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

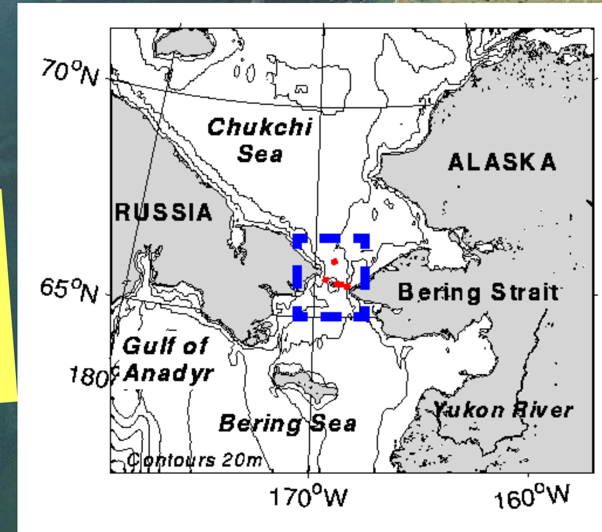
New Climatology and Bering Strait products

The long-sought “Pacific-ARCTIC” pressure head forcing

NASA

The Bering Strait, *… on a good day*

Only oceanic gateway between the Pacific Ocean and the Arctic Ocean



Russia

~ 85 km wide, ~ 50 m deep

- divided into 2 channels by the Diomede Islands

- split by the US-Russian border

- ice covered ~ Jan - April

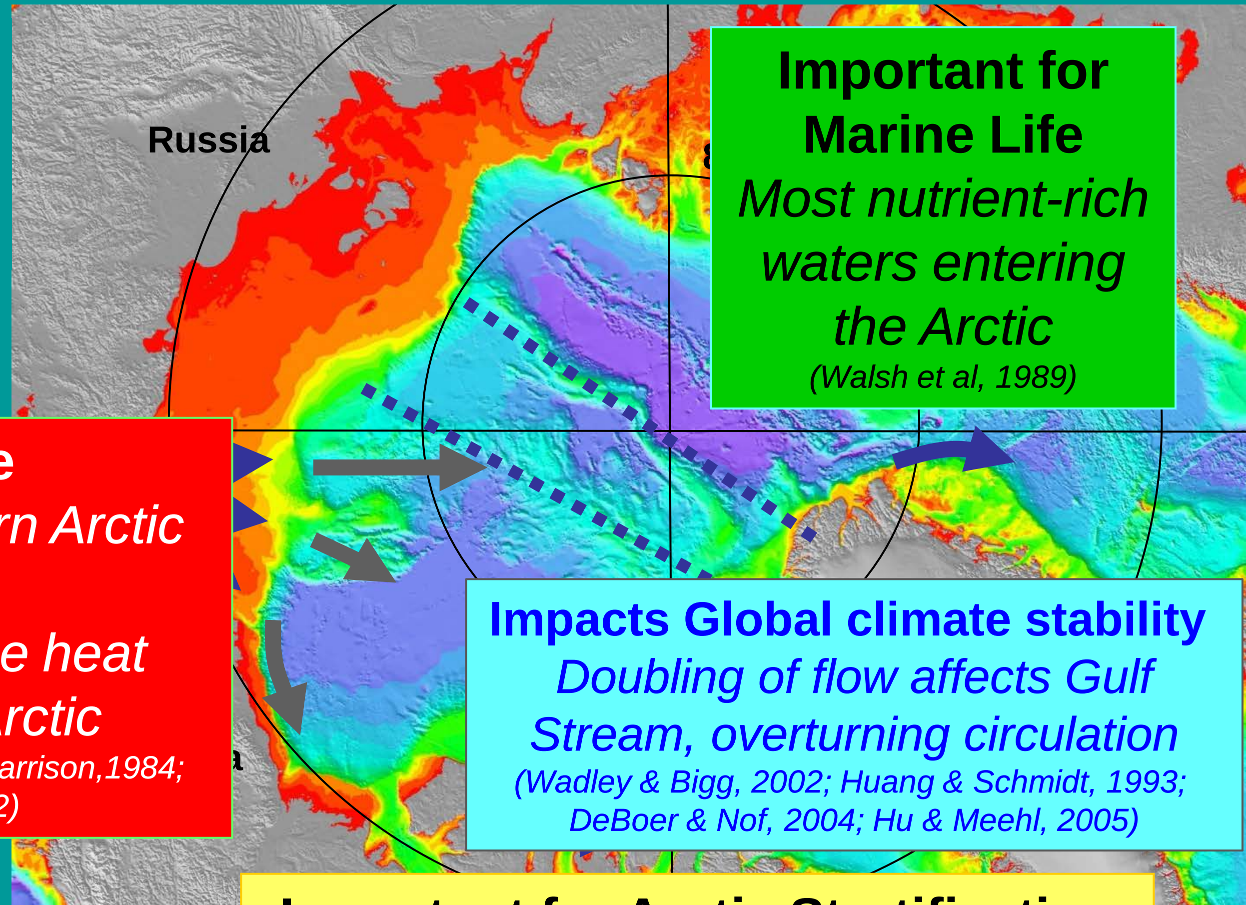
LOCALLY:

- is an integrator of the properties of the Bering Sea

- dominates the water properties of the Chukchi Sea

8th July 2010 Ocean Color
oceancolor.gsfc.nasa.gov
(from Bill Crawford)

... influences ~ half of the Arctic Ocean



Important for Marine Life

Most nutrient-rich waters entering the Arctic

(Walsh et al, 1989)

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)

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)

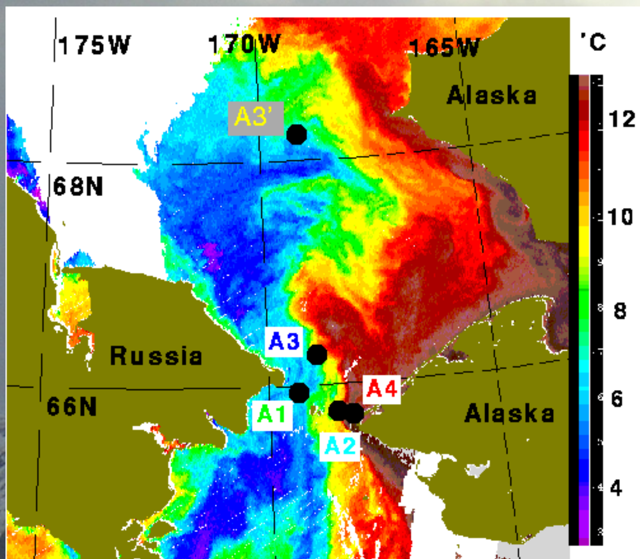
Important for Arctic Stratification

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

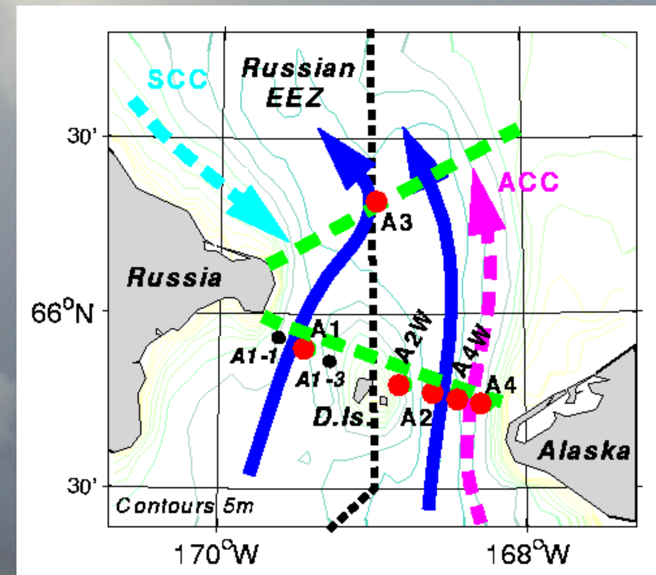
(Shimada et al, 2001, Steele et al, 2004)

Figure from Woodgate, 2013, Nature Education

Overview of Bering Strait measurements



MODIS SST 26th Aug 2004



<u>1990 - present</u>
== year-round moorings in
US mid-channel (A1, A2, A3, A3')
== mostly near bottom
== 2001 started measuring the
Alaskan Coastal Current with A4.

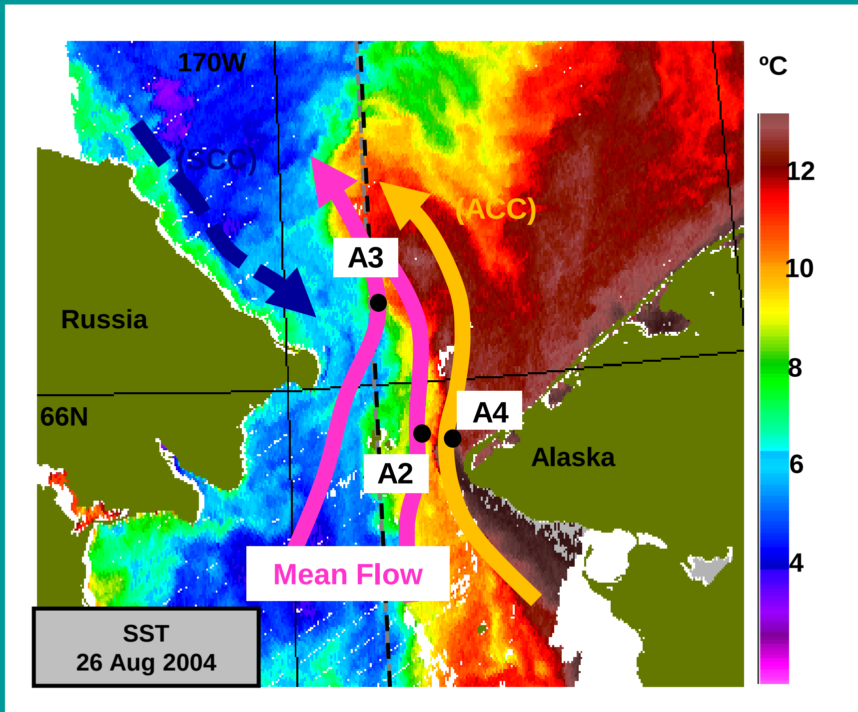
<u>Early 1990s, 2004-2006</u>
== 1+ moorings also in Russian waters.

<u>2007-2011/2012</u>
== ~ 8 moorings (including upper layer) in
"**high-resolution**" US-Russian array

<u>2012-present</u>
== 3 moorings ("**monitoring array**") all
in US waters (A2, A4, and A3 **"climate"**)

Woodgate et al, 2015, Bering Strait Synthesis,
RUSALCA special issue of Oceanography, doi:10.5670/oceanog.2015.57

NSF-AON Bering Strait Moorings 2014 - 2018



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

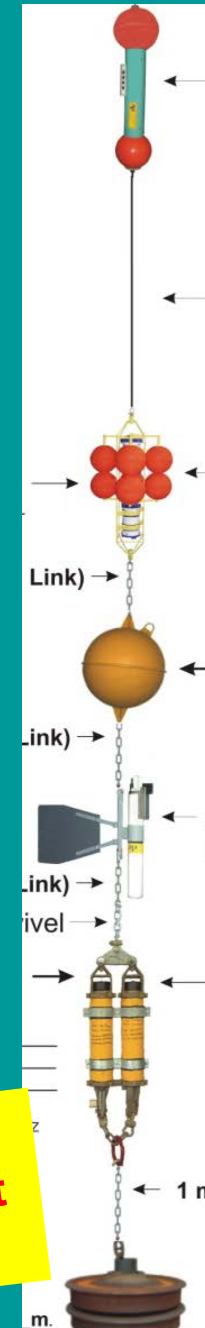
= ***Lower (~40m) and upper (~15m) layer*** **temperature and salinity**

= **Sea-ice velocity and thickness**

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

Annual servicing

== 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**



Your instrument here?

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

Data, Data …

psc.apl.washington.edu/BeringStrait.html

BERING STRAIT: PACIFIC GATEWAY TO THE ARCTIC

- Mooring Data Archive

For Cruise data (CTD etc), go here

ONR High Latitude
NSF-Polar Programs
NOAA Arctic Research
RUSALCA
Back to High Latitude Dynamics

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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
- Climatologies - 1990-2004 2003-2015
- 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:

Woodgate, R.A., 2018, 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, *Progress in Oceanography, 160, 124-154, doi:10.1016/j.pocean.2017.12.007*

Woodgate, R.A., K.M.Stafford and F.G.Prahl, 2015, A Synthesis of Year-round Interdisciplinary Mooring Measurements in the Bering Strait (1990-2014) and the RUSALCA years (2004-2011) *Oceanography, 28(3):46-67, doi:10.5670/oceanog.2015.57*

And other papers, available on the Bering Strait website.

*** ***PLEASE QUOTE THESE CITATIONS WHEN PUBLISHING RESULTS USING THESE DATA*** ***

Schematic of Mooring Locations and main flows

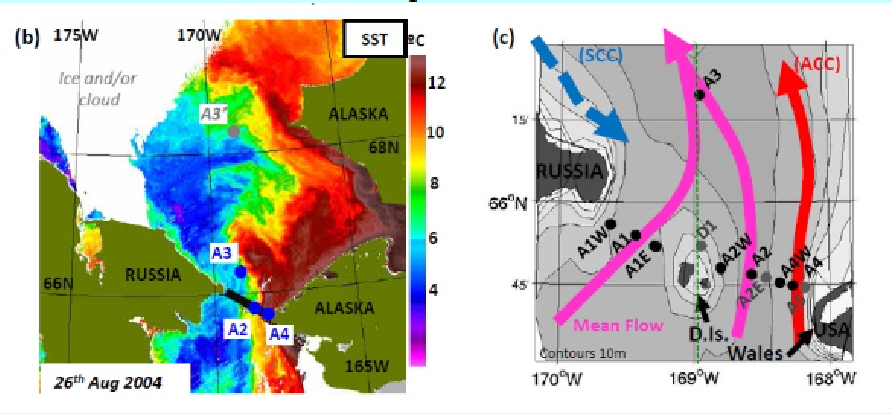
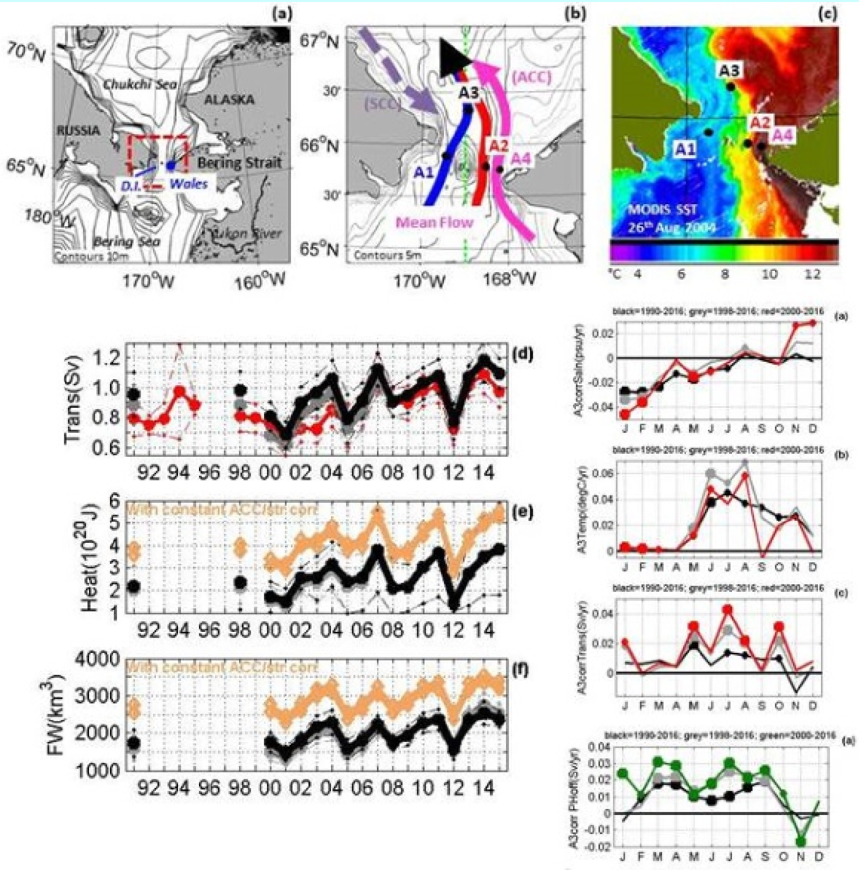


Figure from Woodgate et al, 2015, Oceanography, doi://10.5670/oceanog.2015.57



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

NSF (National Science Foundation) Polar Programs PLR-1304052
Part of the AON (Arctic Observing Network)

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 (3-5x10^{20}J, 2300-3500km^3)

- 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)*

Velocity (cm/s)

Transport (Sv)

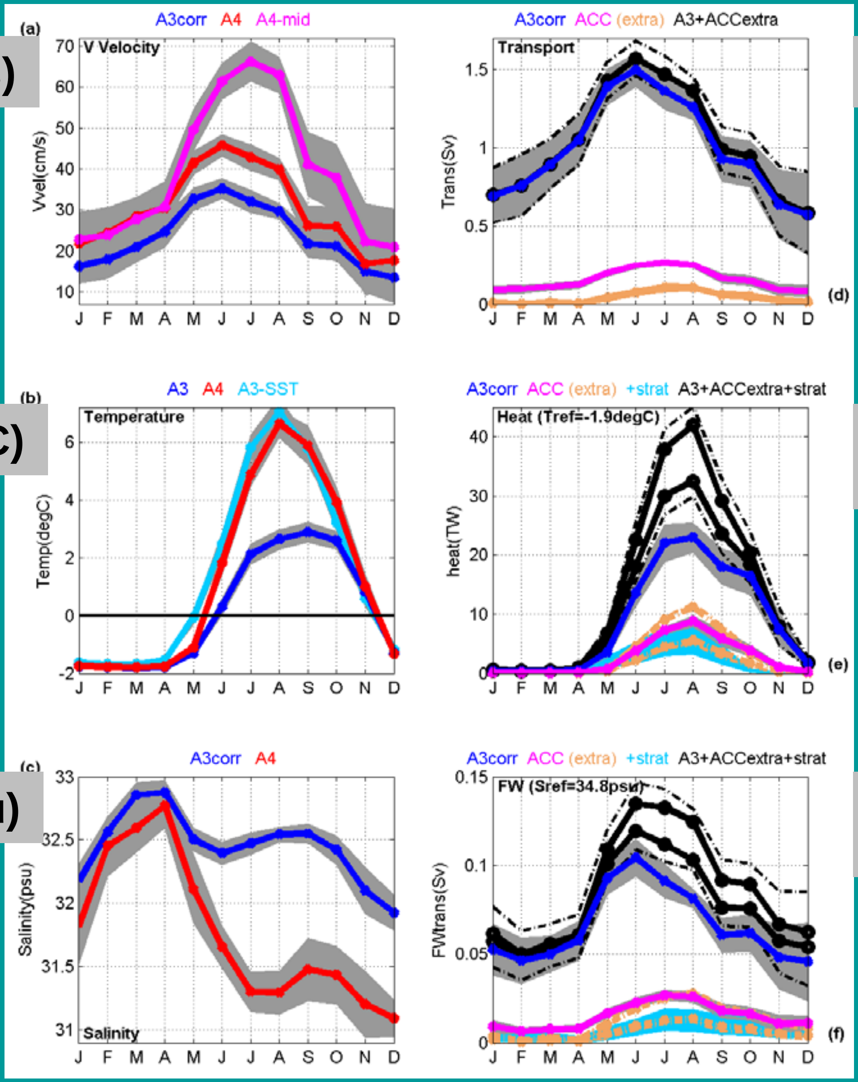
Blue=A3 Data ***Red=A4 Data***
Mag=Alaskan Coastal Current
Cyan=SST/Stratification
Black=All (incl ACC & stratification)

Temperature (°C)

Heat Flux (TW)
Tref=-1.9°C

Salinity (psu)

Freshwater Flux (Sv)
Sref=34.8psu

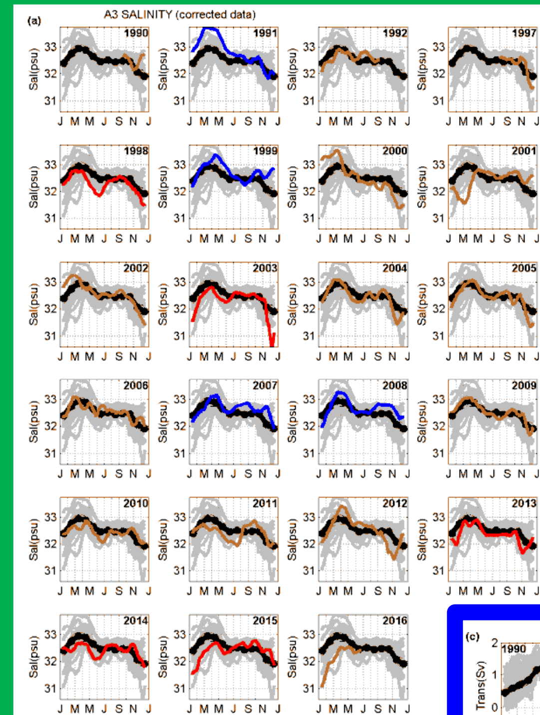


Woodgate, 2018, PiO

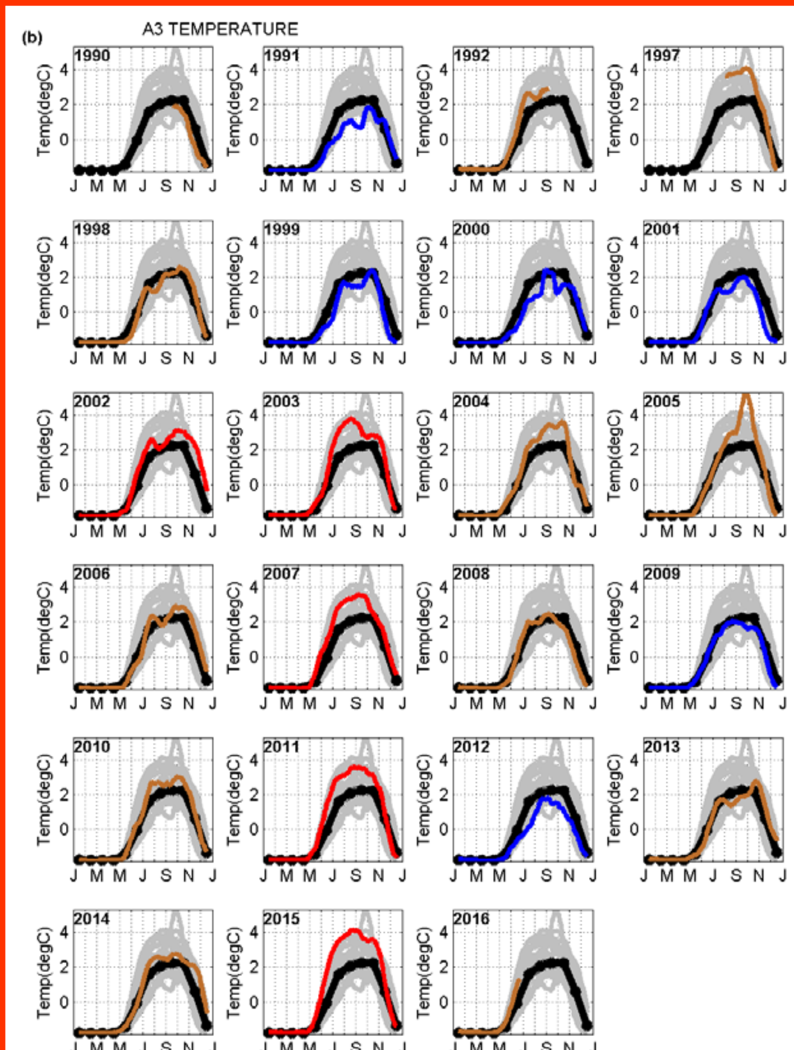
Interannual Change in thirty-day smoothed data

Woodgate, 2018, PiO

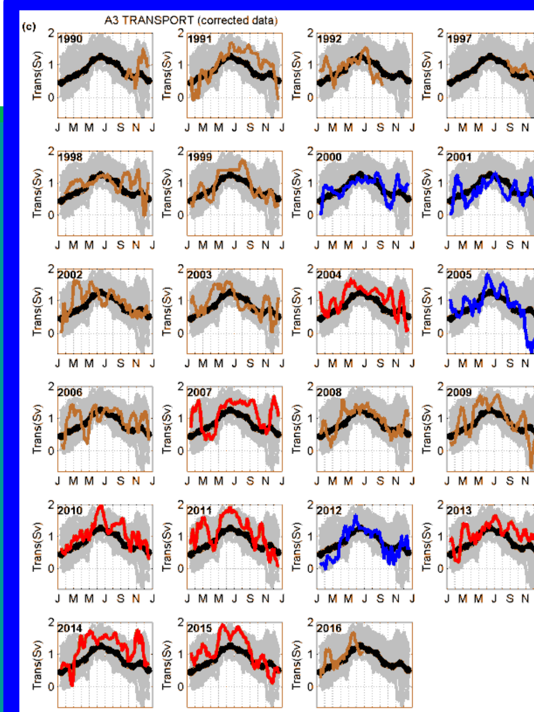
Corrected Salinity



Temperature



Transport



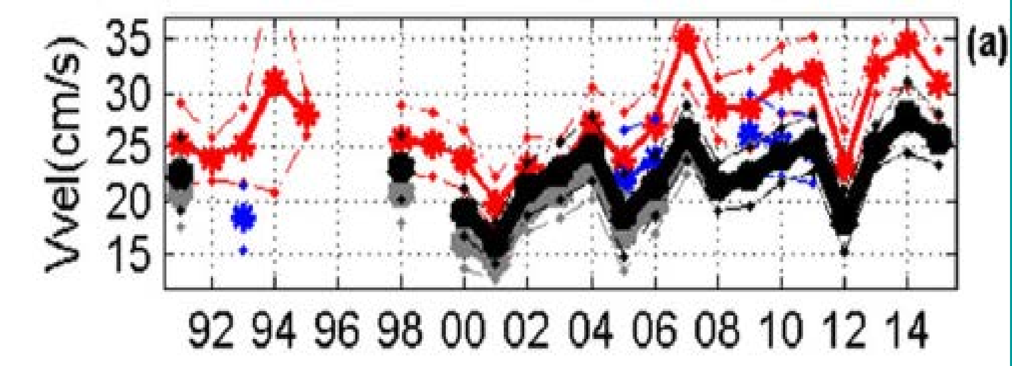
Within each set:

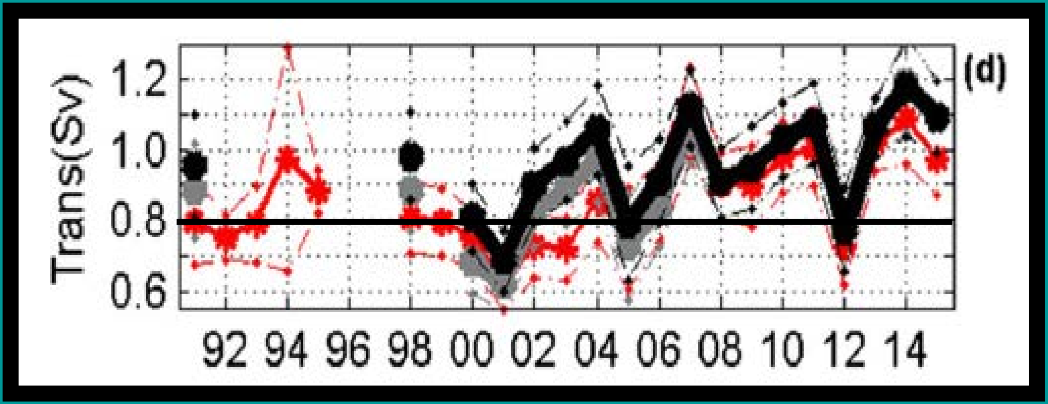
Blue = cold, salty, low transport

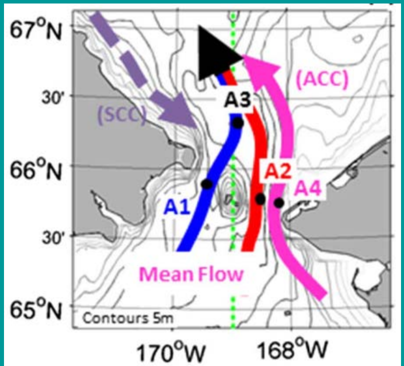
Red = warm, fresh, high transport

Brown = not extreme

Interannual Change – velocity increasing







black=A3,
red=A2,
blue=A1

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

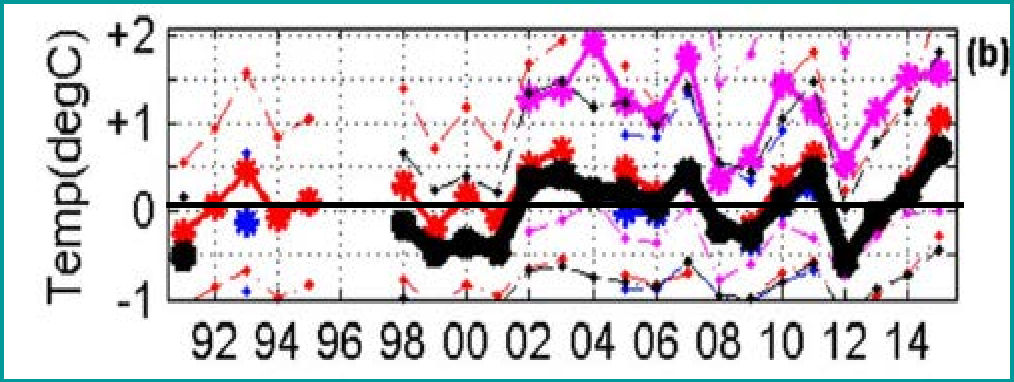
= More stronger flow events

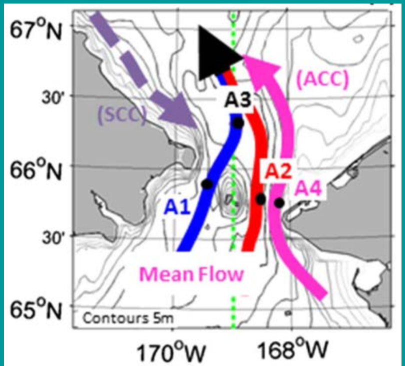
= Velocity mode:
low yrs: < 25 cm/s; high yrs: ≥40cm/s
~ 150% increase in kinetic energy

No trend in Alaskan Coastal Current (ACC)

Woodgate, 2018, PiO

Interannual Change – warming & earlier arrival



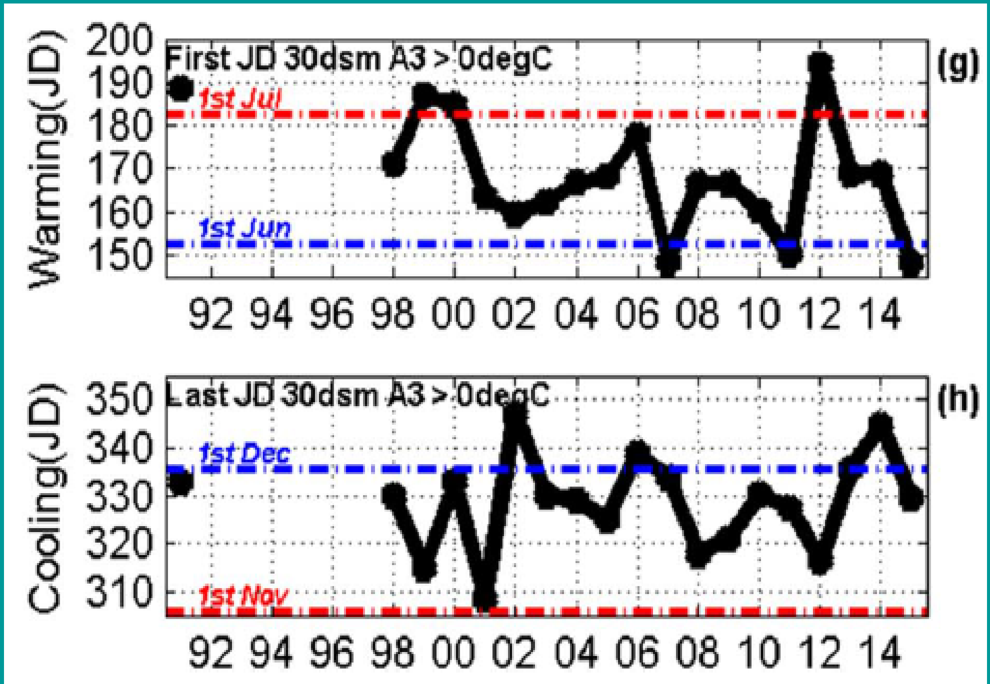


black=A3, red=A2, blue=A1, magneta=A4

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

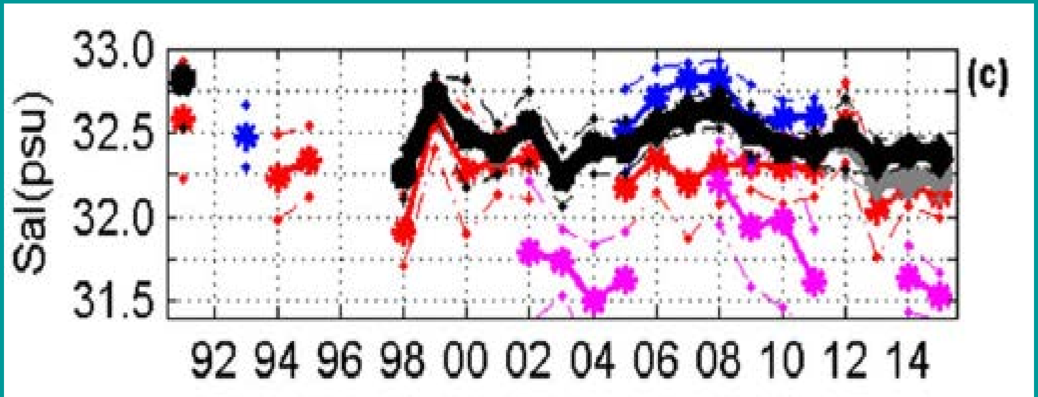
Timing of warm (>0ºC) waters:
- arrival earlier (~1 day/yr)
- departure – no significant trend

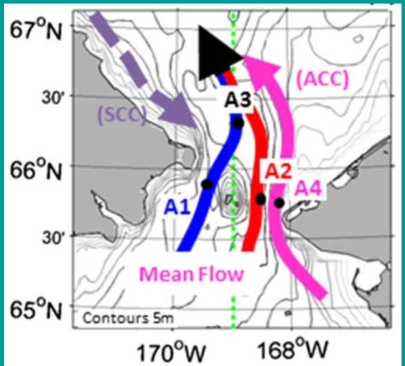
No trend in Alaskan Coastal Current



Woodgate, 2018, PiO

Interannual Change – freshening (weak, *in the annual mean*)





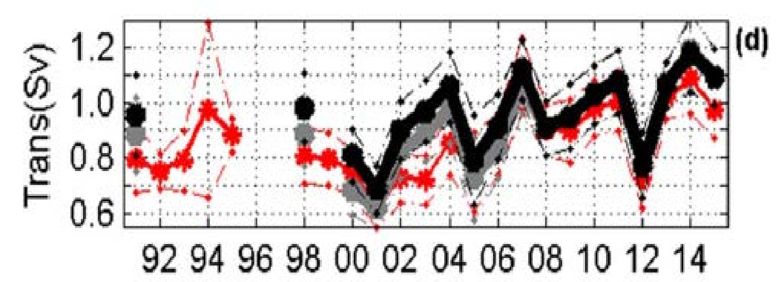
black=A3,
red=A2,
blue=A1
magneta=A4

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

No trend in Alaskan Coastal Current

Woodgate, 2018, PiO

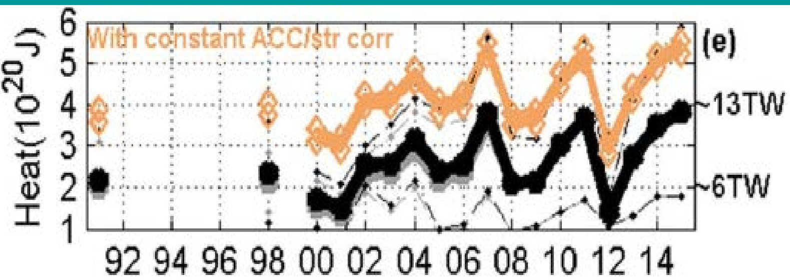
Interannual Change – Fluxes in an Arctic context



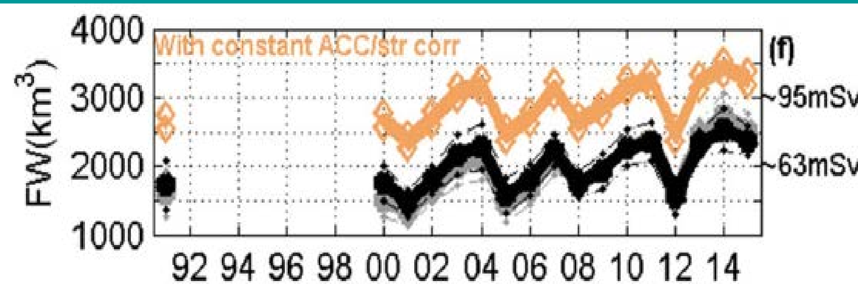
Volume Flux ~ 0.7-1.2Sv
(cf Fram Strait ~ 7Sv)

Significant interannual increases in Annual Mean Heat and Freshwater Fluxes (driven mostly by volume change)

strangely unsatisfying without some understanding



Heat Flux ~ 3-6x10^{20}J
~ 1/3rd of Fram Strait heat
~ enough to melt 1-2x10^{6}km^{2} 1m ice
(summer Arctic ice extent 4-6x10^{6}km^{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}
~ 1/3rd Arctic Freshwater inflow
Greatest source of interannual variability

Heat relative to -1.9^{o}C,
Freshwater relative to 34.8psu

Woodgate et al, 2010, GRL; Woodgate, 2018, PiO

What is driving the interannual change?

As many have done, from DATA we seek a fit of the form:

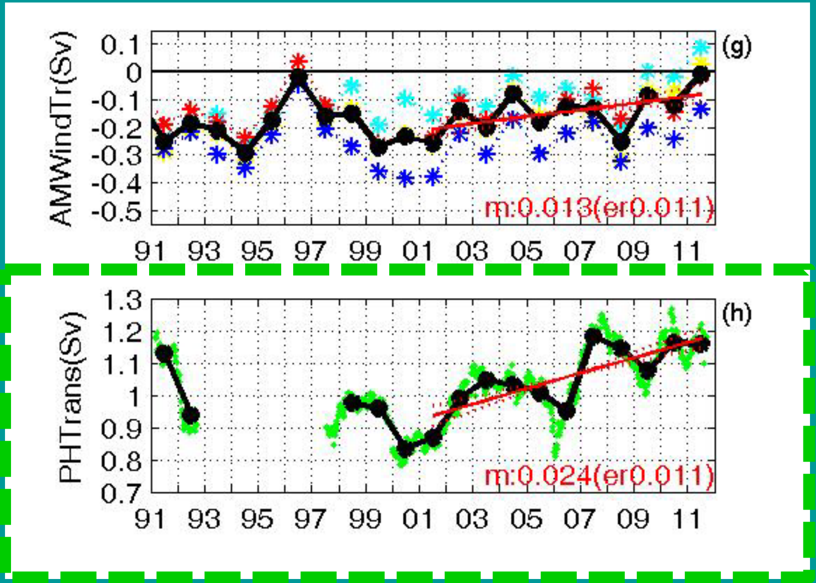
Water Velocity = mmm x Local Wind + Offset

Pick the wind direction which best correlates with the flow
~ 330°, i.e., ALONG strait
Best with W, not W^2

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

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



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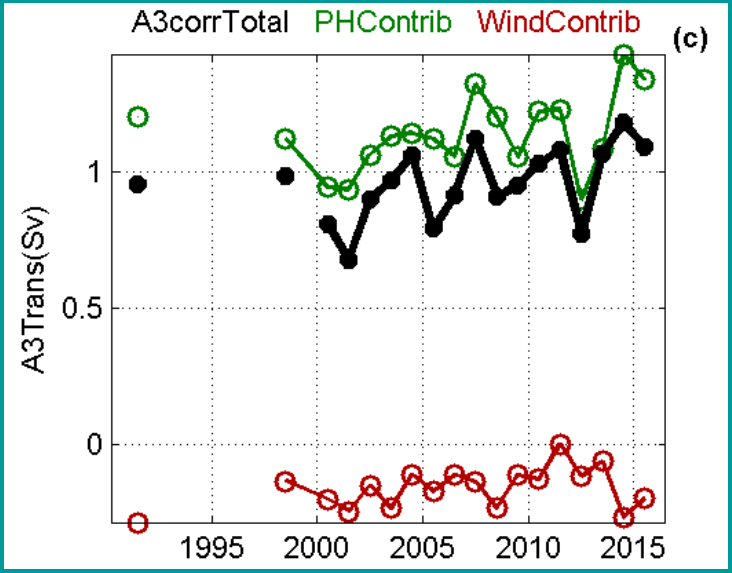


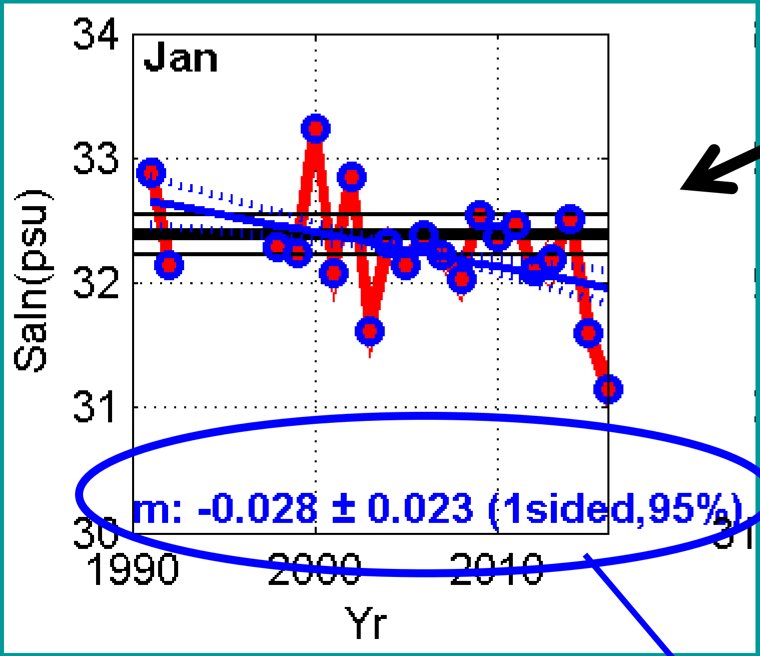
- Increase trend is in Far-Field (Pacific-Arctic) pressure head forcing

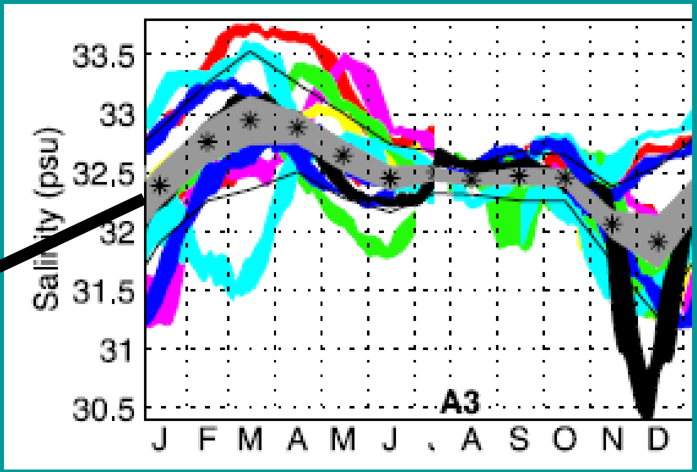
- No significant trend in wind *(using NCEP, JRA, ERA products)*

But for something this seasonal, is understanding the annual mean really helping us?

First – seasonal change in salinity

For each month …

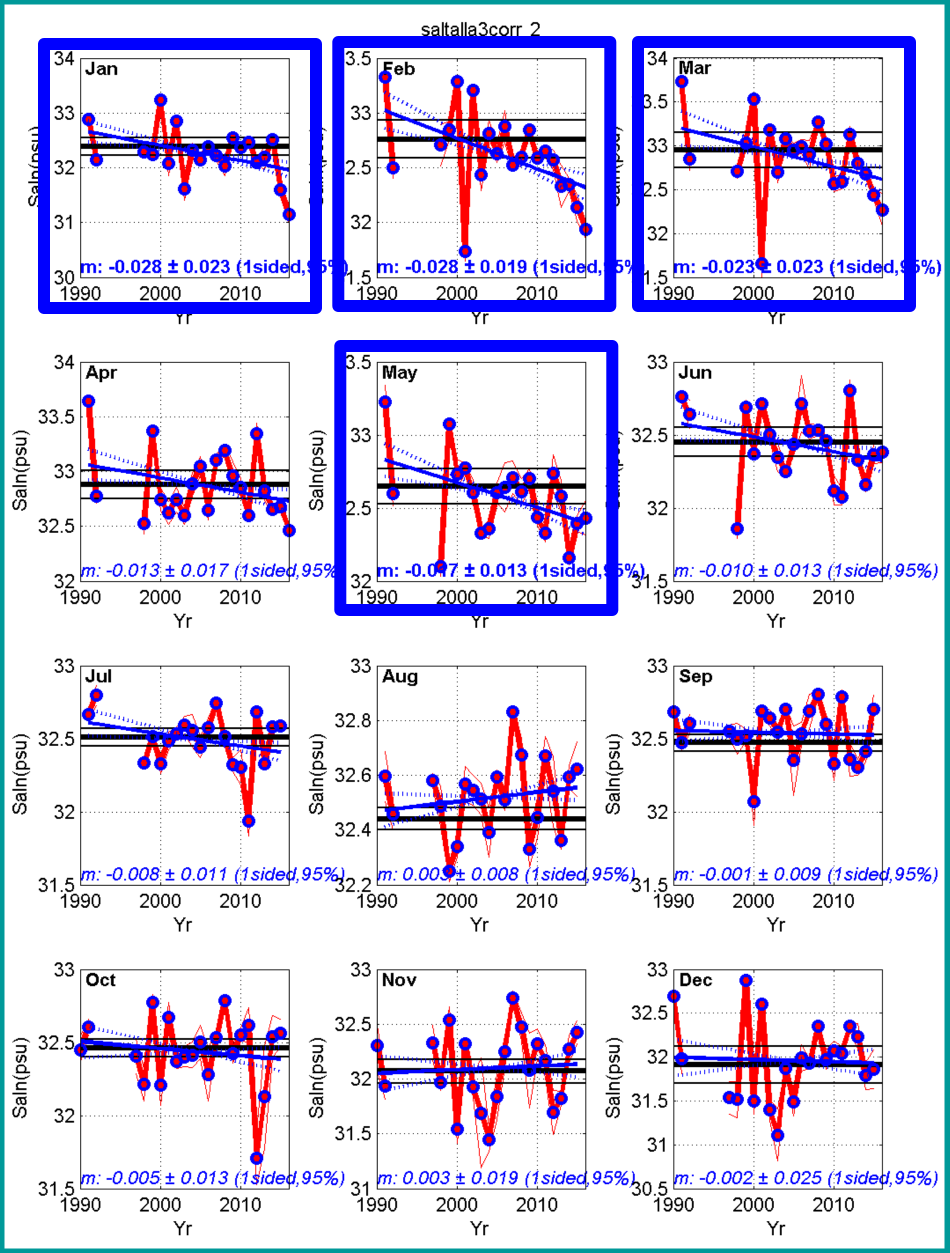




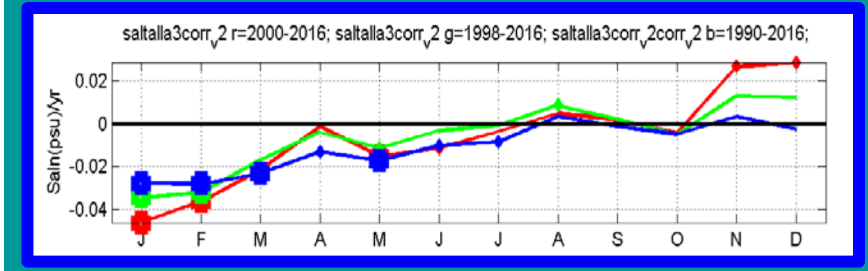
Woodgate et al, 2005, GRL

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

Trends in Salinity in different seasons



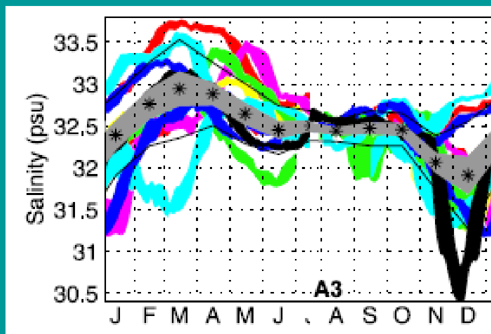
Statistical significant freshening in winter/spring

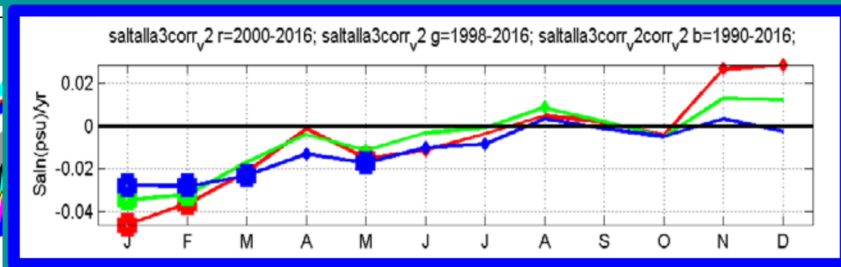


Only SOME months have significant trend

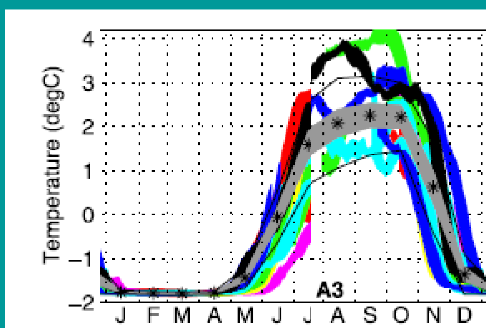
Summarize those trends
by month for different periods
- blue 1990-2016
- green 1998-2016
- red 2000-2016

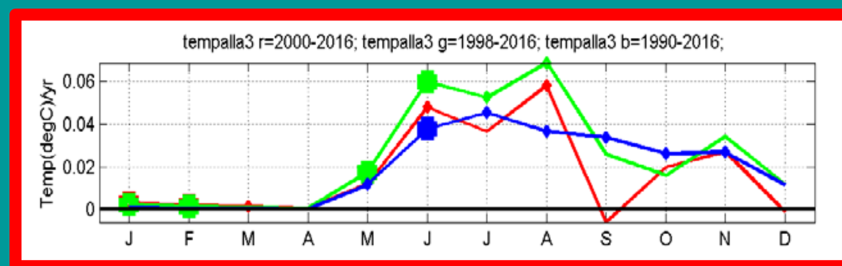
Seasonal Trends in salinity, temperature and volume



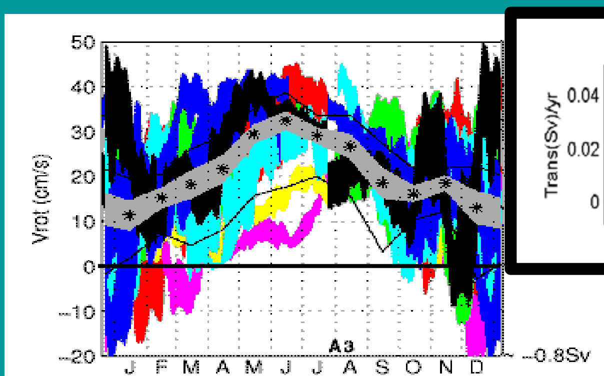


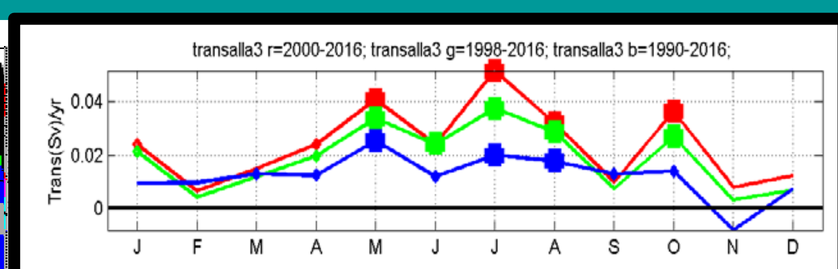
Winter Freshening
Less ice formation?
Earlier ice melt?
More river water?





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



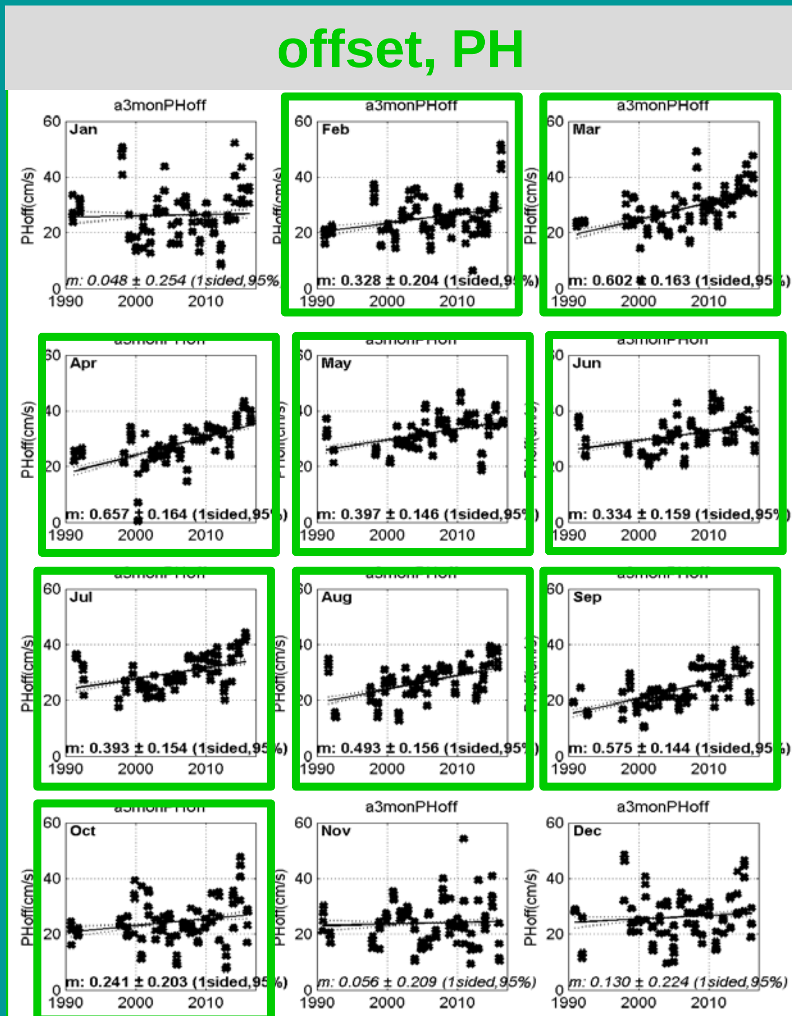


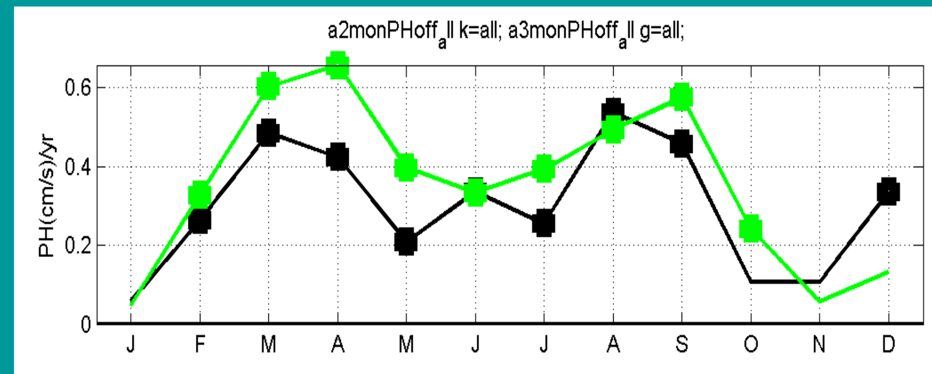
Increasing flow in summer

Grey=climatology
Colors = individual years

Trends for different periods
- blue 1990-2016
- green 1998-2016
- red 2000-2016

Interannual change in monthly Pressure Head





Increasing trend in PH over almost all months

Several indications that PH is driving Bering Strait increase

What IS this pressure head forcing?

A ***sea-surface slope (2.6 x10^{-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 :*

… ~ 0.5m ***assuming a level of no motion of 1100m*** *from the Arctic to the Bering, set up by atmospheric transport of water (Stigebrandt, 1984)*

… ~ 0.7m ***assuming a level of no motion of 800m*** *from the Arctic to the Bering (Aagaard, et al, 2006)*

Steric?

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

Global Winds?

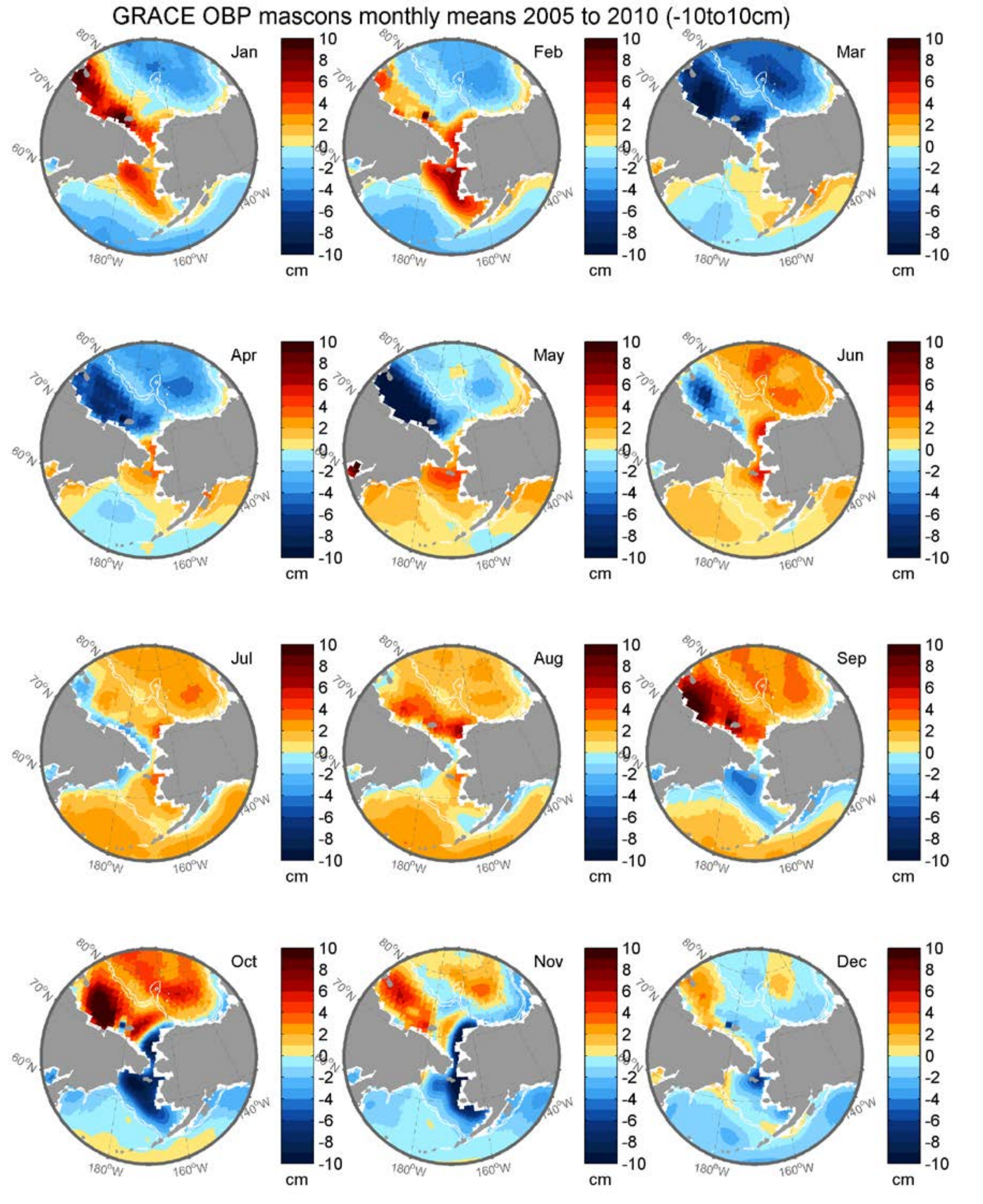
But what does it look like?

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)

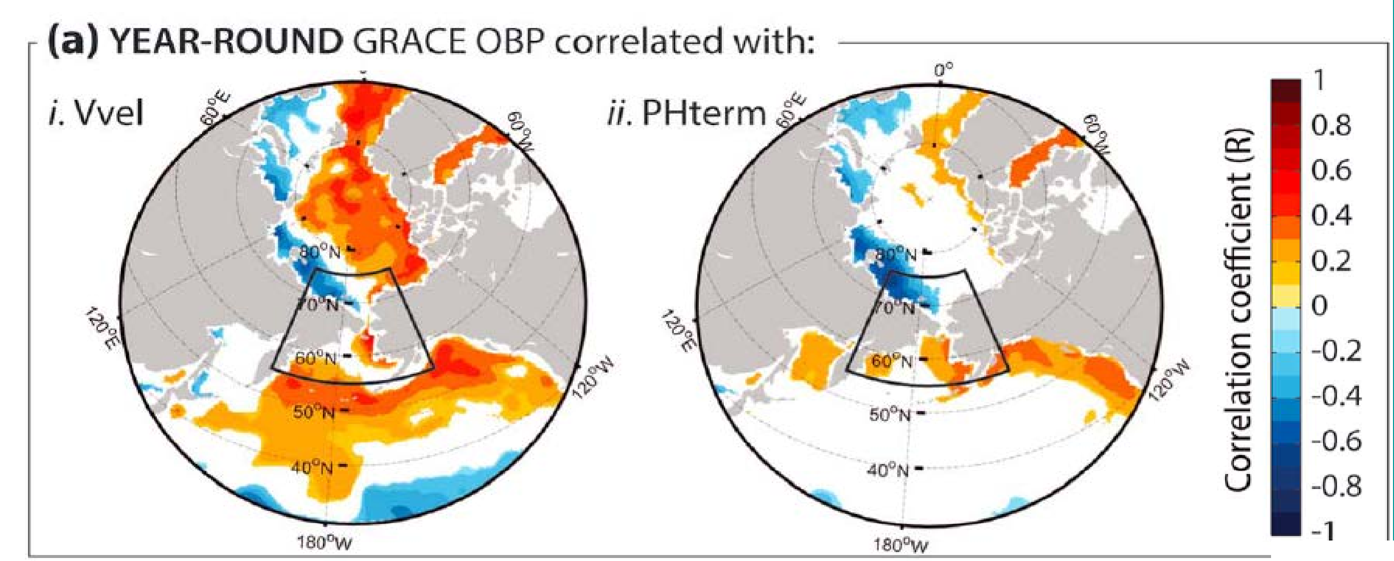
(Peralta-Ferriz & Woodgate, 2017)



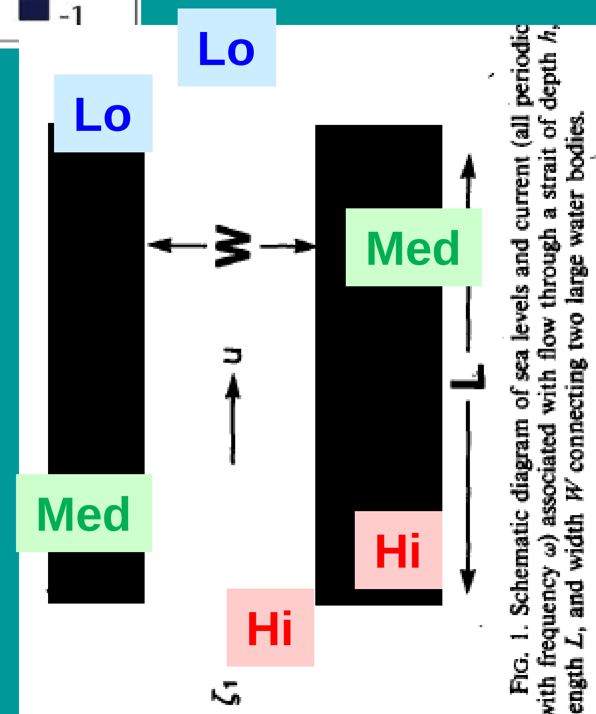
WHICH pressure head?

These are anomalies, not total

Does Ocean Bottom Pressure (OBP) correlate with the flow?



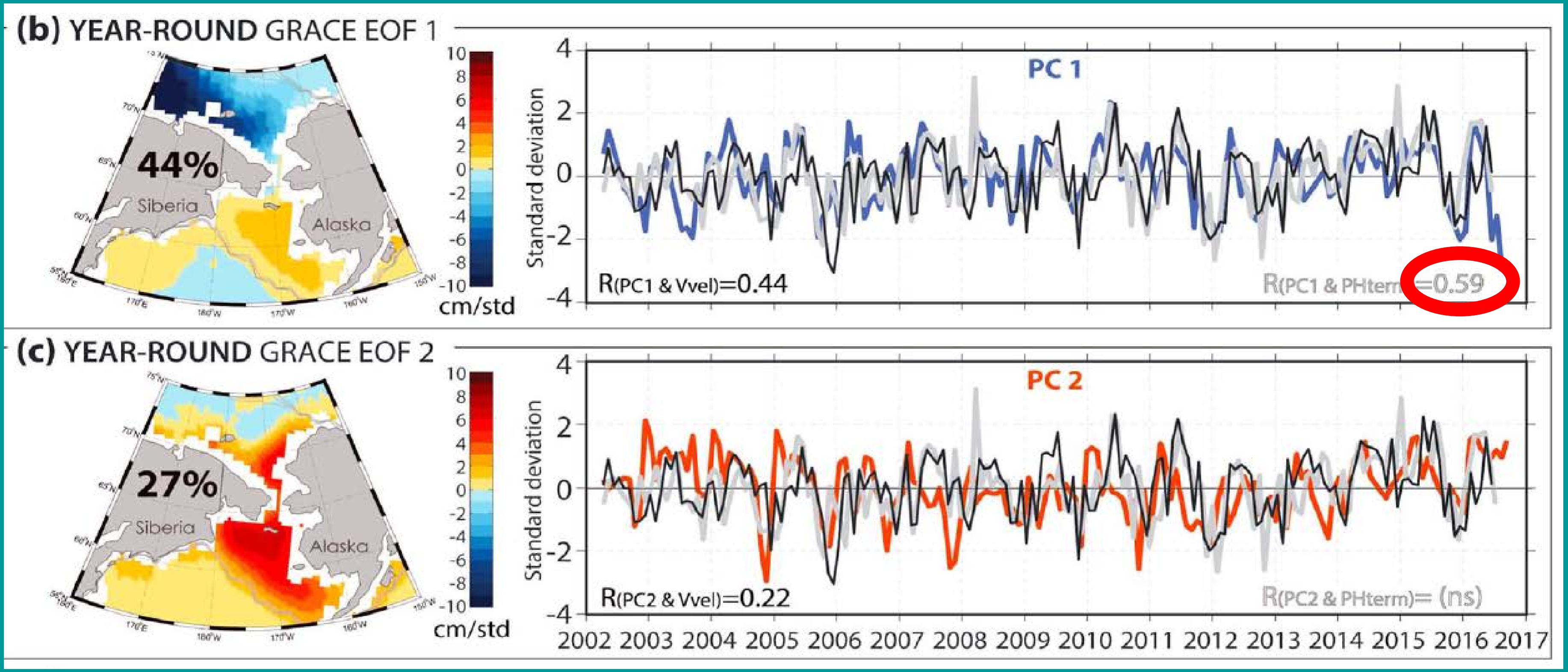
Flow through channel with rotation
(Toulany & Garrett,1984)



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

Peralta-Ferriz & Woodgate, 2017

Is this a common Ocean Bottom Pressure (OBP) pattern?



First EOF of OBP ~ 44% monthly OBP variance

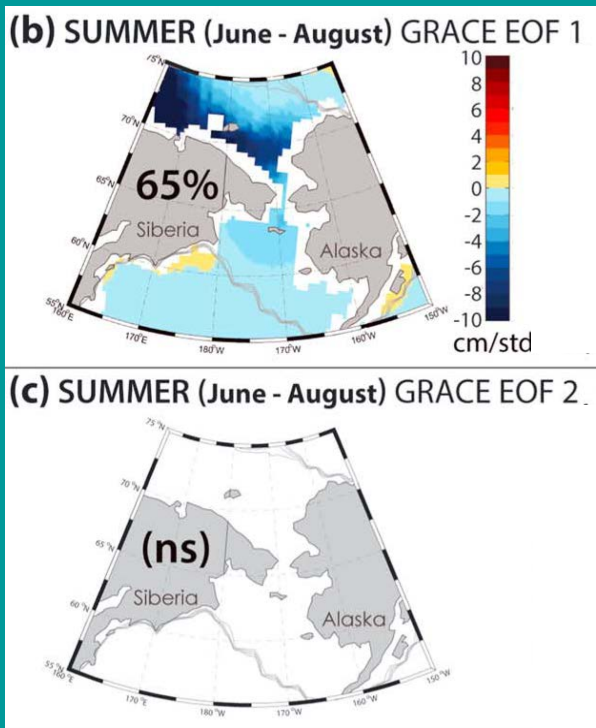
Timeseries of that EOF correlates well (r~0.59) with Pressure head flow

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

Peralta-Ferriz & Woodgate, 2017

That was all year – what about seasons?

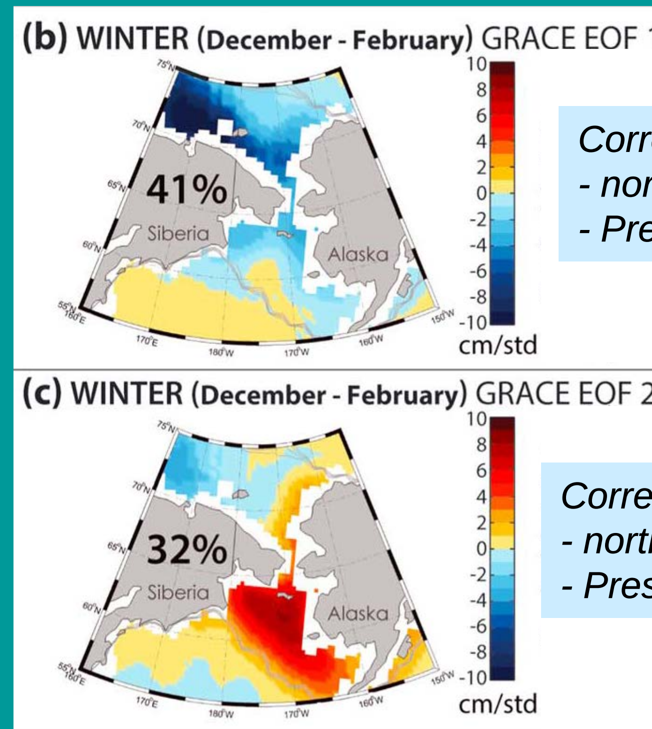
SUMMER



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

*Correlation of **PC1** and ..*
*- northward velocity ~ **0.81***
*- Pressure head flow ~ **0.84***

WINTER



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

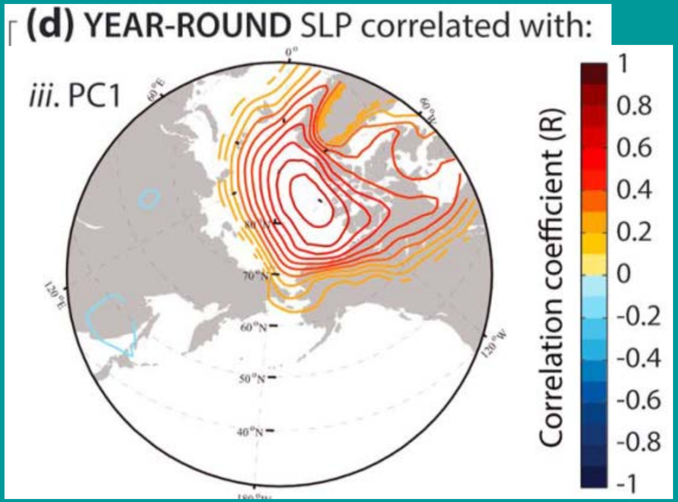
*Correlation of **PC2** and …*
*- northward velocity ~ **0.57***
*- Pressure head flow ~ **0.50***

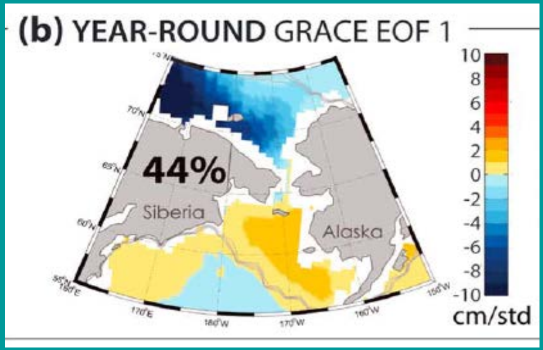
TWO significant EOFs,
1) low in East Siberian Sea
2) high on Bering Sea Shelf
- EOF2 better correlated with flow

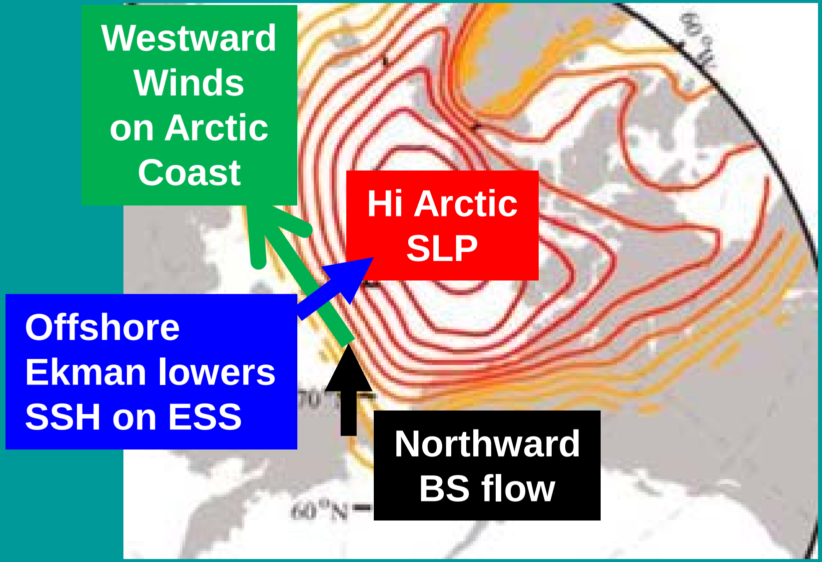
Peralta-Ferriz & Woodgate, 2017

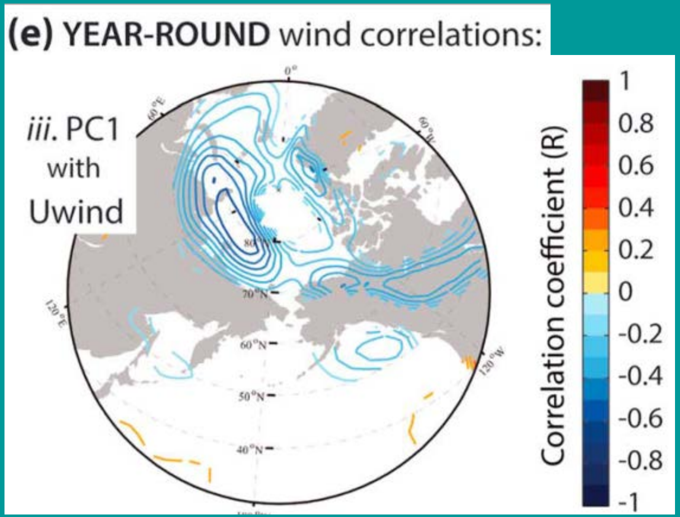
Pattern (low East Siberian Sea, High Bering Sea shelf) same.
In winter, Bering Sea also important

What drives this Ocean Bottom Pressure (OBP) pattern?





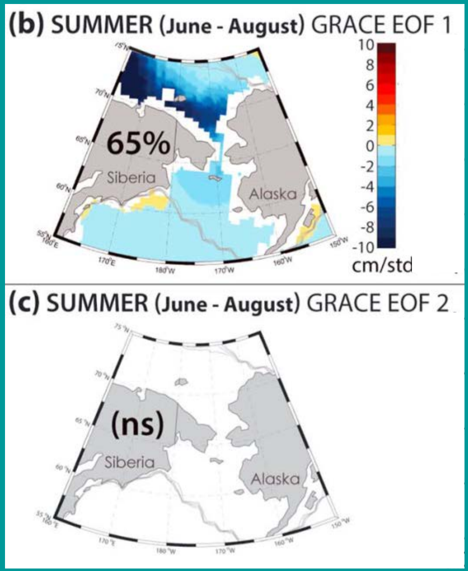




ARCTIC variability is the dominant driver of the flow variability

Peralta-Ferriz & Woodgate, 2017

Driving force by season



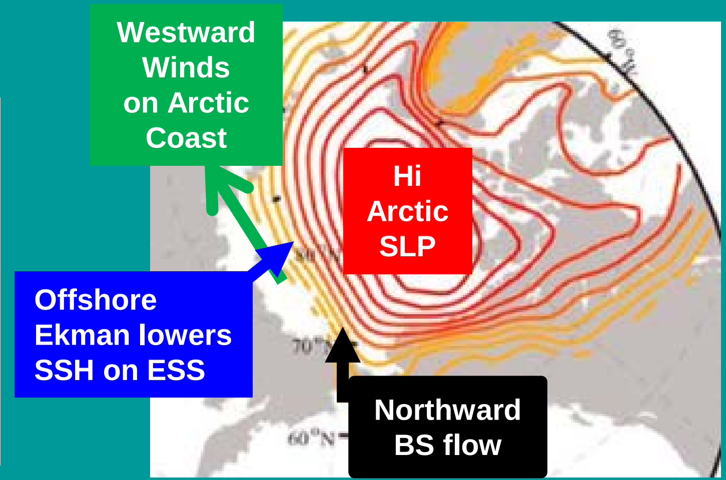
SUMMER

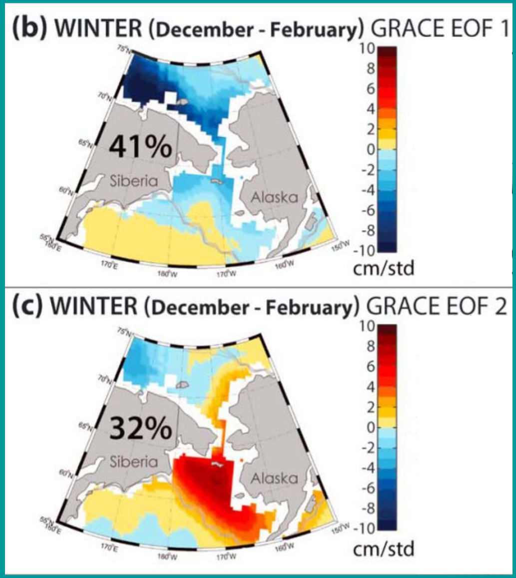
Strait winds weak

1 dominant EOF of OBP

**** Flow driven by:**

- Arctic low-East-Siberian-Sea mechanism





WINTER

Strait winds strong

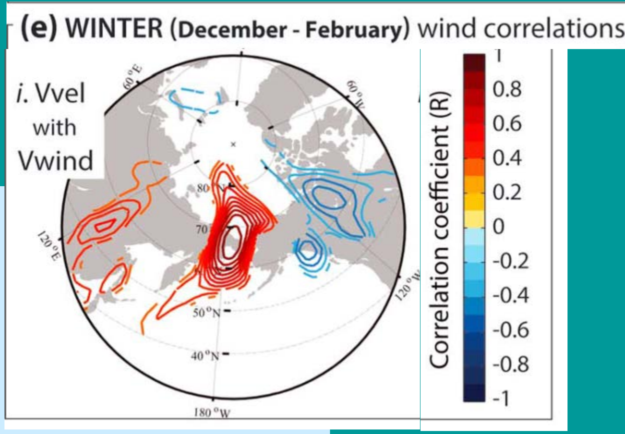
2 dominant EOFs of OBP

**** Flow driven by 3 things:**

- northward wind in strait

- high-Bering-Sea-Shelf mechanism

- Arctic low-East-Siberian-Sea mechanism



Peralta-Ferriz & Woodgate, 2017

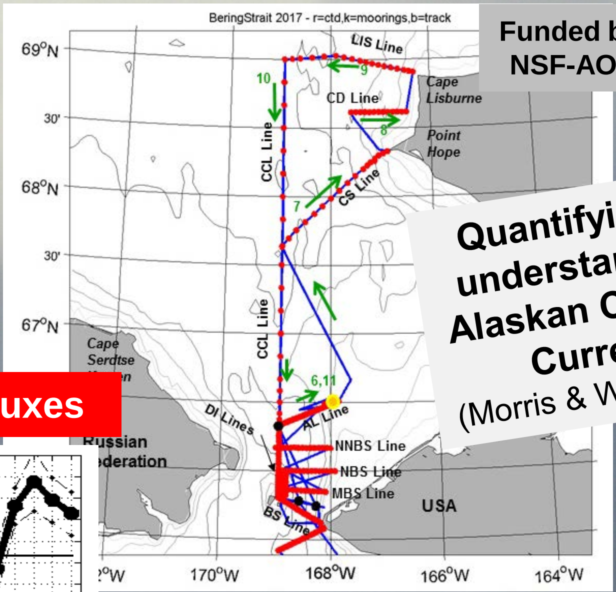
Bering Strait Mooring Program – 2017 Updates

Rebecca Woodgate University of Washington, Seattle, USA

Funded by NSF-AON

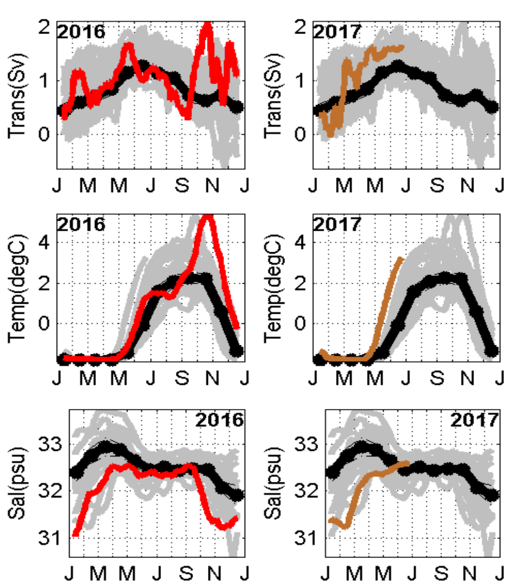
Our July 2017 Norseman 2 cruise recovered & redeployed the 3 Bering Strait moorings, and took CTD sections, finding the Chukchi remarkably warm.

Recovered data show:



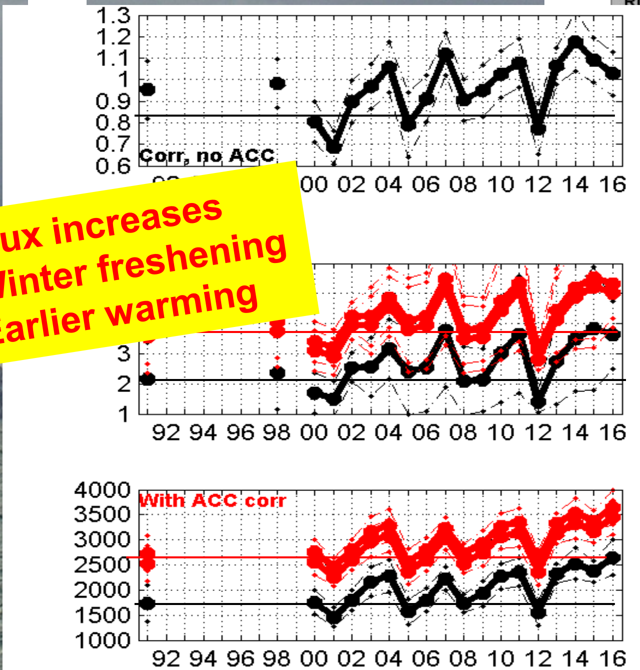
Quantifying & understanding Alaskan Coastal Current
(Morris & Woodgate)

2016/2017 Remarkably warm & fresh



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

Still Increasing annual mean fluxes



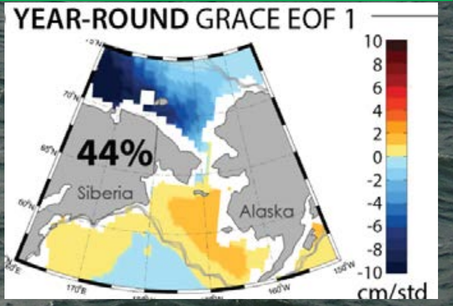
Flux increases
Winter freshening
Earlier warming

Thin horizontal lines ~ relevant prior climatologies

Trans ≥1Sv; FW~3500km^3/yr ***(cf 34.8psu)***
Heat ~5x10^{20}J/yr ~15TW ***(cf -1.9°C)***

**** 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***

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