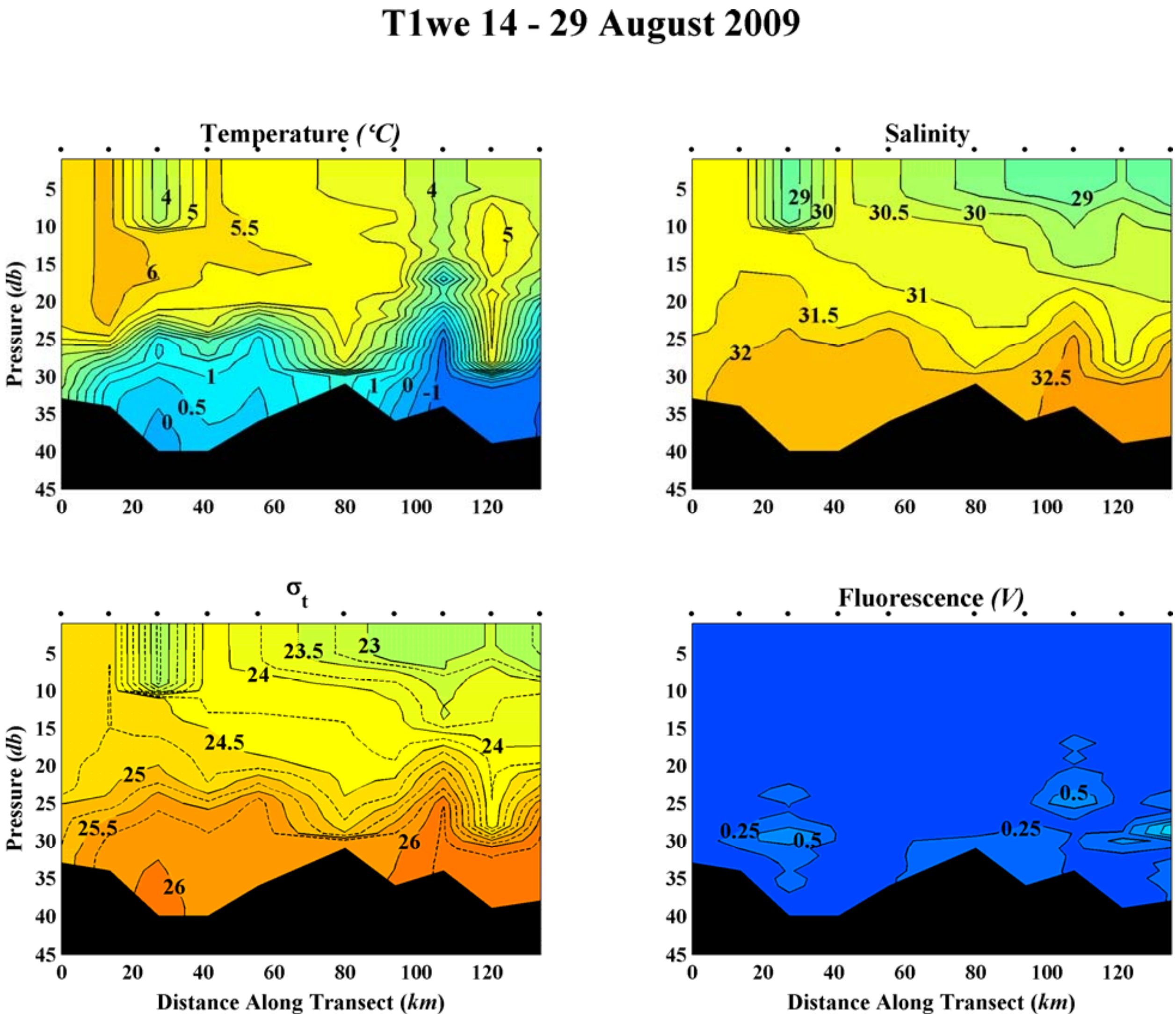

Figure 35. West-east section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 14-29 August survey.

T1 14 - 29 August 2009

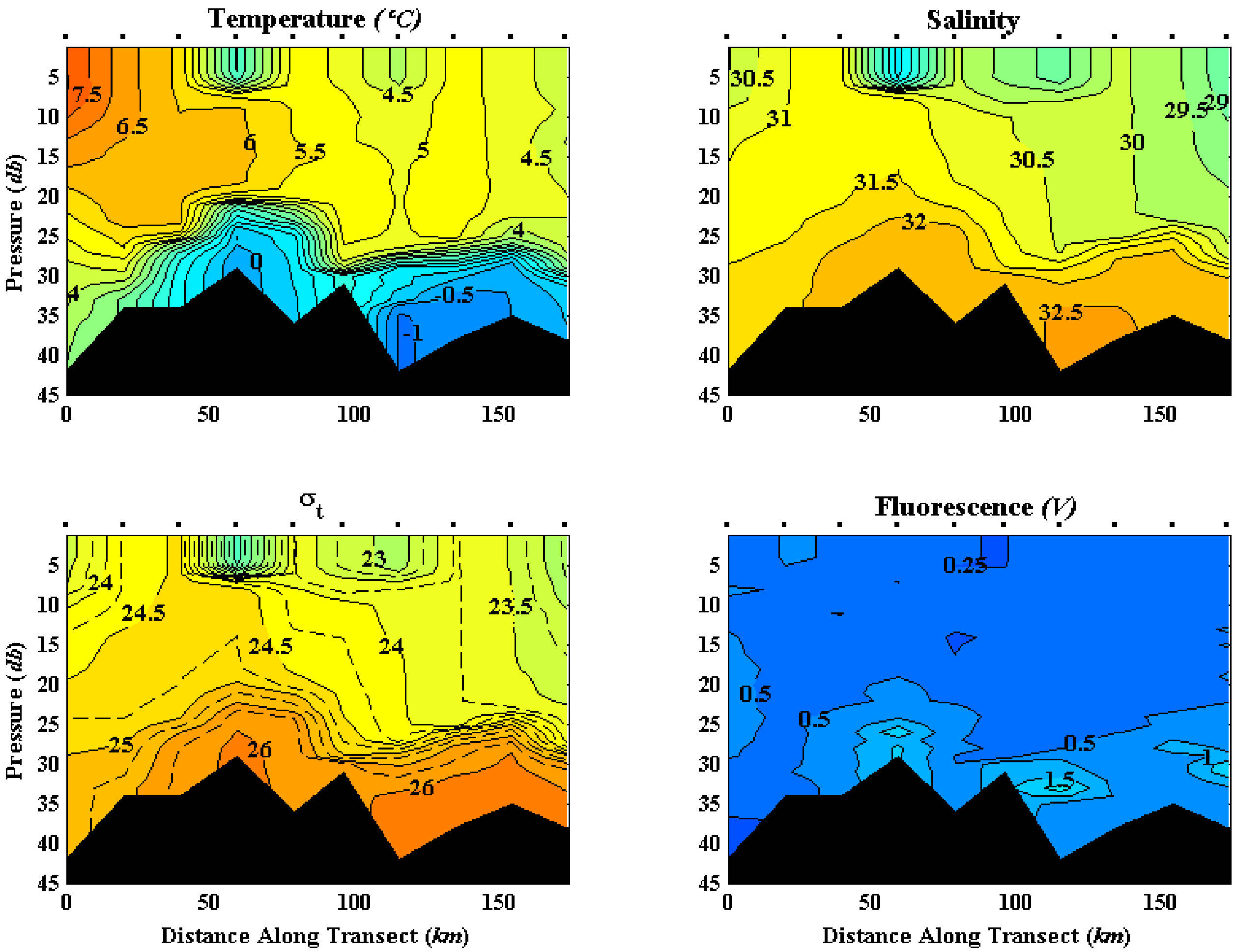

Figure 36. Southwest-northeast section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 14-29 August survey.

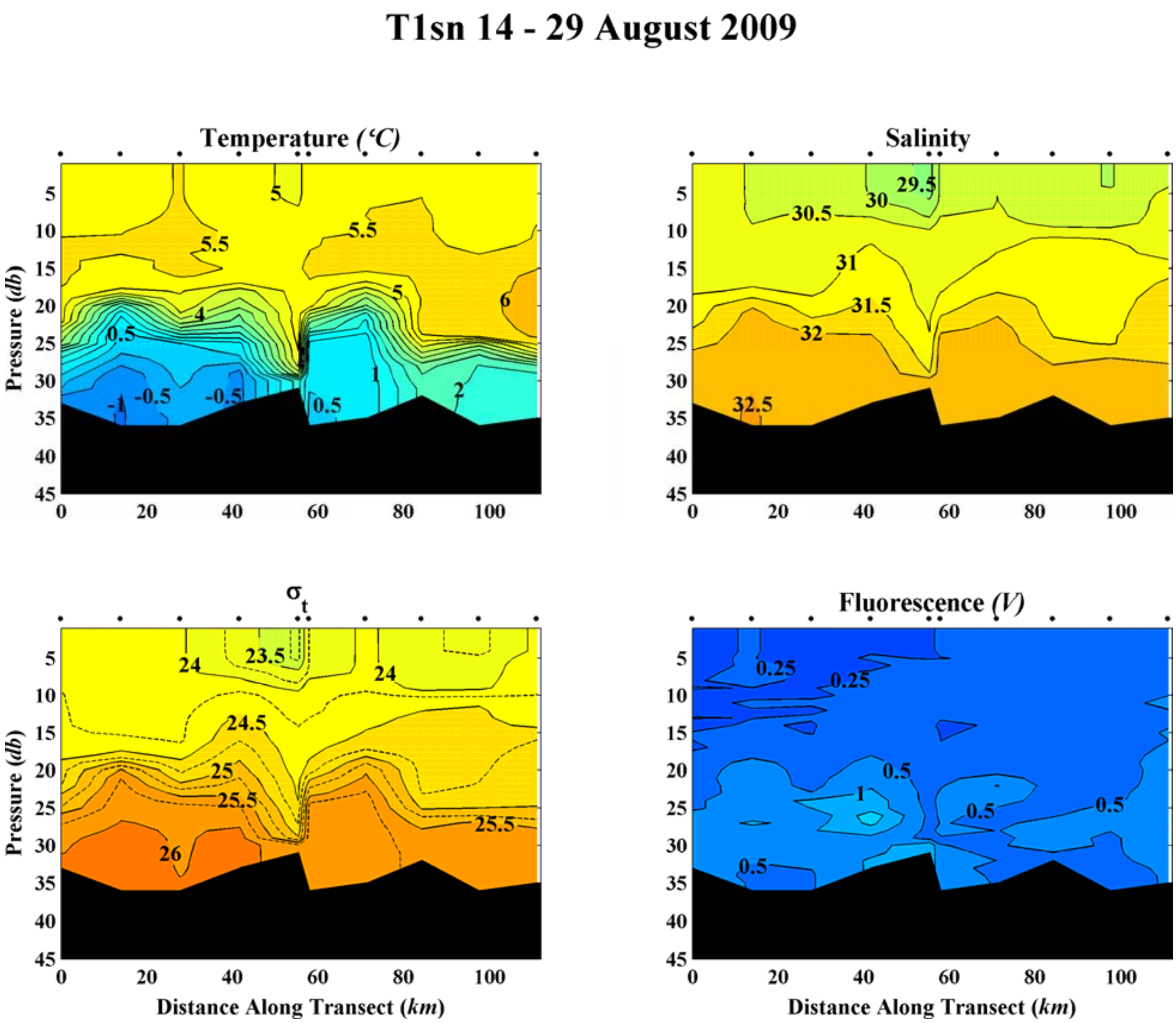

Figure 37. South-north section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 14-29 August survey.

September 5 – 19 2009 Survey

The west-east, southwest-northeast, and south-north transects for this survey are shown in **Figures 38 - 40**. Conditions at this time were remarkably uniform in that both surface and bottom properties show little horizontal variability. Upper ocean salinities vary between 30 and 31.4 and temperatures range from 5.5 to 4.25°C. In comparison to the previous survey the upper layer has deepened so that the pycnocline is thinner and at a depth of ~30 m, is also deeper. Deep water properties have also changed, with deep temperatures having warmed to above 0°C and salinities decreased to between 32 and 32.4. These changes reflect seasonal changes associated with cooling and wind mixing in the upper ocean and the replacement, presumably by the currents, of the very cold, saline winter bottom water by somewhat warmer and fresher water from the Bering Sea. Not surprisingly, fluorescence is low on all of these fall transects.

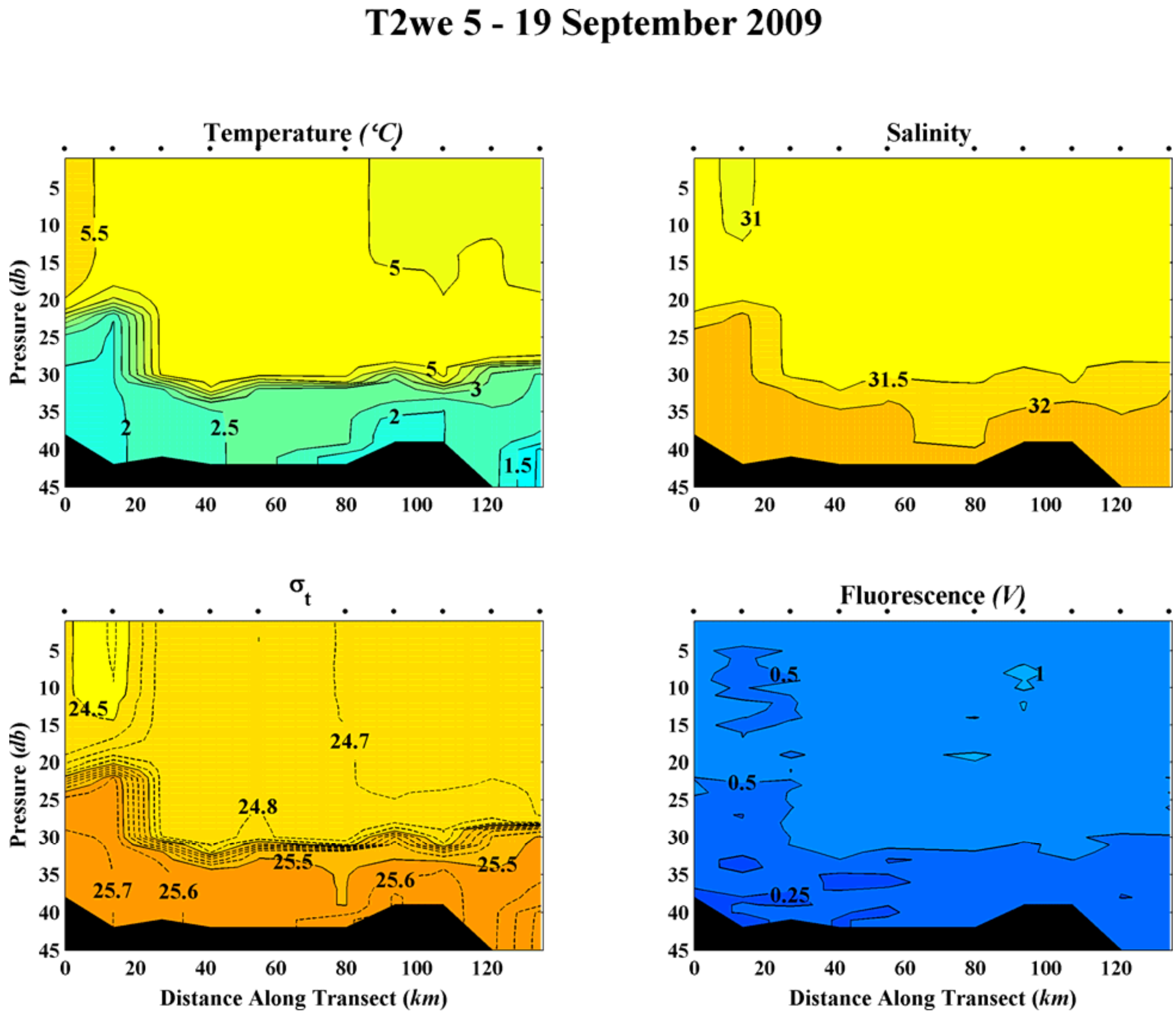

Figure 38. West-east section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 5-19 September survey.

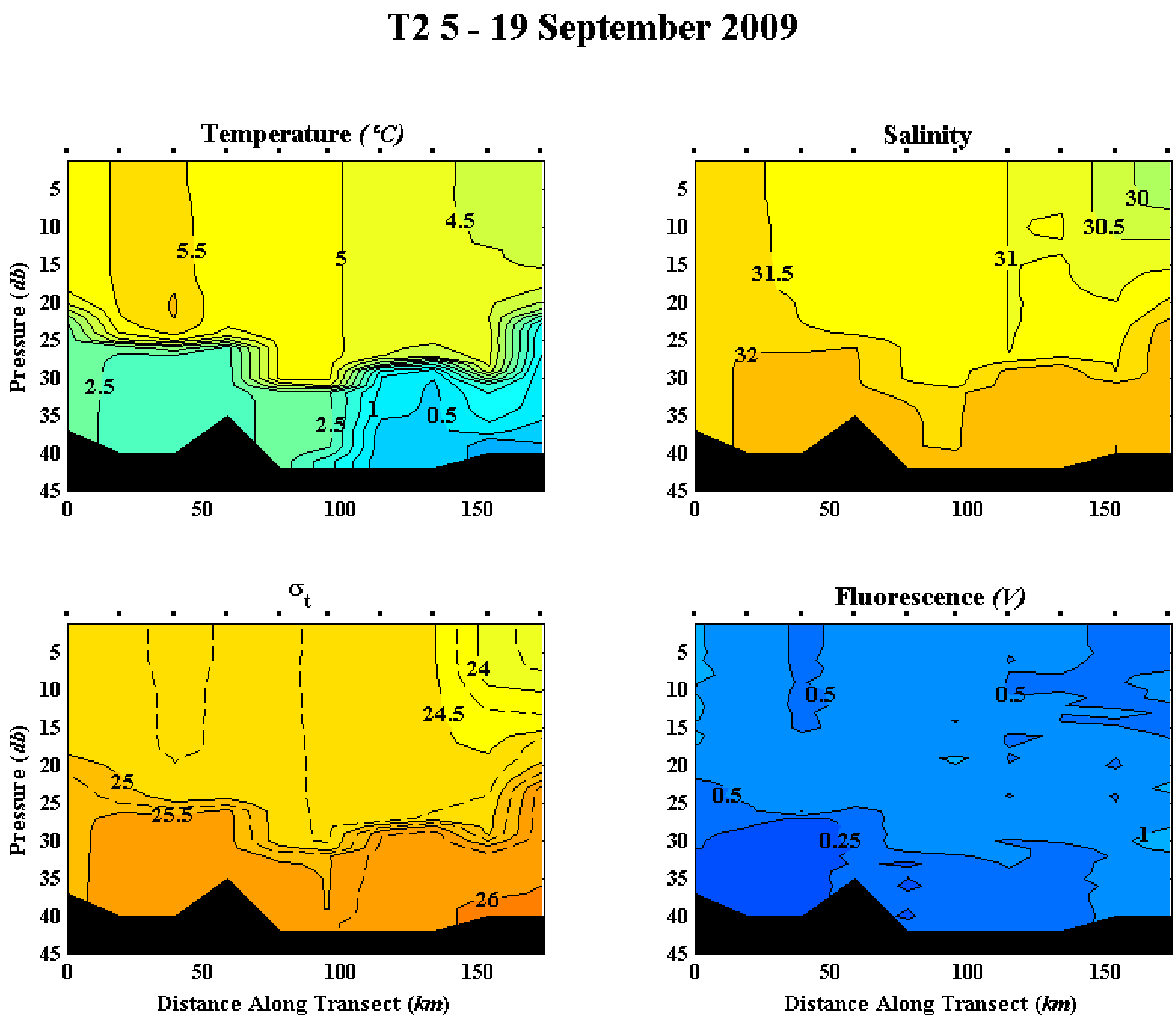

Figure 39. Southwest-northeast section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 5-19 September survey.

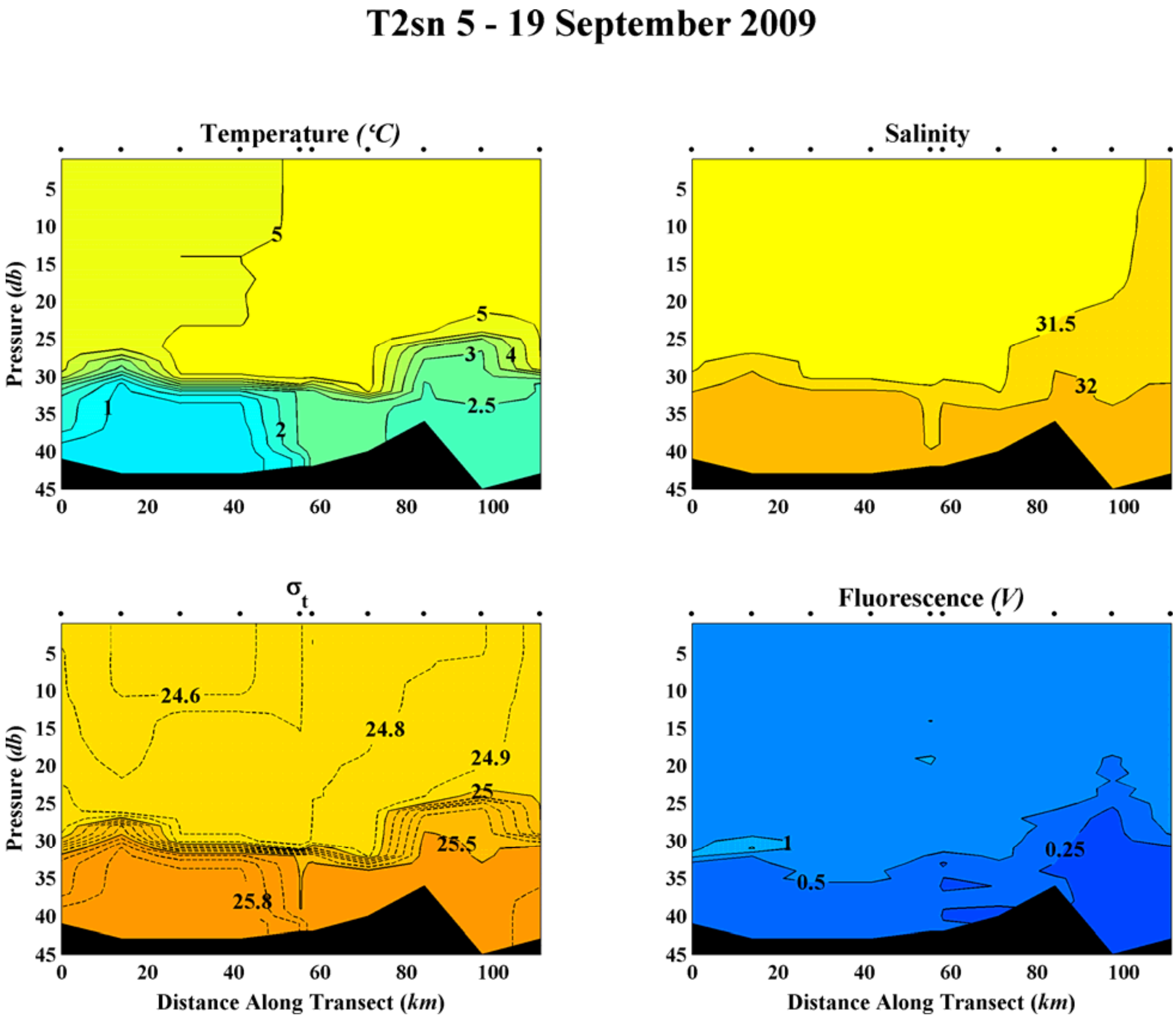

Figure 40. South-north section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 5-19 September survey.

September 26 – October 10 2009 Survey

The west-east, southwest-northeast, and south-north transects for the final 2009 survey are shown in **Figures 41 - 43**. Temperatures above the pycnocline have cooled to ~4^{o}C or less over the upper ocean and the pycnocline has deepened to ~35 m and further eroded over most of both survey areas. The warmest waters are found at the westernmost stations (**Figures 41 and 42**) again reflecting the influence of Bering Sea waters flowing into the Central Channel. The stations at the northeast corner of Burger (**Figure 42**) are cooler and fresher than in the previous survey as are the southernmost stations in the Klondike prospect (**Figure 43**). Recall that the winds prior to and during this survey were from the northeast and so tend to impel southwestward surface flow and coastal upwelling along the northwest coast of Alaska. Indeed surface current mapping, shore-based radars (see http://www.ims.uaf.edu/hfradar/ for maps and movies of the surface flow along the coast of Alaska) recorded southwesterly flow in the northeast Chukchi Sea between Barrow and Wainwright and also over Hanna Shoal.

Southwestward flow into the Burger prospect would tend to advect cooler and fresher waters into the region from the northeast and Hanna Shoal. Similarly, coastal upwelling and offshore Ekman transport would tend to advect cooler and fresher Alaskan Coastal Waters offshore.

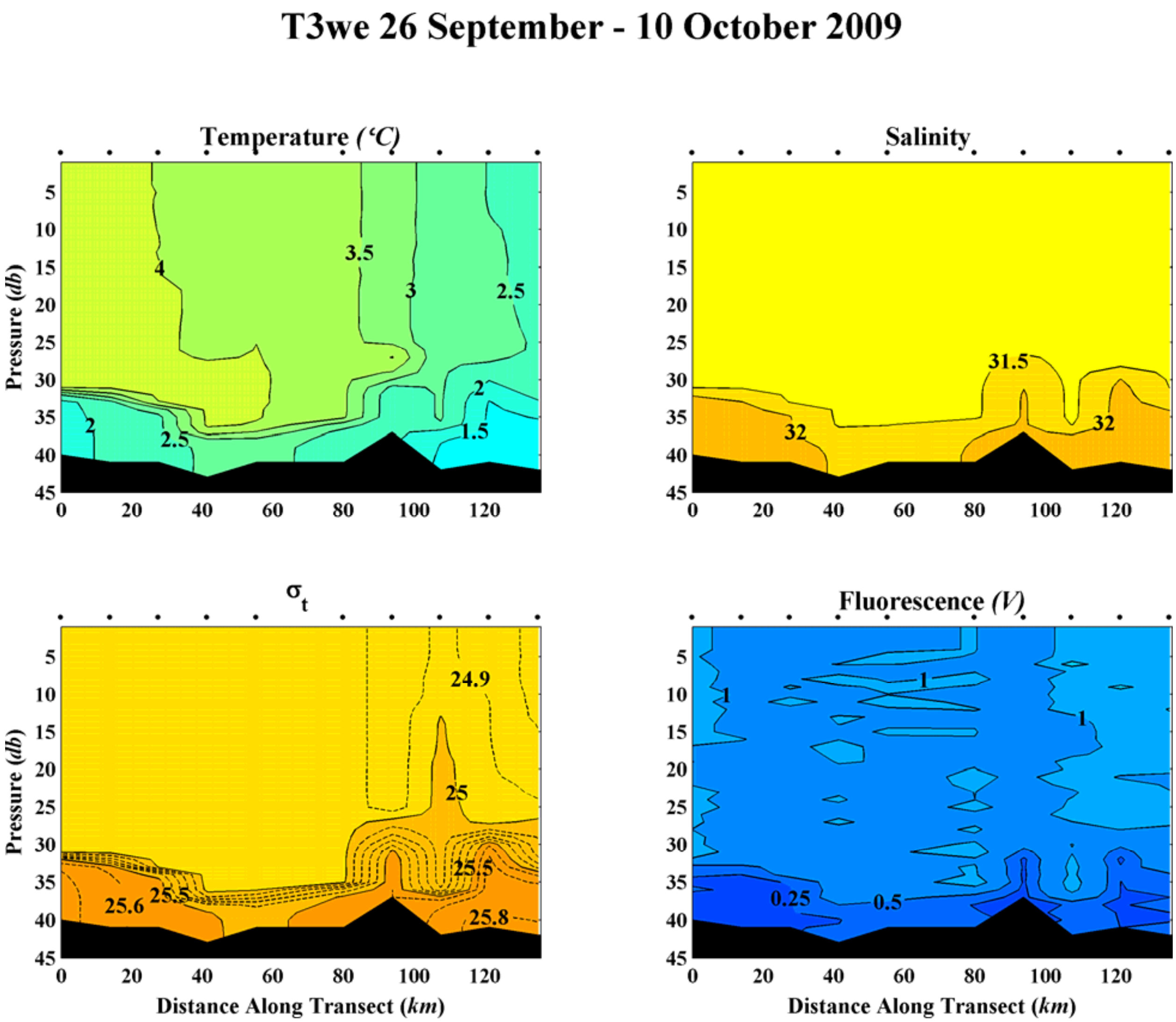

Figure 41. West-east section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 26 September-10 October survey.

T3 26 September - 10 October 2009

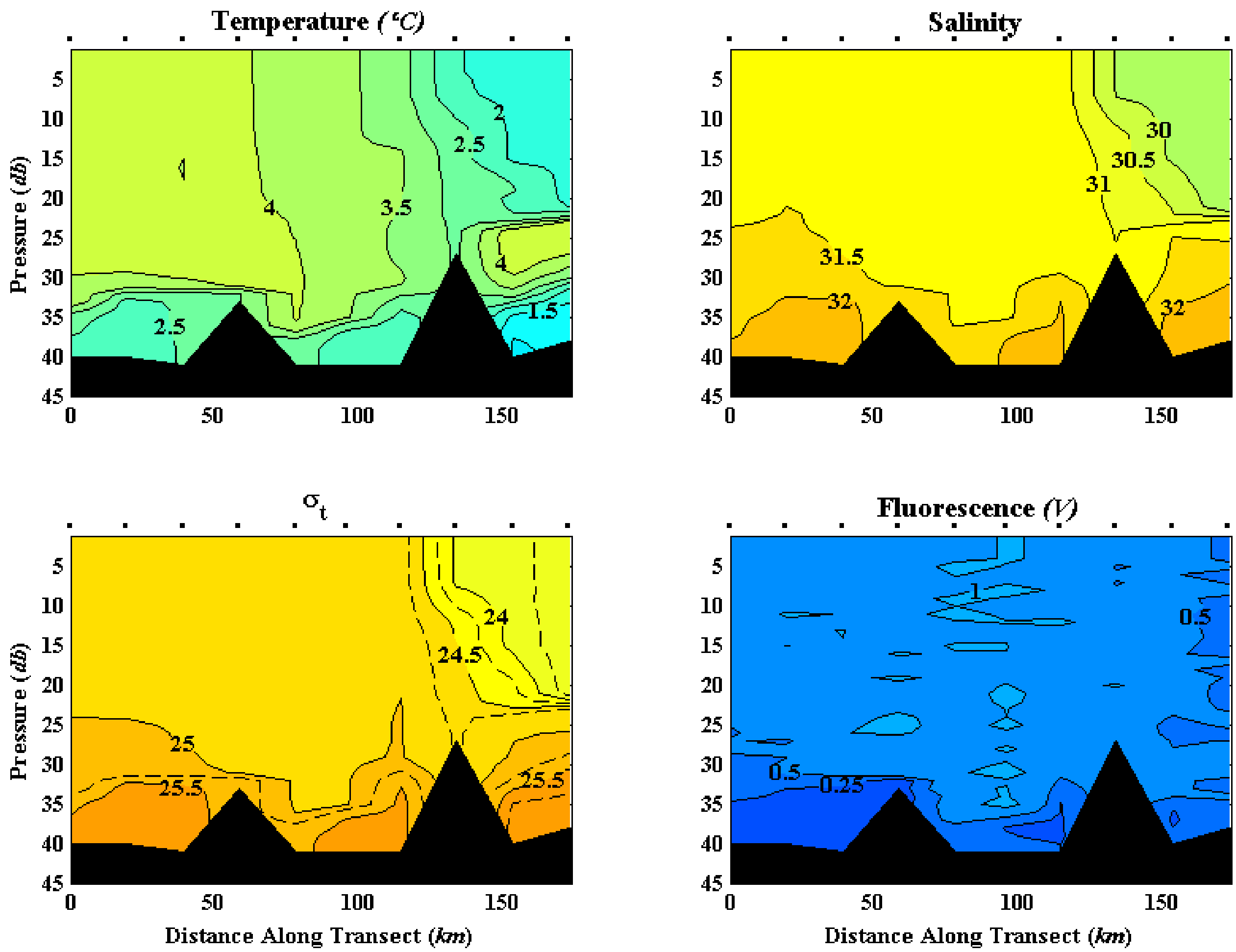

Figure 42. Southwest-northeast section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 26 September-10 October survey.

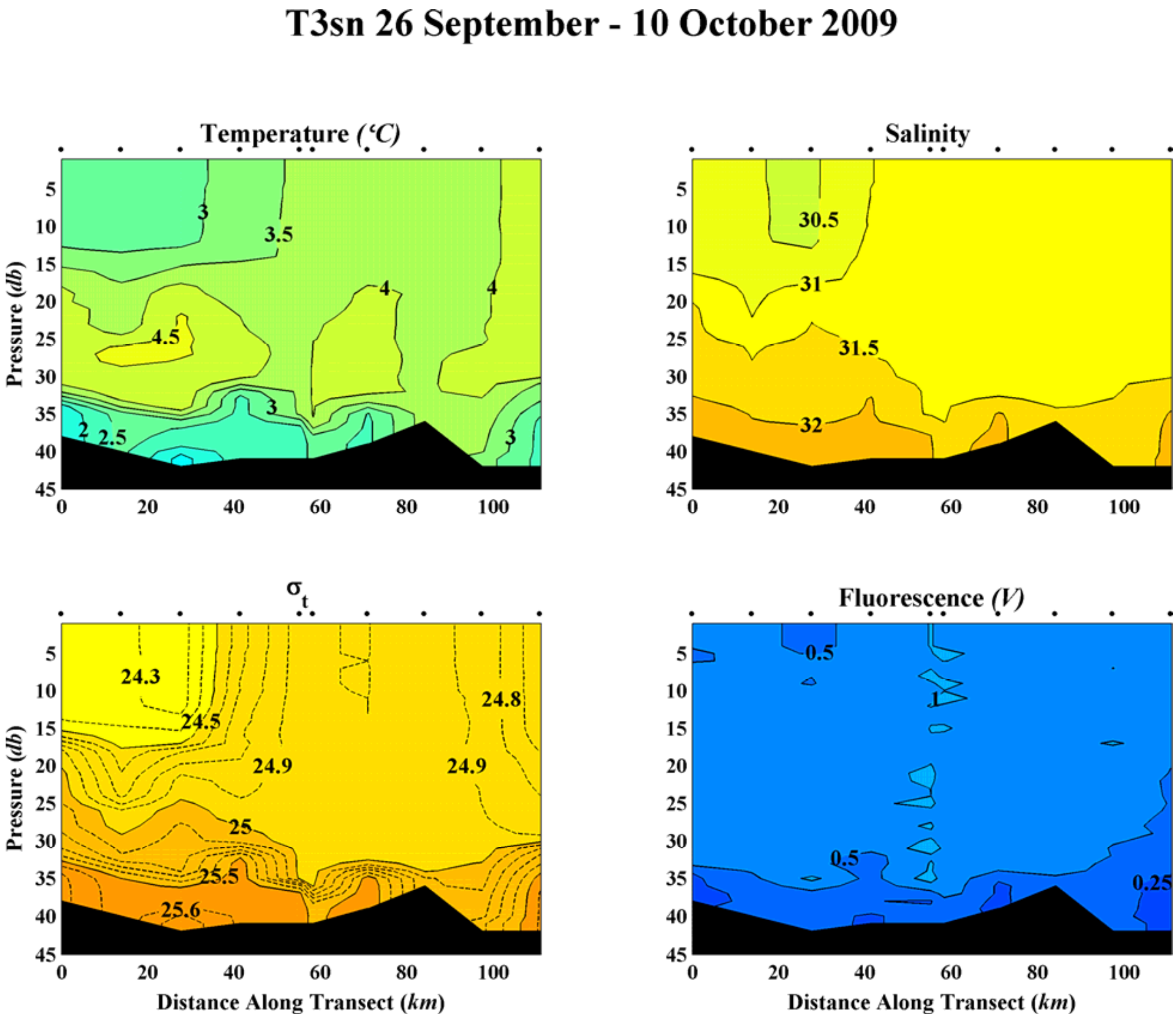

Figure 43. South-north section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 26 September-10 October survey.

Figures 44 and 45 are maps of the 0 – 10 m averaged temperatures for each survey in 2009. These may be compared directly with their 2008 counterparts (**Figures 24 and 25**). Upper ocean horizontal temperature and salinity gradients were much weaker in 2009 than in 2008. For example, upper ocean temperatures differed by only 1 to 2°C in 2009 whereas in 2008 the

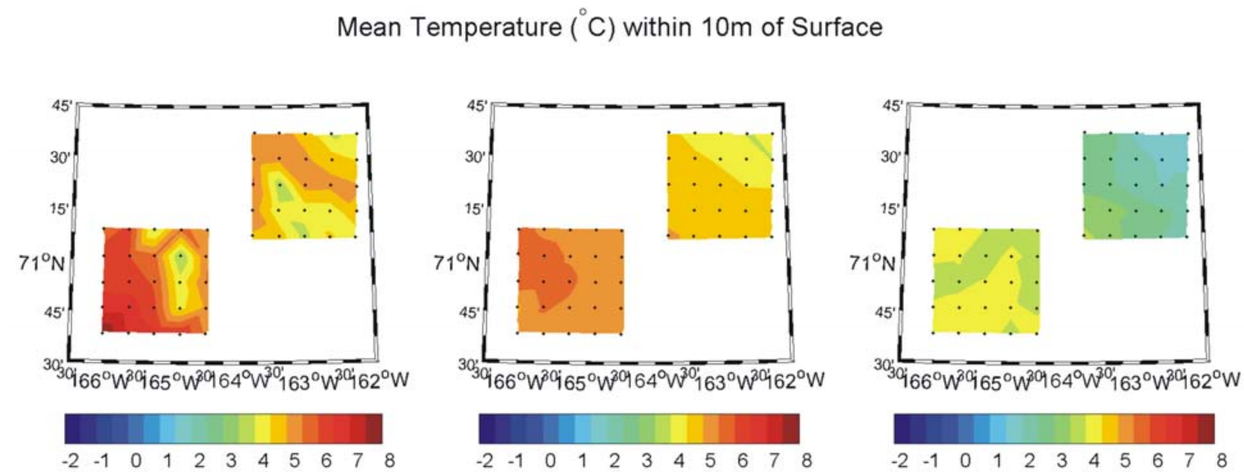

Figure 40. Plan view of the mean temperature over the upper 10 m of the water column for the 14-29 August survey (left), the 5-19 September survey (middle) and the 26 September – 10 October survey (right).

differences were as large as 4 to 5.5°C. Similarly, horizontal salinity differences were also smaller in 2009 than in 2008.

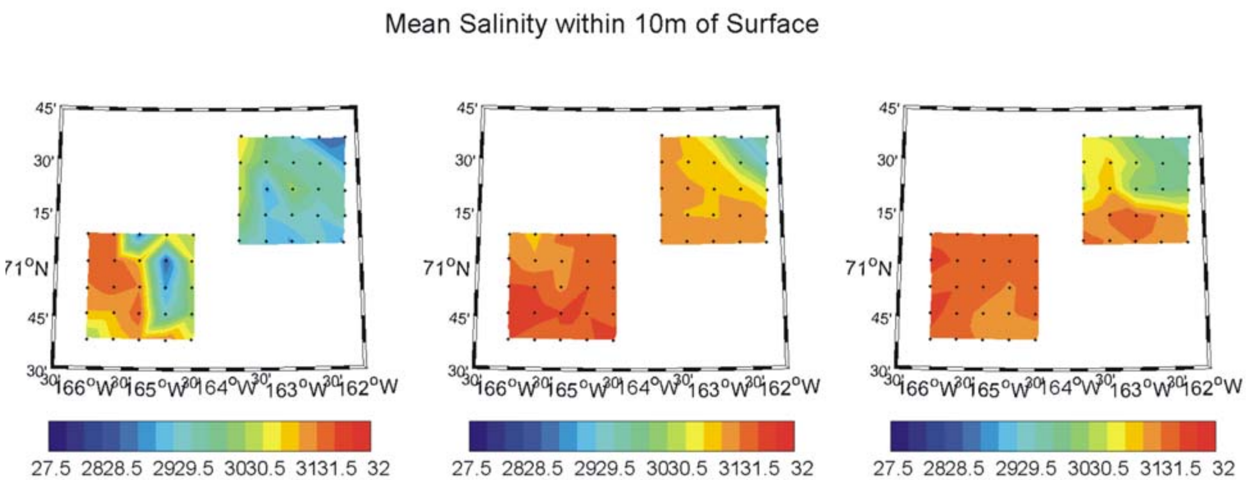

Figure 41. Plan view of the mean salinity over the upper 10 m of the water column for the 14-29 August survey (left), the 5-19 September survey (middle) and the 26 September – 10 October survey (right).

The corresponding maps for the bottom temperature and salinity averages are show in **Figures 42 and 43**. Bottom temperatures were warmer in 2009 than in 2008 and bottom temperatures generally increased from August through October 2009 and were greater than 2°C, whereas bottom temperatures remained relatively cold (<0°C) throughout the 2008 survey period.

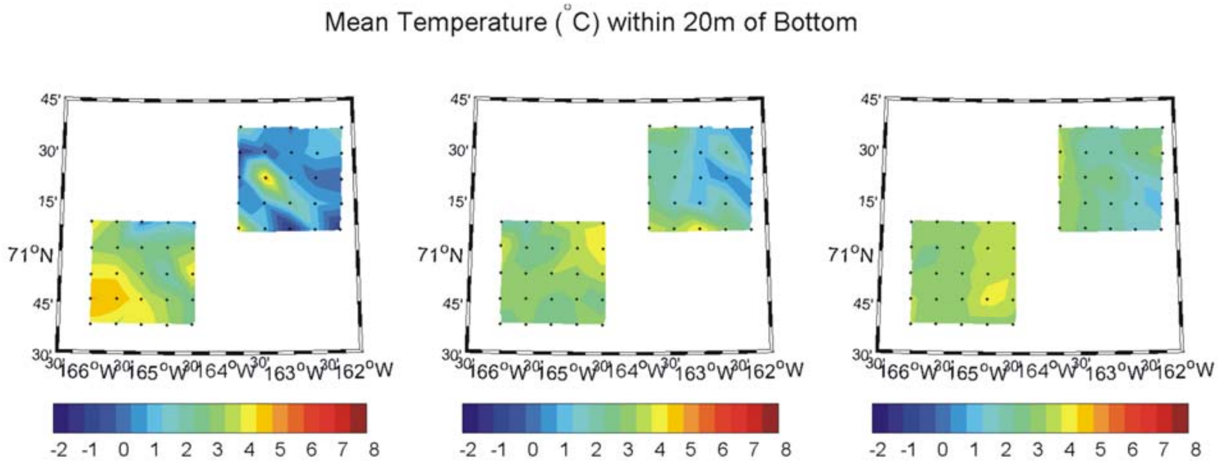

Figure 42. Plan view of the mean temperature over the bottommost 20 m of the water column for the 14-29 August survey (left), the 5-19 September survey (middle) and the 26 September – 10 October survey (right).

Bottom salinities were also greater in 2008 than in 2009, especially in Burger where very saline water (>32.5) remained into fall. In contrast, in 2009 bottom salinities were everywhere <32.5.

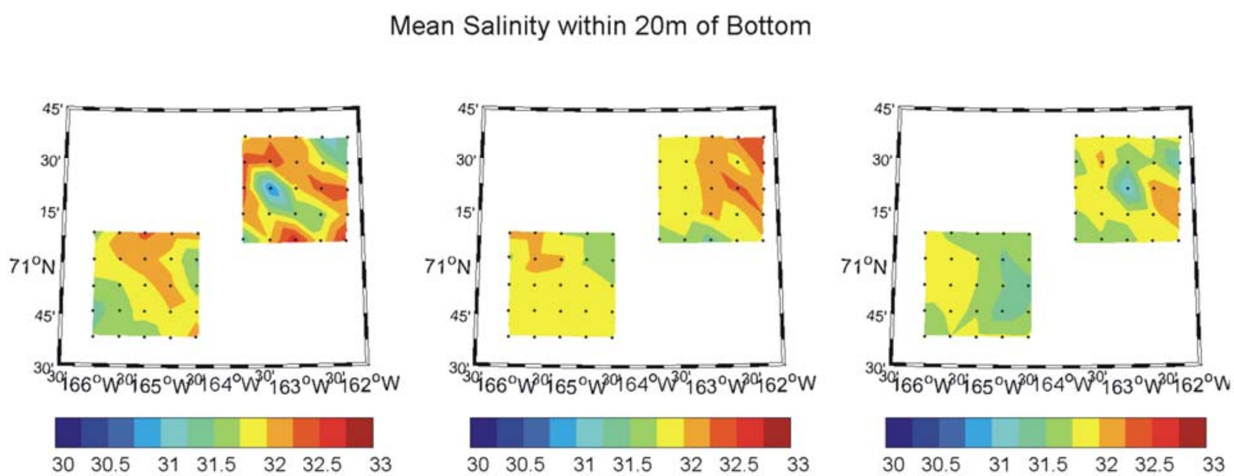

Figure 42. Plan view of the mean salinity over the bottommost 20 m of the water column for the 14-29 August survey (left), the 5-19 September survey (middle) and the 26 September – 10 October survey (right).

Discussion and Summary

The results presented here for both years are consistent with prior notions of the circulation and hydrography of the northeast Chukchi Sea shelf as outlined in the Introduction. In particular, the results from both years suggest that the western edge of the Klondike prospect lies along the eastern side of the Central Channel, where the flow is northward on average at about 10 – 15 cm s^{-1} (*Weingartner et al.*, 2005). This inflow tends to bring warm and moderately saline Bering Shelf water into the region, gradually replacing the cold, saline bottom water formed the previous winter. Bering Shelf and/or Alaskan Coastal Water gradually spread throughout the

Klondike prospect and eventually enters Burger. However, bottom waters in the Burger prospect remained very cold and salty in 2008, whereas in 2009 the bottom waters here gradually warmed and freshened

In general, the upper ocean was warmer and more saline in 2009 than in 2008 due to an earlier ice retreat and a marked decrease in the presence of ice meltwater. In addition the pycnocline was between 25 and 35 m and only 5 – 10 m thick in 2009 whereas in 2008 the pycnocline was shallower and more diffuse. Again these differences are largely attributable to the relative lack of meltwater and the more rapid reduction in cold, salty bottom water in 2009.

We suggest that there are several reasons for the differences between years. In comparison to 2009, the winds in the summer of 2008 were more frequently from the north or northeast than in 2009. Northeasterly winds tend to retard the northward flow of warmer waters from Bering Strait, inhibit the northward retreat of sea ice, especially over Hanna Shoal, and advect cooler air over the Chukchi Sea shelf. Each of these factors contributes to retarding the rate of ice retreat or ablation over the shelf. In contrast, in 2009 the winds blew more frequently from the south, which thereby promoting ice retreat, northward advection of warmer water into the Northeast Chukchi Sea, and warmer air temperatures. In addition, June ice charts (not shown), indicate that ice began to retreat earlier across the Chukchi Sea in 2009 compared to 2008. Indeed by the end of June 2009 sea ice concentration charts, prepared by the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E), show a wide avenue of open water extending along the northwest Alaskan coast nearly to Barrow. In 2008, open water extended only as far as Icy Cape by this date. Because of the albedo difference between sea ice and seawater, an early retreat tends to rapidly warm shelf waters, which when brought into contact with ice enhances lateral melting.

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