ECCO Arctic
(summary of efforts in the Arctic and its marginal seas)

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ECCO Summer School 2019

Challenges of 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

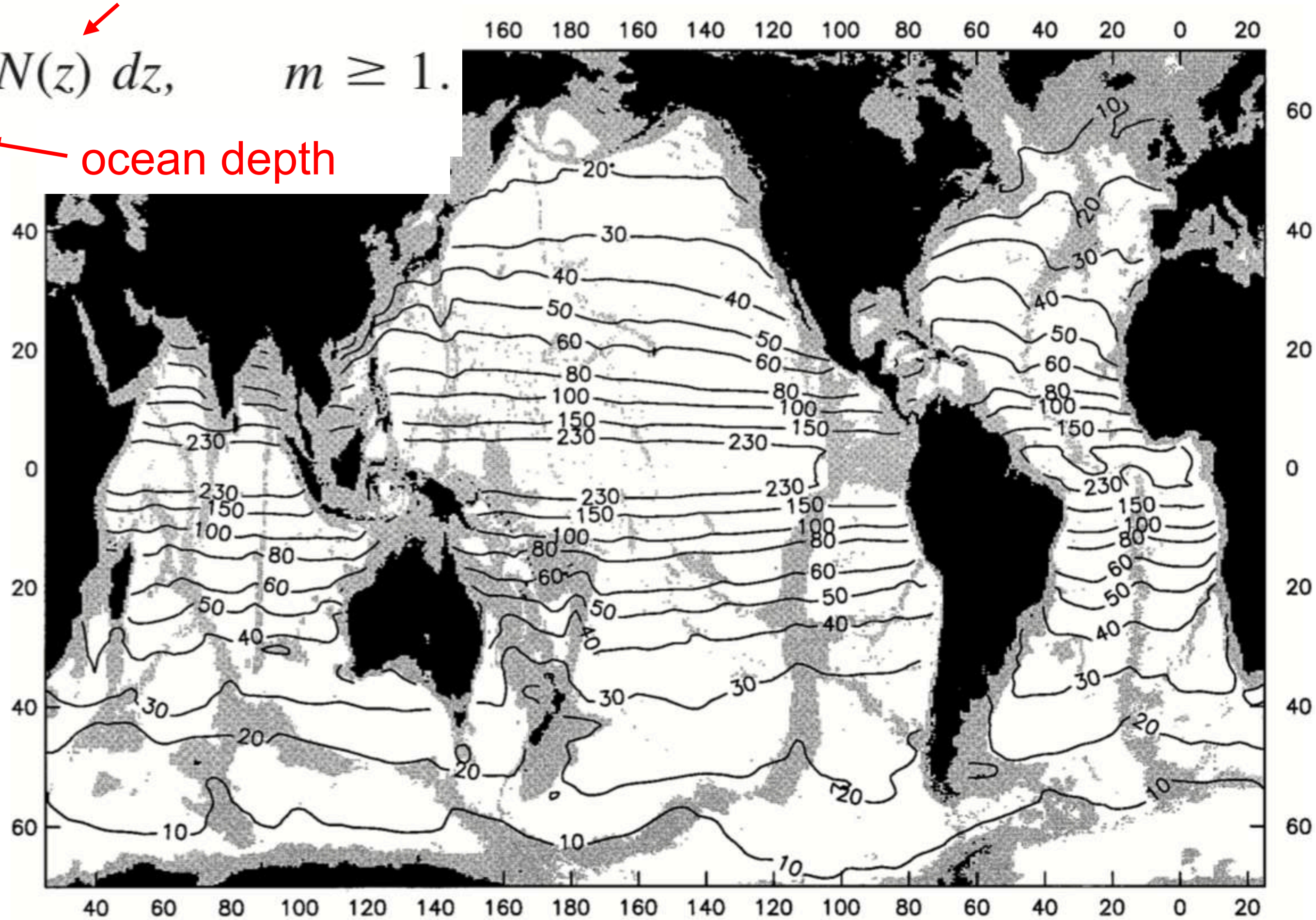


Fig. 6. Global contour map of the 1° × 1° first baroclinic Rossby radius of deformation λ_1 in kilometers computed by Eq. (2.3) from the first baroclinic gravity-wave phase speed shown in Fig. 2. Water depths shallower than 3500 m are shaded.

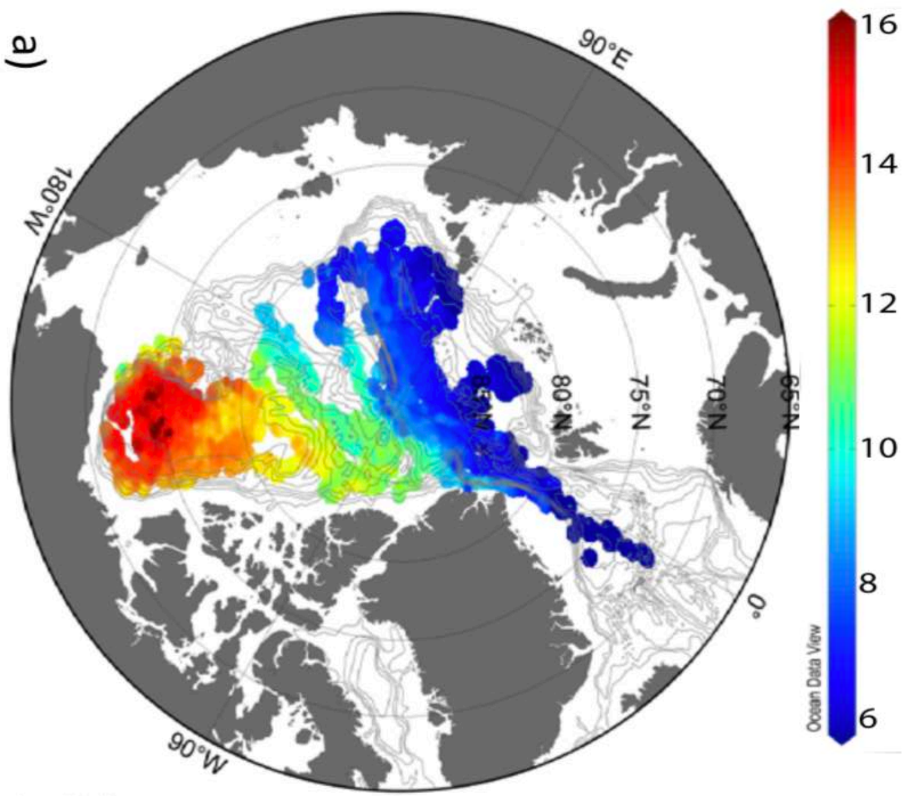
Chelton et al. [1998]

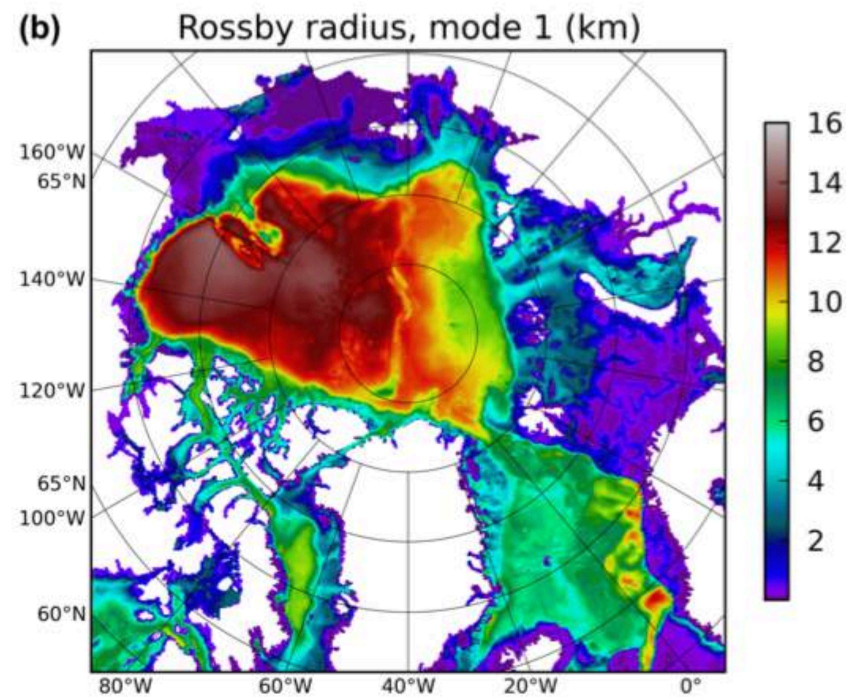
Challenges of modeling the Arctic

stratification

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

ocean depth





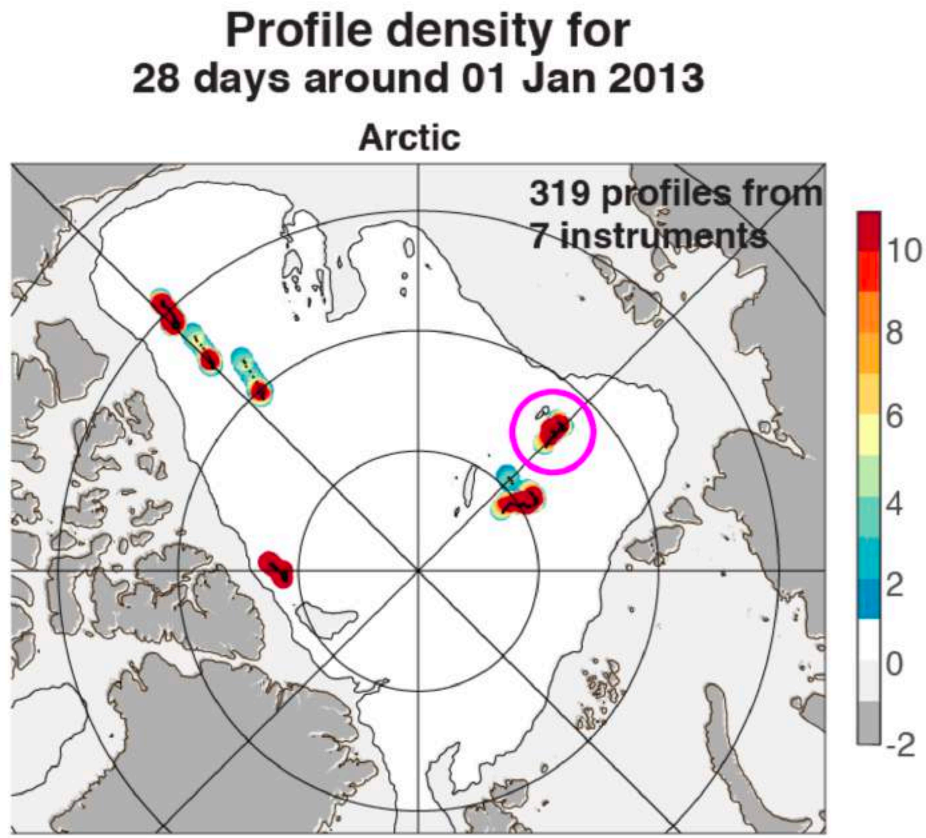
Nurser & Bacon [2014]

Zhao et al. [2014]

Challenges in obtaining Arctic state estimates

Lack of Observations
Unconstrained parameters & forcings

General: true in the world ocean, but exacerbated in Arctic due to harsh conditions and presence of sea ice

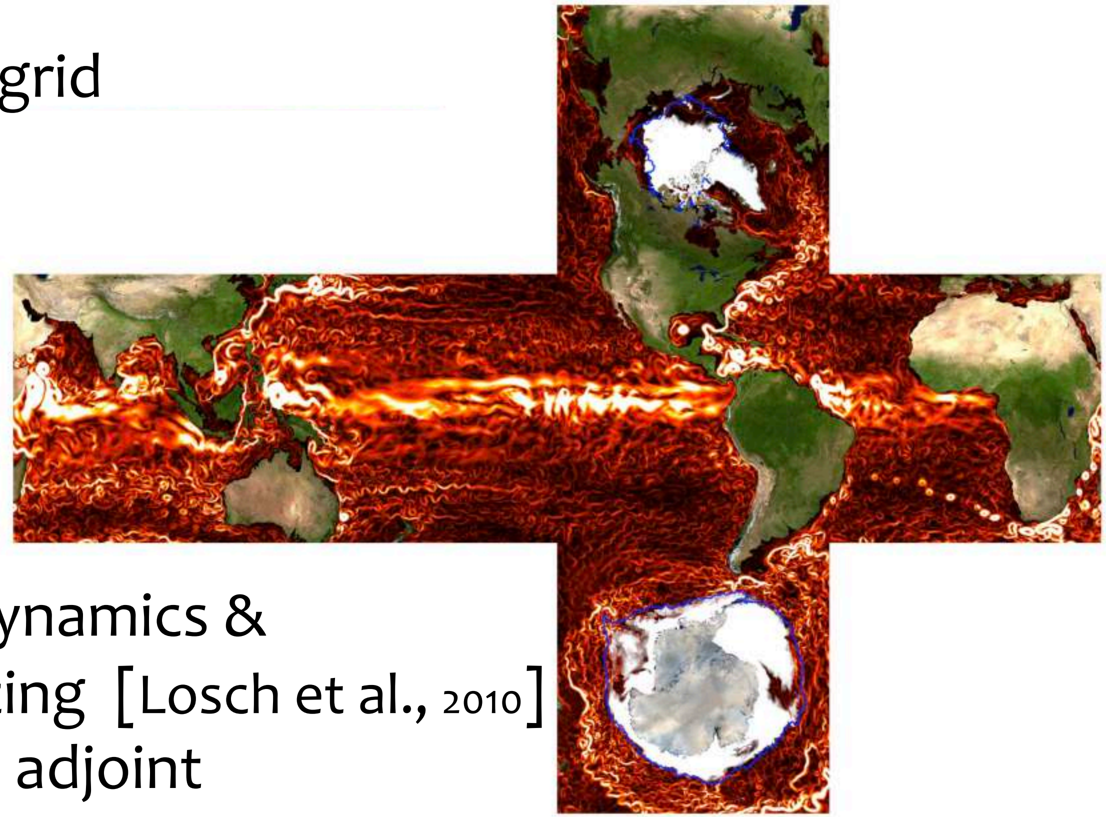


Nguyen et al., 2019, in prep

What separates ECCO from other Arctic Ocean-Sea ice Modeling Efforts?

ECCO-Arctic: the beginning

ECCO phase II (ECCO2):
18-km global, cubed-sphere grid



Sea ice code "history"

1. Dimitris Menemenlis adapted existing sea ice code [Zhang et al., 1998], for MITgcm
2. Martin Losch improved dynamics & performed extensive testing [Losch et al., 2010]
3. Patrick Heimbach: sea ice adjoint
4. Ian Fenty's improved sea ice code (Ph.D. thesis)
5. Further modifications
6. Ian Fenty + Arash Bigdeli: sea ice thermodynamic adjoints

1992– 2007 synthesis, using a Green's Function approach (Menemenlis, et al., 2005a; Menemenlis, et al., 2008)

ECCO-Arctic : A Green's function approach

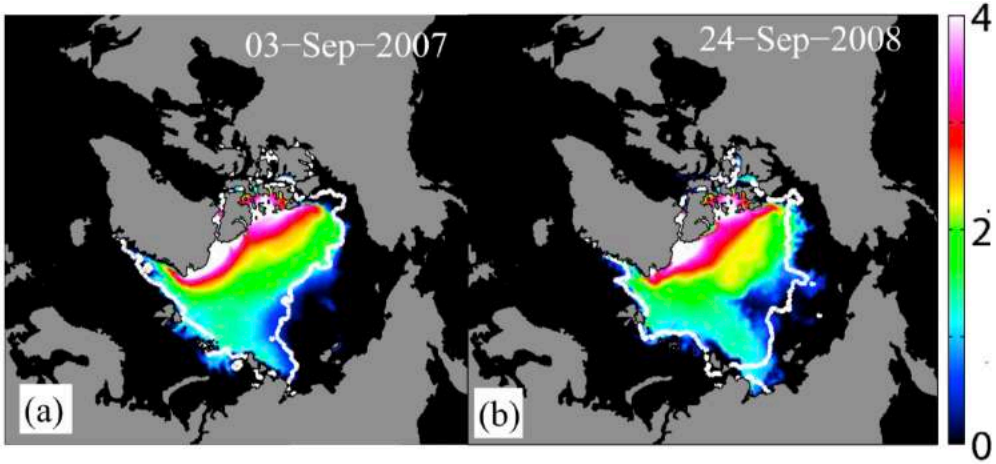
Arctic ice-ocean simulation with optimized model parameters:
Approach and assessment [Nguyen et al., 2011]

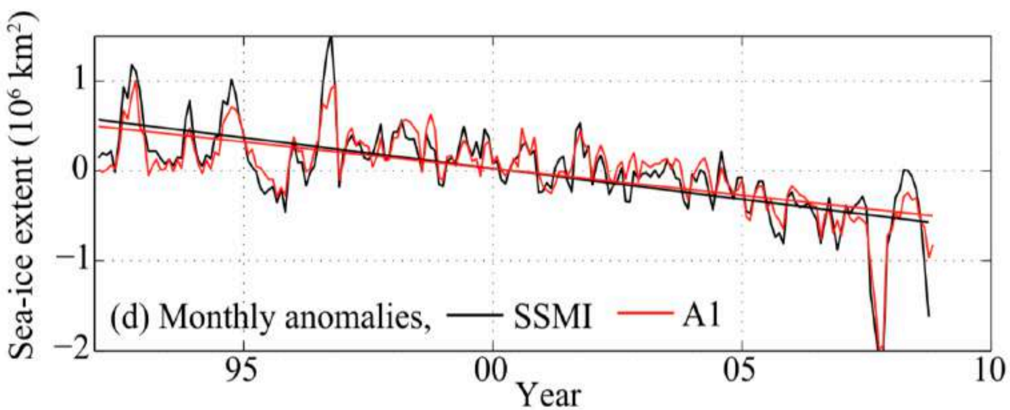
Given a model
$\mathbf{x}(t+1) = \mathbf{A}\mathbf{x}(t) + \mathbf{G}\mathbf{u}(t) = F(\mathbf{x}(t),\mathbf{u}(t))$

a perturbation satisfies
$F(\mathbf{x}(t),\mathbf{u}(t)+\delta) \approx F(\mathbf{x}(t),\mathbf{u}(t)) + \mathbf{G}\delta$

δ:
Atmospheric forcings (JRA-55)
Initial conditions (WOA09)
Ocean albedo
Sea ice albedos
Sea ice strength + lead closing params
Air-sea ice drag coefficient
Sea ice
Vertical mixing parameter ($5.4 \bullet 10^{-7}$ m^2/s)
River runoff contribution

(salt plume parameterization
[Nguyen et al. 2009])

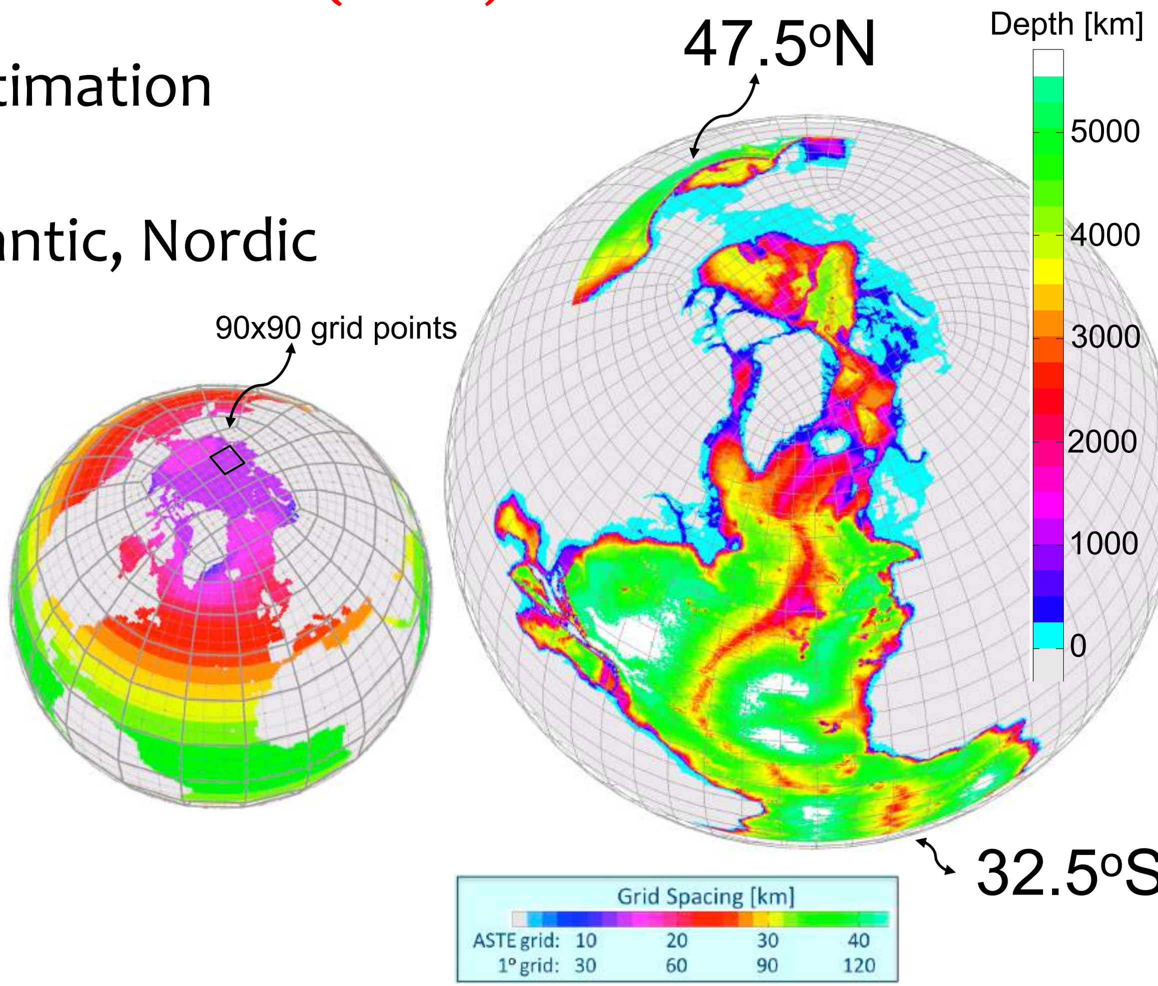




ECCO-Arctic: adjoint method

Arctic Subpolar gyre sTate Estimate (ASTE)

- Adjoint-based state estimation
- Synthesis of North Atlantic, Nordic Seas, and Arctic data
- Higher horizontal resolution than ECCOv4



Arctic Subpolar gyre sTate Estimate (ASTE) – Release 1

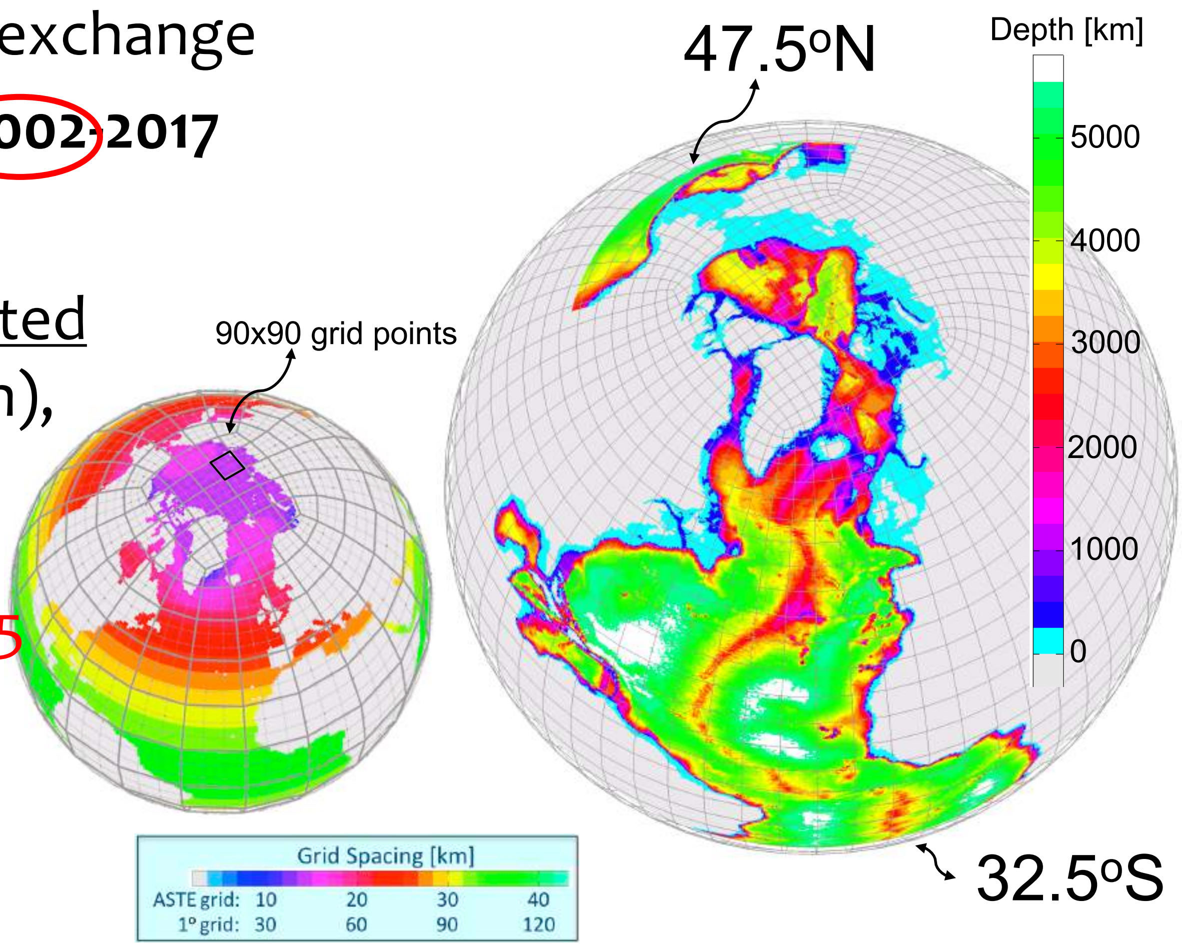
- Mean & time-varying ocean & sea ice states
- Arctic – Subpolar gyre exchange
- Optimization period: **2002-2017**

- <u>Initial conditions: adjusted</u>
  - WOA14 spin-up (ocean),
  - PSC spin-up (ice)

- <u>Forcing</u>: adjusted JRA55

- <u>OBCs</u>: ECCO-v4

- **<u>Control variables</u>:**
  - initial conditions
  - time-varying atmospheric state,
  - 3-D ocean mixing parameters



ASTE atmospheric forcing

Temperature bias in the high latitudes in ERA-interim:

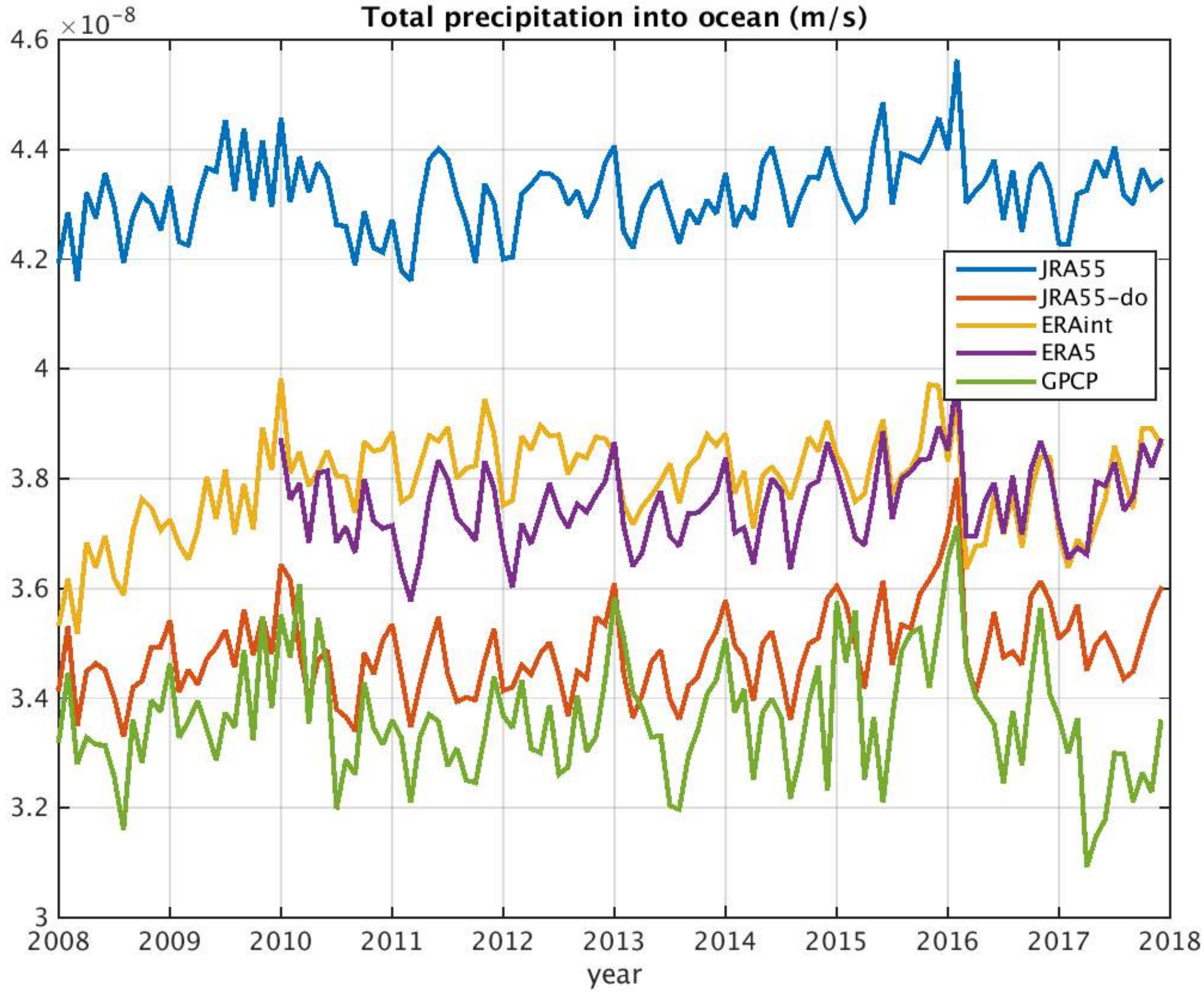
"ERA-Interim shows a widespread warm bias in Antarctica in every season, ranging from +3 to +6°C" , **Fréville, et al. (2014)** The Cryosphere, 8, 1361–1373, doi:10.5194/tc-8-1361-2014.

"ERA40 air is warmer in polar regions of both hemispheres, especially in the north where the temperature is about 1°C greater. This is particularly marked in winter over ice where ERA40 locally shows seasonal excess of temperature up to 5°C" , **Brodeau et al., (2009)** Ocean Modelling, 31, 88-104, doi: 10.1016/j.ocemod.2009.10.005

Beesley, et al., (2000), Lupkes et al. (2010), Jakobson et al. (2012)

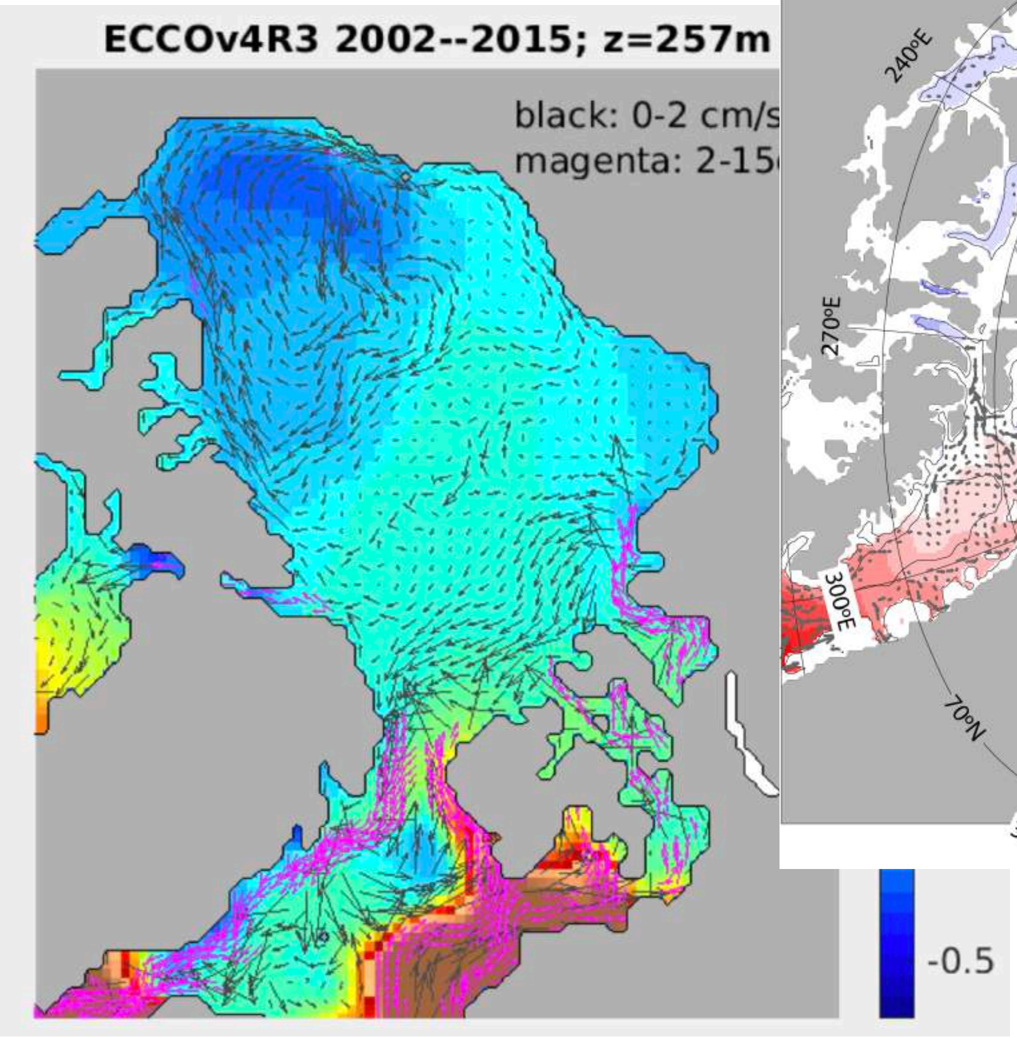
Nguyen et al. 2011: JRA55 is "best" in the Arctic

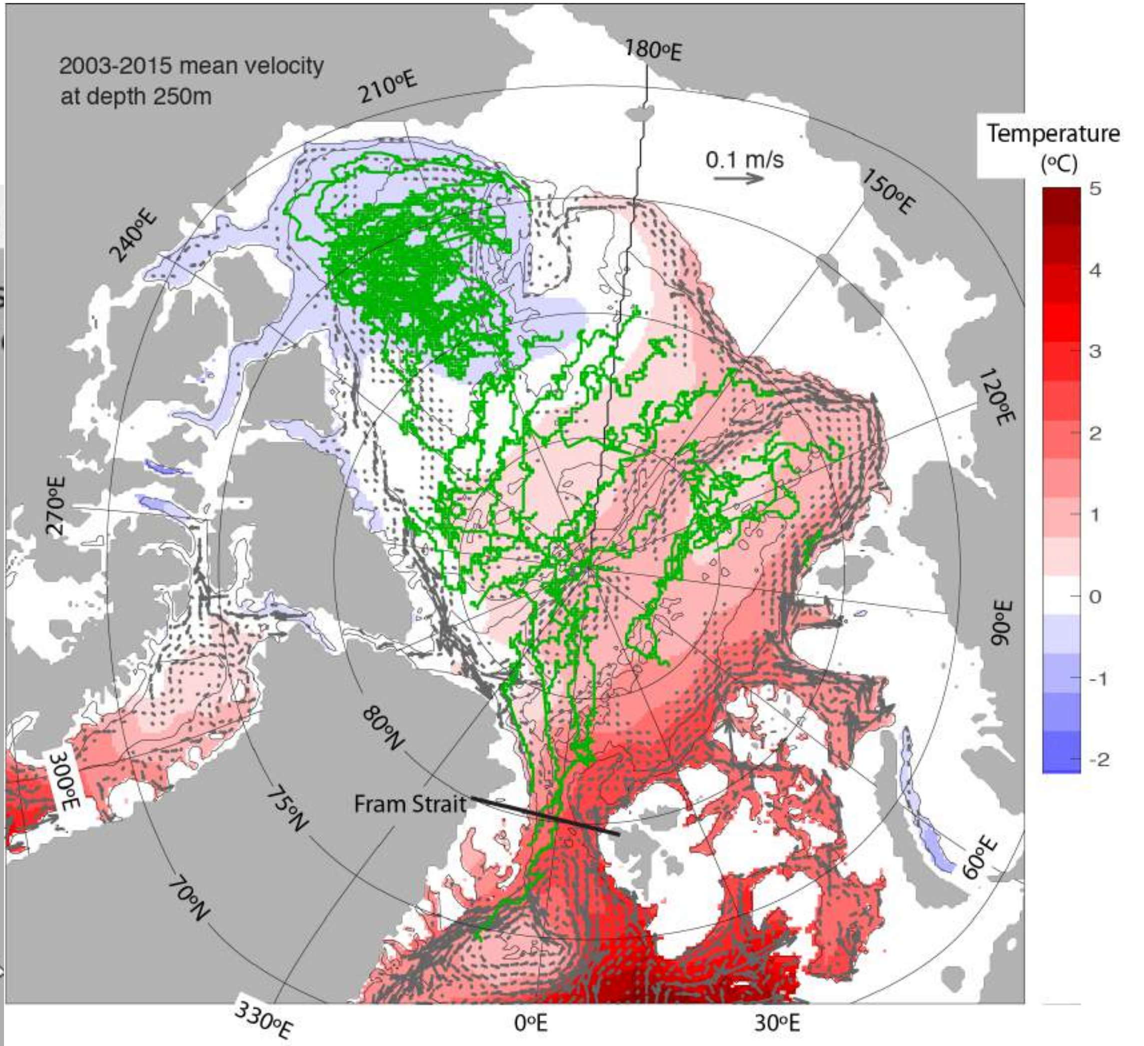
ASTE atmospheric forcing



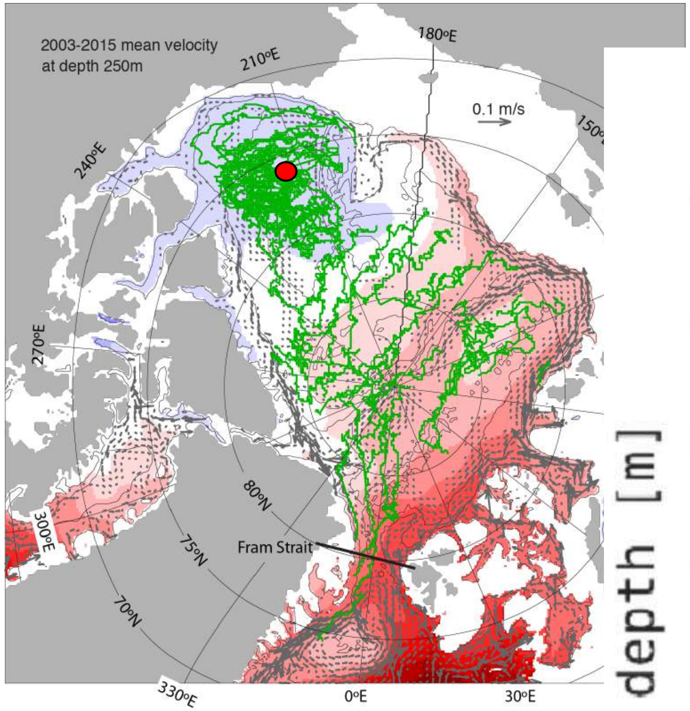
Hong Zhang's figure

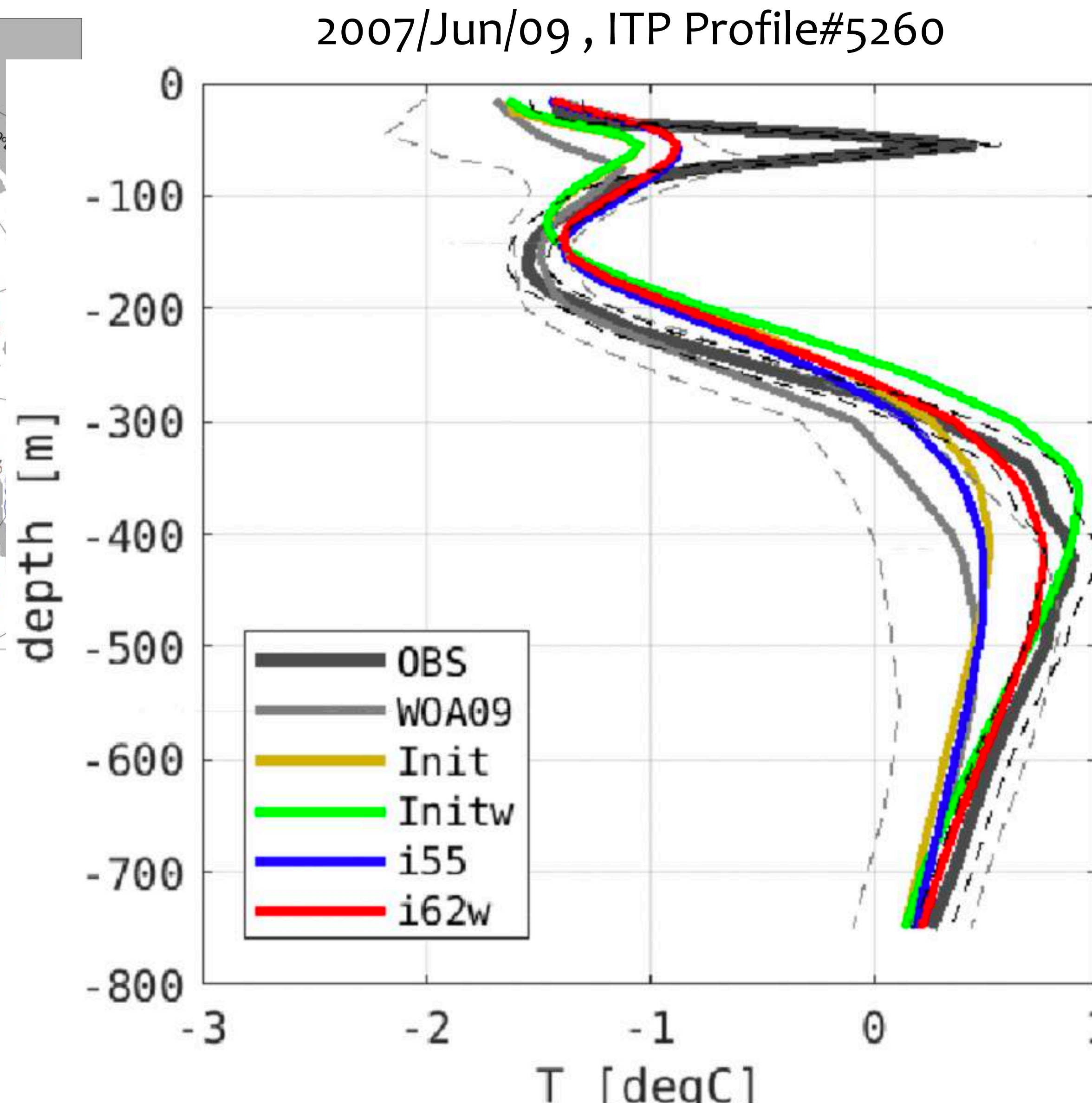
ASTE initial conditions





ASTE – sensitivity between data and model control space



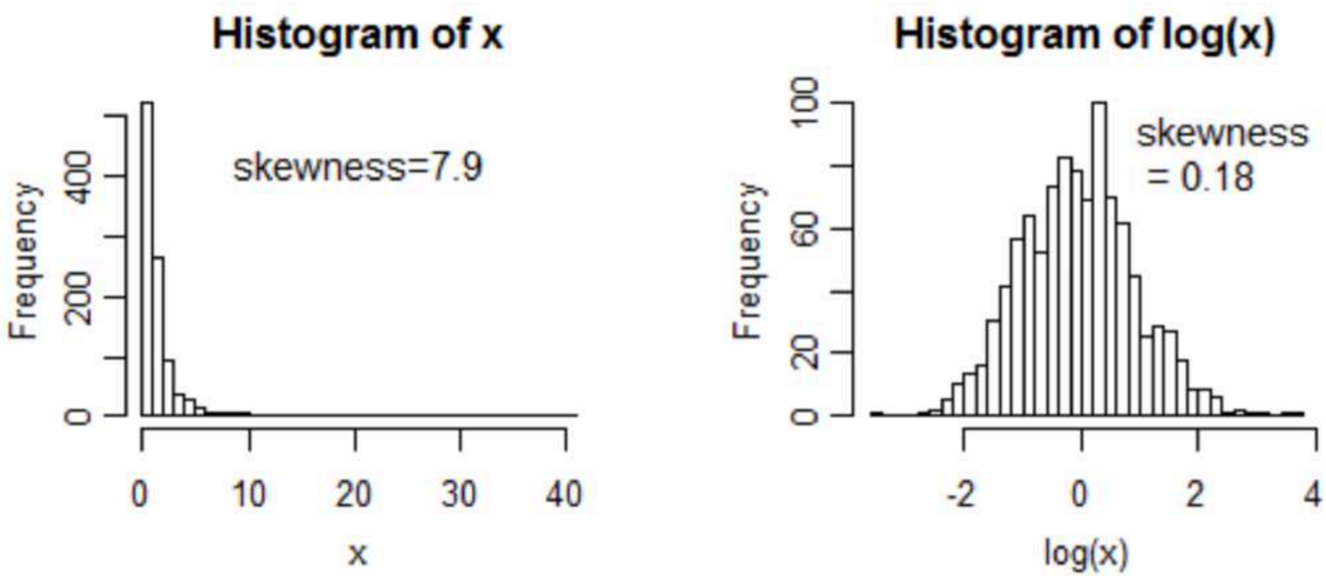


Initial conditions: 2002

What data are available?

ASTE – sensitivity between data and model control space

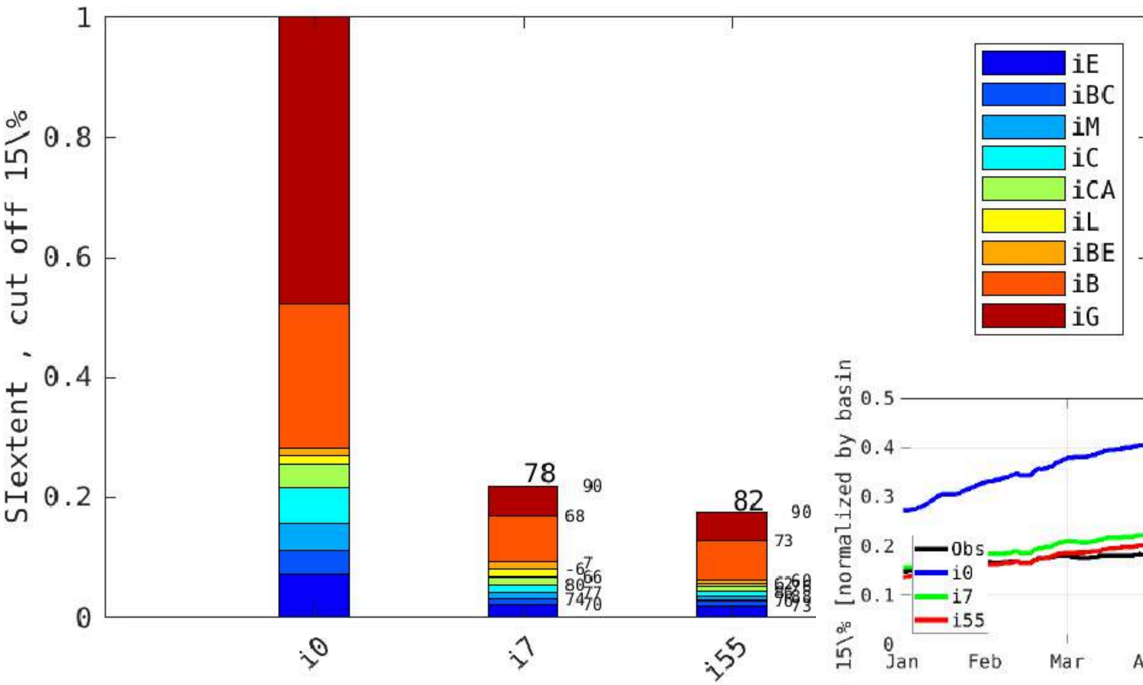
Appropriate physics? ill-behaved parameter? (vertical mixing)

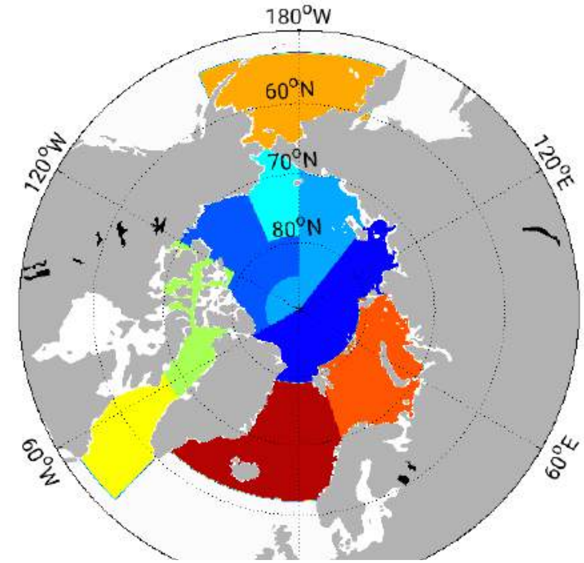


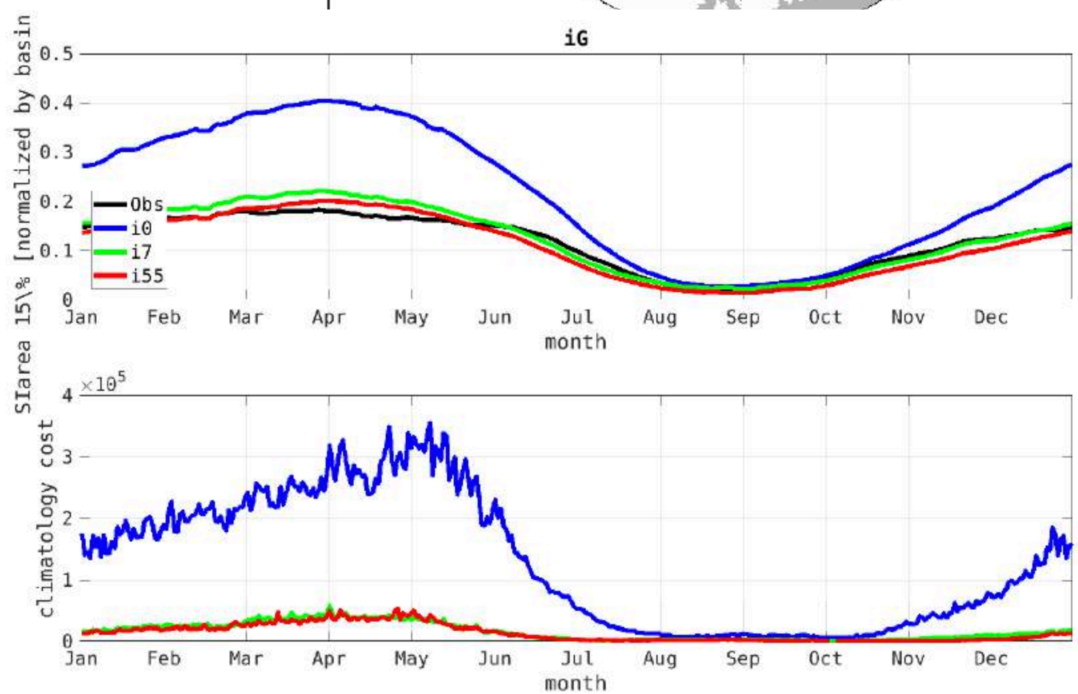
Recasting vertical mixing coefficient into log10 framework (Bigdeli et al., 2019, in prep, need to check code in ☺).

Arctic Subpolar gyre sTate Estimate (ASTE) – Release 1

- Arctic ocean-sea ice state representation:
  - Sea ice state







ASTE – hydrographic improvements

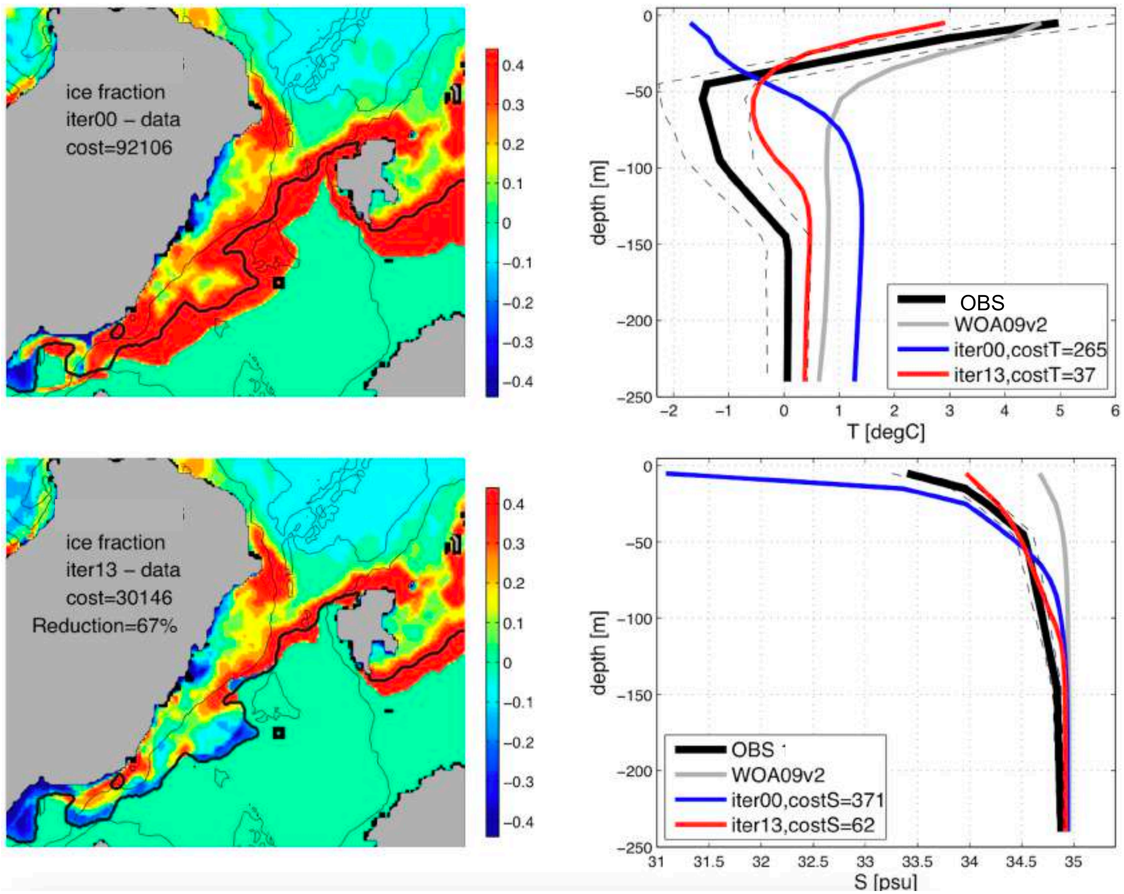
Improved sea ice edge yields improved hydrography:

Iter0:

- excessive sea ice
- SST near T_{freeze}
- SSS too fresh due to excessive melt where ice edge meets recirculated AW

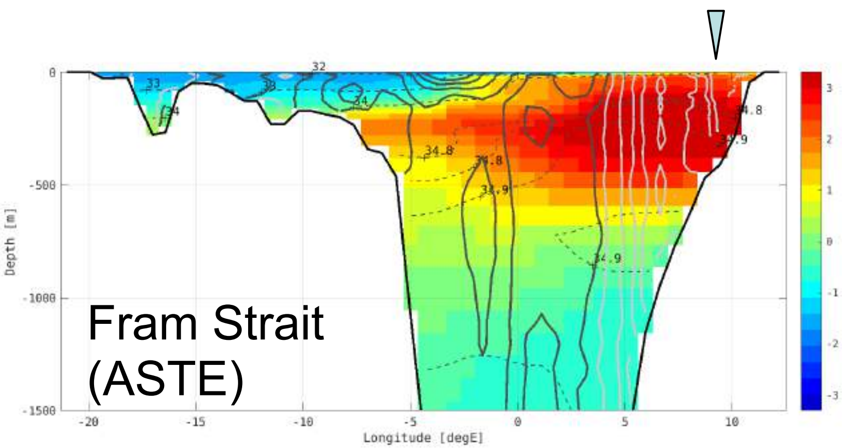
Iter13:

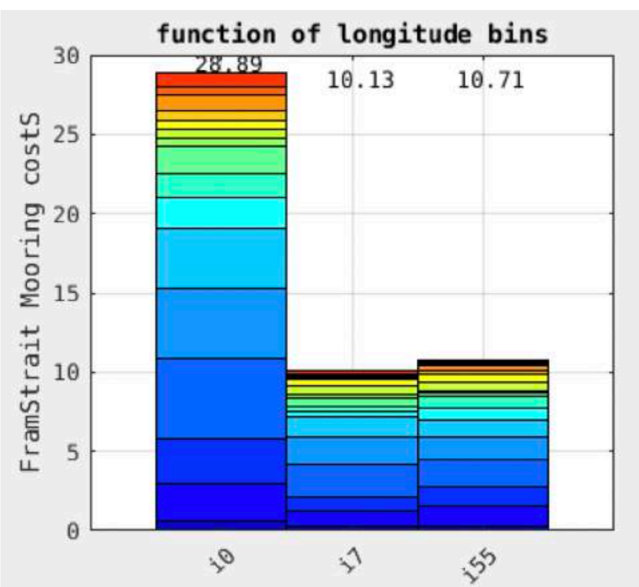
- sea ice edge consistent with observation
- T(z) profile consistent with recirculated AW near the surface
- improved S(z)

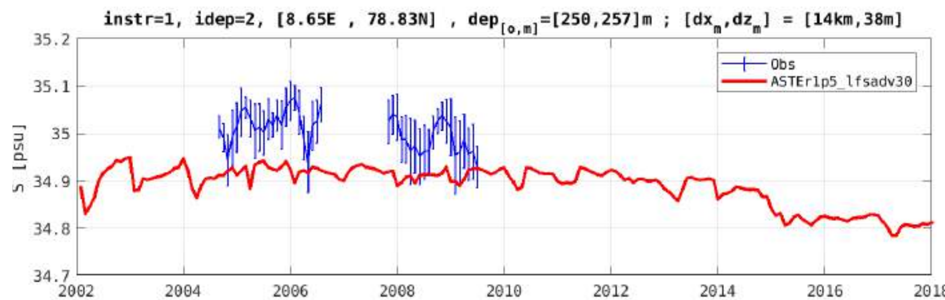


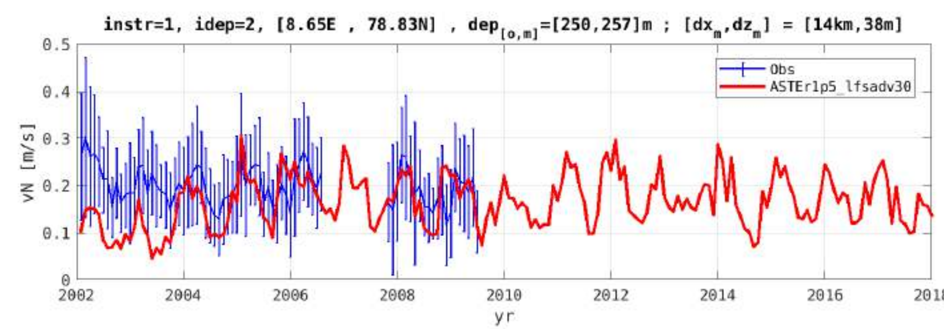
ASTE – Release 1

- Arctic ocean representation:
  - Arctic gateway transports

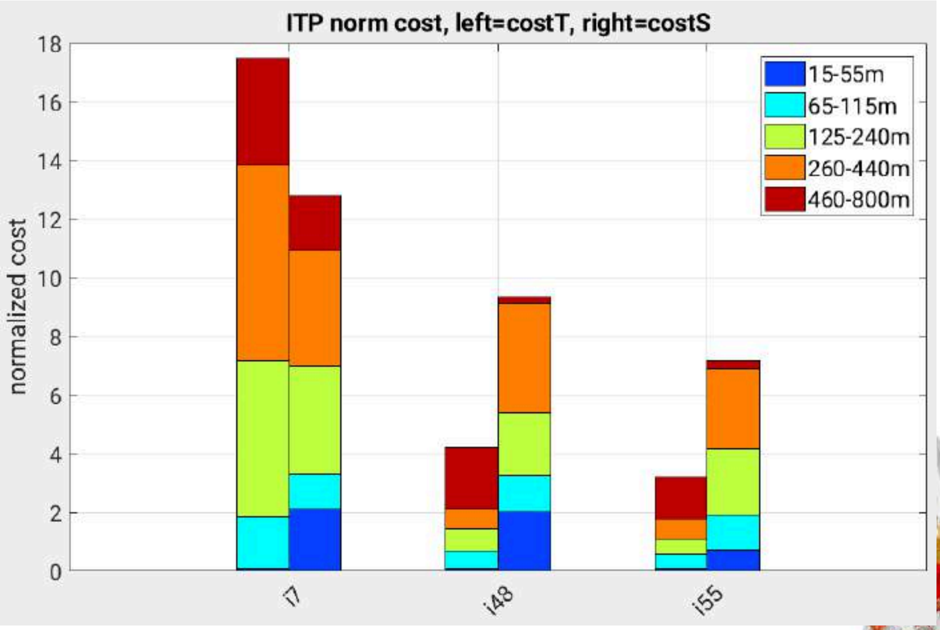


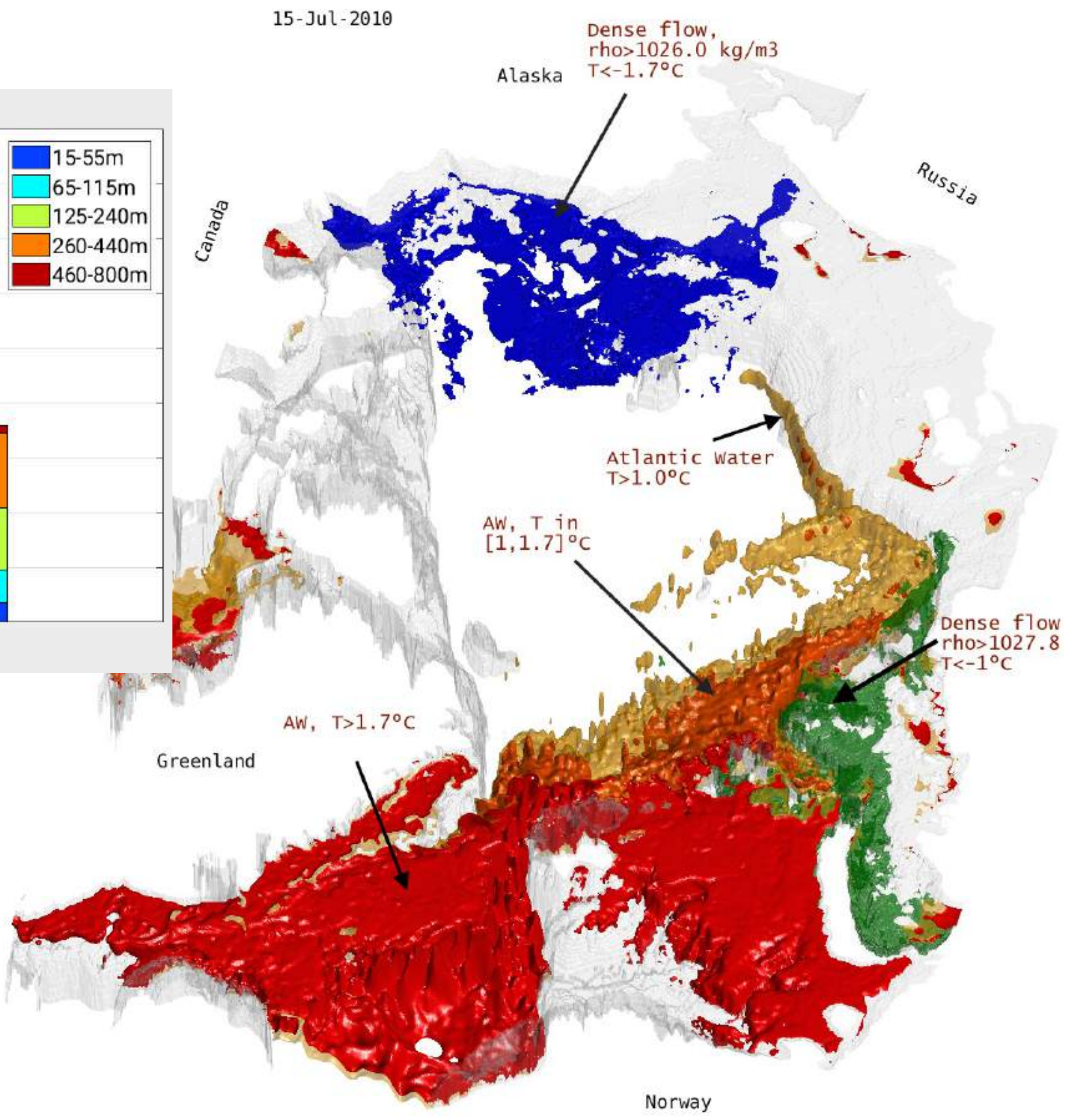






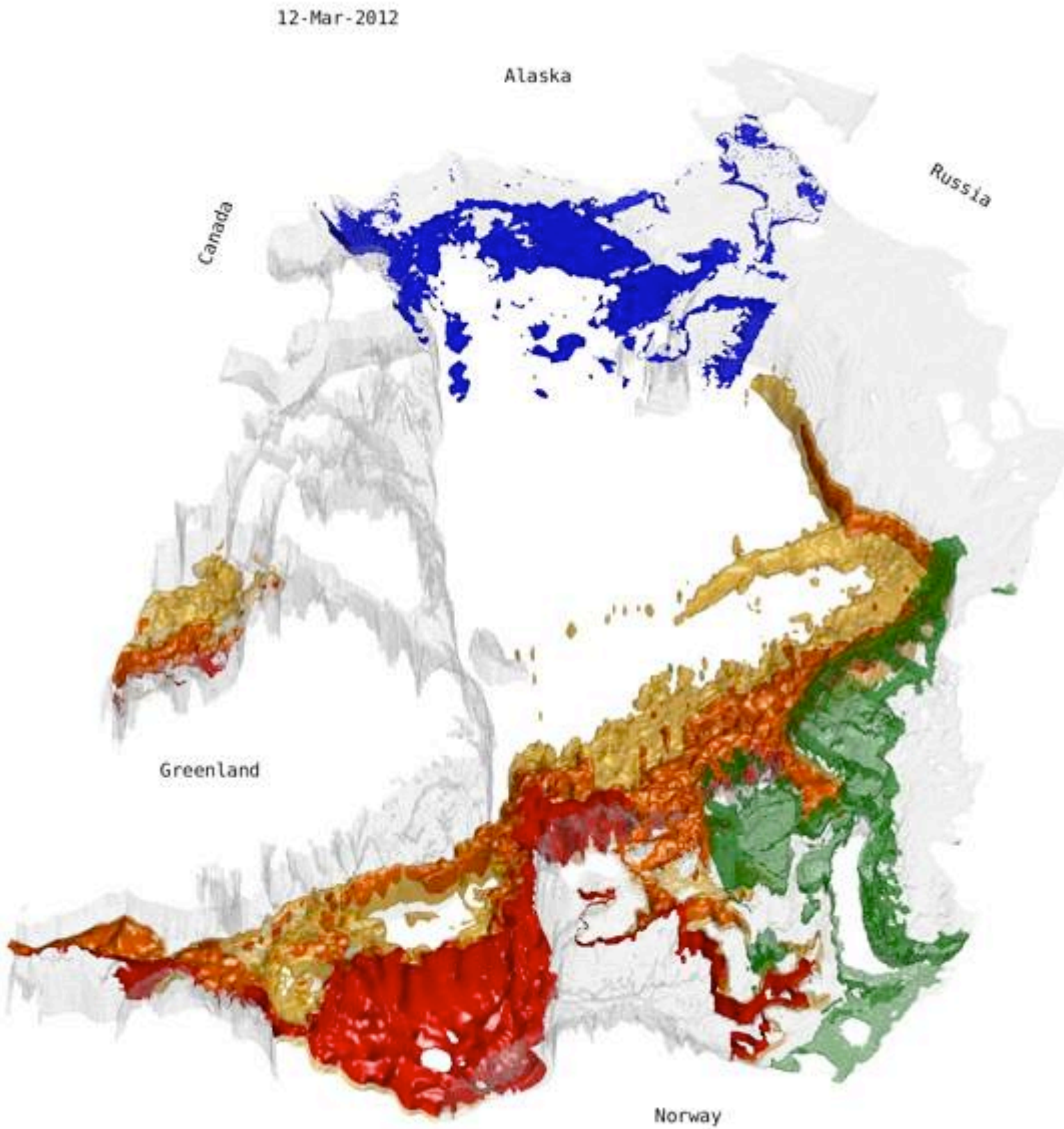
ASTE – watermass representation





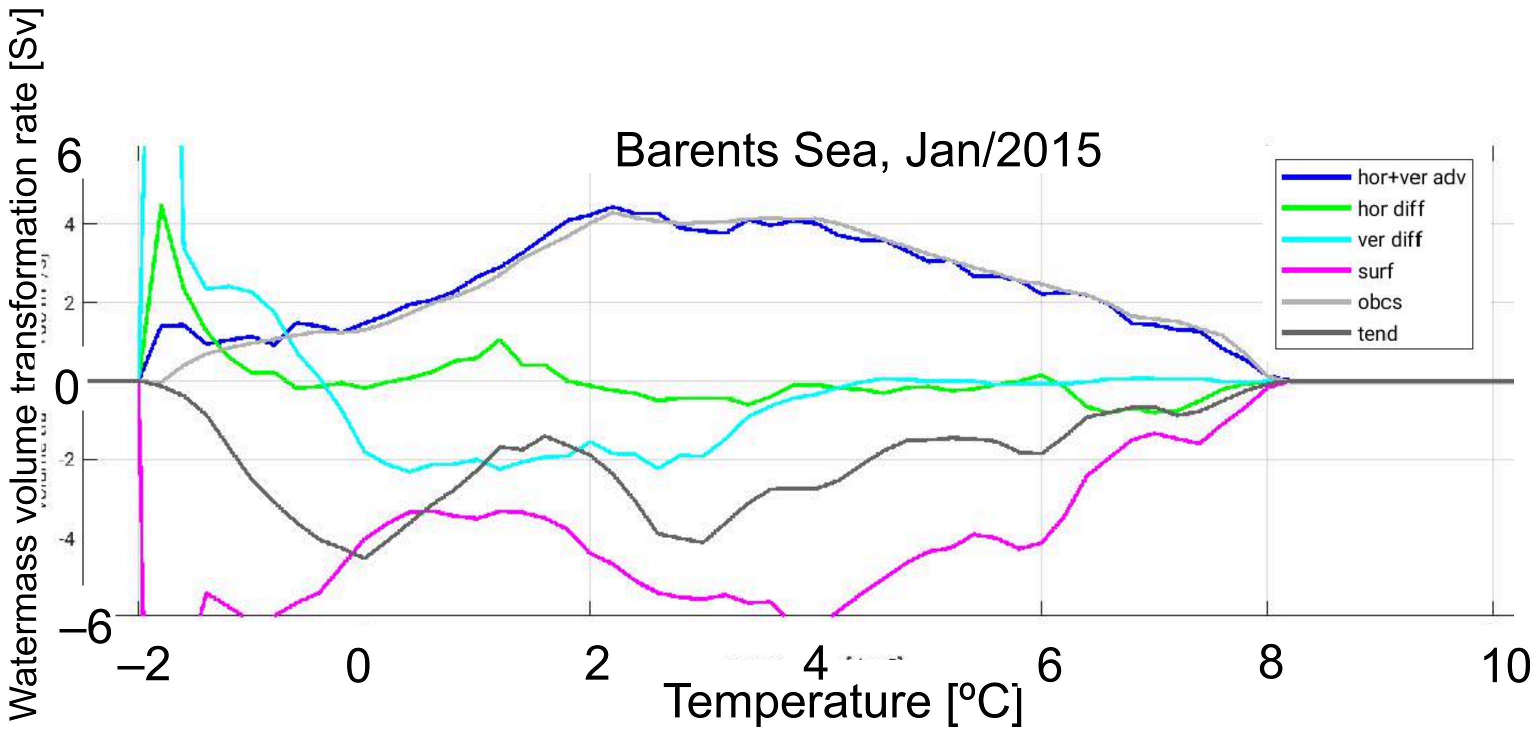
2. Watermass production & transformation

movie



Arctic Subpolar gyre sTate Estimate (ASTE) – Release 1.5

- Arctic ocean representation:
  - watermass transformation (pkg/layers , budget closed)



Nguyen et al., 2019, in prep, ASTE

Applications / Users

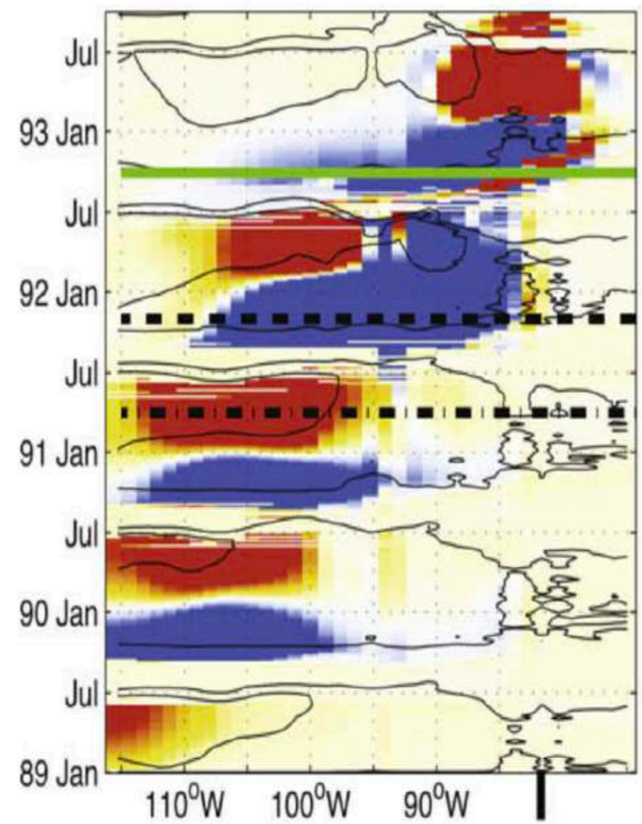
- Arctic physical oceanography (WHOI, UAF, UW, URI)
- Arctic ocean-sea ice system changes (WHOI, UAF)
- Arctic – SubArctic exchange (WHOI, John Hopkins)
- **Acoustic wave propagation (URI, NERSC, ARL-UT)**
- Forcings and initializations (UT-Austin, NERSC)
- Coupled ASTE-BioGeoChemistry (Columbia)
- Budget analyses (UW, MIT)
- Adjoint sensitivity studies – identification of dominant control mechanism (John Hopkins, UT-Austin, UW)
- Arctic Observing System (Simulation) experiment (UW, WHOI)
- Arctic / Nordic Seas observing system assessment (U. Bergen)
- Arctic sea ice prediction skills (UAF, UT-Austin)

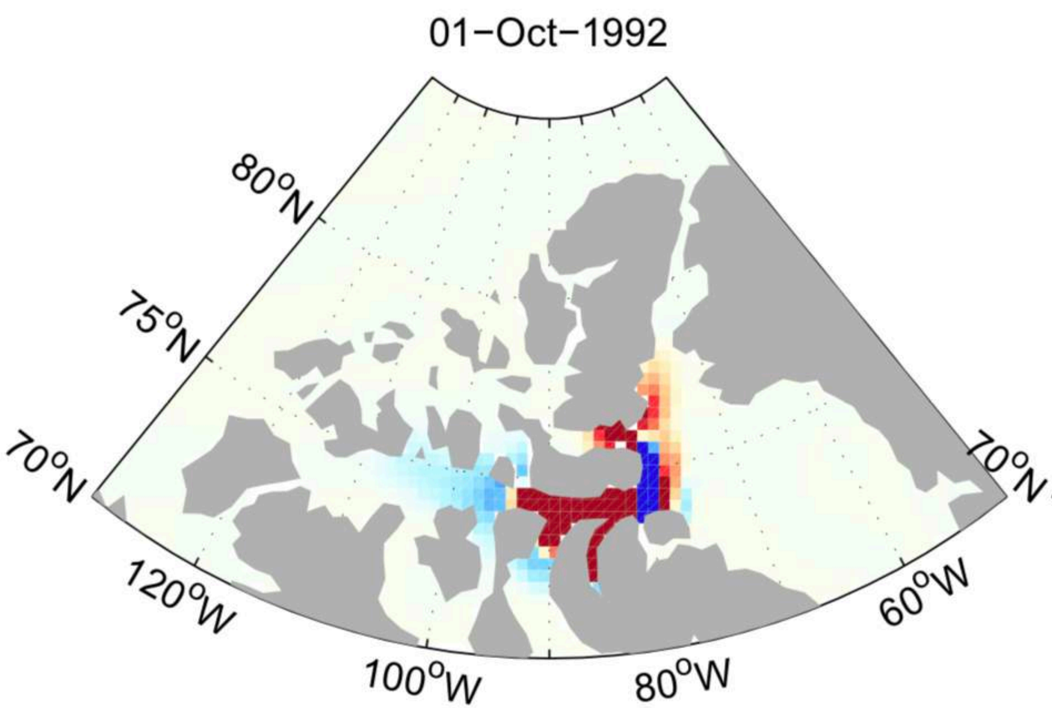
Sea ice thermodynamic adjoint

Heimbach et al, 2010

$$J = \frac{1}{\rho_{fresh}} \int_{\mathrm{Oct}\,92}^{\mathrm{Sep}\,93} \int_{\mathrm{LS}} (\rho h c + \rho_s h_s c)\, u\, ds\, dt$$

∂J/∂precip





∂J/∂hc (1 year lag)

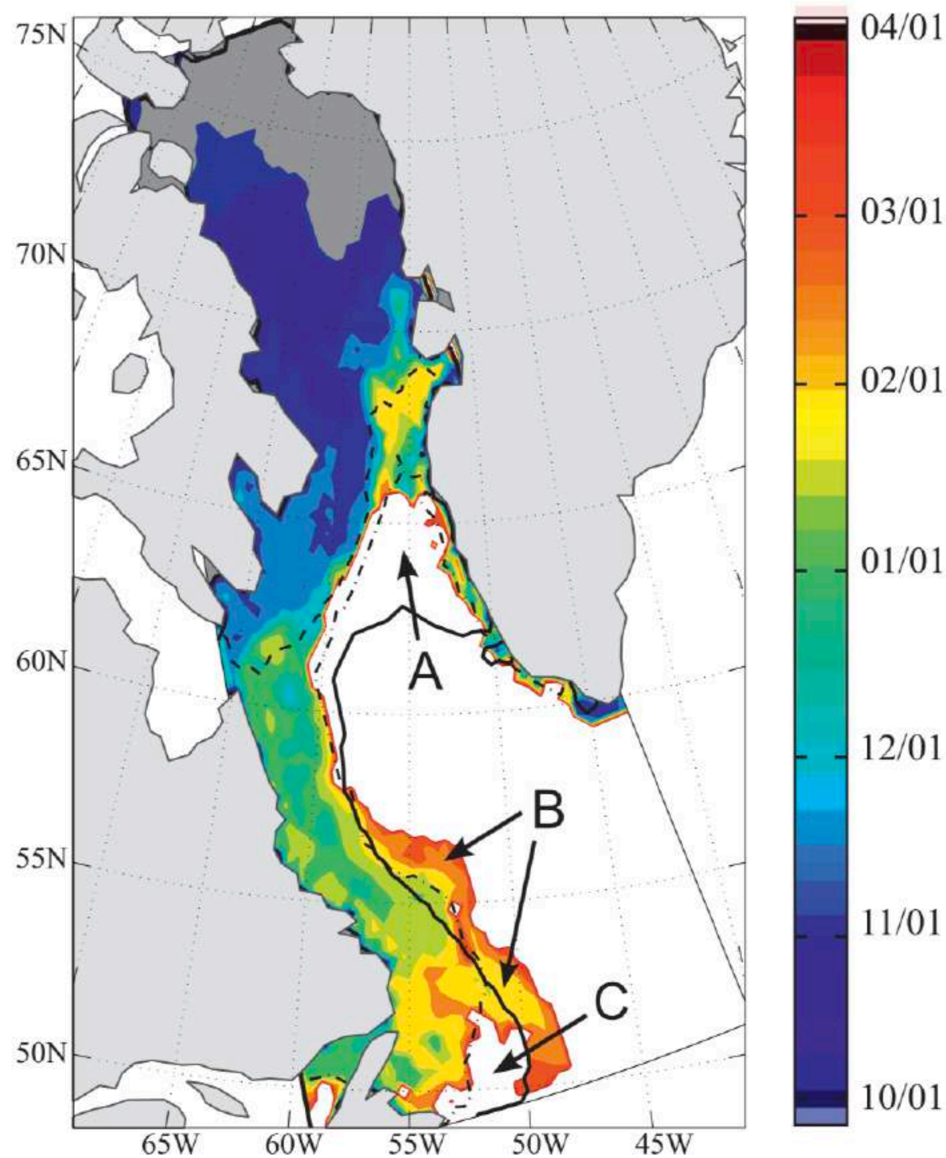
Sea ice thermodynamic adjoint

Fenty and Heimbach, [2013a,b]

Hydrographic pre-conditioning: facilitate the advancement of sea ice in the marginal ice zone

Near surface water pre-conditionally favored for ice growth (e.g., fresh, large stratification)

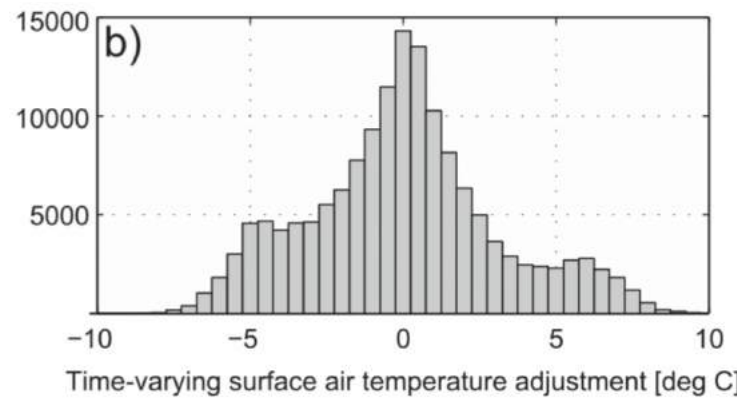
→ ice melt → surface more fresh + water column more stratified → less heat convergence from below → net ice melt < net ice convergence → advancement of sea ice edge



Sea ice thermodynamic adjoint

Fenty & Heimbach [2013b]

- Ocean-sea ice state estimate (1-yr, 96/97) of the Baffin Bay + Labrador Sea
- Energy and buoyancy budgets in the marginal ice zone (MIZ)



1. Role of sea ice advection
2. Role of ocean advection
3. Role of upper-ocean hydrography
4. sea ice–ocean feedbacks

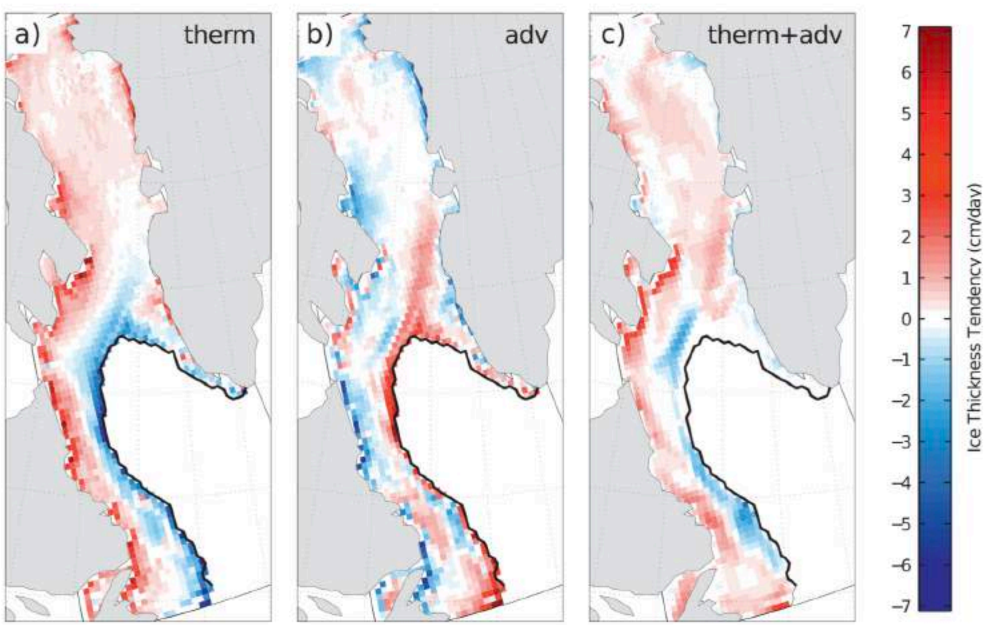
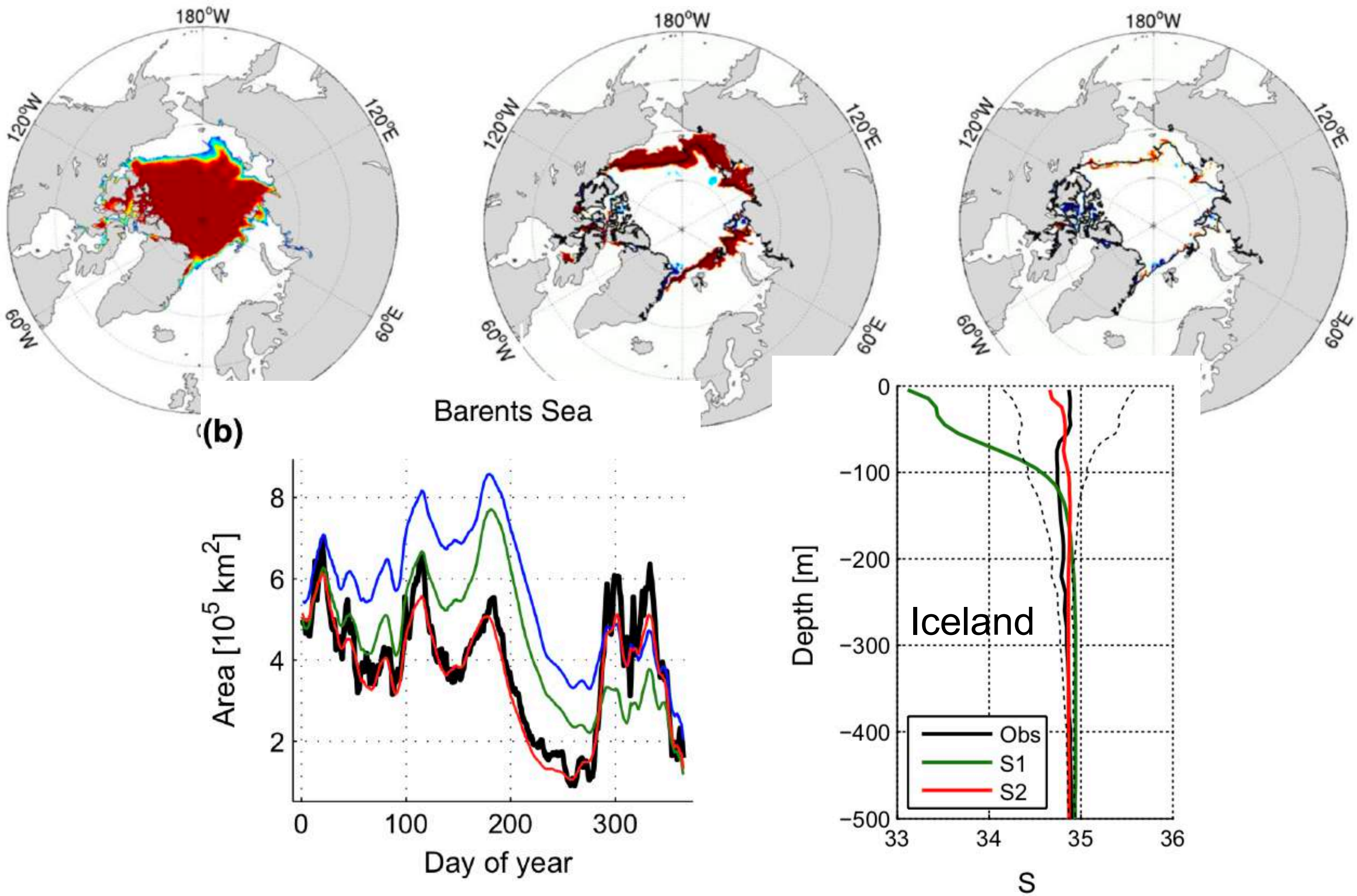


FIG. 11. Sea ice thickness growth rate tendencies averaged during the quasi-equilibrium period 21 Feb–20 Mar 1997. Thickness tendencies are presented as (a) thermodynamic, (b) advective terms, and (c) and their sum. Solid lines denote each the maximum sea ice extent during quasi-equilibrium.

Sea ice thermodynamic adjoint

Fenty et al., [2015]   Global 18-km cubed-sphere 2004 state estimate

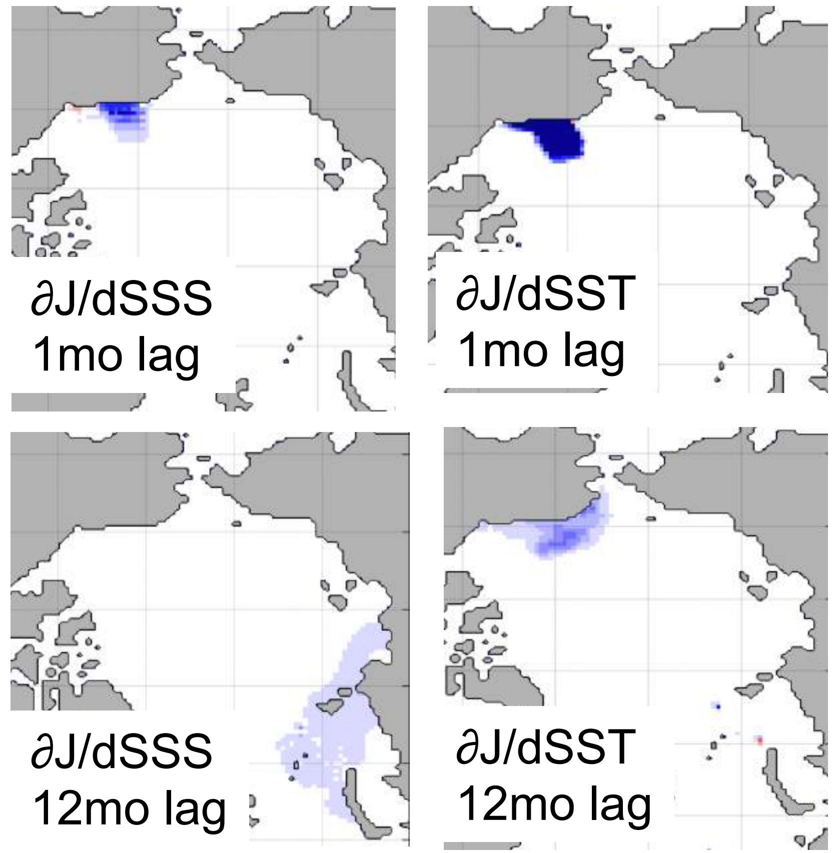


Sea ice thermodynamic adjoint

Bigdeli et al., 2019 [in prep] :

- using mini-ASTE
- mechanism controlling sea ice volume in the Western Arctic marginal ice zone
- Testing linearity assumption

J= ice volume in box



Gas exchange at air-ocean interface in presence of sea ice

Bigdeli et al., 2017, 2018, 2019 [in prep], Ph.D. thesis

Arctic 36km, 9km, llc4320 (forward, using Nguyen et al., 2011 optimized parameters), 1-D column: adjoint method to optimized initial T/S conditions

→ Gas exchange rate parameterization

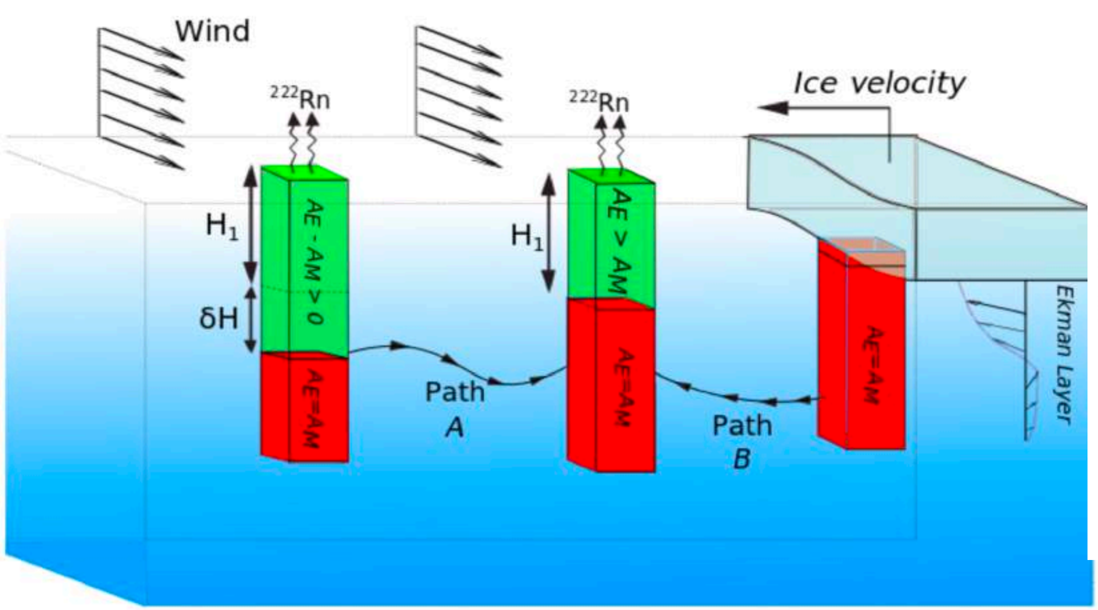
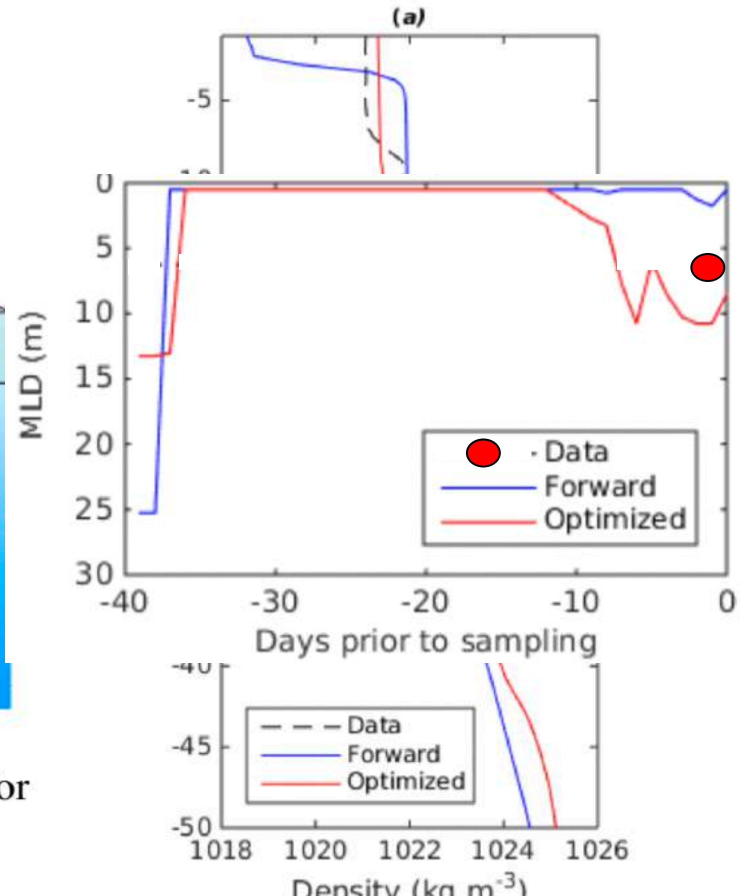


Figure 1. A graphic illustration of two possible back trajectories for a single sampling station.

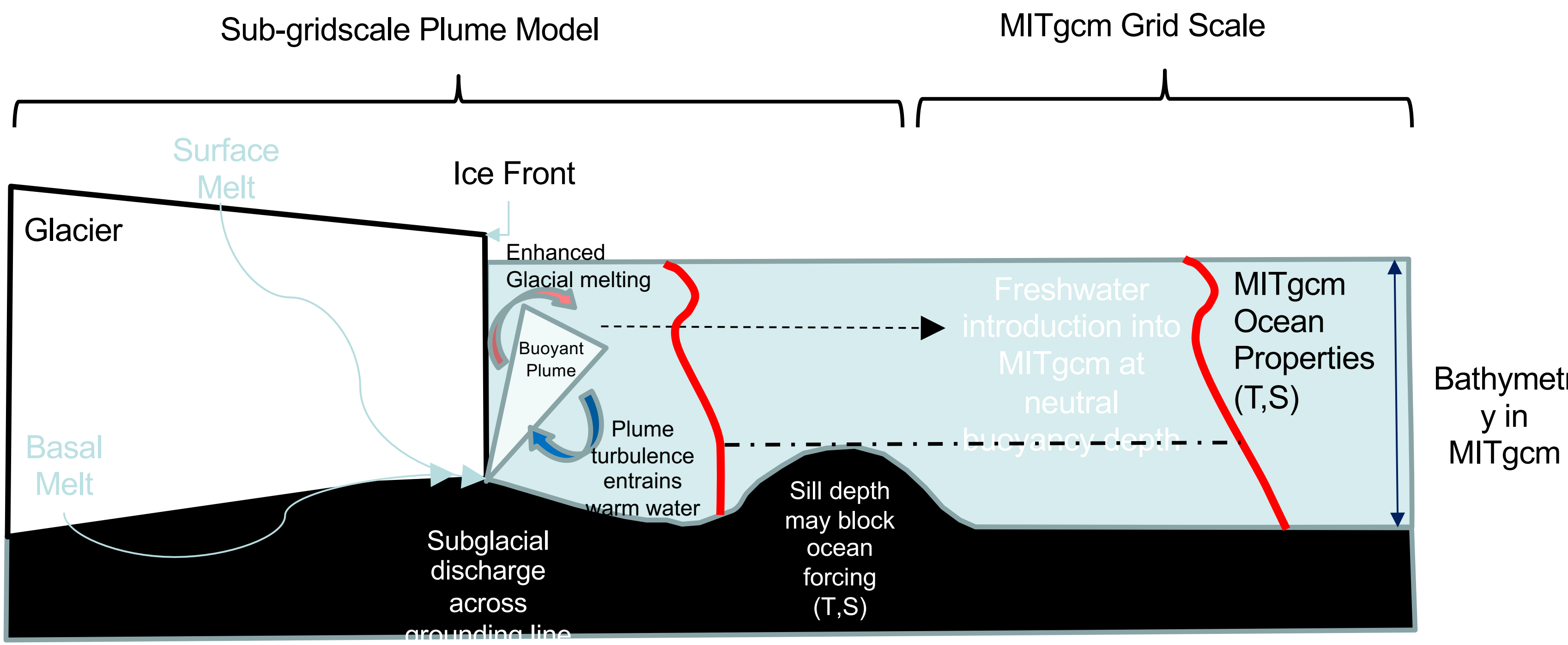


Sub-grid scale plume modeling

Habbal et al., [in prep]

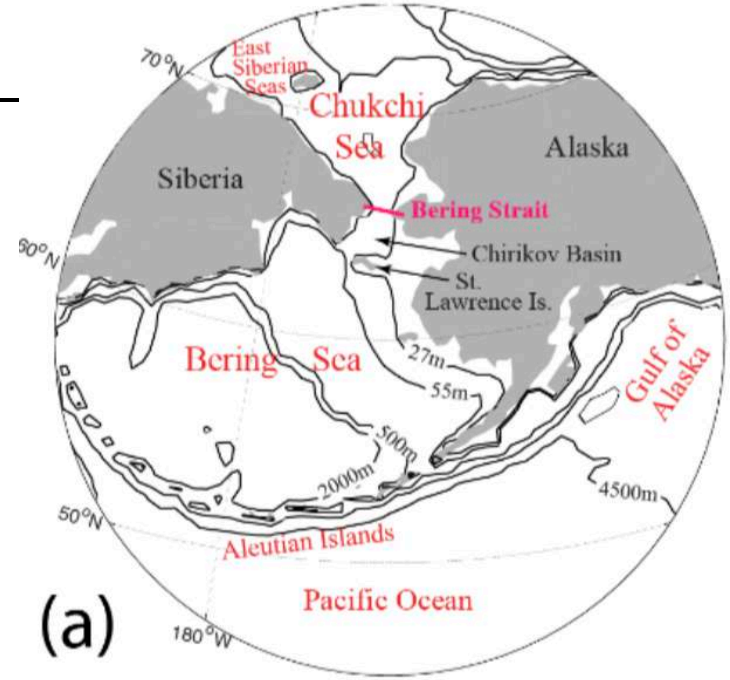
- Aiming to capture enhanced melting of glaciers and freshwater production due to entrainment of warm water into buoyant plume at depth that is driven by subglacial freshwater discharge ***without*** resolving the scales of the glacier and fjord system in MITgcm

Approach: Use thermodynamic equations combined with buoyant plume theory to calculate enhanced melt-rates of glaciers (for ice-sheet models) and introduce enhanced freshwater production at neutrally-buoyant depth into MITgcm grid



Adjoint sensitivity

Investigation of the Mechanisms Controlling the Bering Strait throughflow variability, Nguyen et al. [2019] in prep.



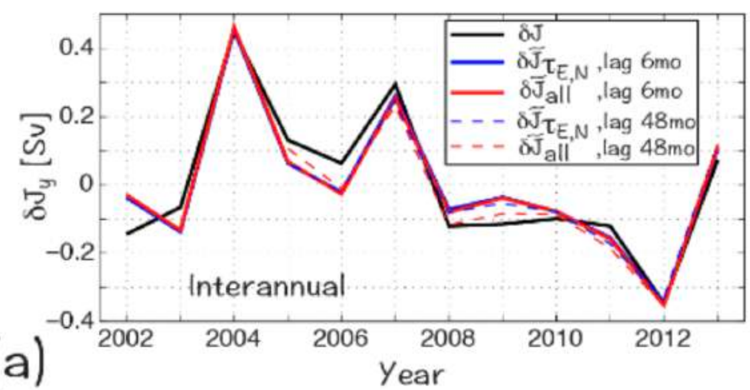
(a)

Bering Strait:
- Connection to the Pacific Ocean
- Freshwater, heat, nutrients inputs
- marginal ice zone, shallow shelves
  → impact ecosystem
  → Arctic Ocean stratification
  → further downstream: freshwater to the Atlantic ocean

$$J(t) \equiv \frac{1}{T} \int_{t-T/2}^{t+T/2} \int_A \mathbf{u}(t') \cdot \hat{\mathbf{n}} \, dA \, dt'$$

Mechanism controlling transport:
- "thought" to be due to ΔSSH Pac-Atl and local winds

Interannual to decadal variability:
winds? ΔSSH?



(a)

Adjoint sensitivity

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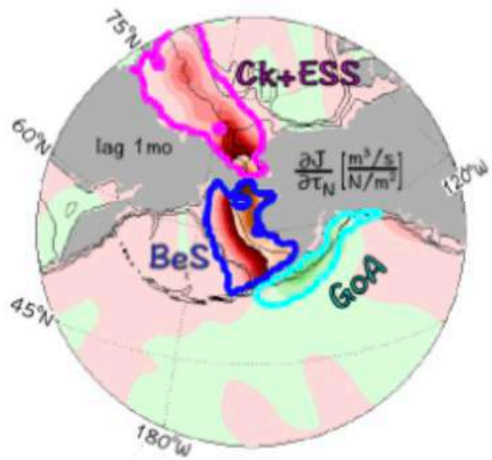
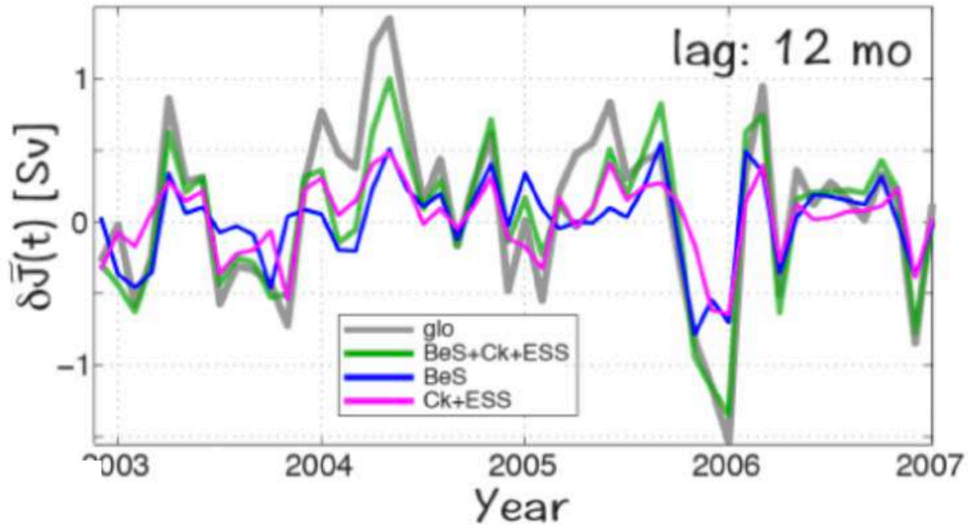
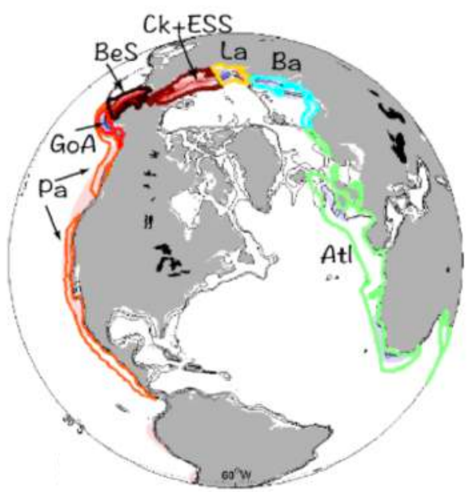
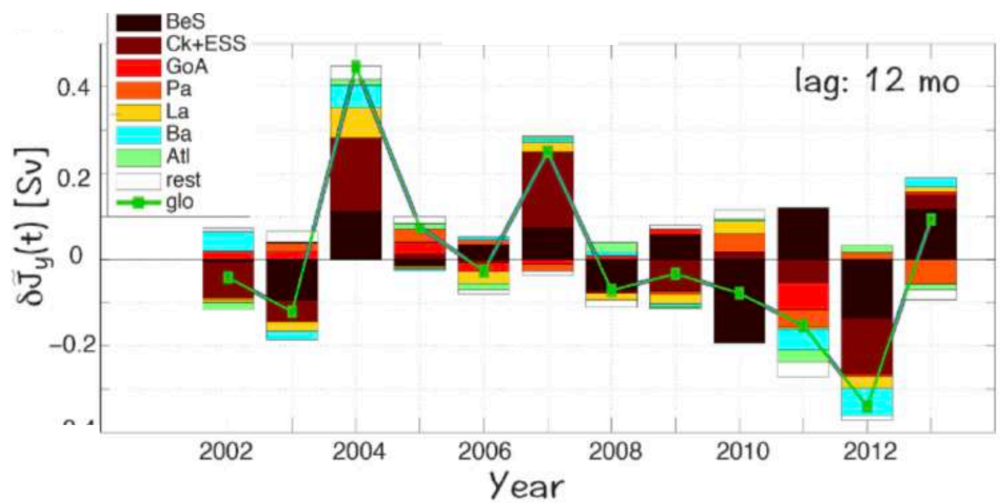




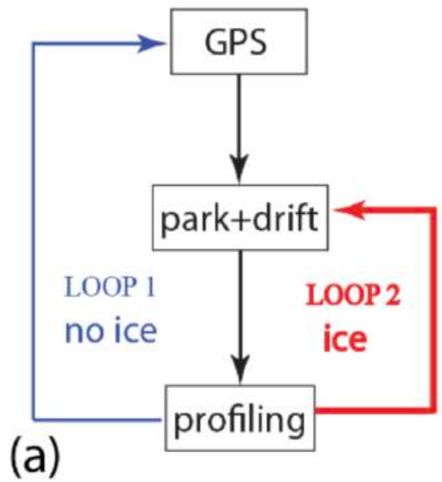


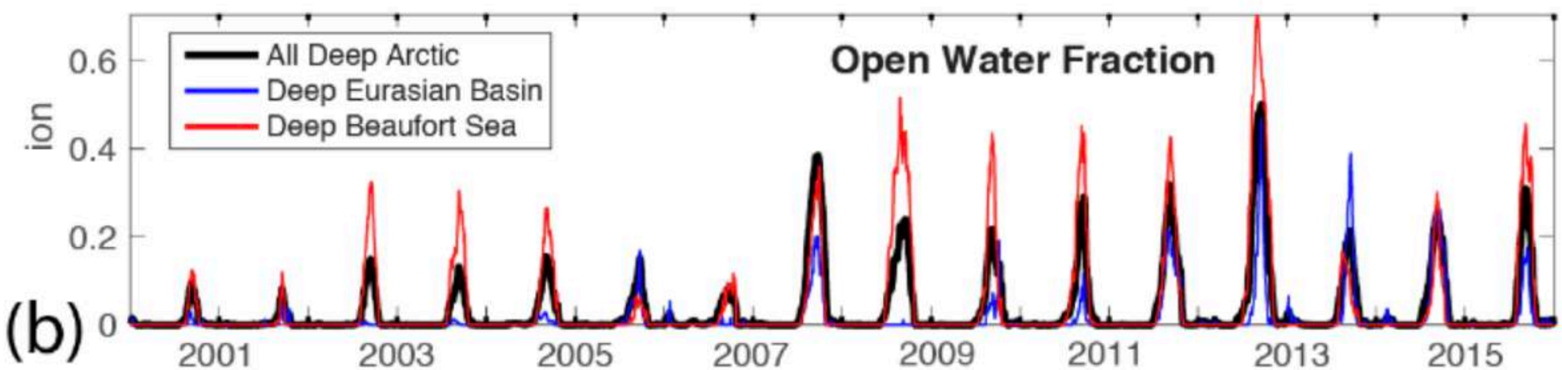


Observing system simulation experiment (OSSE)

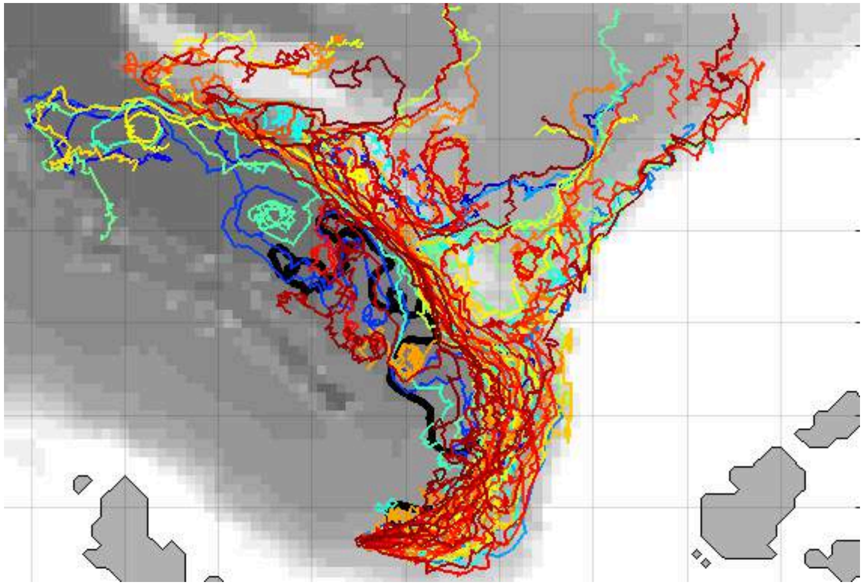
Impact of Synthetic Arctic Argo-type floats in a Coupled Ocean-Sea Ice State Estimation Framework,
Nguyen et al., [2017, 2019 in preps]

Quantify the usefulness of a float's measurements in the Arctic when we do not know it's trajectory





Observing system simulation experiment (OSSE)



Trajectory:

position vector

$$\tilde{\mathbf{U}} \approx N(\overbrace{\mathbf{U}_m}^{\text{ASTE time-mean}}(\mathbf{x}), \sigma_{\mathbf{U}})$$

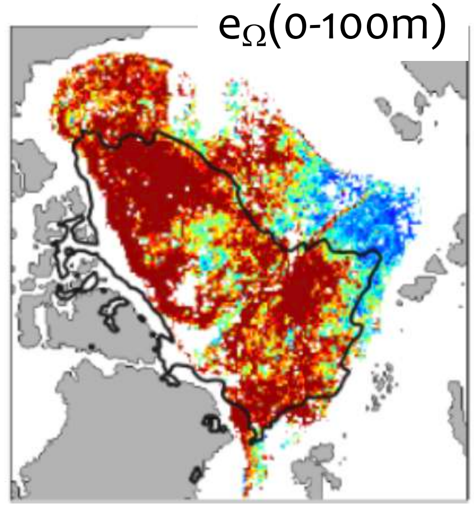
Error in T or S (generalized as Ω)

$$e_\Omega = \sqrt{\left(\frac{\Omega(\mathbf{x}(t)) - \tilde{\Omega}(\tilde{\mathbf{x}}(t))}{\sigma_\Omega}\right)^2}$$

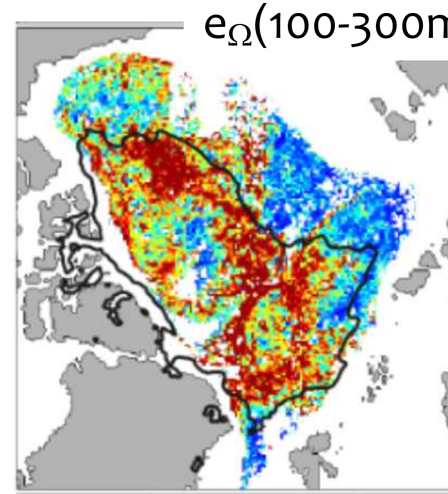
Upper 100m: conditions change quickly
→ Small error in $\mathbf{x}(t)$ yields $e_\Omega > 1 \bullet \sigma_\Omega$

Below 100m: conditions change less quickly in addition to large σ_Ω
→ $e_\Omega < 1 \bullet \sigma_\Omega$ in seasonal ice zones

e_Ω(0-100m)



e_Ω(100-300m)



Ocean observing system design (Nora Loose)

- Ocean observing systems are expensive to build and maintain.
- But: We need long-term and sustained ocean observations!

Example: The OSNAP array

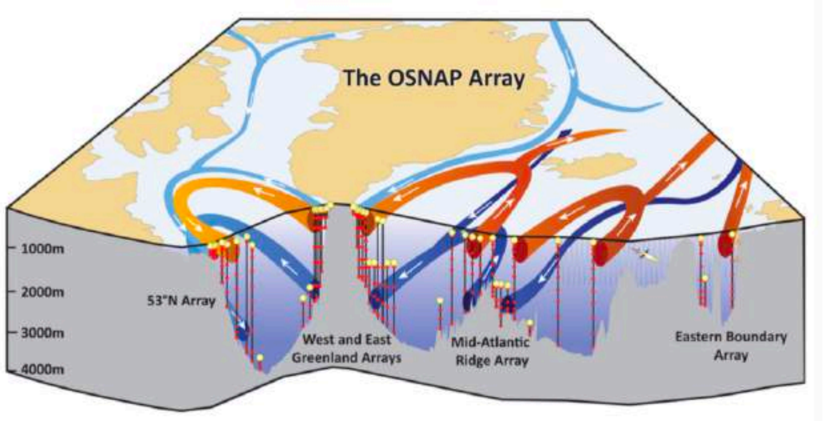


Figure: `http://www.o-snap.org`

- launched in 2014
- relies on short-term funding (as many observational efforts)
- designed to monitor *local* subpolar overturning and transports

Key questions:

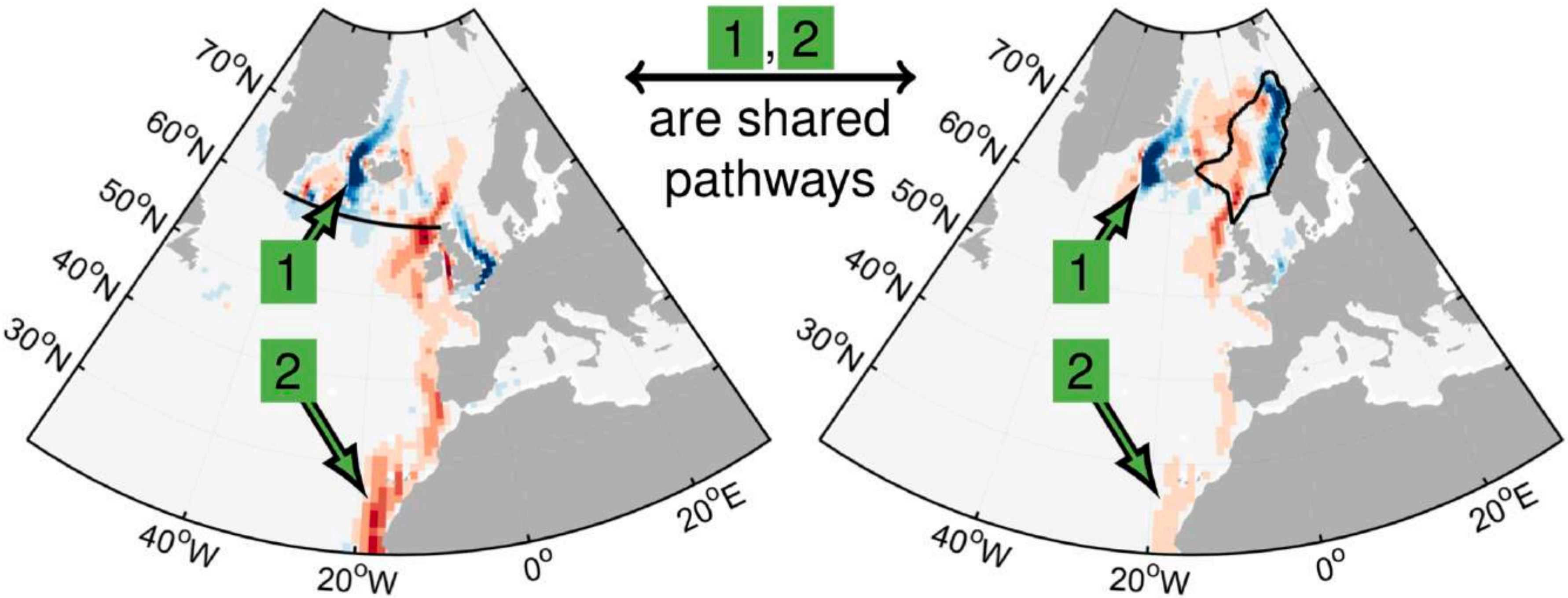
- What information is contained in already existing observing systems, such as OSNAP, also away from the instruments?
- How can we build a long-term, cost-efficient Atlantic observing system?

Adjoint sensitivities reveal mechanisms & pathways

Wind stress (τ_y) sensitivity of

observed
OSNAP-East heat transport

unobserved
Nordic Seas heat content

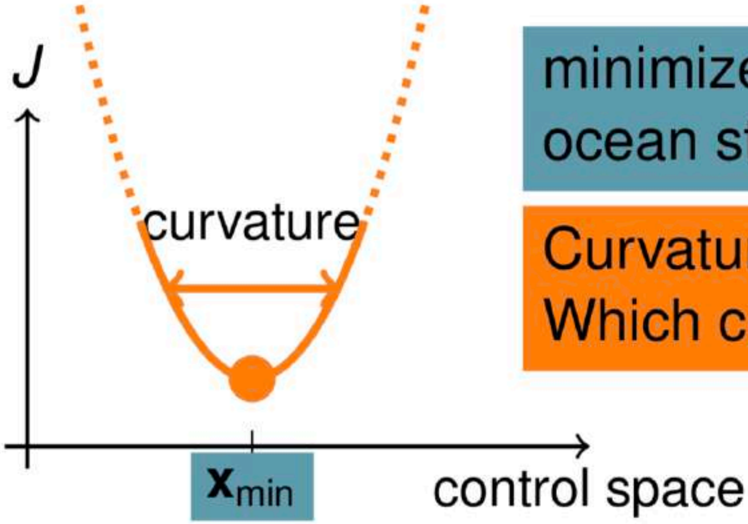


1, 2: Pressure anomalies communicated via coastal boundaries

OSNAP contains information about remote & unobserved quantities, due to shared dynamical mechanisms and pathways.

How to quantify this?

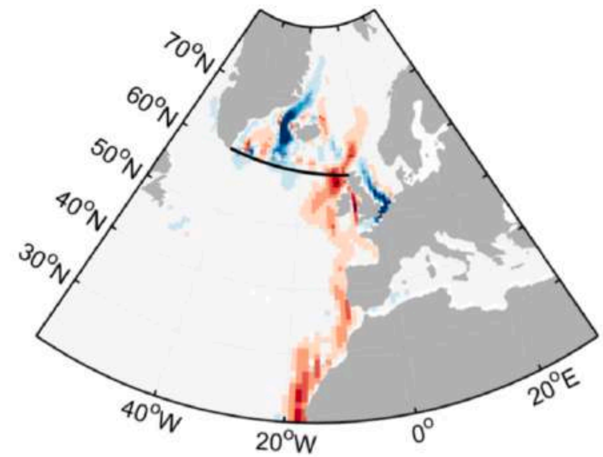
Via Uncertainty Quantification within the ECCO state estimate!



minimizer $\mathbf{x}_{\min}$:
ocean state estimate ("buest guess")

Curvature (Hessian) at $\mathbf{x}_{\min}$:
Which components are well/poorly constrained?

informed components of control space = eigenvectors of Hessian $\widehat{=}$ adjoint sensitivities of observations (from previous slide)



The details are in Nora's PhD Thesis (to be submitted tomorrow!):
Loose, Nora, (2019). Adjoint Modeling and Observing System Design in the Subpolar North Atlantic. PhD dissertation, University of Bergen.

High resolution, Tides

ASTE: use as initial and boundary conditions for higher resolution regional models

llc540 ASTE (Helen Pillar, adjoint method)
- improve circulation and watermass representation in the North Atlantic, Nordic, and Labrador Seas

llc1080 (Green's function)
- 90 vertical levels, with and without tides,
- investigate near inertial and tidal feedback on sea ice

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
→ a difficult state estimation problem

ECCO-related efforts:
→ the time-mean and variability of the ocean-sea ice states
→ adjoint tools: allows for studies of attribution
→ informing/optimizing observation networks

2. Arctic Ocean Circulation

movie