Combining adjoint sensitivities and ECCOv4-r4 air-sea fluxes to determine dominant drivers of North Atlantic subpolar gyre variability

… BONUS: implications for state estimation

Dan Amrhein
National Center for Atmospheric Research

Dafydd Stephenson
[C]Worthy

LuAnne Thompson
University of Washington

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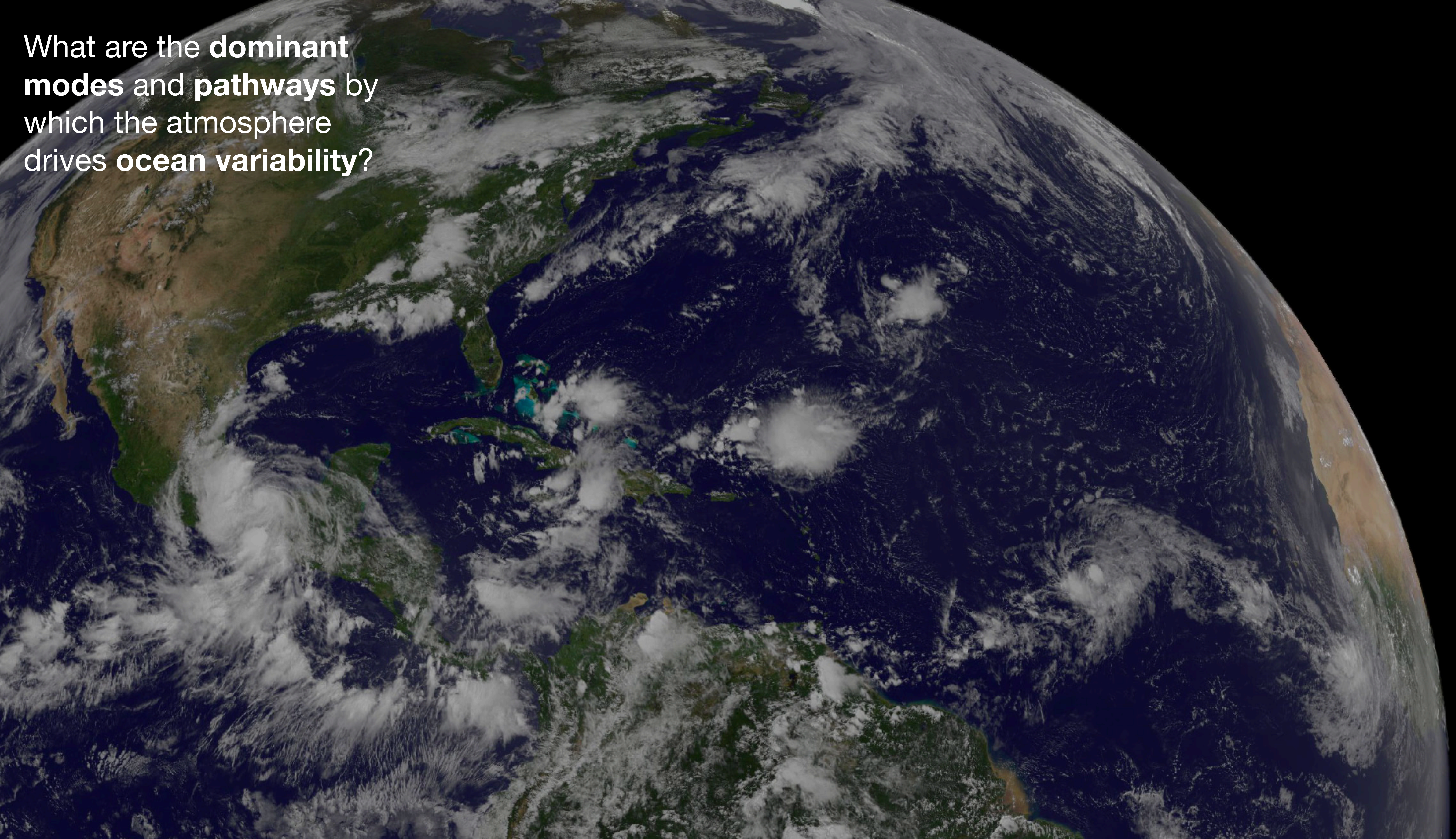


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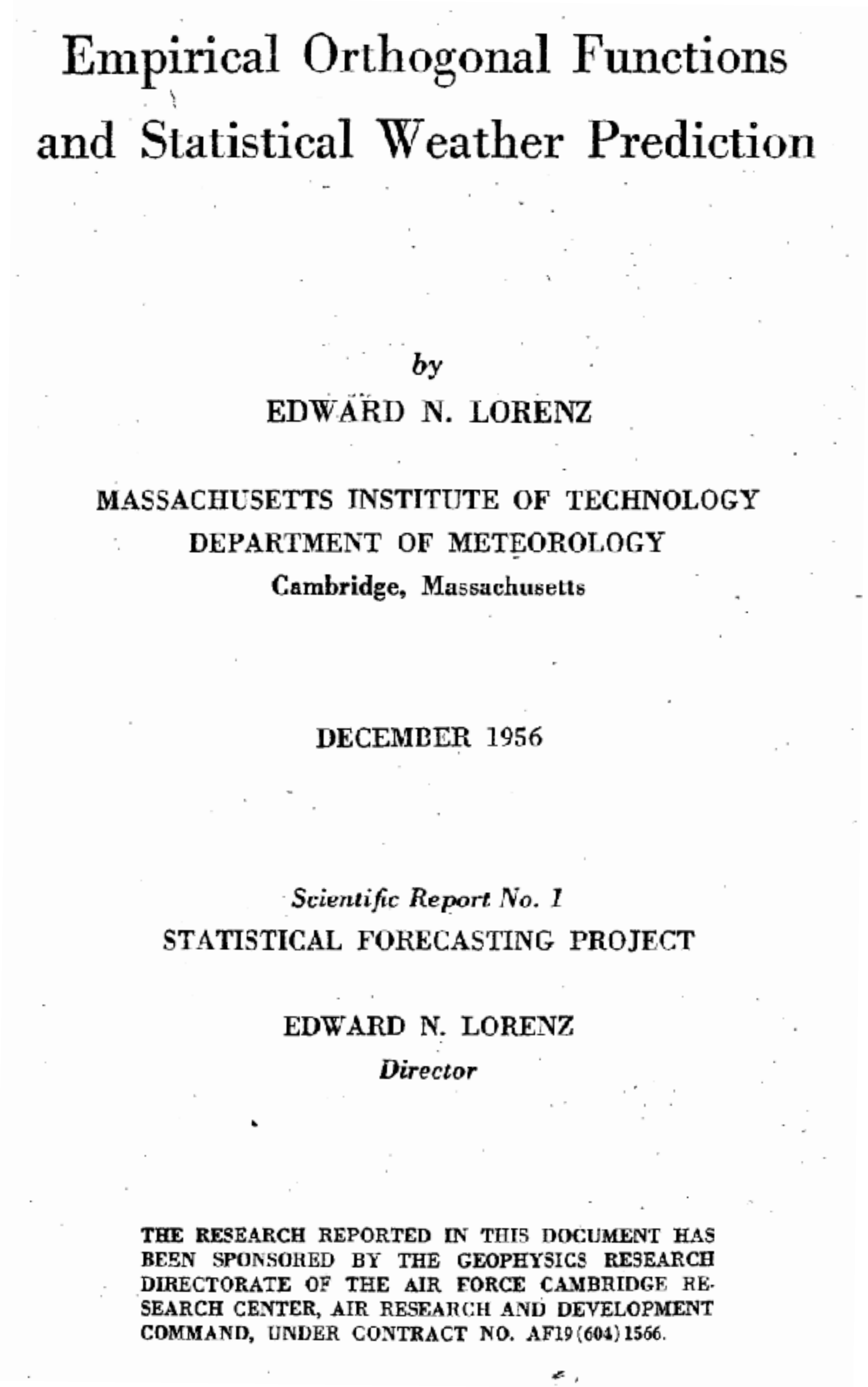

Empirical Orthogonal Functions and Statistical Weather Prediction

by
EDWARD N. LORENZ

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF METEOROLOGY
Cambridge, Massachusetts

DECEMBER 1956

Scientific Report No. 1
STATISTICAL FORECASTING PROJECT

EDWARD N. LORENZ
Director

THE RESEARCH REPORTED IN THIS DOCUMENT HAS BEEN SPONSORED BY THE GEOPHYSICS RESEARCH DIRECTORATE OF THE AIR FORCE CAMBRIDGE RESEARCH CENTER, AIR RESEARCH AND DEVELOPMENT COMMAND, UNDER CONTRACT NO. AF19(604)1566.

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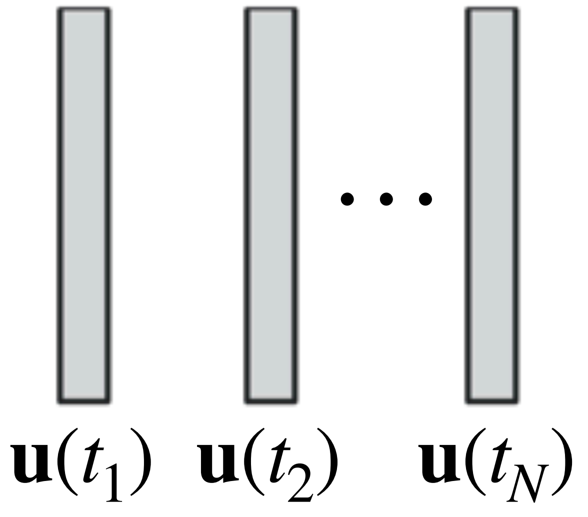

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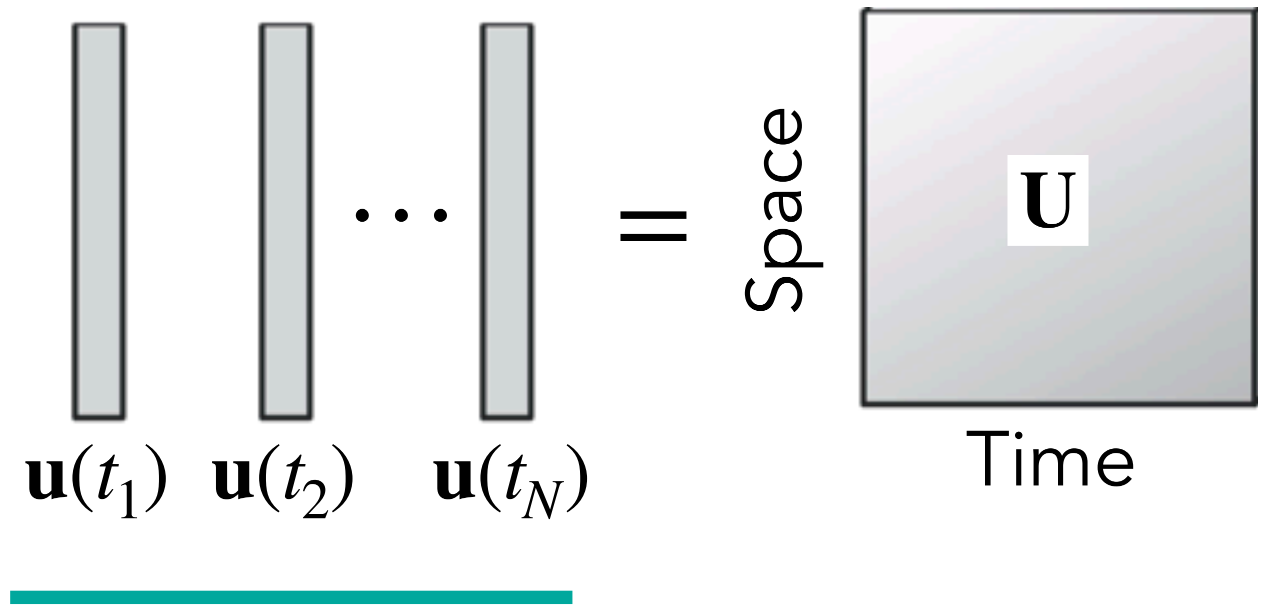

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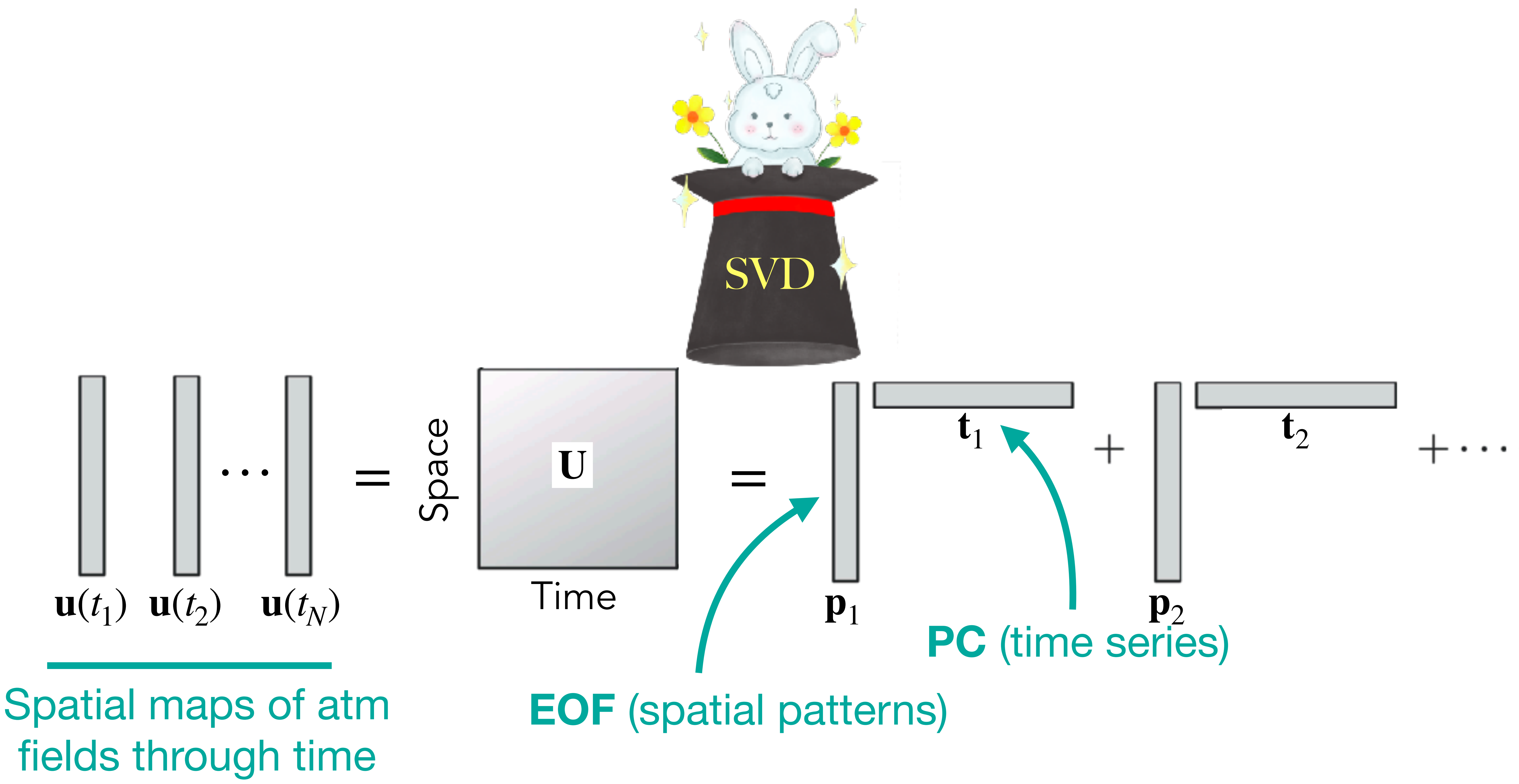

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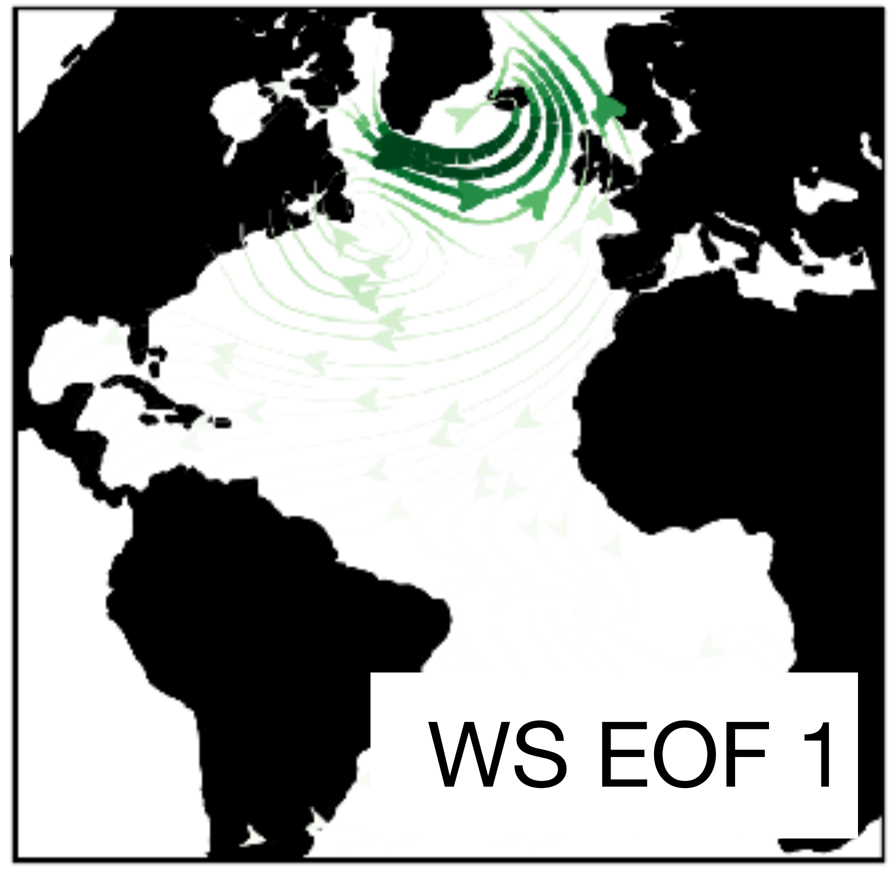

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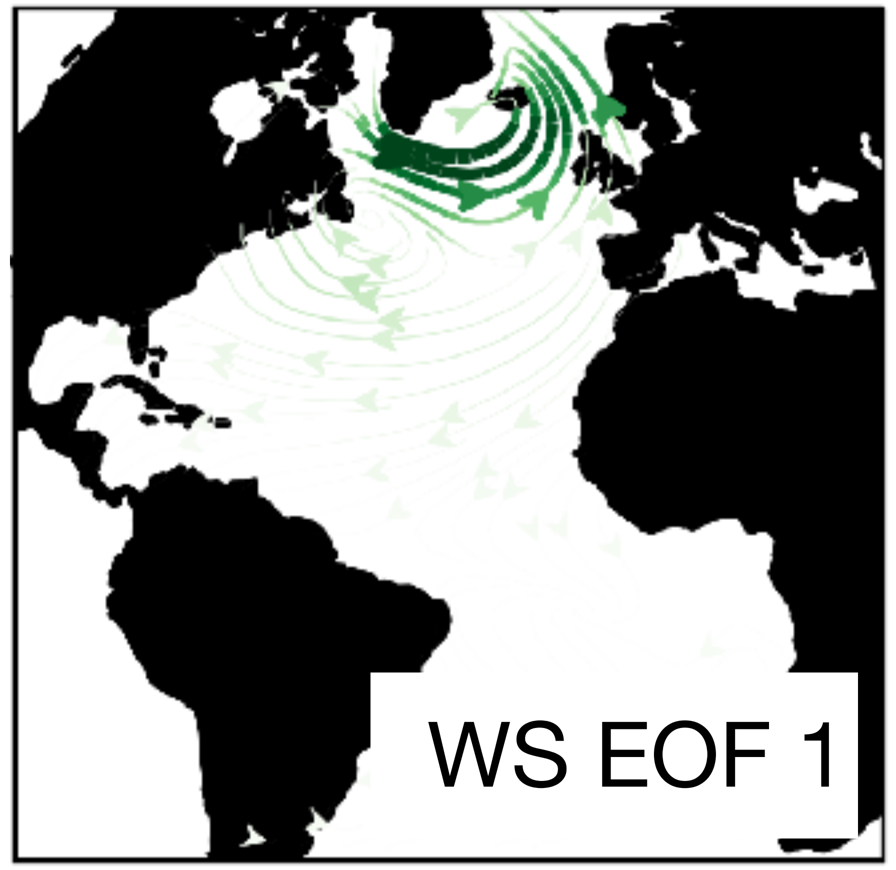

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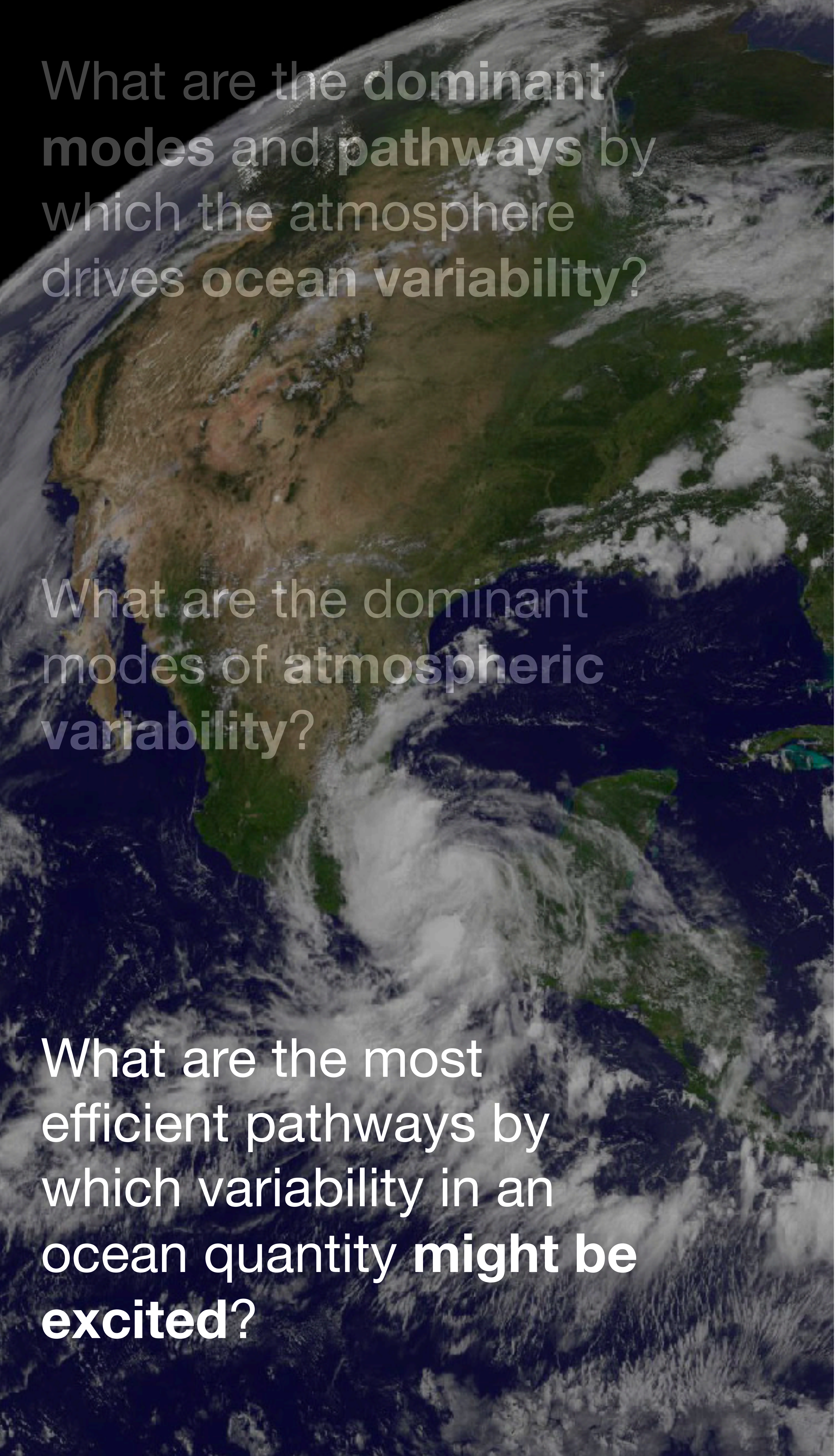

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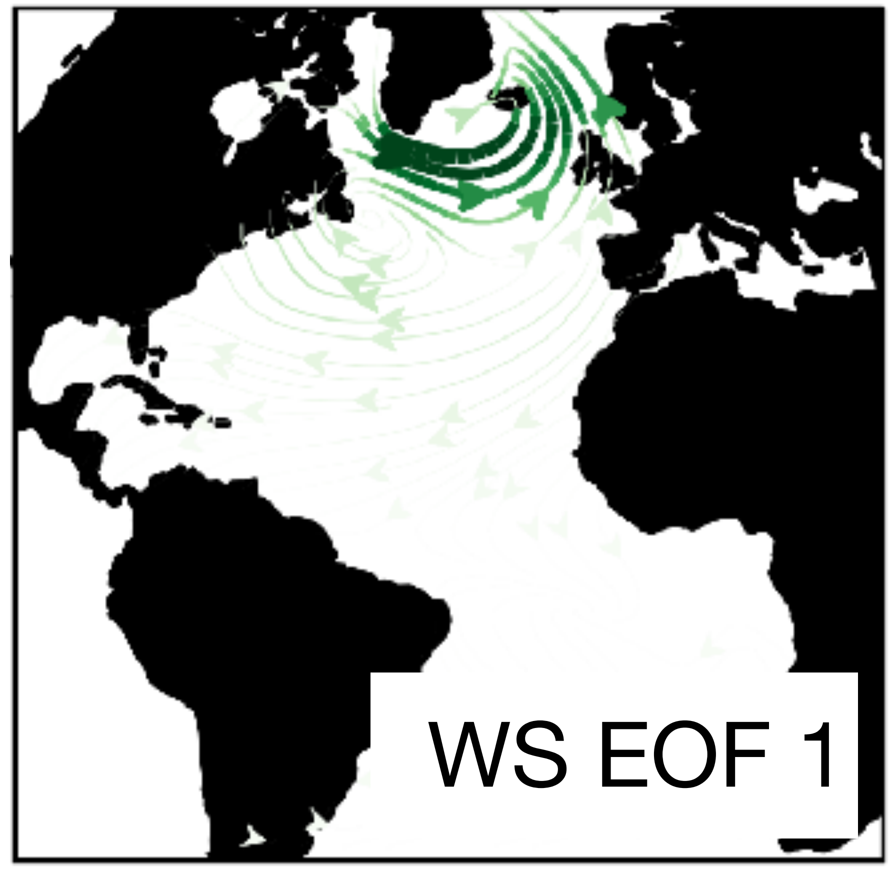

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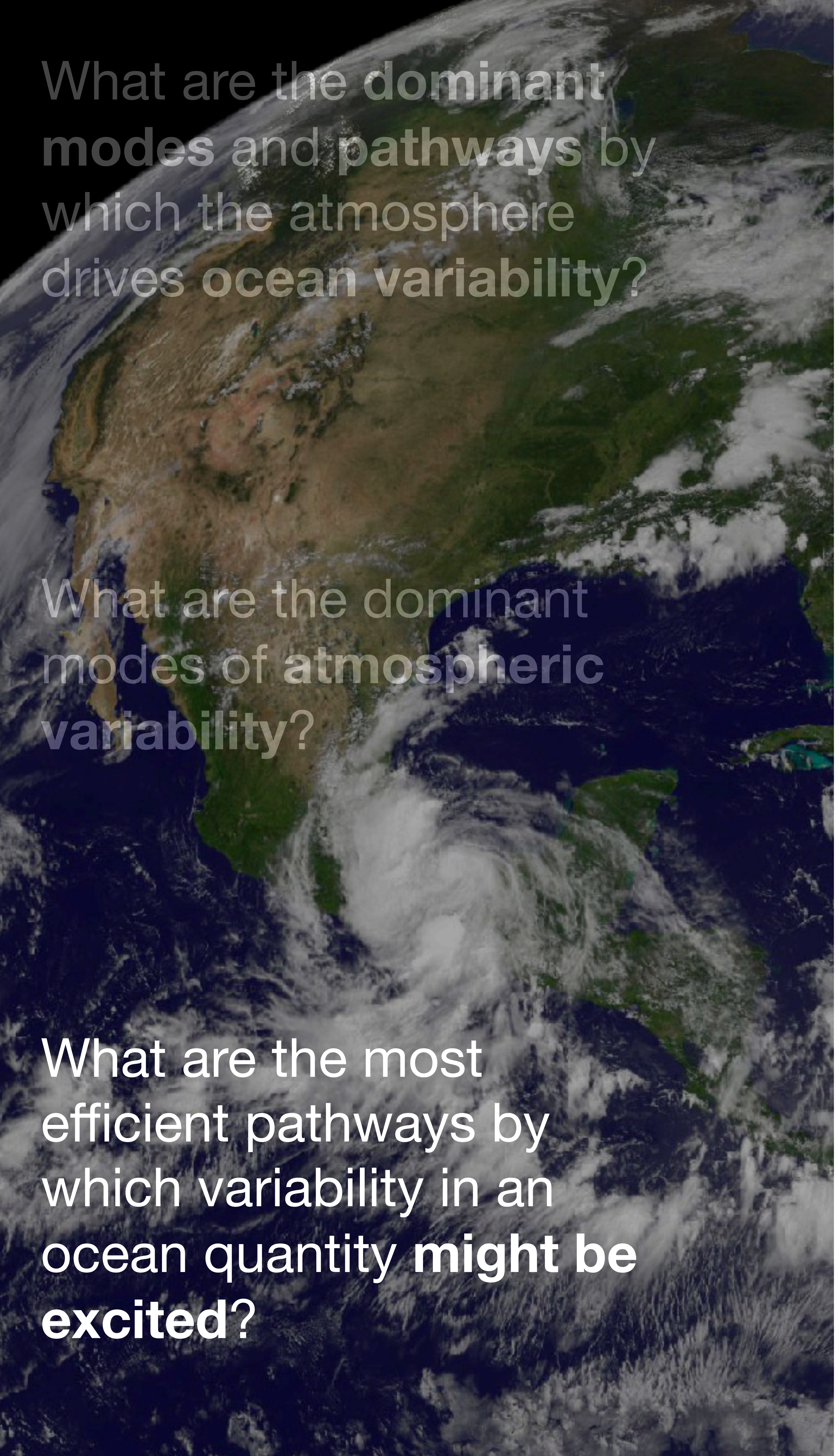

Generalized Stability Theory. Part I: Autonomous Operators

BRIAN F. FARRELL AND PETROS J. IOANNOU*

Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts

(Manuscript received 19 July 1995, in final form 31 January 1996)

A Theory for the Limitation of ENSO Predictability Due to Stochastic Atmospheric Transients

RICHARD KLEEMAN

Bureau of Meteorology Research Centre, Melbourne, Victoria, Australia

ANDREW M. MOORE

Nova Southeastern University Oceanographic Center, Dania, Florida

(Manuscript received 28 December 1995, in final form 10 July 1996)

The answer: “**stochastic optimals**.”

$$\mathbf{s}(\tau) = \frac{\partial x}{\partial \mathbf{u}(\tau)}$$

Ocean sensitivities $\mathbf{s}(\tau)$ are a linear estimate of *when*, *where*, and *how* to change an ocean quantity.

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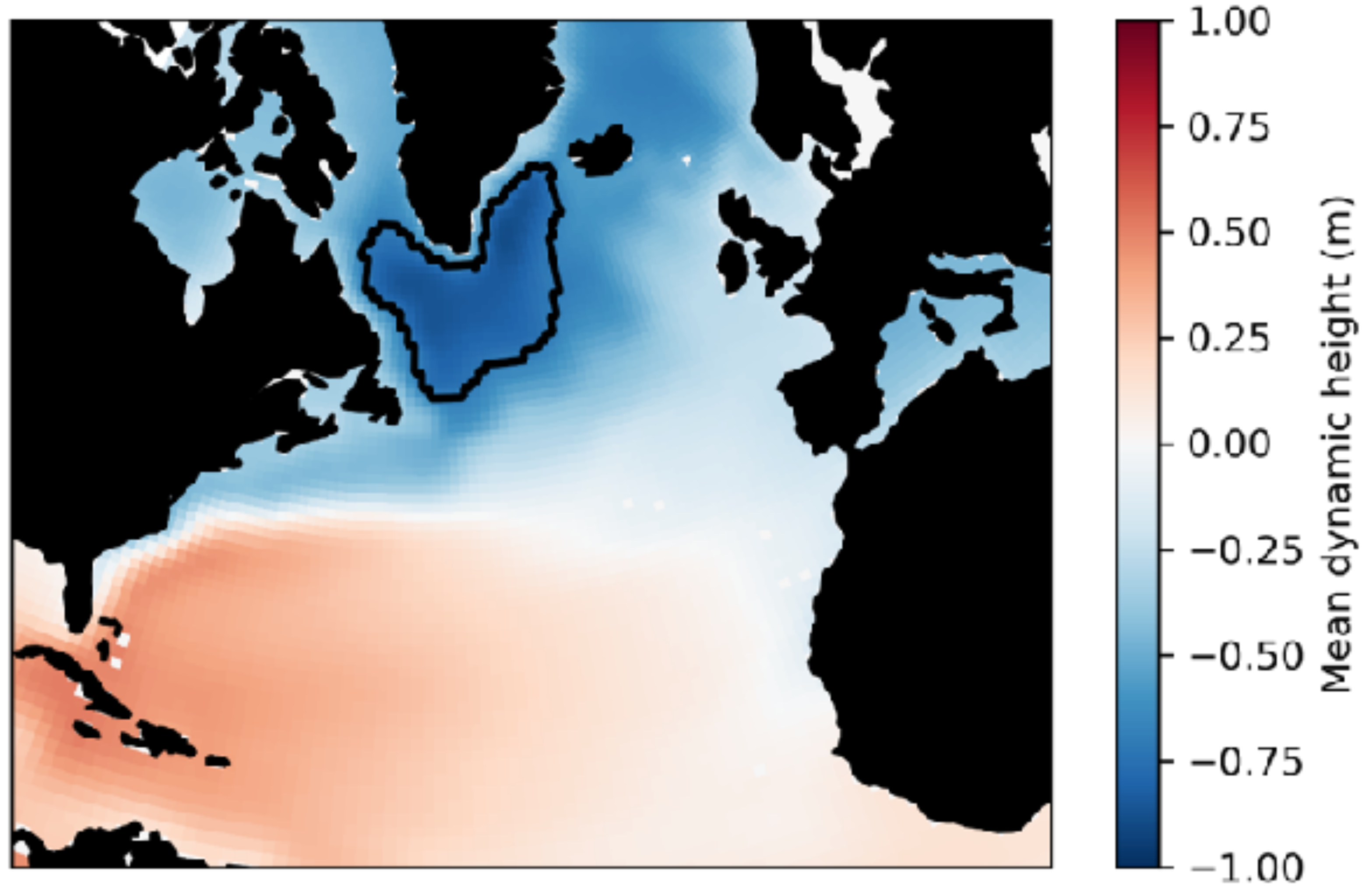

This talk:

x: OHC above 700m in the North Atlantic subpolar gyre

$\mathbf{u}$: wind stress (WS) and heat fluxes (HF)

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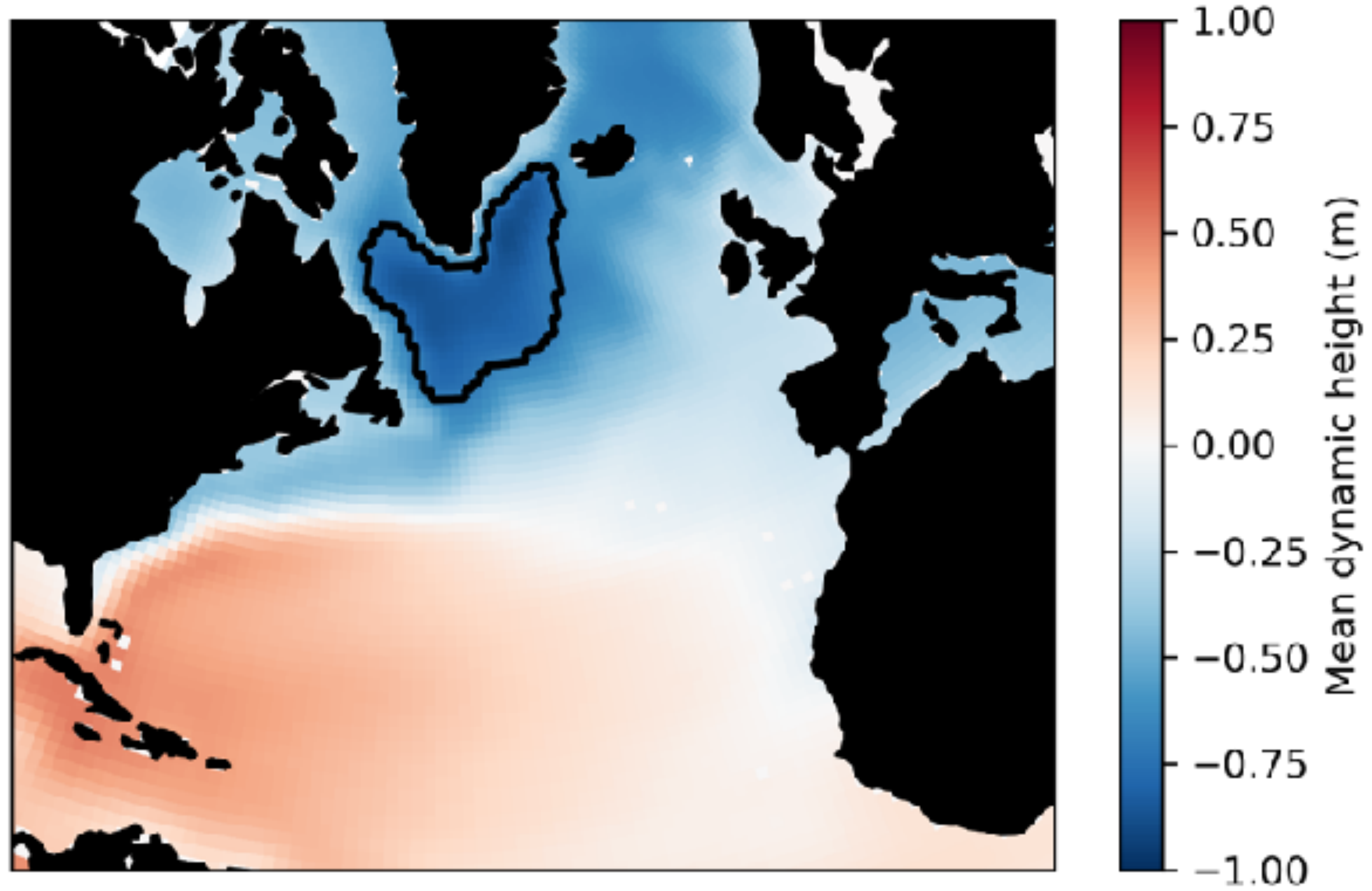

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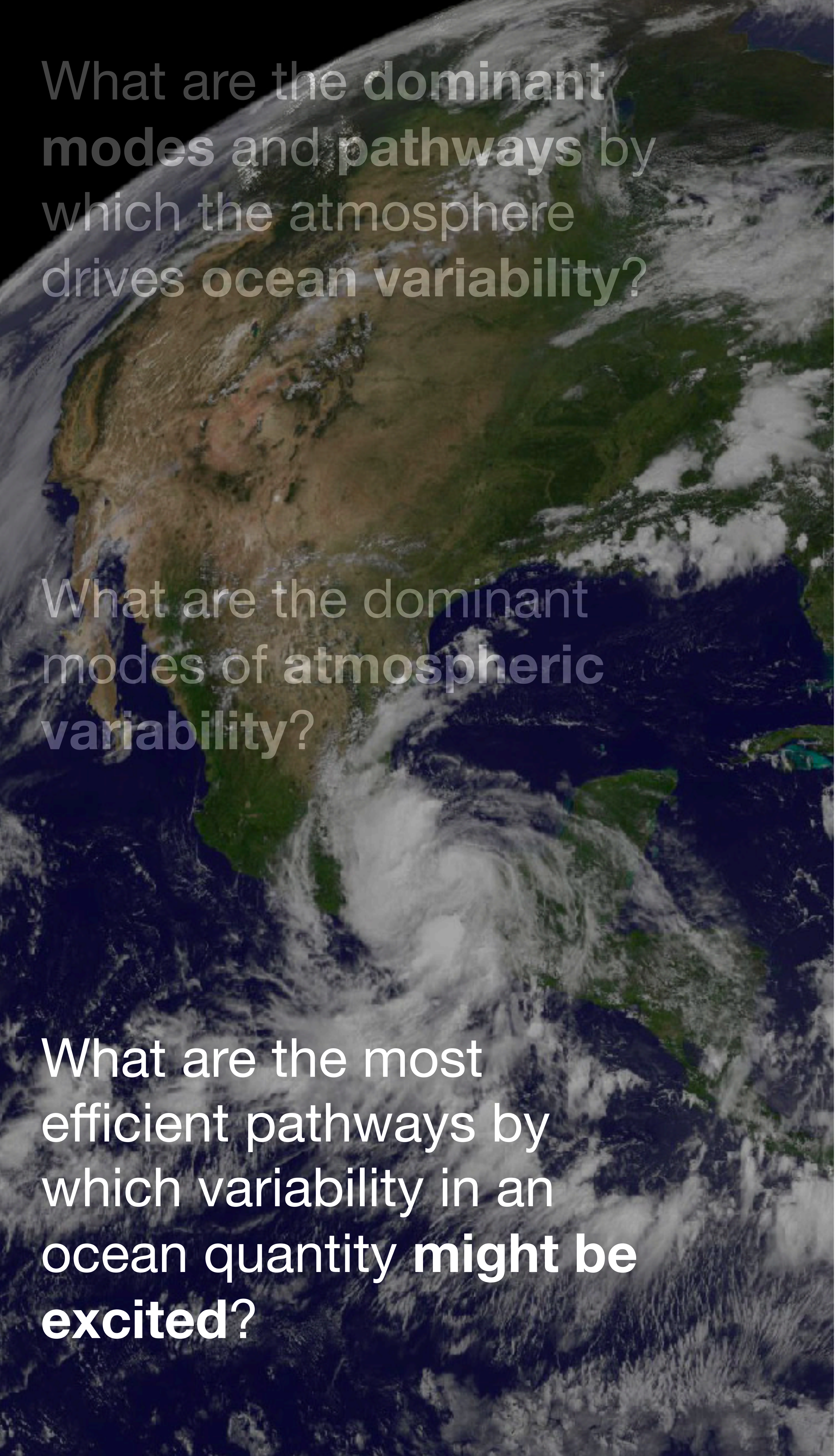
1° resolution **MITgcm ECCO v4 flux-forced configuration**

Adjointed to compute sensitivities of annual-mean upper 700m heat content in the subpolar gyre to weekly heat fluxes and wind stress



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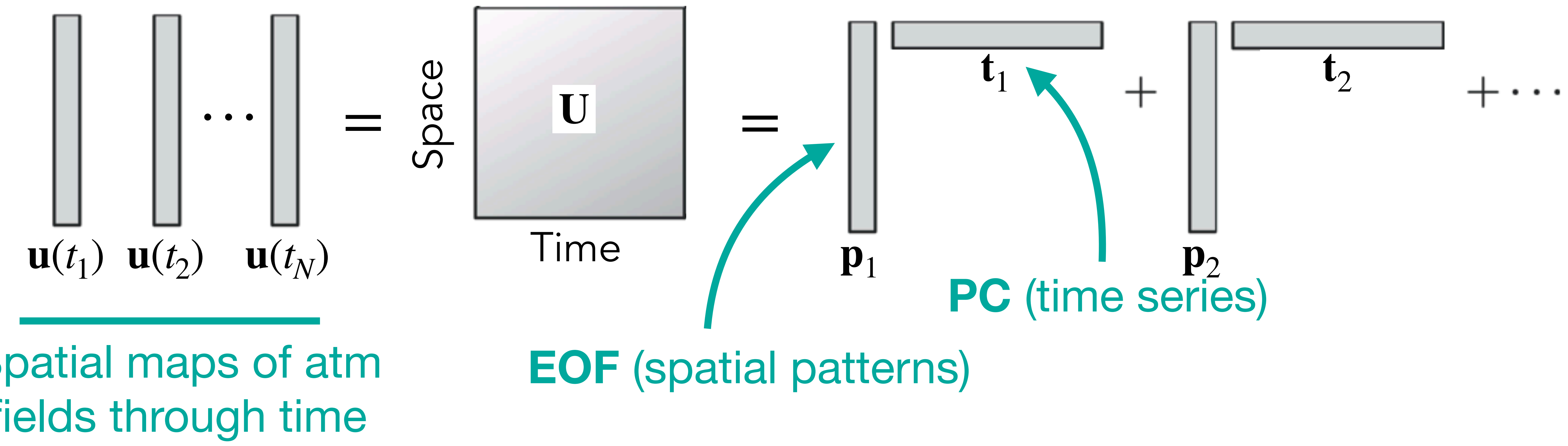

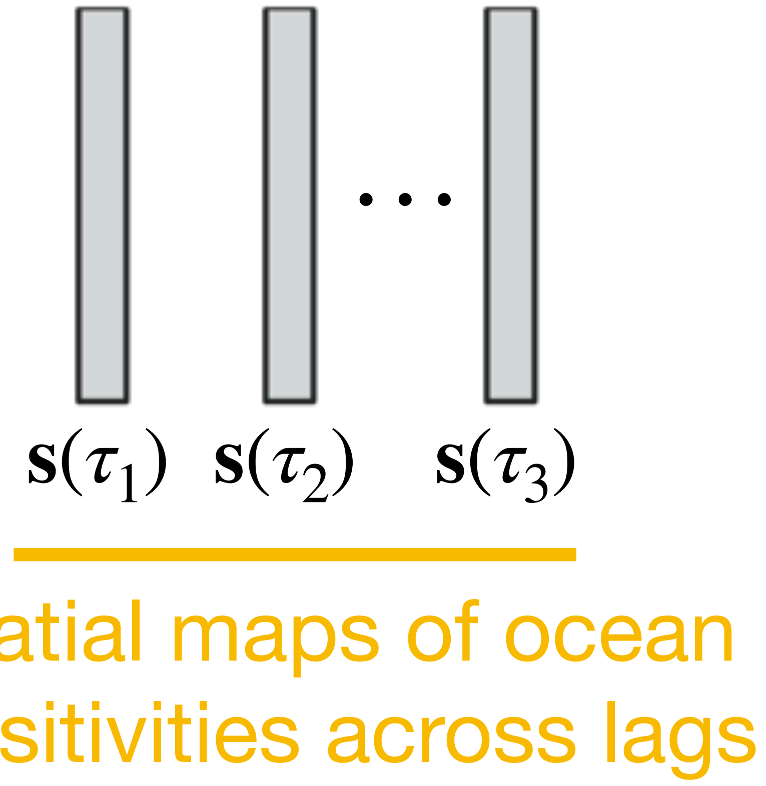

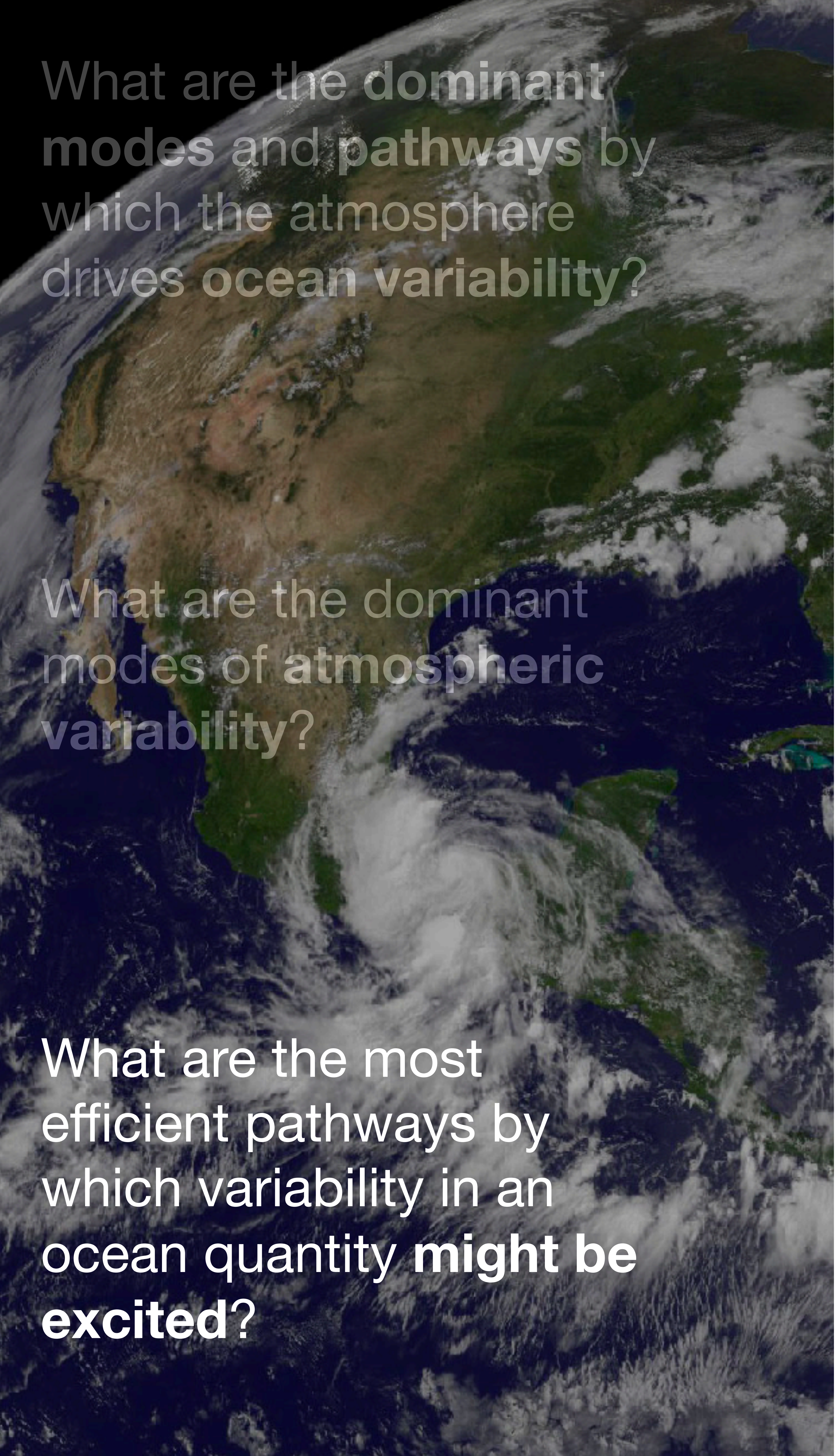
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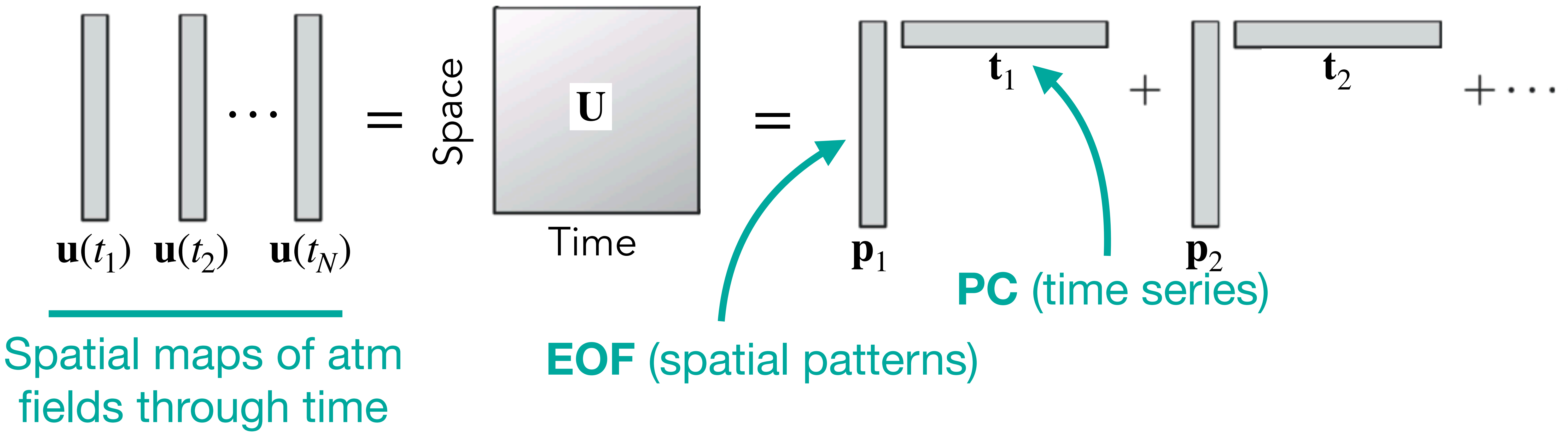
$\mathbf{u}(t_1)$ $\mathbf{u}(t_2)$ $\mathbf{u}(t_N)$
Space
$\mathbf{U}$
Time
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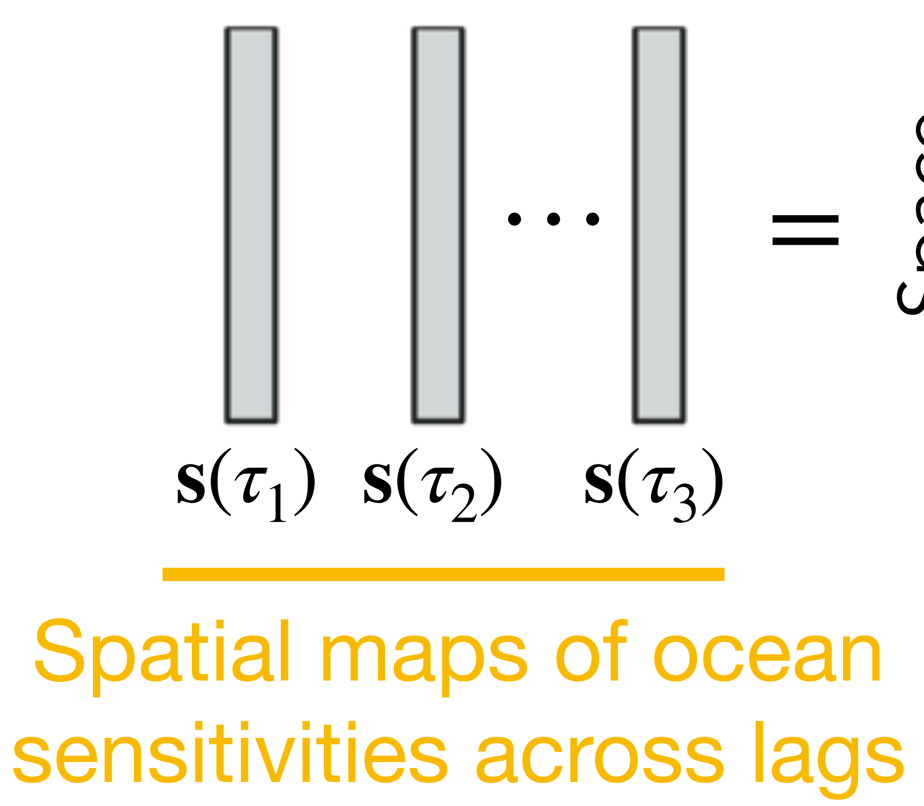
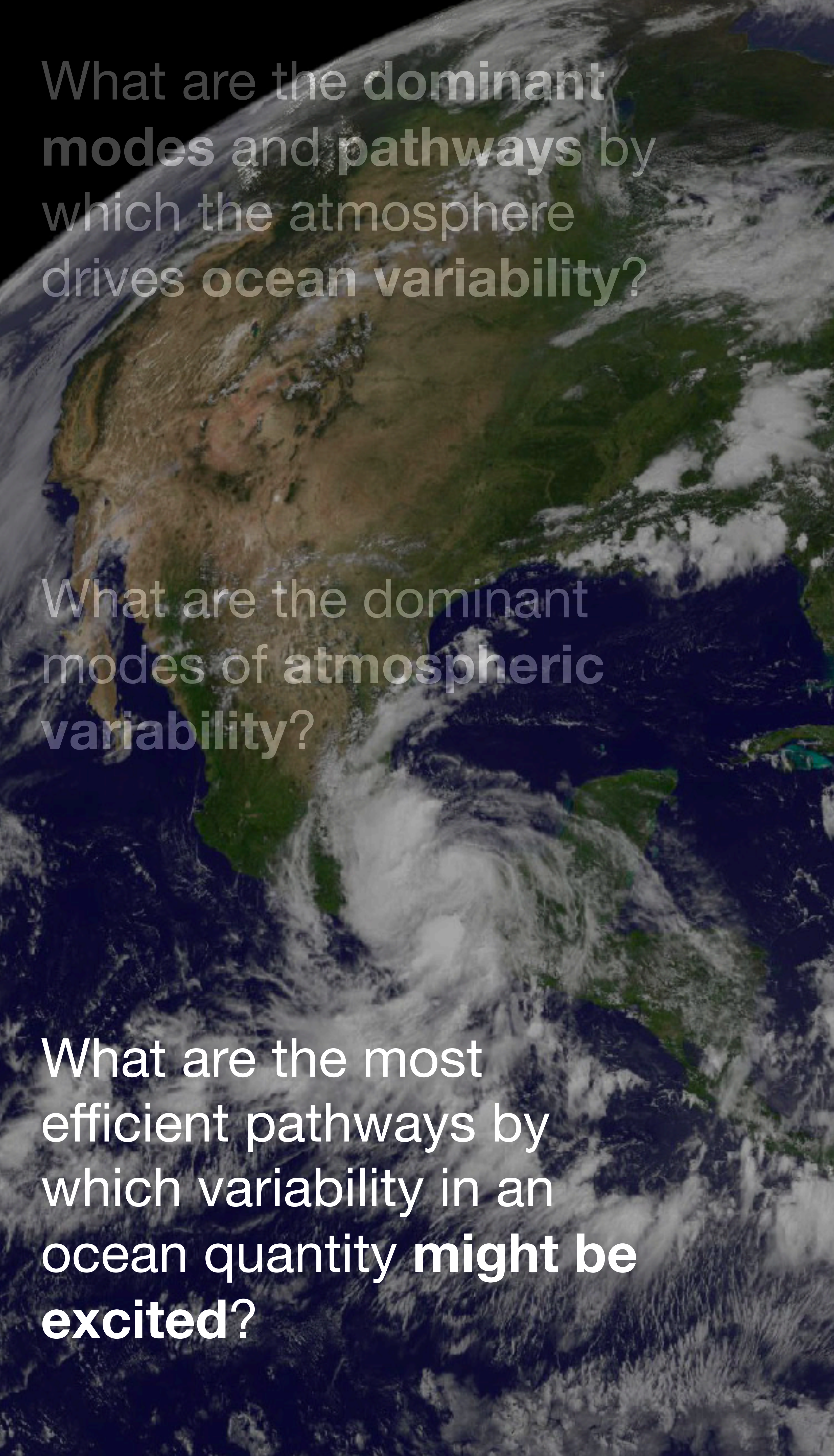
Spatial maps of atm fields through time
EOF (spatial patterns)
PC (time series)


$\mathbf{s}(\tau_1)$ $\mathbf{s}(\tau_2)$ $\mathbf{s}(\tau_3)$
Space
$\mathbf{S}$
Lag
Spatial maps of ocean sensitivities across lags



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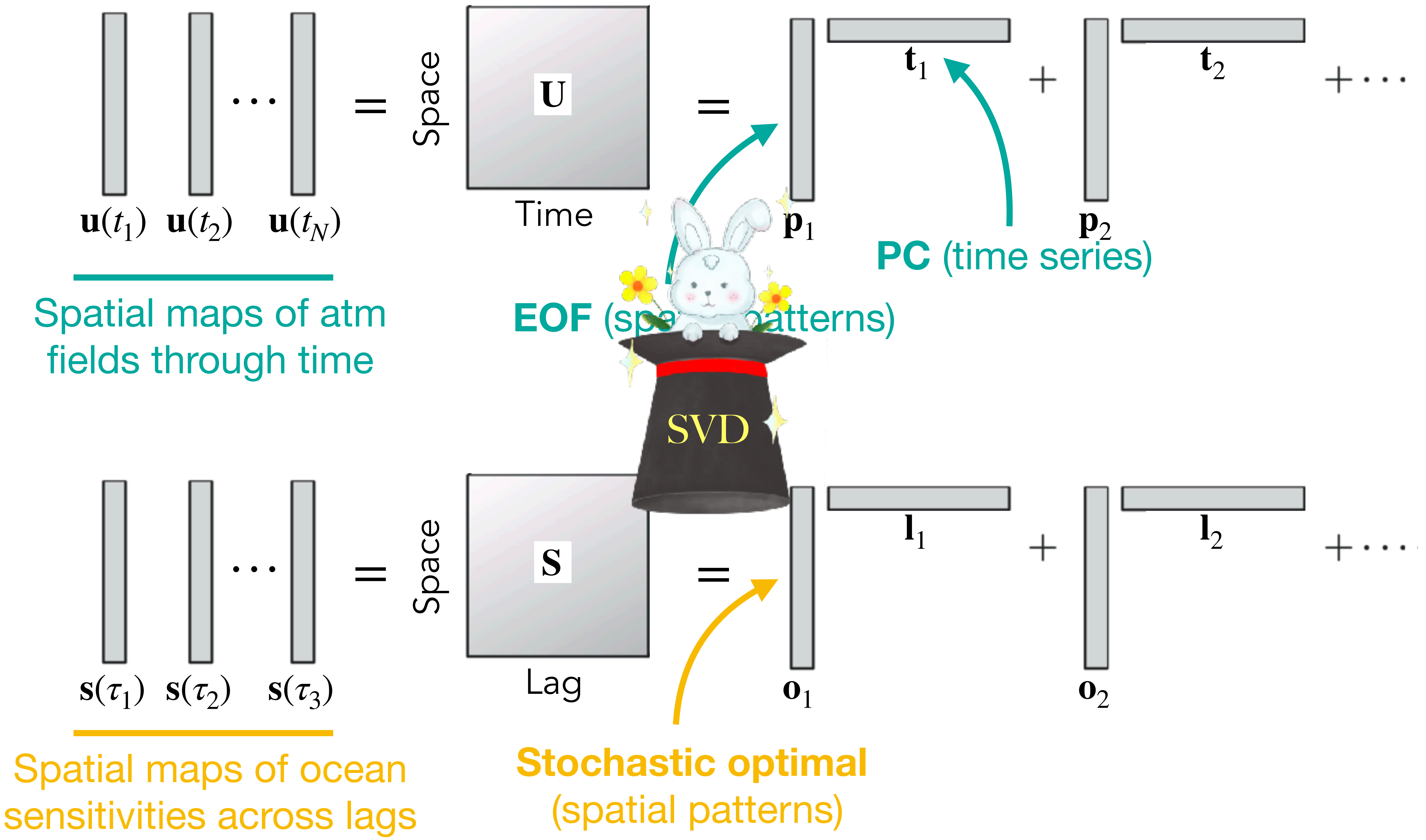

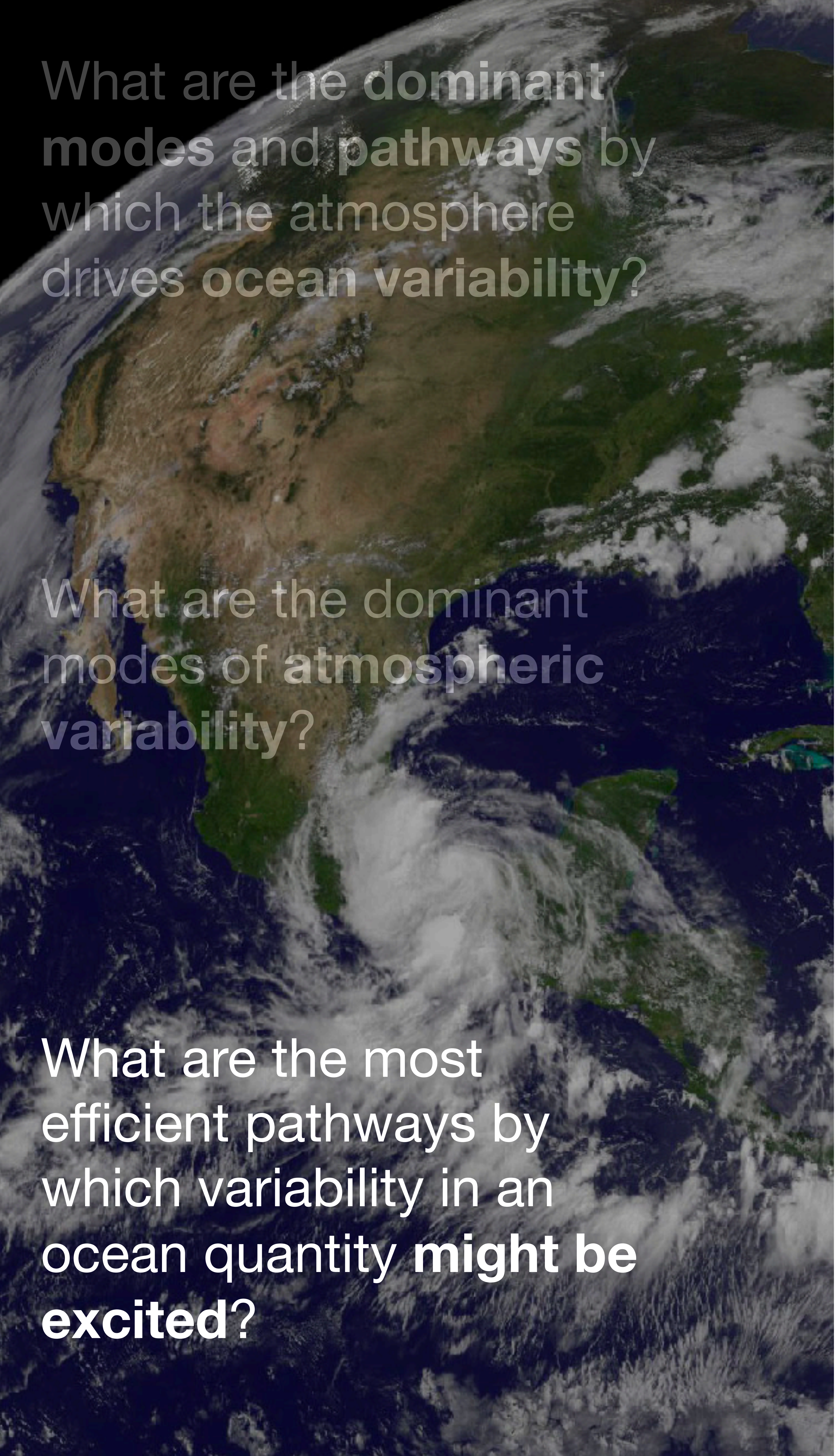

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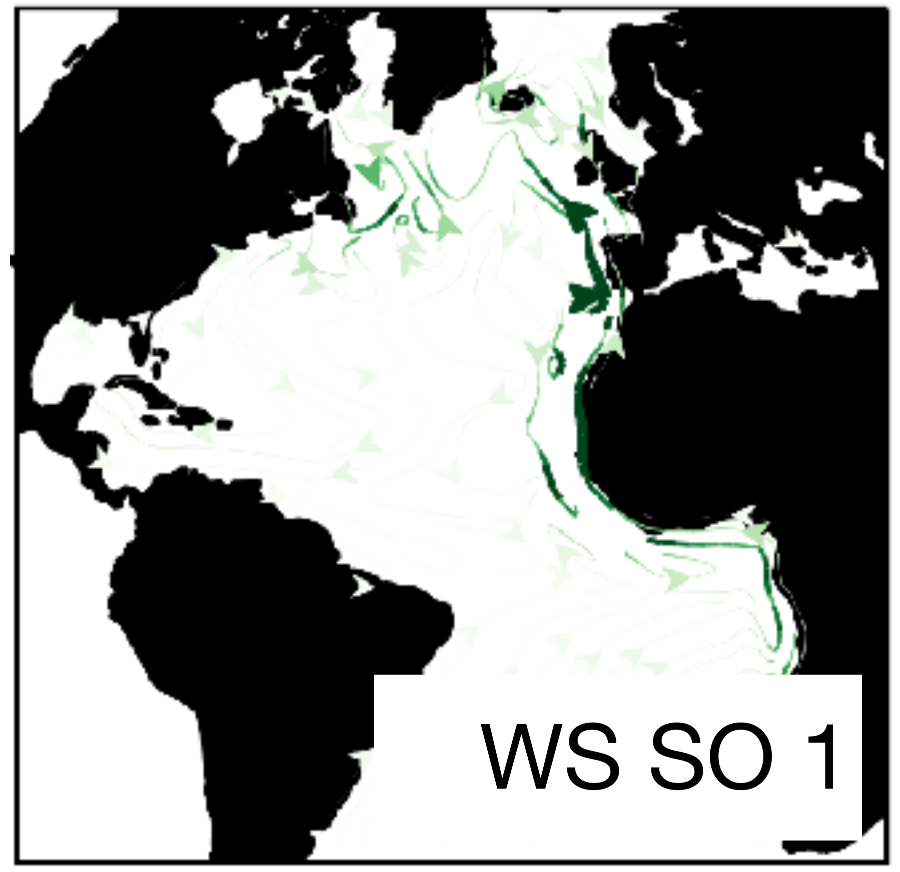

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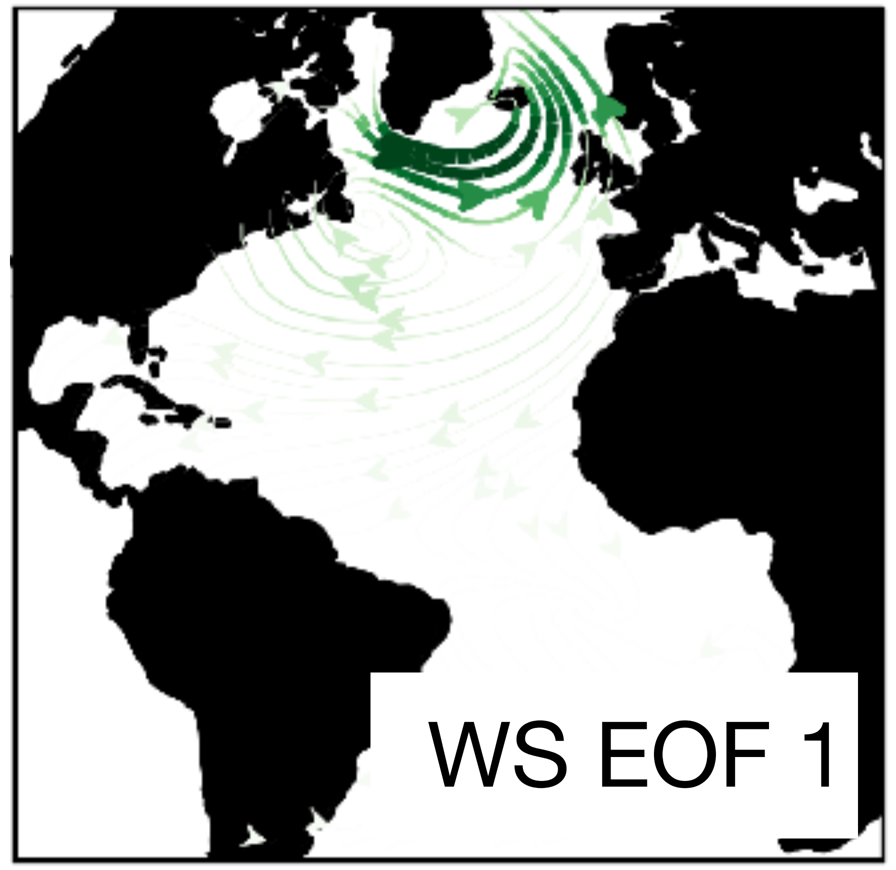

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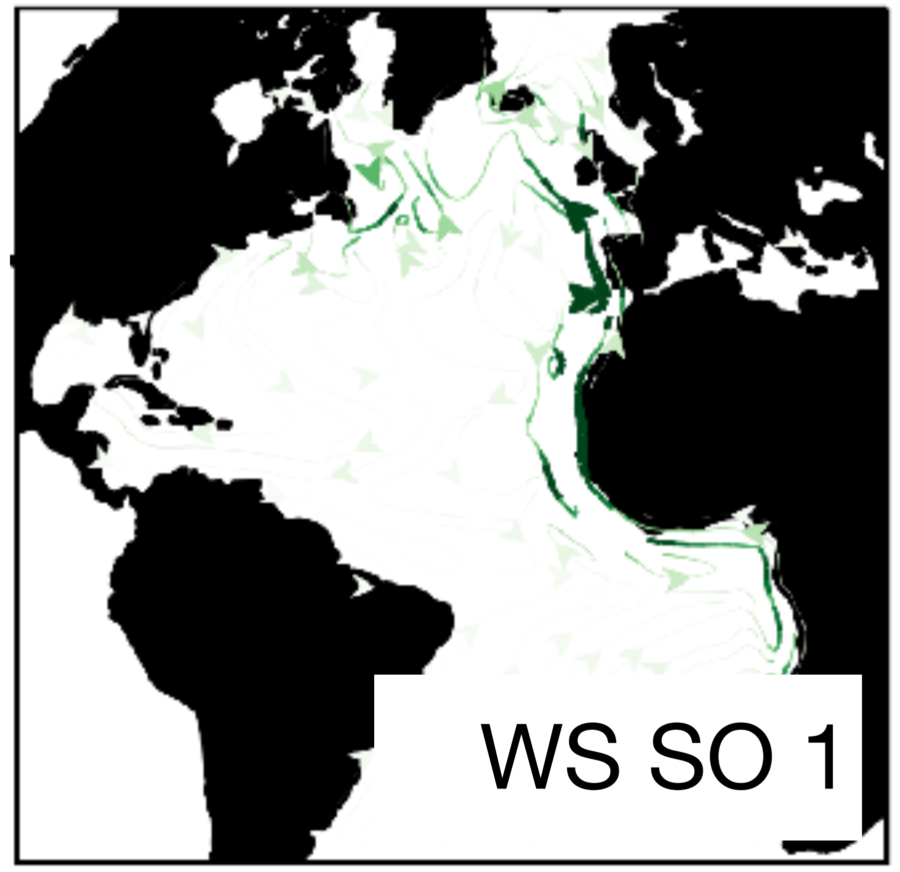

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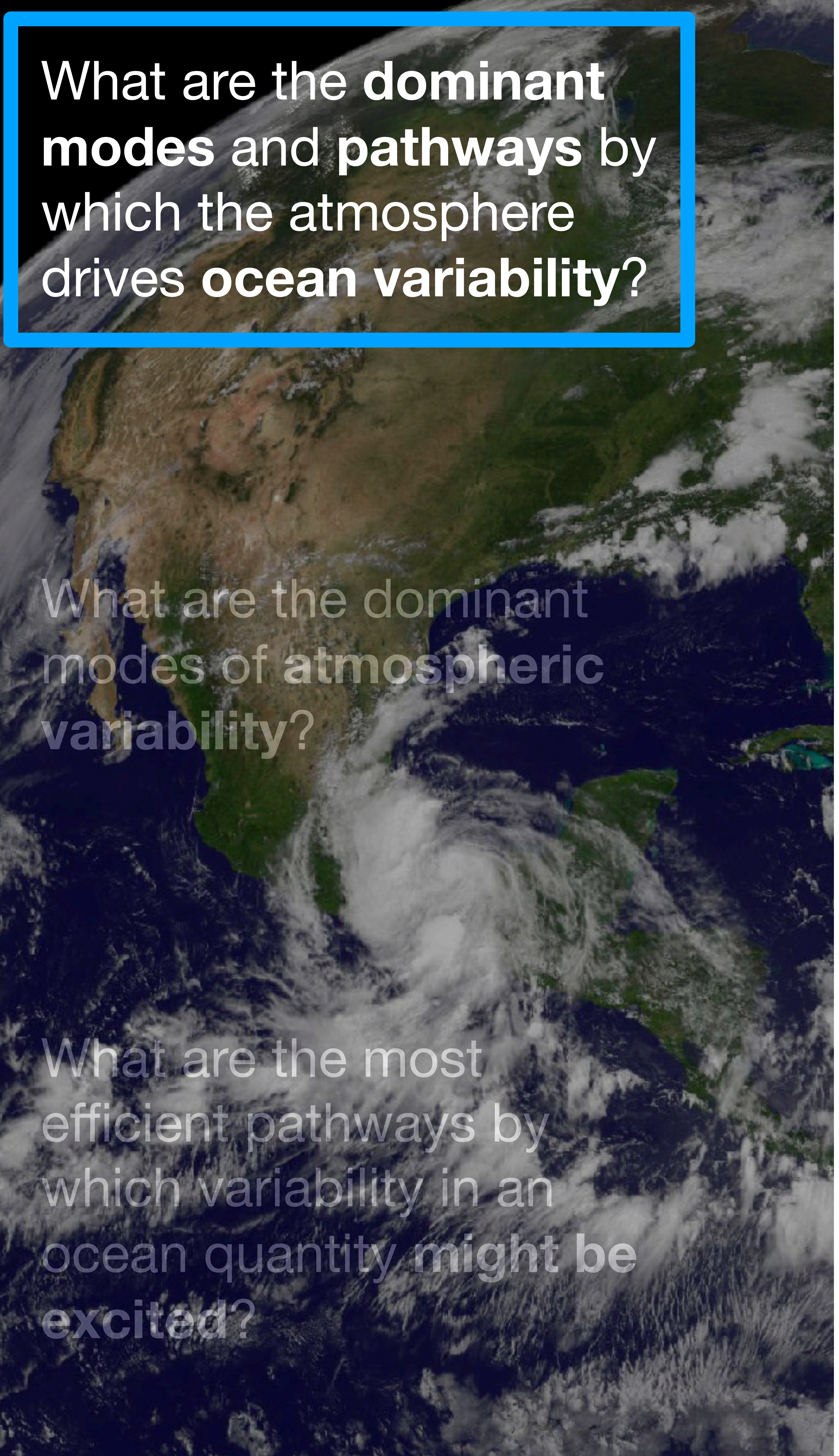

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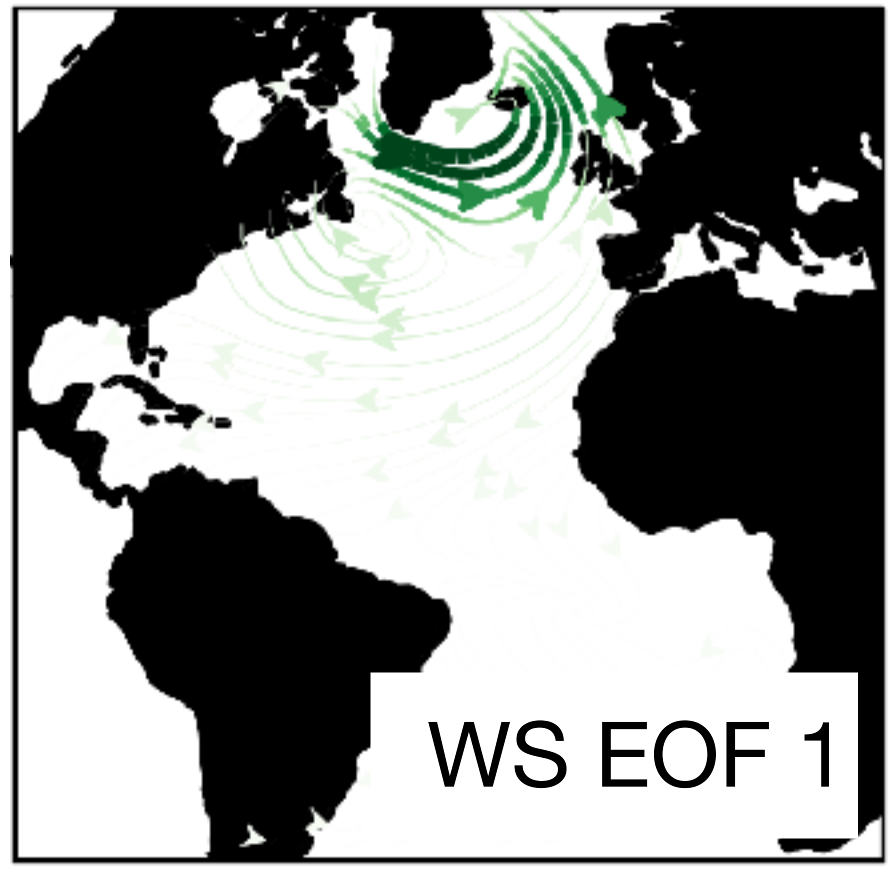

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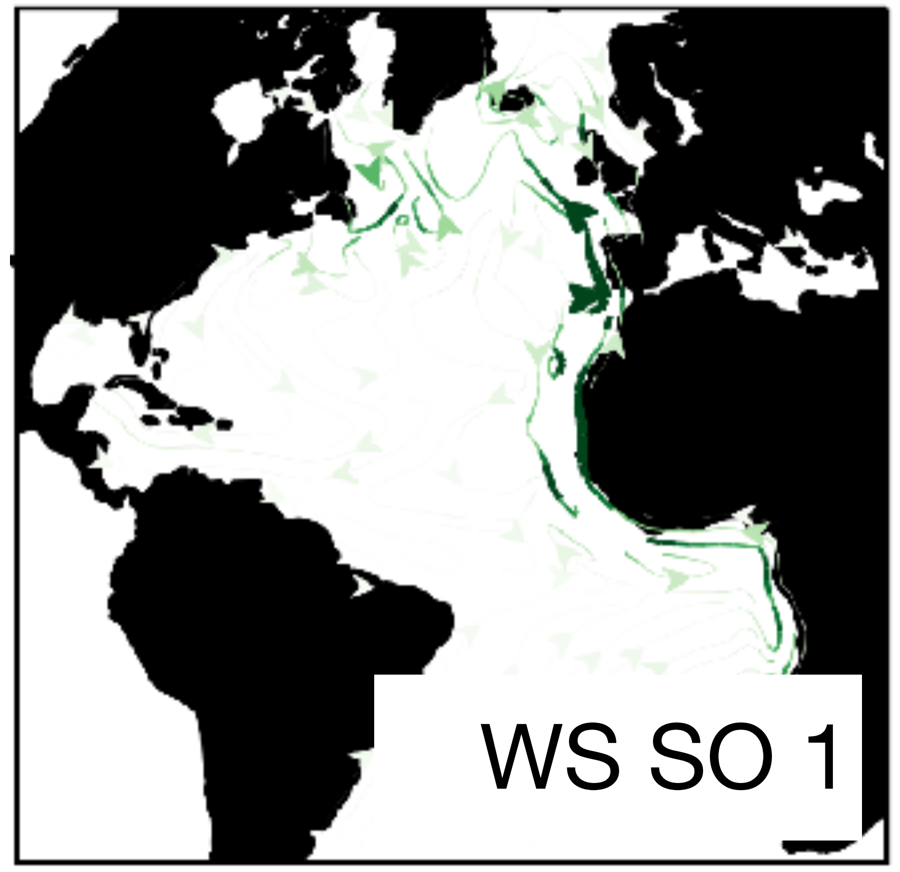

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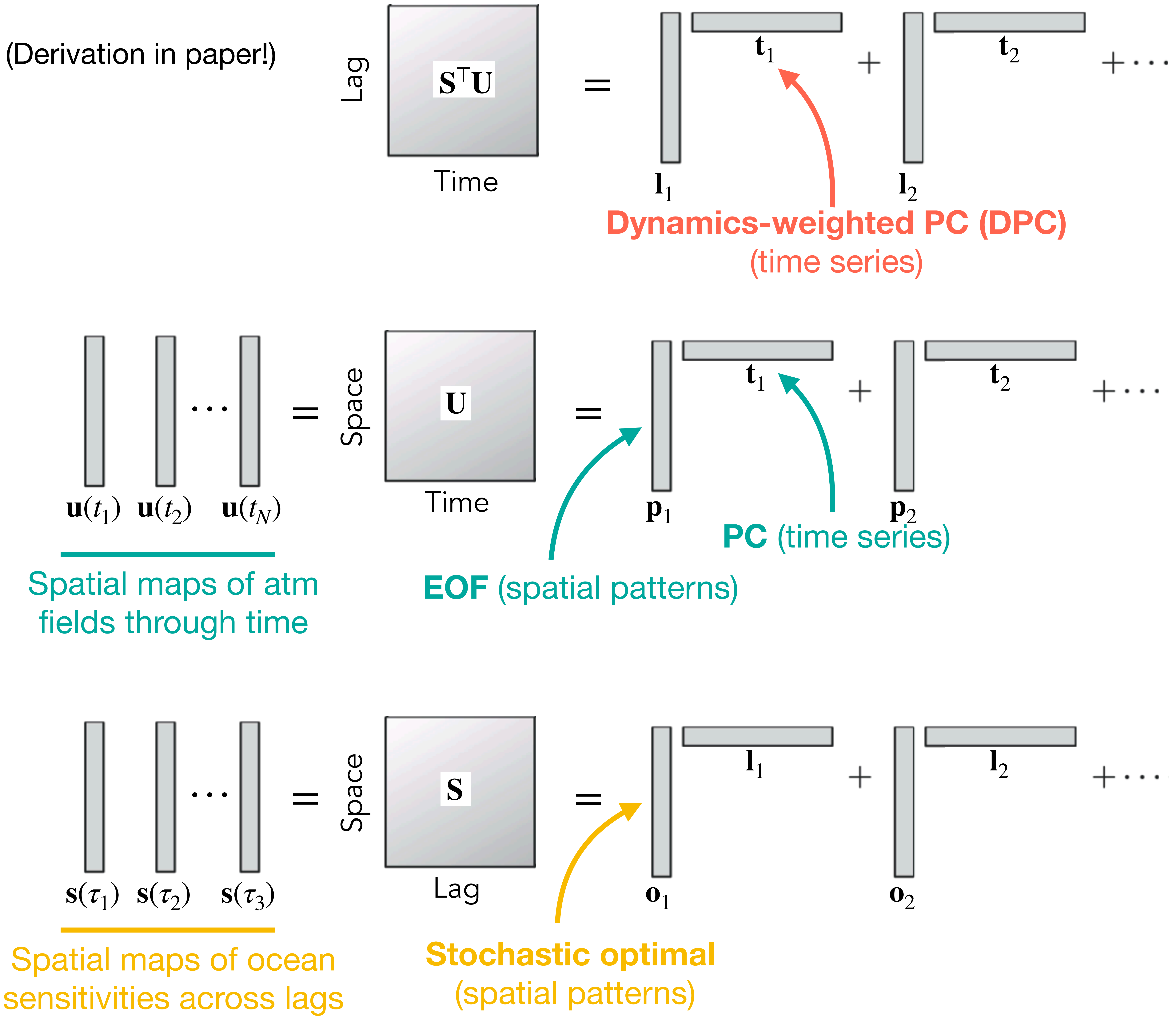

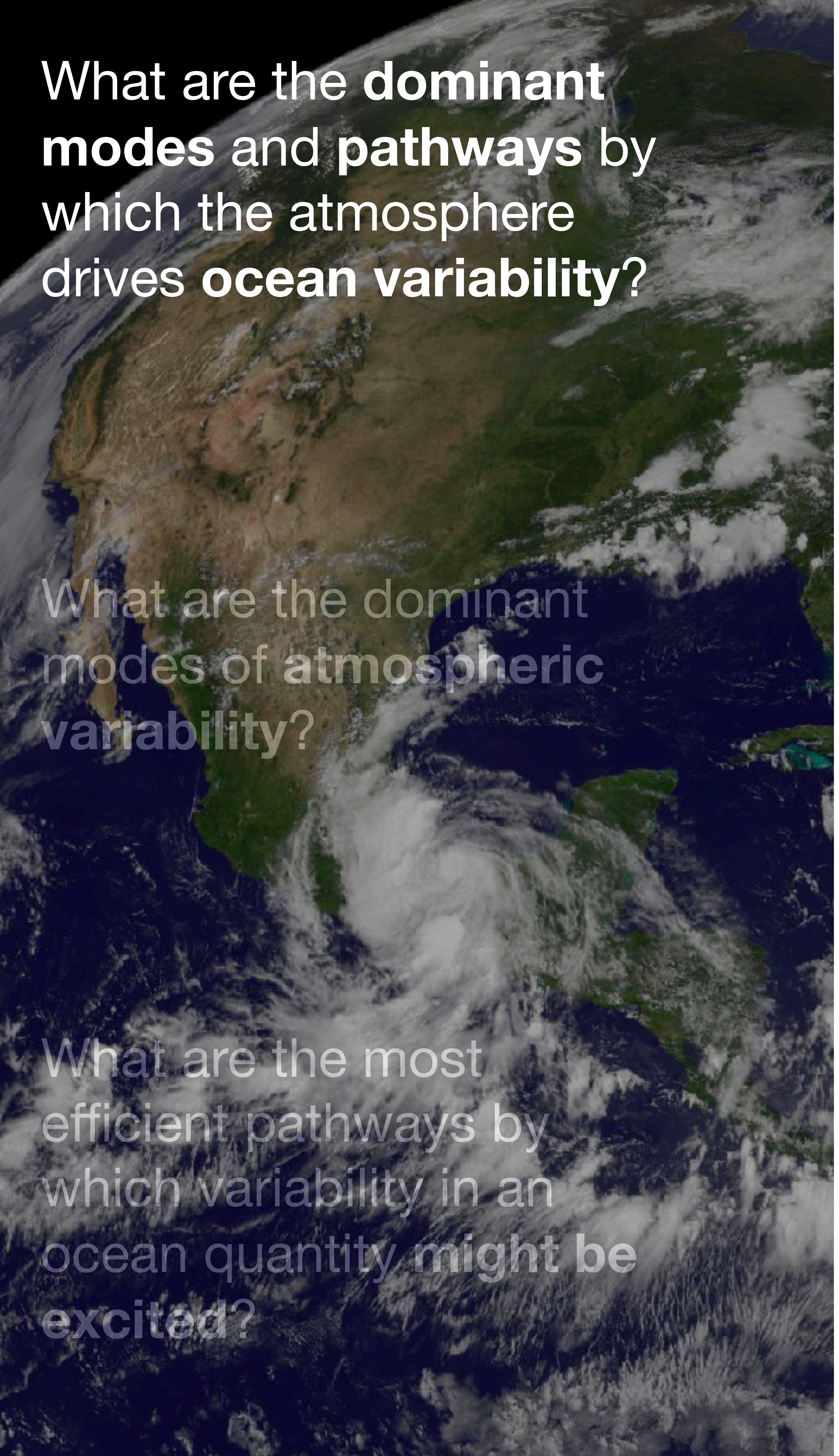

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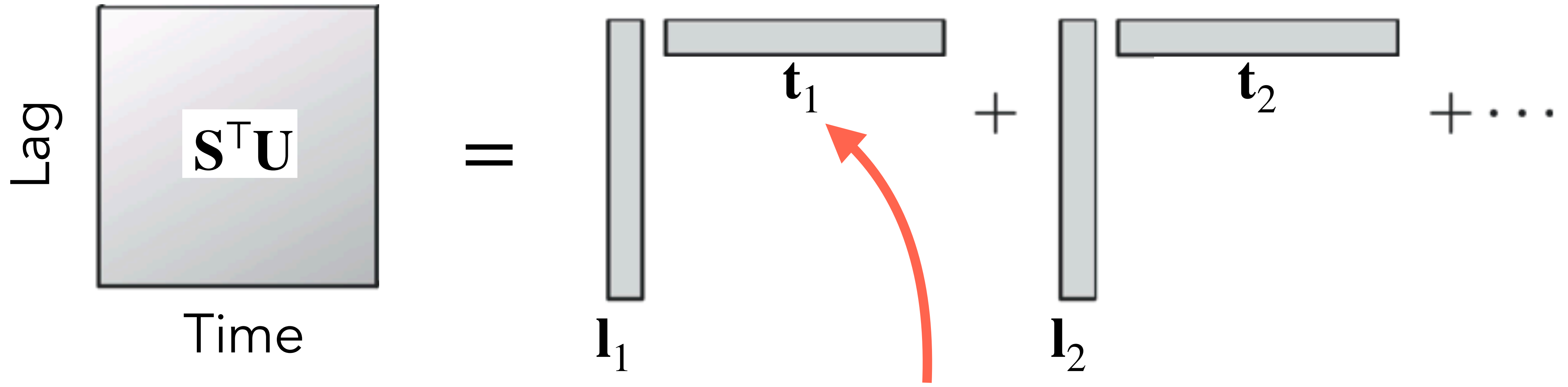
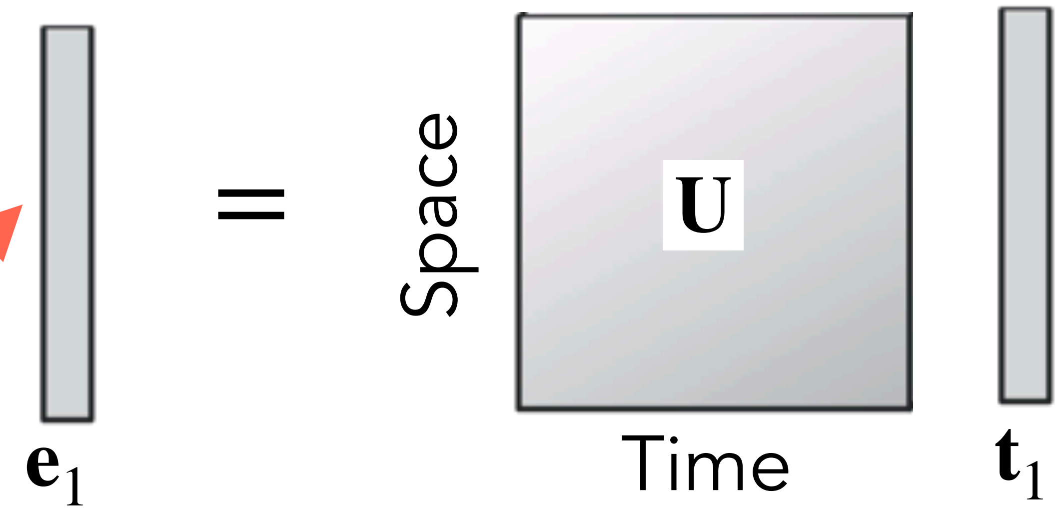


Dynamics-weighted PC (DPC)
(time series)



"Empirical-dynamical function" (EDF)
(spatial pattern)

Under appropriate conditions, EDFs recover EOFs and SOs!

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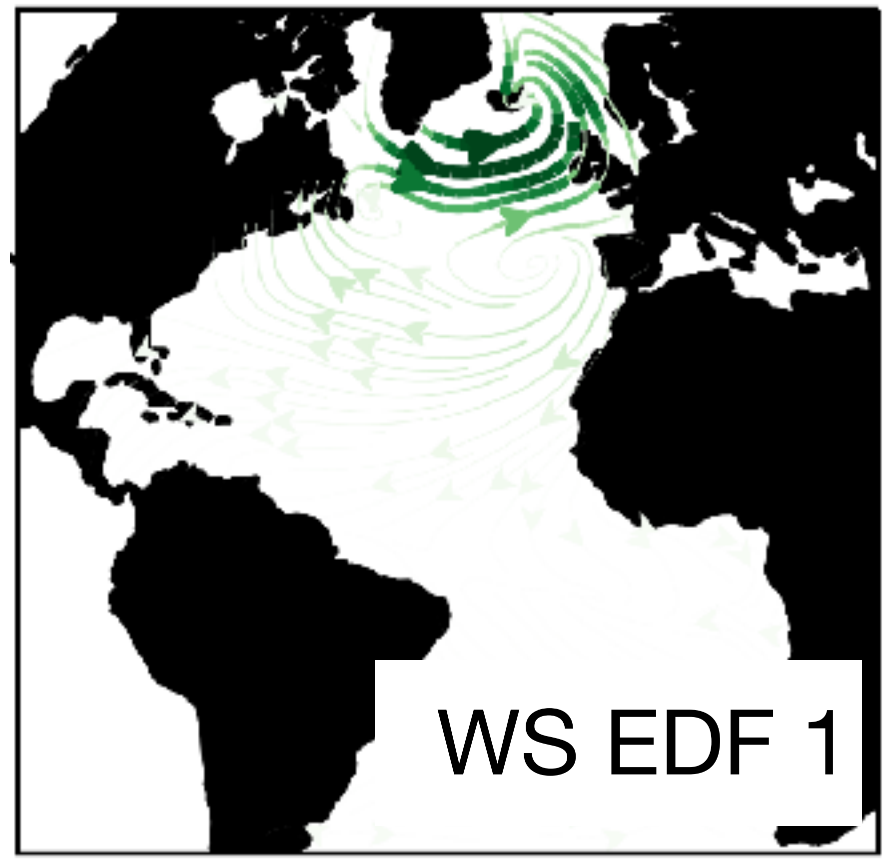
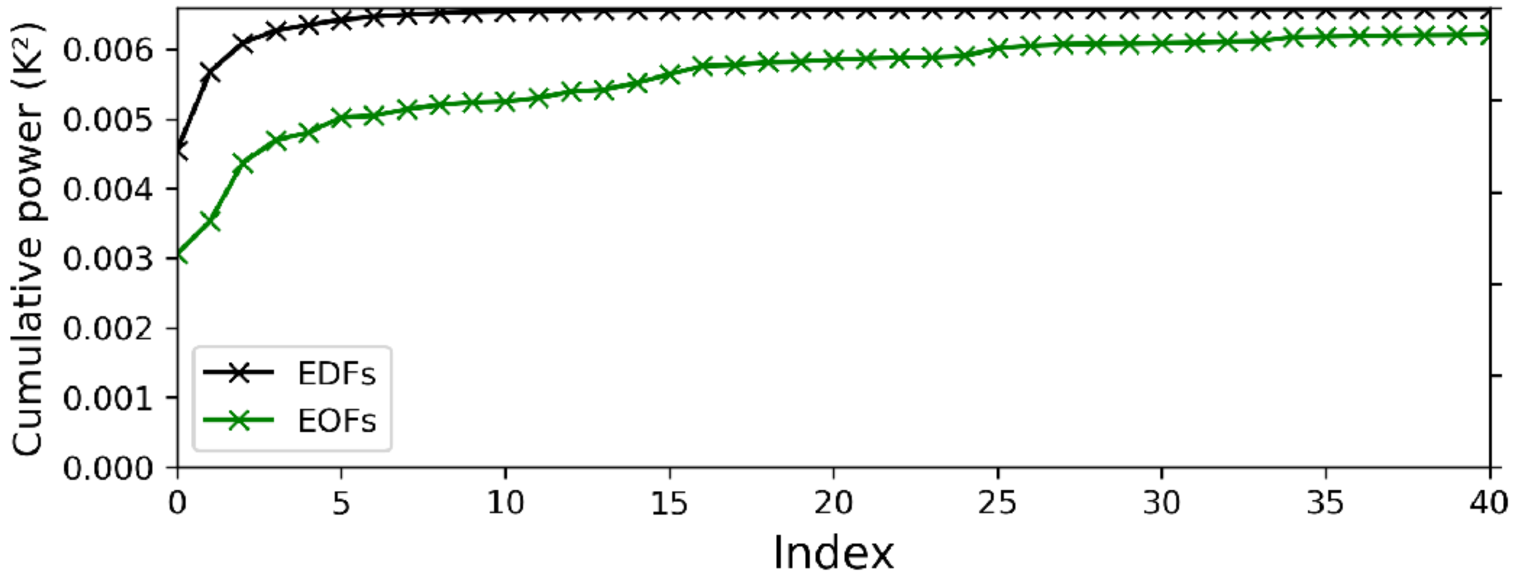


The **leading EDF** and EOF are qualitatively similar. Nevertheless, EDF 1 explains substantially more SPG HC variability.



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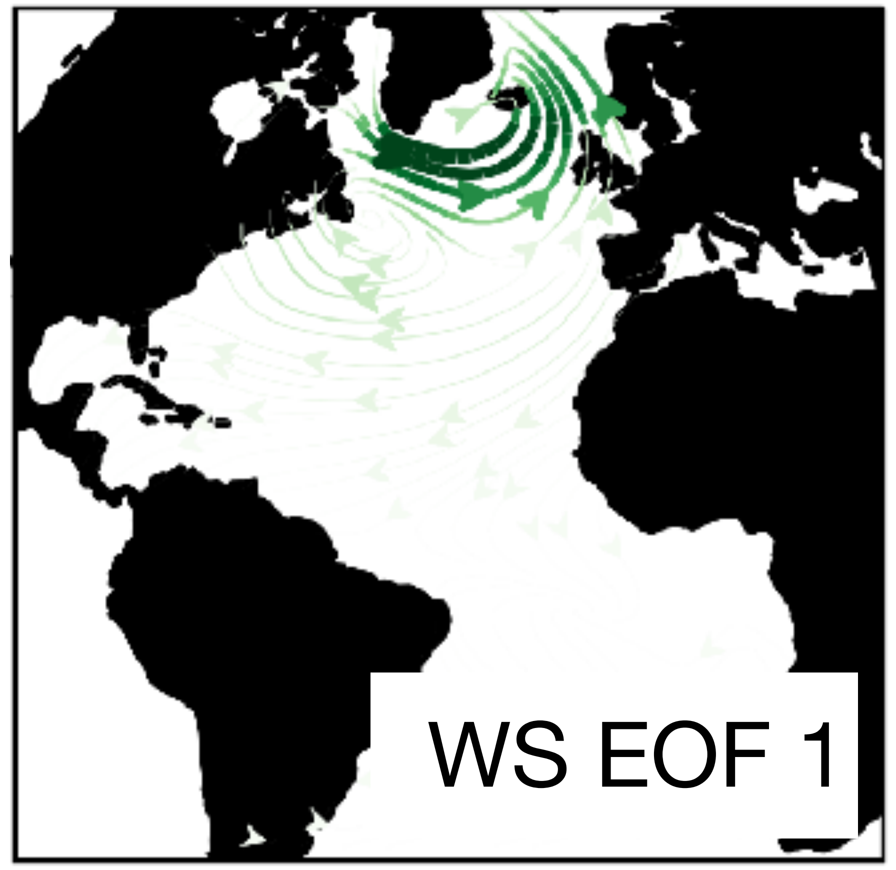

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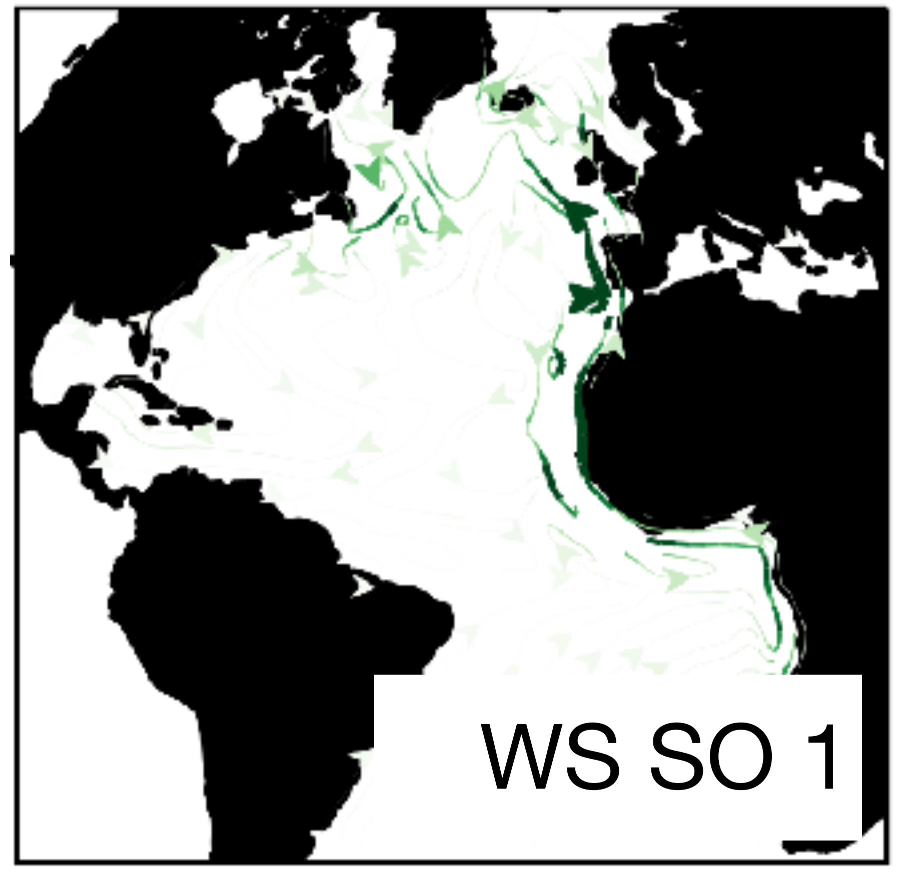

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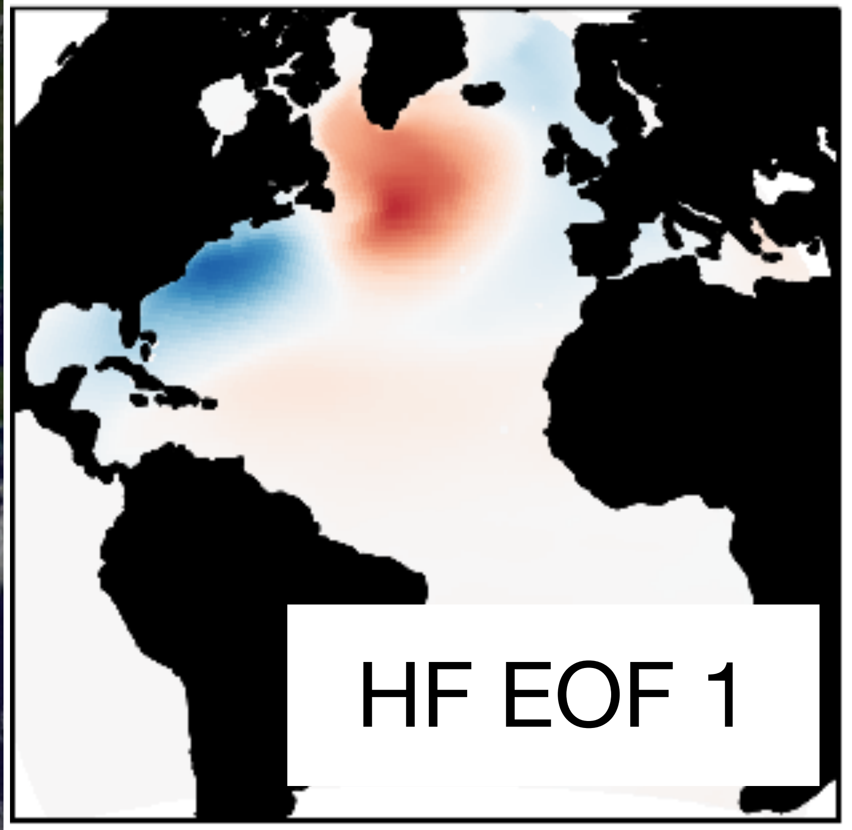
Now for heat fluxes!



The leading EOF has a primarily **dipolar** structure.

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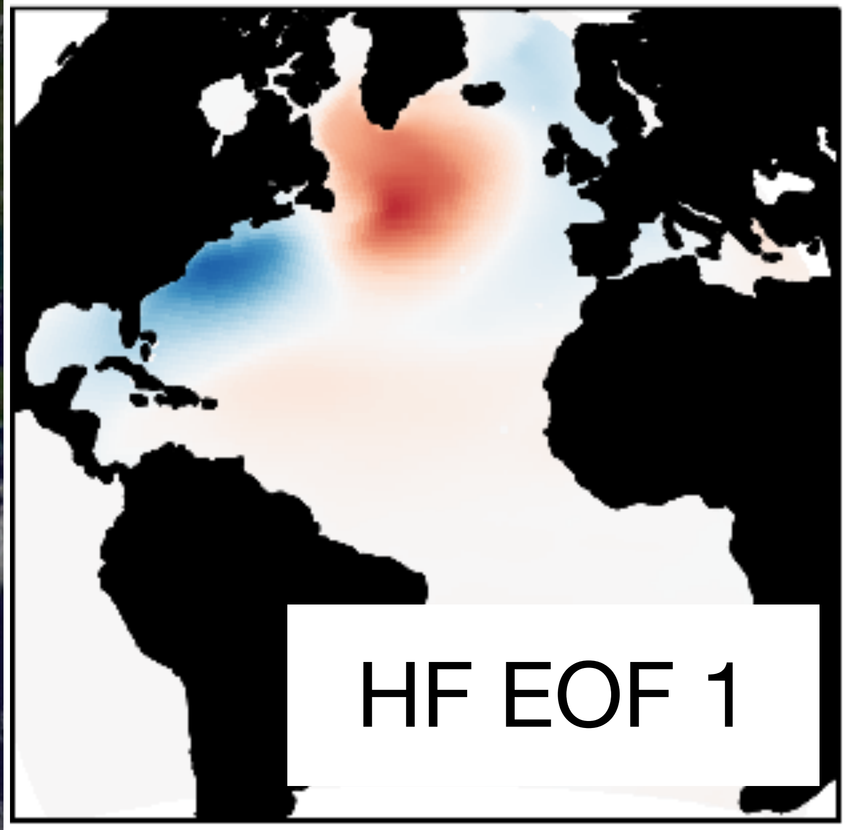

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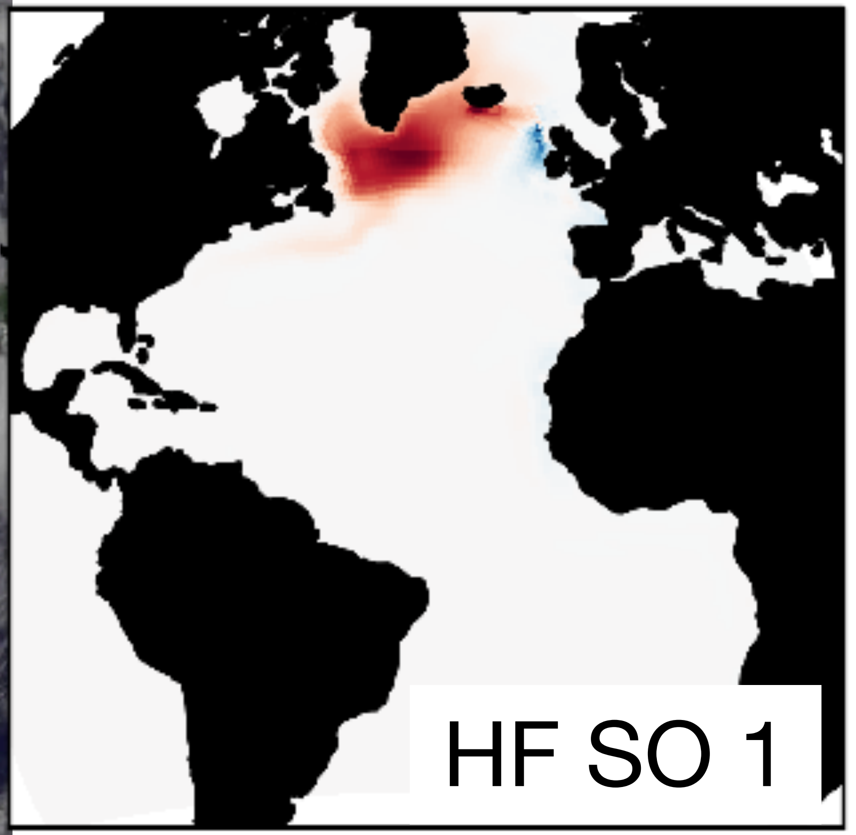

Local heat fluxes are a leading driver of annually-averaged SPG heat content.

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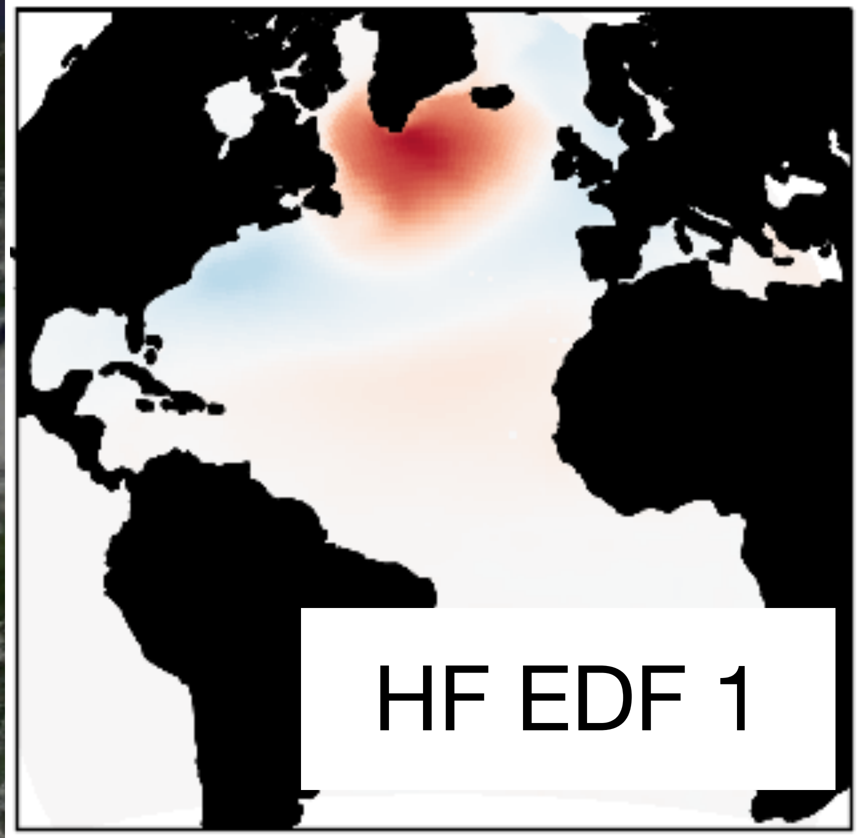
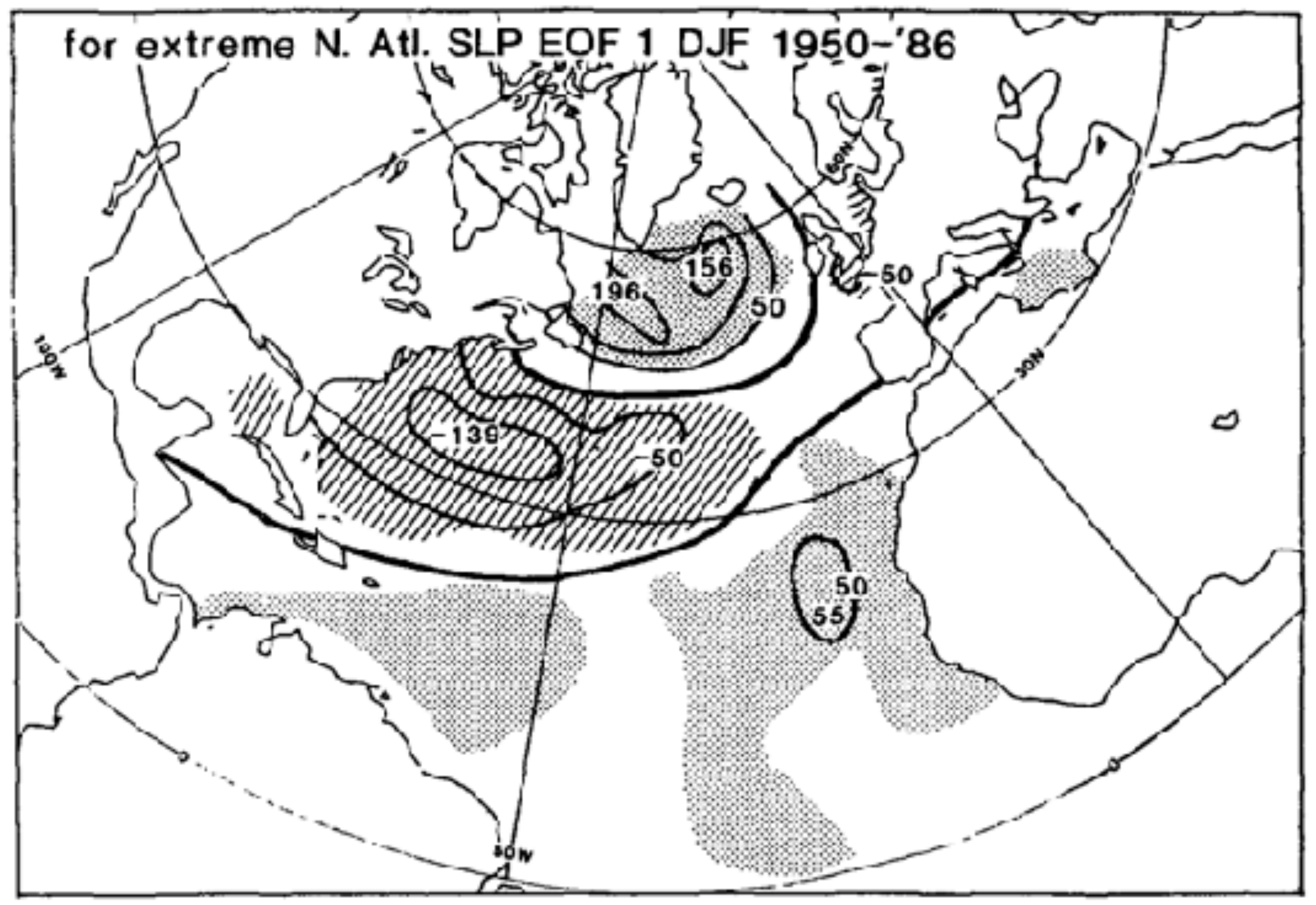
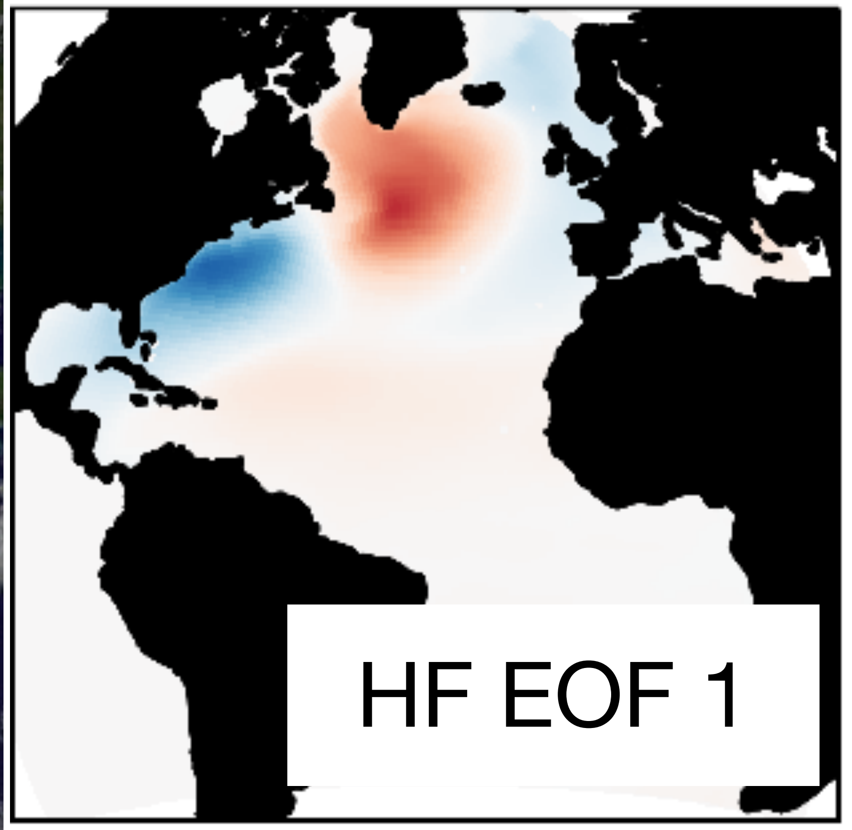


The leading EDF has a pattern correlation of 94% with the NAO.



NAO heat flux (Wm^{-2}; Cayan, 1992)



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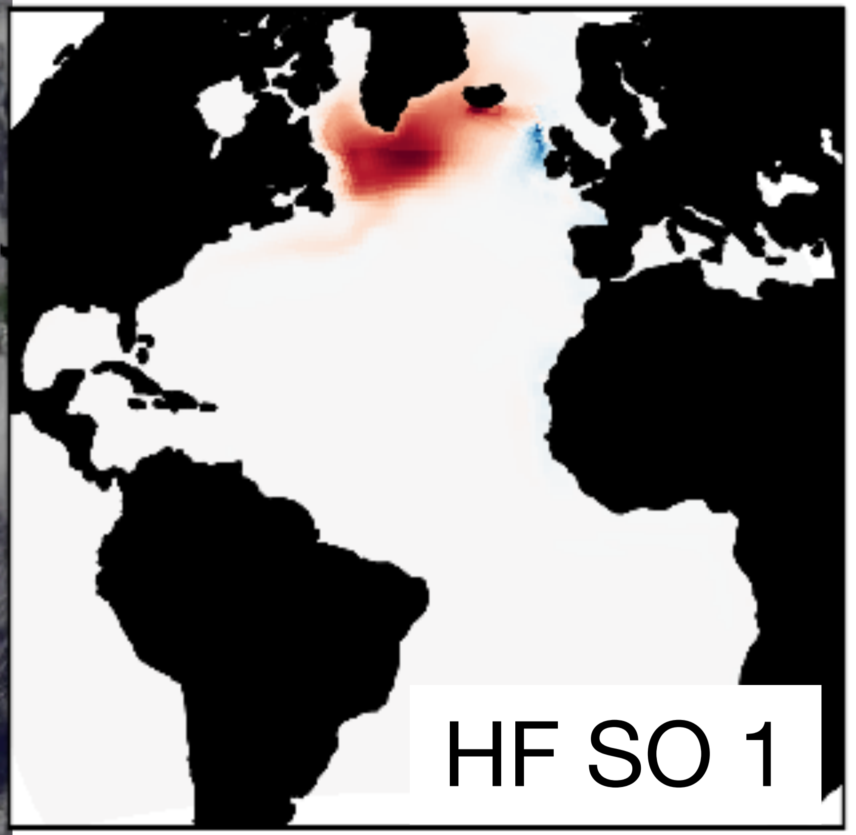

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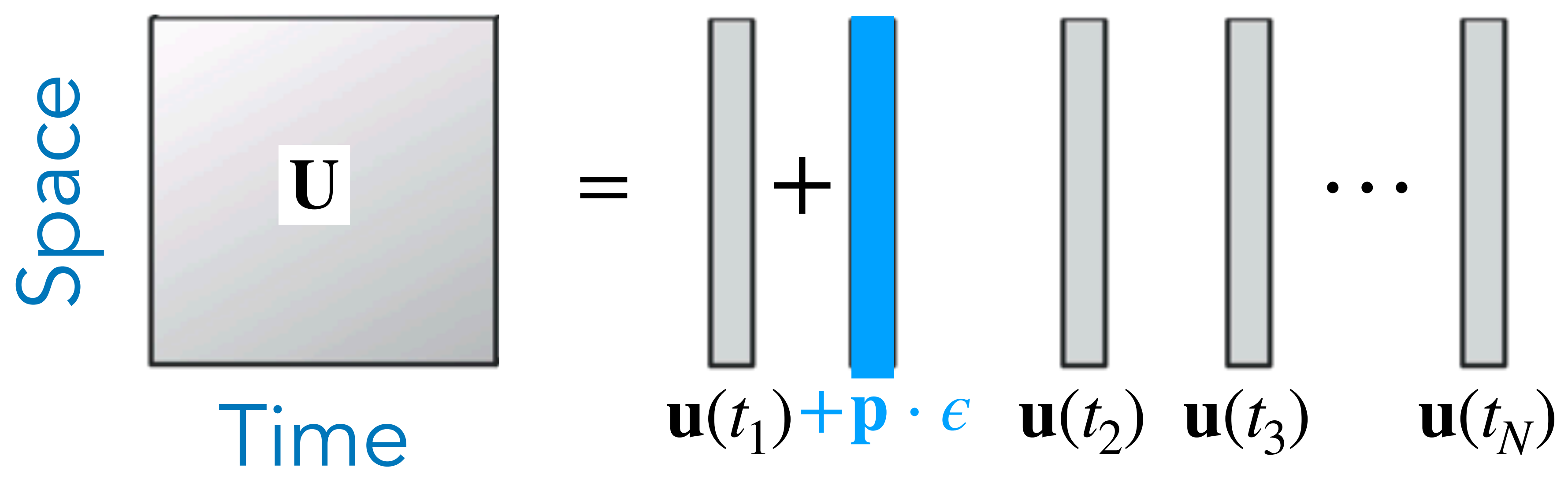
Using ECCO as a climate sandbox

The ECCO state estimate is a **forward run of the MITgcm**

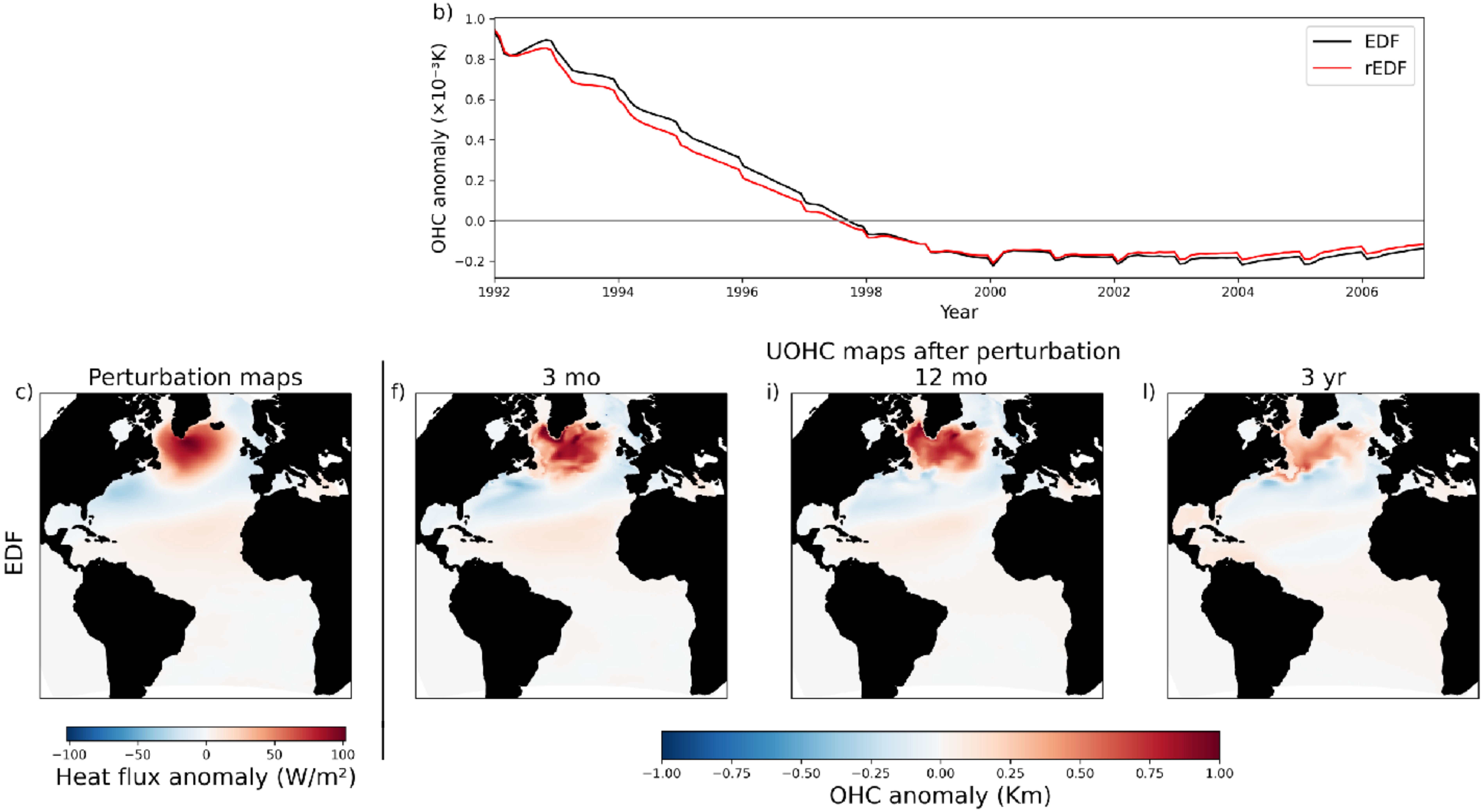
…so we can make **changes** to the forcing and rerun the MITgcm to evaluate **impacts** and **mechanisms** of atmospheric forcings.

Perturbing ECCO fluxes with the leading EDF



Pathways of stochastic variability

Anomalies resulting from a 24-hour **heat flux** perturbation at the beginning of the ECCO period decay similarly to a **Hasselmann-like response.**



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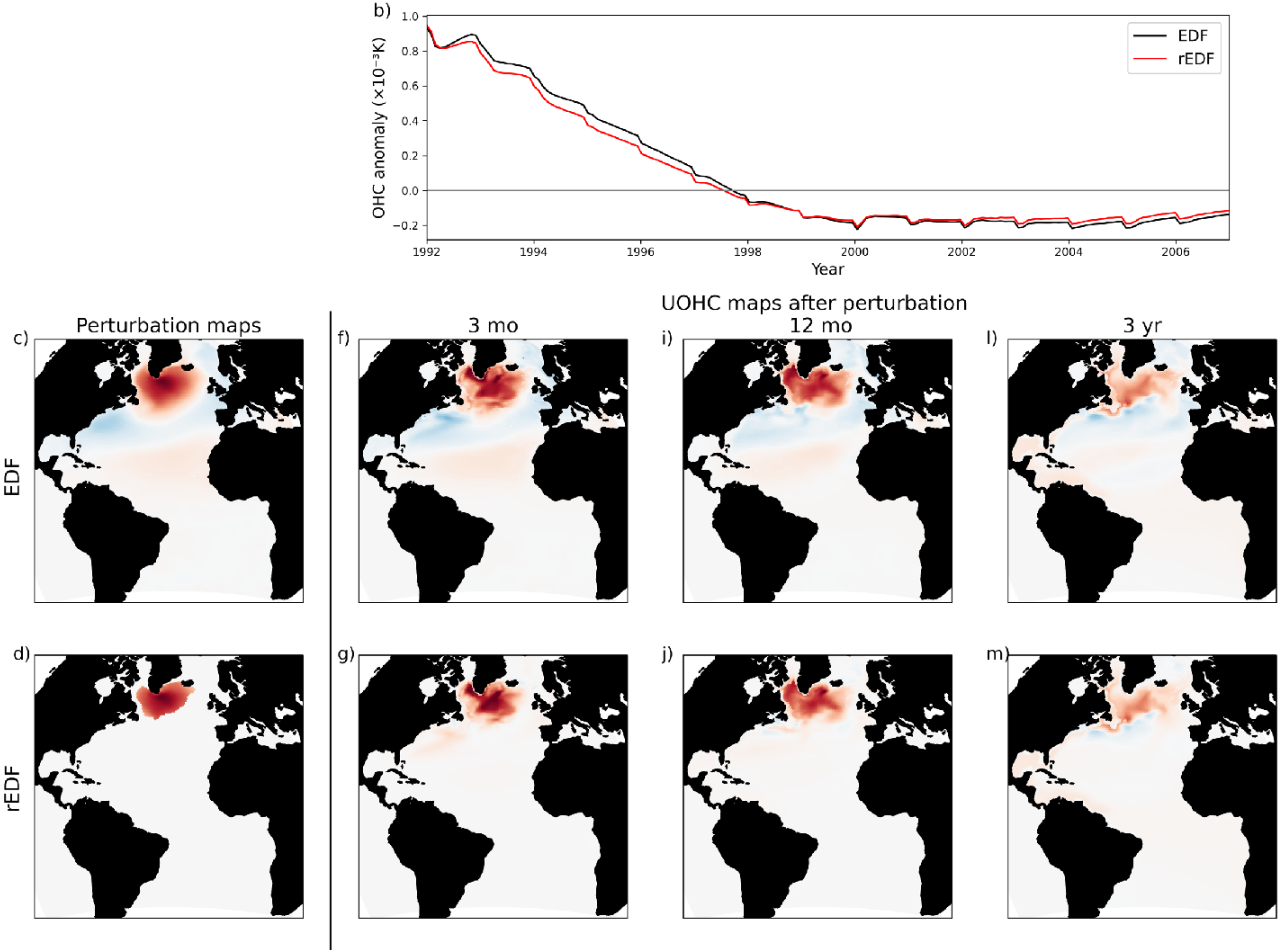

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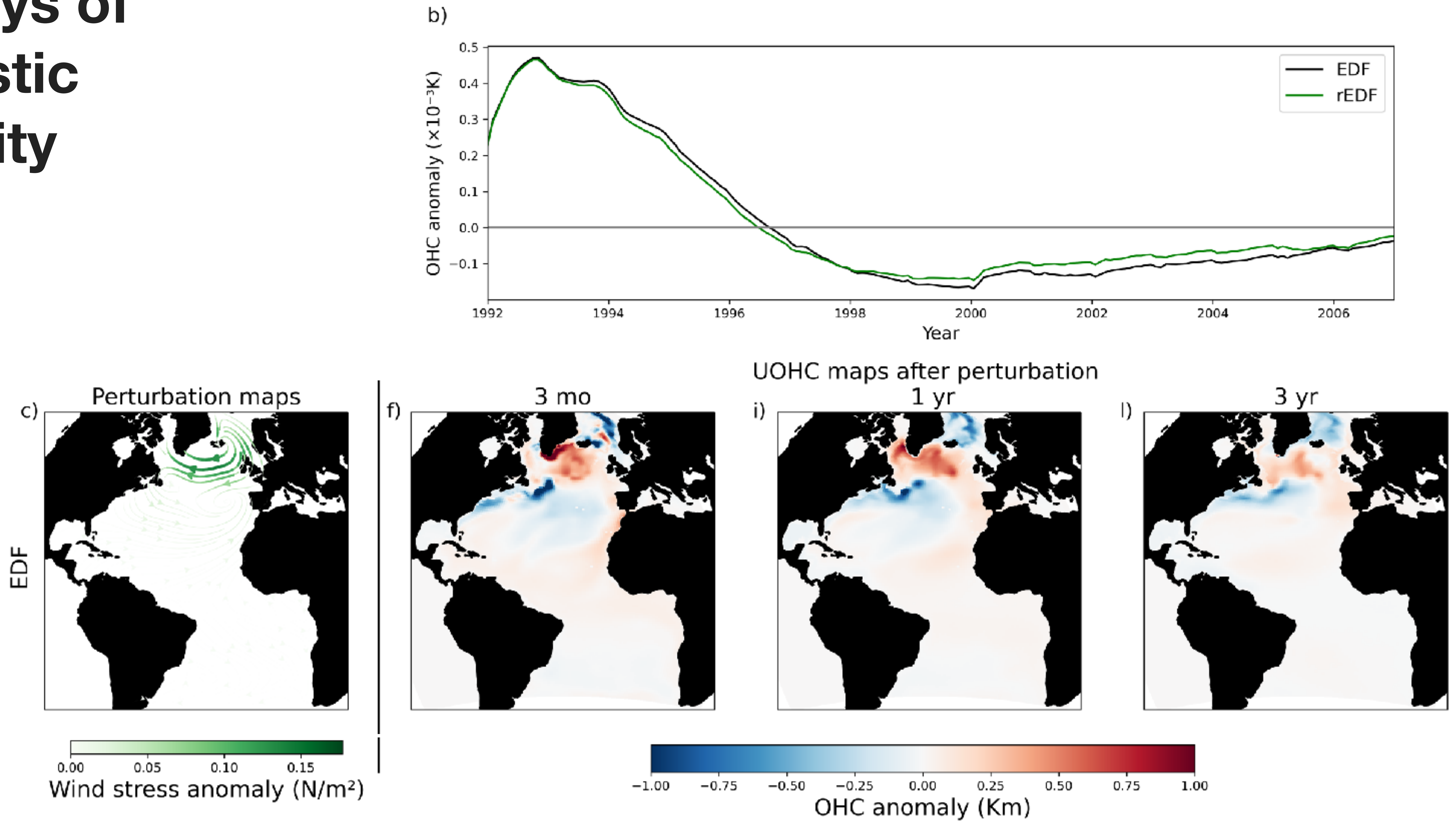
"Reduced EDFs" — different perturbation, ~same response!

Pathways of stochastic variability



The response to wind stress has a **delayed peak**, suggesting a role for spin-up of the subpolar gyre and increased ocean heat flux convergence from lower latitudes (e.g., Desbruyéres et al. 2021).

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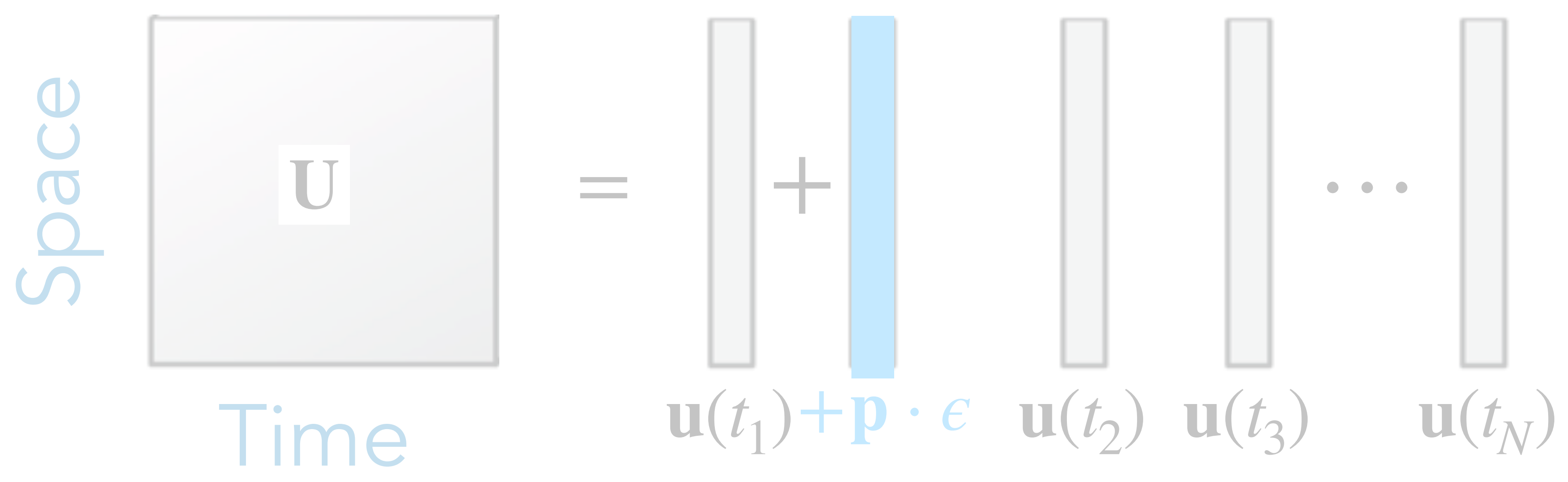
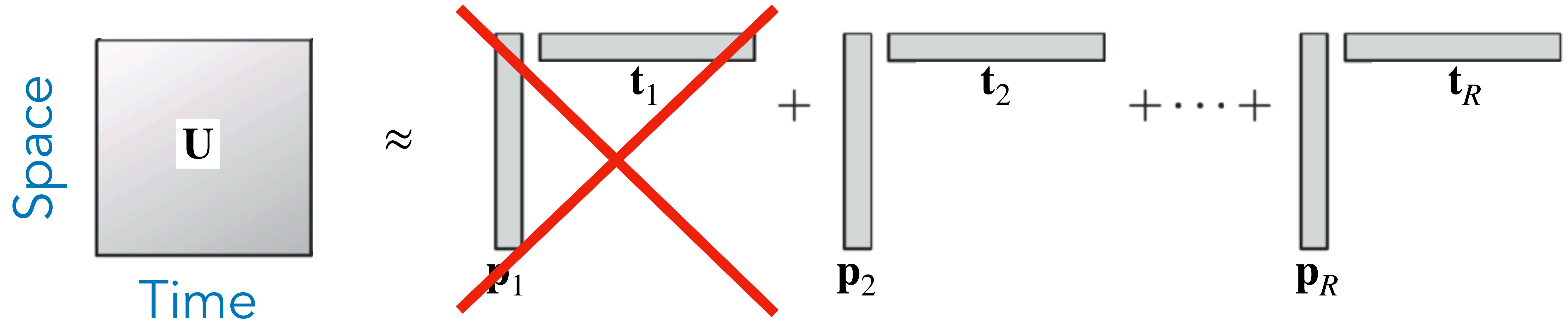
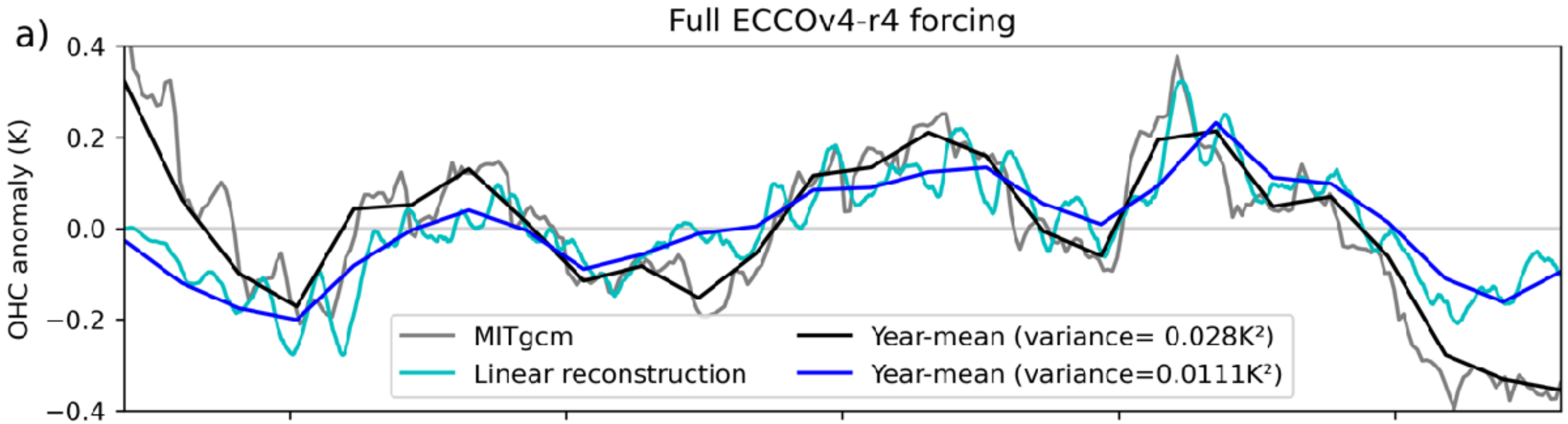


Omitting a leading EDF



“Turning down” ocean variability in ECCOv4-r4

Linearly reconstructed SPG HC variability from HF correlates with ECCOv4-r4.



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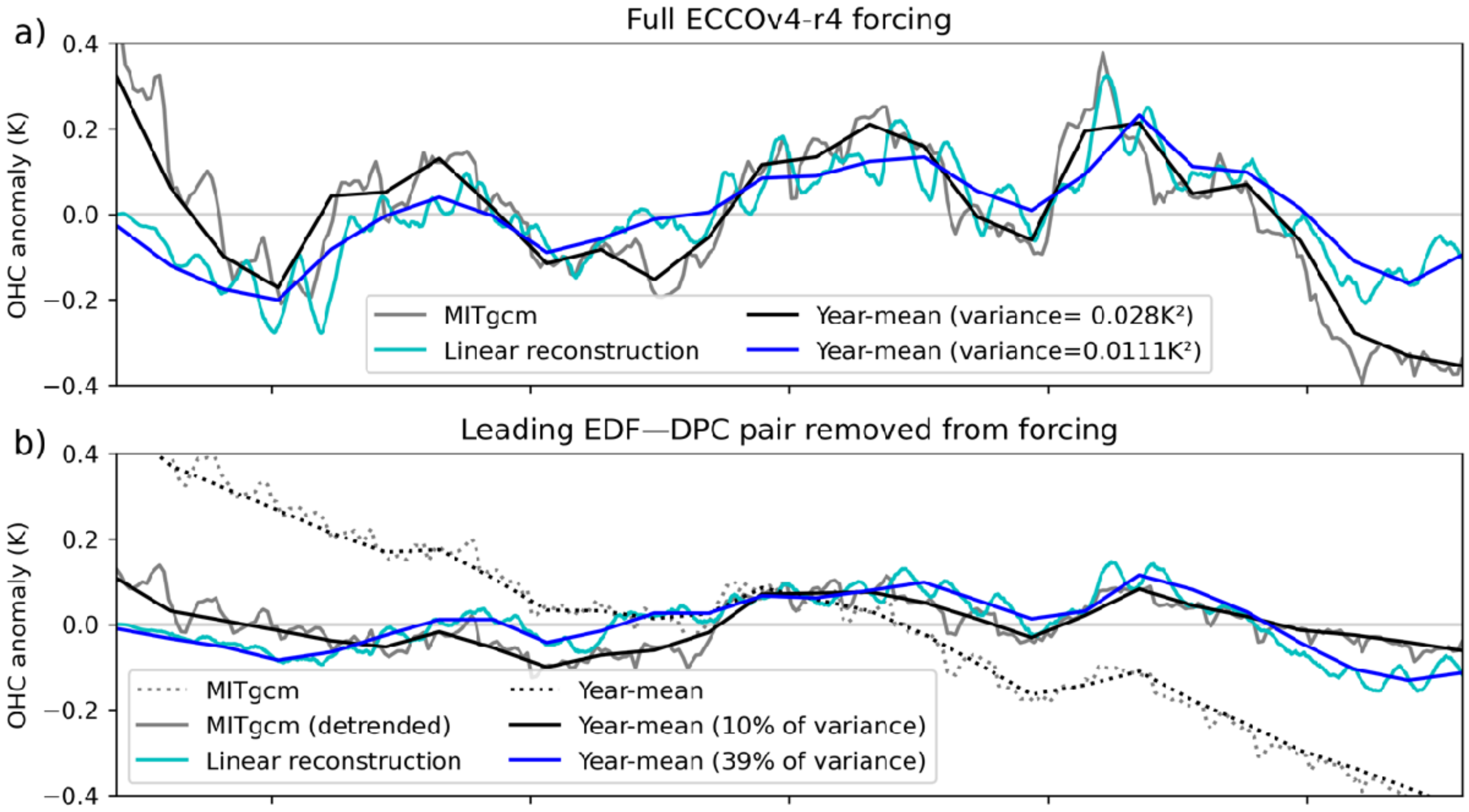
Linearly reconstructed SPG HC variability from HF correlates with ECCOv4-r4.

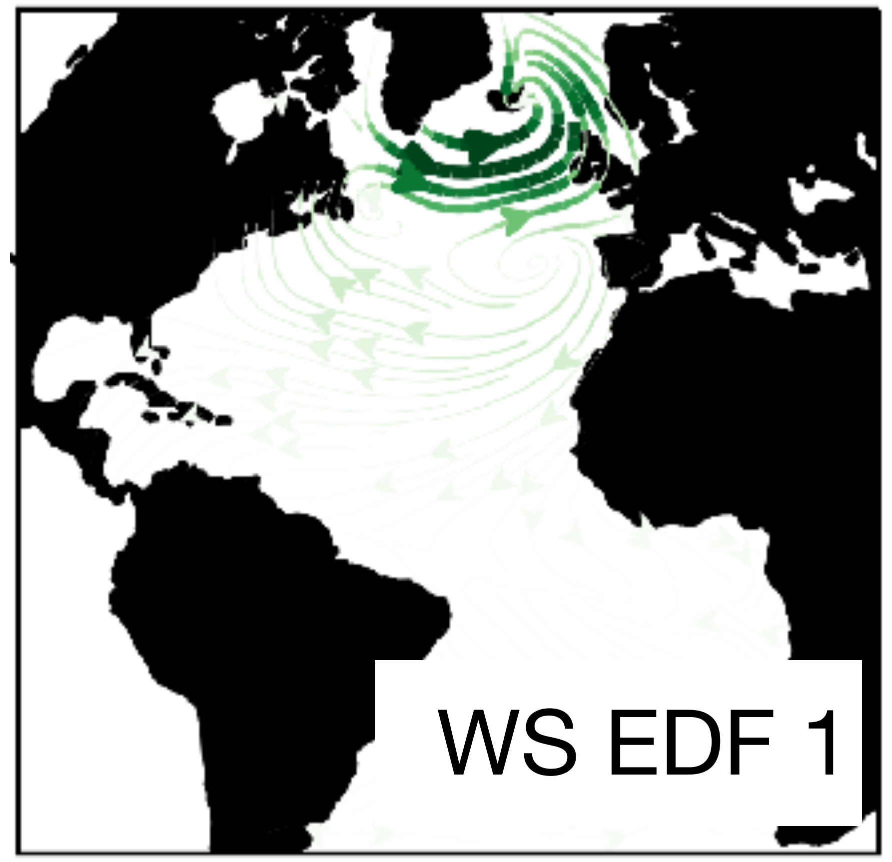
Removing the leading EDF in the MITgcm yields a trend in SPG HC, likely from missing HF feedbacks.

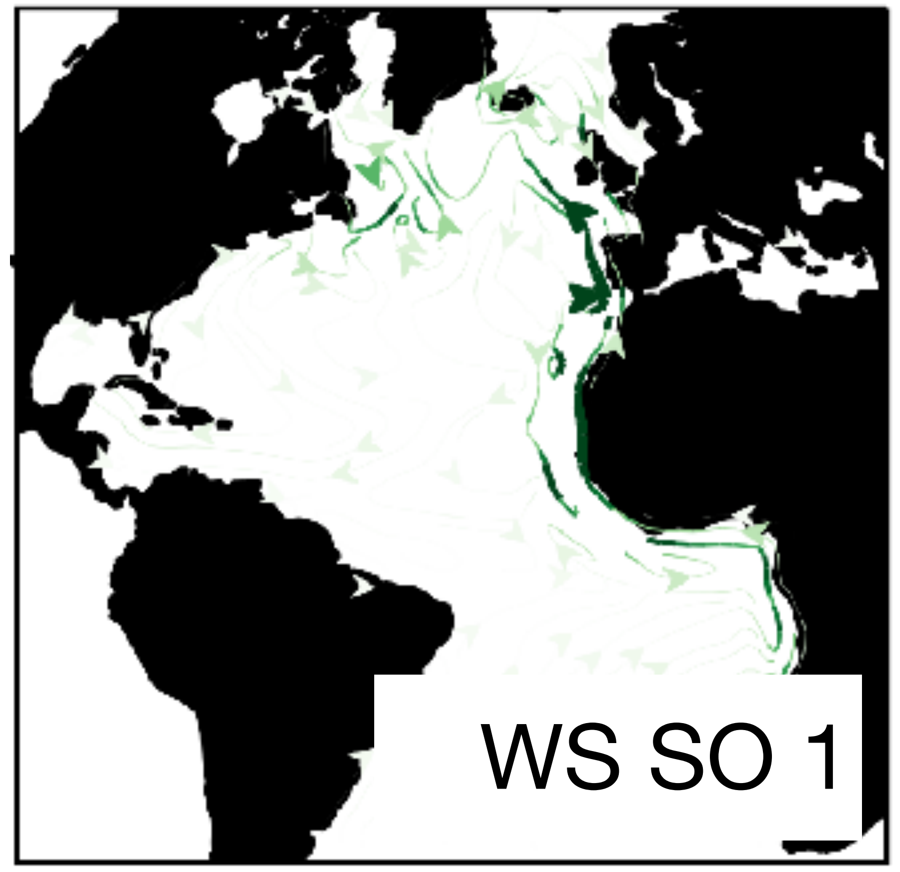
Superimposed on this trend is strong attenuation of interannual ocean variability.

Wind stresses are qualitatively similar, without the nonlinear trend.



Relevance for state estimation





$$\mathbf{p} \sim \underline{\mathbf{C}}\mathbf{s}$$

Flux adjustment covariance

Suggestion: Applying knowledge of control covariances offers a statistically principled way of smoothing control adjustments for state estimation.

This is important especially where control adjustments can be large (e.g., past climates).

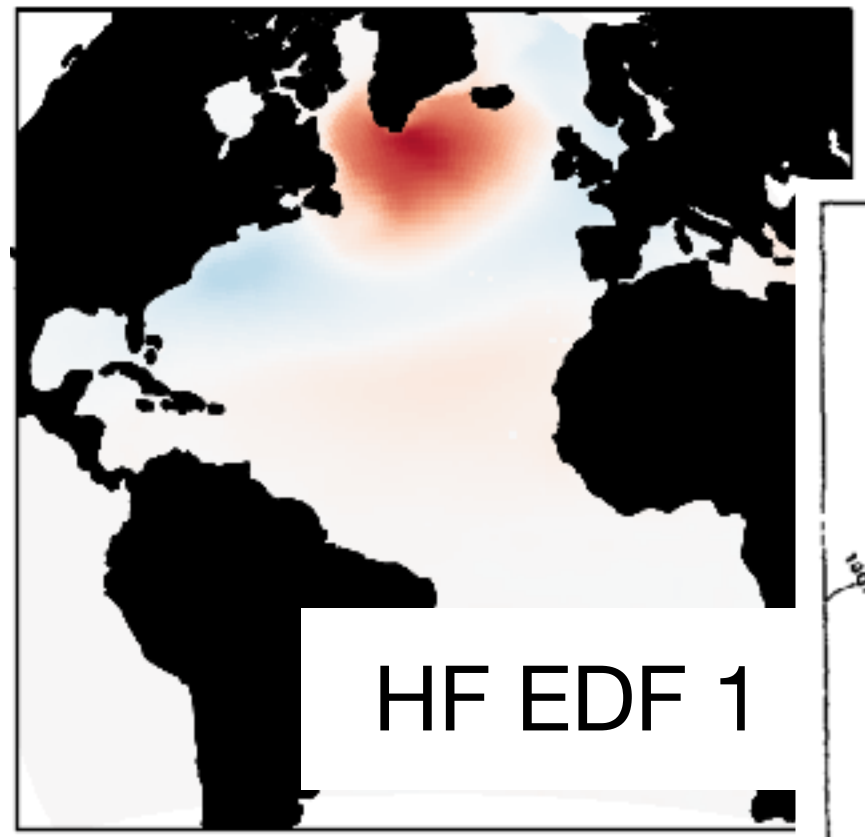
There is also an opportunity to assimilate atmospheric observations for coupled DA by writing down a second Lagrange multiplier problem!

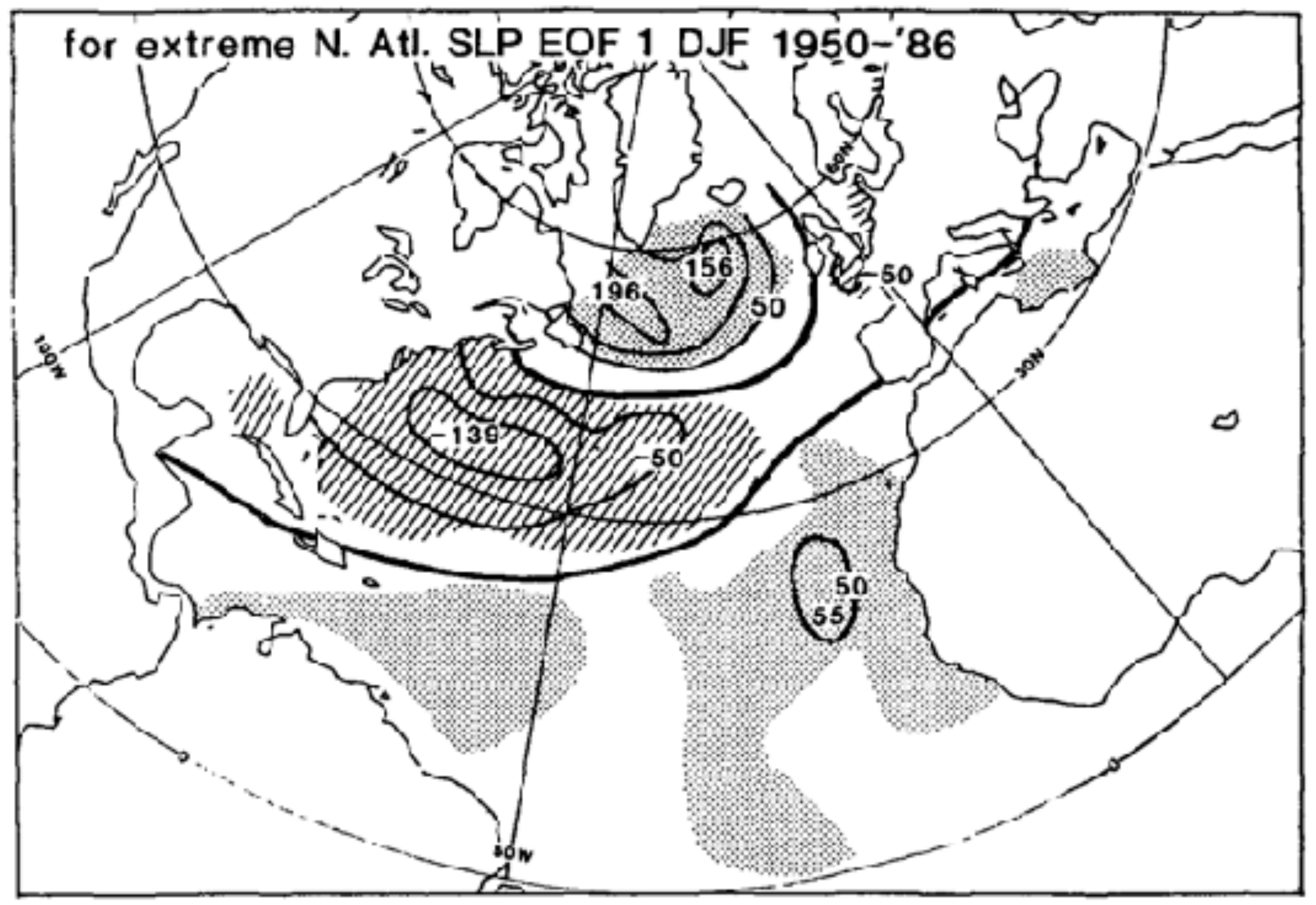
Conclusions and future work

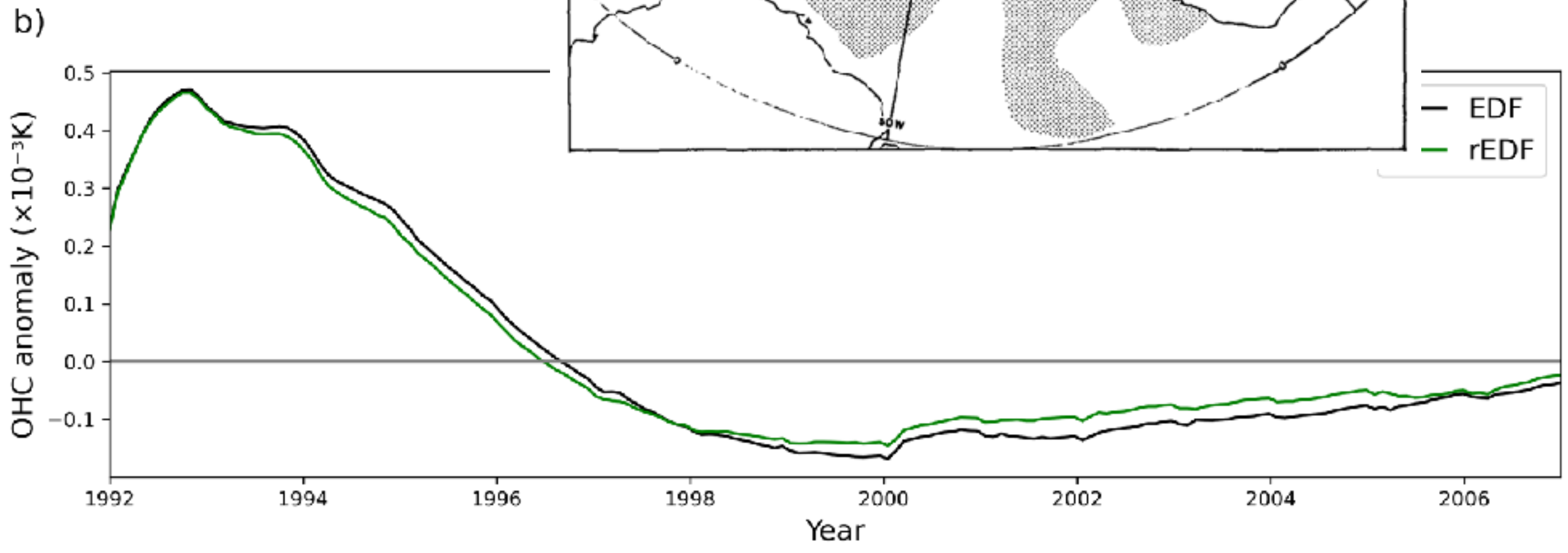
By combining adjoints and atmospheric statistics, we can identify ***atmospheric*** structures that dominate ***ocean*** **variability.**

When applied to annual-mean SPG HC, **NAO-like heat flux and wind stress patterns** dominate interannual variability through both passive and active ocean roles.

Caveats: Using a **1°**, **ocean-only, flux-forced** model. No guarantee of **significance** of atmospheric modes estimated over short flux periods. Solving separately for wind stress and buoyancy fluxes.





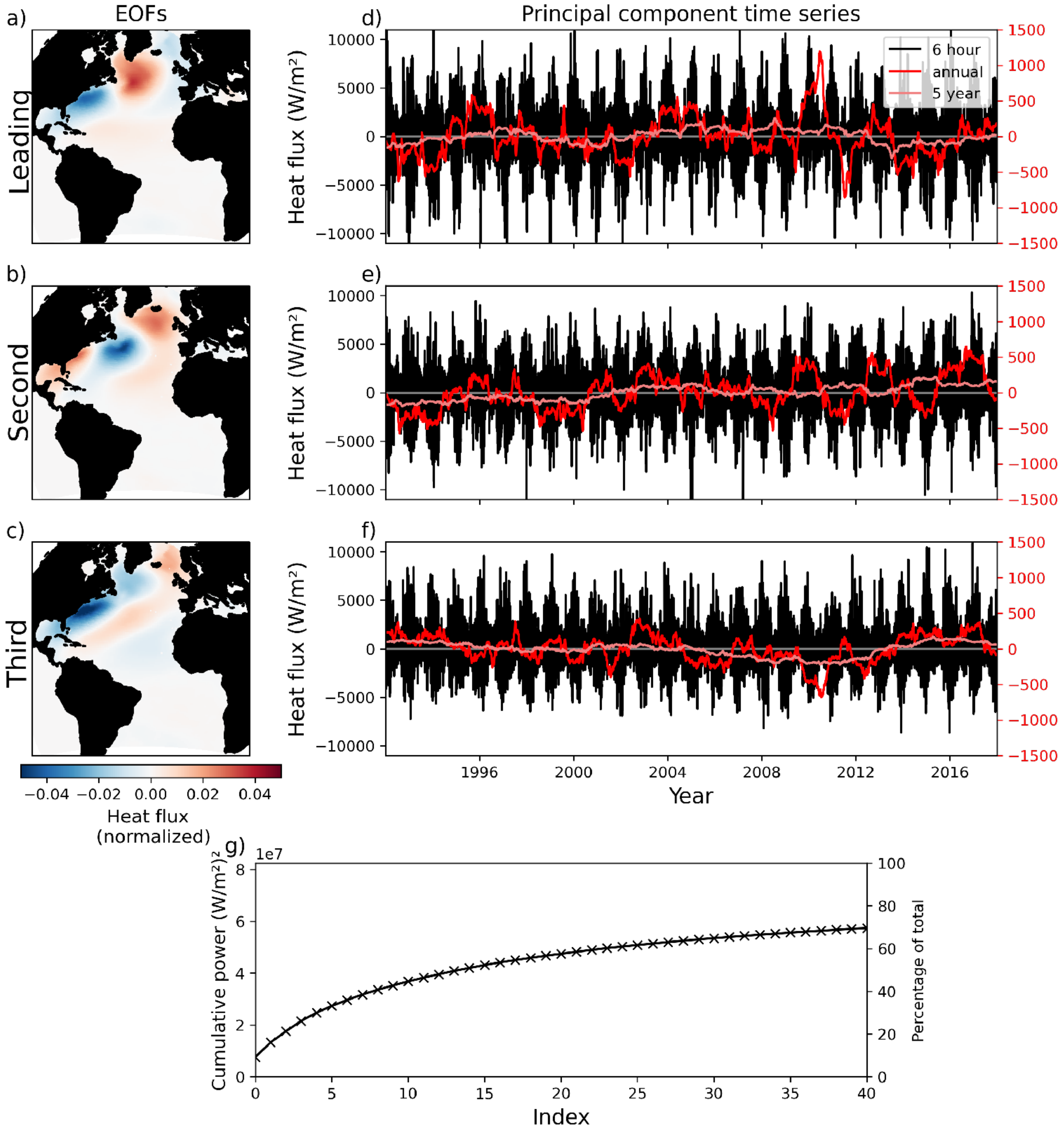


damrhein@ucar.edu

Dan Amrhein, Dafydd Stephenson, and LuAnne Thompson:
A dynamics-weighted principal components analysis of dominant atmospheric drivers of ocean variability with an application to the North Atlantic subpolar gyre. *Journal of Climate*, 2024

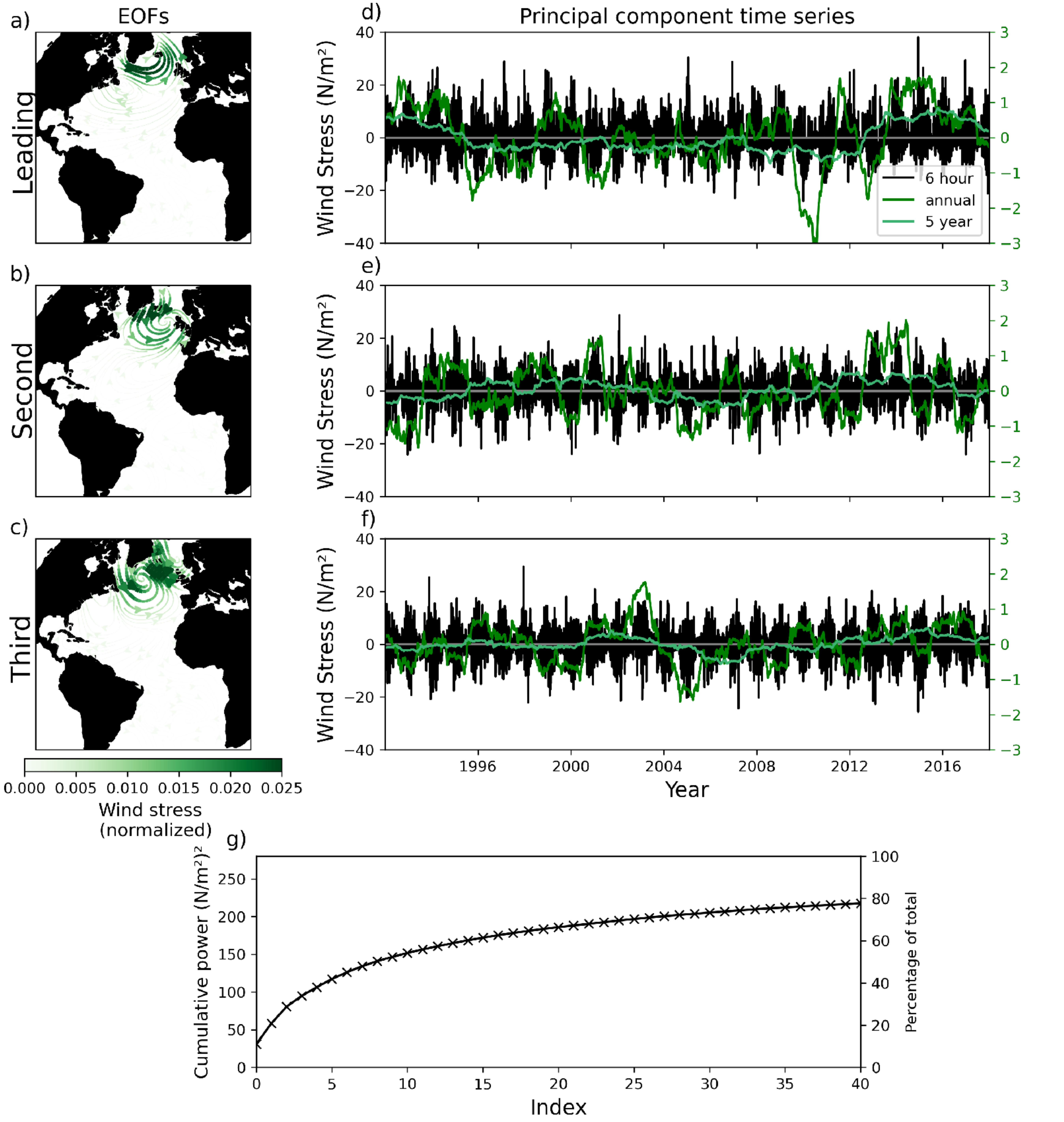
Leading **EOFs** show that a diversity of patterns contribute to North Atlantic heat fluxes.

Although the seasonal cycle has been removed, there is a notable seasonal cycle in variance.



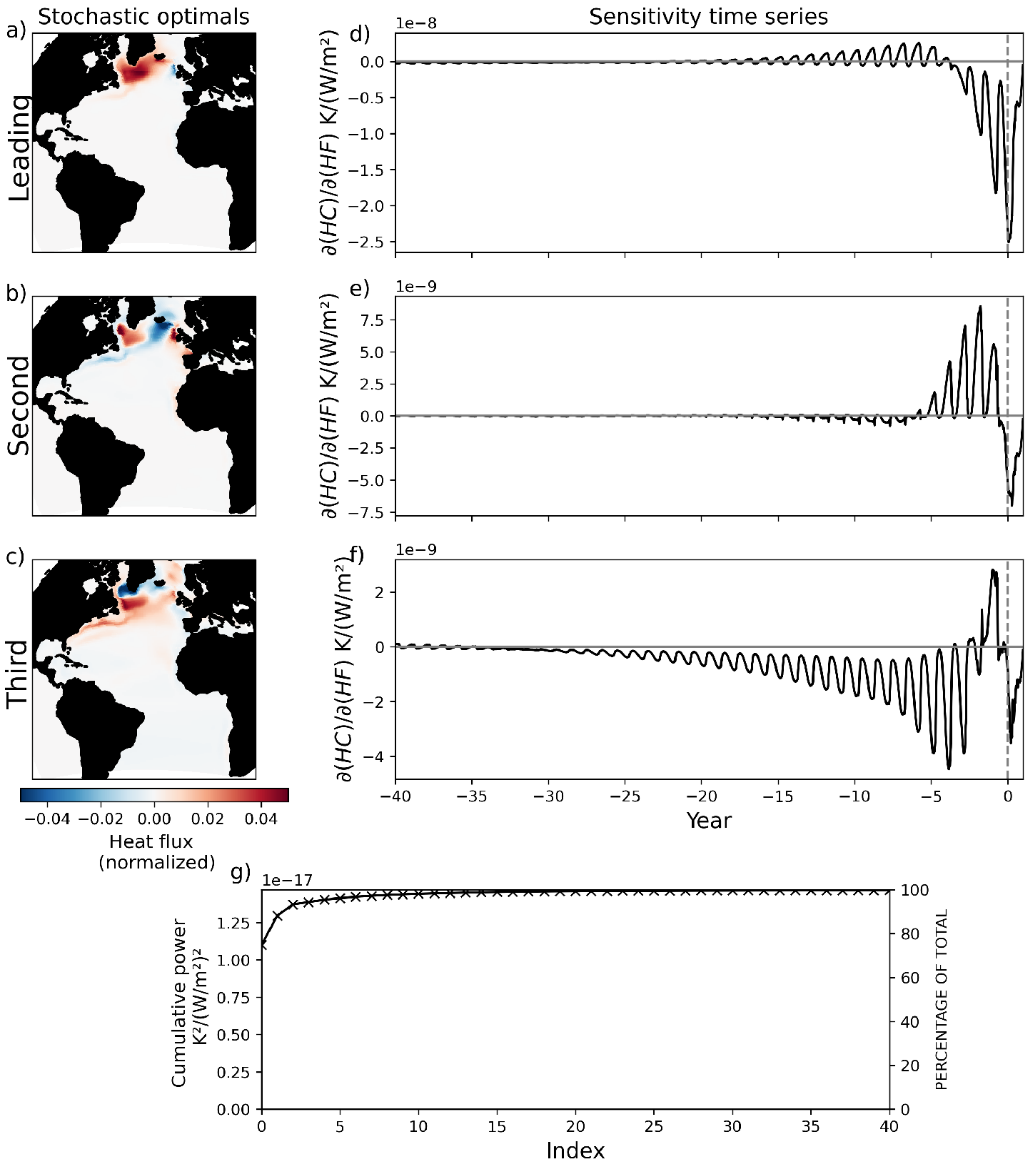
Leading **EOFs** show that a diversity of patterns contribute to North Atlantic heat fluxes.

For wind stress, there is a (less) notable seasonal cycle in variance.



Leading **stochastic optimals** reveal that **local heat fluxes** are a leading driver of annually-averaged SPG heat content.

Note the strong seasonality in sensitivity ("Stommel's demon").



Proc. Natl. Acad. Sci. USA
Vol. 76, No. 7, pp. 3051–3055, July 1979
Geophysics

Determination of water mass properties of water pumped down from the Ekman layer to the geostrophic flow below

(subtropical gyre/Ekman pumping/water mass origins)

HENRY STOMMEL

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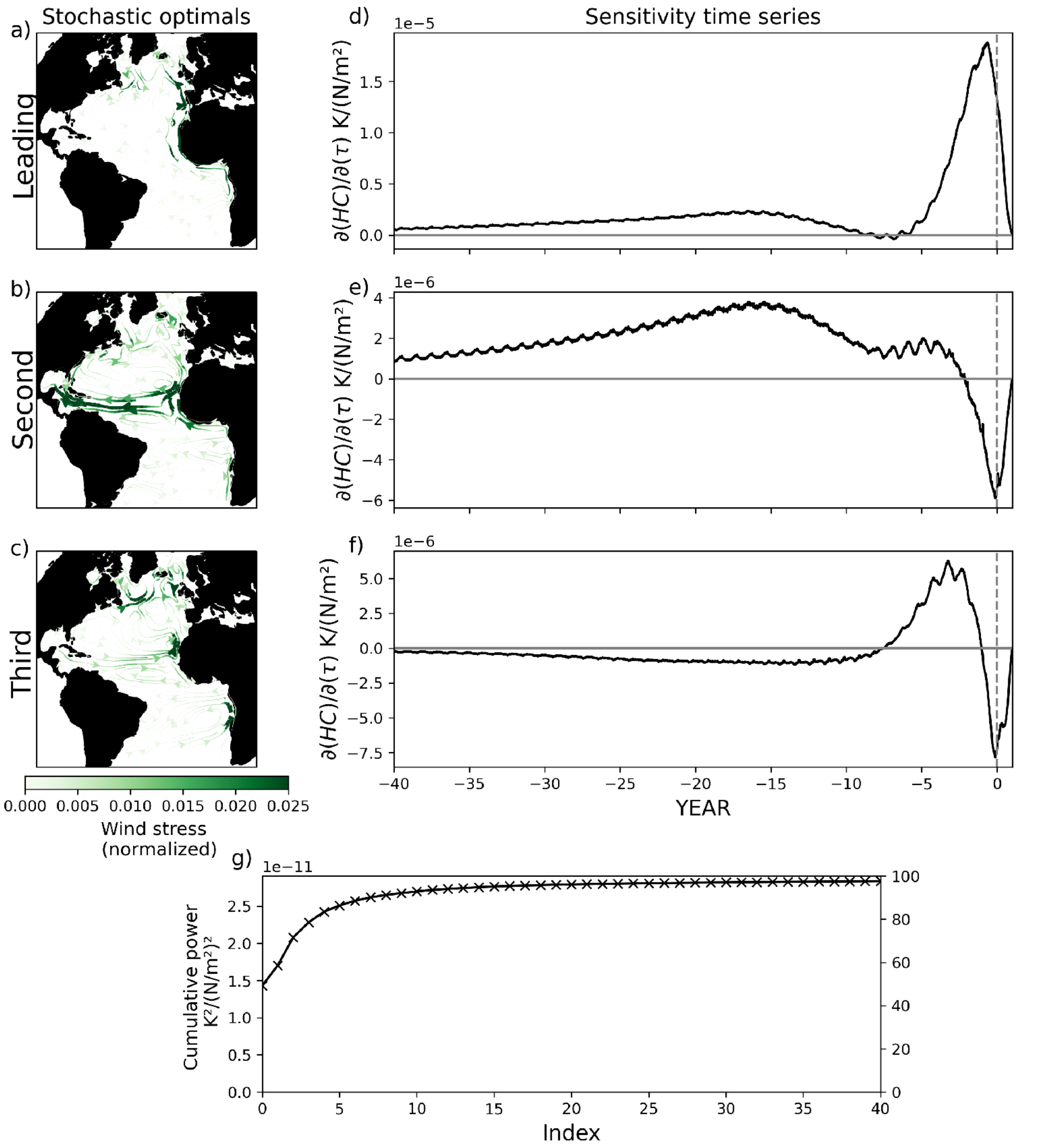
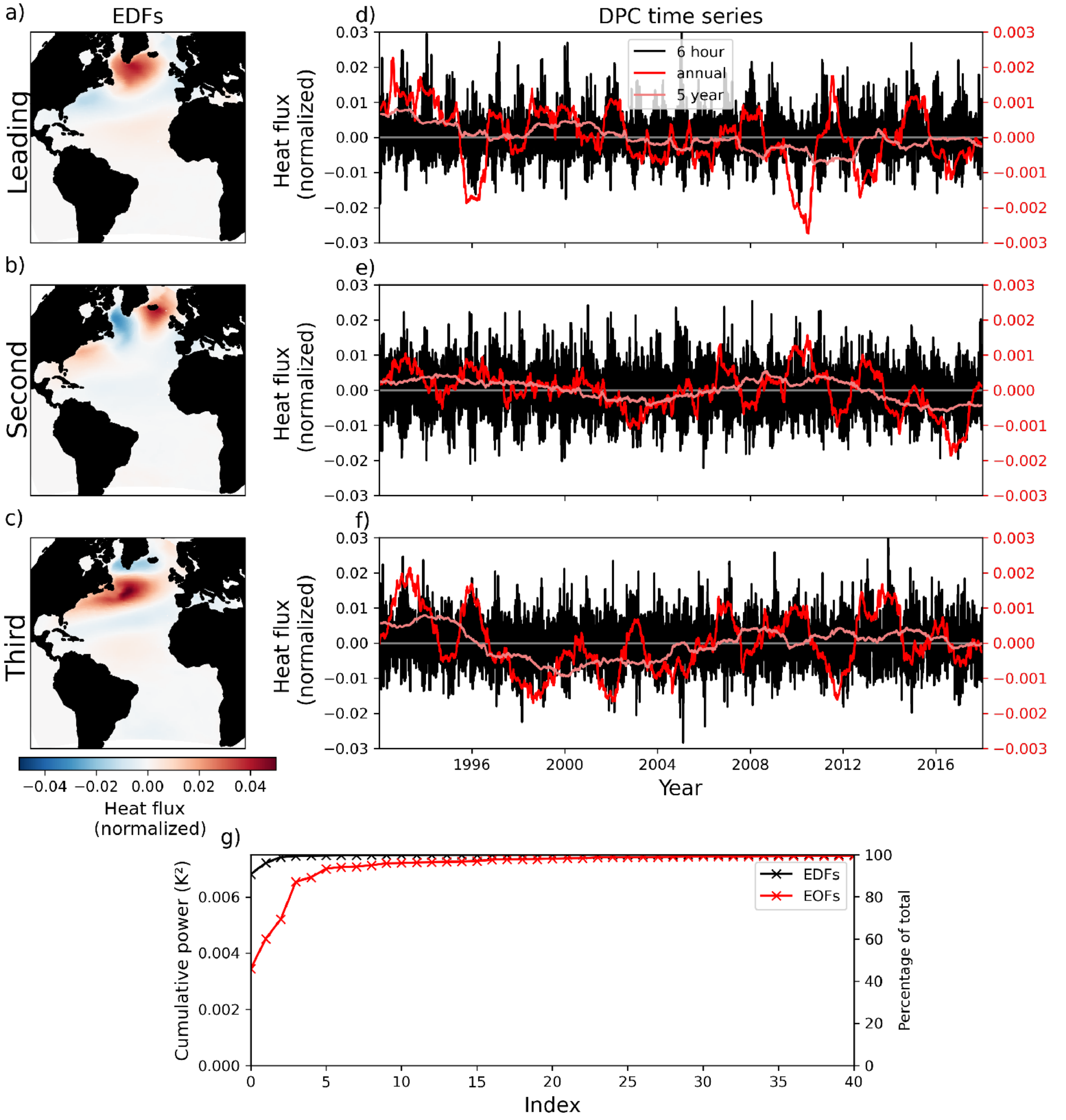
Leading **stochastic optimals** reveal roles for **remote wind stress forcing**, particularly exciting equatorial and Kelvin waves that eventually heave isopycnals in the SPG (cf. Jones et al. 2018)



Dynamics-weighted principal components collapses the space of potential forcings onto a pattern with a high pattern correlation (~94%) with the canonical North Atlantic Oscillation



Dynamics-weighted principal components collapses the space of potential forcings onto a pattern with a high pattern correlation (~94%) with the canonical North Atlantic Oscillation