Quantifying the impact of subsurface in-situ observations at important Arctic and Nordic Seas gateways on the Arctic Supolar gyre sTate Estimate

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Focus

Representativeness of ocean observations:
A recurring issue in the analysis and interpretation of observational data, as well in the use of these data for model validation and data assimilation, is how their representativeness in space and time are dealt with. This issue is of particular relevance for in-situ data such as oceanic measurements from profiling devices or time series data from mooring locations.

… dealing with questions related to representativeness and uncertainties in observations, what these mean for the observational analysis as well as the usefulness of the data in modelling, and ways forward in resolving those issues in particular in regions of sparse data coverage.

Outline

- Frameworks:
  - Ocean State Estimation / Data Assimilation
- Uncertainty
- Measurements at gateways as constraints

What is data assimilation?

It's all about …

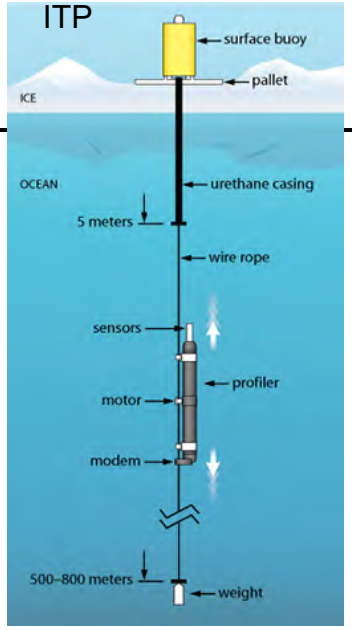
- making optimal use of,
- consistently extracting,
- or combining

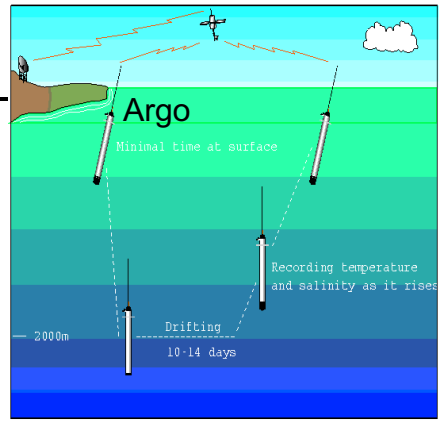
information contained in *observations* and physical laws expressed through a *model*, and taking into account all *uncertainties*.

Combine two incomplete information sources

Observations ("data"):

- incomplete/sparse probing of the physical system
  - spatial sampling
  - temporal sampling
  - incomplete state

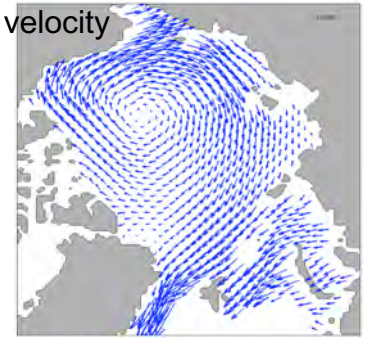




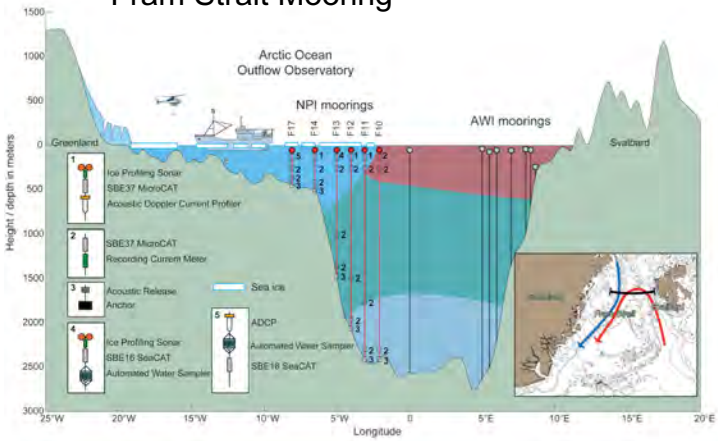
SNAP
OVERTURNING IN THE SUBPOLAR NORTH ATLANTIC PROGRAM

- different physical variables
- heterogeneous data streams
- measurement errors
- representation errors (later)

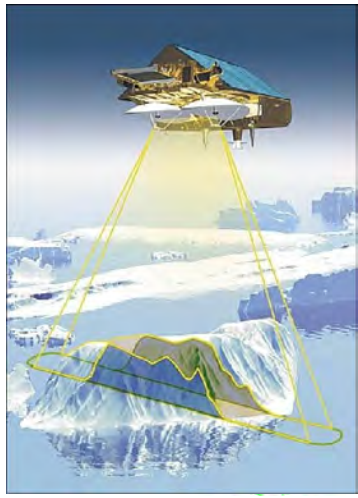
Ice velocity



Fram Strait Mooring



Cryosat-2



Combine two incomplete information sources

Physical model:

- representation of time-evolving state via equations of motion, conservation laws, theory, …

$$
\begin{aligned}
\frac{D\vec{\mathbf{v}}_h}{Dt} + f\hat{\mathbf{k}} \times \vec{\mathbf{v}}_h + \frac{1}{\rho_c}\nabla_z p &= \vec{\mathcal{F}} \\
\epsilon_{nh}\frac{Dw}{Dt} + \frac{g\rho}{\rho_c} + \frac{1}{\rho_c}\frac{\partial p}{\partial z} &= \epsilon_{nh}\mathcal{F}_w \\
\nabla_z \cdot \vec{\mathbf{v}}_h + \frac{\partial w}{\partial z} &= 0 \\
\rho &= \rho(\theta, S) \\
\frac{D\theta}{Dt} &= \mathcal{Q}_\theta \\
\frac{DS}{Dt} &= \mathcal{Q}_s
\end{aligned}
$$

- An interpolator

- uncertainties/errors:
  - initial conditions
  - boundary conditions (surface, bottom, lateral)
  - model parameters
  - "model errors" (formulation, discretization, …)

Misfits & Jacobian

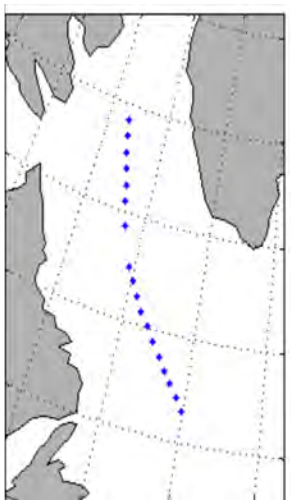
Three important ingredients are needed for state estimation:

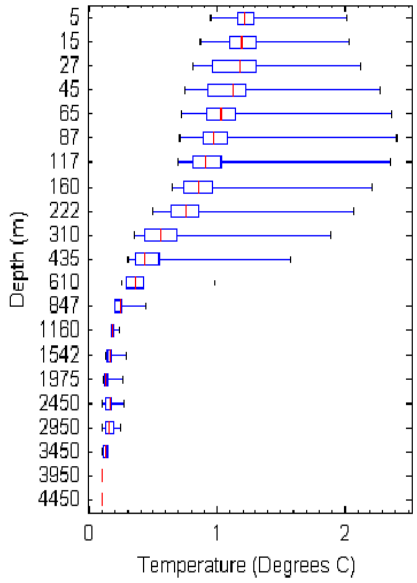
1. the model
2. the data
3. "useful"/credible uncertainty estimates

$$J = \sum_{t=1}^{t_f} [\mathbf{y}(t) - \mathbf{E}(t)\mathbf{x}(t)]^{\mathbf{T}} \mathbf{R}(t)^{-1} [\mathbf{y}(t) - \mathbf{E}(t)\mathbf{x}(t)]$$

$$+ [\mathbf{x}_0 - \mathbf{x}(0)]^{\mathbf{T}} \mathbf{P}(0)^{-1} [\mathbf{x}_0 - \mathbf{x}(0)]$$

$$+ \sum_{t=0}^{t_f - 1} \mathbf{u}(t)^T \mathbf{Q}(t)^{-1} \mathbf{u}(t)$$





J = f (a,b,...) , a,b: parameters

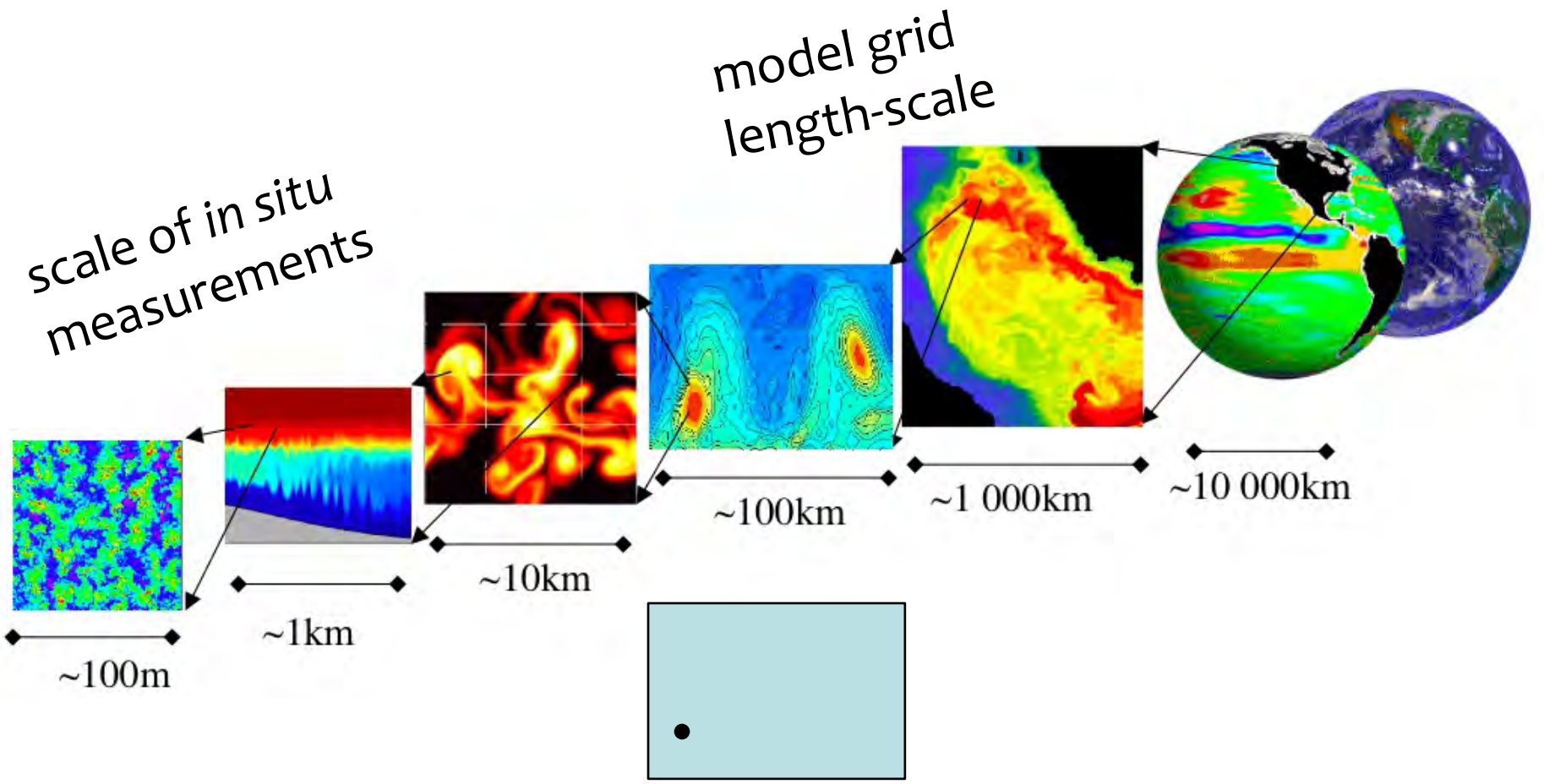
$\delta J = \partial J/\partial a \, \delta a + \partial J/\partial b \, \delta b + \ldots$

If want to reduce J (misfits), adjust model parameters δa,δb,... within **error bounds**

Uncertainty quantification

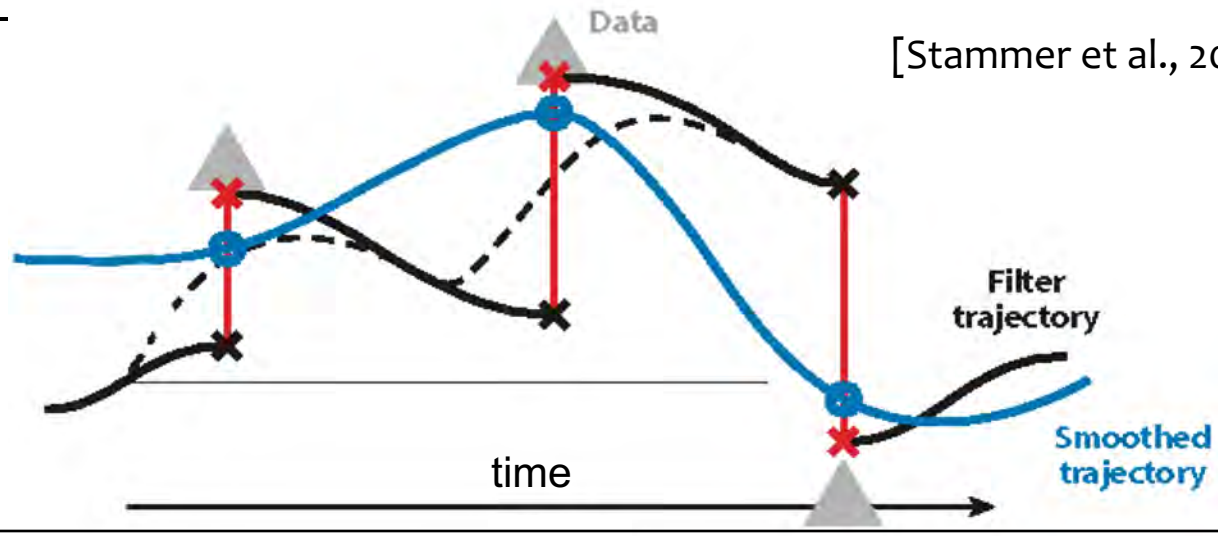
how to represent variability?

→ <u>uncertainty</u>



Data Assimilation can mean very(!) different things to different people

[Stammer et al., 2016]



State Estimation (smoother/adjoint):

- Bring all observations into a dynamically consistent description of the past and recent time-varying ocean circulation.
- Strictly obeys model physics at all time
- Study ocean dynamics and variability, global-scale and regional energy, heat, and water budgets.
- Decadal to multi-decadal timescale.

Data Assimilation (filter):

- Bring all observations into a model for the purpose of prediction / forecasting
- Model updates can break conservation law.
- Update: weighting between prior knowledge and data-model misfits
- Initialization, operational
- days to months timescale

Science goal / application → determines the framework

ASTE – Release 1.5

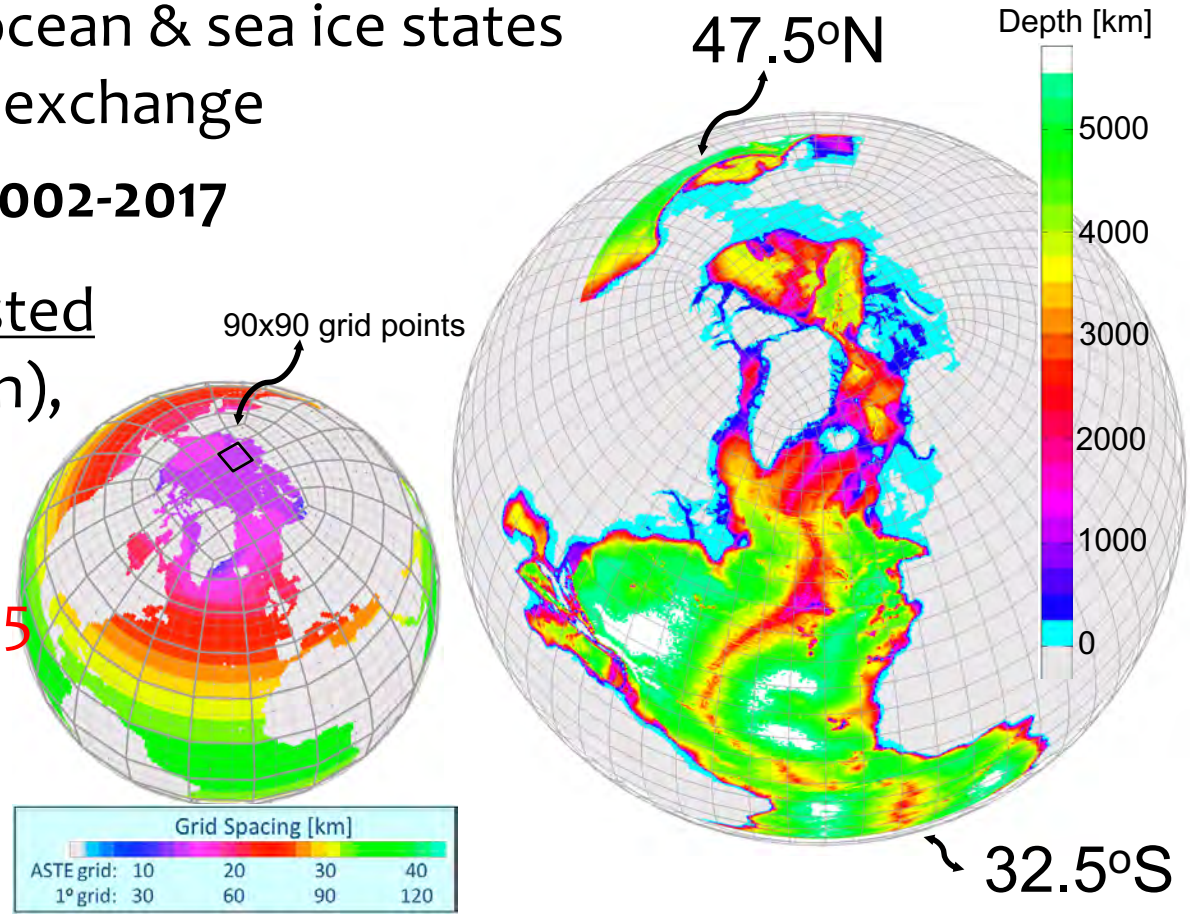
- Adjoint-based (nonlinear inversion) state estimation
- Mean & time-varying ocean & sea ice states
- Arctic – Subpolar gyre exchange
- Optimization period: **2002-2017**

- <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



Primary data constraints:

Low latitudes:

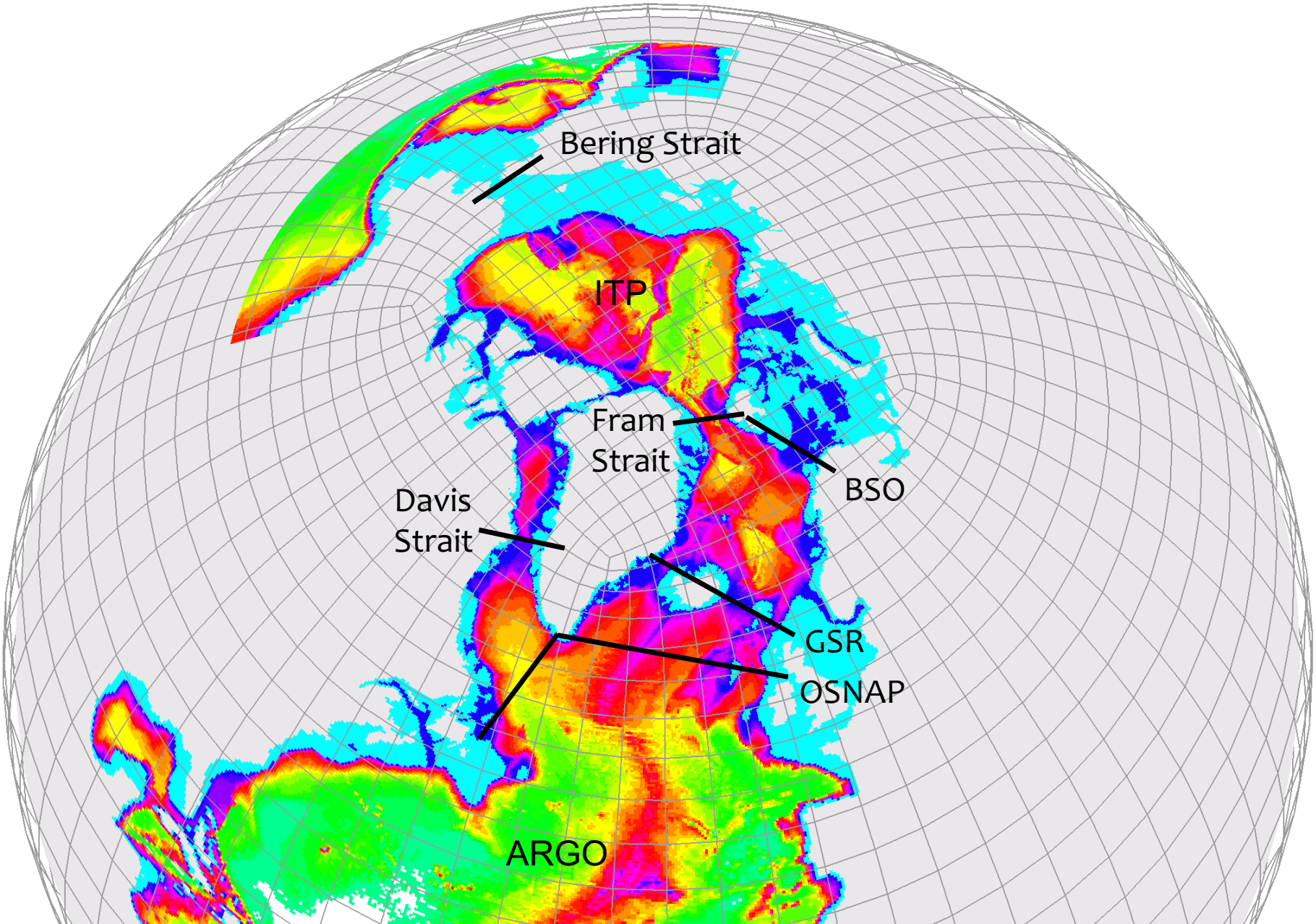
- ECCO-v4 standard obs.
  (SSH, SST, Argo, XBT, CTDs, seal, mean DMT)
- Line-W (John Toole), Gulf Stream (Robert Todd), AR07 lines, ICES database

High latitudes:

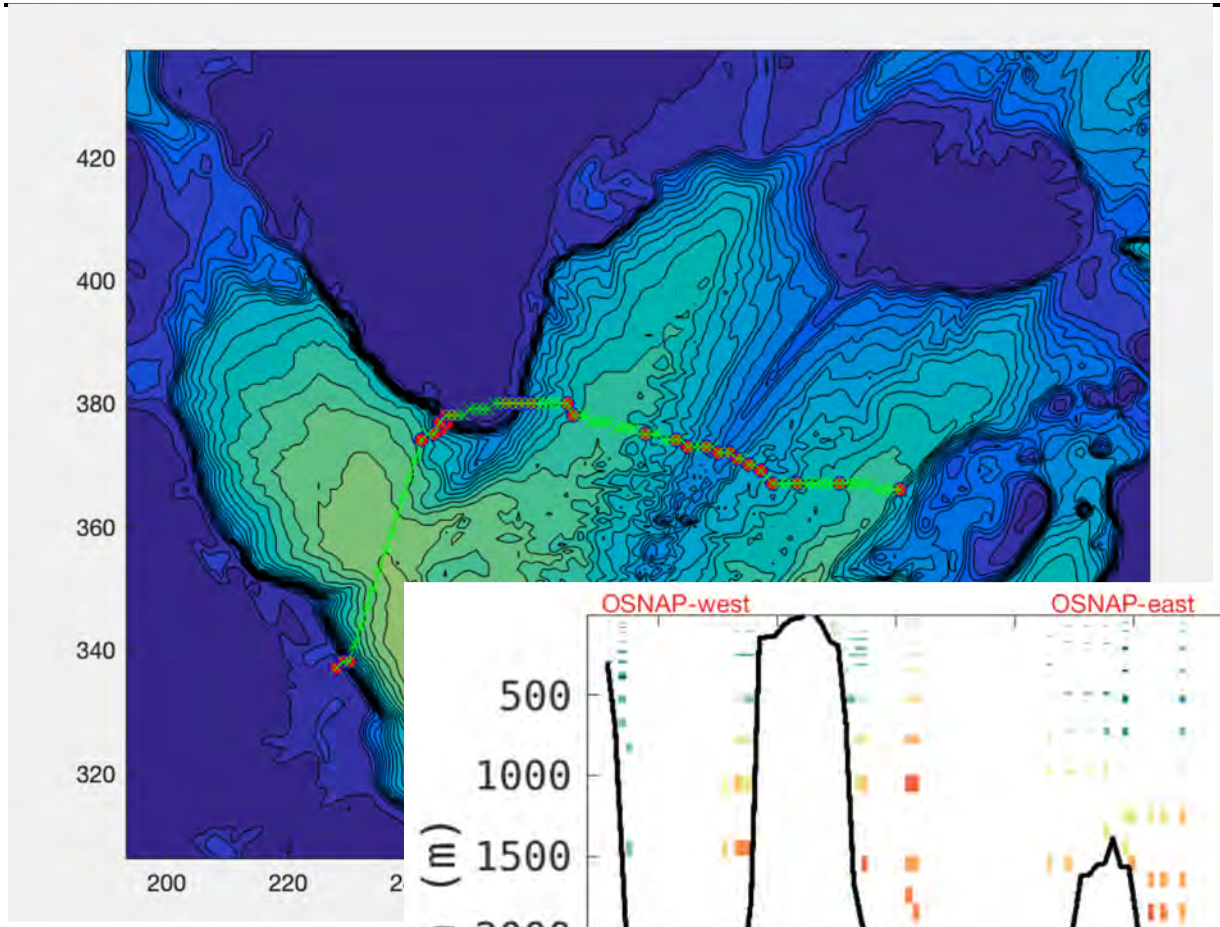
- Sea ice:
  - concentration (OSISAF, daily, 2002-2017)
  - thickness (ICESat, CryoSat, SMOS)
  - ice drift
- ocean T/S/U/V
  e.g., ITP, NABOS/CABOS, BGEP (2002-2017)

- Arctic main gateways: Fram, Davis, Bering straits, etc.

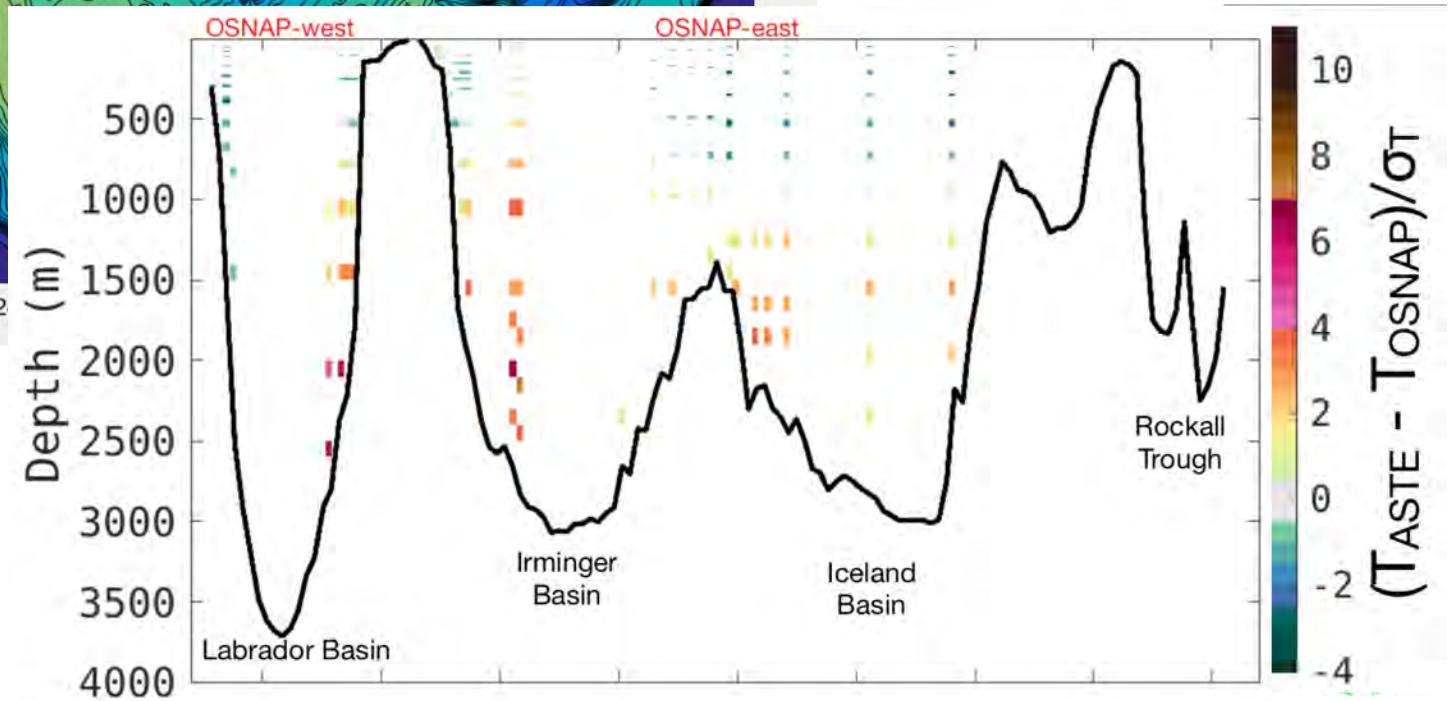
Gateways


Bering Strait
ITP
Fram
Strait
BSO
Davis
Strait
GSR
OSNAP
ARGO

Example of constraints: OSNAP



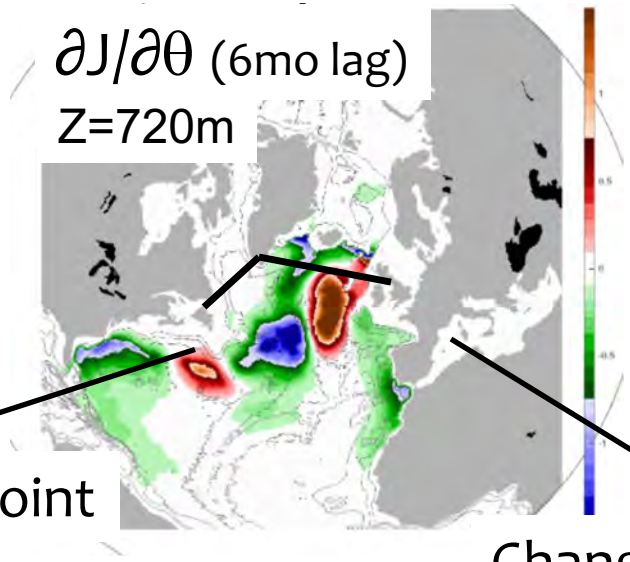
Figures courtesy of Helen Pillar



State Estimation (smoother) vs. Data assimilation (filter):

Positive $\partial J/\partial\theta$: If want ↓ J, then ↓ θ at these locations.

Q. HOW to change temperature?

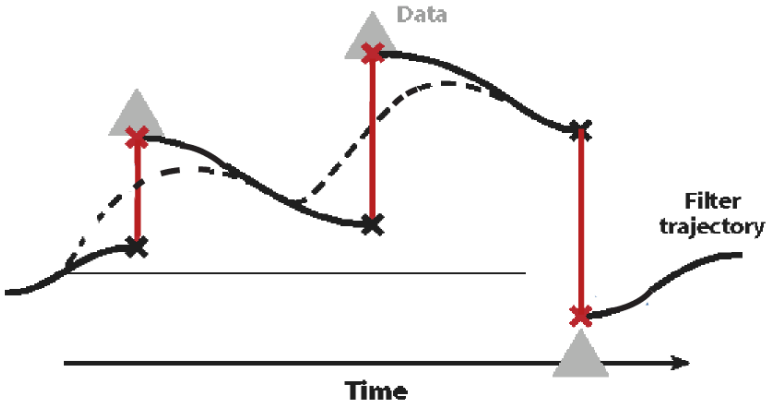


Smoother/adjoint

Filter

Change the temperature!

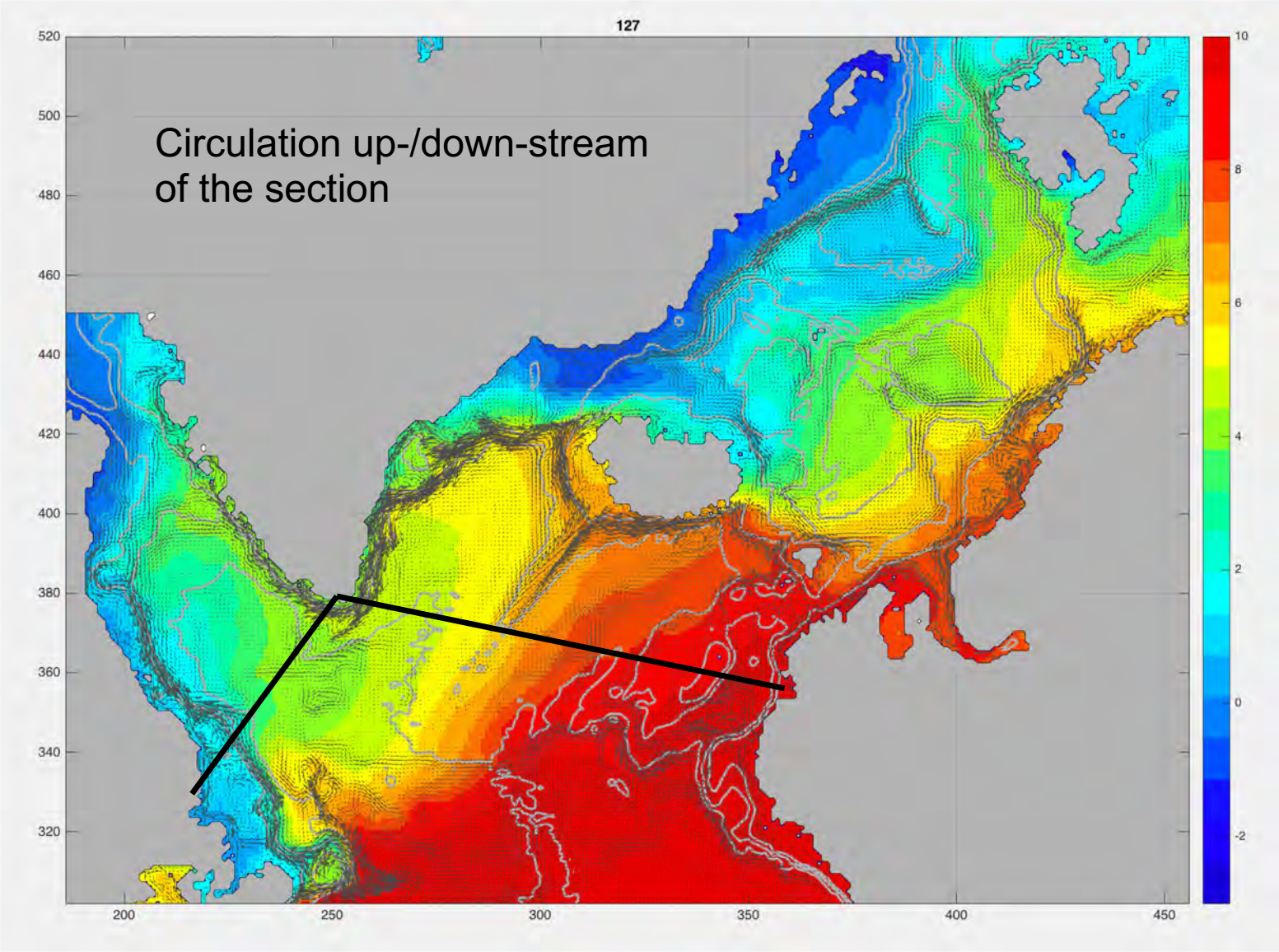
Adjust "control parameters",
e.g., internal mixing,
surface forcings
initial conditions



Capture processes upstream

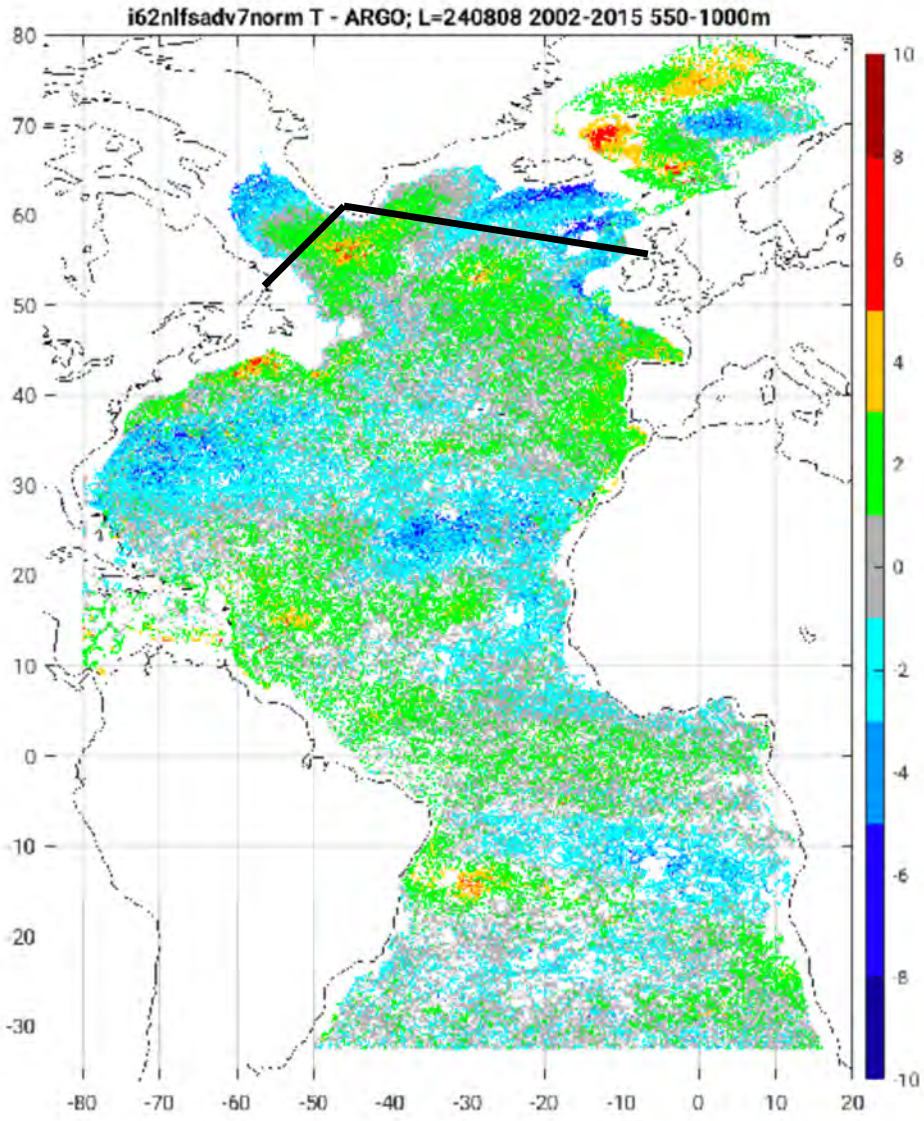
Violates conservation laws

What happens up-/down-stream of OSNAP?



What happens up-/down-stream of OSNAP?

Argo data



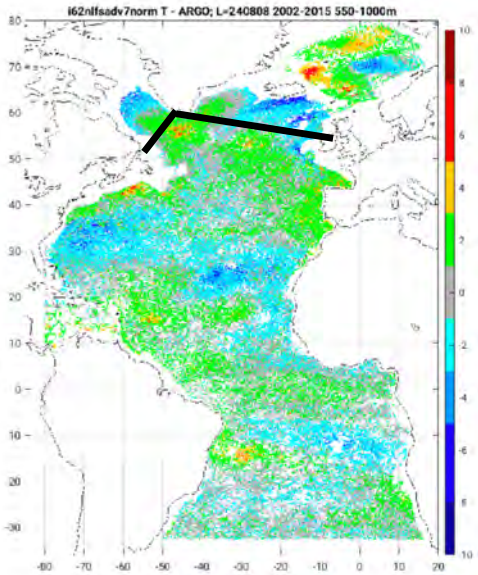
Gateways:
- Boundary currents
- Exchanges between basins

Fits to observations:
- Need to be consistent with watermasses up-/down-stream

Ensure dynamical consistency?
(no jumps, no unknown source/sinks)

Allow for <u>representation errors</u>

What happens up/down-stream of OSNAP?



(larger) Representation vs (smaller) obs errors

Smoothers (adjoint)

- Adjust uncertain *input* parameters
- More** weights on representation errors
- Not nesc fitting obs point-wise (focus on integrated quantities)

Filters

- Adjust T(t) , S(t)
- More* weights to obs
- Better fit obs point-wise

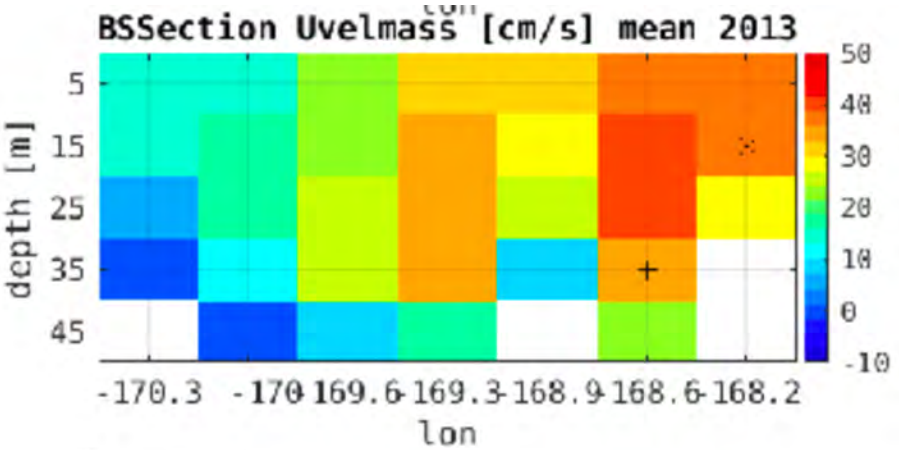
Transports & exchanges at gateways?

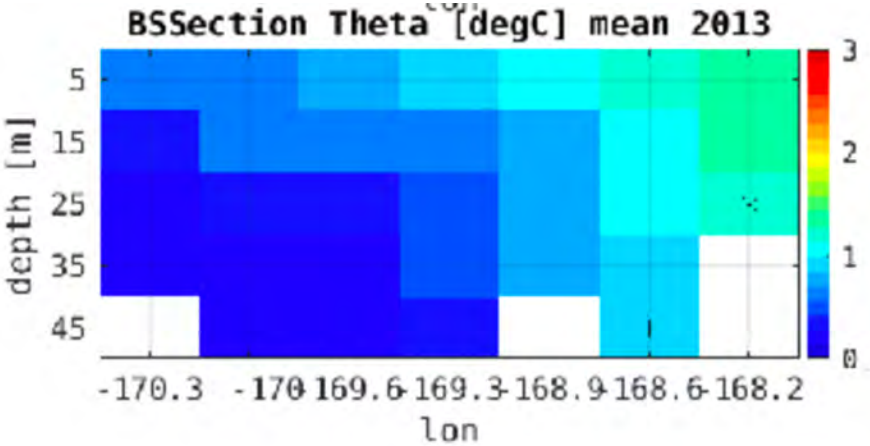
- Conserving
- Unknown sources/sinks
- Meaning of integrated transports?

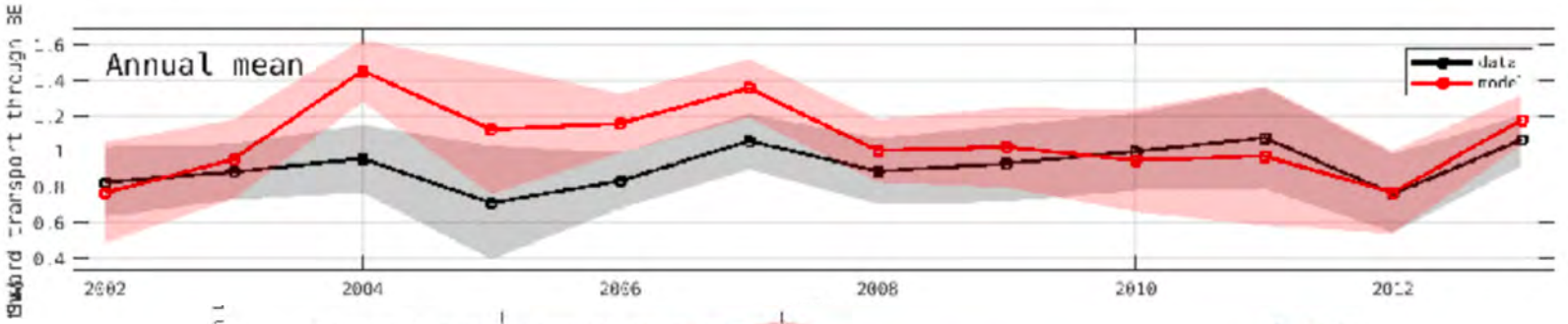
* trust obs more → put more emphasis on observations to adjust T(t) , S(t)

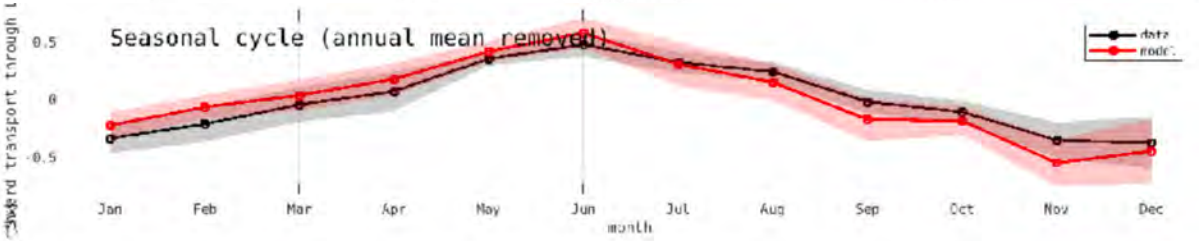
** rely on model (imperfect) physics and its representation errors (not practical for real-time operational applications)

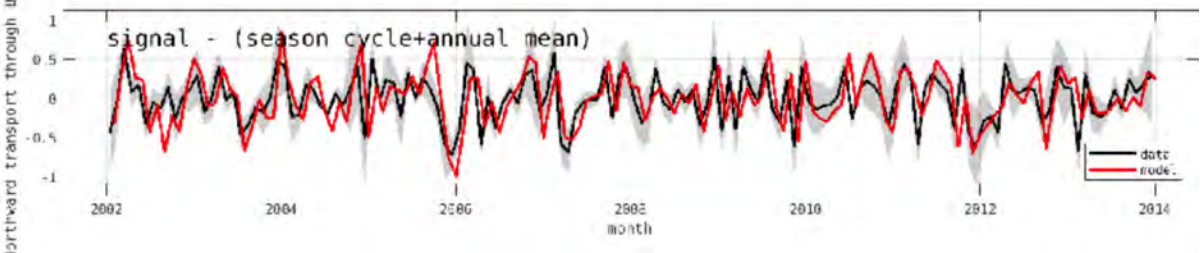
Example of constraints: Bering Strait





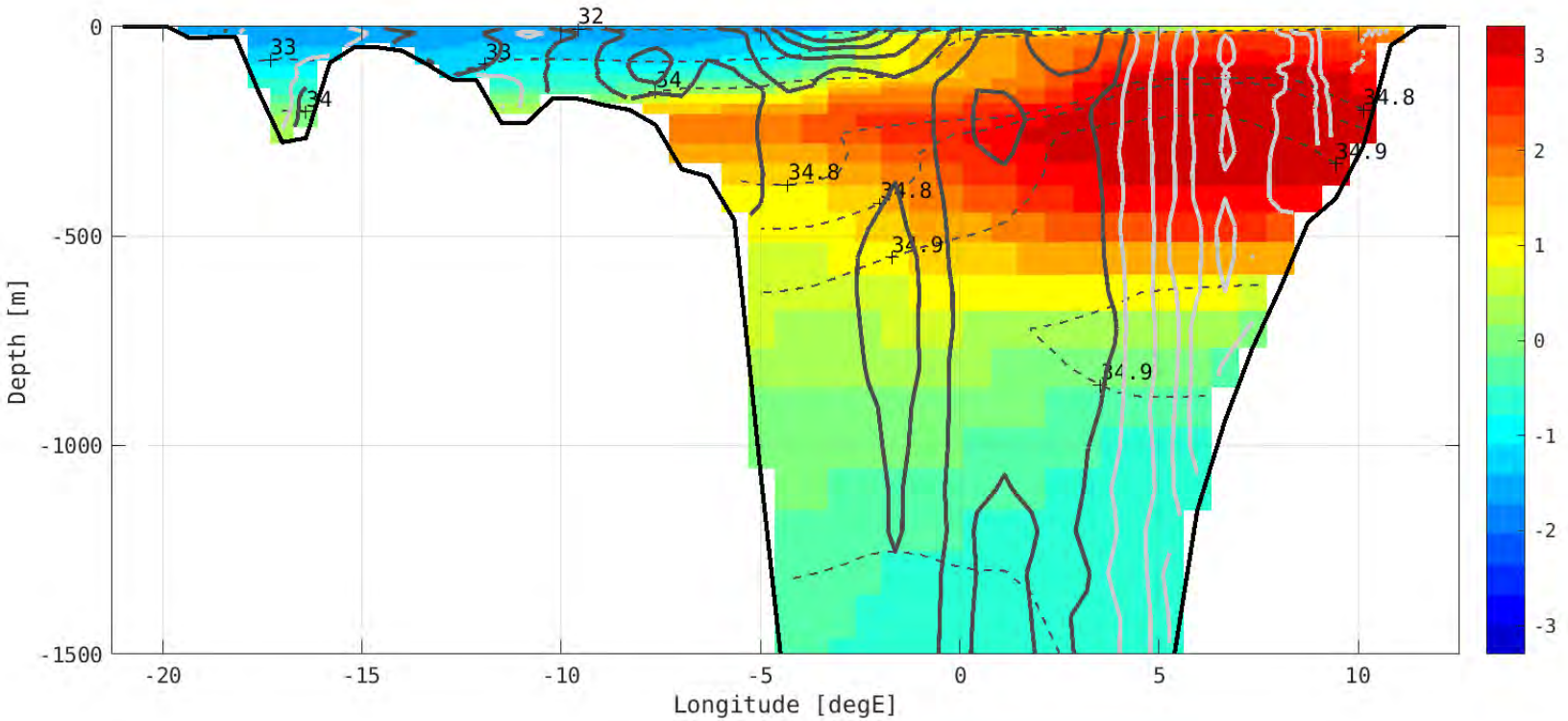




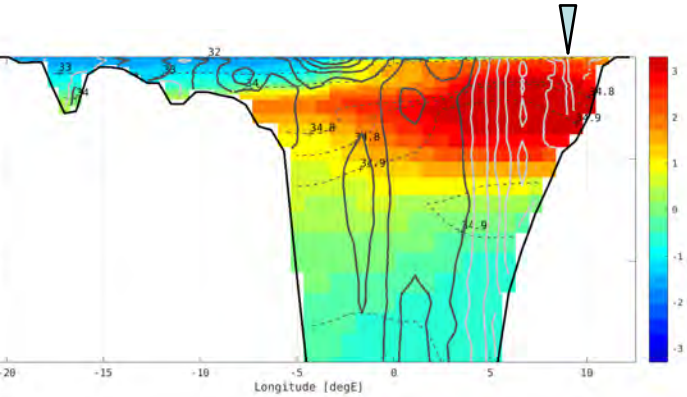


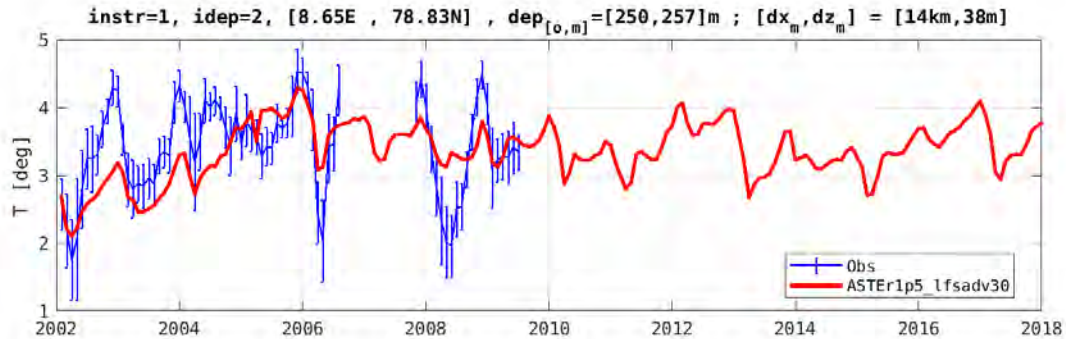
Example of constraints: Fram Strait

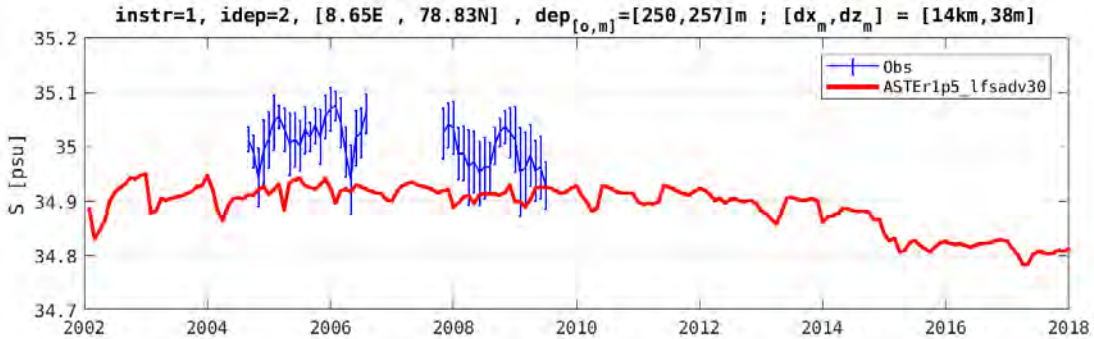
ASTEr1p5 , 2003–2017 mean

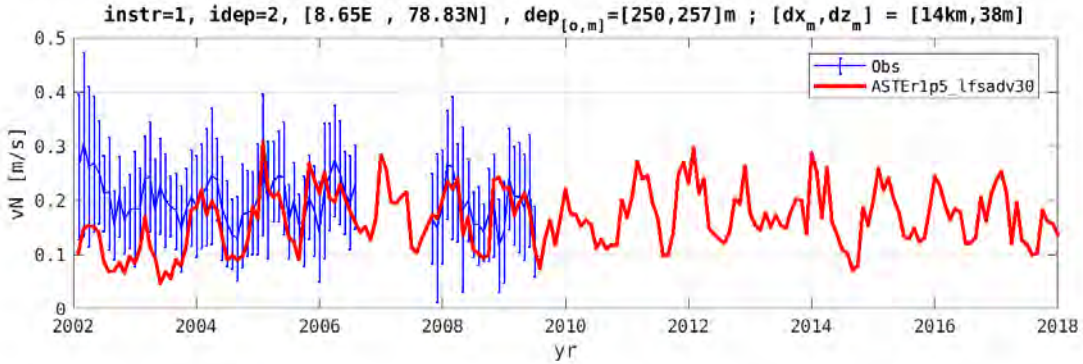


Example of constraints: Fram Strait



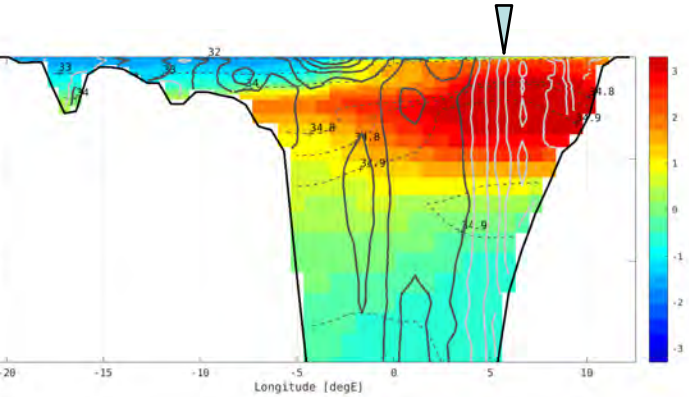


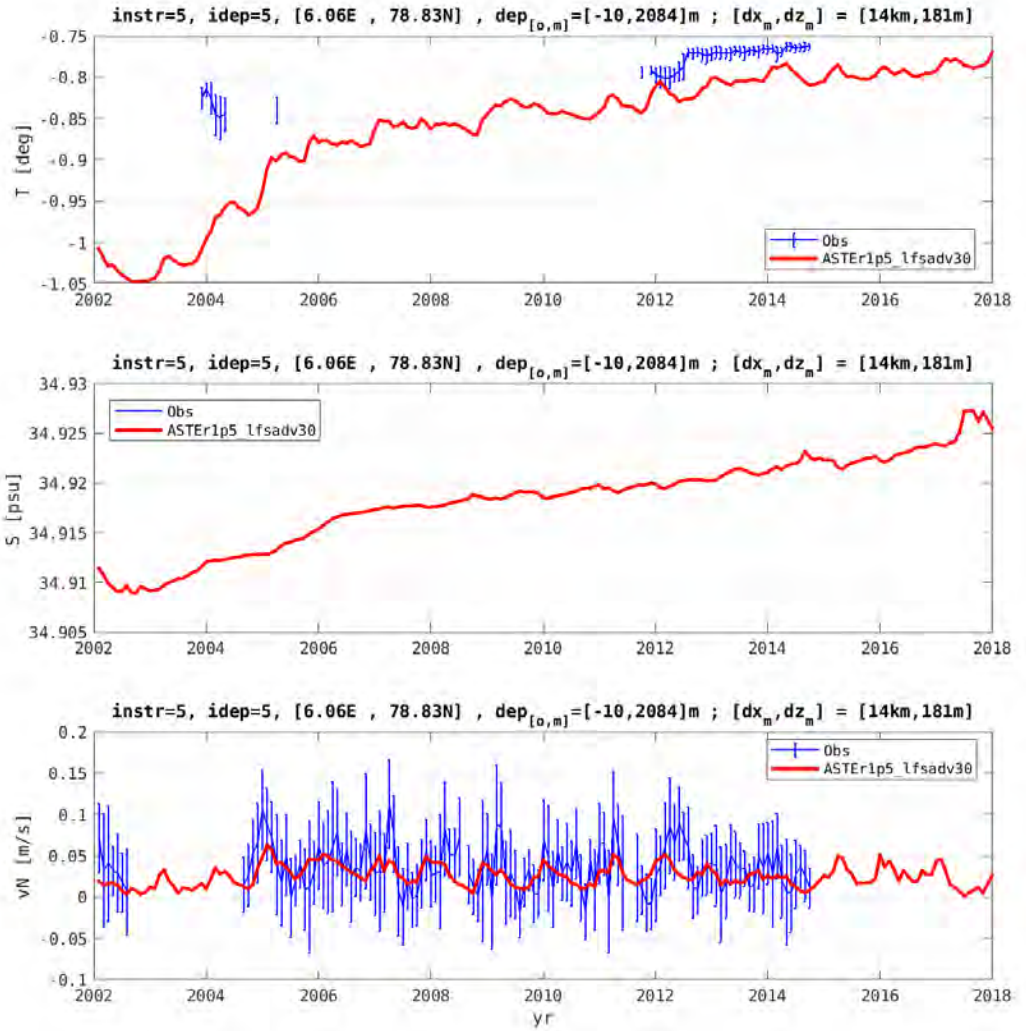




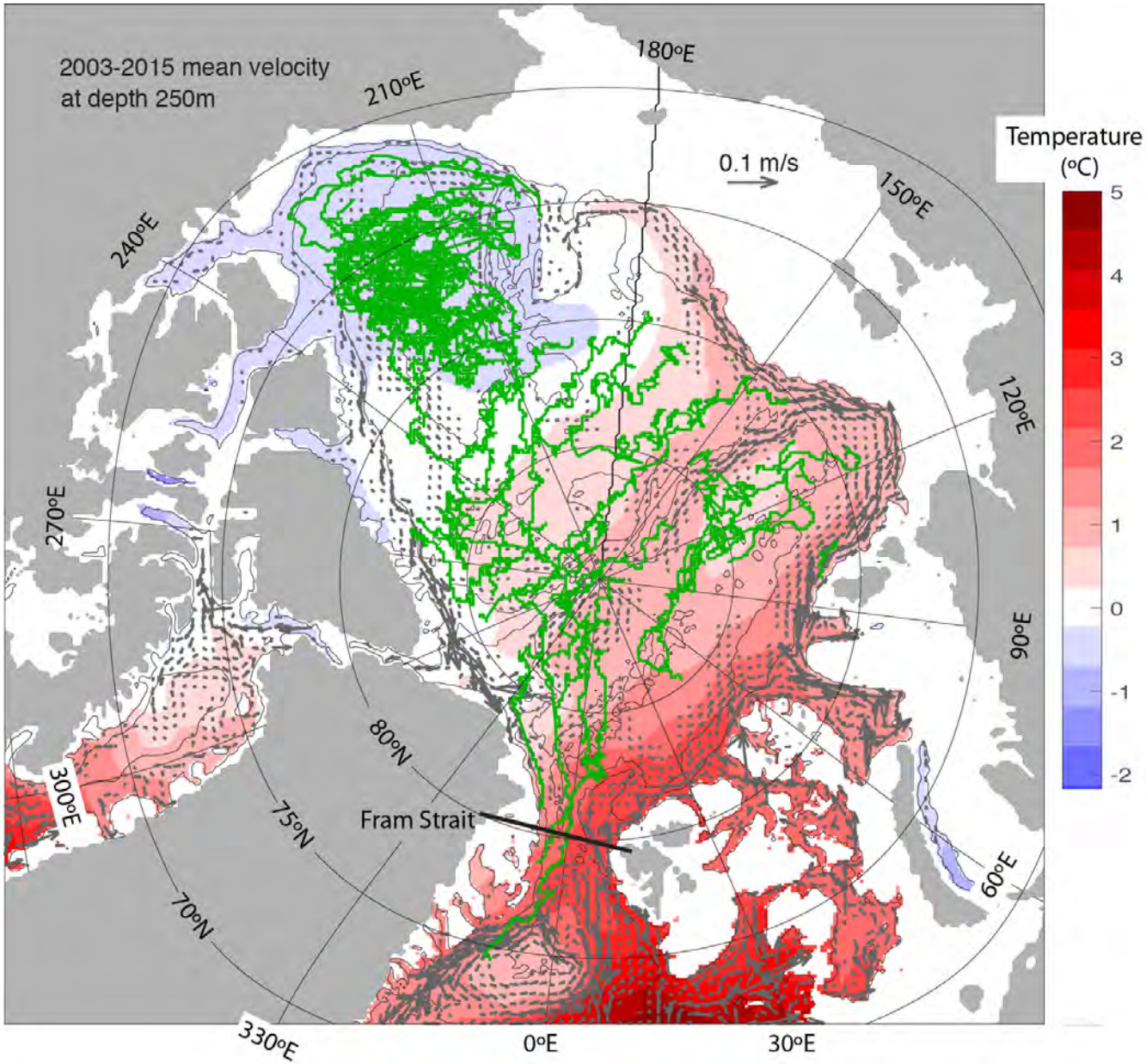
Boundary current strength?
T/S properties?

Example of constraints: Fram Strait





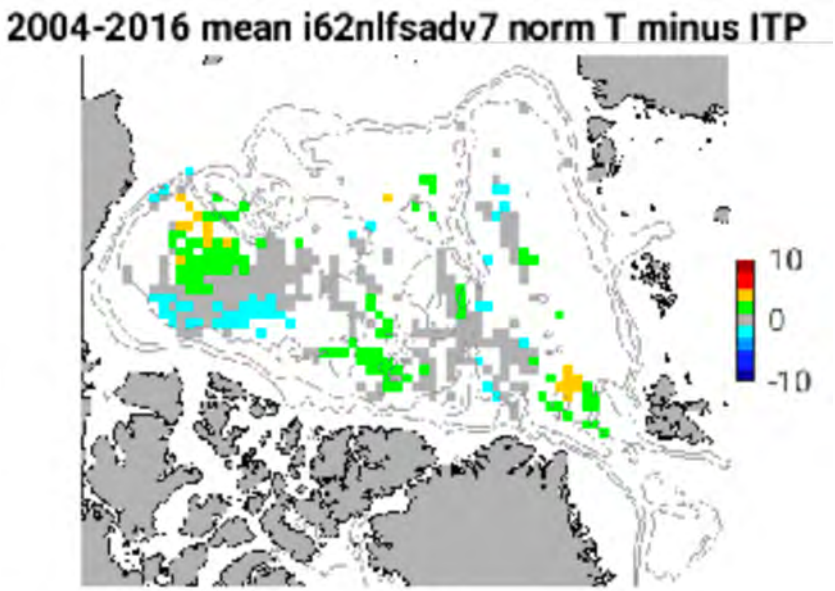
Downstream of Fram Strait

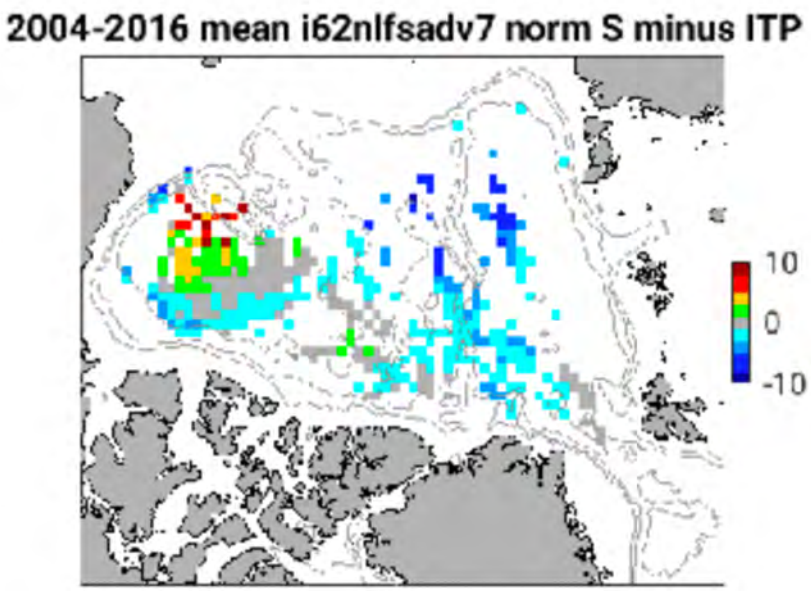


Requirement:

Consistency between Fram Strait transports & watermass much further downstream in the Canada Basin

Downstream of Fram Strait





Requirement:

Consistency between Fram Strait transports & watermass much further downstream in the Canada Basin

→ Decadal time-scale

→ Taken into account model representation errors

→ account for non-uniqueness of adjustments to uncertain parameters

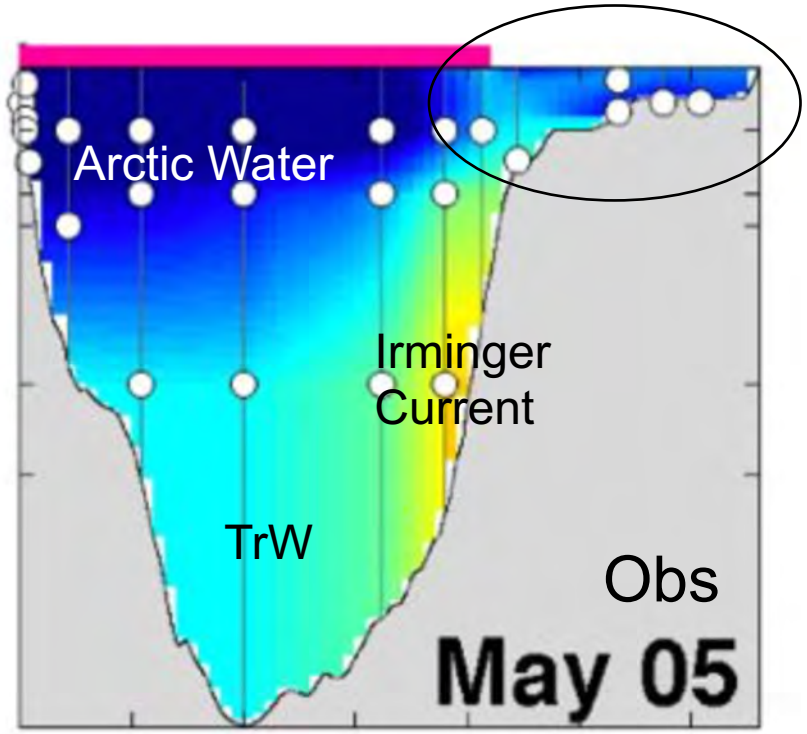
→ Not "over-fitting" obs at gateways (and elsewhere)

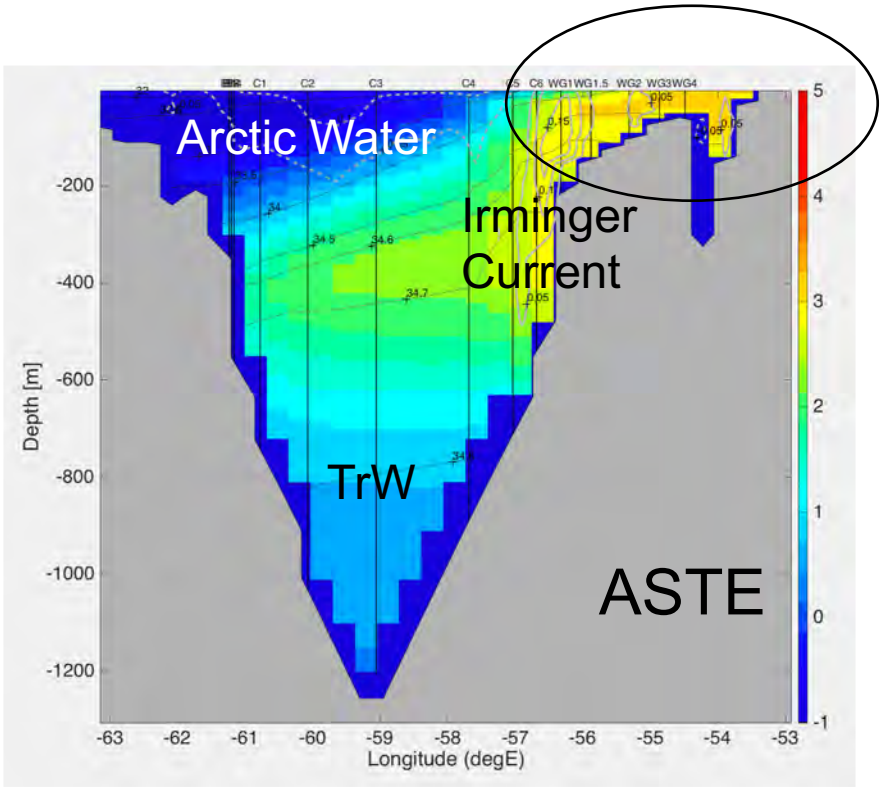
Example of constraints: Davis Strait

Source:

(a) East Greenland Current (**exiting from Fram Strait**)

(b) Greenland glacial melt (solid and liquid)





Problem much further upstream that needs to be addressed?
Missing source term?

Use of observations as constraints

- State estimates:
  - follows conservation laws (momentum, tracers, mass)
  - → dynamical interpolator of observations at different space/time scales
  - source/sink accounted for → budgets, circulation
  - always have bias/representation errors

- Usefulness of observations as constraints:
  - understand processes up-/down-streams of gateways
  - importance of continuous sub-surface measurements
  - Sparseness of obs: lack of velocity constraints

- Comparison with care
  - integrated quantities vs point-to-point
  - model: representation errors. Obs: interpolation assumptions