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ARCTIC OCEAN CIRCULATION(S): MODELS AND OBSERVATIONS - SOME RANDOM THOUGHTS

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Why models?

- Their underlying equations of motion remain our best shot at peaking into the future
- Their underlying equations of motions conserve properties, globally and locally (at the fluid parcel level)
- They serve as “dynamics-respecting interpolators” of sparse data
- They enable us to ask WHAT–IF experiments
  - addressing fundamental question of system sensitivity

- We know uncertainties are basic ingredients of models:
  - Initial condition uncertainty
  - Boundary condition (surface forcing, lateral & basal boundary conditions, …)
  - Model parametric uncertainties
  - Model structural uncertainties (model inadequacy)
  - …

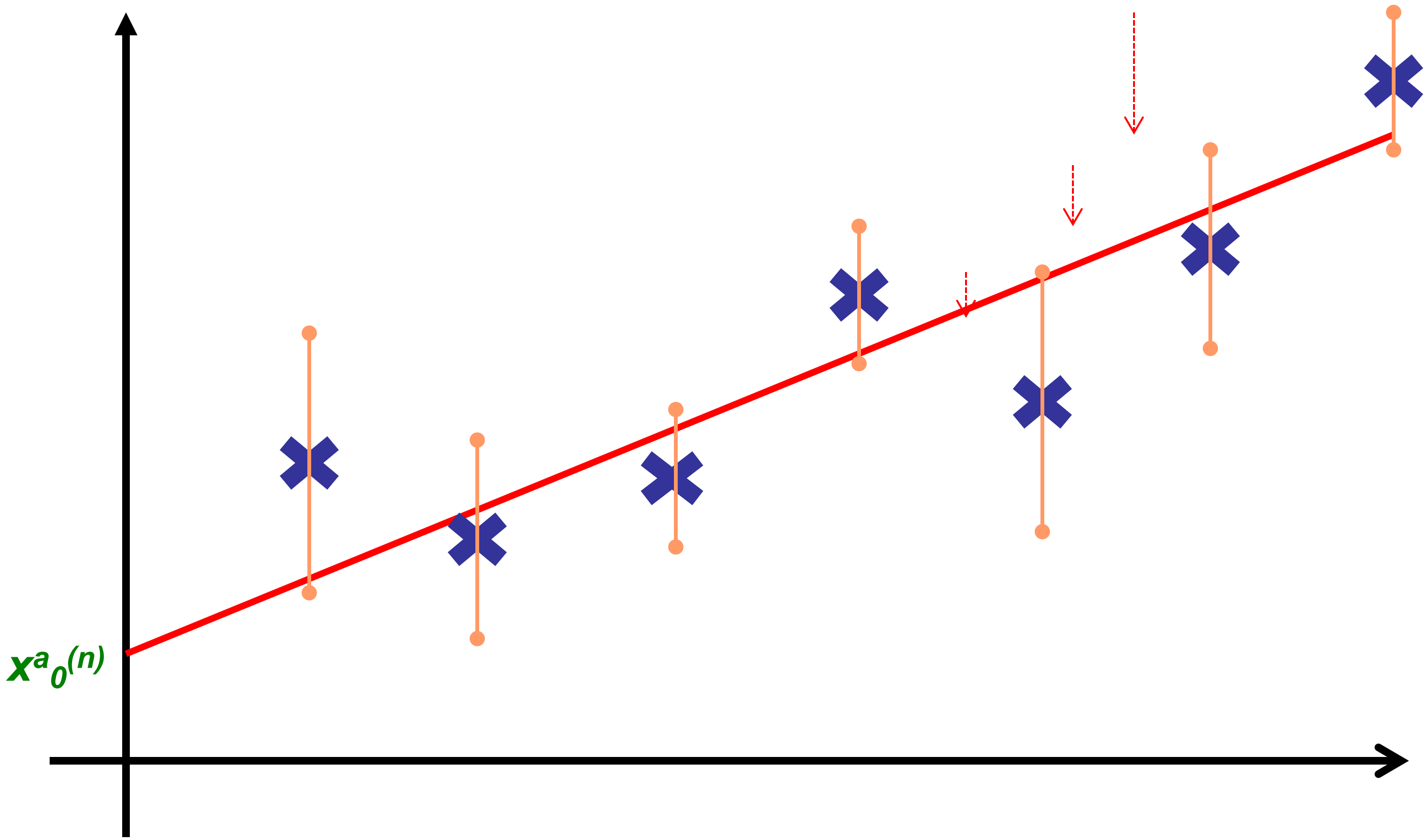
What do we mean by "validating the models"?

When we "validate" models …

… we ***WILL*** find misfits!

NOW WHAT?

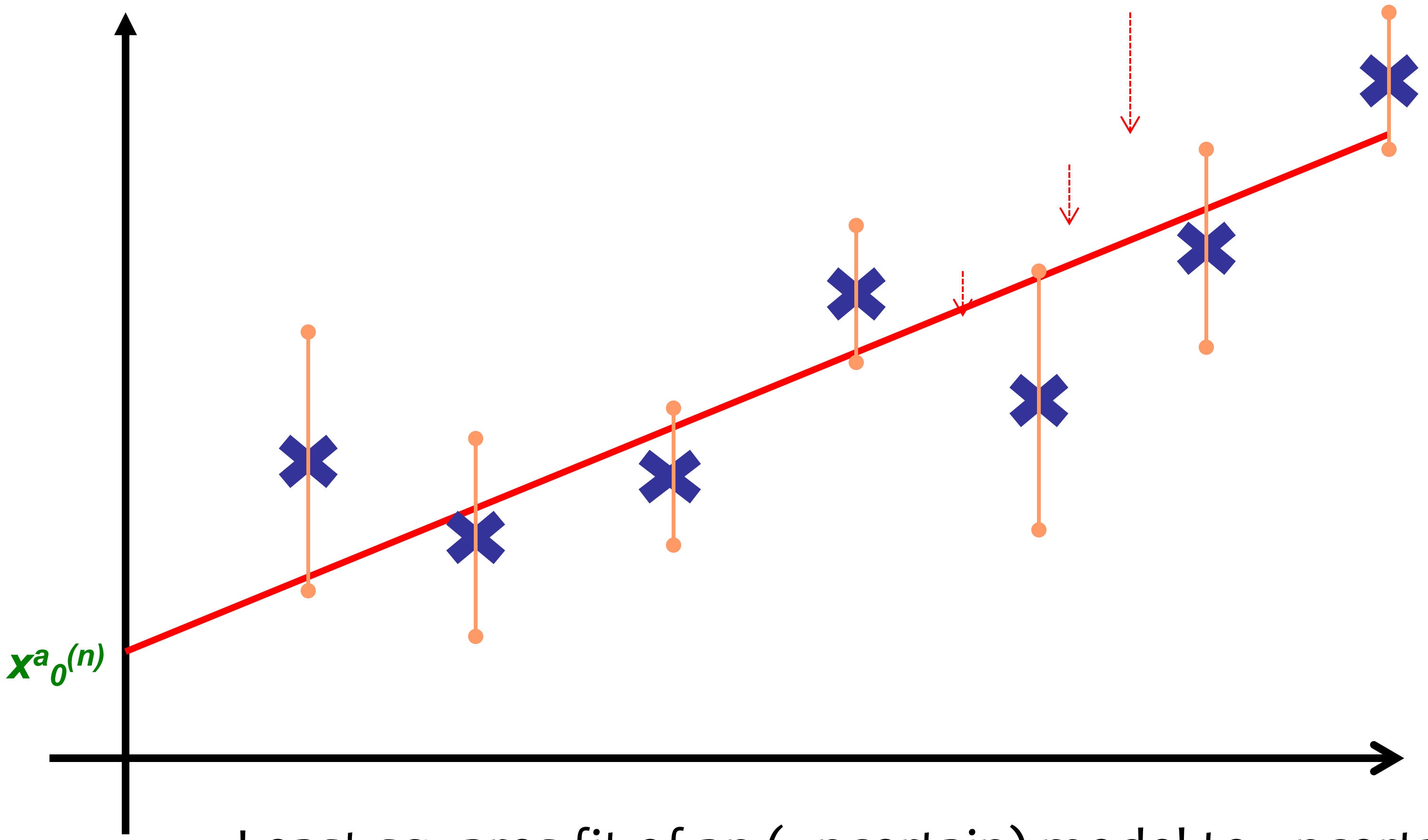
What do we mean by "validating the models"?



$$x(t) = a + b\,t$$

a*, *b *are uncertain model inputs*

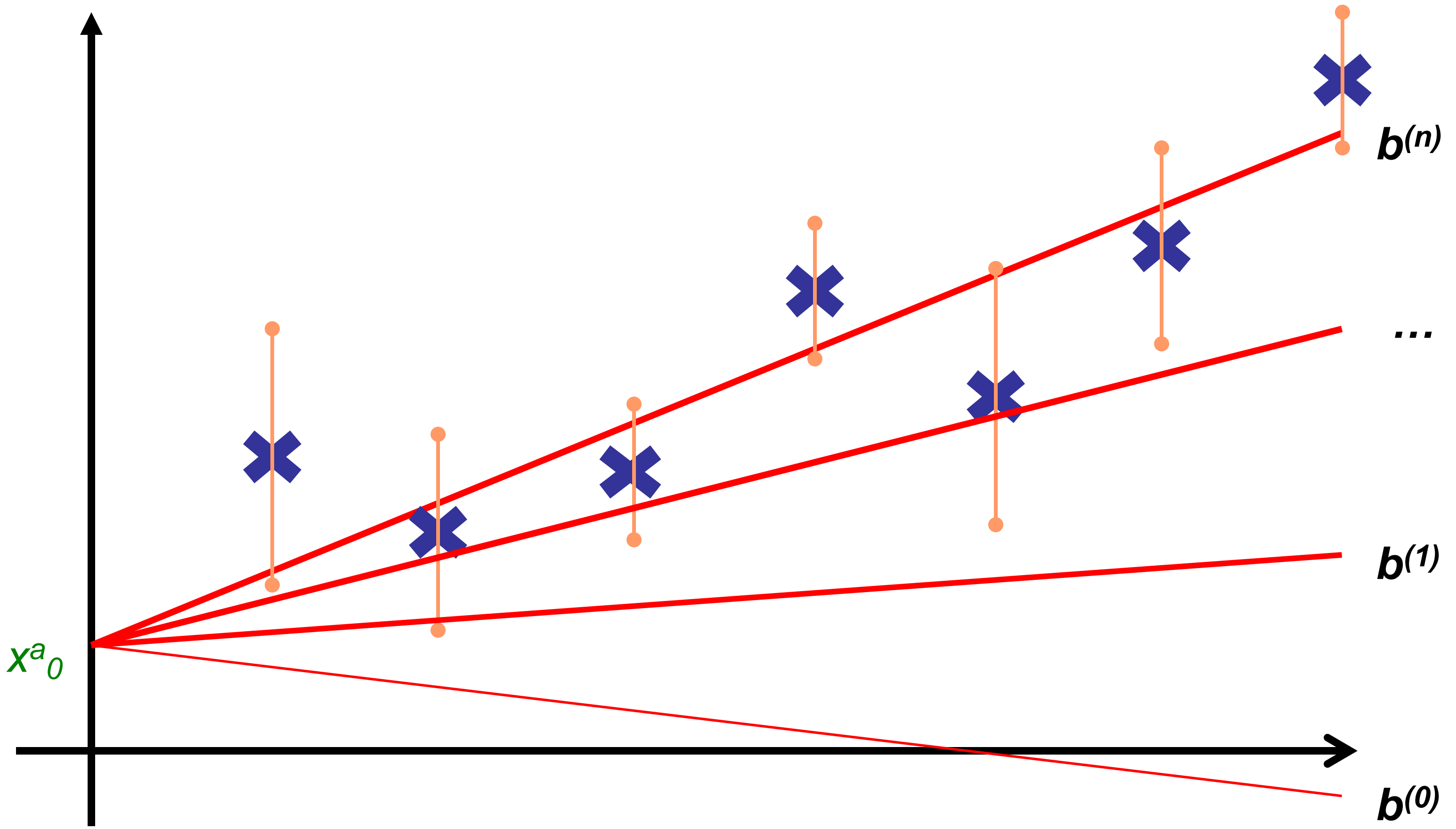
What do we mean by “validating the models”?



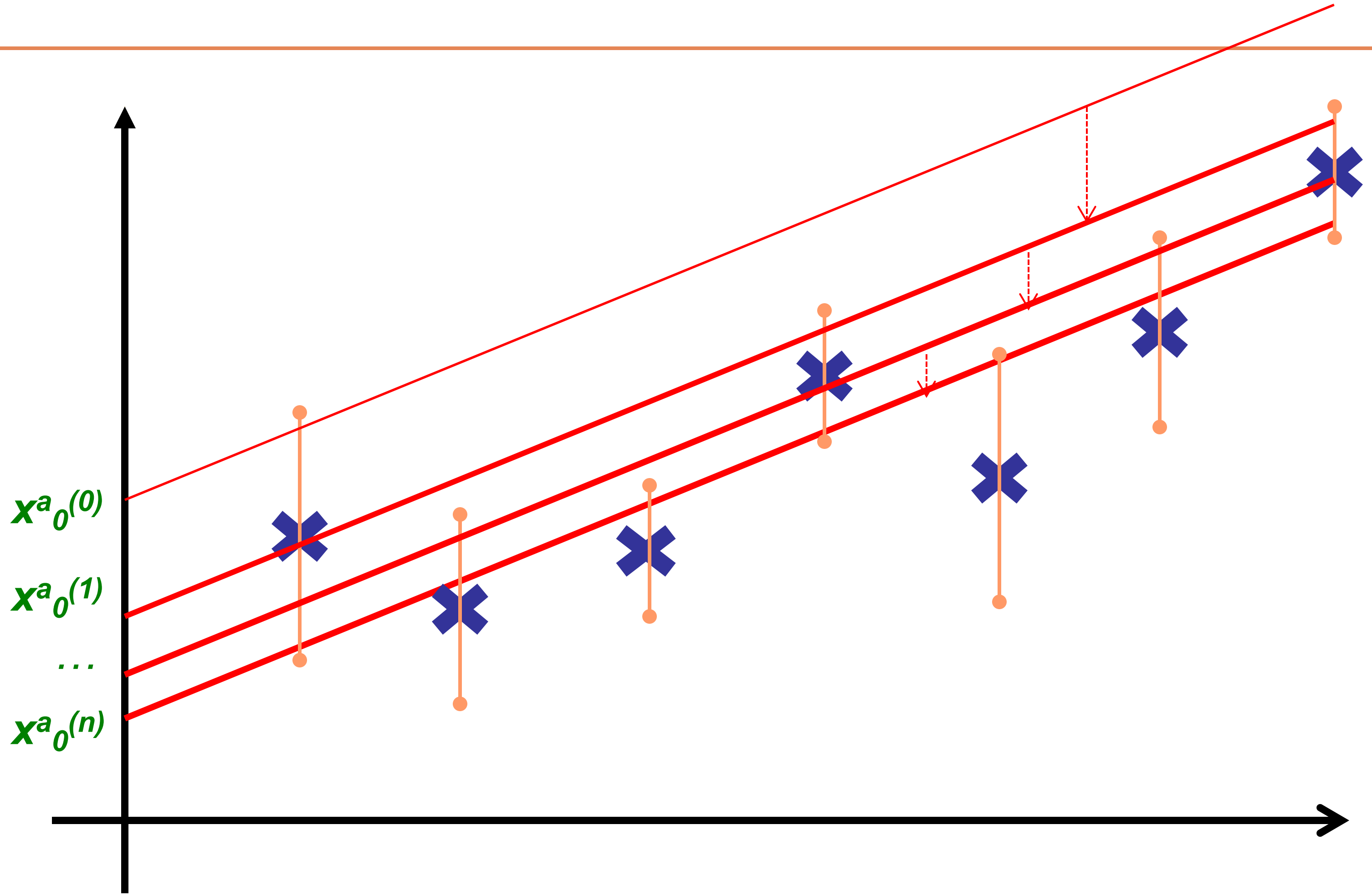
Least-squares fit of an (uncertain) model to uncertain data

$$x(t) = a + b\,t$$

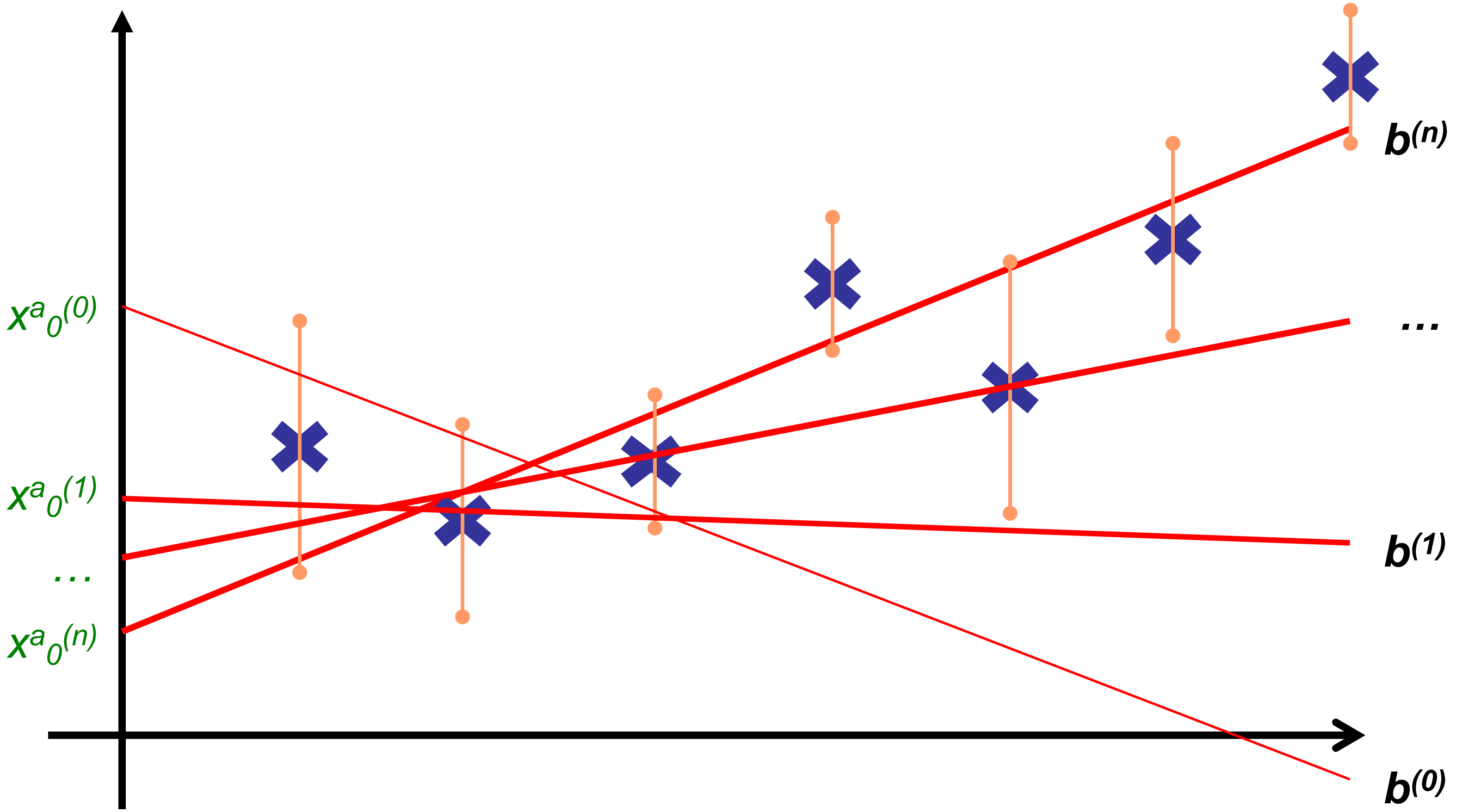
Think of ***b*** *(slope) as* *<u>model parameter</u>;* ***a*** *(intercept) as ”<u>initial condition</u>”*



- for model $x(t) = a + b\,t$
  - vary slope (i.e., “model parameter”) b
  - model calibration



- for model $\boldsymbol{x(t) = a + b\,t}$
  - vary constant (i.e., intercept) $\boldsymbol{a}$
  - model "initialization"



- for model $\boldsymbol{x(t) = a + b\, t}$, <u>*simultaneously vary*</u>
  - initial condition (i.e. "model state") $\boldsymbol{x^a(0) = a}$
  - and slope (i.e. "model parameter") $\boldsymbol{b}$

What do we mean by "validating the models"?

- **The purpose of Data Assimilation (or Bayesian inference):**

  combine imperfect knowledge in model, data, and priors, for "optimal"
  - parameter estimation – calibration
  - state estimation – reconstruction
  - model initialization for prediction (the classic NWP problem of DA)
  - flux inversion (e.g., CO_2)

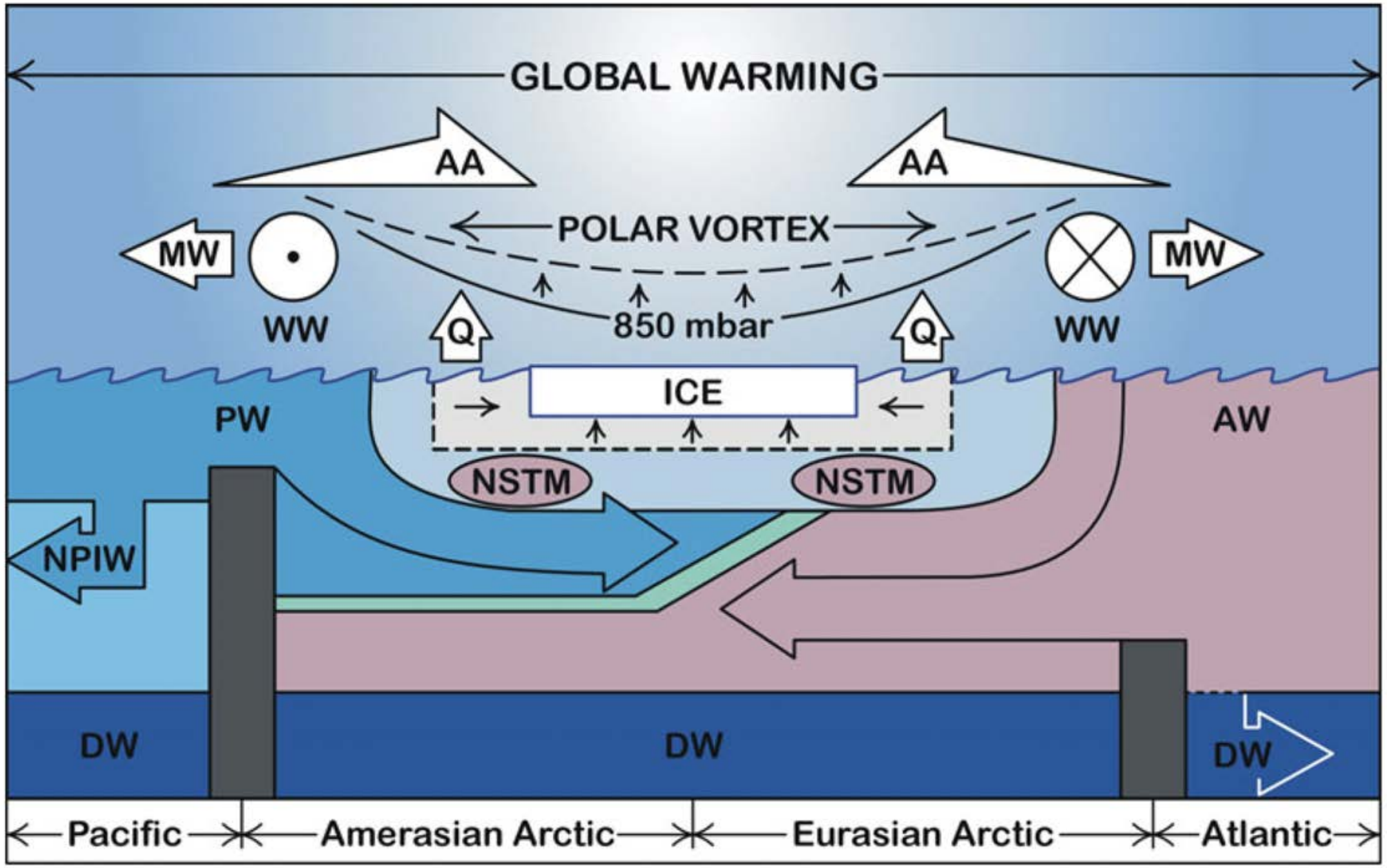
- **Data Assimilation comes with uncertainties too!**
  - Observation errors
  - Observational sampling: sparsity, inhomogeneity, …
  - Approximation of error covariances needed
  - DA methods differ

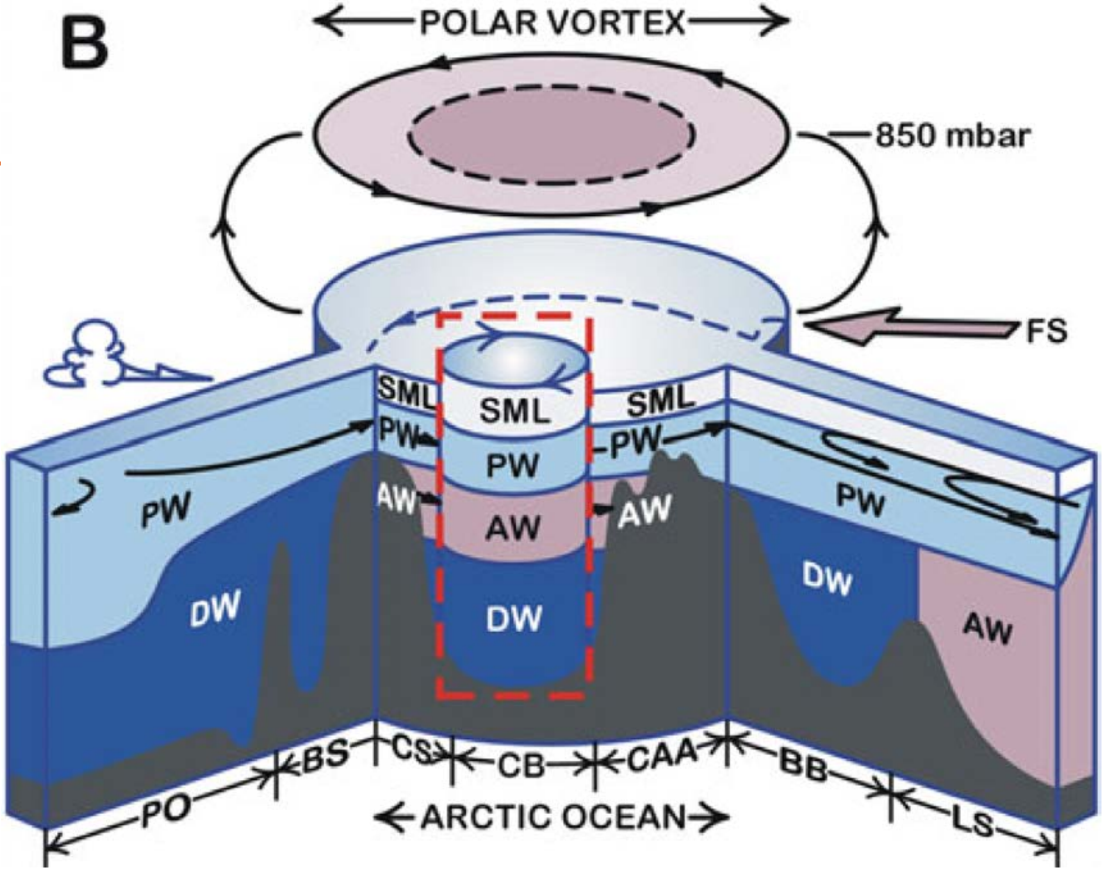
Let’s come back to:

“Models enable us to ask WHAT-IF experiments”

– Fundamental question of **system sensitivity**

Local vs. remote influences
Carmack et al. (AMBIO, 2012)

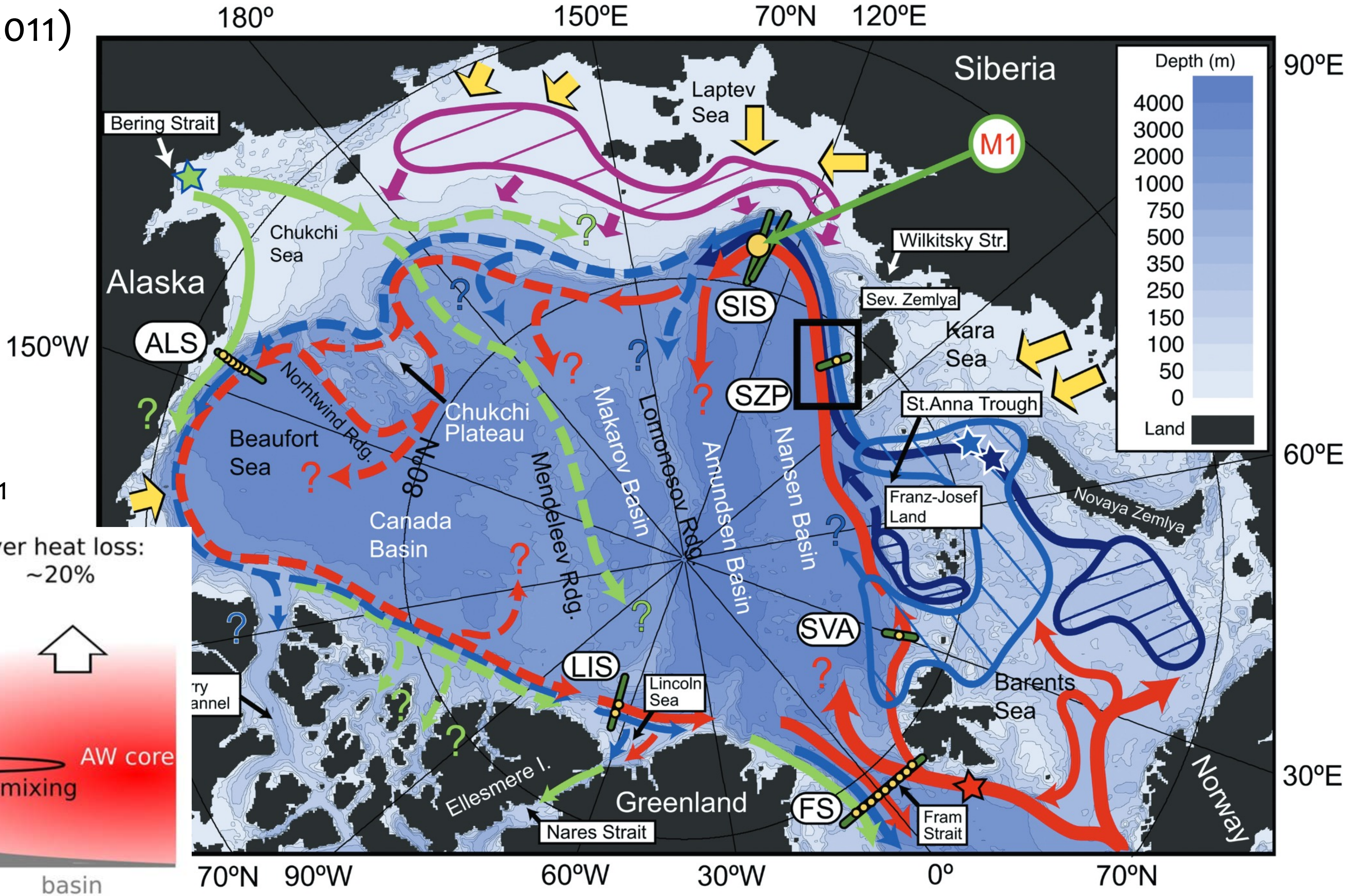




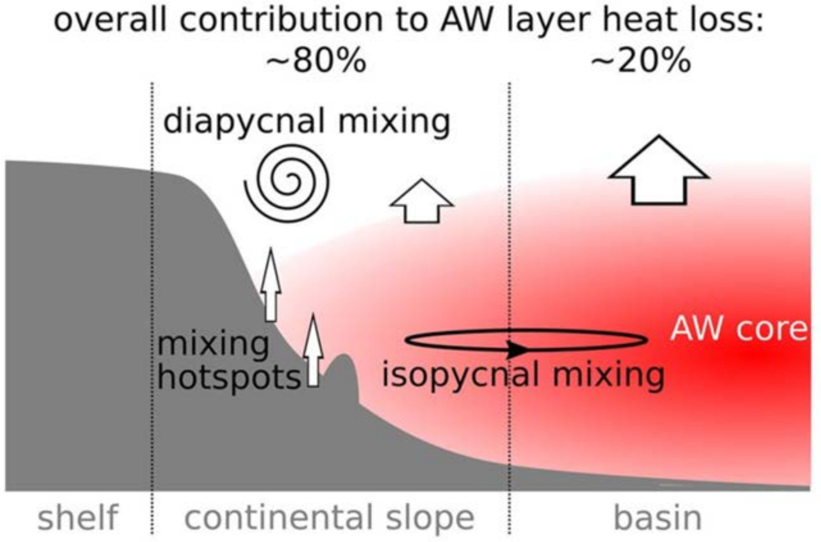
When we think about transport of heat vs. freshwater across the Arctic, we probably have different parts of "the circulation" in mind(?) E.g.:

- surface vs. depth
- locally vs. remotely forced

Arctic Circumpolar Boundary Circulation
Aksenov et al. (2011)



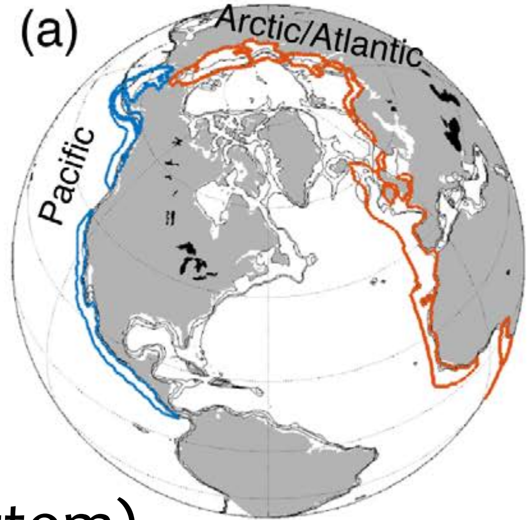
also Schulz et al., JGR, 2021

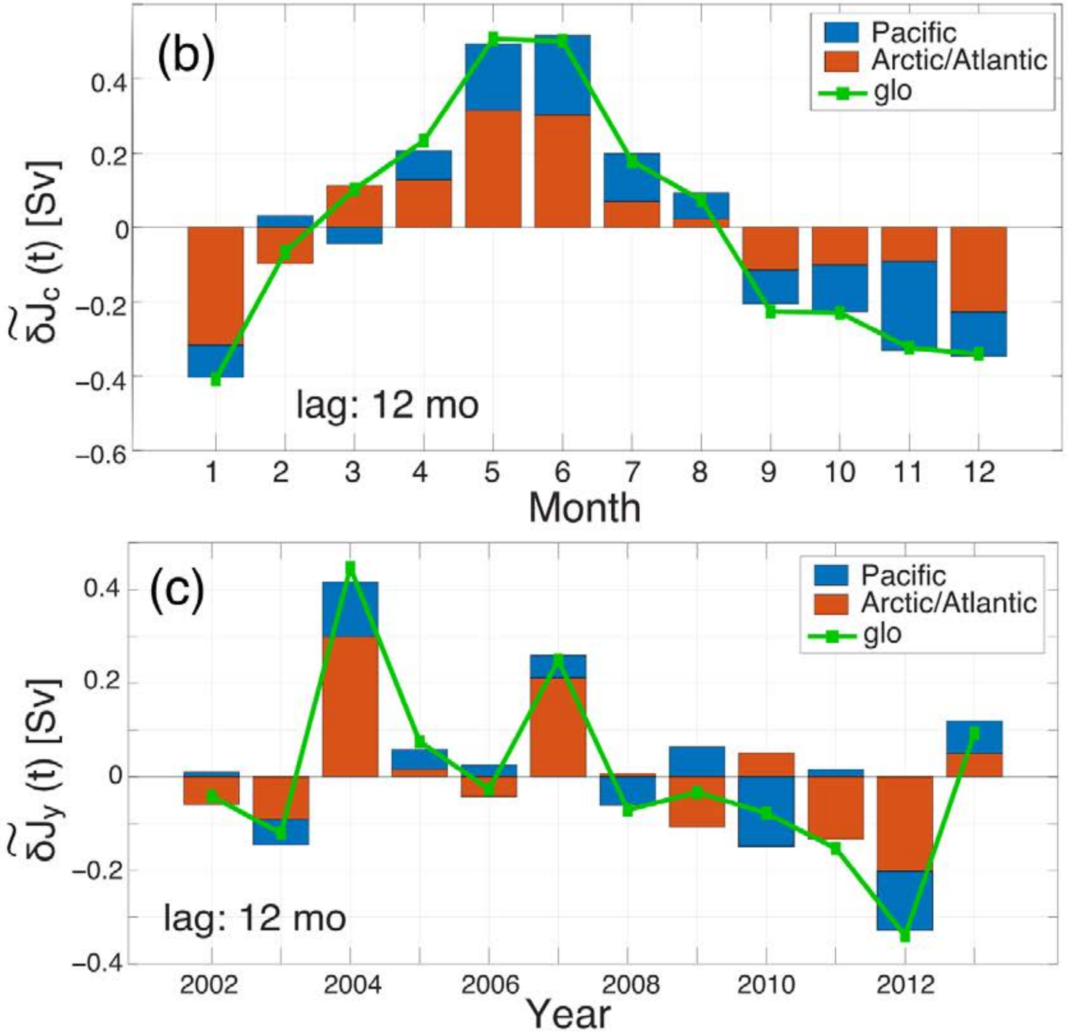


From conceptual drawings & correlation analysis to dynamical reconstruction of local vs. remote "drivers"

Case 1: Elucidating large-scale atmospheric controls on Bering Strait throughflow variability
<u>*Nguyen et al. (JGR, 2020)*</u>

$$\widetilde{\delta J}(t) = \sum_k \widetilde{\delta J}_k(t) = \sum_k \int_{t_0}^{t} \int_{x_1} \int_{x_2} \frac{\partial J}{\partial \Omega_k}(x_1, x_2, \alpha - t)\, \delta\Omega_k(x_1, x_2, \alpha)\, dx_1\, dx_2\, d\alpha,$$





Reconstruction of origins of

- seasonal cycle (top)
- interannual variability (bottom)

of volume transport through Bering Strait (= ***J***)

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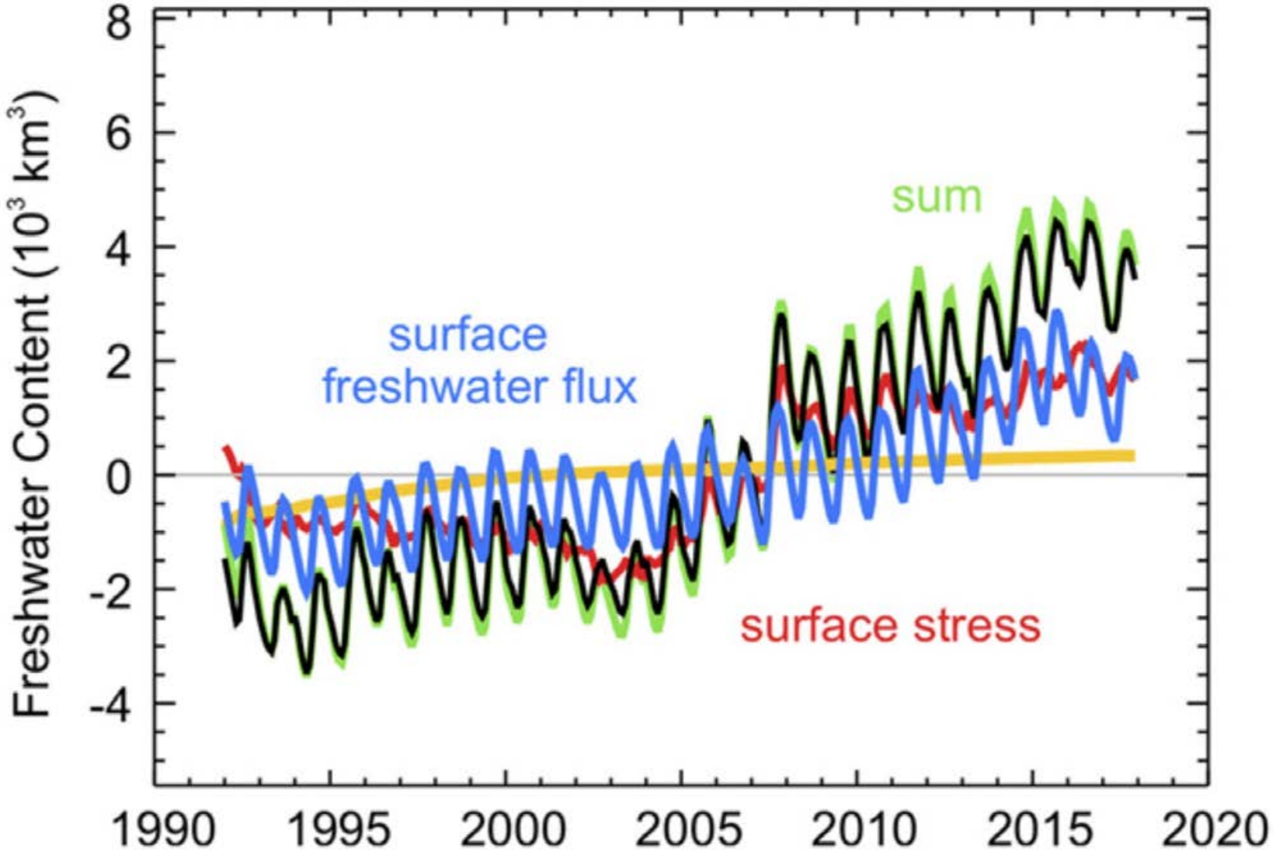
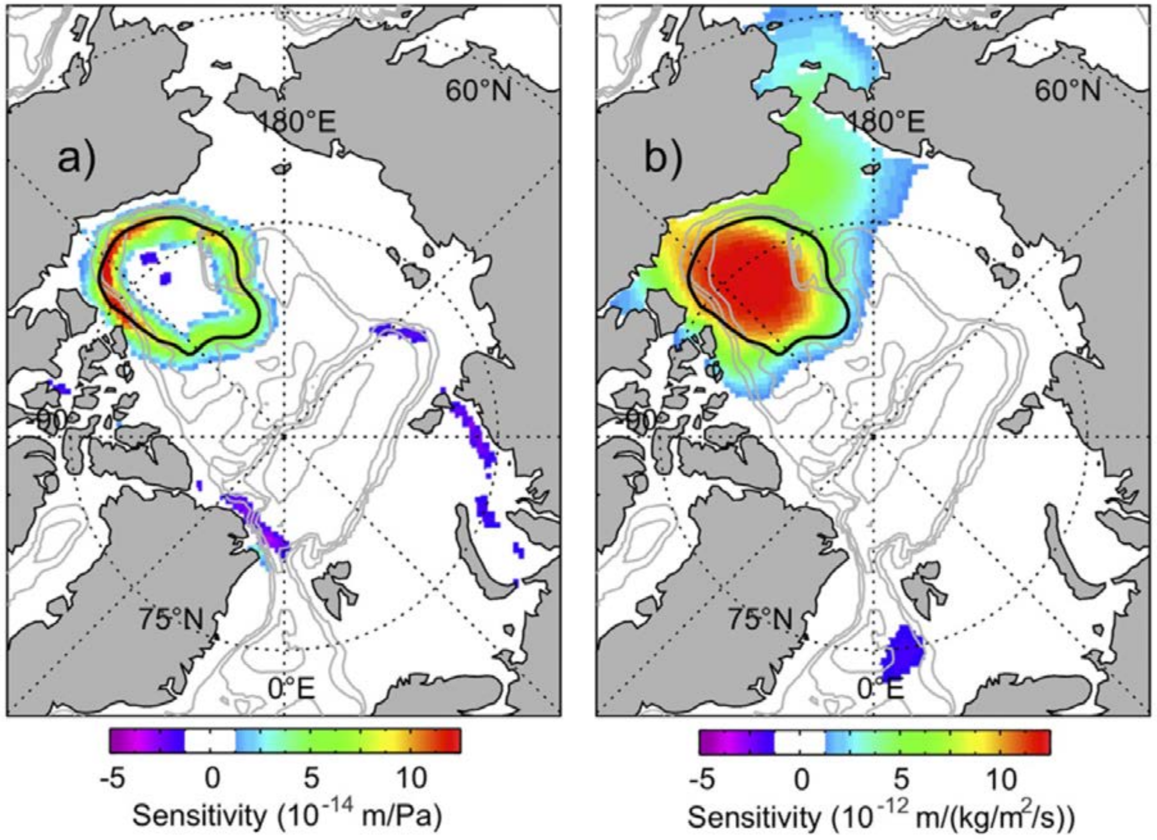
Case 2: Causal Mechanisms of Sea-level and Freshwater Content Change in the Beaufort Sea

Fukumori et al. (JPO, 2021)

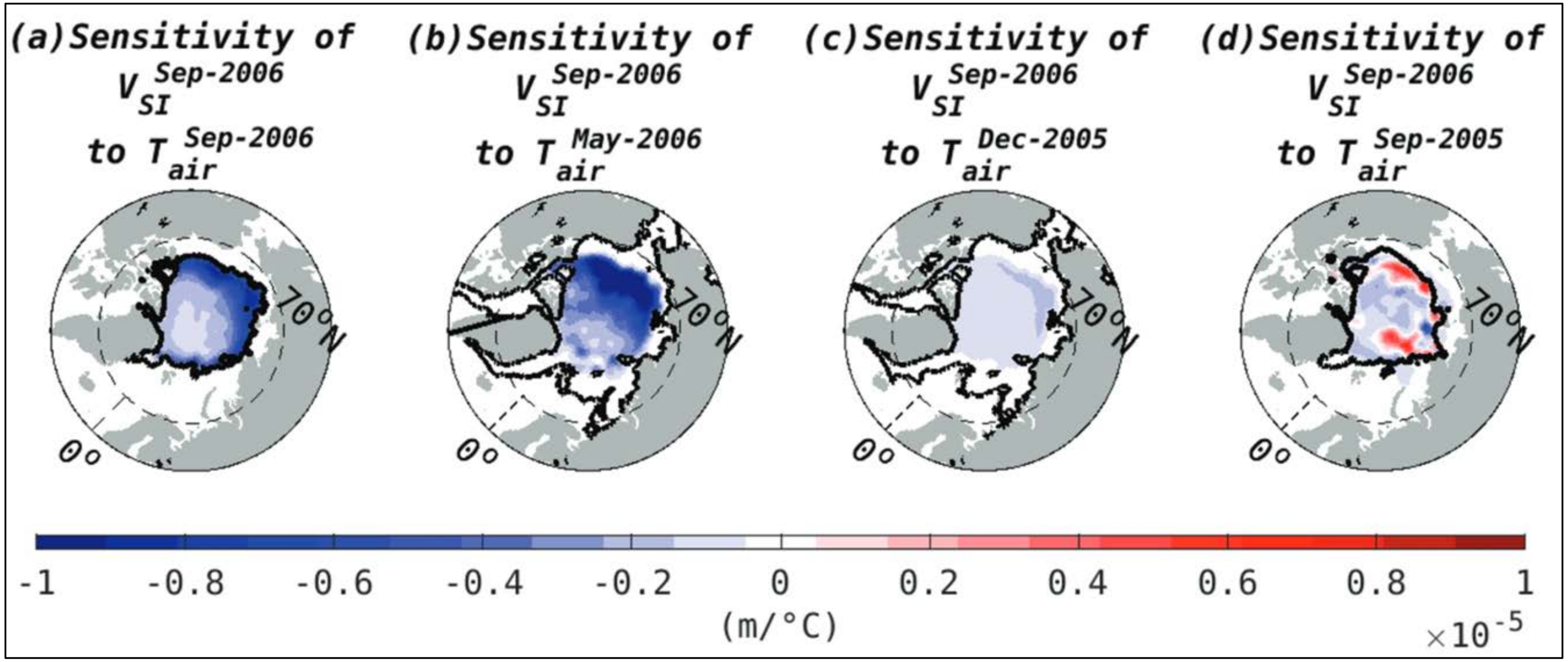
Reconstruction based on space-time resolved sensitivity patterns of ***J*** to different surface forcings

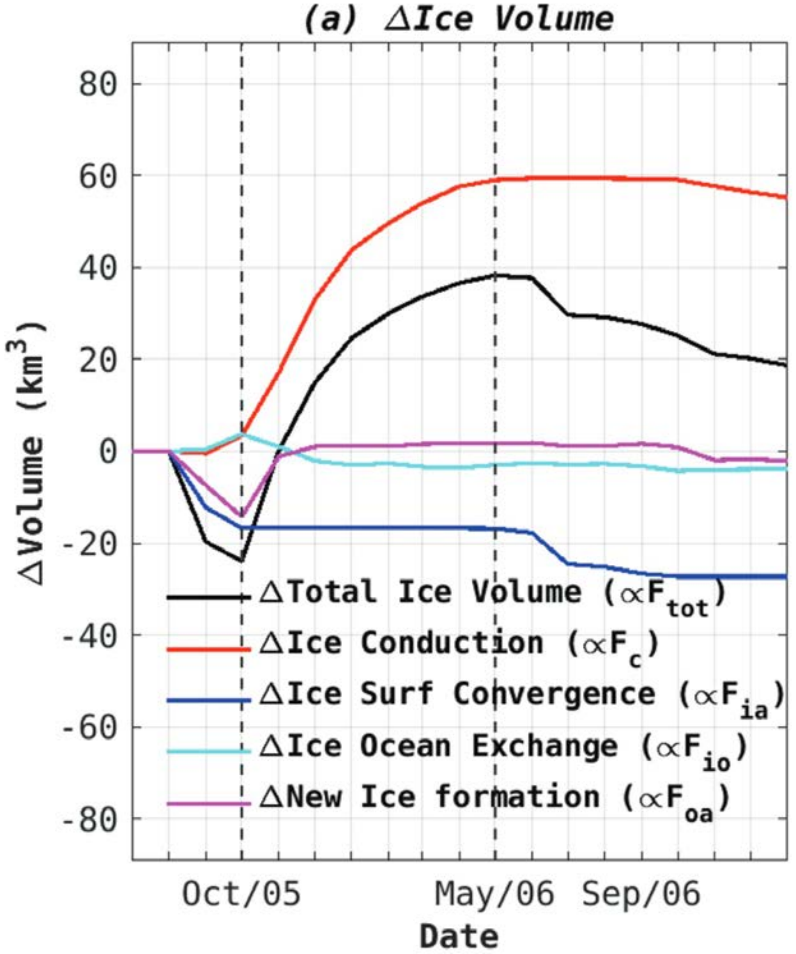
$$\delta J(t) \approx \sum_i \sum_{\mathbf{r}} \sum_{\Delta t} \frac{\partial J}{\partial \phi_i}(\mathbf{r}, \Delta t)\bigg|_{t_g} \delta\phi_i(\mathbf{r}, t-\Delta t).$$





Case 3: Role of snow cover in modulating Arctic sea ice growth
Bigdeli et al. (GRL, 2020)





snow-melt-conductivity feedback

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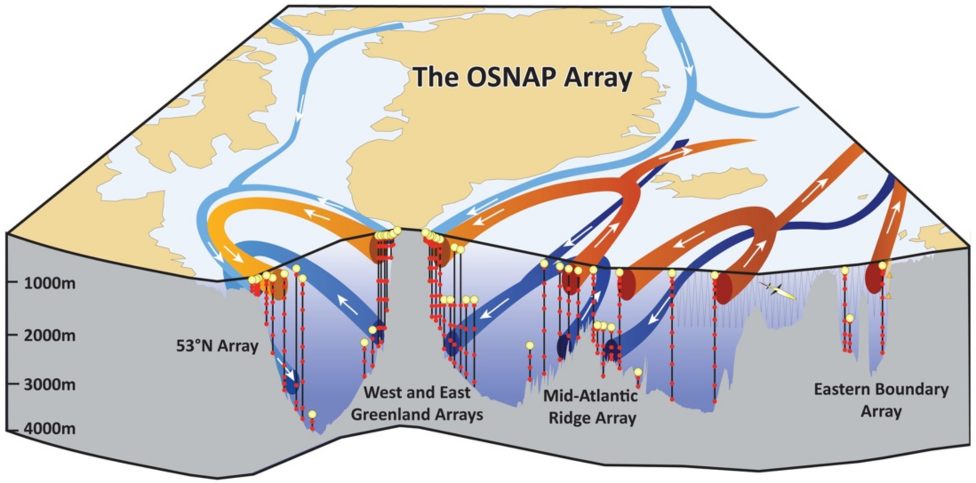
(How) can we use sensitivity information for quantitative observing system design?

Ocean Observing Systems



… are crucial for understanding the ocean's role in climate
… but are difficult & expensive to build and maintain

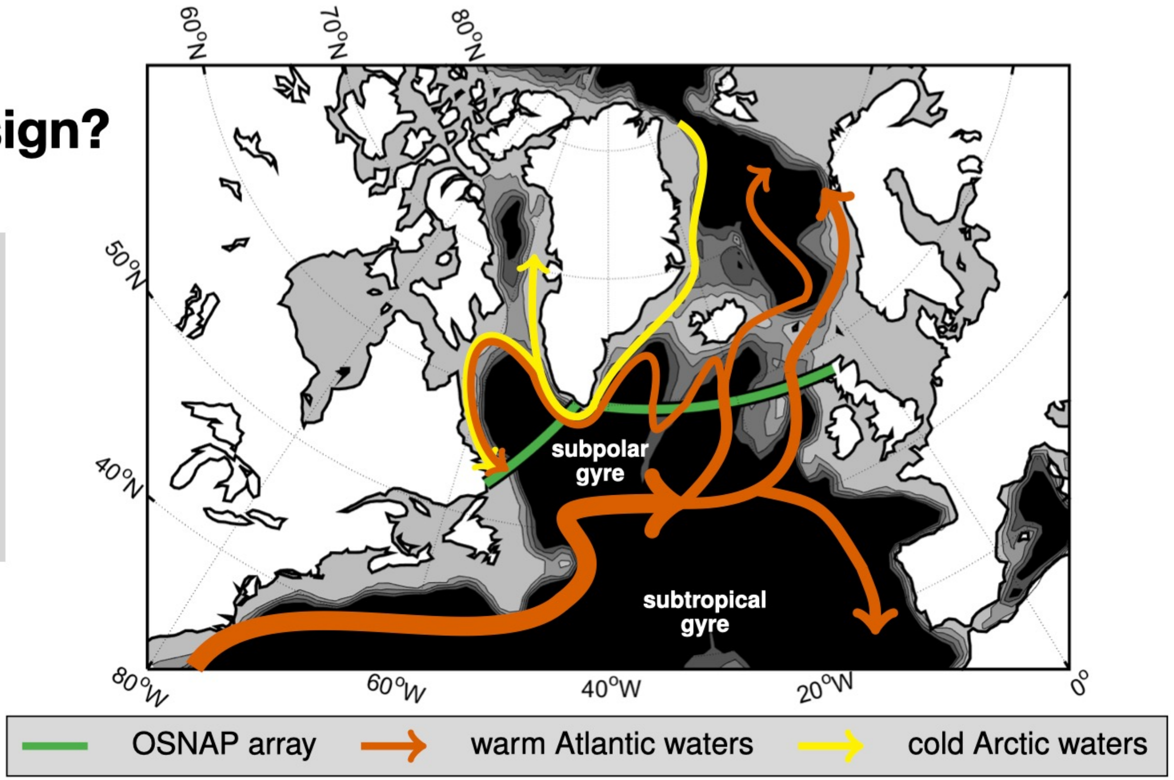
Overturning in the Subpolar North Atlantic Program (OSNAP)
http://www.o-snap.org
Lozier et al., 2019

How can ocean models inform observing system design?

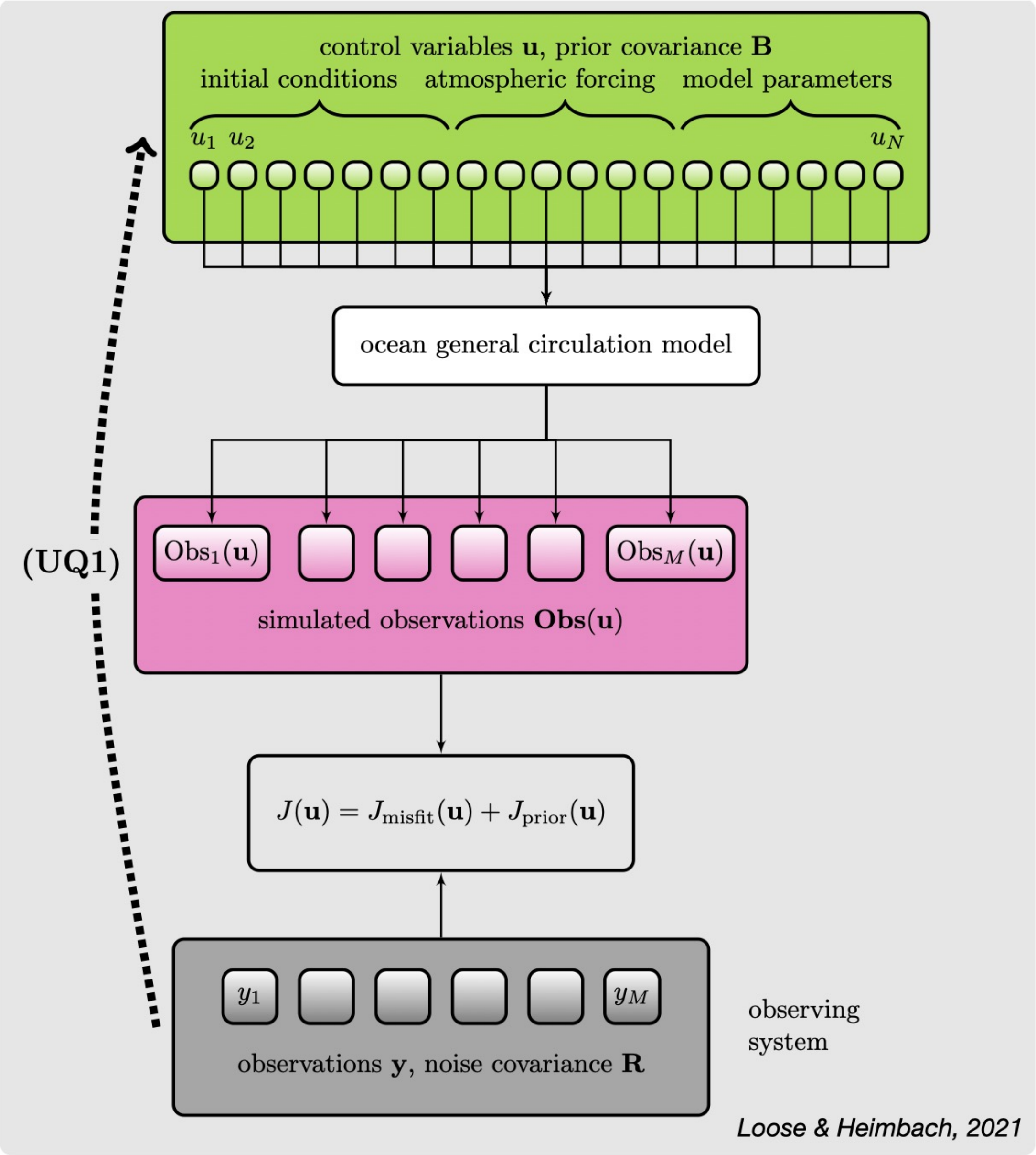
Idea:

- Use *oceanic teleconnections* that propagate observational constraints over long distances and can be exposed via the adjoint state
- Combine *adjoint-based estimation framework* with adjoint-based sensitivity analysis

→ **Quantitative design of ocean observing systems**



Uncertainty Quantification (UQ)



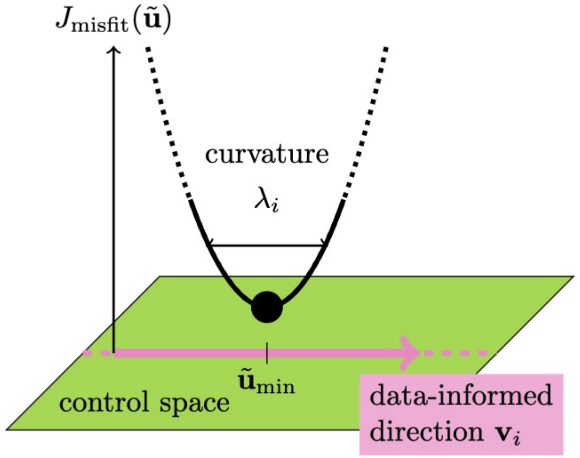
(UQ1): Inverse uncertainty propagation

From prior to posterior uncertainty

Observations — Simulated observations — First guess

$$J(\mathbf{u}) = \underbrace{\frac{1}{2}(\mathbf{y} - \mathbf{Obs}(\mathbf{u}))^T\, \mathbf{R}^{-1}\, (\mathbf{y} - \mathbf{Obs}(\mathbf{u}))}_{J_{\mathrm{misfit}}(\mathbf{u})} + \underbrace{\frac{1}{2}(\mathbf{u} - \mathbf{u}_0)^T\, \mathbf{B}^{-1}\, (\mathbf{u} - \mathbf{u}_0)}_{J_{\mathrm{prior}}(\mathbf{u})}\,.$$

Uncertain model inputs — Observation uncertainties — Prior uncertainties



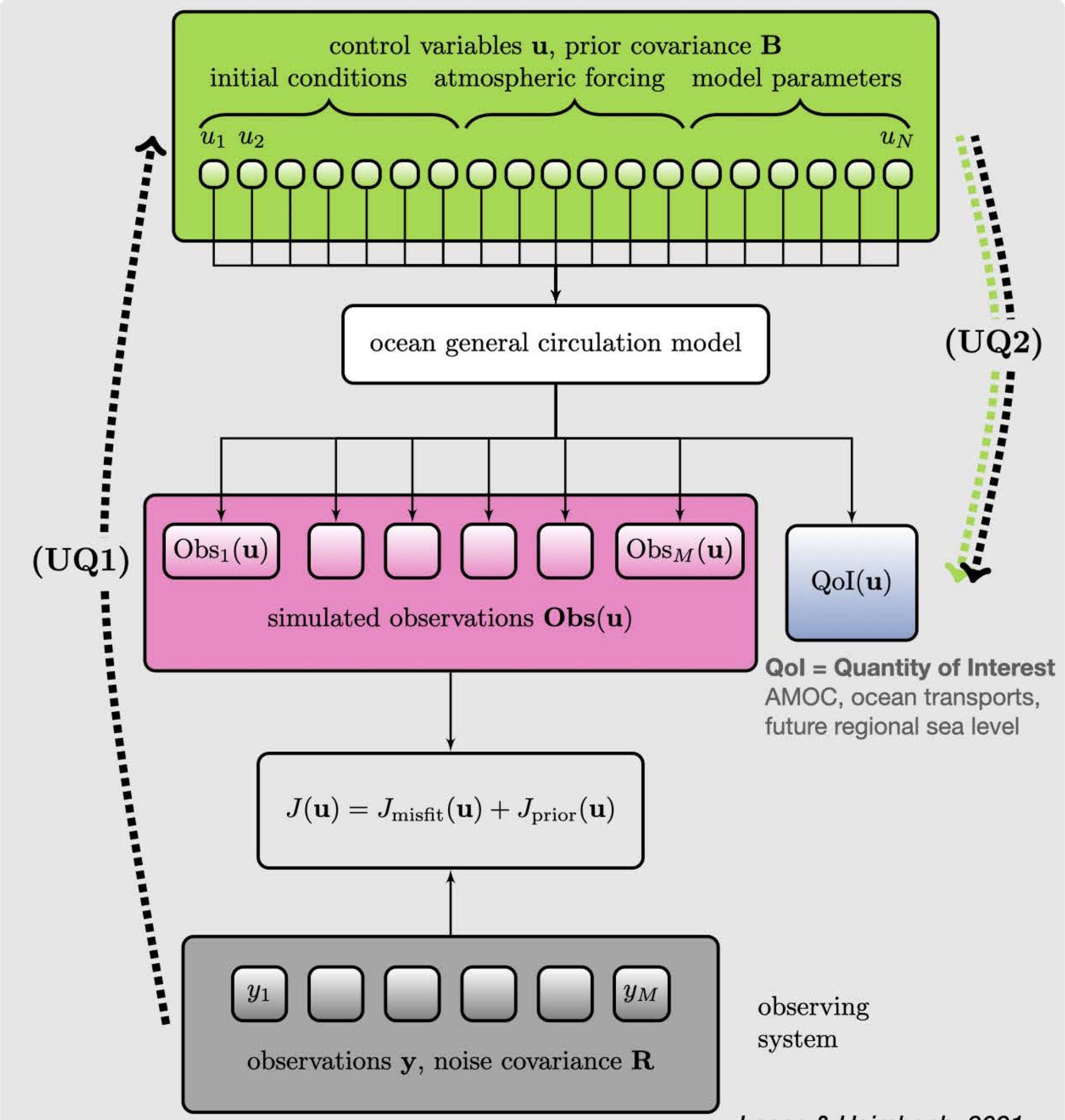
Hessian of cost function J

$$\mathbf{H}_J \approx \sum_{i=1}^{M} \lambda_i \mathbf{v}_i \mathbf{v}_i^T$$

Thacker, 1989

***posterior uncertainty** ~ inverse Hessian of J*

Uncertainty Quantification (UQ)



Loose & Heimbach, 2021

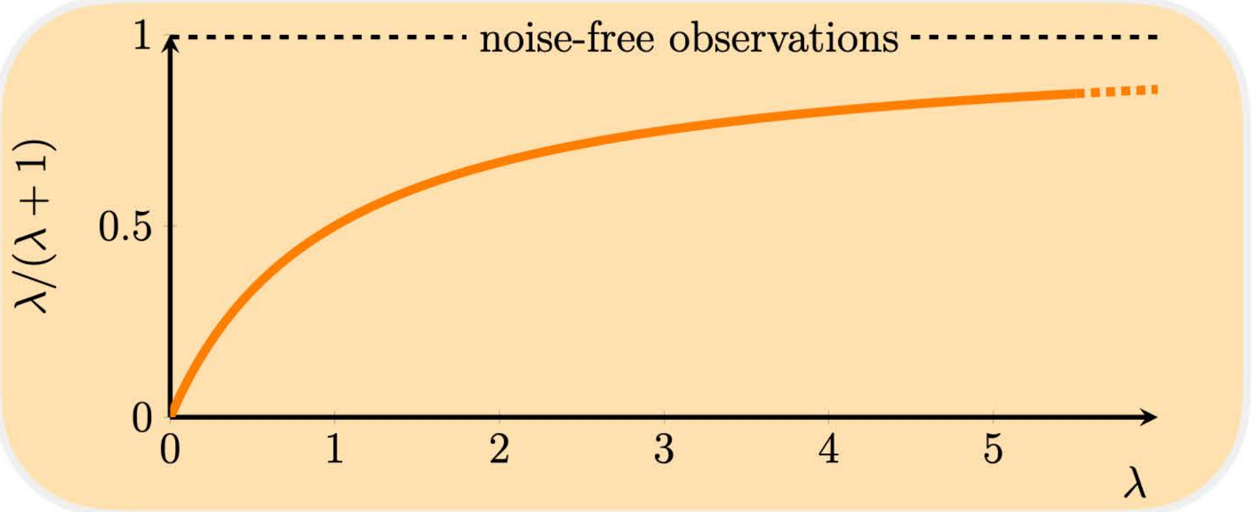
(UQ2): Forward uncertainty propagation

From posterior to QoI uncertainty

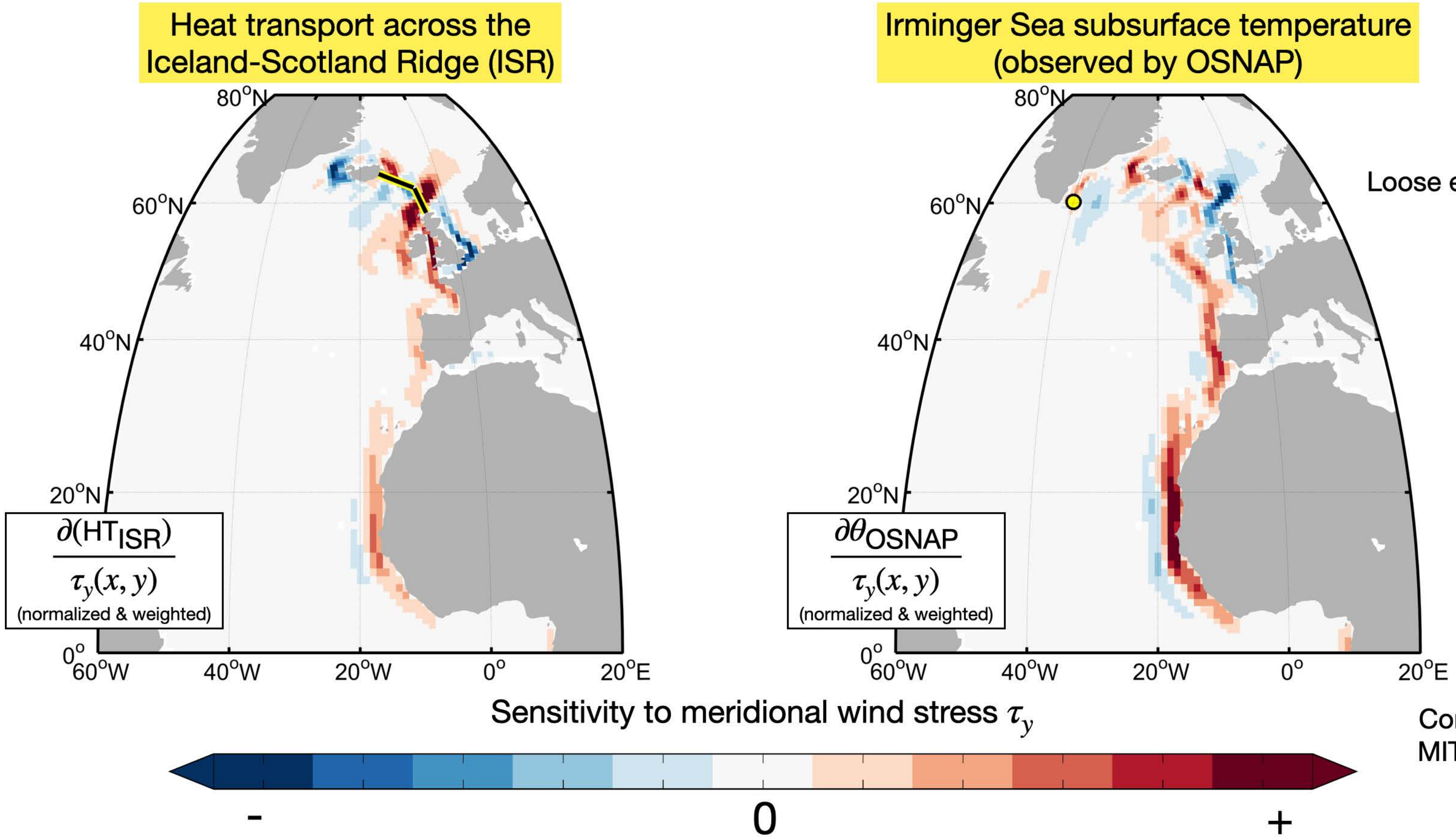
Uncertainty reduction in quantity of interest (QoI) by observing system:

$$\sum_{i=1}^{M} \frac{\lambda_i}{\lambda_i + 1} (\mathbf{q} \bullet \mathbf{v}_i)^2 \in [0, 1) \qquad \text{where} \qquad \mathbf{q} = \frac{\mathbf{B}^{T/2}\,\nabla_u \mathrm{QoI}}{\|\mathbf{B}^{T/2}\,\nabla_u \mathrm{QoI}\|}$$

$(\mathbf{q} \bullet \mathbf{v}_i)^2$ = Degree of shared adjustment mechanisms between observing system and QoI



Sensitivity maps identify shared adjustment mechanisms & pathways

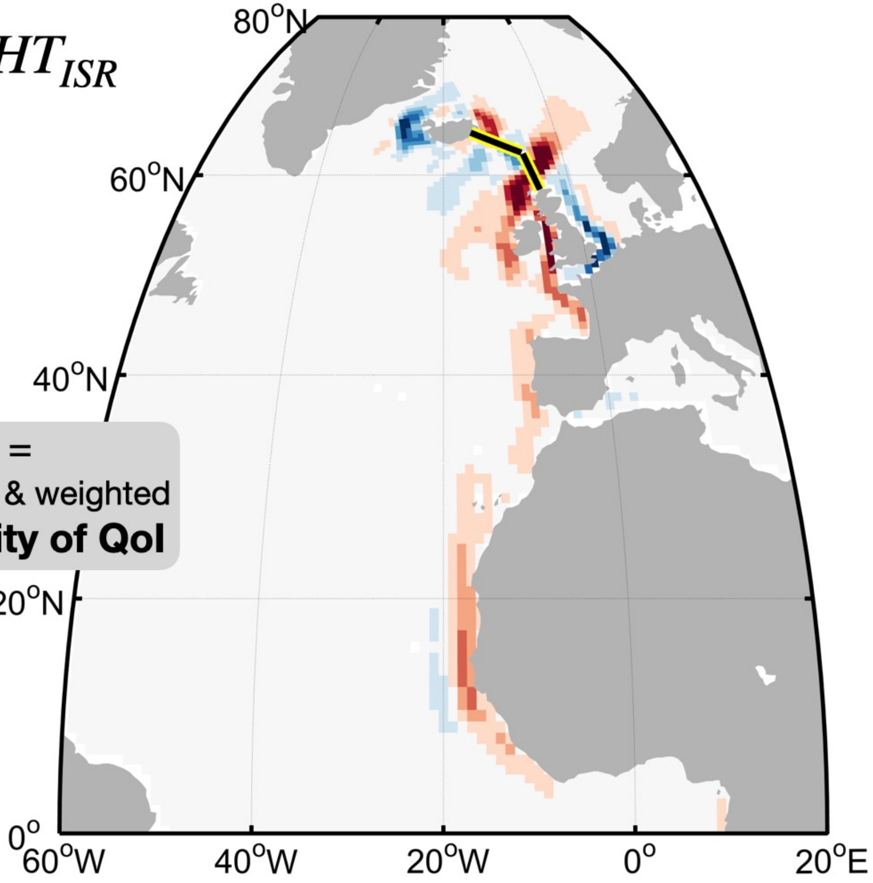


Loose et al., 2020

Computed with MITgcm adjoint model

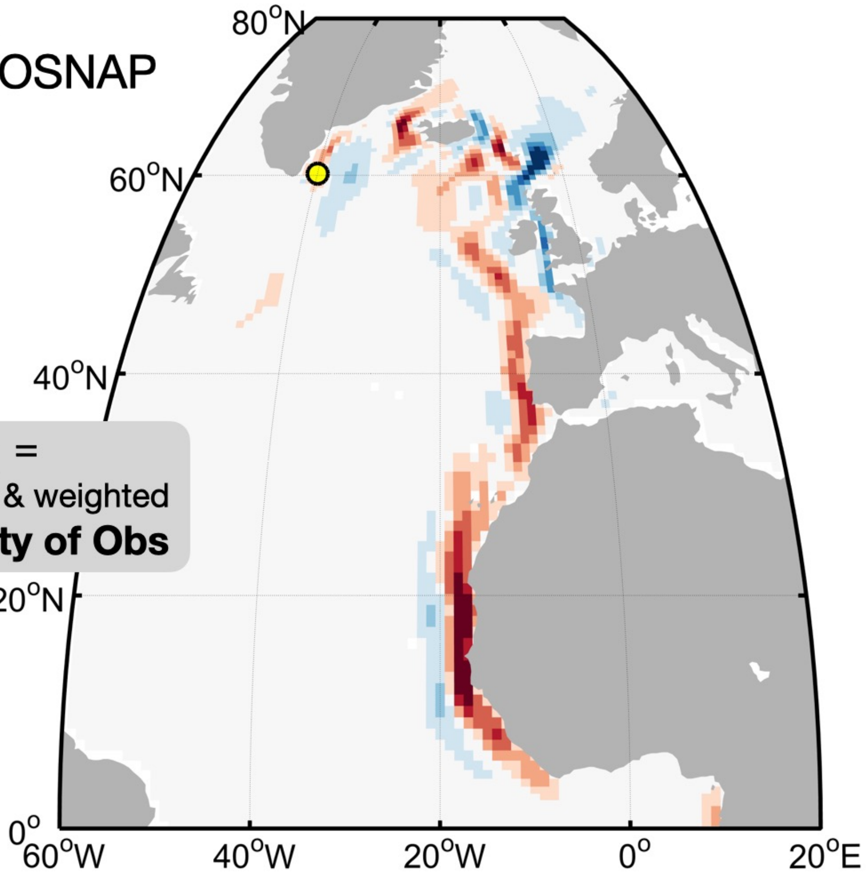
Sensitivity maps re-interpreted in the context of UQ

QoI: HT_{ISR}



$\mathbf{q}$ =
normalized & weighted
sensitivity of QoI

Obs: θ_{OSNAP}

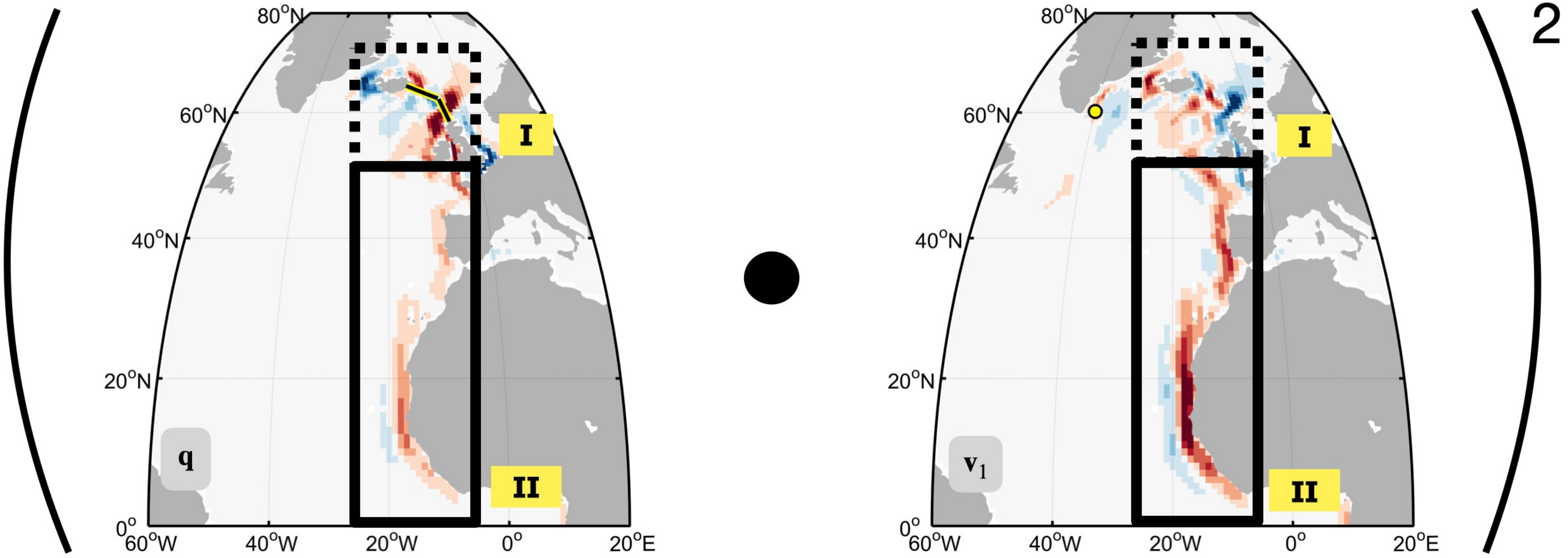


$\mathbf{v}_1$ =
normalized & weighted
sensitivity of Obs

$\mathbf{v}_1$ = **Hessian eigenvector** (in ECCO)

$\left(\mathbf{q} \bullet \mathbf{v}_1\right)^2$ = uncertainty reduction in HT_{ISR} by noise-free θ_{OSNAP} observation

Uncertainty reduction via oceanic teleconnections

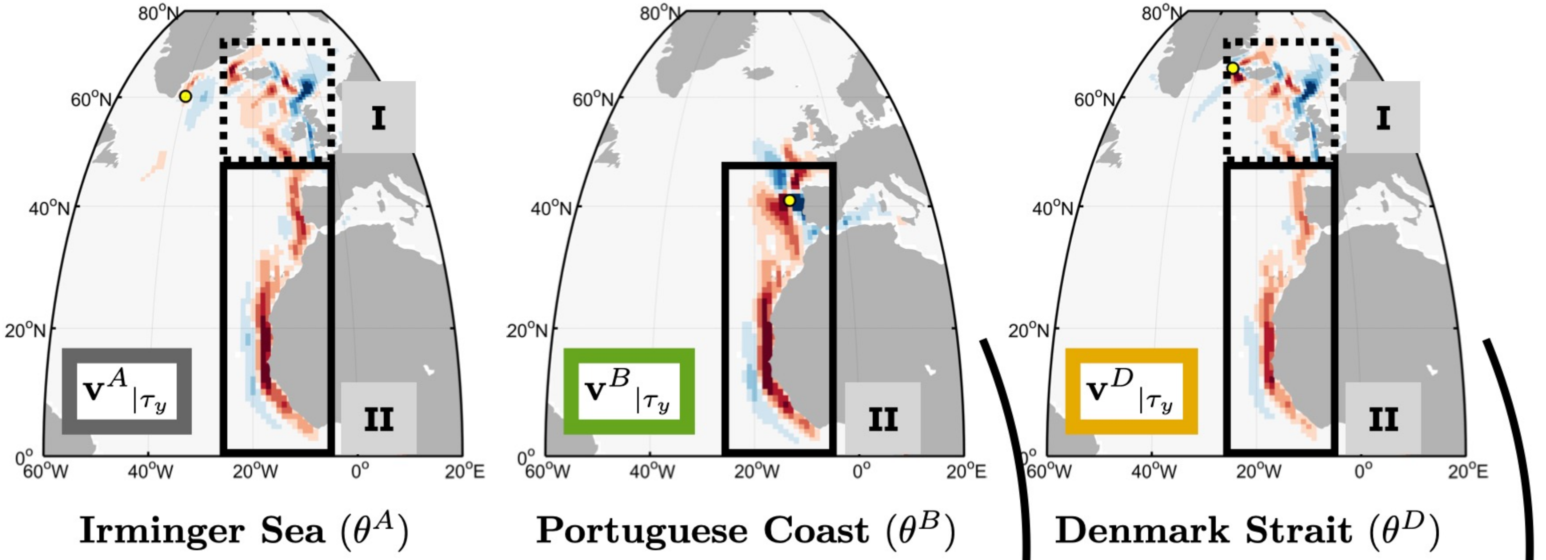


Uncertainty reduction in HT_{ISR} by noise-free θ_{OSNAP} observation:

$$\boxed{(\mathbf{q} \bullet \mathbf{v}_1)^2} = (\underbrace{[\mathbf{q} \bullet \mathbf{v}_1]_+}_{\text{II}} + \underbrace{[\mathbf{q} \bullet \mathbf{v}_1]_-}_{\text{I}})^2 = (0.15 + (-0.59))^2 = (-0.44)^2 = 19\%$$

- **Shared adjustment mechanisms lead to large uncertainty reduction**
- **BUT: destructive interference is possible**

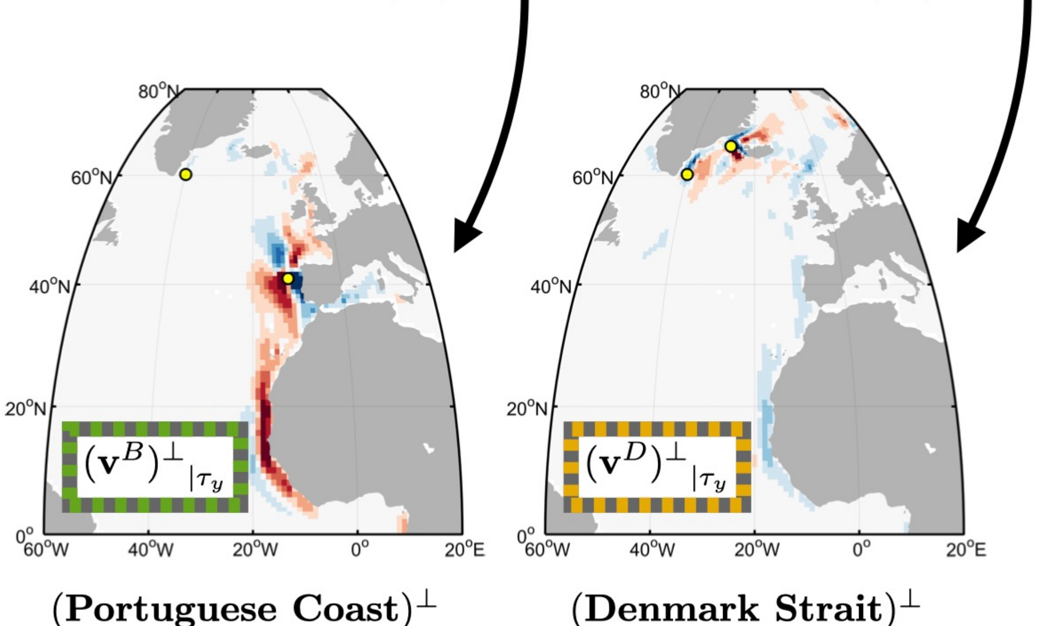
Assessing data redundancy vs. complementarity



Orthonormalization
(Hessian eigenvectors are orthonormal)

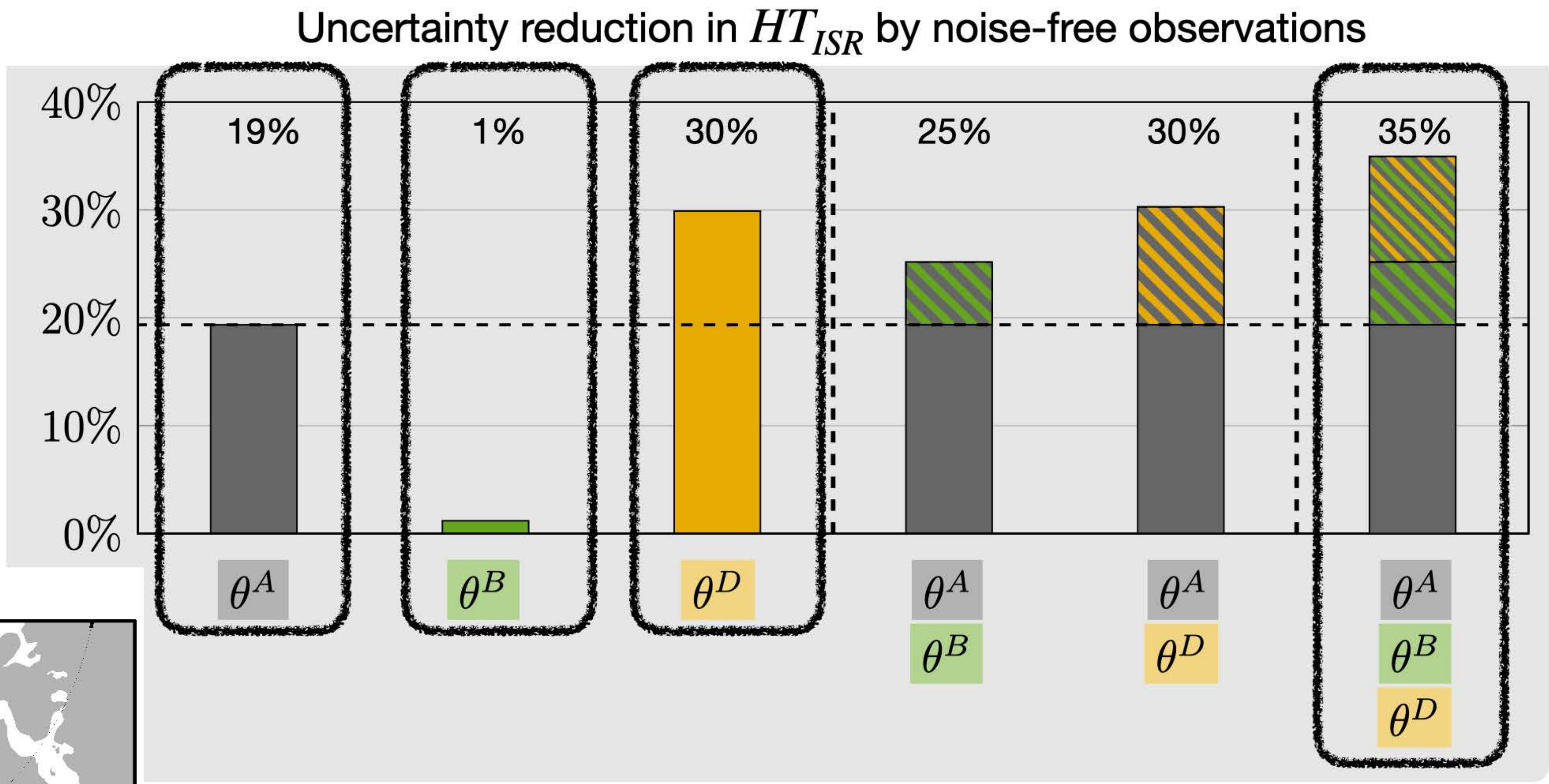
↓

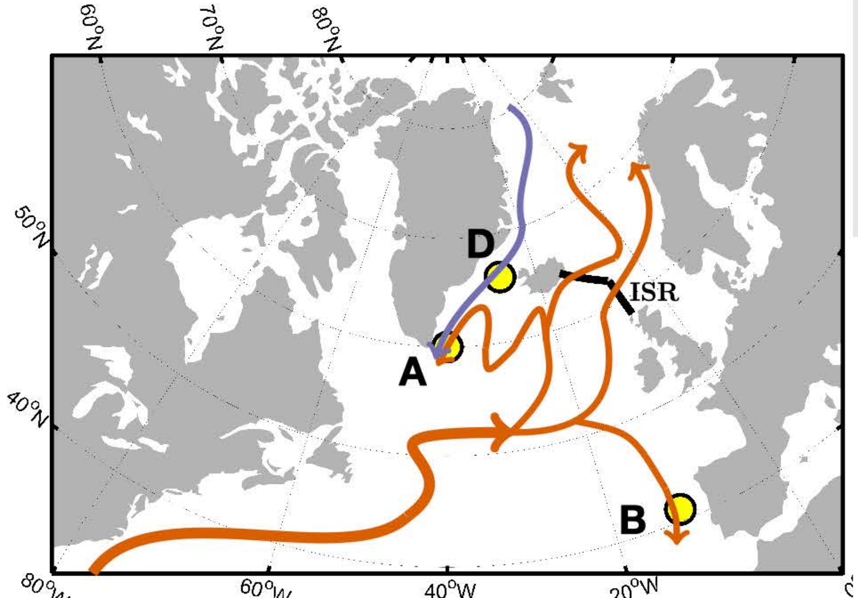
Removal of redundant information



Loose & Heimbach, 2021

Assessing data redundancy vs. complementarity





- Adding observation A (in the Irminger Sea) to observation D (in Denmark Strait) gives no extra information due to **data redundancy**
- Observation A (in the Irminger Sea) and observation B (off Portugal) show **data complementarity**

Conclusion: try to formulate what are we after?

- Documenting ”circulation changes” in response to climate change?
  - What “circulation”?
  - Can we develop compelling metrics?
- Assessing …
  - freshwater storage, transports, changes?
  - heat storage, transports, changes?
  - changes in biogeochemical cycles and ecosystems (some of which constrained by the physics)?

  Those are likely different (different sources, different key depths, …)
- Air-ice-ocean interactions
  - Relevant for both near-surface atmosphere & ocean
  - Both poorly observed / constrained
- …