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FOR COMPUTATIONAL ENGINEERING & SCIENCES

THE ARCTIC / SUBPOLAR NORTH ATLANTIC STATE & PARAMETER ESTIMATION

An T. Nguyen (!)
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& ECCO colleagues

At present an eclectic Arctic observing system

- Heterogeneous data streams
- Disparate variables being sampled
- Spatio-temporally non-uniform sampling
- …

How best to synthesize the information contained in the data into a single framework?

A major goal of DA:

- making optimal use of / …
- consistently extracting / …
- combining …

… information contained in

- all available multi-variate observations
- and physical laws expressed through a model,

… taking into account all sources of uncertainty

Recent Arctic intercomparisons of **global** DA systems

Clim Dyn
DOI 10.1007/s00382-016-2985-y

CrossMark

Intercomparison of the Arctic sea ice cover in global ocean–sea ice reanalyses from the ORA-IP project

Matthieu Chevallier[1] · Gregory C. Smith[2] · Frédéric Dupont[3] · Jean-François Lemieux[2] · Gael Forget[4] · Yosuke Fujii[5] · Fabrice Hernandez[6,7] · Rym Msadek[8,9] · K. Andrew Peterson[10] · Andrea Storto[11] · Takahiro Toyoda[5] · Maria Valdivieso[12] · Guillaume Vernieres[13,14] · Hao Zuo[15] · Magdalena Balmaseda[15] · You-Soon Chang[16] · Nicolas Ferry[6] · Gilles Garric[6] · Keith Haines[12] · Sarah Keeley[15] · Robin M. Kovach[14] · Tsurane Kuragano[5] · Simona Masina[11,17] · Yongming Tang[10,15] · Hiroyuki Tsujino[5] · Xiaochun Wang[18]

Received: 20 February 2015 / Accepted: 8 January 2016

Recent Arctic intercomparisons of **global** DA systems

Climate Dynamics
https://doi.org/10.1007/s00382-018-4242-z

CrossMark

An assessment of ten ocean reanalyses in the polar regions

Petteri Uotila[1] · Hugues Goosse[2] · Keith Haines[3] · Matthieu Chevallier[4] · Antoine Barthélemy[2] · Clément Bricaud[5] · Jim Carton[6] · Neven Fučkar[7,8] · Gilles Garric[5] · Doroteaciro Iovino[9] · Frank Kauker[10] · Meri Korhonen[11] · Vidar S. Lien[12] · Marika Marnela[11] · François Massonnet[2,7] · Davi Mignac[3] · K. Andrew Peterson[13] · Remon Sadikni[14] · Li Shi[15] · Steffen Tietsche[16] · Takahiro Toyoda[17] · Jiping Xie[18] · Zhaoru Zhang[19]

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- *Snapshot of a moving target, products are constantly evolving and updated regularly.*
- *Performance may remain representative for a while.*
- *Many polar diagnostics carried out for the first time, insufficient output.*
- *Common metrics across the climate modeling & reanalysis communities.*

Few regional efforts so far that would be comparable to the Southern Ocean State Estimate – SOSE

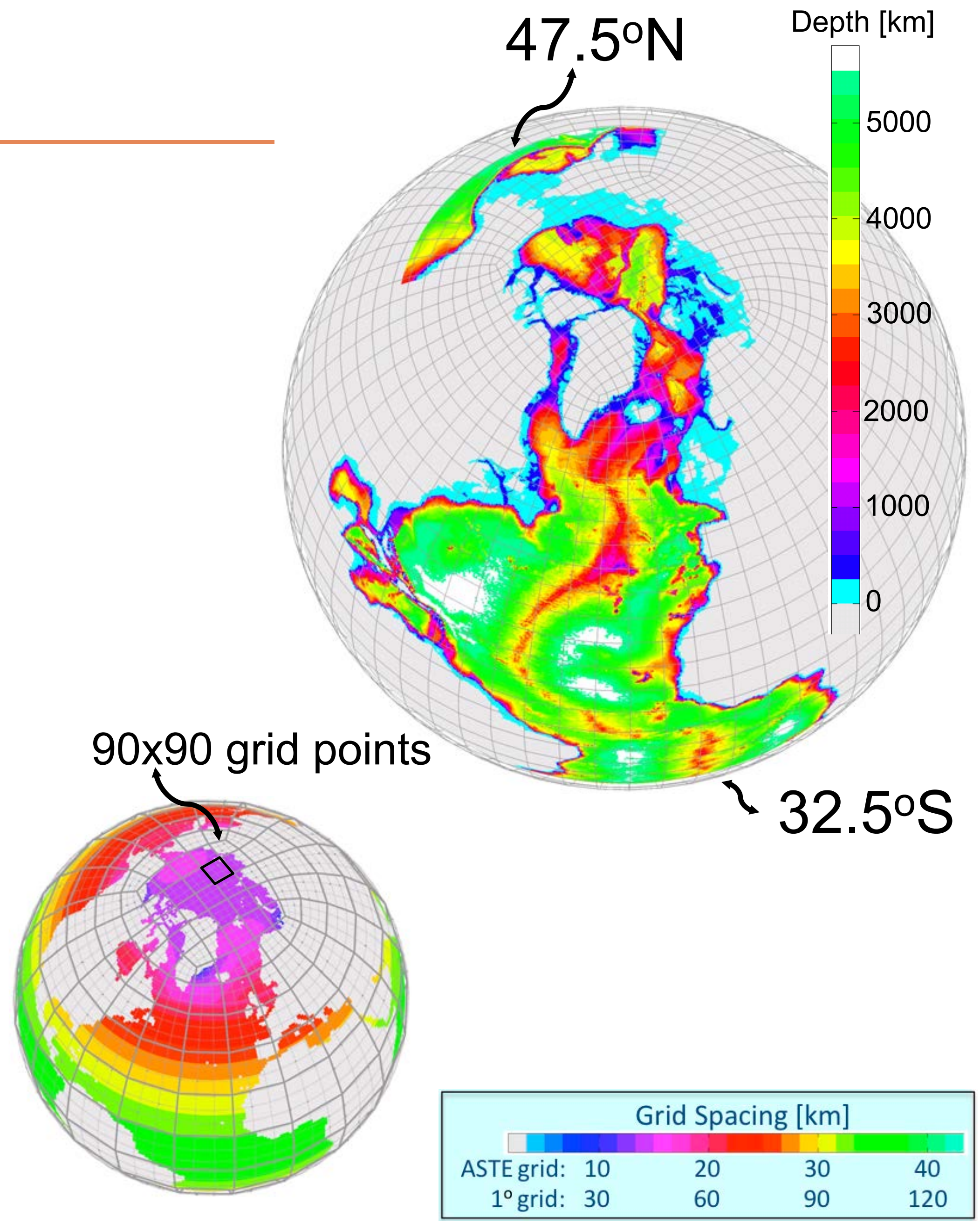
In the following, brief introduction to ~~NOSE~~ :

The Arctic Subpolar North Atlantic State Estimate (ASTE)

(NSF funded, but using NASA-developed ECCO framework)

ASTE v1: some configuration details

- Adjoint-based ("4D-Var")
- Period: 2002 – 2017
- Time-evolving ocean & sea ice states
- Arctic – Subpolar gyre exchanges
- Initial condition priors(!):
  - WOA14 spin-up (ocean)
  - PSC spin-up (ice)
- Forcing priors(!): JRA-55
- Open boundary conditions: ECCO-v4



Primary observational constraints

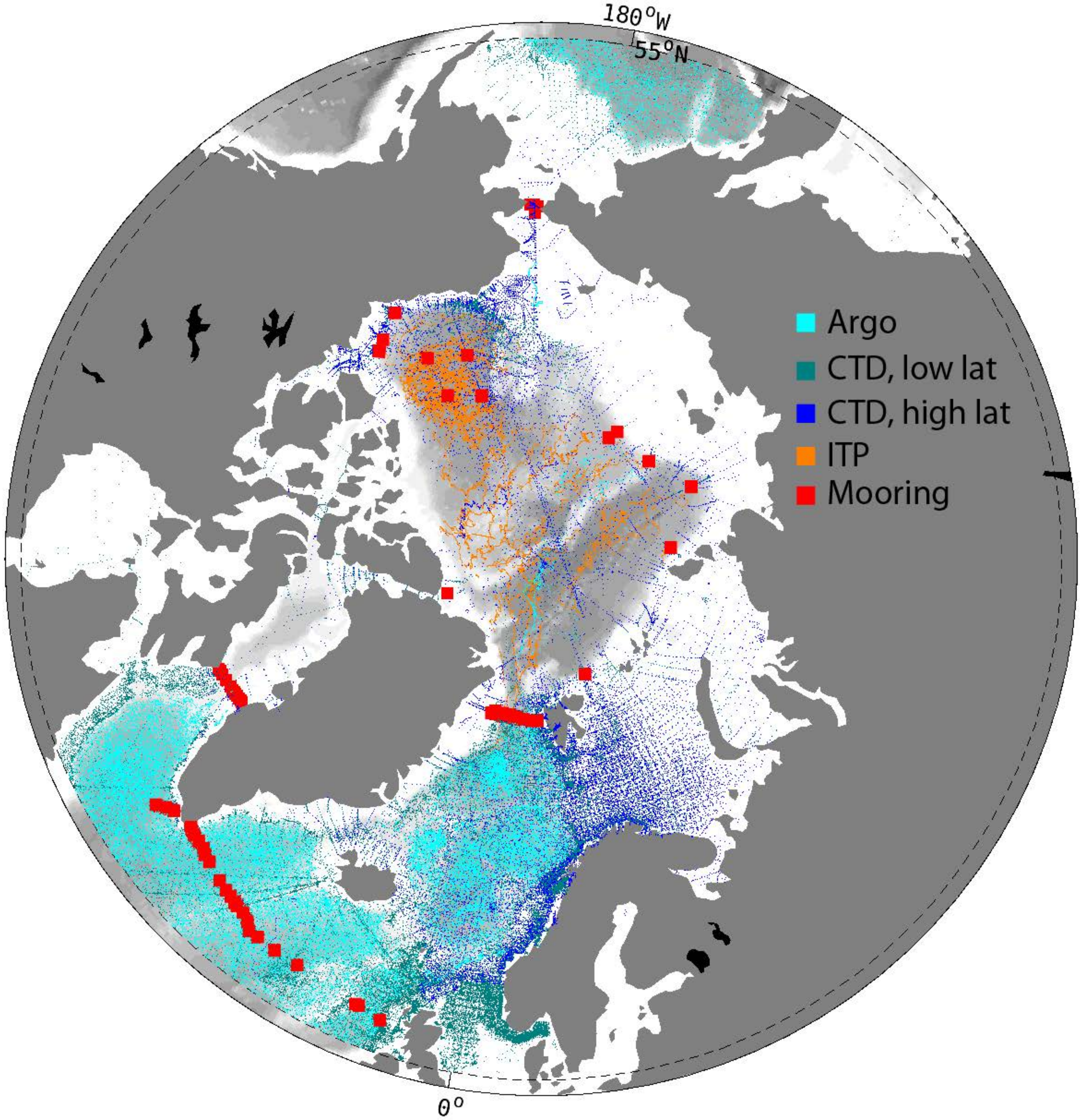
Low latitudes:

ECCO-v4 standard obs.

- Satellite: SSH, SST, MDT
- In-situ: Argo, XBT, CTDs, seals (MEOP)
- Others: Line-W (J. Toole), Gulf Stream (R. Todd), AR07 lines, ICES database

High latitudes:

- ocean T/S/U/V, e.g., ITP, NABOS/CABOS, BGEP (2002-2017)
- Arctic main gateways: Fram, Davis, Bering straits, etc.



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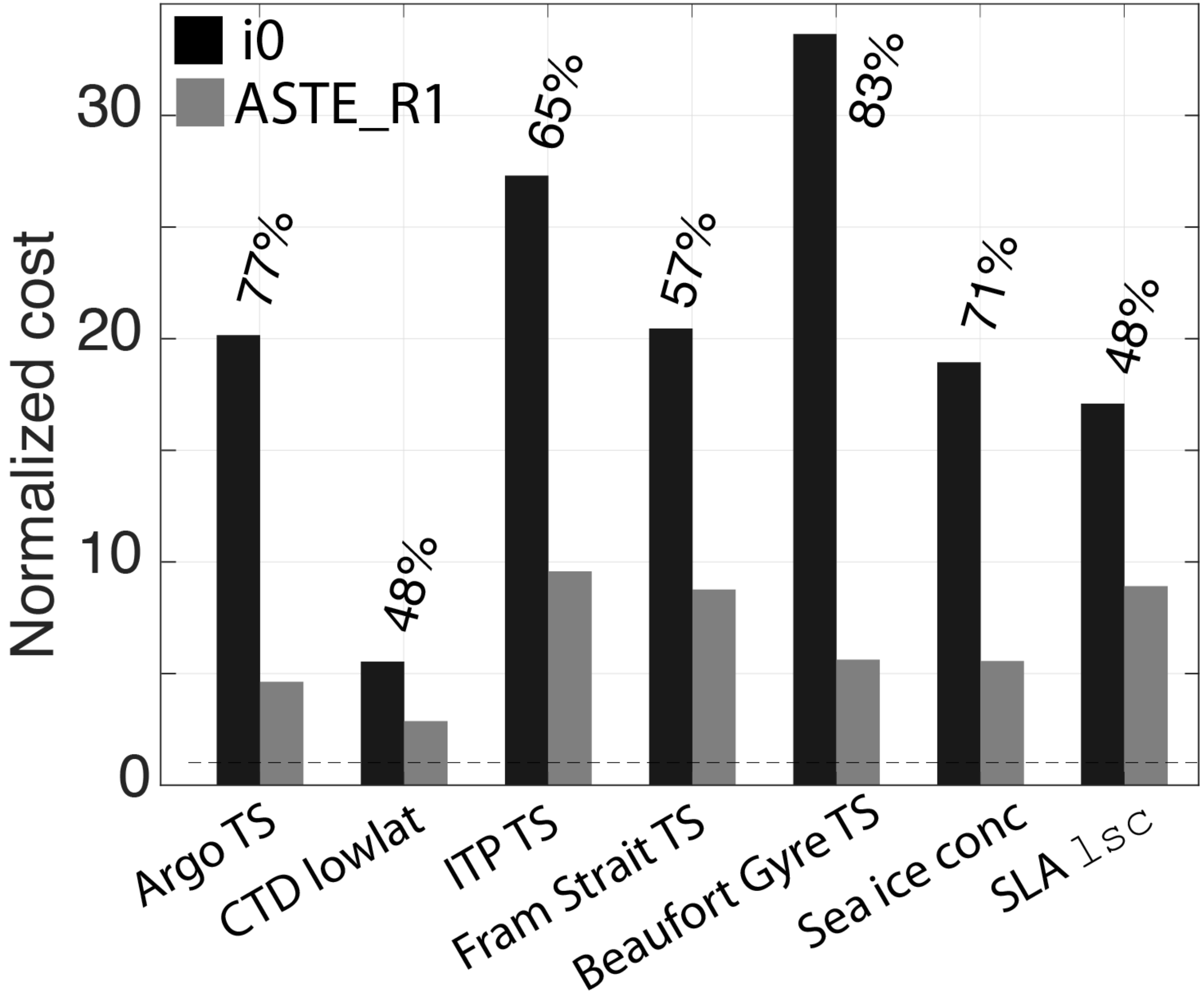


Misfit reduction:
Ice Tethered Profilers

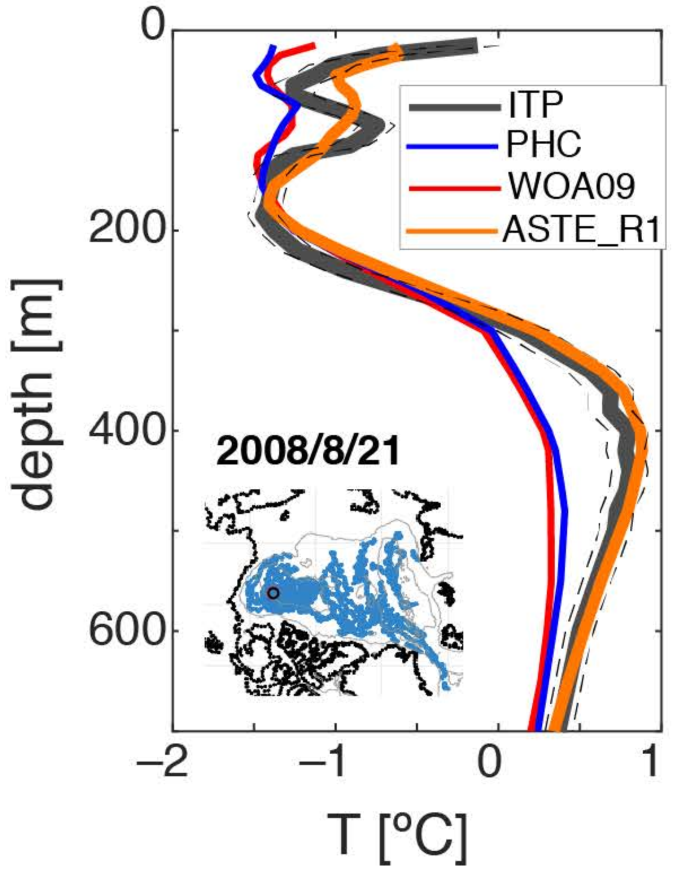
Comparison:

ITP vs. ASTE

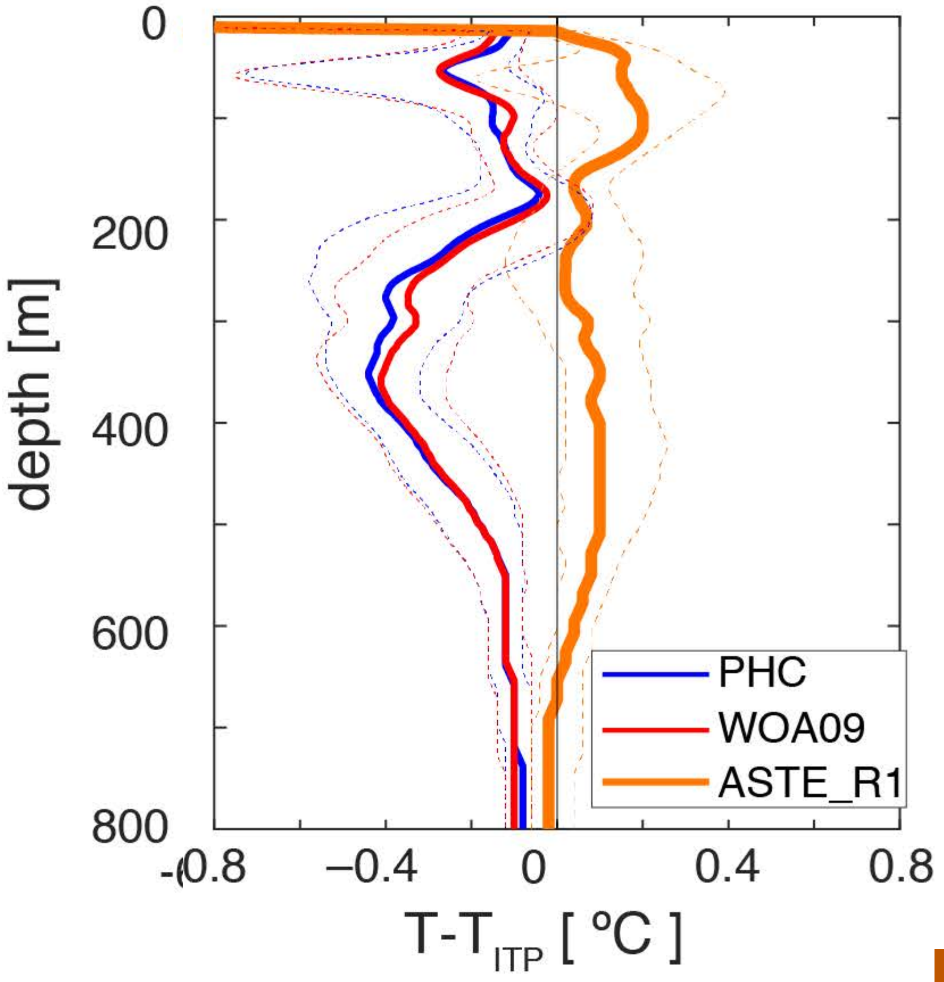
ITP vs. PHC

ITP vs. WOA09

Example: one ITP profile to show the consistent cold bias in both PHC and WOA09 in the core AW water in the Canada Basin



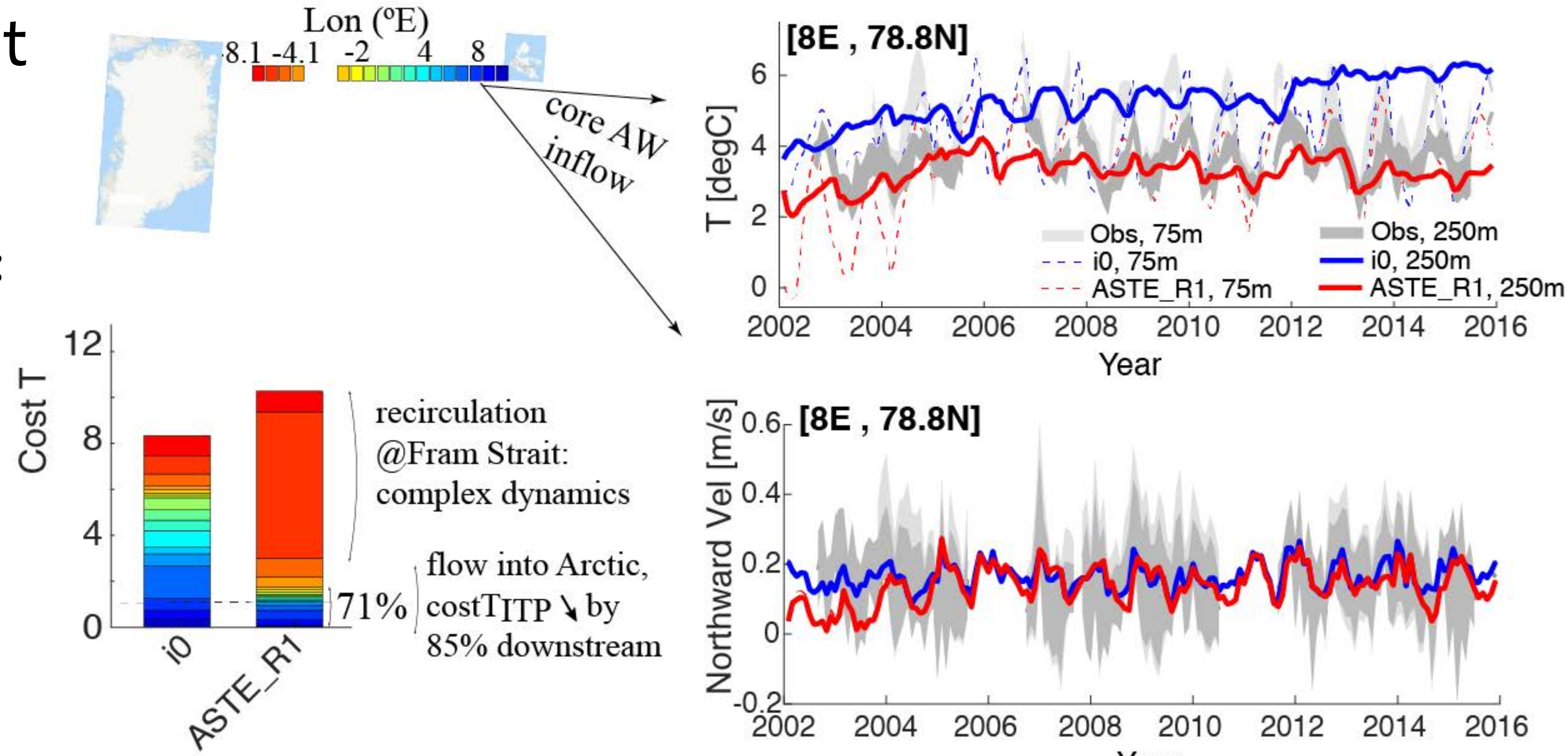
2004-2017 raw T misfits
[30,50,70] percentiles
All ITP profiles in Canada Basin,



Fram Strait Transport

Color coding:

Misfit reductions of moorings from west to east of Fram Strait



ASTE version 1, release 1, is about to be released at:

https://web.corral.tacc.utexas.edu/OceanProjects/ASTE/

(same repo as that mirroring ECCO version 4 data from JPL/PO.DAAC)

Over the coming year plans are to

- Data will be within cloud analysis-enabled data portal
- Metadata will be communicated / linked to NSF's Arctic Data Center **https://arcticdata.io**

Needs

Modeling:

- Various, (ice dynamics & thermodynamics; resolution; Arctic halocline; mixing), but a very important one:
  - Atmospheric state and implied ocean-sea ice forcing

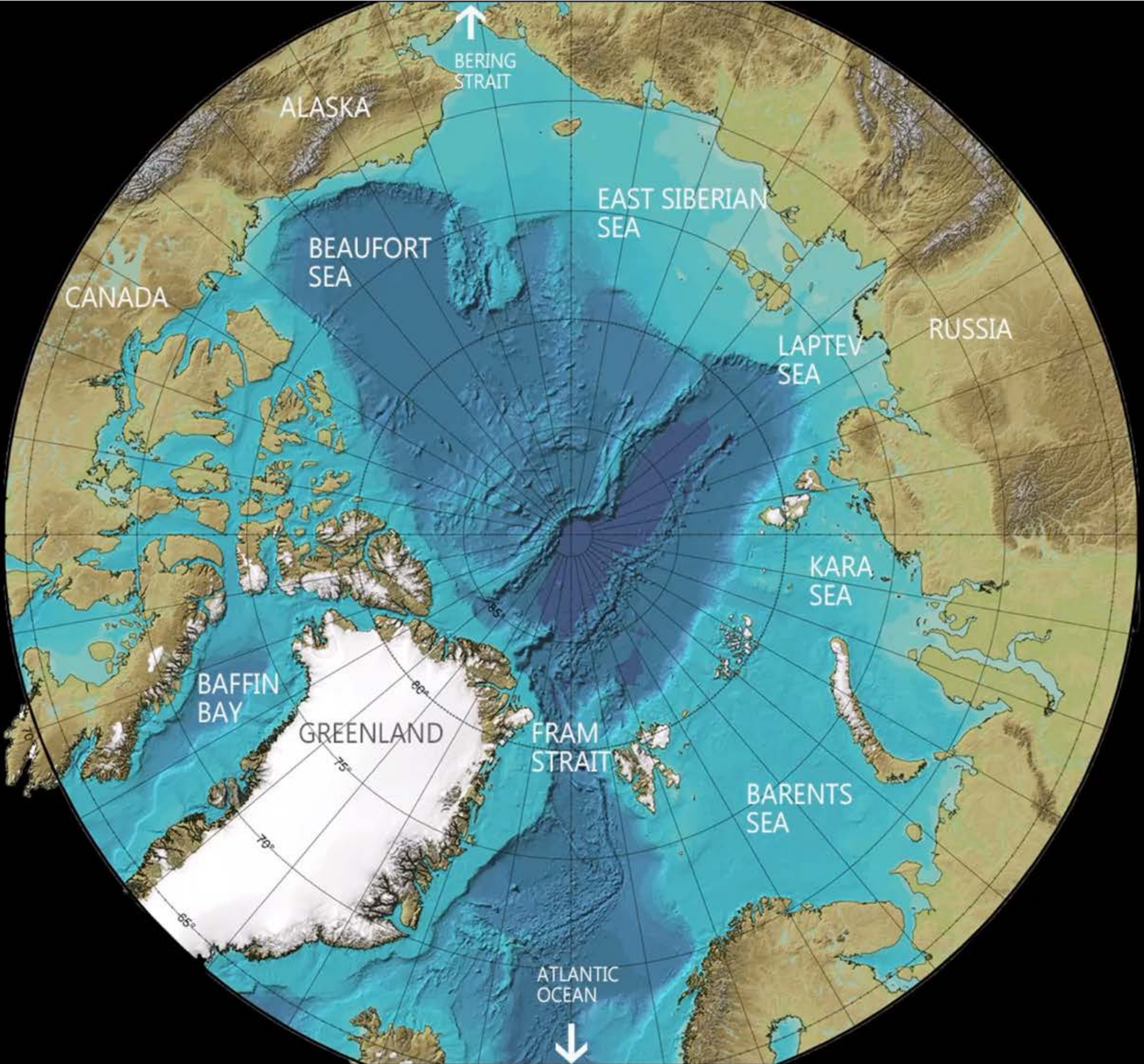
Model output:

- Output to diagnose tracer & volume budgets
- Metrics across OMDP, CMIP, GSOP/ORA-IP, …

Observations:

- All of Siberian Shelf
- Inflow water masses
- Deep Arctic Ocean

DA & UQ: Investigation and application of methods for observing system design



Source: Jakobsson, et al. (2012)
The International Bathymetric
Chart of the Arctic Ocean (IBCAO)
Version 3.0,
Geophysical Research Letters,
doi: 10.1029/2012GL052219

Needs:
Model output

Full suite of fields required to perform accurate tracer budget calculations, following recommendations by

CLIVAR Ocean Model Development Panel (OMDP); Griffies et al., GMD (2016)

At issue: proper diagnostic of discretized volume & tracer conservation:

$$\underbrace{\frac{\partial\left(s^{*}\theta\right)}{\partial t}}_{G^{\theta,tot}} = \underbrace{-\nabla_{z^{*}}\left(s^{*}\theta\mathbf{v}_{res}\right) - \frac{\partial\left(\theta w_{res}\right)}{\partial z^{*}}}_{G^{\theta,adv}} + \underbrace{s^{*}\mathcal{F}_{\theta}}_{G^{\theta,forc}} + \underbrace{s^{*}D_{\theta}}_{G^{\theta,diff}}$$

See Chris Piecuch (2017), DSpace@MIT: http://hdl.handle.net/1721.1/111094

Needs:

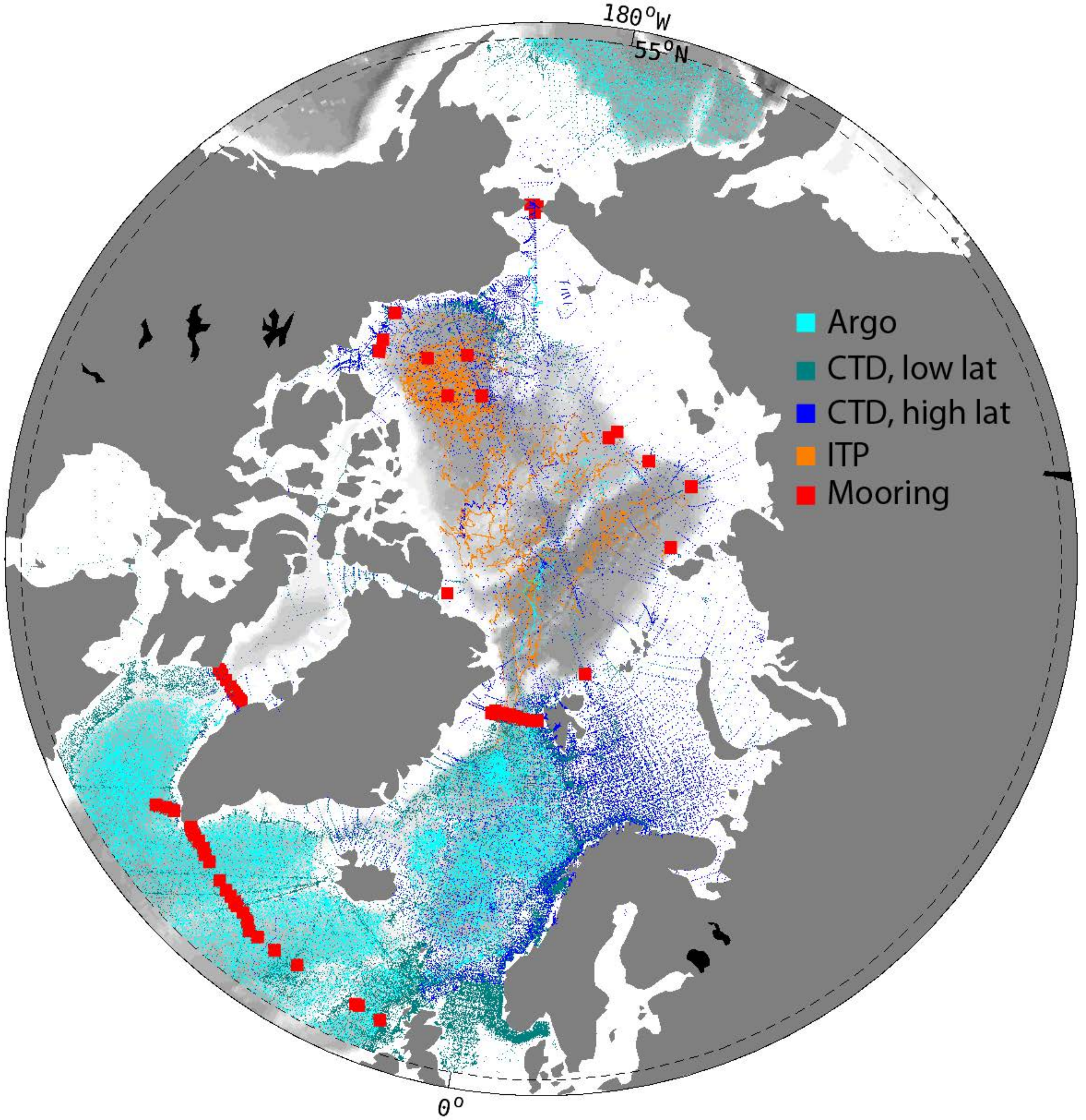
Model output

At issue: proper diagnostic of discretized volume & tracer conservation

Diagnostic	Time	Description (Units)
ETAN	Snapshot	Surface height anomaly (m)
THETA	Snapshot	Potential temperature (°C)
TFLUX	Average	Total heat flux (W m^{-2})
oceQsw	Average	Net shortwave radiation (W m^{-2})
ADVr_TH	Average	Vertical advective flux of pot. temp. (°C m^3 s^{-1})
ADVx_TH	Average	Zonal advective flux of pot. temp. (°C m^3 s^{-1})
ADVy_TH	Average	Meridional advective flux of pot. temp. (°C m^3 s^{-1})
DFrI_TH	Average	Implicit vertical diffusive flux of pot. temp. (°C m^3 s^{-1})
DFrE_TH	Average	Explicit vertical diffusive flux of pot. temp. (°C m^3 s^{-1})
DFxE_TH	Average	Explicit zonal diffusive flux of pot. temp. (°C m^3 s^{-1})
DFyE_TH	Average	Explicit meridional diffusive flux of pot. temp. (°C m^3 s^{-1})

See Chris Piecuch (2017), DSpace@MIT: http://hdl.handle.net/1721.1/111094

Needs
Observations!!!



How well does each observing system constrain the solution & relevant QoIs? Optimal Experimental Design

Prior & posterior variances of Quantity of Interest $\mathcal{Q}$

$$\mu_{prior} = \left(\frac{\partial \mathcal{Q}}{\partial x}\right)^T B \left(\frac{\partial \mathcal{Q}}{\partial x}\right), \quad \mu_{post} = \left(\frac{\partial \mathcal{Q}}{\partial x}\right)^T P \left(\frac{\partial \mathcal{Q}}{\partial x}\right)$$

Case of only 1 observation:

Uncertainty reduction of QoI $\mathcal{Q}$ through observation $\mathcal{J}$

$$1 - \frac{\mu_{post}}{\mu_{prior}} = d_1 \left\langle \frac{B^{1/2}\left(\frac{\partial \mathcal{Q}}{\partial x}\right)^T}{\|B^{1/2}\left(\frac{\partial \mathcal{Q}}{\partial x}\right)^T\|}, \frac{B^{1/2}\left(\frac{\partial \mathcal{J}}{\partial x}\right)^T}{\|B^{1/2}\left(\frac{\partial \mathcal{J}}{\partial x}\right)^T\|} \right\rangle$$

$$= d_1 < \text{info required by } \mathcal{Q}, \text{ info transmitted by } \mathcal{J} >$$

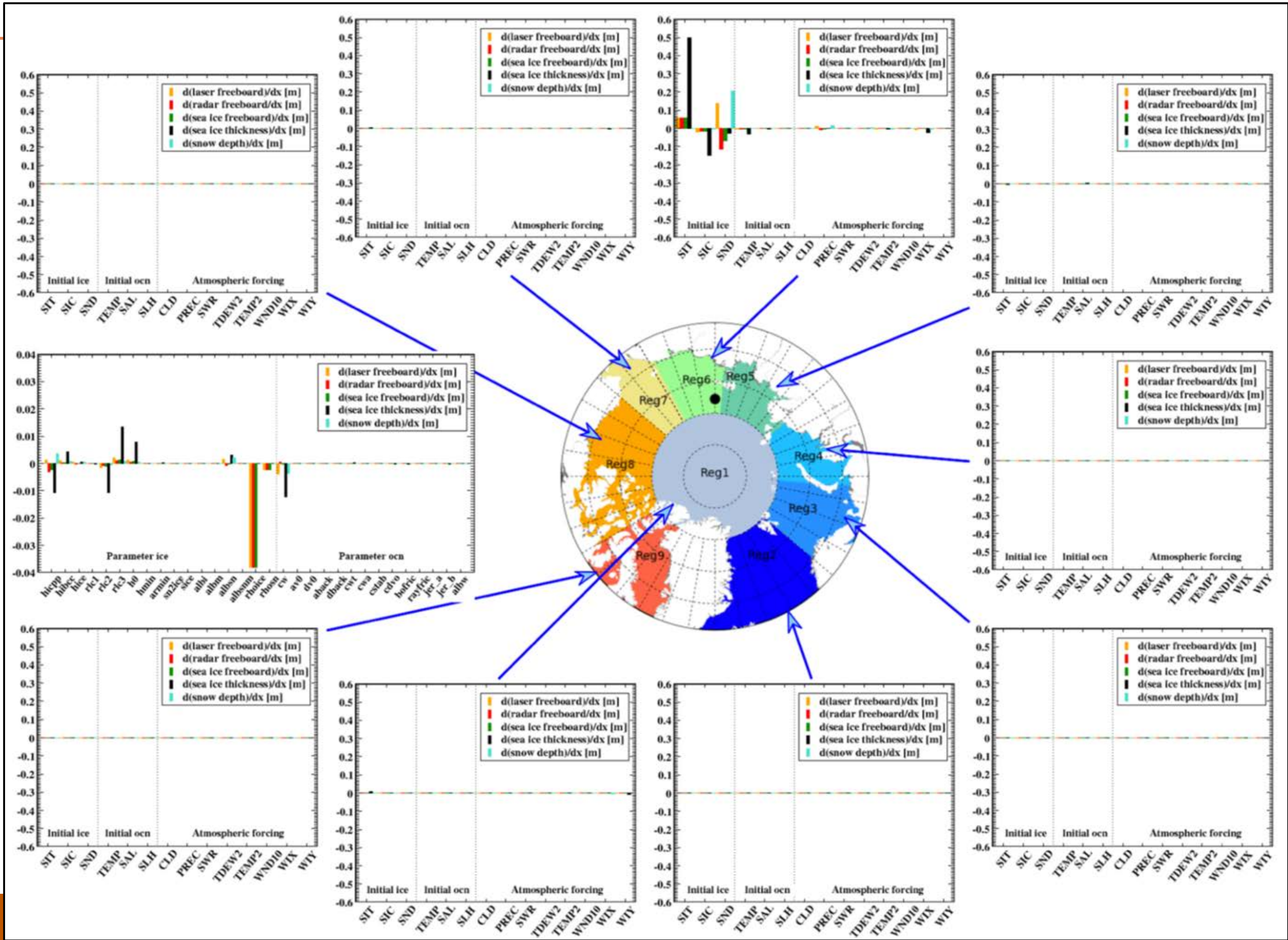
Kaminski et al., The Cryosphere (2015, 2018)

Observation sensitivities

(information communicated by observations)

Here:

Operation IceBridge (and CryoSat-2) flight lines

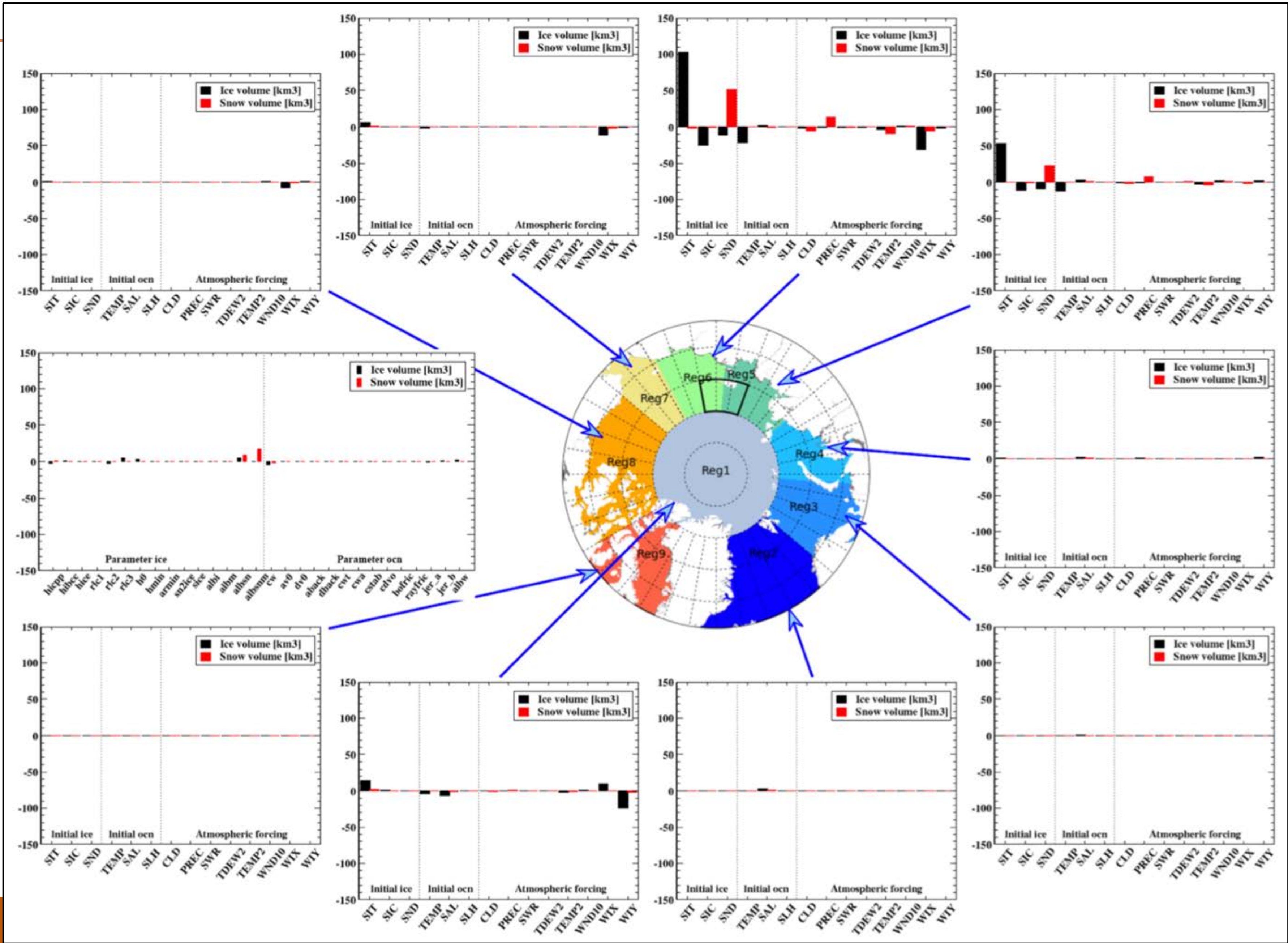


Kaminski et al., The Cryosphere (2015, 2018)

Quantity of Interest sensitivities

(information required by Quantity of Interest)

Here:
regional
ice & snow forecast



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Kaminski et al., The Cryosphere (2015, 2018)

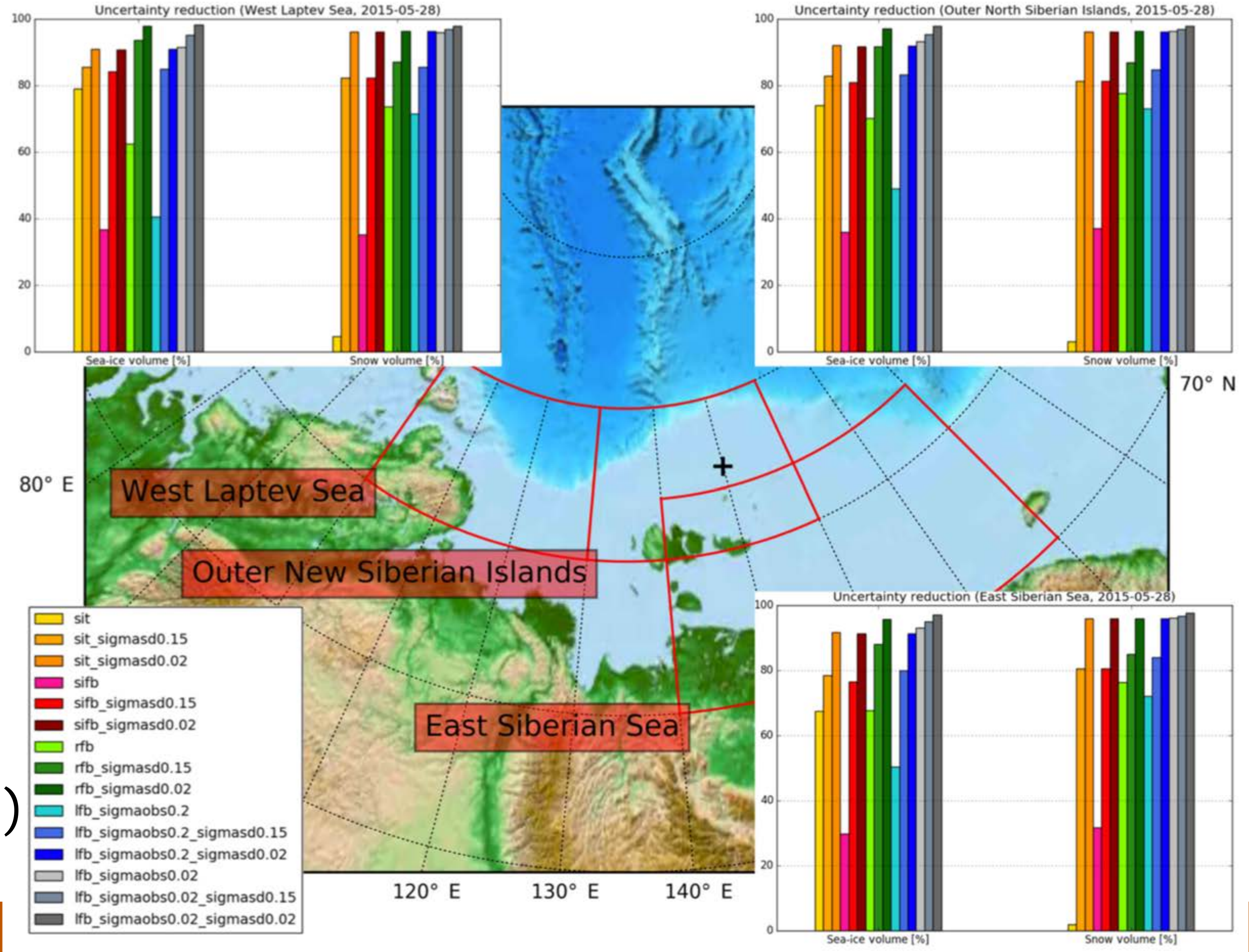
Uncertainty Reduction:

Projects observation uncertainties onto QoI uncertainties

(a simplified statement on how to evaluate posterior error covariance by means of inverse Hessian)

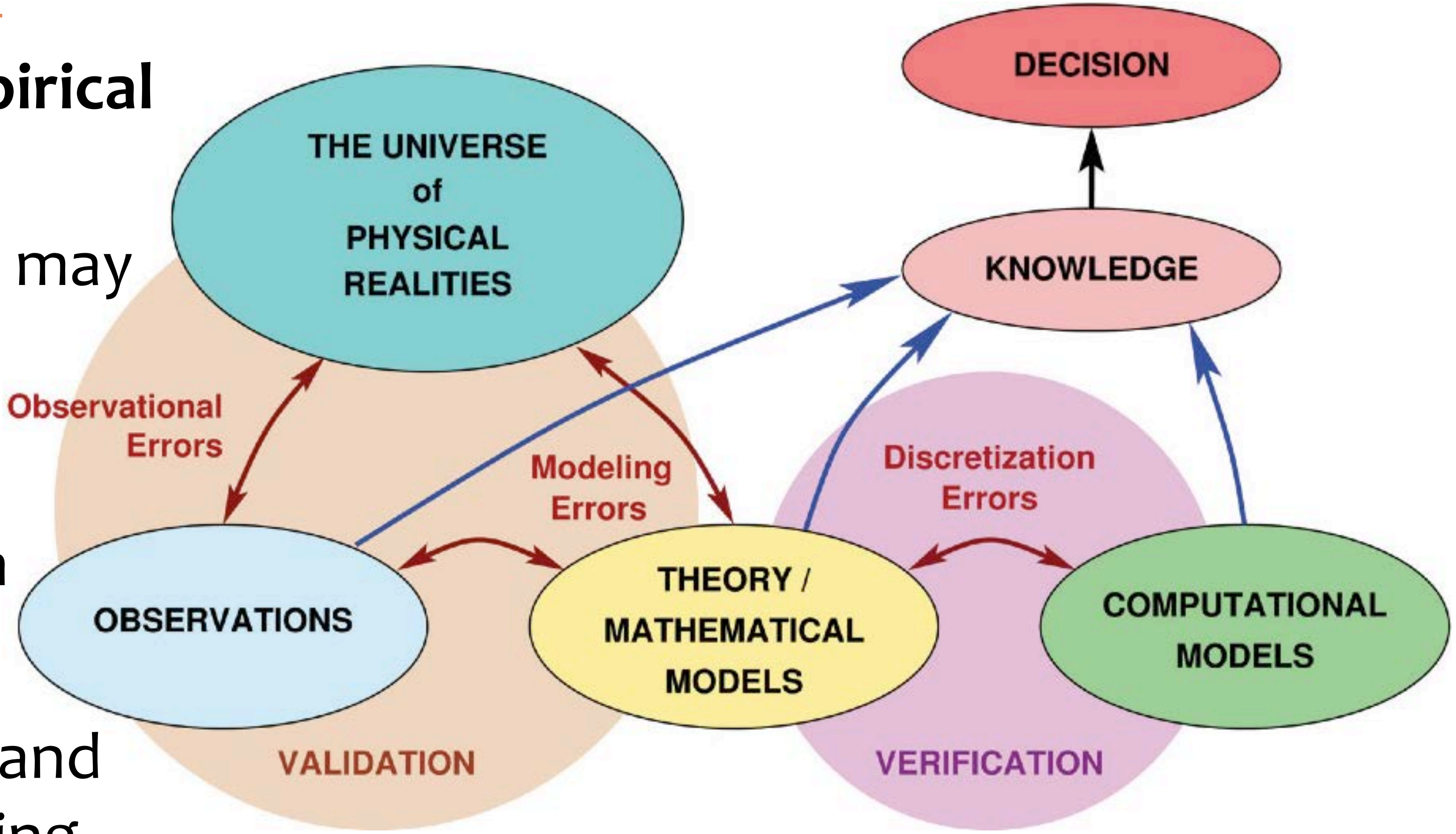
Find data-informed subspaces (Hessian eigen-decomposition)

Find data complementarity vs. redundancy (not just “a lot of data”)



“Looking at the data through the lens of (physical) models”

- **Constitutive laws are empirical**
  - uncertain structure & parameters (and which may vary in 3+1-dimensions)
- **Discretization requires numerical approximation & parameterization**
  - e.g.: related to surface and bottom-intensified mixing
- **Uncertain external forcings**



Oden, Moser, Ghattas, SIAM News (2010)
Computer predictions with quantified uncertainties

THE END

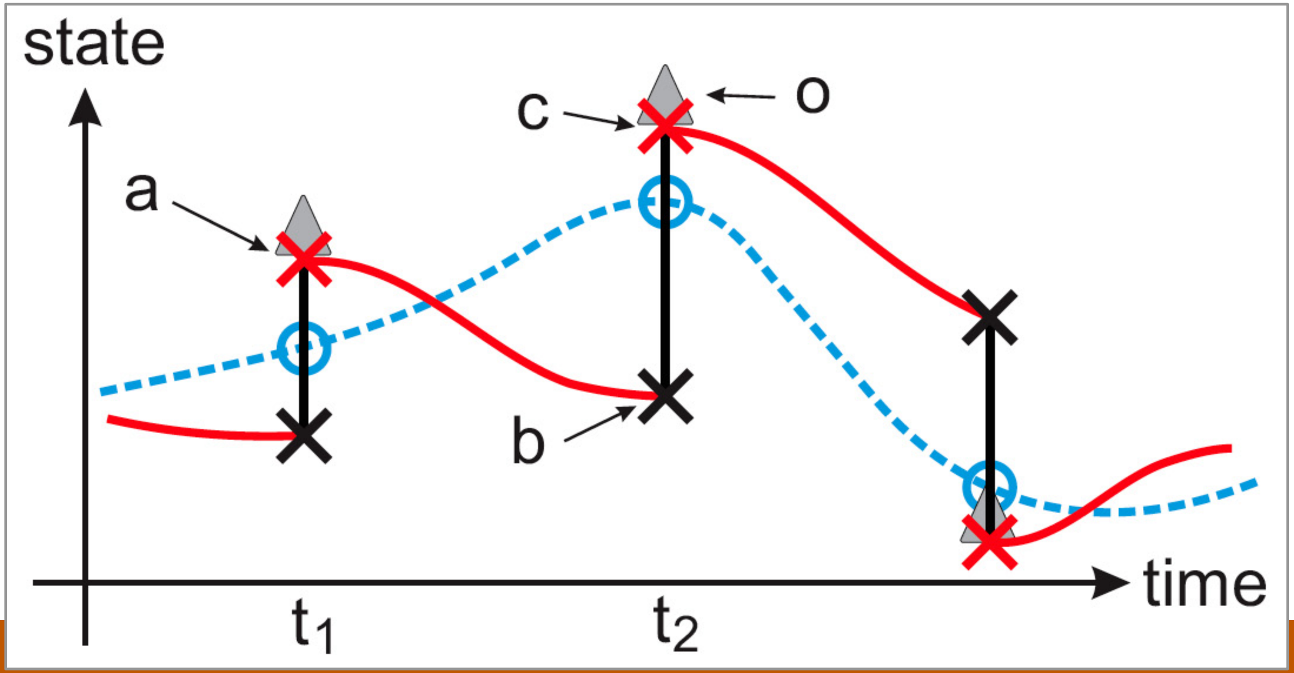
How do we practice ocean state & parameter estimation? And why?

Some of the challenges:

Why adjoints: dynamical & kinematical consistency in DA

Numerical Weather Prediction (NWP) – a filtering problem

- Relatively abundant data sampling of the 3-dim. atmosphere
- NWP targets optimal forecasting
  - ➔ find initial conditions which produce best possible forecast;
  - ➔ *dynamical consistency or property conservation NOT required*



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Ocean state estimation/reconstruction – a smoothing problem

- Sparse data sampling of the 3-D. ocean
- Understanding past & present state of the ocean is a major goal all by itself
  - ➔ use observations in an optimal way
  - ➔ *dynamic consistency & property conservation ESSENTIAL* for climate