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Circulation on the North Central Chukchi Sea Shelf

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Final Report

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by

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Table of Contents

List of Tables

List of Figures

Abstract

Current meter moorings (sponsored by the CMI, the National Science Foundation, the Office of Naval Research, and the Japan Marine Science and Technology Center) were deployed on the north central and northeast shelf of the Chukchi Sea between September 1993-95 to investigate shelf circulation processes. Data from a portion of this array form the basis of this final report. The results from moorings and shipboard measurements show that, on average, waters move northward and eastward across the central Chukchi shelf, parallel to the isobaths, but opposite to the prevailing wind direction. The mean circulation is primarily established by the sea-level slope between the Pacific and Arctic oceans. The mean flow probably advects biologically rich water from the central shelf to the Alaskan coast and transports relatively dense shelf waters into the subsurface, eastward flowing boundary current along the Chukchi-Beaufort continental slope.

The bathymetry markedly influences the flow and from spring through fall steers a northward flow of relatively warm water across the shelf. This flow exerts an important thermodynamic control on the ice pack as it retreats across the shelf from spring through fall. These warm waters are a source of heat and they are likely responsible for the perennial formation of large embayments in the ice edge at several locations along the retreating pack. There is circumstantial evidence for relatively stagnant flow around Herald Shoal in the central Chukchi Sea and Hanna Shoal in the northeast Chukchi Sea and these results corroborate recent conclusions deduced from satellite imagery.

Much of the flow variability is wind-forced although the effects of seasonal thermohaline processes can be substantial. Horizontal density gradients (fronts) were present throughout winter. The strength and sign of these fronts varied due to the seasonal effects of sea ice formation and advection of different water masses from the southern Chukchi shelf and northern Bering Sea. These gradients appear sufficient to force baroclinic currents with magnitudes comparable to the mean flow.

In the winter of 1994-95, cold, hypersaline waters formed within the extensive coastal polynyas which lie along the northwest coast of Alaska. The data suggest that dense water propagates along the bottom into the central Chukchi Sea as eddy-like features with speeds of 0.1 - 0.2 m s^{-1} and length scales of 10-20 km. The data corroborate theoretical model results that predict that dense water, formed within polynyas, generates vigorous eddies via baroclinic instability. These findings suggest that bottom-confined eddies are a potentially significant transport mechanism on arctic shelves. These eddies conceivably ventilate the subsurface layers of the Arctic Ocean with shelf waters and they might even be precursors to the eddies that populate the Canada Basin.

There is considerable interannual variability in wintertime thermohaline structure and production of dense water on the Chukchi Sea shelf. For example, in 1993-94 water column temperatures became isothermal at the freezing point by mid-December and extensive coastal polynyas formed

in January. Substantial volumes of hypersaline water (S>34) formed in this winter. By contrast, in 1994-95, water column temperatures were still above freezing on some parts of the shelf through early February, and only small polynyas formed. Consequently, virtually no hypersaline water formed in the winter of 1994/95. The differences between these two years are related to the fall-early winter evolution of the shelf ice cover. In fall 1993 extensive open water areas existed over the Chukchi shelf exposing large areas to freezing. In fall 1994, thick ice from the previous winter covered much of the shelf and effectively prevented the loss of heat from the water during fall-early winter cooling.

1.0 Introduction

The Chukchi Sea is unique among the arctic shelf seas in that its circulation and physical properties are strongly influenced by waters of Pacific Ocean origin. The mean pressure gradient between the Pacific and Arctic Oceans, referred to herein as the secular pressure gradient, forces a northward flow through Bering Strait and across the Chukchi shelf. This inflow is substantially modified by thermodynamic and momentum exchanges with the atmosphere and the sea-ice. Both the secular pressure gradient and the modification processes profoundly influence the shelf dynamics of the eastern Chukchi Sea and consequently the dispersal of any pollutants introduced onto this shelf. Figure 1 shows the shelf bathymetry which contains several prominent features: Bering Strait in the southern Chukchi Sea, Barrow Canyon in the northeast corner of the shelf, and Herald Valley in the northwest. Other noteworthy features include Hope Valley, which is the broad depression extending from Bering Strait to Herald Valley, and two shallow regions; Herald Shoal on the central shelf and Hanna Shoal to the east of Barrow Canyon. As will be shown these features are influential in "steering" the circulation on this shelf. Presently, there are no marine industrial activities in the Chukchi Sea, but four exploratory wells were drilled in 1989 and 1990 to the west and south of Hanna Shoal. Future work might include joint US-Russian oil exploration ventures in Hope Valley which might involve work in both the US and Russian Exclusive Economic Zones. US Arctic industrial activities are concentrated in the Beaufort Sea. The work reported herein has relevance to those activities because outflow from the Chukchi Sea feed waters flowing along the Beaufort shelfbreak.

This study focused on determining the circulation over the north central Chukchi shelf where no long term ocean current and water property measurements exist. The field program sought to resolve existing contradictory information, understand mechanisms responsible for departures from the mean flow field and test the hypothesis that, on average, the subsurface flow on the outer shelf is northeastward. The basis for this hypothesis is that the secular pressure gradient should be aligned parallel to the isobaths and force an along-isobath flow, e.g., that the flow obeys barotropic, geostrophic dynamics.

Limited data yield contradictory interpretations of the circulation field. Coachman et al. (1975) inferred that flow over the central shelf was southeastward and eastward between Herald and Hanna shoals. In contrast, Weingartner et al. (1998) found a mean monthly northward flow east of Herald Shoal throughout the year. A three week velocity time series from Johnson (1989) from northwest of Hanna Shoal showed a persistent eastward near-bottom flow even when northeasterly winds were strong and the flow along the Alaskan coast reversed to set southwestward. In contrast, the sea ice drift trajectories reported by Muench et al. (1991) suggest that the flow over the outer shelf is westward in response to the prevailing northeasterly winds.

Two mechanisms for departure of the flow from the mean have been postulated. Weingartner et al. (1998) concluded that alongshore flow convergence within the coastal current forced offshore spreading (to the northwest and across the central Chukchi shelf) of coastal water in the winter of 1991-92. This flow advected cold, hypersaline (dense) water masses, formed in polynyas along the northwest coast of Alaska (between Cape Lisburne and Barrow) onto the central Chukchi shelf. However, Gawarkiewicz and Chapman (1995) concluded that baroclinic processes (frontal instabilities and eddy generation) could also force a significant cross-shelf transport of dense water. That possibility was apparent to Weingartner et al. (1998) but their mooring array could not address it. The present study deployed the AC- and C- moorings were deployed to detect eddy propagation and the northwestward spread of dense water across the isobaths and away from the coastal polynyas.

2.0 Data and Methods

To resolve these issues moored instruments arrays were deployed in September 1994 and recovered in September 1995 in the north central and northeast Chukchi Sea to measure temperature, salinity, and water velocity. Figure 2 is a detailed map of the northeast Chukchi Sea showing the locations of the moorings. Table 1 provides details on the water depth, instrument configurations and depths, and positions of the moorings. The moored instrument arrays were sponsored by the Office of Naval Research (ONR), the National Science Foundation (NSF) and the Japan Marine Science and Technology Center (JAMSTEC). The full array represents a collaborative effort with K. Aagaard of the University of Washington and Y. Sasaki of JAMSTEC, and the author. A subset of the mooring array focused on Barrow Canyon processes and is not considered in this report (WBC, EBC, PBC, and J1). Data recovered from moorings deployed between September 1993 and September 1994 at approximately the same location as C1 and C2 are also discussed. Hereafter C1-93 and C2-93 will refer to data collected during 1993/94 and C1-94 and C2-94 will refer to data collected in 1994-95. The mooring data are supplemented with shipboard measurements made during deployment and recovery cruises. In addition, hydrographic data from an NSF and JAMSTEC sponsored cruise in 1992 are also used to illustrate several features on the north central Chukchi Sea shelf.

Each mooring included an Aanderaa current meter equipped with temperature and salinity sensors suspended about 1 meter above a SeaBird SBE-16 temperature/conductivity recorder (Seacat). The latter was suspended about 5 meters above the seabed. The Seacats were calibrated by the manufacturer before deployment and after recovery. The pre- and post-calibration values were weighted as a function of time in computing the final estimates of temperature and salinity. The maximum salinity drift over the deployment period was ~0.05 (more typical drifts were <0.02) and the maximum temperature drift was < 0.01°C. These values were derived from the pre- and post-calibration are taken to be representative of the maximum measurement errors. The Seacat data quality was excellent at all moorings except at C1-93 where the instrument failed at deployment. In place of Seacat data is the less accurate C1-93 current meter salinity record. This record is useful in illustrating only short period, relative salinity changes because the salinity drifted by ~0.3 over the deployment period. There were several problems with the current meters. The clock on AC2 began malfunctioning on January 17, 1995, so data recorded after that date are not used. Rotor stalling frequently occurred on AC1 and we suspect that jellyfish fouled the rotors on C1-94 and C3-94 beginning in August 1995. We use the AC1 velocity record for qualitative purposes only and we truncate the C1-94 and C3-94 velocity records on July 31, 1995. Similarly, the C1-93 record was heavily contaminated by rotor stalls over most of the deployment period and is not used. Velocity data from C2-93 and C2-94 and EUBC were good. Table 2 shows the record lengths for each instrument.

Table 1. Specifics of current meter moorings deployed in September 1994. For all moorings, except J1, the instruments at the indicated depth consist of an Aanderaa current meter situated 1 meter above a SeaBird temperature/conductivity recorder. The ADCP instrument indicated for J1 measures current velocity at four meter depth intervals from between 10 and 60 m below the sea surface. The "*" indicates that data from these instruments are used in this report

Area	Mooring Name	Latitude (N)	Longitude (W)	Bottom Depth (m)	Instrument Depths (m)	Funding Source
Central Chukchi Sea	*C1-93	70° 39.68'	167° 00.93'	50	45	ONR
	*C2-93	71° 16.73'	164° 16.38'	47	42	ONR
	*C1-94	70° 37.03'	167° 05.06'	54	48	MMS
	*C2-94	71° 20.09'	164° 27.21'	46	40	MMS
	*C3	71° 41.08'	167° 11.37'	49	43	MMS
Upper Barrow Canyon	J1	71° 3.90'	159° 28.98'	79	ADCP (10-60)	JAMSTEC
	*EUBC	71° 3.10'	159° 31.68'	76	70, 50	NSF
Middle Barrow Canyon	WBC	71° 24.91'	157° 44.69'	120	114, 95, 80, 60	ONR-NSF
	EBC	71° 20.75'	157° 37.22'	107	100, 85, 70, 55	ONR-JAMSTEC
	PBC	71° 15.30'	157° 31.29'	62	56	ONR-NSF
Alaska Coastal Current	*AC1	69° 59.38'	166° 13.52'	46	40	ONR
	*AC2	70° 45.02'	163° 17.47'	46	40	ONR

Table 2. Record lengths for current meters and SEACATs deployed in 1994-95 and 1993-94 and discussed in this report.

Mooring Identifier	Record Start (UT)	Seacat Record END (UT)	RCM Record END (UT) 1995
C1-93	2000 September 21, 1993	NO DATA	2200 September 25, 1994
C2-93	0900 September 24, 1993	0100 September 28, 1994	0000 September 28, 1994
C1-94	1700 September 27, 1994	2100 September 13, 1995	2300 July 31, 1995
C2-94	0400 September 28, 1994	0000 September 13, 1995	1000 August 1, 1995
C3	1700 September 28, 1994	1400 September 13, 1995	2300 July 31, 1995
AC1*	1800 October 6, 1994	0100 September 4, 1995	0500 September 14, 1995*
AC2	1900 September 26, 1994	2300 September 3, 1995	1200 January 17, 1995
EUBC	2100 September 25, 1994	1500 March 19, 1995	0100 September 11, 1995

The shipboard measurements consist of acoustic Doppler current profiles (ADCP) and conductivity-temperature-depth profiles obtained from the University of Alaska's *R/V Alpha Helix*. Velocity profiles were collected continuously as the vessel transited the region using a 300 kHz ADCP. The profiles were ensemble-averaged into 2 or 3 minute blocks consisting of velocity estimates from a 4 m depth cell beginning 14 m below the surface and extending to within 15% of the bottom. The ADCP data were corrected for bias and alignment following Joyce (1989). The accuracy of the ensemble velocity estimates is ~2 cm s^{-1}. The CTD data were collected with a Neil Brown CTD (in 1992 and 1993) and a SeaBird 911 CTD (in years 1994 and 1995) at discrete stations. CTD salinities were compared with bottle salinities and the instruments were post-calibrated after the cruises. Overall, the accuracy of the salinity, temperature, and pressure sensors are better than 0.01, 0.005°C and 1 db, respectively.

3.0 Results

3.1 Circulation

Figure 3 shows a map of the regional mean subsurface circulation constructed from the record-length velocities listed in Table 3 for the 1994-95 moorings, as well as the means obtained from earlier mooring deployments in the northeast Chukchi Sea (Weingartner et al., 1998), the Beaufort Sea continental slope (Aagaard et al., 1988). The eastward flow over the outer Chukchi shelf and slope is inferred from hydrography and water mass analysis (Swift et al., 1998; Aagaard et al., 1996; Aagaard, 1984) as there are no long-term current measurements from this region. At all locations the vectors lie approximately parallel to the local bathymetry. The mean flow was northward at ~8 cm s^{-1} east of Herald Shoal (C1), ~5 cm s^{-1} northeastward over the outer shelf (C3), and ~4 cm s^{-1} east-southeastward along the south flank of Hanna Shoal (C2). The C3 and C2 results suggest that outer shelf waters are diverted to either side of Hanna Shoal. The vectors from offshore of Cape Lisburne and the AC moorings represent the path of the Alaska Coastal Current (Coachman et al., 1975, Johnson 1989) and depict an alongshore flow of ~5 cm s^{-1}. Coastal current waters merge with those from the central shelf flowing along the south flank of Hanna Shoal (as suggested by C2) at the head of Barrow Canyon and feed the swift (~20 cm s^{-1}) northeastward flow at EUBC. Although the mean current set was north or northeast over the shelf, the mean wind velocity was southwestward over the northeastern Chukchi shelf (Table 3) and therefore direct against the currents. Hence the influence of the secular pressure gradient on the mean circulation must exceed that of the mean winds.

The principal axes of variance for each mooring (Table 3) reflect the influence of the bathymetry as each axis lies approximately parallel to the local isobaths. The bathymetric steering effect was greatest in Barrow Canyon (EUBC) where nearly 96% of the velocity variance lies along the canyon's axis. It was weakest along the south edge of Hanna Shoal (C2) where the bathymetric slope is gentlest. Maximum current speeds (Table 3) were many times greater than the magnitude of the mean velocity. In Barrow Canyon the maximum speed was ~100 cm s^{-1} while elsewhere on the shelf the maxima were ~30 - 50 cm s^{-1}. Note that the record length statistics at C1 from 1991-92 and at C2 from 1993-94 were quite similar to those from 1994-95. The wind statistics for each of these years are also similar.

Figure 4 shows time series of the current component projected onto the principal axis of variance at C1 - C3 and EUBC. Each of these time series was low-pass filtered with a Butterworth filter having a half-power point at 35 hours to remove fluctuations at diurnal and shorter periods. Currents were quite variable and occasionally reversed; most often between October and January. However, on a monthly basis, the mean currents were nominally northward (toward the Arctic Ocean). In this respect 1994-95 differed from 1991-92 when there was no net flow over the shelf for a two-month period from late fall 1991 to early winter 1992 (Weingartner et al., submitted). The time series of Figure 4 are visually correlated with one another suggesting a spatially coherent flow field. This impression was confirmed by calculating the empirical orthogonal functions (EOFs) from the records shown in Figure 4. Nearly 89% of the velocity variance is accounted for by the first EOF. Thus circulation variability on the central and northeast Chukchi shelf was coherent over a spatial scale of at least 300 km in zonal extent. These scales are much larger than the 25 - 60 km coherence length scales characteristic of the California shelf (Winant, 1983; Dever, 1997). The contrast in scales between these shelves is most likely related to differences in depth and stratification with the California shelf being deeper (~100 m versus ~40 m) and more stratified than the Chukchi Sea. The California shelf is also much narrower than the Chukchi shelf (20-50 km versus 800 km) so it might be more susceptible to forcing from the deep ocean.

The broad spatial coherence of the flow and the similarity in the integral time scales of the currents and wind (Table 3) suggests that the winds are also coherent with the current variations. Coherence squared and phase spectra determined between the winds and the currents at EUBC

Table 3. Summary statistics for current meters and FNOC Winds.

Mooring Identifier	**Net Velocity**		**Principal Axis of Variance**			
	Speed ($cm\ s^{-1}$)	**Direction (°T)**	**% Variance Explained**	**Direction (°T)**	**Maximum Speed ($cm\ s^{-1}$)**	**Integral time scale (days)**
C1-91	8.2	350	77	355	36	4.5
C1-94	8.3	357	88	1	46	3.4
C2-93	3.9	90	73	90	34	4.5
C2-94	4.2	101	67	65	32	3.5
C3	5.3	26	82	30	29	4.5
AC1	(4.0)	(35)	-	-	-	-
AC2	5	70	90	53	50	3.0
EUBC	23.3	71	97	61	95	3.3
Winds 70°N, 165°W	**($m\ s^{-1}$)**				**($m\ s^{-1}$)**	
10/91 - 9/92	2.0	260	62	43	25	5.8
10/93 - 9/94	3.0	241	65	32	22	4.0
10/94 - 9/95	2.2	233	59	8	21	3.0

and C2 and shown in Figures 5 and 6 confirm this hypothesis. At both locations, the currents were significantly coherent with the winds over most frequencies. The phase spectra show that, where coherent, the currents lag the winds by ~24 hours.

The present findings pertaining to spatial coherence scales and the wind-current relationship are similar to those of Weingartner et al. (1998). Their results, with these, imply that the mean and fluctuating flow components are primarily barotropic and geostrophic. However, as will be shown later there are important exceptions to this conclusion.

3.2 Temperature and Salinity

This section begins with a description of the dominant characteristics of the shelf water mass properties and then compares and contrasts these among the mooring sites. This information serves as an introduction to the subsequent discussion of the seasonal evolution of shelf water masses and the shelf's horizontal density structure. For each mooring, frequency distributions were compiled on the number of occurrences during the deployment period of a water type according to its temperature (T) and salinity (S). These T/S distributions are shown in Figure 7. The predominant water mass mode, with near-freezing temperatures (< -1.7°C) and salinities of ~32.5, is a product of cooling and salt rejection from sea ice formed on the shelves of the Bering and Chukchi seas (Coachman et al., 1975) in winter. The salinity of the dominant mode tends to increase moving northeastward across the shelf; with the lowest salinity (32.3) within the coastal current at AC1 and the highest salinity (32.7) in Barrow Canyon bottom waters at EUBC. Although the properties of the dominant winter water mass mode were similar among the moorings, the less dominant modes differed considerably from one location to another. For example, temperatures along the south flank of Hanna Shoal (C2) and in upper Barrow Canyon (EUBC) never exceeded 0°C whereas temperatures greater than 0°C were often measured in the coastal current (AC1) and along the east flank of Herald Shoal (C1). The warm waters at AC1 and C1 were relatively dilute (salinity < 32.1) and characteristic of the Alaska Coastal Water (ACW) mass described by Coachman et al. (1975). The ACW forms primarily on the Bering Sea shelf as a result of solar heating of a river discharge - Bering Sea shelf water mixture. The Herald Shoal (C1) T/S distribution includes a broad limb in T-S space that extends from the ACW mode into near-freezing, saltier waters. Waters on this limb consist of a continuum between cold (< 2.0°C) ACW and colder and saltier Bering Shelf Water (Coachman et al., 1975). The latter is a composite of Bering Sea shelf water and water upwelled from along the Bering Sea shelfbreak (Coachman et al., 1975). The water types on this limb occurred frequently within the coastal current at AC2 and over the outer shelf at C3, but they seldom occurred along the south flank of Hanna Shoal (C2), and they were completely absent in Barrow Canyon (EUBC). Bottom depths were nearly the same (~50 m) at all the moorings except EUBC where the water depth was ~80m. The absence of ACW at mooring EUBC is most likely due to its low density relative to the other water masses. Consequently it did not extend to depths greater than ~50 m. Alaska Coastal Water frequently flows through the canyon in the surface layers in summer and fall (Coachman et al., 1975, Johnson, 1989, Münchow and Carmack, 1997). However, differences in the abundance of ACW at the other moorings reflects circulation differences rather than stratification effects. As examples, the water mass analysis is consistent with the depiction in Figure 3 of circulatory connections between the east side of Herald Shoal (C1) and the outer shelf (C3) and between AC1 and AC2 in the coastal current. On the other hand, the water mass census suggests that C2 is relatively isolated from these locations.

The C1, C2, and C3 T/S distributions from 1994-95 include a number of sub-dominant modes that lie along the freezing point but with salinities lower than the winter water mass mode. Two such modes were observed along the east flank of Herald Shoal (C1); one with a central salinity of ~31.1 and the other with a central salinity of ~31.9. Only one mode of this type was observed along the south side of Hanna Shoal (C2) and on the outer shelf (C3) and these had central salinities of ~31.5 and ~31.7, respectively. As shown below these modes occurred in late fall and early winter. Either they were eventually advected into the surface layer of the Arctic Ocean or transformed into more saline water masses by the addition of salt rejected from sea ice growth.

The seasonal evolution of temperature and salinity on the Chukchi shelf is discussed with reference to the time series of these variables shown in Figure 8. Broadly viewed, the seasonal cycle of temperature consisted of: 1) a fall cooling period that began in early November and that lowered water temperatures to nearly freezing, 2) a 6 - 8 month period from winter through late spring during which temperatures remained at the freezing point, and 3) a spring-summer warming which signaled the arrival of warmer water from the Bering Sea. There are differences in the timing of these seasonal thermal transitions among mooring sites however indicating that warming or cooling rates do not proceed uniformly over the shelf. For example, temperatures began decreasing along the south flank of Hanna Shoal (C2) and in upper Barrow Canyon (EUBC) later in the fall than at the other mooring sites. Site C2 was also the last to begin warming in the summer; temperatures did not rise above 0°C here until late August and nearly 45 days after they first exceed 0°C at AC2 in the coastal current.

We approximated an advective time scale for various portions of the shelf using the difference in arrival times of either the -1°C or 0°C isotherm between several of the mooring pairs. Our estimate assumes continuity in the flow between the two points and that temperature was conserved following the flow. The results suggest that for the portion of the shelf circumscribed by AC1, AC2, and EUBC the advective time scale is about one month corresponding to a mean current speed of about 10 cm s^{-1}. This estimate agrees with the time scale for the same region of the shelf reported by Weingartner et al. (submitted) from 1991-92 data. The advective time scale between Herald Shoal (C1) and the outer shelf (C3) is ~20 days and corresponds to a mean speed of ~6 cm s^{-1}. Finally we assumed that the trajectory of the warm water that eventually arrived along the south flank of Hanna Shoal (C2) in late August 1995 came by way of either Herald Shoal (C1) or within the coastal current (AC1). In either case, the advective time scale is ~45 days implying a mean speed of ~2 - 4 cm s^{-1} between these two sites and C2. The speeds deduced from the temperature data corroborate those determined from the velocity records (Figure 2 and Table 3). Moreover, the advective time scales further suggest that the south flank of Hanna Shoal (C2) is relatively isolated from the adjacent shelf regions.

At all mooring sites, except Barrow Canyon, maximum salinities were associated with the winter water mass mode and occurred in May. Within the coastal current (AC1 and AC2) salinities began decreasing in late May as less saline summer water arrived from the Bering Sea. Over the central and outer shelf (C1, C2, and C3) only gradually decreased through the summer months. The seasonal cycle was quite different in Barrow Canyon. Maximum salinity (~34.5) occurred in mid-November and was associated with warm (~0.5°C) water advected upcanyon during a period of strong southwestward flow (cf. Figure 4). This water mass originates in the Atlantic Layer of the Arctic Ocean at depths >250 m. While it is frequently intrudes into the lower half of the canyon it seldom extends up into the head of the canyon where EUBC was situated. The water is forced upcanyon by local or remote wind-forcing of the ocean (Aagaard and Roach, 1990; Weingartner, submitted). Other differences in salinities among the moorings include magnitudes (as discussed with respect to Figure 7) and rates of salinity change. For example, minimum salinities (<31.0) occurred in November and December at AC1 while at moorings AC2, C1, C2, and C3 the minimum salinities (31.0 - 31.5) occurred between early December - March. Moreover, the salinity at AC1 began increasing in late December well before the salinities at the other mooring sites began increasing. These differences imply the presence of horizontal salinity (density) gradients and therefore a thermohaline circulation. We will consider the significance of this effect in a subsequent section.

3.3 Shipboard ADCP Current Measurements and Hydrography

The quasi-synoptic shipboard measurements enable the mooring results to be viewed from a wider perspective. Figure 9 shows the near-surface current vectors over the northern half of the Chukchi shelf for 1993, 1994, and 1995. (The subsurface vectors are similarly oriented and thus not shown). Although details of the flow field vary from year to year due to differences in the wind field and ice conditions, several consistent patterns emerge from these observations. First, the flow in Herald Valley is strongly sheared horizontally; strong northward flow hugs the eastern half of the canyon and weaker flow occurs over the western half. This pattern holds throughout the year according to year-long current meter records collected from 1990-91 Aagaard's (pers. comm.). Most of this outflow probably continues northward along the axis of Herald Valley, however the vectors north of 71°N and east of 175°W suggest that a portion of it veers eastward and northeastward over the outer shelf. The vector pattern suggests that water moves anticyclonically around the northwest rim of Herald Shoal to merge with the northward flow east of Herald Shoal (C1). The flow along the south side of Hanna Shoal is weaker and more variable compared to other locations. Ice conditions allowed only the 1993 cruise to work close to Hanna Shoal and those measurements depict a very weak flow here. Finally, in 1993 and 1994, strong (50 - 100 cm s^{-1}) northeastward flow occurred in Barrow Canyon while the 1995 sampling captured a wind-driven reversal of the coastal current that extended from Barrow Canyon southward along the northwest coast of Alaska. In summary, the ADCP data suggest a generally eastward movement of water along the outer Chukchi shelf (including the north flank of Herald Shoal) with water moving eastward to either side of Hanna Shoal. The weak eastward flow along the south flank of the shoal feeds the outflow through Barrow Canyon. The circulation inferred from the ADCP data is consistent with the deductions made using the current meter data.

Figure 10 shows the location of CTD stations from nearly zonal transects made across the Chukchi Sea in 1992, 1993, and 1995. Figure 11 shows contours of temperature and salinity as a function of depth and distance along these transects. Note that the deep water along the western wall of Herald Valley is colder (<0.0°C) and often saltier than the water along the east wall. The juxtaposition of these two waters masses creates a strong cross-canyon density gradient that accelerates northward flow on the east side of the valley. The water along the east wall is Bering Shelf Water while on the subsurface water along the west wall is shelf water remnant from winter or water advected into the region from the Arctic Ocean. Fresh, cold surface waters present on the western side of Herald Valley in each year are ice melt products. The second feature to note is the relatively cold bottom water (<0.0 in 1992 and 1993) observed on the east flank of Herald Shoal. This water lies slightly to the east of mooring C1 and is probably trapped here by the confluence of flow moving northward to the east side of the shoal and the anticyclonic flow around the north side of the shoal. This water is probably slowly replaced throughout the summer by Bering Shelf Water. Finally note the very cold (< 1.0°C) and salty (32.2) water at kilometer 625 in the northeast Chukchi Sea in 1993. This water was present at the station over Hanna Shoal. Its presence here further confirms that this region is isolated from the circulation to the west, south, and east.

3.4 Inferred Baroclinic Circulation Effects

Although the results of the preceding sections are consistent with barotropic, geostrophic dynamics, baroclinic effects might be significant on occasion. We showed earlier that the salinity data suggested the presence of horizontal salinity gradients over the shelf from fall through spring. Might these gradients force a significant baroclinic circulation field? We show that they are capable of doing so using data from AC2 and C2 which are 80 km apart in conjunction with the vertically integrated thermal wind relation:

$$\Delta u = \frac{hg}{\rho f}\frac{\partial \rho}{\partial y}.$$

Here Du is the difference between the surface and bottom of the zonal velocity component, h is the water depth and y is the meridional coordinates, g is gravity, f is the Coriolis term, and r is the water density. The calculation assumes that the salinity difference extends throughout the water column and that the velocity at the bottom is zero. From December through February AC2 salinities were ~0.5 greater than those at C2. The corresponding density gradient implies a westward baroclinic velocity component of ~2 cm s^{-1}. The sign of the salinity gradient between these two moorings reversed from March through June when the average salinity difference was ~0.2 (a density difference of ~0.2 kg m^{-3}). The density gradient corresponds to an eastward baroclinic velocity component of ~1 cm s^{-1}. While the magnitudes of the baroclinic velocities are small relative to the wind-driven flows, they are significant in comparison to the mean flow. On seasonal time scales the baroclinic circulation field might be important in transporting material between the central Chukchi shelf and Barrow Canyon and the Alaskan coast. In the examples cited, the density gradients persisted for 3 - 4 months. If the baroclinic flow was the sole component of the circulation field it would displace particles ~250 km during this period. Note however, that these thermal wind calculations reflect the cross-sectional average baroclinic current between the moorings. The instrument spacing was most certainly too coarse to adequately resolve the width scale of the density gradients. The AC2 salinity record (Figure 8) shows several events from January to early March when salinity varied by 0.5 - 2.0 over a period of 1 - 10 days. These changes probably reflect the back and forth passage of a front across the mooring. Assuming that the frontal width was 3 - 4 times the baroclinic radius of deformation (which on arctic shelves is about 5 km) then the frontal width scale is ~20 km. By the thermal wind equation, the corresponding baroclinic speeds would be ~5 - 10 cm s^{-1}.

As further evidence of winter time baroclinicity we show in Figure 12 time series of temperature and salinity from 1993-94 east of Herald Shoal (C1-93) and south of Hanna Shoal (C2-93) Recall that absolute values of the C1-93 salinity record are suspect and only relative changes should be considered. At both sites, salinities decrease from early October to the record-length minima in November and December. Beginning in late December, salinities undergo a sequence of pulse-like changes at each location. At Herald Shoal (C1-93) salinity increased rapidly by ~3 over a two week period beginning late December, remained elevated (> 34.0) through January, and then decreased by ~3.0 over a 5-day period in mid-February. There is another, smaller pulse, also with rapid salinity increases and decreases in March at C1-93. Note that the nature of these mid-winter salinity changes is qualitatively different from the more gradual increase that begins in mid-May and peaks in mid-July. Recall that this increase was ascribed to the arrival of high-salinity (winter) water from the Bering Sea shelf. Along the south side of Hanna Shoal (C2-93), two salinity pulses occurred, each of about 2 weeks duration in January. These are followed by a month long (February) pulse when salinities averaged about 34.4. Another pulse of low-salinity water occurs in early March which was followed by a prolonged period (mid-March through mid-May) of moderately saline (33.0 - 34.0) water. The temporal differences in these pulses between C1-93 and C2-93 clearly imply substantial horizontal salinity gradients. Further, the rapidity of the salinity changes on the rising and falling edges of the pulses suggest fronts advecting past the moorings. Figure 13 examines these pulses in more detail at C2-93 by means of time series of salinity, temperature, currents and winds between December 1993 and March, 1994. Throughout this portion of the record salinity and temperature vary out-of-phase with temperature tracking the freezing point. The current fluctuations are energetic O(10 -20 cm s^{-1}) and show little relation to changes in the wind field. On the other hand, the current fluctuations of early and mid-January and through the first three weeks of March coincide with changes in salinity variations. That correspondence suggests that the velocity fluctuations are associated with baroclinic pressure gradients. Note that the magnitudes of the currents associated with these fronts correspond with those inferred from the thermal wind relation discussed above.

3.5 Interannual Thermohaline Variability

Although the winters of 1993-94 and 1994-95 were similar in suggesting a substantial baroclinic circulation on the Chukchi shelf in mid-winter, they are profoundly different with respect to the seasonal thermohaline evolution and modal water mass properties. In comparing Figures 8 and 12, maximum salinities occurred in January and February 1994 along the east flank of Herald Shoal (C1-93) and the south side of Hanna Shoal (C2-93), while in 1995, maximum salinities occurred in April and May at these locations. Further, minimum salinities appeared in January and February 1995 at C2-94. Another point of difference is that water temperatures decreased to freezing by mid-December in 1993, but remained above freezing into early February 1995 (e.g., at C1-94). As will be discussed, these differences are most likely related to the distinctly different seasonal evolutions of the shelf ice cover (due to advection and growth) in these years.

An additional example of interannual T/S differences is seen in Figure 14 which shows the frequency of occurrence of water types from the south side of Hanna Shoal (C2-93 and C2-94).

In 1994-95, there were essentially only two water mass modes. The dominant mode had a salinity of ~32.7 and temperatures clustered near the freezing point (-1.8°C) but ranging as high as 0.5°C. The secondary mode was fresher (salinity of ~31.5) with temperatures also at the freezing point (~-1.7°C). By contrast, five relatively distinct modes formed in 1993-94 at C2-93. All had temperatures close to or at the freezing point and salinities ranging from 31.3 to 34.5.

Chukchi shelf waters eventually cross the shelfbreak (according to the flow paths described earlier) and enter the Arctic Ocean interior. The depth to which these waters sink in the basin is a function of water density (which on Arctic shelves depends primarily on salinity) which could be modified by mixing as the water parcels flow across the shelf. The mixing of dense shelf water is poorly understood but theoretical and observational indications (Price and Barringer, 1994 and Weingartner et al., submitted) suggest that little occurs before the water crosses the shelfbreak (at ~200m isobath). Assuming that the water mass modes in Figure 14 do not mix moving across the shelf the depths in parenthesis are those that a parcel, having the indicated modal properties, would descend to along the continental slope.

The interannual differences in density have implications on pollutant dispersal. For example, the less dense water masses enter the mixed layer (≤50 m depth) of the Arctic Ocean which, on average, drifts westward seaward of the Chukchi shelf. The denser fractions ventilate the halocline (100-250 m) and will be carried eastward along the continental slope (e.g., Figure 3). Moreover, the dense water outflows will affect the slope circulation with the nature of that influence depending on the outflow density and transient behavior of the outflow. Thus outflows propagating as sharp fronts (e.g., as in winter 1994) across the shelfbreak are likely to initiate strongly non-linear shelfbreak motions including mesocale eddy formation (Jiang and Garwood, 1995). In contrast a gradual increase in outflow density will presumably allow the shelf circulation field to adjust quasi-geostrophically. In either case, these outflows are likely to result in eastward propagating fluctuations in the alongslope flow (Nof, 1988).

The contrast in water mass properties between 1993-94 and 1994-95 corroborates an expanding suite of observations that indicate that dense (hypersaline) water formation on arctic shelves is not an annual event (Aagaard and Roach, 1990; Roach et al., 1995, Melling, 1993; Weingartner et al., submitted). We believe that the differences between the winters of 1993-94 and 1994-95 are related to the seasonal evolution of the shelf ice cover. Figure 15 shows the changes in open water area as determined from the Special Sensor Microwave/ Imager (SSM/I) satellite imagery (Cavalieri, 1994) and the mean monthly winds. In 1993, large expanses of the Chukchi shelf were ice-free through November but open water diminished rapidly beginning late November and through December as a consequence of vigorous sea ice production and southward advection of pack ice by the northeasterly winds which were very strong and persistent (as indicated by steadiness values of ~80%). The same wind pattern continued into January, creating broad open water areas (polynyas) along the northwest coast of Alaska. Extensive freezing and salt rejection within polynyas can rapidly salinize shelf waters (Schumacher et al., 1983; Martin and Cavalieri, 1989; Cavalieri and Martin, 1995). In contrast, thick (~2 m), multi-year ice enveloped the Chukchi shelf north of 70°N in October 1994 as a consequence of persistent northerly winds that blew from September through October. The heavy ice conditions of autumn 1994 effectively insulated the northernmost portion of the shelf from atmospheric cooling through fall and early winter. Thereafter the winds were relatively weak and had an onshore component which inhibited polynya formation and vigorous ice production. Consequently, the salinizing effects of brine rejection were comparatively mild in 1994-95. Note also that mooring AC1 remained in ice free waters later into the fall than the more northerly moorings. The absence of an insulating ice cover resulted in temperatures at AC1 (the southernmost mooring) reaching the freezing point a full month earlier than those at either C1-94 or C2-94. The more extensive ice cover in fall 1994 would also explain why temperatures reached the freezing point later in that year than in fall 1993.

4.0 Discussion

In their classic treatise, Coachman et al. (1975) described two circulation branches along which waters from Bering Strait flowed across the Chukchi Sea to the Arctic Ocean. The first is a coastal flow that moves northeastward around Cape Lisburne to Barrow Canyon and which carries nutrient- and carbon poor Alaska Coastal Water (Walsh et al., 1989). The second route extends northwestward through Hope Sea Valley and thence northward through Herald Valley. This branch transports Bering Shelf Water which is relatively rich in nutrients and marine carbon (Hansell et al., 1993; Walsh et al., 1989). These pathways are evident in the data sets presented here. However, there is also a third well-defined northward flow across the central Chukchi shelf through the depression to the east of Herald Shoal. It consists of a mixture of Alaska Coastal Water and Bering Shelf Water. The various data sets described here suggest that the outer portion of the central shelf is bathed by water from the central and western branches. Although we are not in a position to estimate transport magnitudes through the eastern and western branches we can estimate the transport along the central branch. The hydrography, ADCP, and bathymetric data all suggest a width scale of ~50 km for this branch and the current meter data indicates a mean northward flow of ~8 cm s^{-1}. These numbers imply a transport of ~1.6×10^5 m^3 s^{-1} using a mean depth of 40 m. By comparison, the mean annual transport through Bering Strait is about 8×10^5 m^3 s^{-1} (Roach et al., 1995).

The mean flow on the outer shelf is northeastward, parallel to the isobaths but directly opposite to the prevailing winds. Hence the secular pressure gradient is more important in the dynamics of the mean circulation than the winds. On the Chukchi shelf, the secular pressure gradient between the Pacific and Arctic oceans sets up a sea-level field such that the resulting geostrophic flow is parallel to the isobaths. This interpretation and the mean flow results agree with the barotropic model predictions of Proshutinskiy et al. (1996). The dynamics and the data also indicate that Herald Shoal diverts central shelf waters around the north and south flanks of the shoal. The waters along the southern flank of Hanna Shoal exchange relatively slowly with shelf waters to the west and south so that pollutants released or advected into this vicinity might accumulate. In a similar fashion Herald Shoal causes an anticyclonic circulation about its north flank and the CTD data suggest that water is trapped to the shoal and exchanges slowly with the other parts of the shelf. These findings corroborate the conclusions of Martin and Drucker (1997) based on ice drift data collected from satellite microwave data over the shoals.

While the mean flow is forced by the secular pressure gradient, flow variations are primarily wind-driven with the magnitudes of these wind-forced currents being many times those of the mean flow. The ice-drift is also primarily wind-driven and on average it drifts westward in response to the prevailing winds (Muench et al., 1990). There must be then, at least on occasion, a strong velocity shear over the water column between the surface boundary layer and the sub-surface flow. The depth of the former will vary throughout the year depending on ice thickness, keel depth, keel frequency, and wind speed.

Eastward flow around the south flank of Hanna Shoal implies that some water from the central shelf will eventually join the coastal flow draining through Barrow Canyon. This eastward flow could be biologically important by advecting nutrients and carbon into a section of the shelf that is otherwise bathed by nutrient- and carbon-poor ACW. As such, this flow could sustain the benthic populations and the large numbers of walrus that forage on the benthos of the northeast Chukchi Sea (Feder et al., 1994; Fay, 1982; Moore and Clarke, 1986). On the other hand, this flow represents a potential pathway by which pollutants from the outer shelf can be carried into the coastal waters adjacent to Alaska.

Figure 3 implies that the outflow through Barrow Canyon is drawn from a relatively broad area of the central and northeast shelf. Shelf water densities are generally equal to or greater than those of the Arctic Ocean's surface layer. Winter water masses are dense enough to ventilate depths from 50 to 250 m in the Arctic Ocean. Even some of the low-salinity summer water (ACW) would sink beneath the summer mixed layer of the Arctic Ocean. Consequently, the outflow from Barrow Canyon will feed the subsurface layers of the Arctic Ocean and contribute to the Beaufort Undercurrent that flows eastward along the continental slope adjacent to Alaska's north slope (Aagaard, 1989). This boundary current advects waters of Atlantic Ocean origin (which enter the Arctic Ocean from the Barents and Greenland seas) and contributions from the shelves of Eurasia eastward as a subsurface flow. Figure 3 shows the hypothesized path of this current along the northern Chukchi borderlands. The outflow from Herald Valley and the central shelf waters that cross the Chukchi shelfbreak north of Hanna Shoal should also feed the undercurrent. Hence, the undercurrent is a potential pollutant transport mechanism that can distribute contaminants from one shelf location (e.g., the Chukchi and/or the Eurasian shelf seas to the west) over a broad area of the Arctic Ocean. Shelfbreak upwelling of waters from within the undercurrent (Aagaard and Roach, 1990 and as discussed in reference to the data from EUBC in Figure 8) would transport these contaminants back onto shelves far distant from the pollutant source region. Hence pollutants released in the southern or the western Chukchi Sea might effect Alaskan coastal waters either by being carried eastward across the outer Chukchi shelf or upwelled back onto the shelf from within the undercurrent.

An important goal of this program was to examine the spread of cold, hypersaline water formed within the polynyas that develop in winter along the northwest coast of Alaska. The 1993-94 results suggested that the dense water was associated with fronts or eddies that propagated across the central Chukchi Sea. The 1994-95 sampling scheme was meant to investigate this further and to permit comparisons with the model results of Gawarkiewicz and Chapman (1995). Cold, hypersaline water did not form in 1994-95 so comparisons with their model were not possible. However, the data suggest that even in years when dense water does not form on the Chukchi shelf, strong horizontal density gradients are present in winter which might force substantial baroclinic flows. Indeed, the observations suggest that strong fronts, apparently not associated with polynyas, can form on the shelf in winter and that the baroclinic jets associated with these fronts could have speeds of ~10 cm s^{-1}. It also appears these baroclinic flows could be quite variable as the magnitude and sign of the mid-shelf density gradients changes throughout the winter. These observations were surprising insofar as the mid-winter CTD sections of Aagaard (1988) on the Chukchi shelf show little evidence of fronts except adjacent to the coastal polynyas.

In early winter, the horizontal density gradient forced a westward baroclinic flow tendency. This gradient developed as low salinity water spread across the outer shelf and more saline water formed over the more southerly reaches of the shelf. The seasonal evolution of the ice pack in 1994-95 likely contributed to these density contrasts. Thick (~2 m) first- and multi-year ice with concentrations >75% covered much of the outer shelf during the fall 1994 mooring deployment cruise and anomalously northerly winds advected this ice southward through the fall. Where present, thick ice effectively insulated shelf waters from atmospheric cooling throughout autumn. In contrast, sea ice was absent over the more southerly portions of the shelf where rapid cooling occurred. These differences in ice cover caused temperatures at AC1 to decrease to the freezing point one month earlier than those at C2 or C3. The subsequent addition of salt by the formation of 1 meter of ice between mid-November and late December would have been sufficient to elevate shelf salinities from ~31.5 to ~32.0 at AC1 over this period. Since little new ice formed over the northern portions of the shelf, salinities remained at ~31.5 through much of the winter.

In late winter the horizontal density gradient reversed sign as low-salinity waters on the outer shelf were replaced by the northward advection of more saline water from the south. At the same time less saline water from the northern Bering Sea arrived in the Chukchi Sea and spread over the southern portion of the mooring array.

If this hypothesis is correct then horizontal density gradients are likely to develop every year although their magnitudes will vary in accordance with the seasonal development of the sea-ice. Since fall sea-ice distribution (thickness and extent) varies enormously from year-to-year we surmise that winter density gradients are likely to do so as well.

The northward flow of warm water from spring through fall represents a heat flux to the northern shelf which can be estimated from the observed horizontal temperature gradients and the inferred velocity field (assuming that both are uniform throughout the water column), e.g.,

$$Q_{adv} = vh\rho C_p \frac{\partial T}{\partial y}$$

where Q_{adv} is the advective heat flux (W m^{-2}), h is the water depth (50 m), r is seawater density (1025 kg m^{-3}), C_p is the specific heat of water (3990 J-[kg °K]$^{-1}$) and $\partial T / \partial y$ is the temperature gradient along the flow path (°K m^{-1}). We estimated Q_{adv} between Herald Shoal and the outer shelf (pair C1 and C3) and along the Alaska Coastal Current (pair AC1 and EUBC) using the currents speeds deduced from the advective time scales and the June - July temperature gradients estimated from Figure 8. For C1 - C3, Q_{adv} is ~150 W m^{-2} and for AC1 - EUBC, Q_{adv} is ~230 W m^{-2}. If these heat fluxes were made available to the overlying ice pack, they would melt ice at a rate of 4 - 6 cm day^{-1}. The net incoming shortwave radiation received at the ice surface in mid-summer (for cloud conditions typical of the Chukchi Sea and assuming a surface albedo of 0.7 [Maykut, 1986]) is comparable to the magnitudes of Q_{adv}. Hence, Q_{adv} might play a prominent role in the thermodynamics of the Chukchi Sea summer ice pack. Moreover, in fall when atmospheric cooling begins, the northward advection of heat must delay sea-ice formation. Indeed relative to either the East Siberian or the Alaskan Beaufort shelves, sea ice retreats advances later on the Chukchi shelf. Similarly, ice retreat begins earlier in the Chukchi Sea in spring in comparison to the adjacent shelves. The oceanic heat flux is not uniformly distributed along the front of the ice edge but is channeled along the primary circulation paths (Herald Valley, east of Herald Shoal, and Barrow Canyon). Summer and fall ice maps show prominent northward indentations in the ice-edge along each of these circulation pathways (Paquette and Bourke, 1981). Such indentations might be of significance biologically for they 1) extend the total ice-edge perimeter (hence walrus, bearded and ringed seal habitat) on the Chukchi shelf and 2) lead to upwelling (downwelling) on the windward (leeward) side of the indentation (Hakkinen, 1986). Her model suggests that ice-edge production in the northern Chukchi Sea might vary dramatically in time and space as the winds shift relative to the orientation of these embayments. The perennial nature of the ice-edge embayments on the Chukchi shelf was well-known to 19th century whalers. Indeed they used the embayment on the north central shelf as a rendezvous point for ships venturing to and from the Chukchi whaling grounds (Bockstoce, 1986). The ice-edge indentations over Barrow Canyon and the central shelf are often separated by a tongue of ice that extends southward over Hanna Shoal often as far as the C2 mooring site. This ice edge feature is further evidence that the shelf surrounding Hanna Shoal is relatively isolated from the adjoining waters.

5.0 Conclusions

The principal conclusions of this study are:

1. On the outer shelf of the Chukchi Sea, the sea-level slope between the Pacific and Arctic oceans forces a mean north and northeasterly flow that parallels the isobaths. The mean flow is directly opposite to the prevailing winds.
2. On average, there is a weak flow along the south flank of Hanna Shoal that advects carbon- and nutrient-rich Bering Shelf Water eastward from the central shelf to Barrow Canyon.
3. Current variability is primarily wind-driven and the magnitudes of the wind driven flows can be many times that of the mean currents.
4. There is compelling evidence for the formation in winter of horizontal density gradients that are not associated with polynyas but rather with the fall distribution of sea-ice and the properties of water advected onto the Chukchi shelf from the northern Bering Sea. These density gradients are capable of forcing a baroclinic circulation field with magnitudes comparable to the mean flow.
5. The bathymetric steering of the circulation field and the oceanic heat flux along these circulation paths significantly affects the seasonal advance and retreat of the ice edge and the formation of ice-edge embayments.

6.0 References

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Figure 1.Bathymetric map of the Chukchi Sea showing regional place names.

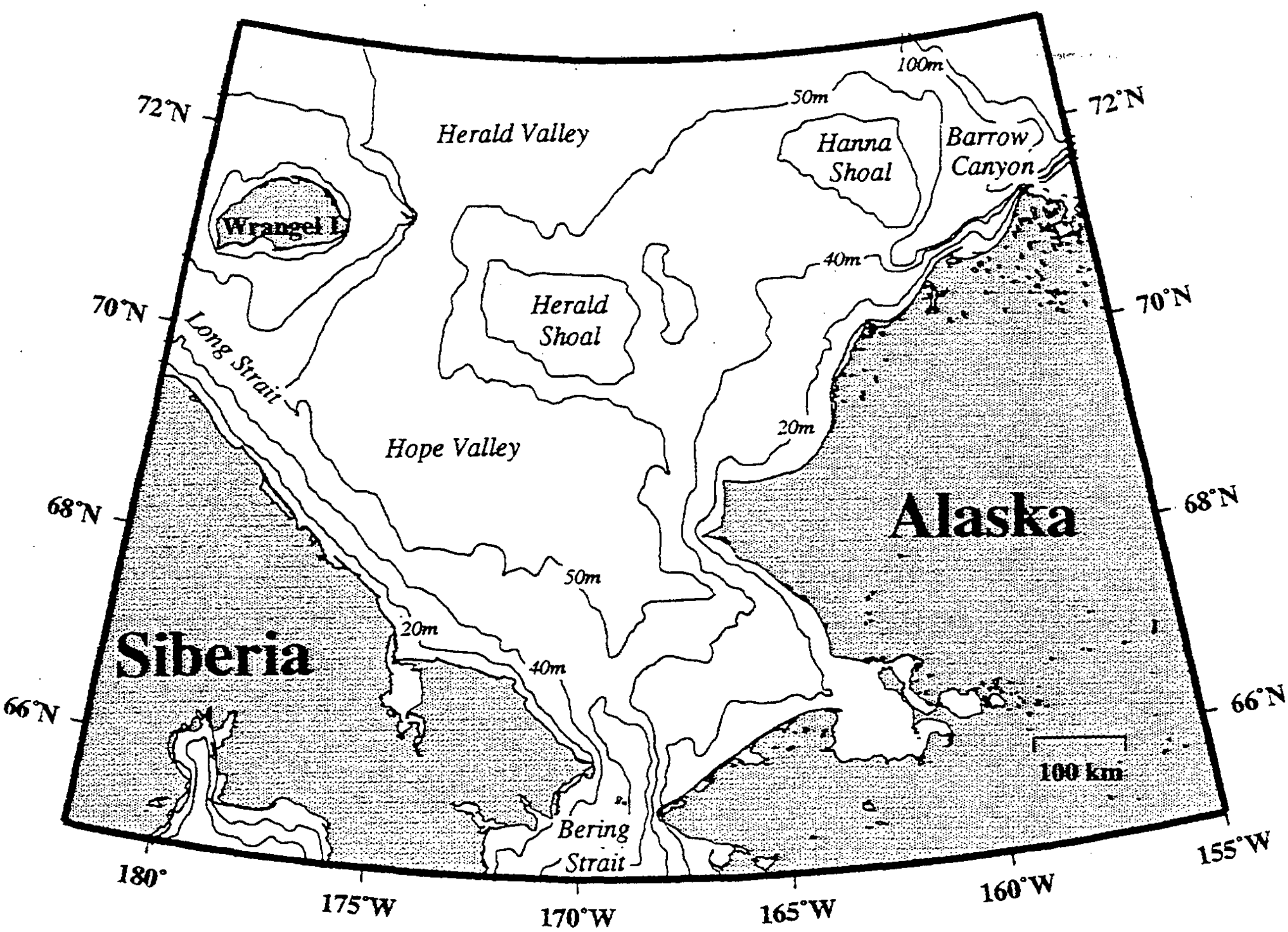


Figure 2.Location of moorings discussed in the text and deployed in the northeast Chukchi Sea from September 1994 - September 1995.

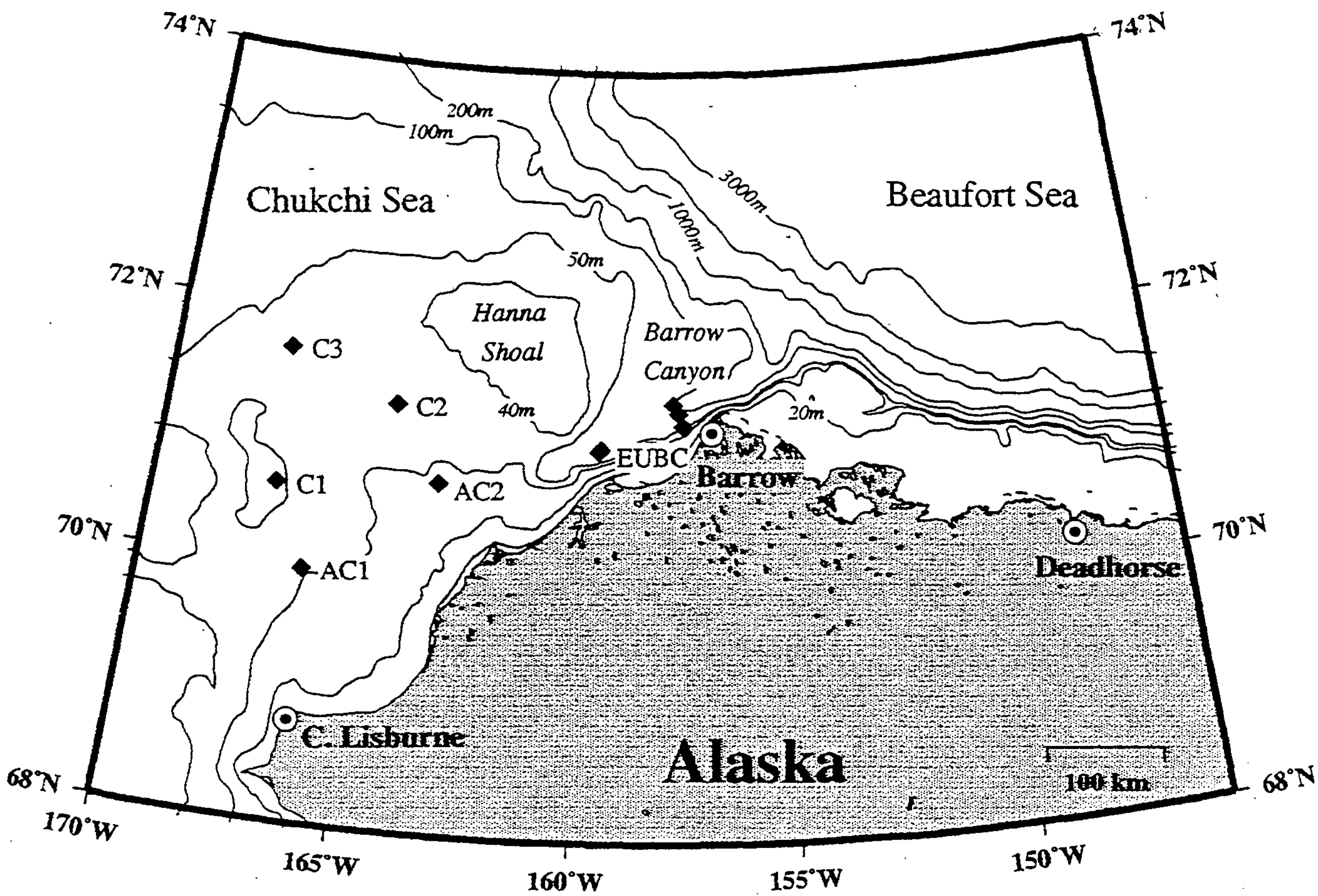


Figure 3.Plan view of the northeast Chukchi Sea shelf, slope and north coast of Alaska with mean current vectors superimposed. The vectors along the Beaufort Sea continental slope reflect the flow at ~100 m depth from data collected by Aagaard et al., (1989).

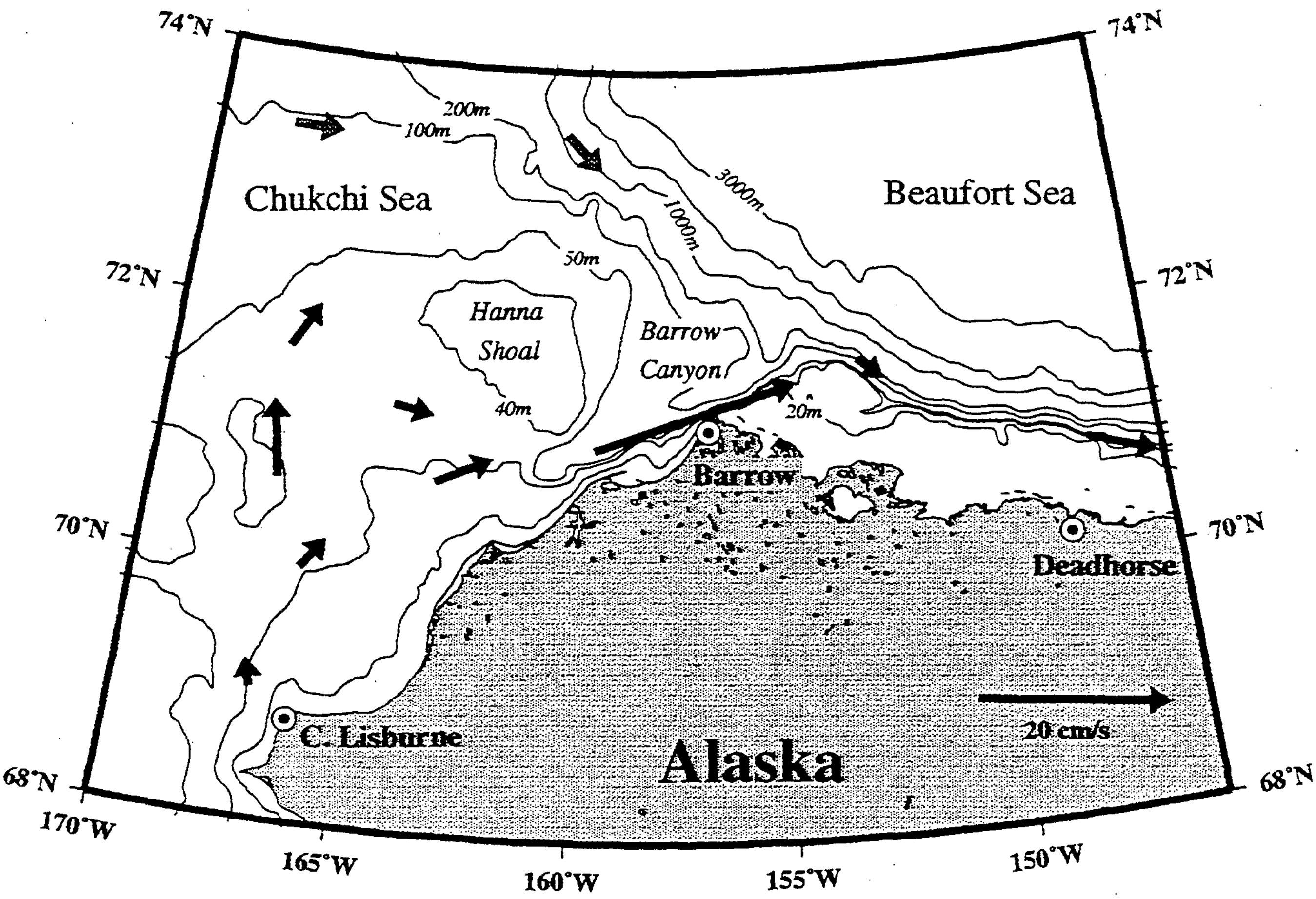


Figure 4.Time series of the current velocities projected onto the principal axis of variance for each mooring. From bottom to top the data are from moorings C1, C2, C3, and EUBC. The directions of the principal axes of variance are indicated to the right of each time series.

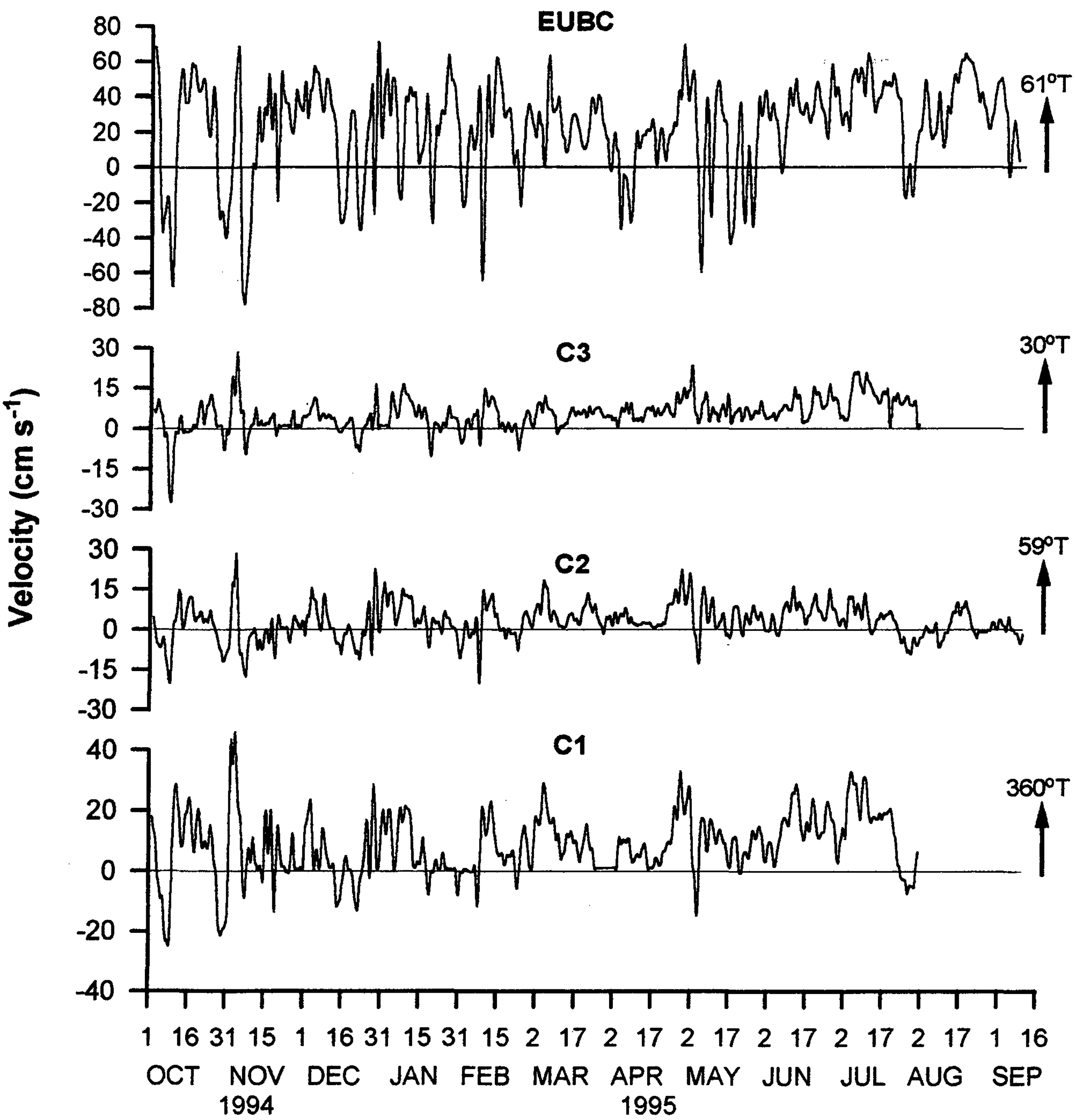


Figure 5.Coherence square (g^2) and phase (f; in radians) spectra between winds and currents at EUBC. The horizontal line indicates the a = 0.05 significance level for g^2.

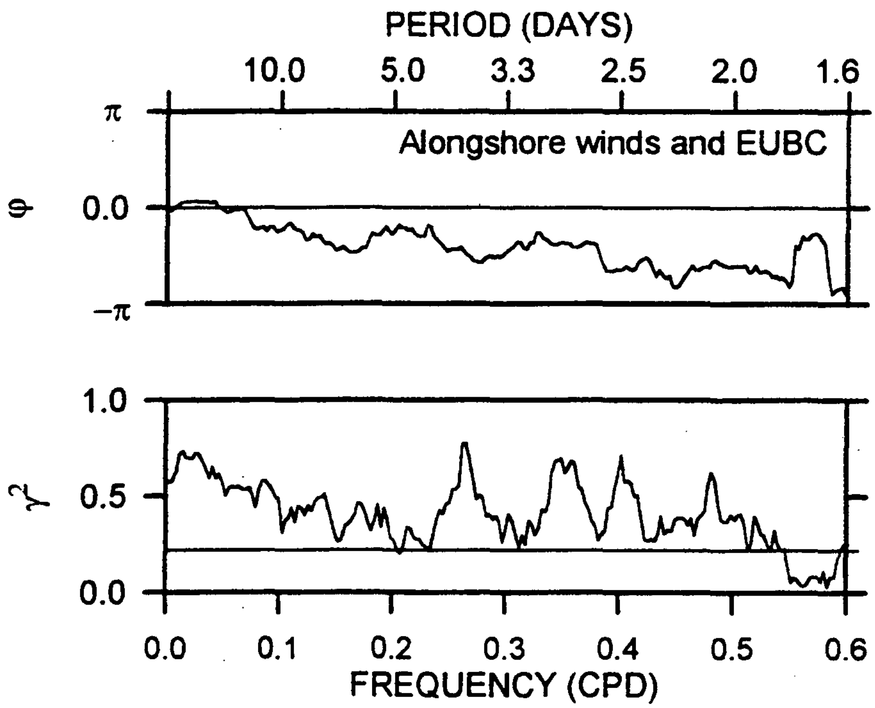
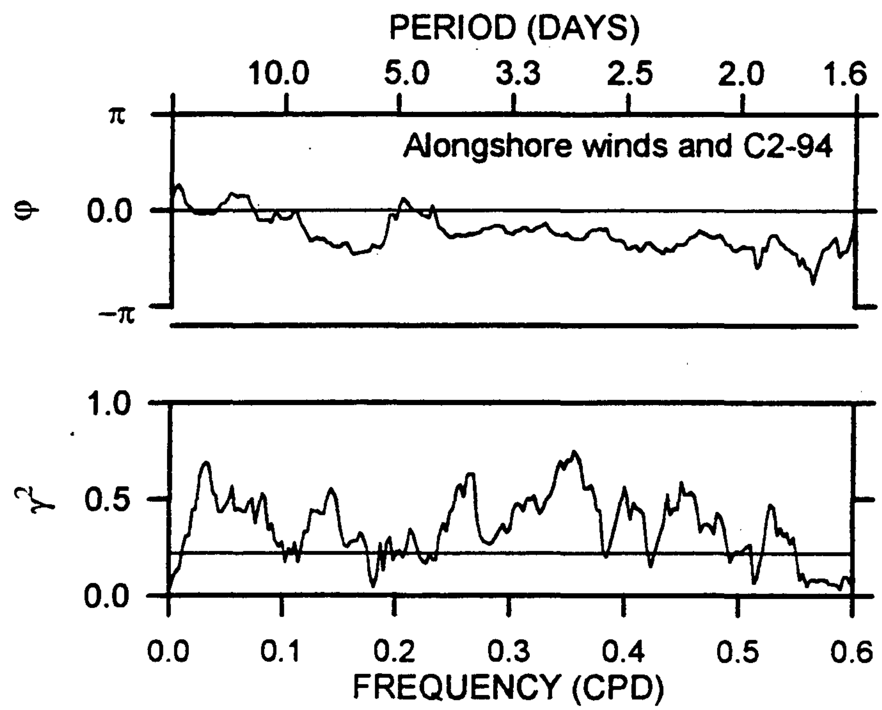


Figure 6.Coherence square (g^2) and phase (f; in radians) spectra between winds and currents at C2. The horizontal line indicates the a = 0.05 significance level for g^2.



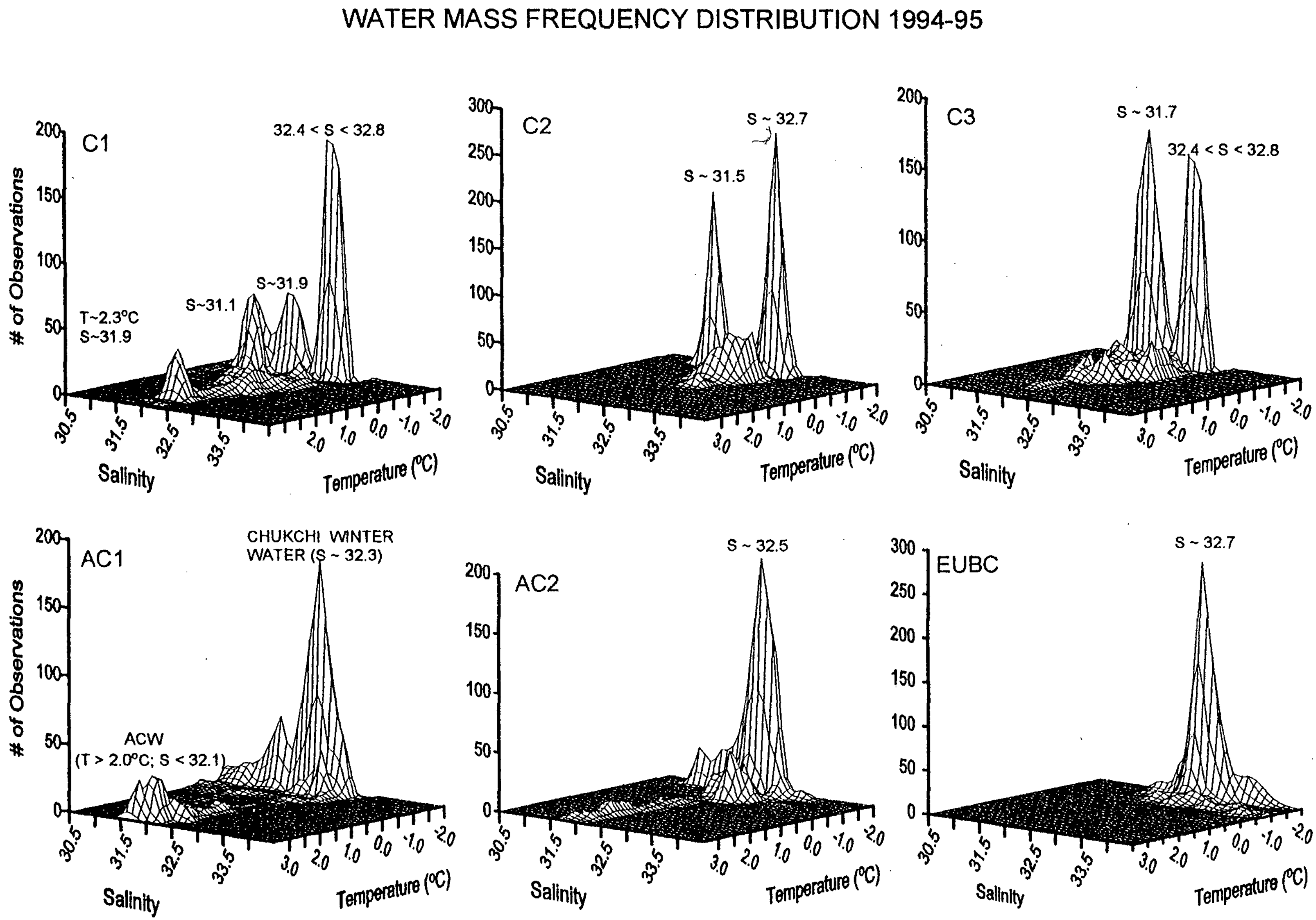


Figure 7.Water mass frequency distributions for AC1, AC2, EUBC, C1, C2, and C3.

Figure 8.Time series of temperature and salinity at (from bottom to top) moorings AC1, AC2, C1, C2, C3, and EUBC. Solid line is temperature and dashed is salinity.

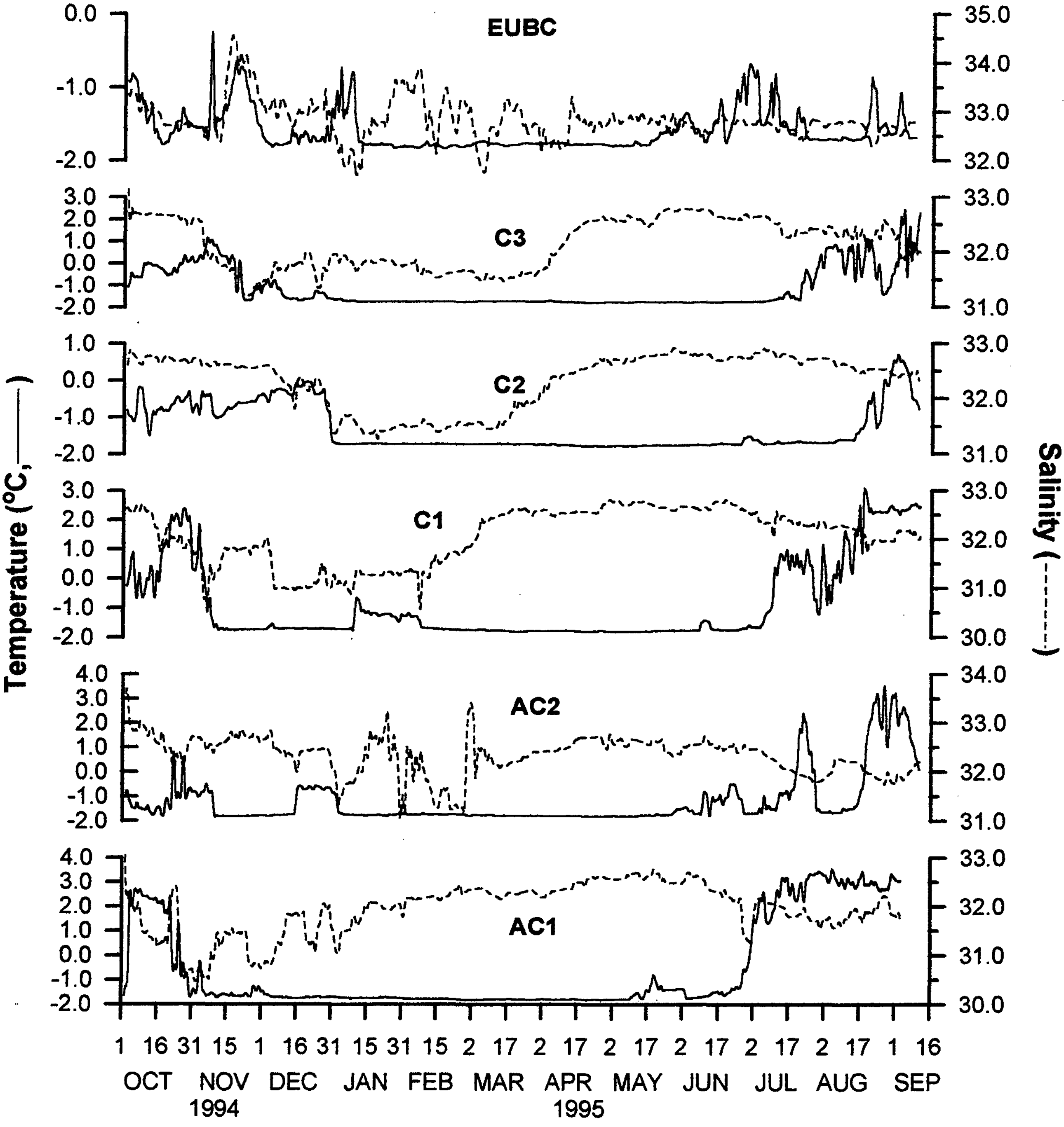


Figure 9.(a) Near-surface (14 m depth) current vectors over the northern Chukchi Sea from a hull-mounted ADCP in September 1993.

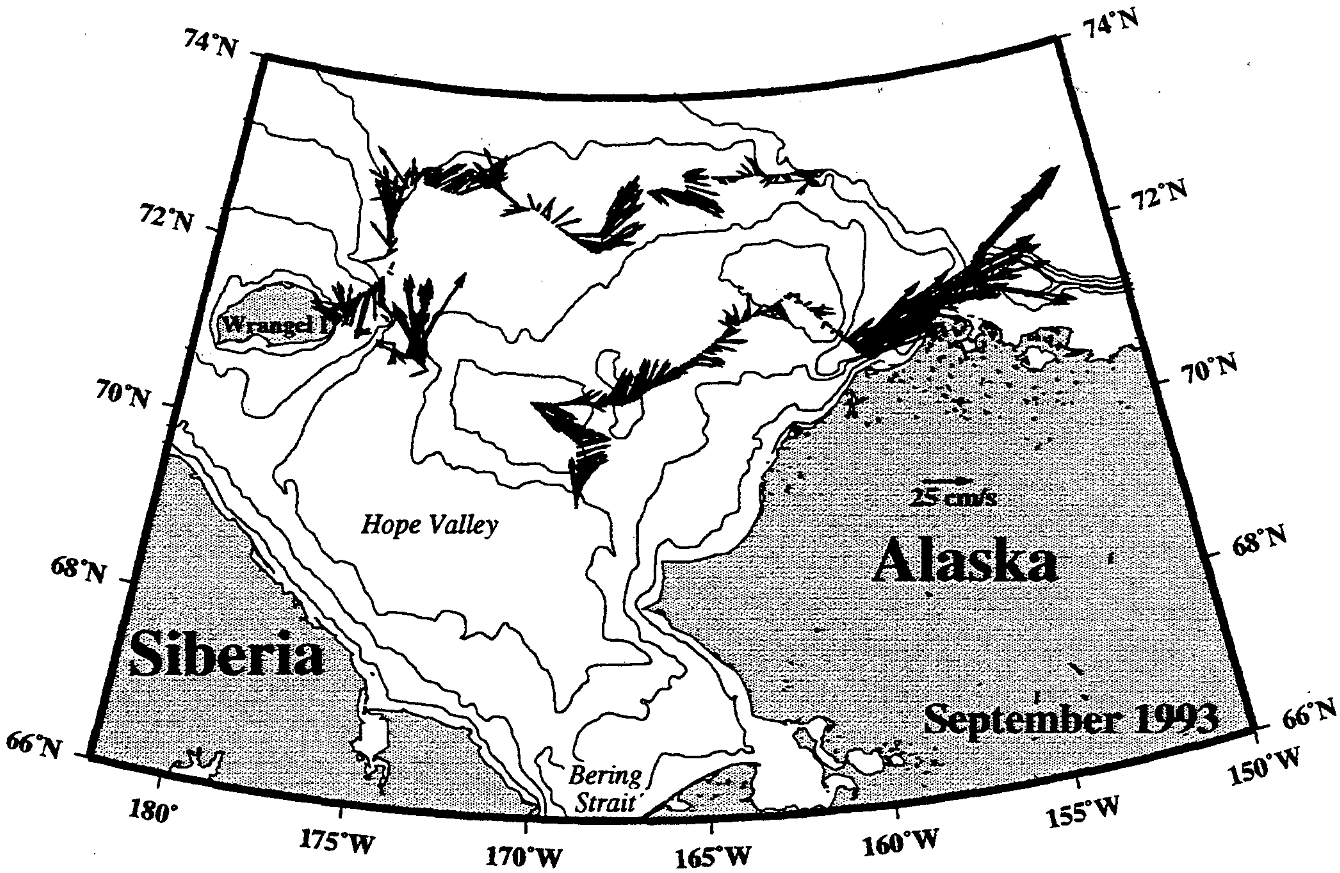


Figure 9. (b). Near-surface (14 m depth) current vectors over the northern Chukchi Sea from a hull-mounted ADCP in September 1994.

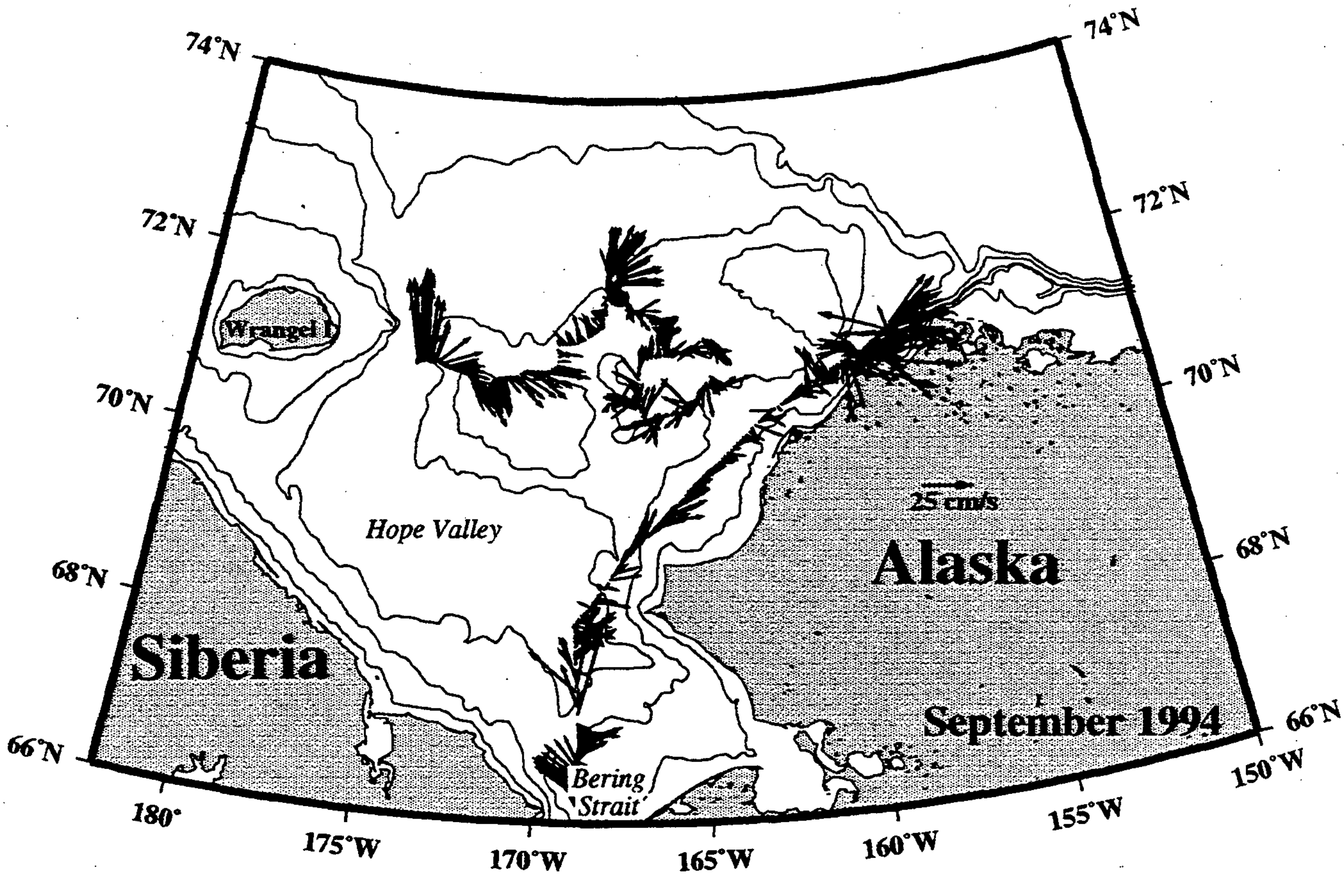


Figure 9. (c). Near-surface (14 m depth) current vectors over the northern Chukchi Sea from a hull-mounted ADCP in September 1995.

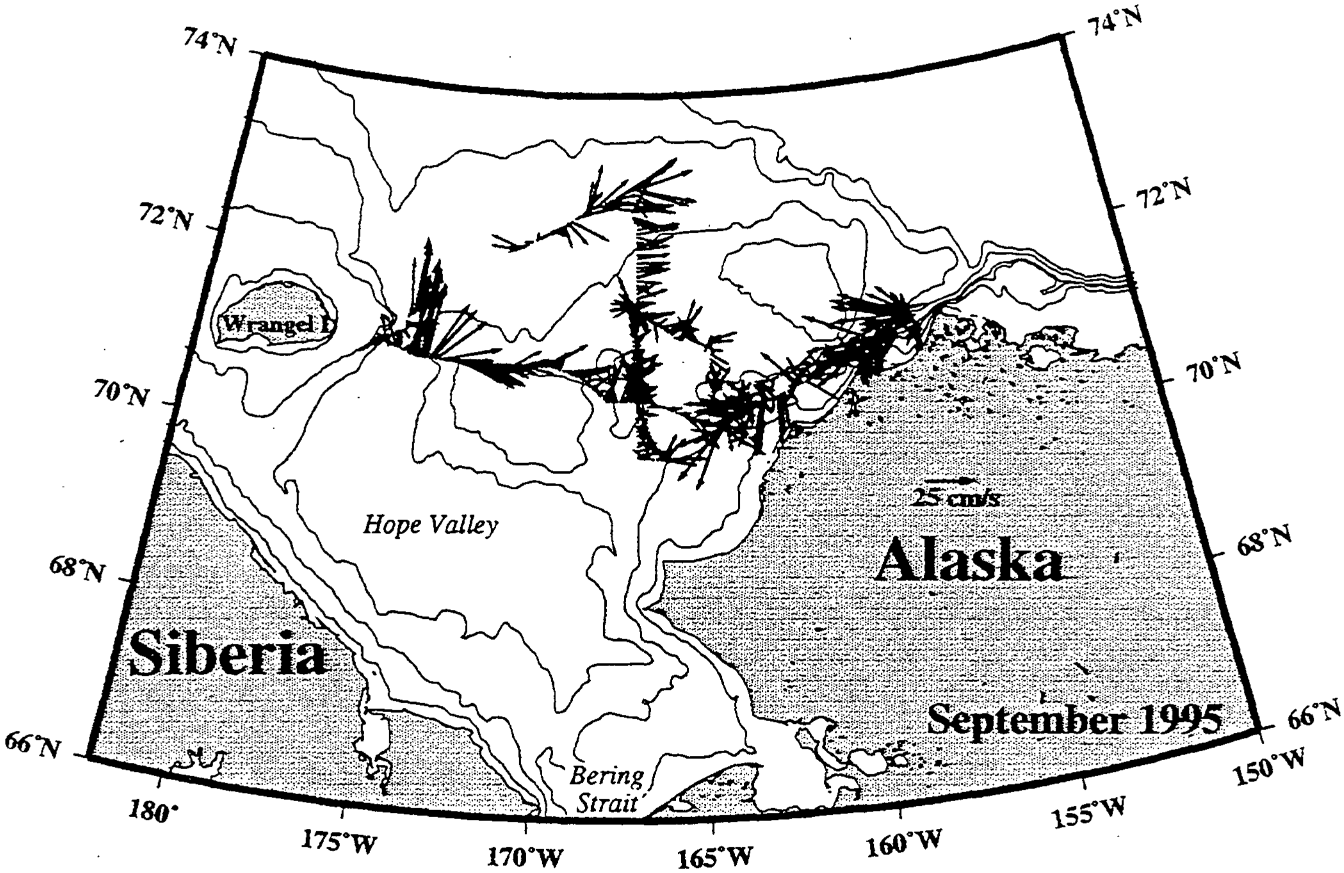


Figure 10.CTD station locations in September 1992, 1993, and 1995. Data from these stations were used in constructing Figure 11.

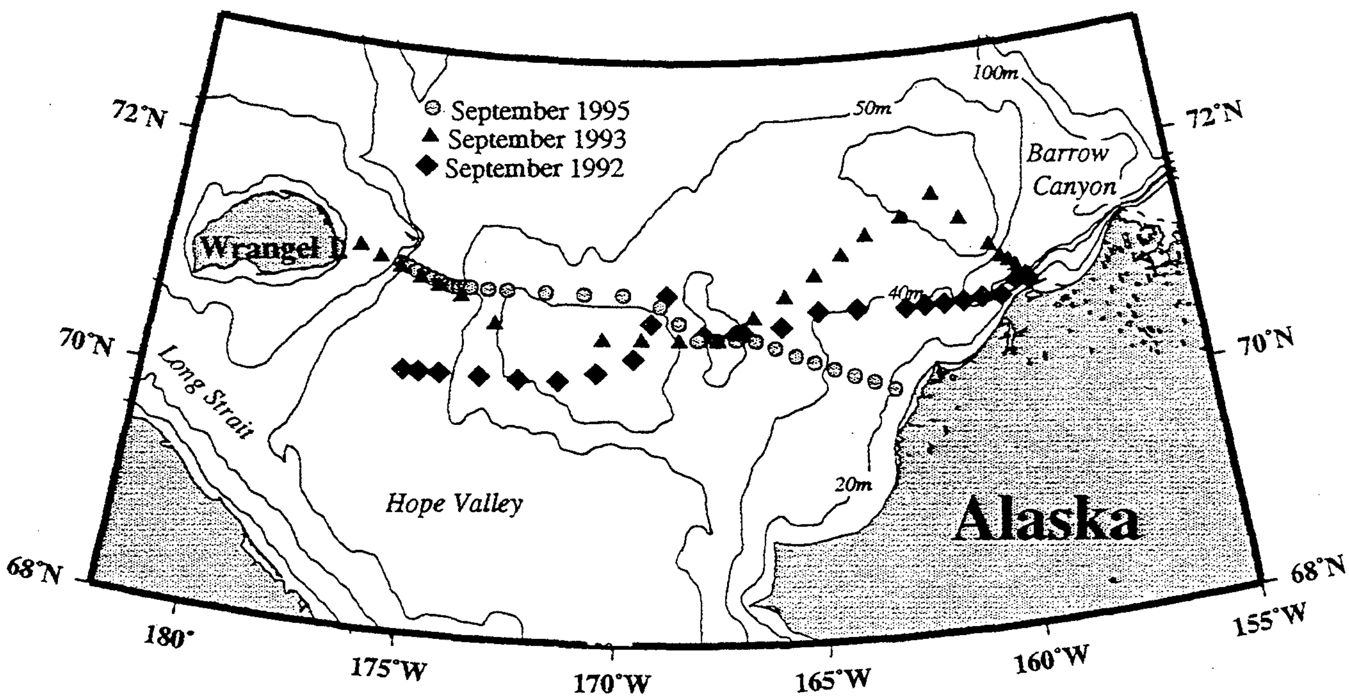


Figure 11.(a). Contour plots of temperature and salinity from the transects shown in Figure 10 (1992).

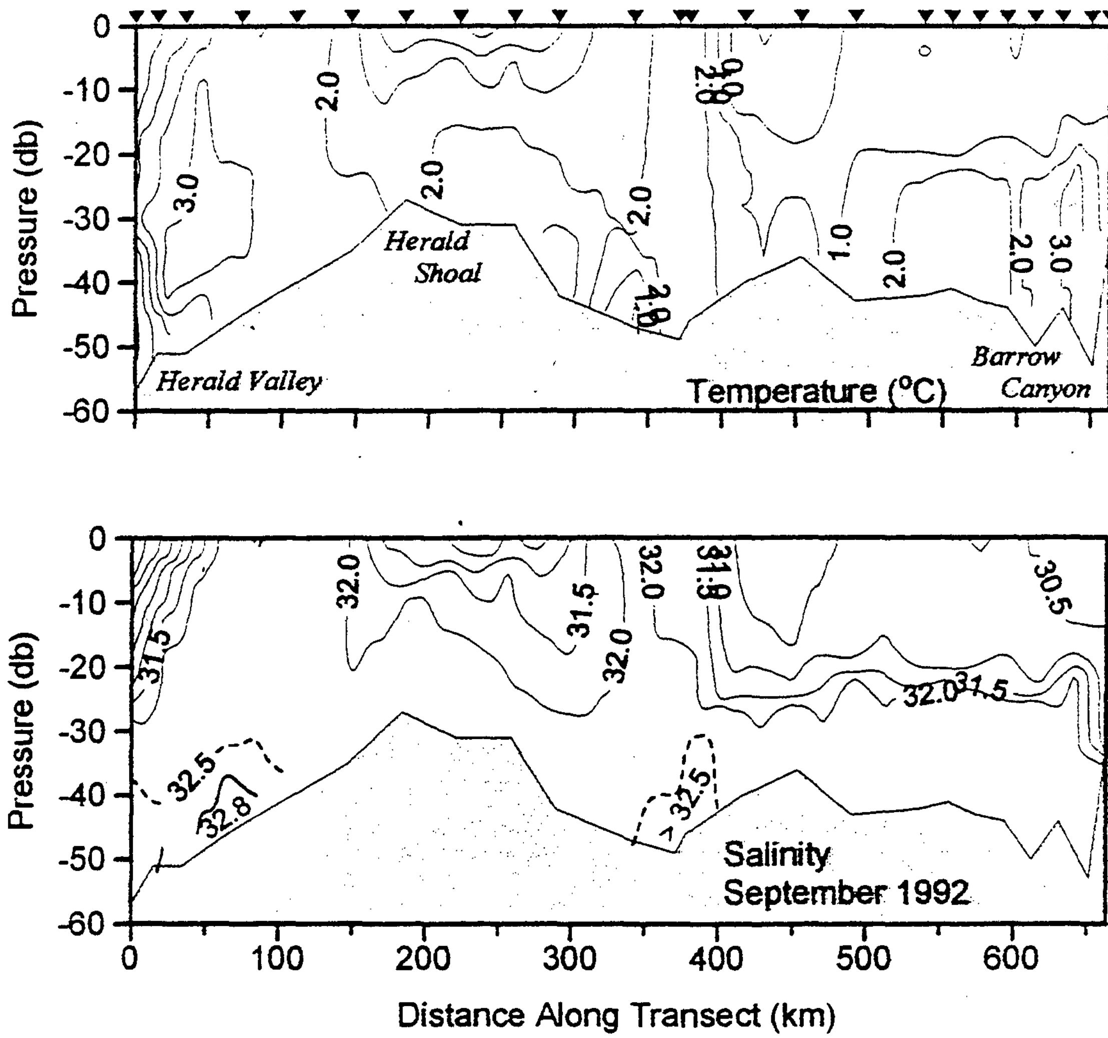


Figure 11.(b). Contour plots of temperature and salinity from the transects shown in Figure 10 (1993).

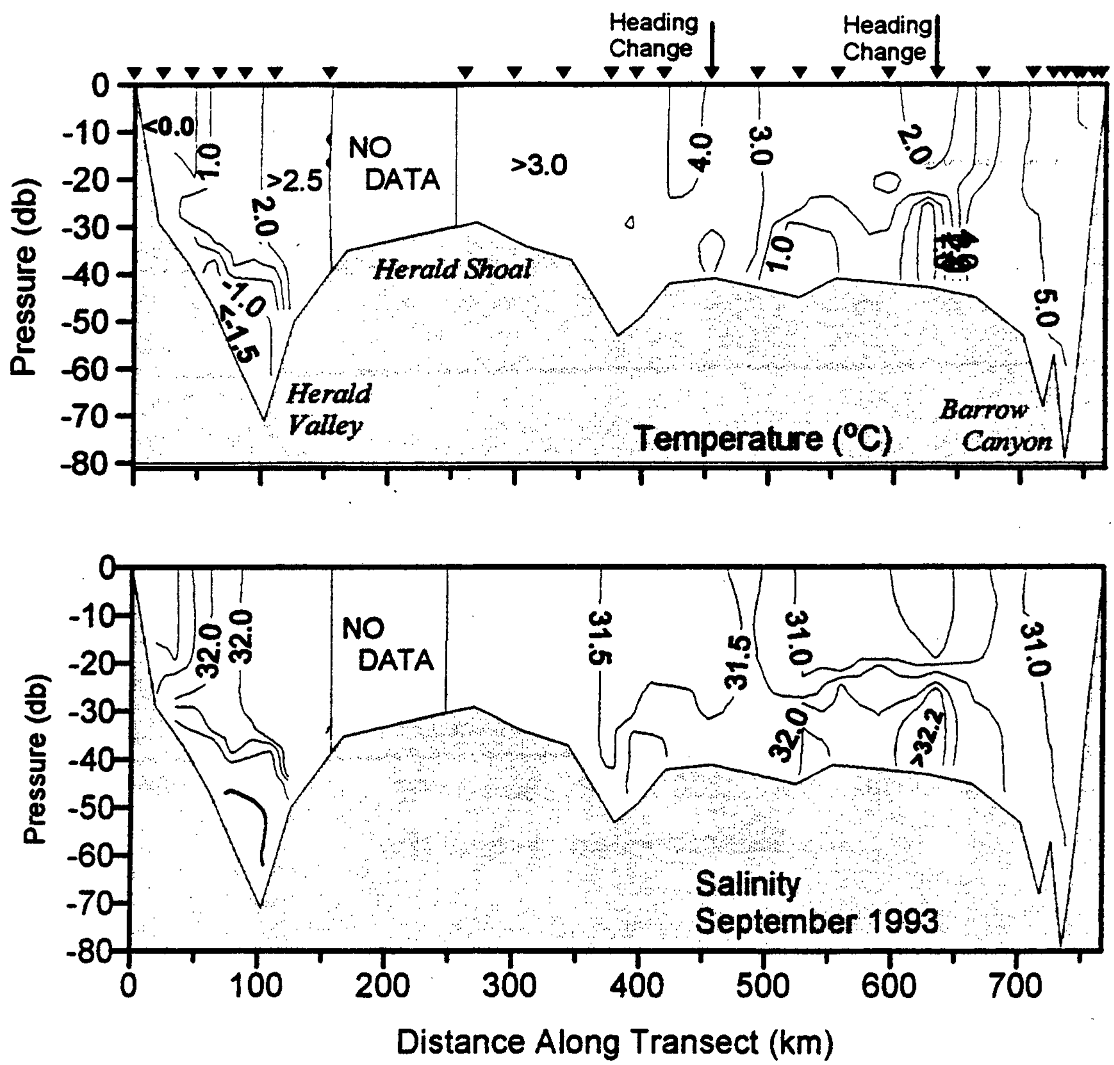
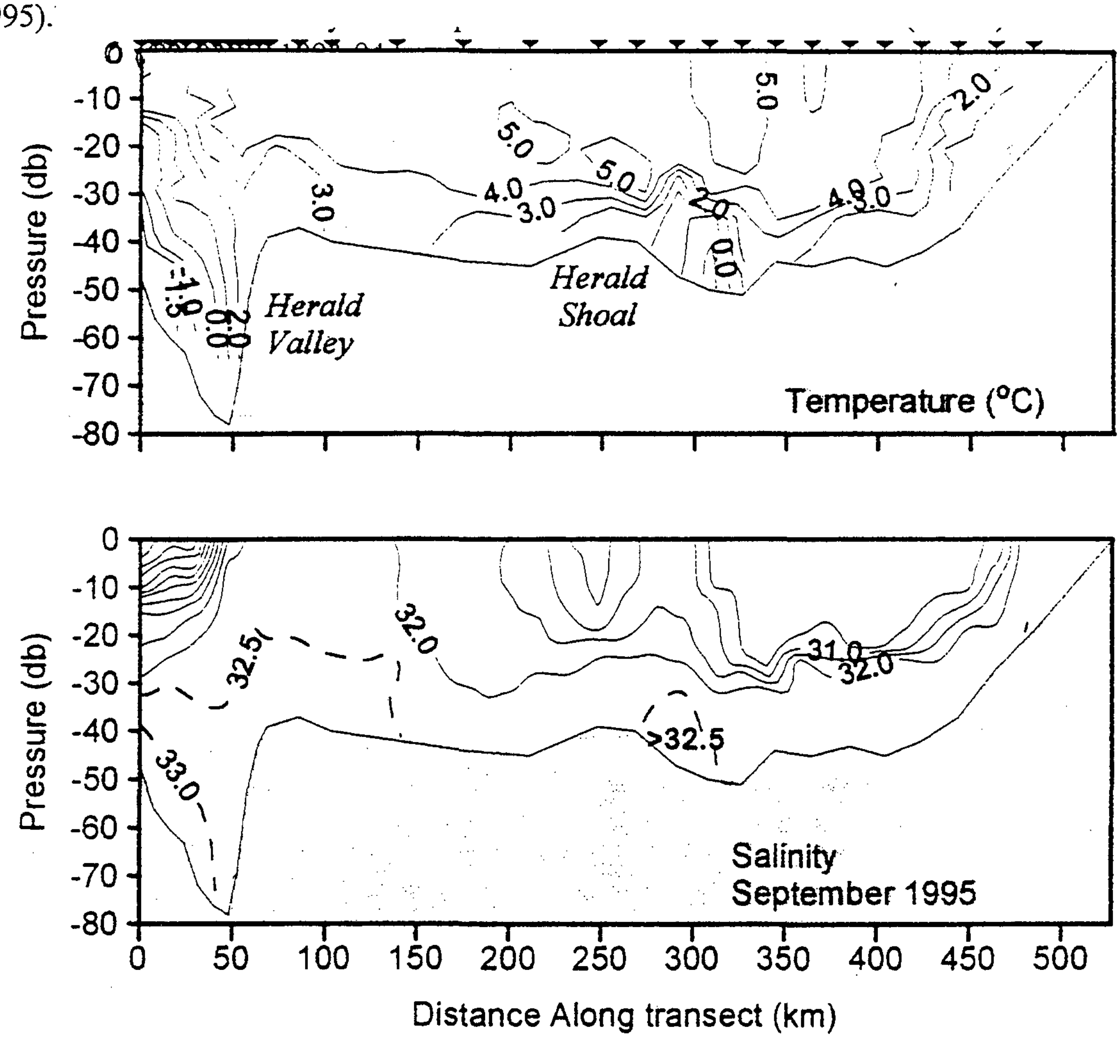


Figure 11.(c). Contour plots of temperature and salinity from the transects shown in Figure 10 (1995).



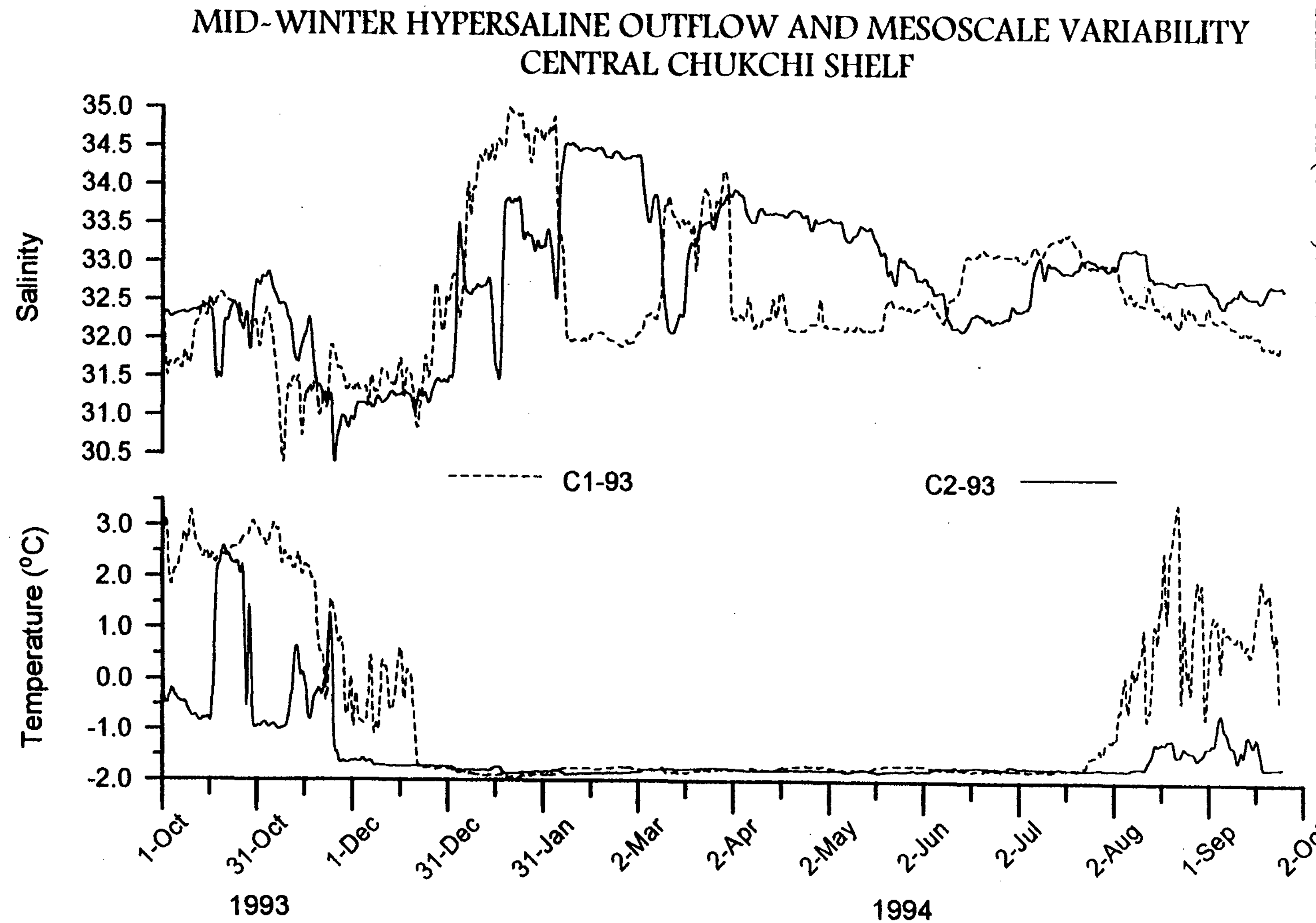


Figure 12. Time series of salinity and temperature from east of Herald Shoal (C1-93) and south of Hanna Shoal (C2-93) in 1993-94.

Figure 13.From bottom to top, time series of salinity, temperature, current velocity from C2-93 and winds over the northeast Chukchi Sea from December 1993 through March 1994.

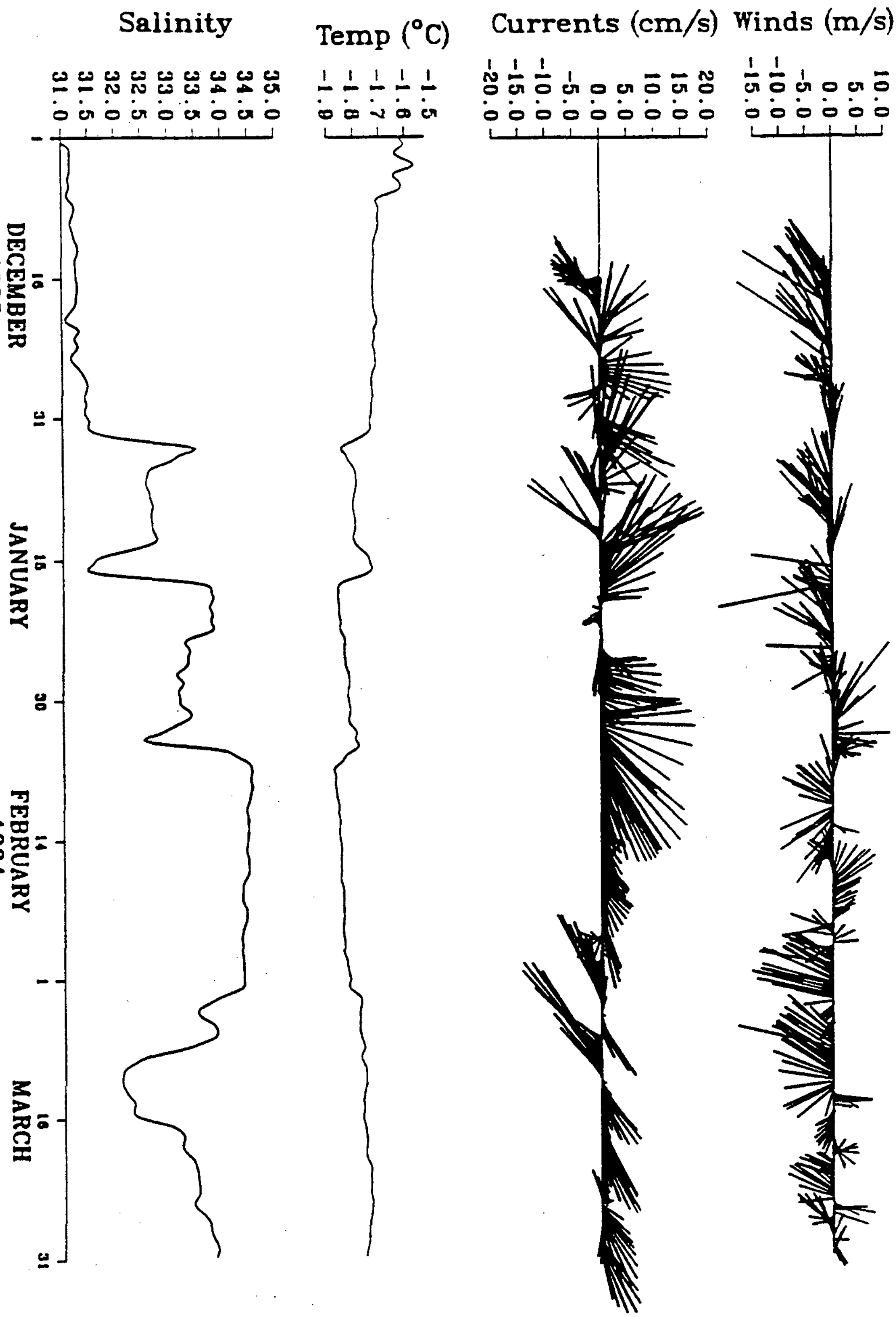


Figure 14.Comparison of the temperature/salinity frequency distribution from along the south flank of Hanna Shoal (mooring C2) in 1993-94 and 1994-95. The modal salinity values are indicated. The depths in parentheses indicate the nominal depth that the indicated mode would sink to along the continental slope if no further mixing of the modal properties occurs.

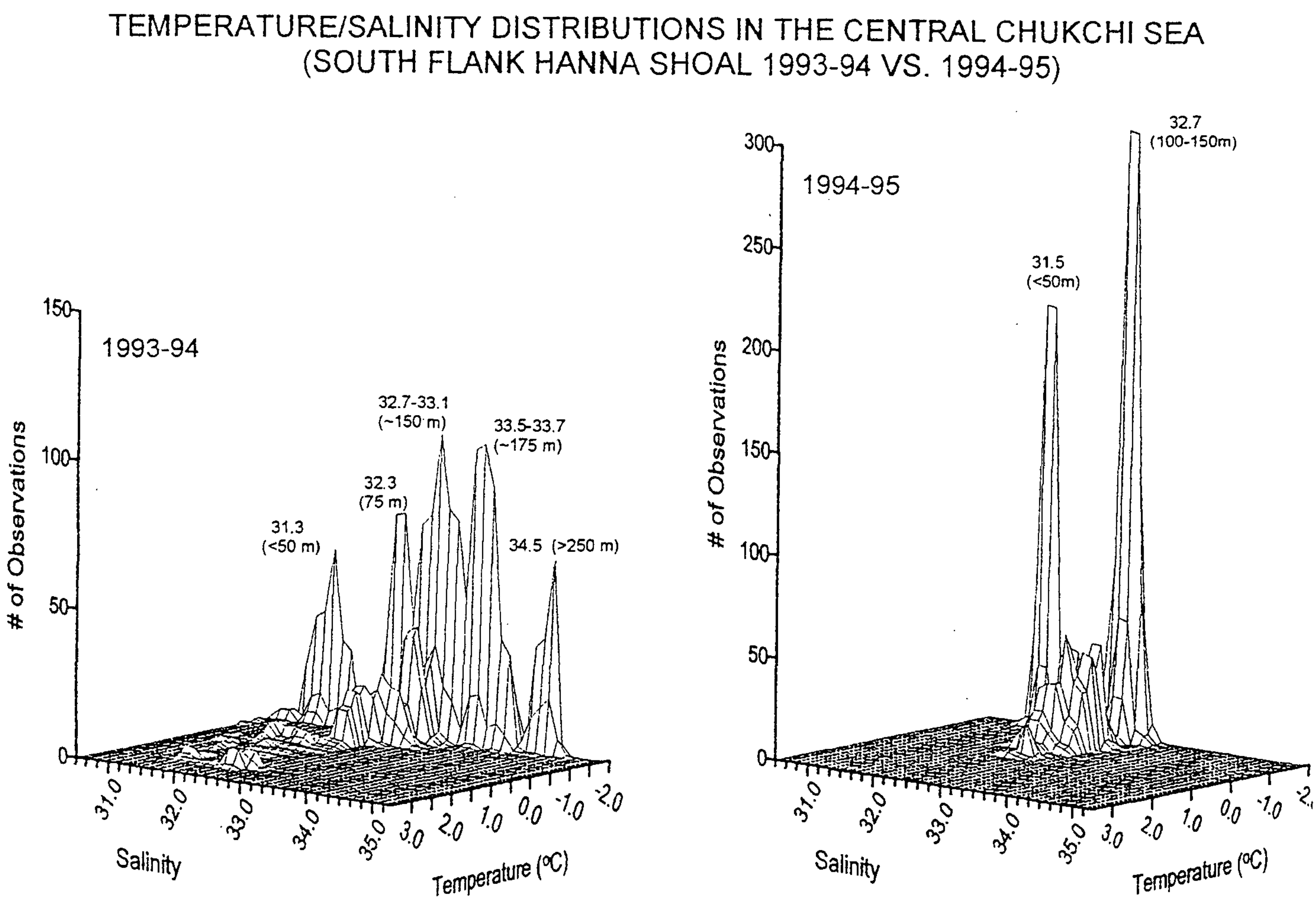
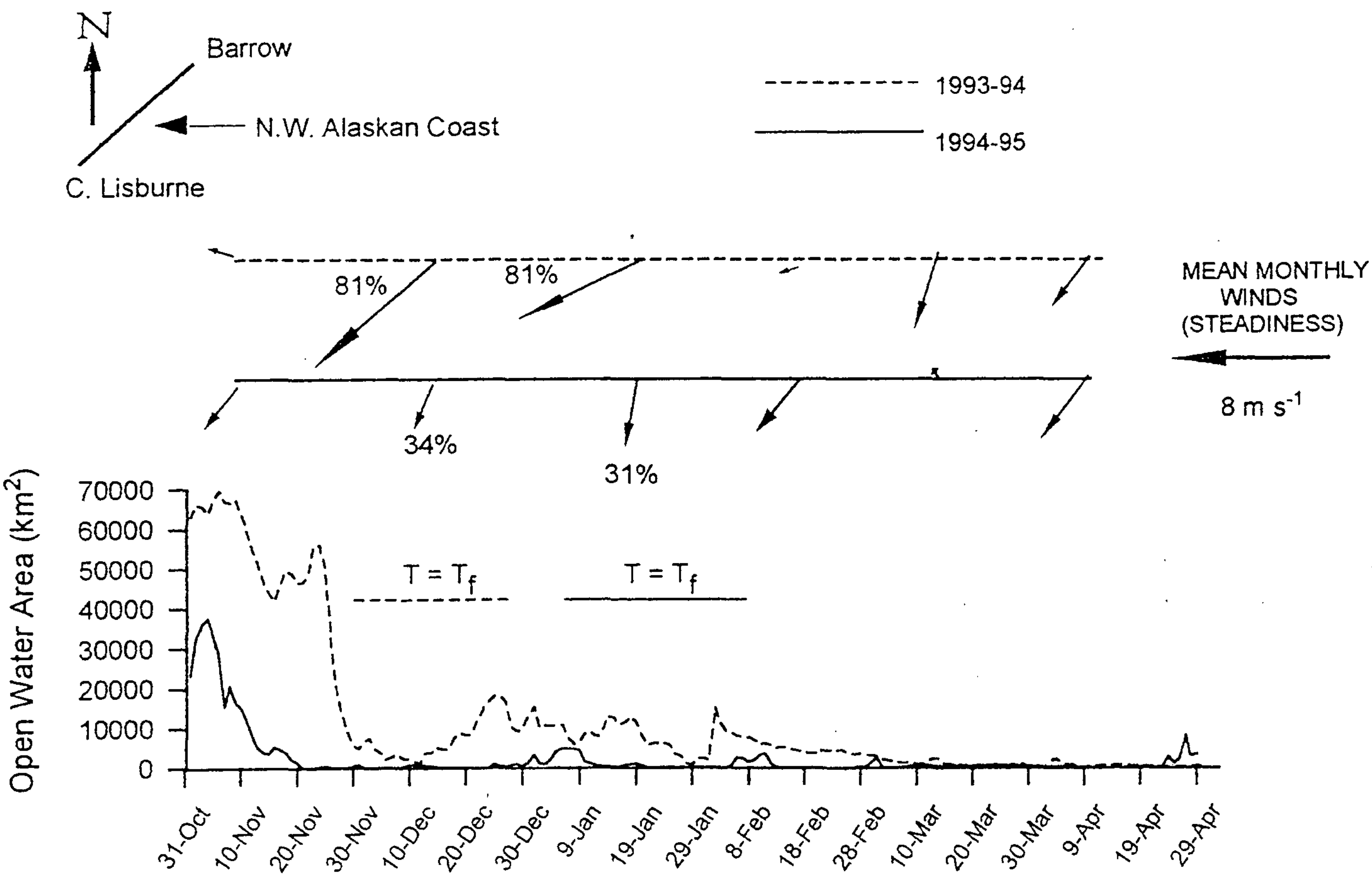


Figure 15. Time series of open water area in 1993-94 and 1994-95 over the northeast Chukchi Sea derived from SSM/I data. The legend $T = T_f$ refers to seawater temperature at the freezing point. The dashed or solid horizontal line below this legend indicates the time period over which shelf water temperatures reached the freezing point. Those times are derived from the data in Figures 8 (except mooring EUBC) and 12. The mean monthly wind vectors for these years are also shown. The percentages below several of the wind vectors refer to the wind steadiness or the percentage of time that the winds are similar to the mean. The schematic in the upper left hand corner indicates the orientation of the northwest Alaska coast.



The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Royalty Management Program** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic