INTERANNUAL CHANGES IN THE BERING STRAIT FLUXES OF VOLUME, HEAT AND FRESHWATER BETWEEN 1991 AND 2004

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ABSTRACT

Year-round moorings (1990 to 2004) illustrate interannual variability of Bering Strait volume, freshwater and heat fluxes, which affect Arctic systems including sea-ice. Fluxes are lowest in 2001 and increase to 2004. Whilst 2004 freshwater and volume fluxes match previous maxima (1998), the 2004 heat flux is the highest recorded, partly due to ~ 0.5ºC warmer temperatures since 2002. The Alaskan Coastal Current, contributing about 1/3rd of the heat and ¼ of the freshwater fluxes, also shows strong warming and freshening between 2002 and 2004. The increased Bering Strait heat input between 2001 and 2004 (> 2×10^{20} J) could melt 640,000 km^2 of 1 m thick ice; the 3-year freshwater increase (~ 800 km^3) is about ¼ of annual Arctic river run-off. Weaker southward winds likely explain the increased volume flux (~ 0.7 to ~ 1 Sv), causing ~ 80% of the freshwater and ~ 50% of the heat flux increases.

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 Bering Strait, ~ 85 km wide, ~ 50 m deep, is the only Pacific gateway to the Arctic Ocean. Although the Bering Strait throughflow is only ~ 0.8 Sv (1 Sv = 10^6 m^3/s) [*Roach et al.*, 1995], this nutrient-rich flow [*Walsh et al.*, 1989] dominates the Chukchi Sea [*Woodgate et al.*, 2005c]; provides ~1/3rd of Arctic freshwater [*Woodgate and Aagaard*, 2005]; influences western Arctic ice melt [*Paquette and Bourke*, 1981]; ventilates and stratifies the upper Arctic Ocean [*Shimada et al.*, 2001; *Steele et al.*, 2004; *Woodgate et al.*, 2005a]; and affects the Atlantic overturning circulation [e.g., *Wadley and Bigg*, 2002] and possibly world climate [*De Boer and Nof*, 2004].

The early 2000s have shown substantial changes, especially in ice extent, in the Bering and Chukchi seas and the western Arctic in the region of the Pacific inflow to the Arctic [e.g., *Stroeve et al.*, 2005]. Thus, this paper examines interannual changes observed in the properties of the Bering Strait throughflow since 1990, with special emphasis on the late 1990s and early 2000s, when more consistent data coverage is available.

DATA

Since 1990 (almost continuously), year-round moorings in the Bering Strait region (Figure 1) recorded velocity, temperature (T) and salinity (S) of the throughflow ~ 9 m above bottom at up to four sites – the western channel (A1); the eastern channel (A2); north of the strait (A3), and, since 2001, in the Alaskan Coastal Current (A4) (http://psc.apl.washington.edu/BeringStrait.html) [*Woodgate et al.*, 2005b]. Rarely are all moorings deployed in one year. From these near-bottom measurements, we estimate properties of the entire throughflow, with caveats relating to both vertical stratification and the warm, fresh Alaskan Coastal Current (ACC) (of riverine origin) which is present seasonally in the east of the eastern channel [*Paquette and Bourke*, 1974] (Figure 1).

One year of moored ADCP data [*Roach et al.*, 1995] and four summer ship-ADCP surveys suggest that near-bottom velocity data estimate the depth-averaged flow to within ~ 10% at mid-channel sites (A1, A2) and at A3. Moreover, the flows at all three sites are well correlated both with each other and with the local wind [*Woodgate et al.*, 2005c]. Velocity does, however, vary significantly with depth in the ACC, and since 2002 this is measured by a moored ADCP at A4.

In general, waters in the western channel (A1) are colder and saltier than in the eastern channel (A2). Previous comparisons suggest that the northern site A3 is a useful average of T-S at A1 and A2 [*Woodgate et al.*, 2005c]. Between 1995 and 2004, we lack A1 data and thus use A3 as the best available estimator of strait properties. Although the water column is to some extent mixed by storms (year-round) and surface cooling and brine rejection on ice formation (in winter), stratification from summer/autumn CTD data suggest that water column means are probably ~ 0.5 to 1 psu fresher and 1 to 2ºC warmer than near-bottom measurements in summer/autumn [*Woodgate et al.*, 2005b]. (The designator "psu" indicates salinity measured on the Practical Salinity Scale.) Due to the risk of ice-keels, year-round shallower measurements have not yet been made, however there is at least some correspondence between the near-bottom T-S at A4 and the ACC water column stratification [*Woodgate and Aagaard*, 2005].

INTERANNUAL VARIABILITY OF 30-DAY MEANS

Thirty-day smoothed time-series (Figure 2) show that, in addition to dominant seasonal variability [*Woodgate et al.*, 2005b], the Bering Strait throughflow exhibits strong interannual variability, especially in temperature.

For velocity, aside from still unexplained anomalously strong flows in 1994, short timescale variability (highly correlated with the local wind) is larger than any interannual variability. However, since 2002, northward velocities are more frequently > 30 cm/s.

For temperature, maximum monthly-mean summer temperatures increase by ~ 2ºC from 1991 to a maximum around 1996 or 1997 (a missing year of data obscures the actual year). Thereafter, summer maximum temperatures decrease until 2001, and then increase again until the last year of the present data (2004). The most recent rise in temperature is particularly marked at A4, which measures T-S at the bottom of the ACC. These changes coincide with some changes in the North Pacific sea surface temperature (NPSST) climate indices – e.g., the Pacific Decadal Oscillation, the leading principal component of monthly mean NPSST, [*Mantua et al.*, 1997], in the 1990s (i.e., the rise in 1997); and the Victoria Pattern, the second principal component [*Bond et al.*, 2003], in the 2000s (i.e., the temperature increase in 2001). However, with so few years of data, such correlations are mostly speculative.

In salinity, short timescale variability (especially the timing of the annual maximum and minimum) is again greater than interannual variability. There is little obvious pattern in these data, although the maximum salinities (which occur in spring) are higher in 1991 than in any year following, and the minimum salinities (which occur in late autumn/early winter) are lowest in 2003, see e.g., A3 data (blue curves) of Figure 2.

ANNUAL MEAN CHANGES

The interannual variability is also clear in the annual means. Since velocity, temperature and freshwater content are all climatologically at a minimum in winter, we estimate annual mean values based on calendar years (Figure 3) for a clear interannual comparison. Mooring deployments start in summer/autumn, thus to form one annual mean requires two consecutive years of mooring data, and a year of missing data (e.g. 1996-1997) compromises two annual means (1996 and 1997). So far only 1 set of annual means (1993) is available from A1, and the record at A3 is broken by a shift of the mooring from ~ 66ºN (A3) to ~ 68ºN (A3') between summer 1992 and 1995. (A3' data are not shown.) Annual means from A4 are available only since 2002.

The annual mean velocities (top panel, Figure 3) show clearly the anomalous flow in 1994. They also suggest a weakening of the flow from 2000 to 2001, and a subsequent increase from 2001 to 2004. In transport (fourth panel, assuming barotropic flow, homogeneous across the strait), this latter increase is from ~ 0.7 to ~ 1 Sv, suggesting that in recent years flows exceed the long term climatology of ~ 0.8 Sv [*Roach et al.,* 1995].

Annual mean temperatures (second panel) show a step increase of ~ 0.5ºC from 2001 to 2002 to consistently warmer temperatures at A2 and A3, although the higher temperatures are still comparable with 1993. The number of days per year with near-bottom temperatures above 0ºC (not shown) ranges from 120 to 190 days at A2 and A3 and is also consistently high since 2002, suggesting a longer warm season. This is in agreement with Bering Sea shelf observations of a reduced ice season [*Stroeve et al.*, 2005]. Data from A4, the base of the ACC, (available since 2002) also indicate a warming to 2004.

For salinity (third panel), the 1991 annual mean is saltier than the rest of the record. The 1998 mean is the freshest, but at A2 and A3 there is little convincing temporal trend. In contrast, A4 (the base of the ACC) does show a freshening of ~ 0.3 psu between 2002 and 2004.

Heat and freshwater fluxes (panels 5-6) are estimated from hourly transport and T-S data, assuming vertical homogeneity, and T-S references of 34.8 psu (~ Arctic Ocean mean salinity) for freshwater and -1.9ºC (~ freezing point of Bering Strait waters) for heat, the latter reflecting that Pacific waters lose most of their heat before exiting the Arctic Ocean [*Steele et al.*, 2004]. Both fluxes show an increase since 2001 – for heat, from ~ 1.3×10^{20} J/yr in 2001 to ~ 2.9×10^{20} J/yr in 2004 (errors ~ 30%), and for freshwater, from ~ 1300 km^3/yr in 2001 to ~ 2100 km^3/yr in 2004 (errors ~ 10-15 %). The increase in volume flux is responsible for ~ 80% of the increased freshwater flux and ~ 50% of the increased heat flux. (Note these flux estimates neglect contributions from the ACC and water column stratification, which are discussed below.)

CONTRIBUTION OF THE ALASKAN COASTAL CURRENT (ACC) AND STRATIFICATION

The warm, fresh, fast-flowing ACC and seasonal water column stratification contribute significantly to the Bering Strait fluxes [*Woodgate and Aagaard*, 2005], however, due to lack of year-round upper layer T-S measurements we can only estimate these contributions.

For 2003 and 2004 (the only ACC data available), a moored ADCP at A4 recorded annual mean velocities in the ACC that increase towards the surface, with annual mean velocity at 11 m depth ~ 40 – 50 cm/s, compared to ~ 20 – 30 cm/s near-bottom at A2. CTD data suggest a wedge-like flow structure of horizontal scale ~ 10 km, which yields a transport estimate for the ACC ~ 0.15 Sv, with a modest (~ 0.03 Sv) increase between 2003 and 2004. This would increase the estimate of total Bering Strait volume flux by ~ 10% (~ 0.07 Sv) since some of this flow is already estimated by A2.

The contributions to heat and freshwater fluxes are much larger. If the near-bottom T-S at A4 were to represent the mean properties of the ACC, the ACC contribution would increase the prior Bering Strait estimates of heat flux by over $0.5\text{x}10^{20}$ J/yr and freshwater flux by over 400 km^3/yr. In both cases, the increase would be greater in 2004 than in 2003. These are undoubtedly underestimates since summer CTD sections indicate near-bottom values at A4 are a significant underestimate of the ACC properties. Assuming (based on CTD surveys) annual mean corrections of 2ºC and 1 psu brings the ACC contribution to ~ $1\text{x}10^{20}$ J/yr and ~ 600 km^3/yr.

Additionally, accounting for stratification (also poorly measured) will increase the fluxes. Applying summer stratification estimates (1 - 2ºC and 0.5 – 1 psu [*Woodgate et al.*, 2005b]) for half the year suggests increases of ~ 0.5 – $1.0\text{x}10^{20}$ J/yr and ~ 200 – 400 km^3/yr.

Thus, although the ACC adds only ~10% of the annual mean volume flux, it can increase the annual mean heat flux by a third and the annual mean freshwater flux by a quarter. Likewise, stratification effects outside the ACC, although adding less than 10% to the volume flux, likely increase the heat flux and freshwater fluxes by significant amounts. Thus year-round upper layer measurements are necessary to constrain heat and freshwater flux estimates.

DRIVING MECHANISMS FOR INCREASED BERING STRAIT FLUXES

Between 2001 and 2004, ~ 80% of the freshwater and ~ 50% of the heat flux increases are attributable to increased northward volume flux. The Bering Strait throughflow is usually attributed to a pressure head gradient, opposed by the local wind [see e.g., *Woodgate et al.*, 2005c]. Annual mean NCEP (National Centers for Environmental Prediction model) winds, which are southward, weaken by ~ 2 m/s between 2000 and 2004 (bottom panel, Figure 3). By the wind-throughflow regression of *Woodgate et al.* [2005b], this decrease would correspond to an increase in northward water flow of ~ 7 cm/s, close to that observed. Similarly, the weakening of the Bering Strait throughflow between 1998 and 2001 generally coincides with a strengthening of the southward wind, although the correlation is not perfect suggesting that other factors are also important, perhaps some variability in the pressure head forcing [*Woodgate et al.*, 2005c].

Temperature variability in the Bering Strait relates, presumably, to a combination of water properties of the Bering Sea, sea-ice processes and atmospheric forcing. In the southern Bering Sea, 1997 and 1998 were anomalously warm [*Stabeno et al.*, 2001], and more recently the reduced ice extent [*Stroeve et al.*, 2005] reflects (possibly drives) warmer water temperatures. However, there is not a one-to-one correspondence between

Bering Sea surface temperatures (www.beringclimate.noaa.gov) and Bering Strait temperatures, indicating that the relationship is more complex than simple advection.

Bering Strait salinity variability also reflects a combination of Bering Sea water properties (including Gulf of Alaska inputs), river outflow and sea-ice processes. Note, however, that even just the increase in freshwater input between 2001 and 2004 (~ 800 km^3 over the 3-year period) is significantly greater than the entire annual Bering Sea riverine input, (~ 300 km^3/yr [*Lammers et al.*, 2001], which in any case shows a decrease since 2001, http://nwis.waterdata.usgs.gov/usa/nwis/discharge), and is comparable with the estimated Gulf of Alaska annual freshwater influx, (~ 500 km^3/yr [*Weingartner et al.*, 2005]). Thus, the variability of the Bering Strait freshwater flux is likely dependent not only on the volume of freshwater sources to the south, but also on the salinity and northward flux of the Bering Sea waters [see also *Aagaard et al.*, submitted].

CONCLUSIONS AND IMPLICATIONS FOR THE ARCTIC

Bering Strait fluxes of volume, heat and freshwater show sizeable interannual variability. Fluxes are lowest in 2001 and increase significantly to 2004, when the heat flux is at a record-length high. Much of the heat and freshwater increase is due to the volume flux increase, plausibly related to interannual change in the local winds. However, variability of T-S properties also influences fluxes significantly. The Alaska Coastal Current and seasonal stratification likely contribute over 1/3rd of the heat and ¼ of the freshwater flux through the strait, yet due to paucity of data, these contributions are still only poorly quantified.

Most topically, the area of most dramatic ice-retreat in the Arctic is in the region of the Pacific inflow to the Arctic. Although the volume flux is small, Bering Strait heat fluxes (1-3 $x10^{20}$ J/yr) are remarkably about 1/5th of the Fram Strait heat fluxes (5 - 13 $x10^{20}$ J/yr [*Schauer et al.*, 2004]). Furthermore, the low density of the Pacific waters puts them high in the Arctic water column, where they could have significant influence on sea-ice. Whilst ice advection has a role in ice retreat [*Rigor and Wallace*, 2004], recent studies suggest only 40% of the ice retreat can be explained by atmospheric heat fluxes [*Francis et al.*, 2005], leaving a significant role for oceanic fluxes, either by redistribution of oceanic heat [*Shimada et al.*, 2006] or by increased heat flux into the Arctic [*Maslowski et al.*, 2006]. The Bering Strait heat flux increase between 2001 and 2004 (from ~ $1x10^{20}$ J/yr to ~ $3x10^{20}$ J/yr (errors ~ 30%) to which the ACC and stratification can add 1 - $2x10^{20}$ J/yr) is sufficient over the 3-year period to melt ~ 640,000 km^2 of 1 m thick ice, an area comparable with the observed reduction in September ice extent (~ 700,000 km^2) between 2001 and 2004 [*Stroeve et al.*, 2005]. Thus, although likely not all this increased heat flux contributes to melting ice, Bering Strait heat flux variability is large enough to have a significant role in Arctic sea-ice retreat.

The increase in freshwater flux since 2001 (from ~ 1300 km^3/yr to ~ 2100 km^3/yr, to which the ACC and stratification likely add 800 - 1000 km^3/yr) shows Bering Strait freshwater variability is ~ 25% of the total annual Arctic river run-off (estimated at ~ 3200 km^3/yr by *Serreze et al.* [submitted]), and thus could be important to the Atlantic meridional overturning [*Wadley and Bigg*, 2002].

Finally, since the Bering Strait throughflow carries the most nutrient-rich waters found in the Arctic [*Walsh et al.*, 1989], an increased Bering Strait throughflow could have implications for Arctic ecosystems.

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FIGURES

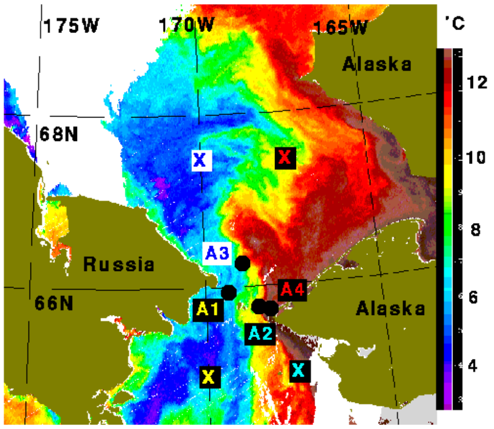

Figure 1. The Bering Strait region, with mooring locations (dots) and NCEP wind grid points (crosses), showing sea surface temperature for 26th August 2004 (MODIS/Aqua level 1 image courtesy of Ocean Color Data Processing Archive, NASA/Goddard Space Flight Center). White areas indicate clouds.

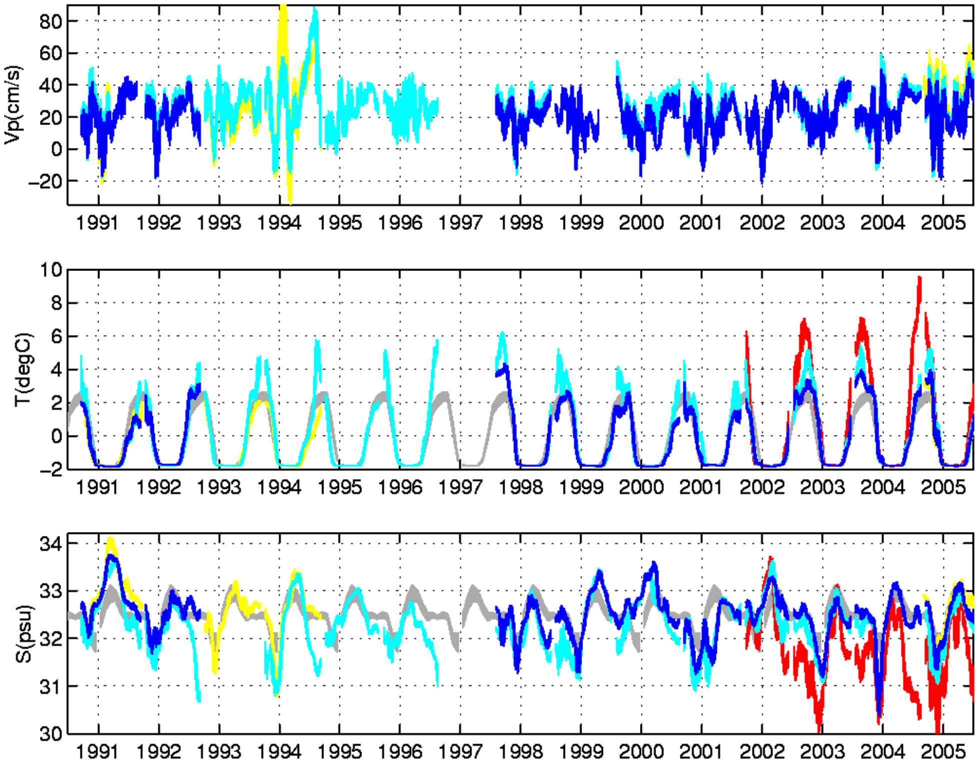

Figure 2. Thirty-day smoothed time-series of near-bottom principal component (~ northward) of velocity (Vp), temperature (T), salinity (S) from the Bering Strait moorings (A1-yellow; A2 – cyan; A3 - blue), with A4 (red) included in the T and S time-series. Colors as per locations in Figure 1. Grey background is the climatological T-S from A3 [*Woodgate et al.*, 2005b]. Line thickness indicates uncertainty in the means.

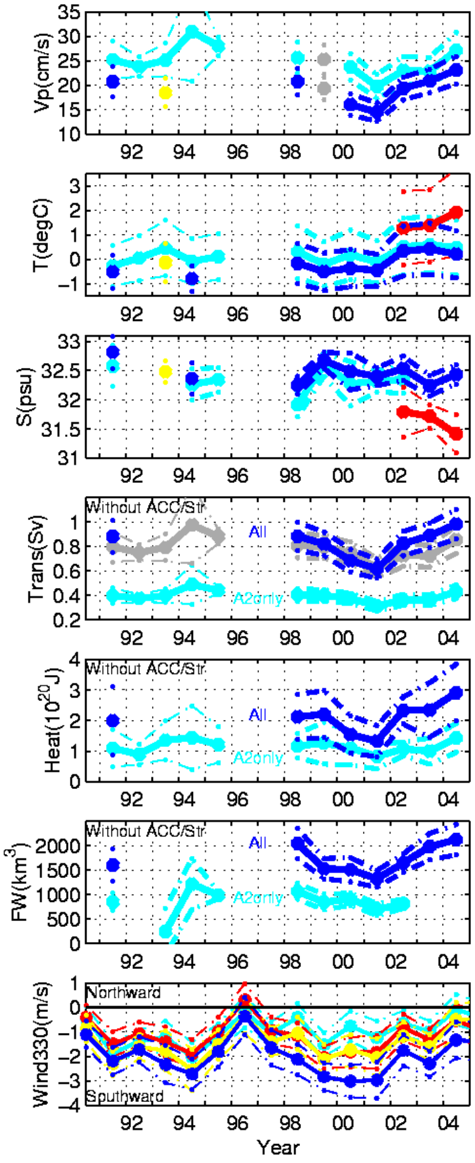

Figure 3. Annual means (A1 – yellow; A2 – cyan; A3 – blue; A4 – red) of near-bottom principal component (~ northward) of velocity (Vp), temperature (T) and salinity (S) (top three panels); and estimates of transport, heat flux, and freshwater flux (panels 3-6). For transport and flux estimates, blue (from A3) are for the entire strait and cyan (from A2) are only for the eastern channel. For transport, gray line is the entire strait transport as estimated from A2 only. Corrections for stratification and the ACC (not included) are ~ 1 - 2x10^{20} J/yr (heat) and 800 - 1000 km^3/yr (freshwater). Dashed lines indicate estimated errors in the means. Grey dots in Vp indicate results from partial years (used for flux estimates). Bottom panel is annual mean NCEP wind at heading 330º, colors indicating location as per crosses in Figure 1.

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