Local winds drive interannual variability of the Gulf Stream North Wall Path Results from an adjoint sensitivity analysis (PL24B-2665)

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1. Gulf Stream North Wall

- The north edge of the Gulf Stream is marked by strong temperature front referred to as the **North Wall**.
- The North Wall **migrates meridionally** by up to 2° on interannual timescales.
- Changes in the position of the North Wall have significant impacts on local biology and climate, and has even been shown to influence biogeochemical cycles in European lakes and estuaries (e.g., Taylor 1995).

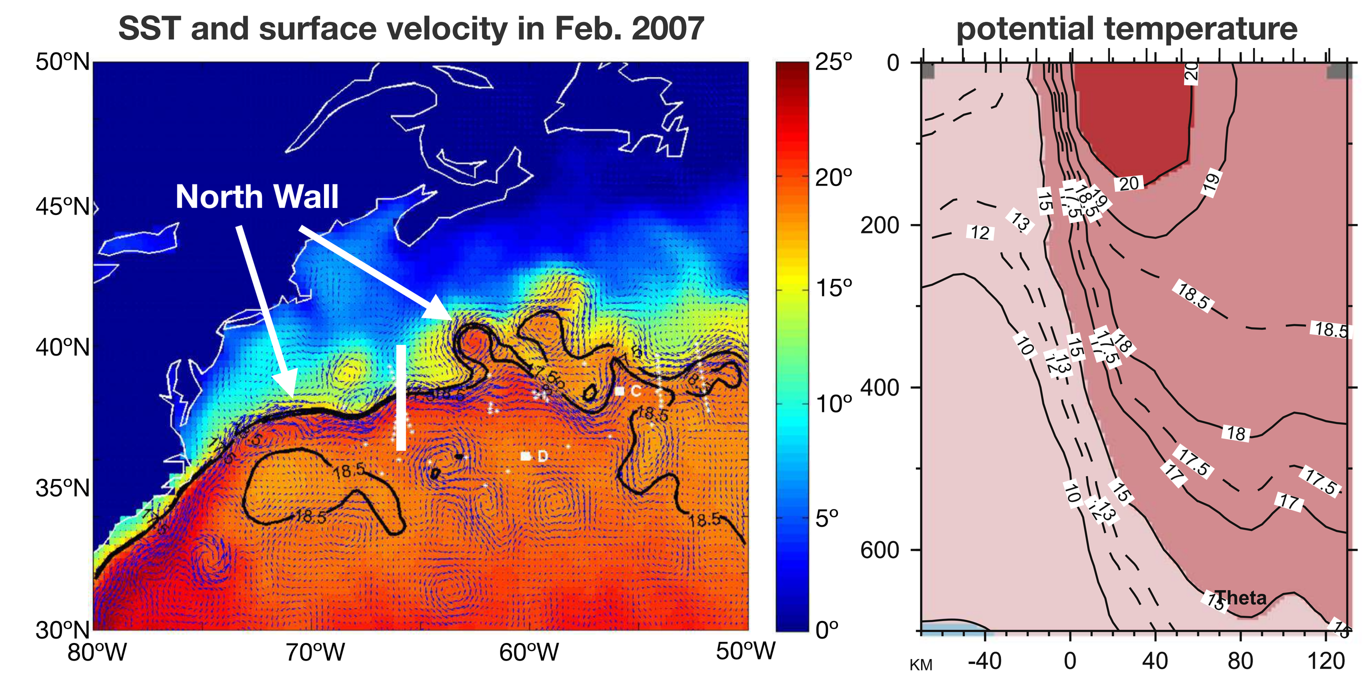


Figure 1: Left: Mean SST and surface velocity in the Gulf Stream region during the 2007 CLIMODE experiment. **Right:** Potential temperature section along the white line shown in the left panel (north on the left). Source: Joyce et al. (2013).

Atmospheric forcing, the North Wall, and the North Atlantic Oscillation

- North Wall shifts are correlated with the North Atlantic Oscillation (NAO) with a lag of 0–2 years. Proposed mechanisms include
  - **Rossby waves** excited by changes in wind stress curl (e.g., Marshall et al. 2001; Taylor and Gangopadyay 2001; Sasaki and Schneider 2011); however, the lag between the NAO and North Wall is short compared to the Rossby wave crossing time (4+ years)
  - Advection in boundary currents of thermal or mechanical signals generated at **high** (Rossby 1999) or **low** latitude (Hameed et al. 2018)
- Here we use an adjoint sensitivity analysis to show that **most interannual variability is driven by winds** over and immediately east of the Gulf Stream extension.

2. Data and Background

Gulf Stream Index

- The North Wall is typically colocated with the 15°C isotherm (Fig. 1); the position of the **15°C isotherm at 200 m depth** (T_{200} = 15°C) serves as an operational definition of the North Wall position
- Joyce et al. (2000): the **Gulf Stream Index (GSI)** is the first PC of 200-m temperature at a sequence of points located along the mean path of the North Wall.
- The EOF is **single-signed**—representing **a coherent north-south shift** of the North Wall—and captures more than 50% of the variance on interannual time scales.

ECCOv4 Release 2

- ECCOv4r2 is a **dynamically consistent** estimate of the ocean state from 1992–2011 based on a wide range of remote and *in situ* observations (Forget et al. 2015)
- Comes with well-developed adjoint modeling system
- ECCOv4 has the **best representation of the Gulf Stream** of coarse-resolution ocean reanalyses (Chi et al. 2018)
- **GSI in ECCOv4r2:**
  - Explains >75% of the interannual variance of temperature at the points in figure 2a
  - Is **significantly correlated** (r = 0.60) with the observed GSI—not an exact match, but captures the gross features of the index

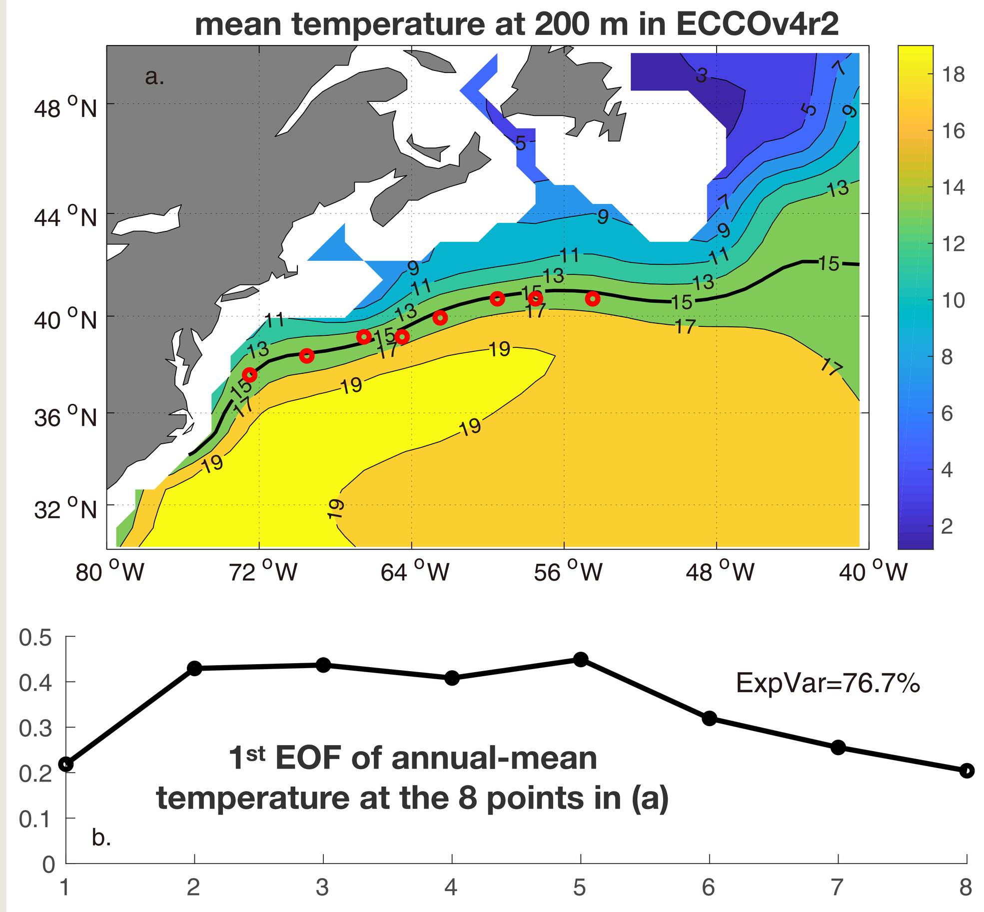
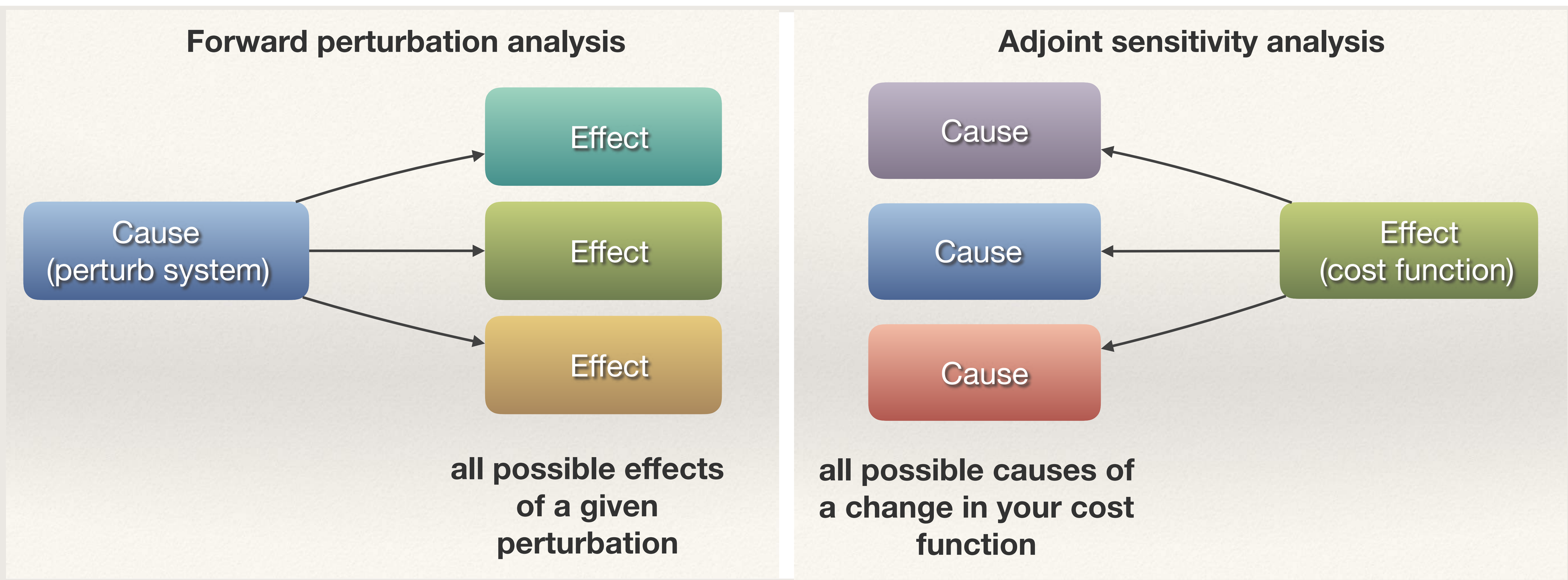


Figure 2: (a) Mean temperature at 200 m in ECCOv4r2. Red circles indicate the 8 points used to calculate the GSI. (b) Loading pattern of the GSI.

3. Adjoint Sensitivity of the Gulf Stream Index



- The adjoint provides gradients of the cost function (i.e., sensitivities) with respect to control parameters
- Here, the **cost function is the GSI** (temperature weighted by EOF in figure 2) and the controls are atmospheric forcing fields
  - Caveats: 1) Sensitivities are **linear** 2) Adjoint is **approximate** (some "nasty" physics are simplified)

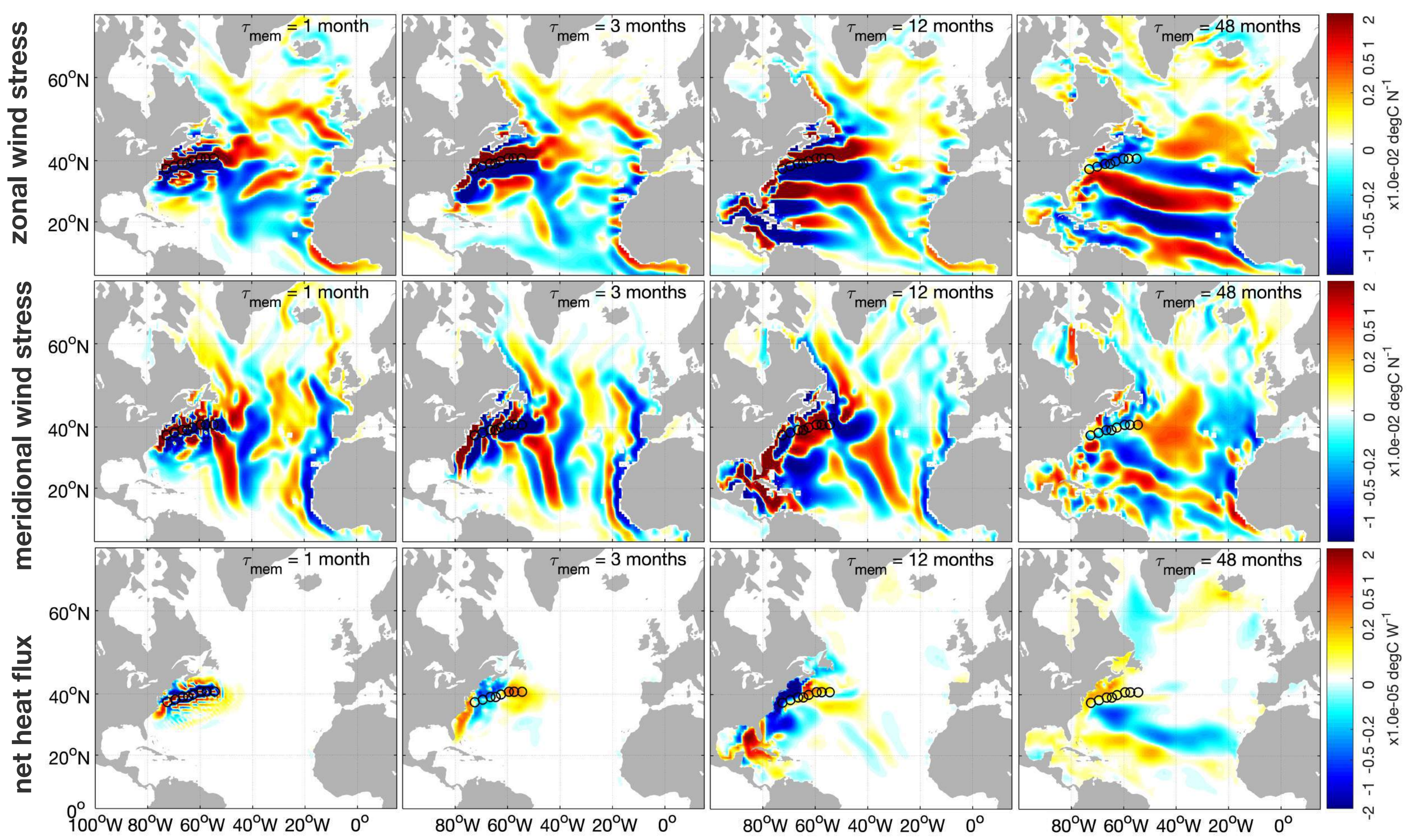


Figure 3: Adjoint sensitivity of the Dec. 2002 GSI to atmospheric forcing for different lead times, τ_{mem}, scaled by grid-cell area. The color scale is nonlinear to show detail near zero. Black circles give the location of the points used to calculate the GSI. The sensitivity to freshwater forcing (not shown) is very similar to the sensitivity to heat flux.

4. Reconstructions

- Actual response to forcing can be reconstructed from the sensitivities using a **convolution integral:**

$$J_{rec}(t,\tau_{mem}) = \sum_k \int_{t-\tau_{mem}}^{t} \int_A \frac{\partial J}{\partial F_k}(\mathbf{x}', t-s)\, \delta F_k(\mathbf{x}', s)\, dA\, ds$$

- Complete variation of cost function can be reconstructed from sensitivities and forcing fields, **if**
  - All **memory** is used ($\tau_{mem} \to \infty$)
  - All **forcing fields** are used
  - The adjoint is **exact**
  - The response is **linear**

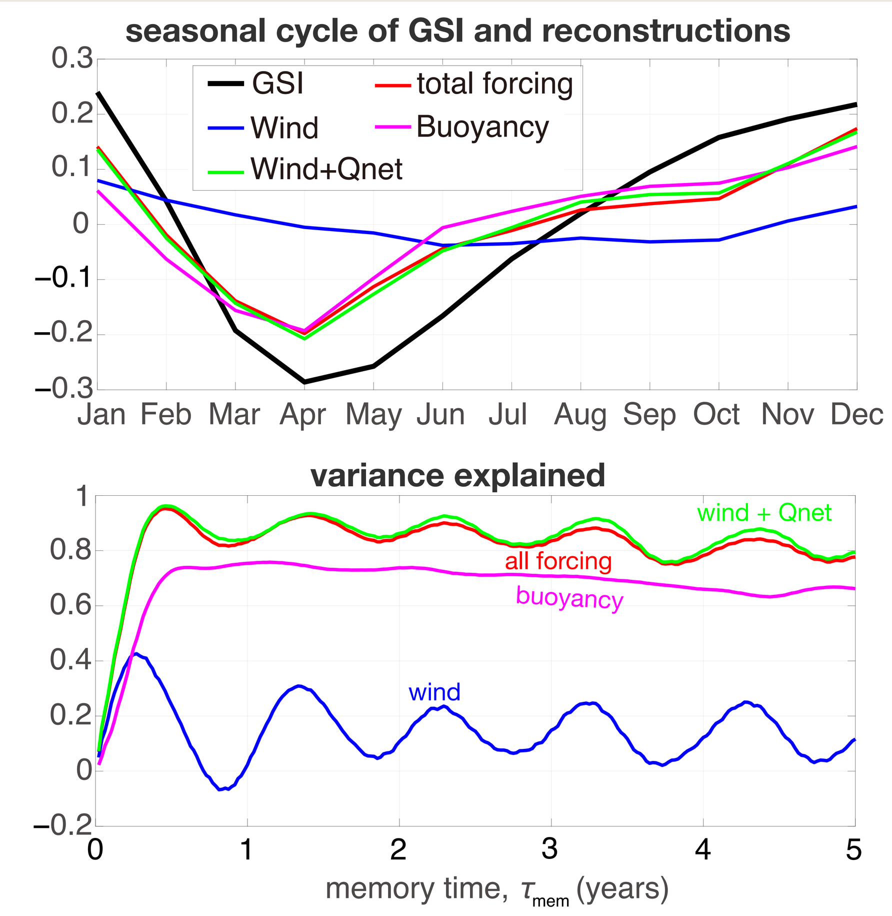
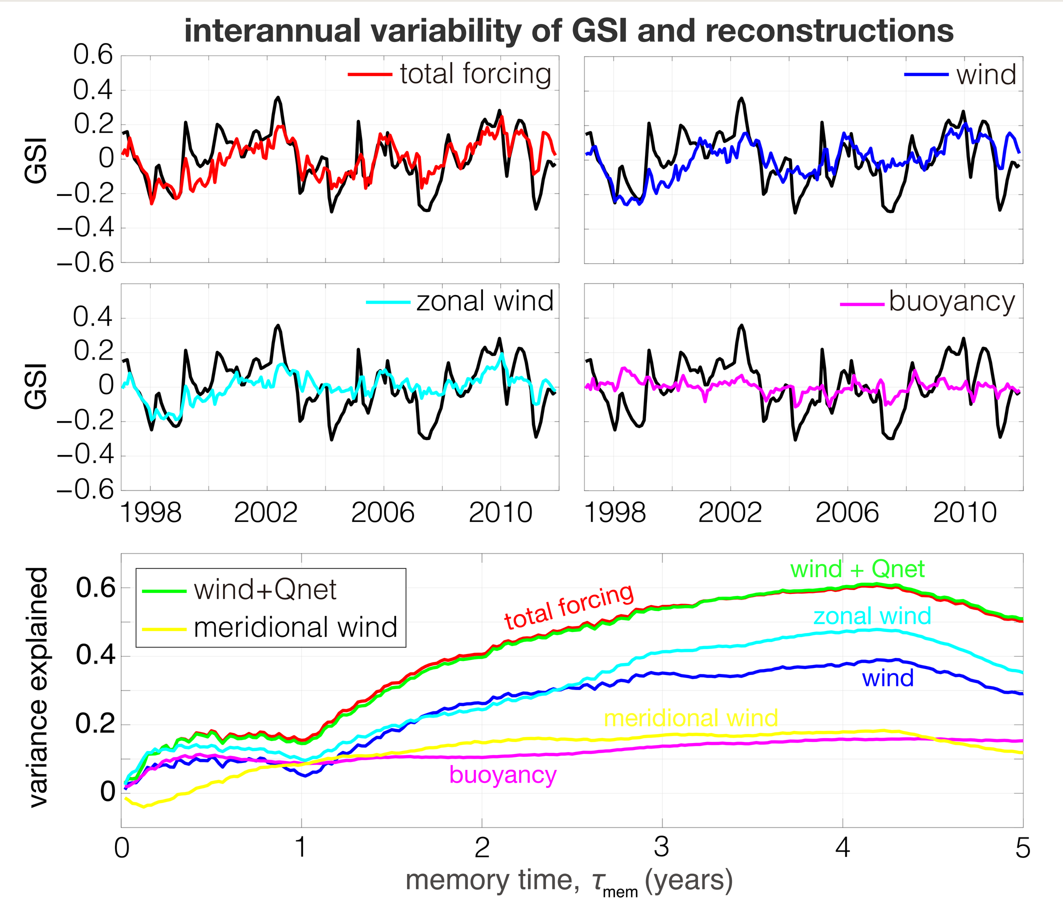


Figure 4:

Upper panels: Seasonal cycle (**left**) and interannual variability (**right**) of the GSI and reconstructions using 5 years of memory.

Lower panels: Variance explained by the partial reconstructions as a function of memory:

$$1 - \frac{\mathrm{var}\,[J(t) - J_{rec}(t,\tau_{mem})]}{\mathrm{var}\,[J(t)]}$$



- Seasonal cycle dominated by **buoyancy forcing**
  - Saturates after ~6 months of memory
- Contribution of wind forcing sometimes **negative**
  - Accounting for wind sometimes **worse than persistence**!
- Interannual variability driven by (mostly zonal) **winds**
  - **Saturates** after ~4 years of memory (approx. Rossby wave crossing time)
  - First 2 years of memory make largest contribution
- Buoyancy forcing saturates in ~6 months of memory—**no effect** on subsequent years!

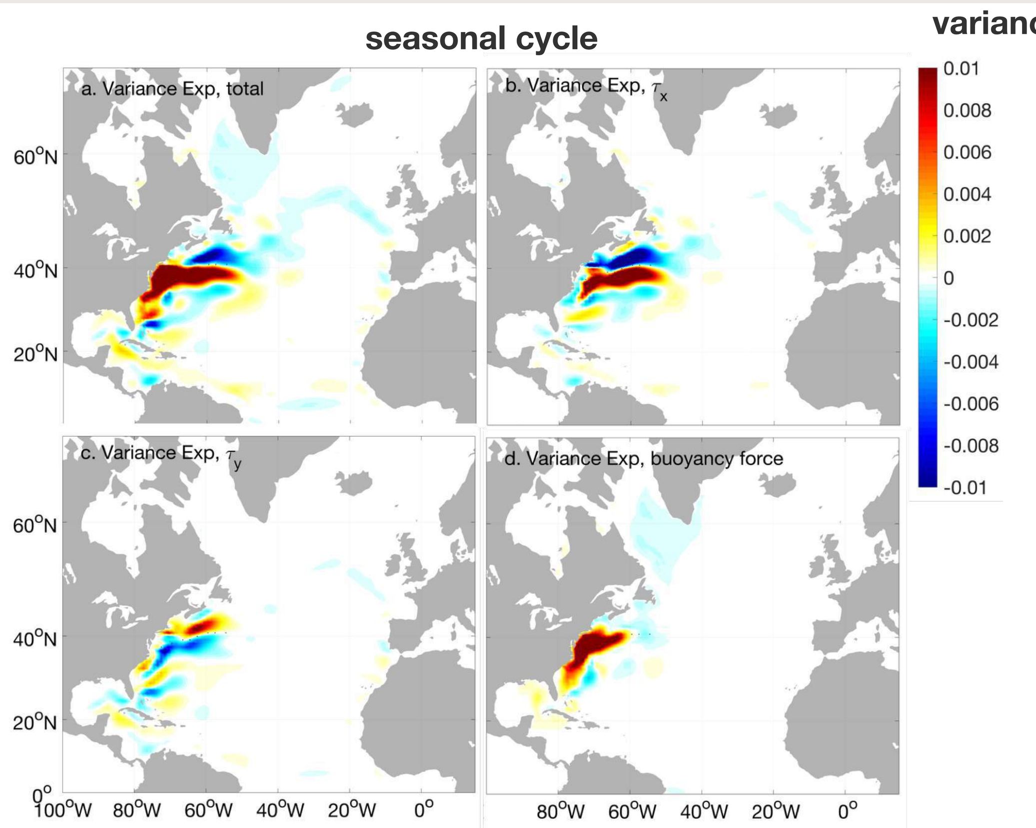
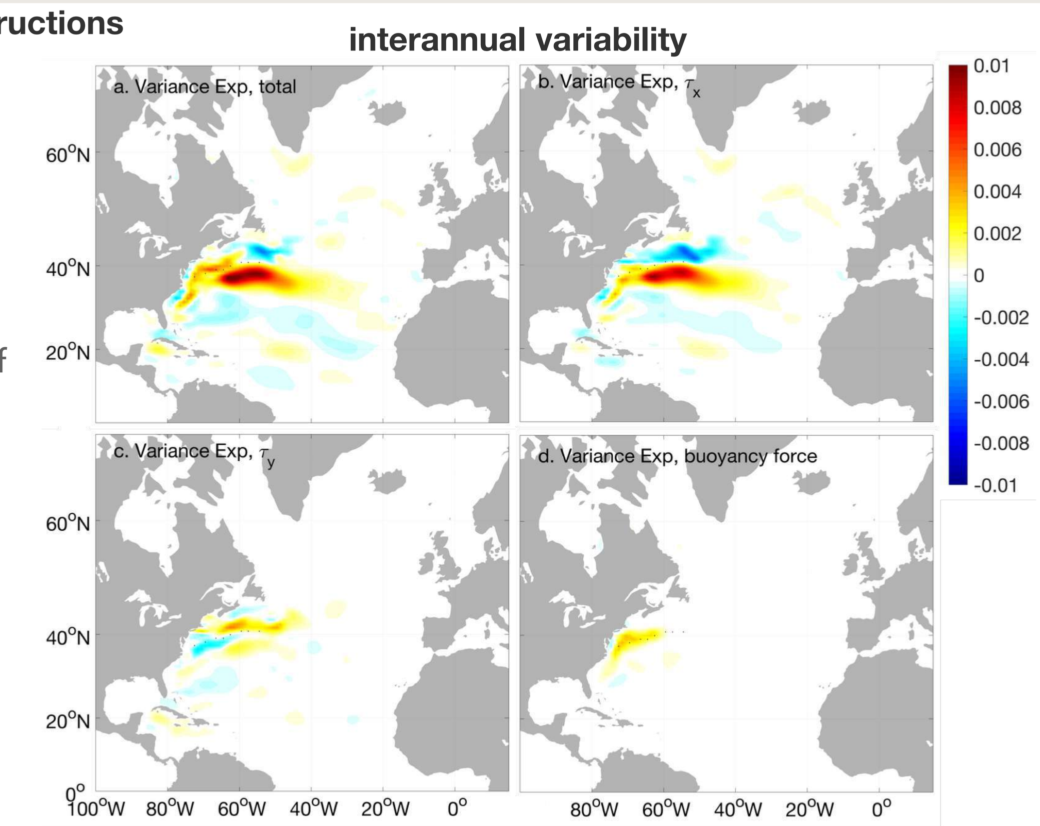
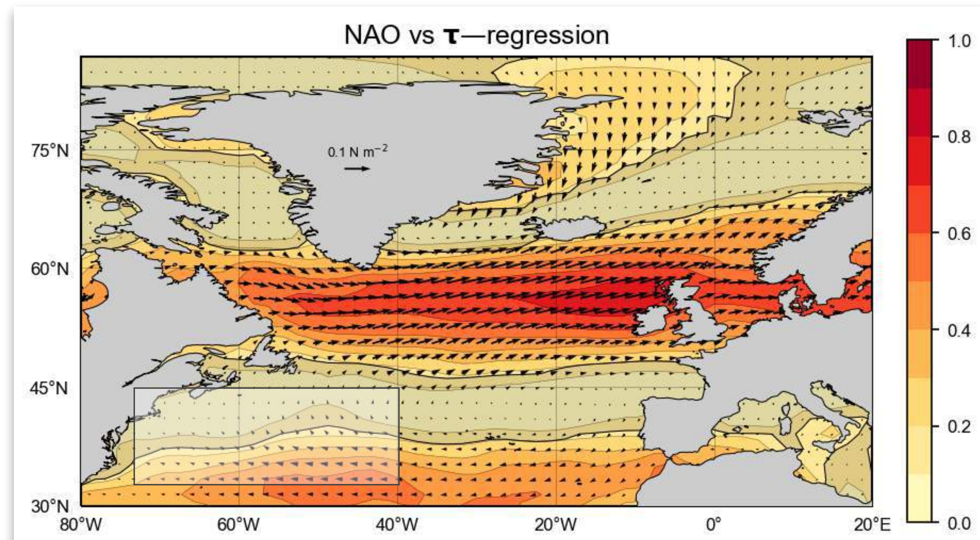


Figure 5: Spatial distribution of contributions to the variance explained by partial reconstructions of the seasonal cycle (**left**) and interannual variability (**right**) of the GSI using 5 years of memory



- **Local forcing** dominates both seasonal cycle and interannual variability
  - Interannual variability: contributions of decreasing magnitude extending eastward
- Response to wind a **residual** between large **positive** and **negative** contributions
  - Residual is **small for seasonal cycle**
  - Long memory of zonal wind perturbations due to **baroclinic Rossby waves**.
    - Most of the signal arrives within 2 years → waves excited **near** Gulf Stream
- NAO has small, but statistically significant, loading in the region where 0–2 year lags are possible
- NAO-forced perturbations **do not** propagate from the subpolar region to the Gulf Stream
- NAO-forcing in the eastern midlatitudes *could* propagate to the Gulf Stream, but project on regions with **opposite sensitivities** and the signal **attenuates** before reaching the Gulf Stream



Contacts & Acknowledgements

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