The Arctic Ocean

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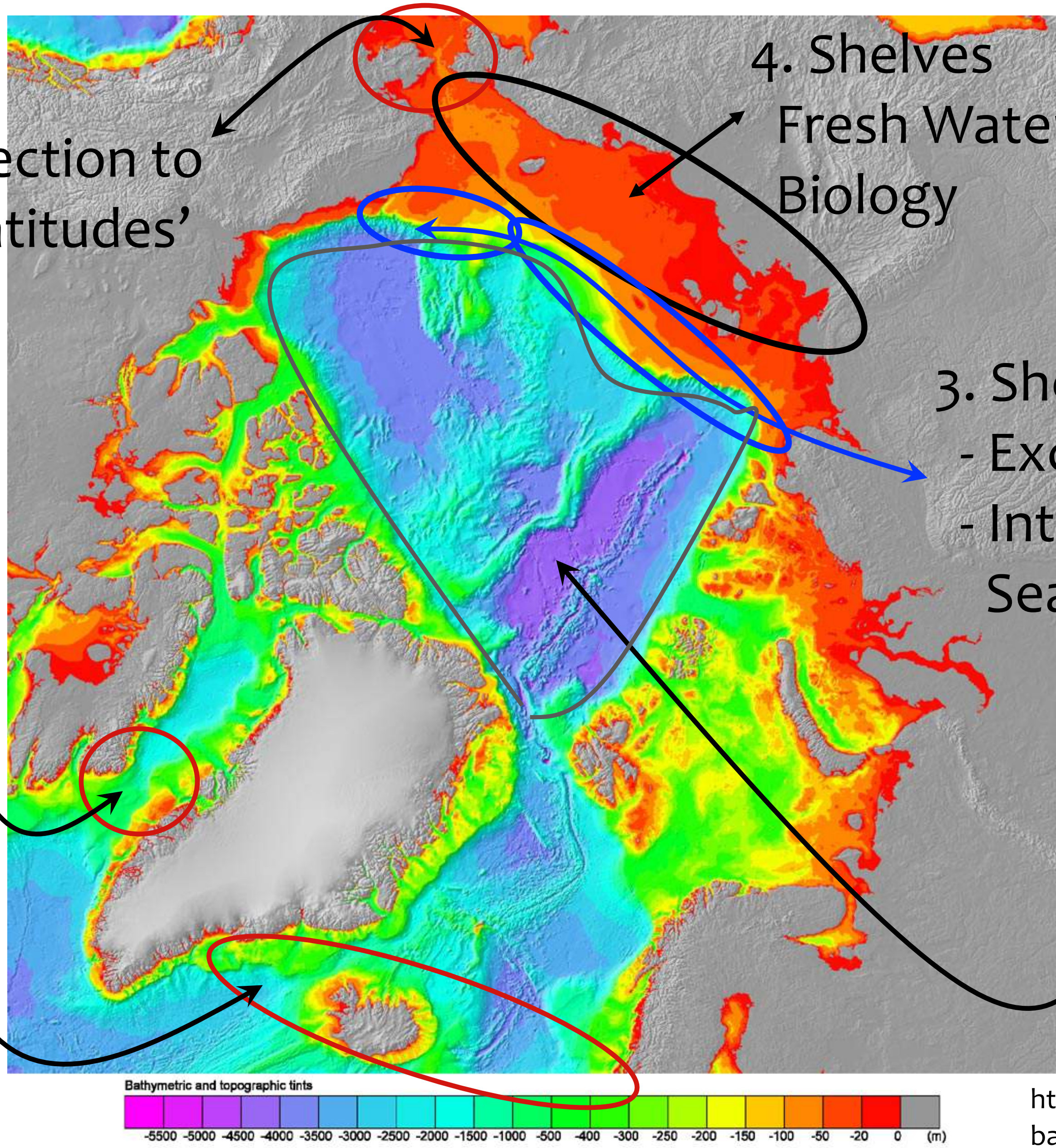
The changing Arctic system

. Currently, the Arctic Ocean is freshening [*Proshutinsky et al.*, 2009; *McPhee et al.*, 2009; *Rabe et al.*, 2011; *Haine et al.*, 2015], warming [*Polyakov et al.*, 2005, 2012; *McLaughlin et al.*, 2009], losing sea ice [*Kwok et al.*, 2009; *Stroeve et al.*, 2012a, 2012b; *Cavalieri and Parkinson*, 2012; *Comiso*, 2012], and its ice cover is changing properties and moving faster [*Barber et al.*, 2009; *Rampal et al.*, 2009, 2011; *Kwok et al.*, 2013; *McPhee*, 2013].

Carmack et al., [2016]

The Arctic Ocean



1. Connection to lower latitudes' oceans

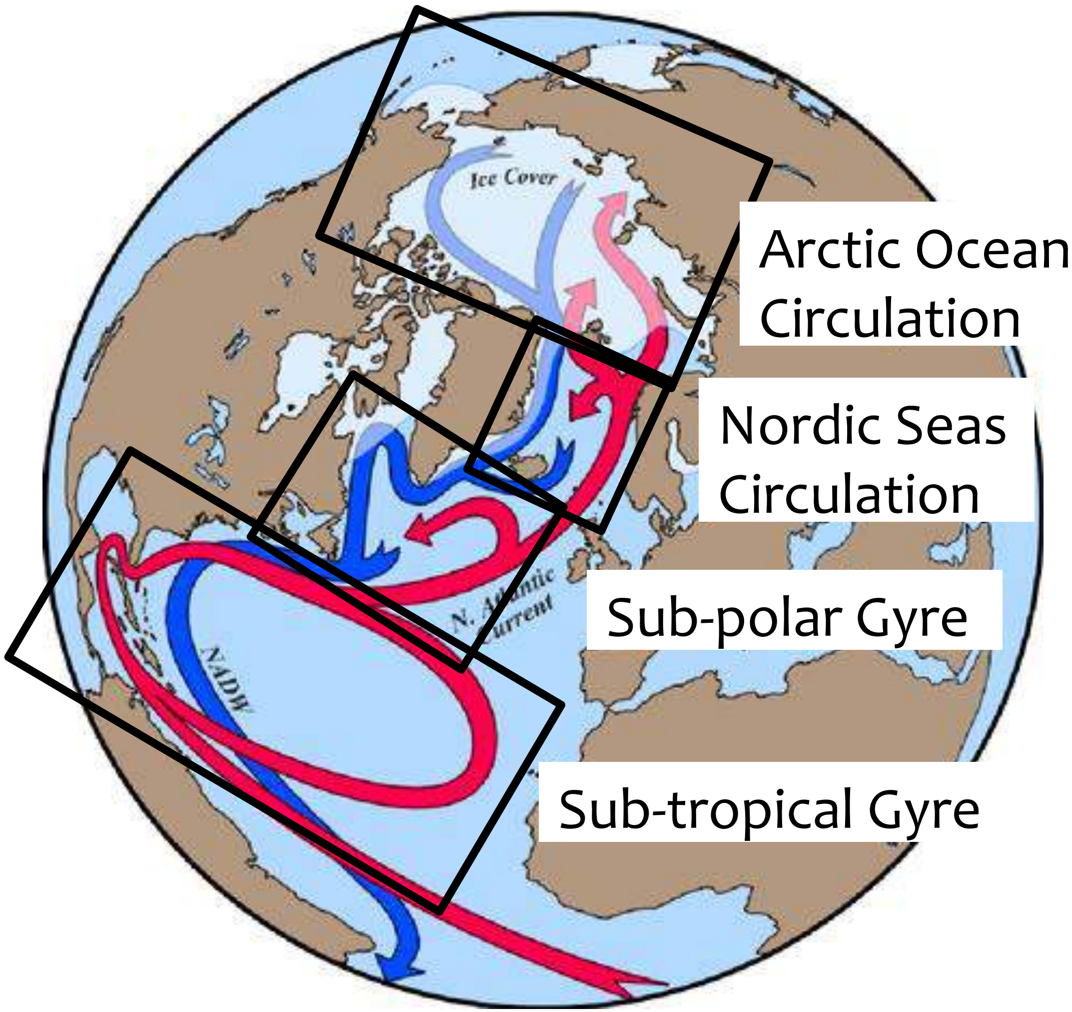
2. Deep Basin
Circulation
Heat storage

3. Shelf-Basin slope
- Exchange
- Interaction with Sea Ice

4. Shelves
Fresh Water
Biology

https://www.ngdc.noaa.gov/mgg/bathymetry/arctic/currentmap.html

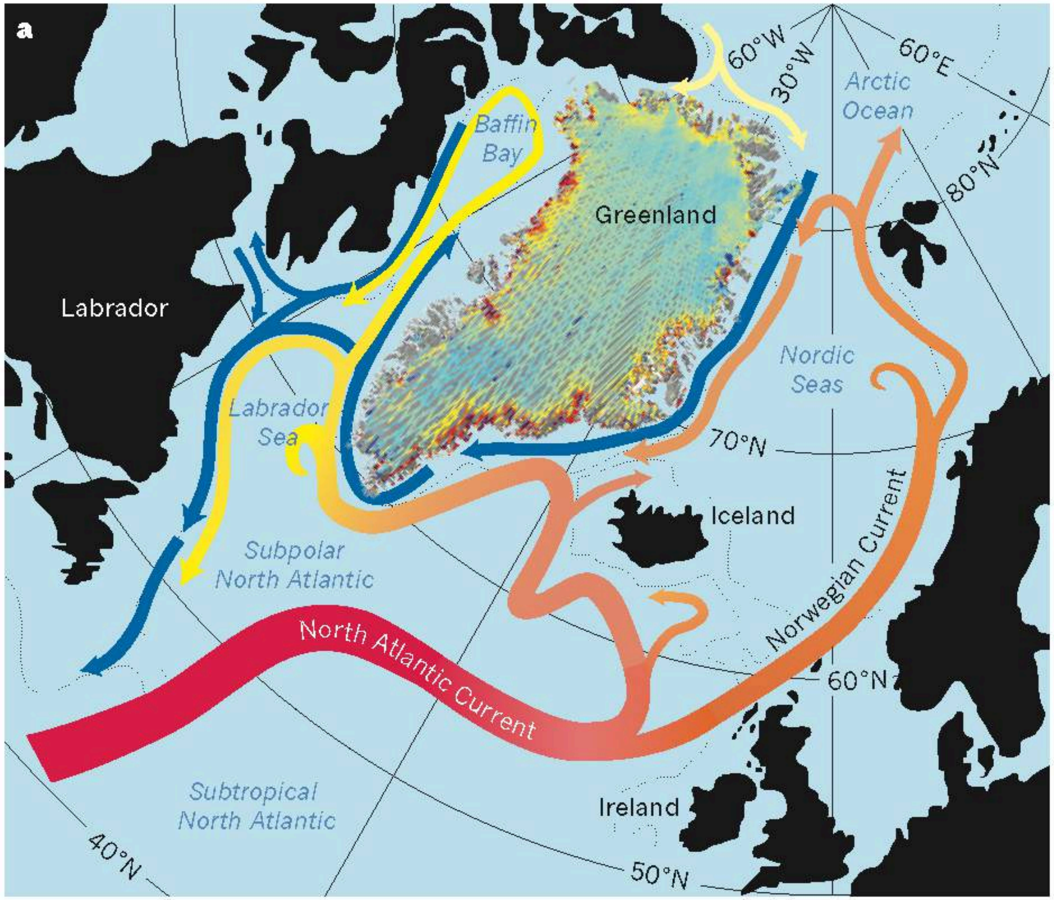
1. North Atlantic Meridional Overturning Circulation (MOC)



1. High latitude ocean circulation

Subpolar Gyre + Nordic Seas

- Circum-Greenland current
- Warm Atlantic Water
  → Greenland Fjords
  → into Arctic Ocean
- Dense water in Labrador and Nordic Seas
- Freshwater from Greenland Ice Sheet



[Straneo & Heimbach, 2013]

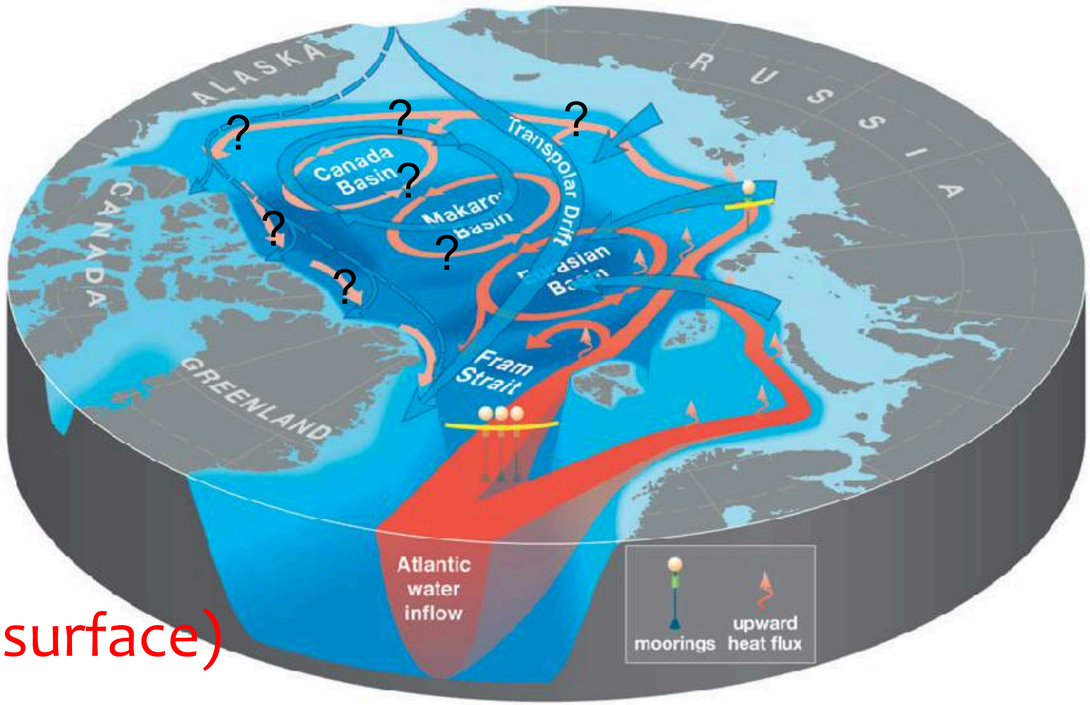
2. Arctic Ocean circulation

[Woodgate, 2012;
Polyakov et al., 2013]

Atlantic Water (deep)

- Enters at Fram Strait + Barents Sea Opening

→ subducts to mid-depth
→ follow topography
→ potential heat source to melt surface sea-ice



Pacific Water (mid depth & surface)

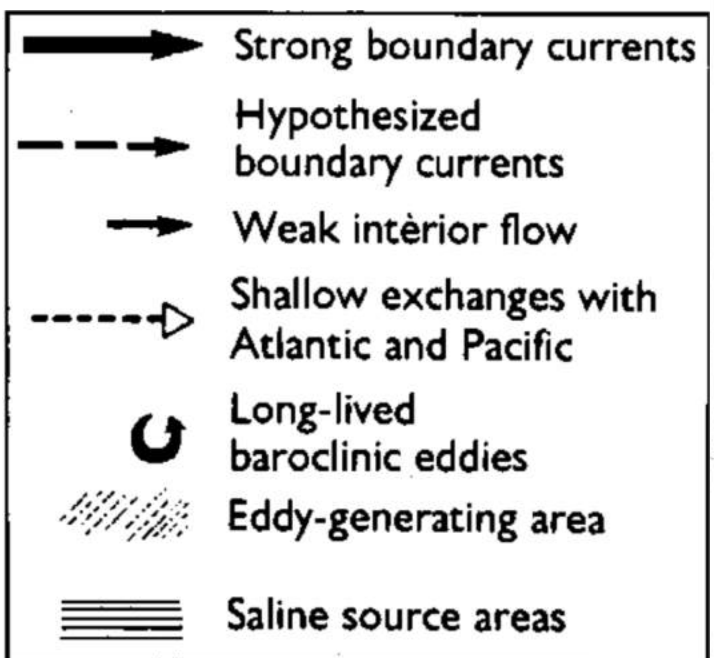
- Enters at Bering Strait
- Fresher water (33% of Arctic FW budget)
- Heat: near surface
- Wind driven circulation

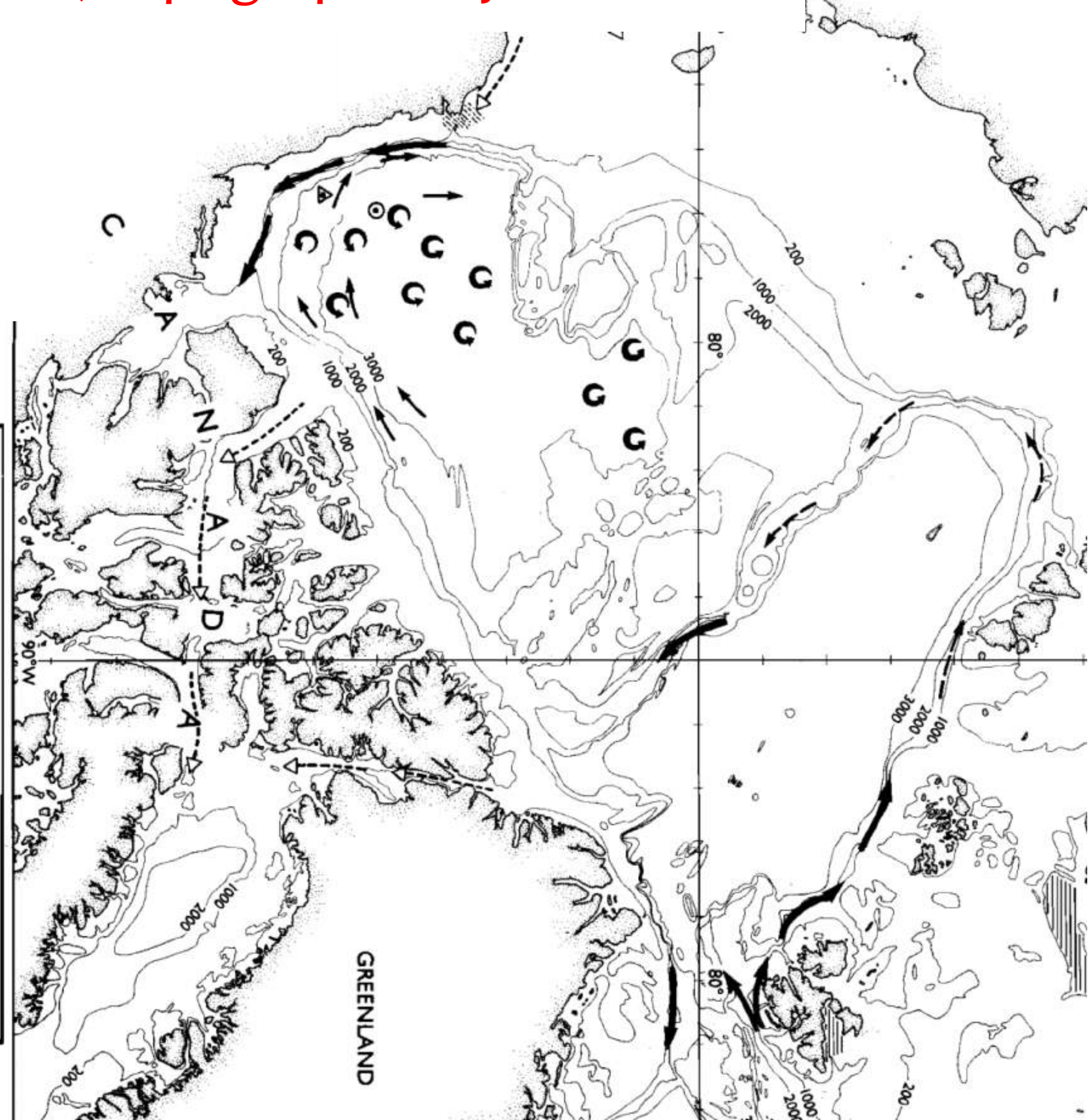
2. Arctic Ocean circulation

Boundary currents: cyclonic, topographically steered

Descriptive:

Helland-Hansen & Nansen [1909];
Aagaard, [1989, 1994];
Rudels [1994]; Holloway [2011];



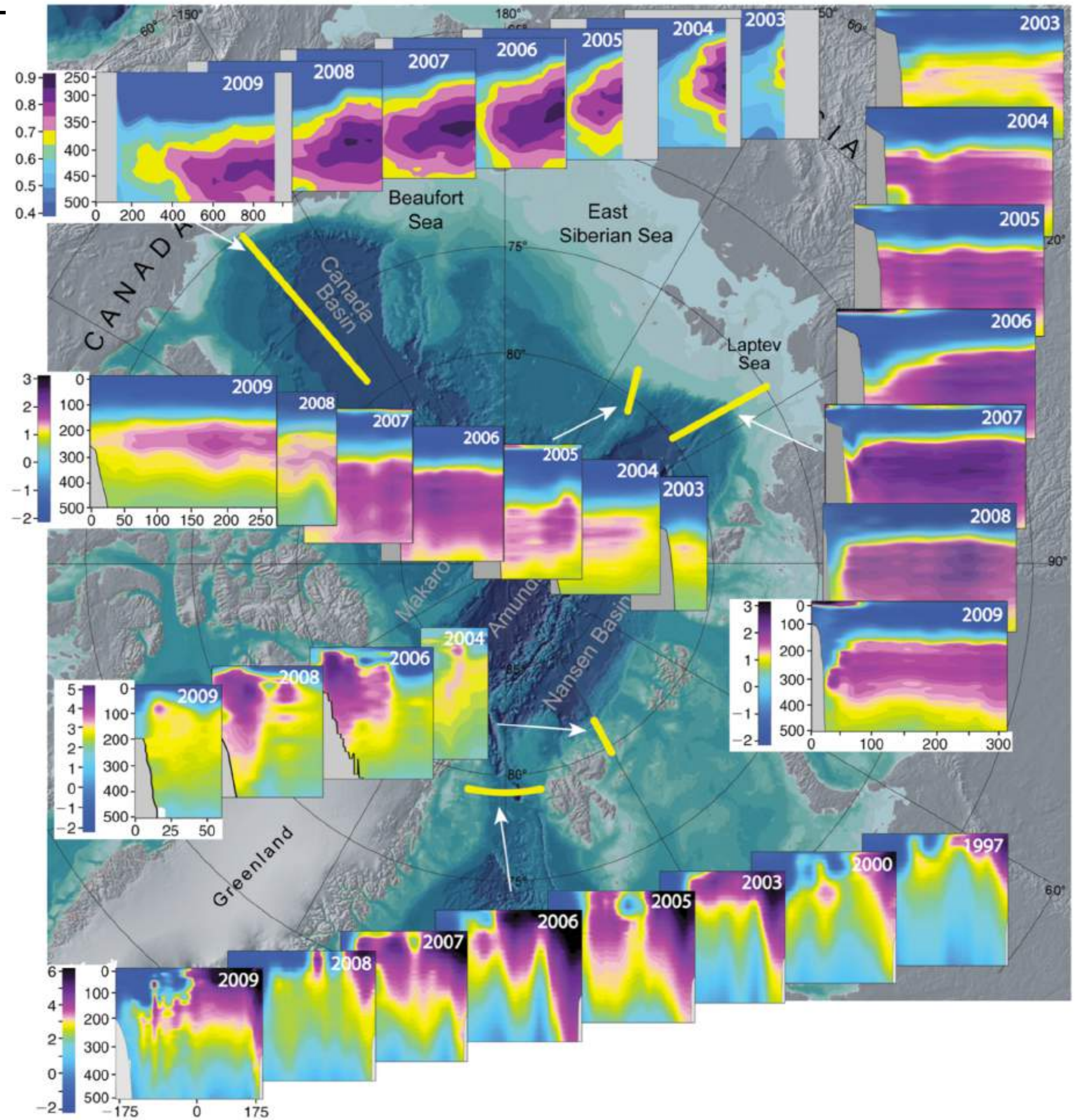


2. Arctic Ocean circulation

Boundary currents:
cyclonic,
topographically
steered

Descriptive:

Polyakov [2013]



2. Arctic Ocean circulation

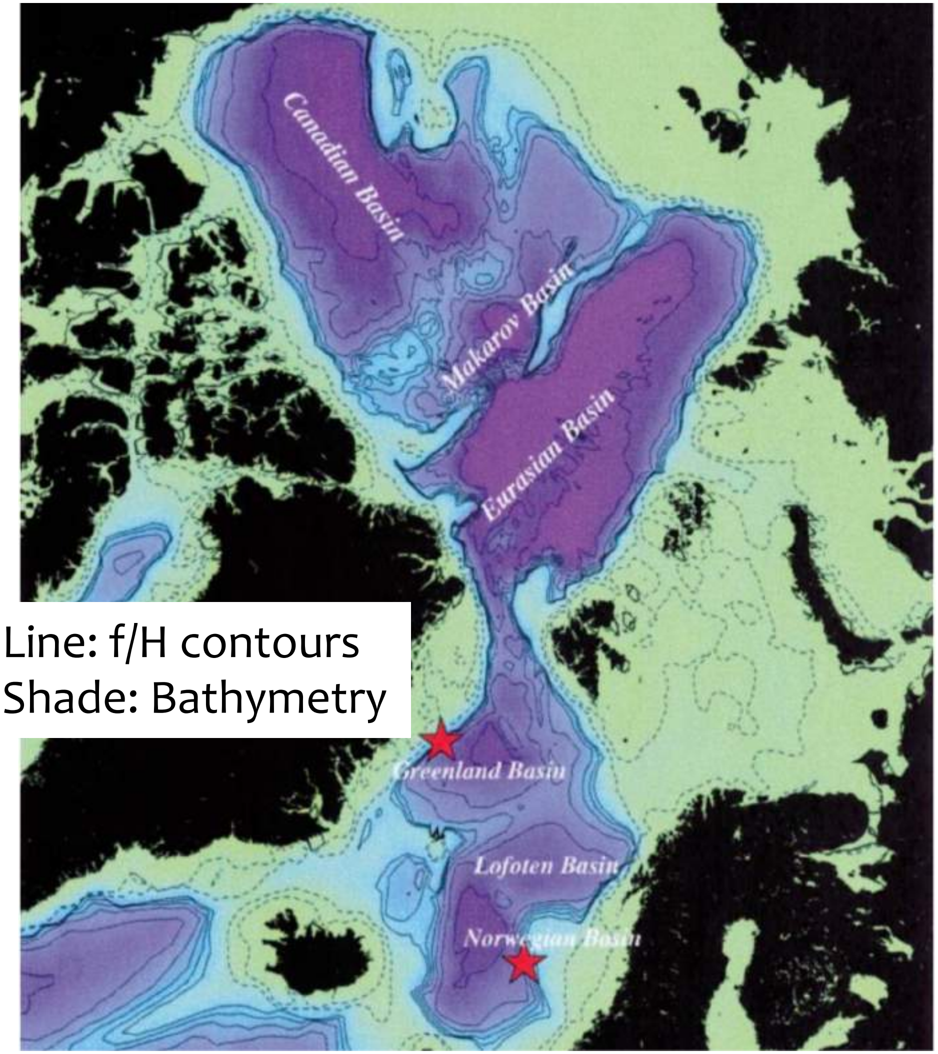
Boundary currents: cyclonic, topographically steered

<u>Theory & idealized model:</u>

Isachsen, JPO [2003]:

$$\frac{\partial}{\partial t}\mathbf{u} + \mathbf{k} \times f\mathbf{u} = -g\nabla\eta + \frac{\boldsymbol{\tau}}{\rho H} - \frac{R\mathbf{u}}{H}$$

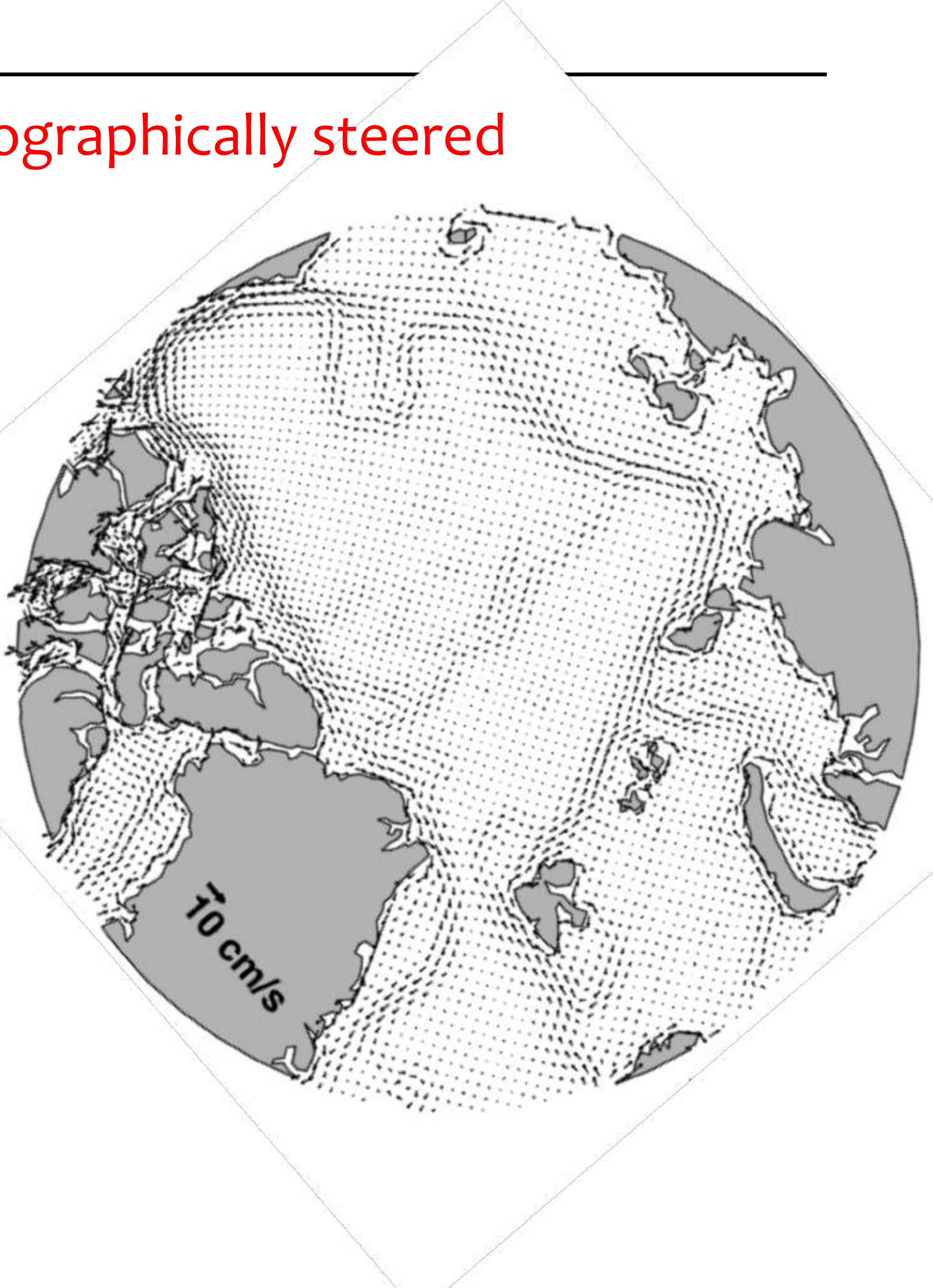
- barotropic model
- homogeneous fluid
- assumes balance between surface & bottom Ekman transports in region bounded by closed f/H contour
- winds (or ice) stress at surface
- analytical solution for barotropic currents
- **bottom Ekman drag**
  $R = (\nu f/2)^{-1/2}$, ~ 1.0×10^{-3} m s^{-1},



Line: f/H contours
Shade: Bathymetry

2. Arctic Ocean circulation

Boundary currents: cyclonic, topographically steered



Theory & idealized model:
Carnevale & Frederiksen [1987]
Holloway [1984, 1992, 2004, 2008, 2009, 2011]
Merryfield et al. [2000]

- interaction between eddies and bathymetry: rectified mean flow

→ steady flow along f/H contours

$\tau = \mathbf{f} \times \mathbf{u} \bullet \nabla H$: + in the world ocean, increasing poleward.

u: flow with shallower topography to the right in the Northern Hemisphere

2. Arctic Ocean circulation

Boundary currents: cyclonic, topographically steered

Theory & idealized model:

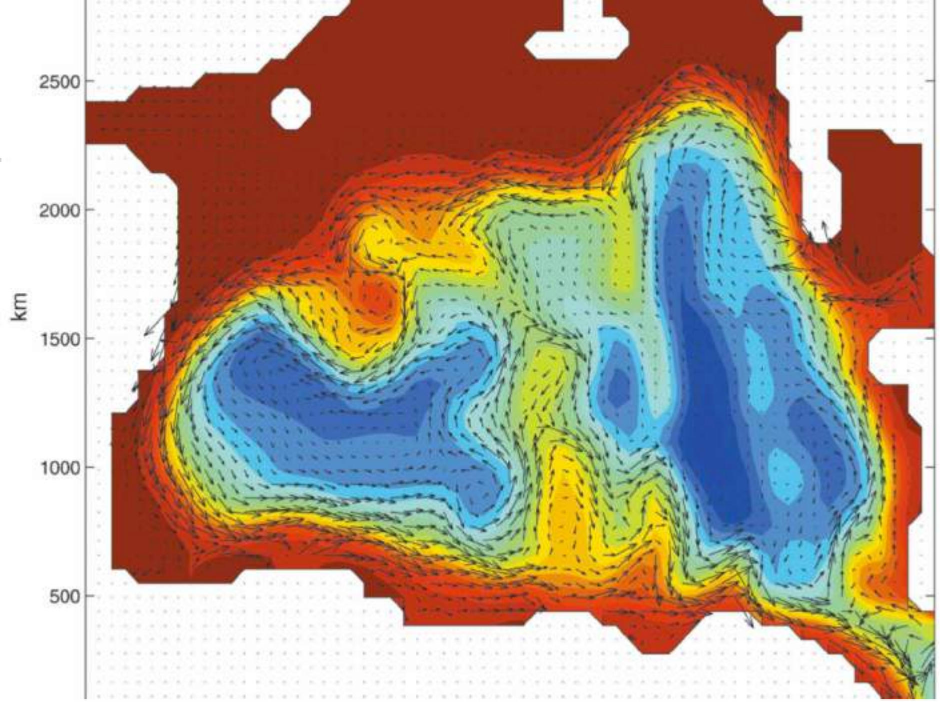
Yang, [2005]

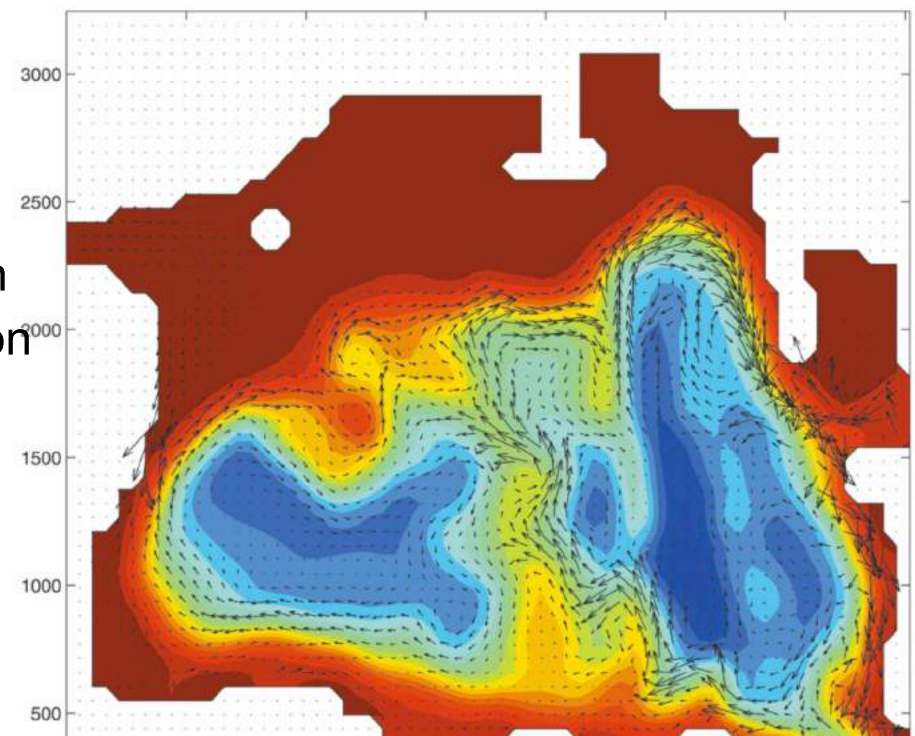
$$\frac{Du}{Dt} - fv + g\frac{\partial h}{\partial x} = \frac{A_H}{H}\nabla\cdot(H\nabla u) + F^x,$$

$$\frac{Dv}{Dt} + fu + g\frac{\partial h}{\partial y} = \frac{A_H}{H}\nabla\cdot(H\nabla v) + F^y,$$

$$\frac{DH}{Dt} + H\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = 0,$$

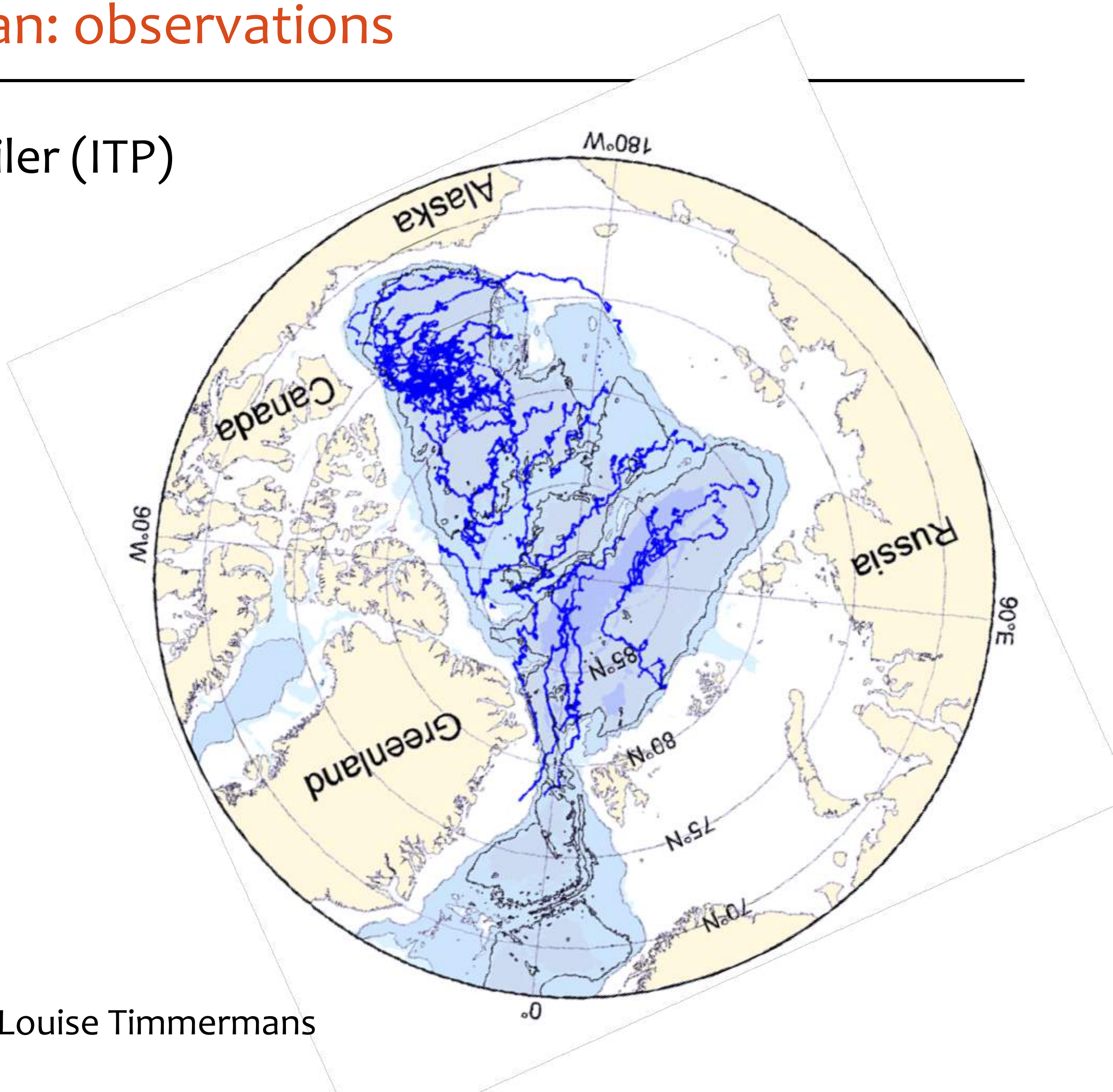
- net flux of PV: controls circulation direction
- net lateral PV inflow balances PV dissipation along the boundary
- barotropic model, forced ONLY by net flux of PV





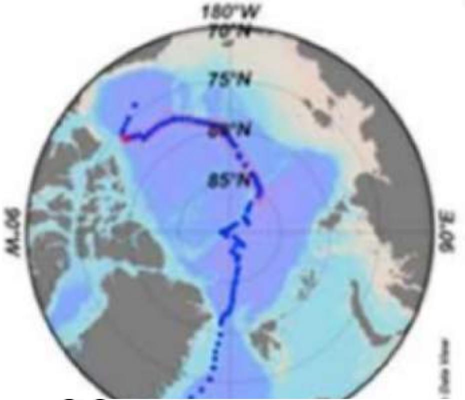
2. Arctic Ocean: observations

Ice-Tethered Profiler (ITP)



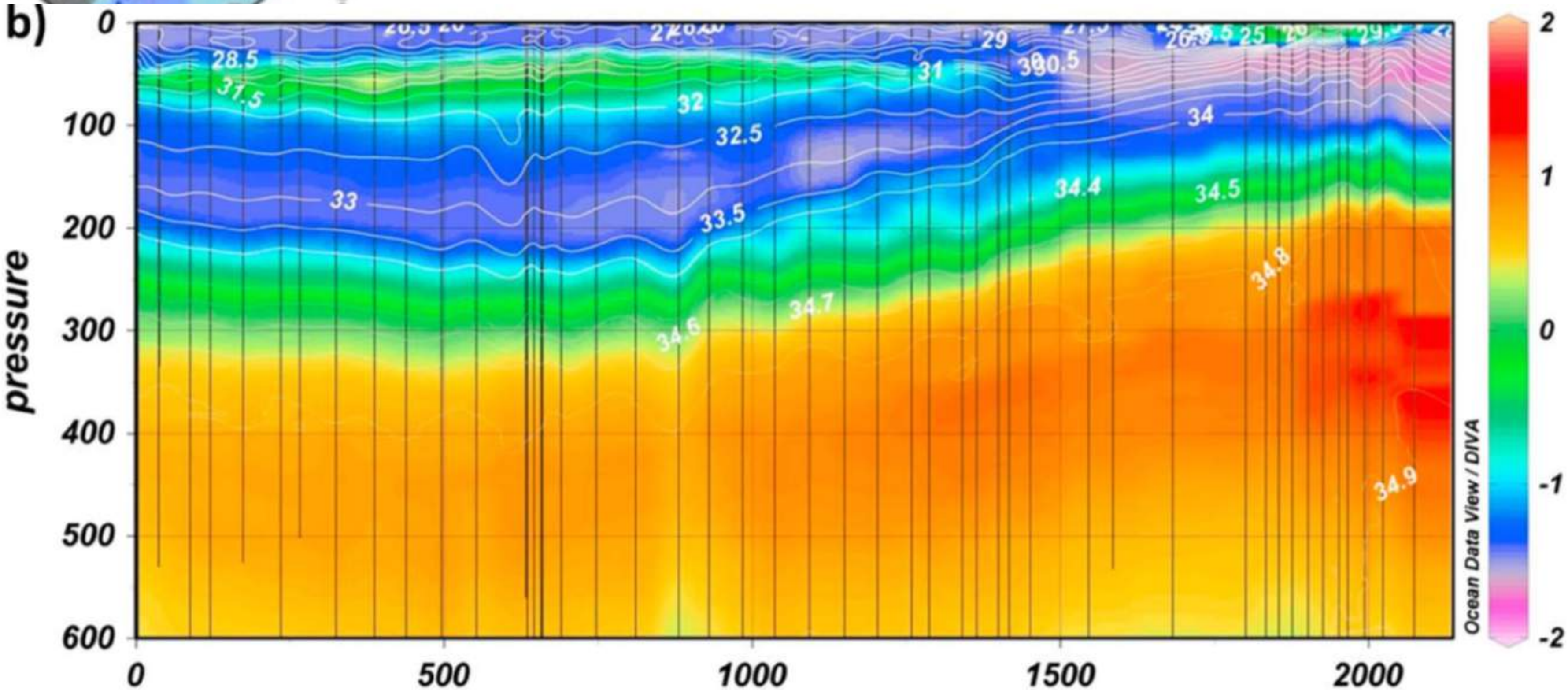
slide courtesy of Mary-Louise Timmermans
see www.whoi.edu/itp

2. Arctic Ocean temperature structure

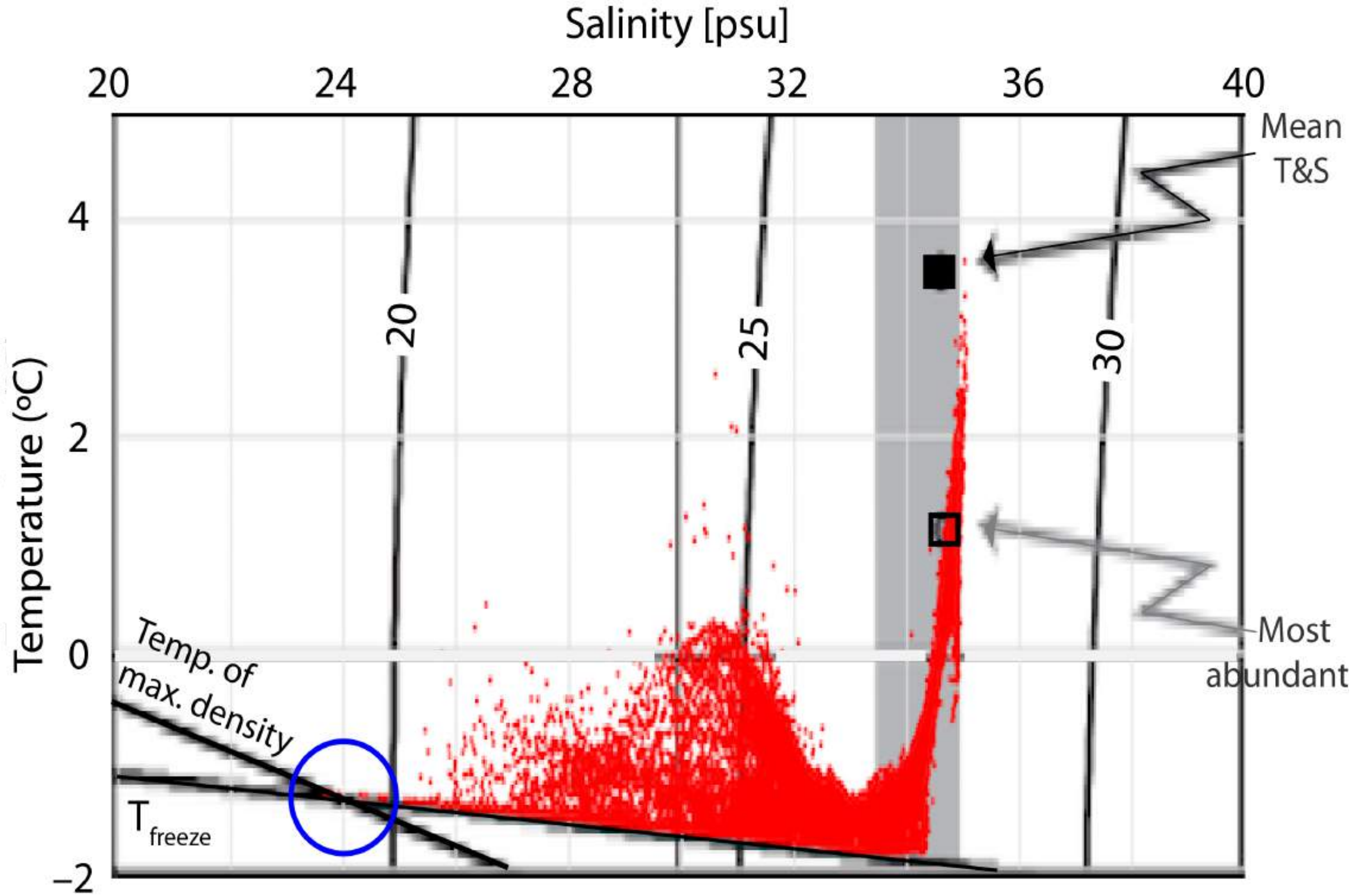


Warm water below cold water!

[Carmack et al., 2017]



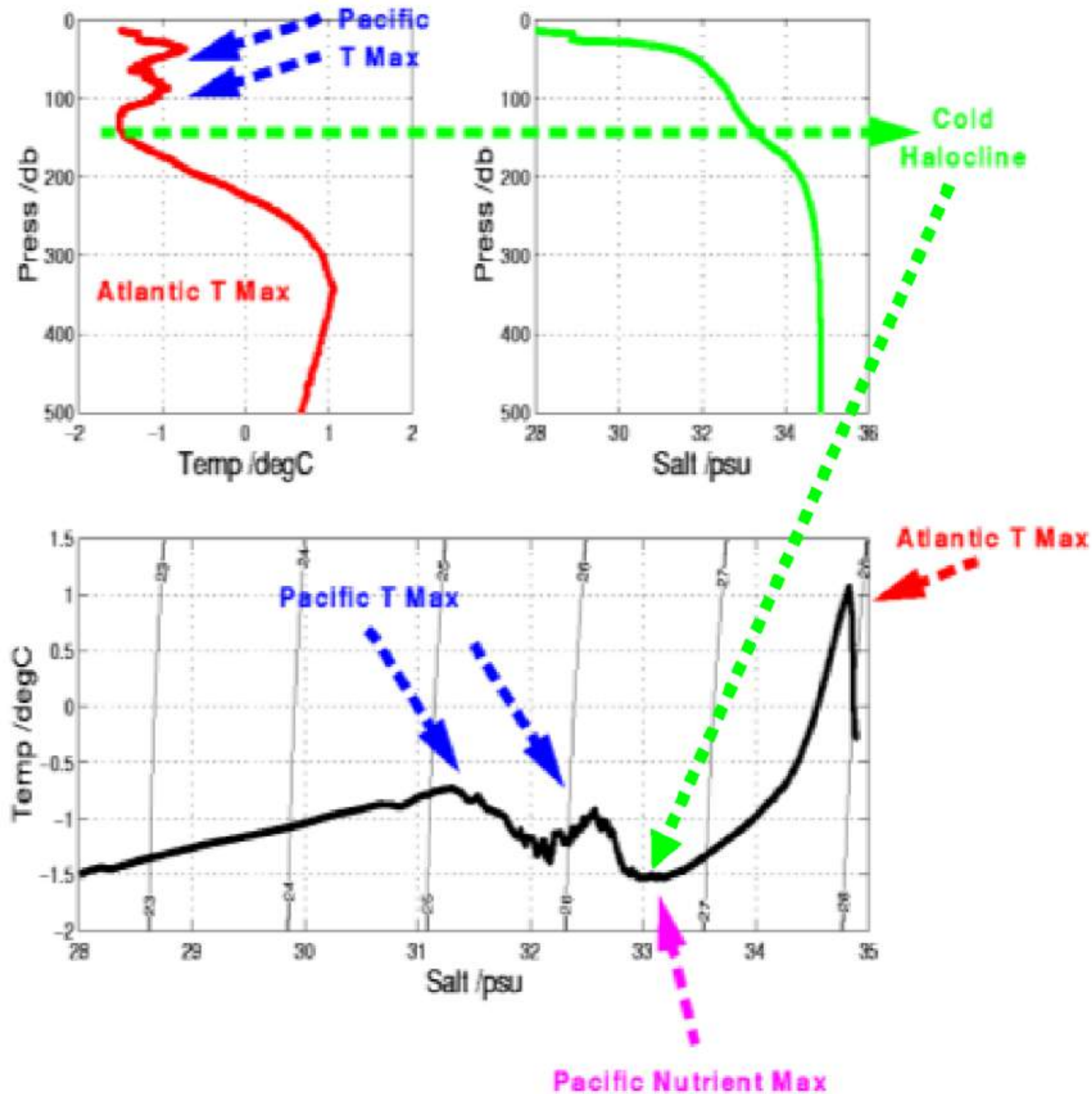
2. Arctic T/S structure



[Talley, "Descriptive physical oceanography"], ITP data

2. Arctic Ocean: T/S structure

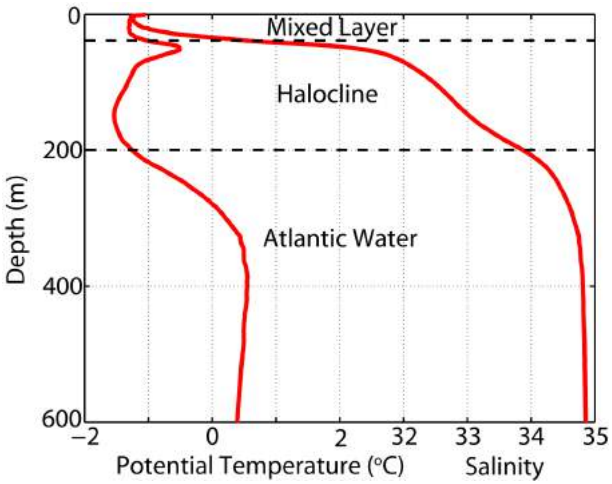
The "Accent" of Sea Water - Pacific and Atlantic Waters in TS space

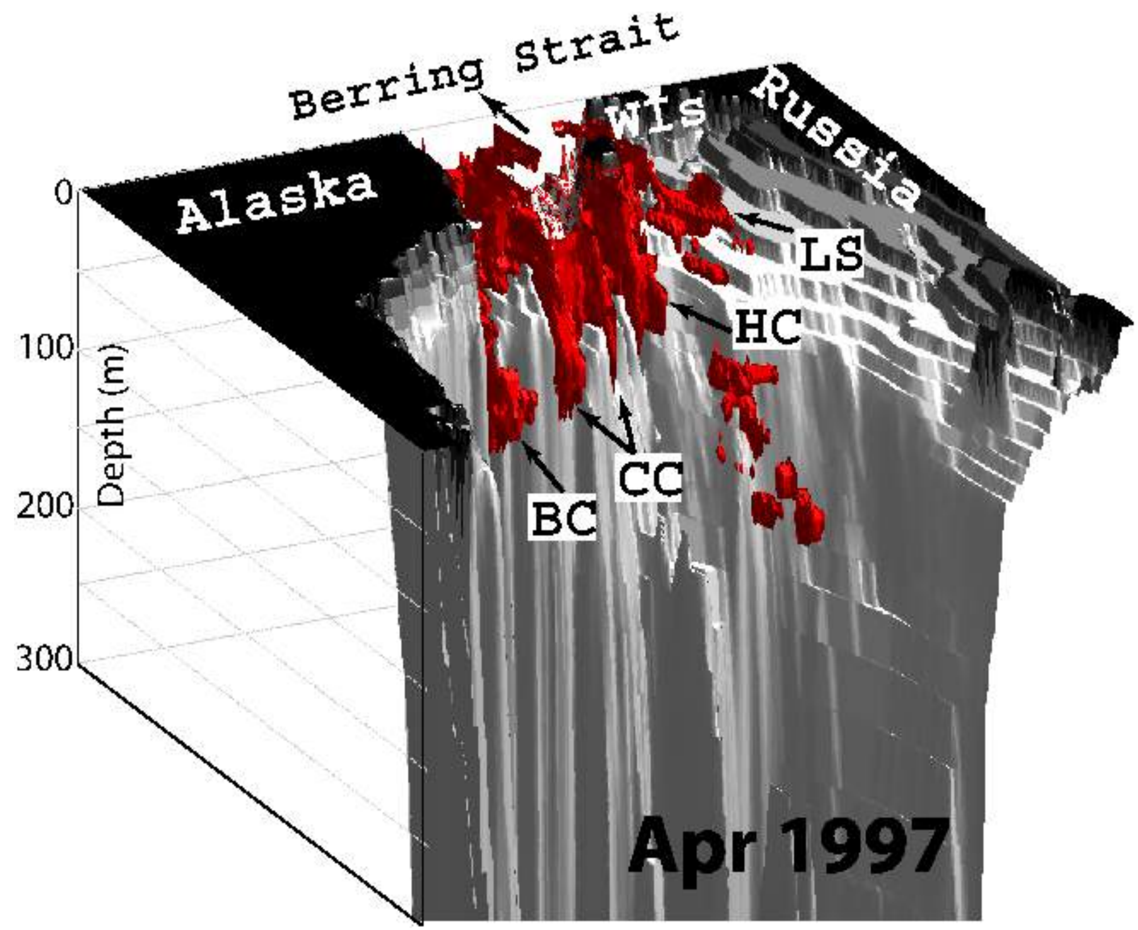


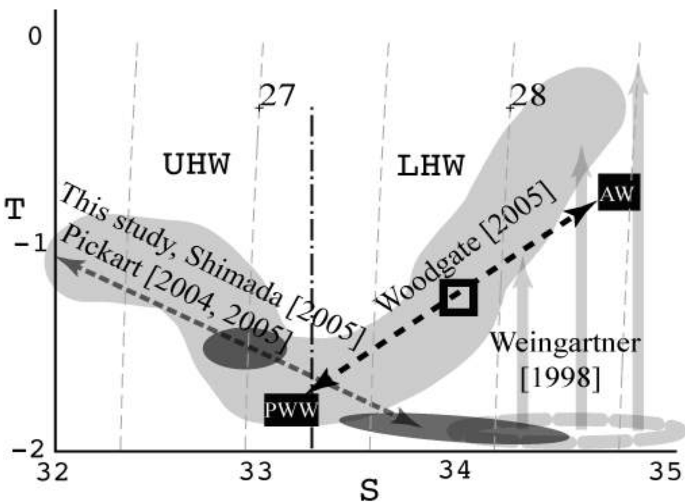
- density determined mostly by salinity at T < 2 deg C

slide courtesy of Rebecca Woodgate

2. Arctic Ocean: T/S structure: the halocline

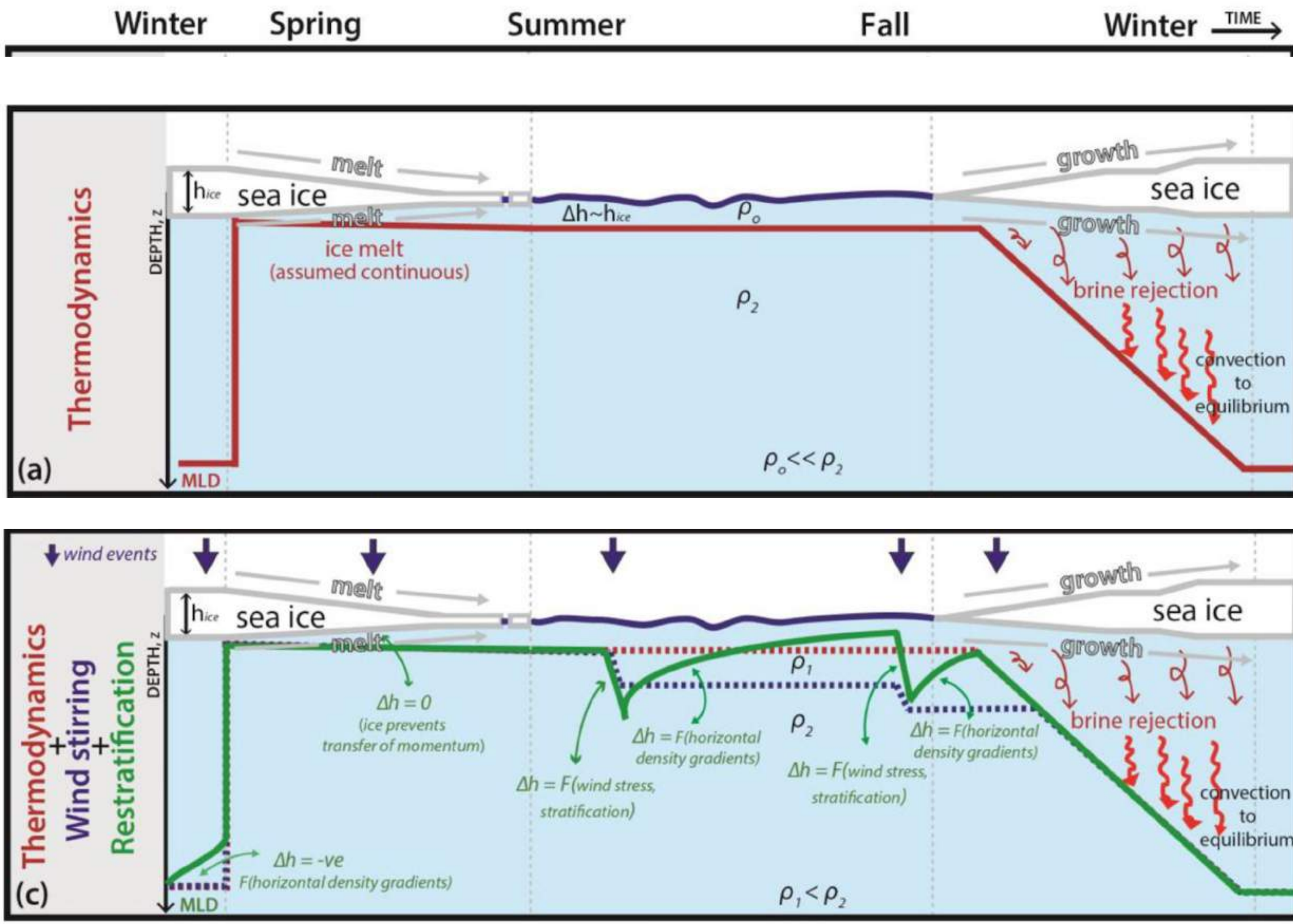






[Nguyen et al., 2009, 2012]

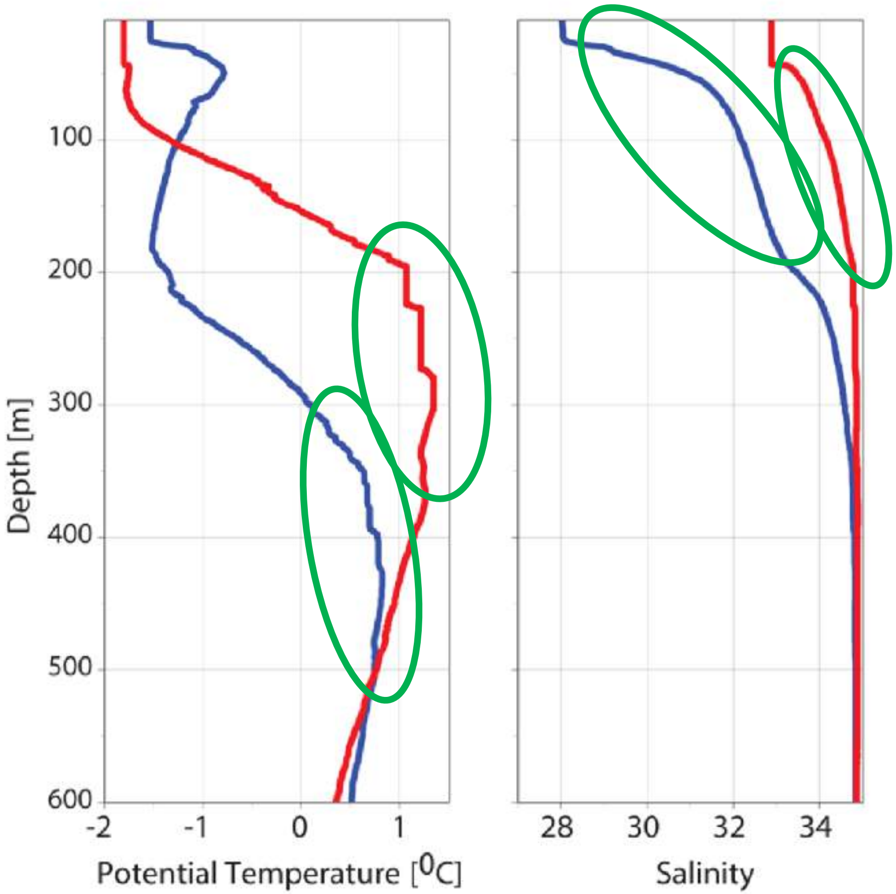
2. Arctic Ocean: T/S structure: the mixed layer



[Peralta-Ferriz and Woodgate, 2014]

2. Arctic Ocean: Getting the heat up?

Through the halocline?



Work needed to bring much heavier water up 150-350m

<u>Mechanism</u>:
- Advection?
- Diffusion?
- Eddy stirring?
- Horizontal vs vertical?
- Basin interior vs continental shelves?

<u>Energy source:</u>
- Winds (at surface)
- Tides (next to topography)
- Eddy shedding (off strong boundary currents)

2. Arctic Ocean: mixing at depths

Double diffusion: stratified fluid, two components having different molecular diffusivities
Sea water: temperature diffuses ~ 100x faster than salt

Case 1: Salt fingering:

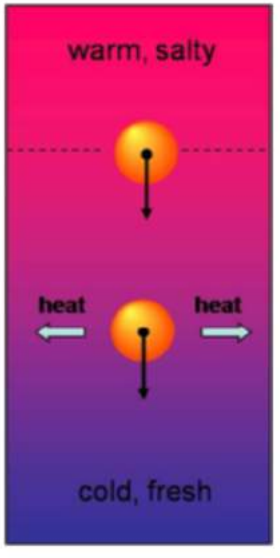


Figure 1: Schematic of the salt finger mechanism.

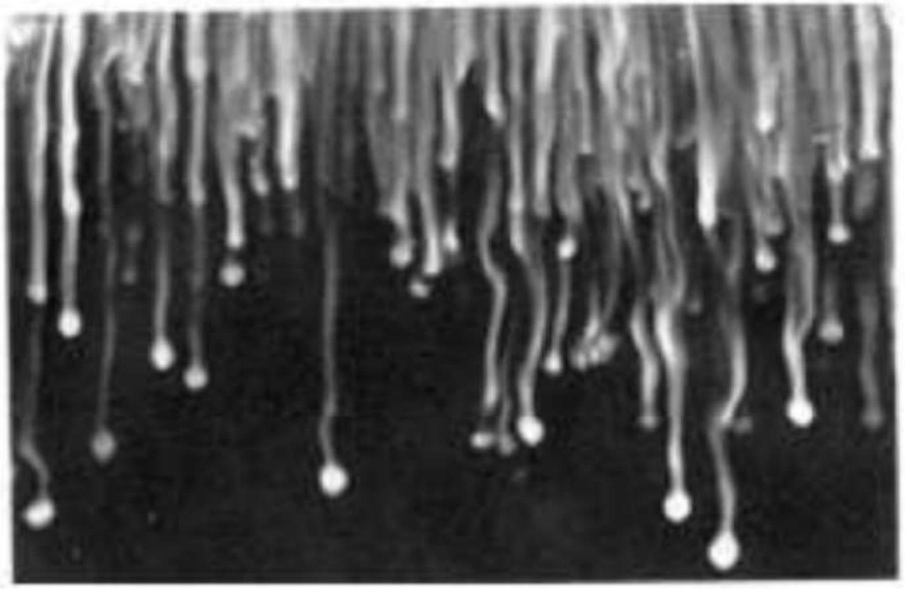


Figure 2: Salt fingers in a laboratory experiment [3].

Radko , "Double-Diffusive Convection" lecture, https://www.whoi.edu/fileserver.do?id=136325&pt=10&p=85733
Turner 1974, "Double-Diffusive Phenomena", Annu Rev Fluid Mech .

2. Arctic Ocean: mixing at depths

Double diffusion: stratified fluid, two components having different molecular diffusivities
Sea water: temperature diffuses ~ 100x faster than salt

Case 2: Diffusive convection:

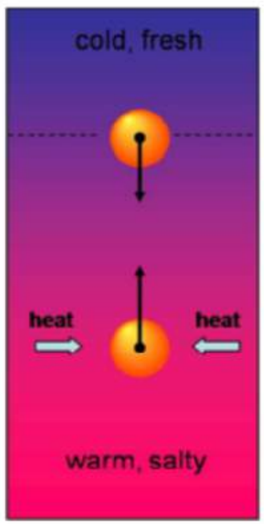
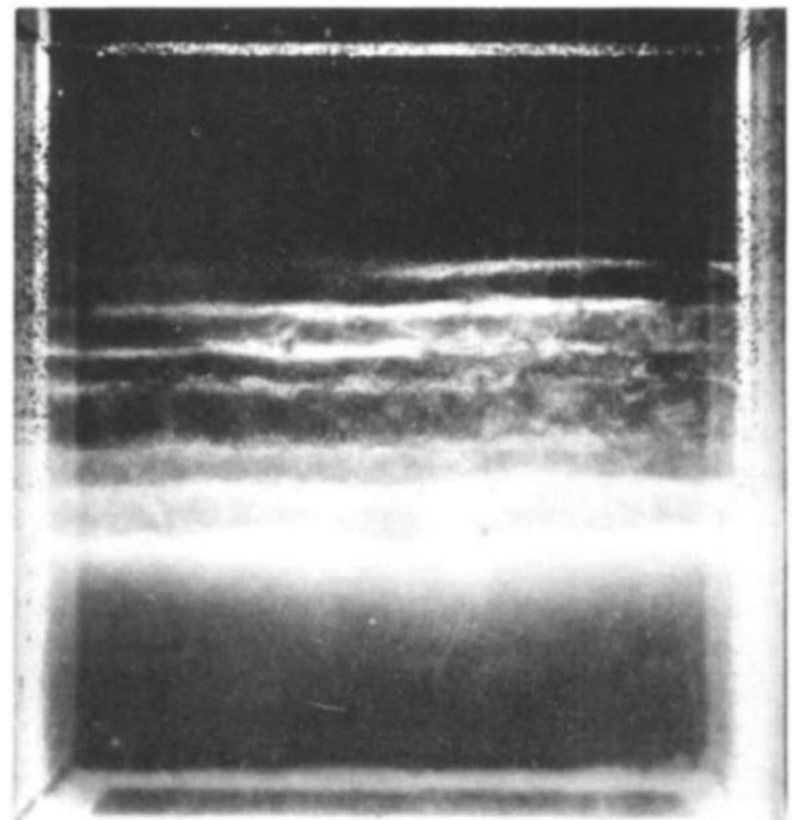


Figure 3: Schematic of the diffusive convection mechanism.

at the top. Strong turbulent convection persists in each layer, driven by the heat flux across the interfaces, while much of the salt is left behind to maintain a mean density distribution that is lighter at the top.



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2. Arctic Ocean: mixing at depths

Staircases:

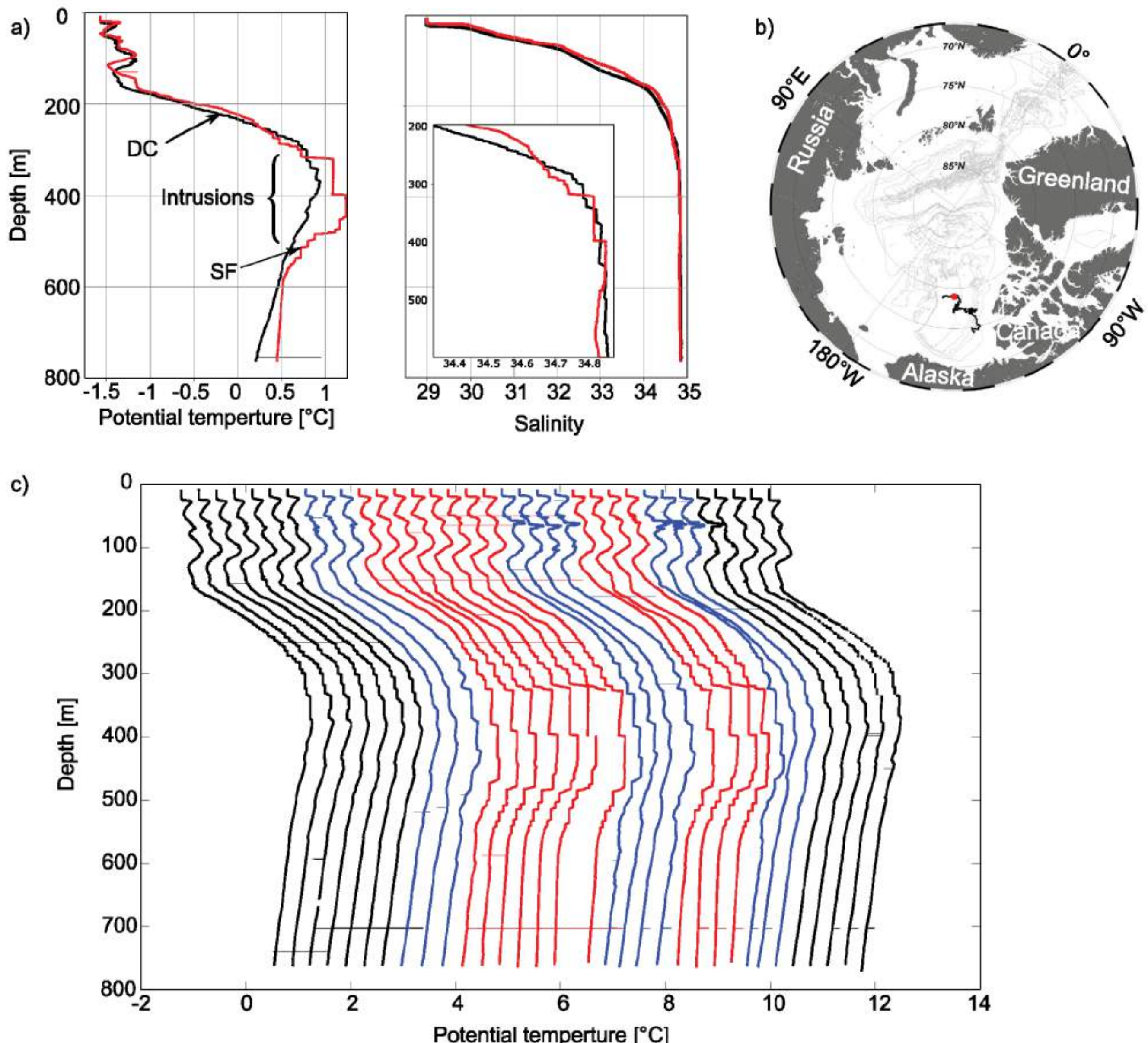
Observed throughout the Arctic ocean interior

Lateral extent ~5000km

Processes:
- Diffusive convection
- Salt fingering

(molecular level, **below instrument noise level!**)

“quiet ocean?”



Bebieva & Timmermans [2015]

2. Arctic Ocean: mixing at depths

Eddies:

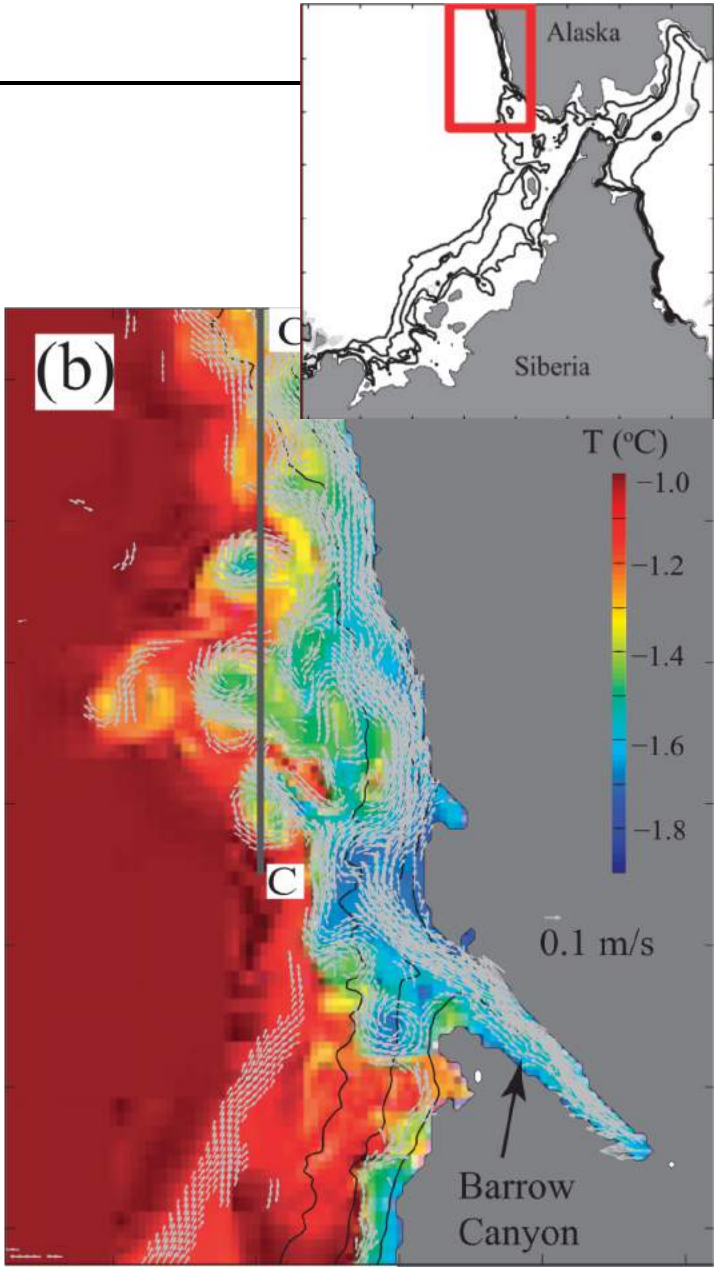
Western Arctic interior:

+ L ~ 13km [Zhao et al., 2014, ITP data]
+ "halocline eddies" , at depths 50-250m
+ anticyclonic, cold (west) and warm (east) cores

Eastern Shelf-basin slopes [Pnyushkov 2018]

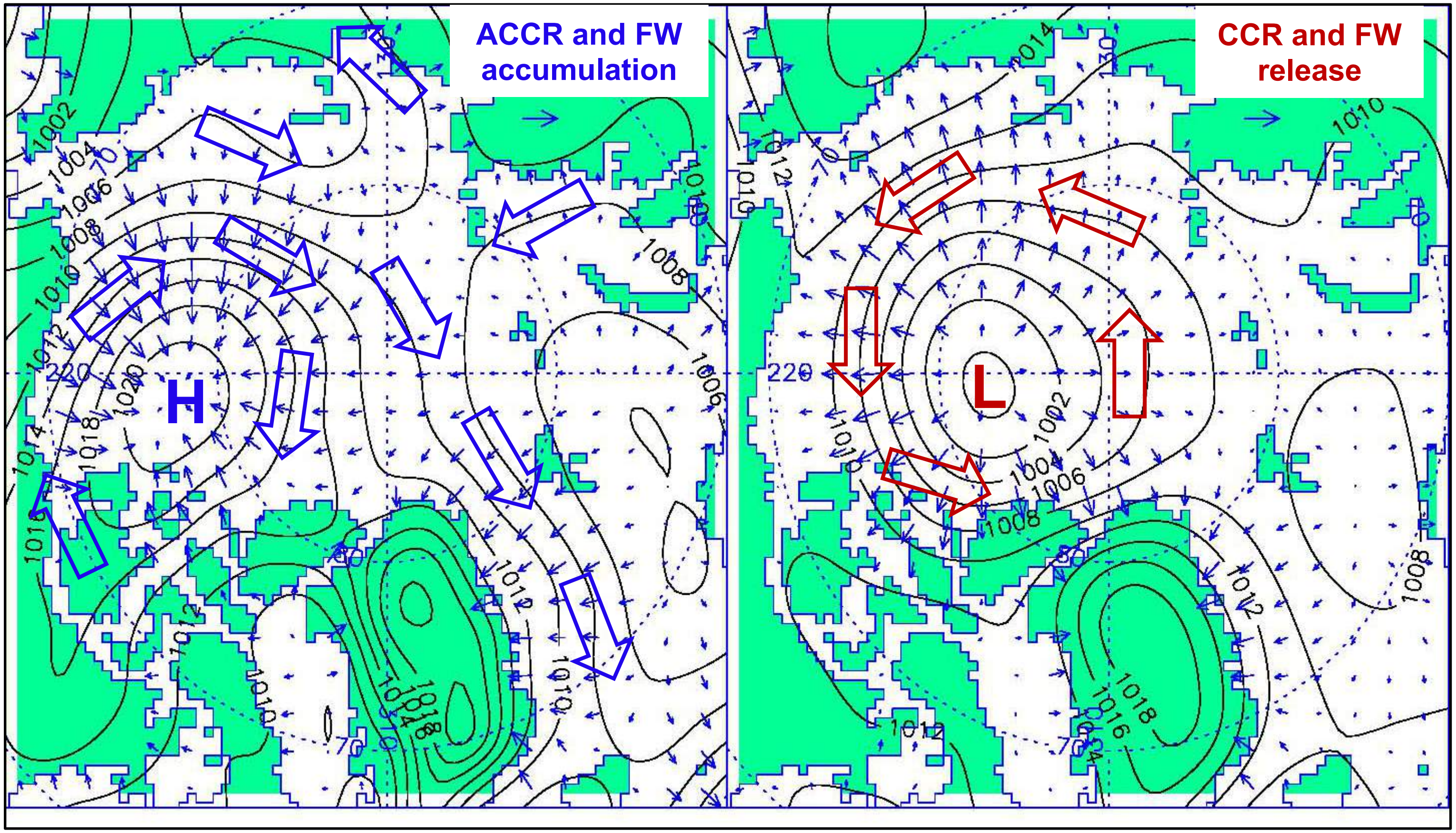
+ L ~10km
+ 600-800m vertical extent
+ 1 eddy/month (passing by mooring)
+ generated at Fram Strait and at St Anna Trough (merge of two incoming AW branches)
+ enhancing diapycnal mixing

Life time 0.9-5 years
[Zhao et al., 2014, Padman et al., 1990]



[Nguyen et al. 2012]

1. Arctic Ocean: surface currents – wind driven



Panels shows SLP (black lines, hPa) wind directions (large arrows) and Ekman transport (blue small arrows) typical for ACCRs (left) with Ekman transport converging; and CCRs (right) with Ekman transport diverging.

Slide from A.Proshutinsky

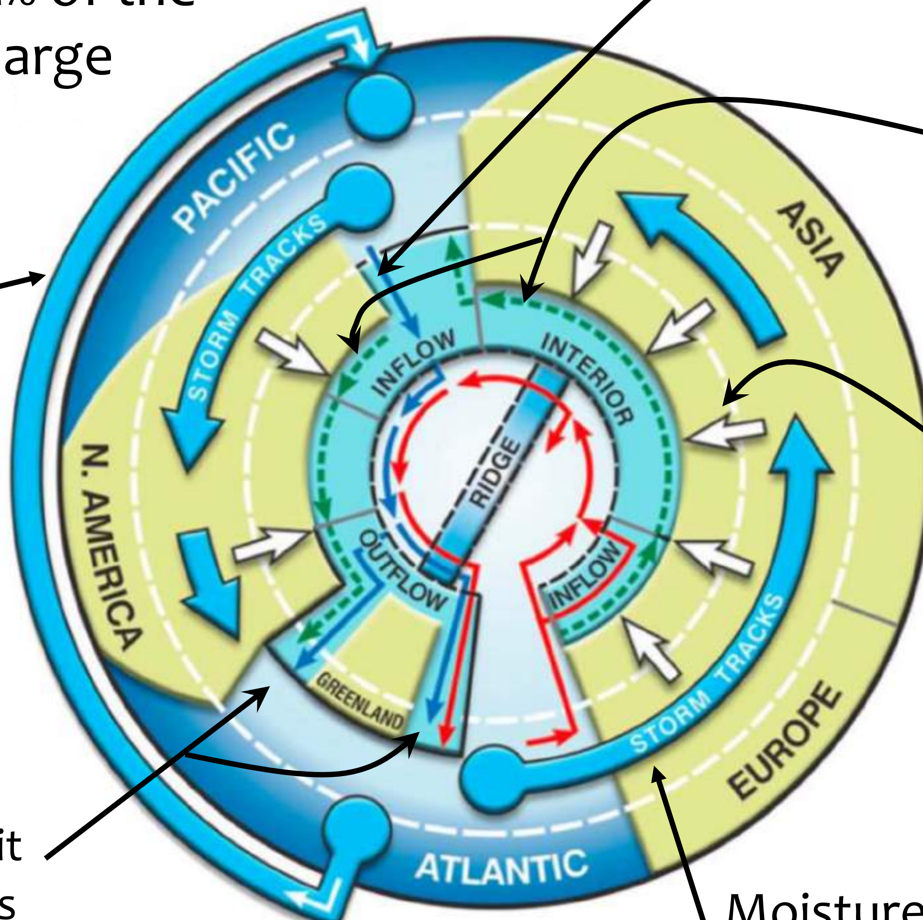
1. Arctic Ocean: Fresh Water inputs

1% and 3% global ocean volume & surface area, receives >11% of the global river discharge

Inflow through Bering Strait, Surface circulation,

initial spreading within the Riverine Coastal Domain

moisture transported in the subtropical via the Trade Winds



Draining from catchments into the Arctic Ocean

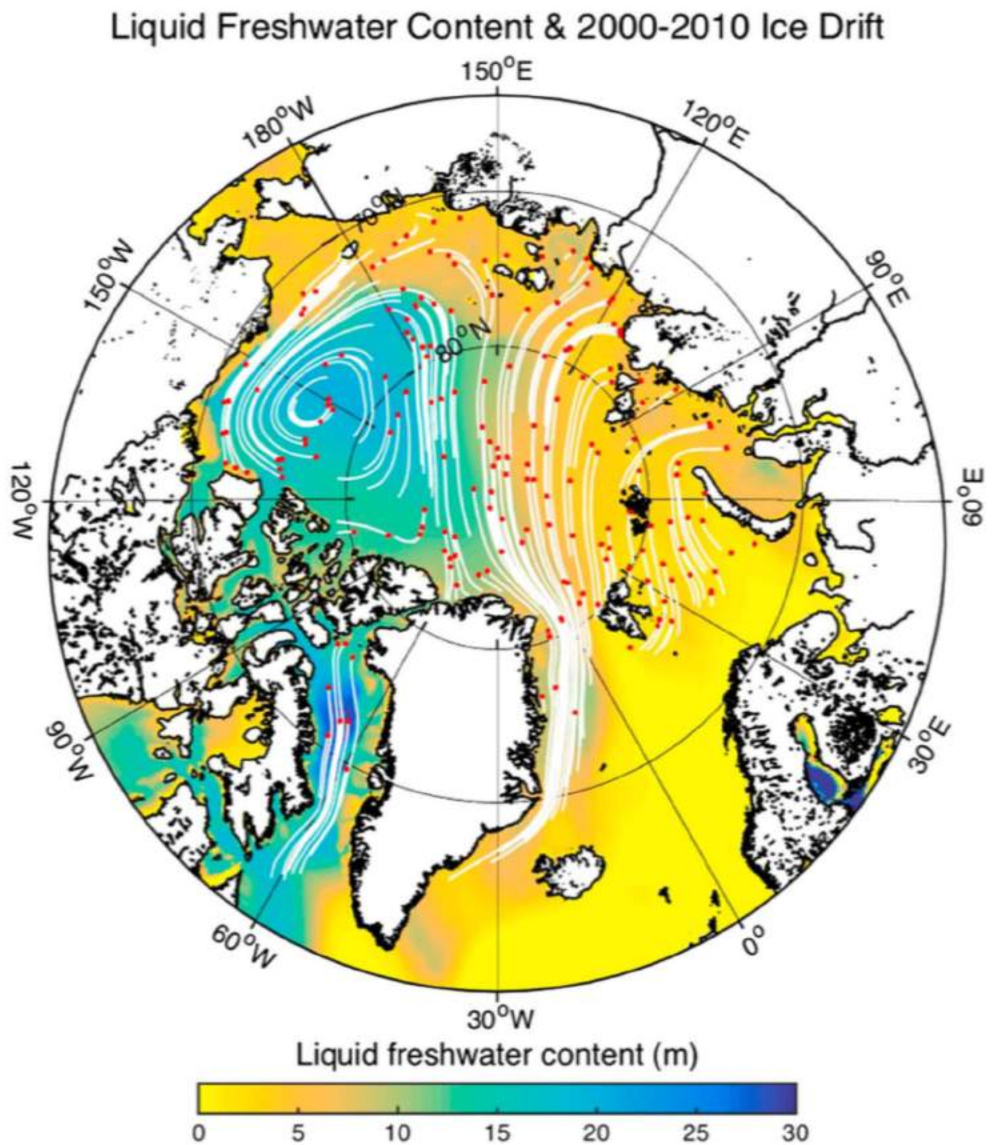
Outflow through CAA & Fram Strait to lower latitudes

Moisture transported to the Arctic catchment basins by mid-latitude (Westerlies) storm tracks

Carmack et al., [2016]; Prowse et al. [2015a, 2015b]

1. Arctic Ocean: surface currents – Fresh Water distribution

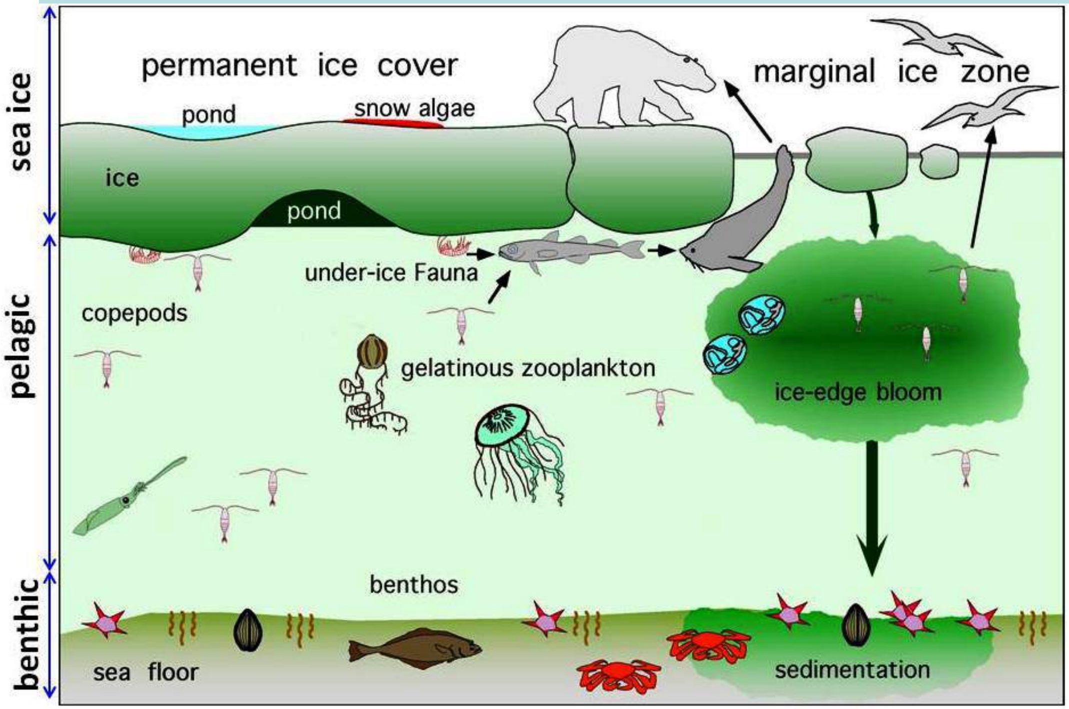
- Recirculation pathway: dissolved and particulate materials
- Surface freshening:
  ↘ primary production
- Export to lower latitudes:
  1. carbon & nutrients
  2. ΔSSS and dense water formation
- sea ice decline:
  → feedback to the atmosphere
  → jet stream and storm tracks over the North America and Eurasia

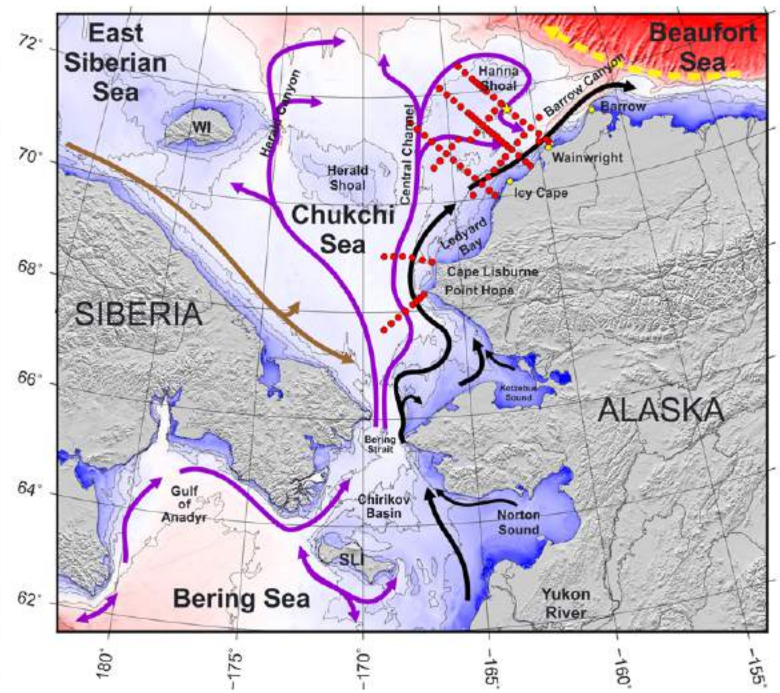


Carmack et al., JGR-Biogeosciences 2016: "Freshwater and its role in the Arctic Marine System: Sources, disposition, storage, export, and physical and biogeochemical consequences in the Arctic and global oceans"

4. Arctic Ice-Ocean Interaction and biology

https://ioos.noaa.gov/news/year-1-results-arctic-marine-biodiversity-network/
http://www.marinebon.org , https://ambon-us.org





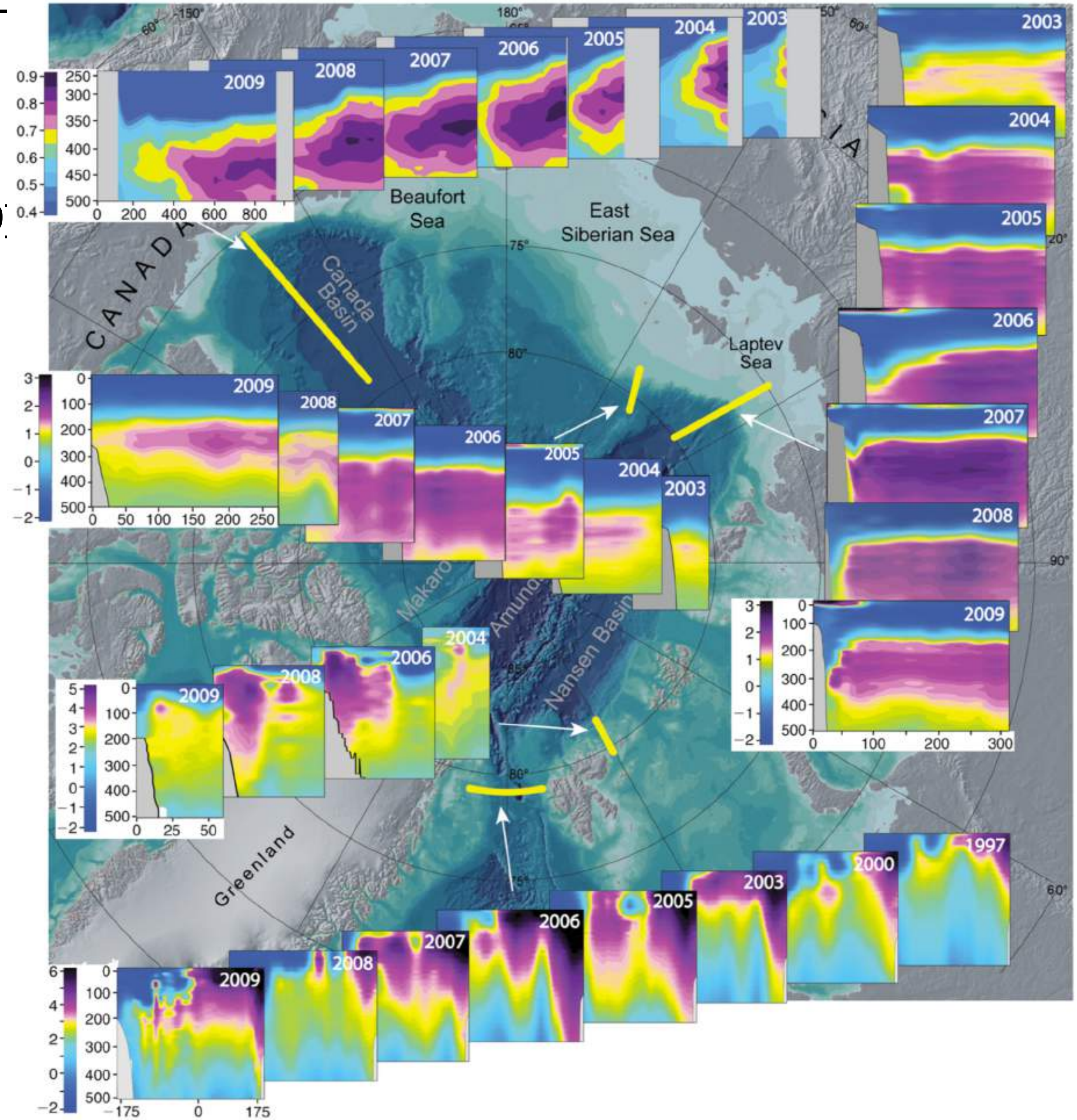
The simulated increase in the area fraction as well as primary productivity and chlorophyll *a* biomass is linked to an increase in light availability, in response to a decrease in sea ice and snow cover, and an increase in nutrient availability in the upper 100 m of the ocean, in conjunction with an intensification of ocean circulation.

Zhang et al., 2015, “The influence of sea ice and snow cover and nutrient availability on the formation of massive under-ice phytophankton blooms in the Chukchi Sea”

3. Arctic Atlantification

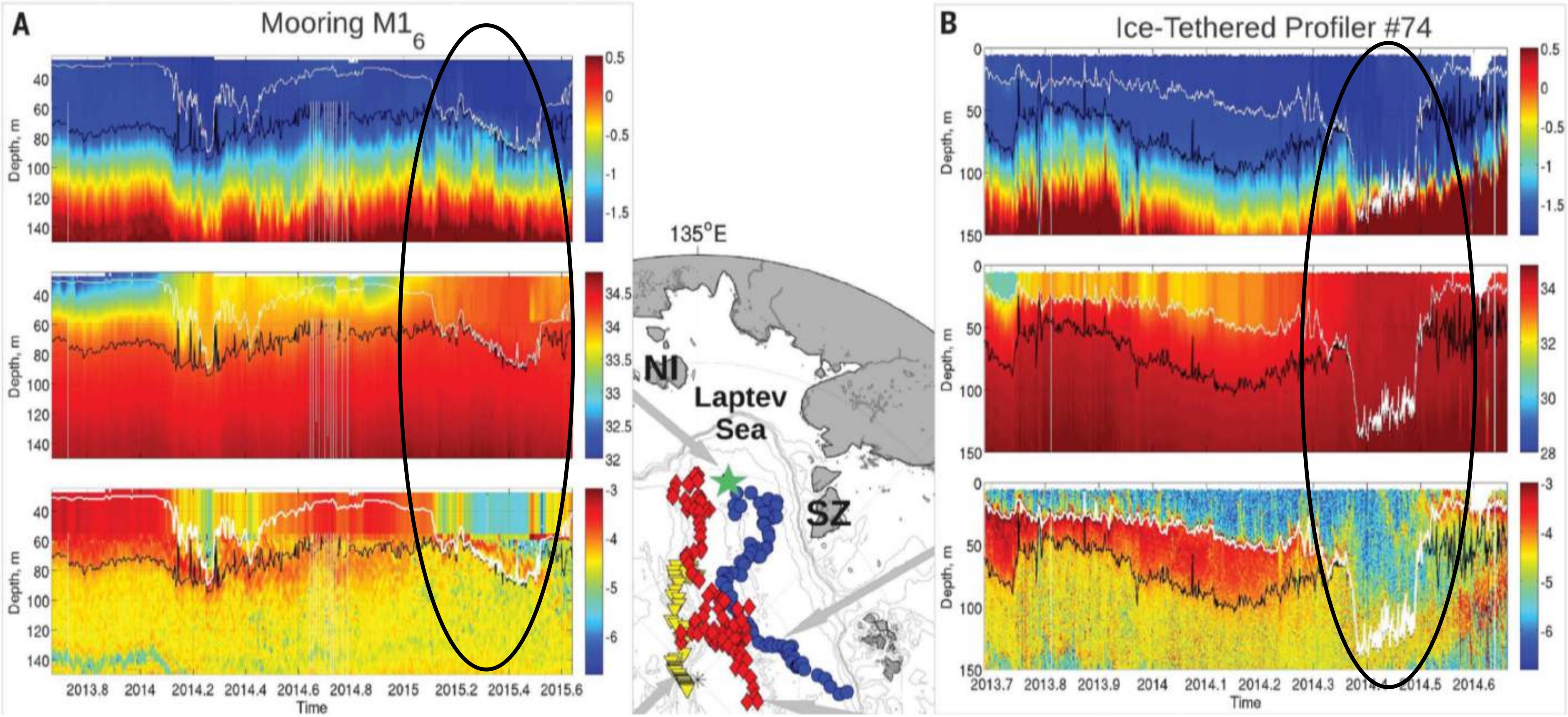
2000's: warm pulses of Atlantic Water into Arctic interior

Polyakov et al. [2012, 2013, 2019]
Dmitrenko et al. [2008]
Beszczynska-Möller et al. [2012]



3. Arctic Atlantification

Polyakov et al. [2017]

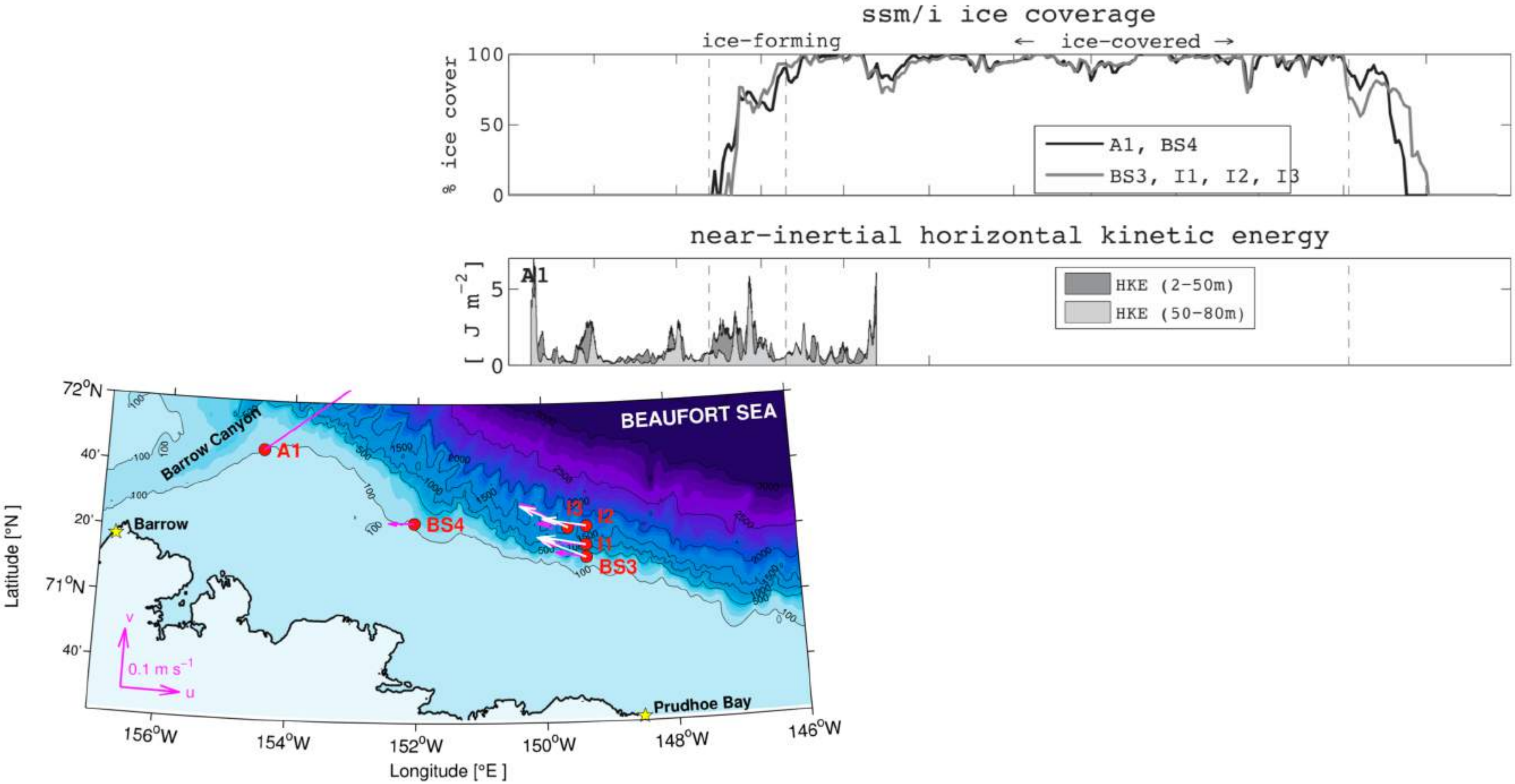


Direct communication between surface mixed layer and top of Atlantic Water layer

3. Arctic Ice-Ocean interaction – Shelf-Basin exchange

Martini et al., JPO 2014, "Near-Inertial Internal Waves and Sea Ice in the Beaufort Sea"

When ice is absent, from July to October, energy is efficiently transferred from the atmosphere to the ocean, generating near-inertial internal waves. When ice is present, from November to June, storms also cause near-inertial oscillations in the ice and mixed layer, but kinetic energy is weaker and oscillations are quickly damped. Damping is dependent on ice pack strength and



Some thoughts

Arctic system changes: local and global impact

- ecosystem, food supply
- transports
- oil drilling

In order to assess/understand changes:

- need to understand circulation and dynamics of the system

Arctic ocean: still highly under-observed

→ ECCO-related efforts!