What are the dominant atmospheric drivers of interannual AMOC variability?

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University of Washington

Also thanks to Ichiro Fukumori, Yavor Kostov



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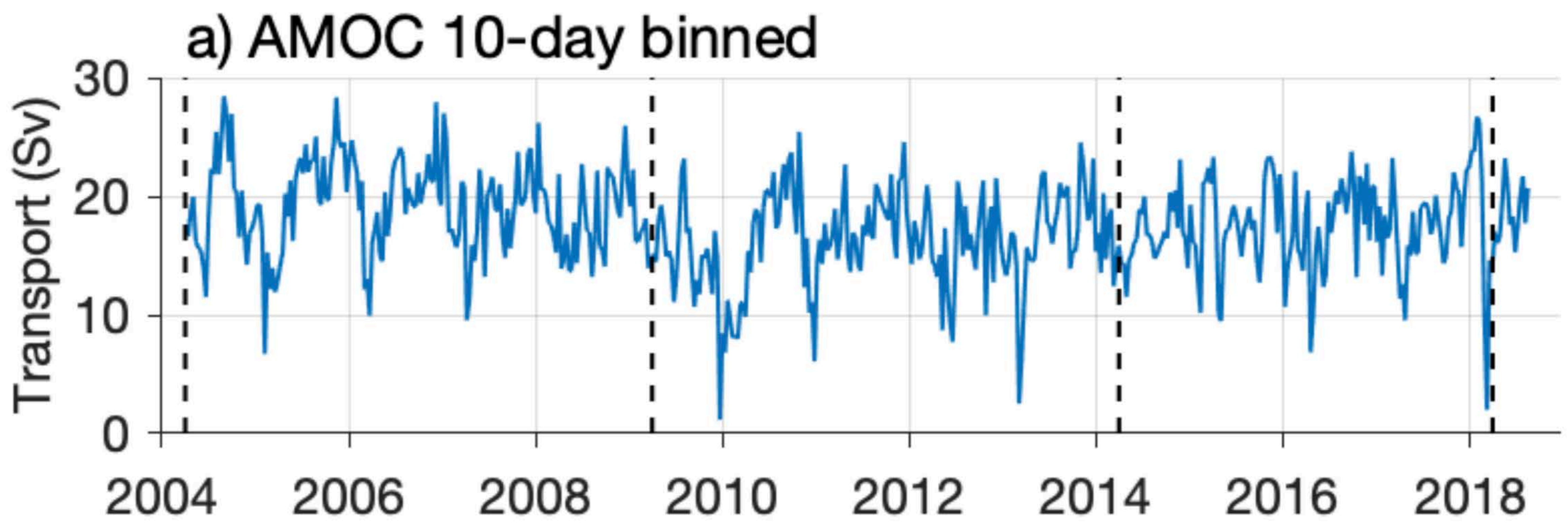
“Variance budgets” describe contributions to ocean variability



$$X_{\text{amoc}} = X_\tau + X_b + \ldots$$

$$\text{var}\left(X_{\text{amoc}}\right) = \text{var}\left(X_\tau\right) + \text{var}\left(X_b\right) + 2\text{cov}\left(X_b, X_\tau\right) + \ldots$$

Moat et al. 2020

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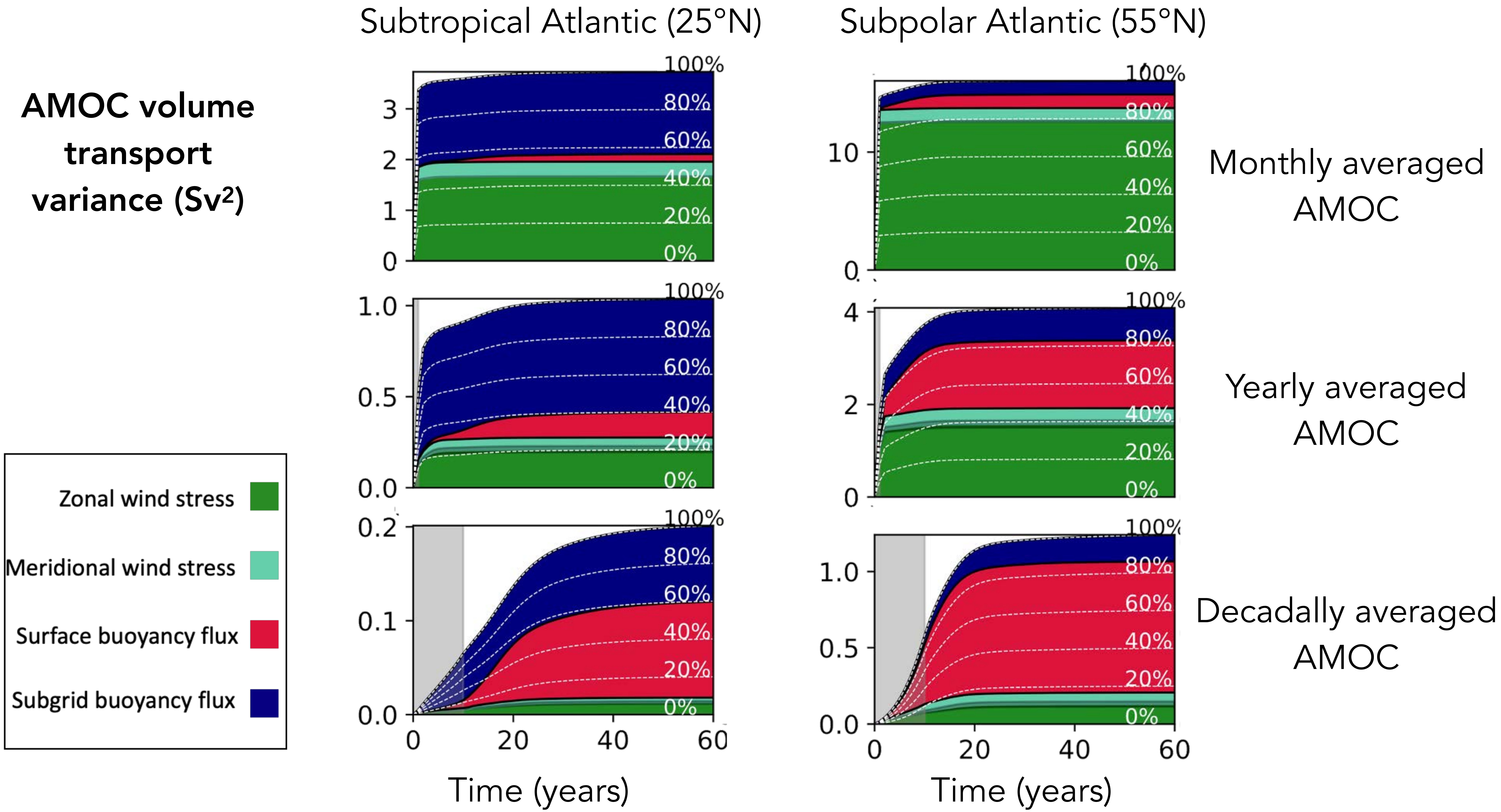


Stephenson and Sevellec 2021a: The Active and Passive Roles of the Ocean in Generating Basin-Scale Heat Content Variability, GRL
2021b: Dynamical Attribution of N. Atlantic Interdecadal Predictability to Oceanic and Atmospheric Turbulence under Diagnosed and Optimal Stochastic Forcing, J Clim
Close et al. 2020, Jamet et al. 2020…

Ocean model adjoint sensitivities diagnose dominant drivers

$$\underline{\mathbf{s}} = \frac{\partial \underline{x}}{\partial \underline{\mathbf{q}}}$$

“Quantity of interest”

Any function of the model state
(e.g., AMOC strength)

“Controls”

Vector in time and space of ocean model inputs that can change x
(e.g., surface heat fluxes)

Adjoint sensitivity

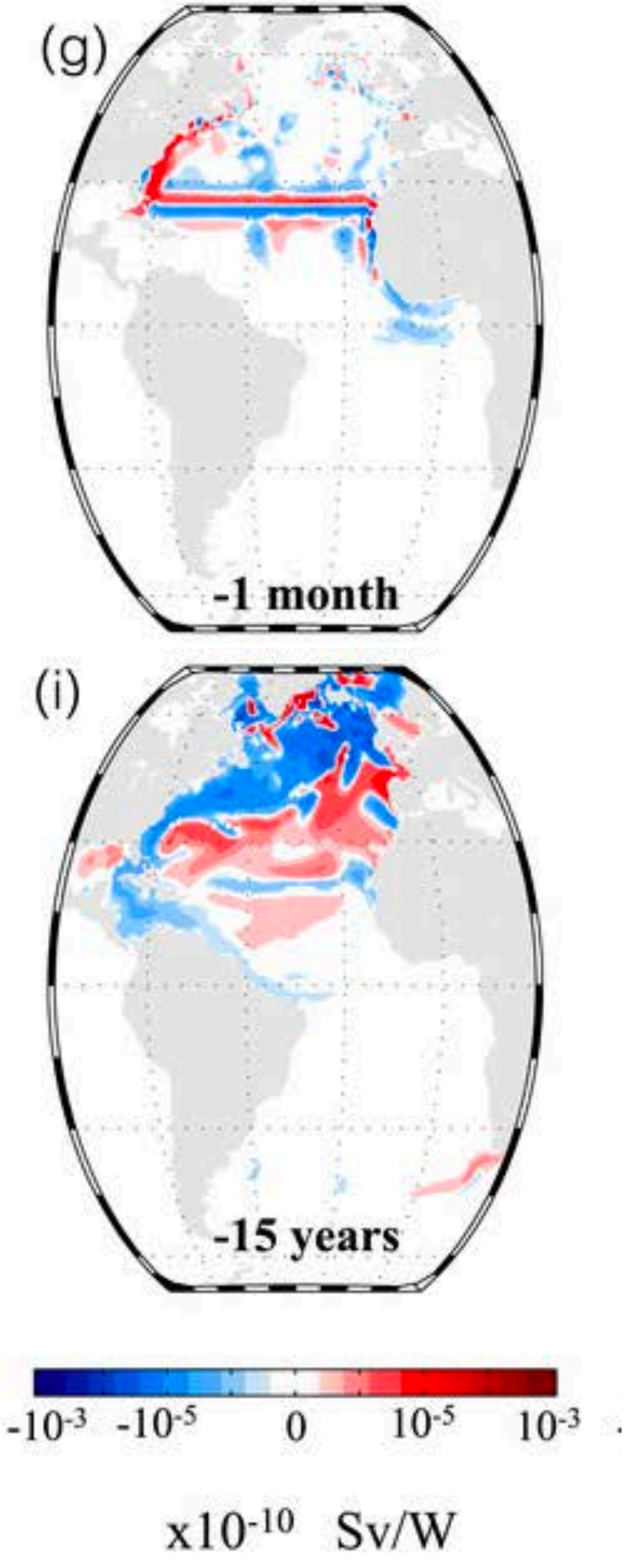
How much will changing $\mathbf{q}$ change x?
(A *locally linear* estimate)

Ocean model adjoint sensitivities diagnose dominant drivers

$$\mathbf{s} = \frac{\partial x}{\partial \mathbf{q}}$$

AMOC strength
@ 26N in January

Surface heat fluxes



Pillar et al. 2016
Also Heimbach and Wunsch 2011; Jones et al. 2018;
Kostov et al. 2019, 2021; Fukumori et al. 2021

Ocean model adjoint sensitivities diagnose dominant drivers

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Surface heat fluxes

Sensitivities reveal **"optimal"** drivers of x that reflect **ocean** length and time scales.

In the spirit of variance budgets, can we derive sensitivities to derive atmospheric patterns that contribute most to *ocean* variance?

Pillar et al. 2016
Also Heimbach and Wunsch 2011; Jones et al. 2018;
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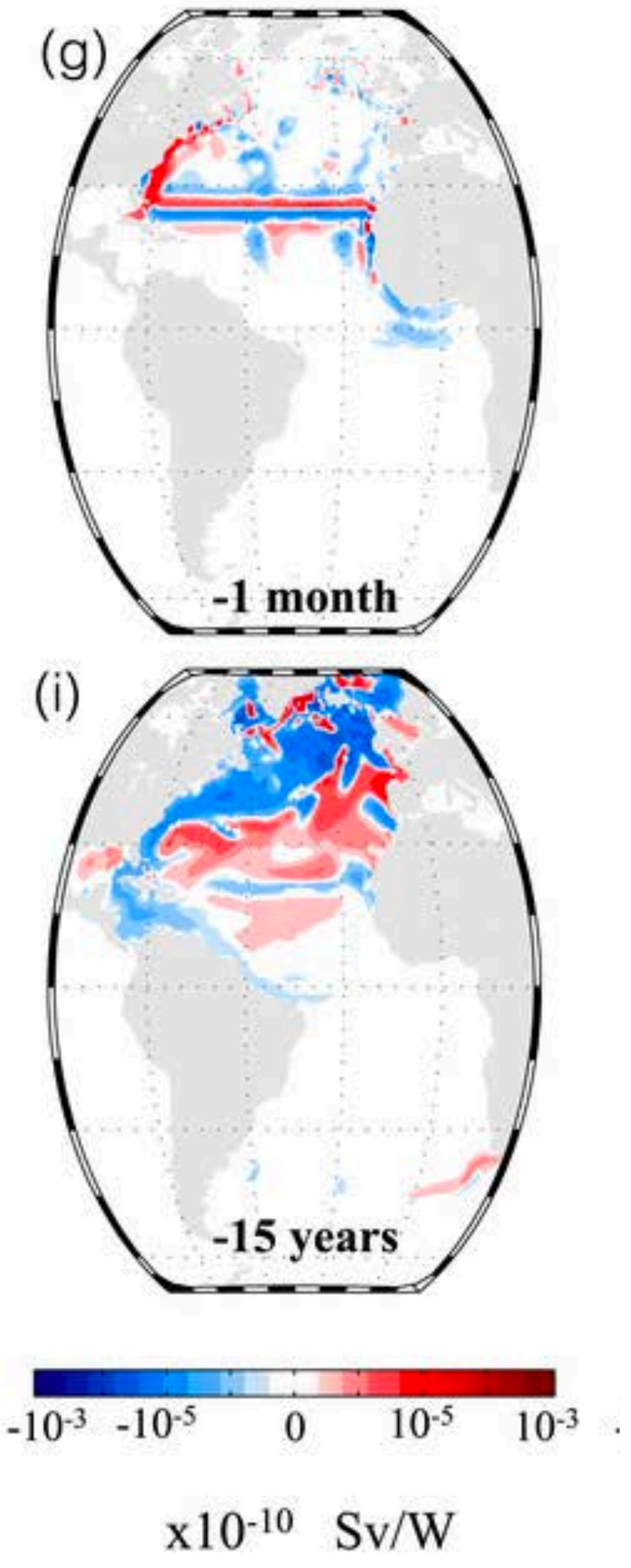

Can we find the dominant *atmospheric* contributions to *ocean* variance?

$$x = \mathbf{s}^\top \mathbf{q}$$

Sensitivities allow us to write x (AMOC) as a linear function of fluxes q…

$$\text{var}(x) = \mathbf{s}^\top \mathbf{C} \mathbf{s}$$

… and the variance of x in terms of the (*space-time*!) covariance of q.

$$= \text{tr}\left(\mathbf{S}^\top \mathbf{C}_s \mathbf{S}\right)$$

Assuming q is white noise simplifies to a function of purely *spatial* covariances

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$$\mathbf{P}\boldsymbol{\Lambda}\mathbf{P}^{\top} = \mathbf{C}^{1/2}\mathbf{S}_s^{\top}\mathbf{S}_s\mathbf{C}^{\top/2}$$

Eigenvectors ($\mathbf{p}_j$) are atmospheric patterns whose variability **maximizes var** $\left(x^2\right)$.

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If $\mathbf{C} = \mathbf{I}$ ($\mathbf{q}$ is white noise in space), $\mathbf{p}_j$ are **optimal patterns for stochastic excitation** (e.g., Farrell and Iaonnou 1996)

If $\mathbf{S}_s^{\top}\mathbf{S}_s = \mathbf{I}$ (e.g. adjoint sensitivities are orthonormal in time), $\mathbf{p}_j$ are **atmospheric EOFs**

Can we find the dominant *atmospheric* contributions to *ocean* variance?

Voila, an eigenvector problem!

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"COFs" = combined orthogonal functions

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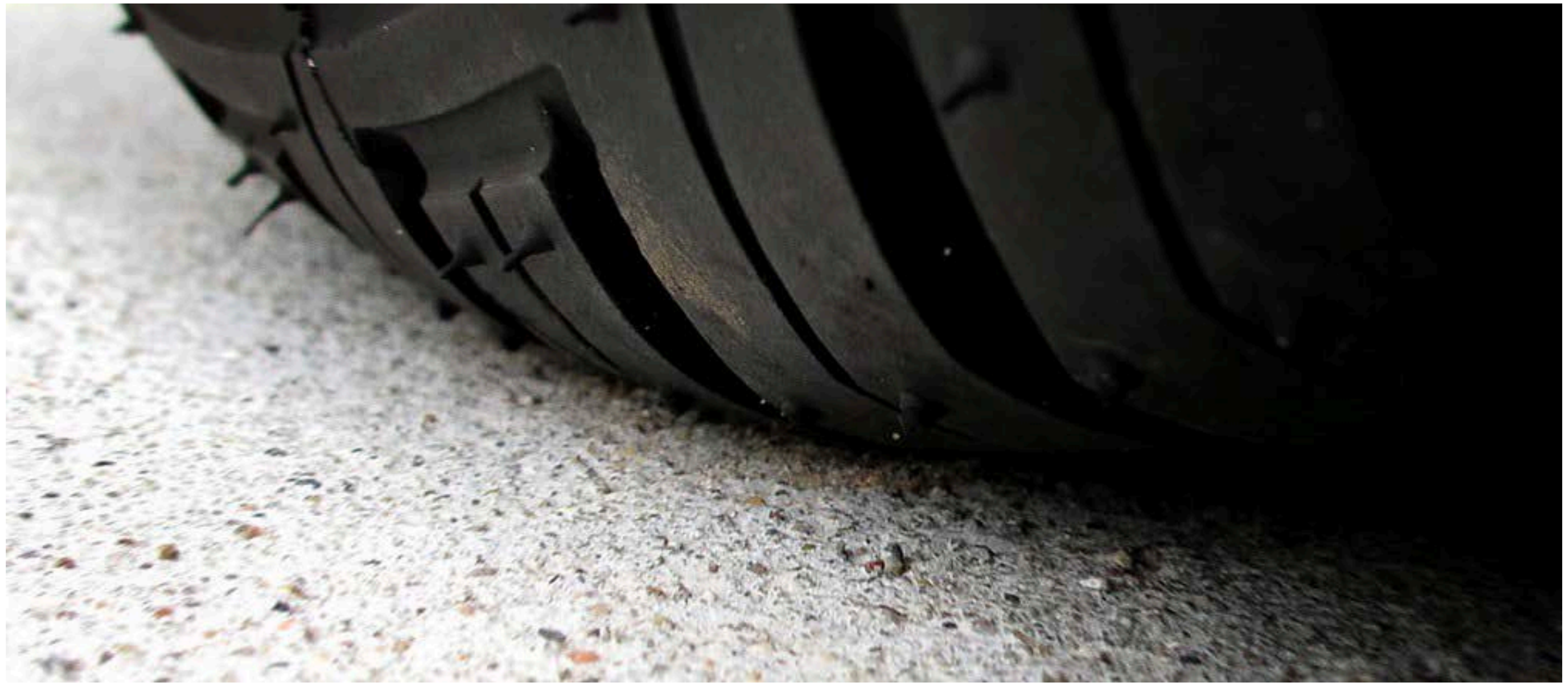
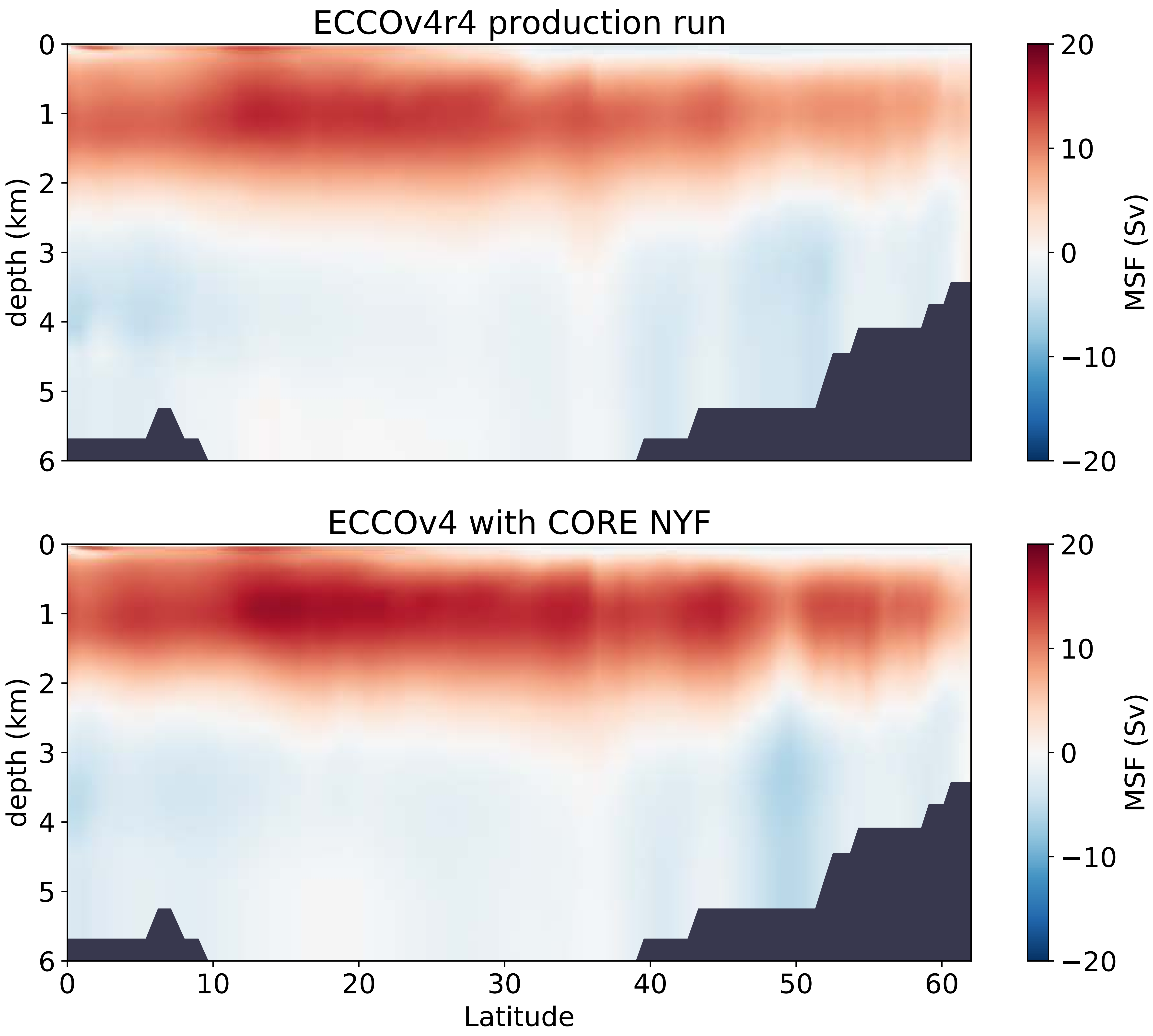


~1° resolution MITgcm ECCO v4 configuration
Ocean and sea ice components spun up under 4800 years following *Wolfe et al. 2017).*

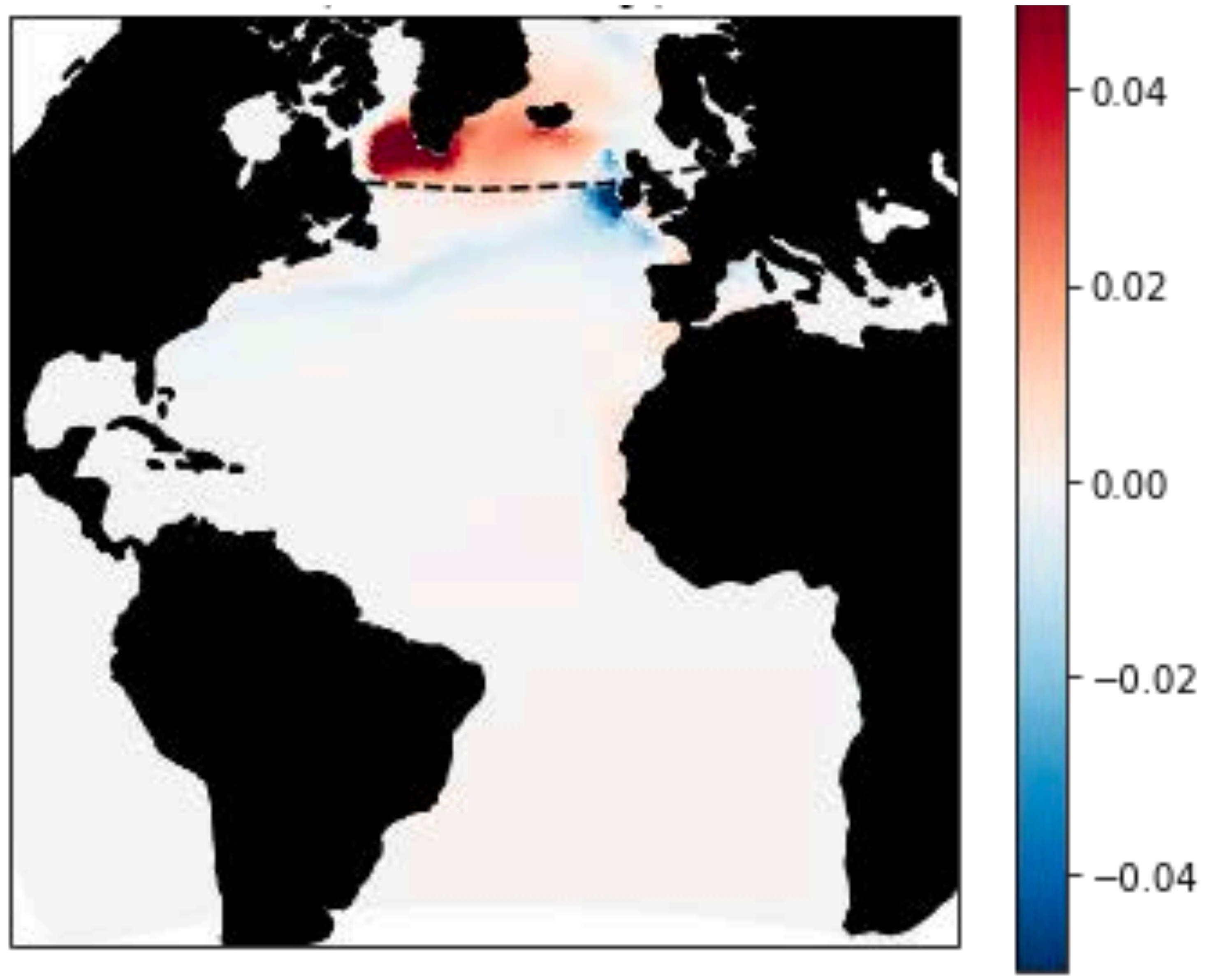
Adjointed and run to compute sensitivities of AMOC transport at climatological maximum depth at annual and decadal averages across several latitudes.

Fluxes are 6-hourly from ECCO v4r4.



ECCO: Forget et al. 2015; CNYF: Large and Yeager 2009

Leading patterns are intermediate between stochastic optimals and atmospheric EOFs



Leading stochastic optimal for AMOC variance at 55N by heat fluxes

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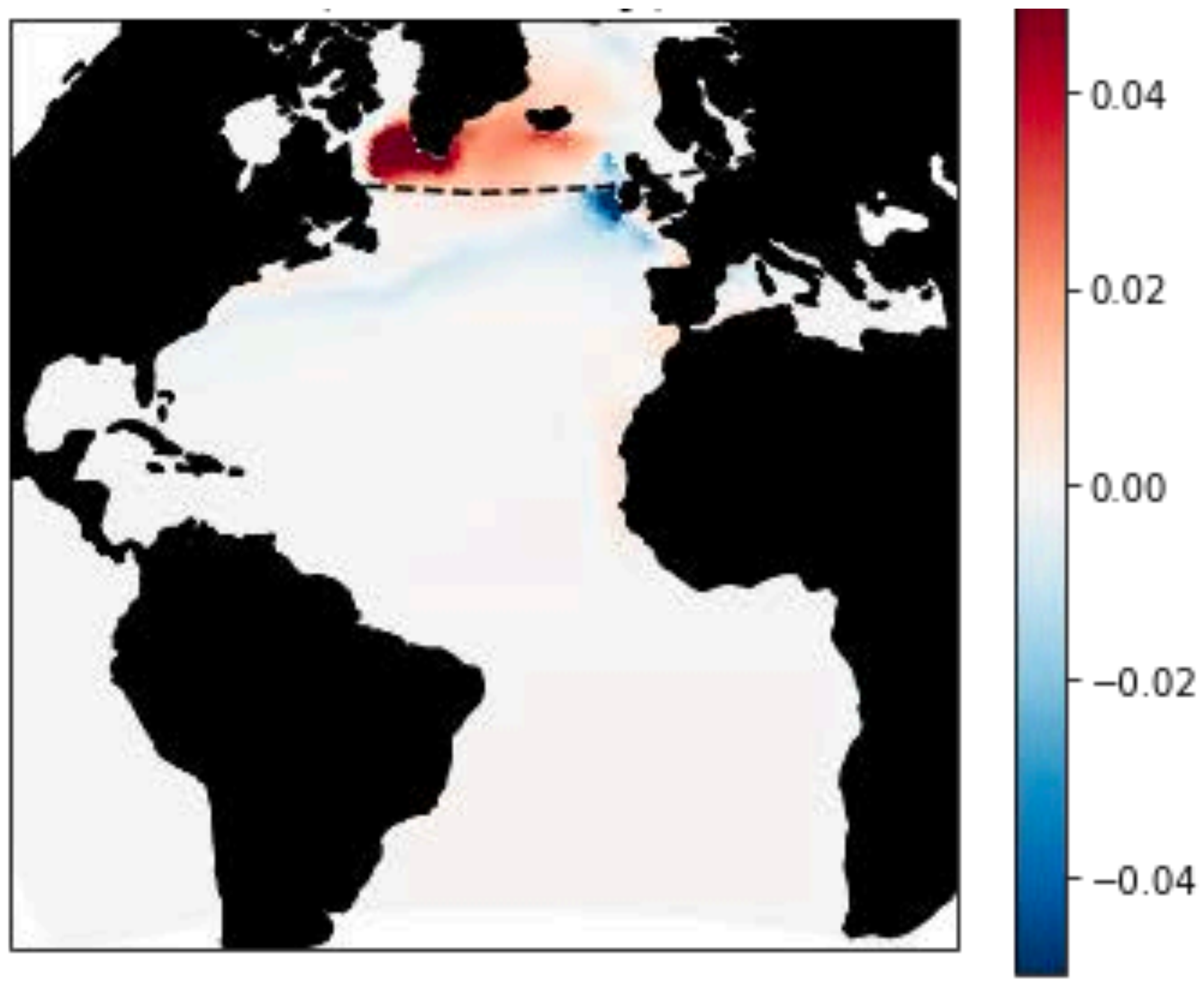

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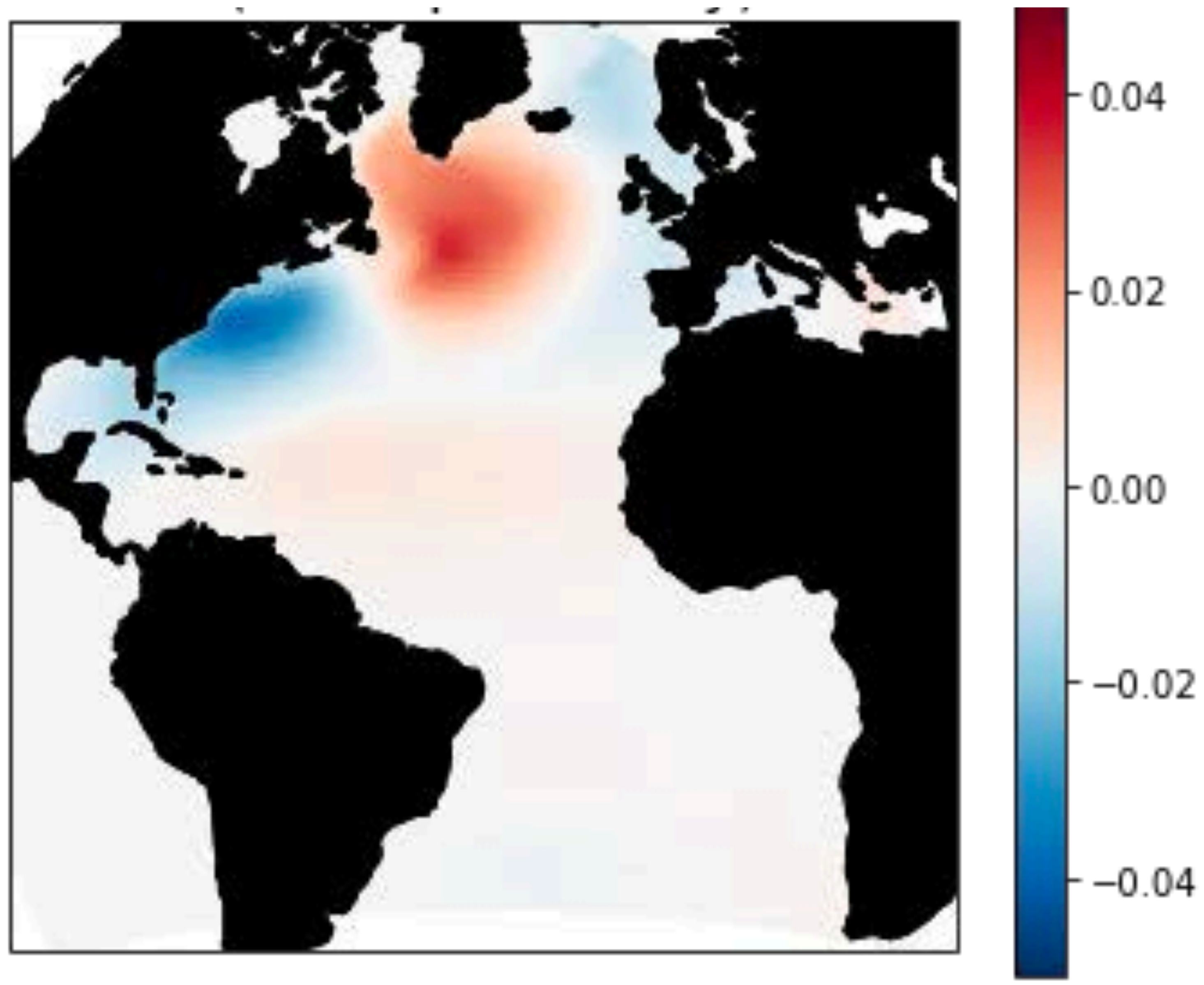

Leading EOF of ECCO v4r4 heat fluxes

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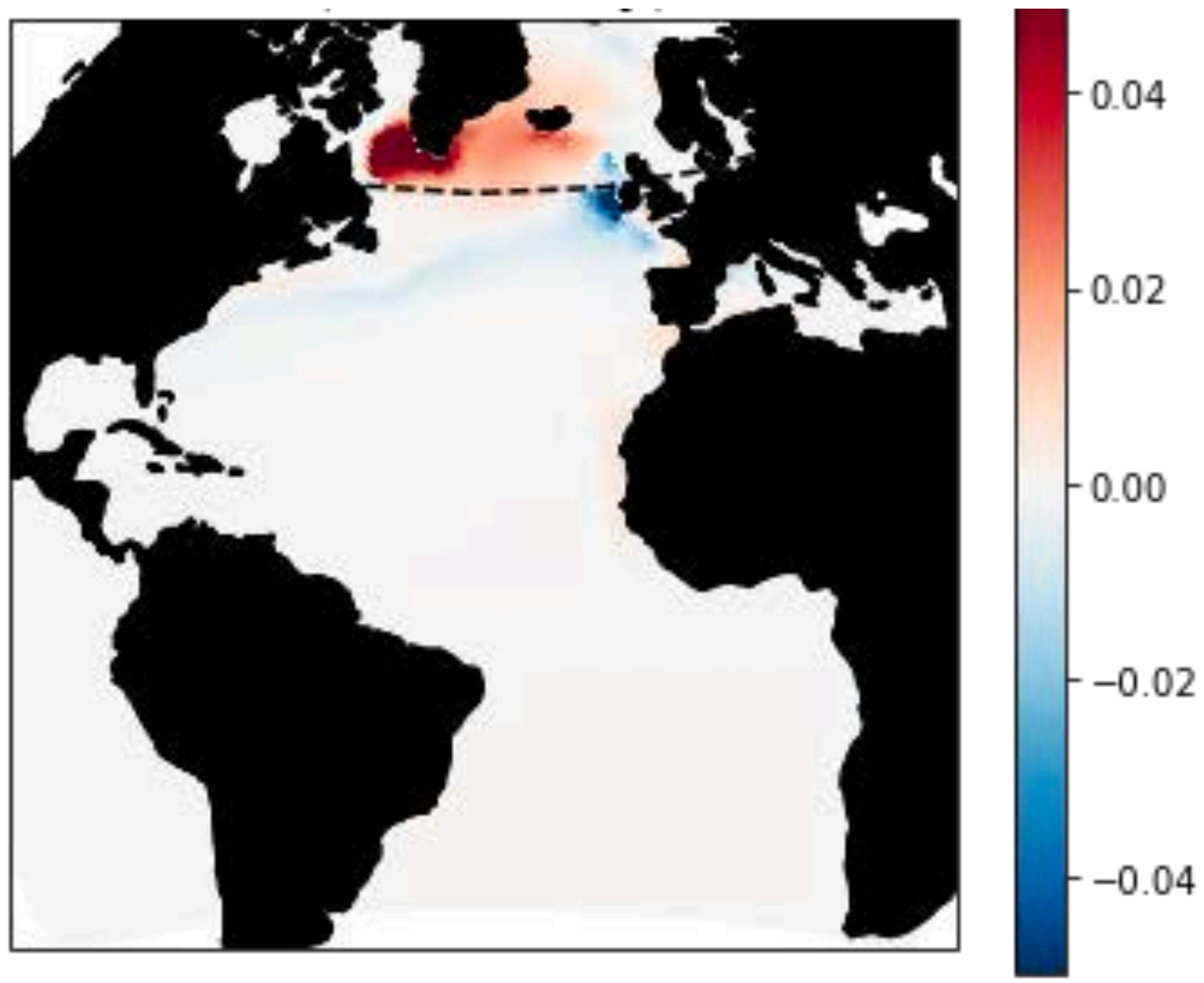

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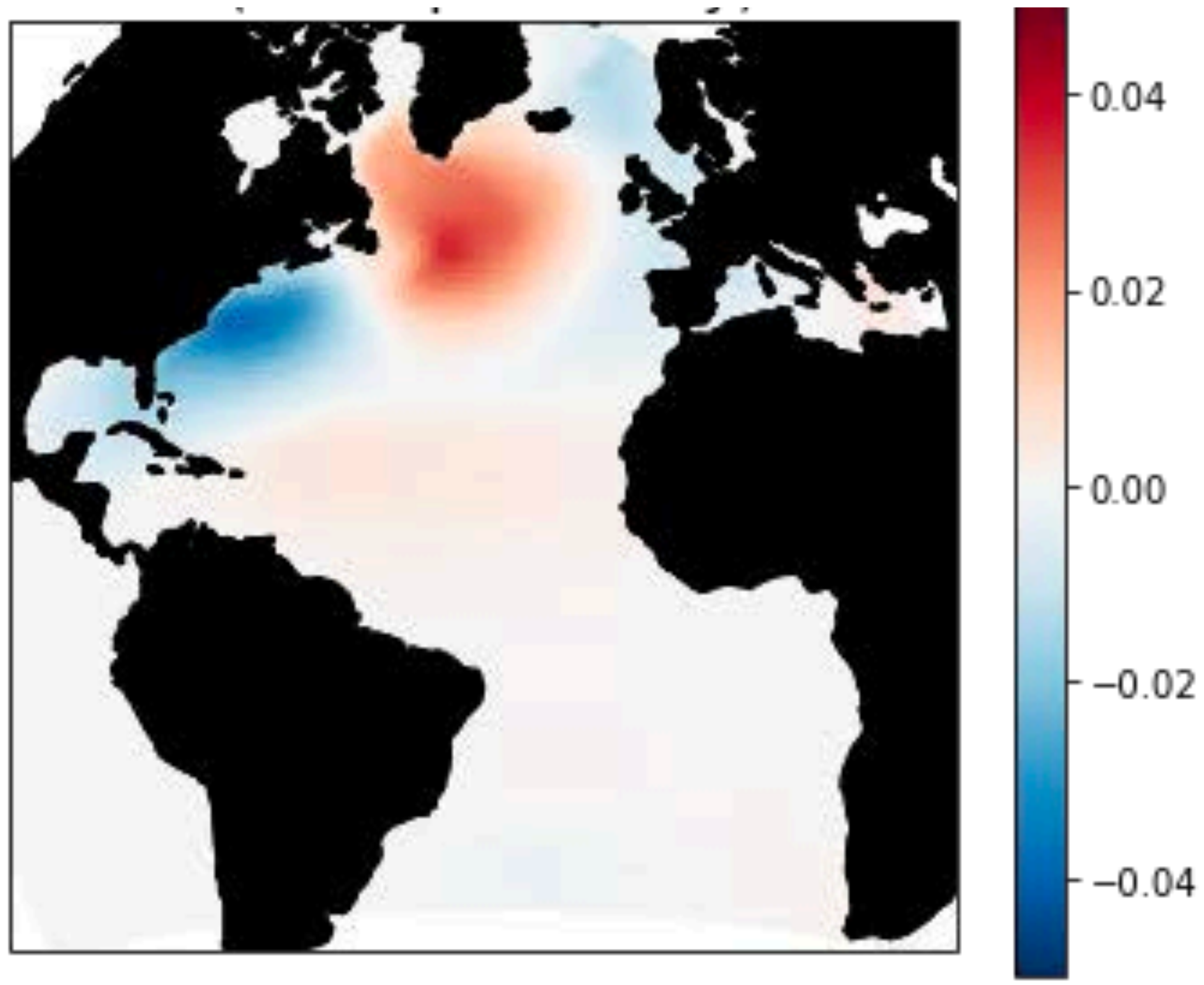

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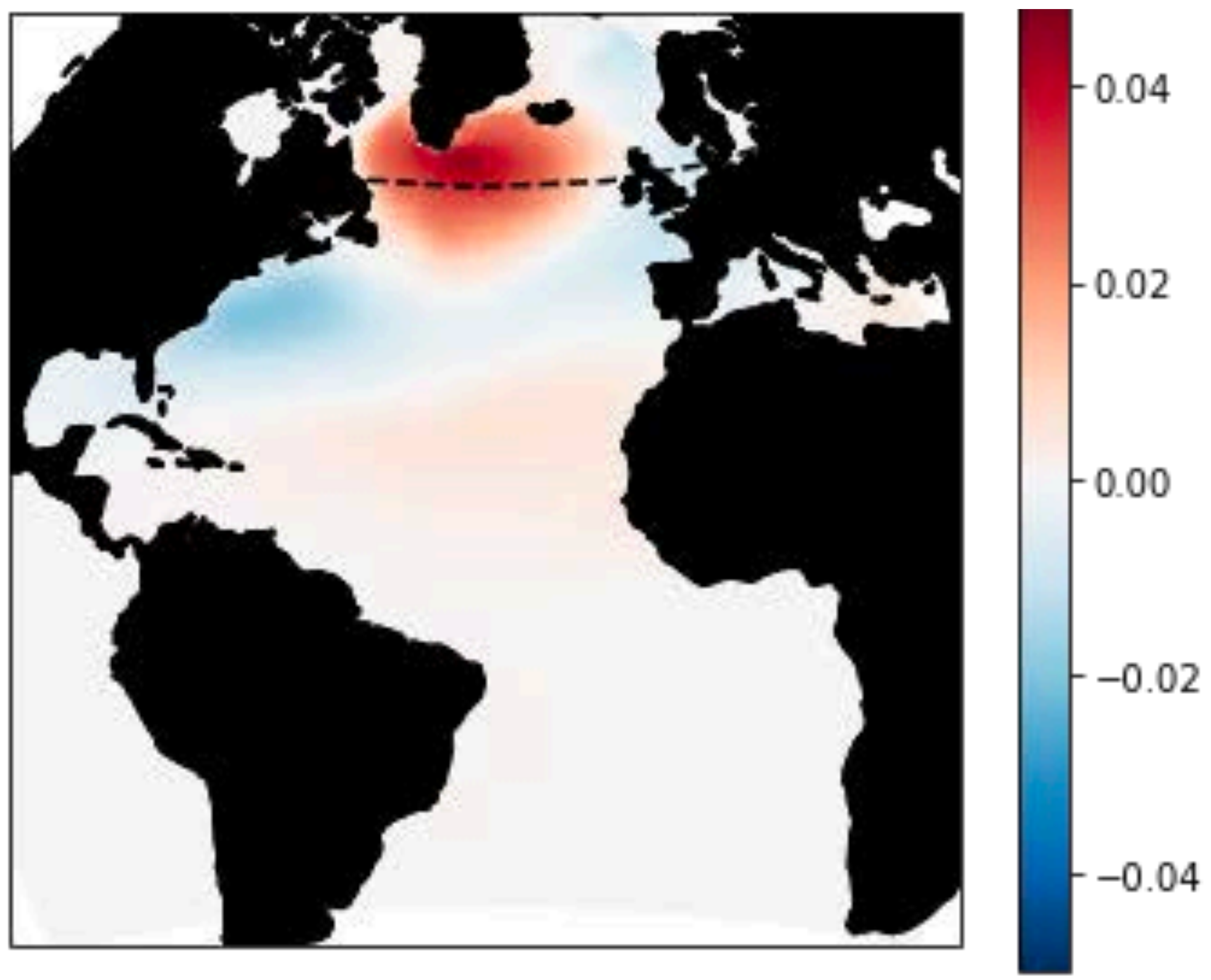

Leading heat flux COF contributing to decadal-mean AMOC variability

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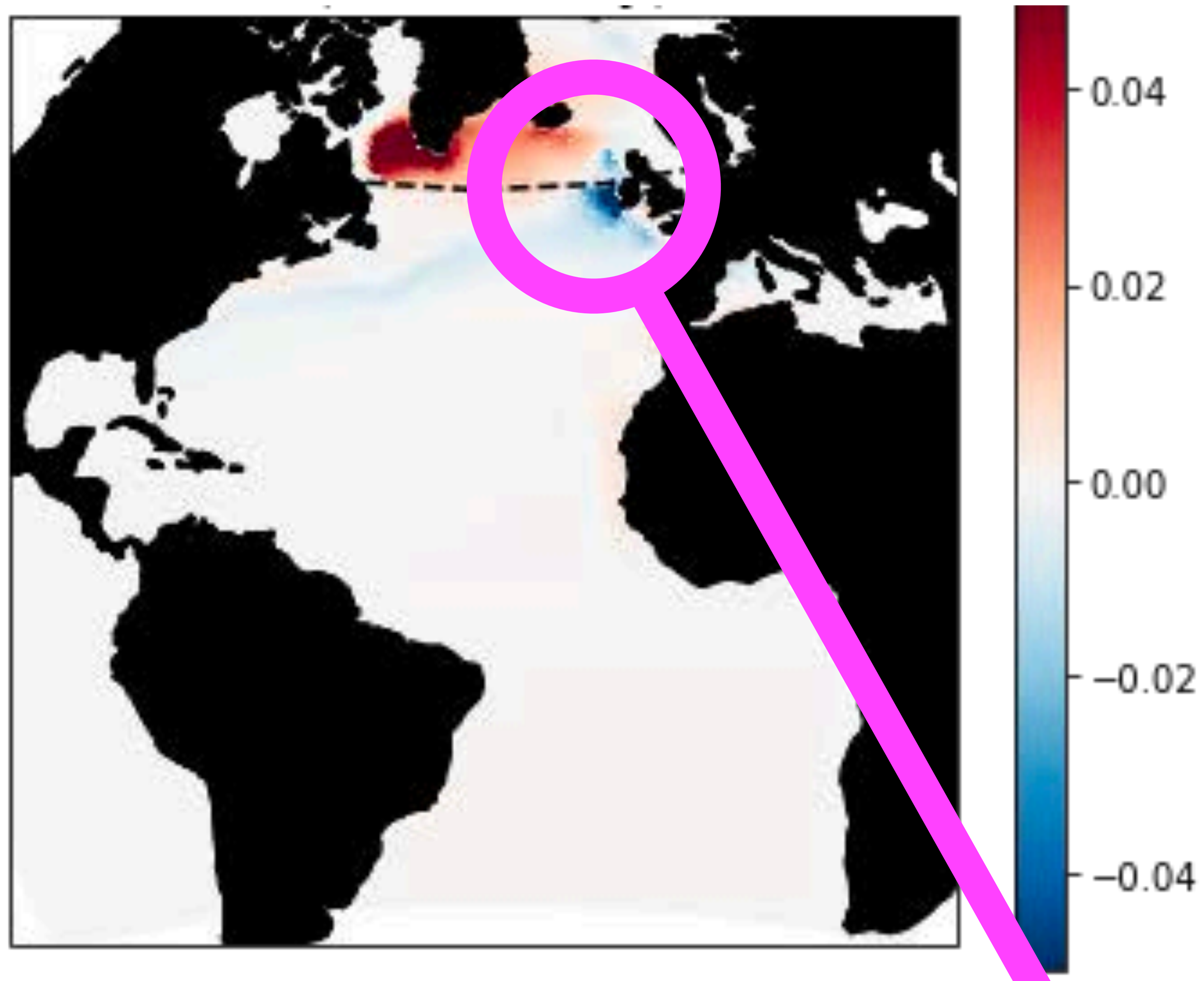

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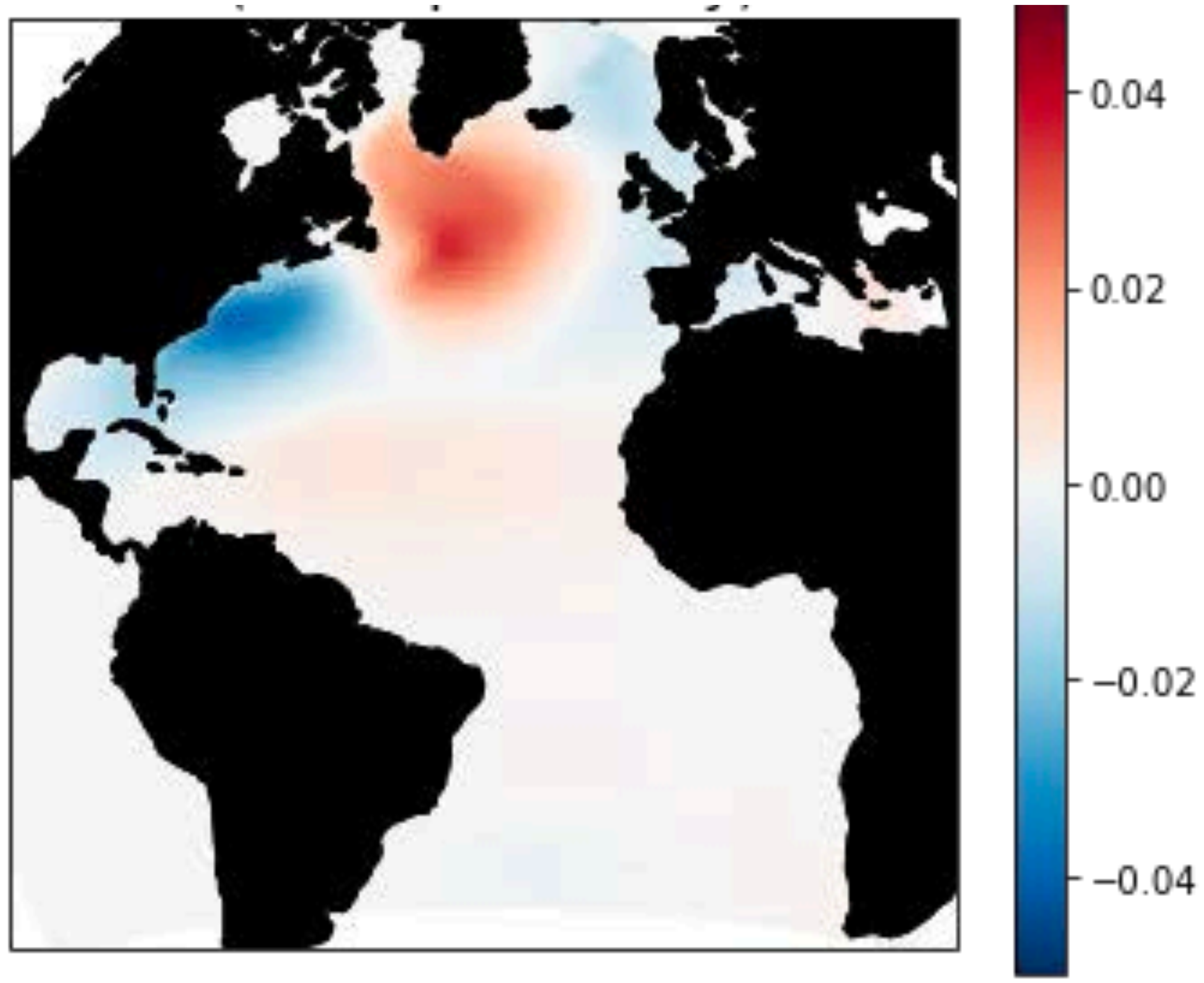

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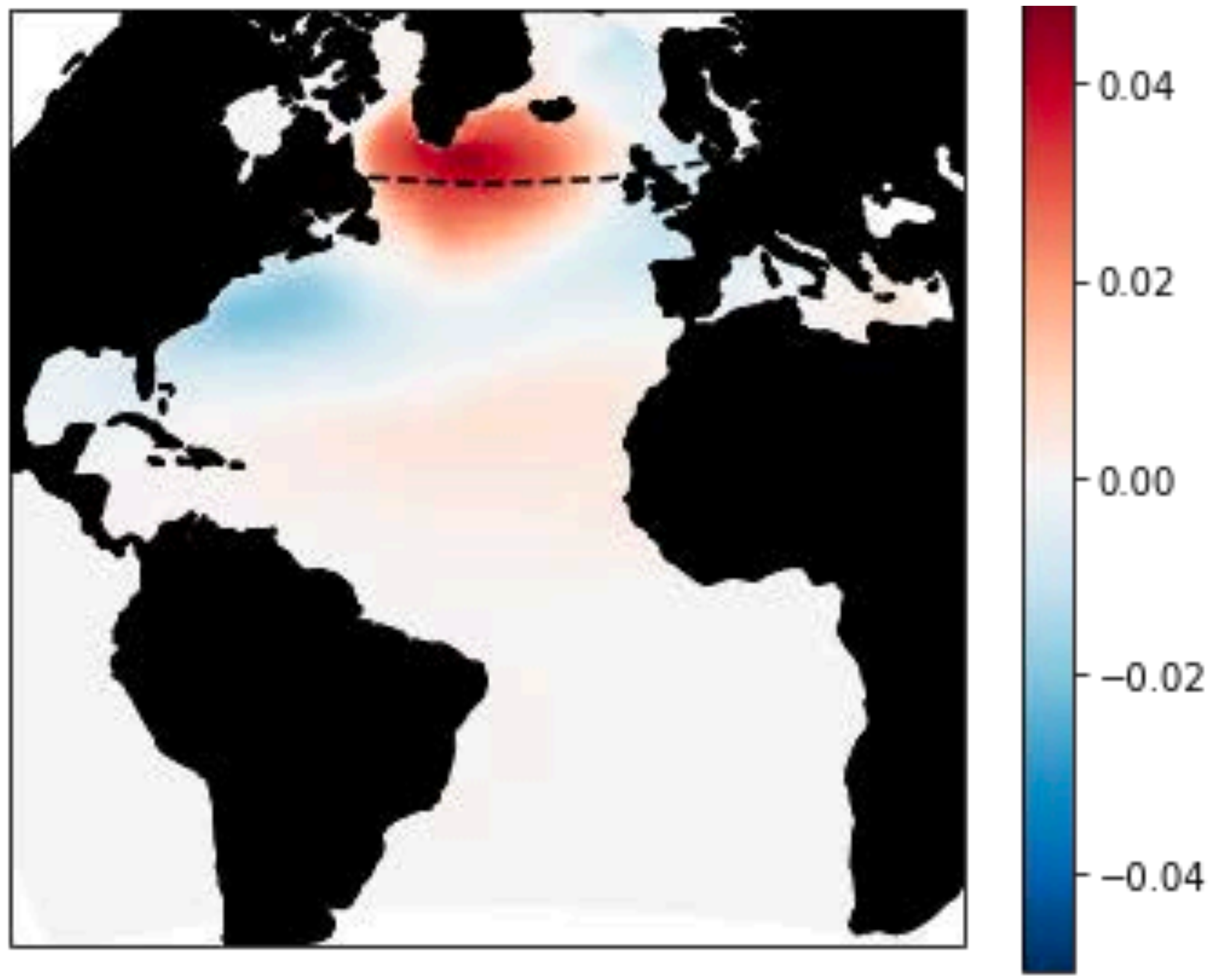
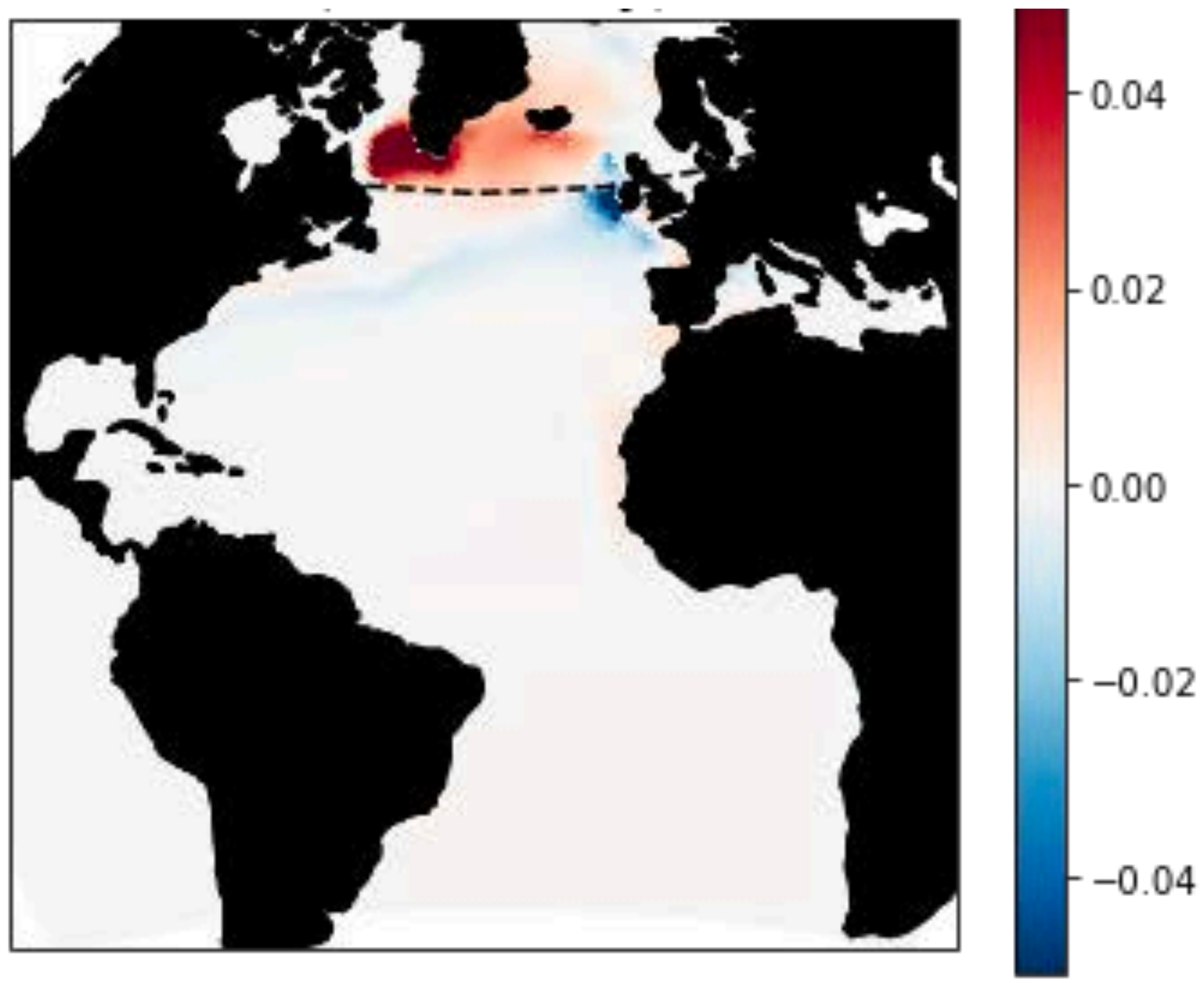


Leading heat flux COF contributing to decadal-mean AMOC variability

A region of "latent" AMOC variance production?

Leading patterns are intermediate between stochastic optimals and atmospheric EOFs



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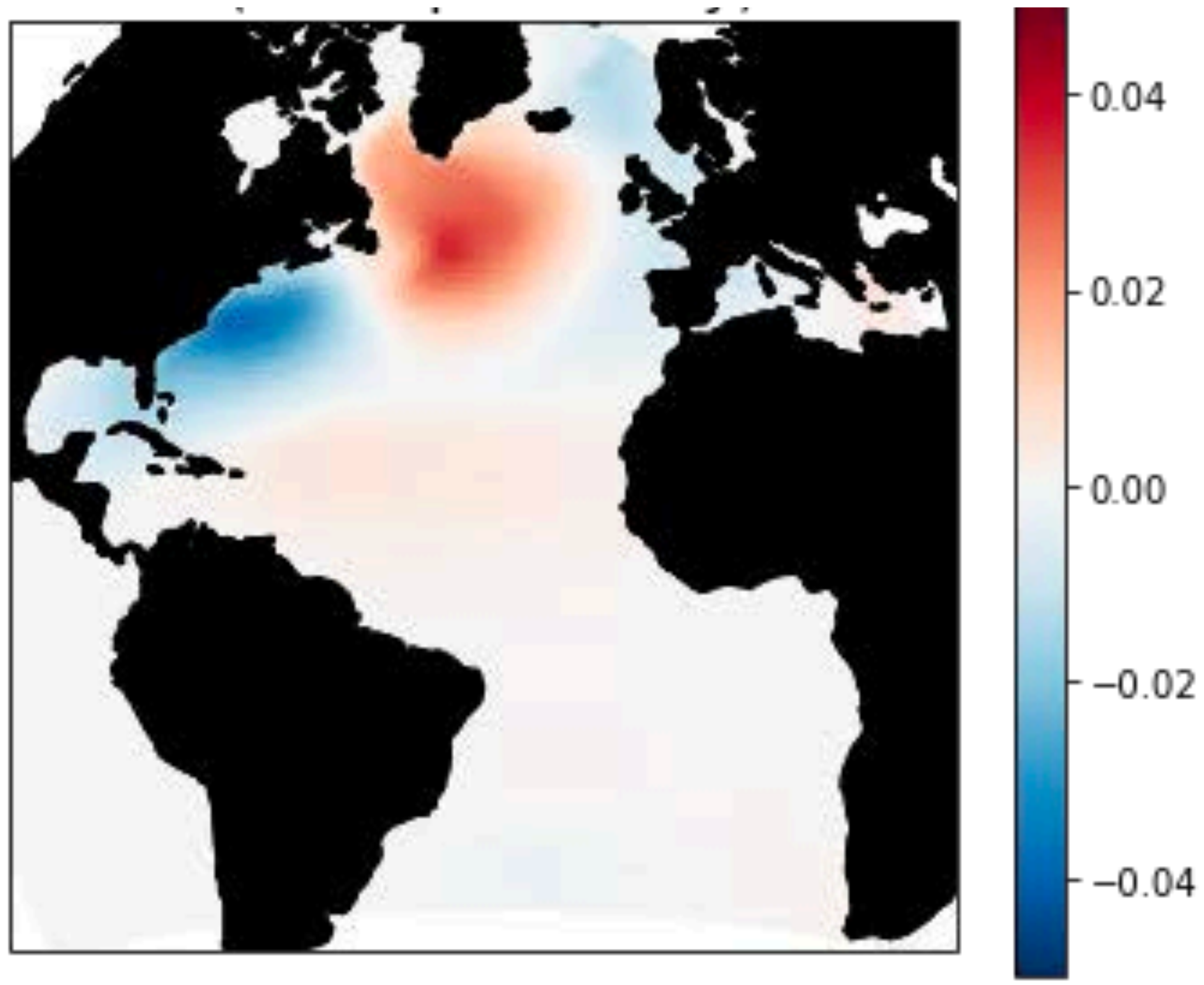

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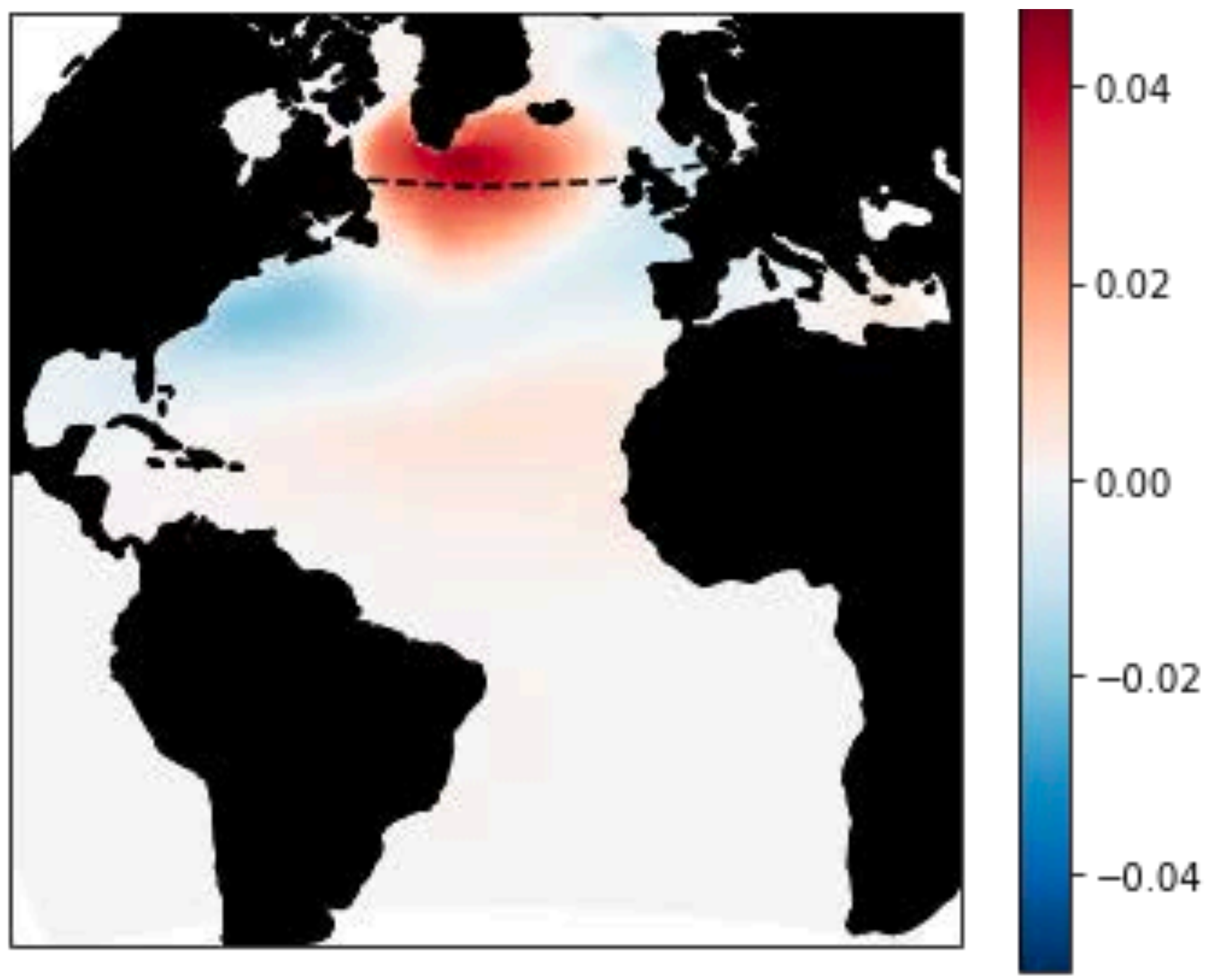
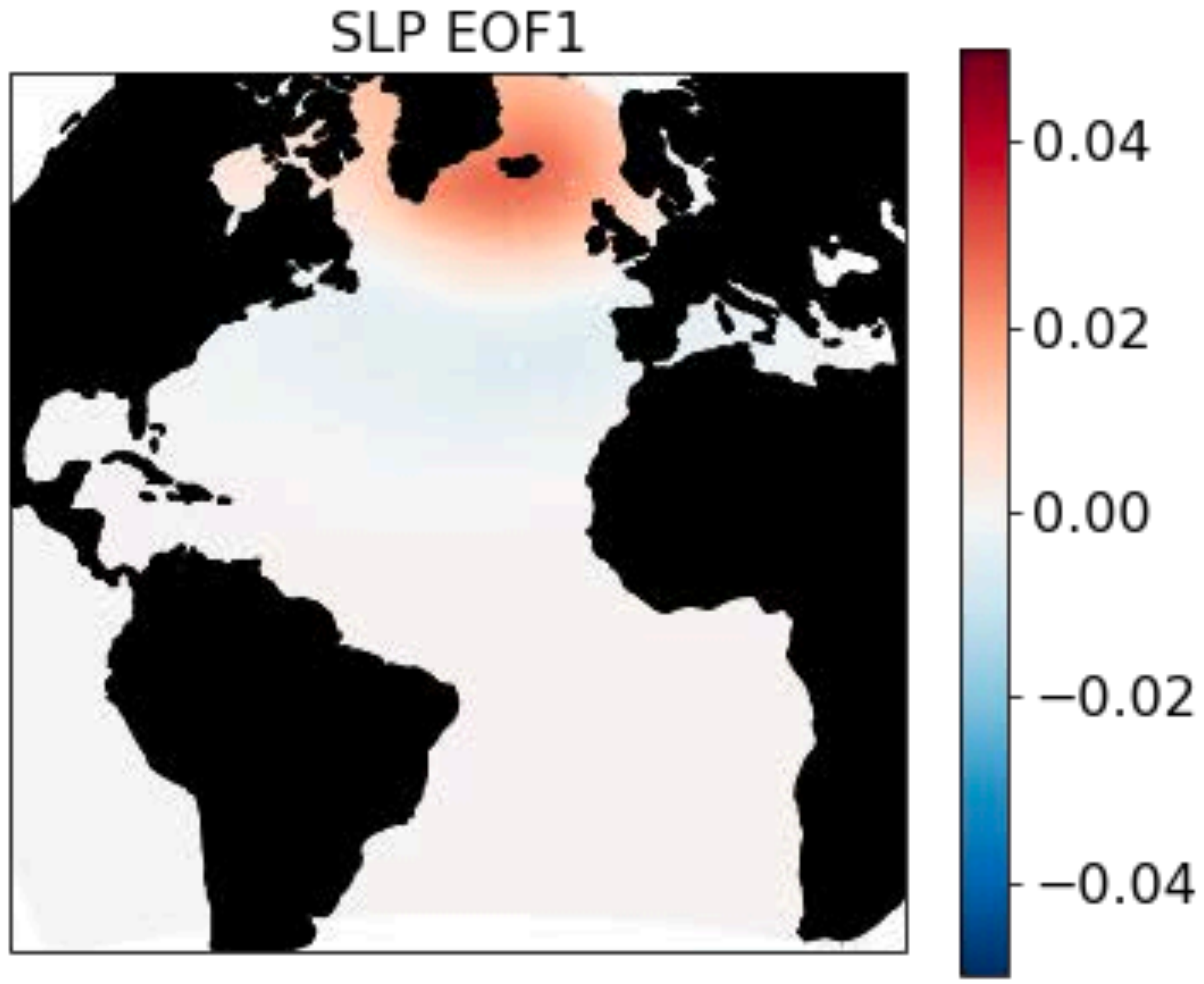
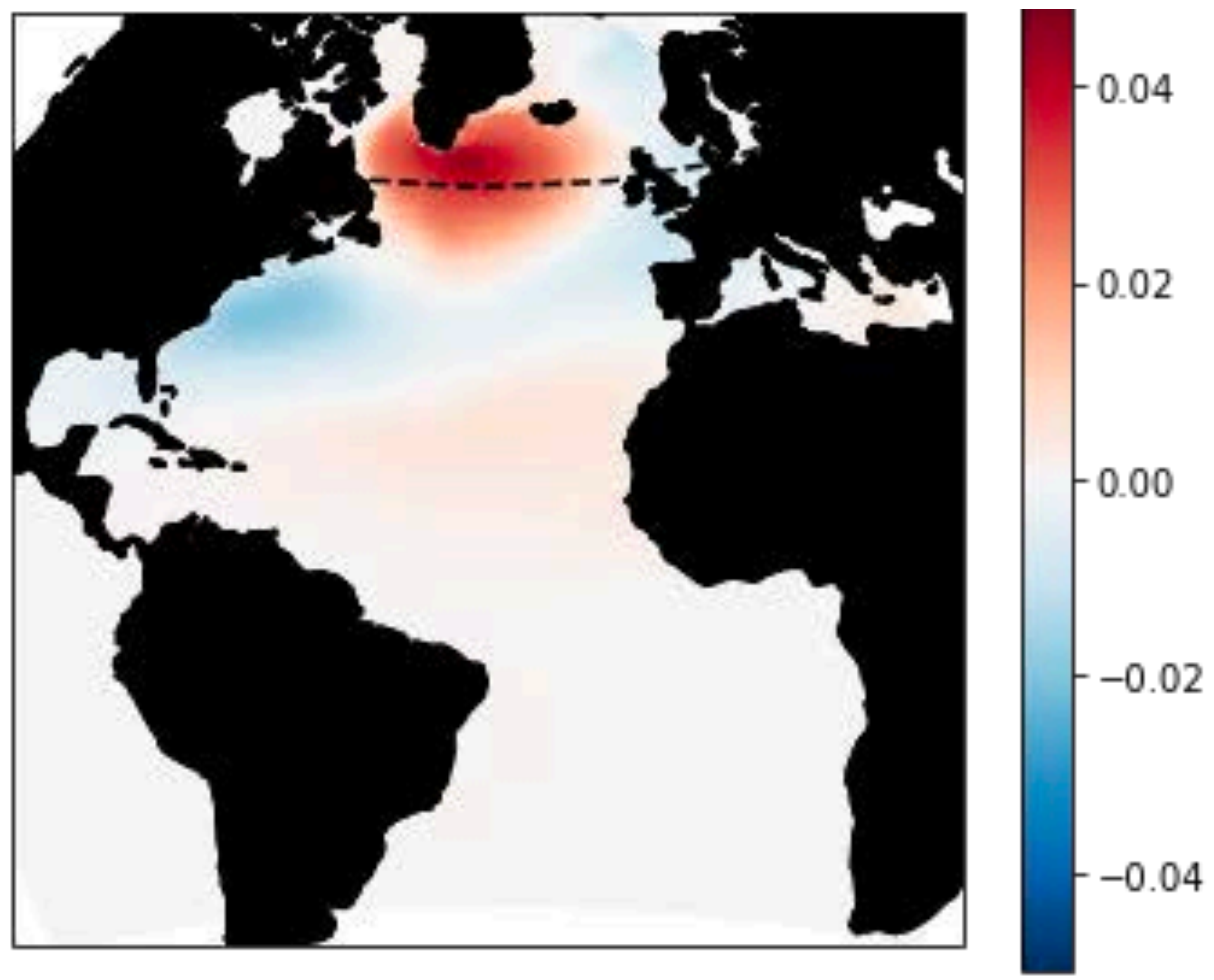


Leading heat flux COF contributing to decadal-mean AMOC variability

Very similar leading patterns (r~.99) were found across latitudes and when targeting annual and decadal AMOC variability.

Looking familiar?





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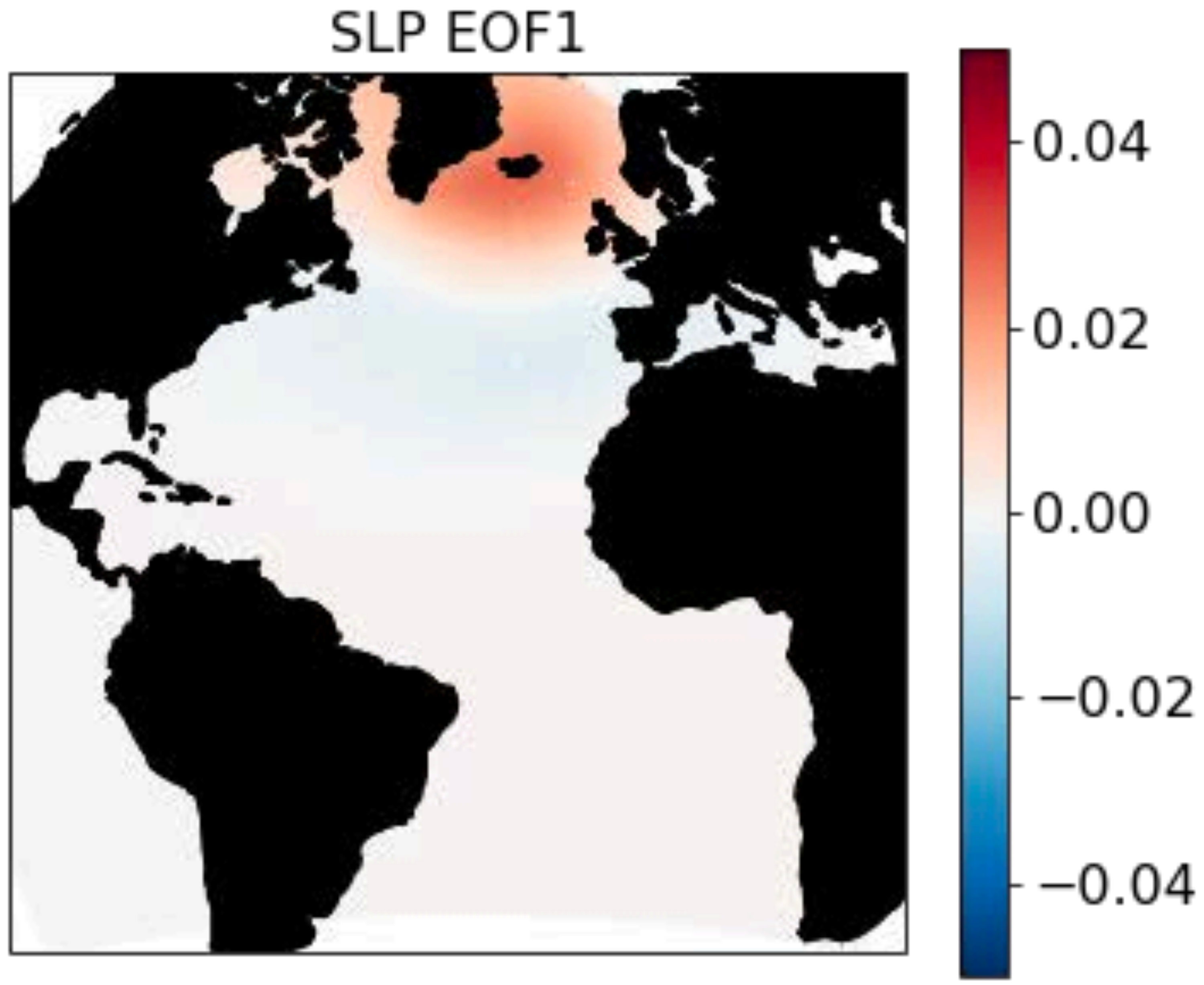
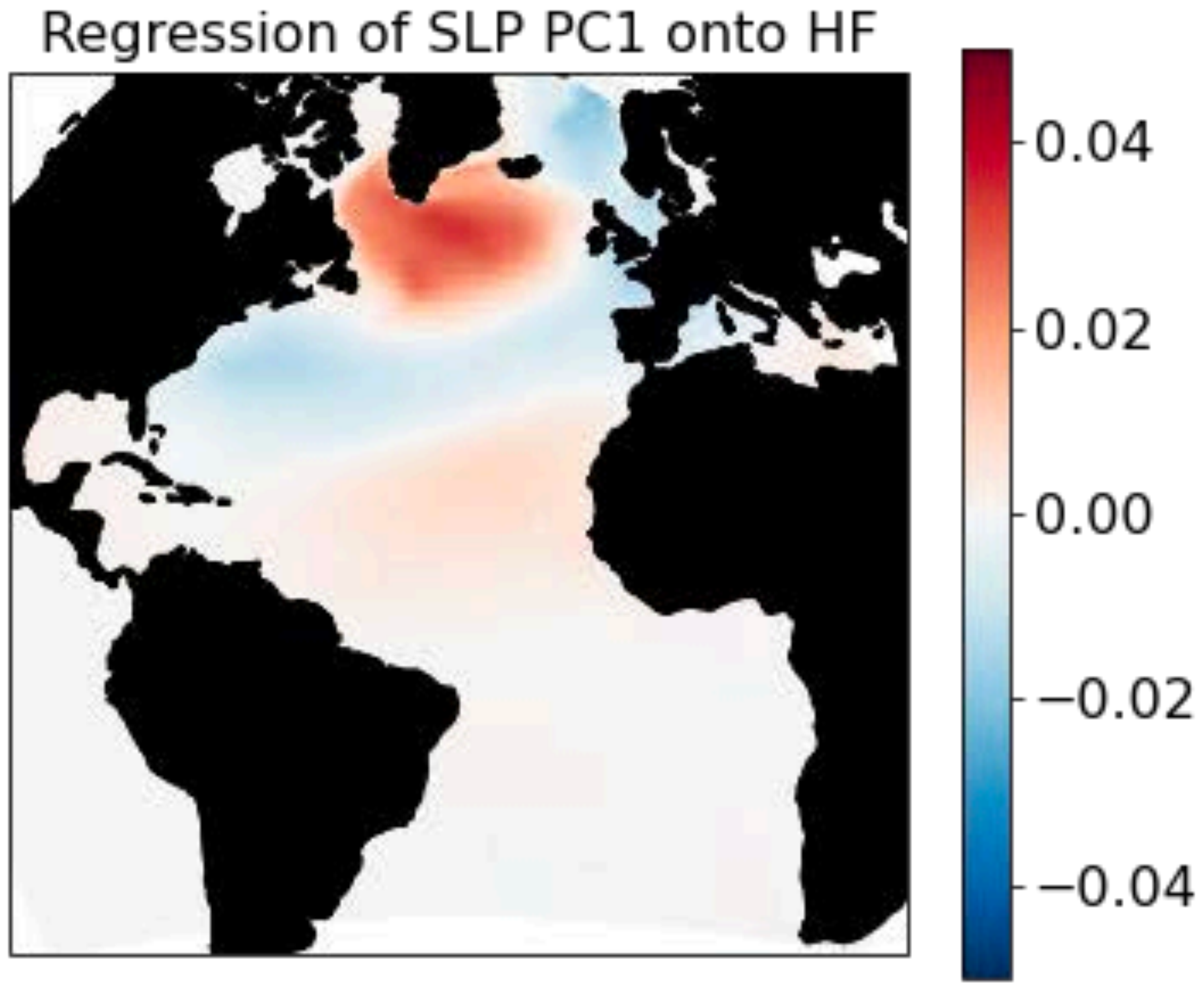
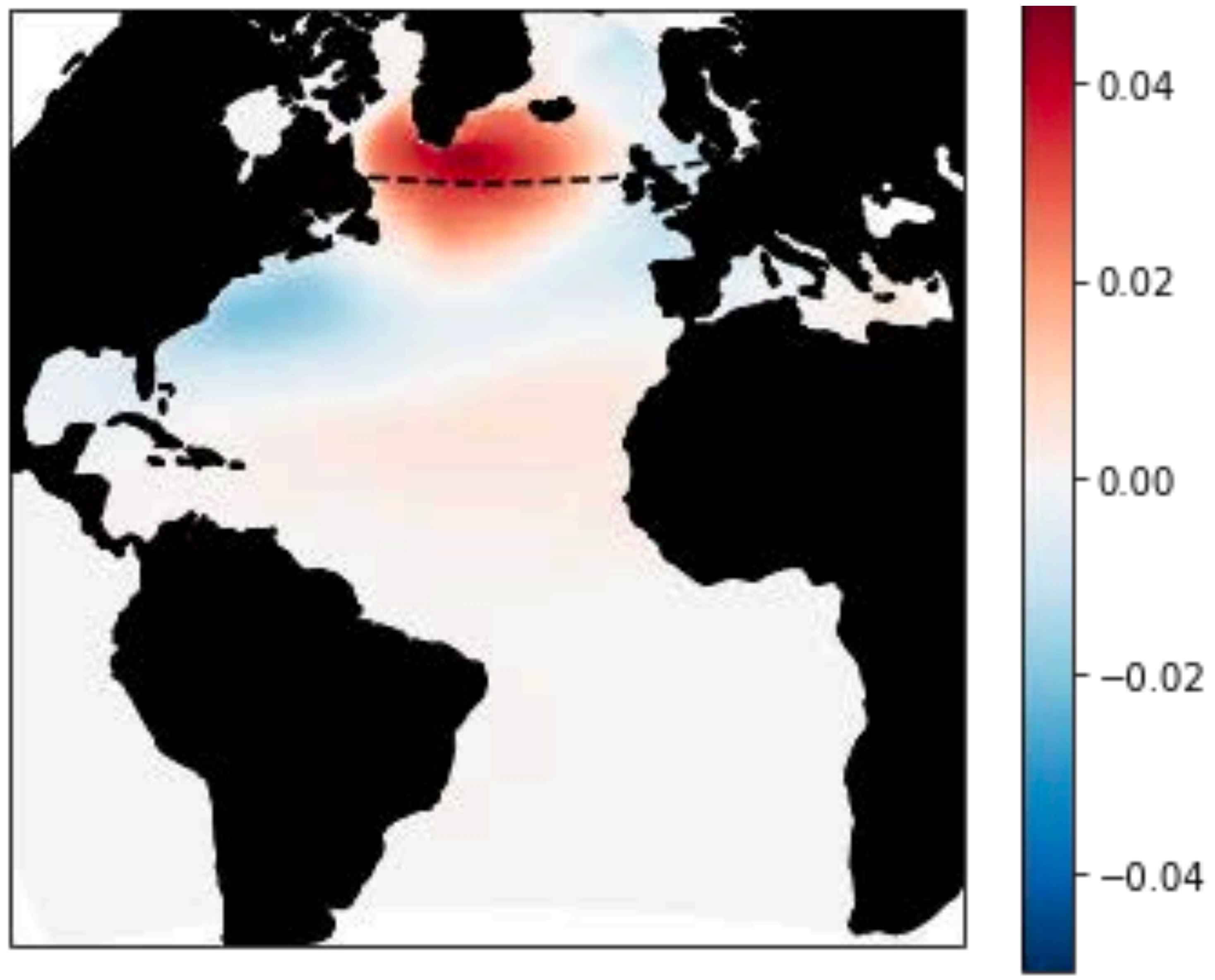
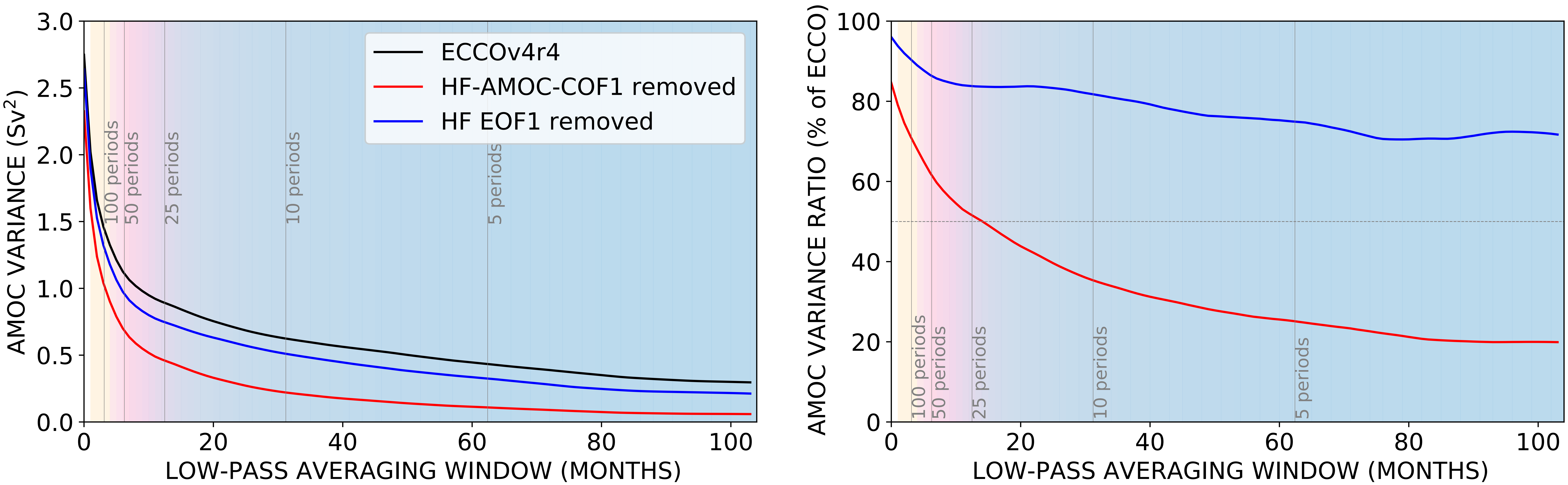






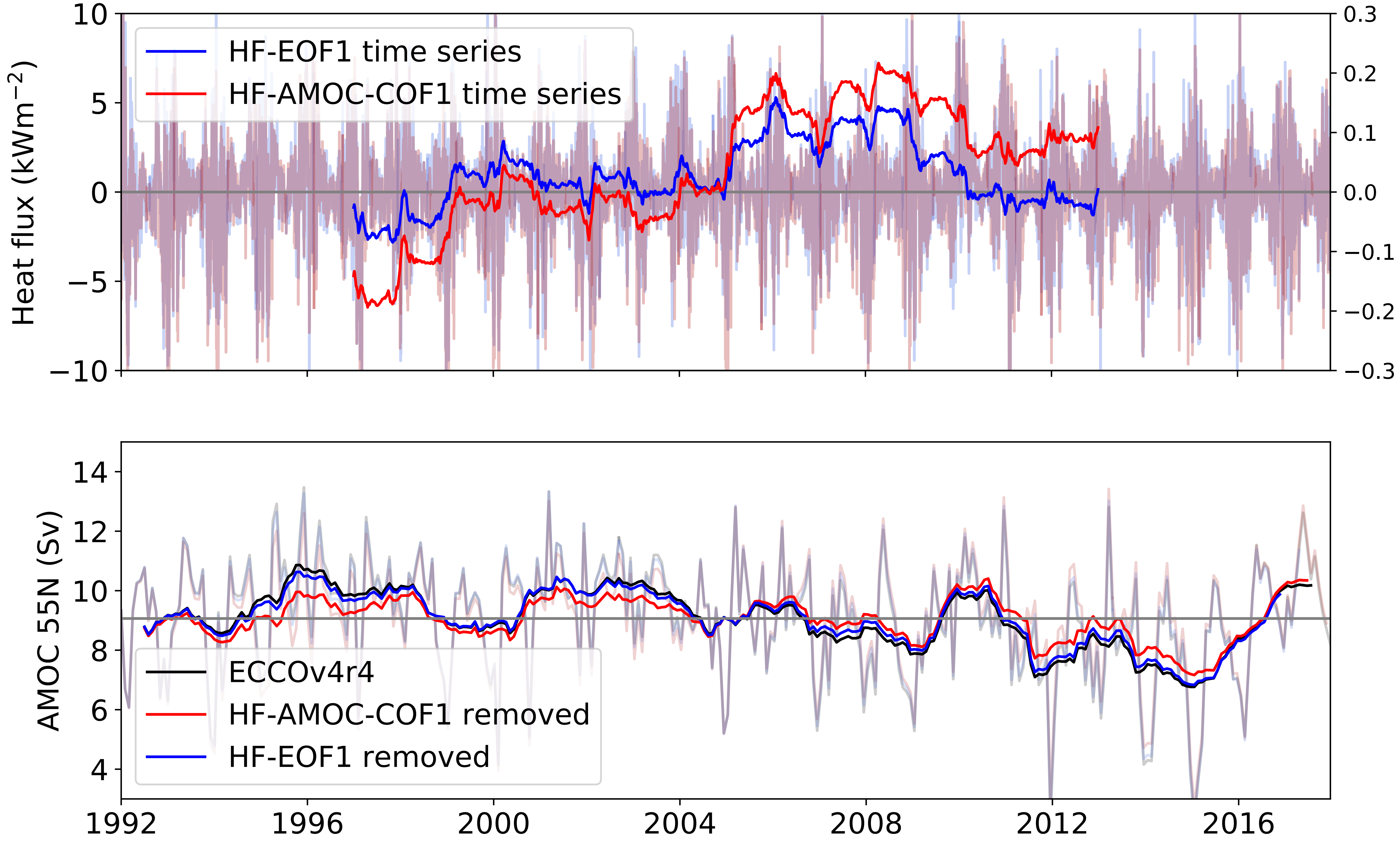
Leading heat flux COF contributing to decadal-mean AMOC variability

In “perturbed ECCO” simulations, removing the leading COF from ECCO forcing drives more AMOC variance than the leading EOF across time scales



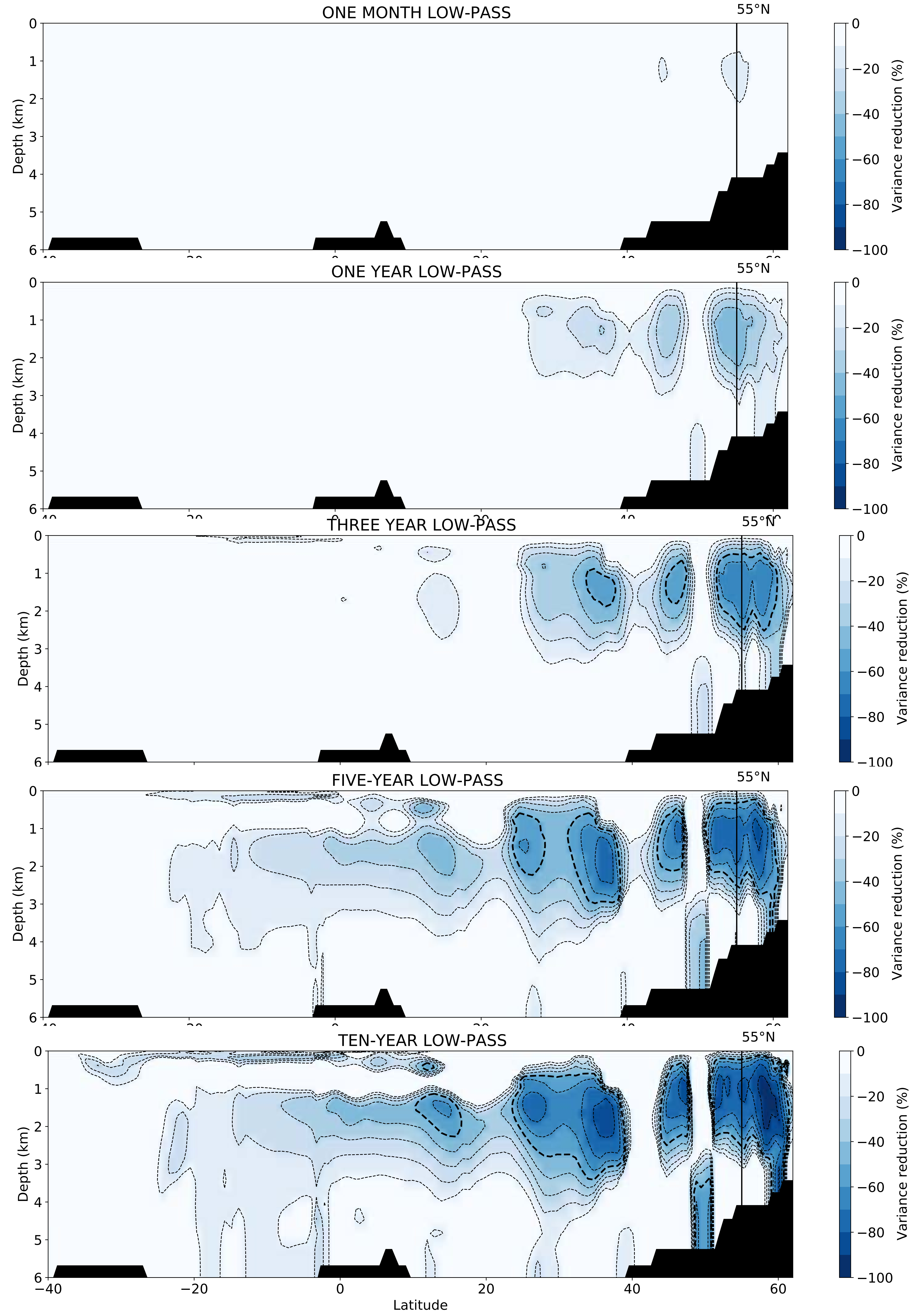
“Perturbed ECCO” simulations run in a **“flux-only” configuration** to isolate contributions from different fluxes *(Fukumori et al. 2021).*

In “perturbed ECCO” simulations removing heat flux patterns, the leading COF drives more AMOC variance than the leading EOF across time scales



“Perturbed ECCO” simulations run in a **“flux-only” configuration** to isolate contributions from different fluxes *(Fukumori et al. 2021).*

Longer time scales of AMOC variability are reduced most and have greatest meridional extent



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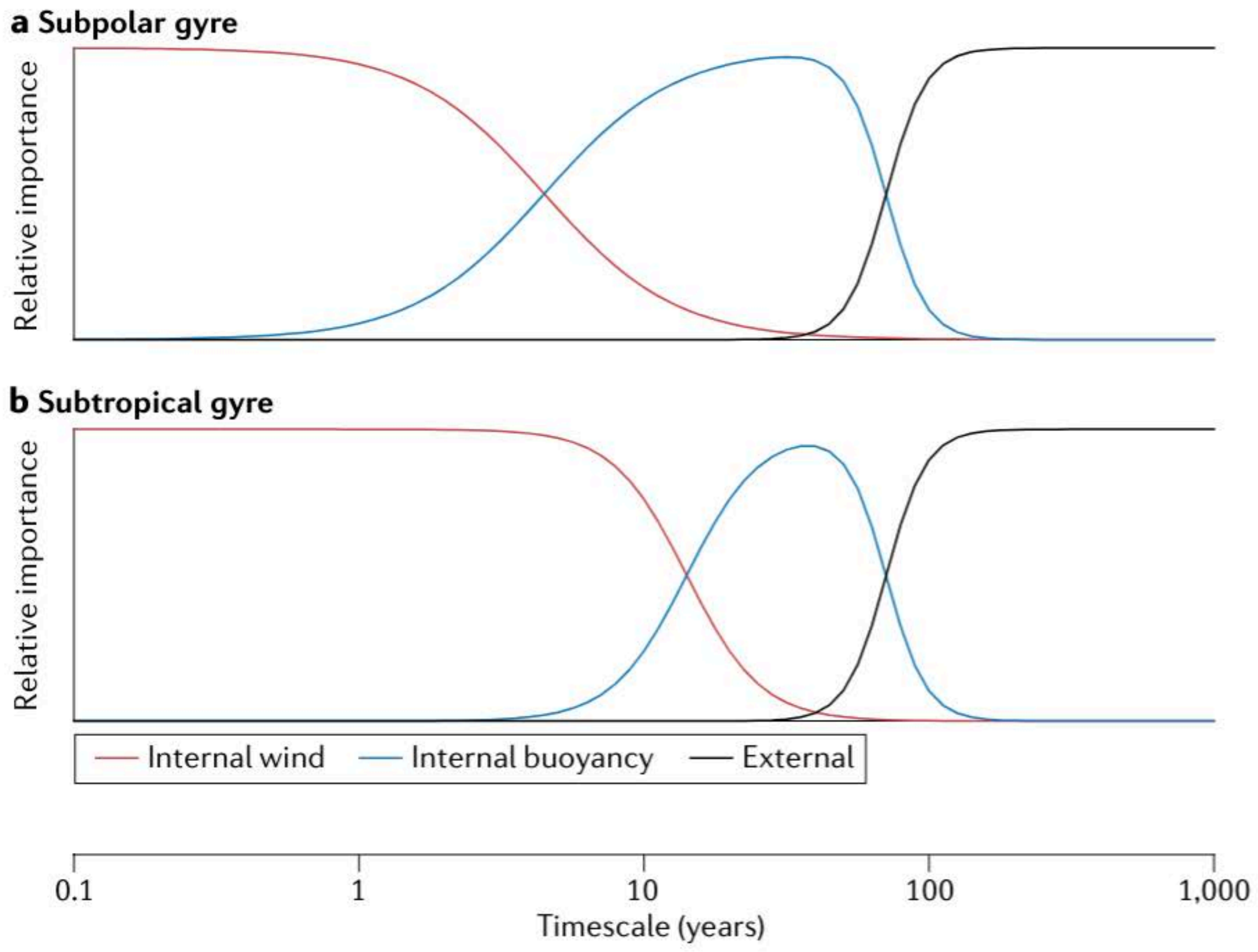
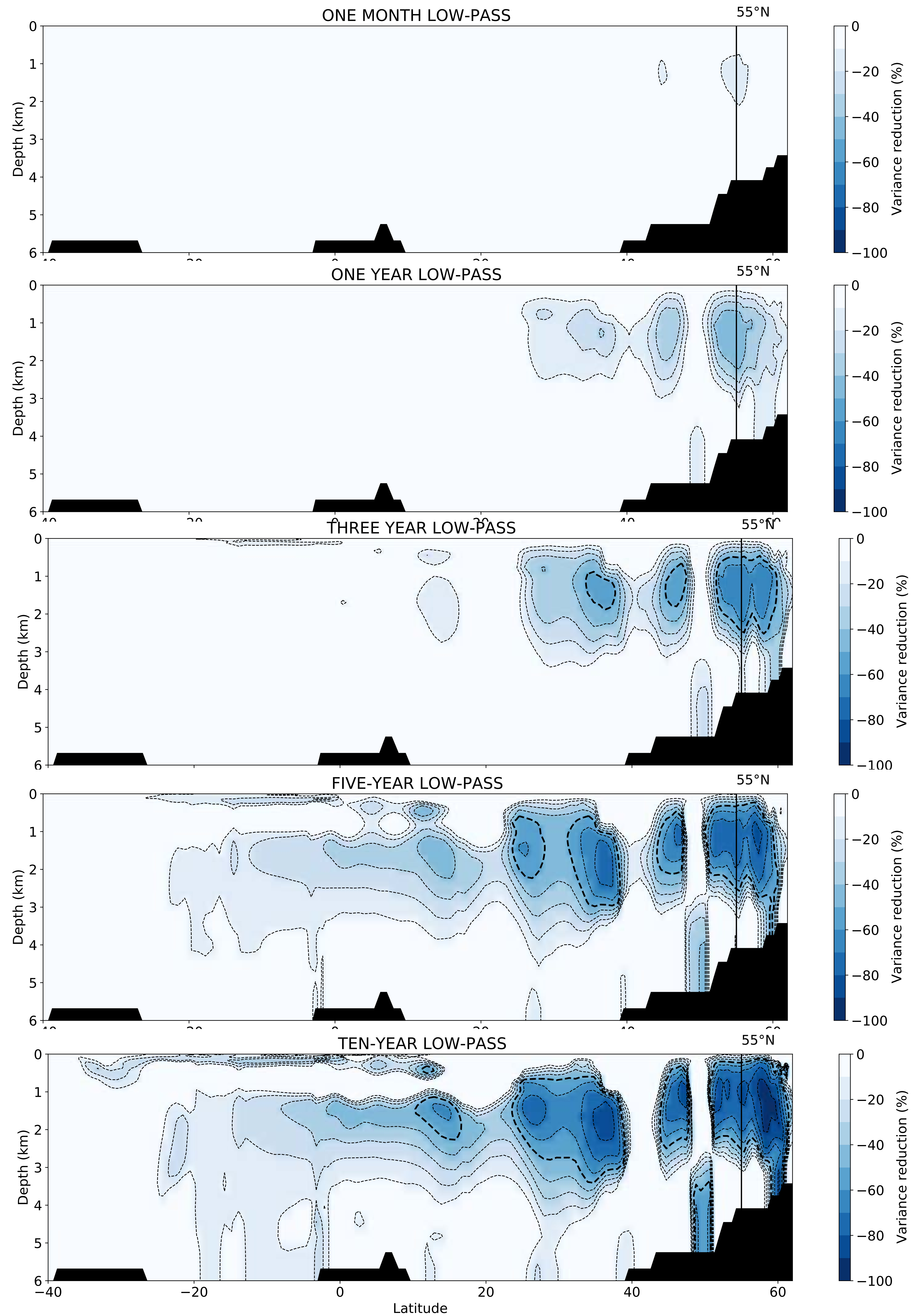
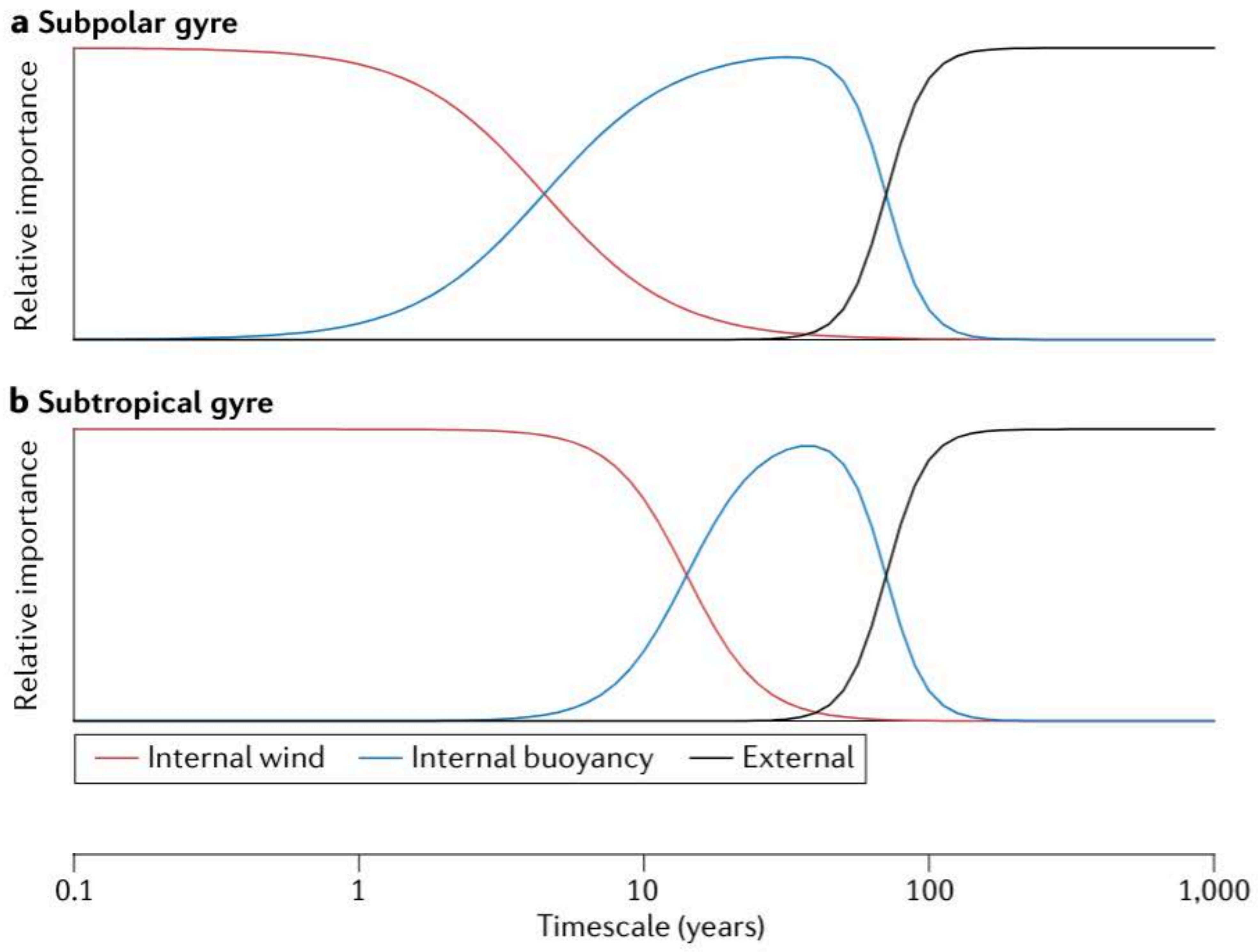
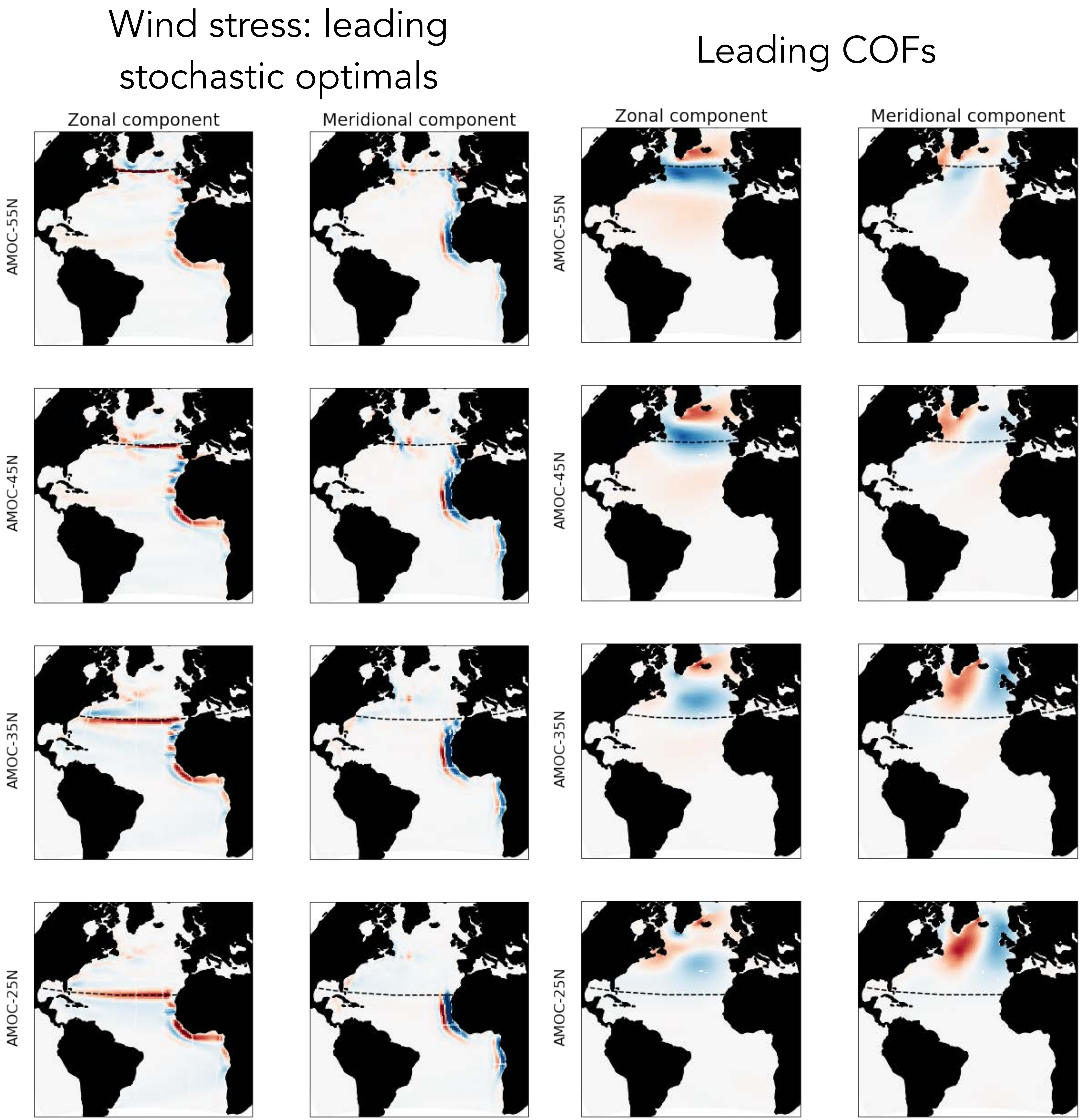




Jackson et al. 2022

Might non-NAO, decadal-scale wind be important for *meridional asynchrony*?

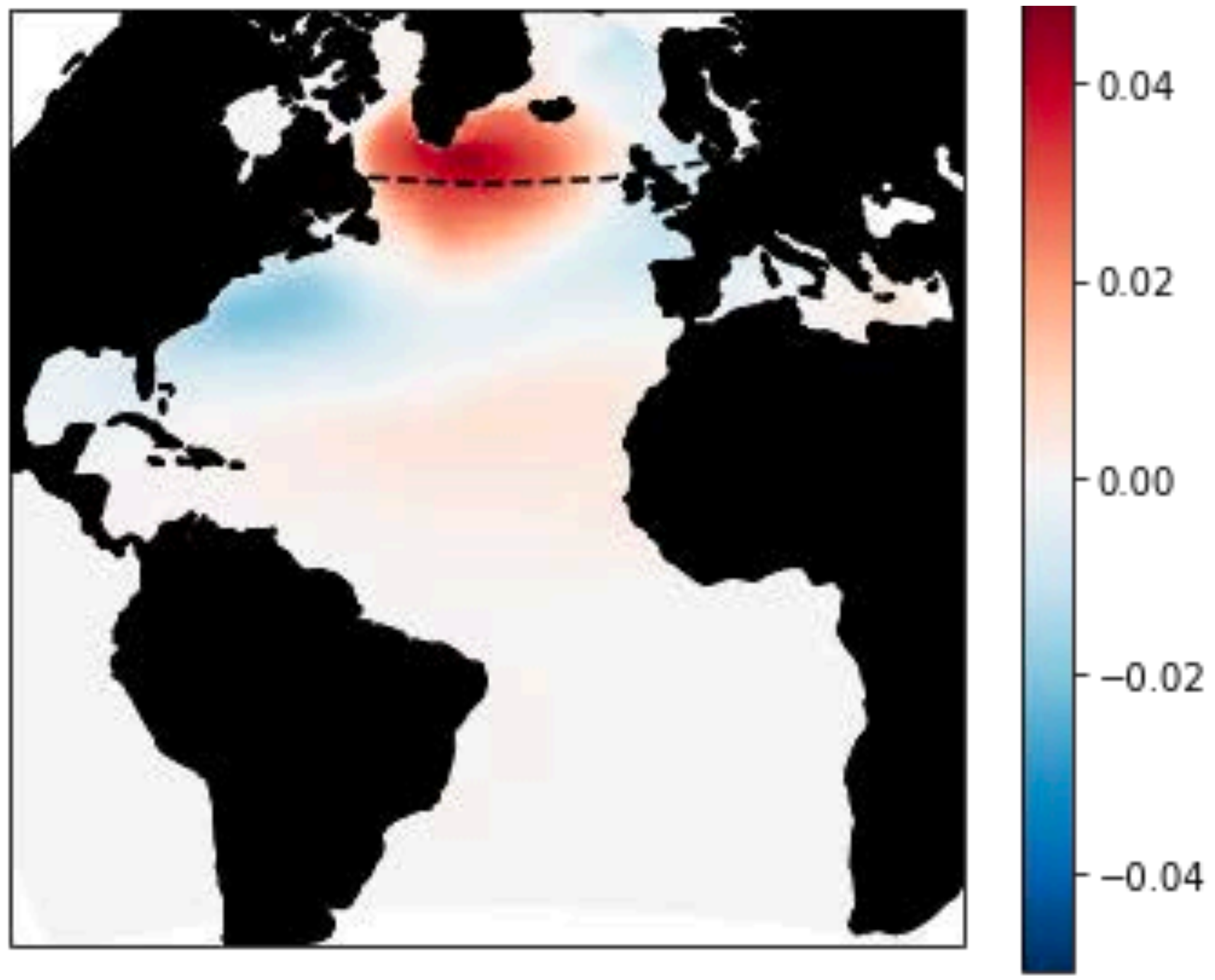




Jackson et al. 2022
see e.g. Häkkinen et al. 2011; Barrier et al. 2014; Kim et al. 2016…

Conclusions and future work

Adjoints tell us what the **ocean wants from the atmosphere.**
Atmospheric EOFs describe **dominant atmospheric patterns.**
By combining adjoints and atmospheric statistics, we identify causal ***atmospheric*** structures that dominate ***ocean*** **variability.**



When applied to AMOC on annual- and decadal-average time scales, a common **NAO-like heat flux pattern** dominates variance change across time scales and latitudes by reducing density anomaly amplitudes in the SPG.

A related procedure permits smoothing adjoint sensitivities to reflect prior atmospheric covariances and additional observations of the atmosphere. These procedures are useful in **state estimation** (especially paleo!).

Caveats: **Linear** sensitivities. Covariances assume **stationary** fluxes. Using a **1° ocean-only** model.

From Dafydd: Please reach out if you're interested in setting up or running an ocean adjoint model! dafydd@ucar.edu