A 23-years Arctic ice-ocean reanalysis with TOPAZ
With emphasis on TOPAZ as an EPS

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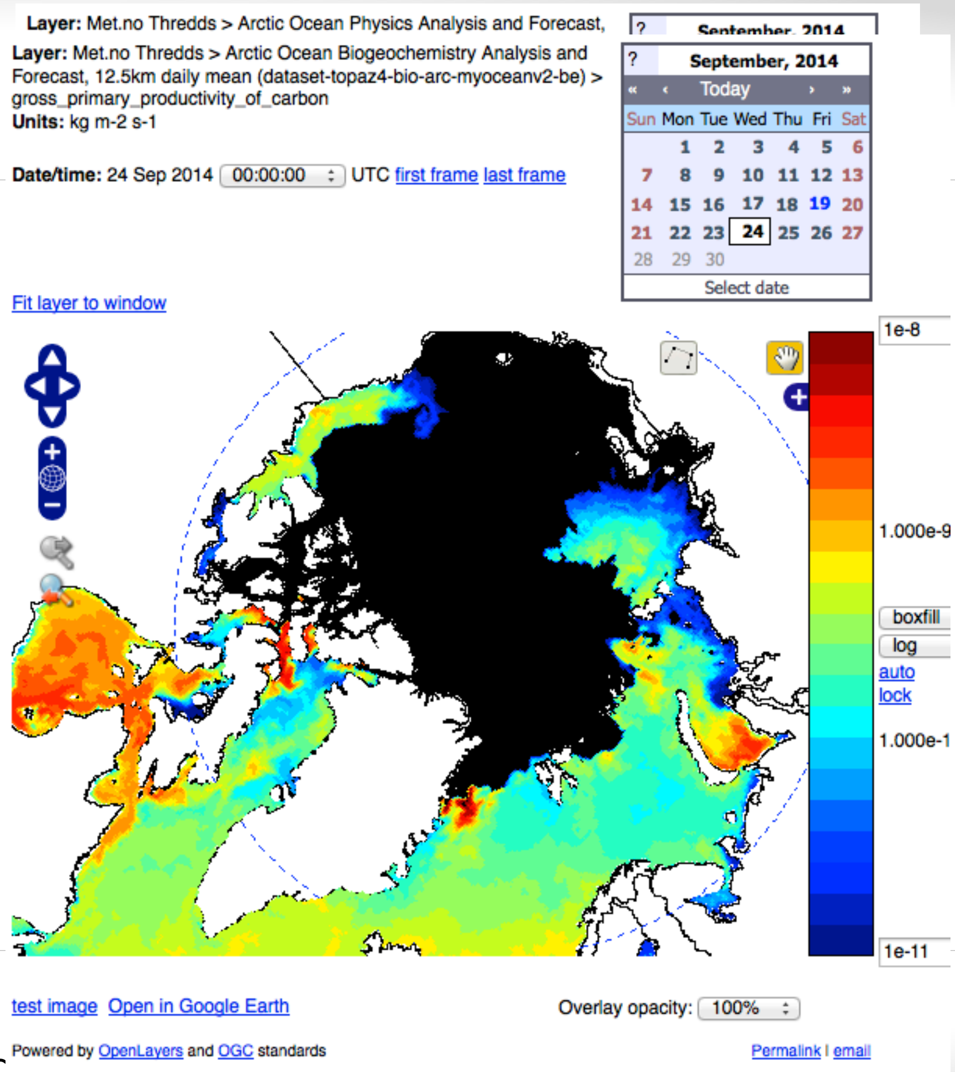
Seminar at GFI, 10th August 2015

Outline

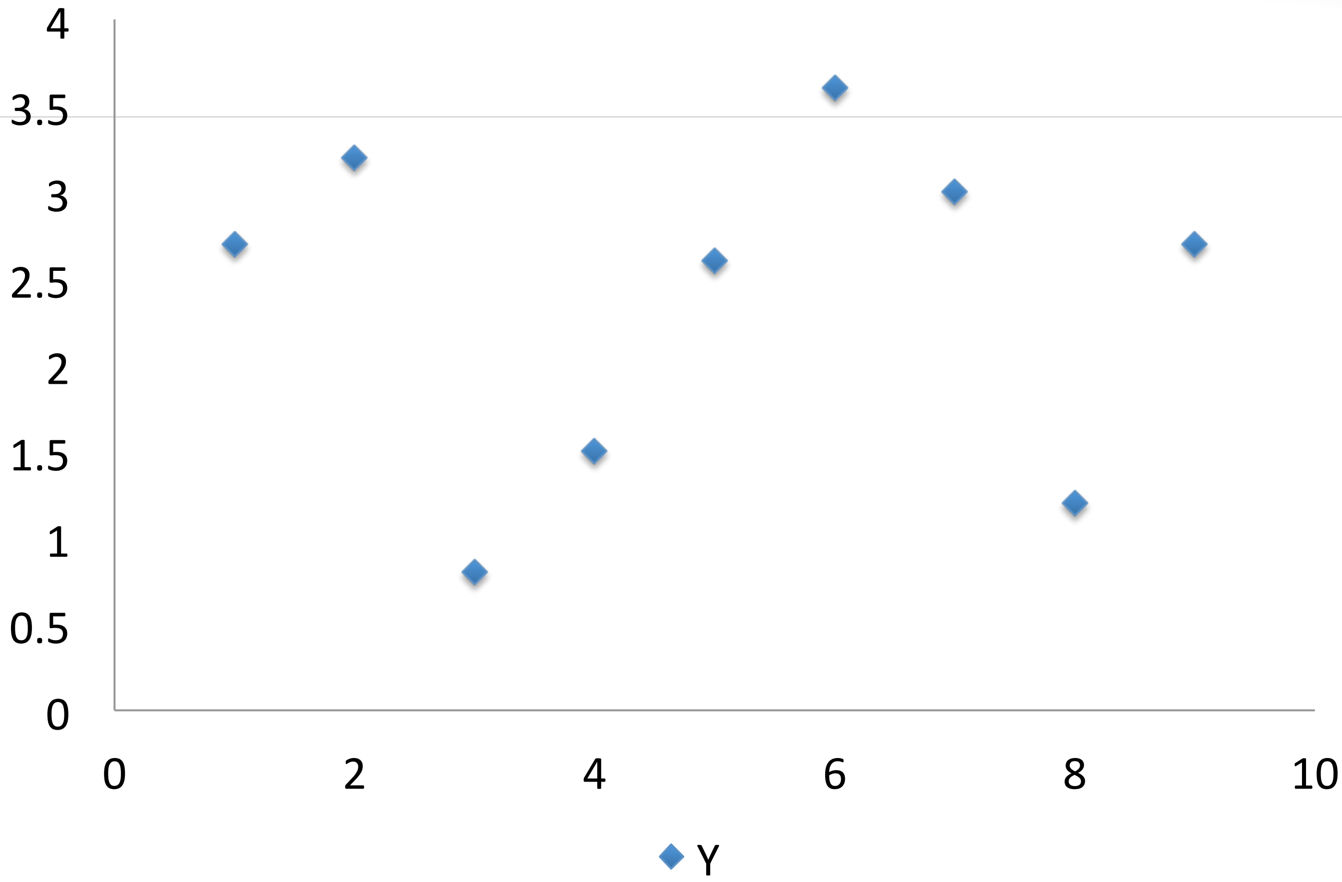
- Presentation of the system
  - What kind of reanalysis?
  - TOPAZ ensemble setup
  - *Good health* of an EnKF used in reanalysis?
- Performance of the 23-years reanalysis
  - Longest realistic EnKF run so far (1200 cycles)
  - Can the ice-ocean synthesis satisfy *all* data inputs?
  - How large are the expected dynamical imbalances?
    - Sea level rise
    - Heat and salinity budgets?
- Future evolutions

The TOPAZ system

- Exploited operationally at MET Norway
  - Since 2008
  - Ecosystem coupled online in Jan. 2012
- 23 years reanalysis at NERSC
  - Took 2 years to produce
  - ~ 4 million CPU hours
- 3-years ecosystem reanalysis
  - Assimilation of both physical and ocean colour data
- MyOcean (Arctic MFC)
  - 10-mems ensemble forecast
  - Free distribution of data (average)
  - Dynamical viewing (Godiva2)
- RT Data used by ECMWF wave forecast model
  - Surface currents



What kind of reanalysis?



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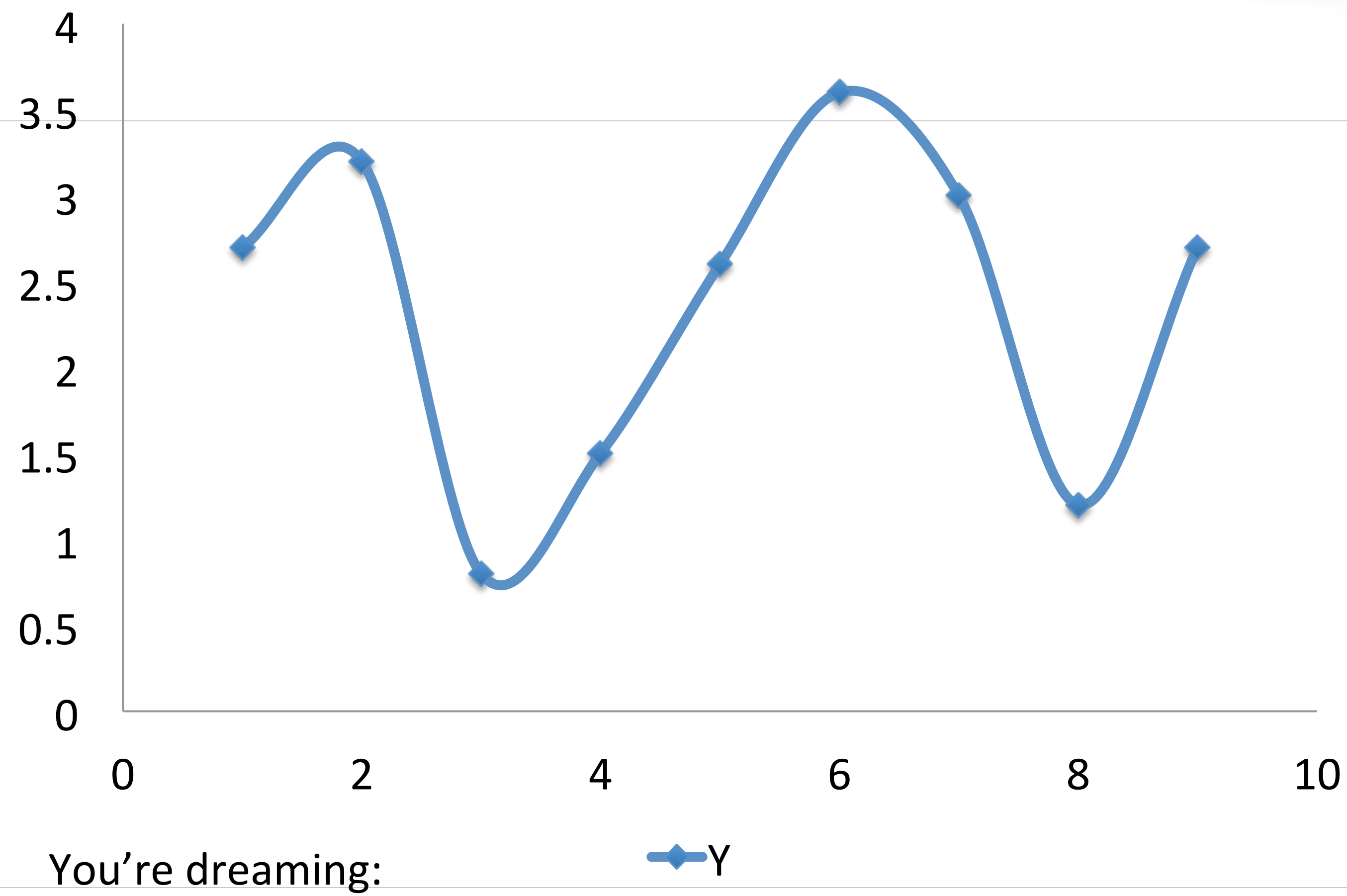
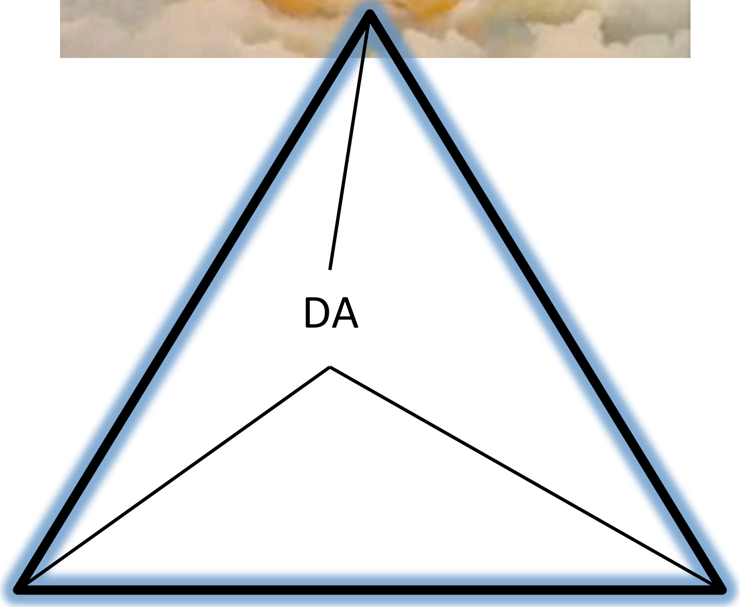


You're dreaming:
Too many observations

Data assimilation: what for?



Model

$$\left(\frac{dV}{dt} = \tau_w + \tau_o + \nabla\cdot\sigma\right)$$

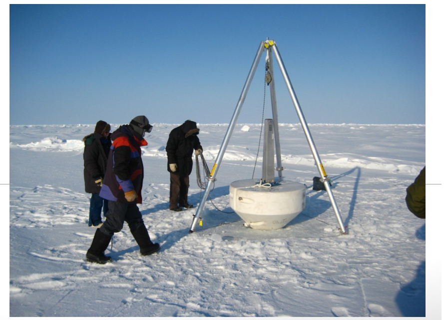
Physical consistency

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

$$\frac{D\mathbf{v}}{Dt} = -\frac{1}{\rho}\nabla p - 2\Omega \times \mathbf{v} + \mathbf{g} + \mathbf{F}_r$$

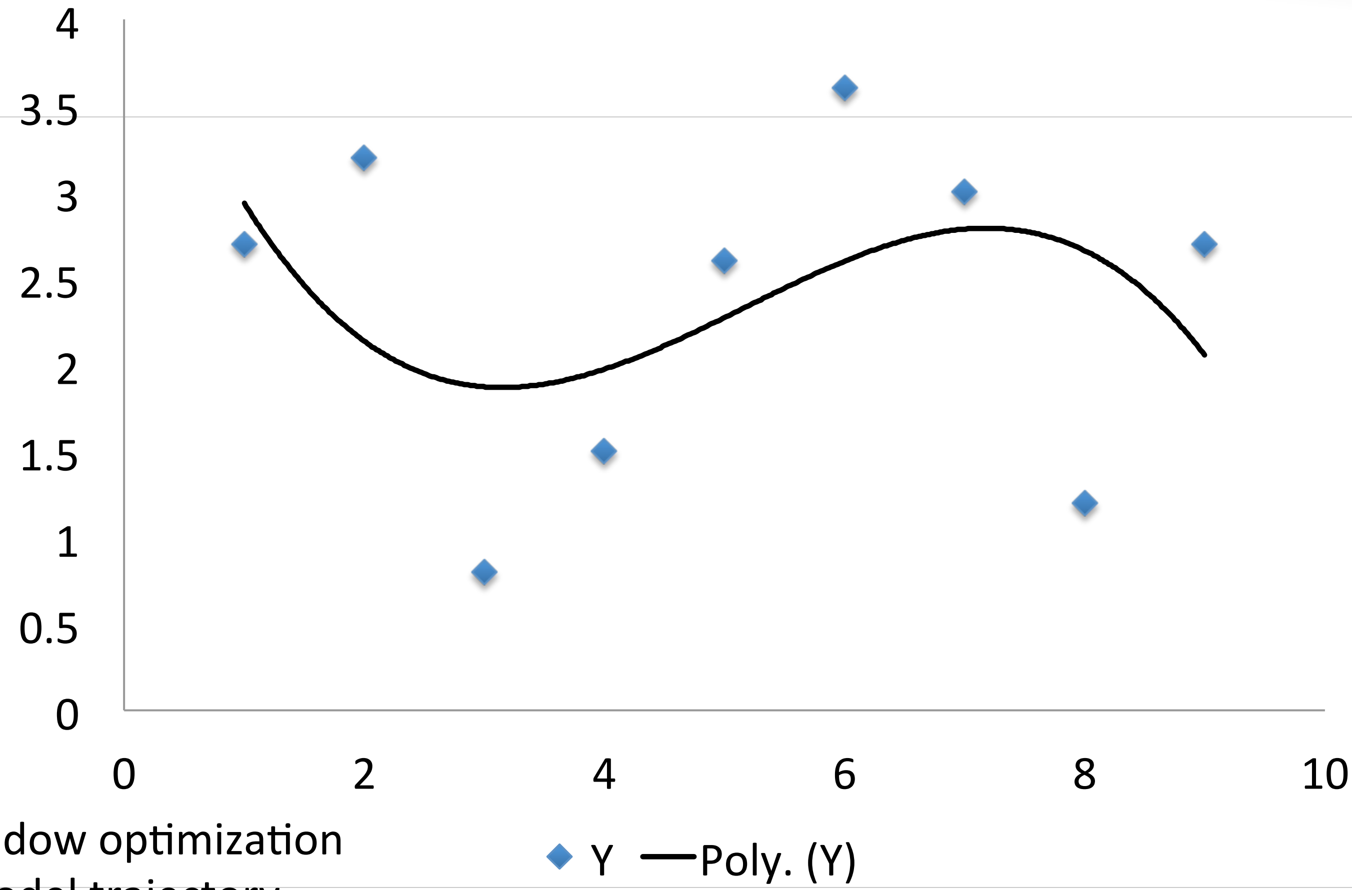
Observations

Accuracy



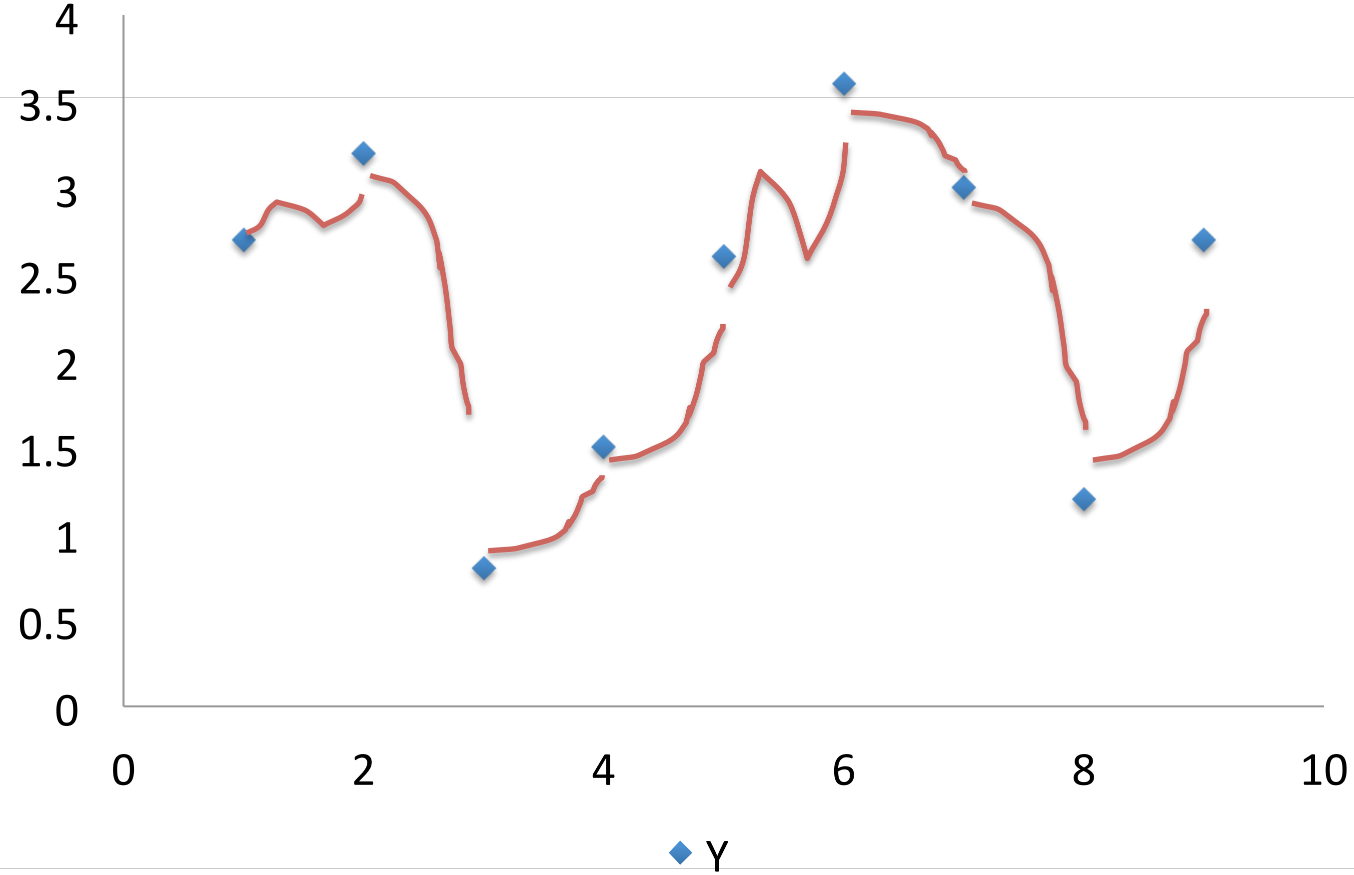
POPS buoy, C. Provost, UPMC

What kind of reanalysis?



Long window optimization
Single model trajectory

What kind of reanalysis?



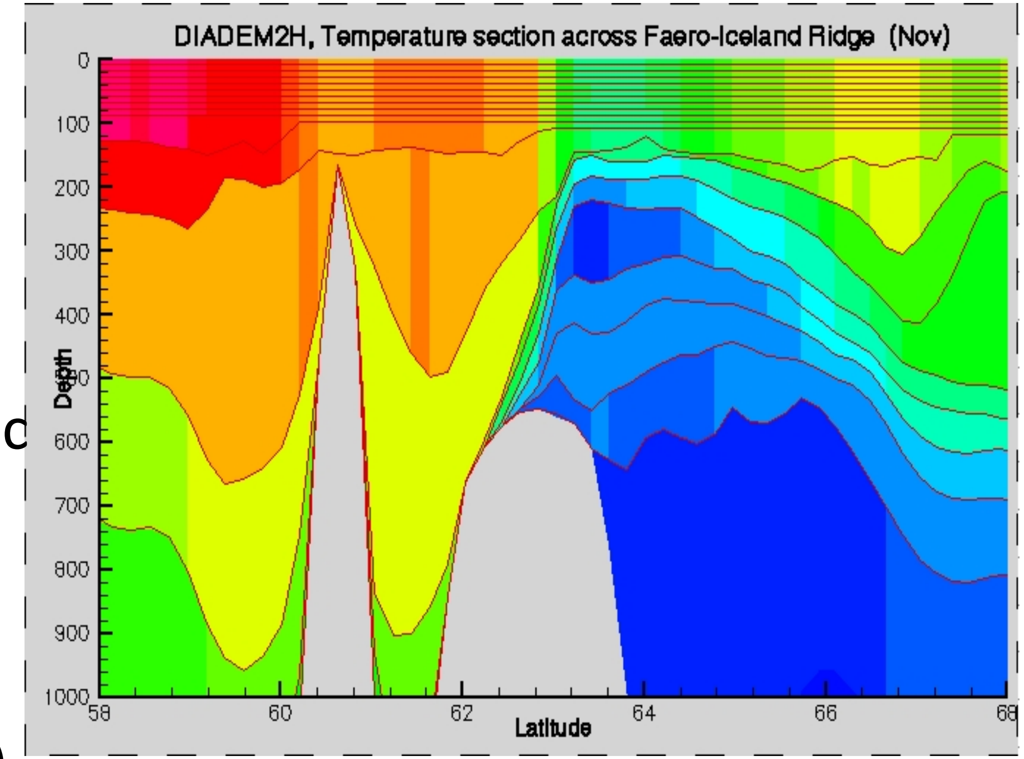
Short windows optimization
More accurate, but interrupted

Reanalysis strategy

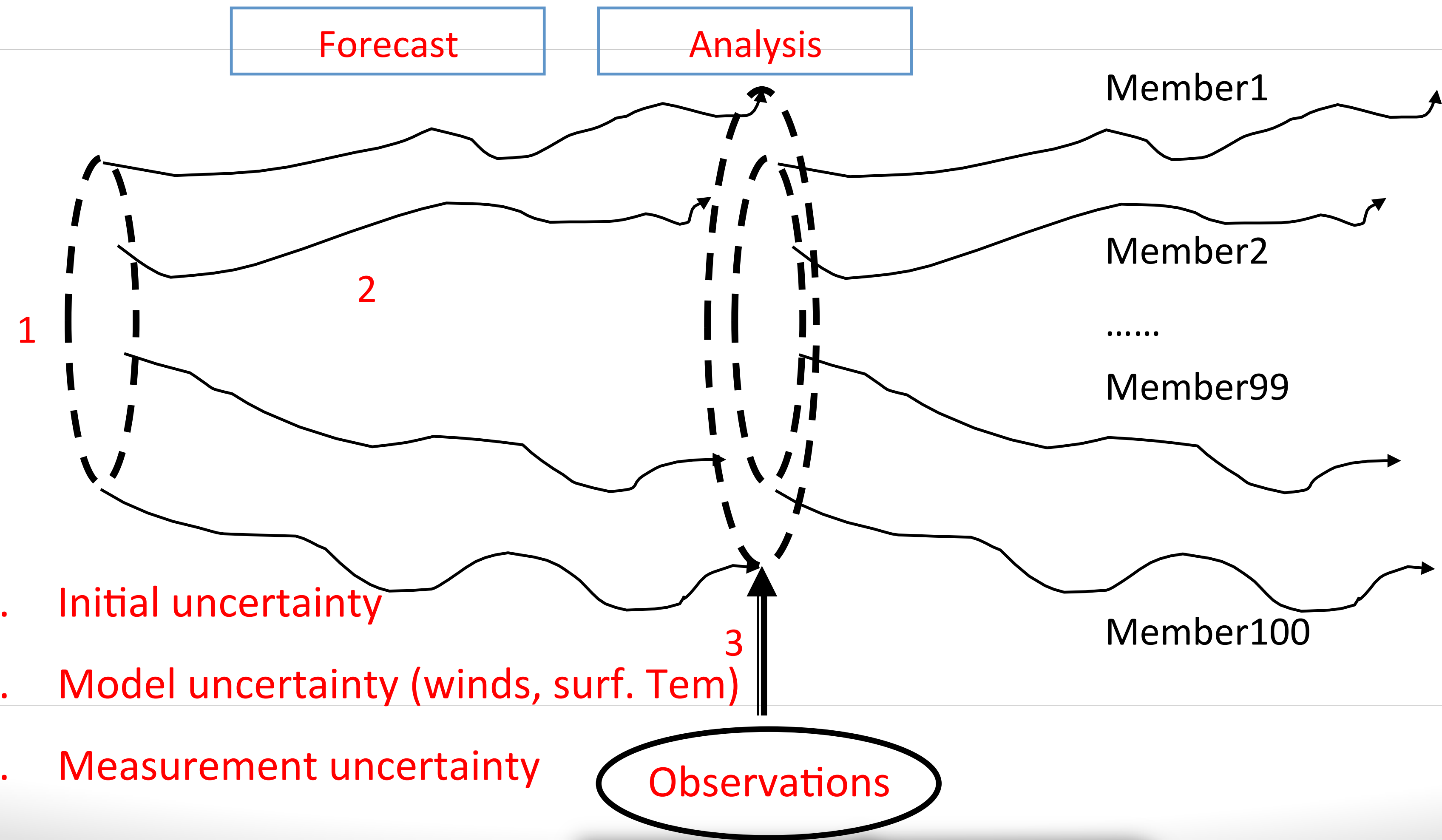
- Short windows (1 week)
  - Easier to match observations and events
  - Closer to *linear regime*
  - <u>But</u> frequent discontinuities at assimilation times
    - How large? Integral effect?
- Filtering method (EnKF)
  - Information flows only forward.
  - Cheaper than smoothing / iterative methods
    - <u>But</u> less efficient for parameter estimation
  - Identical to the real-time forecasting system
- Inhomogeneous observations network (1991-2013)
  - Implies inhomogeneous reanalysis results

The HYCOM model at NERSC

- 3D numerical ocean model
  - Hybrid Coordinate Ocean model, HYCOM (U. Miami), 12 km grid
- Hybrid vertical coordinate
  - Isopycnal in the interior
  - Z-coordinate at the surface
  - TOPAZ4 uses 28 layers
- Hybrid coordinates in the Arctic
  - High stability of the Arctic water column
  - Sharp pycnocline
  - Less spurious diapycnal mixing (critical at high model resolution)



Ensemble Kalman filtering

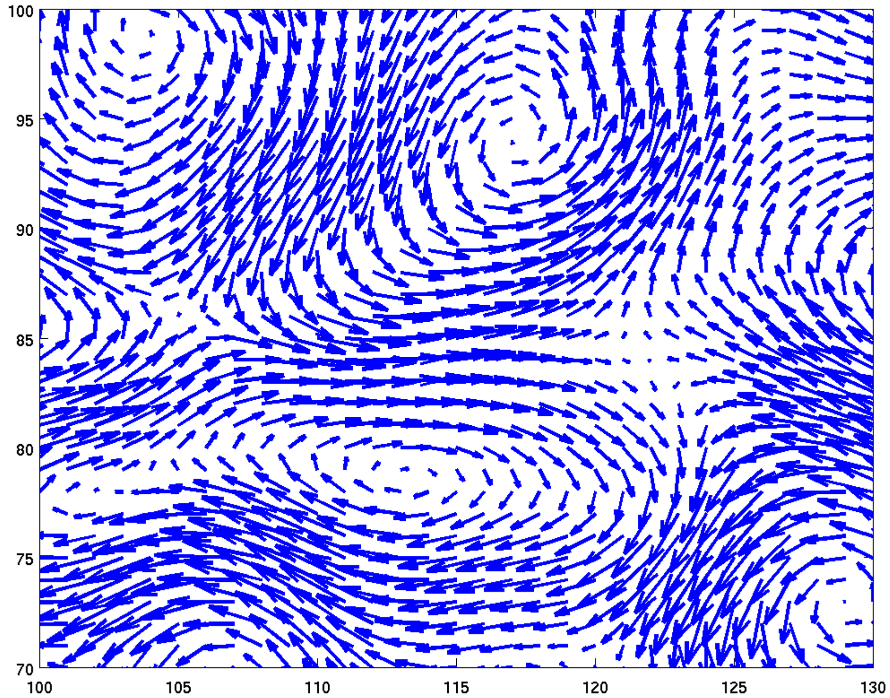


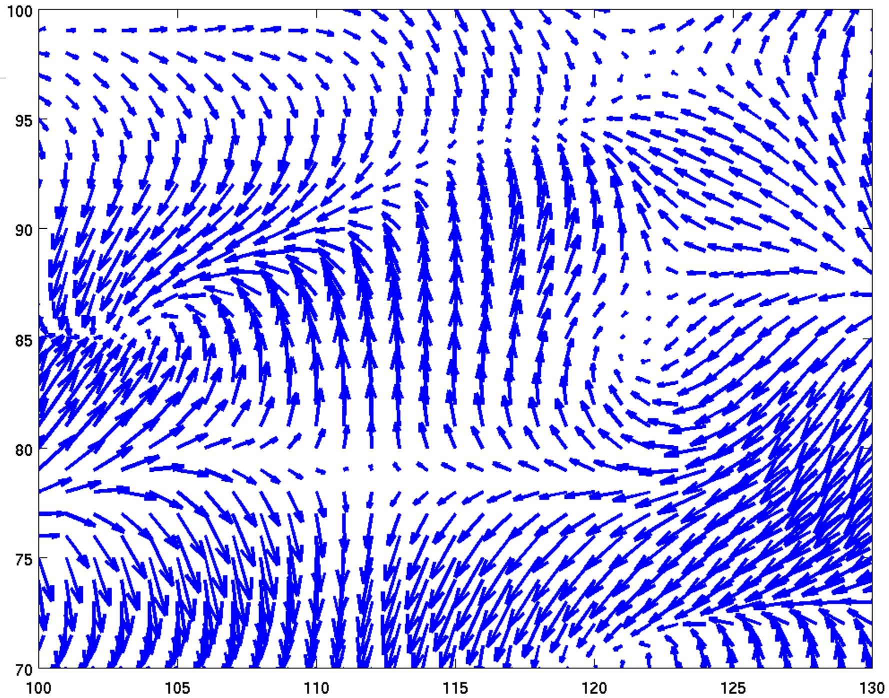
1. Initial uncertainty
2. Model uncertainty (winds, surf. Tem)
3. Measurement uncertainty

TOPAZ ensemble setup

- Initial error (2 months before the first assimilation cycle)
  - "Time warp" of members extracted from a 20-years free run
  - Sampled on the same season.
  - Meant to represent errors due to model spinup.
- Model errors
  - Random perturbations of heat fluxes, winds, precipitation, clouds
  - Horizontal correlation = 200 km
  - Time correlation = 3 days
  - Amplitude: 2m air temp = 3 deg C, radiative fluxes = 0.07 W/m^2,
  - Winds perturbed non-divergent (in geostrophic balance)
    - From SLP perturbation, 10 mBar amplitude
  - Internal parameters of sea ice dynamics
  - Constant bias detection for
    - SSH and SST offsets

Random perturbations of winds



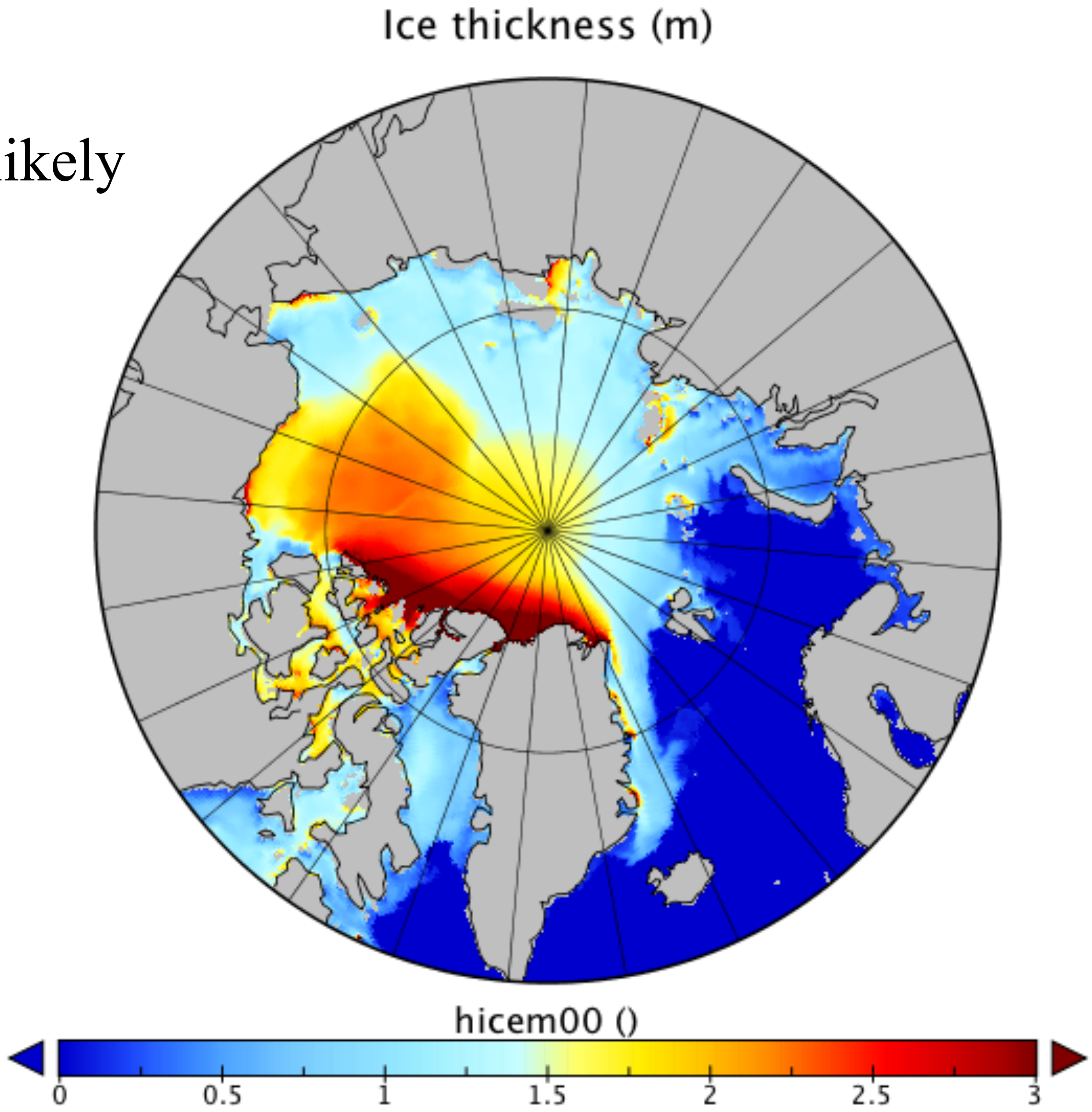


Geostrophic winds from SLP perturbations
Non-divergent
Our preferred option

U10 and V10 perturbed independently
Convergence and divergence increase

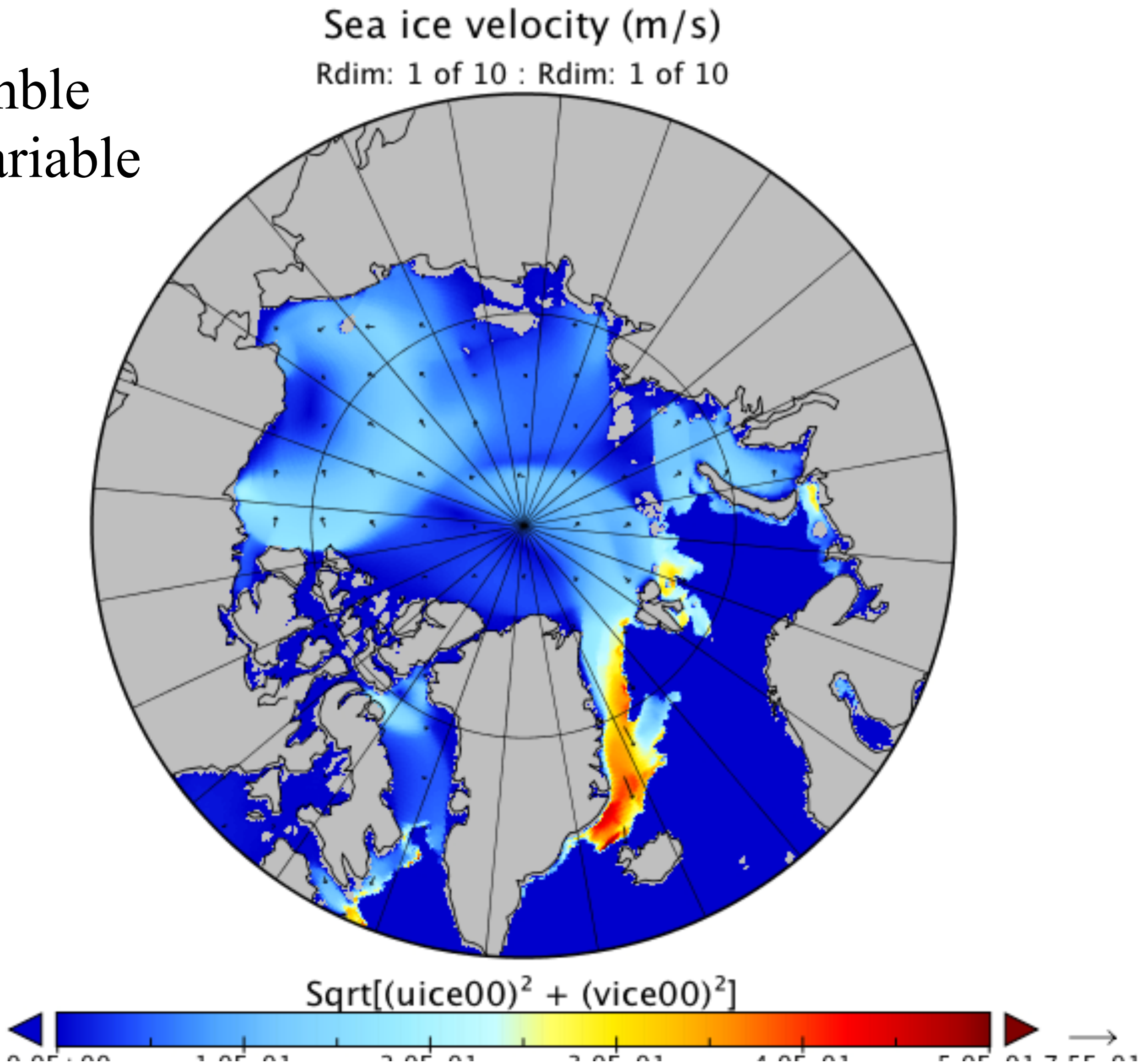
Example of ensemble

10 members
All equally likely

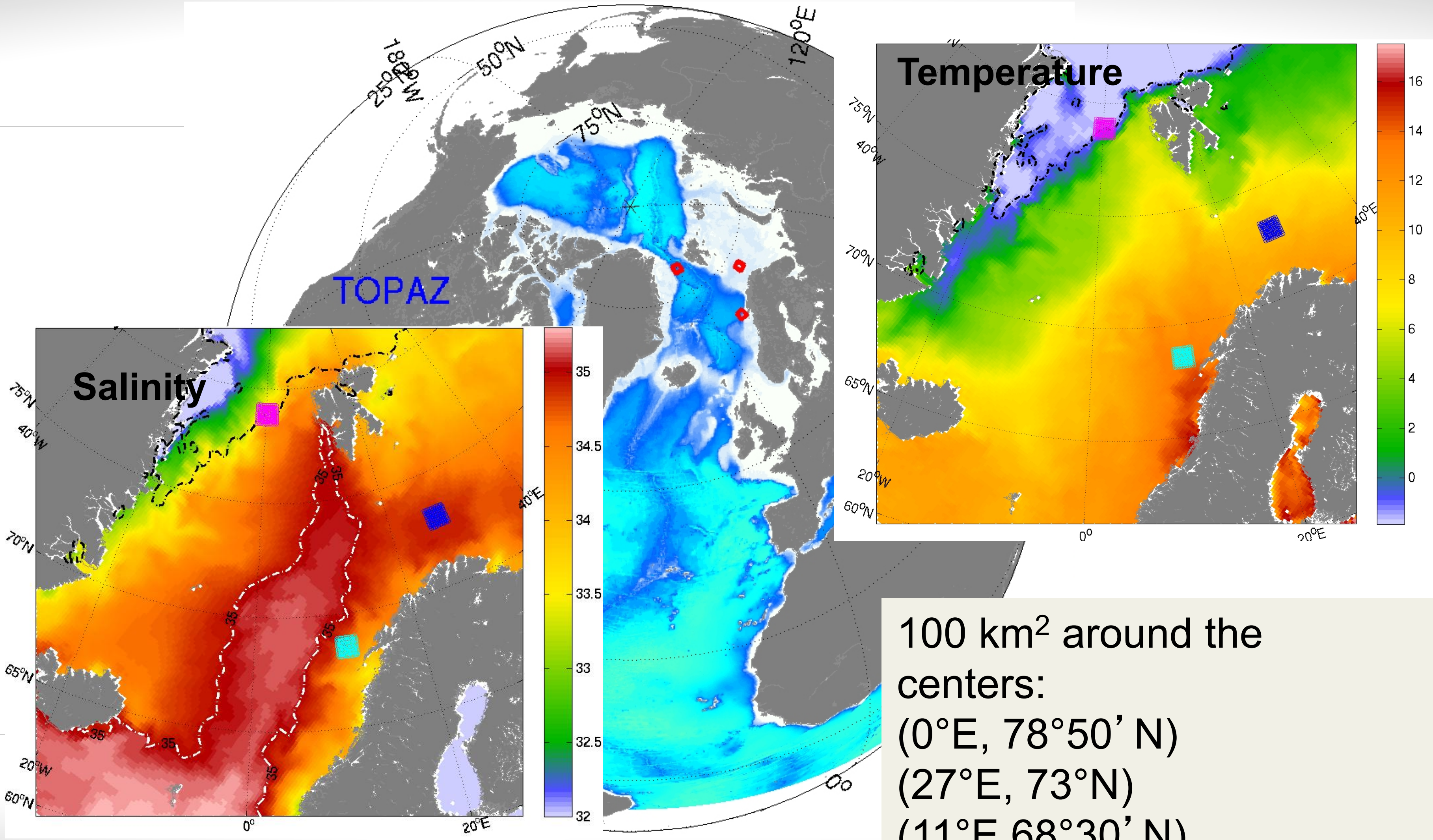


Example of ensemble

Same ensemble
Different variable



TOPAZ domain and the locations of the sampling profiles



100 km^2 around the centers:
(0°E, 78°50' N)
(27°E, 73°N)
(11°E,68°30' N)

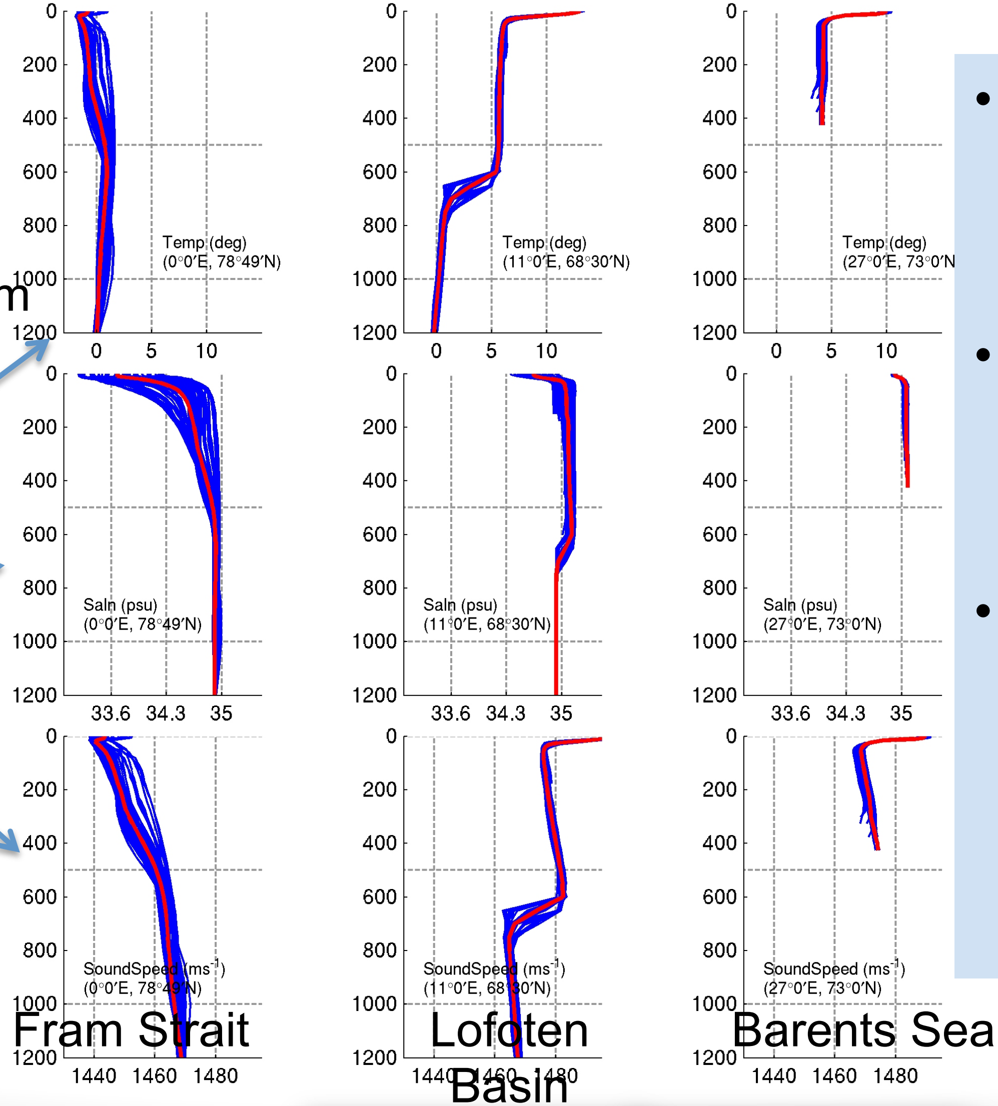
Spatial variability 100 km box

Member #1
in a 100 km x100 km Box

Temperature

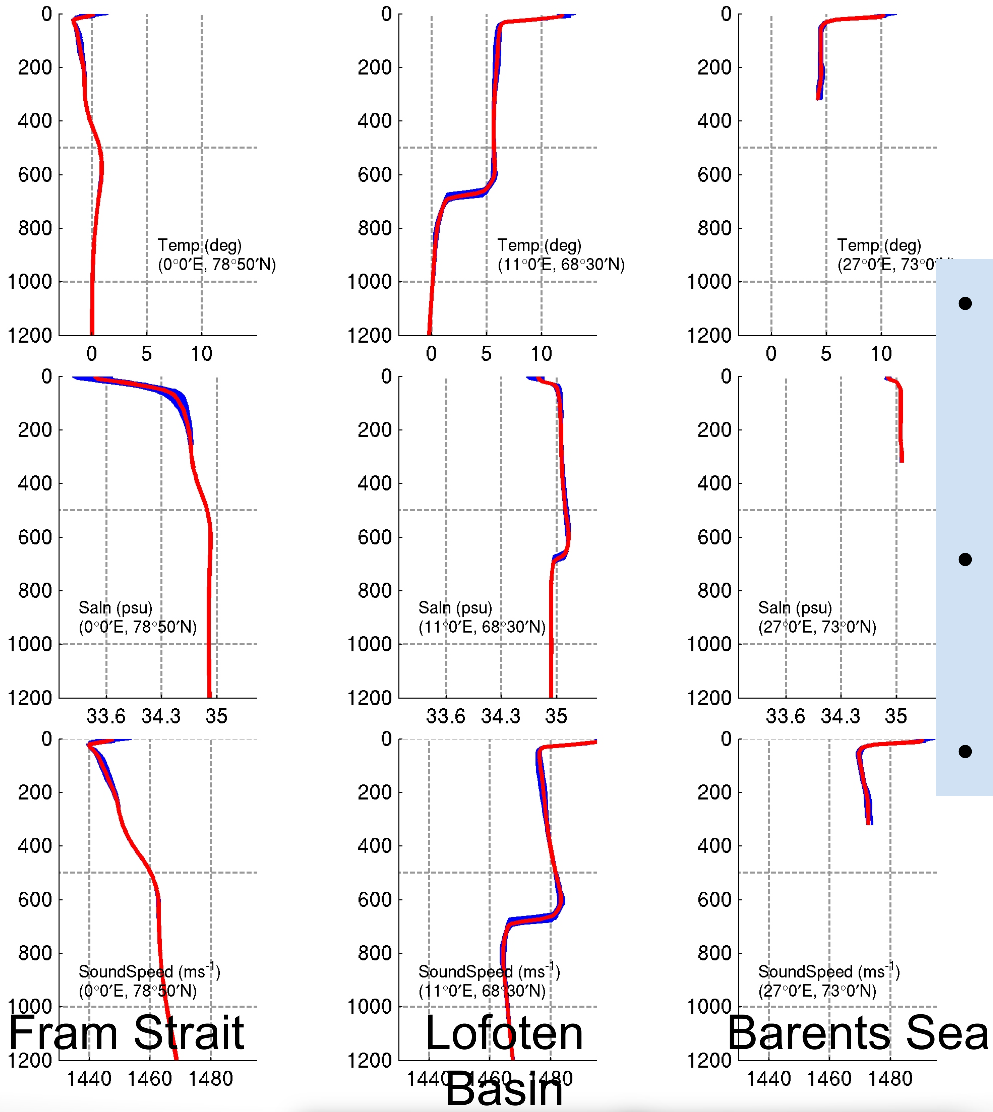
Salinity

Sound speed



- 100 profiles member #1 – from each location
- Red is the average over all the #1 mem. profiles
- The profile ensemble limited by the local square region (100 km) on 5-July-2013

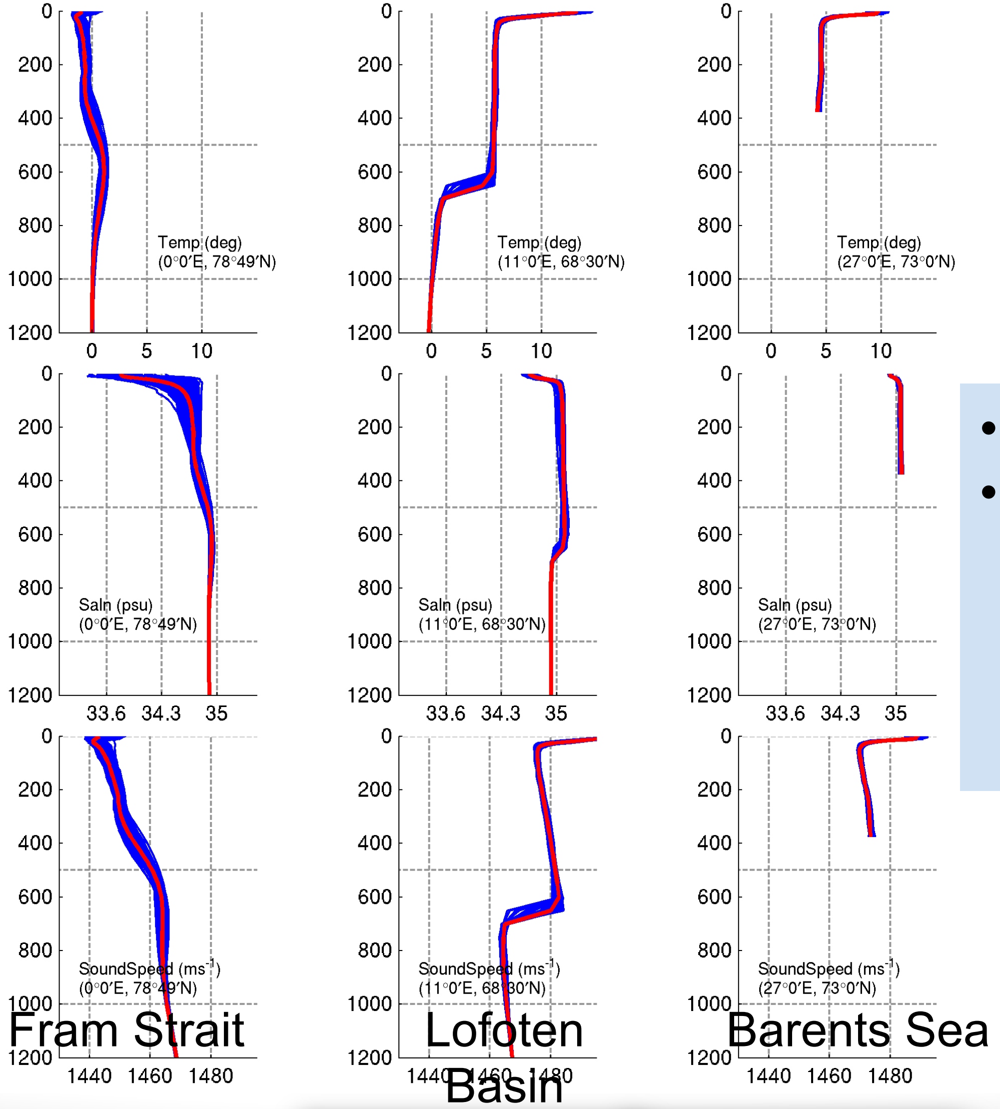
Temporal variability (20 days)



- Member #1 is integrated forward in time (hourly output).
- 480 profiles in same location over 20 days
- Time: July 2013

Ensemble uncertainties

Same time,
Same location,
All members



- 100 members
- The model ensemble used by the TOPAZ Reanalysis on 5-July-2013

Ensemble DA methods

- Ensemble update

$$\psi^a_n = \psi^f_n + K_n\,(d_n - H\psi^f_n)$$

- Factorize by ψ^f_n (Evensen 2003)

$$\psi'^a_n = \psi'^f_n \,.\, T$$

T: Transform matrix (size 100 x 100)

- Advantages:
  – Solution lies within the ensemble subspace
  – Linear balances conserved
- Drawbacks:
  – Solution lies within the ensemble subspace
  – Non-linear balances "linearized" around ensemble mean

<u>EnKF Kalman gain:</u>

$$K_n = \psi_n{}^f \psi'^f_n{}^T H^T \,.$$

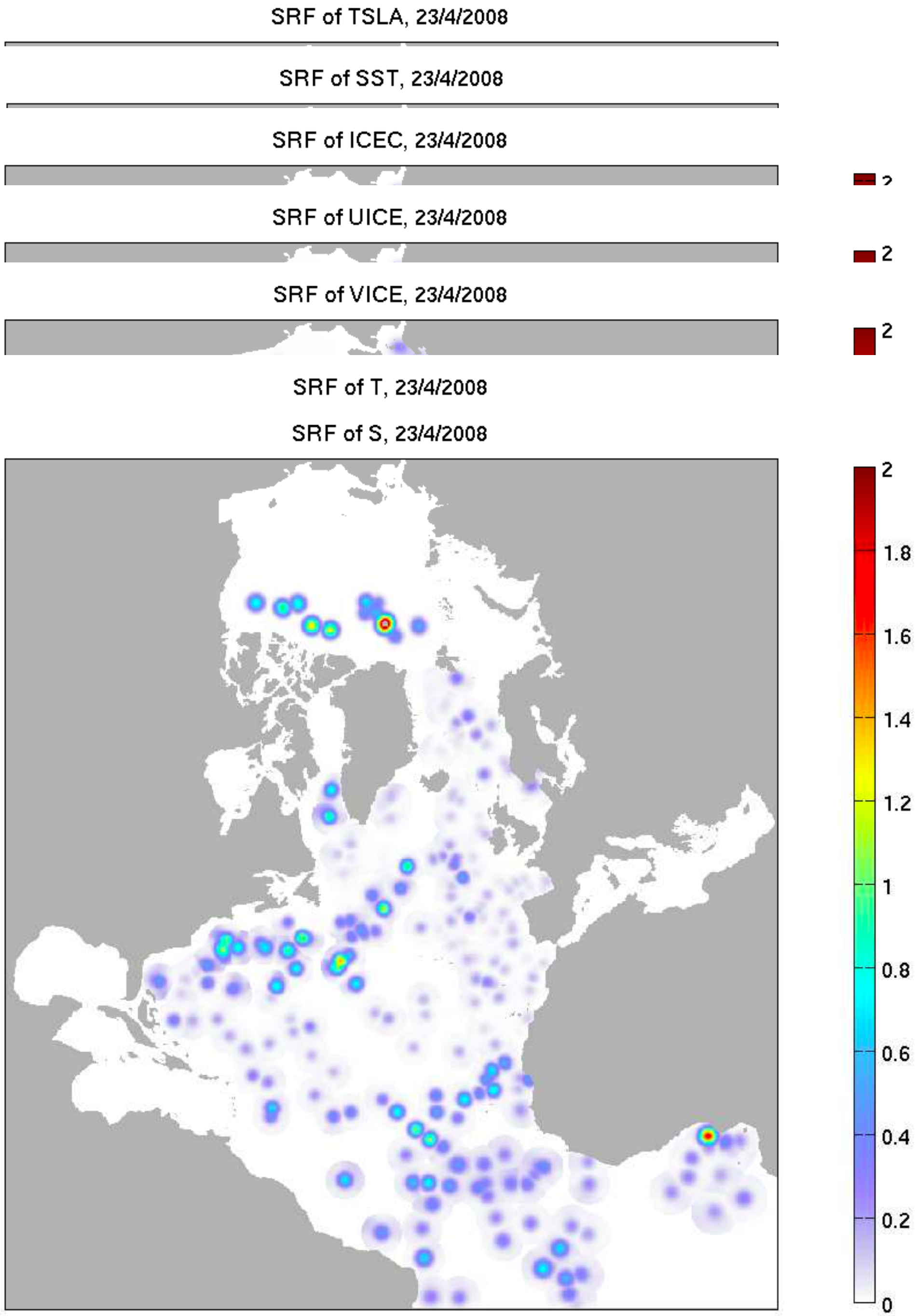
$$(H\,\psi'^f_n \psi'^f_n{}^T H^T + R)^{-1}$$

Assimilation

- DEnKF, asynchronous
  - 100 members
  - Local analysis (~90 km radius)
  - Ensemble inflation by 1% (mult.)
    - Bad idea in non-observed areas …
- Observations (400.000):
  - Sea Level Anomalies (CLS)
  - SST (NOAA, then UK Met)
  - Sea Ice Concentr. (OSI-SAF)
  - Sea ice drift (CERSAT)
  - T/S profiles (Coriolis, IPY)

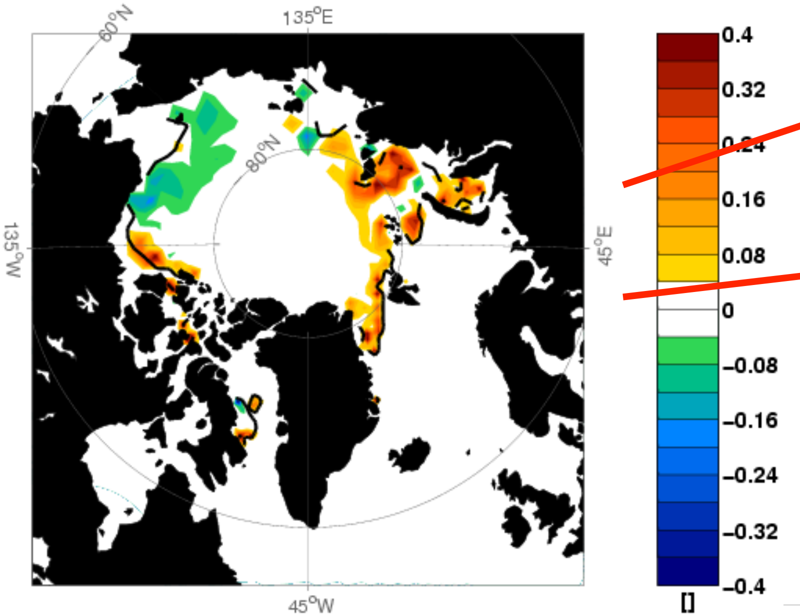
SRF: local spread reduction factor

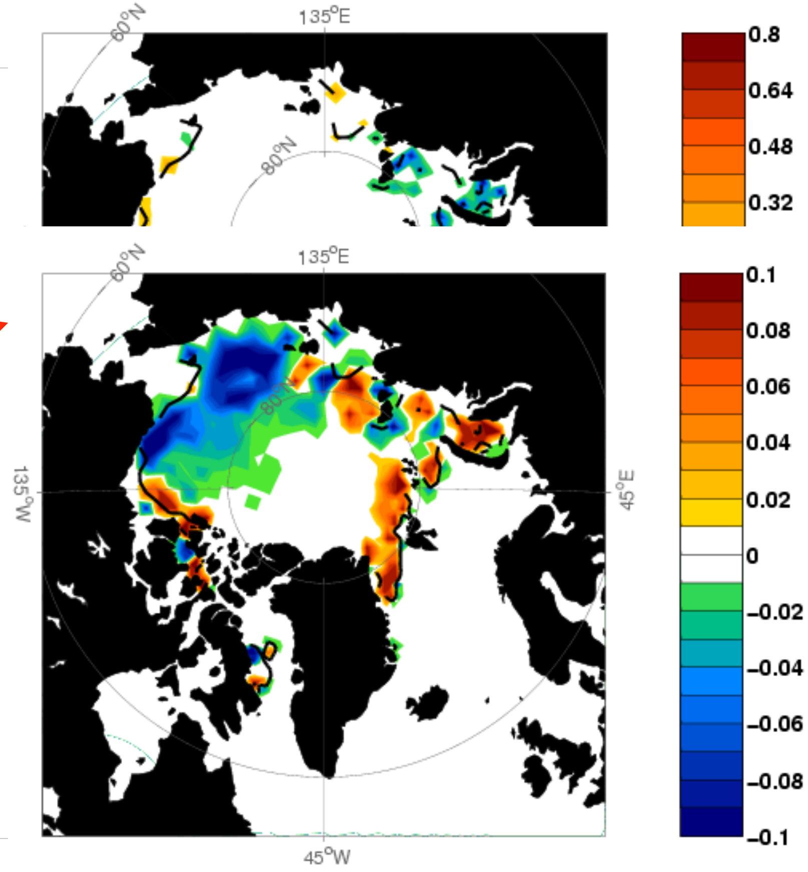
$$\mathrm{SRF} = \sqrt{\frac{\mathrm{tr}(\mathbf{H}\mathbf{P}^f\mathbf{H}^\mathrm{T}\mathbf{R}^{-1})}{\mathrm{tr}(\mathbf{H}\mathbf{P}^a\mathbf{H}^\mathrm{T}\mathbf{R}^{-1})}} - 1$$



Ice concentration multivariate update
summer

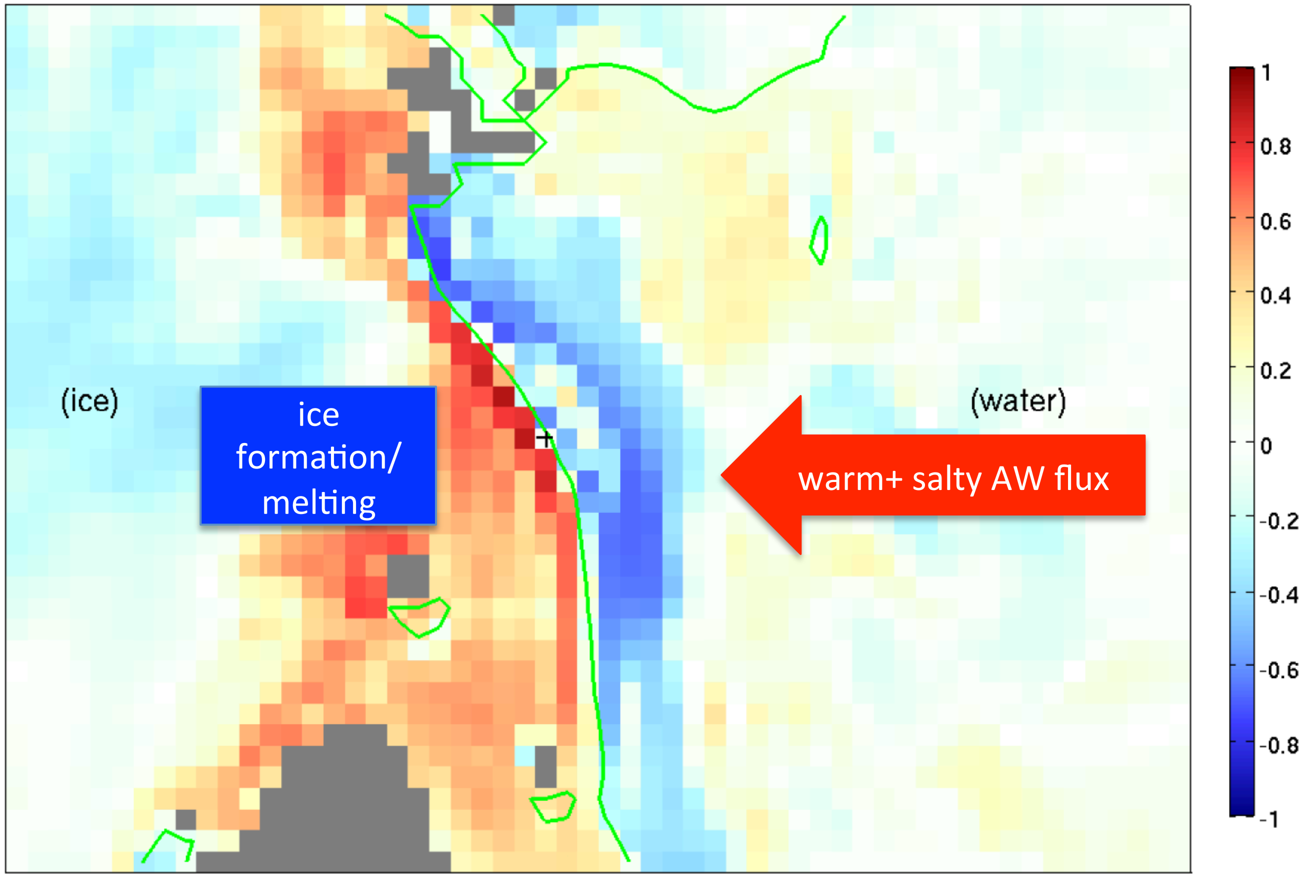
[K.A. Lisæter et al. *2003]*





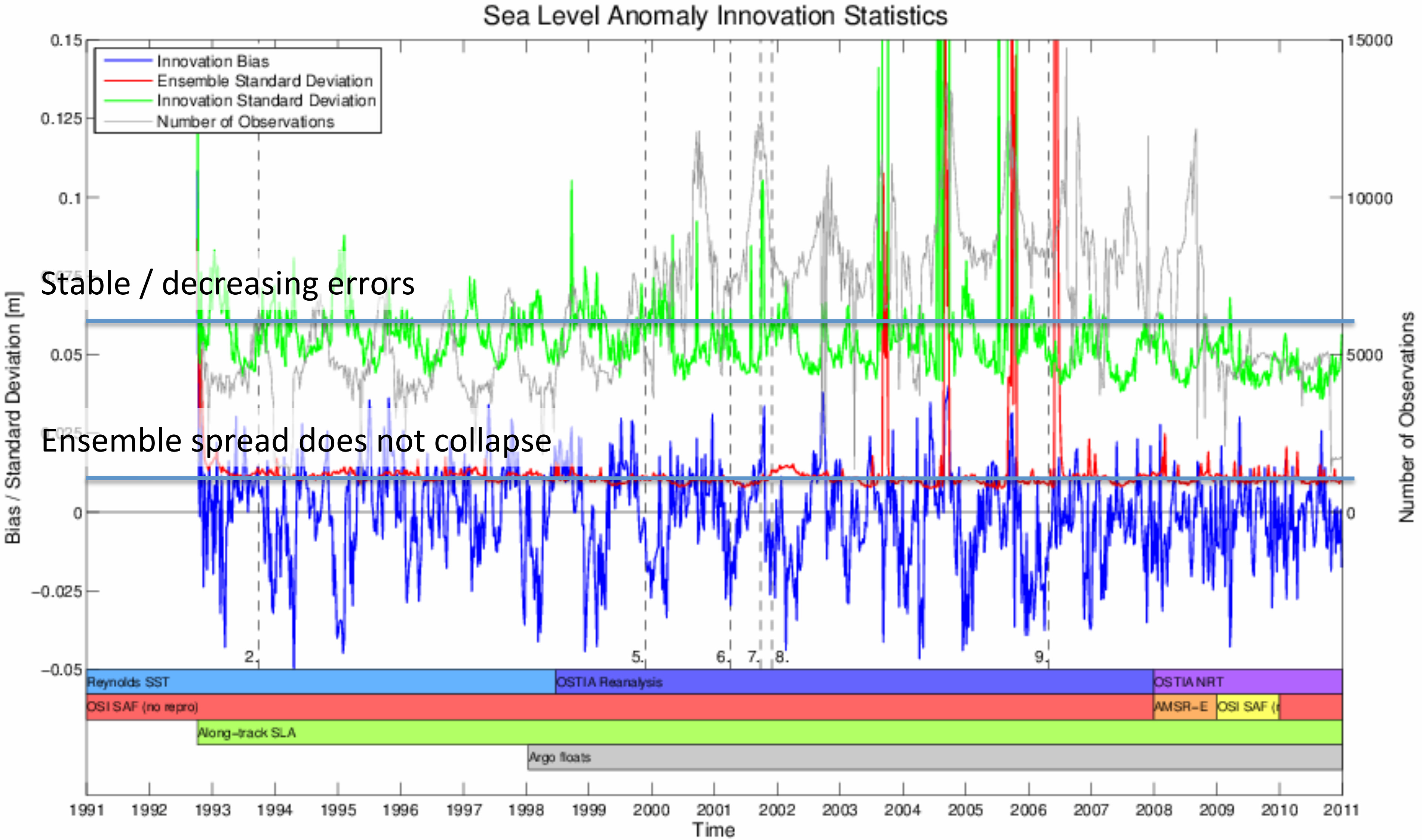
Impact on salinity

Why dynamic Data Assimilation in the Arctic?
Example of ice-salinity correlations in the Barents Sea

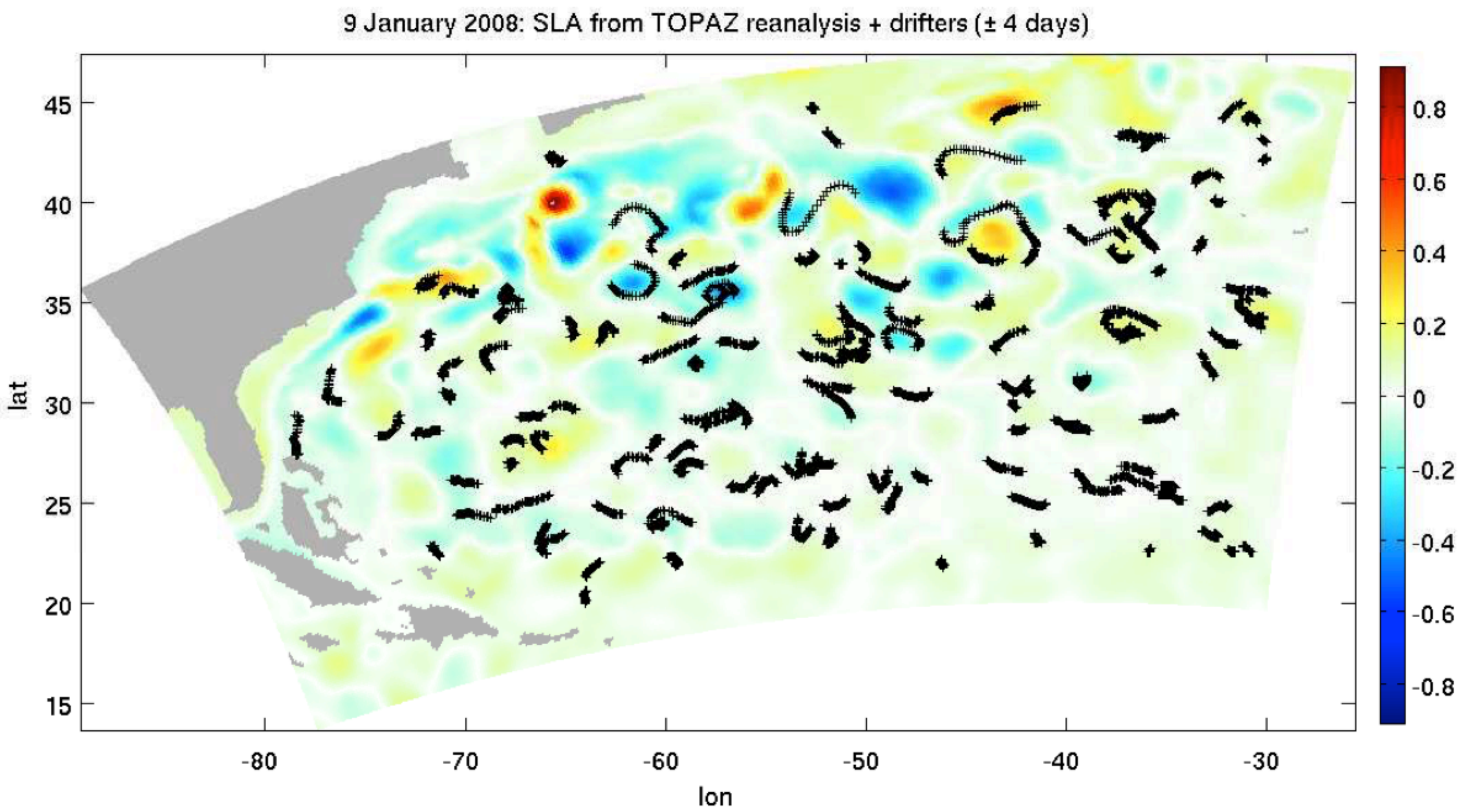


Sakov et al., the TOPAZ4 system, OS 2012
Also see *Lisæter et al.* Oc. Dyn. 2003

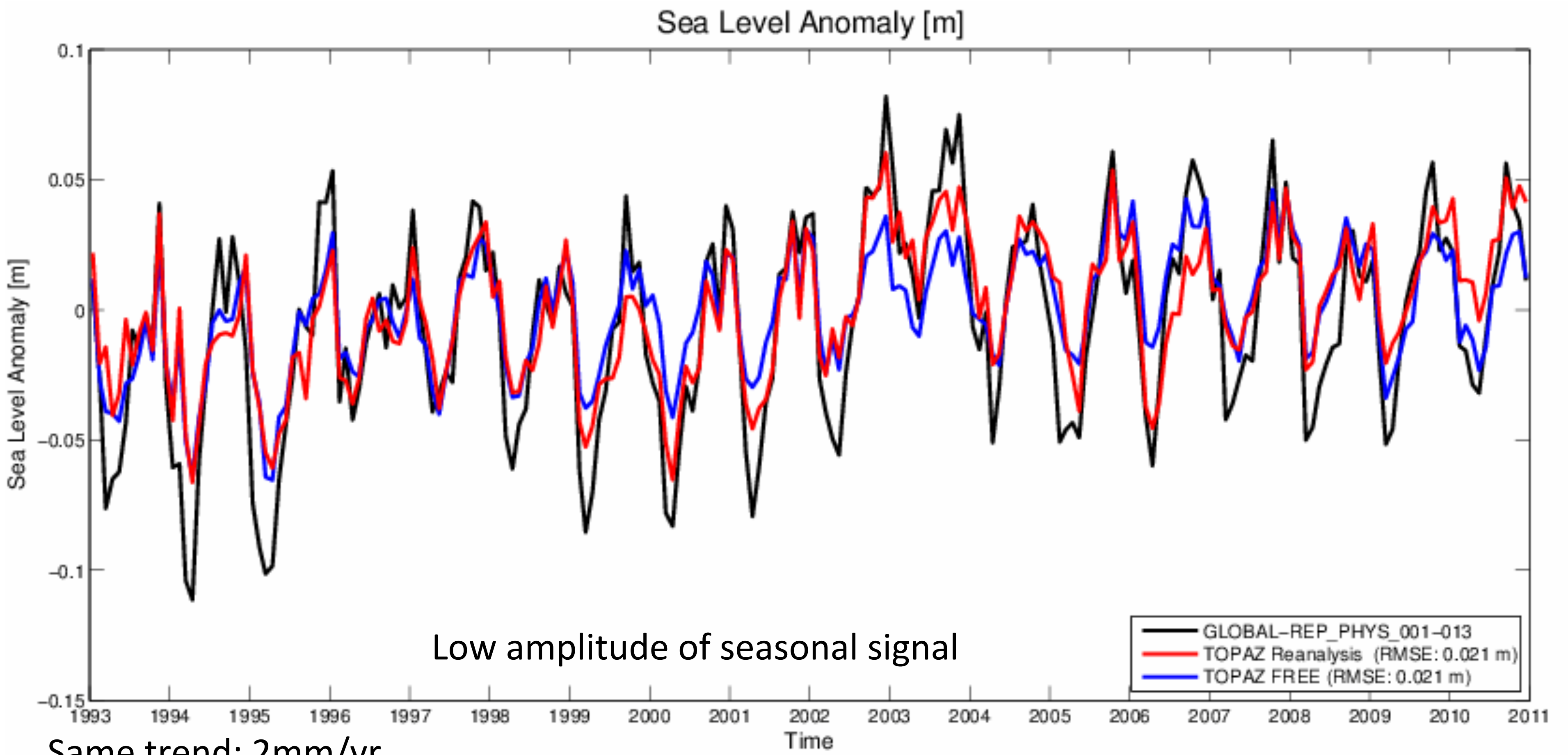
Data assimilation statistics SLA



Independent data: surface drifters



Arctic-wide sea level change

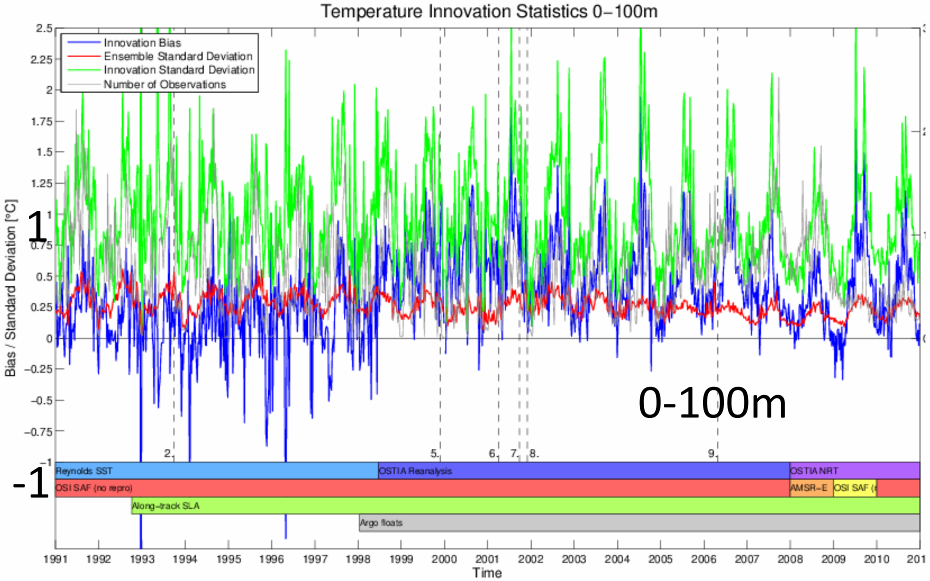


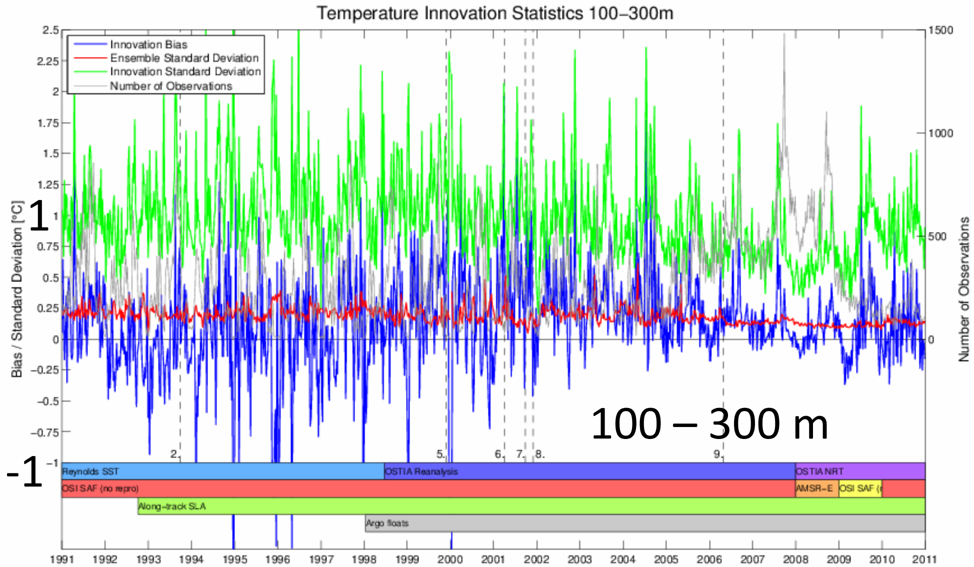
Same trend: 2mm/yr

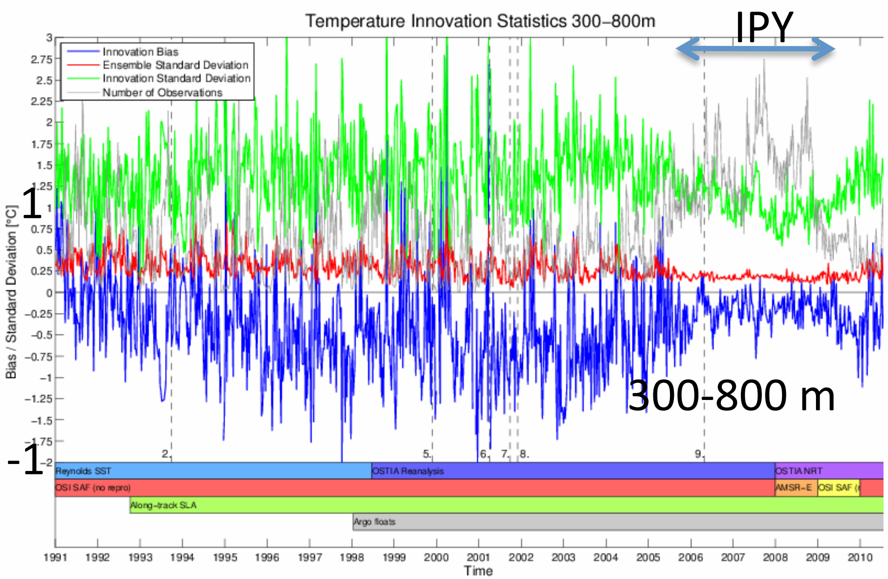
Same performance wrt tide gauges

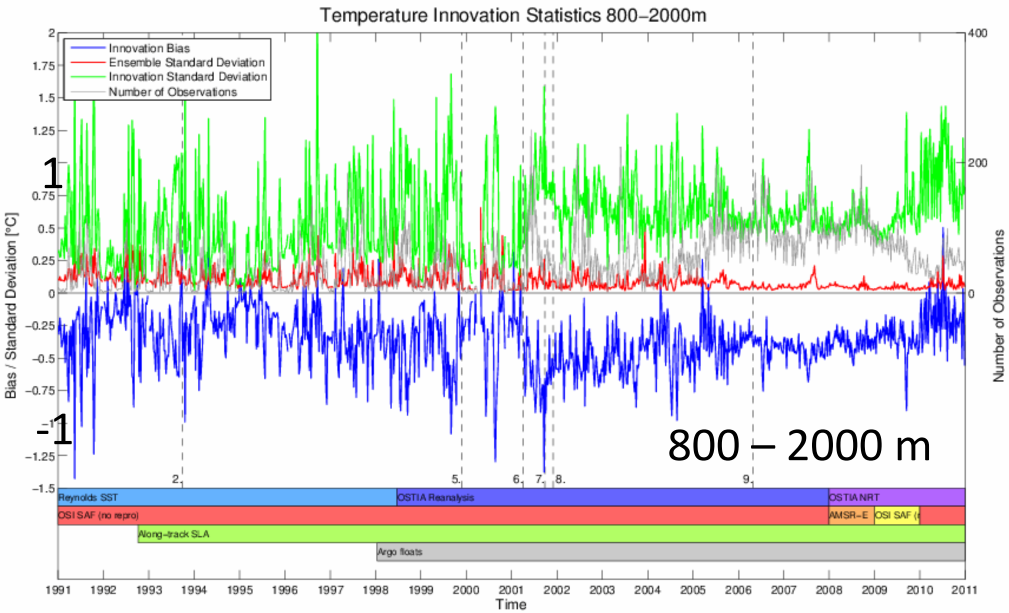
No improvements, no degradation

Insitu TEM statistics

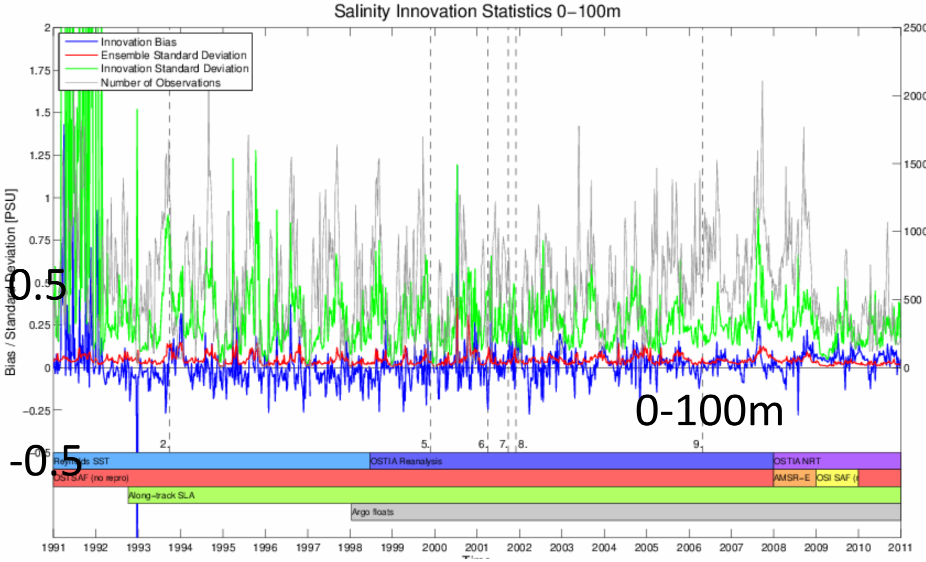


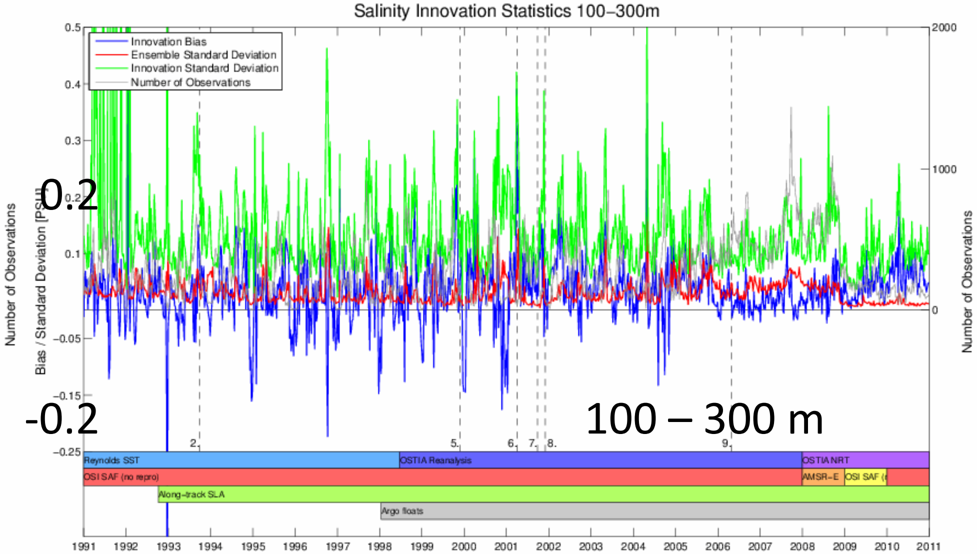


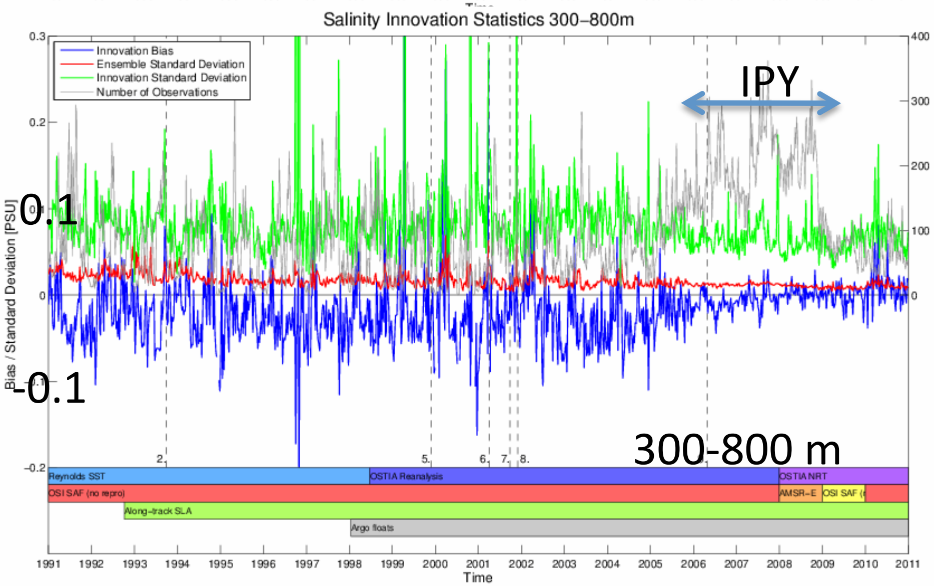


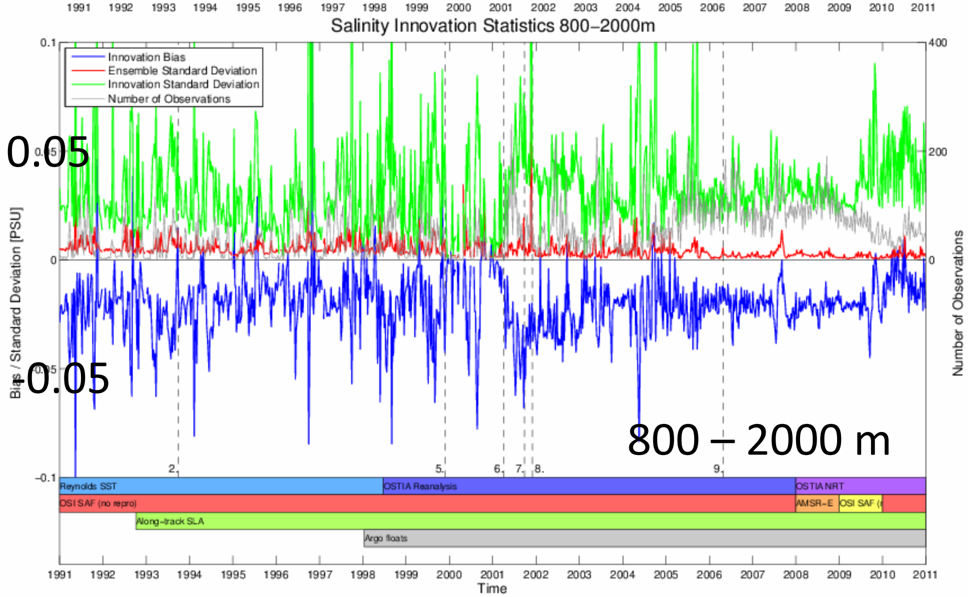


Insitu SAL statistics

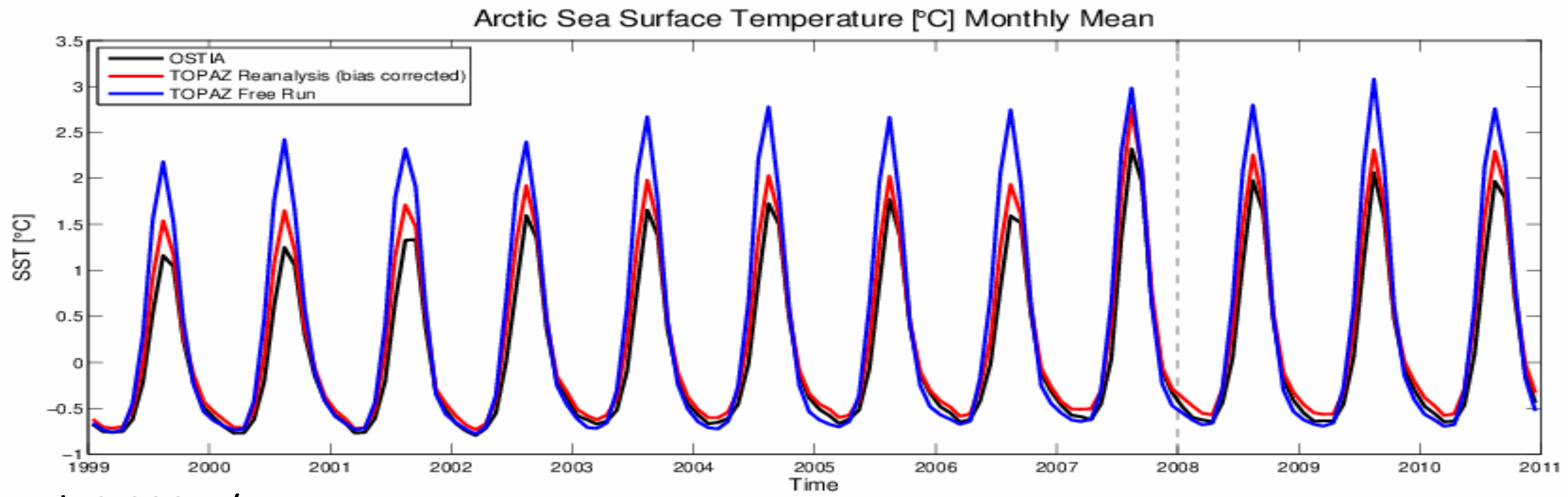






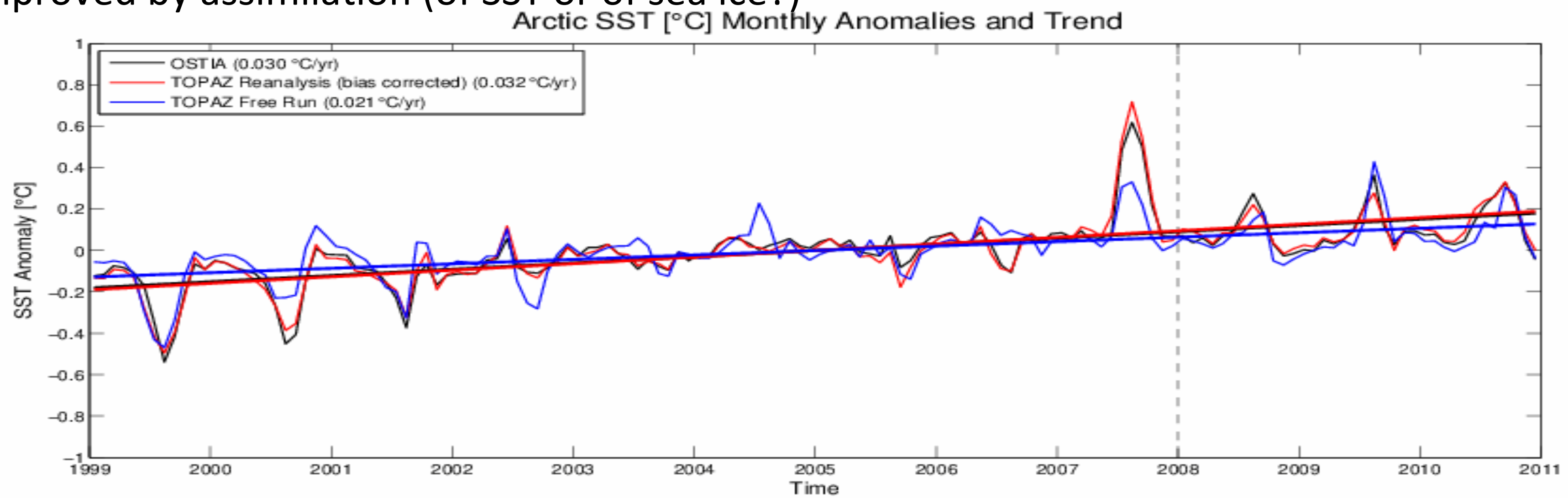


Arctic SST trend

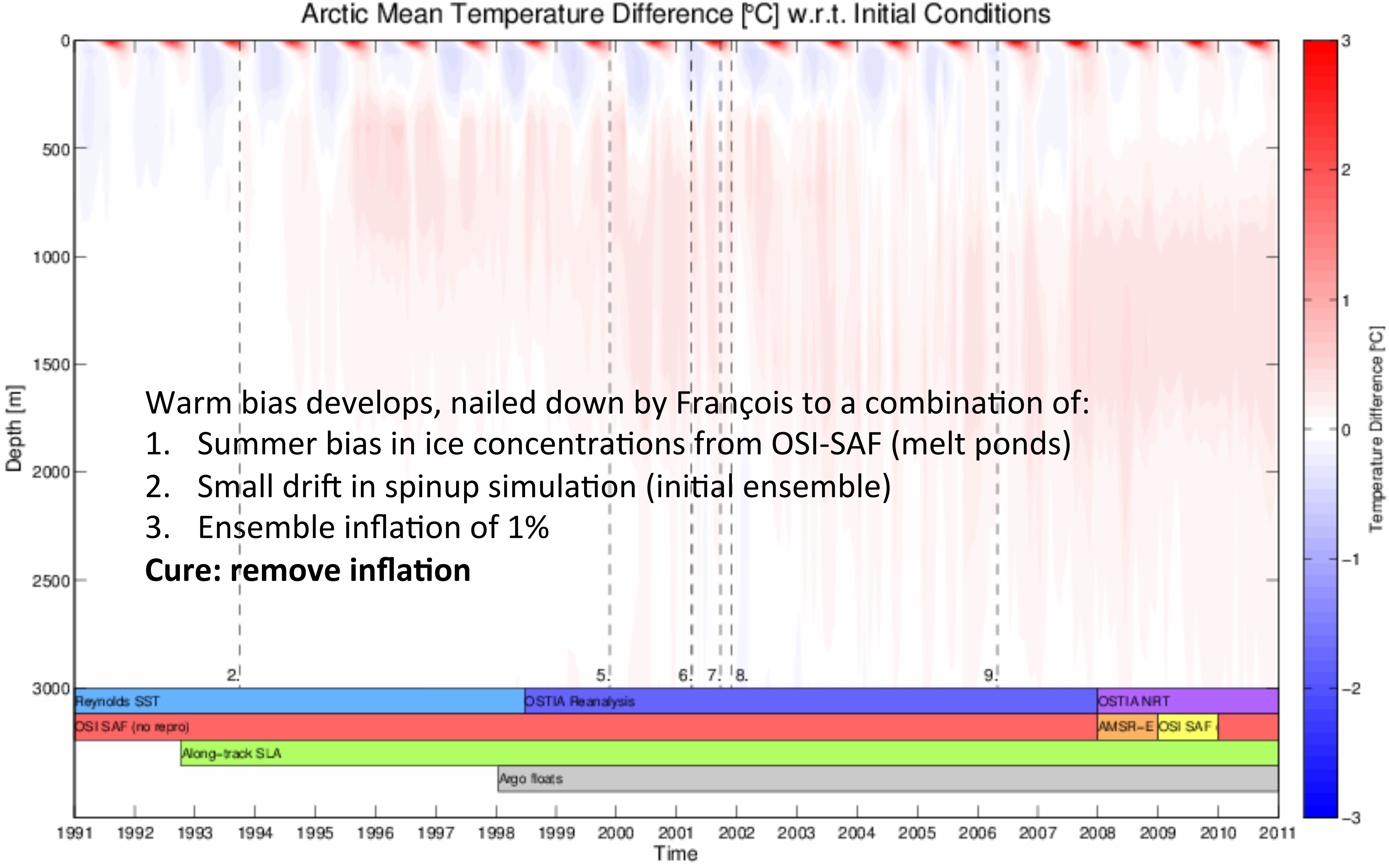


Trend: 0.032 K/yr

Improved by assimilation (of SST or of sea ice?)



Evolution of Tem at depths

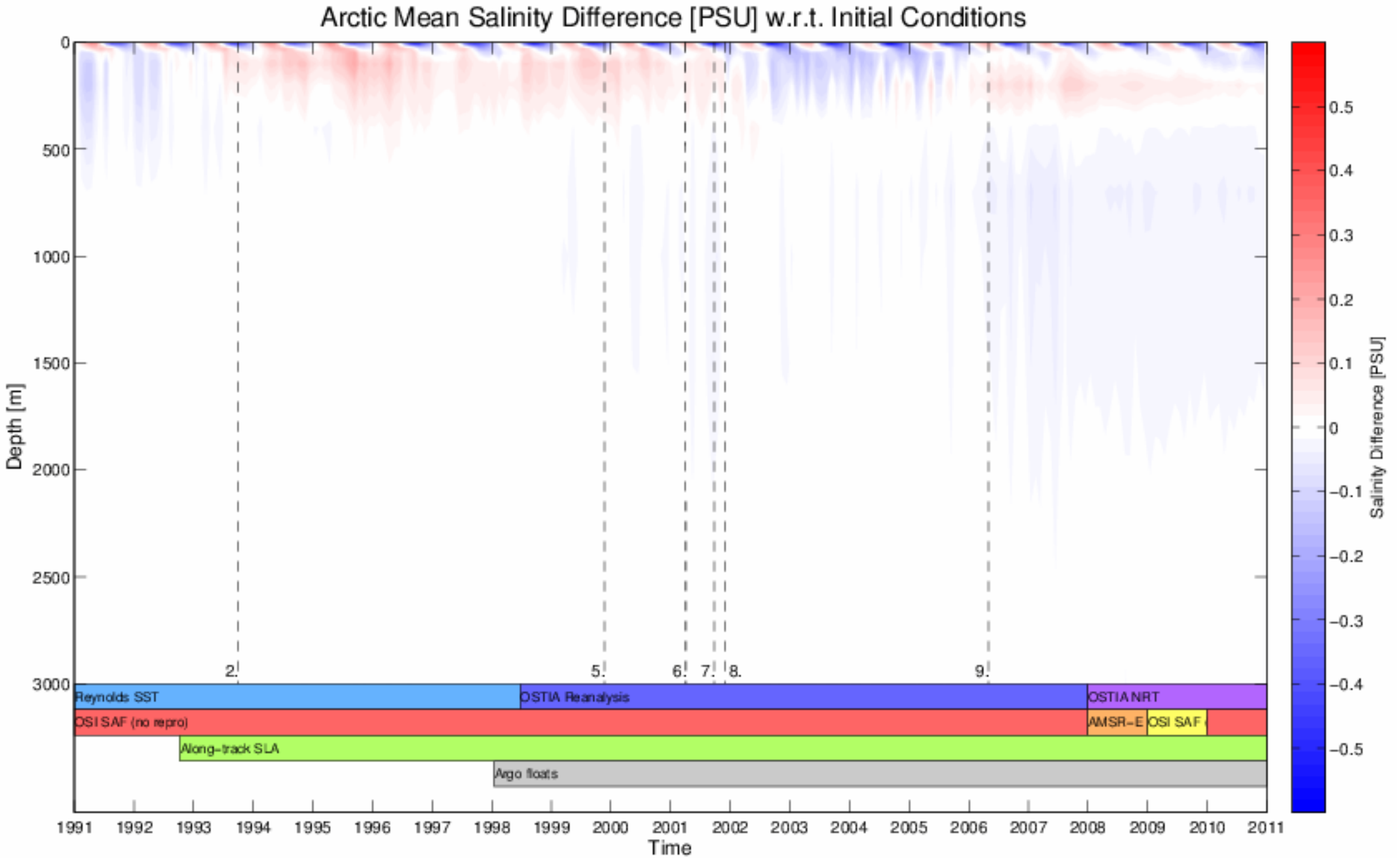


Warm bias develops, nailed down by François to a combination of:

1. Summer bias in ice concentrations from OSI-SAF (melt ponds)
2. Small drift in spinup simulation (initial ensemble)
3. Ensemble inflation of 1%

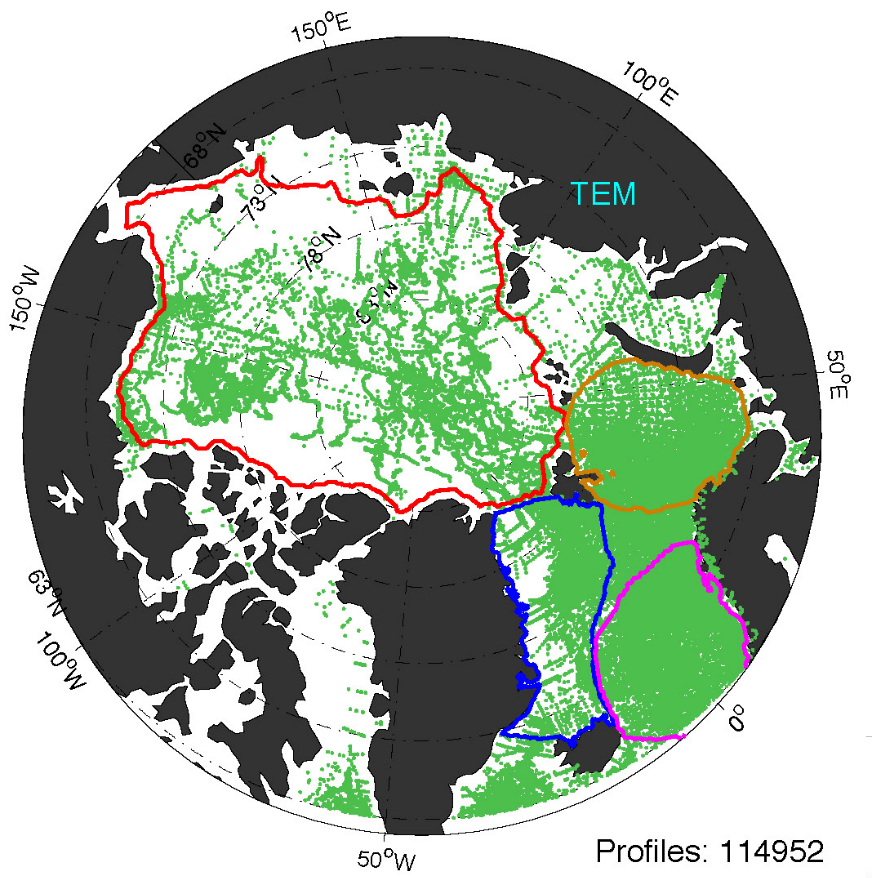
Cure: remove inflation

Evolution of Sal at depths

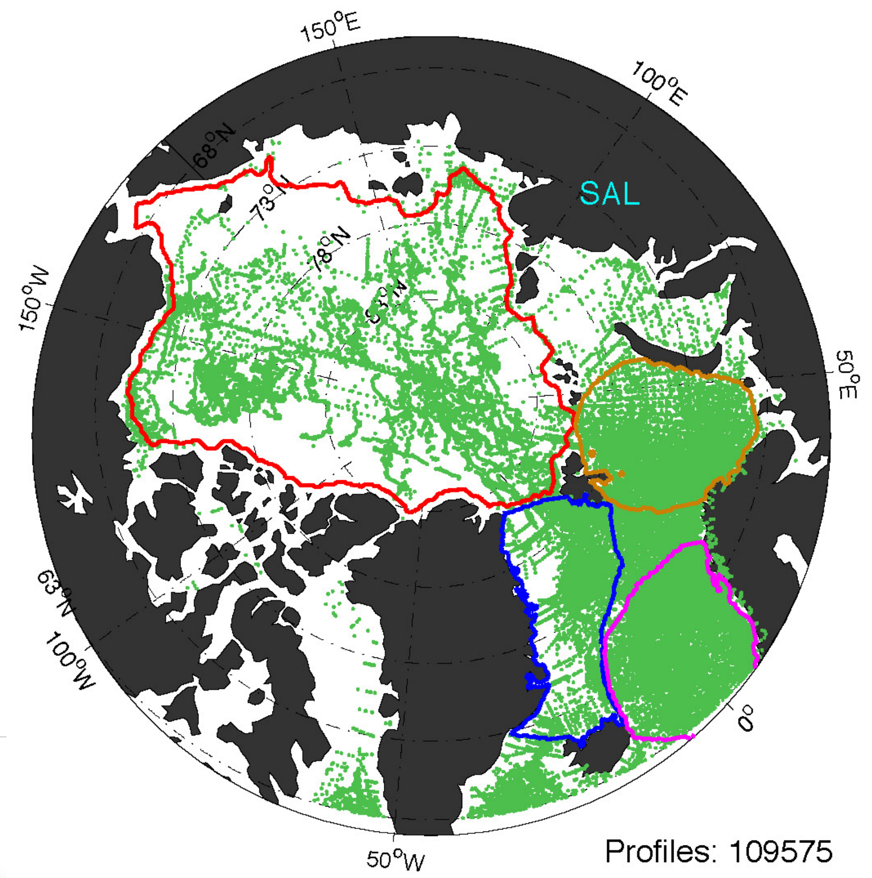


Assimilated profiles

Temperature



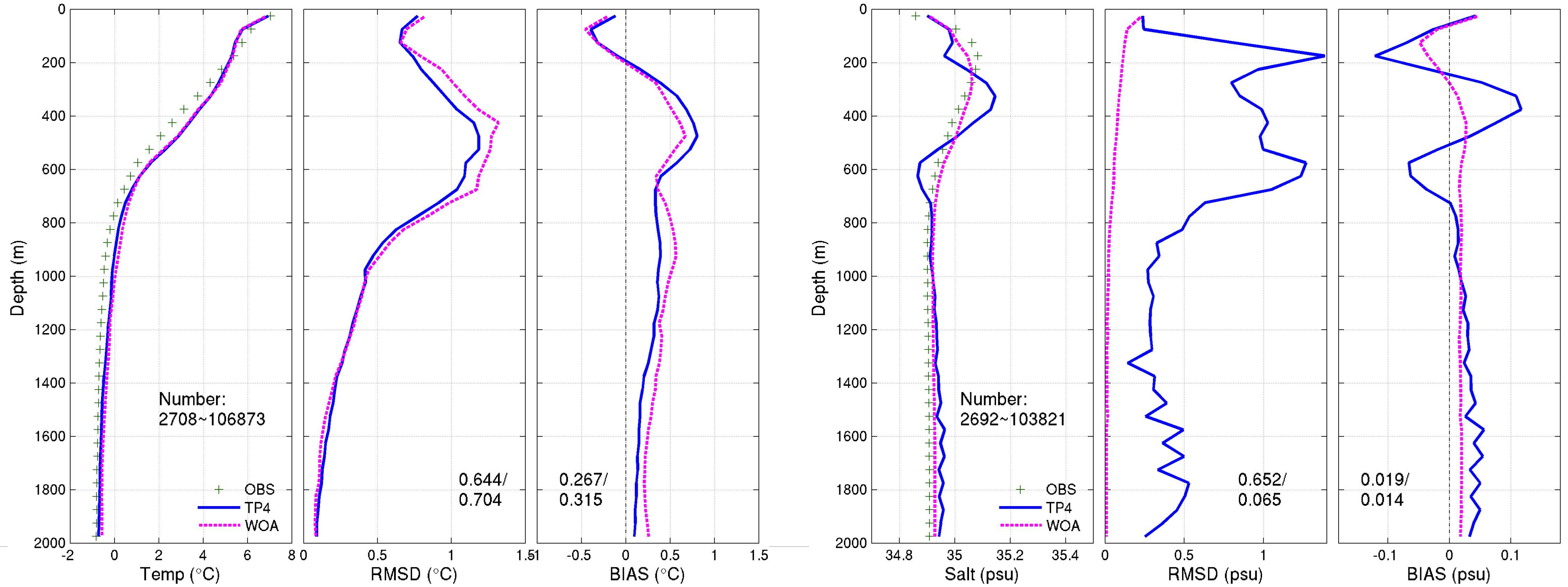
Salinity



Profiles in Norwegian Sea

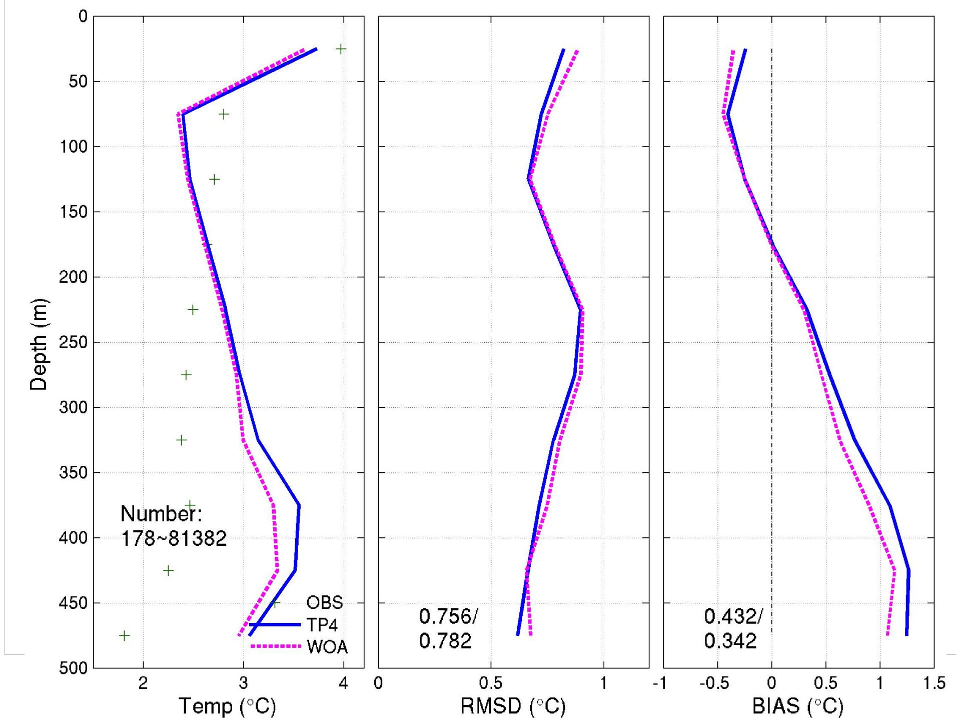
Temperature

Salinity

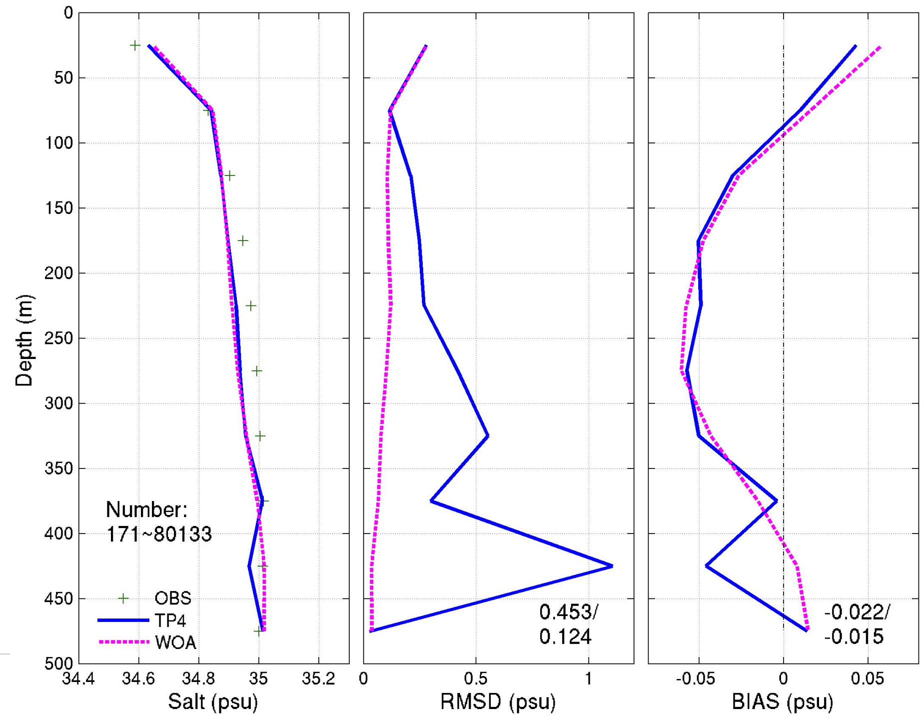


Profiles in Barents Sea

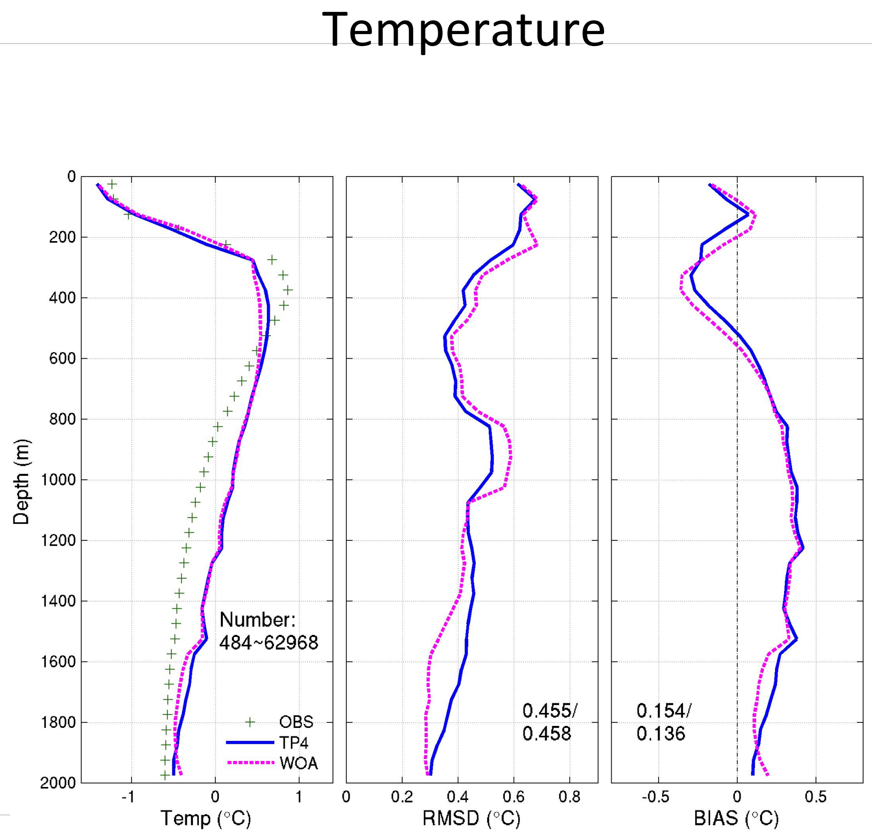
Temperature

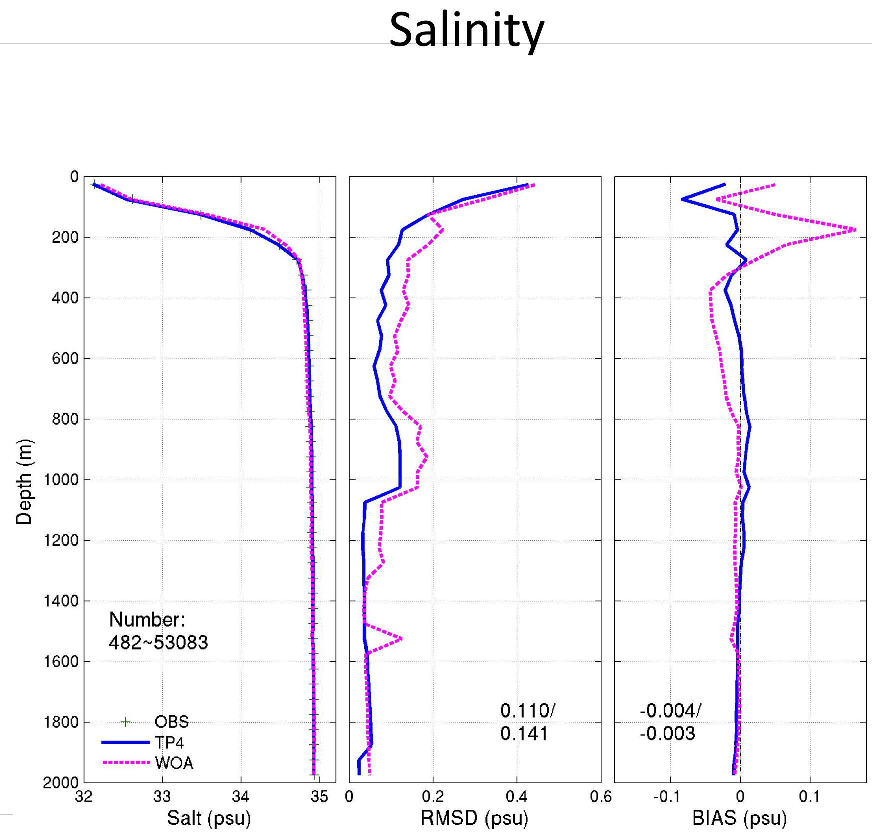


Salinity



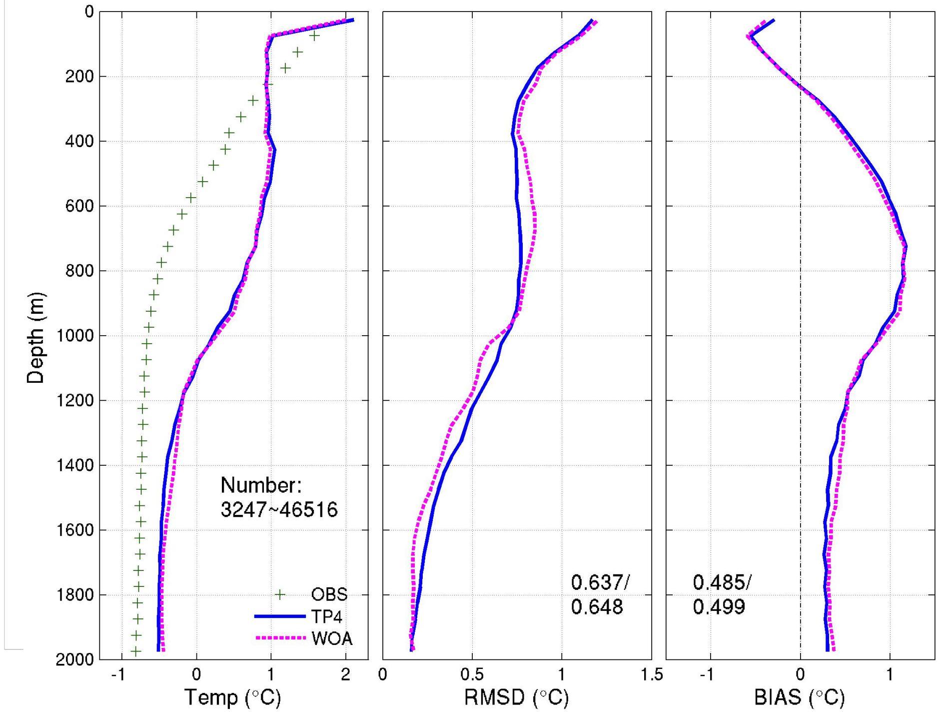
Profiles in Central Arctic



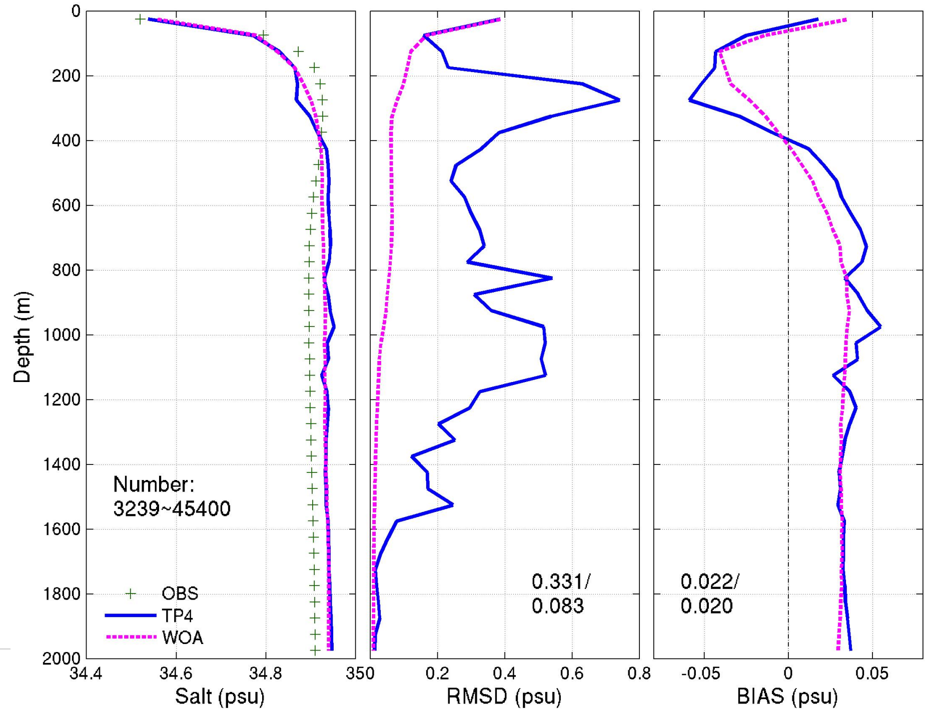


Profiles in Greenland Sea

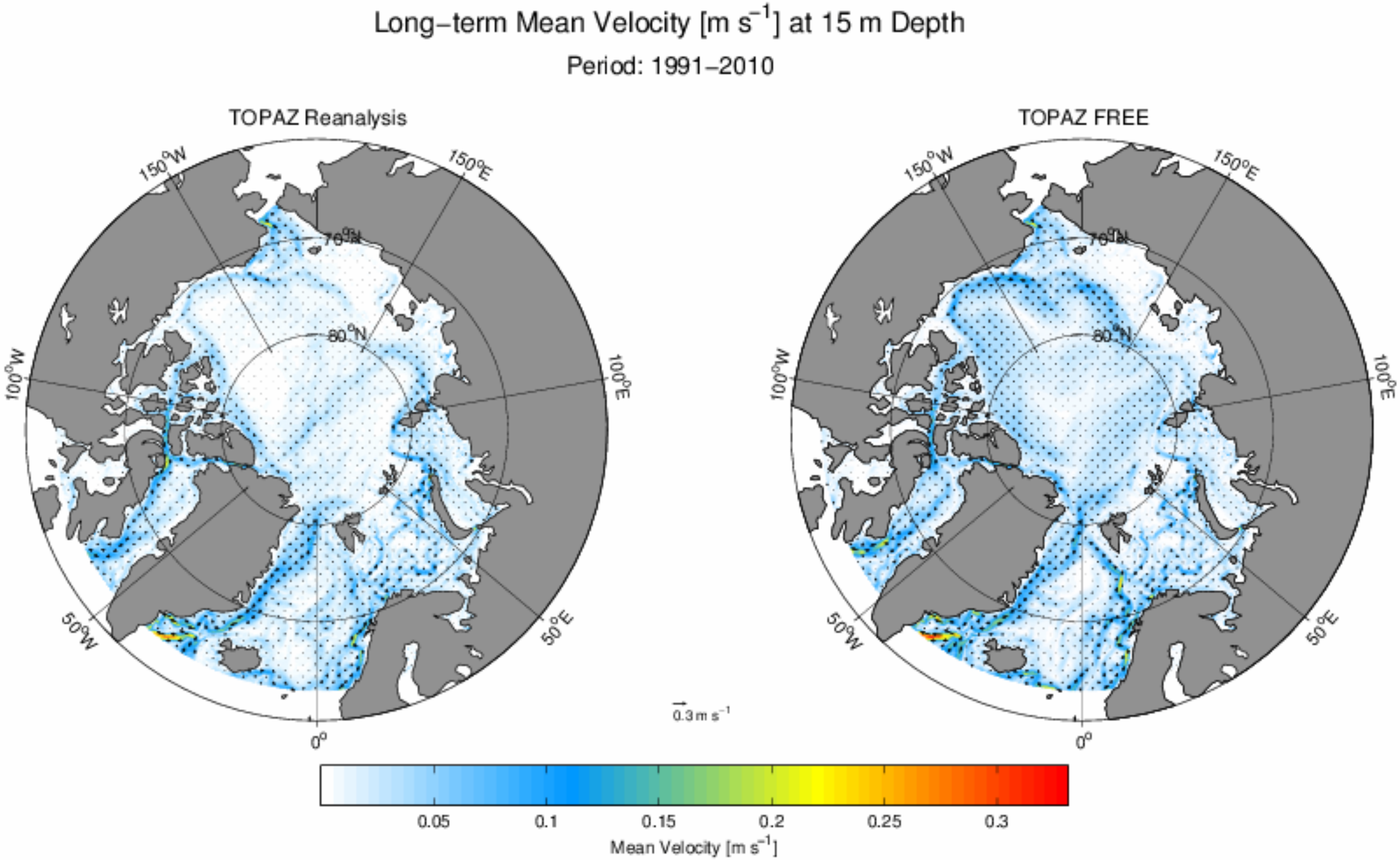
Temperature



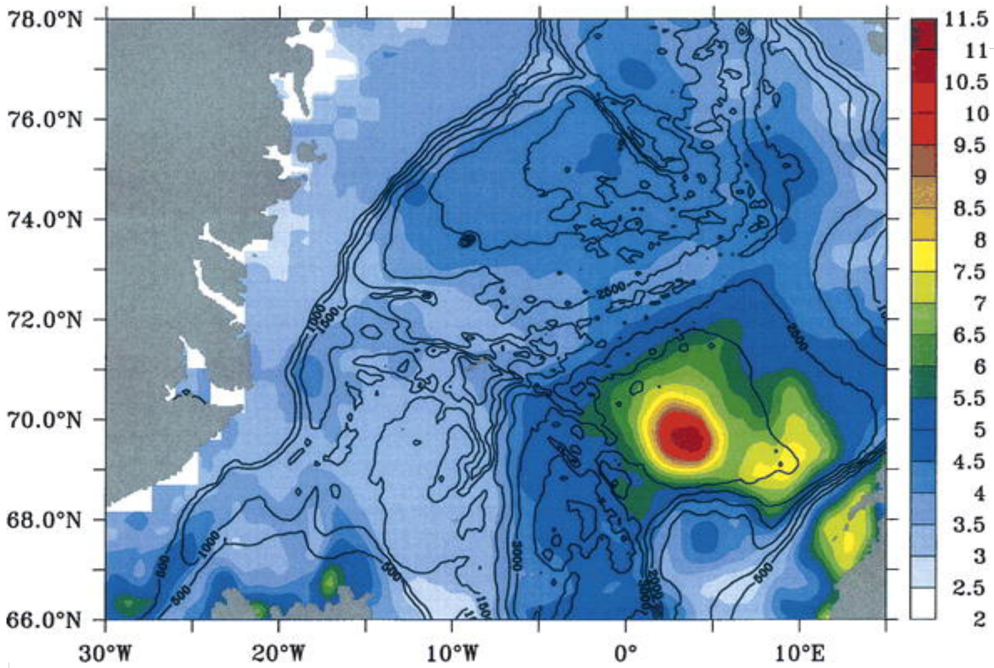
Salinity



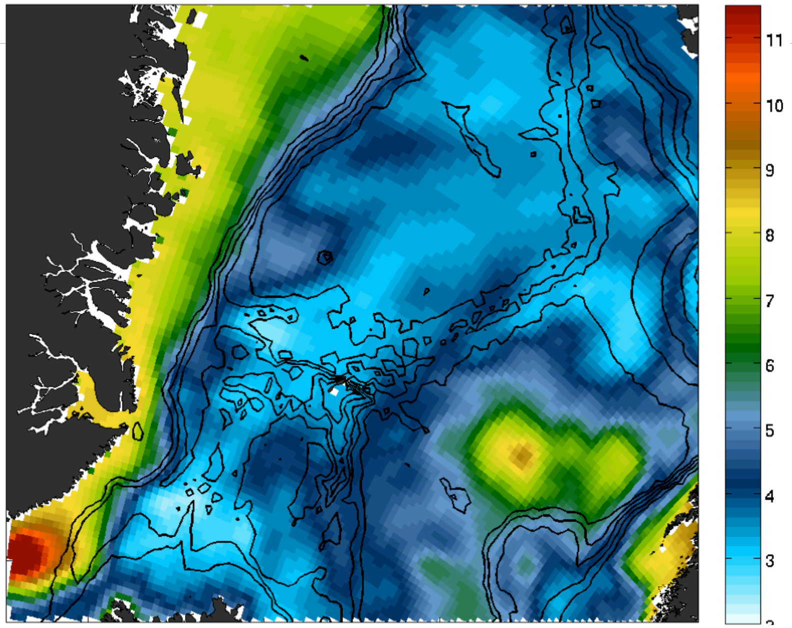
Current velocities near surface



Variability of sea surface heights

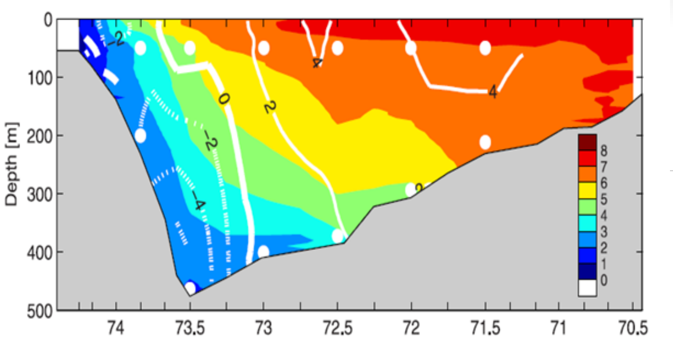


Computed from altimetry data(2003-2008)
Köhl, JPO 2007.

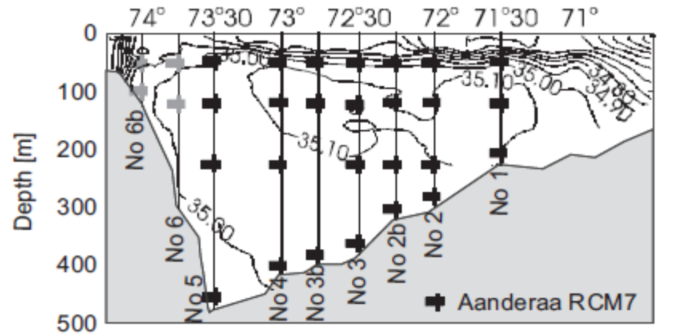


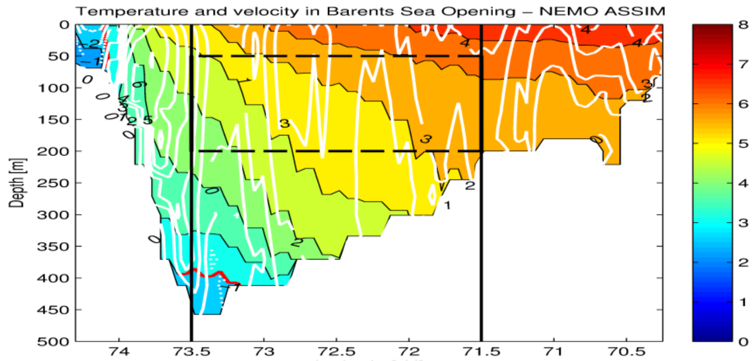
Model std of SSH in 2003-2008

Barents Sea Opening



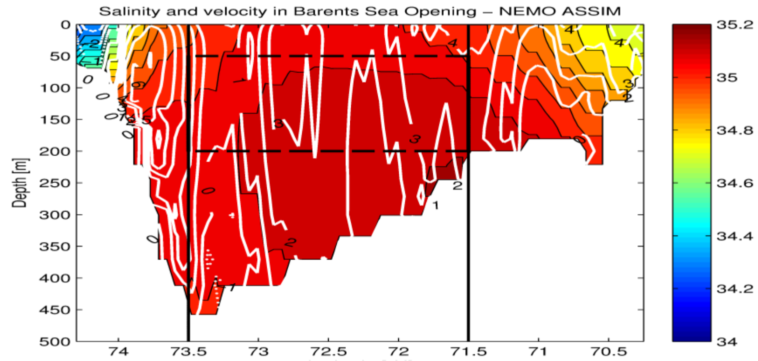
Obs

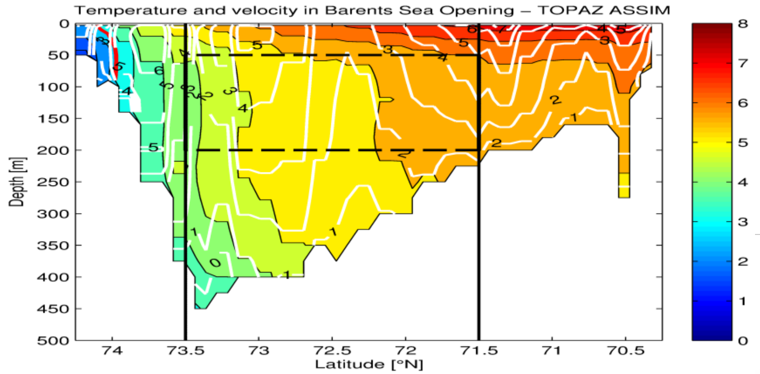




NEMO assim

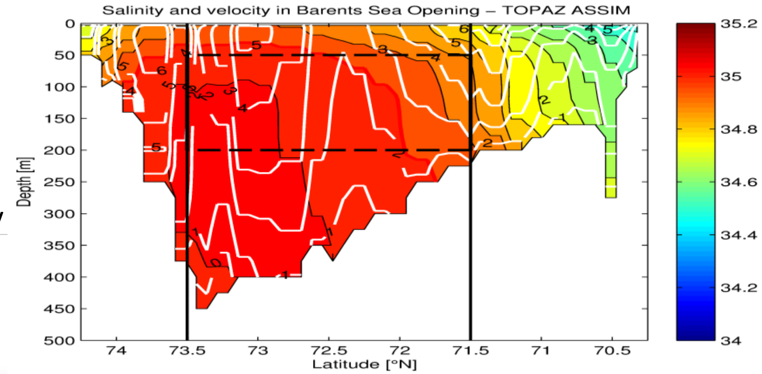
Too weak currents? Well-defined sub-surface AW salinity core, but too saline?



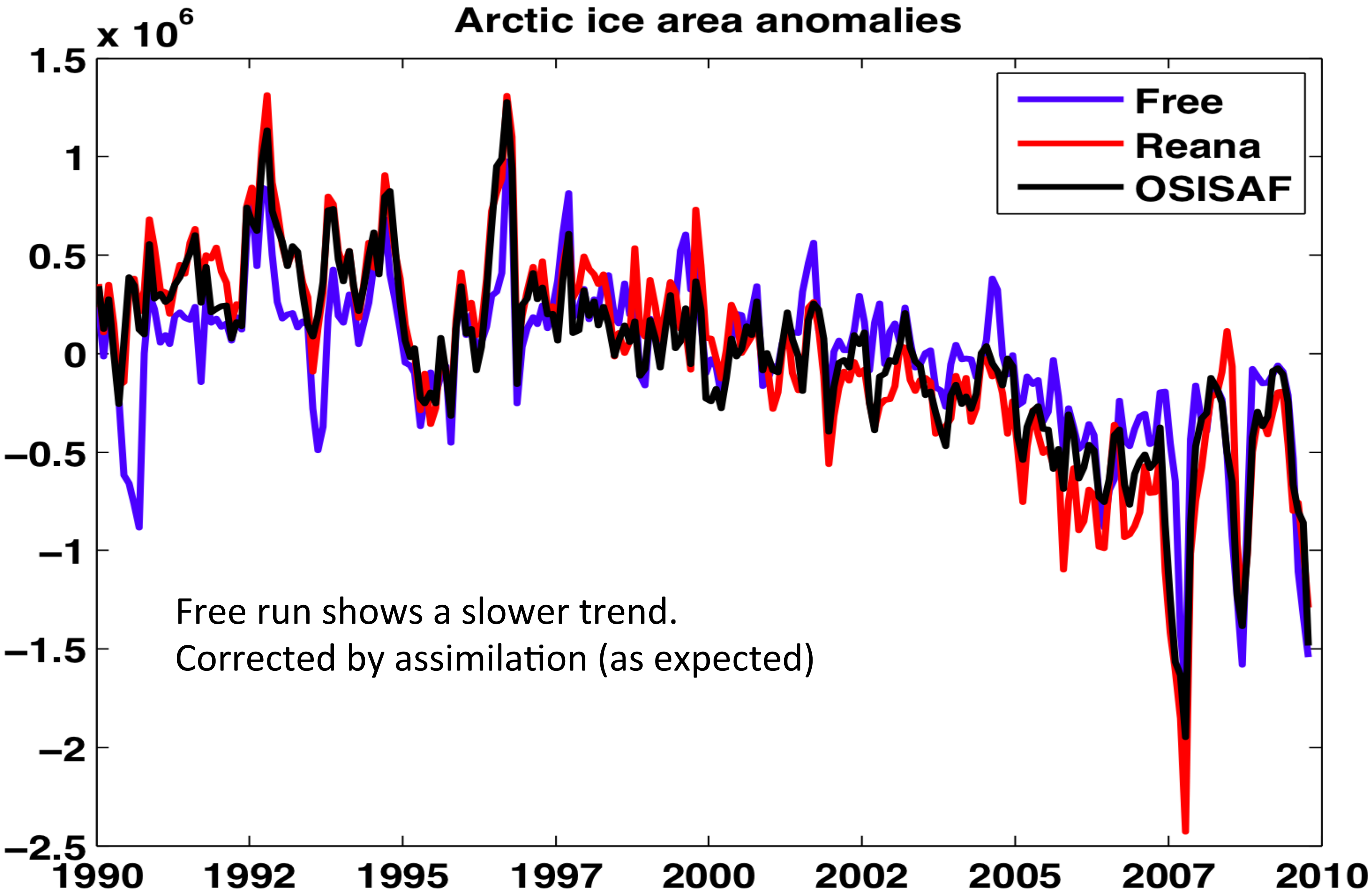


TOPAZ assim

Realistic currents with two well-defined cores, but slightly shifted south? Salinity max too far north?

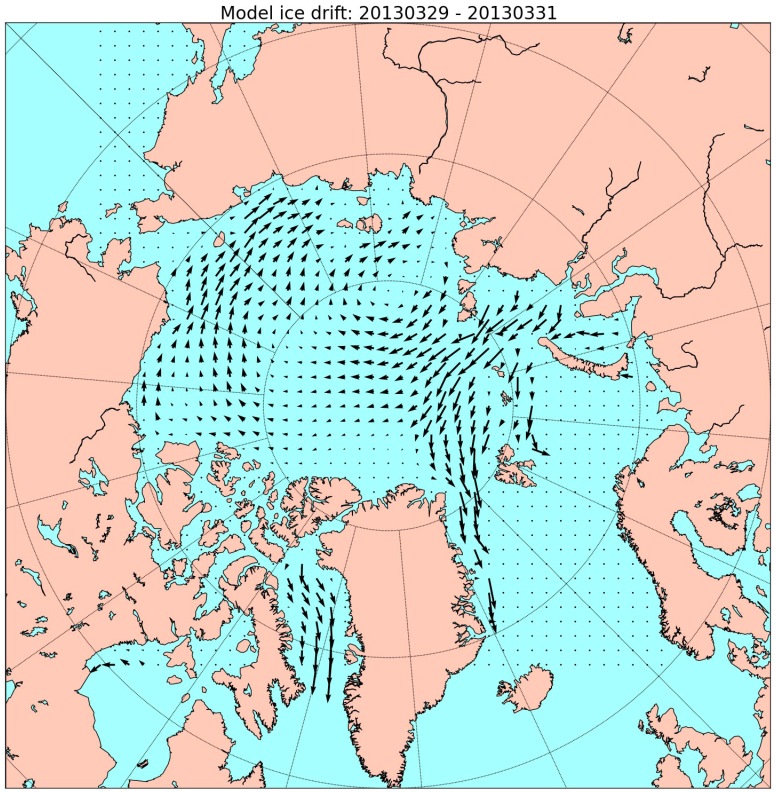


Icea area anomalies

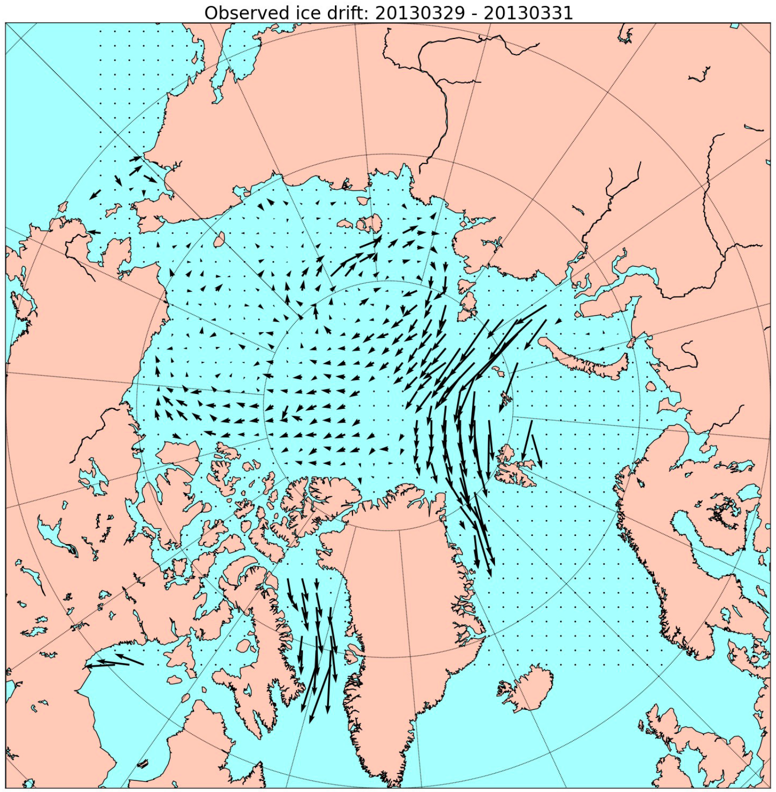


Ice drift in the model

Example 3-days end of March 2013



TOPAZ



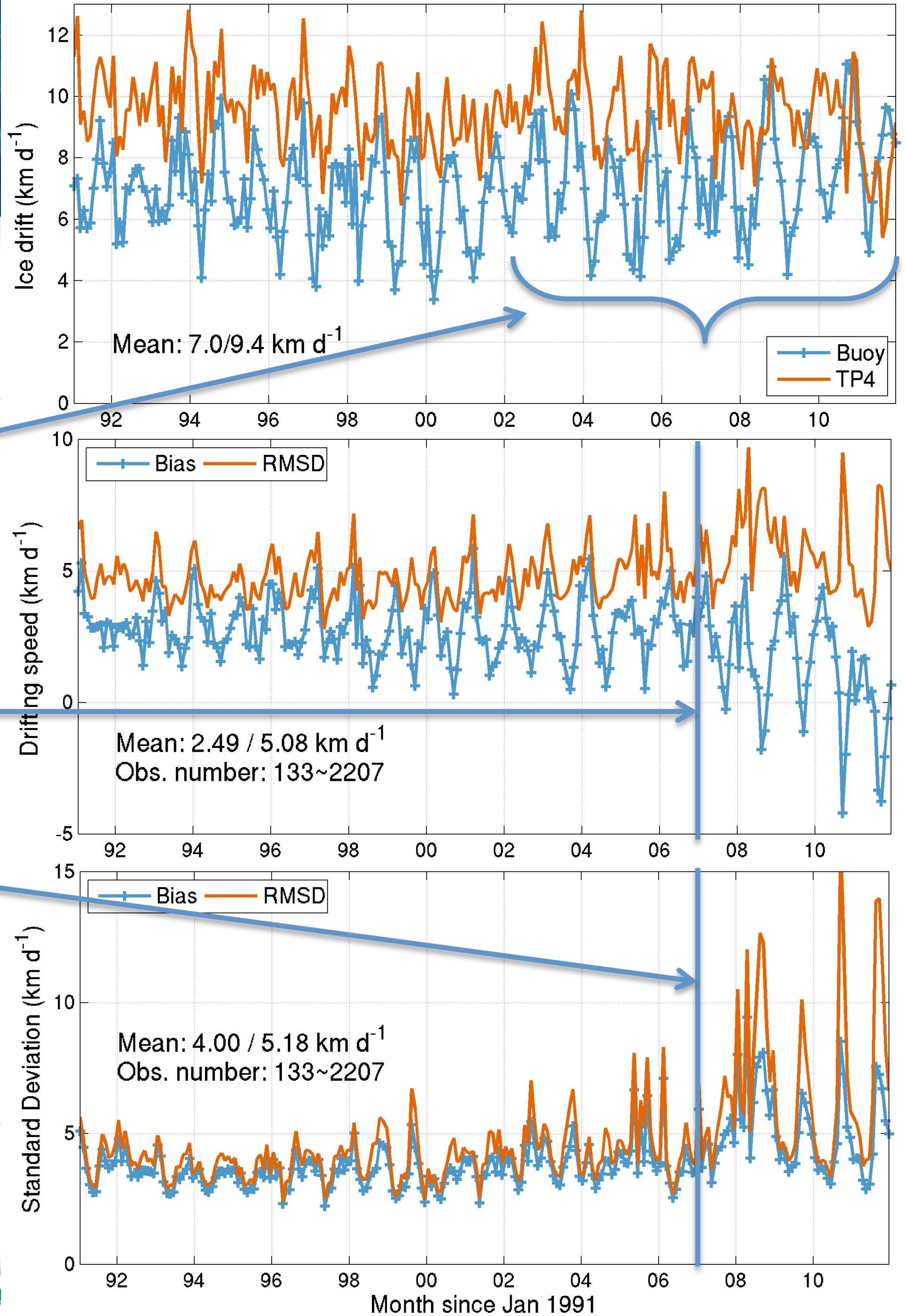
OSI-SAF

Ice drift validation

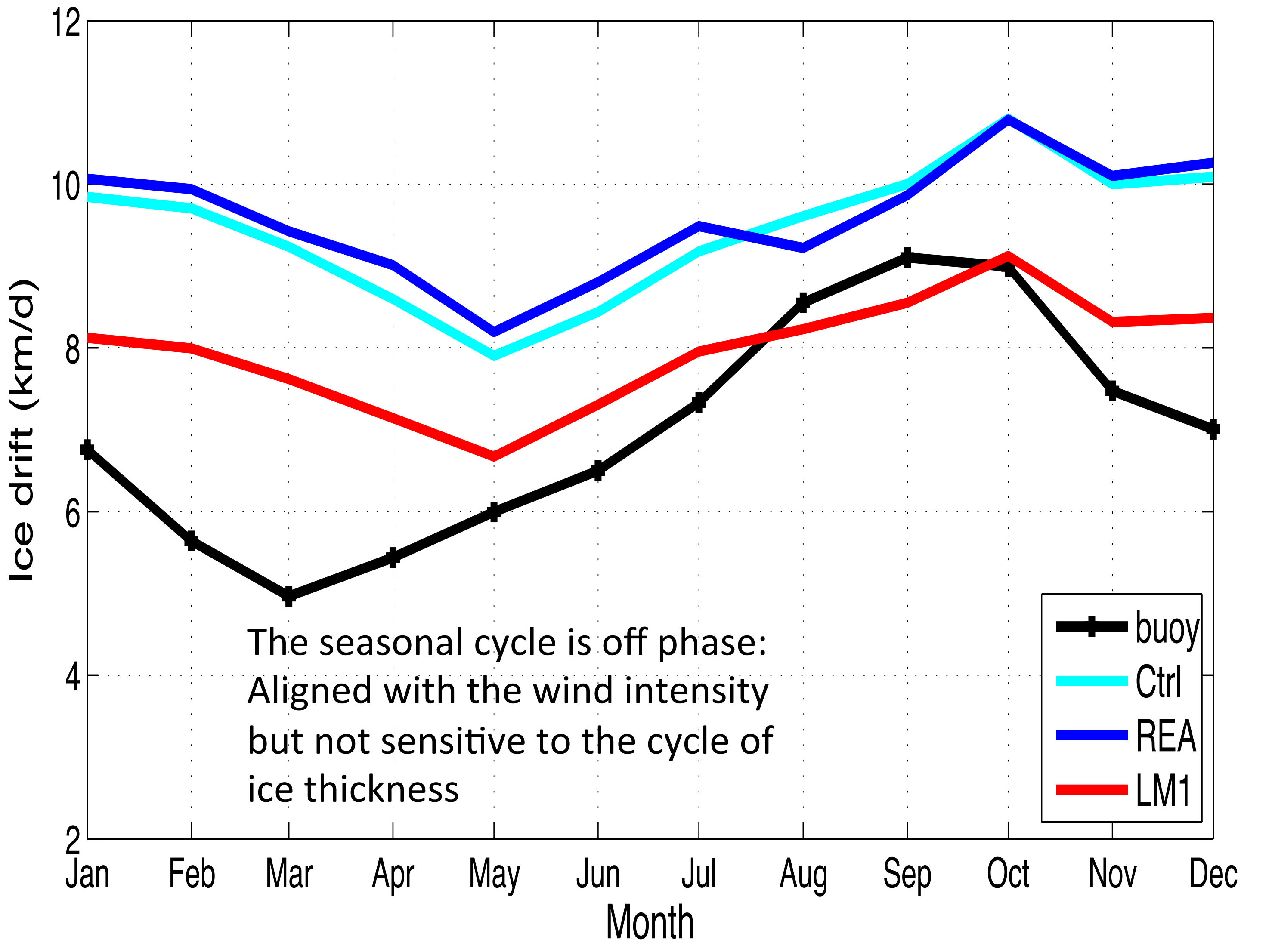
IABP buoys, TP4: Reanalysis

Assimilation of ice drift data from scatterometers / PMW
Does not help

Faster acceleration after 2007 (Buoys only)
Increased spatial variability after 2007 (buoys only)



Ice drift seasonality shortcoming of the EVP rheology



Ice thickness validation

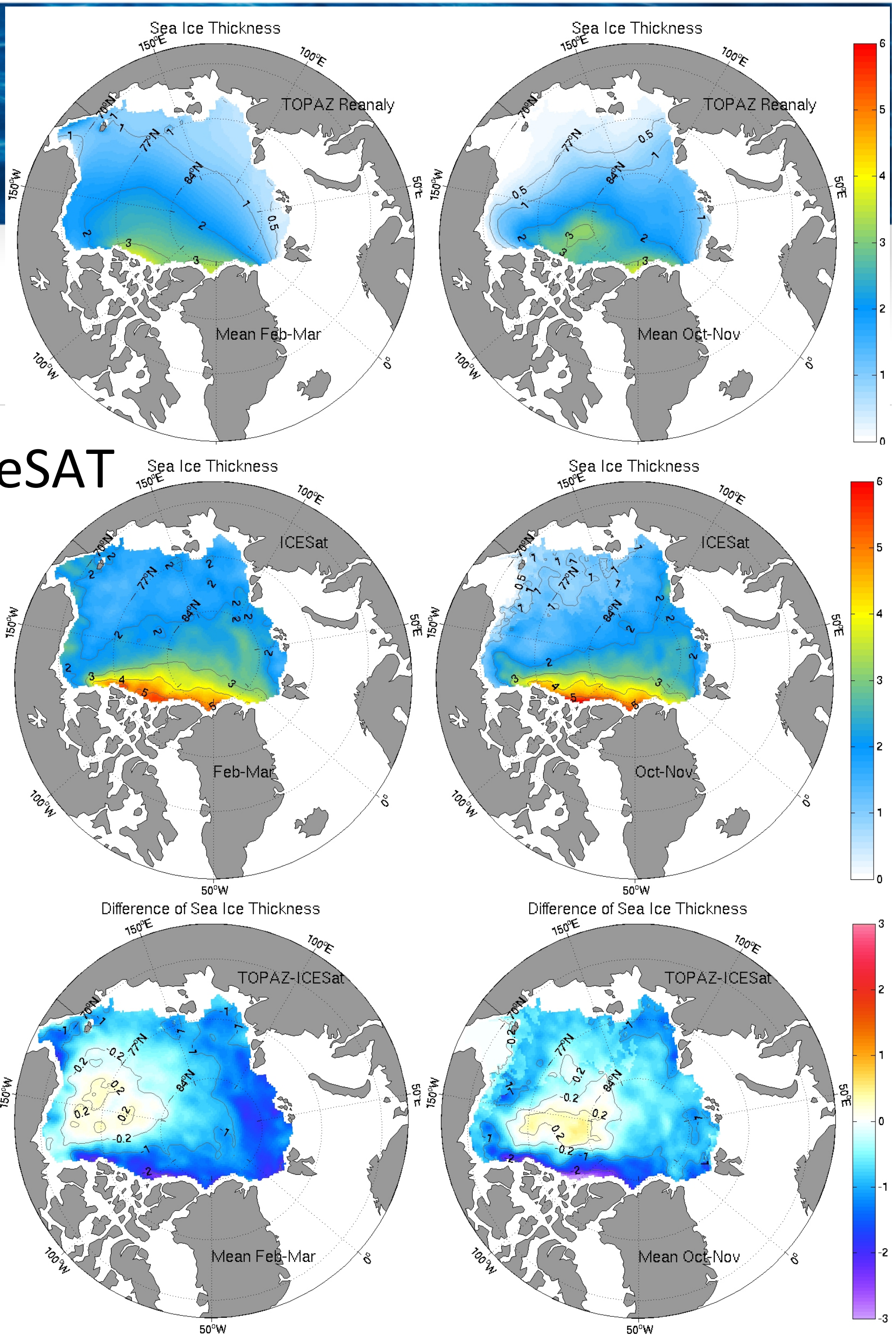
TOPAZ reanalysis

Independent satellite IceSAT (Kwok, JPL)

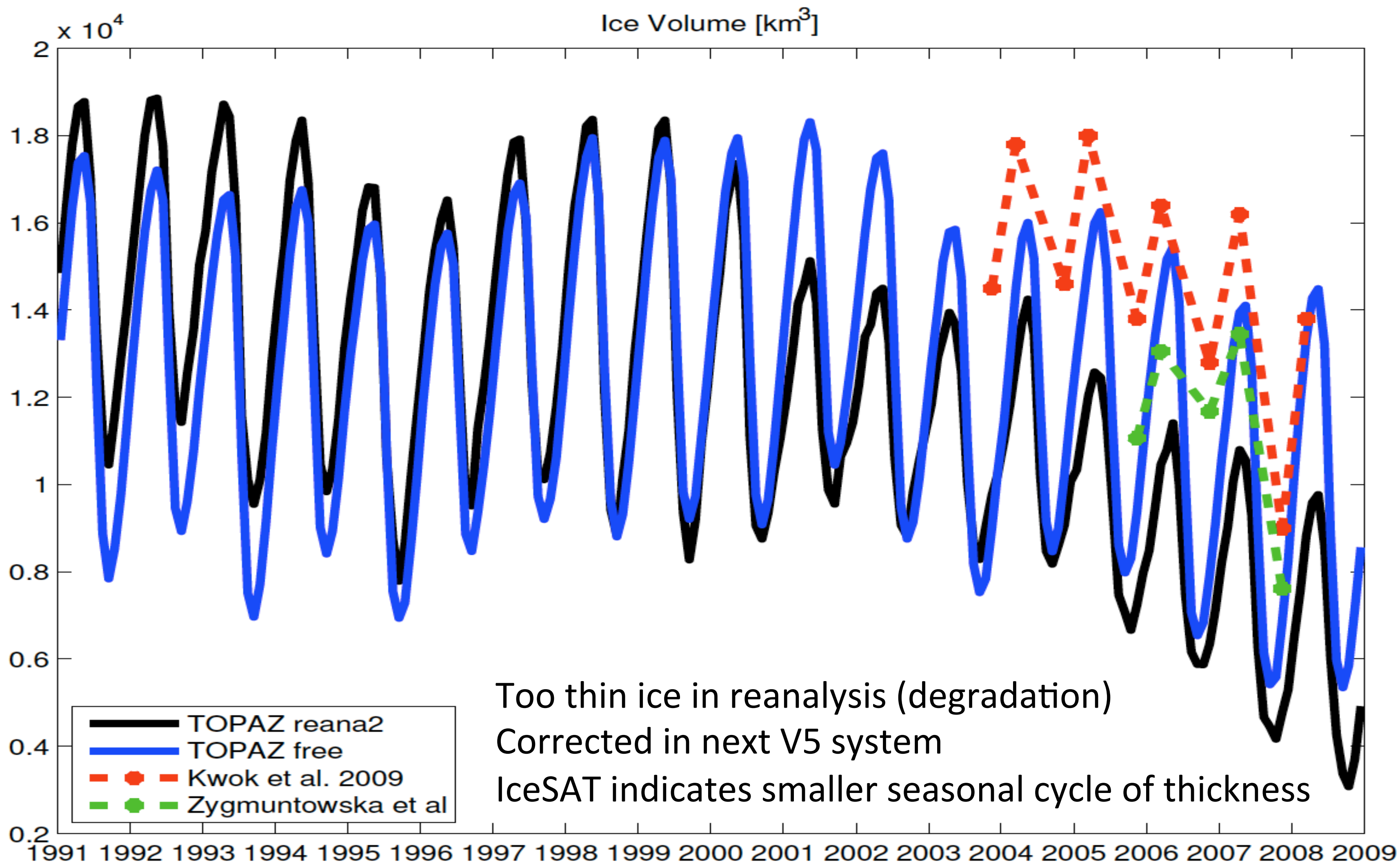
Underestimates thick ice

Overestimates thin ice

Common feature of other models (Johnson et al. JGR 2012)



Ice thickness validation



Too thin ice in reanalysis (degradation)
Corrected in next V5 system
IceSAT indicates smaller seasonal cycle of thickness

Summary reanalysis performance

- Good added value from observations
  - Sea ice extent
  - Sea surface temperature
  - Surface circulation
  - T&S Intermediate water masses (0-300 m depths)
- No improvement/degradation against the free run
  - Sea level seasonal signal
  - Deep waters
  - Sea ice drift velocities + seasonal cycle off (dynamics)
  - Seasonal cycle of ice thickness
    - Improved by mistake …
- Degradations
  - Snow depths (mistake)
  - Too thin sea ice (consequence)

NEEDS HIGHER RESOLUTION (v+h)

CANNOT BE TUNED, NEEDS BASIC DEVELOPMENTS