MONTHLY TEMPERATURE, SALINITY AND TRANSPORT VARIABILITY OF THE BERING STRAIT THROUGHFLOW

Rebecca A. Woodgate, Knut Aagaard,
Polar Science Center, Applied Physics Laboratory, University of Washington, Seattle, WA.
Thomas J. Weingartner,
Institute of Marine Science, University of Alaska, Fairbanks, AK
Corresponding Author: Rebecca Woodgate,
Applied Physics Laboratory, University of Washington,
1013 NE 40th Street, Seattle, WA98105, USA, woodgate@apl.washington.edu

ABSTRACT

The Bering Strait throughflow is important for the Chukchi Sea and the Arctic and Atlantic oceans. A realistic assessment of throughflow properties is also necessary for validation and boundary conditions of high resolution ocean models. From 14 years of moored measurements, we construct a monthly climatology of temperature, salinity and transport. The strong seasonality in all properties (~ 31.9 to 33 psu, ~ -1.8 to 2.3°C and ~ 0.4 to 1.2 Sv) dominates the Chukchi Sea hydrography and implies significant seasonal variability in the equilibrium depth and ventilation properties of Pacific waters in the Arctic Ocean. Interannual variability is large in temperature and salinity. Although missing some significant events, an empirical linear fit to a local (model) wind yields a reasonable reconstruction of the water velocity, and we use the coefficients of this fit to estimate the magnitude of the Pacific-Arctic pressure-head forcing of the Bering Strait throughflow.

INDEX TERMS: 4207 General Oceanography: Arctic and Antarctic oceanography (9310, 9315); 4215 General Oceanography: Climate and interannual variability (1616, 1635, 3305, 3309, 4513); 4223 General Oceanography: Descriptive and regional oceanography; 4227 General Oceanography: Diurnal, seasonal, and annual cycles (0438).

INTRODUCTION

The temperature, salinity and volume of the Bering Strait throughflow are critical for the Chukchi Sea [e.g., *Coachman et al.*, 1975; *Woodgate et al., accepted,* henceforth *Wetal*] and the upper Arctic Ocean [e.g. *Shimada et al.,* 2001; *Steele et al.,* 2004]. In addition to its role in the global freshwater cycle [e.g., *Aagaard and Carmack,* 1989; *Wijffels et al.*, 1992; *Woodgate and Aagaard*, 2005, henceforth *WA*], the flux also influences the Atlantic Ocean overturning circulation [see e.g. *Wadley and Bigg,* 2002, for discussion], the Atlantic deep western boundary current and the separation point of the Gulf Stream from the American coast [*Huang and Schmitt,* 1993], and possibly world climate [*DeBoer and Nof,* 2004]. Yet, many high resolution models of the Arctic Ocean [*Steele et al.,* 2001] erroneously either consider the Bering Strait as closed or prescribe a constant influx.

In fact, the Bering Strait flow has strong seasonal variability, resulting in large variations in waters supplied to the Arctic. Using 14 years of mooring data, we calculate a monthly climatology of temperature (T), salinity (S) and transport for the Bering Strait throughflow, by averaging monthly means of T, S and velocity measurements taken between 1990 and 2004 from ~ 9 m above bottom at three sites (A1, A2 and A3; Figure 1).

TEMPERATURE-SALINITY (T-S)

Of the two channels of the Bering Strait (Figure 1), the eastern channel (A2) is generally warmer and fresher than the western channel (A1), which carries the nutrient-rich Anadyr waters. Near-bottom measurements at site A3 (just north of the strait) represent a useful combination of eastern and western channel (near-bottom) waters and thus form the basis of the monthly climatology (Figure 2). Strong seasonal cycles exist. After the maximum temperatures in October, a 2-month cooling coincides with a freshening to the minimum salinity in December, probably related to surface cooling and storms mixing fresher surface waters down [*Wetal*]. From January to April, sea-ice is generally present, temperatures are at freezing (Tf), and salinity increases until March, when ice starts to melt and salinities fall. Temperatures increase through the summer from May to October, although salinities remain almost constant after June. The magnitude of these cycles is -1.8°C to 2.3°C and 31.9 psu to 33.0 psu. This is colder and saltier than the 1950-1988 NODC data averages of *Björk* [1989] (-1.8°C to ~4.7°C; 31.45 ppt to 32.35 ppt), however, his data were south of the Bering Strait (64°N-65°N) and the difference maybe either spatial or temporal.

Note our climatology implies a change in the equilibrium depth of Pacific waters in the Arctic halocline from ~ 50 m in summer to ~ 120 m in winter. Thus, at different times of the year, the Pacific waters ventilate significantly different parts of the Arctic halocline with waters of significantly different properties (both T-S and nutrients). Recognizing this seasonality is important for understanding of Pacific waters in the Arctic.

For mean water column properties, we must also consider vertical stratification and seasonally present boundary currents - the warm, fresh Alaskan Coastal Current (ACC) in the east [*Paquette and Bourke,* 1974; *Ahlnäs and Garrison*, 1984; Figure 1] and occasionally the cold, fresh Siberian Coastal Current (SCC) in the west [*Weingartner et al.,* 1999, henceforth *W99*]. Although few upper-layer winter measurements exist, other data suggest the water column is well mixed by storms and surface cooling/freezing in winter [*Wetal*]. Summer/autumn CTD measurements from 2000-2004 [*http://psc.apl.washington.edu/BeringStrait.html*] suggest that, at least in these months, mean water column values are ~ 0.5 to 1 psu and 1 to 2°C fresher and warmer than near-bottom measurements.

Interannual variability is large. The winter season (T~Tf) may be 30-60 days longer than climatology and summer maximum 30-day mean temperatures may deviate -1°C (1991, 2000, 2001) to +2°C (1997, 2003) from the climatology. The maximum salinities, which vary in timing by ~ 1 month, are 1 psu greater than the mean in early 1991, 1999 and 2000. Extreme minimum salinities occur in March 2001 and late 2003. The characteristic autumn freshening, probably related to fresher surface layers mixing down [*Wetal*], is absent in late 1991, 1999 and 2001.

TRANSPORT

The velocities at all sites are highly correlated with each other [r>0.9, *Wetal*] and with the local wind [e.g. *Coachman and Aagaard,* 1981]. Since flows are strongly rectilinear, we consider the principal component of velocity. The monthly means (Figure 4) from the near-bottom A3 records (heading 329°) varies from ~10 cm/s (January) to ~ 30 cm/s (June), similar to shorter time-series estimates [*Roach et al.,* 1995]. This cycle is, however, deceptive. Whilst summer velocities are fairly represented, winter monthly-mean velocities range from -20 cm/s to +40 cm/s, and daily mean values (not shown) vary from -50 cm/s to + 50 cm/s.

For lack of data, transports calculations assume velocity homogeneity over suitable cross-section areas. An ADCP record just north of the strait [*Roach et al.,* 1995] implies our near-bottom values underestimate the depth-averaged velocity by ~ 10%. High correlations between moorings (r>0.9) suggest that, away from boundary currents, horizontal interpolation is reasonable, although, given also ambiguity in the endpoints, we estimate this adds a ~ 5% error. Neglected boundary currents - the seasonally present ACC, ~ 0.1 Sv northward [*WA*], and the occasionally present SCC, ~ 0.1 Sv southward [*W99*], - add another ~10% uncertainty. Combined, these factors yield errors ~20% in our transport estimates. To this, we must also add the errors implied by velocity variability, which are ~10%.

It is generally believed a combination of a Pacific-Arctic pressure-head (PH) and local wind effects drive the Bering Strait throughflow (see *Wetal* for discussion). Indeed, velocities recreated from an empirical linear fit to a local (model) wind field (Figure 5) are more realistic than the climatology. This fit suggests the PH flow is order 30 cm/s within the Bering Strait region, which is greater than the annual mean (order 25 cm/s), emphasizing that in the annual mean the wind-driven flow opposes the PH flow. Note that the wind field is unable to predict anomalously high flow events, such as summer 1994.

CONCLUSIONS

Based on 14 years of near-bottom measurements, we present a monthly climatology for the water properties and volume of the Bering Strait throughflow, including an assessment of errors and interannual variability. Seasonal cycles in temperature, salinity and volume indicate the Pacific ventilation of the Arctic halocline varies significantly throughout the year, not only in properties, but also in ventilation depth. This result has implications for our understanding of the role of Pacific waters in the Arctic. An empirical linear fit to a local model wind gives a reasonable representation of the flow, however, some strong current events are not predictable solely from the wind field. This fit quantifies the Pacific-Arctic pressure head which dominates the throughflow, although in the annual mean local winds oppose this forcing.

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TABLES:

	T (degC)	S (psu)	V (cm/s)	Vol (Sv)
Jan	-1.77(.01)	32.39(.16)	11.4(3.3)	0.4
Feb	-1.79(.01)	32.76(.17)	15.3(2.2)	0.6
Mar	-1.80(.01)	32.95(.20)	18.2(3.0)	0.7
Apr	-1.78(.01)	32.88(.13)	21.7(3.0)	0.8
May	-1.44(.08)	32.65(.12)	29.5(2.0)	1.2
Jun	-0.06(.20)	32.45(.10)	32.5(2.0)	1.3
July	+1.59(.30)	32.51(.06)	29.2(1.6)	1.1
Aug	+2.07(.31)	32.44(.04)	26.8(2.6)	1.0
Sep	+2.25(.27)	32.47(.06)	18.6(3.2)	0.7
Oct	+2.22(.26)	32.46(.06)	16.1(1.7)	0.6
Nov	+0.62(.35)	32.07(.11)	18.6(1.5)	0.7
Dec	-1.36(.15)	31.91(.21)	13.1(3.5)	0.5
AM	**-0.1(0.2)**	**32.5(0.1)**	**20.9(2.5)**	**0.8**

Table 1. Climatological near-bottom temperature (T), salinity (S) and principal component (V) of velocity (heading 329°) at A3, with estimated errors in brackets (grey areas on Figures 2, 3, 4, and 5). Standard deviations (thin black lines on Figures 2, 3, 4, and 5) are ~3 times these errors. Estimated transports (Vol) have errors ~ 25%. Water column means are probably ~ 0.5 to 1 psu fresher and 1 to 2°C warmer than these values during summer/autumn (~ May - October). AM = annual mean.

FIGURES:

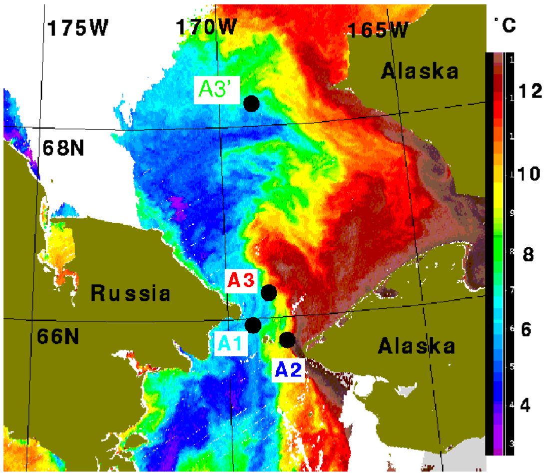

Figure 1. Sea-surface temperature for 26th August 2004 in the Bering Strait region, with mooring sites, A1, A2, A3 and A3' (black dots). (MODIS/Aqua level 1 image courtesy of Ocean Color Data Processing Archive, NASA/Goddard Space Flight Center.) Note the warm Alaskan Coastal Current in the east. White areas indicate clouds.

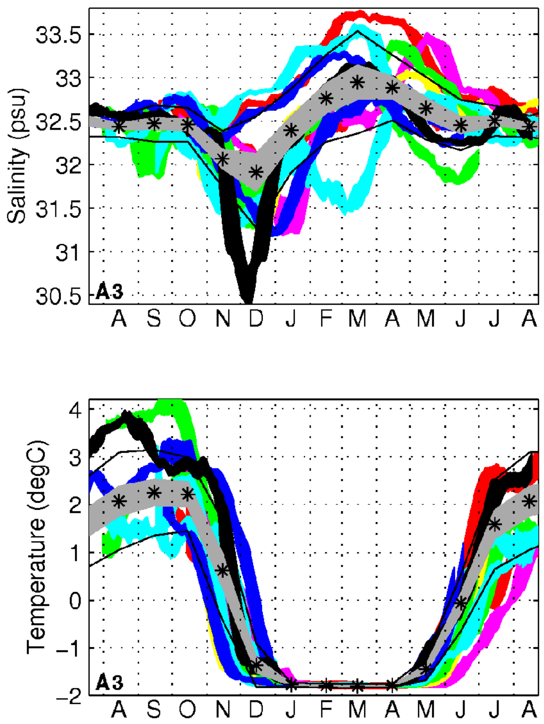

Figure 2. Salinity (top) and temperature (bottom) from ~ 9 m above bottom at site A3 and A3'. Horizontal axis is time starting in August with letters indicating calendar months. Black stars mark the 14-year monthly climatology of Table 1; thin black lines, the standard deviation; and the grey band, errors obtained from variance of the monthly means. Colored curves are 30-day running mean (with errors) from the various years (red= deployed in 1990 or 1991; magenta=1992, 1993; yellow=1994, 1995, green=1997, 1998, cyan=1999, 2000; blue=2001, 2002, black=2003). A3' (deployed summer 1992 to summer 1995) data is not included in the climatology. Water column means are probably ~ 0.5 to 1 psu fresher and 1 to 2°C warmer than these values during summer/autumn.

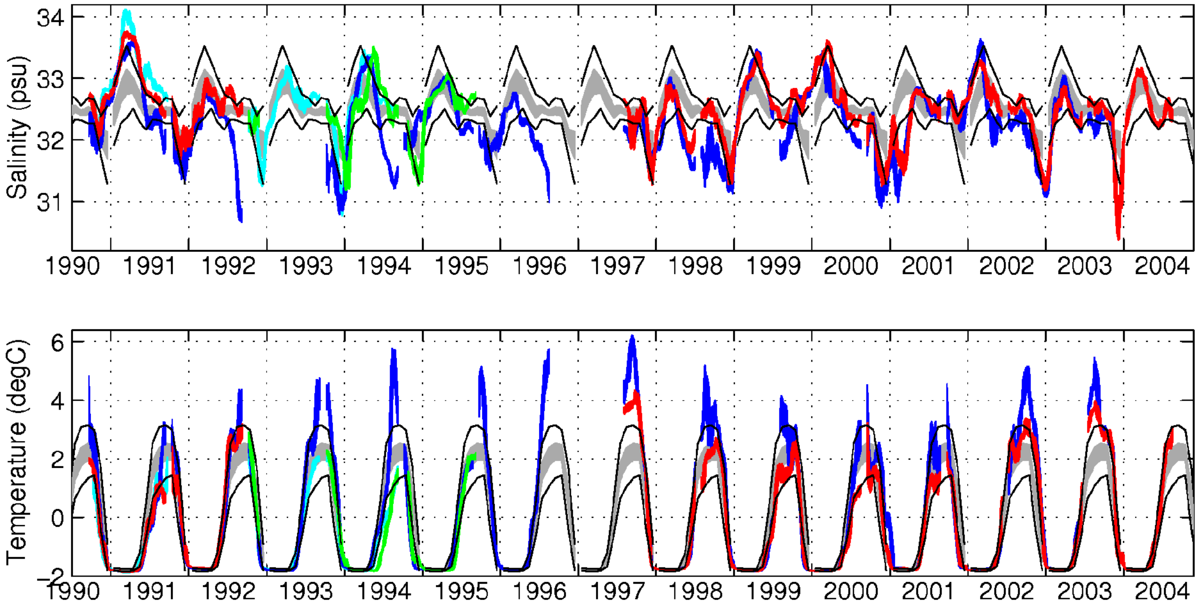

Figure 3. Fourteen year 30-day smoothed time-series of salinity (top) and temperature (bottom) from ~ 9 m above bottom at A1 (cyan), A2 (blue), A3 (red) and A3' (green - summer 1992 to summer 1995). Line width indicates errors. Grey area and black lines are the climatology of Figure 2. Water column means are probably ~ 0.5 to 1 psu fresher and 1 to 2°C warmer than these values during summer/autumn.

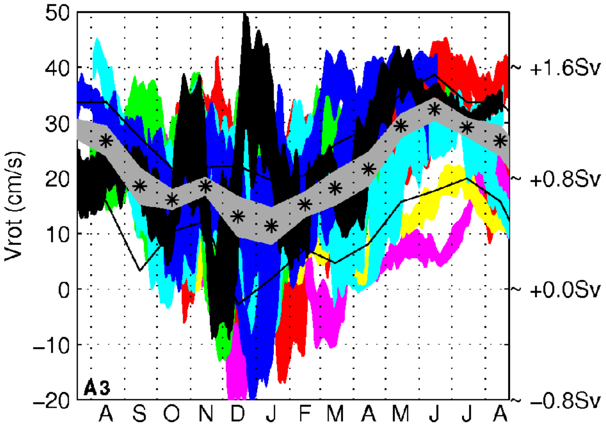

Figure 4. Principal component of velocity (true heading 329°) at A3 and A3', illustrated as per Figure 2. Estimated transports (labeled on right axis) are as per Figure 5.

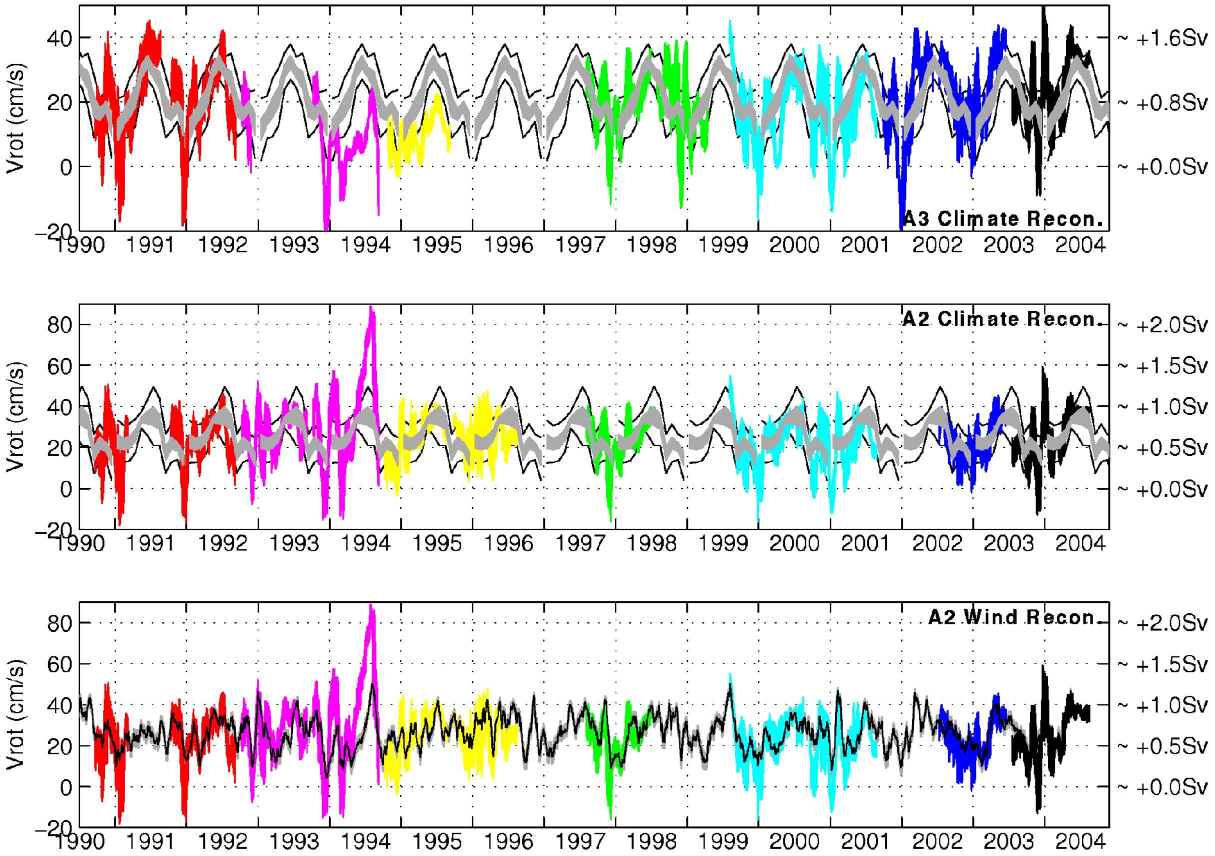

Figure 5. Fourteen year 30-day smoothed time-series of principal component of velocity (top) at A3 and A3' (true heading 329°) and (middle and bottom) at A2 (true heading 0°). Velocity climatologies from A3 and A2 (with errors and standard deviation) are marked in top and middle figures. A3' (deployed summer 1992 to summer 1995) data is not included in the climatology. Thin black line on bottom figure marks 30-day smoothed reconstruction of velocity from a linear fit to the NCEP 6 hourly winds (i.e. reconstructed velocity (cm/s) = 32 + 3.4 x NCEP 10 m wind component (m/s) at heading of 330°). (Coefficients obtained from a least squares fit, see *Wetal*). Grey here indicates errors in the coefficients. Colors are as per Figures 2 and 4. Conversions to transports (using cross-section areas of ~ 2.6 km^2 at A2 and ~ 3.9 km^2 at A3) are marked on the right axis. These transports are subject to ~ 20% errors in addition to those indicated by error bars on the plots.