The Pacific Gateway to the Arctic: Recent change in the Bering Strait - observations, drivings and implications

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Recent Change in the Bering Strait
New Climatology and Bering Strait products
The long-sought “Pacific-ARCTIC” pressure head forcing
The Bering Strait, ... on a good day

- is an integrator of the properties of the Bering Sea
- dominates the water properties of the Chukchi Sea

~ 85 km wide, ~ 50 m deep
- divided into 2 channels by the Diomede Islands
- split by the US-Russian border
- ice covered ~ Jan - April

Only oceanic gateway between the Pacific Ocean and the Arctic Ocean

LOCALLY:

8th July 2010 Ocean Color oceancolor.gsfc.nasa.gov (from Bill Crawford)
... influences
~ half of the Arctic Ocean

Heat to melt ice
In spring, trigger western Arctic melt onset
Year-round subsurface heat source in ~ half of Arctic
(Paquette & Bourke, 1981; Ahlnäs & Garrison, 1984; Woodgate et al, 2010; 2012)

Important for Marine Life
Most nutrient-rich waters entering the Arctic
(Walsh et al, 1989)

Impacts Global climate stability
Doubling of flow affects Gulf Stream, overturning circulation
(Wadley & Bigg, 2002; Huang & Schmidt, 1993; DeBoer & Nof, 2004; Hu & Meehl, 2005)

Significant part of Arctic Freshwater Budget
~ 1/3rd of Arctic Freshwater
Large (largest?) interannual variability
(Wijffels et al, 1992; Aagaard & Carmack, 1989; Woodgate & Aagaard, 2005)

Important for Arctic Stratification
In winter, Pacific waters (fresher than Atlantic waters) form a cold (halocline) layer, which insulates the ice from the warm Atlantic water beneath

Figure from Woodgate, 2013, Nature Education
Overview of Bering Strait measurements

Early 1990s, 2004-2006
== 1+ moorings also in Russian waters.

2007-2011/2012
== ~ 8 moorings (including upper layer) in “high-resolution” US-Russian array

2012-present
== 3 moorings (“monitoring array”) all in US waters (A2, A4, and A3 “climate”)

NSF-AON Bering Strait Moorings 2014 - 2018

== 3 moorings in US waters to measure
- water and ice properties ~ hrly year-round
- volume, freshwater and heat fluxes
- seasonal and interannual change
- Total flow from climate site A3 + A4 Alaskan Coastal Current

= Velocity (from ADCP) at multiple depths from bottom to near surface

= Lower (~40m) and upper (~15m) layer temperature and salinity

= Sea-ice velocity and thickness

Moorings also carry
- marine mammal recorders (Stafford)
- opportunistic chemistry sensors (e.g., Juraneck)

Annual servicing

Continuity of this now 28+year Arctic Ocean time-series at a time of critical system change
Funded to recovery in 2018; new proposal in review for 2018 onwards
BERING STRAIT: PACIFIC GATEWAY TO THE ARCTIC

- Mooring Data Archive  For Cruise data (CTD etc), go here

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OVERVIEW
- Data Overview
- Research Overview
- Known Data Issues
- Citation for the data
- Bering Strait homepage

DATA FILES
- Links by year to data in ascii format, readme and archiving information

DATA PRODUCTS
- Processed Annual Means (properties and fluxes)
- Processed Monthly Means (properties and fluxes)
- Plots (1990-2002, later plots are in cruise reports)
- Links to cruise reports

Overview: This site contains data from mooring sites in the Bering Strait region, deployed from 1990 to present day, under various funding sources. Not all moorings are deployed all years. Data are generally from ca. 10m above bottom, as discussed in the header to the data files.

For research overview, please see two recent review papers:


And other papers, available on the Bering Strait website.

*** PLEASE QUOTE THESE CITATIONS WHEN PUBLISHING RESULTS USING THESE DATA ***
Increases in the Pacific inflow to the Arctic from 1990 to 2015, and insights into seasonal trends and driving mechanisms from year-round Bering Strait mooring data

Woodgate, R.A., 2018, Progress in Oceanography

**HIGHLIGHTS**

- The Bering Strait inflow to the Arctic increased from 2001 (~0.7Sv) to 2014 (~1.2Sv)
- This is due to increasing far-field, pressure-head forcing, not local wind changes
- Concurrently heat and freshwater fluxes strongly increased (3-5x10²⁰J, 2300-3500km³)
- Seasonal data show:
  - winter freshening,
  - early summer warming,
  - summer/fall flow increase
- We present a new climatology (1Sv) for the strait, including seasonality for heat and freshwater
A new Bering Strait Seasonal Climatology for the 2003-2015, including the Alaskan Coastal Current and stratification

* For 2000s, annual average ~ 1.0Sv (not 0.8Sv of 1990-2004 climatology)

Woodgate, 2018, PiO
Interannual Change in thirty-day smoothed data

Within each set:

Blue = cold, salty, low transport

Red = warm, fresh, high transport

Brown = not extreme

Woodgate, 2018, PiO
Interannual Change – velocity increasing

**Annual mean transports:**

= Greater than 0.8Sv climatology

Since 2002, all except 2 years above 0.8Sv

= Annual Mean:
  2001: 0.7 Sv; 2014 = 1.2 Sv
  change in flushing time of Chukchi from 7.5 – 4.5 months

= Significantly increasing trend

= More stronger flow events

= Velocity mode:
  low yrs: < 25 cm/s; high yrs: ≥40cm/s
  ~ 150% increase in kinetic energy

No trend in Alaskan Coastal Current (ACC)

black=A3, red=A2, blue=A1

Woodgate, 2018, PiO
Annual mean temperature
- significant but weak warming
(since 2002, most years >0ºC)

Timing of warm (>0ºC) waters:
- arrival earlier (~1 day/yr)
- departure – no significant trend

No trend in Alaskan Coastal Current

Woodgate, 2018, PiO
Interannual Change – freshening (weak, \textit{in the annual mean})

Annual mean salinity
- significant, but weak freshening
  (if include 1991)

\textbf{No trend in Alaskan Coastal Current}

Woodgate, 2018, PiO
Interannual Change – Fluxes in an Arctic context

**Volume Flux** ~ 0.7-1.2Sv
(cf Fram Strait ~ 7Sv)

**Heat Flux** ~ 3-6x10^{20}J
~ 1/3^rd of Fram Strait heat
~ enough to melt 1-2x10^6km^2 1m ice
(summer Arctic ice extent 4-6x10^6km^2)
~ same as solar input to Chukchi
~ 2-4W/m^2 in Arctic (Surface Net ~ 2-10W/m^2)
~ trigger for Arctic Sea ice melt

**Freshwater Flux** ~ 2500-3500km^3
~ 1/3^rd Arctic Freshwater inflow
Greatest source of interannual variability

Heat relative to -1.9°C,
Freshwater relative to 34.8psu

Woodgate et al, 2010, GRL; Woodgate, 2018, PiO
As many have done, from DATA we seek a fit of the form:

\[
\text{Water Velocity} = m \times \text{Local Wind} + \text{Offset}
\]

Far-Field Forcing
i.e., the “Pressure Head”
(Bit we can’t explain with local wind)

Pick the wind direction which best correlates with the flow
~ 330°, i.e., ALONG strait
Best with W, not W²

But what drives change in annual mean?
~ 1/3rd due to changes in wind
~ 2/3rds due to Pressure Head
(i.e., can’t infer from the wind)

Woodgate et al, 2012, GRL
As many have done, from DATA we seek a fit of the form:

$$\text{Water Velocity} = \text{mmm} \times \text{Local Wind} + \text{Offset}$$

Far-Field Forcing
i.e., the
"Pressure Head"
(Bit we can’t explain
with local wind)

Pick the wind direction which best correlates with the flow
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What is driving the interannual change?
- Increase trend is in Far-Field (Pacific-Arctic) pressure head forcing
- No significant trend in wind (using NCEP, JRA, ERA products)

But for something this seasonal, is understanding the annual mean really helping us?
First – seasonal change in salinity

For each month …

Linear trend of monthly mean over years (Italic = not significant at 95%)

Woodgate et al, 2005, GRL
Trends in Salinity in different seasons

Statistical significant freshening in winter/spring

Summarize those trends by month for different periods
- blue 1990-2016
- green 1998-2016
- red 2000-2016

Only SOME months have significant trend
Seasonal Trends in salinity, temperature and volume

Winter Freshening
Less ice formation?
Earlier ice melt?
More river water?

Warming, esp in early summer
Earlier onset of warming
(Winter warming due to freshening)

Increasing flow in summer

Grey=climatology
Colors = individual years

Trends for different periods
- blue 1990-2016
- green 1998-2016
- red 2000-2016
Interannual change in monthly Pressure Head offset, PH

Increasing trend in PH over almost all months

Several indications that PH is driving Bering Strait increase
A sea-surface slope \((2.6 \times 10^{-6})\) between the Pacific and the Arctic, magnitude assumed by balancing with bottom friction in the strait (Coachman and Aagaard, 1966)

A steric sea surface height difference of:

\[ \ldots \sim 0.5m \text{ assuming a level of no motion of } 1100m \text{ from the Arctic to the Bering, set up by atmospheric transport of water} \) (Stigebrandt, 1984)

\[ \ldots \sim 0.7m \text{ assuming a level of no motion of } 800m \text{ from the Arctic to the Bering} \) (Aagaard, et al, 2006)

A sea surface height difference set up by global winds driving water north, Pacific (DeBoer and Nof, 2005)

But what does it look like?

With a few exceptions (Nguyen et al, 2012), models often do poorly in recreating Bering Strait throughflow variability (Clement-Kinney et al, 2014)
What IS this pressure head forcing?

Satellite measured (GRACE) Ocean Bottom Pressure anomalies – monthly means (2005-2010)
(Peralta-Ferriz & Woodgate, 2017)

WHICH pressure head?

These are anomalies, not total
Does Ocean Bottom Pressure (OBP) correlate with the flow?

Northward flow and especially pressure head part of flow correlate well with:
- high OBP over the Bering Sea shelf
- low OBP over the East Siberian Sea

Flow through channel with rotation (Toulany & Garrett, 1984)
Is this a common Ocean Bottom Pressure (OBP) pattern?

First EOF of OBP ~ 44% monthly OBP variance

Timeseries of that EOF correlates well (r~0.59) with Pressure head flow

EOF1 dominated by East Siberian Sea variability (not Bering Sea variability)

Peralta-Ferriz & Woodgate, 2017
That was all year – what about seasons?

**SUMMER**

- 65% of OBP variance
- v highly correlated with flow

**WINTER**

- 41% of OBP variance

**Correlation of PC1 and ..**
- northward velocity ~ 0.25
- Pressure head flow ~ 0.31

**Correlation of PC2 and ..**
- northward velocity ~ 0.57
- Pressure head flow ~ 0.50

Only one significant EOF, low in East Siberian Sea
- 65% of OBP variance
- v highly correlated with flow

TWO significant EOFs,
1) low in East Siberian Sea
2) high on Bering Sea Shelf
- EOF2 better correlated with flow

Pattern (low East Siberian Sea, High Bering Sea shelf) same.

In winter, Bering Sea also important

Peralta-Ferriz & Woodgate, 2017
What drives this Ocean Bottom Pressure (OBP) pattern?

**Peralta-Ferriz & Woodgate, 2017**

**Diagram (d)**: YEAR-ROUND SLP correlated with:
- Hi Arctic SLP
- Northward BS flow
- Westward Winds on Arctic Coast
- Offshore Ekman lowers SSH on ESS

**Diagram (e)**: YEAR-ROUND wind correlations:
- Hi Arctic SLP
- Northward BS flow
- Offshore Ekman lowers SSH on ESS

**Text**

**ARCTIC variability is the dominant driver of the flow variability**
Driving force by season

**SUMMER**
Strait winds weak
1 dominant EOF of OBP
** Flow driven by:
- Arctic low-East-Siberian-Sea mechanism

**WINTER**
Strait winds strong
2 dominant EOFs of OBP
** Flow driven by 3 things:
- northward wind in strait
- high-Bering-Sea-Shelf mechanism
- Arctic low-East-Siberian-Sea mechanism
Bering Strait Mooring Program – 2017 Updates
Rebecca Woodgate University of Washington, Seattle, USA

Our July 2017 Norseman 2 cruise recovered & redeployed the 3 Bering Strait moorings, and took CTD sections, finding the Chukchi remarkably warm.

Recovered data show:

**2016/2017**
Remarkably warm & fresh

<table>
<thead>
<tr>
<th>Year</th>
<th>Trans (Sv)</th>
<th>Temp (°C)</th>
<th>Sal (psu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
<td><img src="image3.png" alt="Graph" /></td>
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<tr>
<td>2017</td>
<td><img src="image4.png" alt="Graph" /></td>
<td><img src="image5.png" alt="Graph" /></td>
<td><img src="image6.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

Color=2016 or 2017 30 day smoothed data. Black = climatology; Grey=all past years

* Oct 2016 & June 2017 both 3°C warmer than climatology
* ~20 day late cooling in 2016
* ~15 day early warming in 2017
* Salinities 0.5-1psu fresher than climatology

Flux increases
Winter freshening
Earlier warming

Recent papers document:
* trends in seasonal changes;
* flow increase driven by pressure head, far-field forcing;
* new 1Sv climatology for 2000s;
* patterns of the pressure head forcing, finding flow dominantly driven from the Arctic

Woodgate 2018 PiO
Peralta-Ferriz & Woodgate 2017 GRL

Find data, reports and papers at:
psc.apl.washington.edu/Bstrait.html

Trans ≥1Sv; FW~3500km³/yr (cf 34.8psu)
Heat ~5x10²⁰J/yr ~15TW (cf -1.9°C)