Rusalca: The Pacific Gateway to the Arctic
Quantifying and Understanding Bering Strait Oceanic Fluxes

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1. PROJECT SUMMARY

The Bering Strait, a narrow (~ 85 km wide), shallow (~ 50 m deep) strait at the northern end of the Pacific, is the only ocean gateway between the Pacific and the Arctic. Although the flow through the strait is small in volume (~ 0.8 Sv northward in the annual mean), due to its remarkable properties (high heat and freshwater content, low density, high nutrients) it has a startling strong influence, not only on the Chukchi Sea and the Arctic Ocean, but also on the North Atlantic overturning circulation and possibly world climate. Draining the Bering Sea shelf to the south, the Bering Strait throughflow is an integrated measure of Bering Sea change. The comparatively warm, fresh throughflow contributes ~ 1/3rd of the freshwater input and possibly ~ 1/5th of the oceanic heat input to the Arctic, and provides the most nutrient-rich waters entering the Arctic Ocean. Furthermore, the low density of these waters keeps them high in the Arctic water column, giving them a key role in upper ocean ecosystems and physical processes including ice-ocean interactions. At the time when dramatic change, especially the retreat of sea-ice, is observed in the Bering and Chukchi seas and the Arctic, we measured significant increases of Bering Strait fluxes of volume, freshwater and heat, the heat flux in 2004 being the maximum recorded in the last 15 years up to 2004 [Woodgate et al., 2006].

Yet, our understanding of what sets the properties and variability of the Bering Strait throughflow is still rudimentary. Indeed, our ability to measure these fluxes accurately has, in the past, been constrained by lack of data, both from the most nutrient-rich western half of the strait (which lies in Russian waters), and from the upper water column (due to potential ice-keel damage to instrumentation), where stratification and coastal boundary currents (especially the Alaskan Coastal Current in the eastern channel) contribute significantly to freshwater and heat fluxes.

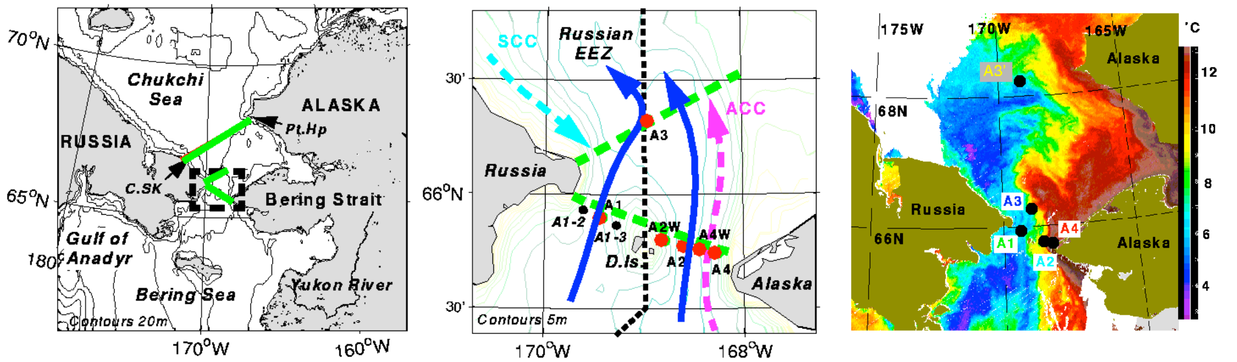


Figure 1. Left: The Bering Strait region, with proposed CTD lines (green). **Middle:** Detail of the Bering Strait, with schematic flows, proposed mooring locations (red dots=this proposal; black dots=collaborative Russian sites) and CTD lines (green). The main northward flow through the strait passes through both channels (dark blue arrows). Topography diverts the western channel flow eastward near site A3. The warm, fresh Alaskan Coastal Current (ACC) (pink dotted arrow) is present seasonally in the east. The cold, fresh Siberian Coastal Current (SCC) (light blue dotted arrow) is present in some years seasonally in the west, on occasion reaching the strait. All these currents may reverse on timescales of days to weeks. **Right:** MODIS sea surface temperature image from 26th August 2004, with historic mooring locations (A1, A2, A3, A3' and A4), occupied variously since 1990. C.SK=Cape Serdtse Kamen. Pt.Hp=Point Hope. D.Is.=Diomede Islands. Black dotted line = EEZ (Exclusive Economic Zone).

This joint NOAA-NSF project (part of the NOAA RUSALCA – Russian US Long Term Census of the Arctic – project) addresses these deficiencies, by providing (in collaboration with Russian, Canadian and Japanese colleagues), an observationally focused study of the entire Bering Strait region, consisting of a high resolution mooring array, deployed from 2007-2010, covering the two channels of the strait and one "climate" site to the north of the strait, supported by annual CTD surveys and mooring servicing, satellite data, and theoretical and modeling results.

In August/Sept 2007, a joint US (UW and UAF) and Russian mooring team deployed the first 8-mooring, high resolution array in the Bering Strait from the Russian vessel Sever [Woodgate et al., 2008a]. Three moorings were deployed across the western (Russian) channel of the strait. Four moorings were deployed across the eastern (US) channel of the strait. A final 8th mooring was deployed ~ 30 nm north of the strait at a "climate site" occupied since 1990 and hypothesized to be a useful average of the flow through the strait. The 8 sites are a combination of 3 sites established in the 1990s, 3 sites established since 2001/2004 and 2 new sites. Together they give the highest resolution to date in the Bering Strait. These moorings included 6 upward looking ADCP (Acoustic Doppler Current Profilers) to measure water velocity in ~ 2 m bins to the surface, and upper-layer temperature salinity sensors in ice-resistant housings (ISCATs). These are the first long-term moored upper-layer measurements made in the strait. Also, during the cruise, one high resolution CTD section was taken across both channels of the strait, to give a spatial setting for the mooring data.

In Oct 2008, a joint US (UW and UAF) and Russian mooring team recovered and redeployed these moorings from the Russian vessel Lavrentiev [Woodgate et al., 2008b]. The mooring operations were successful, despite extreme biofouling especially on the western of the eastern channel. The lateness of the cruise (Oct rather than Aug) was dictated by changes in the ship schedule. We lost 3 days of ship time to bad weather, and returned to port early due to forecasts of extreme icing conditions. This reduction in operational time meant no high resolution CTD section was completed this year. Preliminary finds are discussed below.

The moorings deployed in Oct 2008 are due to be recovered in August 2009. Since all moorings are subsurface (due to ice), data cannot be transferred to satellites during the mooring deployment.

Metadata for all the Bering Strait moorings have been deposited at CADIS (Cooperative Arctic Data and Information System). All calibrated mooring data have been archived at the National Ocean Data Center, are available via our website (http://psc.apl.washington.edu/BeringStrait.html) and are cross linked with CADIS. Voluntary registration at our data website, (averaging 30-50 registrations a month), indicates the data are in demand for studies ranging from climate modeling to King Crab fishing, and our major publications since 2005 have, to date, over 100 citations.

Woodgate, R. A., K. Aagaard, and T. J. Weingartner, 2006: Interannual changes in the Bering Strait fluxes of volume, heat and freshwater between 1991 and 2004, *Geophys. Res. Lett.*, 33, L15609, doi:10.1029/2006GL026931.

Woodgate, R. A., 2008a: Mooring Cruise report for RUSALCA Sever cruise to the Bering Strait - Aug/Sept 2007, 17 pp, University of Washington.

Woodgate, R. A., 2008b: Mooring Cruise report for RUSALCA Lavrentiev to the Bering Strait, October 2008, 24pp pp, University of Washington.

available at http://psc.apl.washington.edu/BeringStrait.html.

2. ACCOMPLISHMENTS

At the time of writing, we are engaged in shipping for the August 2009 mooring recovery and deployment cruise, which is entirely NOAA funded.

We report here also on results from the previous 2007-2008 data, recovered in October 2008, which was funded by NSF with ship-support from NOAA. Preliminary results are:

1) Calendar year 2007 has the highest heat flux recorded since mooring records began, and volume and freshwater fluxes match previous maximum values.

Figure 2a shows calendar year means for northward velocity (Vp), temperature (T), salinity (S), Transport (Trans), Heat flux relative to -1.9 deg C (Heat) and freshwater flux relative to 34.8 psu (FW). Colors represent estimates from different moorings. Dark blue is the best estimate for the entire strait, based on mooring A3, the "climate" site just north of the strait. Cyan is the estimate for the eastern channel of the strait based on mooring A2 in the central eastern channel (dark grey is the estimate from A2 for the entire strait). Red shows results from mooring A4 in the Alaskan Coastal Current. Dotted lines indicated estimated uncertainties. All these calculations are based only on near-bottom data, and thus neglect the effects of stratification and contributions to the heat and freshwater fluxes from the ACC. These effects may add 1-2x 10^20 J/yr and 800-1000km3/yr respectively.

These simple calculations suggest that the Bering Strait throughflow in 2007 was around 1 Sv, on a par with previous years of high flow. A slight increase in mean temperature, combined with this high flow, yields the highest heat fluxes yet recorded, ~ 3.5 x 10^20 J/yr, an increase of 0.5-1 x 10^20 J/yr over previous years' measurements. For scale, note that 1 x 10^20 J/yr is enough to melt an area of ~ 300,000 km2 (e.g., 550 km by 550 km) of 1 m thick ice. These estimates are important for the debate about causes of the remarkable 2007 sea-ice retreat.

Results also suggest an increase in freshwater flux to match the previous high value in 2004. This increase is due to the increase in flux, which offsets a slight increase in salinity. The impacts of this increased freshwater flux on the Arctic and beyond are a subject of research.

Both freshwater and heat flux calculations need to be revised in light of the upper layer temperature and salinity data obtained for the first time during these mooring deployments.

2) We have the first ever moored estimate of year-round stratification in the Bering Strait.

- Figure 2b shows preliminary results from the upper-layer ISCAT system on mooring A4 in the Alaskan Coastal current for the first 200 days of the deployment (Sept 2007 to ~ March 2008). Magenta indicates data from the ISCAT deployed at ~ 15m. Black indicates data from the conventional Seabird temperature-salinity sensor at ~ 42 m depth. The top panel shows the depth of the instruments. Strong currents in early winter pull the ISCAT down to ~ 30 m. The bottom two panels show temperature and salinity data from both instruments. The upper layer is warmer and significantly fresher for some months in late summer – the difference in salinity is at times is sizeable, about 4 psu. By January most of the stratification in the water column has gone. The next step is to quantify the contribution of this stratification to the estimates of fluxes for the entire strait.

- Risk of damage from sea ice in the strait has prevented deployment of instruments in the upper layer in previous years. The ISCATs telemeter their data down to a logger at a safe depth, incase the temperature-salinity sensor is itself lost during the deployment. Of the 6 ISCATs deployed in the strait in 2007, only 1 ISCAT upper sensor survived the entire year, the other ISCAT upper sensors were lost at various times in early spring, likely relating to the break-up of ice. Yet, up to the time of loss, the telemeter system worked well and we have recovered the valuable data from the ISCATs up to the time of loss. For 2008, the ISCATs have been deployed uniformly ~ 2 m deeper, in an attempt to mitigate loss, but, the necessity of recording the upper layers means the instruments have to be placed in the ice-risk zone. Note that since the moorings are deployed in the summer, even if instruments are lost in the spring break-up of ice, before that loss they will record what is likely the time of greatest stratification in the strait, i.e., summer through to winter. The ADCP velocity data will also be used to assess stratification, by consideration of velocity shear. This information, combined with ISCAT data, will be used to quantify the importance and estimate the most cost-effective method of monitoring the upper layers.

3) Prior to the recovery of these moorings, older Bering Strait data has been used to assist two efforts to estimate the Bering Strait heat fluxes.

- In collaboration with Jinlun Zhang of UW [Zhang et al., submitted], we considered the role of Pacific water in the dramatic retreat of Arctic Sea ice in 2007. This was primarily a model based study, with model estimates of Bering Strait fluxes compared to mooring estimates. Once verified, the model can then be used to estimate terms not measured by observational data. By tracking model terms, the work concludes that the Pacific water plays a role in ice melting in the Chukchi and Beaufort region all summer long in 2007, likely contributing to up to 0.5 m per month additional ice melting in some area of that region.

- A complementary approach is to use satellite/atmospheric data and statistical relationships based on prior data. In collaboration with Kohei Mizobata of IARC [Mizobata et al., submitted], we considered such an effort, using wind and satellite sea surface height data to estimate the flow and satellite sea surface temperature and an empirical fit to CTD data to estimate vertical temperature structure, combining the two results to estimate heat flux. It will be interesting to compare this approach to the recovered mooring data, which will give information on how the vertical structure of the water column varies through the year.

Zhang, J., M. Steele, and R. Woodgate: The role of Pacific water in the dramatic retreat of arctic sea ice during summer 2007, *Journal of Polar Science*, submitted.

Mizobata, K., K. Shimada, R. Woodgate, S.-I. Saitoh, and J. Wang: Estimation of heat flux through the eastern Bering Strait, *Journal of Oceanography*, submitted.

Figure 2a

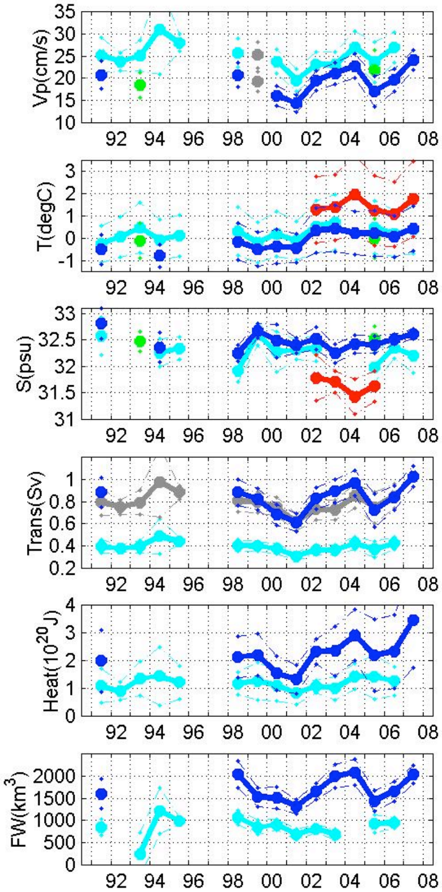
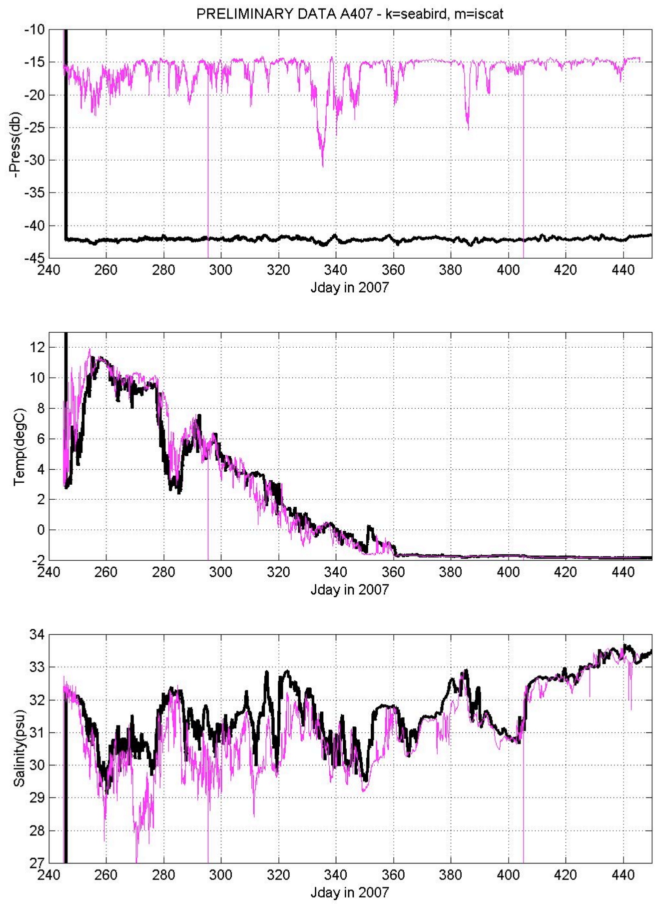


Figure 2b



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3. TRAINING AND DEVELOPMENT

By providing input to University of Washington student classes, this project aids in the training and development of new oceanographers (see Outreach section). Furthermore, the 2008 fieldwork gave an opportunity for on-the-job technical training of a UW technician, Wendy Ermold, previously unfamiliar with mooring work, and UAF students.

4. OUTREACH ACTIVITIES

Our website - http://psc.apl.washington.edu/BeringStrait.html – gives an overview of Bering Strait activities. Our outreach activities on this project are three-fold:

1) To the Science Community – our website includes data access, and links to journal publications. We also present results at national and international conferences. Woodgate was an invited speaker at a retreat considering the 2007 Arctic sea-ice retreat. Information on the Bering Strait throughflow is in popular demand for other Arctic and international projects, including biological studies, model intercomparisons, the ASOF (Arctic SubArctic Ocean Fluxes) studies, freshwater and heat budgets studies. The work is part of the Arctic Observing Network, and contributes to International Polar Year projects Bering Strait, IAOOS (International Arctic Ocean Observing System), and C3O (Canada's three oceans).

2) To students – results of this project are part of an interdisciplinary course "The Changing Arctic Ocean" taught by Woodgate and Deming at the University of Washington School of Oceanography.

3) To the general public – the importance of the Pacific input to the Arctic is one message brought to the public via various outreach activities, including the Polar Science Weekend, held in spring each year at the Pacific Science Center, Seattle's major science museum. This 4-day event (with 2 days focused on school visits) drew over 10,000 visitors in 2007. Woodgate also gave a very well received evening public lecture in February 2008 on the Changing Arctic Ocean as part of the University of Washington's Alumni "Arctic Adventure" series.
Woodgate is an active member of the Arctic Icebreaker Coordination Committee, the WCRP Arctic Climate Panel of the CliC (Climate and Cryosphere) program, and is on the advisory board for the University of Washington's Program on Climate Change and the International Science Steering Committee for the ASOF (Arctic Sub-arctic Ocean Fluxes) community.

5. PUBLICATIONS

5.1. Books or Other One-time Publications

Woodgate, R.A., K.Aagaard and T.Weingarter, 2007: First steps in calibrating the Bering Strait Throughflow, APL internal report, 20pp, http://psc.apl..washington.edu/BeringStrait.html.

Woodgate, R. A., 2008a: Mooring Cruise report for RUSALCA Sever cruise to the Bering Strait - Aug/Sept 2007, 17 pp, University of Washington.
available at http://psc.apl.washington.edu/BeringStrait.html.

Woodgate, R. A., 2008b: Mooring Cruise report for RUSALCA Lavrentiev to the Bering Strait, October 2008, 24pp, University of Washington.
available at http://psc.apl.washington.edu/BeringStrait.html.

5.2. Papers

White, D., L. Hinzman, L. Alessa, J. Cassano, M. Chambers, K. Falkner, J. Francis, B. Gutowski, M. Holland, M. Holmes, H. Huntington, D. Kane, A. Kliskey, C. Lee, J. McClelland, B.Peterson, F. Straneo, M. Steele, R. Woodgate, D. Yang, K. Yoshikawa, T. Zhang, 2007: The Arctic Freshwater System: changes and impacts, *Journal of Geophysical Research*, 112, G04S54, doi:10.1029/2006JG000353.

Melling, H., K.K.Falkner, R.A.Woodgate, S.Prinsenberg, A.Muenchow, D.Greenberg, T.Agnew, R.Samelson, C.Lee, B.Petrie, 2008: Freshwater Fluxes via Pacific and Arctic Outflows across the Canadian Polar Shelf, ASOF special volume, Springer-Verlag.

Zhang, J., M. Steele, and R. Woodgate: The role of Pacific water in the dramatic retreat of arctic sea ice during summer 2007, *Journal of Polar Science*, submitted.

Mizobata, K., K. Shimada, R. Woodgate, S.-I. Saitoh, and J. Wang: Estimation of heat flux through the eastern Bering Strait, *Journal of Oceanography*, submitted.

Woodgate, R. A., R. Lindsay, K. Aagaard and T. Weingartner: On the Bering Strait Heat Flux and its influence on Arctic Sea ice, in preparation.

5.3. Website

http://psc.apl.washington.edu/BeringStrait.html
Home page for Bering Strait activities, including links to data access and cruise reports.

5.4. Abstracts/Invited talks

Woodgate, R.A., K.Aagaard, T.Weingartner, T.Whitledge, R.Lindsay: The Pacific Gateway to the Arctic – change and implications of the Bering Strait Throughflow. 2007, invited talk at ONR site visit.

Woodgate, R.A., T. Weingartner, T.Whitledge, I.Lavrenov, K.Aagaard, R.Lindsay: Pacific Gateway to the Arctic: Recent measurements of the Bering Strait Throughflow, invited talk Dec 2007, Moscow.

Woodgate, R.A.: The Changing Arctic Ocean, First in a 3 part UW Alumni Public Lecture Series entitled 'Arctic Adventure: Tales of Currents and Creatures', organized by UW-COFS (College of Ocean and Fisheries Science), February 2008.

Woodgate. R.A., T. Weingartner, R.Lindsay, T.Whitledge: Bering Strait AON project, invited talk at AON meeting at Palisades, New York, April 2008.

Woodgate, R.A.: The Ocean's role in the 2007 Arctic Sea-ice Minimum, invited talk at NY Sea-ice retreat workship, Palisades, New York, April 2008.

Woodgate. R.A., T. Weingartner, R.Lindsay, T.Whitledge, K.Aagaard: Pacific Inflow to the Arctic Ocean – changes in the Bering Strait throughflow, invited talk at NOAA Climate Division Annual System Review, Washington DC, Sept 2-5 2008.

Woodgate R.A.: Bering Strait: Pacific Gateway to the Arctic, invited talk at 2008 ASOF (Arctic Subarctic Ocean Fluxes) meeting in Halifax, 12-14th Nov 2008.

Panteleev, G., T.Kikuchi, D.Nechaev, A.Proshutinsky, R.Woodgate, M.Yaremchuk, J.Zhang, 2008: Toward the reanalysis of the circulation in the Chukchi and East Siberian Seas, abstract AGU 2008.

Hunt, G., P.Stabeno, R. Woodgate, 2008: Advective Processes in the Eastern Bering Sea, invited talk at fall 2008 ESSAS meeting in Nova Scotia.

Woodgate et al: The Pacific Gateway to the Arctic Ocean. Changes in the Bering Strait throughflow. April 2009, NODC Seminar, given over the internet.

Woodgate et al: The Pacific Gateway to the Arctic Ocean. Changes in the Bering Strait throughflow. May 2009, invited speaker at Bering Strait Observatory Planning Workshop in Pac Forest Center, Seattle.

Woodgate et al: The Pacific Gateway to the Arctic Ocean. Changes in the Bering Strait throughflow. June 2009, invited speaker at ESSAS (Ecosystem Studies of Sub-Arctic Seas) Meeting in Seattle.

5.5. Data or databases

Year-round measurements of temperature, salinity and velocity in the Bering Strait.
Data base publicly available via http://psc.apl.washington.edu/BeringStrait.html.
Data also available at NODC and CADIS.

6. CONTRIBUTIONS

6.1. Contributions within Discipline

By providing an improved evaluation of the Bering Strait fluxes, this project will contribute to local, Arctic and global studies.

Most topically, with the startling retreat of the Arctic sea-ice, quantifying the heat flux through the Bering Strait and the impacts of the Bering Strait throughflow on Arctic stratification become urgent issues in the quest to understand causes of Arctic sea-ice retreat.

Within regional oceanography, the work provides vital information for physical, biological and biogeochemical studies within the Bering Strait and Chukchi Sea, since the physical oceanography of the Chukchi Sea is dominated by the properties of the Bering Strait throughflow. Since the Bering Strait is fed from the south, the Bering Strait throughflow is also some indicator of conditions on the Bering Sea shelf, an economically important zone for U.S. fisheries and the focus of the NSF BEST (Bering Ecosystem Study) Program.

The Bering Strait throughflow is also the Pacific input to the Arctic Ocean, which is important for maintaining the Arctic Ocean halocline and providing nutrients for Arctic ecosystems. The Pacific inflow also brings heat into the Arctic. The fate of Pacific waters in the Arctic (especially their ventilation depth) relates to their density which is, to a large extent, set by the time the waters traverse the Bering Strait.

Globally, the Bering Strait throughflow is an important part of the global freshwater budget. Models suggest that an increase in the Bering Strait freshwater flux may weaken the Atlantic meridional overturning circulation. Other modeling studies count the Bering Strait flow as critical for the stability of world climate.

Thus, a better observational estimate of the Bering Strait flow and its variability is critical for a wide range of studies.

6.2. Contributions to Other Disciplines

Bering Strait data have been used in various research areas including non-physical oceanography and areas beyond oceanography, such as biological studies of sea-birds and mammals. Voluntary registration at our data site shows the data is in demand for work ranging from climate modeling to King Crab fishing, including a wide variety of studies covering local, Arctic and global subjects (North Pacific, Gulf of Alaska, Bering Sea, Chukchi Sea, Arctic Ocean, Arctic Ocean outflows, North Atlantic), with topics including ocean circulation; multidisciplinary shelf-basin exchange; eddy processes; benthic-pelagic coupling; ocean sedimentation; hydrology; heat, freshwater and nitrogen budgets; biogeochemistry, including CDOM, POC, and PIC; modeling and observational studies of present-day, future and paleo conditions, including analysis of sediment cores; future climate predictions (including Arctic and Atlantic meridional overturning circulation investigations); present-day and paleo climate stability; recent studies of accelerated retreat of Arctic sea-ice; changes in the fate of Pacific water in the Arctic; and ecosystems and ecosystem change, including effects on algae, plankton, euphasiids, seabirds, grey and bowhead whales.

The moorings also provide a potential logistics platform for other projects. In the past the moorings have carried water sampling devices and various bio-optics systems. We are involved in on-going discussions to include whale acoustic sensors (proposed) and pCO2 sensors (in discussion) on future versions of the moorings.

6.3. Contributions to Human Resource Development

This project is a joint US-Russian collaboration. By joint nationality cruises and meetings, it promotes cultural exchange on scientific and humanitarian topics.

6.4. Contributions to Resources for Research and Education

The results are part of an interdisciplinary graduate course on the Changing Arctic Ocean, being taught by Woodgate and Deming, as a highlight for IPY (International Polar Year) activities. This course is also listed within the University of Washington Program on Climate Change.

6.5. Contributions Beyond Science and Engineering

Through outreach activities, the project has increased community awareness of the Arctic and Arctic research, for example via the University of Washington evening lecture series on the Arctic, and through a Polar Science Weekend at the Pacific Science Center, Seattle's main science museum. The work is part of the Arctic Observing Network and International Polar Year projects.