The Arctic Freshwater Balance: A Network Perspective

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Freshwater and Arctic Change

A Framework for Quantifying & Understanding Change:

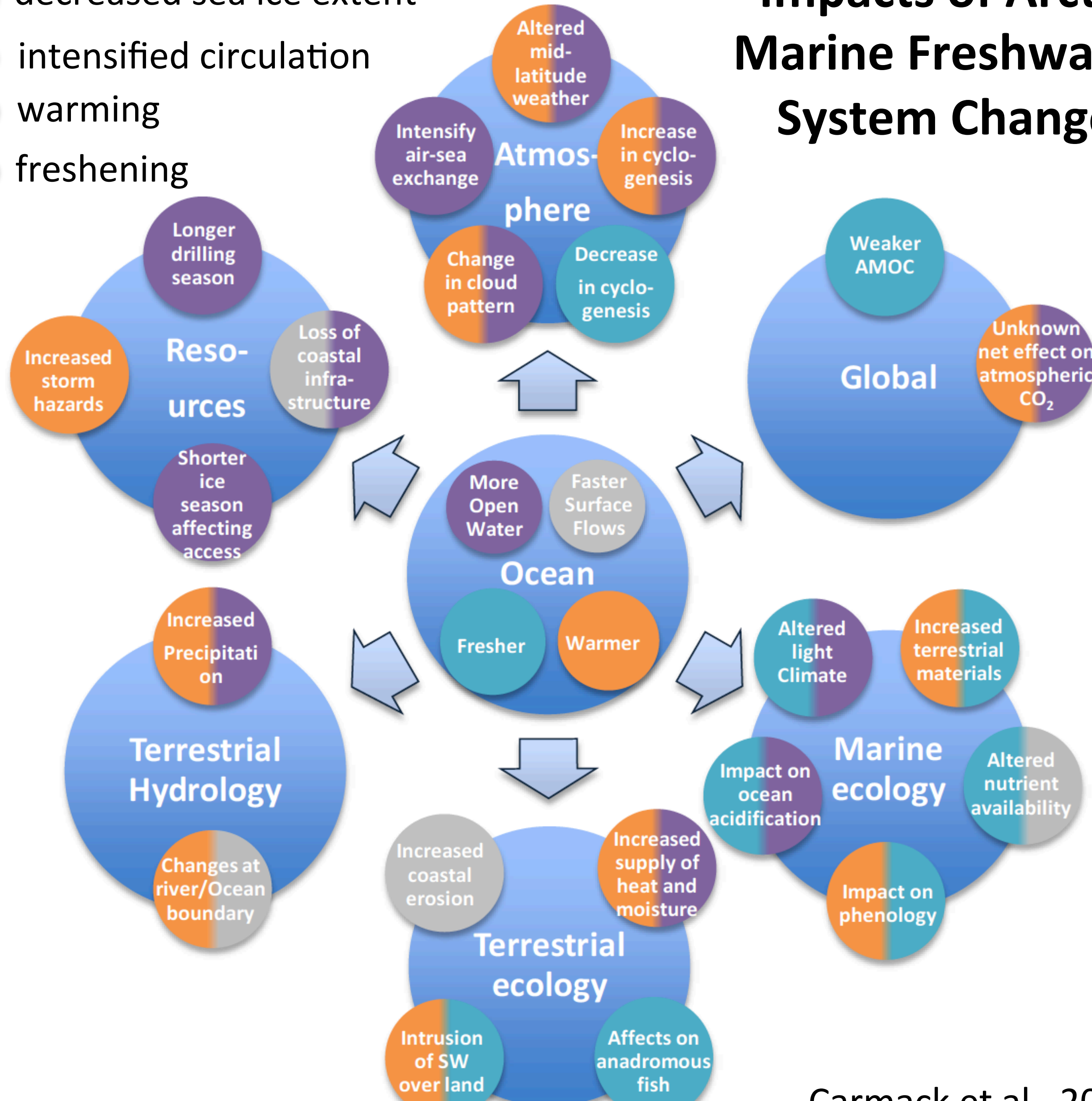
- Salinity controls Arctic Ocean stratification ('β ocean', Carmack, 2007).
- Cold, buoyant surface layer isolates sea ice from heat stored below.
- Modulates sea ice evolution, coupling between atmosphere & ocean.

Global Impacts

- Sea ice growth and melt important component of meridional atmospheric energy transport (Nakamura and Oort, 1988).
- Atlantic Meridional Overturning Circulation (AMOC) sensitive to buoyant Arctic outflow into deepwater formation regions (e.g. Holland et al., 2001; Arzel et al., 2008).
- Changes in Arctic freshwater outflow also modulate:
  - Extent and strength of the North Atlantic subpolar gyre.
  - Northward penetration of warm subtropical waters. Impacts fisheries (Hátún et al., 2009) and carbon uptake and storage (e.g. Schuster and Watson, 2007).

Impacts of Arctic Marine Freshwater System Change

- decreased sea ice extent
- intensified circulation
- warming
- freshening



Carmack et al., 2015

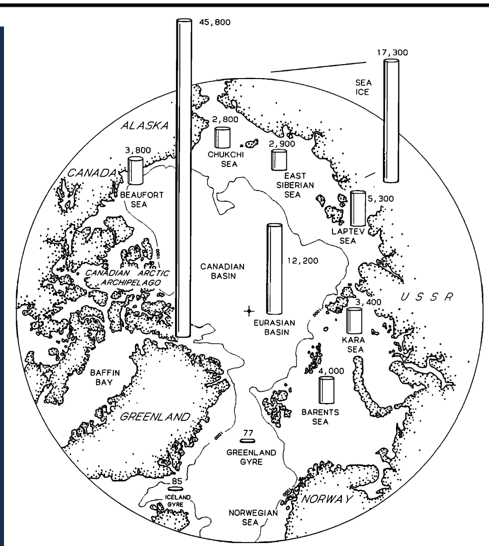
A Freshwater Synthesis: Aagaard and Carmack (1989)

S_0 = 34.8
Average Arctic Ocean salinity

TABLE 1. Fresh Water Budget for the Arctic Ocean

Source or Sink	Transport, $km^3\ yr^{-1}$	Yield, $cm\ yr^{-1}$
Ice export through Fram Strait	−2790	−29
Water export through Fram Strait	−820	−9
Runoff	3300	35
Precipitation less evaporation	900	9
Water import through Bering Strait	1670	18
Water export through Canadian archipelago	−920	−10
Import with Norwegian Coastal Current	250	3
Saline water import through Barents Sea	−540	−6
Saline water import with West Spitsbergen Current	−160	−2
Net	890	9

- Sparse data – surveys (snapshots), some time series.
- Measurements not contemporaneous.
- Large uncertainties, difficult to discern change.

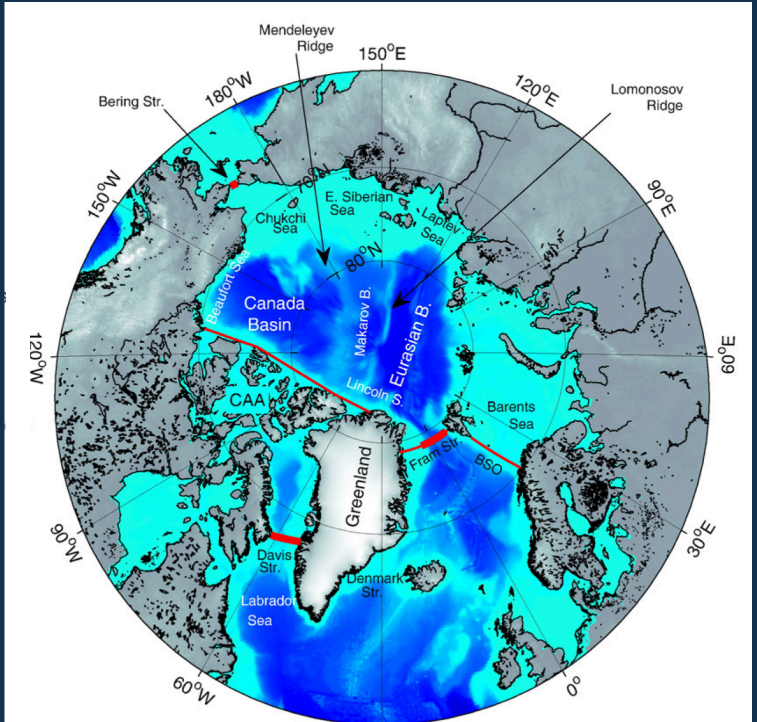


$$FW_{transport} = \sum V_i \frac{S_0 - S_i}{S_0} A_i$$

Storage (liquid): 80,000 km^3
Storage (ice): 17,300 km^3

Challenges

- Distributed water column measurements in Arctic interior.
- Resolve dynamically wide straits.
- Measure near ice-ocean interface.
- Sea ice volume.
- Resolve broad range of timescales… seasonal (and shorter) to interannual.
- System undergoing rapid change during observing period.
- Measurements entire FW system.
- Constrain uncertainties to resolve anticipated changes.
- Sustained measurements required to resolve secular change.



Haine et al., 2015

Serreze et al. 2006 (NSF FWI)

Inflow

- River runoff (3900 ± 390 km^3/yr)
- Bering Strait liquid (2400 ± 300 km^3/yr)
- P-E (2000 ± 200 km^3/yr)
- Greenland melt (330 ± 20 km^3/yr)
- Bering Strait sea ice (140 ± 40 km^3/yr)

Storage

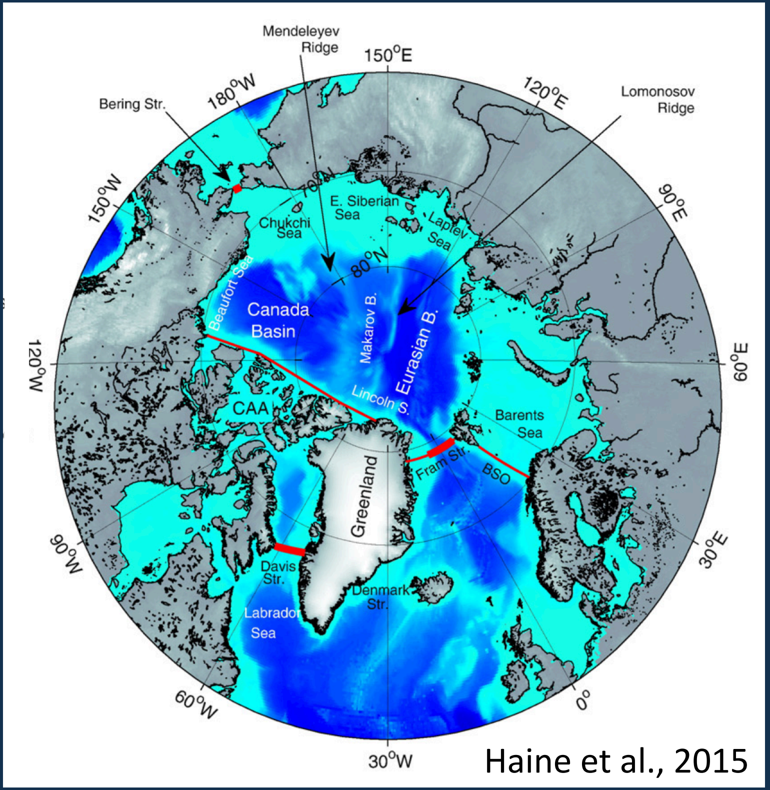
- Liquid FW (93,000 km^3)
- Seasonal sea ice (13,000 km^3)
- Multi-year sea ice (10,900 km^3)

Outflow

- CAA/Davis Strait liquid (-3200 ± 320 km^3/yr)
- Fram Strait liquid (-2700 ± 530 km^3/yr)
- Fram Strait sea ice (-2300 ± 340 km^3/yr)
- Hudson Strait (-200 ± ? km^3/yr)
- Davis Strait sea ice (-160 ± ? km^3/yr)
- Barents Sea Opening (-90 ± 90 km^3/yr)

UP
DOWN
NO EST

- 1980-2004 composite.
- Terrestrial and oceanic measurements with reanalysis products.
- Exploits early data from gateway moorings.
- Interior from PHC climatology.
- Large jump in available data.

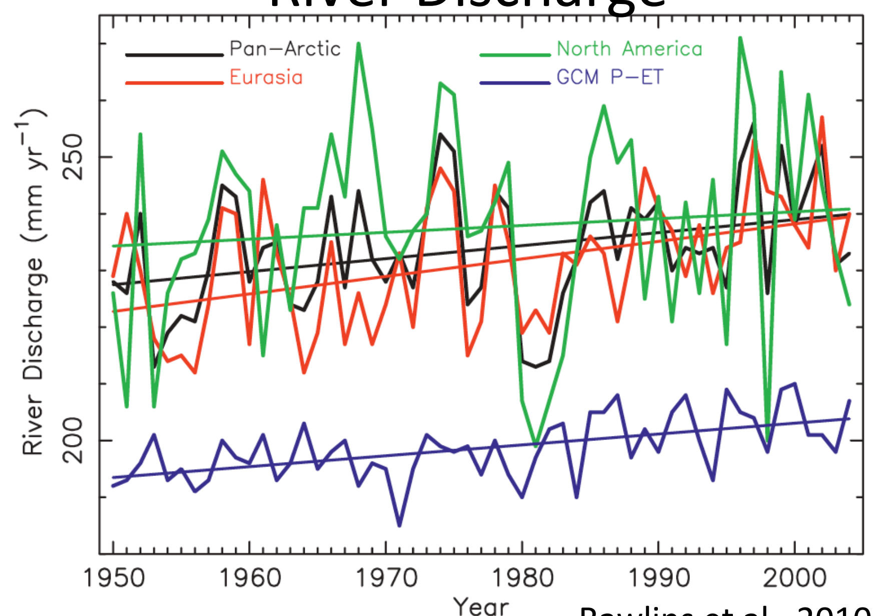


Haine et al., 2015

Quantifying River Discharge

Major River Inflows and Pathways

Carmack et al., 2015



Rawlins et al., 2010

- Major rivers gauged.
- Long records.

Bering Strait

R. Woodgate, K. Aagaard
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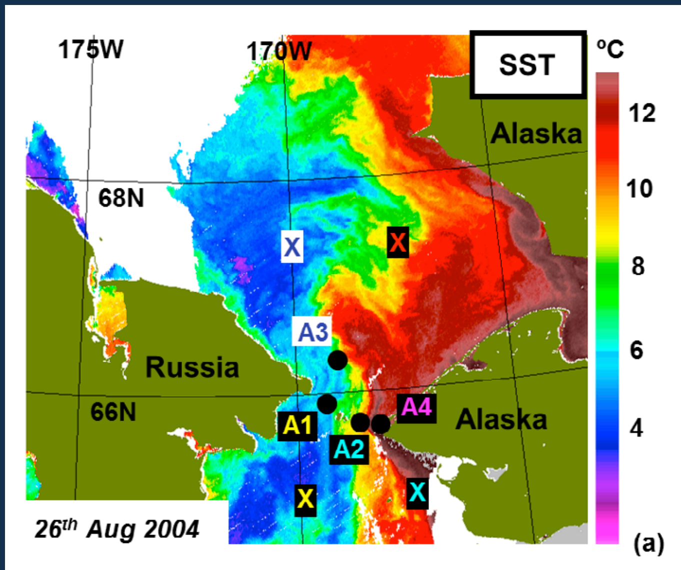
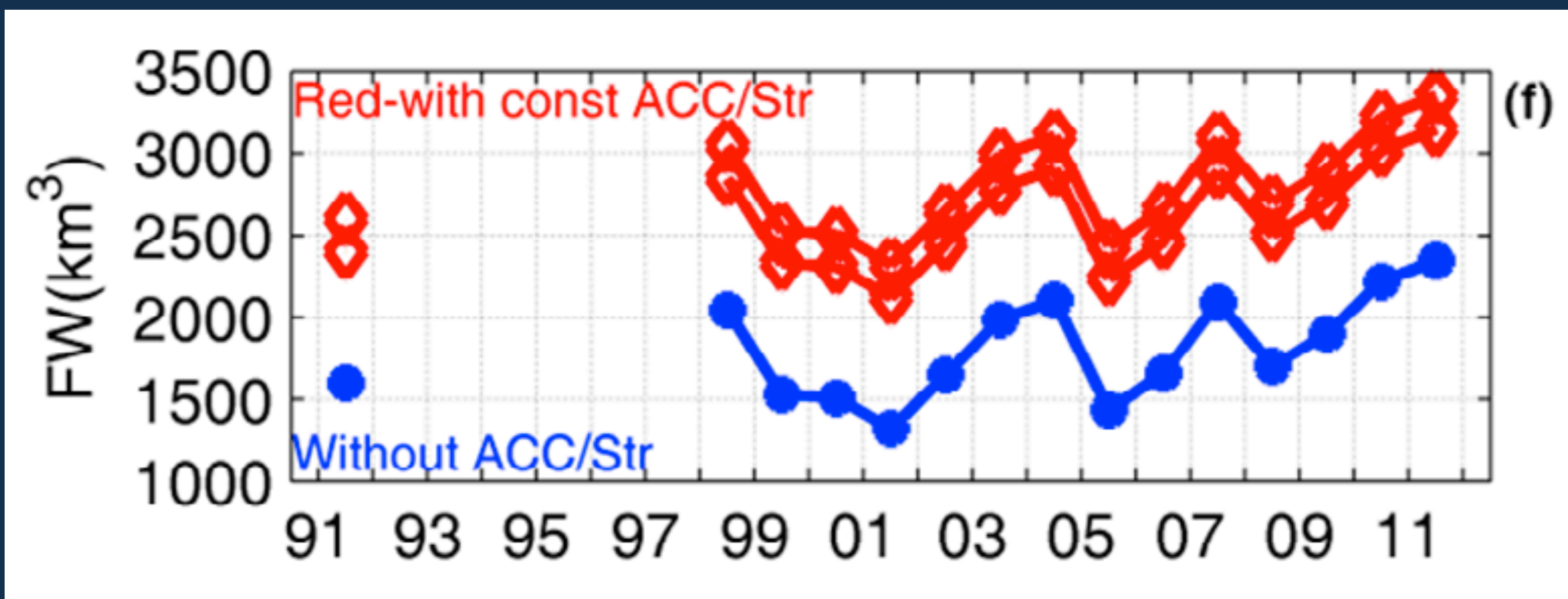
T. Weingartner
UAF



- Corrections for shallow Alaska Coastal Current (ACC).
- ACC resolved in more recent measurements.
- Variability exceeds other inputs.
- Measurements to 2015, future status TBD.



Davis Strait

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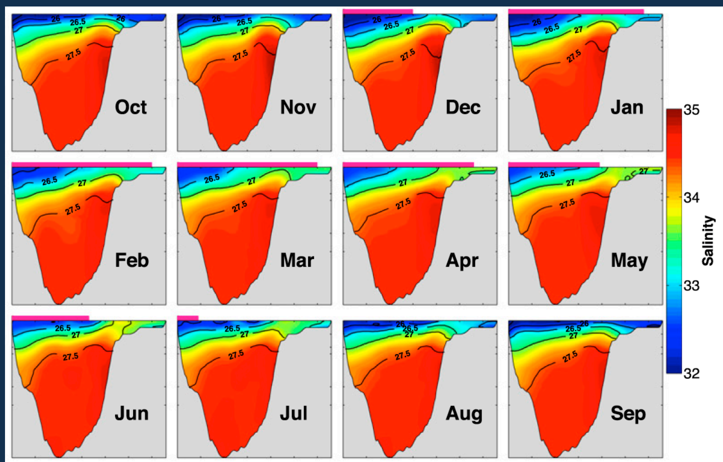
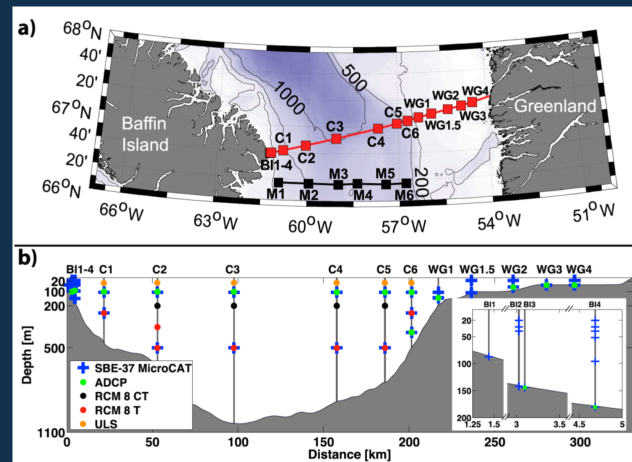
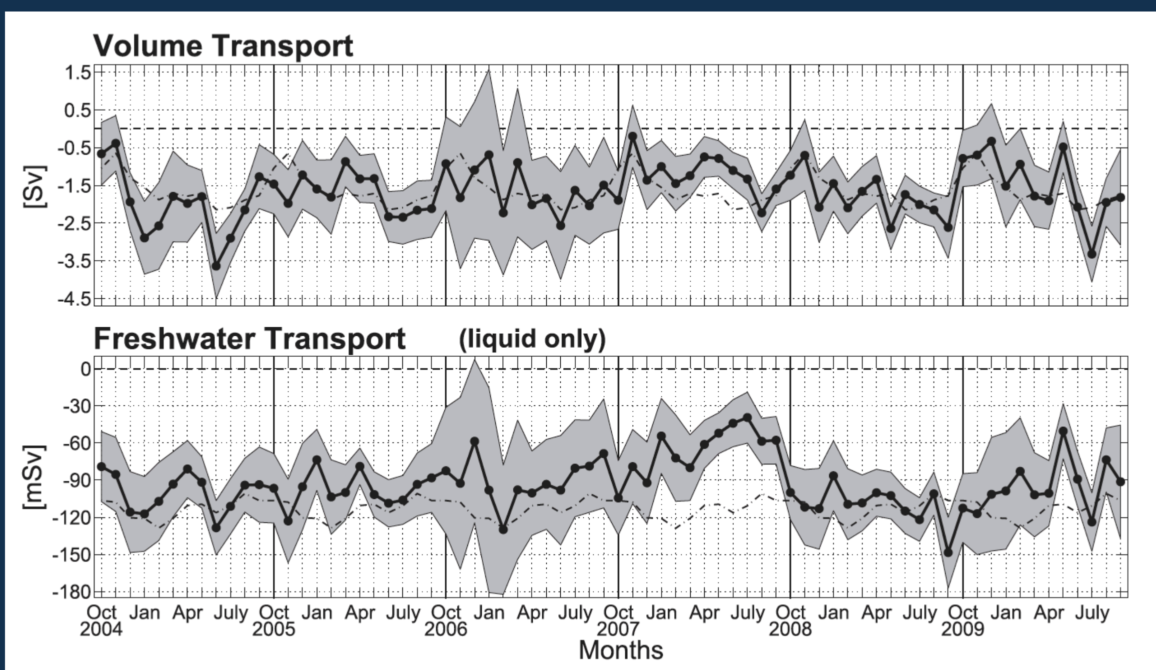
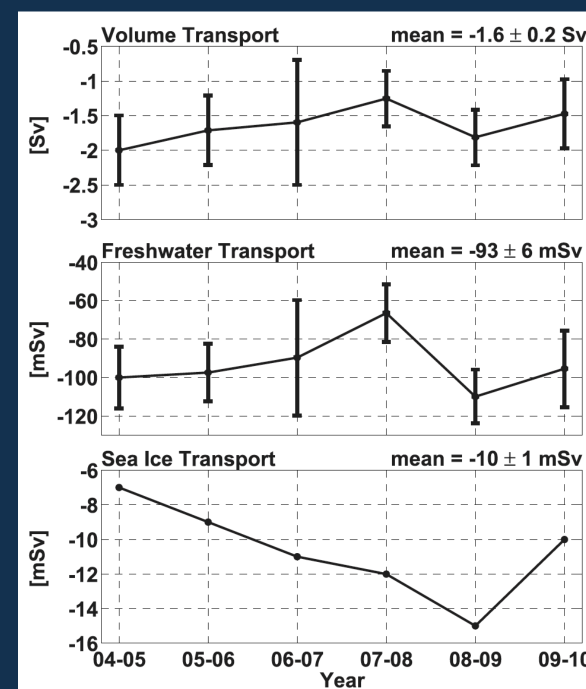
B. Petrie, K. Azetsu-Scott
BIO







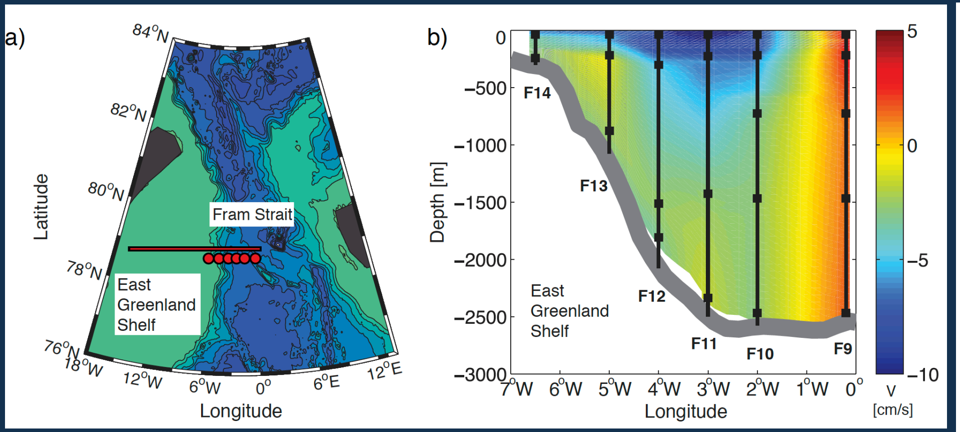


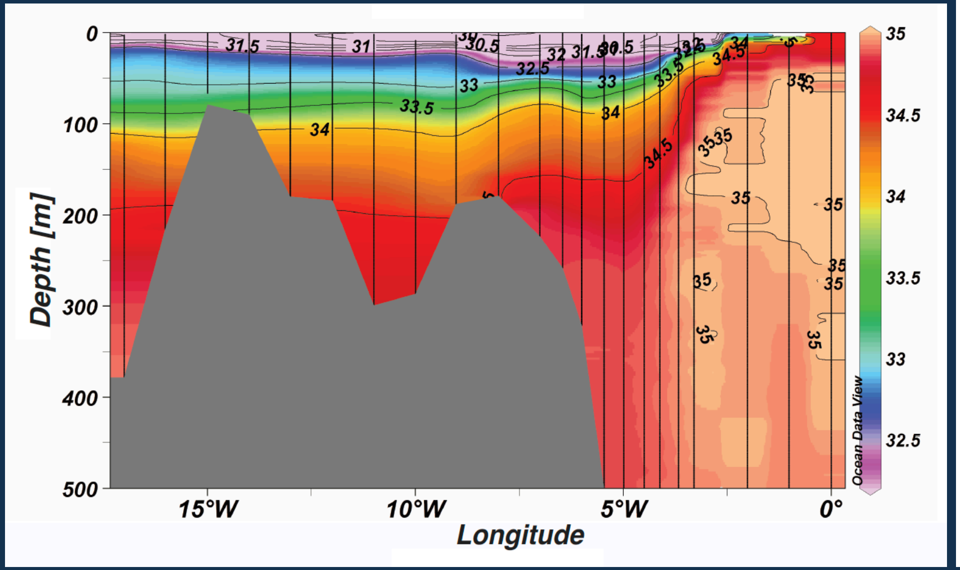
- Mooring, gliders & hydrography.
- 2004 -2015
- Future status TBD

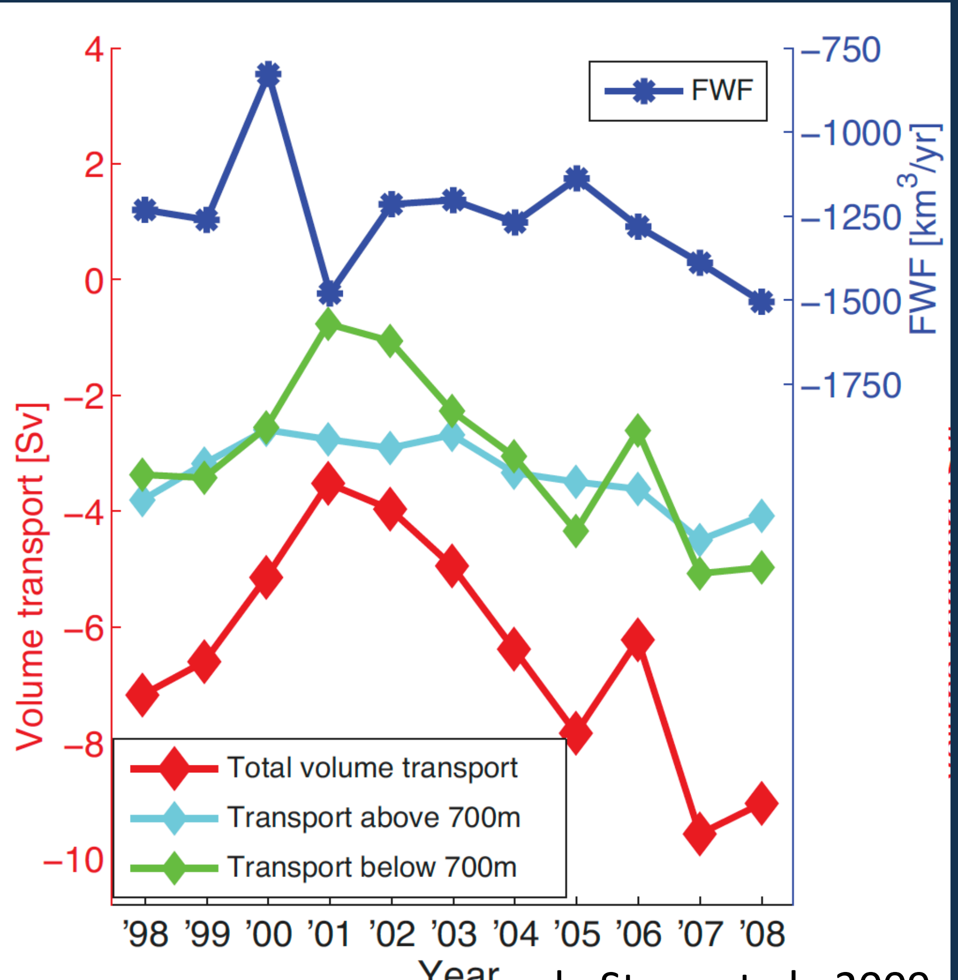
Fram Strait

E. Hansen, L. de Steur, P. Dodd
Norwegian Polar Institute

U. Schauer, A. Beszczynska-Moller. T. Kanzow, E. Fahrbach
Alfred Wegner Institute







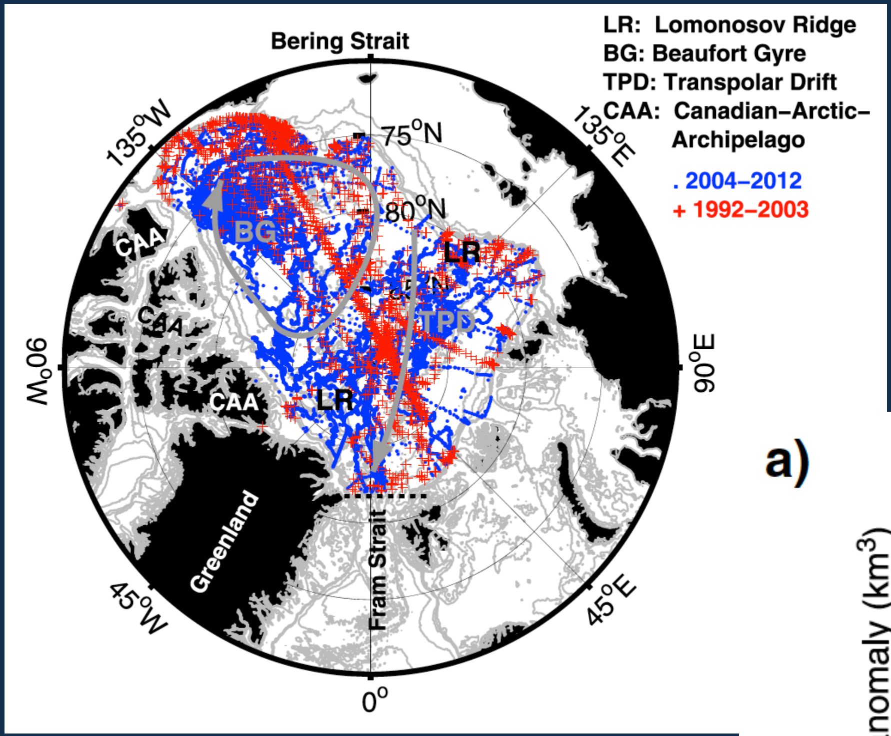
de Steur et al., 2009

- East Greenland Shelf, ice-ocean interface poorly resolved.
- Measurement program ongoing as of 2015.

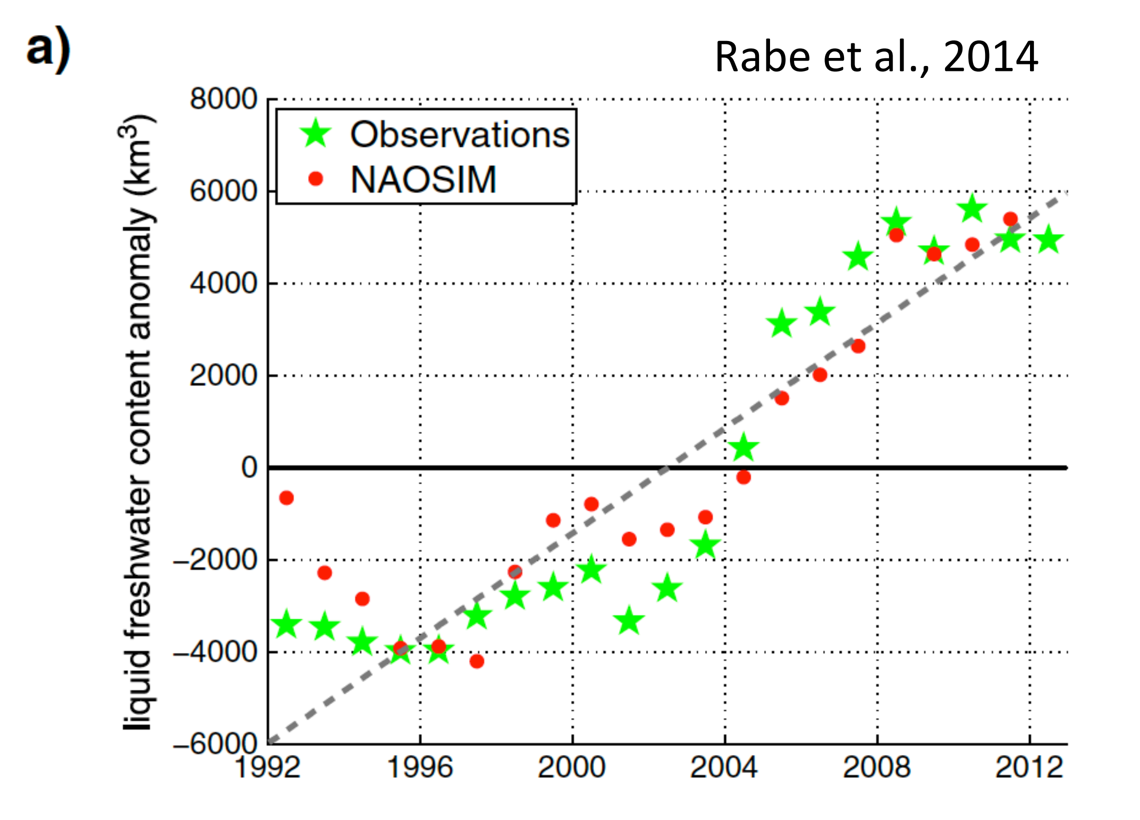
J. Toole, R. Krishfield (ITP)
WHOI

Storage

Numerous others (CTD, XCTD)



- Good agreement between observational estimates and NAOSIM model.
- Trend 600 ± 300 km^3/yr.
- Increased Bering inflow, decreased Davis outflow, increased multi-year ice melt?



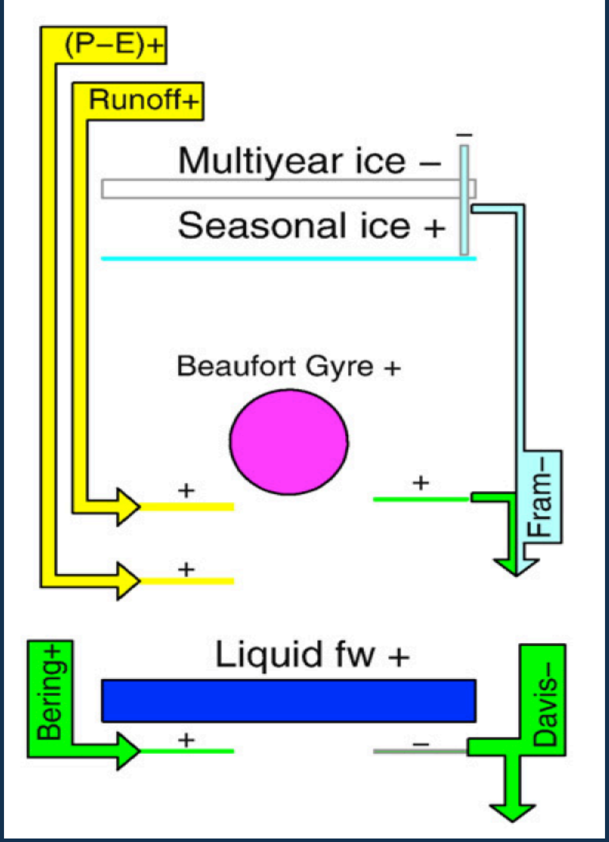
- Distributed measurements from ships, Ice Tethered Profilers and other buoys.
- Increased autonomous sampling critical.
- $S_0 = 35$

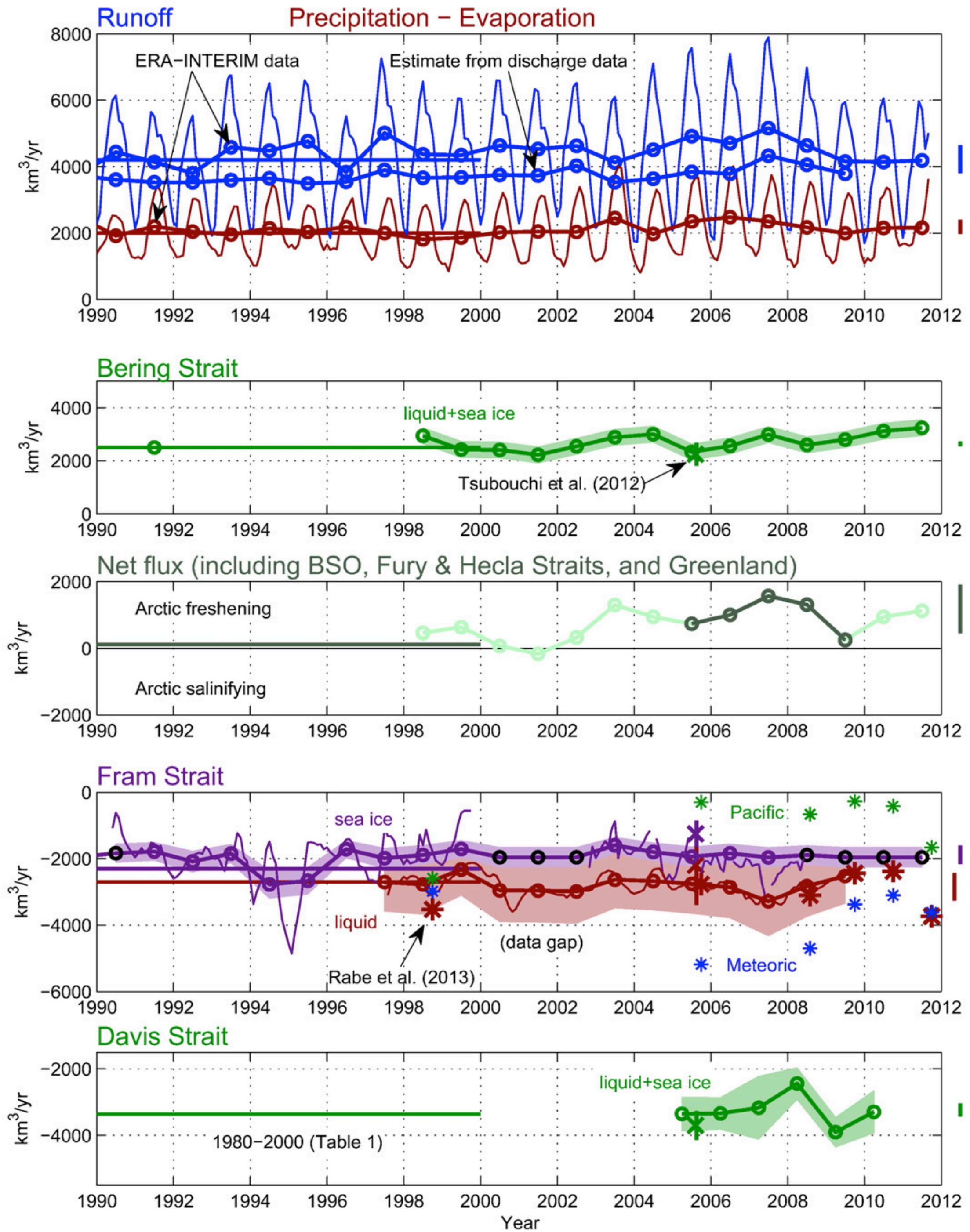
Freshwater Budget

Haine et al., 2015

- 2004-2010 with all gateways quantified.
- Ice storage from PIOMAS assimilation product.

Difference
2000-2010 vs 1980-2000





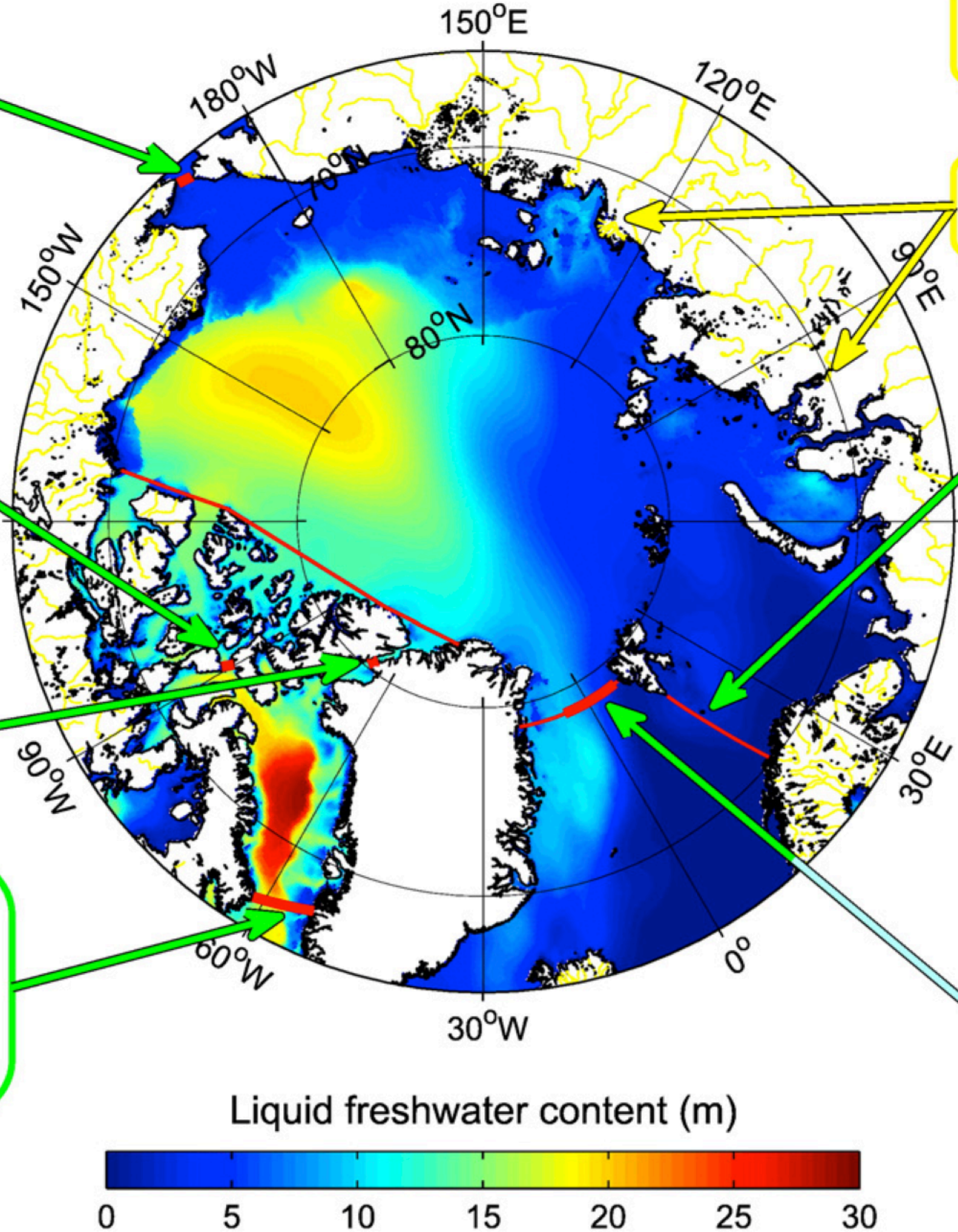
Mechanisms of FW Flux

Bering Strait
$\phi_{FW} \propto \phi_{vol}$
$\phi_{vol} \propto \Delta SSH$
$\phi_{vol} \propto v_a$

Barrow Strait
$\phi_{FW} \propto \phi_{vol}$
$\phi_{vol} \propto \Delta SSH$
$\Delta SSH \propto$ Beaufort Sea wind

Nares Strait
$\phi_{vol} \propto \Delta SSH$
$\phi_{vol} \propto v_a$ (summer)

Davis Strait
Two-way exchange
$\phi_{FW} \propto \phi_{vol}$
$\phi_{FW} \neq \phi_{FW}^{Nares} + \phi_{FW}^{Barrow}$
NAO influences ϕ_{vol}
Seasonality different to Nares and Barrow



Precip. - Evap.
Precip. var. dominates
Arctic Osc. important

Runoff
Precip. var. dominates
Arctic Osc. important

Barents Sea Opening
$\phi_{FW} \approx 0$ for $S_{ref} = 34.80$

Fram Strait Liq.
Two-way exchange
$\phi_{FW} \not\propto \phi_{vol}$

Fram Strait Ice
$\phi_{ice} \propto v_a$
v_a depends on NAO, (with exceptions)
Large ϕ_{ice} needs large upstream ice load

Haine et al., 2015

Conclusions

FW budgets based on contemporaneous timeseries indicate:

- FW is accumulating in the Arctic, CAA and Baffin Bay.
- Changes in Bering inflow and Fram + Davis outflow below uncertainties.
- Observed increase in storage consistent with increase runoff and P-E, and loss of FW as sea ice.
- Surface winds exert strong controls on FW export and storage.
- No significant change in FW export (Fram + Davis), but release likely to occur in response to changes in wind patterns.

Sustained, contemporaneous measurements of all primary components allows pan-Arctic inverse calculations (e.g. Tsubouchi et al, 2012) to produce self-consistent, pan-Arctic budgets.

Understanding the Arctic FW system requires a network