The Arctic Subpolar gyre sTate Estimate (ASTE)

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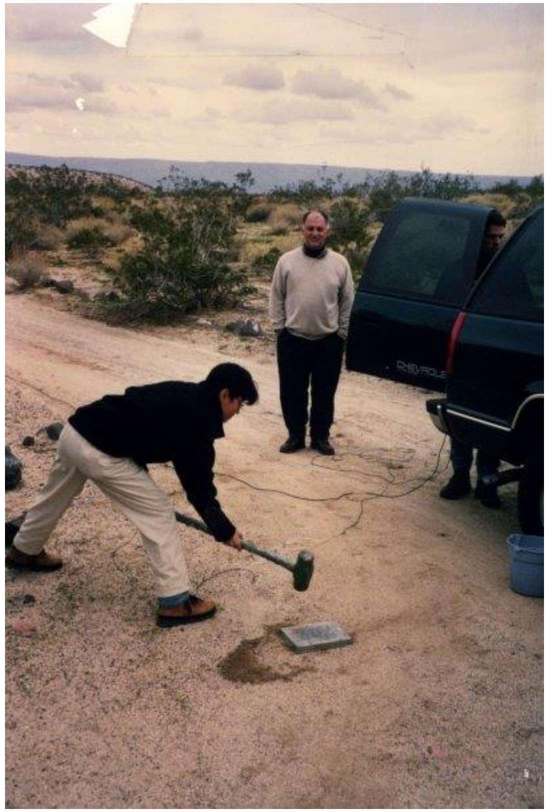
(University of Texas, Austin)

Estimating the Circulation and Climate of the Ocean

Summer School 29 May 2025

The University of Texas at Austin
Oden Institute for Computational Engineering and Sciences

Who am I



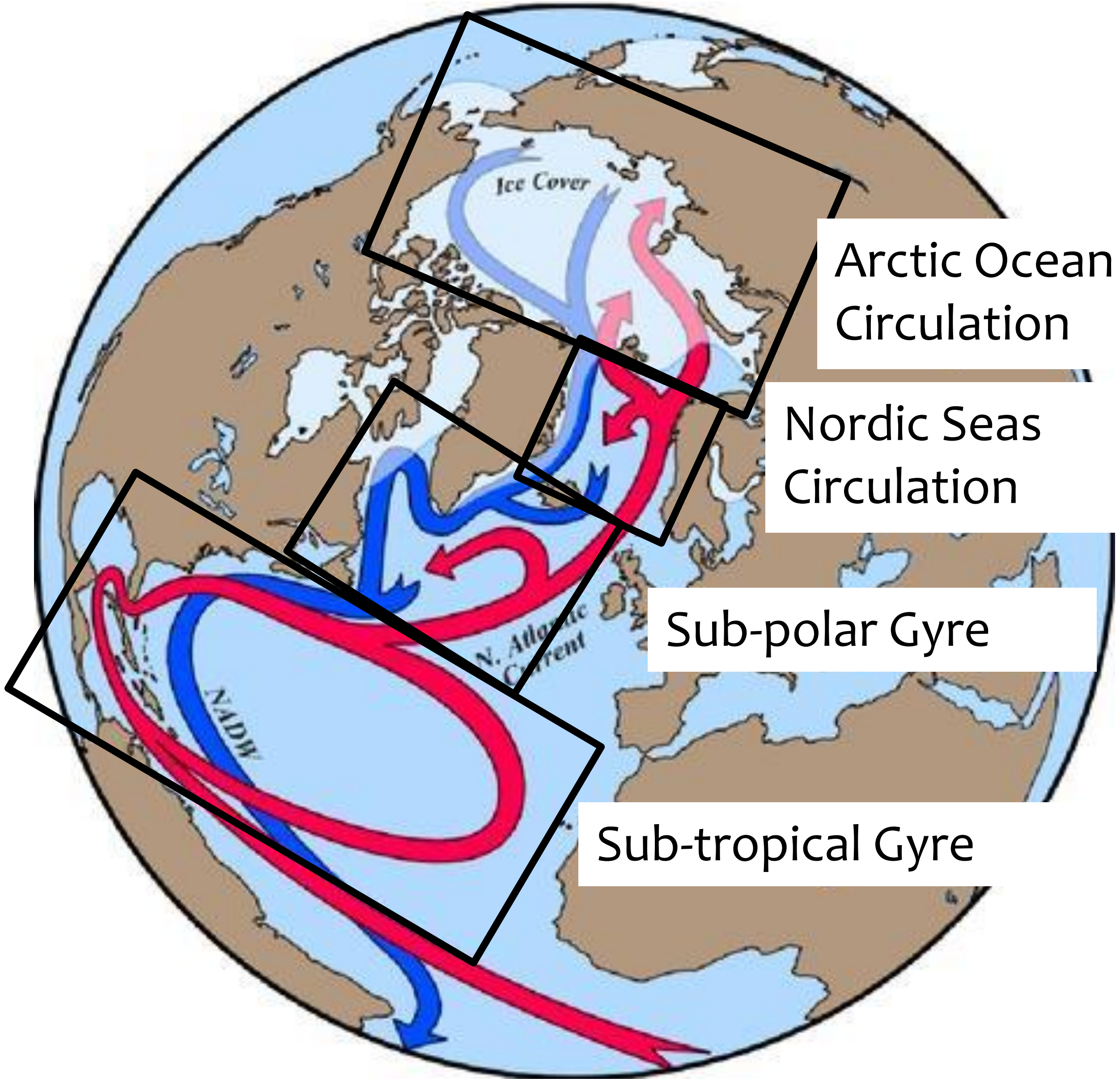
From Vietnam

Undergraduate: UCLA , applied Geophysics

Ph.D. : MIT, Geophysics: satellite altimetry to detect change in Ice Sheet

Postdoc & the rest: ECCO

North Atlantic Meridional Overturning Circulation (MOC)



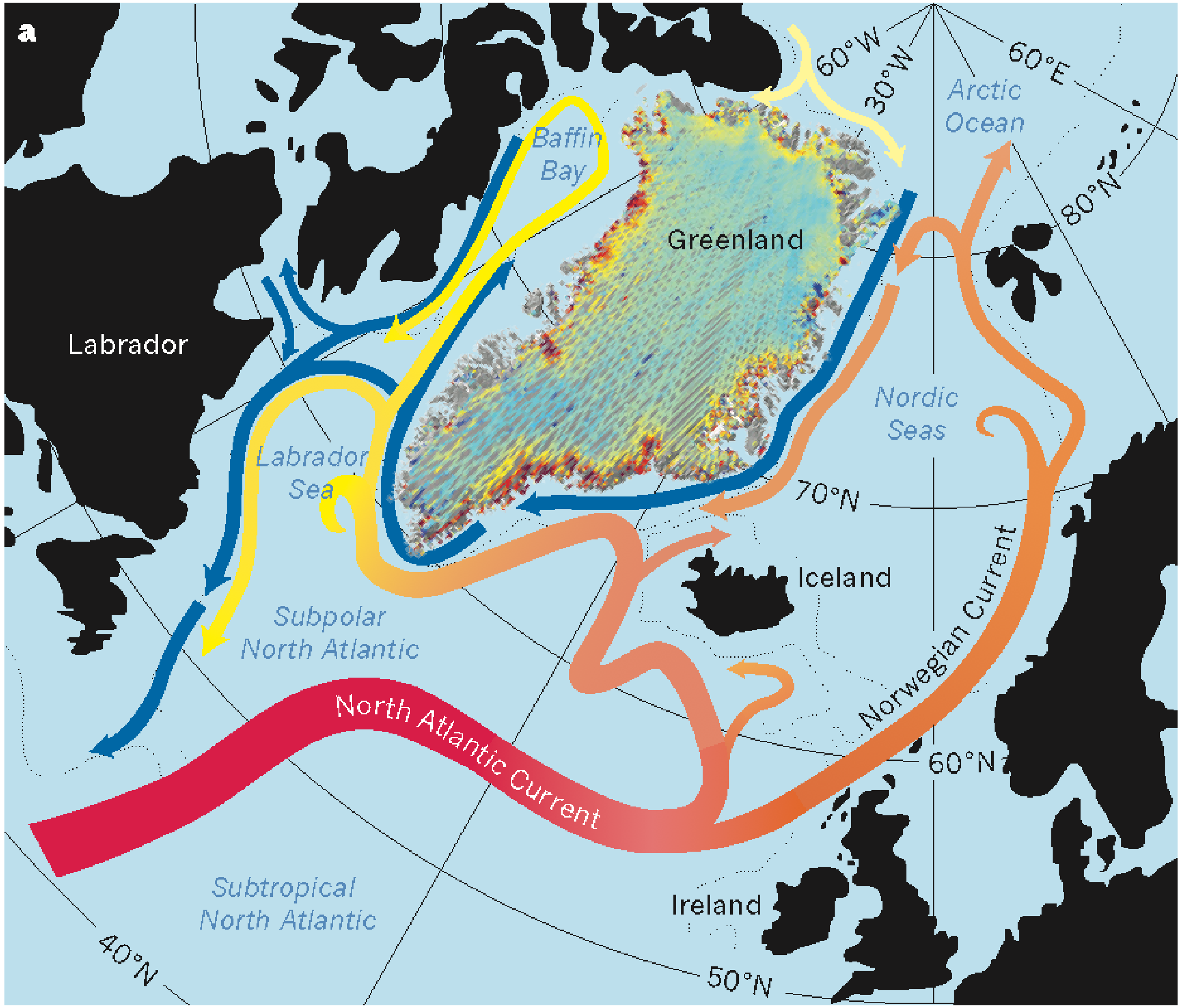
High latitude ocean circulation

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]

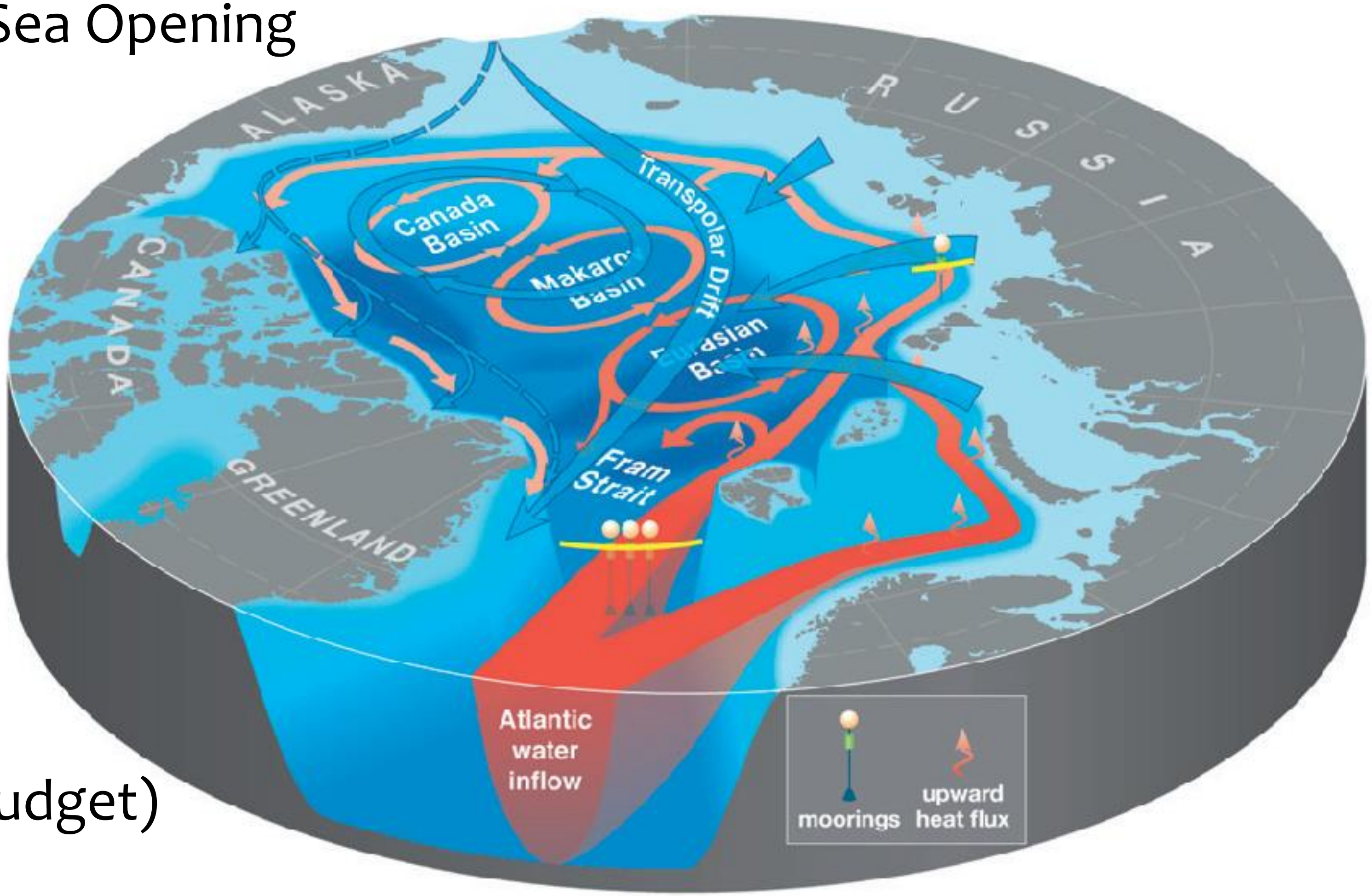
Arctic Ocean circulation

Atlantic Water (deep)

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

- Enters at Fram Strait + Barents Sea Opening

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

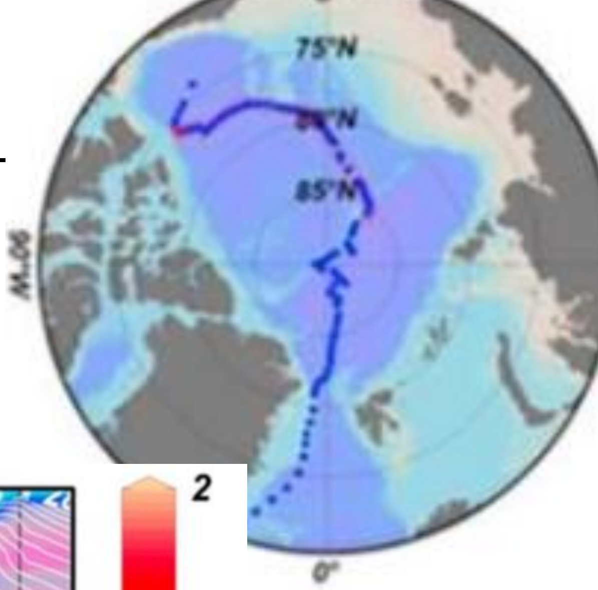


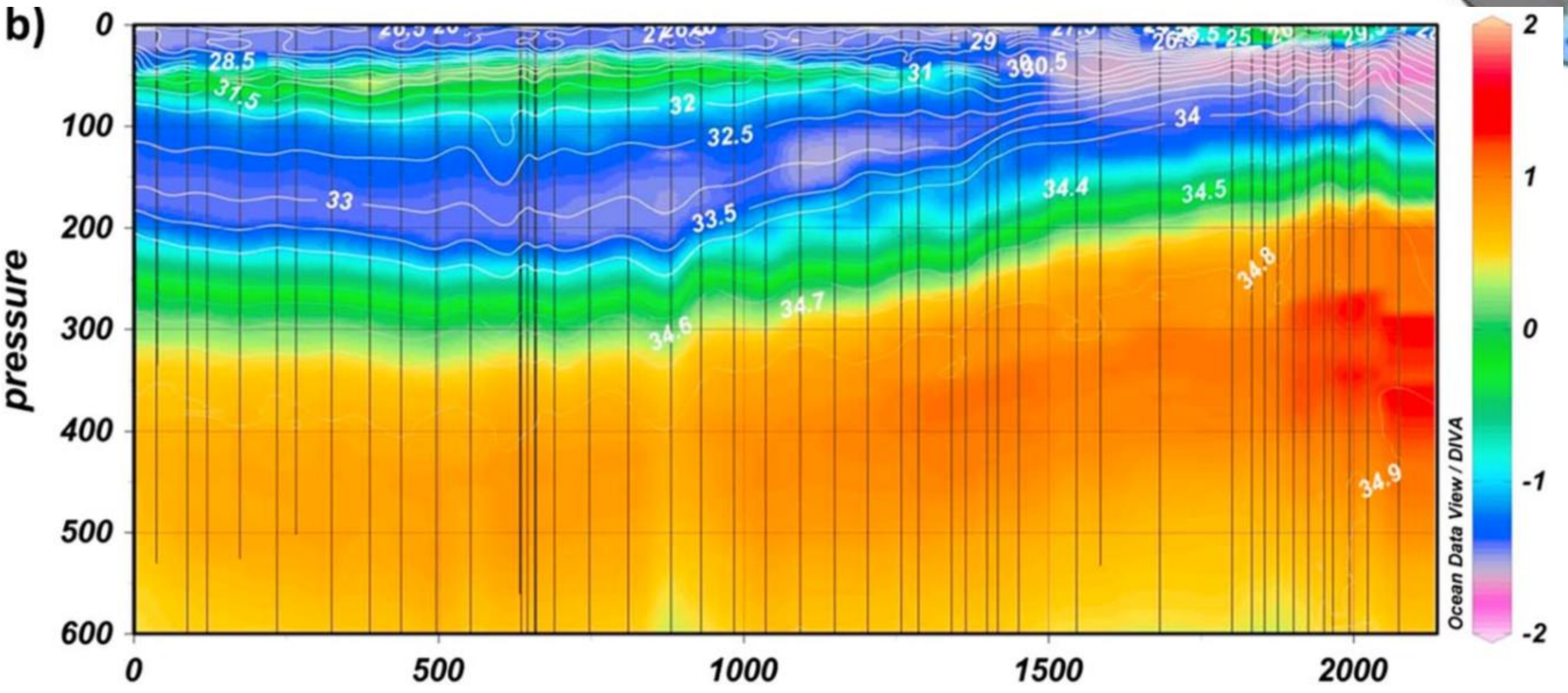
Pacific Water
(mid depth & surface)

- Enters at Bering Strait
- Fresh water (33% of Arctic FW budget)
- Heat: near surface

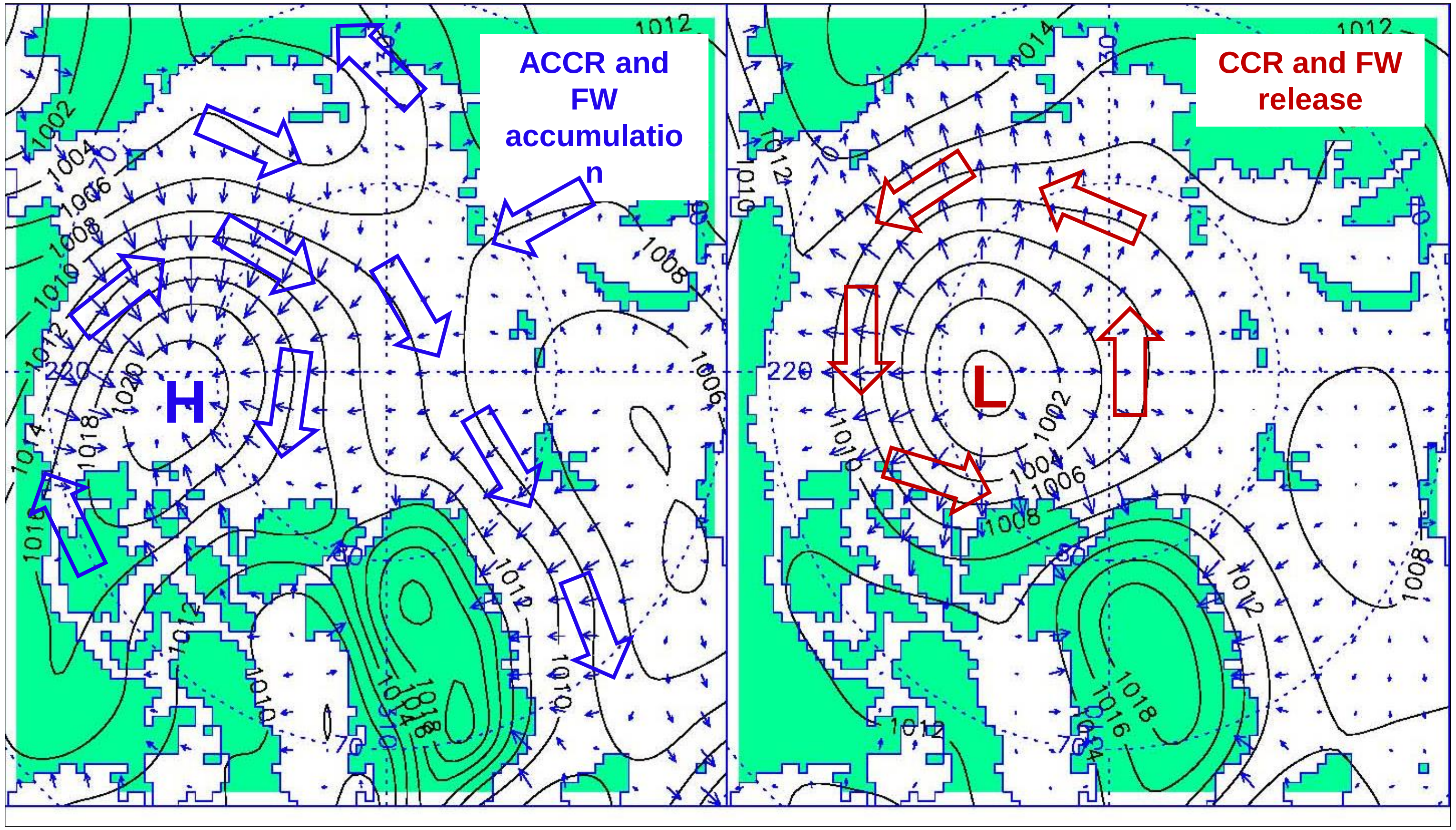
Arctic Ocean temperature structure

[Carmack et al., 2017]





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

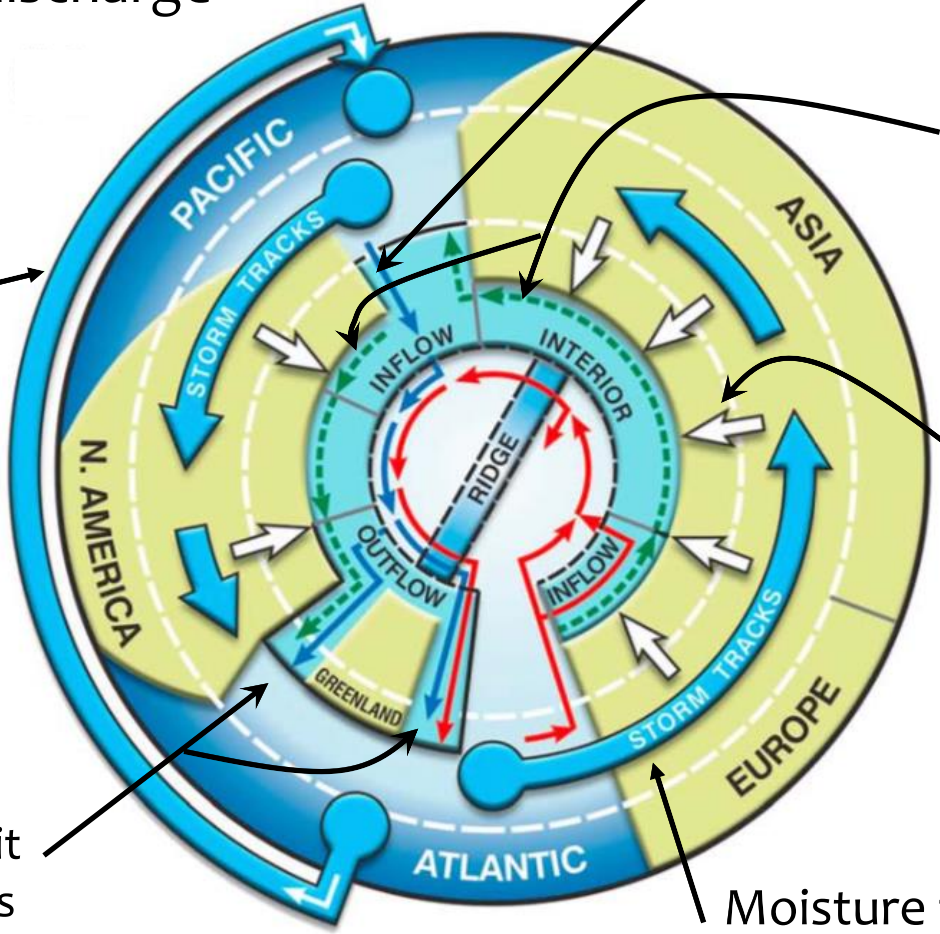
Arctic Ocean: Important to global Fresh Water cycle

1% and 3% global ocean volume & surface area, receives >11% of 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]

Challenges of (forward) modeling the Arctic

Small baroclinic radius of deformation
(lengthscale of fastest instability growth)

stratification

$$\lambda_m^{\mathrm{WKB}} = \frac{1}{|f|m\pi} \int_{-H}^{0} N(z)\, dz, \qquad m \geq 1.$$

ocean depth

Coriolis param
(2Ωsinθ)

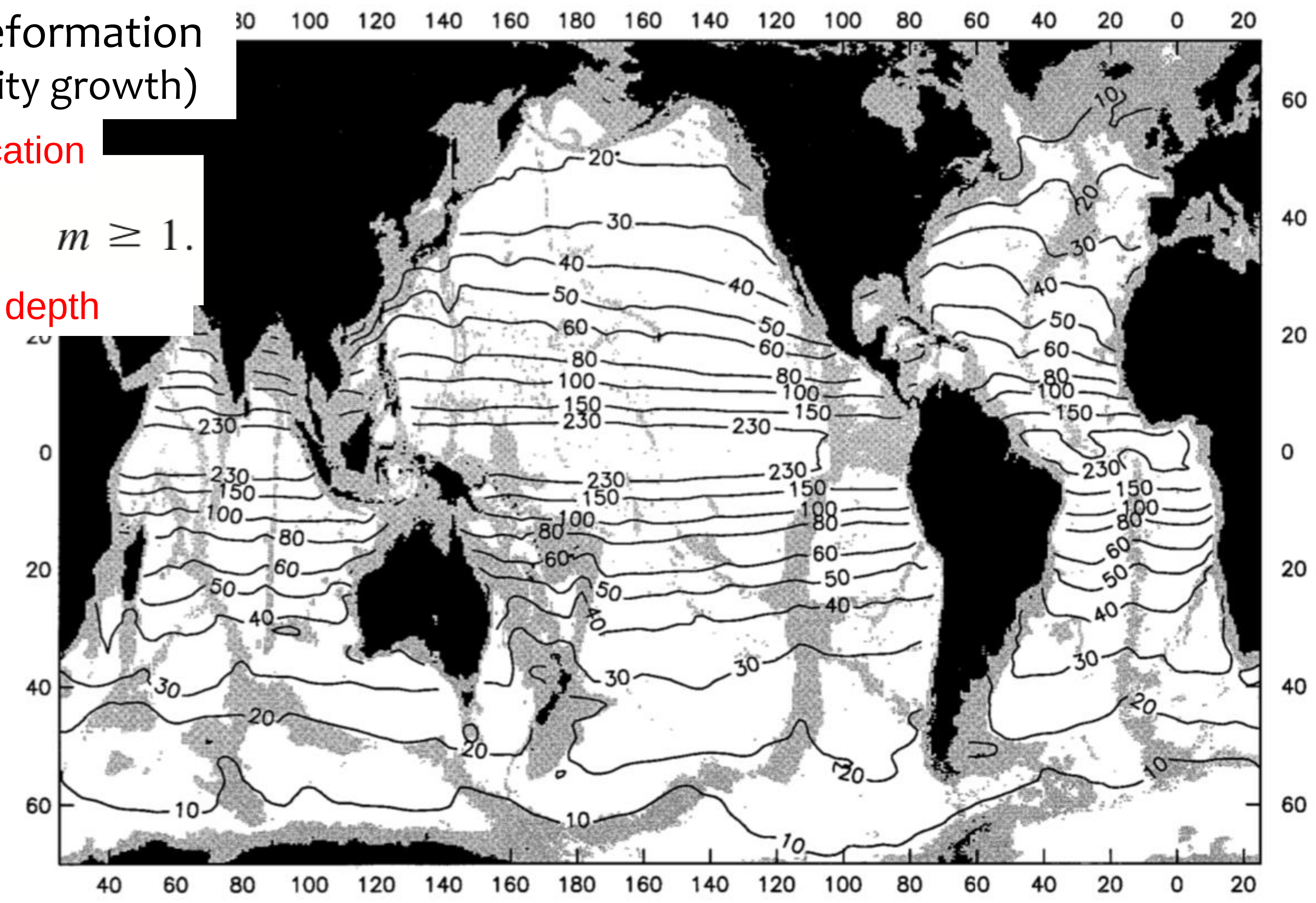


FIG. 6. Global contour map of the 1° × 1° first baroclinic Rossby radius of deformation λ_1 in kilometers computed by Eq. (2.3) from the first baroclinic gravity-wave phase speed shown in Fig. 2. Water depths shallower than 3500 m are shaded.

Chelton et al. [1998]

Challenges of (forward) modeling the Arctic

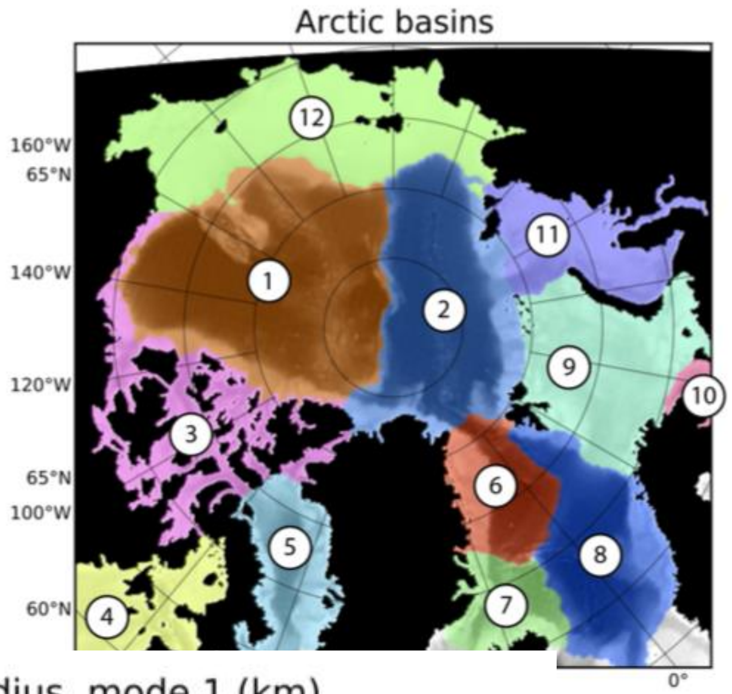
stratification: weak

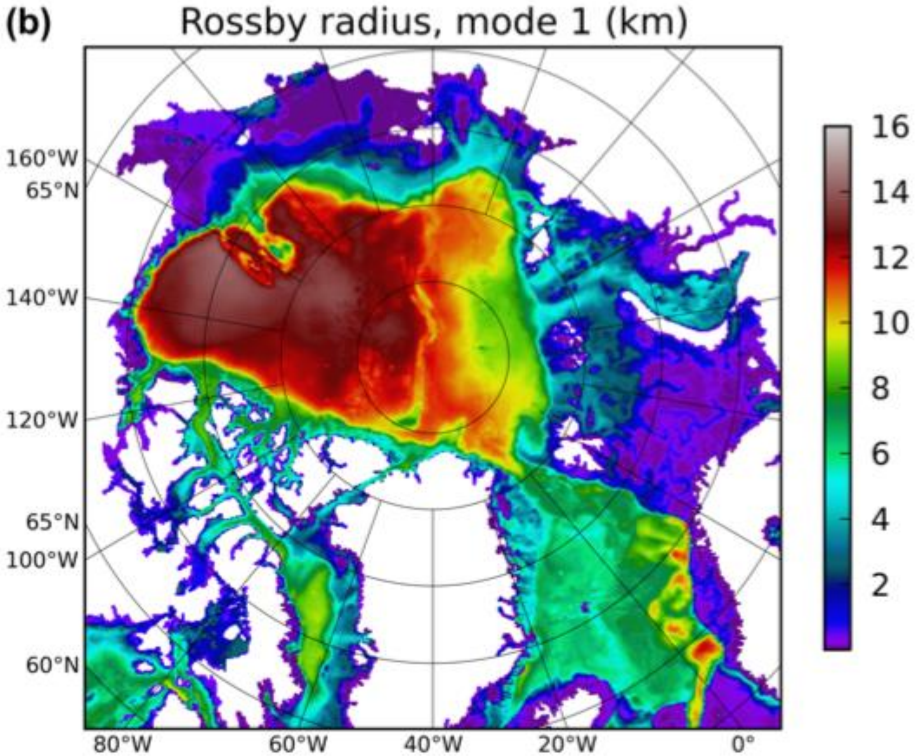
$$\lambda_m^{\mathrm{WKB}} = \frac{1}{|f|m\pi} \int_{-H}^{0} N(z)\, dz, \qquad m \geq 1.$$

large

ocean depth: shallow

Region	Key	Mode 1 (km)			Mode 2 (km)
		Summer	Winter	Annual	Annual
Deep Arctic Ocean					
Amerasian Basin	1	11.2	11.0	11.1	5.2
Eurasian Basin	2	7.9	7.7	7.8	4.6
Environs of Canadian waters					
Canadian Archipelago	3	6.3	5.9	6.1	2.9
Hudson Bay & Foxe Basin	4	4.8	2.7	3.7	1.9
Baffin Bay	5	6.3	5.4	5.8	2.9
Nordic seas					
Greenland Sea	6	5.1	4.4	4.7	2.6
Iceland Sea	7	5.0	3.8	4.3	2.4
Norwegian Sea	8	7.2	6.5	6.9	3.0
Eurasian Shelf seas					
Barents Sea	9	3.3	1.9	2.5	1.3
White Sea	10	3.5	2.4	2.7	1.4
Kara Sea	11	4.6	3.0	3.8	1.9
East Siberian Shelf seas	12	3.7	2.5	3.1	1.4



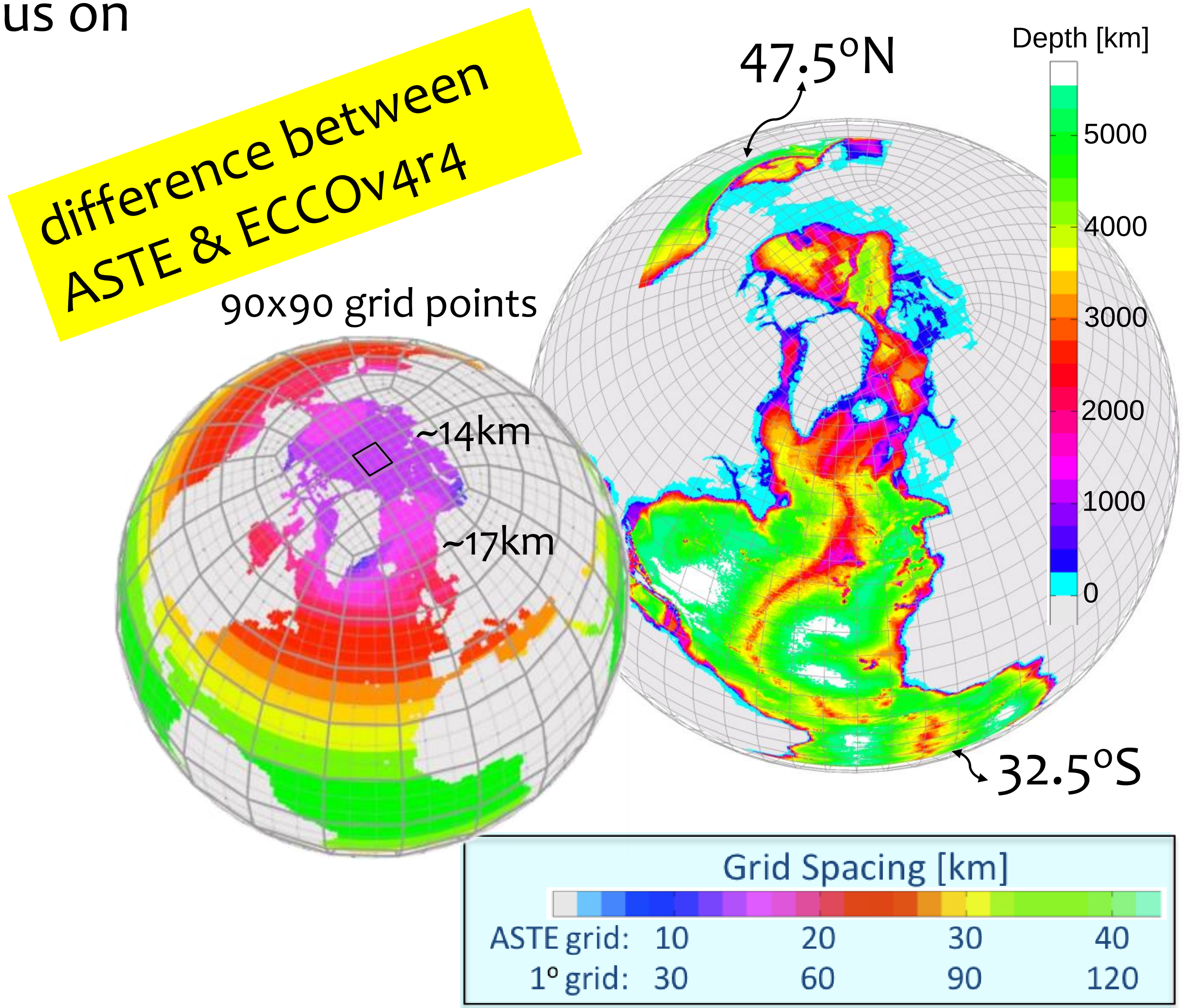


Nurser & Bacon [2014]

Arctic Subpolar gyre sTate Estimate (ASTE)

[Nguyen et al., 2021]

- Higher resolution (llc270 based) with focus on Arctic and subpolar North Atlantic
- OBCs: ECCOv4R* 1° global state estimate
- Initial conditions:
  - T/S: spin up from WOA13v1
  - sea ice: spin up from PSC Jan/2002
- atmospheric forcings: JRA-55
- 3-D ocean mixing parameters:
  - initial guesses
- 2002-2017
  - starts of ICESat & GRACE
  - better coverage of Argo
  - begin of ITP deployment (2004)



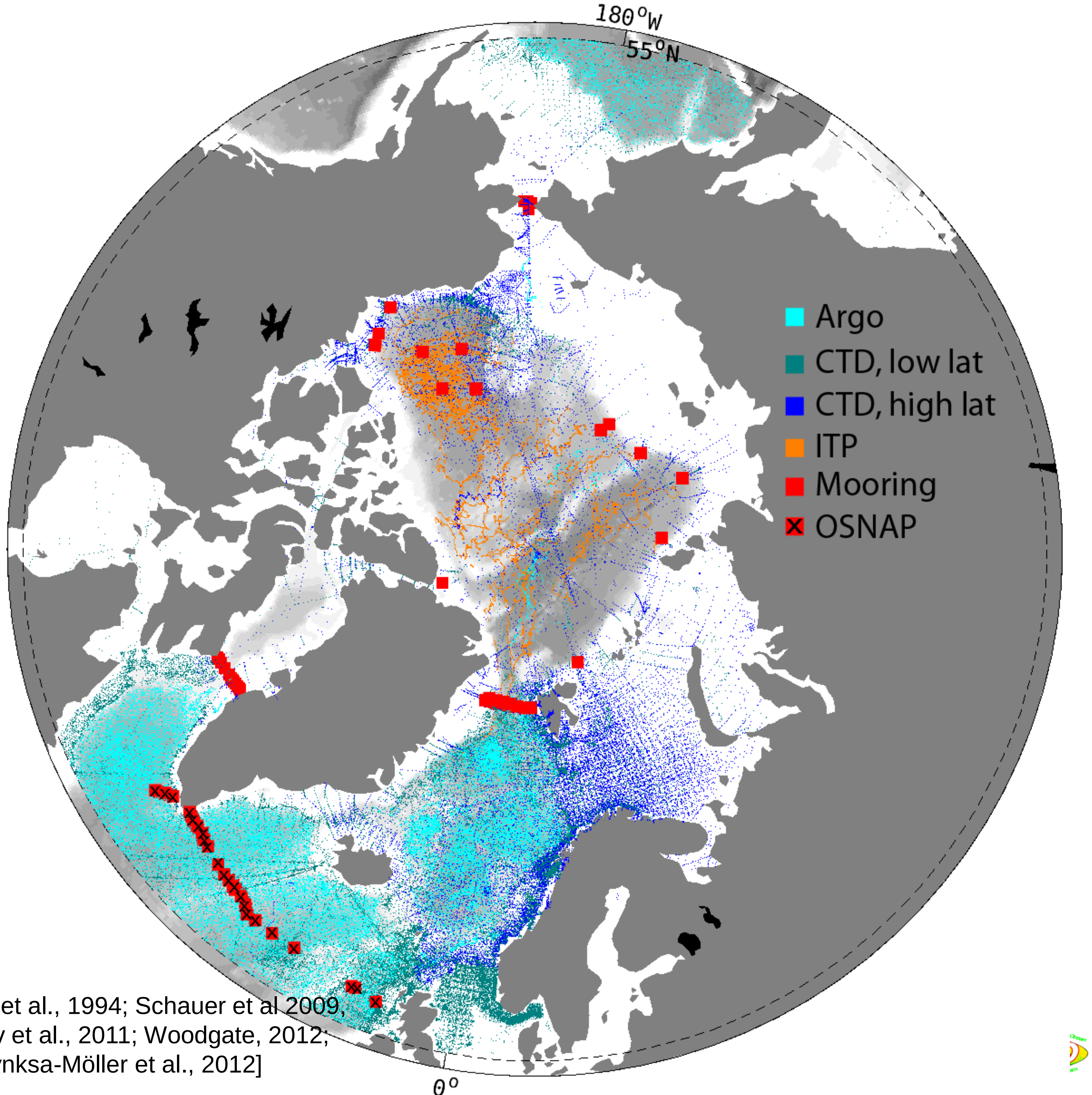
Primary data constraints:

Low latitudes:

- ECCOv4r* standard obs. (SSH, SST, Argo, XBT, CTDs, seal, mean DMT)
- Line-W, Gulf Stream

High latitudes:

- Ice concentration (OSISAF)
- Ice thickness (SMOS+ CryoSat, ICESat), ice drifts
- moored T/S/U/V & hydrographic section, *e.g.*, ITP, NABOS/CABOS, BGEP/BGOS, WHOI & ICES databases
- Arctic main gateways
  e.g., Fram, Davis, Bering straits



[Rudels et al., 1994; Schauer et al 2009, Aksenov et al., 2011; Woodgate, 2012; Beszczynksa-Möller et al., 2012]

ASTE control space

Initial Greens Function's params optimized from Nguyen et al. 2011:

- Sea ice drags
- Sea ice albedos
- Internal turbulence mixing $O(10^{-7})$

Important Forward Parameter(s):

- **Viscous dissipation (circulation)**

Adjustable parameters (control space) :

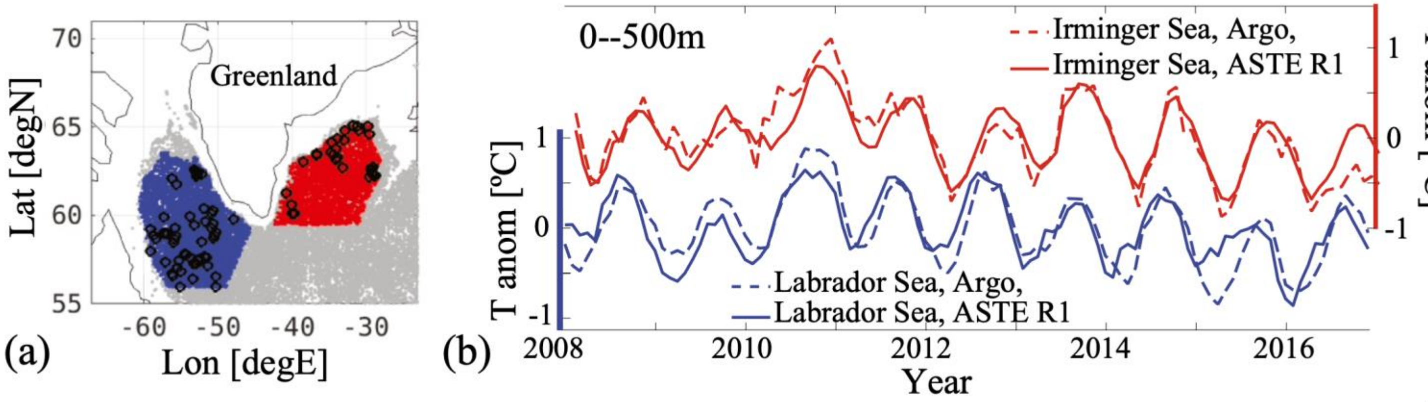
- initial T/S conditions
- time-varying atmospheric forcings
- **3-D internal turbulence mixing**
- Unresolve mesoscale eddies
  - **Redi (isopycnal diffusion of tracers)**
  - **GM (bolus transport)**

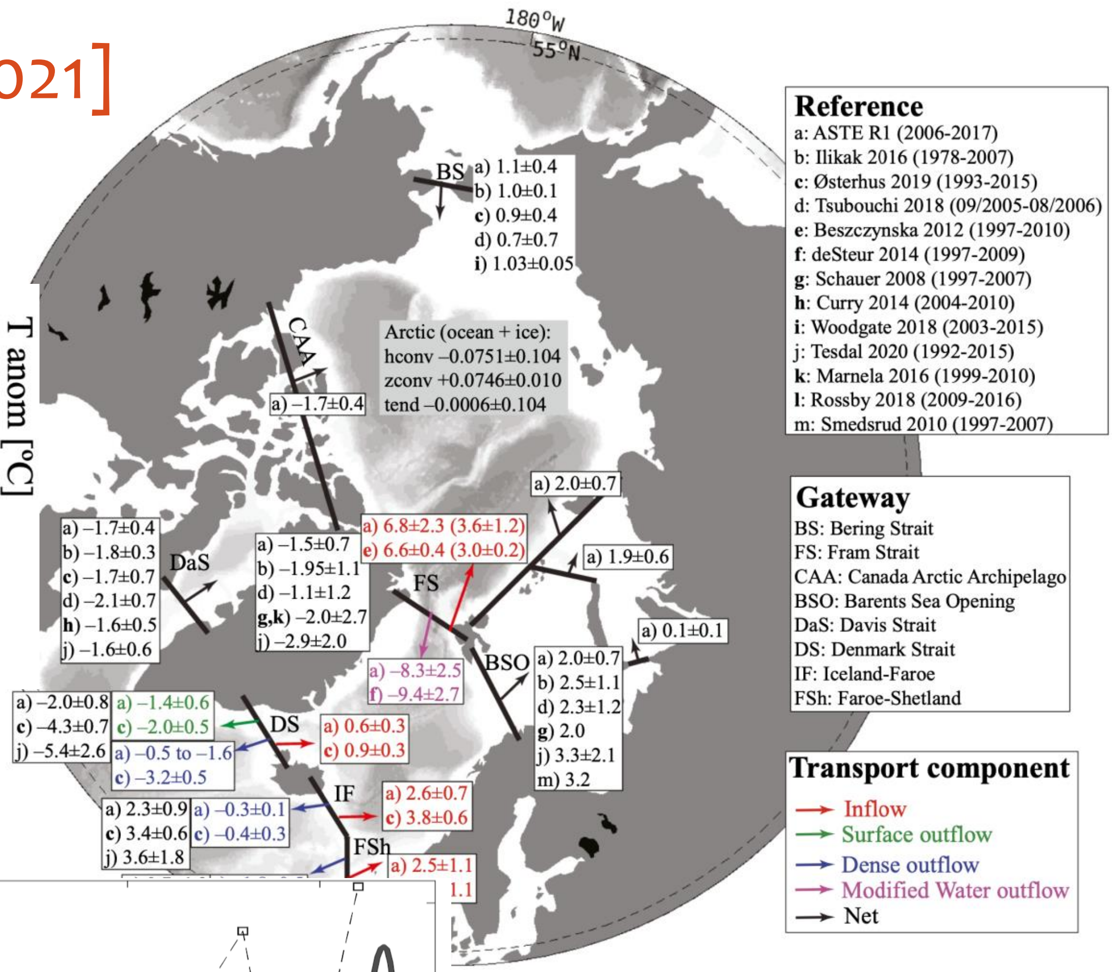
Requires:

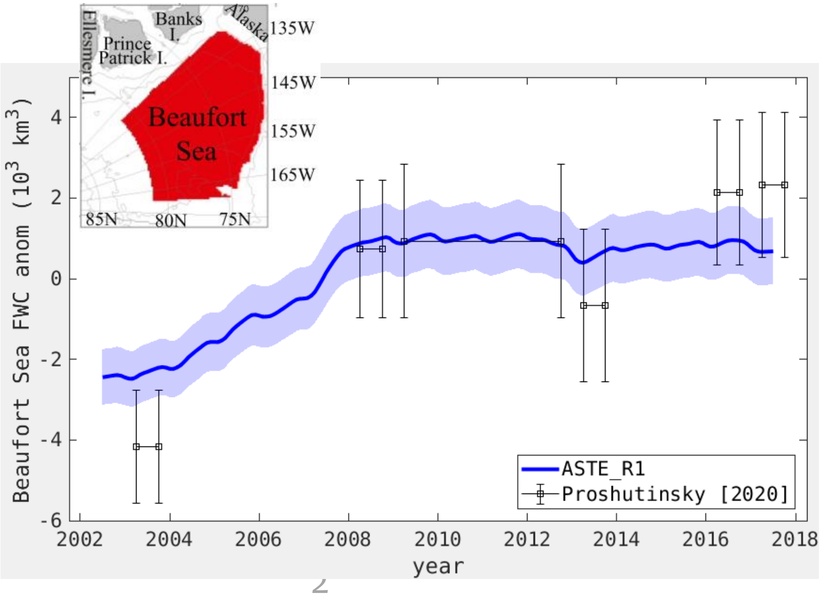
- Good knowledge of regional oceanography
- Good initial guess of ocean/ice state and input parameters

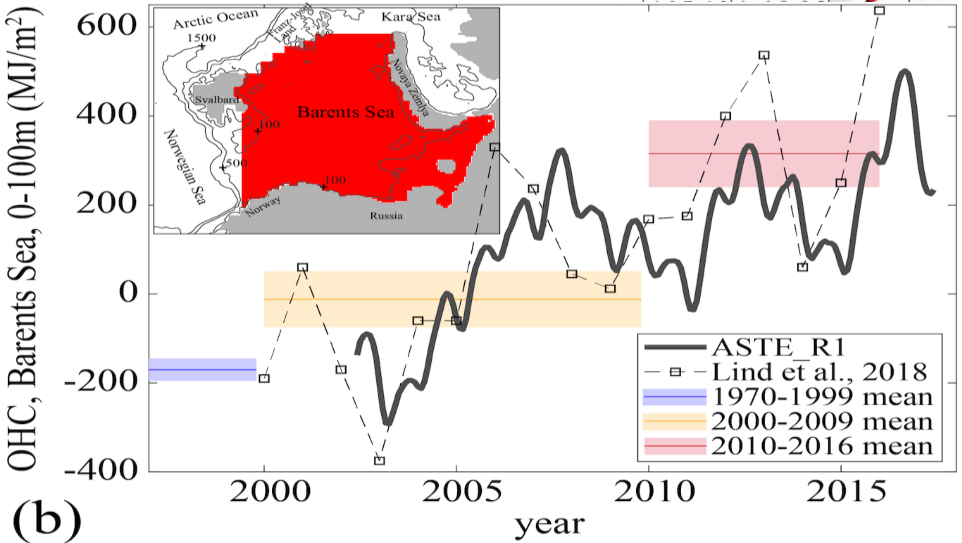
ASTE Release 1 2002–2017 [Nguyen et al., 2021]

Extensive analyses on misfits, bias, budgets



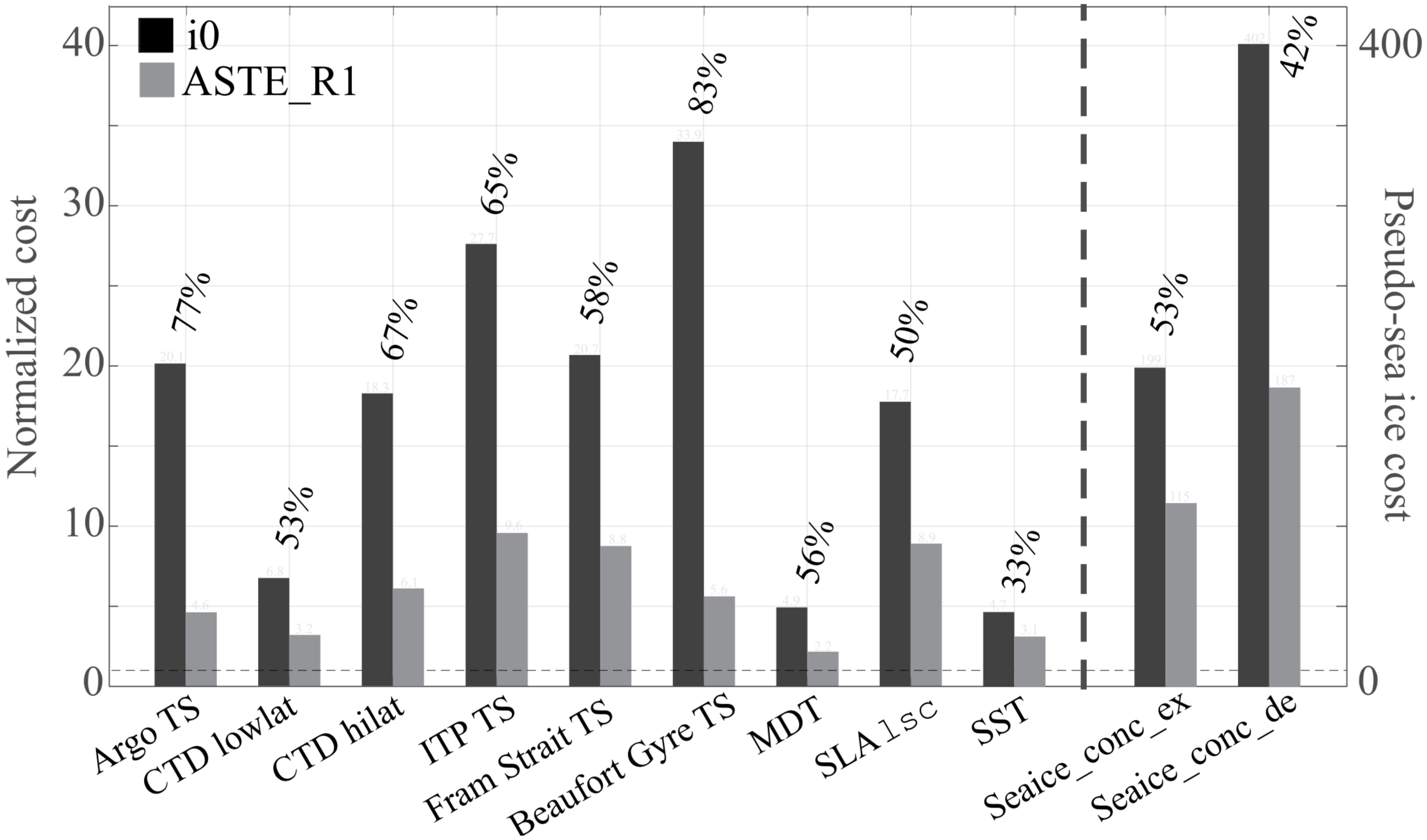




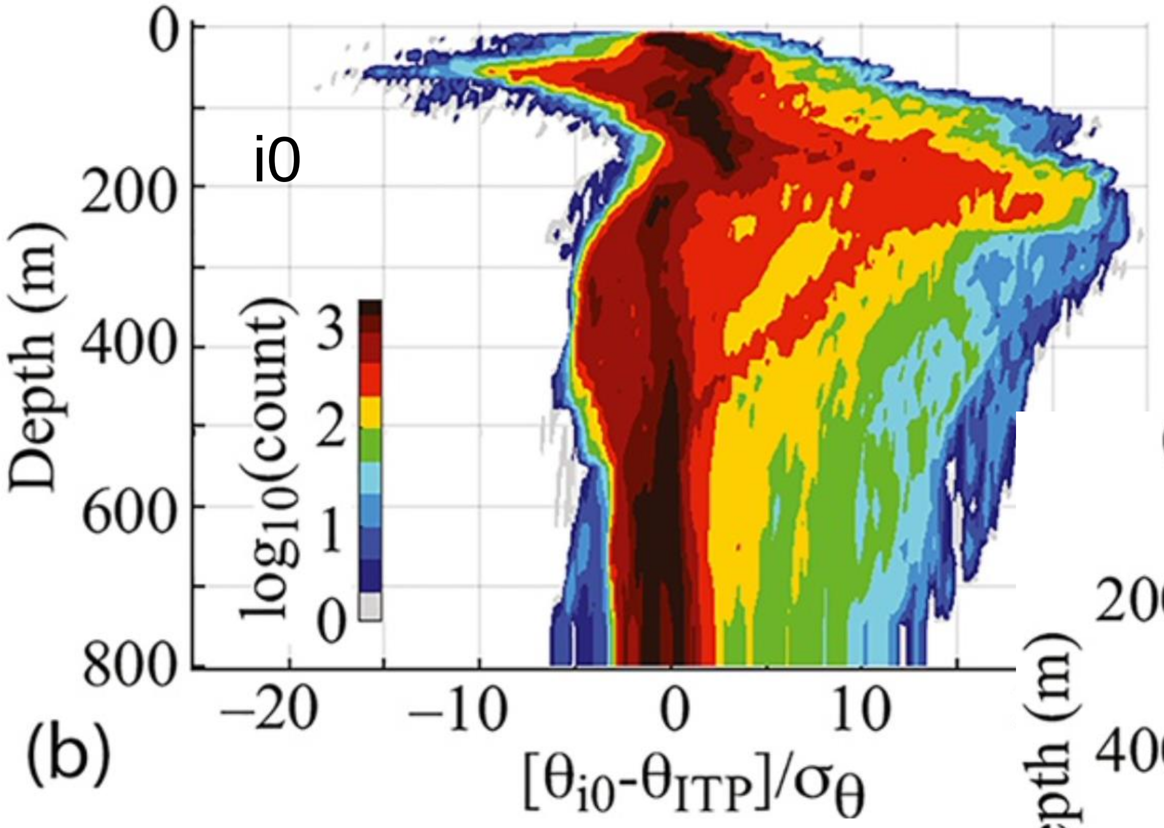


- Data at Arctic Data Portal (arcticdata.io) & UT ECCO-mirror site https://web.corral.tacc.utexas.edu/OceanProjects/ASTE/Release1/

Misfit reductions: Assessment of most impactful datasets

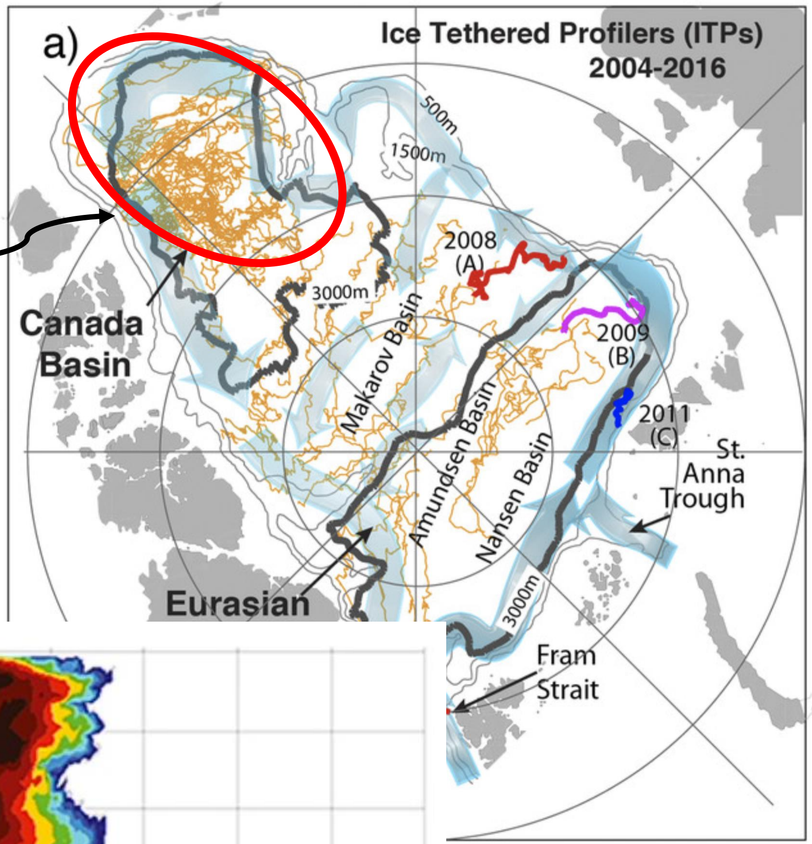


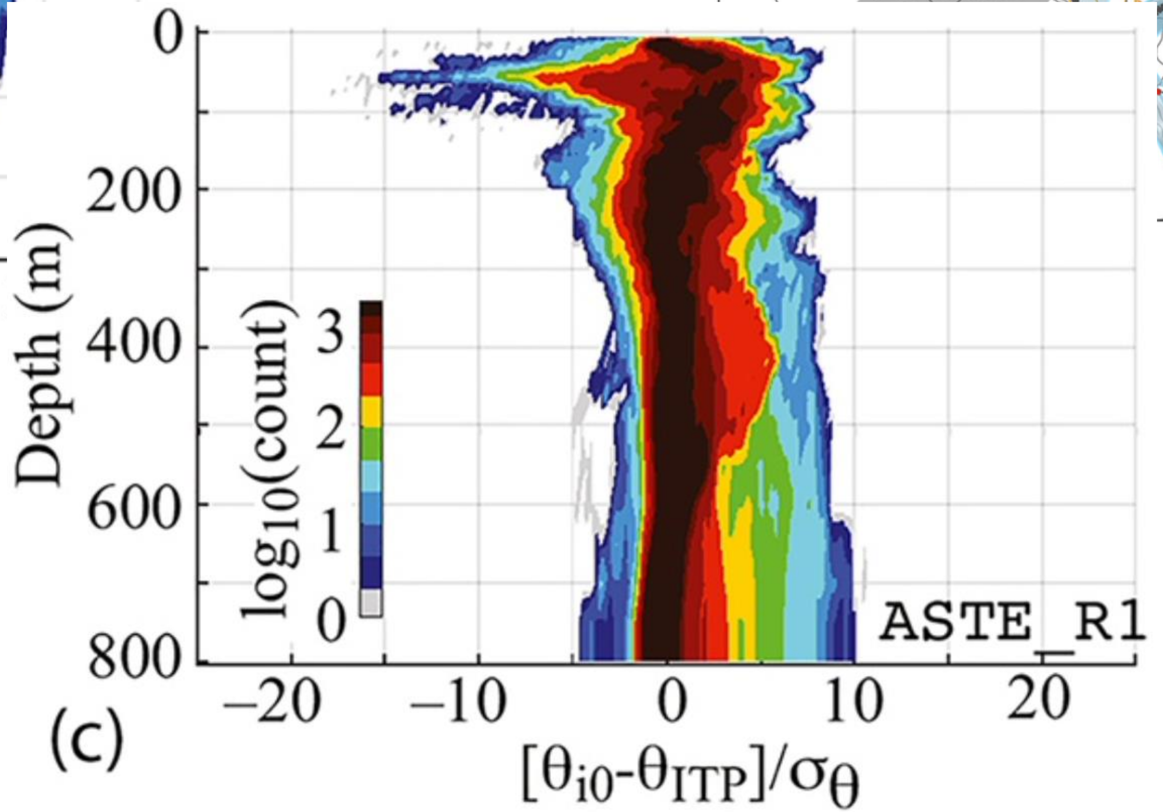
Ice-Tethered Profilers (ITP)



(b)

ITP data in the Canada Basin interior



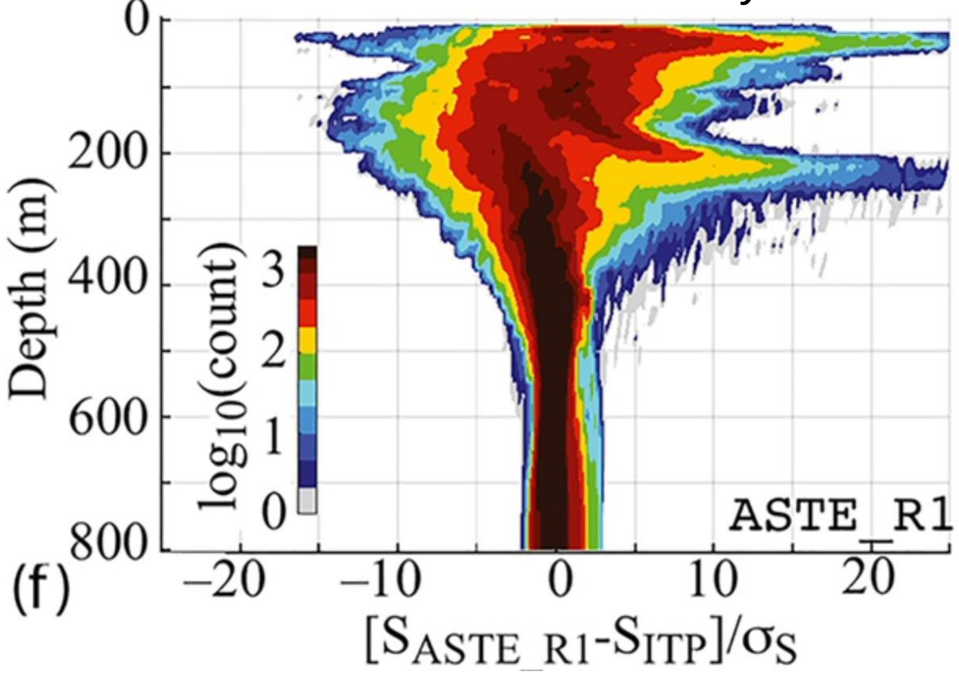


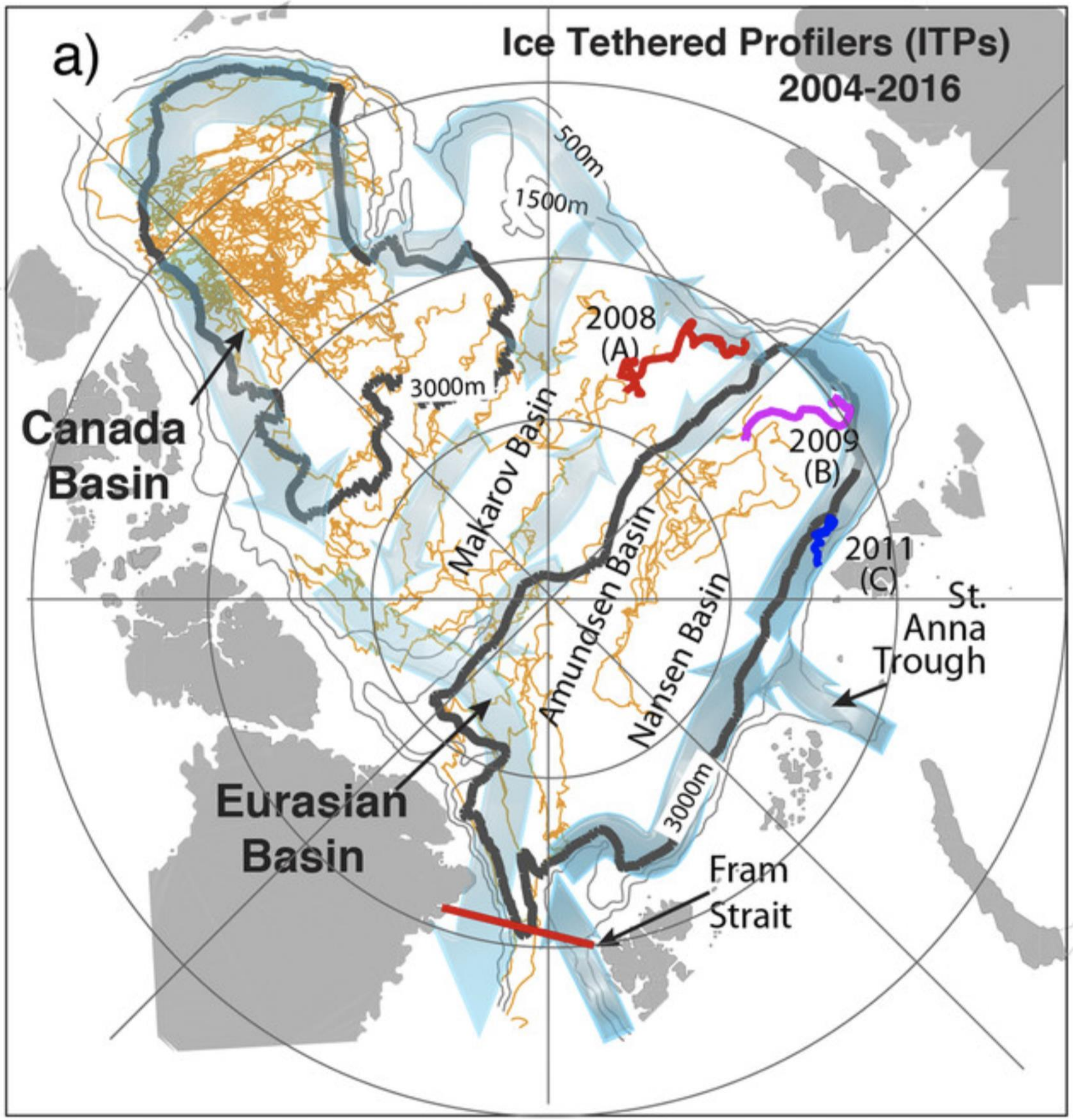
(c)

Data distribution

- Inhomogeneous

Eurasian model-data salinity misfit





Data distribution

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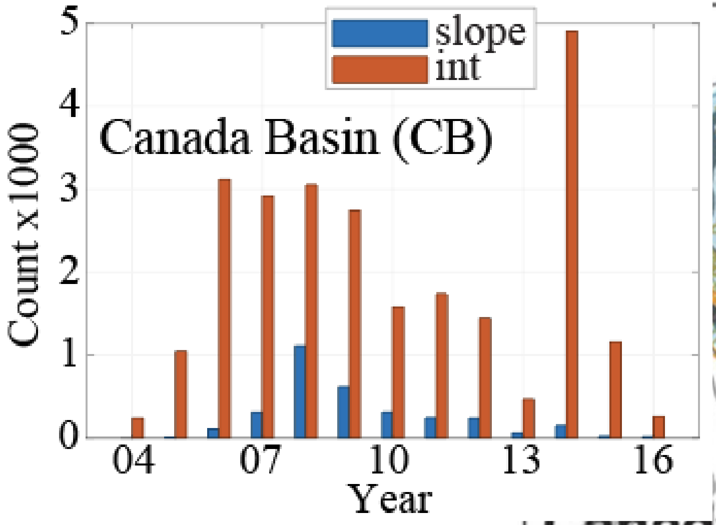
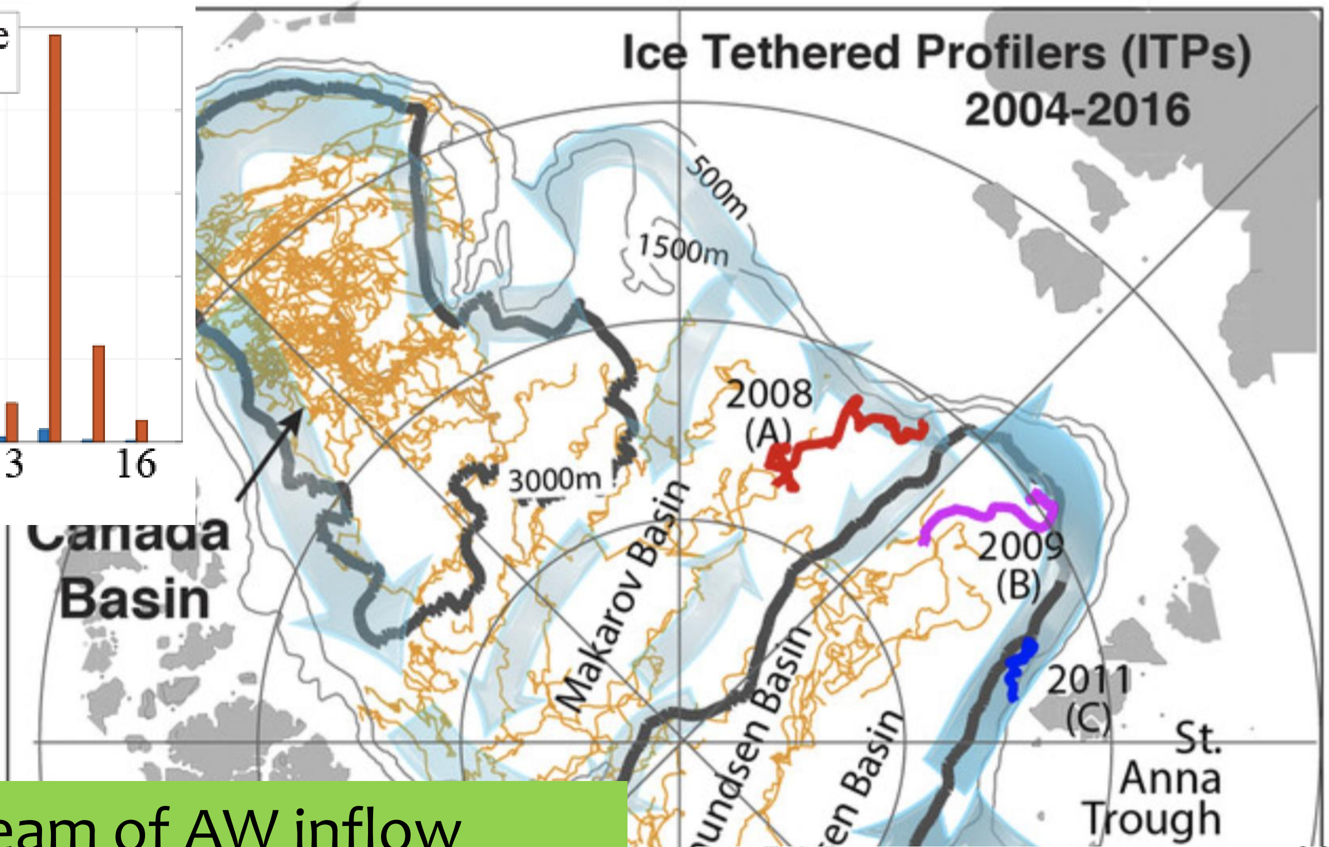
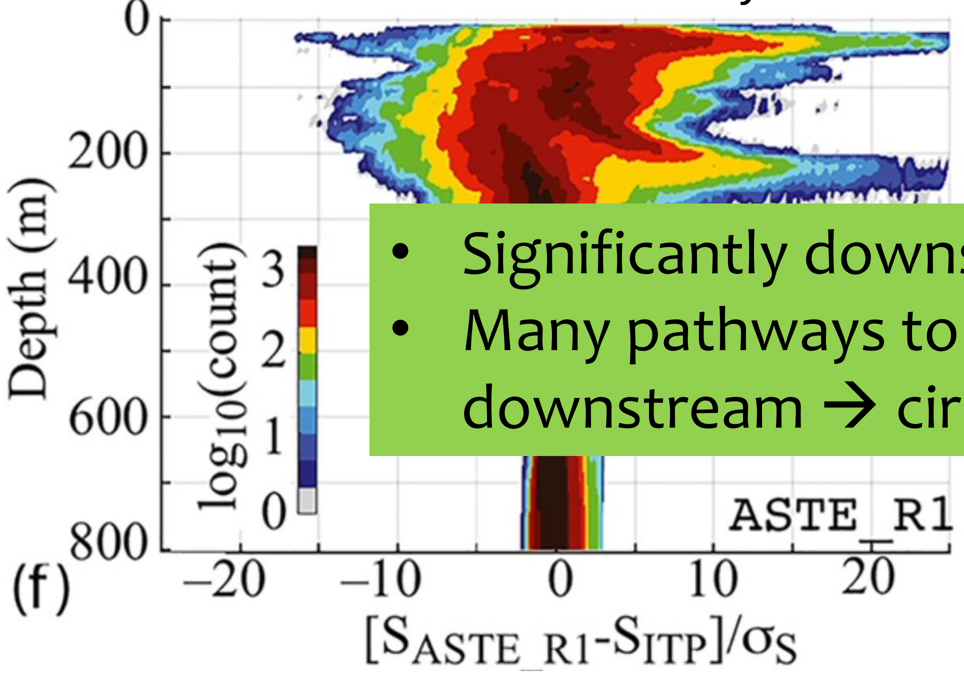
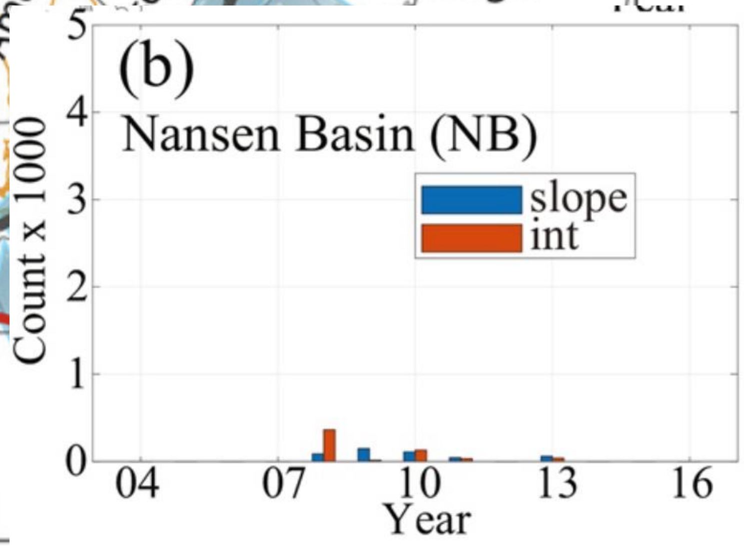




Eurasian model-data salinity misfit



- Significantly downstream of AW inflow
- Many pathways to reduce misfits downstream → circulation not well inform



From idealized / theoretical: constraint on circulation

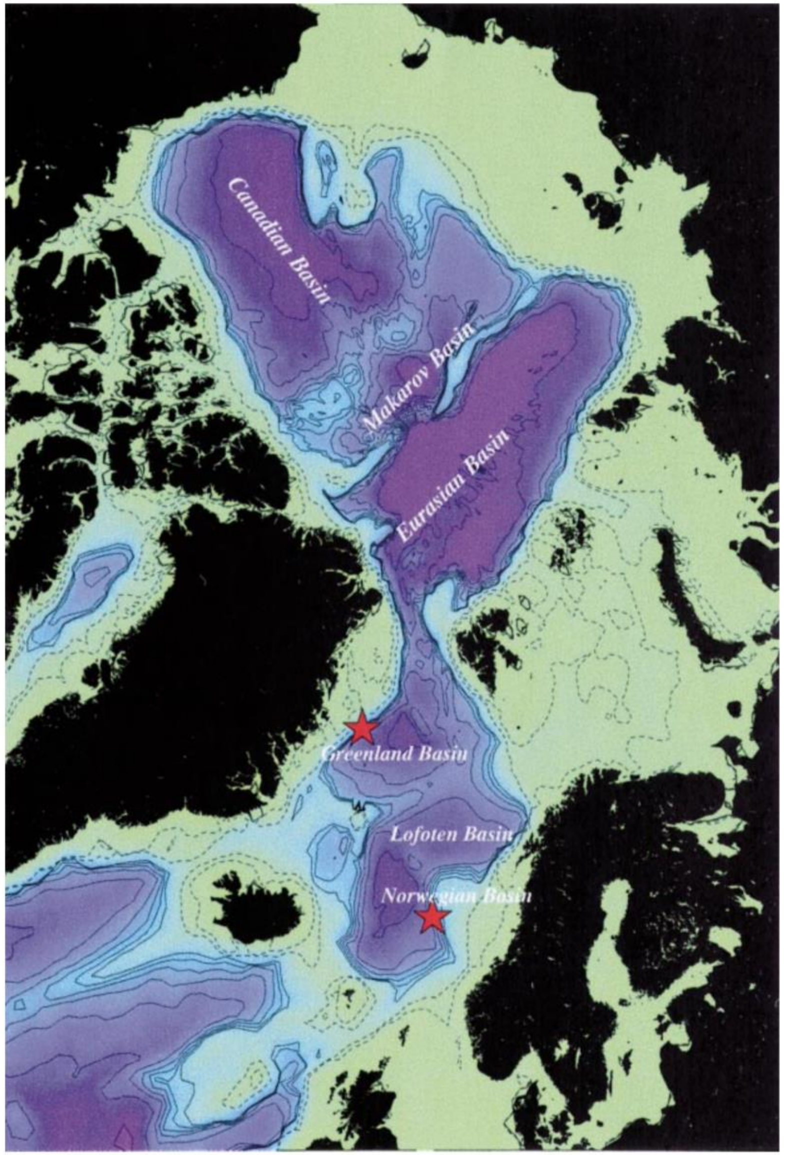
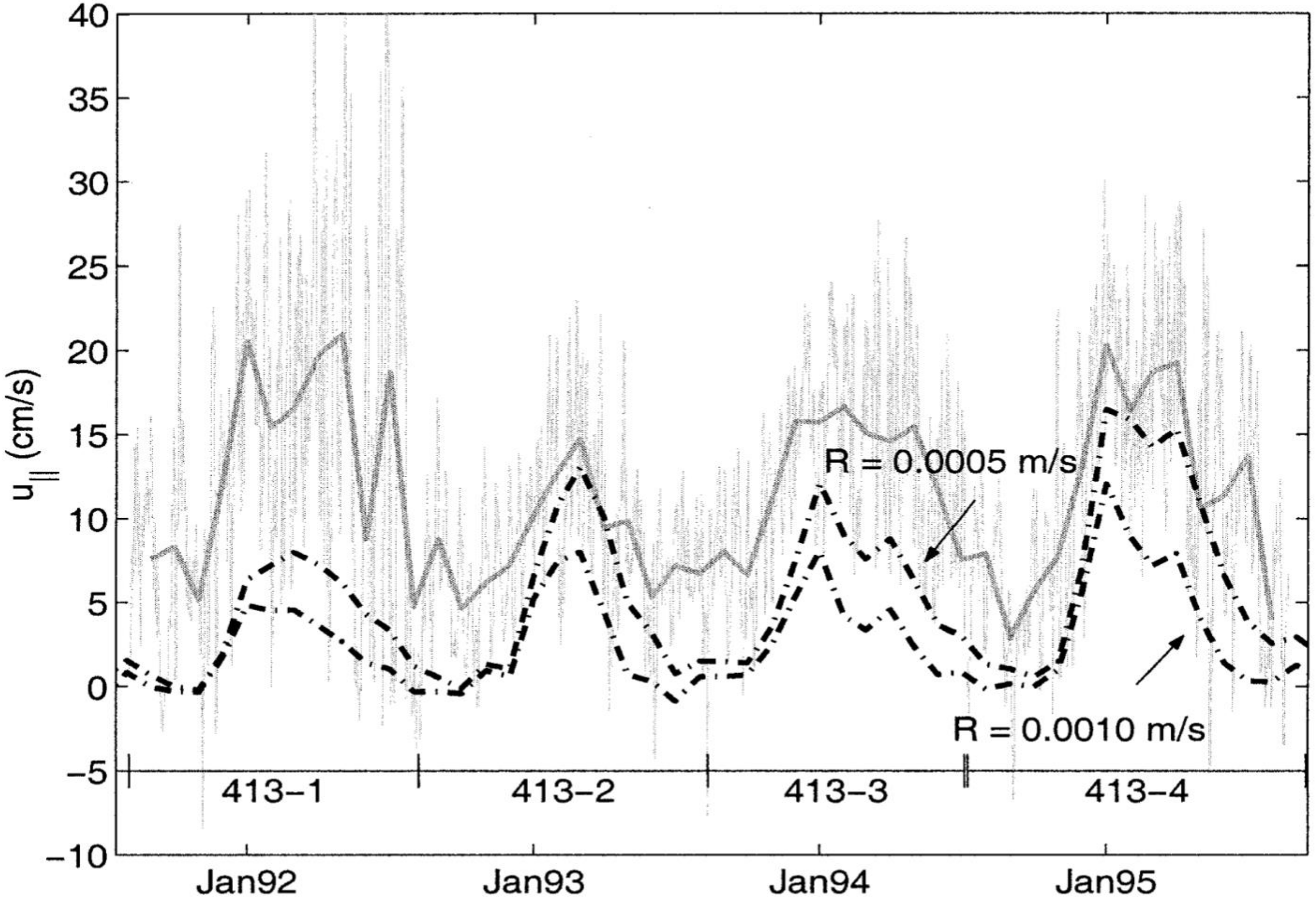


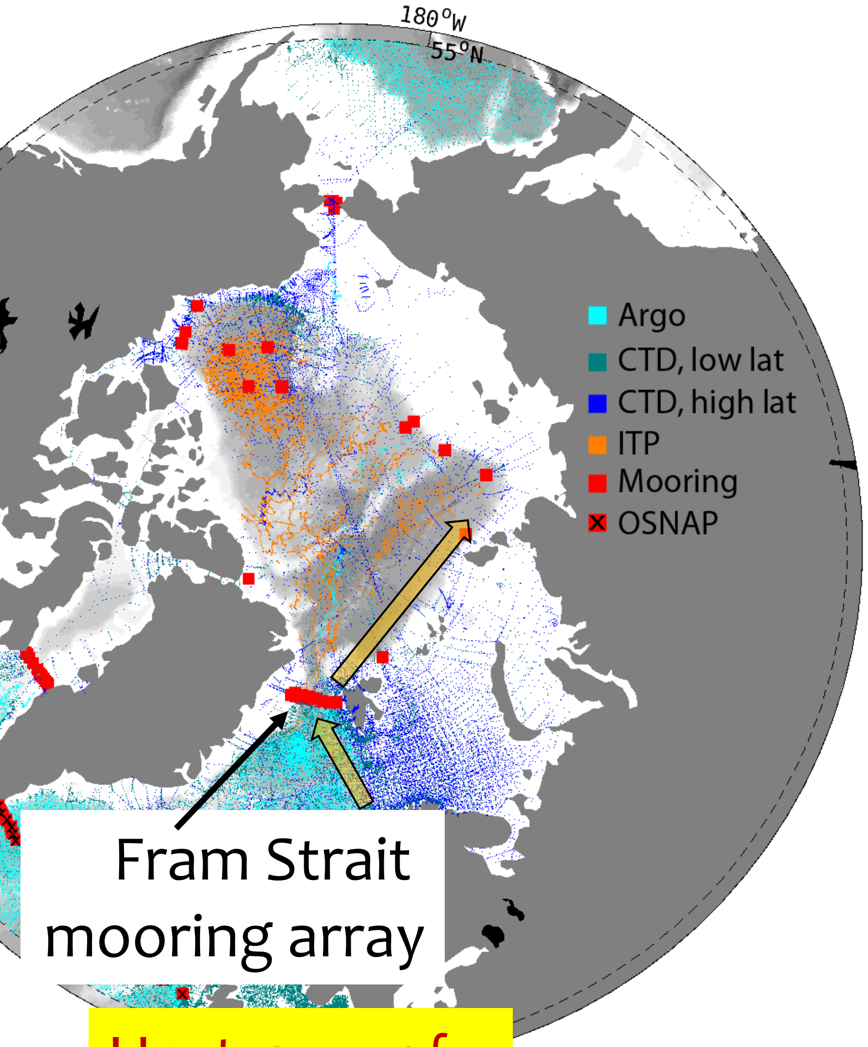
FIG. 3. The f/H field (lines) and bathymetric field (shades) for the Nordic seas and Arctic Ocean. The location of two moorings discussed later are shown with stars. Note the f/H contours approximately follow the isobaths.

western moorings (numbers 410–413), the principal components of the currents align closely with the local tangent of the f/H contours. This component explains more than 85% of the total variance when currents are



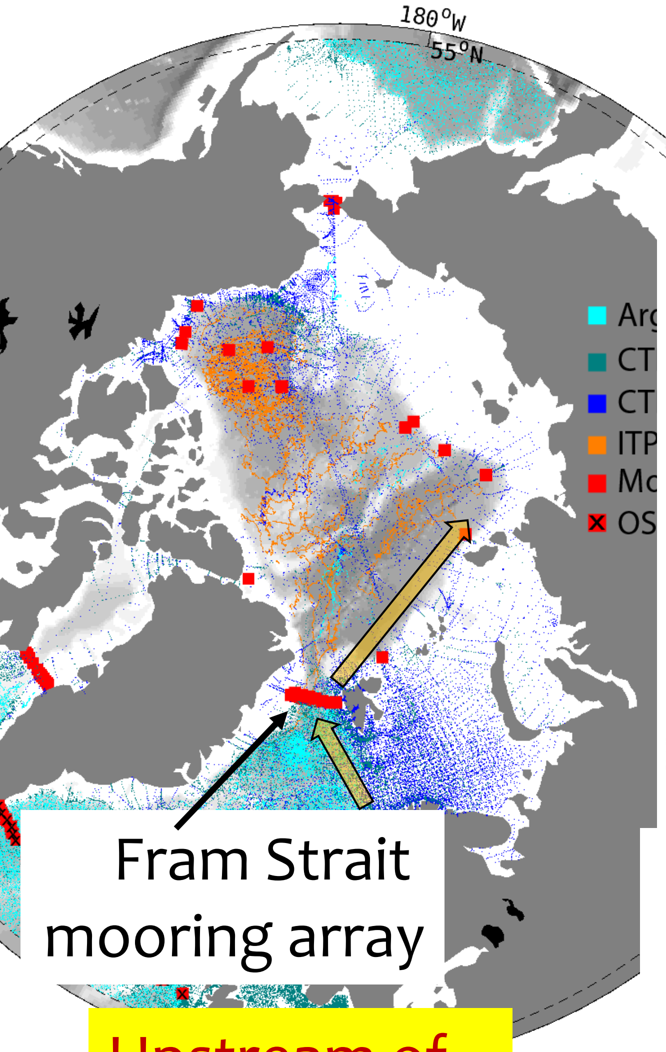
Isachsen et al., JPO 2003

Fram Strait Mooring Array

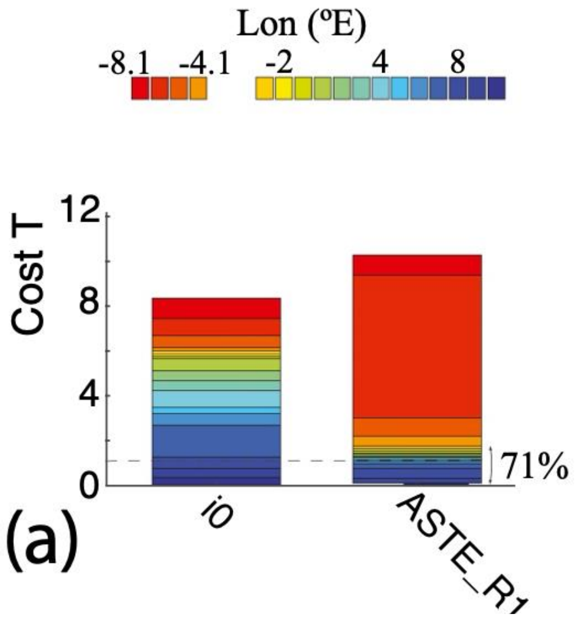


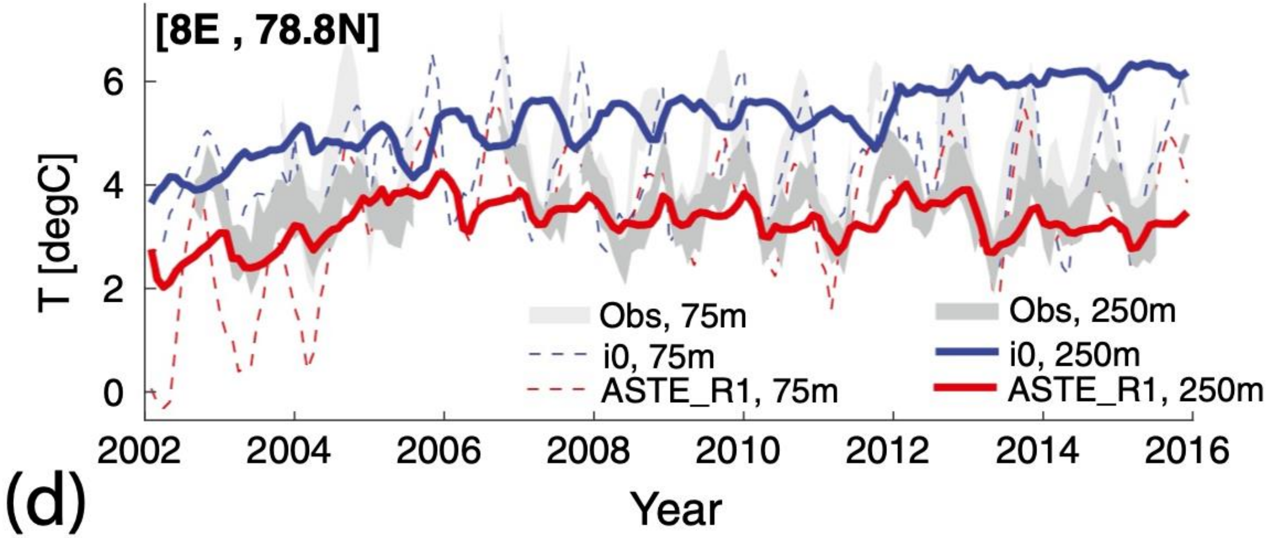
Upstream of AW inflow to Eastern Arctic

Fram Strait Mooring Array



Upstream of AW inflow to Eastern Arctic



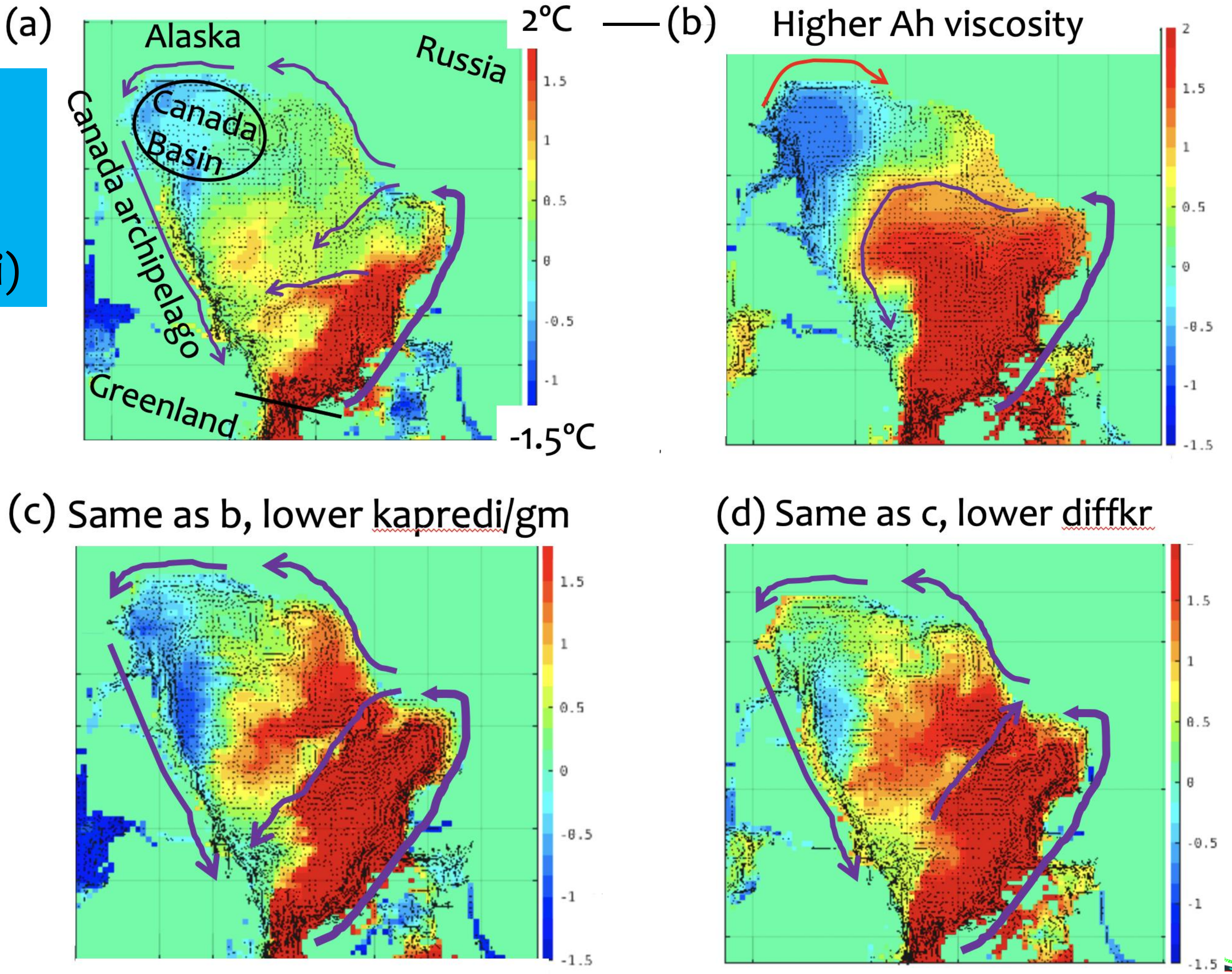


Parameter estimation:

Uncertain parameters:
- **Viscous dissipation (circulation)**
- **3-D internal turbulence mixing**
- Unresolve mesoscale eddies (**Redi**)

When all parameters are highly uncertain
→ non-unique pathway to reduce indirect misfits

Core AW ~225m



Mixing at depths

Staircases:

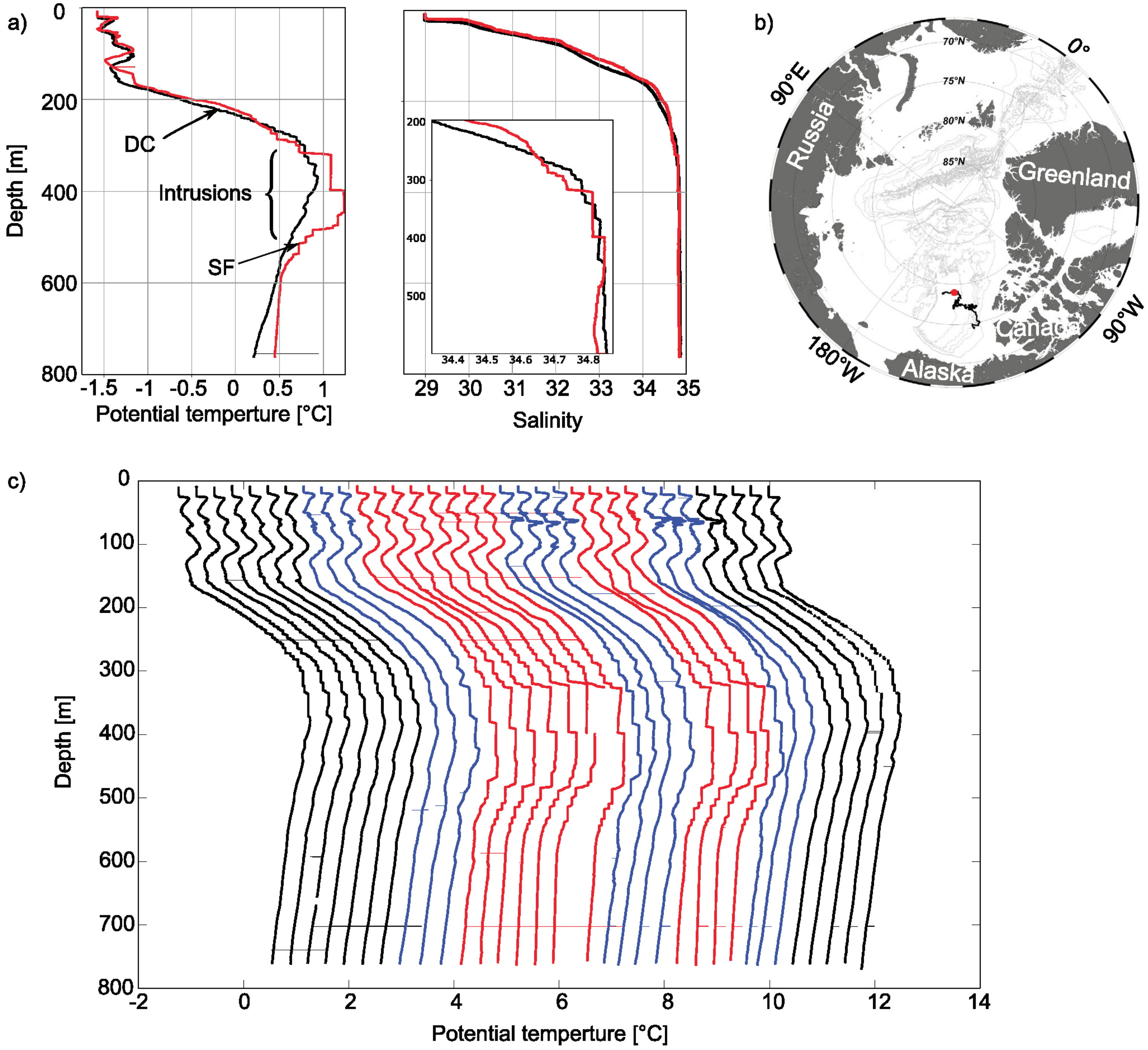
Observed throughout the Arctic ocean interior

Lateral extent ~5000km

Processes:
- Diffusive convection
- Salt fingering

(molecular level)

“quiet ocean?”

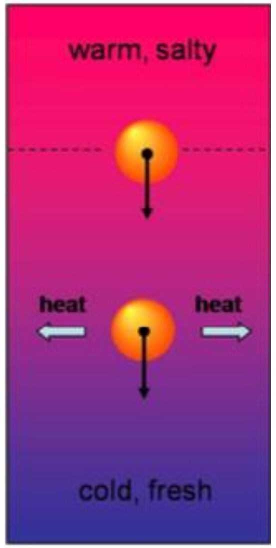


Bebieva & Timmermans [2015

Arctic Ocean: interior mixing

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

Case 1: Salt fingering:



hematic of the salt fin

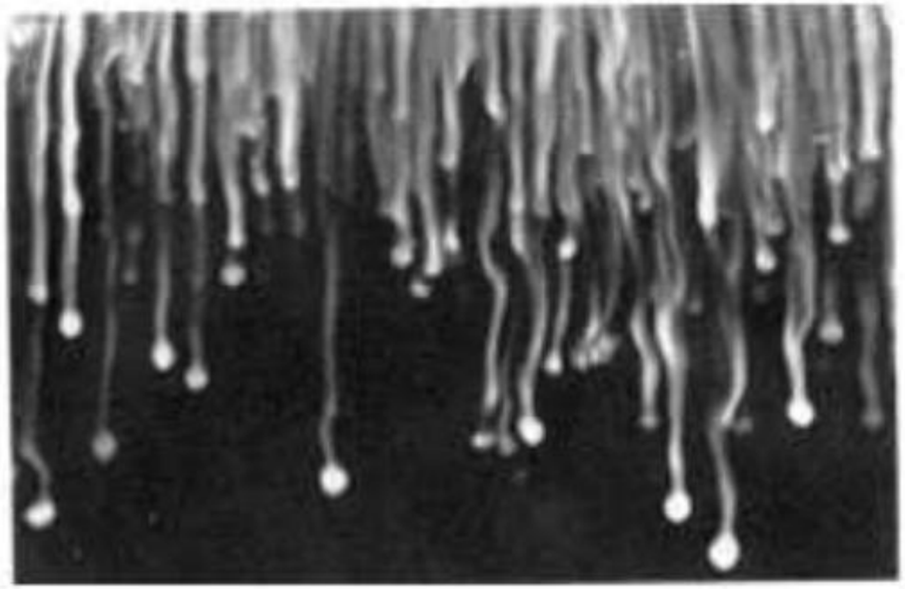
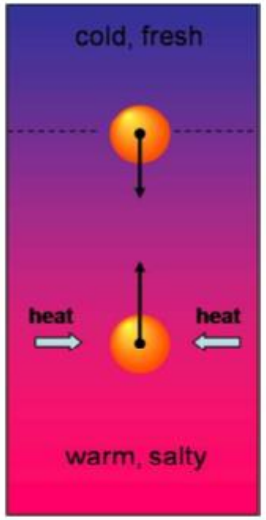
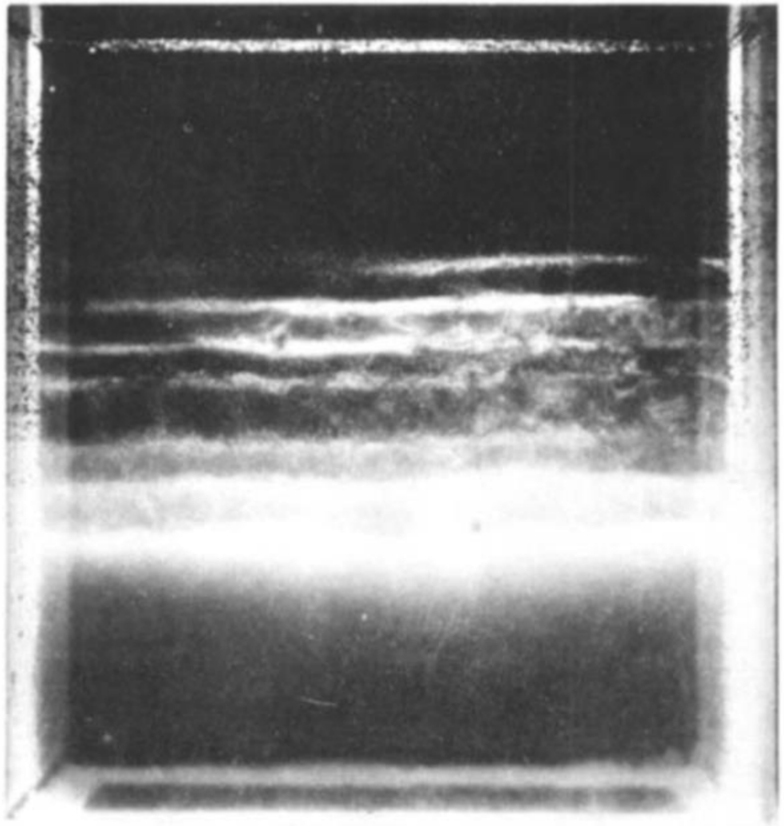


Figure 2: Salt fingers in a laboratory experiment [3].

Case 2: Diffusive convection:



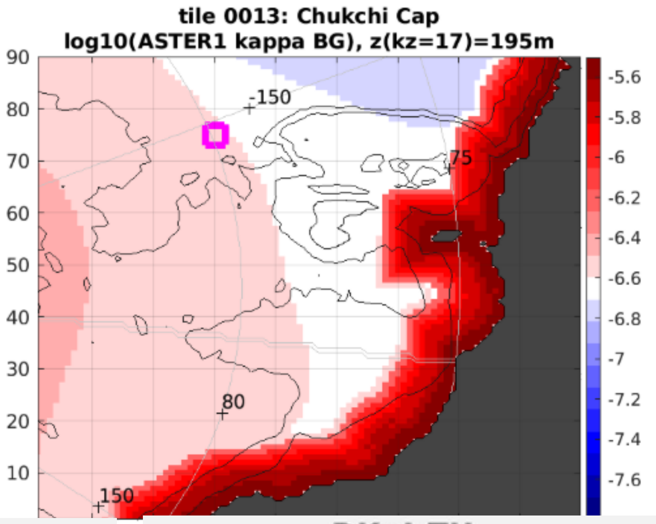
chematic of the diffusive con

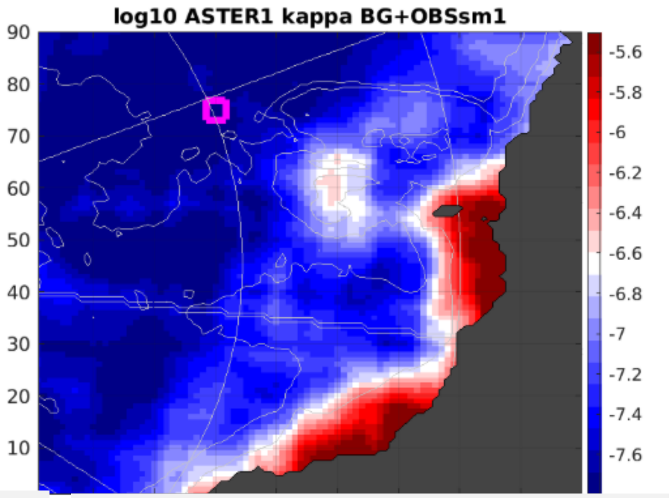


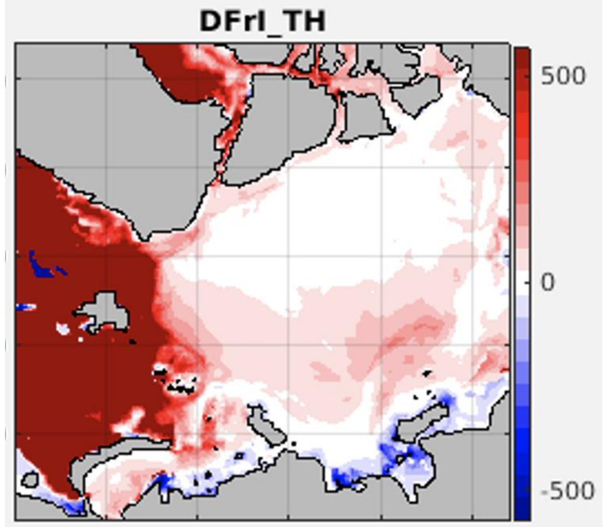
Radko , "Double-Diffusive Convection" lecture, https://www.whoi.edu/fileserver.do?id=136325&pt=10&p=85733
Turner 1974, "Double-Diffusive Phenomena", Annu Rev Fluid Mech .

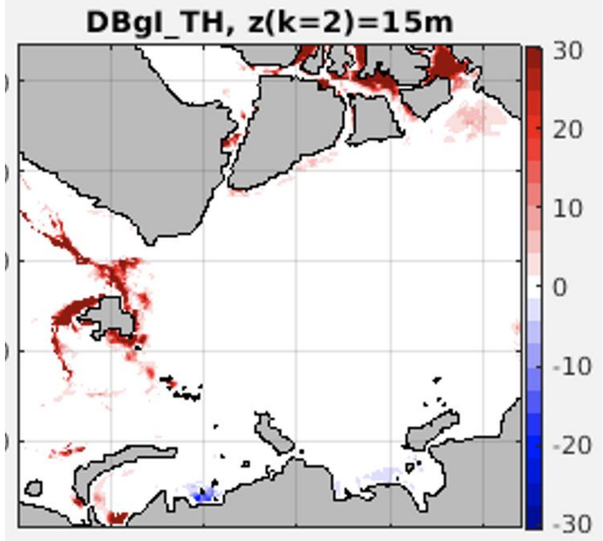
Improving ASTE:

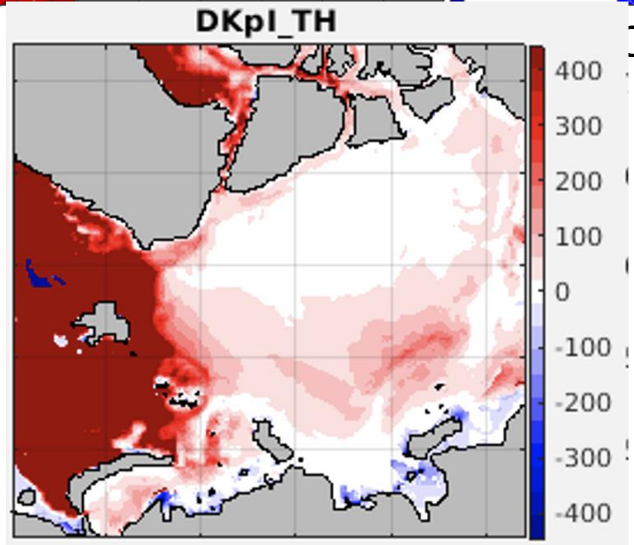
Diffusive flux budget
(Aidan Parfett, UBC)

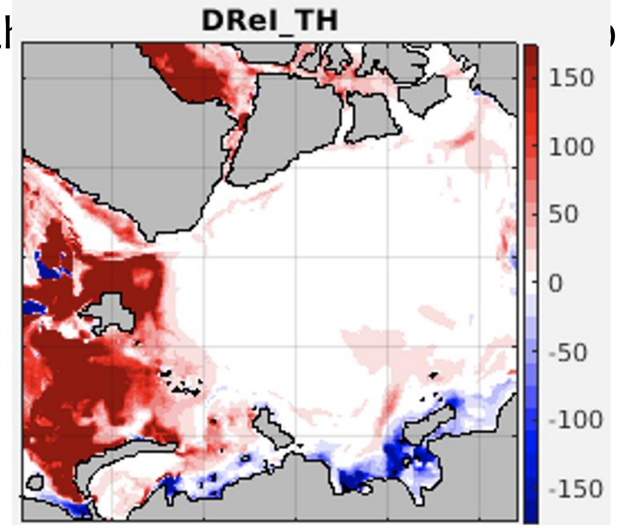












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Diffusive flux budget
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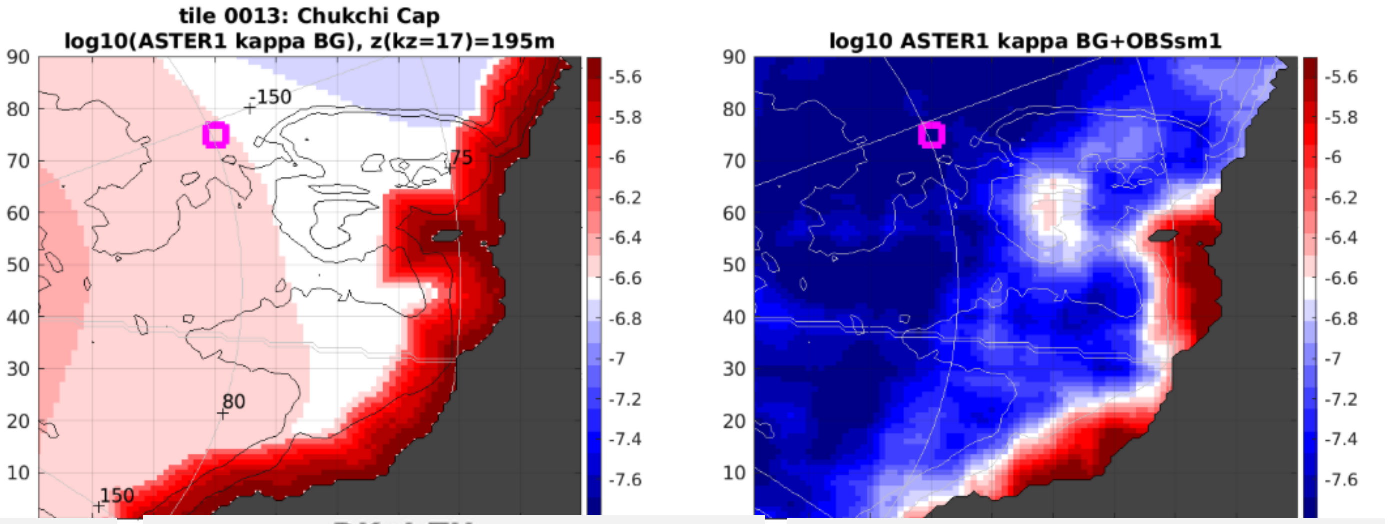
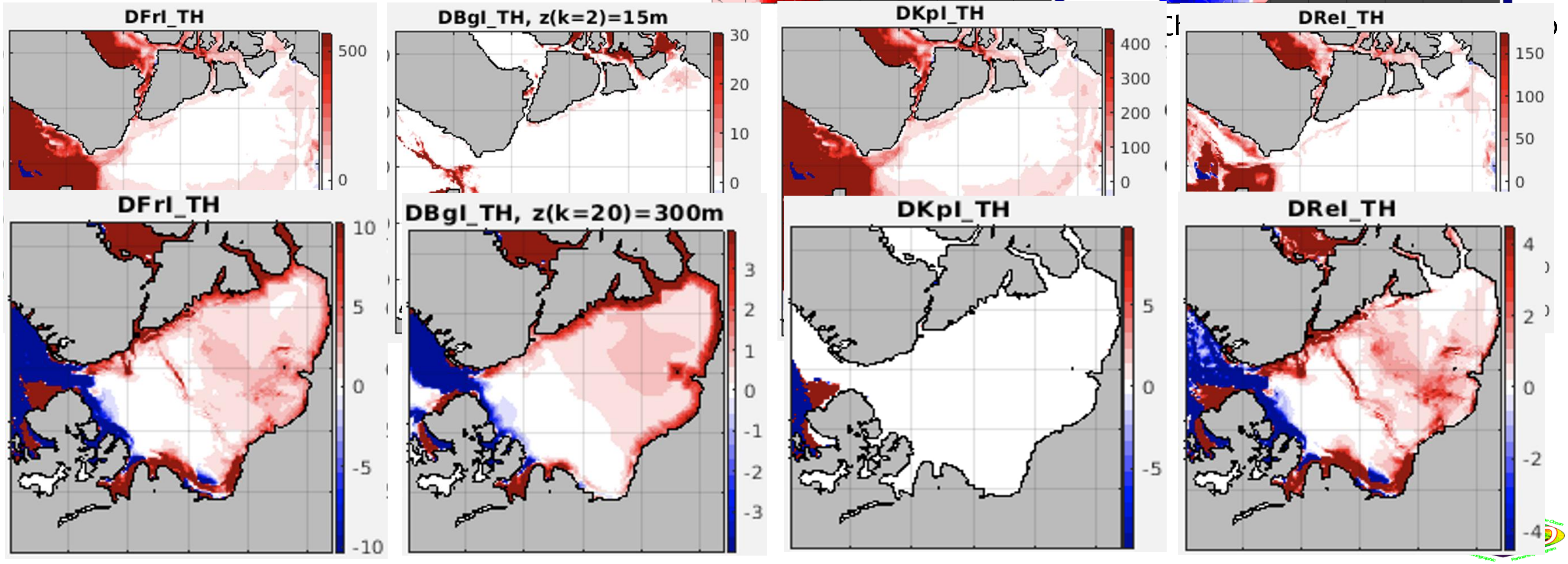
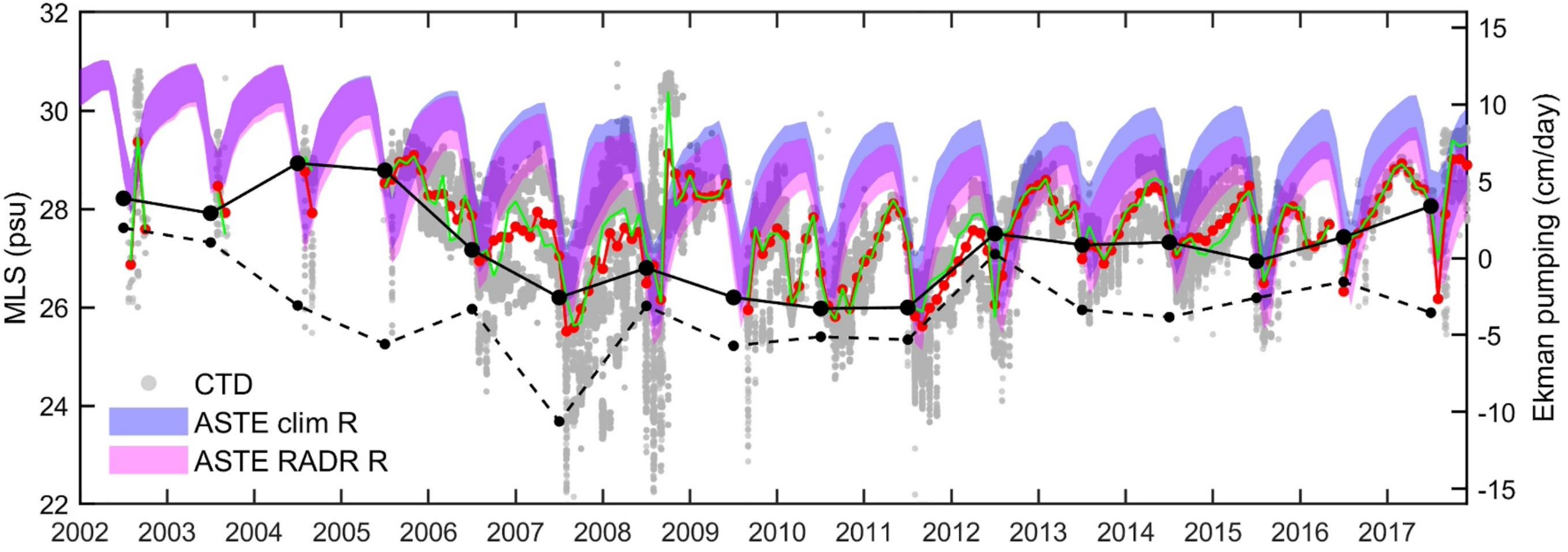




Improving ASTE: ML salinity budget in Beaufort Sea

Zhong et al., 2024



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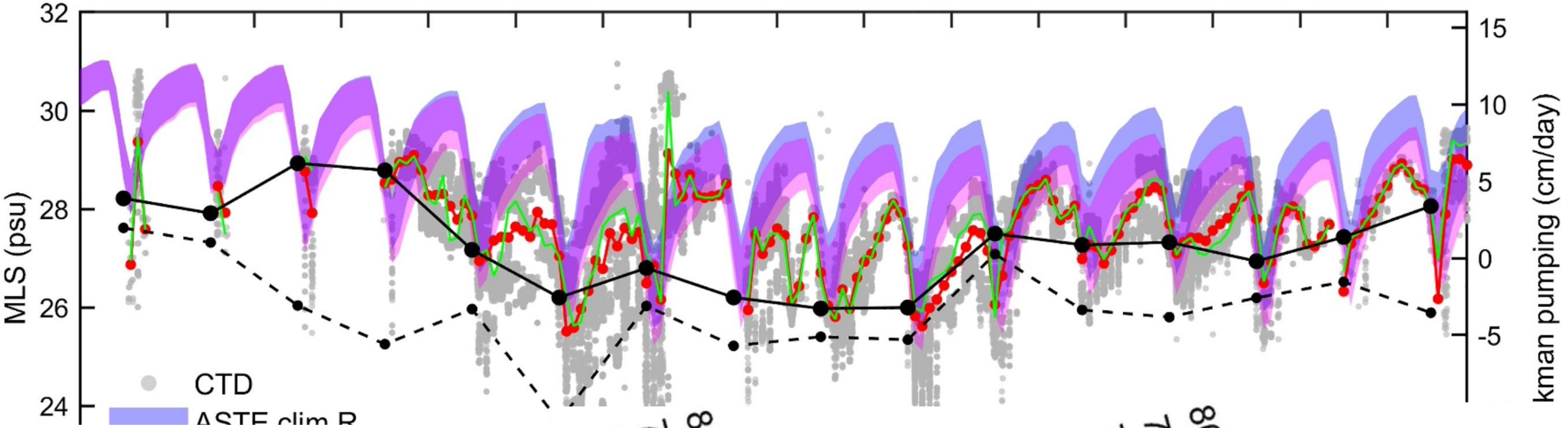

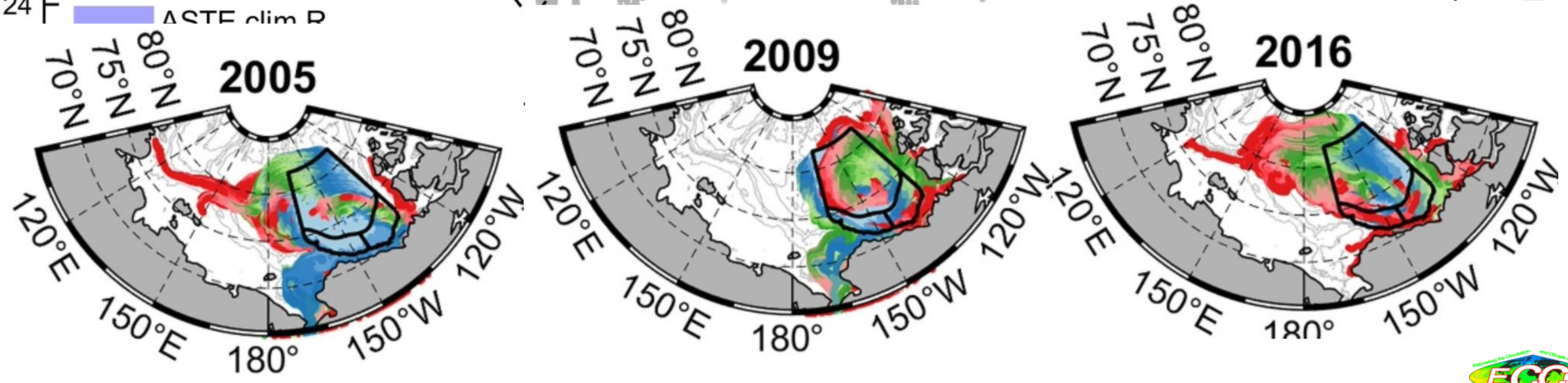

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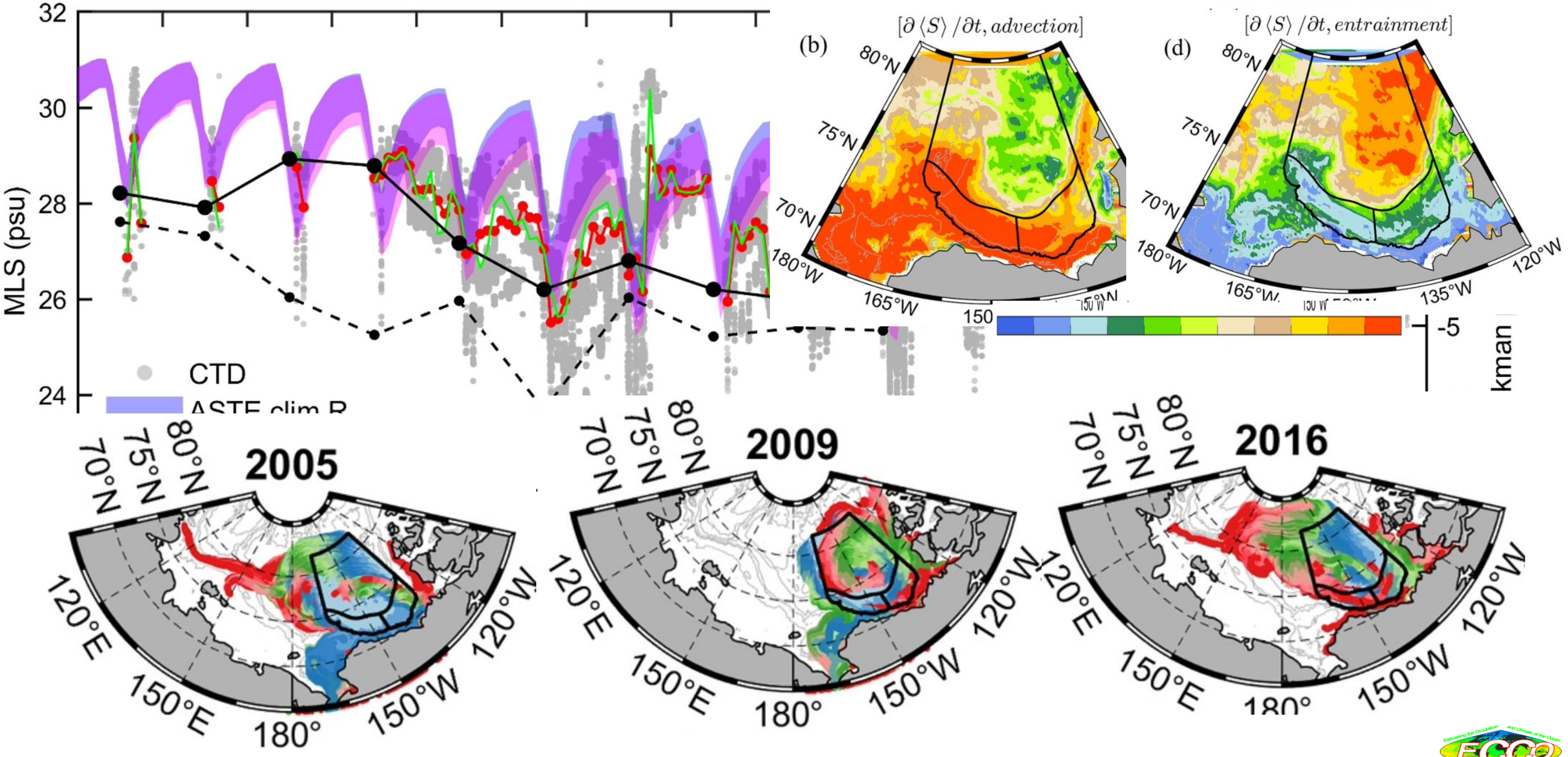
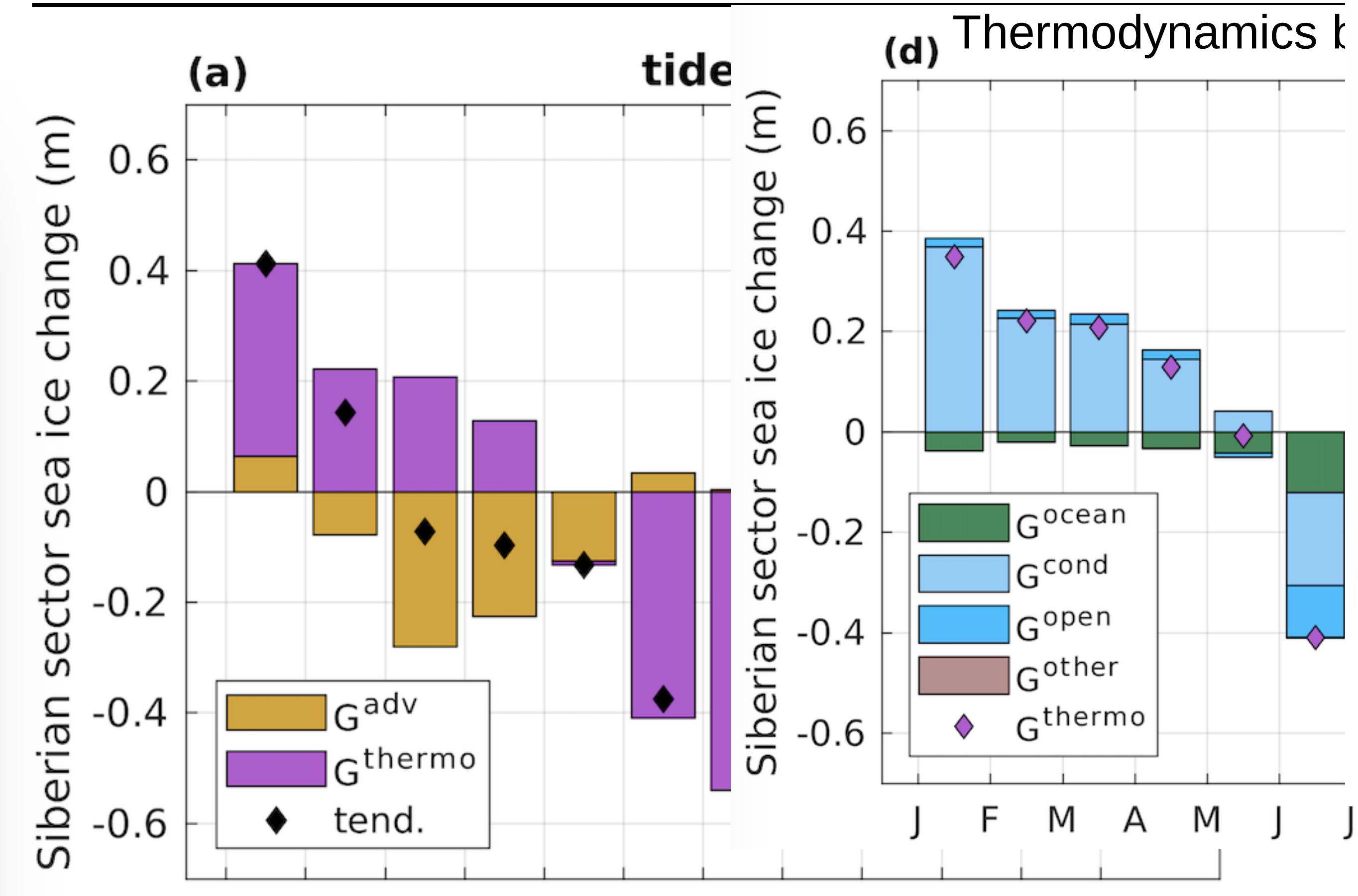
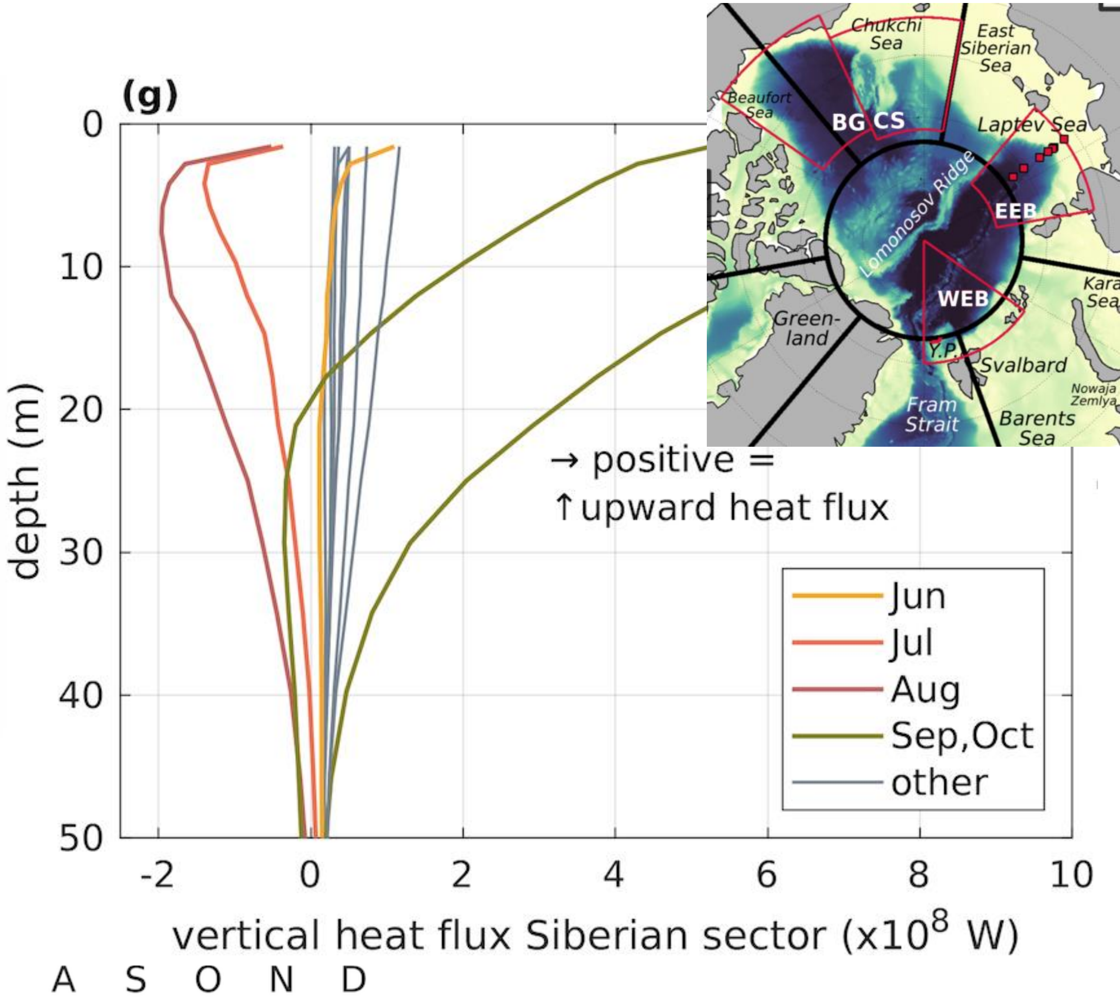


Improving ASTE: Tides and sea ice

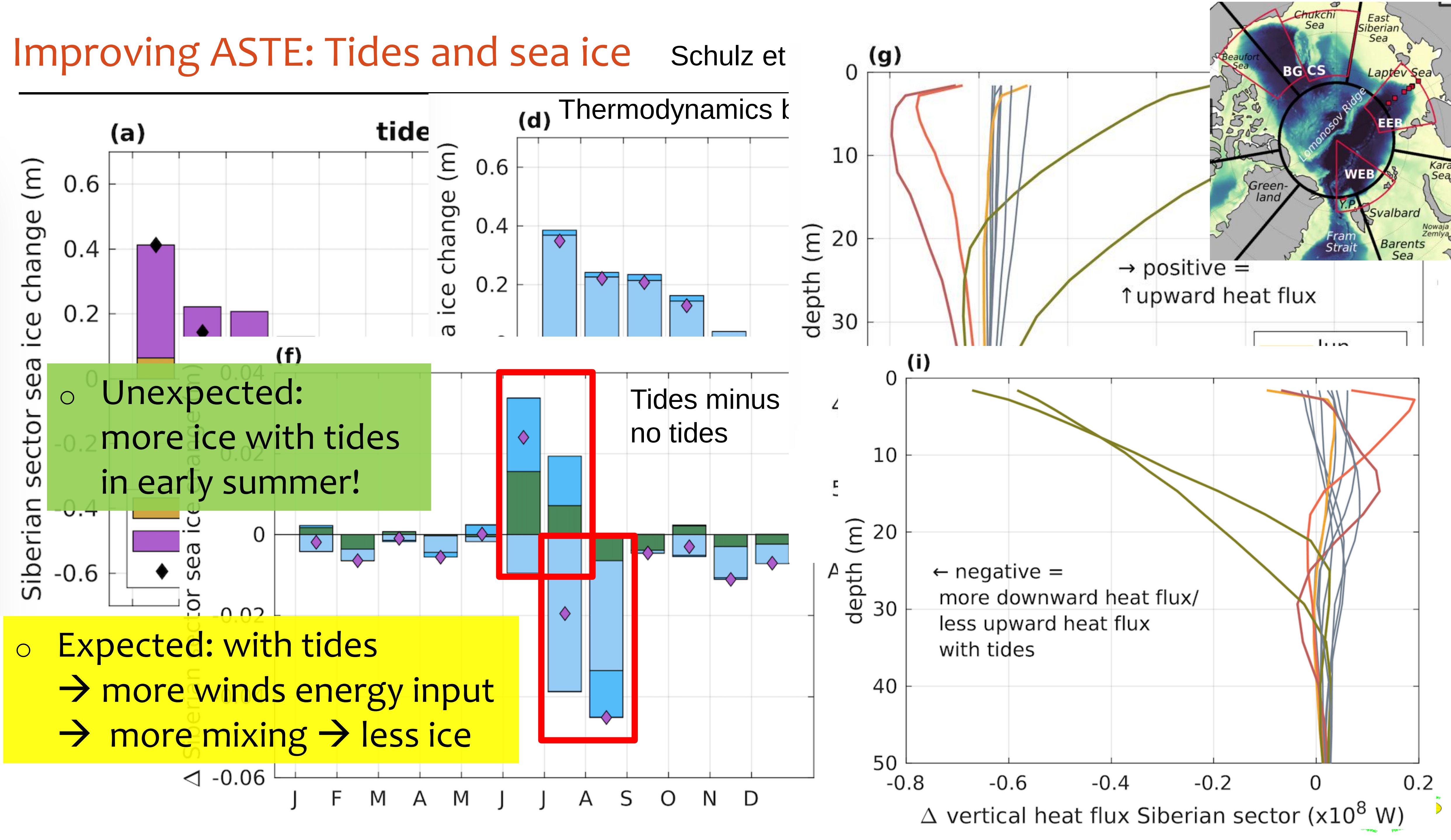
Schulz et





Improving ASTE: Tides and sea ice

Schulz et

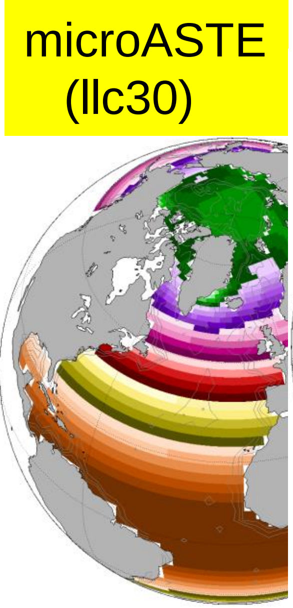


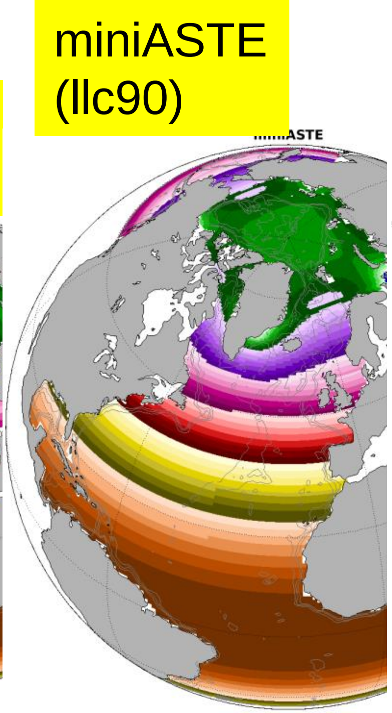
- Unexpected: more ice with tides in early summer!

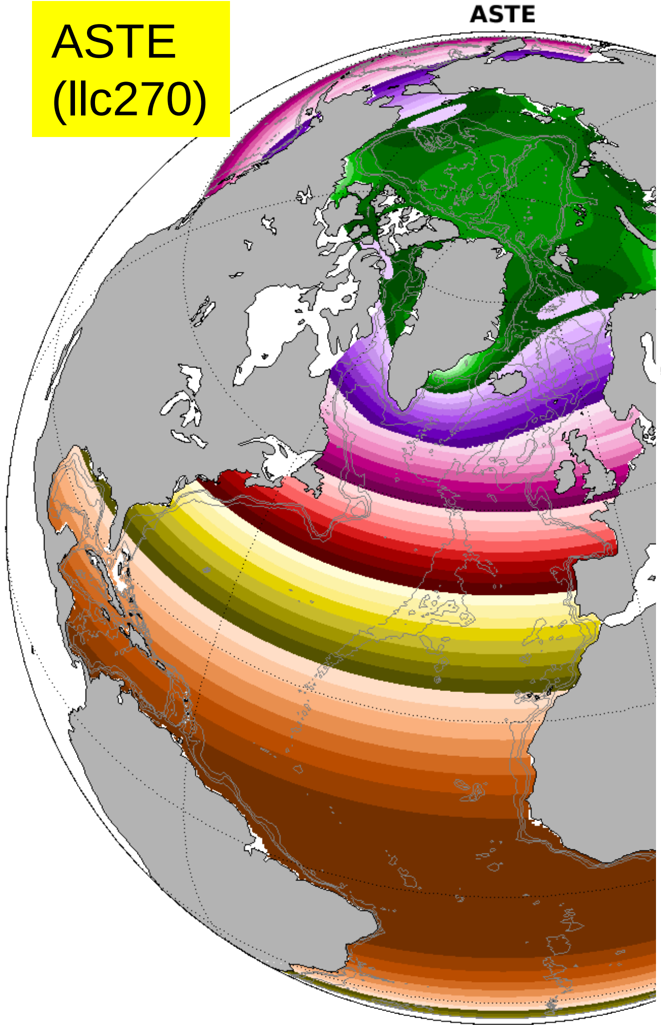
- Expected: with tides
  → more winds energy input
  → more mixing → less ice

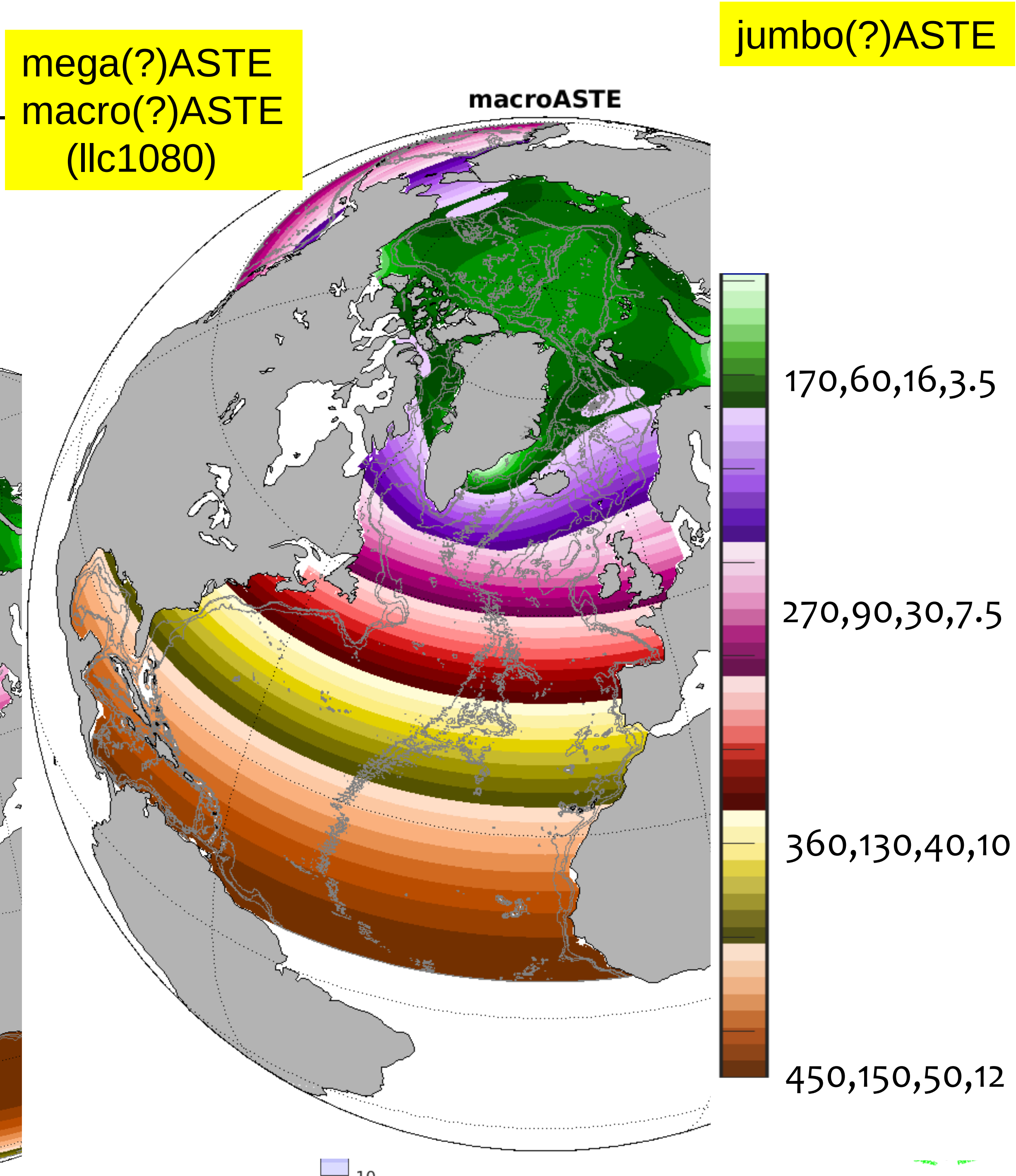
ASTE Extension (to end of 2023)

- Inputs update
  - Forcing
  - River runoff
  - Mixing maps
- Data updates
- Toward highres
- WMT



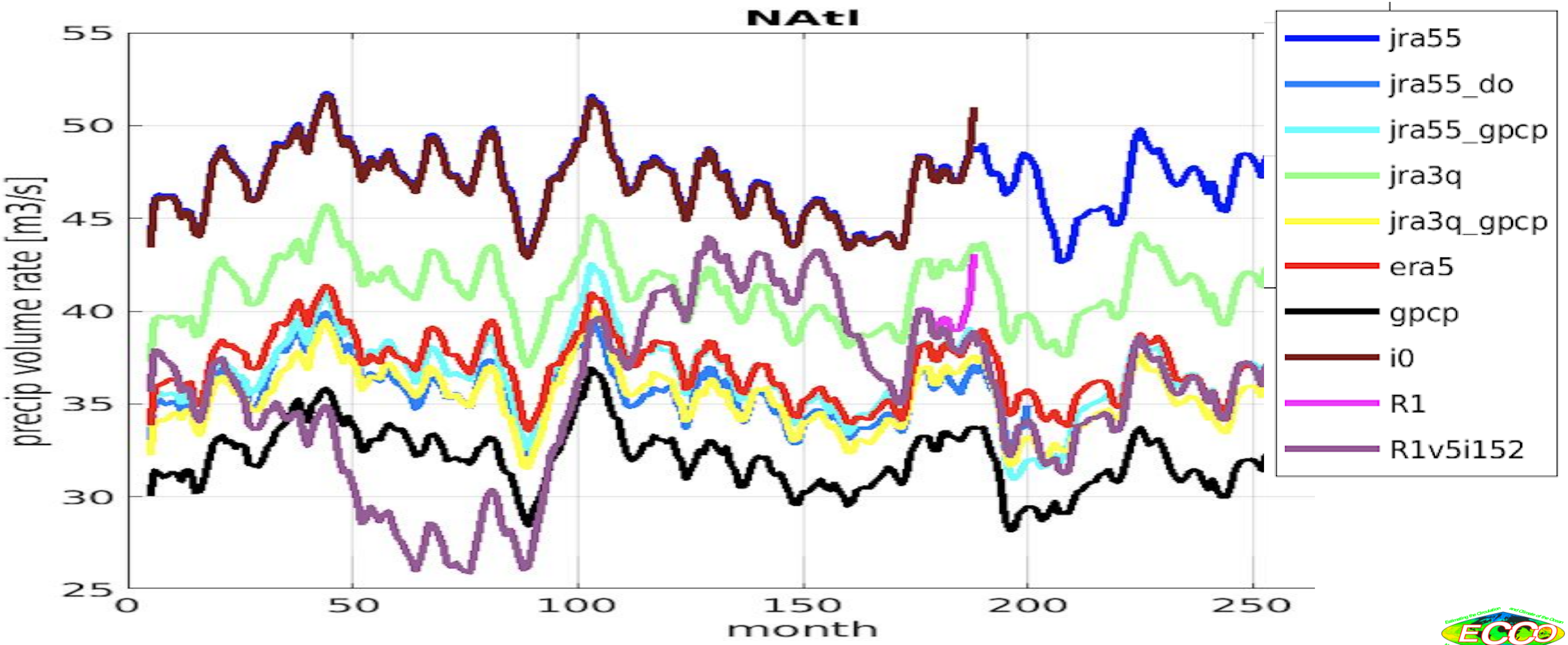






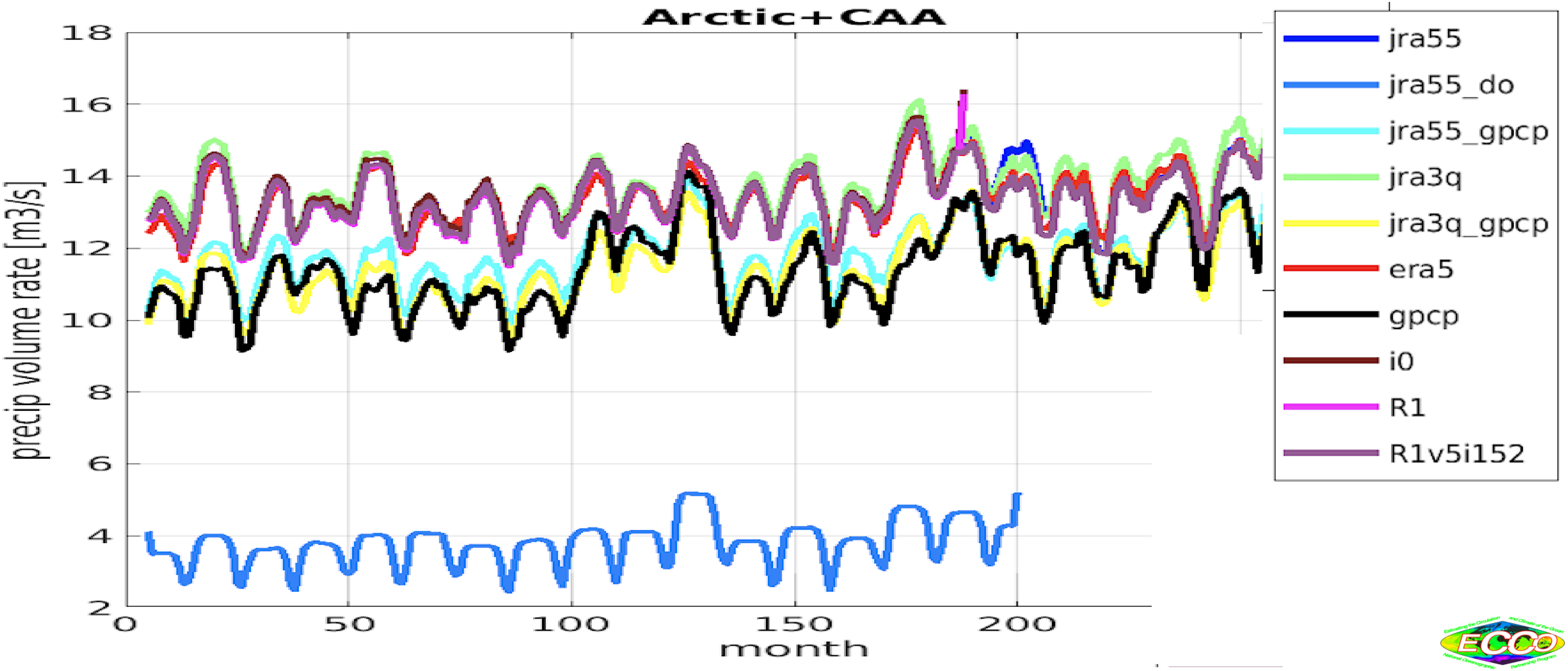
ASTE Extension

- to end of 2023
- Update to forcing: JRA-3Q [https://jra.kishou.go.jp/JRA-3Q/index en.html]



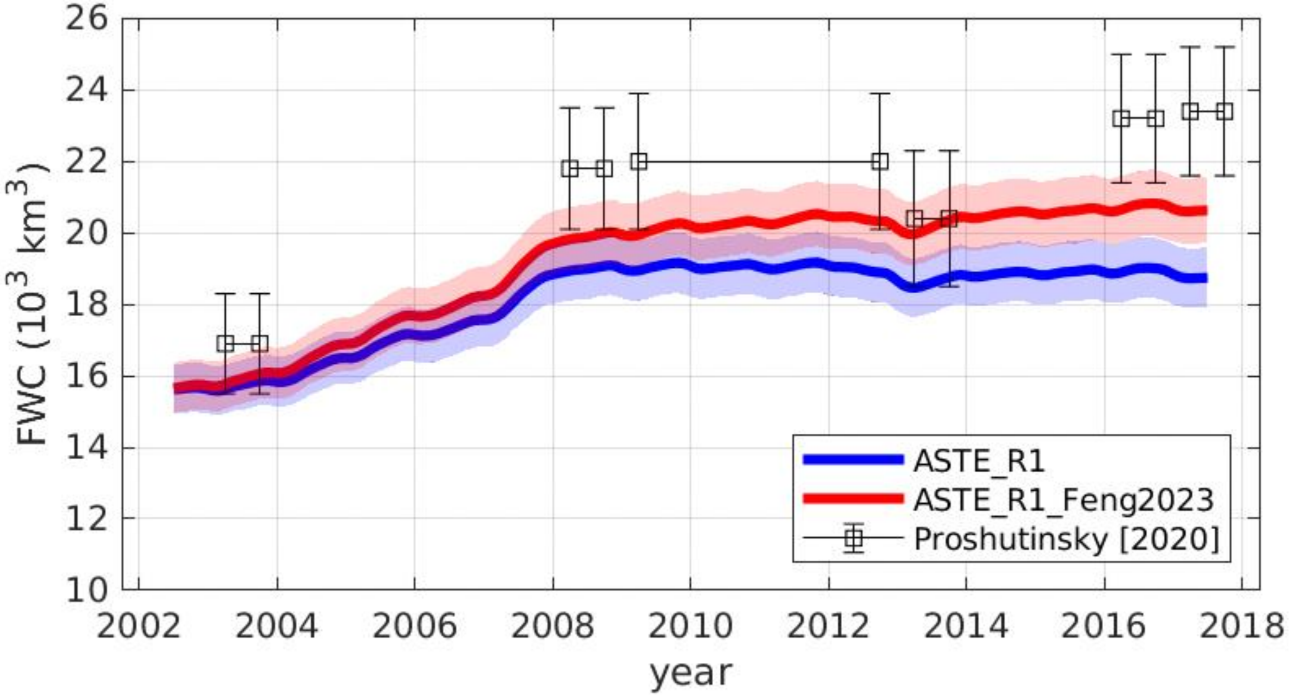
ASTE Extension

- to end of 2023
- Update to forcing: JRA-3Q [https://jra.kishou.go.jp/JRA-3Q/index en.html]



ASTE Extension – river runoff (with help from Wenli Zhong)

- Updating river runoff: [Feng et al. 2021]
  - pan-Arctic Remotely-sensed Arctic Discharge Reanalysis (RADR) for 1984-2018
  - Assimilated product, of 9.18mil discharge obs from 227 mil river width measurements from Landsat images



ARTICLE

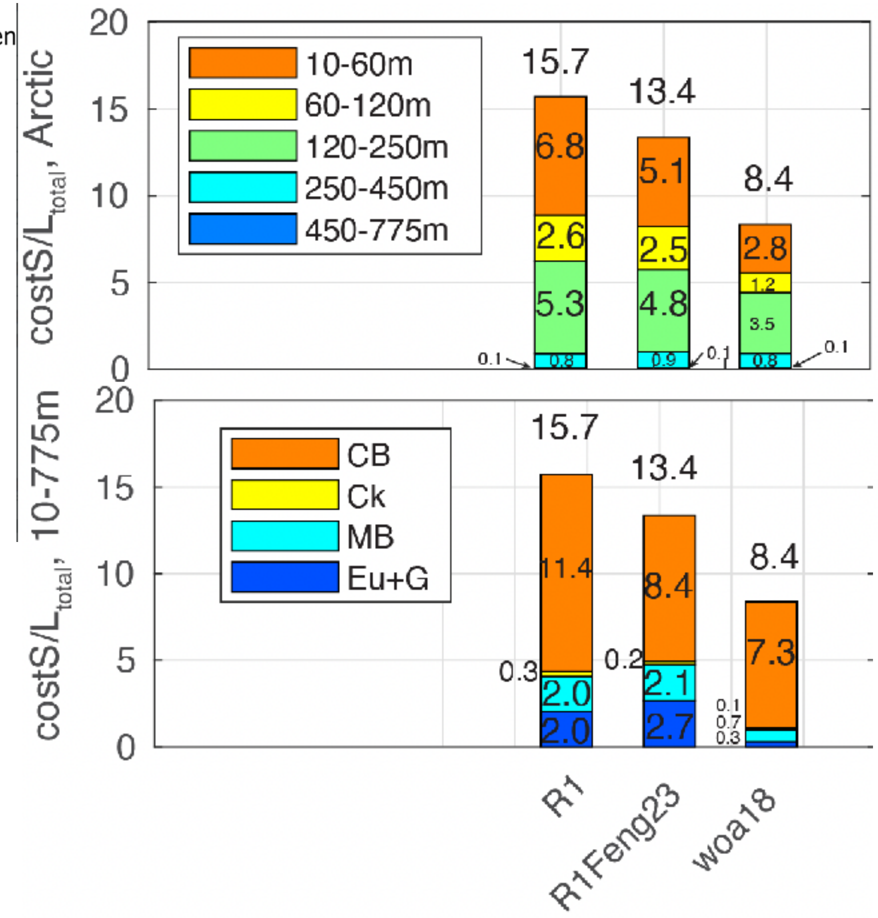
https://doi.org/10.1038/s41467-021-27228-1

OPEN

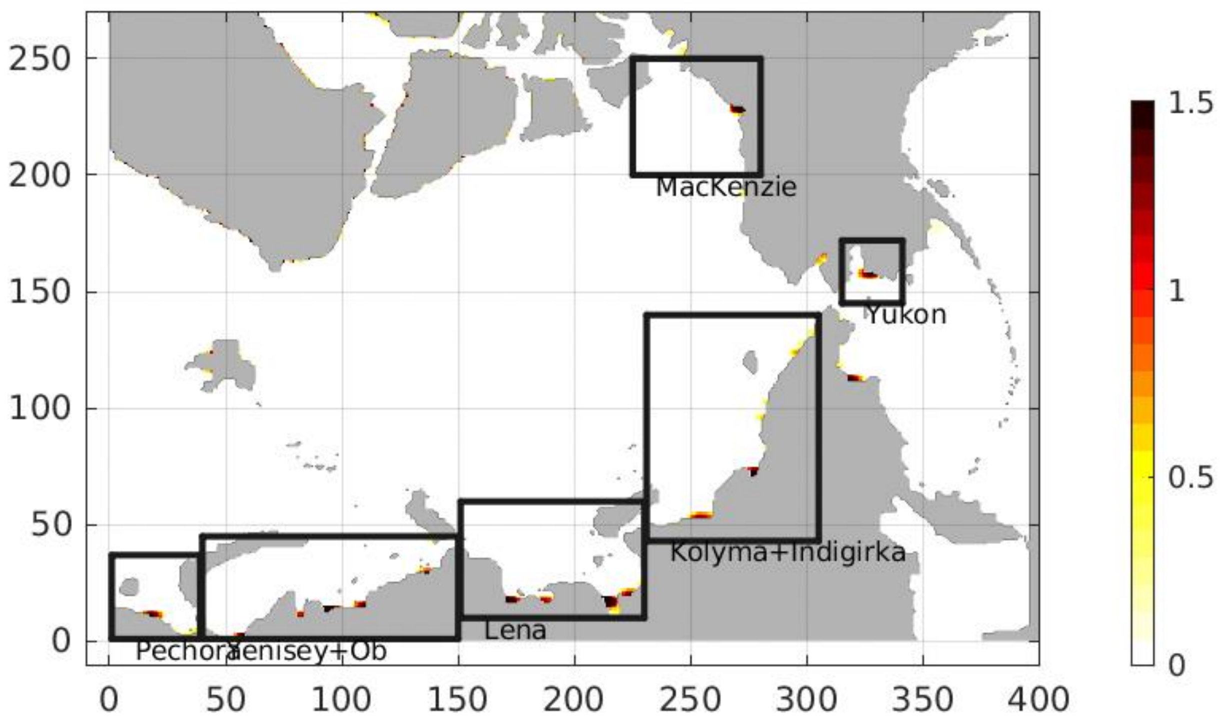
Recent changes to Arctic river discharge

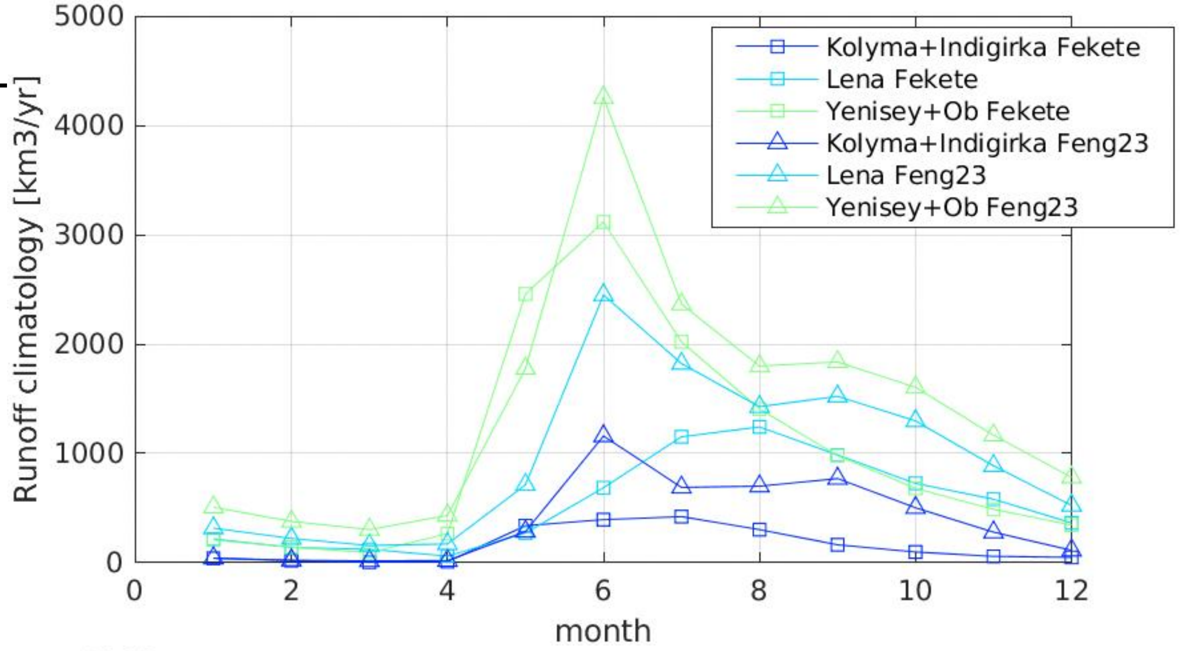
Dongmei Fen

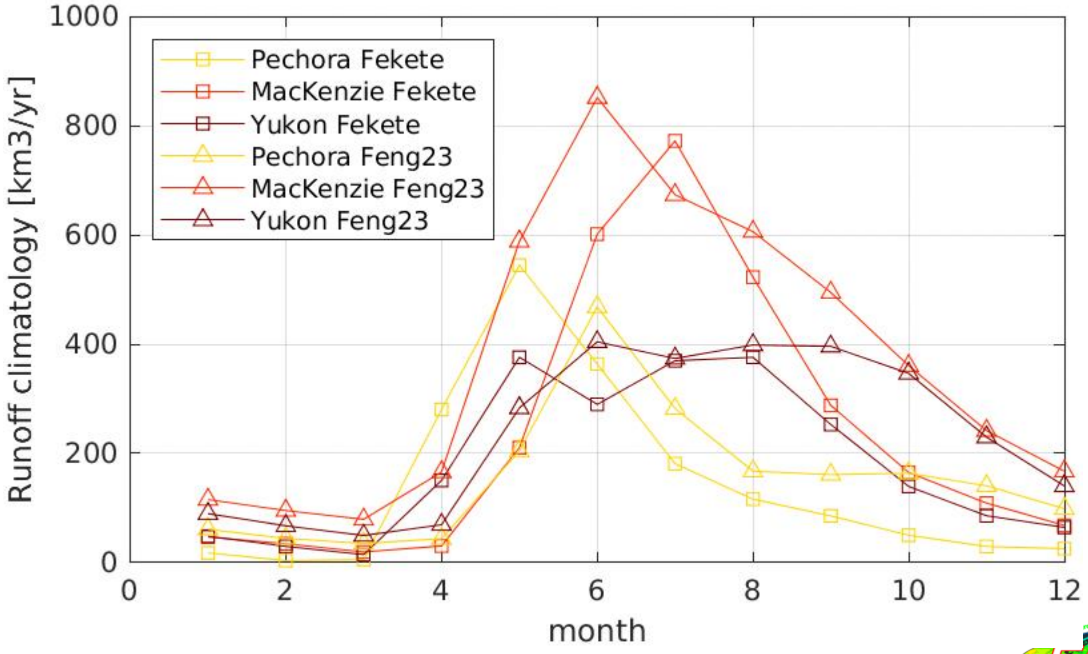
Ishitsuka[1]



ASTE Extension – river runoff







Note: change in seasonal cycle

ASTE Extension – data sets

Thanks Ian for satellite obs, Matt for Argo

- MOSAiC
- Mooring arrays across GSR: http://www.oceansites.org/tma/gsr.html
- A-Twain data: [Våge16,PerezHernandez17,Renner18]
  https://data.npolar.no/dataset?page=1&q=A%20Twain&location=arcticOcea
  https://openpolar.no/Record/npolardata:oai:npolar.no:dataset%2Fd3a5adc2-aa97-4934-893d-83427f7134ad
- Davis Strait data: not avail after 2015, already sent email to C. Lee to ask.
- GIS ridge: http://kogur.whoi.edu/php/index.php, http://kogur.whoi.edu/Historical_Data/ [Våge13, 18]
- Iceland Greenland Project (IGP, Huang21): https://web.whoi.edu/all0118/ , (only ctd, not underway vel)
- UDASH: [Behrendt17, Behrendt18], 1980--2015, https://doi.pangaea.de/10.1594/PANGAEA.872931
- International Council for the Exploration of the Seas (ICES): https://data.ices.dk/
- Faroe-Island data: http://www.envofar.fo
- GreenlandScotlandRidge: http://www.oceansites.org/tma/gsr.html (transp avail, contact people for indiv)
- FramStrait [in/out]flow (start here, already downloaded publication from year 2023)
  https://www.pangaea.de/?q=von+Appen%2C+Wilken-Jon&f.pubyear%5B%5D=2022&f.project%5B%5D=FRAM
  https://www.npolar.no/en/projects/fram-strait-arctic-outflow-observatory/\#toggle-project-dataset;
  https://data.npolar.no/dataset/c4d80b64-25f6-4afd-b392-696430c3fd14
- NABOS (Igor Polyakov)

ASTE Jupyter notebook

https://github.com/crios-ut
/aste/blob/master
/aste_llcreader_example.ipynb

aste / aste_llcreader_example.ipynb

↑ Top

Preview | Code | Blame | 1088 lines (1088 loc) · 787 KB

Raw

https://doi.org/10.1145/3311790.3396656

In [1]:

```
import numpy as np
import warnings
import matplotlib.pyplot as plt
import xarray as xr
import cmocean
from dask.distributed import Client

from xmitgcm import llcreader
import ecco_v4_py
```

Get an xarray dataset with *all* ASTE_R1 variables, depth levels, and time steps

File display

The function `get_dataset` by default grabs all available output, at all depth levels and all time steps, where each time step represents a monthly mean for that field. This may be suboptimal when operating on a machine with limited memory, for instance on a laptop. See the llcreader documentation for more examples on how to subset the data with the get_dataset method, including how to grab specific variables, vertical slices, or time steps.

In [2]:

```
aste = llcreader.CRIOSPortalASTE270Model()
```

In [3]:

```
ds = aste.get_dataset()
```

Grab a single monthly average

Here we subset the dataset to show the ASTE ocean state during a single month, September 2012. Alternatively, one can provide the corresponding iteration to the `iters` option in `get_dataset` to achieve the same behavior.

In [4]:

```
ds = ds.sel(time='2012-09')
```

Questions?

ASTE Extension / Devel

- Higher res: llc1080-based ASTE (exists in forward mode)
  - Multigrid
    – following ECCO efforts, also testing tape saving capability (Matt Mazloff's code)

- Adjusted parameters:
  - (initial velocities)
  - (open boundaries)
  - (Ice thickness & area ICs)
  - (time-mean spatially-varying ice drags?)

ASTE Extension (to end of 2023)

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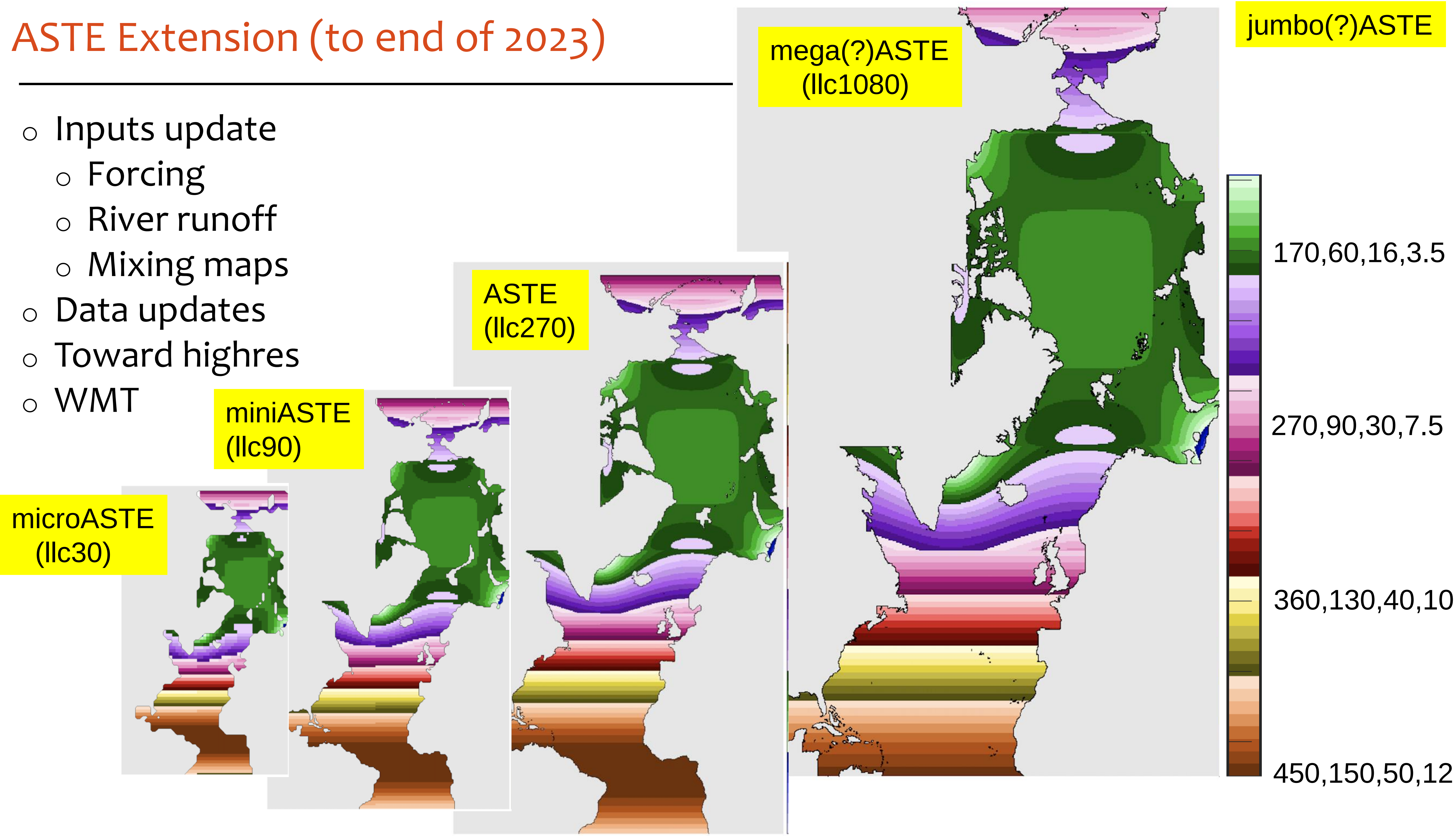

From idealized / theoretical: constraint on circulation

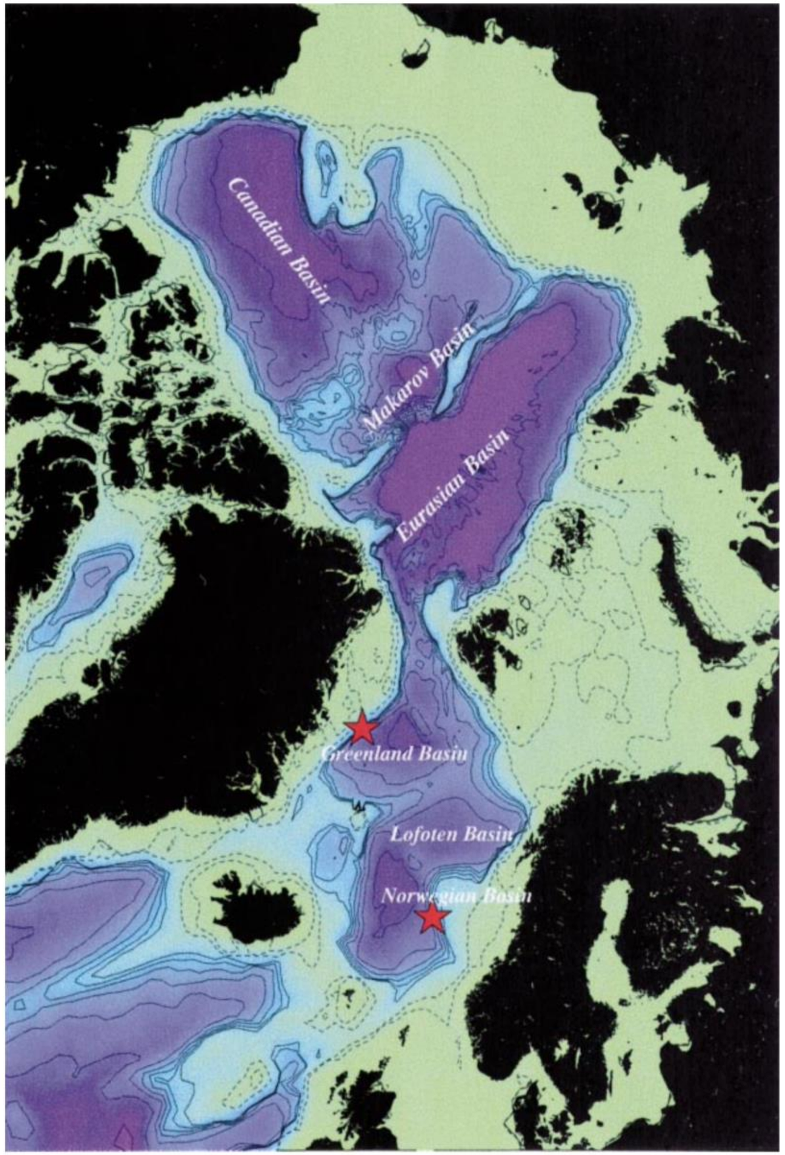

FIG. 3. The f/H field (lines) and bathymetric field (shades) for the Nordic seas and Arctic Ocean. The location of two moorings discussed later are shown with stars. Note the f/H contours approximately follow the isobaths.

- **Viscous dissipation (circulation)** -- uncertain
- **3-D internal turbulence mixing** – uncertain
- Unresolve mesoscale eddies (**Redi**) -- uncertain

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

$$\frac{\partial}{\partial t}\oint \mathbf{u}_0 \cdot d\mathbf{l} = \oint \frac{\boldsymbol{\tau}}{H} \cdot d\mathbf{l} - \oint \frac{\mathbf{u}_0}{H} \cdot d\mathbf{l}. \qquad (7)$$

The terms on the rhs of (7) represent the transports in the surface and bottom Ekman layers; any imbalance between them alters the circulation in the bounded region.

western moorings (numbers 410–413), the principal components of the currents align closely with the local tangent of the f/H contours. This component explains more than 85% of the total variance when currents are

Isachsen et al., JPO 2003