Physical oceanographic measurements in the Klondike and Burger prospects of the Chukchi Sea

Thomas Weingartner
Institute of Marine Science
University of Alaska
Fairbanks, AK 99775

Introduction

The Chukchi (and Beaufort) seas are the northernmost shelf seas 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 is sustained by a large-scale pressure gradient between the Pacific and Atlantic oceans [*Coachman et al.,* 1975; *Aagaard et al.*, 2006].

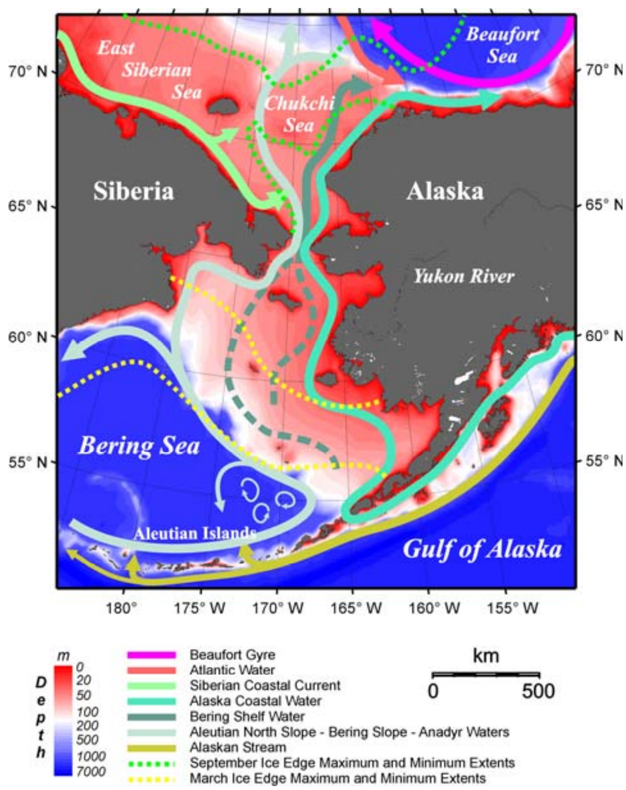


Figure 1. Schematic circulation map of the Bering-Chukchi-Beaufort shelves.

The northward flux of mass, heat, nutrients, carbon, and organisms through the strait bequeaths the Chukchi shelf with physical and ecological characteristics that are unique among arctic shelves. For example, the spring retreat (fall onset) of sea ice is occurs earlier (later) 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].

Much of our understanding of the Chukchi shelf derives from the early syntheses of *Coachman et al.* [1975] and *Walsh et al.* [1989] and from the observational studies of *Paquette and Bourke* [1974], *Mountain et al.* [1976], *Paquette and Bourke* [1981], *Ahlnäes and Garrison* [1984], *Aagaard et al.*, [1985], *Aagaard* [1988], *Johnson* [1989], *Aagaard and Roach* [1990], *Hansell et al.* [1993], *Cooper et al.* [1997], *Münchow and Carmack*, [1997], *Weingartner et al.* [1998], *Weingartner et al.* [1999], *Münchow et al*. [1999], *Münchow et al.* [2000], *Pickart* [2004], *Steele et al.* [2004], *Pickart et al.* [2005], *Weingartner et al*. [2005b], *Pickart et al*. [in press], *Codispoti et al.* [2005], *Woodgate et al.* [2005b], *Shimada et al*. [2006], *Nikoloupolis et al.* [in press], the modeling and theoretical work of [*Gawarkiewicz and Chapman*, 1995], *Weingartner and Proshutinsky* [1998], *Winsor and Chapman* [2002, 2004], *Spall* [2007], *Spall et al.*, [2008], and the sea-ice studies of *Muench et al*. [1991], *Cavalieri and Martin* [1994], *Liu et al*. [1994], and *Drucker and Martin* [1997]. The following summary is drawn from these sources.

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 due to the Pacific-Arctic pressure gradient and opposes the prevailing northeasterly winds. 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. While most of this outflow probably descends through Herald Valley, some of it spreads eastward across the central shelf. A second branch flows northward through the Central Channel 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. The third branch flows northeastward along the Alaskan coast towards Barrow Canyon at the junction of the Chukchi and Beaufort shelves. In summer this flow includes the northward extension of the Alaskan Coastal Current (ACC) that originates south of Bering Strait. At the head of Barrow Canyon the ACC is joined by waters flowing eastward from the central shelf, with the merged flow then continuing downcanyon as a narrow, but strong, coastal jet.

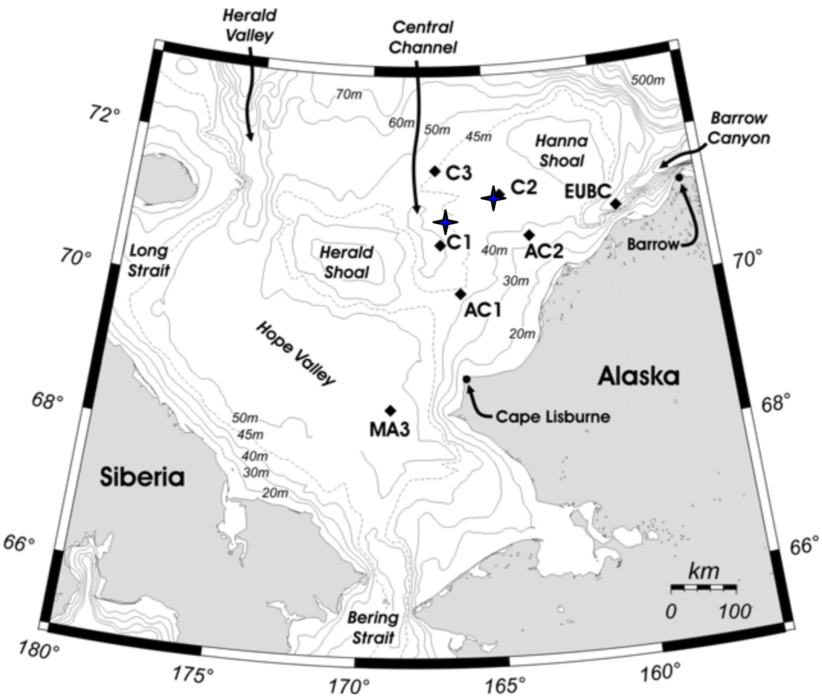


Figure 2. Bathymetric map of the Chukchi Sea shelf showing the Herald Valley, Central Channel, Barrow Canyon and two prominent shoals: Herald and Hanna. Also shown are the locations of current meter moorings deployed from 1994-1995. The blue stars are the approximate locations of the Klondike and Burger 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}. Estimates of transit time from Bering Strait to Barrow Canyon are from 3 – 4 months in summer and longer in winter. 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. Instead some of the outflow is entrained into shelfbreak eddies that drift into the deep basin, some appears to spill over onto the inner Beaufort shelf when northeasterly winds are sufficiently weak [Okkonen, pers. comm.], and some appears to drift northwestward from the canyon's mouth and into the Arctic basin. The mean flow outlined from observations is similar to that produced by numerical circulation models of the Chukchi shelf. Of importance to this study are model results that indicate 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 counterclockwise 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" 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 we shall see.

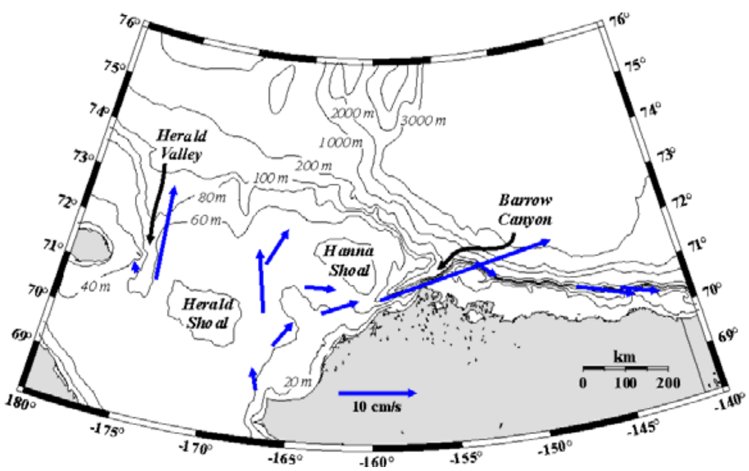


Figure 3. Mean flow vectors (blue arrows) from moorings deployed in the Chukchi Sea and Beaufort slope deployed between 1990-1995 and with record lengths exceeding 9 months.

In general, relatively warm (>2^{o}C) and salty (salinity >32.4) "summer" water from Bering Strait is found in Herald Valley and the Central Channel. 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. 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. 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. The stratification increases from spring through summer and then erodes in fall as strong winds, cooling and freezing mix the water column. The bottom half of the water column usually contain relatively cold, salty water remnant from the prvious winter, whereas the surface layer consists of ice melt, and/or mixtures of Alaskan Coastal Water or water flowing throught eh 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 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, 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. 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 topography (Central Channel and Barrow Canyon) than in areas of gentler bottom relief. On occasion, and most frequently in fall and winter, strong northeasterly storm winds can reverse the shelf flow field or even re-distribute the flow from one of the main flow pathways to another.

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 the surface currents. 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. In addition, several passive acoustic recorders prematurely released in summer 2008 drifted westward out of the lease sale area [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.

In the following sections we discuss the weekly variations in the winds and sea ice fields over the survey area and briefly compare the ice conditions in 2008 with those of 2007. These results are then followed by a discussion of the conductivity-temperature-depth (CTD) measurements, which describe the seasonally varying hydrography of the Klondike and Burger prospects. These results are based on 1-meter averages of the CTD data collected at the various stations established in each prospect.

Results

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 QuikSCAT satellite and obtained from Remote Sensing Systems (http://www.remss.com/qscat/scatterometer_data_weekly.html). These wind fields are based on 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 around Bering Strait for example) and the red circle denotes the location of Barrow. For the week of July 26, prior to the beginning of the surveys, winds were northeasterly at 5 – 10 m s^{-1} over the Beaufort Sea and northerly over the Chukchi Sea. Although sea ice had retreated over broad areas of both shelves by late July relatively heavy concentrations remained over Hanna Shoals 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}. Such 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, the winds during the week ending August 9, the winds reversed and were northerly and northwesterly, which would may have caused the ice to move inshore toward the Alaskan coast. Nevertheless, the seasonal progression of melting continued to reduce ice concentrations. Winds over the next two weeks were again toward the southwest on average with mean speeds of 7 - 10 m s^{-1}. Although at the resolution of the scatterometer, the ice appears to have completely dispersed by this time, 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 11 and 12**). This unconsolidated ice likely persisted until the end of the month and 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). It appears that the extensive ice cover over Hanna Shoal contributed contributed a considerable amount of meltwater to much of the Burger prospect through summer and fall (as discussed below). 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 the latter period.

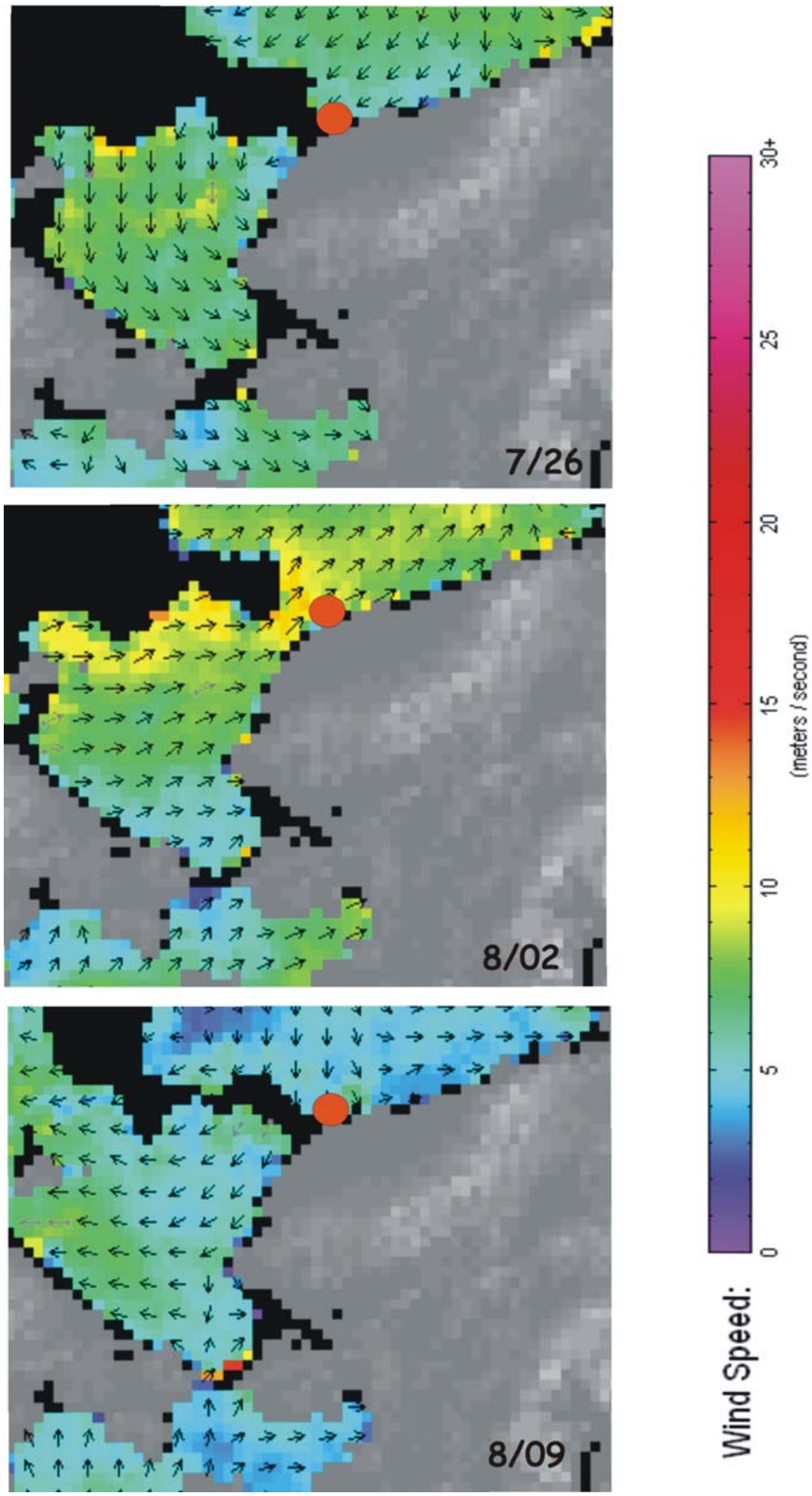


Figure 7. Weekly averaged vector winds and wind speeds over the northeast Chukchi Sea for the week ending July 26 (top), August 2 (middle) and August 9 (bottom).

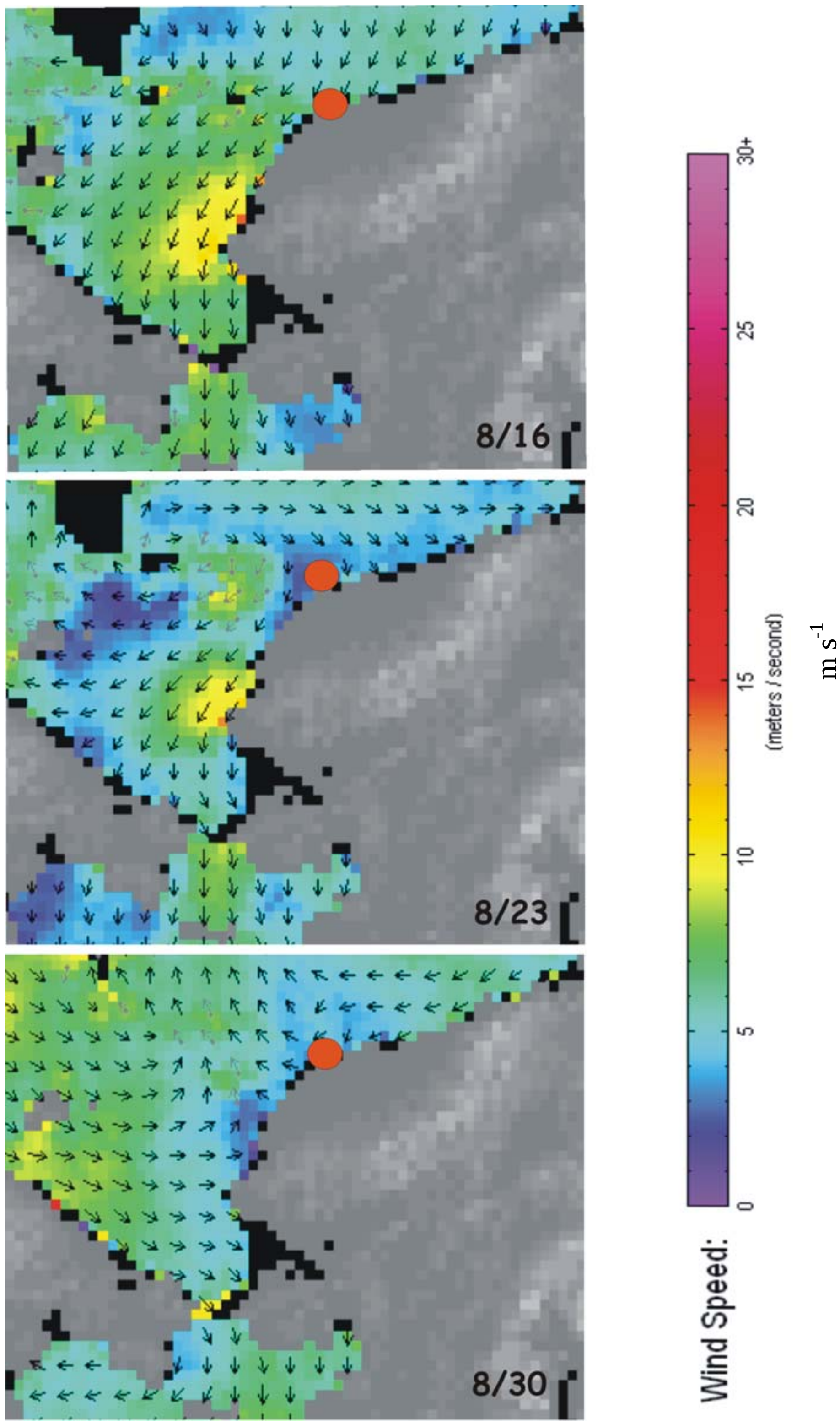


Figure 8. Weekly averaged vector winds and wind speeds over the northeast Chukchi Sea for the week ending August 16 (top), August 23 (middle) and August 30 (bottom).

Figure 9. Weekly averaged vector winds and wind speeds over the northeast Chukchi Sea for the week ending September 6 (top), September 13 (middle) and September 20 (bottom).

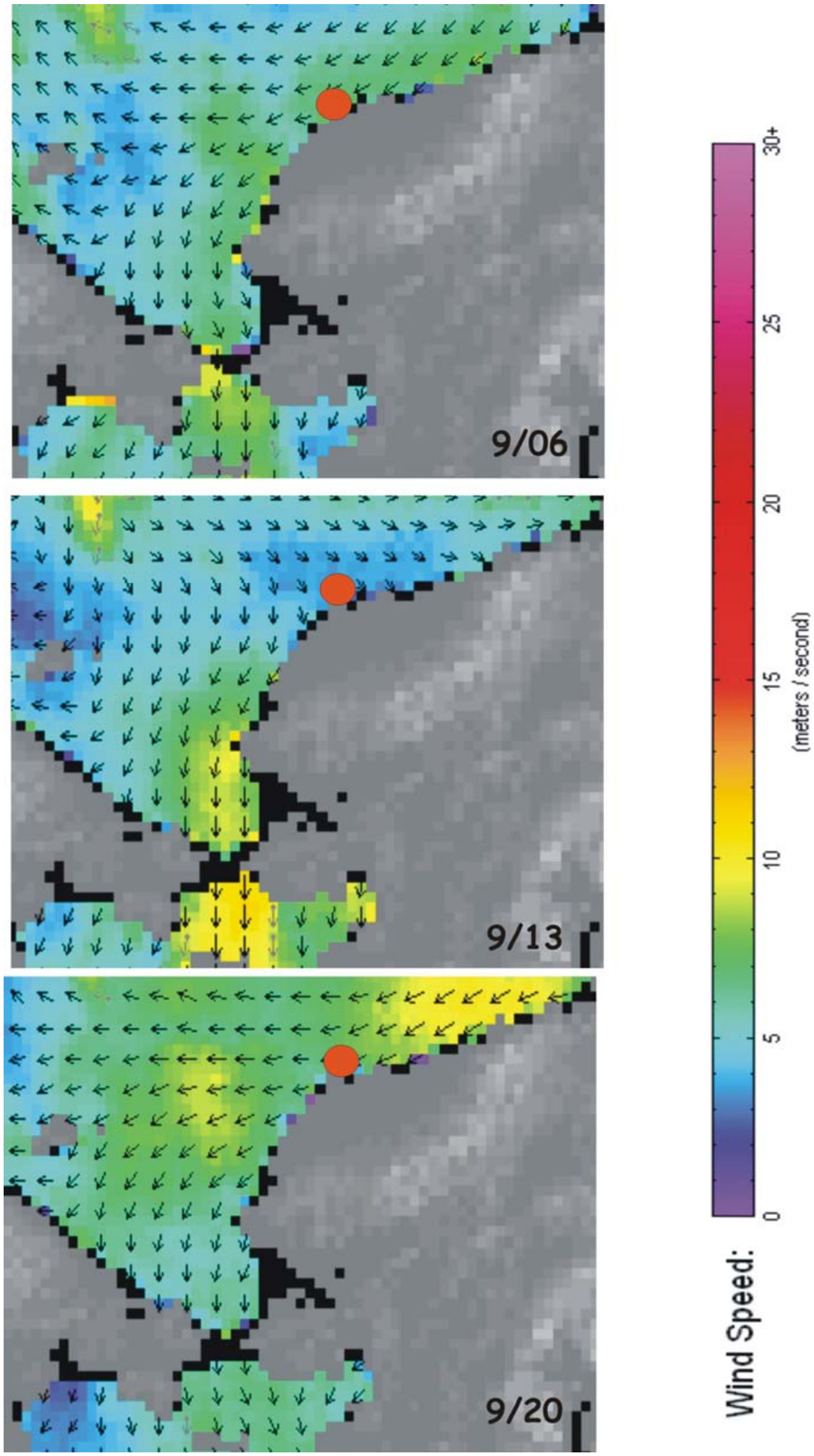
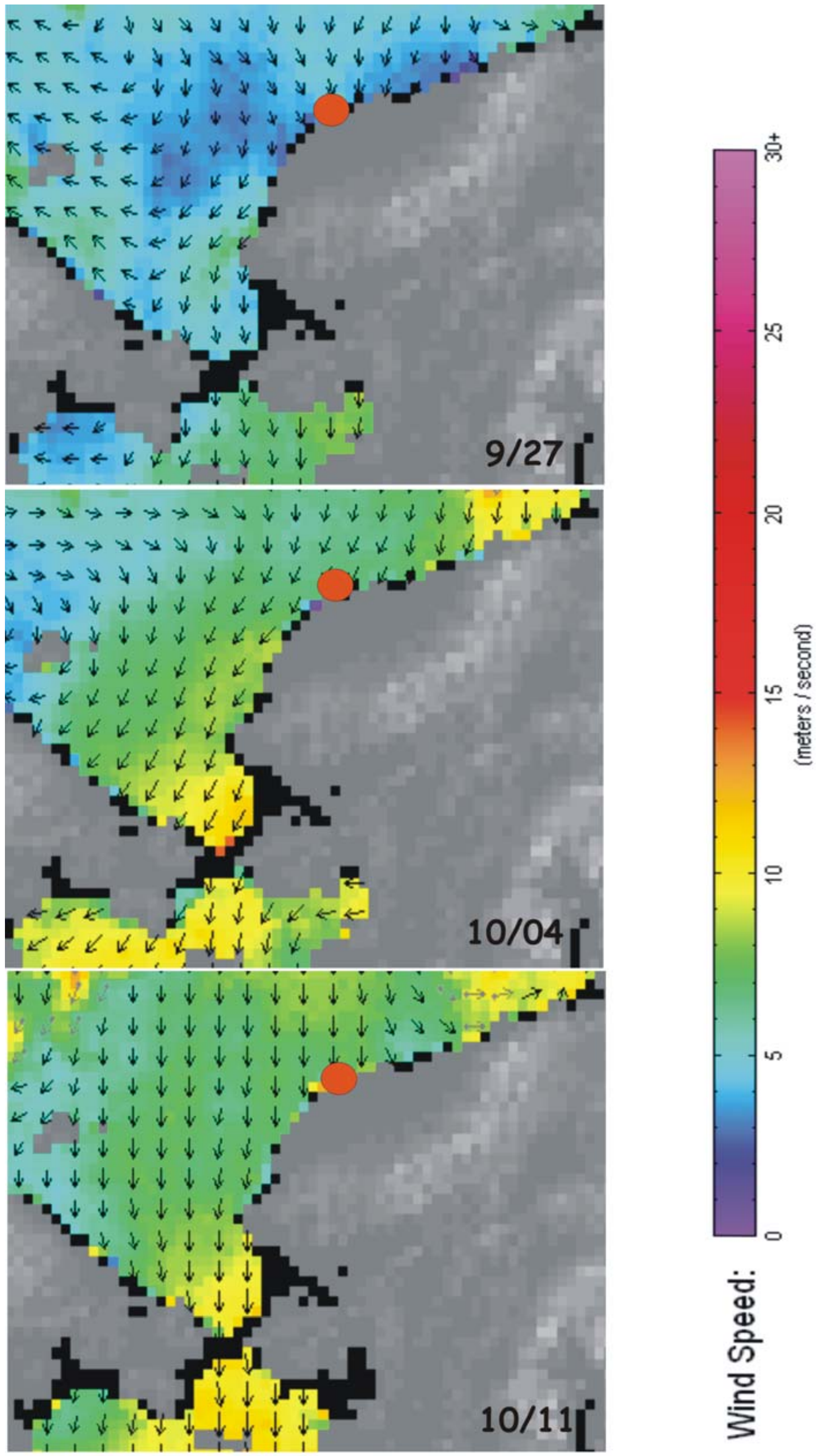


Figure 10. Weekly averaged vector winds and wind speeds over the northeast Chukchi Sea for the week ending September 6 (top), September 13 (middle) and September 20 (bottom).



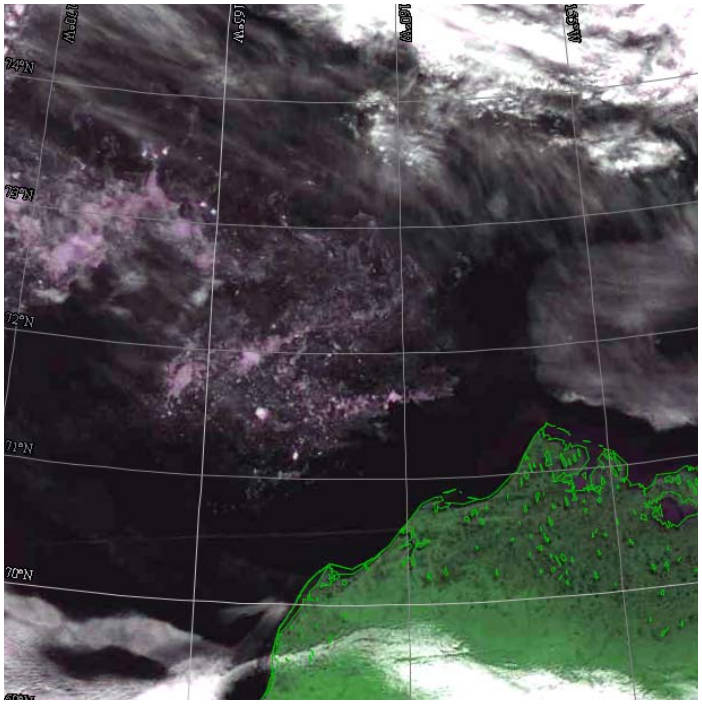


Figure 10. Visible satellite image (August 16, 2008) showing bands of ice over Hanna Shoal and the shelf to the west of the Shoal. The ice extends south of 71°N along about the 164°W meridian.

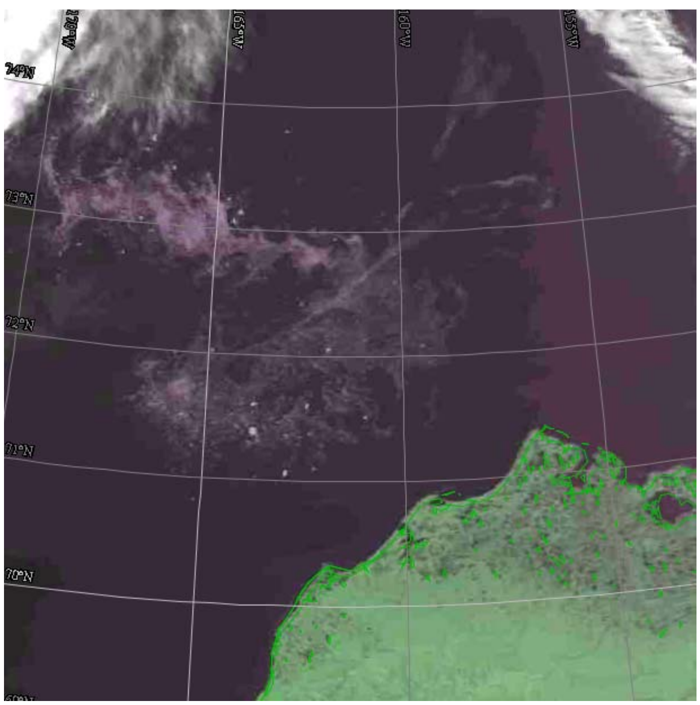


Figure 11. Visible satellite image (August 24, 2008) showing broken ice over Hanna Shoal and the shelf to the west of the Shoal. The ice extends nearly to 71°N along about the 164°W meridian.

The ice conditions in summer 2008 were quite different from those of summer 2007 as shown in **Figure 12**.

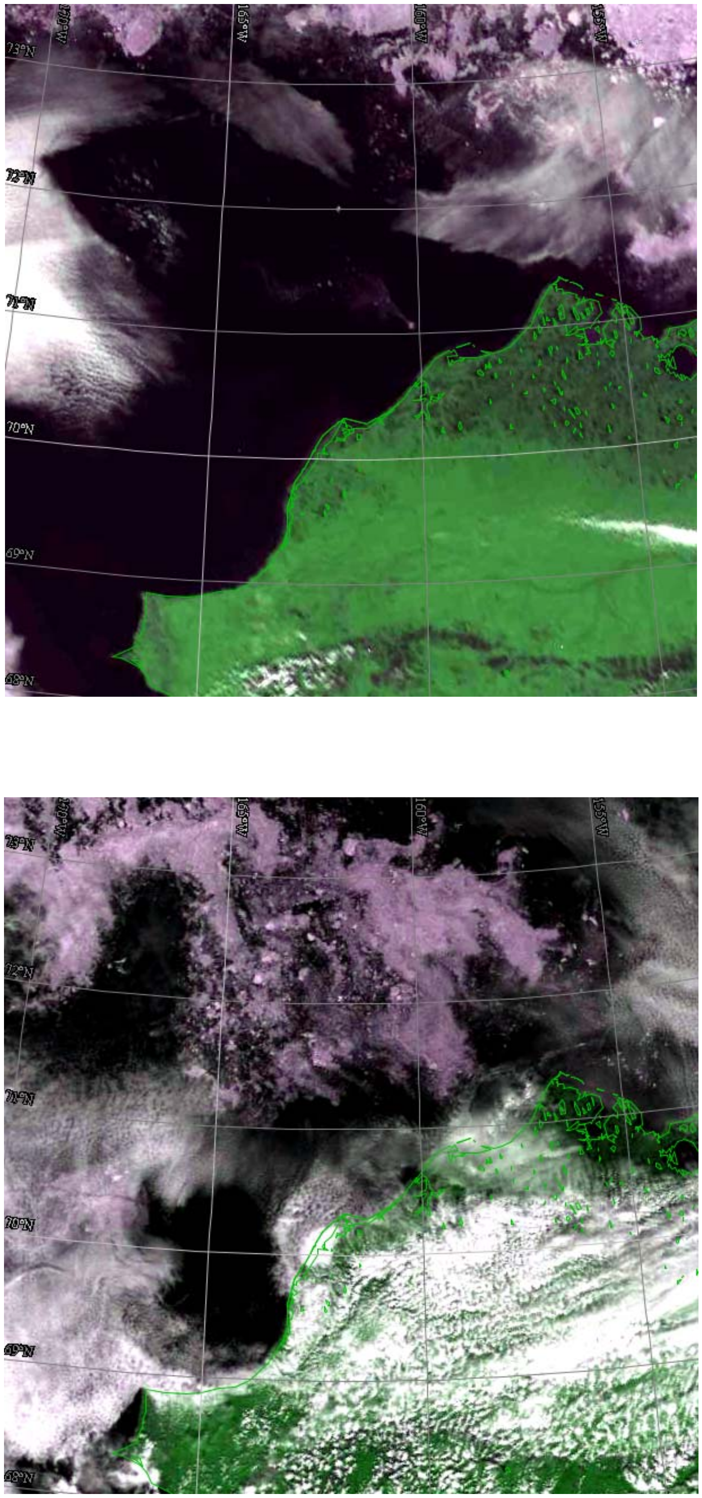


Figure 12. A comparison of ice conditions in the Chukchi Sea on July 23, 2007 (top) and July 23, 2008 (bottom).

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.

Temperature and salinity

Before presenting the spatial distribution of temperature and salinity along the CTD transects we first describe the various water masses that occur in the region 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 a series of 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^{o}C to –1.7^{o}C and salinities ranging from <28 to ~33. The temperature range is greater at Klondike than Burger while the range in salinity is greater at Burger than Klondike. It is also apparent that 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, however, Klondike waters are saltier and warmer than Burger waters for all water types with a salinity <32.5. At greater salinities, the temperatures are or at the freezing point so that the water properties at each station merge. The coldest and most saline waters were formed the previous winter during ice formation and are only slowly removed from this sector of the NE Chukchi shelf in summer (*Weingartner et a*l., 2005). 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. Note also that these winter waters are absent in Klondike during the 20 September- 9 October cruise, although still present in Burger. The relatively cold (<2^{o}C) and fresh (e.g., ~ <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 are chiefly found at Klondike.

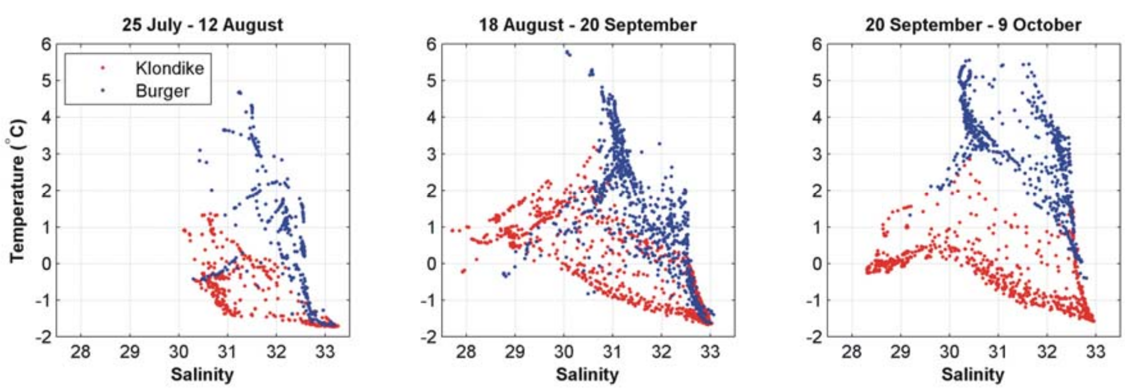


Figure 13. Temperature-salinity diagrams for each survey conducted in 2008.

We next investigate the temperature, salinity, density and fluorescence distributions as a function of distance and depth along a number of transects across both the Klondike and Burger prospects. For each survey, we have constructed transects that extend from east-west, north-south and diagonnally across both prospects. **Figure 14** shows the transects used in these constructions.

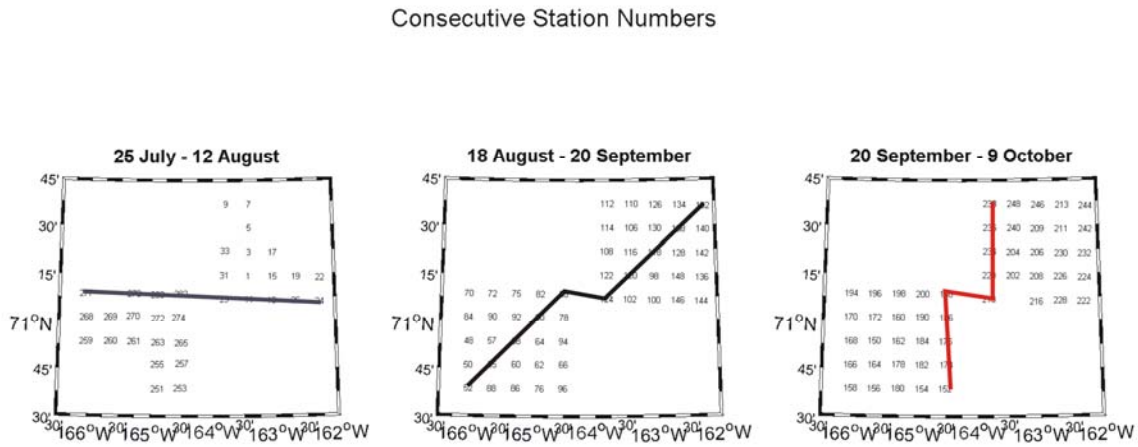


Figure 14. The distribution of stations during each survey. The red line in the 25 July – 12 August survey shows the stations that were used in constructing the east-west transects. The black line in the 18 August- 20 September survey shows the stations used in constructing the diagonal transects. The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

August 3 – 12 Survey

Spatial distributions of water mass properties are shown along several sections constructed from the Klondike and Burger stations. Figure X to XXX are east-west, north-south, and southwest-northeast transects formed from stations occupied in both prospects (Figure X). 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 east-west sections from the 3-12 August survey (Figure S1) suggest an east-west 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. Flourescence is a maximum at mid-depth and generally within the stratified zone, suggesting that here both light and nutrients are abundant enough to foster photosynthesis here. The southwest to northeast section across Klondike and Burger is shown in **Figure 16** and has many of the same features seen in the east-west section.

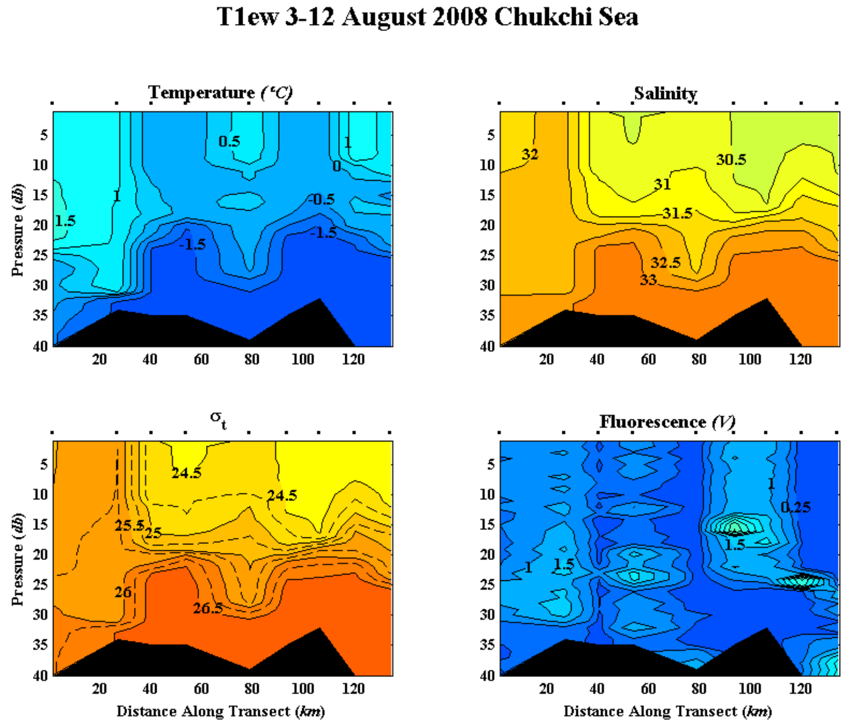


Figure 15. East-west section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 3-12 August survey.

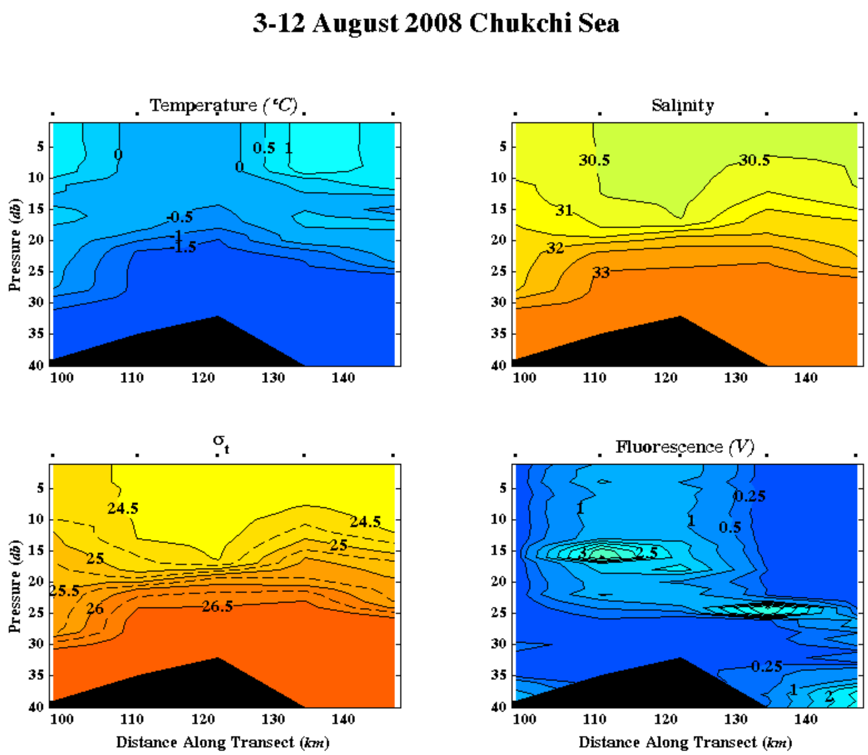


Figure 16. The diagonal section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 3-12 August survey.

The north-south sections (**Figure 17**) from the same survey further illustrate the spatial variations in water properties. Warm (>4^{o}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 across a temperature front by 3^{o}C over a distance of 40 km), before more gradually decreasing to about 0^{o}C at the northern end of the transect. Temperatures are, however, relatively cold beneath the surface layer and range from 0^{o}C at the southern end of the section to -1.5^{o}C at the northern end. The surface temperature front angles downward to the south, suggesting 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 greater 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 frontal structure evident in the isopycnals (sigma-t isopleths), which implies that the density of the fresh, 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 which cross-frontal exchange is inhibited; thus the water masses can easily mix laterally with one another here.

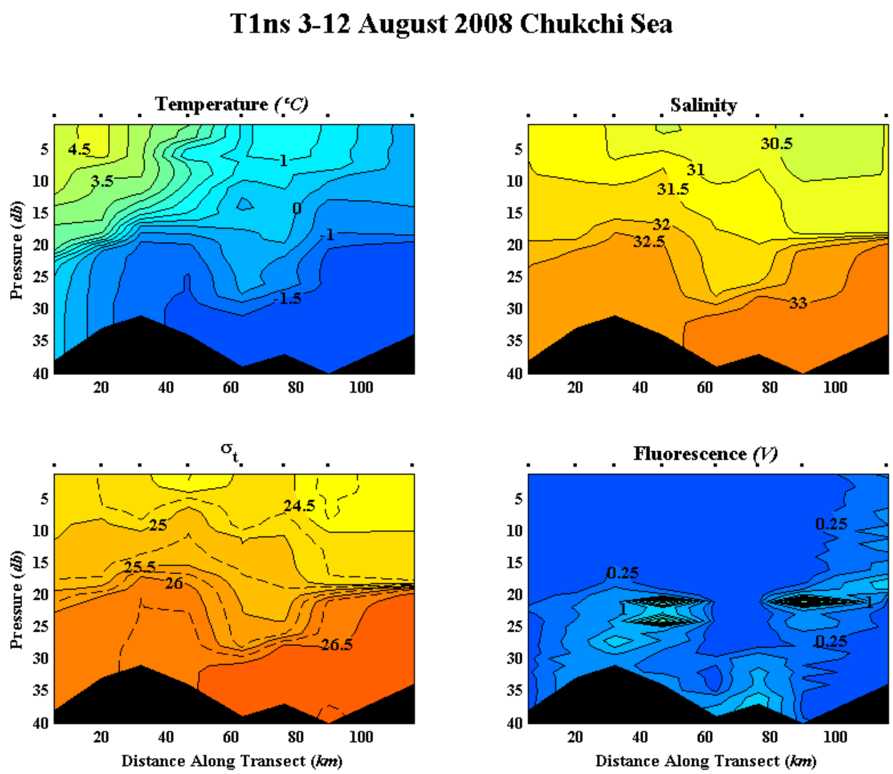


Figure 17. The north-south section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 3-12 August survey.

August 18 – September 20 Survey

The corresponding figures for this survey are shown in **Figure 18** (east-west), **Figure 19** (diagonal) and **Figure 20** (north-south). 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.

T2ew 18 August - 20 September 2008 Chukchi Sea

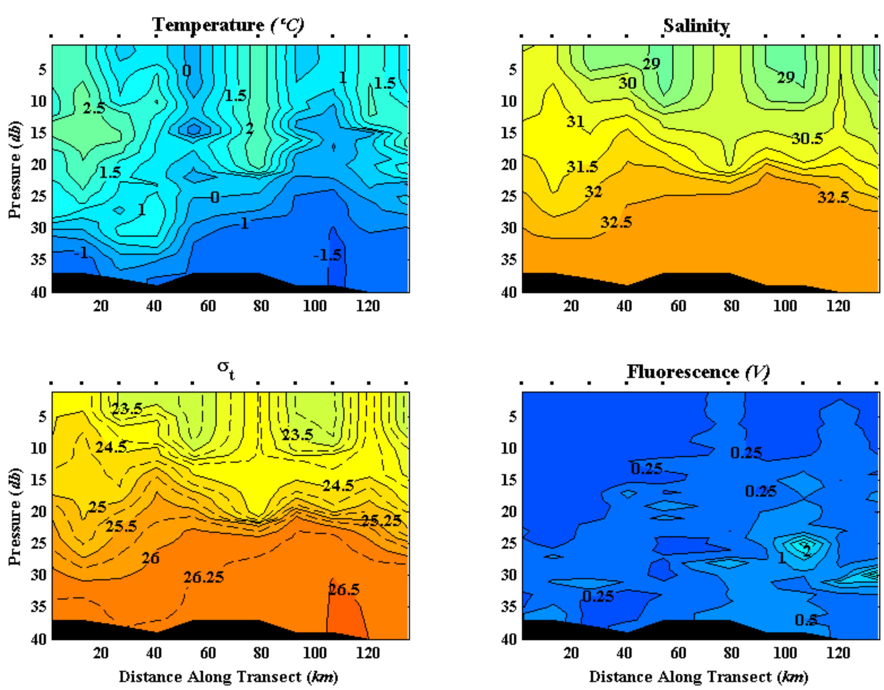


Figure 18. The east-west section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 18 August – 20 September survey.

This was surmised from a review of the satellite imagery and it is also suggested in both the diagonal (**Figure 19**) and north-south (**Figure 20**) transects, which indicate cold (<2°C), low-salinity (<30) water in the upper right hand panel of each figure. As the ice melts stream away from the ice edge front they often meander, break-up, and entrain ambient shelf waters.

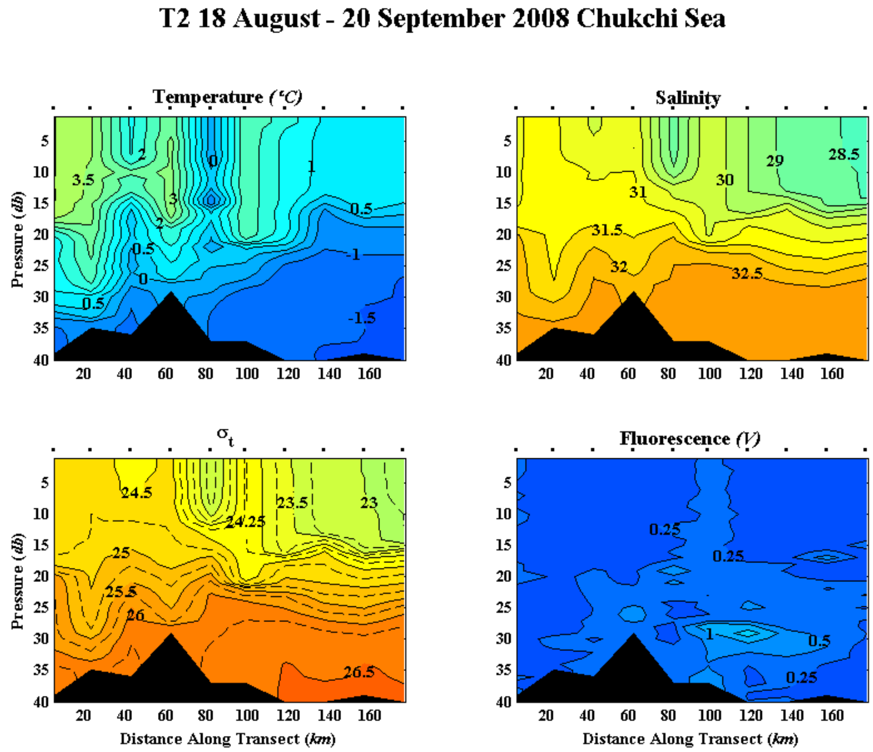


Figure 19. The diagonal section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 18 August – 20 September survey.

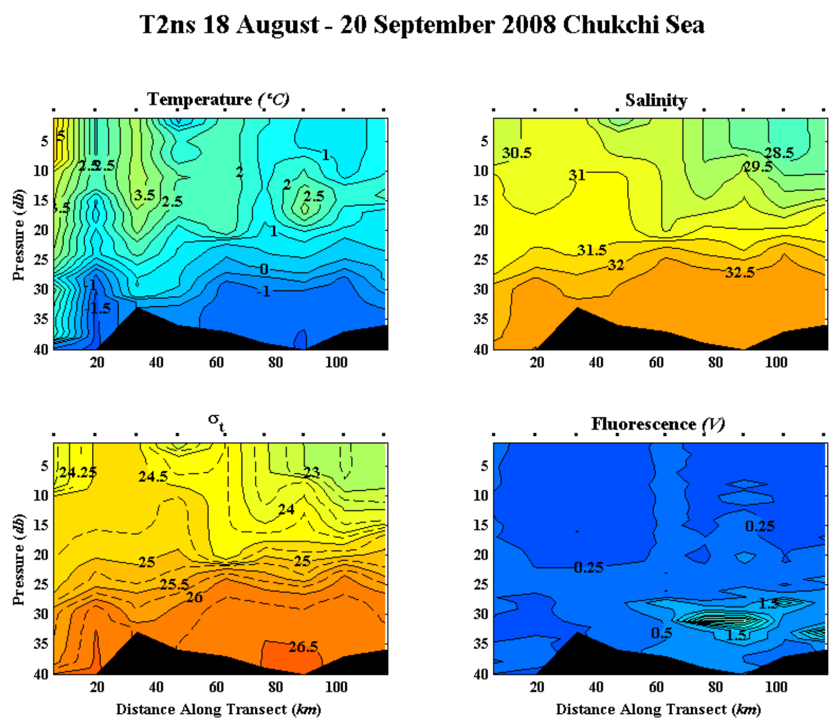


Figure 20. The north-south section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 18 Aug. – 20 Sept. survey.

September 20 – October 9 Survey

Many of the basic features of the hydrography evident during the first two surveys are still 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 east-west 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°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.

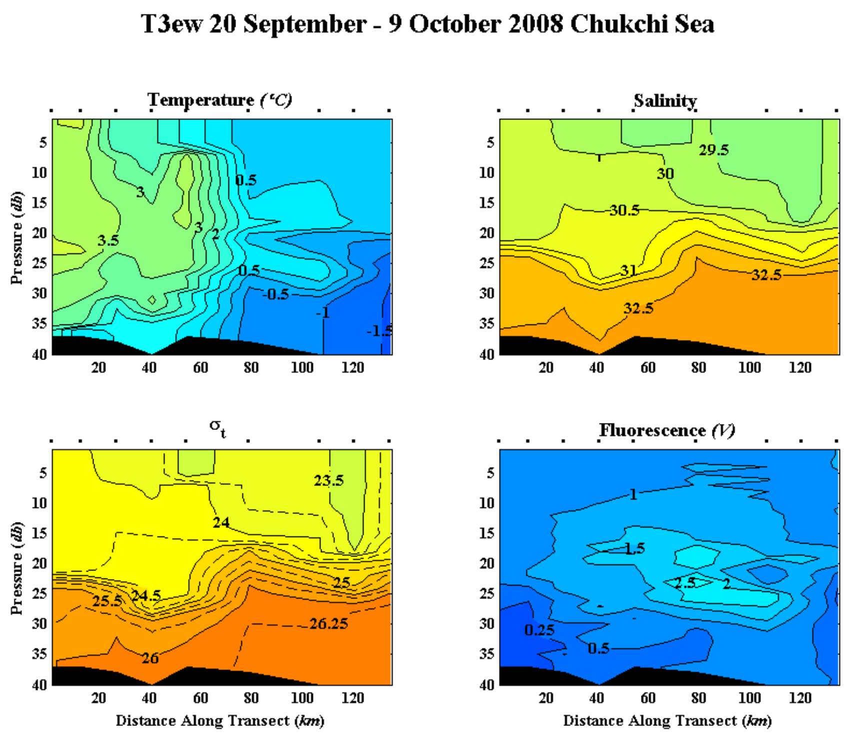


Figure 21. The east-west section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 20 September – 9 October survey.

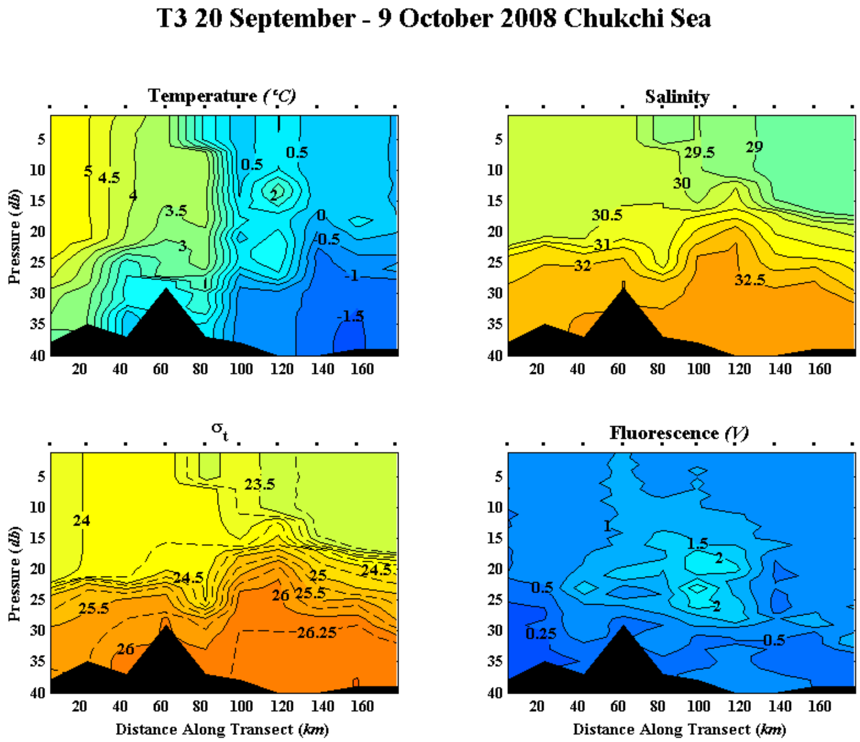


Figure 22. The diagonal section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 20 September – 9 October survey.

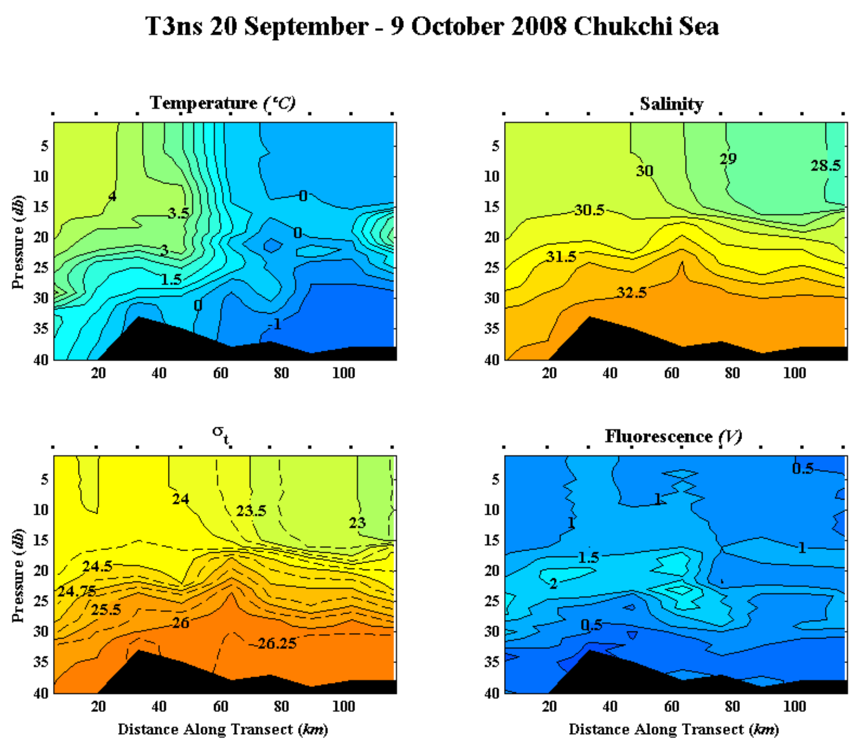


Figure 23. The north-south section of temperature (upper left), salinity (upper right), sigma-t (lower left), and fluorescence (lower right) from the 20 September – 9 October survey.

We close by noting that in all the section 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 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 t have change position throughout the year, although the strength of the thermal gradient is variable.

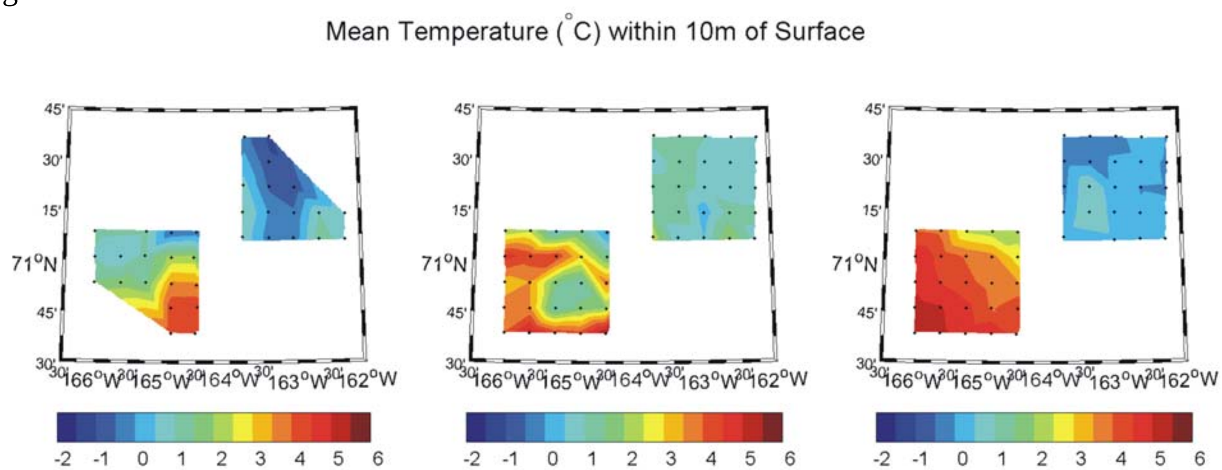


Figure 24. Plan view of mean temperature over the upper 10 m of the water column.

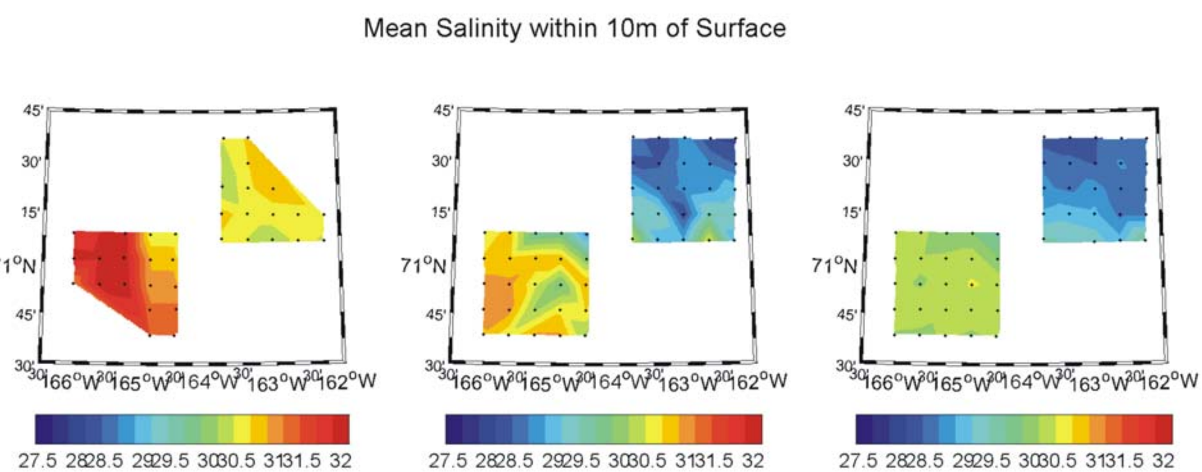


Figure 25. Plan view of mean salinity over the upper 10 m of the water column.

The front is also evident in satellite imagery, which affords a broader scale perspective (**Figure 26**). The satellite 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 northeasterly winds 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.

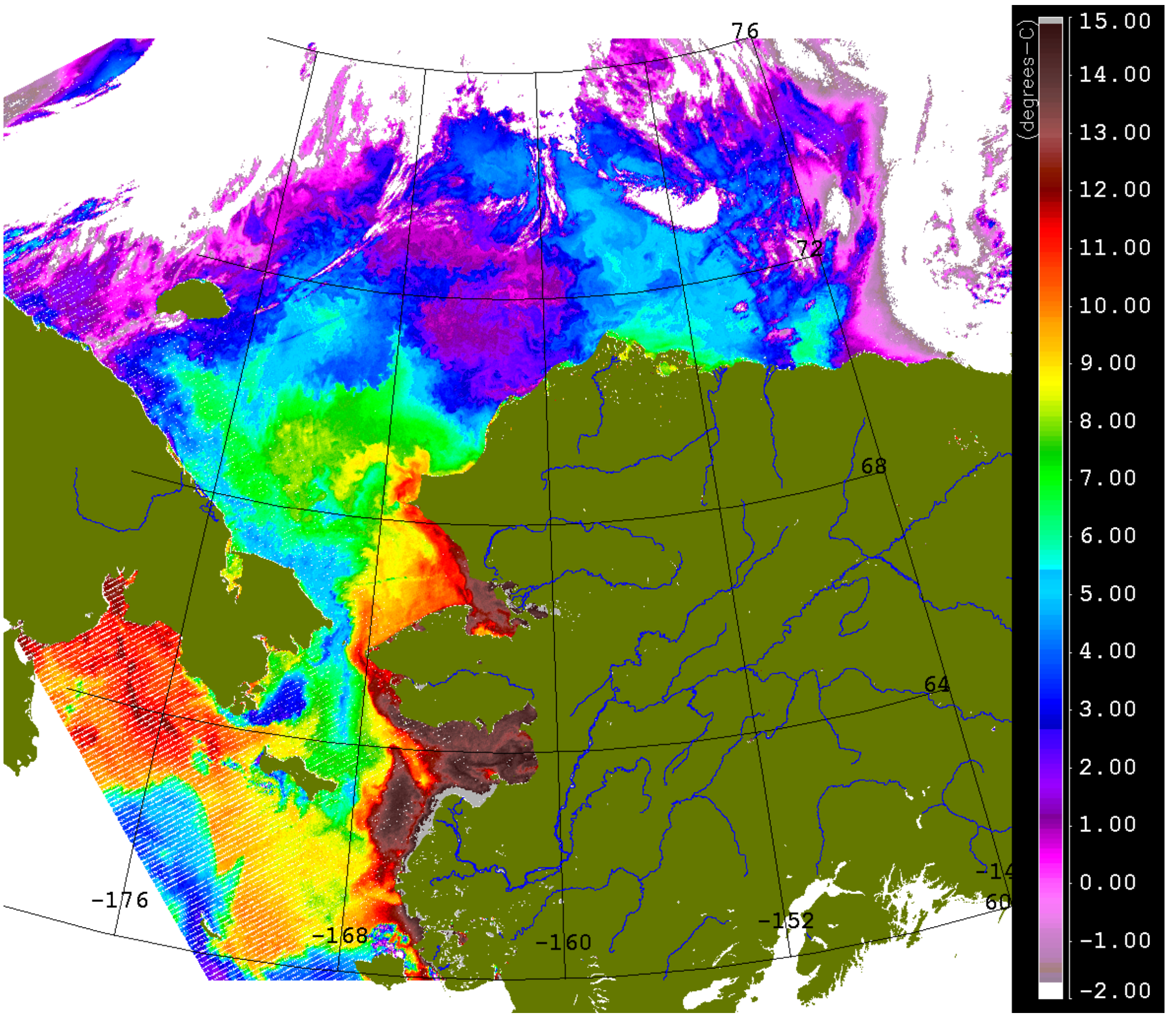


Figure 26 August 22, 2008 MODIS sea surface temperature image of the Chukchi Sea and Bering Strait. (MODIS/Aqua data obtained from Ocean Color Data Processing Archive NASA/Goddard Space Flight Center Greenbelt, MD – USA and available at: http://mather.sfos.uaf.edu/~mschmidt/ims_chukchi_sea_summary.html.

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.

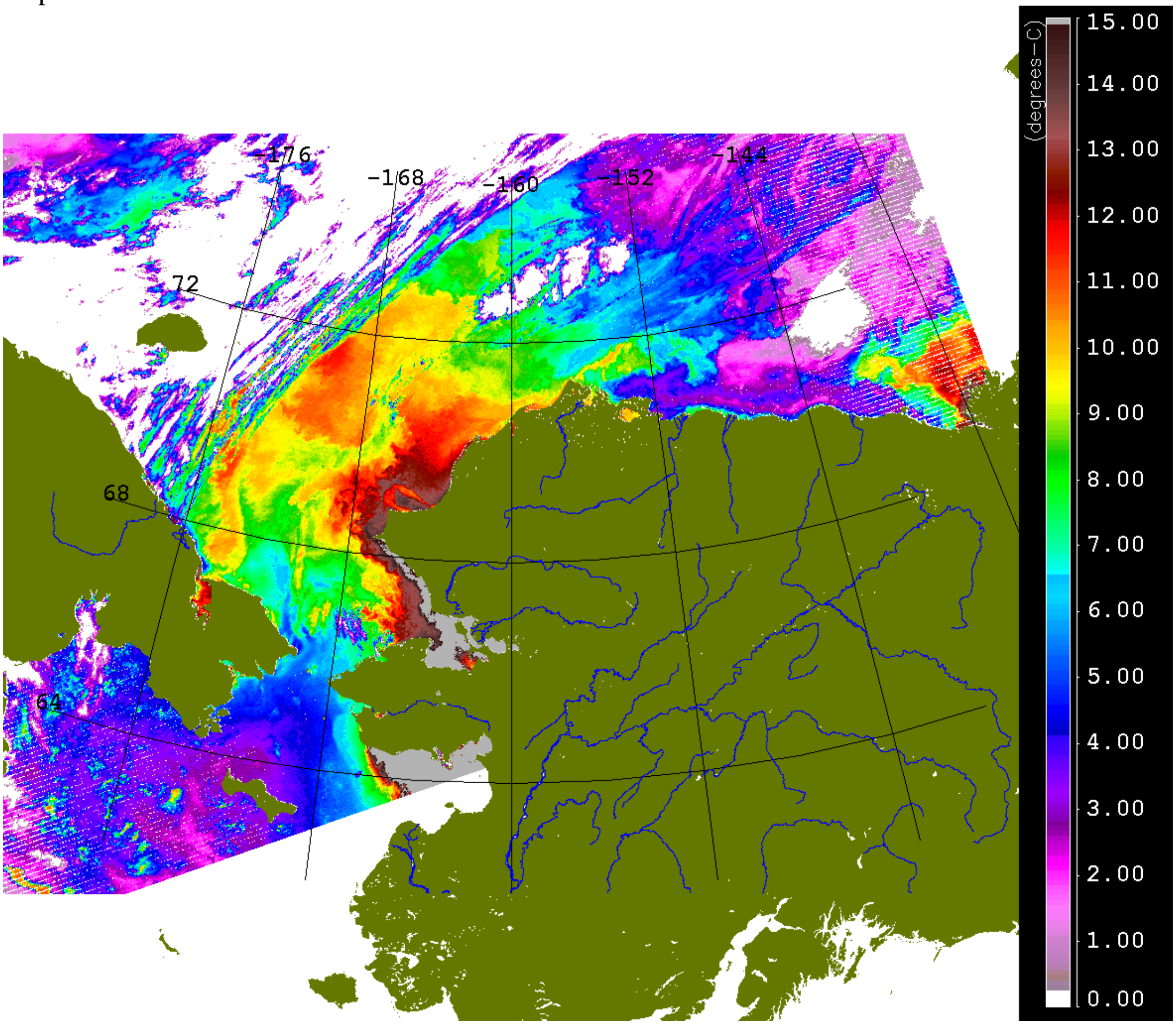


Figure 27 August 24, 2007 MODIS sea surface temperature image of the Chukchi Sea and Bering Strait. (MODIS/Aqua data obtained from Ocean Color Data Processing Archive NASA/Goddard Space Flight Center Greenbelt, MD – USA and available at: http://mather.sfos.uaf.edu/~mschmidt/ims_chukchi_sea_summary.html.

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 changes nearly constant temperature and salinity conditions are maintained in Burger.

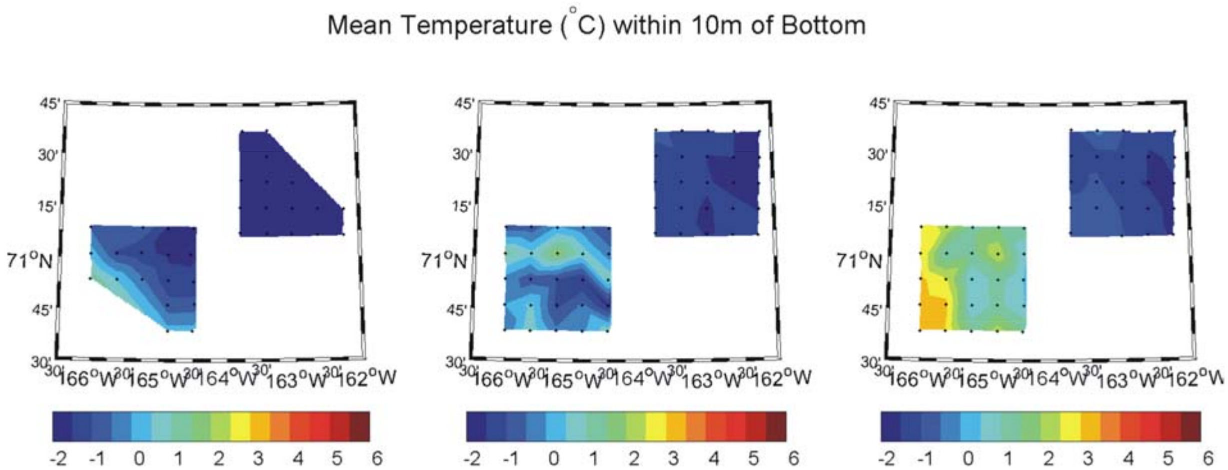


Figure 25. Plan view of mean temperature over the bottom 10 m of the water column.

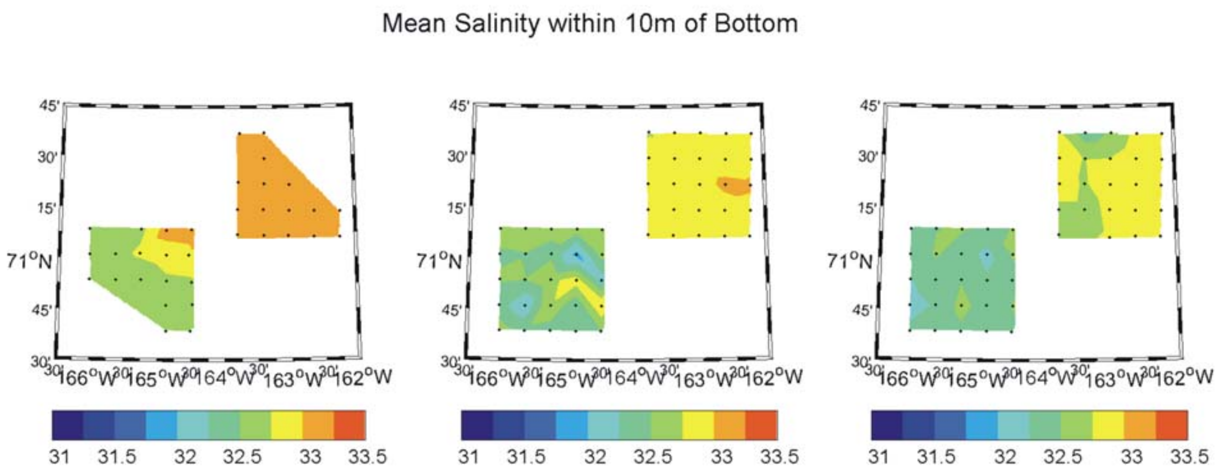


Figure 25. Plan view of mean salinity over the bottom 10 m of the water column.

Discussion

The results presented here are consistent with prior notions of the circulation and hydrography of the northeast Chukchi Sea shelf as outlined in the Introduction. Although an exhaustive retrospective examination of the winds were not undertaken as part of this project it appears, that the winds in the summer of 2008 were more frequently to the south and southwest than normal. In comparison to summer 2007, these winds delayed the retreat of ice over Hanna Shoal and the penetration of warmer water into the northeast Chukchi Sea shelf. The delayed retreat of ice established a reservoir of ice meltwater within the upper 10 – 20 m of the water column within and to the north of the Burger prospect that was evident in all surveys.

Our results also 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). The hydrography also underscores the relatively constant temperature and salinity conditions of the Burger prospect. This is likely due to either a reduced circulation in the area or a counterclockwise flow around Hanna Shoal that continually traps water here and/or replenishes the bottom waters with cold salty water from the north side of the shoal and surface waters with ice meltwater from the same area.

References

Aagaard, K., Current, CTD, and pressure measurements in possible dispersal regions of the Chukchi Sea, Outer Continental Shelf Environmental Research Program, Final Rep., Princ. Invest. 57, pp. 255-333. Dept., of Commerce/Dept. of Interior, Anchorage, AK, 1988.

Aagaard and Roach, Arctic ocean-shelf exchange: Measurements in Barrow Canyon, *J. Geophys. Res.,* 95: 18163-18175, 1990.

Aagaard, K., C. H. Pease, A. T. Roach, and S. A. Salo, *Beaufort Sea Mesoscale Circulation Study – Final Report*, NOAA Tech. Mem, ERL PMEL-90, 114 p., 1989.

Aagaard, K., J.H. Swift, and E.C. Carmack, Thermohaline circulation in the Arctic Mediterranean seas, *J. Geophys. Res*., 90, 4833-4846, 1985.

AMAP Arctic Pollution 2002: Persistent Organic Pollutants, Heavy Metals, Radioactivity, Human Health, Changing Pathways. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, xii+112 pp., 2003.

Carmack, E. C., Circulation and mixing in ice-covered waters, in *The Geophysics of Sea Ice*, edited by N. Unstersteiner, pp. 641 – 712, Plenum, New York, 1986.

Carmack, E,C., and D. C. Chapman, Wind-driven shelf/basin exchange on an Arctic shelf: the joint roles of ice cover extent shelf-break bathymetry. *Geophys. Res. Lett*., 30(14): 1778 doi: 10.1029/203GL017526, 2003.

Coachman, L.K., Aagaard, K., and Tripp, R.B., *Bering Strait: The Regional Physical Oceanography*, 172 pp., University of Washington Press, Seattle, Washington, 1975.

Codispoti, L., G. E. Friederich, C.M. Sakamoto, and L. I. Gordon, Nutrient cycling and primary production in the marine systems of the Arctic and Antarctic, *J. Mar. Systems*, 2: 359 – 384, 1991.

Codispoti, L. and F. A. Richards, Micronutrient distributions in the East Siberian and Laptev seas during summer 1963, *Arctic* 21, 67 – 83, 1968.

Codispoti, L. and F. A. Richards, Micronutrient distributions in the East Siberian and Laptev seas during summer 1963, *Arctic* 21, 67 – 83, 1968.

Cooper, L. W., J. Grebmeier, T. Whitledge, and T. Weingartner, The nutrient, salinity, and stable oxygen isotope composition of Bering and Chukchi sea waters in and near Bering Strait, *J. Geophys. Res*., 102: 12563 – 12578, 1997.

Gawarkiewicz, G and D. C. Chapman, A numerical study of dense water formation and transport on a shallow, sloping continental shelf, *J. Geophys. Res*., 100: 4489-4508, 1995.

Joyce, T., On *In Situ* “calibration” of shipboard ADCPs, *J. Atmos and Ocean. Tech., 6*, 169-172, 1989.

Hansell, D., T.E. Whitledge, and J.J. Georing, Patterns of nitrate utilization and new production over the Bering-Chukchi shelf, *Cont. Shelf Res*., 13, 601 – 627, 1993.

Liu, A. K., C. Y. Peng, and T. J. Weingartner, Ocean-ice interaction in the marginal ice zone using SAR. *J. Geophys. Res*., 99, 22391 – 22400, 1994.

Muench, R. D., C. H. Pease, and S.A. Salo, Oceanographic and meteorological effects on autumn sea-ice distribution in the western Arctic. *Ann. Glaciol*., 15: 171-177, 1991.

Münchow, A., E. C. Carmack, and D. A. Huntley, Synoptic density and velocity observations of slope waters in the Chukchi and East Siberian Seas, *J. Geophys. Res*., 105: 14103-14119, 2000.

Münchow, A., T. Weingartner, and L. Cooper, The summer hydrography and surface circulation of the East Siberian Shelf Sea, *J. Phys. Oceanogr*., 29: 2167 – 2182, 1999.

Münchow, A. and E. C. Carmack, Synoptic flow and density observations near an Arctic shelfbreak, *J. Phys. Oceanogr*., 6, 461 - 470, 1997.

Paquette, R. G., and R. H. Bourke, Ocean circulation and fronts as related to ice melt-back in the Chukchi Sea, *J. Geophys. Res., 86*, 4215-4230, 1981.

Walsh, J.J., C.P. McRoy, L.K. Coachman, J.J. Goering, J.J. Nihoul, T.E. Whitledge, T.H. Blackburn, P.L. Parker, C.D. Wirick, P.G. Shuert, J.M. Grebmeier, A.M. Springer, R.D. Tripp, D.A. Hansell, S. Djenedi, E. Deleersnijder, K. Henriksen, B.A. Lund, P. Andersen, F.E. Müller-Karger, and K. Dean, Carbon and nitrogen cycling within the Bering/Chukchi seas: Source regions for organic matter affecting AOU demands of the Arctic Ocean, *Progr. Oceanogr*., 22, 277-359, 1989.

Walsh, J.J., D.A. Dieterle, F.E. Muller-Karger, K. Aagaard, A.T. Roach, T.E. Whitledge, and D. Stockwell, CO2 cycling in the coastal ocean. II. Seasonal organic loading of the Arctic Ocean from source waters in the Bering Sea, *Cont. Shelf Res*., 17,1-36, 1997.

Weingartner, T., K. Aagaard, R. Woodgate, S. Danielson, Y. Sasaki, and D. Cavalieri, Circulation on the North Central Chukchi Sea Shelf, *Deep-Sea Res., Pt. II*, 52: 3150-3174, 2005b.

Weingartner, T. J., S. R. Okkonen, and Seth L. Danielson. Circulation and Water Property Variations in the Nearshore Alaskan Beaufort Sea, Final Report, OCS Study MMS 2005-028, 103 p., 2005c.

Weingartner, T.J., S. Danielson, Y. Sasaki, V. Pavlov, and M. Kulakov, The Siberian Coastal Current: A wind- and buoyancy-forced Arctic coast current *J. Geophys. Res*., 104: 26697 – 29713, 1999.

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

Woodgate, R.A., K. Aagaard, Weingartner, T. J., Changes in the Bering Strait fluxes of volume, heat and freshwater between 1991 and 2004. (in press, *Geophys. Res. Lett*.)

Woodgate, R. A. and K. Aagaard, Revising the Bering Strait Freshwater flux into the Arctic Ocean *Geophys. Res. Lett*., L02602, doi:10.1029/2004GL021747, 2005.

Woodgate, R. A., K. Aagaard, and T. Weingartner, Monthly temperature, salinity, transport variability for the Bering Strait. throughflow. *Geophys. Res. Lett*., 32, L04601, doi:10.1029/2004GL021880, 2005.

Woodgate, R. A., K. Aagaard, and T. Weingartner, A Year in the Physical Oceanography of the Chukchi Sea: moored measurements from autumn 1990-91, *Deep-Sea Res., Pt II*, 52, 3116-3149, 2005.