Extended Measurements in Bering Strait

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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 more 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

Our objective is to extend direct measurements of velocity, temperature, and salinity in Bering Strait, supplemented by time series measurements of ice thickness and other properties. This upstream information is vital to the Shelf-Basin Interaction (SBI) initiative, since the influx of Pacific waters provides a key forcing for the western Arctic shelf-slope-basin system, including its biogeochemistry [*Walsh et al.*, 1997]. A particularly important dynamical aspect of the Pacific water presence in the Arctic Ocean is its contribution to stabilizing the upper ocean, thereby influencing heat flux and ice thickness [*Aagaard et al.*, 1981; *Killworth and Smith*, 1984; *Aagaard and Carmack*, 1989; *Woodgate et al.*, 2006]. Furthermore, the Pacific influx is a first-order component of the Pacific-Atlantic freshwater cycle, and therefore critical to the larger scale ocean circulation [*Huang and Schmitt*, 1993; *Wadley and Bigg*, 2002; *DeBoer and Nof*, 2004].

APPROACH

We have maintained instrumented moorings in Bering Strait, which in conjunction with earlier measurements provide nearly continuous records of flow and water properties in the strait since 1990. Velocity, temperature, and salinity are the core physical measurements at each mooring, and these are supplemented by extensive hydrographic and ADCP sections within the strait and over the southern Chukchi Sea. Other investigators are making ice thickness measurements using upward-looking sonar, *in situ* nutrient determinations, and optical measurements. Two of our moorings are sited in the eastern

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channel of the strait, while a third mooring north of the Diomede islands, just east of the Russian EEZ, serves as a proxy for the western channel [*Woodgate et al*., 2005a; b]. Together with the extensive shipborne measurements made each year, our instrumented array provides information on the temporal and spatial variability of the flow and water properties in Bering Strait.

Emphases in our analysis include the contribution of the Bering Strait throughflow to the Arctic freshwater budget; the forcing of the variable flow through the strait, including wind and sea level effects; and the control of the throughflow salinity. The latter in turn substantially determines the density of the Pacific waters in the northern Chukchi Sea, where these waters are mixed and subsequently ventilate the Arctic Ocean halocline [*Aagaard et al.*, 1981; *Weingartner et al.*, 2005; *Woodgate et al.*, 2005c].

WORK COMPLETED

The ONR-sponsored field work under this project has been completed, but continuing measurements are being funded by other agencies, building on the earlier work. Our FY 2006 efforts under this grant have therefore been directed at completing the final portion of the data submission, together with analyses and publications.

The entire moored data set from 1990-2005, together with the extensive shipborne measurements, have 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/BeringStrait.html).

Our analysis efforts under this grant have resulted in six published papers, along with numerous presentations at national and international meetings. Several of the published results new this year are described below.

RESULTS

We have examined both the large-scale forcing of the Bering Strait throughflow and the principal processes by which the mean salinity in the strait is controlled [*Aagaard et al.*, in press]. 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 to the Arctic Ocean 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 in steric forcing through the strait. 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 (Figure 1, *Aagaard et al.*, in press). In Bering Strait, therefore, both the throughflow and its salinity are affected by remote events.

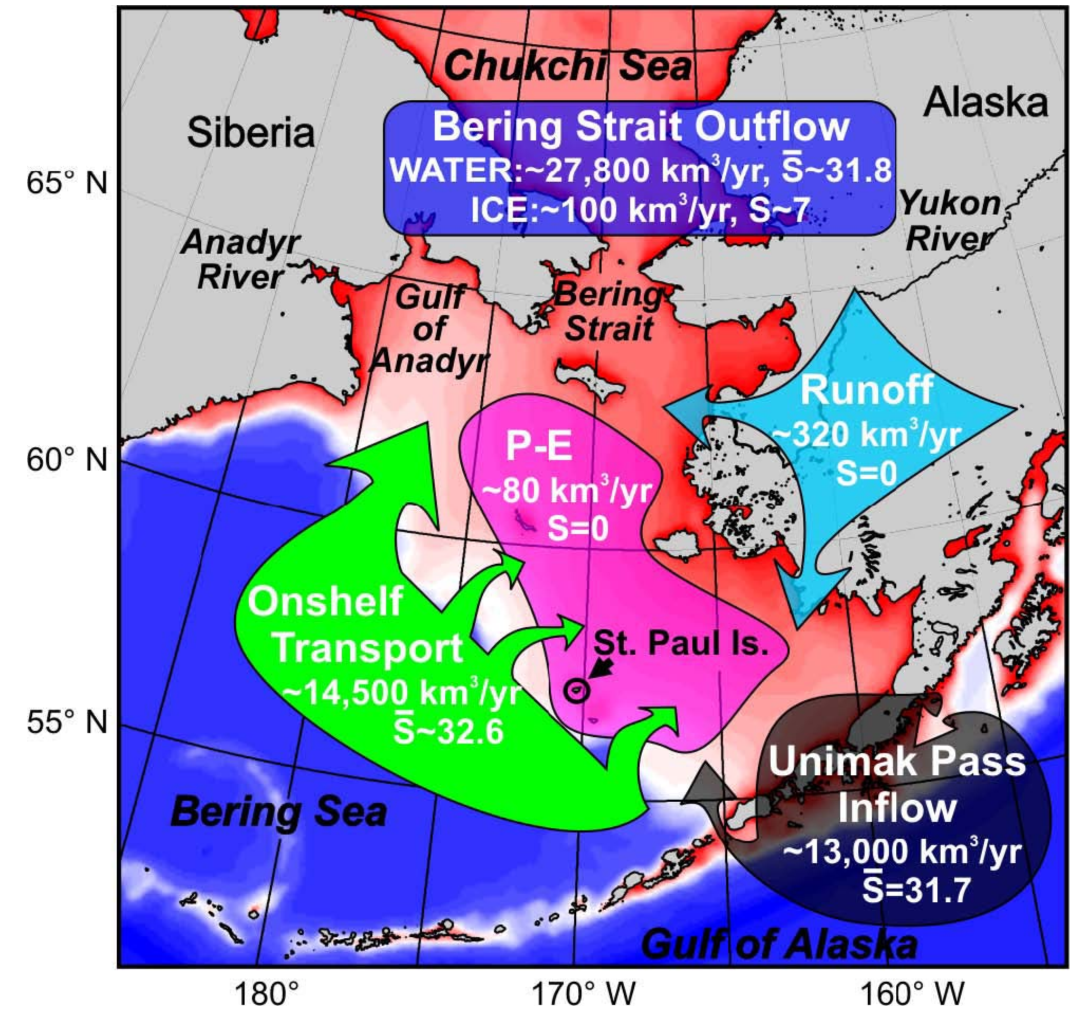

Figure 1: Schematic of the Bering shelf water and salt budgets. Precipitation, evaporation, and salinity are denoted P, E, and S, respectively. Onshelf flow from the deep Bering Sea and inflow from the Gulf of Alaska through Unimak Pass are approximately equal, and together they dominate the mass balance in Bering Strait. The salt balance in the strait is primarily maintained by the different salinities of these two flows, together with freshwater runoff directly onto the Bering shelf.

On the basis of our moored records during 1990-2004, we have also directly examined the interannual variability of the fluxes of volume, freshwater, and heat through Bering Strait (Figure 2, *Woodgate et al.*, 2006). These fluxes were lowest in 2001 and then increased rapidly, so that by 2004 the volume and freshwater fluxes matched the previous high reached in 1998, while the heat flux was the largest recorded, the latter in part due to the very high temperatures after 2002. The Alaska Coastal Current, occupying the easternmost part of the strait and responsible for about one-third the heat flux through the strait and one-fourth the freshwater flux, showed a particularly strong warming and freshening between 2002-2004. The increased heat flux through Bering Strait between 2001 and 2004 (>2x1020 J) is sufficient to melt 640,000 km2 of ice 1 m thick; while the freshwater flux increase during the same period (~800 km3) is about one-fourth the annual runoff to the Arctic Ocean. Weaker northerly winds during this period likely explain much of the increase in volume flux that in turn accounts for about 80% of the increase in freshwater flux and 50% of that of heat.

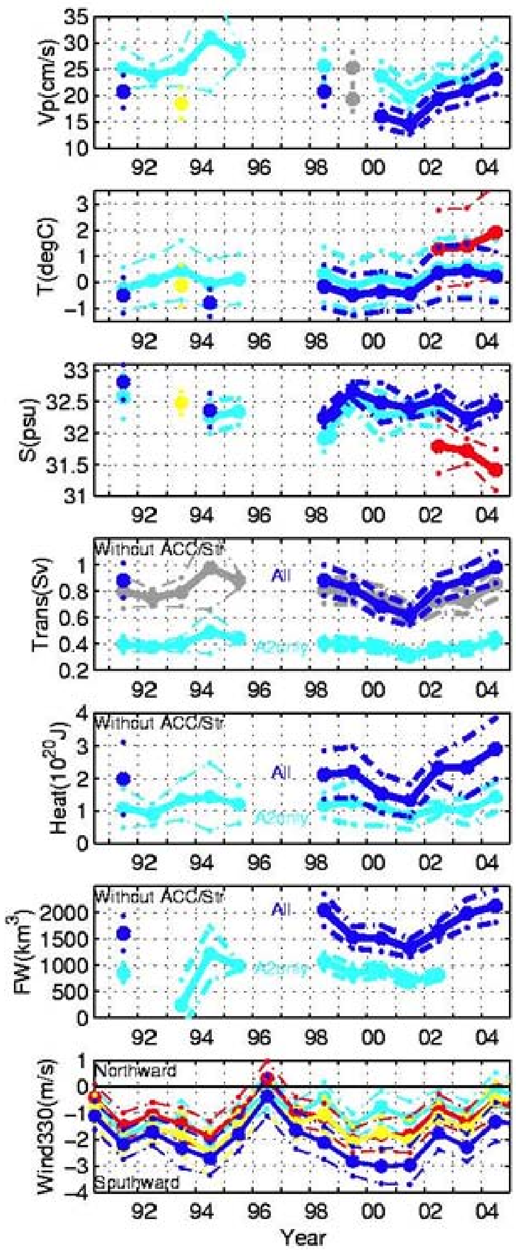

Figure 2: Annual means of near-bottom principal component (~ northward) of velocity (Vp), temperature (T), and salinity (S) in Bering Strait (panels 1-3); estimates of volume transport, heat flux, and freshwater flux through the strait (panels 4-6); and annual mean NCEP wind toward 330ºT at four locations north or south of the strait (bottom panel). For the top three panels, yellow indicates the western channel of the strait; cyan the eastern channel; blue a site just north of the strait that embodies characteristics of both channels; and red the portion of the eastern channel near the Alaska coast, which is occupied by the Alaska Coastal Current (ACC). For transport and flux estimates (panels 3-6), blue represents the entire strait and cyan the eastern channel only. For transport, the gray line is the entire strait transport as estimated from measurements in the eastern channel only. Corrections for stratification and enhanced fluxes in the ACC (not included) are ~ 1 - 2x1020 J/yr (heat) and 800 - 1000 km3/yr (freshwater). Dashed lines indicate estimated errors in the means. Grey dots in Vp indicate results from partial years (used for flux estimates). In the bottom panel, blue and red are north of the strait, cyan and yellow are south.

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 are quantifying the large variability found in the Pacific-origin waters that flush the western Arctic shelves, as well as illuminating the origin of this variability. Much of the latter is generated in the Bering Sea, since our measurements suggest that the salinity of at least the lower water column is not greatly altered during its transit of the Chukchi shelf [Woodgate et al., 2005a], although in some years the northward-flowing waters may 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], in part by topographically steered boundary currents that rim both the Polar Basin and its major ridge structures [Aagaard, 1989], 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 effects and processes is vital to realistically modeling the Arctic Ocean and its global connections[Huang and Schmitt, 1993; Wadley and Bigg, 2002; DeBoer and Nof, 2004].

The accumulated time series from Bering Strait, now a decade-and-a-half long, provide a remarkable record of the upstream forcing of the Chukchi shelf, and ultimately of the ventilation history of the Arctic Ocean halocline. The very high salinities at the beginning of the 1990s have not returned to Bering Strait since. Rather, recent years have seen an alteration between fresh and moderately saline regimes, but with a marked freshening after 2001 [*Woodgate et al.*, 2006]. Therefore, for ventilation of the Arctic Ocean halocline to again be as deep as it may have been in the early 1990s, when the Bering Strait winter waters were exceptionally saline, there would either have to be extensive freezing downstream on the eastern Chukchi shelf, something which in turn depends on fall and winter ice and wind conditions in the Chukchi [*Weingartner et al.*, 2005], or a change in the mixing regime over the Chukchi slope [*Woodgate et al.*, 2005a; c]. With respect to temperature, the pronounced warming after 2002 has brought temperatures in the eastern channel close to the peak in 1997 [*Woodgate et al.*, 2006].

RELATED PROJECTS

In Bering Strait we have worked cooperatively with T. Whitledge and T. Weingartner, UAF, including deployment of *in situ* nitrate and optical sensors (transmissivity, fluorescence, PAR). These measurements are representative of the new techniques that will be required to illuminate biogeochemical cycles in the high-latitude ocean. We have also cooperated with R. Moritz, UW, through deployment of upward-looking sonars to measure ice thickness. These deployments address the need for circumpolar time series measurements of ice thickness, both to illuminate issues of ice mechanics and thermodynamics and to track ice thickness during this time of rapid change in the Arctic. Our work has variously been done in collaboration with Canadian studies in Bering Strait (E. Carmack and J. Cherniawsky, IOS), and with the RUSALCA project (J. Calder, NOAA and AARI, St. Petersburg), the latter project including mooring work in the western channel of Bering Strait by T. Whitledge and T. Weingartner, UAF. Additionally, we have assisted a number of other investigators and students in Bering Strait by providing sampling opportunities during the mooring cruises, including for programs supervised by L. Cooper and J. Grebmeier.

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