Arctic Ocean freshwater budget

PO Observational Seminar: “The New Arctic”
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Last week:

- Anomalous anticyclonic circulation around Beaufort high → stronger easterly winds
- Wood et al. (2013) suggest that such winds warm the Beaufort Sea through multiple mechanisms:
  - Blow sea ice away from the coast, creating more open water & accelerating warming/melt (albedo feedback)
  - Enhance advection of the warm, fresh MacKenzie River plume into the Beaufort Sea
- The additional heat resulting from these anomalous easterlies “undoubtedly” contributed to the acceleration of sea ice loss

→ What about the freshwater?
Arctic Ocean basin liquid freshwater storage trend 1992–2012

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Abstract Freshwater in the Arctic Ocean plays an important role in the regional ocean circulation, sea ice, and global climate. From salinity observed by a variety of platforms, we are able, for the first time, to estimate a statistically reliable liquid freshwater trend from monthly gridded fields over all upper Arctic Ocean basins. From 1992 to 2012 this trend was 600 ± 300 km3 yr−1. A numerical model agrees very well with the observed freshwater changes. A decrease in salinity made up about two thirds of the freshwater trend and a thickening of the upper layer up to one third. The Arctic Ocean Oscillation Index, a measure for the regional wind stress curl, correlated well with our freshwater time series. No clear relation to Arctic Oscillation or Arctic Dipole indices could be found. Following other observational studies, an increased Bering Strait freshwater import to the Arctic Ocean, a decreased Davis Strait export, and enhanced net sea ice melt could have played an important role in the freshwater trend we observed.

1. Introduction

The Arctic Ocean is an important source and pathway for freshwater: 11% of the global continental runoff flows directly into the Arctic Ocean [Pickart et al., 2013]. Freshwater is added and removed by melting and forming sea ice, respectively. Additional freshwater enters the Arctic Ocean from the Pacific through the Bering Strait [Woodgate et al., 2006, 2012]. This water affects the stratification [Korhonen et al., 2012; Rudels et al., 2004], sea ice [MacDonald, 2000], and the regional circulation [McPhee et al., 2009; Giles et al., 2012; Morison et al., 2012] in the Arctic Ocean. Freshwater is also exported from the Arctic to the North Atlantic and the Nordic Seas, where it has the potential to affect deep convection [Stenseng et al., 2007, Rencz and Heimbichner, 2007] and the horizontal gyre circulation [Bjerknes and Ganssen, 2005].

Liquid freshwater from the Arctic Ocean is important for the global thermohaline circulation and climate
Why care about Arctic freshwater?

→ within the Arctic, can drive shifts in circulation & transports

→ export to the North Atlantic could have implications for Atlantic Meridional Overturning Circulation (“ocean conveyor belt”)

→ driven in part by formation of North Atlantic Deep Water by deep convection in Labrador & Irminger Seas

→ if they get too fresh, could deep convection stop & shut down AMOC?

[think “Day After Tomorrow” -- but also real examples like Great Salinity Anomaly]
How is Fresh-Water Content (FWC) defined?

→ choose reference salinity to define upper ocean layer (below reference isohaline \([depth \ z_{\text{lim}}]\), salinity variation is small) -- Rabe et al. choose \(S_{\text{ref}} = 35\)

\[
FWC = \int_{z_{\text{lim}}}^{0} \left(1 - \frac{S(z)}{S_{\text{ref}}}\right) dz
\]

(McPhee et al. 2009, eq. 1)

→ e.g. if reference isohaline is at 200m and the upper layer is completely fresh \((S(z) = 0 \text{ for } z<z_{\text{lim}})\), \(FWC = 200m\).
→ if reference isohaline is at 200m and the upper layer has constant salinity 17.5 (½ of \(S_{\text{ref}}\)), \(FWC = 100m\).
Total Arctic freshwater budget

\[
\frac{d}{dt} [ \text{Sources} = \text{Sinks} + \text{Storage} ]\]

→ steady state: \( \frac{d}{dt} \text{Storage} = 0 \)

\[
\frac{d}{dt} \text{Storage} = \frac{d}{dt} [ \text{Pacific FW (Bering Strait)} + \text{rivers} + \text{precipitation} + \text{net sea ice melt} \ - \ (\text{sea ice export} + \text{liquid FW export} (+ \text{evaporation?}) ) \ + \ \text{FW advection from shelf into basin}^* ]
\]

* because Rabe et al. 2013 exclude continental shelf -- only consider the FWC of the Arctic Ocean with water depth greater than 500m
Total Arctic freshwater budget

d/dt [ Sources = Sinks + Storage ]
→ steady state: d/dt Storage = 0

d/dt Storage = d/dt [ Pacific FW (Bering Strait) + rivers + precipitation + net sea ice melt - (sea ice export + liquid FW export (+ evaporation?)) ]

d/dt Storage = d/dt [ upper layer FWC * upper layer thickness ]

→ \[ \Delta h_{fw} = \Delta hF + h\Delta F + \Delta h\Delta F \]

(Rabe et al. 2013 supplement eq. 4)

(Bars denote time mean for each grid point. Delta is change over 21 years based on trend at each grid point.)
Salinity data sources (supplement table 1):

- Ship based
- Argo
- Ice-based (e.g. landing plane/helicopter on sea ice to collect CTD profiles)
- Airborne (e.g. AXCTDs -- Airborne eXpendable CTD Probes)
- Ice Tethered Profiler (WHOI) →

+ comparison to NAOSIM model
Output (MOM-2 0.25° coupled to sea ice model...see Karcher et al. 2005 for more model info)
Rabe et al. 2013:
→ compile Arctic Ocean salinity observations from 1992-2003

→ from monthly maps of freshwater content (objectively mapped in space & time from available observations), generate timeseries of:
  → area-integrated FWC
  → 34 isohaline depth (i.e. layer thickness)
  → depth-averaged upper layer salinity
(1) **Trend in FWC anomaly:**

600±300 km$^3$ / yr.

Observations agree well with model.

Supplement fig. 3: monthly timeseries of FWC. (Error bars are statistical mapping error, which were used to estimate trend uncertainty.)
(1) Trend in FWC anomaly:
600±300 km$^3$/yr.
Observations agree well with model.

(2) Layer thickness (red squares) accounts for 30% of FWC trend. Layer freshening (blue circles) accounts for 65% of FWC trend.
What does thickening vs. freshening tell us?

**Thickening:** associated with Ekman pumping

**Freshening:** associated with offshore Ekman transport (import of fresher water from coastlines into basin -- think Wood et al. paper from last week)

→ **hypothesis:** strengthening “Arctic sea level pressure high” could explain both: would enhance anticyclonic atmospheric circulation, promoting offshore transport and convergence in the western Arctic Ocean

[this corresponds to the enhanced easterlies along the Alaskan coast that we discussed last week!]
How does that work, again…?

→ “Arctic sea level pressure high” is talking about atmospheric pressure at sea level, like this.

High pressure generates anticyclonic winds (i.e. clockwise in NH).

So, to Alaska…easterly winds!

And to the ocean…offshore transport of freshwater (freshening) and convergence (layer thickening).

(J. Imamura course notes; OpenLearn course notes)
Potentially relevant climate indices

**Arctic Oscillation (AO):** strengthening of Arctic sea level pressure high

**Arctic Dipole (AD):** dipole pattern in sea level pressure between the western and eastern Arctic → positive AD freshens transpolar drift

**Arctic Ocean Oscillation (AOO):** cyclonicity of Arctic Ocean circulation driven by pressure differences between the Canada Basin and Central Arctic → primarily measure of Beaufort Gyre strength
Potentially relevant climate indices

→ only AOO is significantly* correlated (explains 70% of variability)
→ Rabe et al. interpretation: liquid FWC changes are regionally driven

Detrended, de-meaned (normalized etc) timeseries of cumulative climate indices and FWC
→ i.e. can these explain interannual variability on top of trend?

→ only AOO is significantly* correlated (explains 70% of variability)
→ Rabe et al. interpretation: liquid FWC changes are regionally driven
Longer timescale of AOO (etc.) variability

positive AOO phases typically associated with freshwater accumulation and export; negative phases with exports of sea ice & polar water through Fram Strait and onset of “Great Salinity Anomalies” (likely an oversimplification...from here, research group website, not peer-reviewed.)

Is AOO really reflecting interannual variability? When it returns to a negative phase will all this FW be exported?
Back to the freshwater budget...

\[ \frac{d}{dt} \left[ \text{Sources} = \text{Sinks} + \text{Storage} \right] \]

→ steady state: \( \frac{d}{dt} \text{Storage} = 0 \)

\[ \frac{d}{dt} \text{Storage} = \frac{d}{dt} \left[ \text{Pacific FW (Bering Strait)} + \text{rivers} + \text{precipitation} + \right. \]
\[ \text{net sea ice melt} - \left( \text{sea ice export} + \text{liquid FW export} (+ \text{evaporation?}) \right) \]
\[ \left. + \text{FW advection from shelf into basin}^* \right] \]

→ Left hand side is positive, and authors suggest role of atmospheric forcing in driving net import of FW from shelf to basin and increasing storage

→ What about full FW budget? Is there actually more FW coming in to the Arctic as a whole, or is it just being stored more effectively due to this circulation pattern?
Bering Strait freshwater input

- Bering Strait throughflow from the Pacific to Arctic is driven by a combination of local wind and “pressure head” forcing -- sea surface height (SSH) gradient
- Pressure head poorly understood but driven by far field processes
- New study (Peralta-Ferriz and Woodgate 2017) shows that:
  - pressure head forcing dominant in winter
  - variability in pressure head forcing is primarily driven by sea level change in the East Siberian Sea (which is to the west of the Beaufort Sea…)
- Easterly winds along western Arctic coast \(\rightarrow\) reduce SSH on Siberian shelf \(\rightarrow\) enhance pressure difference \(\rightarrow\) drive more FW import into Arctic

\(\rightarrow\) seems like this is analogous to Rabe et al. mechanism!
\(\rightarrow\) potential for negative feedback with dynamic topography?
FWC and dynamic topography

- FW is less dense than saltier water, so increasing FWC in the water column makes it taller
- McPhee et al. (2009) looked at regional variation in FWC anomaly

![Image of FWC and dynamic topography]

- look at transect a-a’ across gyre (B is rotated and zoomed in relative to A)
Effect on Arctic circulation and transport

Accumulating FW in eastern side of transect (SE Canada Basin) completely changed upper ocean circulation and net freshwater transport → geographic distribution of storage is important

(This is from analysis of late winter data from 2008 relative to climatology)

→ If increasing FWC increases SSH, could increased FW import from Bering Sea decrease pressure head? (How important are relative effects?)
Fram Strait freshwater export

Observational studies from early 2000s-2010s found no trend in Fram Strait freshwater export

→ Rabe et al. cite NAOSIM model result (black line) showing FS export decreasing in the late 90s, but note lack of agreement between models (all the other lines)
Fram Strait freshwater export

More recently, de Steur et al. (2018) showed that in fact Fram Strait FW export has increased since 2010.
Is increased Arctic FWC part of a decadal oscillation-type cycle? Should we expect the Arctic to flush all of this freshwater over the next 5-10 years?

It seems like the North Atlantic has freshened before (maybe or maybe not driven by Arctic FW export) and the AMOC hasn’t shut down lately.

(On the other hand, positive AOO phase is associated with relatively cool, dry conditions in the Arctic and negative AOO phase is associated with warm, humid conditions that promote sea ice melt.)
Divided opinions on current AMOC stability

Yang et al. (2016): Greenland+Arctic freshwater are reducing formation of dense Labrador Sea Water → could slow down AMOC

Lozier et al. (2019): Labrador Sea likely does not dominate AMOC variability -- ongoing monitoring

Caesar et al. (2018): model “fingerprint” of AMOC slowdown
More questions?

→ other feedbacks/processes we are missing in discussion so far?

→ lingering questions/frustrations/ideas for future research?

References:


Arctic Ocean Oscillation reference: https://www.whoi.edu/page.do?pid=66578