The Variable Outflow from the Chukchi Shelf to the Arctic Ocean
Final Report

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LONG-TERM GOALS

Our long-term research goals are to understand the circulation and physical properties of the high-latitude ocean, both quantitatively and mechanistically, and to do so in a global context. We also seek to understand the effects of physical processes in the ocean on the ice cover, biology, and chemistry of the marine environment. The variability of that environment is a special focus and concern.

OBJECTIVES

The vast shelves that surround the Arctic Ocean markedly influence the stratification and ice cover of its upper layers [*Aagaard et al.*, 1981], mold the properties of its intermediate waters [*Schauer et al.*, 1997], drive large-scale biogeochemical cycling [*Yamamot-Kawai et al.*, 2006], and are the primary sites for marine production in the Arctic [*Wassmann et al.*, 2006]. Of particular importance are the two great throughflow shelves: the Bering-Chukchi on the Pacific side and the Barents-Kara on the Atlantic side [*Aagaard*, 1998]. The Shelf-Basin Interaction (SBI) initiative, a joint undertaking by ONR and NSF, elected to concentrate on the Western Arctic, and especially on the Chukchi shelf and slope.

The Chukchi Sea has a considerable oceanographic history, beginning with the early opportunistic work by *Sverdrup* [1929] during the *Maud* drift. By the mid-1970s, enough was known of this great epicontinental sea to allow a useful synthesis of the hydrography and circulation [*Coachman et al.*, 1975]. Over the next several decades the observational base expanded further, especially with respect to time series measurements, to provide a description of the full annual cycle of water properties and circulation over nearly the entire shelf [*Woodgate et al.*, 2005]. Meanwhile, work within the Arctic Ocean had identified the Chukchi Sea and its Pacific throughflow as major contributors to the properties of the upper Arctic Ocean and its halocline, the seminal work being that of *Coachman and Barnes* [1961].

At the beginning of the SBI field phase, large questions remained, however, e.g., with respect to the variability of the shelf system, processes at the shelf-basin interface, and downstream consequences for the interior ocean. Our objectives within SBI were therefore to: 1) identify, and where possible quantify, the important physical processes controlling the shelf system; 2) illuminate the mechanisms of shelf-basin exchange; 3) ascertain the variability of the overall arctic shelf-basin system, especially that involving the Pacific sector; and 4) promote further improvements in the rapidly growing array of models of arctic circulation, hydrographic structures, and variability by providing measurements against which to test the fidelity of these models.

Our measurements have concentrated on moored time series, supplemented by hydrographic and other ship-borne data. These measurements have supported a focus on the transformation of Pacific waters crossing the shelf [*Aagaard et al.*, 2006; *Danielson et al.*, 2006; *Weingartner et al.*, 2005; *Woodgate et al.*, 2005a], on processes over the adjacent slope [*Williams et al.*, 2006; *Woodgate et al.*, 2005b], and on providing a larger context in which the SBI studies can be embedded [*Peterson et al.*, 2006; *Swift et al.*, 2005].

APPROACH

Under this grant we have made moored time series measurements of velocity, temperature, salinity, and ice drift in the northern Chukchi Sea during 2002-2004 in direct support of SBI Phase 2. Our moorings were sited downstream of the major western throughflow of Pacific waters that transit the Chukchi shelf via the Hope Sea Valley and Herald Canyon. Herald Canyon itself lies within the Russian Exclusive Economic Zone (EEZ) and was not accessible to us. We therefore chose to make our measurements at two locations near the shelf edge downstream of the canyon at depths of ~70 m (mooring SBI-3) and ~110 m (mooring SBI-4), both within the U.S. EEZ. The shelf edge is relatively regular and smooth at the chosen location. Our moorings included fixed-depth and profiling (ADCP) current meters, the latter with bottom tracking to measure ice drift, and also temperature/conductivity recorders from which salinity can be calculated. At the same time, T. Weingartner, UAF, made similar measurements within the other two principal throughflows of the shelf, viz., in the Central Channel (~50 m depth) and in upper Barrow Canyon (~80 m depth). We also maintained moorings in Bering Strait under a separate ONR grant (N00014-99-1-0345). In closely related efforts, R. Pickart (WHOI) maintained a mesoscale moored array on the Beaufort slope near 152°W, and J. Swift (SIO), L. Codispoti (UMD), and C. Flagg (BNL) provided CTD/rosette/ADCP sections to support the mooring work with hydrography and detailed spatial information about the velocity field.

To provide a context for the process studies and the overall SBI effort, we have also analyzed other data sets that uniquely contribute to understanding the modification on the shelf of the Pacific throughflow, to its contribution within the Arctic Ocean, and to the larger role of arctic shelf-basin interaction in the global ocean.

WORK COMPLETED

Our ONR-sponsored work under this project included three cruises in the Chukchi Sea and adjacent Arctic Ocean during 2002-2004, generally late in the navigational season. We deployed and/or recovered two moorings each year. The data yield was excellent.

The entire moored data set has been processed and submitted to JOSS/EOL for archiving, as designated by the SBI program. The data are also archived at our web site (http://psc.apl.washington.edu/Chukchi.html).

In our analysis we have made a considerable effort to synthesize a variety of data to provide a broad perspective on arctic shelf-basin processes. This effort has resulted in eight papers published in *Deep-Sea Research*, the *Journal of Geophysical Research*, *Geophysical Research Letters*, *Continental Shelf Research*, and *Science*. We have also made nine presentations at national and international meetings.

We discuss the principal scientific results below.

RESULTS

Measurements

The contemporary time series of temperature and salinity from Bering Strait and from the northern edge of the Chukchi shelf during 2002-2004 chronicle the passage and transformation of the Pacific waters as they cross the Chukchi shelf along their western route (**Figures 1** and **2**).

At both SBI-3 and -4 the summer warming arrives nearly 6 months later than in Bering Strait, corresponding to a translation rate across the Chukchi Sea of ~7 cm s^{-1}. Heating of the lower water column on the northern shelf is therefore out of phase with the local surface forcing. The seasonal shelf-edge warming, advective in origin, is much weaker than in the strait, and the duration of elevated temperatures is considerably shorter, consonant with the substantial cooling that a water column experiences as it crosses the Chukchi shelf [cf., *Woodgate et al.*, 2005a]. Note also in **Figure 4** that at the northernmost mooring (SBI-4), the seasonal warming at 60 m is markedly less than at 100 m, reflecting the greater isolation of the deeper waters from the atmosphere. Indeed, the rapid large changes in portions of the 60 m record suggest large vertical gradients near that depth.

Phase information in the salinity records is less clear than in the temperature records, although there are similarities in the salinity time series from the strait and the northern shelf. For example, both the shelf edge and strait records show that seasonal cooling is accompanied by freshening.

A number of the warm events of shorter duration seen in **Figures 1** and **2** are also quite saline, and these represent upwelling. They are most common in the fall, similar to the observations of *Aagaard and Roach* [1990] in Barrow Canyon. Prominent examples are seen near days 260-280 and 680 in **Figure 2**. On occasion the 100 m instrument at SBI-4 registered upwelling salinities greater than 34 and warmer than -0.5°C. Hydrographic sections across the slope show that such water comes from below 200 m over the slope, where typical nitrate values are ~14 μM l^{-1}. Since many of the warm and saline events are recorded at both moorings, and since mooring SBI-3 is located some 30 km south of SBI-4, it is clear that the upwelling can flood large portions of the outer shelf, even in the absence of canyons indenting the shelf.

Figures 3 and **4** show a 300-day portion of the temperature and salinity records from all three moorings (A3, SBI-3, and SBI-4) in the form of T-S correlations, segregated by season. **Figure 3** represents summer in Bering Strait (mid-May to mid-October 2003), when near-bottom waters in the strait sampled at mooring A3 warm to more than 5°C. Meanwhile, water in the northern Chukchi, where it is still oceanographic winter, remains cold (mostly less than about -1°C).

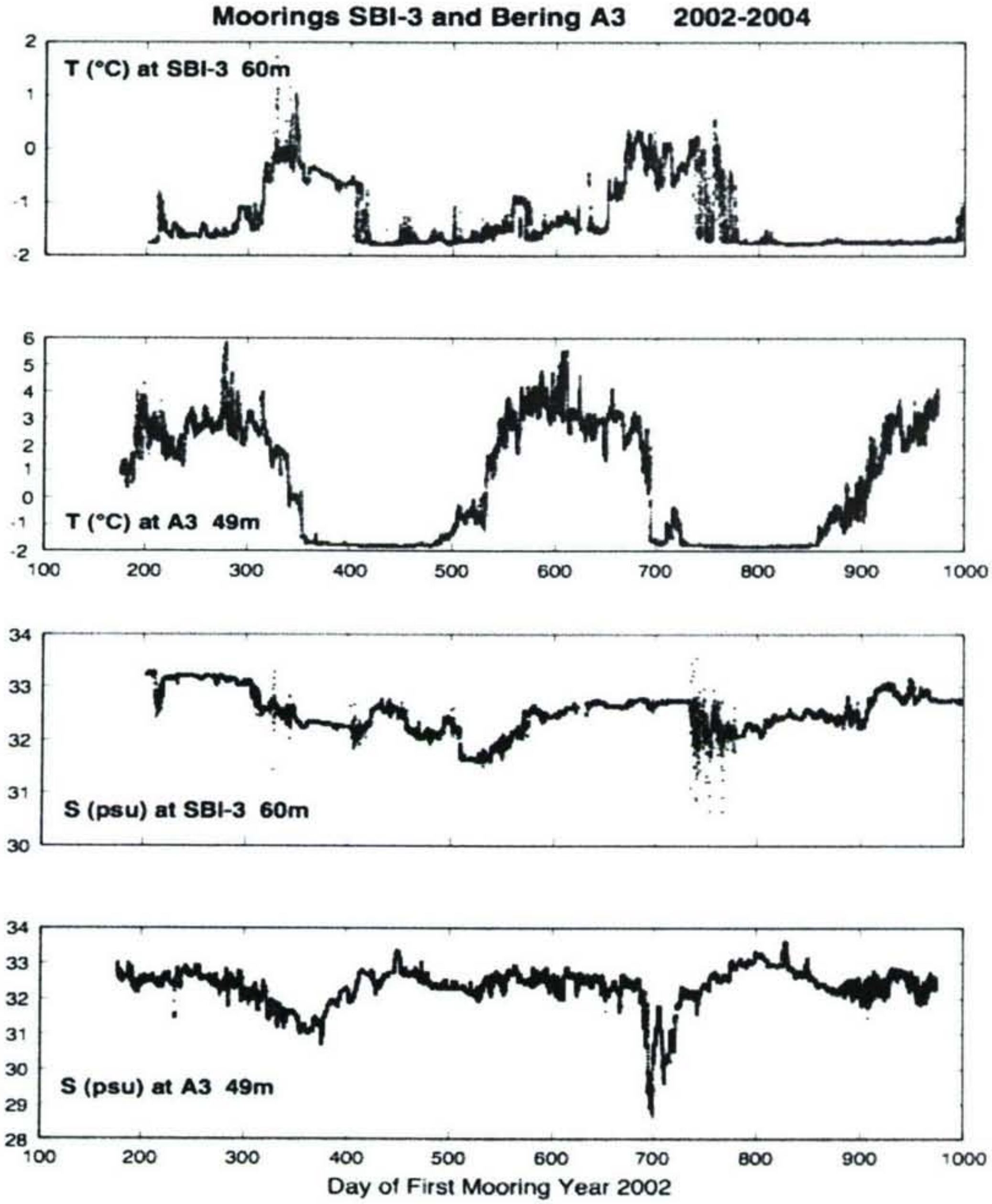

Figure 1: Temperature and salinity during 2002-2004 on the northern Chukchi shelf (SBI-3) and in Bering Strait (A3). Mooring SBI-3 (water depth ~70 m) lies downstream of the Herald Canyon outflow from the Chukchi of Pacific waters, while mooring A3 samples waters entering the Chukchi through both channels of Bering Strait.

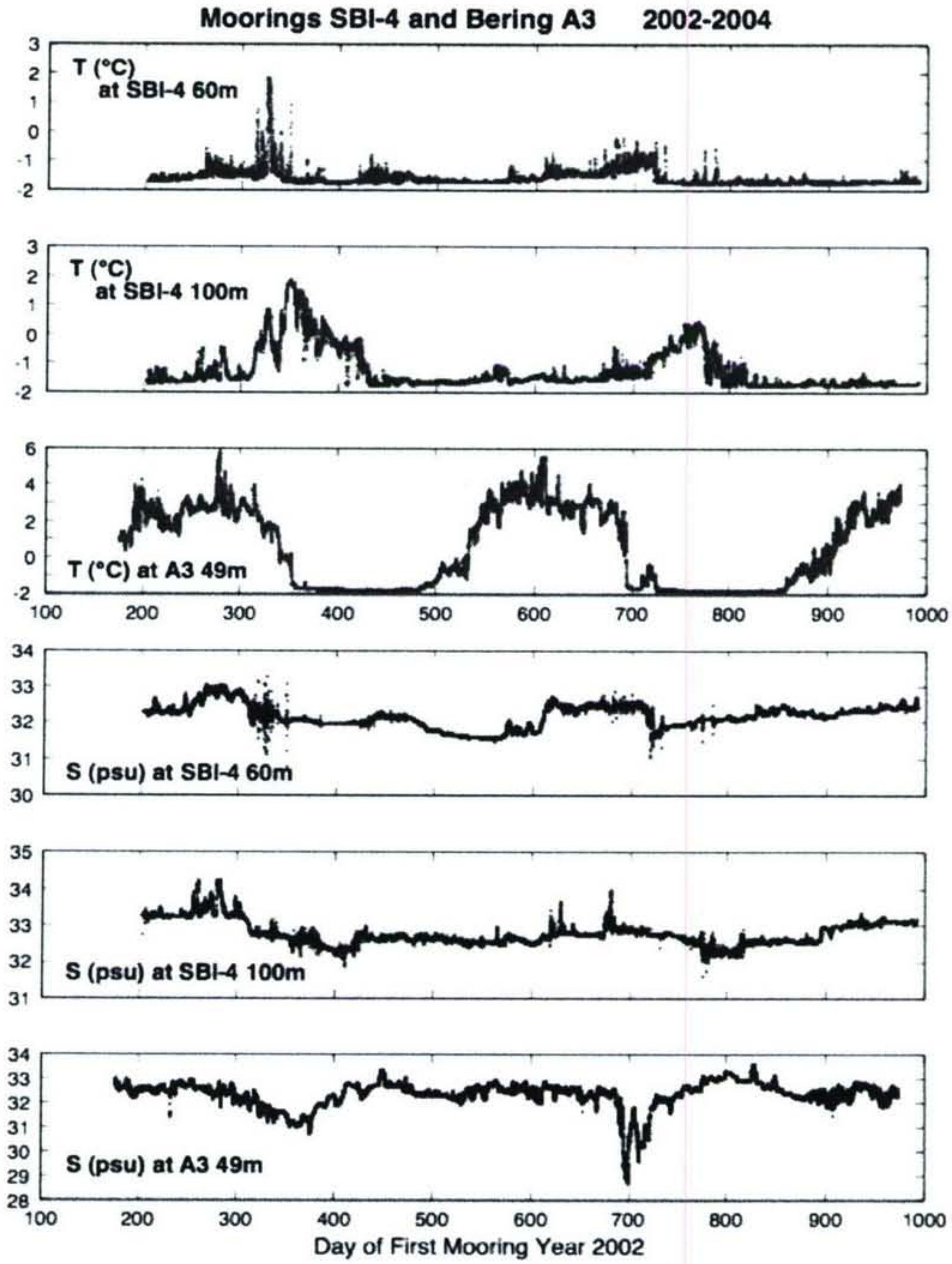

Figure 2: Temperature and salinity during 2002-2004 on the northern Chukchi shelf (SBI-4) and in Bering Strait (A3). Mooring SBI-4 (water depth ~110 m) lies downstream of the Herald Canyon outflow from the Chukchi of Pacific waters, but about 30 km north of mooring SBI-3. Mooring A3 samples waters entering the Chukchi through both channels of Bering Strait.

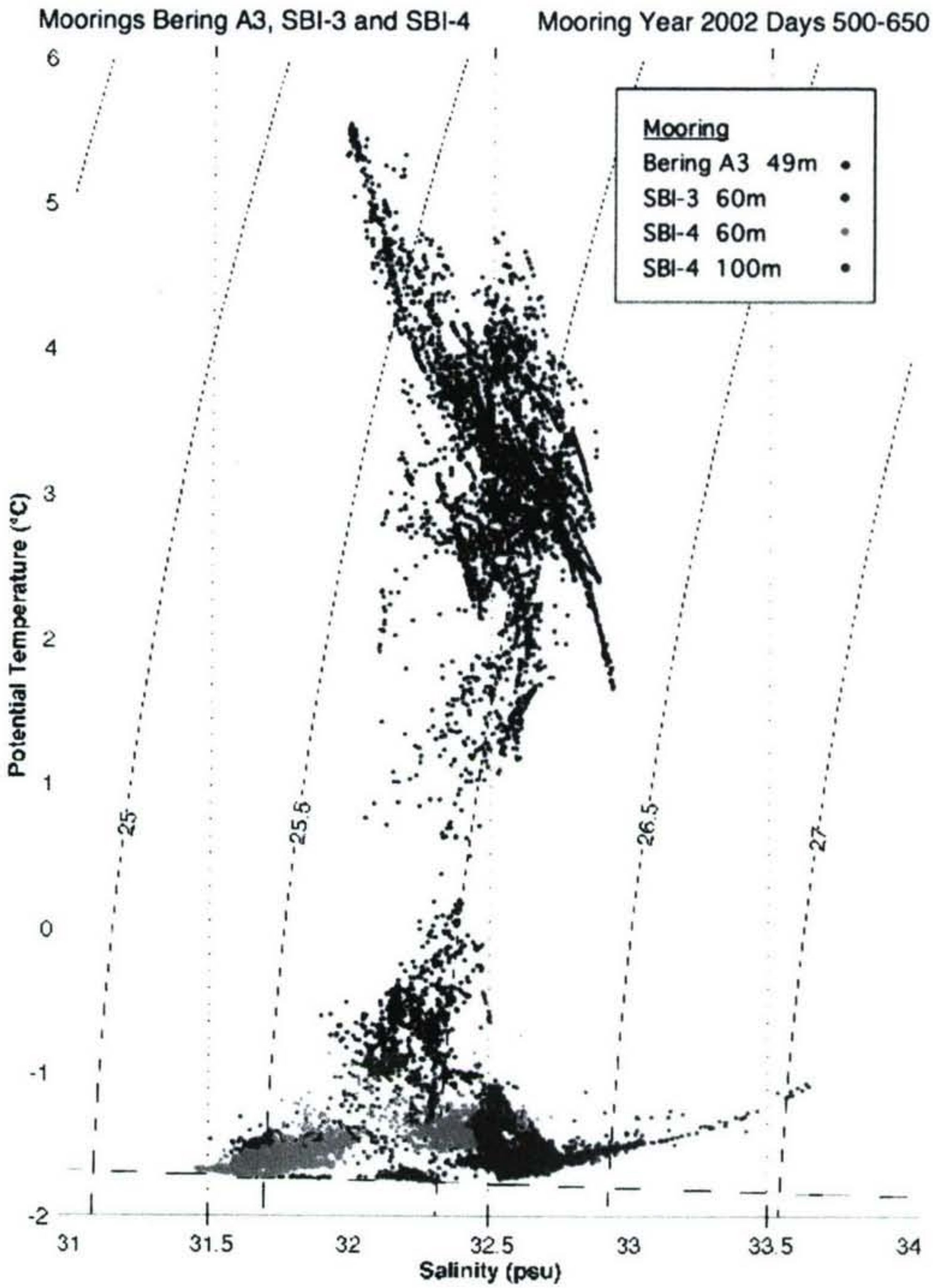

Figure 3. Hourly temperature-salinity correlations during days 500-650 (mid-May to mid-October 2003). Instrument locations are given in the colored legend. The long dashed line represents the freezing point for a particular salinity, while the shorter dashed curves show the density at atmospheric pressure (σ_t).

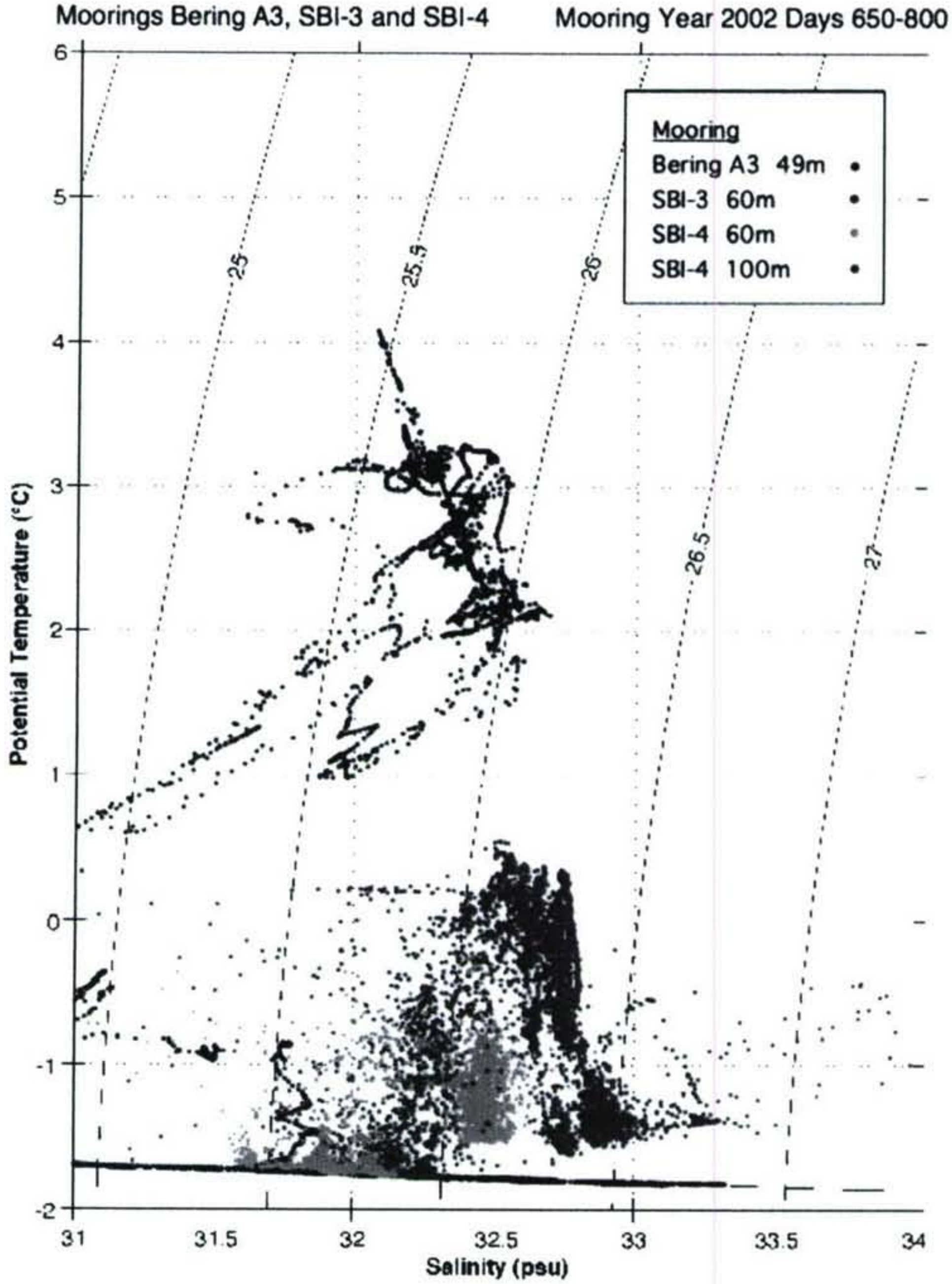

Figure 4. Hourly temperature-salinity correlations during days 650-800 (mid-October 2003 to mid-May 2004). Instrument locations are given in the colored legend. The long dashed line represents the freezing point for a particular salinity, while the shorter dashed curves show the density at atmospheric pressure (σ_t).

Figure 4 represents the transition into winter in Bering Strait (mid-October 2003 to mid-March 2004). The water first cools and freshens during the late fall, before the T-S properties consolidate around the freezing line, with brine formation driving the salinity upward along the freezing line as winter progresses. In this particular winter, freezing created enhanced salinities exceeding 33.3 in the strait. Salinities this high were then seen 4-5 months later at the 100 m instrument at SBI-4 (**Figure 2**). In the northern Chukchi, the waters represented in **Figure 4** are typically 0.5 °C or more warmer than during the earlier period (**Figure 3**), as a result of sub-surface summer conditions in Bering Strait being advected onto the northern shelf.

The fall upwelling is especially obvious at the 100 m instrument at SBI-4, where the T-S correlation points extend well into the range typical of the Arctic Ocean halocline. While the upwelling events recorded during early fall (**Figure 3**) are rather tightly constrained in T-S space, **Figure 4** shows events during the following five months that in total span a much wider range of temperatures.

The corresponding current records from the lower water column are shown in **Figures 5** (hourly and one-day vector averages) and **6** (three-day vector averages). In contrast to the strong and well organized flow in Bering Strait (lower panel in each figure), the currents on the northern shelf are much weaker and noisier. While this is not surprising, given the absence on the shelf of the close lateral boundaries in the strait, the topographic gradient near the shelf edge does provide a dynamical constraint on the flow, so that barring Ekman turning we expect a preference for the current to lie approximately along isobaths, i.e., parallel with the shelf edge. The charts suggest that the 90 m isobath trends approximately 260° - 080°T in this area, i.e., nearly west-east. During both deployment years the current meter is sited ~15 m above the bottom at SBI-3 and ~35 m above the bottom at SBI-4, so that benthic boundary layer effects should not be large. The frequency of sustained northerly flow in these records, i.e., approximately normal to the shelf edge rather than along it, is therefore remarkable (it is most easily seen in the three-day vector means shown in **Figure 6**). Indeed, at SBI-4, such cross-isobath flow predominates.

Figures 7-10 show these features in another way, viz., as progressive vector diagrams (PVDs) for each mooring location during each year. Selected bins from the acoustic Doppler current profilers (ADCPs) have been added to provide a sense of the vertical distribution of currents. Also for comparison purposes, the fixed current meter from the neighboring mooring has been included. In each case, up in the diagram is toward the north, and the numbers along the PVD tracks give the day of the record, beginning 1 January of the deployment year. In addition, the track is marked every six days as indicated in the legend.

At the SBI-3 site (**Figures 7 and 8**), the PVDs show a more easterly set the first year, although the northward displacements are comparable during the two years (~ 150 to 250 km per year, depending on depth). The seasonal evolution of the northward displacement is remarkably similar during the two years, with a small southward set over 2-3 months during the fall of each year, followed by a marked northward movement from late fall until late summer the next year. This behavior only breaks down very near the surface, where the net flow registered in the 2 m ADCP bin is toward the south-southwest the first year, but toward west by north the second year.

The PVDs calculated from the SBI-4 records (**Figures 9 and 10**), some 30 km north of SBI-3 and very near the shelf edge, show a westerly component of set above 75 m, increasing upward. The westward motion is largest the second year, consonant with the decreasing eastward set at SBI-3. The northward

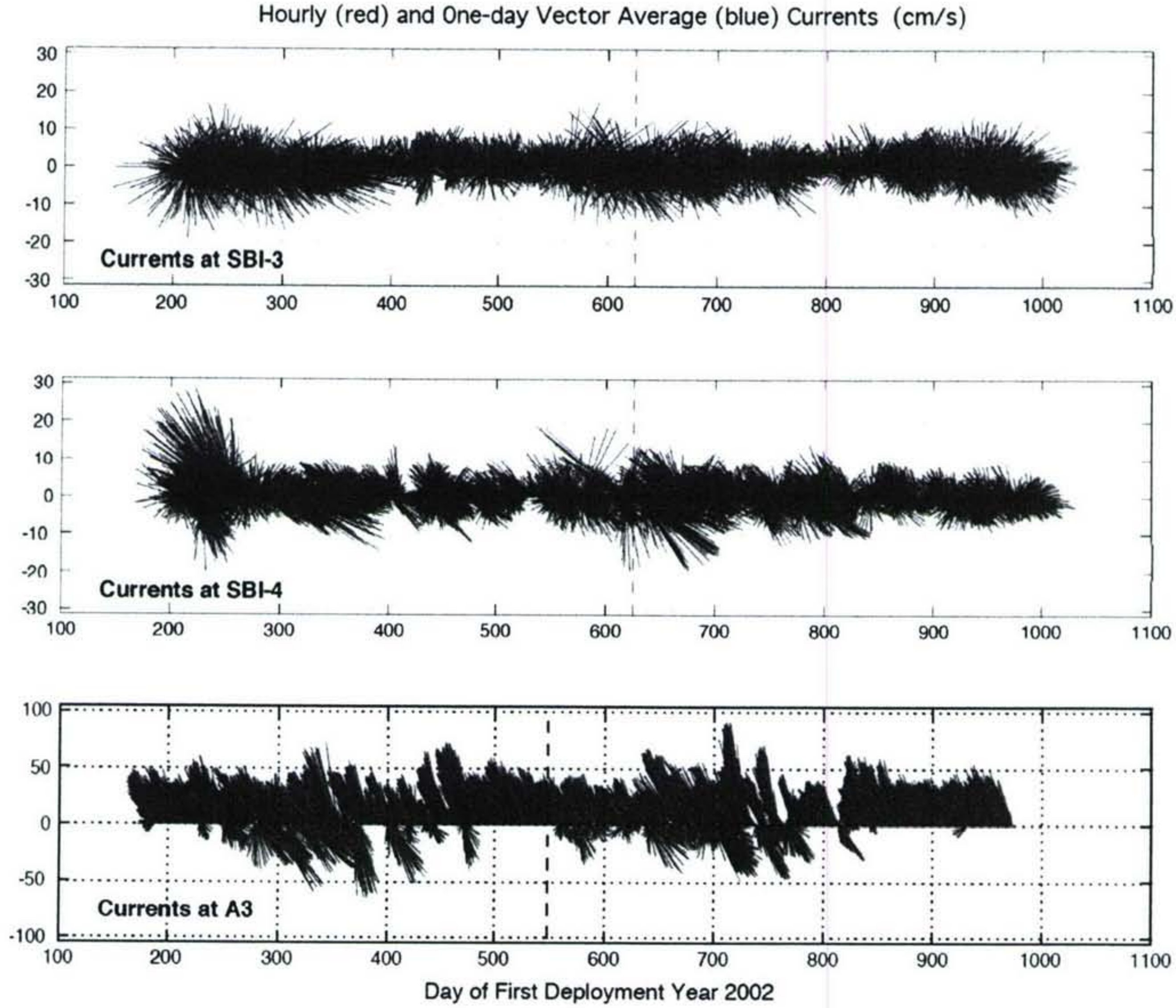

Figure 5. Current at ~55 m at mooring SBI-3 and at ~75 m at mooring SBI-4, both in the northern Chukchi near the shelf edge, and ~50 m in Bering Strait (mooring A3). The hourly measurements are in red and the one-day vector averages are in blue. Up in the figure is toward the north.

component of motion is very pronounced at SBI-4, ~200 to 600 km the first year and ~100 to 400 km the second year, in each case increasing toward the surface. Also, the period of southerly flow in the fall at SBI-4 each year is very brief, lasting only about a month even at 6 m depth. Indeed, this shallowest ADCP bin shows a persistent northerly set that is as strong as, and quite coherent with, the flow deeper in the water column. The 600 km offshore displacement registered at 25 m depth at mooring SBI-4 corresponds to an annual mean northward component of drift of ~2 cm s^{-1} the first mooring year. We note particularly that the offshelf flow at both mooring sites occurs in the absence of canyons or other shelf irregularities, and indeed the mooring sites were selected because of the smooth shelf edge topography in the vicinity.

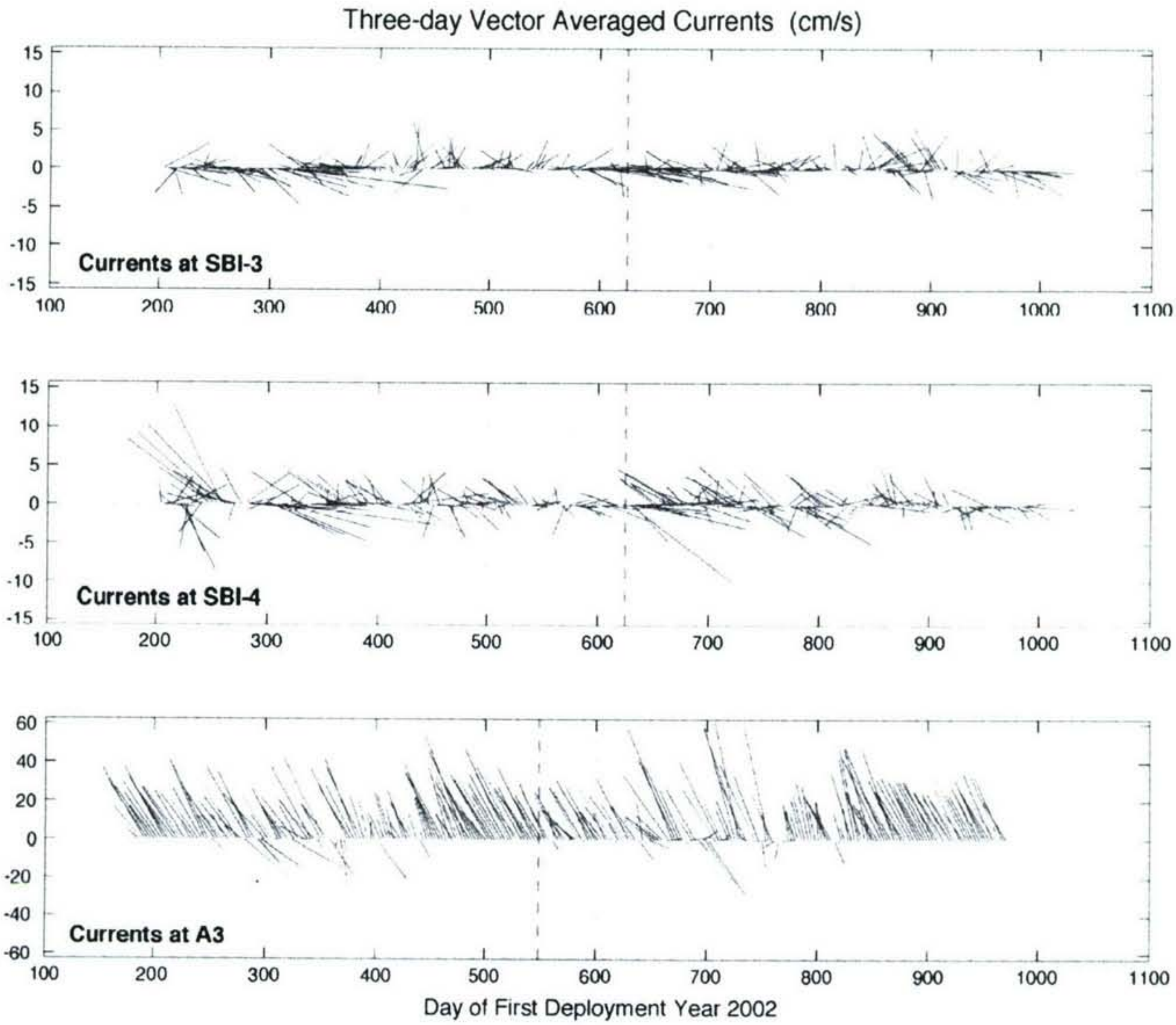

Figure 6. Three-day vector averaged current at ~55 m at mooring SBI-3 and at ~75 m at mooring SBI-4, both in the northern Chukchi near the shelf edge, and ~50 m in Bering Strait (mooring A3). Up in the figure is toward the north.

We have examined the wind field as a possible explanation for the offshelf flow. **Figures 11** and **12** show the progressive northward displacement (essentially a one-dimensional PVD) calculated from both the wind and the current records. The displacements are given as a function of time at both mooring sites during the first year. The mean wind during the year was toward the southwest. It is clear that except for portions of the current record from the 2 m bin at SBI-3, there is little if any resemblance between wind and current components, even at 6 m depth at SBI-4. Indeed, the north-south components of mean wind and current are of opposite sign.

We are left, then, with compelling evidence for persistent offshelf flow throughout most of the year in the northern Chukchi Sea, contrary to *a priori* dynamical expectations that the mean flow would be generally directed along the isobaths, i.e., approximately along the shelf edge. The observed offshelf

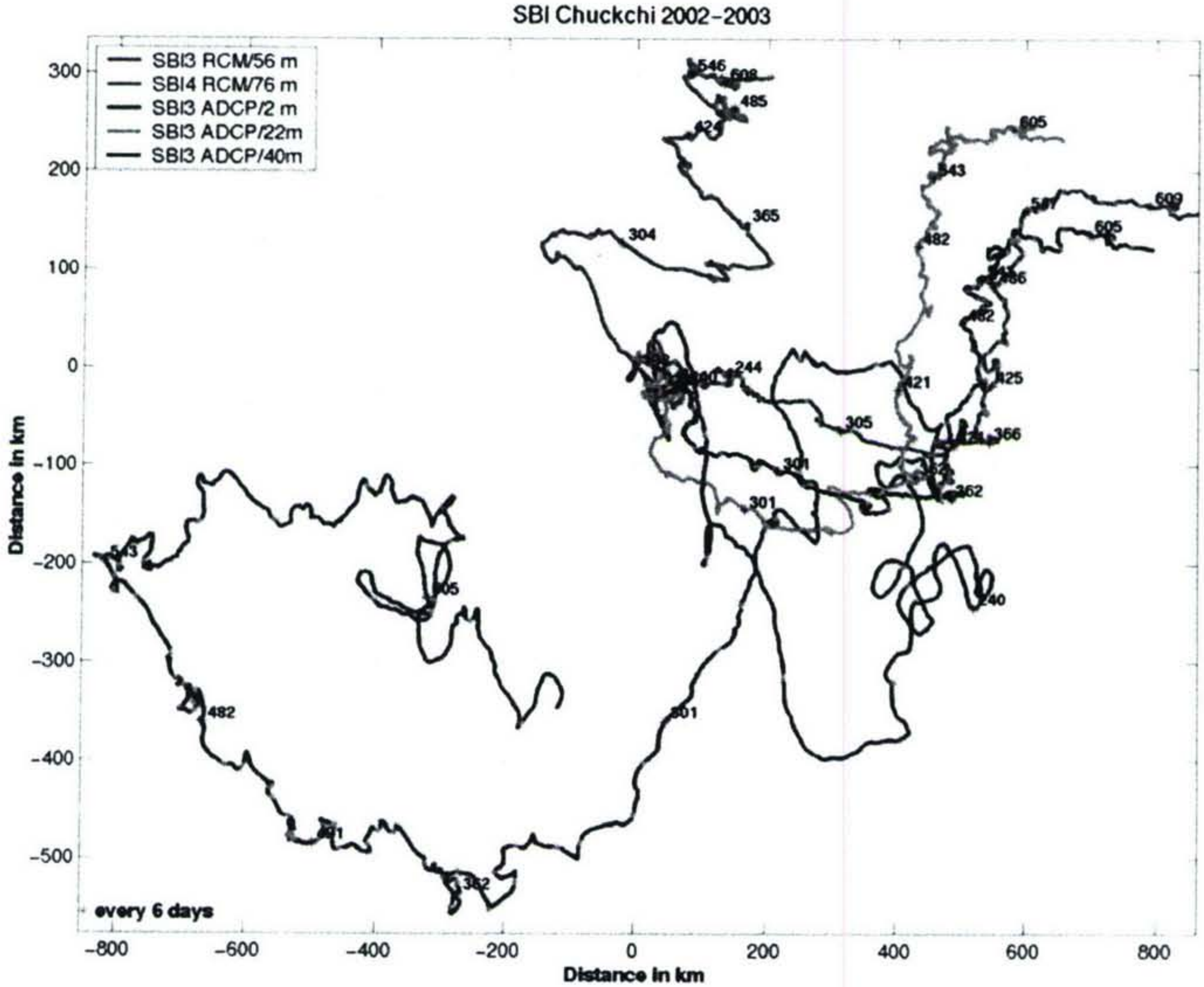

Figure 7. Progressive vector diagram (PVD) for selected current records at SBI-3 during 2002-2003, together with the PVD for ~75 m at mooring SBI-4. Instrument or ADCP bin depths are given in the legend. Time ticks are every six days, and additional year days referenced to 1 January 2002 are printed along each PVD track in black. Up in the figure is toward the north.

flow, directed across the isobaths, does not appear to be wind-driven, and it increases toward the surface. We expect such a flow to be associated with an alongshore pressure gradient in which the pressure increases toward the east.

The direct observational evidence for an alongshore pressure gradient is weak. If we consider an annual offshore displacement of 300 km, corresponding to a mean flow of ~1 cm s^{-1}, a geostrophic balance would require a dynamic height increase of ~0.02 dyn m per 100 km toward the east, relative to an appropriate reference level. The two standard SBI sections crossing the Chukchi slope lie east of about 160°W, i.e., some 200 km east of the mooring sites, and we do not know whether a mean offshore flow comparable to that observed at the moorings is also found at the eastern location where

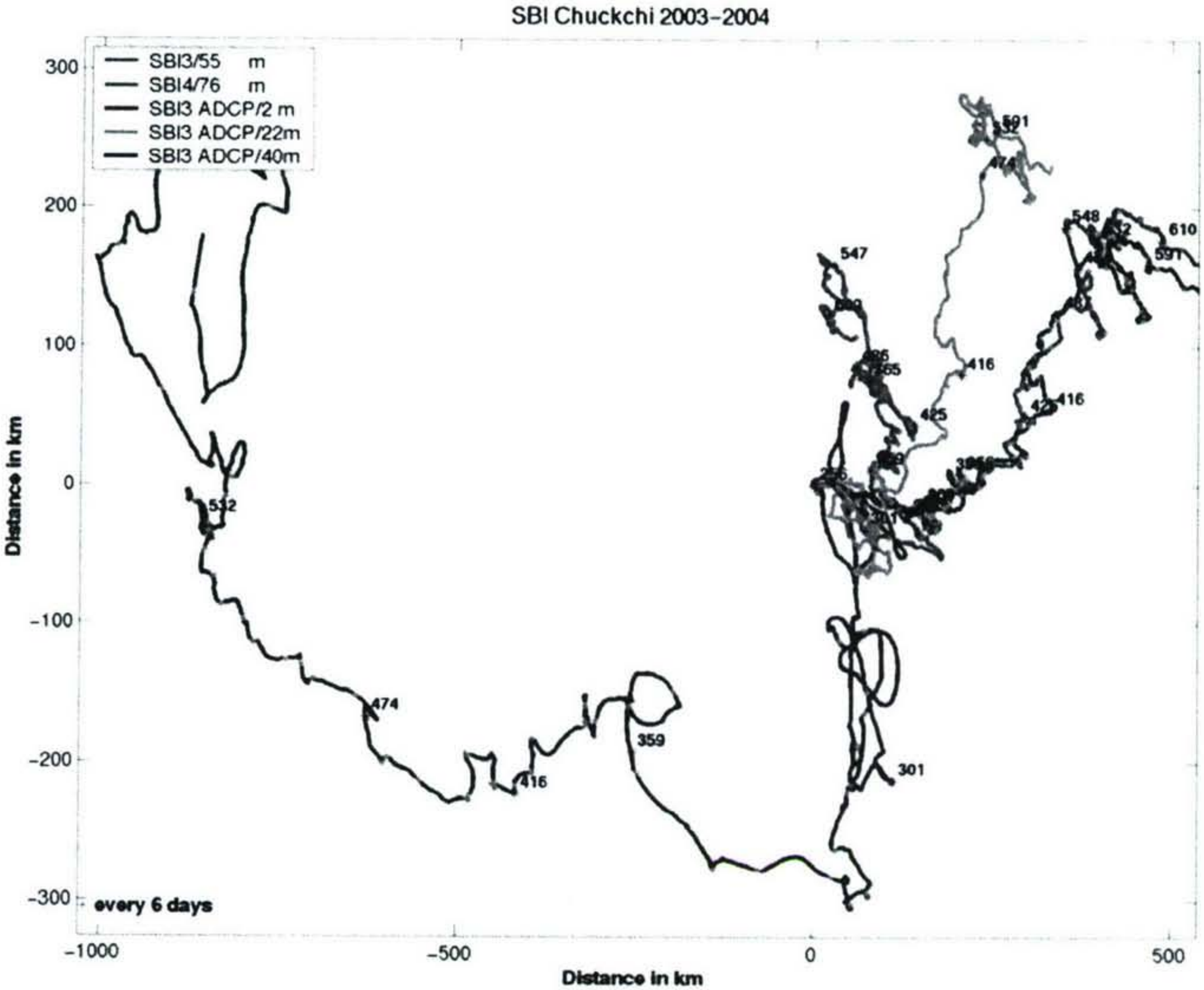

Figure 8. Progressive vector diagram (PVD) for selected current records at SBI-3 during 2003-2004, together with the PVD for ~75 m at mooring SBI-4. Instrument or ADCP bin depths are given in the legend. Time ticks are every six days, and additional year days referenced to 1 January 2003 are printed along each PVD track in black. Up in the figure is toward the north.

The sections were run. In any event, calculation of dynamic height differences between those standard sections to the east, which are separated by ~100 km, shows typical values of ~2 dyn cm, whether integrating over 0/300 db or 0/1000 db. Most of the along-isobath baroclinic pressure gradient is therefore contained in the upper ocean. While the dynamic height difference is of the expected magnitude, the sign is not consistent. For example, the most detailed sections, from the 2003 *Nathaniel Palmer* cruise, indicate northward geostrophic flow, while two of the *Healy* cruises indicate southward flow. Two other sections taken during the *Nathaniel Palmer* cruise farther west, although still somewhat east of the mooring sites, show nearly flat dynamic topography, but do not extend significantly out over the slope. Reference to the current record for the time periods corresponding to the various section occupations indicate flow that is variously directed north or south on a time scale of

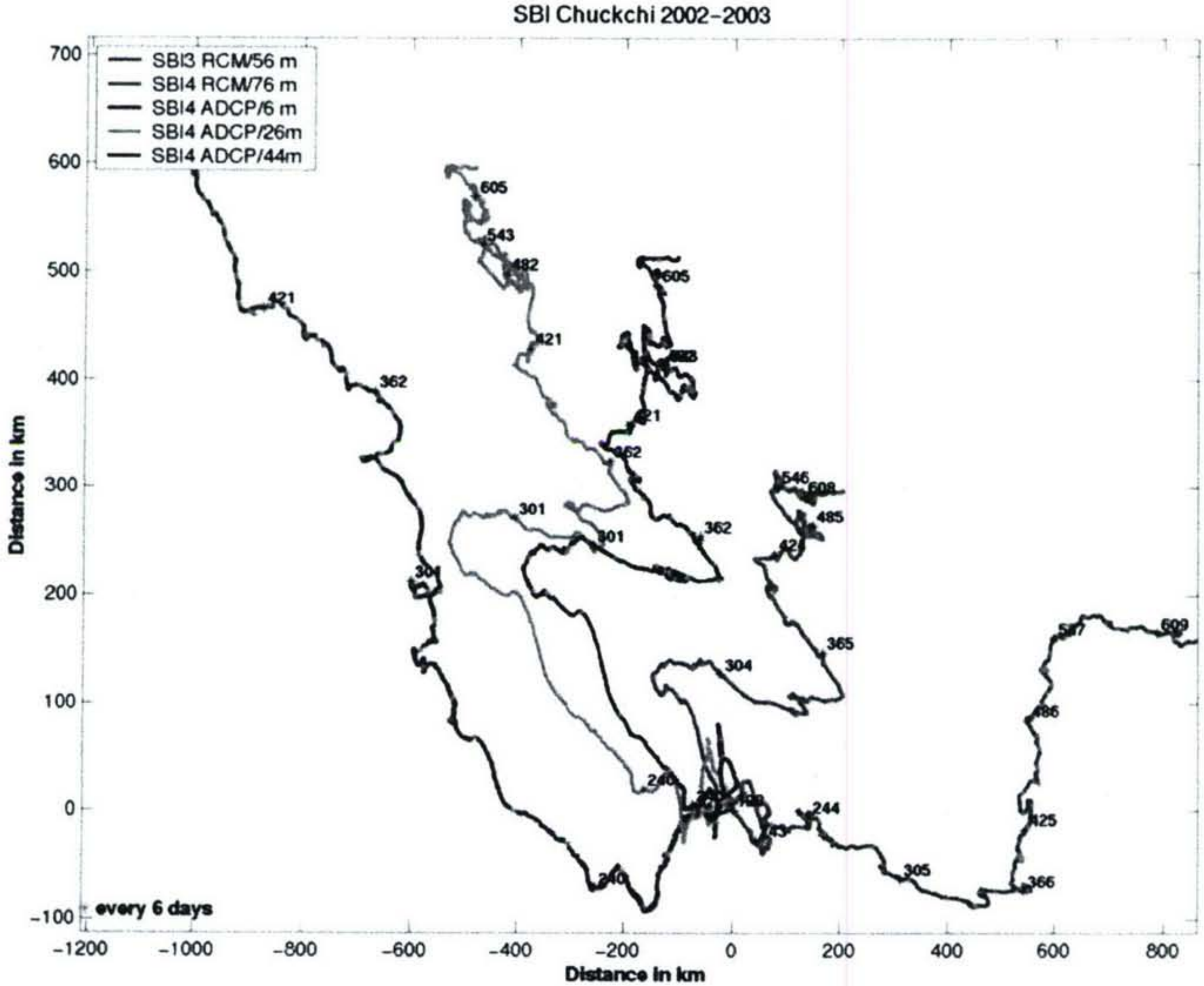

Figure 9. Progressive vector diagram (PVD) for selected current records at SBI-4 during 2002-2003, together with the PVD for ~55 m at mooring SBI-3. Instrument or ADCP bin depths are given in the legend. Time ticks are every six days, and additional year days referenced to 1 January 2002 are printed along each PVD track in black. Up in the figure is toward the north.

days. The available dynamic topography is therefore not helpful in determining whether the weak mean offshore flow is geostrophically balanced. We do note a tendency for the offshore flow to decrease with increasing depth (e.g., see **Figures 9** and **10**), so that a baroclinic contribution to the velocity field is a reasonable expectation.

The importance of the persistent offshelf flow in transferring shelf waters into the Arctic Ocean is unclear, for example what the overall effect is relative to transfer by eddies [*Pickart et al.*, 2005]. A mean northward flow of 1 cm s^{-1} through a section 100 m deep and 100 km wide will transport 0.1 Sv off the shelf, i.e., about one-eight of the Pacific inflow through Bering Strait. We know neither the extent along the shelf edge of the mean offshore flow, however, nor how its strength varies in the

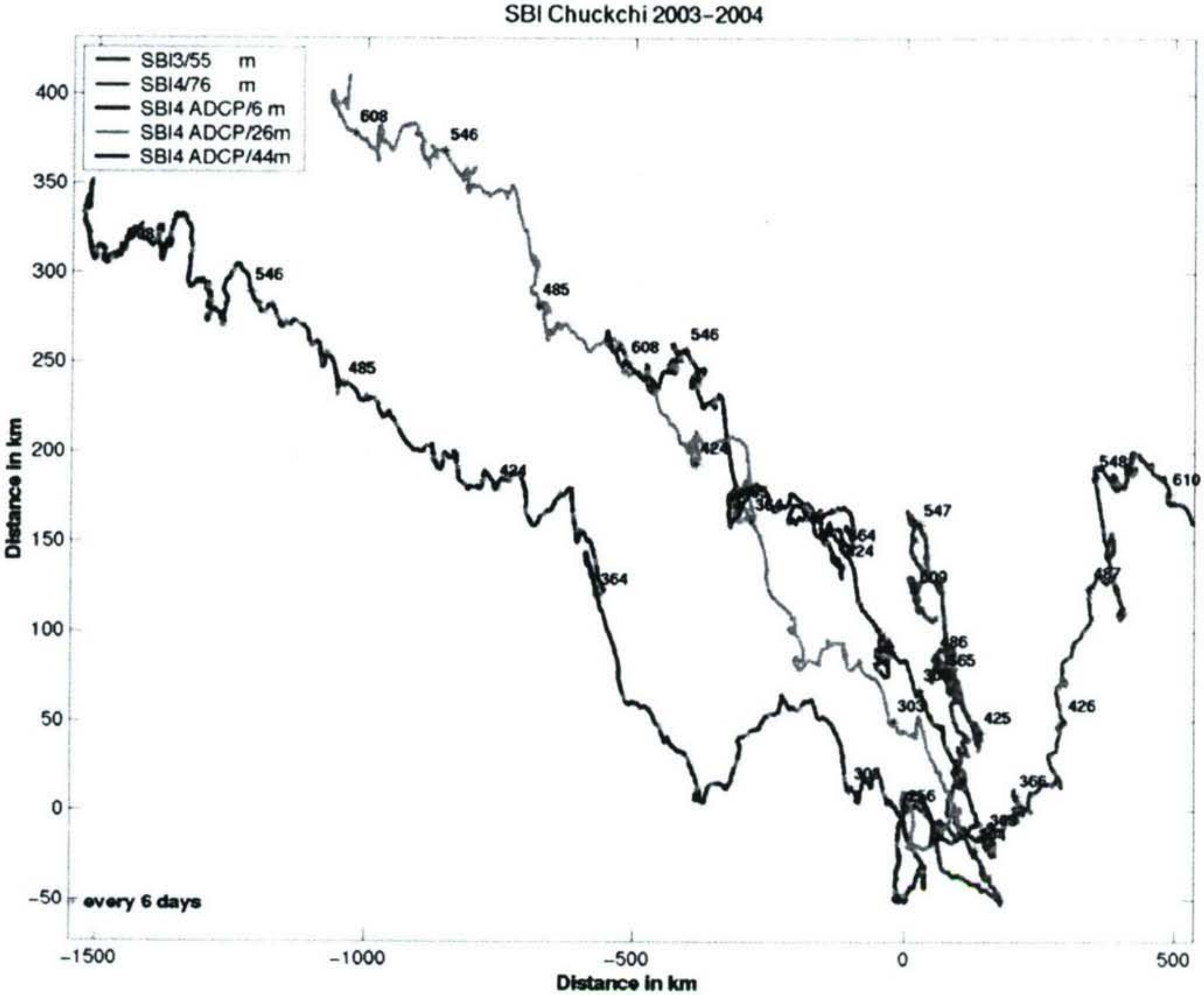

Figure 10. Progressive vector diagram (PVD) for selected current records at SBI-4 during 2003-2004, together with the PVD for ~55 m at mooring SBI-3. Instrument or ADCP bin depths are given in the legend. Time ticks are every six days, and additional year days referenced to 1 January 2003 are printed along each PVD track in black. Up in the figure is toward the north.

alongshelf direction, and we can therefore not make credible estimates of the contribution of the mean offshore flow to the overall mass balance of the shelf. What we can say is that both the magnitude and the dynamics of this offshelf flow should be prioritized in future studies, whether observational or model-based.

Analysis

We have also analyzed and synthesized a variety of data to provide a broad perspective on arctic shelf-basin processes. This work is reported in eight reviewed papers supported by this grant. Six of the papers deal with shelf and slope processes in the Western Arctic, while two papers consider the wider consequences for the Arctic Ocean and North Atlantic of the Pacific throughflow to the Arctic. The

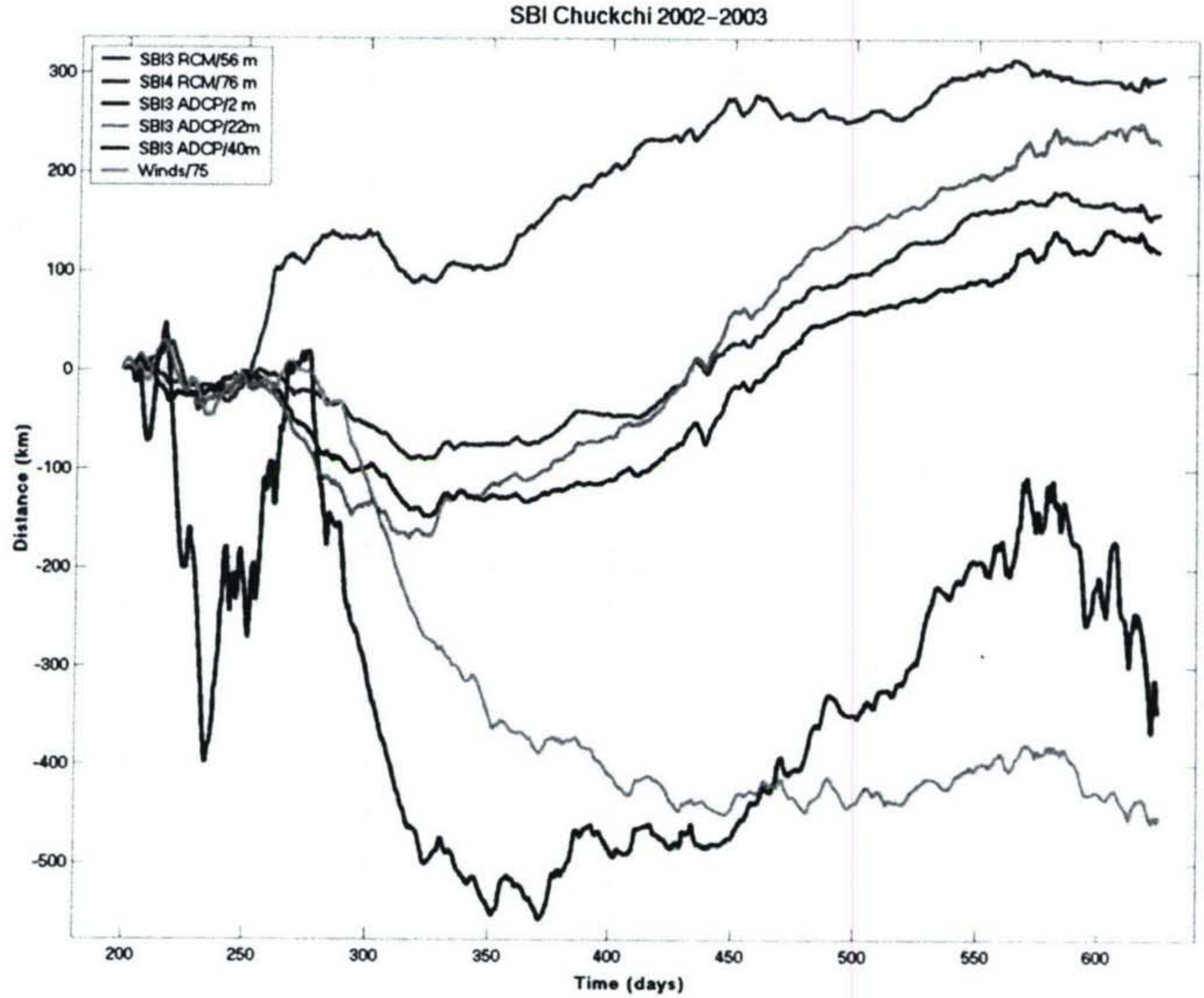

Figure 11. Cumulative northward displacement calculated from selected current records at SBI-3 during 2002-2003, together with the displacement for the current at ~75 m at mooring SBI-4 and for the wind. For the latter we have used the NCEP 10-m wind for 73.3° N, 166.9° W, which has been scaled to match the current displacement. Instrument or ADCP bin depths are given in the legend.

results are summarized below. During 1993–1994, steric forcing of flow through Bering Strait represented a northward sea level drop of ~0.7 m from the Bering Sea Basin to the adjacent deep Arctic Ocean, of which ~2/3 was due to the salinity difference between the basins. Seasonal variability of steric forcing appears small (<0.05 m), in contrast to large seasonal wind effects. Interannual changes in steric forcing may exceed 20%, however, and warm inflow from the North Atlantic, accumulation of freshwater in the southwest Canada Basin, and temperature and salinity changes in the upper Bering Sea have all contributed to recent changes. The mean salinity balance in Bering Strait is primarily maintained by large runoff to the Bering shelf, dilute coastal inflow from the Gulf of Alaska, and on-shelf movement of saline and nutrient-rich oceanic waters from the Bering Sea Basin. In Bering Strait, therefore, both the throughflow and its salinity are affected by remote events. [Aagaard,

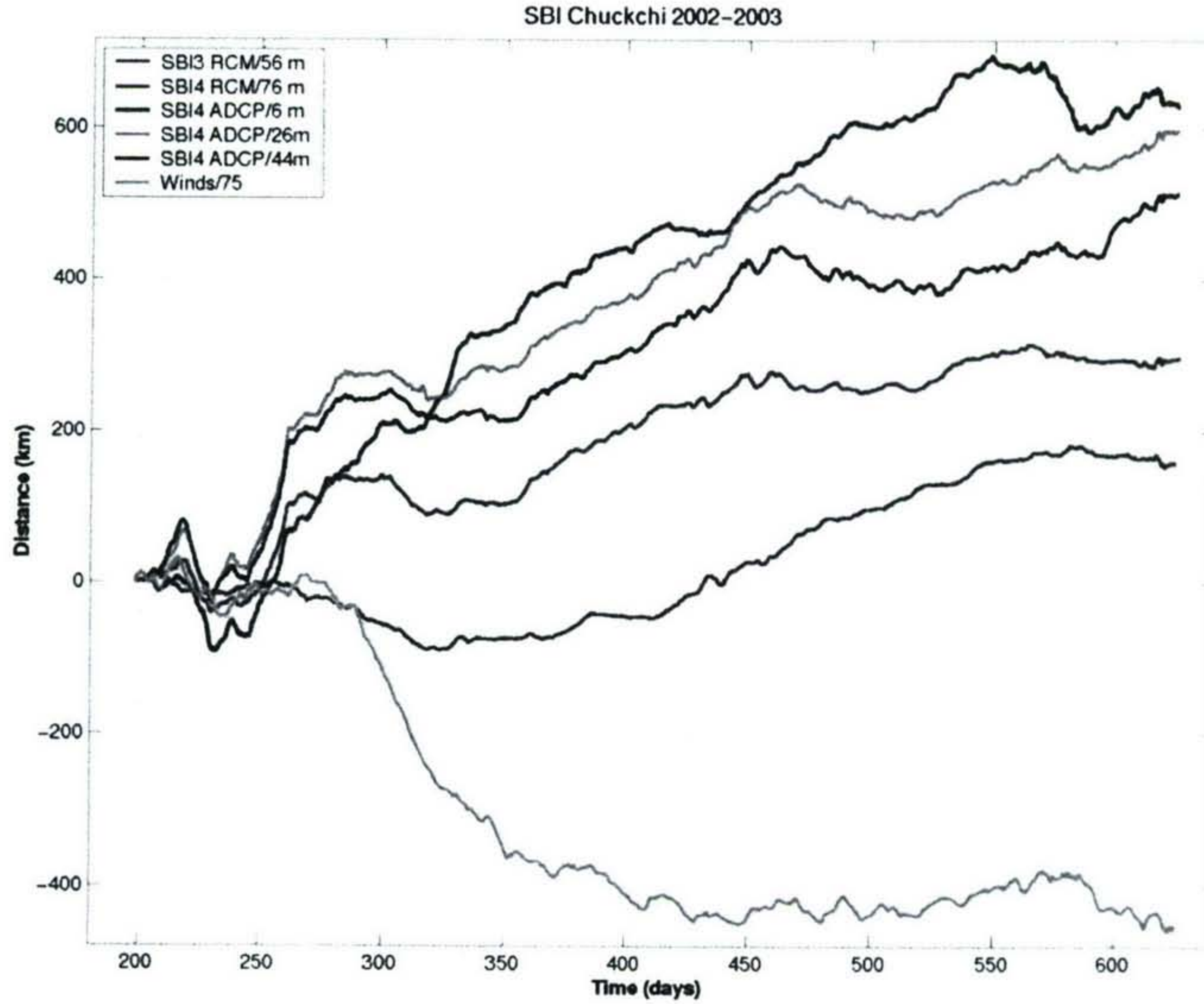

Figure 12. Cumulative northward displacement calculated from selected current records at SBI-4 during 2002-2003, together with the displacement for the current at ~55 m at mooring SBI-3 and for the wind. For the latter we have used the NCEP 10-m wind for 73.3° N, 166.9° W, which has been scaled to match the current displacement. Instrument or ADCP bin depths are given in the legend.

K., T.J. Weingartner, S.L. Danielson, R.A. Woodgate, G.C. Johnson, and T.E. Whitledge, Some controls on flow and salinity in Bering Strait, *Geophys. Res. Lett. 33*, L19602, doi:10.1029/2006GL026612, 2006.]

The annual cycle of freezing and melting of sea ice is of major importance to conditions on the arctic shelves, including the SBI region, and the ensuing shelf conditions also affect the adjacent basins. Much of the ice production has been thought to occur in coastal polynyas, where extremely saline waters may form [*Aagaard et al.*, 1985; *Weingartner et al.*, 2005]. To explore this problem set, we have examined conditions in the St. Lawrence Island polynya on the northern Bering shelf (Figure 2), which feeds the Bering Strait throughflow and downstream Chukchi Sea. Using the records from fourteen year-long instrumented moorings deployed south of St. Lawrence Island, along with oceanographic drifters, we have assessed the circulation over the central Bering shelf and the role of polynyas in forming and disseminating saline waters over the shelf. We have paid particular attention to evaluating the *Gawarkiewicz and Chapman* [1995] model of eddy production within coastal polynyas. Principal results of our analysis include: 1) The northern central shelf near-surface waters exhibit westward flow carrying low-salinity waters from the Alaskan coast in fall and early winter, with consequences for water mass formation and biological production. 2) Within the St. Lawrence polynya, the freshening effect of winter advection is about half as large as the salting effect of surface brine flux resulting from freezing. 3) In aggregate, brine production over the Bering shelf occurs primarily offshore, rather than within the polynyas. 4) We find little evidence for the geostrophic flow adjustment predicted by recent polynya models. 5) In contrast to the theoretical prediction that dense water from the polynya is carried offshore by eddies, we find negligible cross-shelf eddy density fluxes within and surrounding the polynya and very low levels of eddy energy that decrease from fall to winter, even though dense water accumulated within the polynya and large cross-shore density gradients develop. 6) It is possible that dense polynya water was advected downstream of our array before appreciable eddy fluxes materialized. [Danielson, S., K. Aagaard, T. Weingartner, S. Martin, P. Winsor, G. Gawarkiewicz, and D. Quadfasel, The St. Lawrence polynya and the Bering shelf circulation: New observations that test the models, *J. Geophys. Res.*, *111*, C09023, doi:10.1029/2005JC003268, 2006.]

Year-long time-series of temperature, salinity and velocity from 12 locations throughout the Chukchi Sea from September 1990 to October 1991 document physical transformations and significant seasonal changes in the throughflow from the Pacific to the Arctic Ocean for one year. In most of the Chukchi, the flow field responds rapidly to the local wind, with high spatial coherence over the basin scale - effectively the ocean takes on the length scales of the wind forcing. Although weekly transport variability is very large (ca. -2 to +3 Sv), the mean flow is northwards, opposed by the mean wind (which is southward), and presumably forced by a sea-level slope between the Pacific and the Arctic, which these data suggest may have significant variability on long (order a year) time scales. The high flow variability yields a significant range of residence times for waters in the Chukchi (i.e., 1-6 months for half the transit) with the larger values applicable in winter. Temperature and salinity (TS) records show a strong annual cycle of freezing, salinization, freshening, and warming, with sizable interannual variability. The largest seasonal variability is seen in the east, where warm, fresh waters escape from the buoyant, coastally trapped Alaskan Coastal Current into the interior Chukchi. In the west, the seasonally present Siberian Coastal Current provides a source of cold, fresh waters and a flow field less linked to the local wind. Cold, dense polynya waters are observed near Cape Lisburne and occasional upwelling events bring lower Arctic Ocean halocline waters to the head of Barrow Canyon. For about half the year, at least at depth, the entire Chukchi is condensed into a small region of TS-space at the freezing temperature, suggesting ventilation occurs to near-bottom, driven by cooling and brine rejection in autumn/winter and by storm-mixing all year. In 1990-1991, the ca. 0.8 Sv annual mean inflow through Bering Strait exits the Chukchi in four outflows (via Long Strait, Herald Valley, the Central Channel, and Barrow Canyon), each outflow being comparable (order 0.1-0.3 Sv) and showing significant changes in volume and water properties (and hence equilibrium depth in the Arctic Ocean) throughout the year. The clearest seasonal cycle in properties and flow is in Herald Valley, where the outflow is only weakly related to the local wind. In this one year, the outflows ventilate above and below (but not in) the Arctic halocline mode of 33.1 psu. A volumetric comparison with Bering Strait indicates significant cooling during transit through the Chukchi, but remarkably little change in salinity, at least in the denser waters. This suggests that, with the exception of (in this year small) polynya events, the salinity cycle in the Chukchi can be considered as being set by the input through Bering Strait and thus, since density is dominated by salinity at these temperatures, Bering

Strait salinities are a reasonable predictor of ventilation of the Arctic Ocean. [Woodgate, R.A., K. Aagaard, and T. Weingartner, A year in the physical oceanography of the Chukchi Sea: Moored measurements from autumn 1990-1991, *Deep-Sea Res. II, 52* (24-26), 3116-3149, 2005.]

Mooring and shipboard data collected between 1992 and 1995 delineate the circulation over the north central Chukchi shelf. Previous studies indicated that Pacific waters crossed the Chukchi shelf through Herald Valley (in the west) and Barrow Canyon (in the east). We find a third branch (through the Central Channel) onto the outer shelf. The Central Channel transport varies seasonally in phase with Bering Strait transport, and is ~0.2 Sv on average, although some of this might include water entrained from the outflow through Herald Valley. A portion of the Central Channel outflow moves eastward and converges with the Alaskan Coastal Current at the head of Barrow Canyon. The remainder appears to continue northeastward over the central outer shelf toward the shelfbreak, joined by outflow from Herald Valley. The mean flow opposes the prevailing winds and is primarily forced by the sea level slope between the Pacific and Arctic oceans. Current variations are mainly wind-forced, but baroclinic forcing, associated with upstream dense water formation in coastal polynyas might occasionally be important. Winter water mass modification depends crucially on the fall and winter winds, which control seasonal ice development. An extensive fall ice cover delays cooling, limits new ice formation, and results in little salinization. In such years, Bering shelf waters cross the Chukchi shelf with little modification of their salinity. In contrast, extensive open water in fall leads to early and rapid cooling, and if accompanied by vigorous ice production within coastal polynyas, results in the production of high salinity (>33) shelf waters. Such interannual variability likely affects slope processes and the transport of Pacific waters into the Arctic Ocean interior. [Weingartner, T., K. Aagaard, R. Woodgate, S. Danielson, Y. Sasaki, and D. Cavalieri, Circulation on the north central Chukchi Sea shelf, *Deep-Sea Res. II, 52* (24-26), 3150-3174, 2005.]

Pacific winter waters, a major source of nutrients and buoyancy to the Arctic Ocean, are thought to ventilate the Arctic's lower halocline either by injection (isopycnal or penetrative) of cold saline shelf waters, or by cooling and freshening Atlantic waters upwelled onto the shelf. Although ventilation at salinity (S) > 34 psu has previously been attributed to hypersaline polynya waters, temperature, salinity, nutrient, and tracer data suggest instead that much of the western Arctic's lower halocline is in fact influenced by a diapycnal mixing of Pacific winter waters (S ~33.1 psu) and denser eastern Arctic halocline (Atlantic) waters, the mixing possibly occurring over the northern Chukchi shelf/slope. Estimates from observational data confirm that sufficient quantities of Atlantic water may be upwelled to mix with the inflowing Pacific waters, with volumes implying the halocline over the Chukchi Borderland region may be renewed on time scales of order a year. [Woodgate, R.A., K. Aagaard, J.H. Swift, K. Falkner, and W.M. Smethie Jr., Pacific ventilation of the Arctic Ocean's lower halocline by upwelling and diapycnal mixing over the continental margin, *Geophys. Res. Lett., 32*, No. 18, L18609, doi:10.1029/2005GL023999, 2005.]

Mackenzie Trough, a cross shelf canyon in the Beaufort Sea shelf, is shown to be a site of enhanced shelf-break exchange via upwelling caused by wind- and ice-driven ocean surface stresses. To characterize flow within the trough, we analyze current meter mooring data and concurrent wind and ice velocity data from 1993 to 1996, together with CTD/ADCP sections from 2002. Mackenzie Trough is approximately 400 m deep and 60 km wide, but dynamically it is only 2–3 times the baroclinic Rossby radius at its mouth, and patterns of upwelling and downwelling flow within the canyon are similar to those in dynamically narrow canyons. Large upwelling events within the canyon are associated with wind in the short ice-free summer season and with ice motion in winter. Ice motion does not necessarily reflect the wind stress because of internal ice stresses that differentially block downwelling-causing ice motion. The asymmetry between upwelling and downwelling flow within the canyon combined with the predominance of upwelling-causing ice motion, suggests that Mackenzie Trough is a conduit for deeper, nutrient-rich water to the shelf. [Williams, W.J., E.C. Carmack, K. Shimada, H. Melling, K. Aagaard, R.W. Macdonald, and R.G. Ingram, Joint effects of wind and ice motion in forcing upwelling in Mackenzie Trough, Beaufort Sea, *Cont. Shelf Res.*, *26*, 2352-2366, doi:10.1016/j.csr.2006.06.012, 2006.]

We have examined interannual to decadal variability of water properties in the Arctic Ocean using an enhanced version of the 1948–1993 data released earlier under the Gore-Chernomyrdin environmental bilateral agreement. That earlier data set utilized gridded fields with decadal time resolution, whereas we have developed a data set with annual resolution. We find that beginning about 1976, most of the upper Arctic Ocean became significantly saltier, possibly related to thinning of the arctic ice cover. There are also indications that a more local upper ocean salinity increase in the Eurasian Basin about 1989 may not have originated on the shelf, as has been suggested earlier. In addition to the now well-established warming of the Atlantic layer during the early 1990s, there was a similar cyclonically propagating warm event during the 1950s. More remarkable, however, was a pervasive Atlantic layer warming throughout most of the Arctic Ocean from 1964–1969, possibly related to reduced vertical heat loss associated with increased upper ocean stratification. A cold period prevailed during most of the 1970s and 1980s, with several very cold events appearing to originate near the Kara and Laptev shelves. Finally, we find that the silicate maximum in the central Arctic Ocean halocline eroded abruptly in the mid-1980s, demonstrating that the redistribution of Pacific waters and the warming of the Atlantic layer reported from other observations during the 1990s were distinct events separated in time by perhaps 5 years. We have made the entire data set publicly available. [Swift, J.H., K. Aagaard, L. Timokhov, and Ev. G. Nikiforov, Long-term variability of Arctic Ocean waters: Evidence from a reanalysis of the EWG data set, *J. Geophys. Res.*, *110*, No. C3, C03012, doi:10.1029/2004JC02312, 2005.]

The effects of changes in the processing of freshwater in the Arctic and sub-Arctic are of global importance, and the SBI region is an integral part of this problem set. For example, the inflow of freshwater though Bering Strait is equivalent to about three-fourths of the total runoff into the Arctic Ocean [*Woodgate and Aagaard*, 2005; *Woodgate et al.*, 2006; *Serreze et al.*, 2006]. Together with investigators at several other institutions, we have undertaken a synthesis of changes in northern high-latitude freshwater sources and ocean freshwater storage that illustrates the complementary and synoptic temporal pattern and magnitude of these changes over the past 50 years. We find that increasing river discharge anomalies and excess net precipitation onto the ocean contributed ~20,000 km^3 freshwater to the Arctic Ocean and the high-latitude North Atlantic, from lows in the 1960s to highs in the 1990s. Sea ice attrition provided another ~15,000 km^3, and glacial melt added ~2,000 km^3. The sum of anomalous inputs from these freshwater sources matched the amount and rate at which freshwater accumulated in the North Atlantic during much of the period from 1965 through 1995. The changes in freshwater inputs and ocean storage occurred in conjunction with the amplifying North Atlantic Oscillation (NAO) and rising air temperatures. Freshwater may now be accumulating in the Arctic Ocean and will likely be exported southward if and when the NAO enters into a new high phase. [Peterson, B.J., J. McClelland, R. Curry, R.M. Holmes, J.E. Walsh, and K. Aagaard, Trajectory shifts in the arctic and subarctic freshwater cycle, *Science*, *313*, 1061-1066, 2006.]

IMPACT/APPLICATIONS

Major goals of the SBI initiative are to understand the physical processes responsible for water mass modification over the arctic shelves and slopes, and for exchanges with the interior ocean, as well as to understand the variability of this system. Our reported project addresses these goals directly. In particular, we have quantified the large variability found in the Pacific-origin waters that flush the western Arctic shelves, as well as illuminated the origin of this variability. Much of the latter is generated in the Bering Sea [*Woodgate et al.*, 2005a; *Aagaard et al.*, 2006], although the northward-flowing waters may in some years be further modified in the Chukchi, particularly during winter along the Alaskan coast [*Weingartner et al.*, 2005]. The shelf waters are subsequently discharged into the Arctic Ocean, where their seasonal and interannual variability are propagated long distances, in part by long-lived eddies that drift into the interior [*Newton et al.*, 1974; *Manley and Hunkins*, 1985; *Pickart et al.*, 2005], in part by topographically steered boundary currents that rim both the Polar Basin and its major ridge structures [*Aagaard*, 1989; *Woodgate et al.*, 2001], and in part by other features of the circulation. This propagation leads to variability in regions far from the originating shelves [cf., *Swift et al.*, 1997 and *Woodgate et al.*, 2001 for examples]. An understanding of these processes and effects is vital to realistically modeling the Arctic Ocean and its global connections [*Huang and Schmitt*, 1993; *Wadley and Bigg*, 2002; *DeBoer and Nof*, 2004; *Peterson et al.*, 2006].

Our measurements of the time-dependent shelf circulation provide important guidance to investigations of shelf productivity and biochemical cycling. For example, water parcels leaving the northern Chukchi shelf will exhibit substantially different carbon and nutrient loading, depending on their upstream trajectories and the season [*Walsh et al.*, 1997; *Woodgate et al.*, 2005a]. Our work also addresses other prominent issues, including the role of polynyas [*Danielson et al.*, 2006]; the flux and processing of freshwater [*Woodgate and Aagaard*, 2005; *Peterson et al.*, 2006; *Woodgate et al.*, 2006; *Aagaard et al.*, 2006; *Serreze et al.*, 2006]; mixing over the slope [*Woodgate et al.*, 2005b]; and the needs of a variety of arctic simulations for accurate long-term boundary conditions and observational verification.

RELATED PROJECTS

Our work on the northern Chukchi shelf is collaborative with T. Weingartner (UAF), who made similar measurements within the other two principal throughflows of the shelf: the Central Channel and Barrow Canyon. In closely related efforts, R. Pickart (WHOI) maintained a mesoscale moored array on the Beaufort slope near 152°W, and J. Swift (SIO), L. Codispoti (UMD), and C. Flagg (BNL) provided CTD/rosette/ADCP sections to support the mooring work with hydrography and detailed spatial information about the velocity field. Finally, we also maintained moorings in Bering Strait under a separate ONR grant (N00014-99-1-0345), and the data from those moorings have been essential to our work in the Chukchi Sea under the grant reported here.

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[9 presentations at national and international meetings]
[8 refereed papers]

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July 10, 2007

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Subject: Final Report ONR N00014-02-1-0305

Enclosed is my final report for "The Variable Outflow from the Chukchi Shelf to the Arctic Ocean," grant number N00014-02-1-0305. I appreciate ONR's support of this research.

Sincerely,

Mari Litzenberger for
Knut Aagaard
Principal Investigator

Cc: ONR, Seattle, Administrative Grant Officer
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