

Ocean boundary pressure: Its significance and sensitivities

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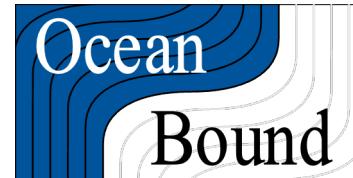
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21st August 2024



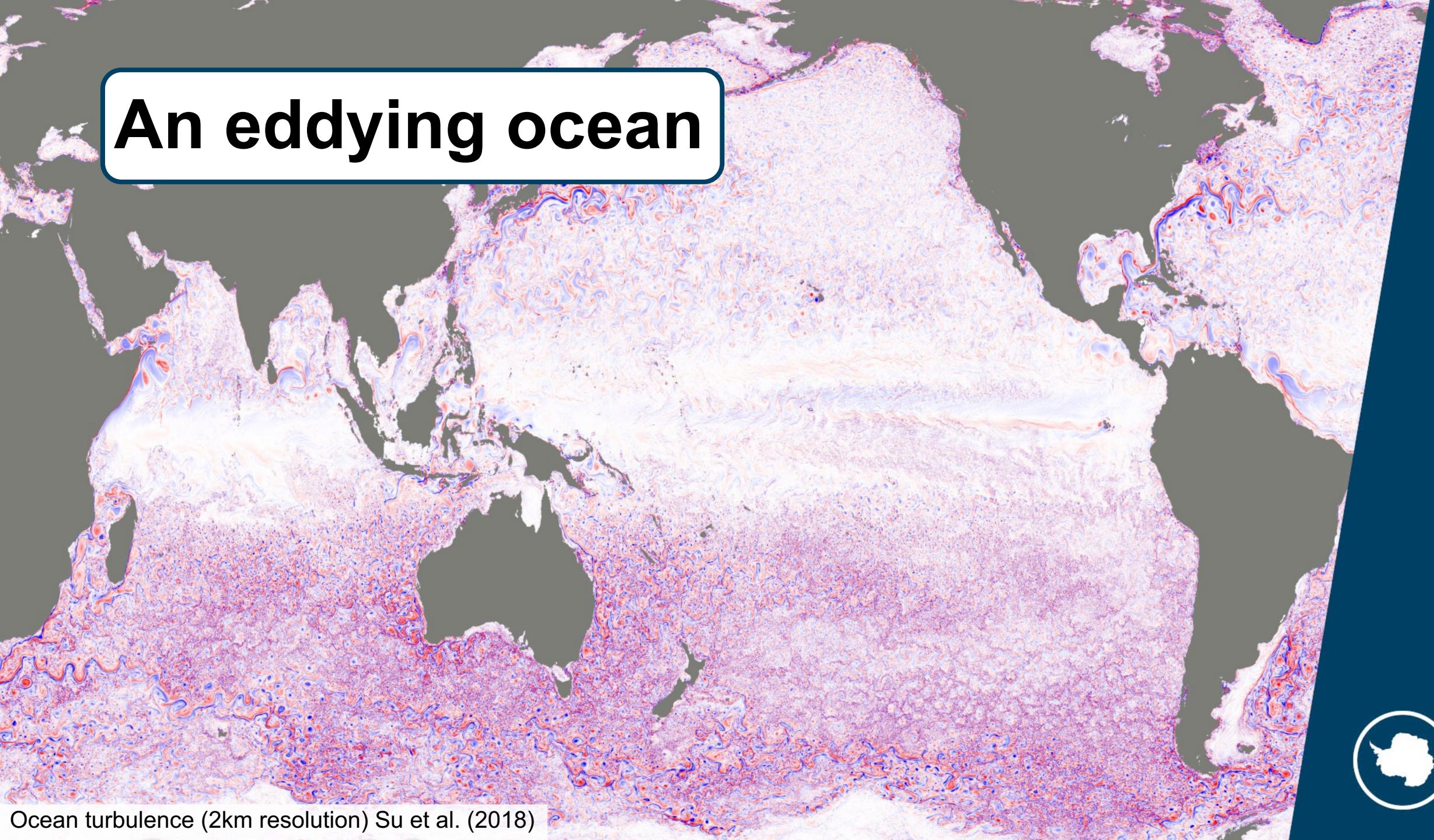
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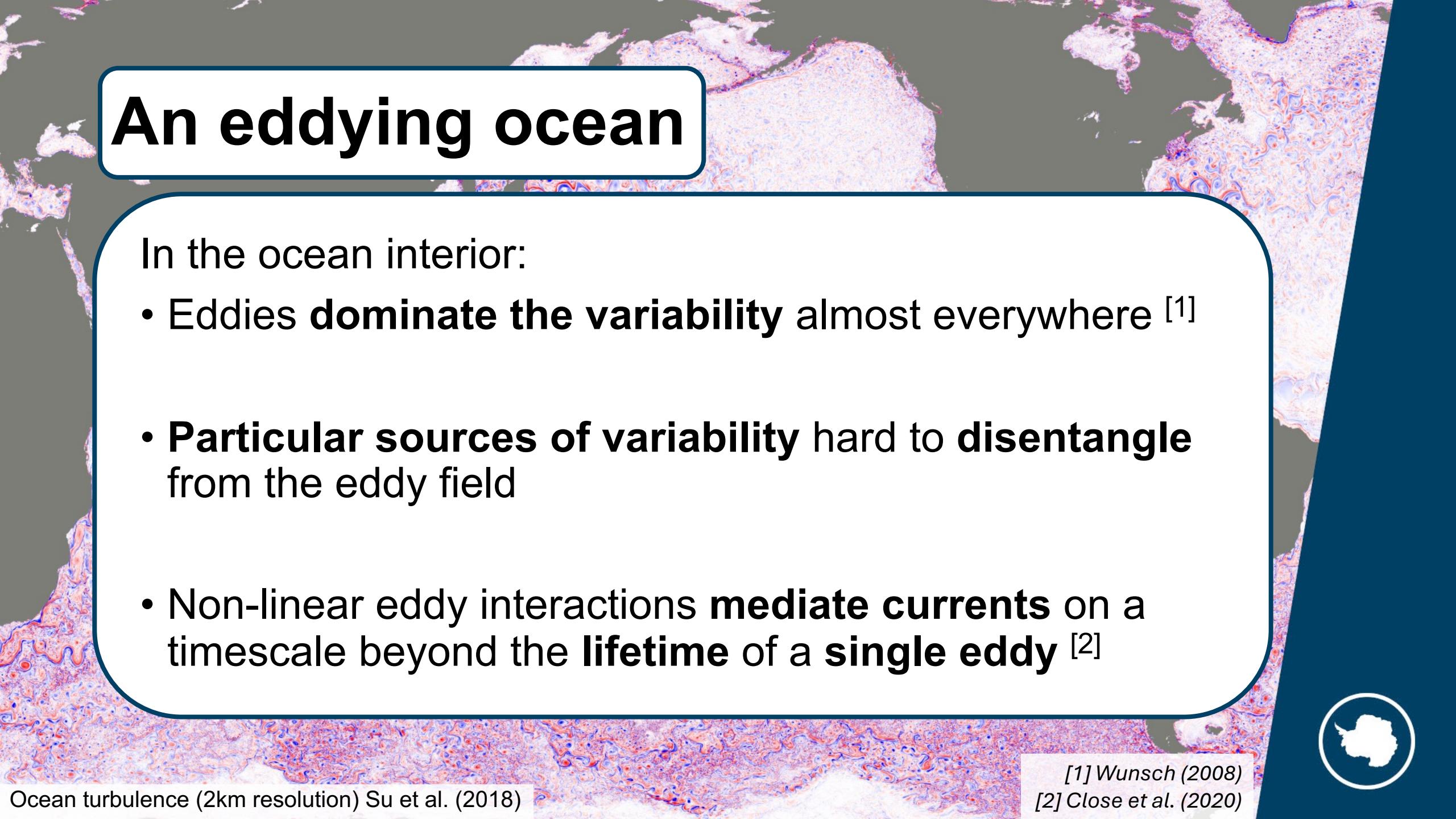
An eddying ocean



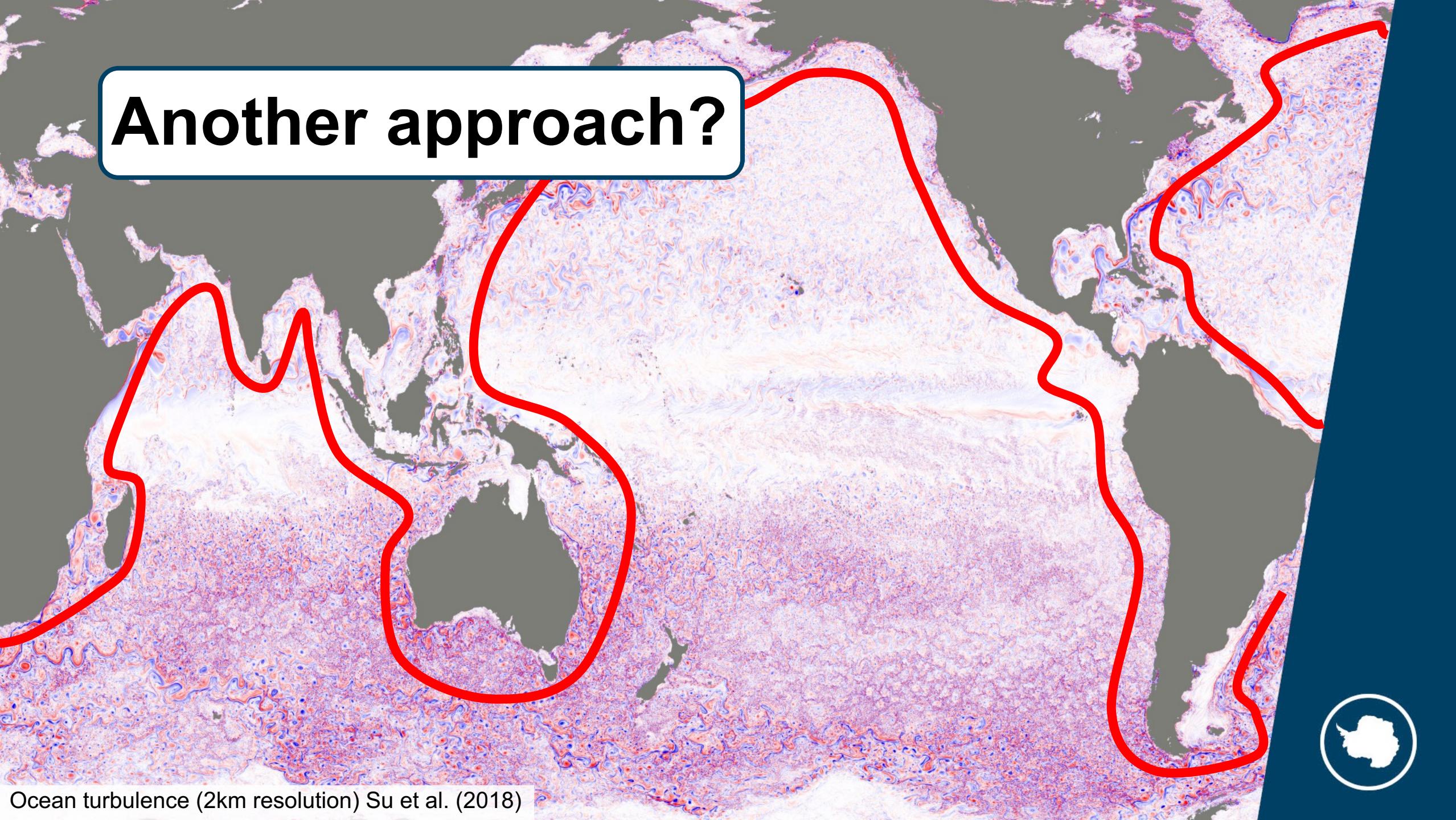
An eddying ocean

In the ocean interior:

- Eddies **dominate the variability** almost everywhere [1]
- **Particular sources of variability** hard to disentangle from the eddy field
- Non-linear eddy interactions **mediate currents** on a timescale beyond the **lifetime of a single eddy** [2]



Another approach?



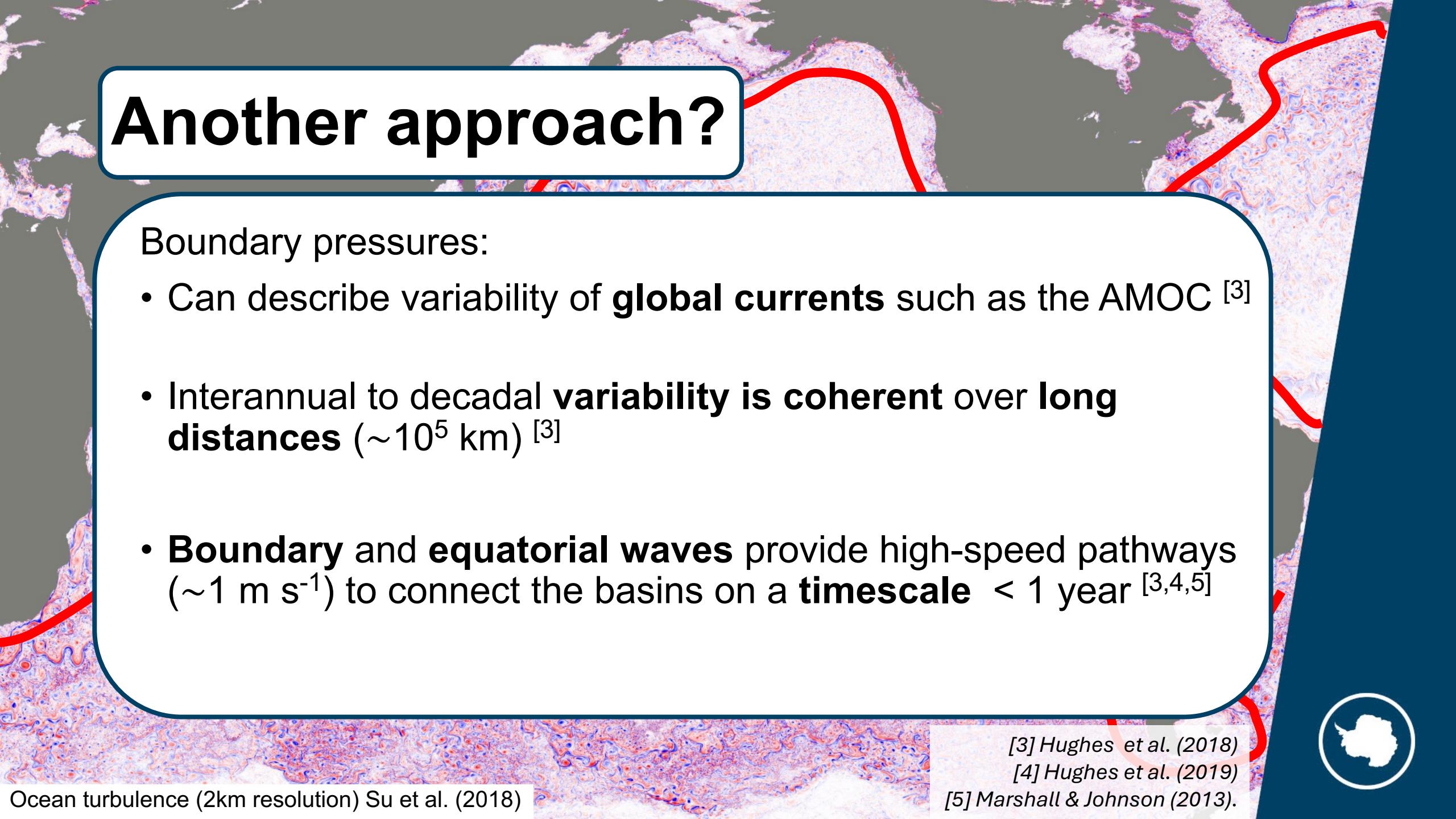
Ocean turbulence (2km resolution) Su et al. (2018)



Another approach?

Boundary pressures:

- Can describe variability of **global currents** such as the AMOC [3]
- Interannual to decadal **variability is coherent over long distances** ($\sim 10^5$ km) [3]
- **Boundary and equatorial waves** provide high-speed pathways ($\sim 1 \text{ m s}^{-1}$) to connect the basins on a **timescale** $< 1 \text{ year}$ [3,4,5]



Explained variability of the MOC

NEMO (ORCA12)
Eddy-rich forced model
54-year time-average

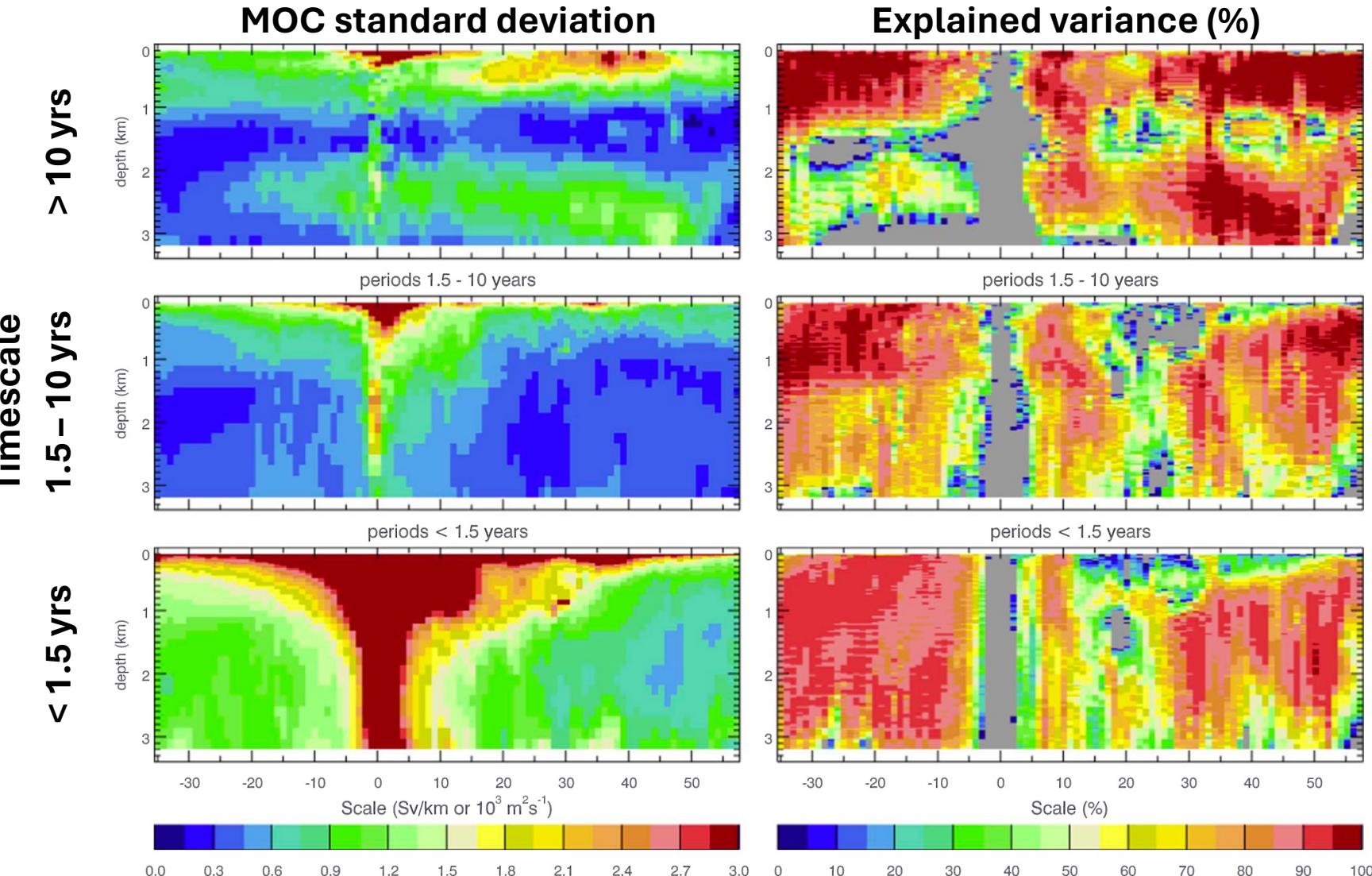


Figure 17 from Hughes et al. (2018)

$$fT(z, y) = p_E - p_W$$

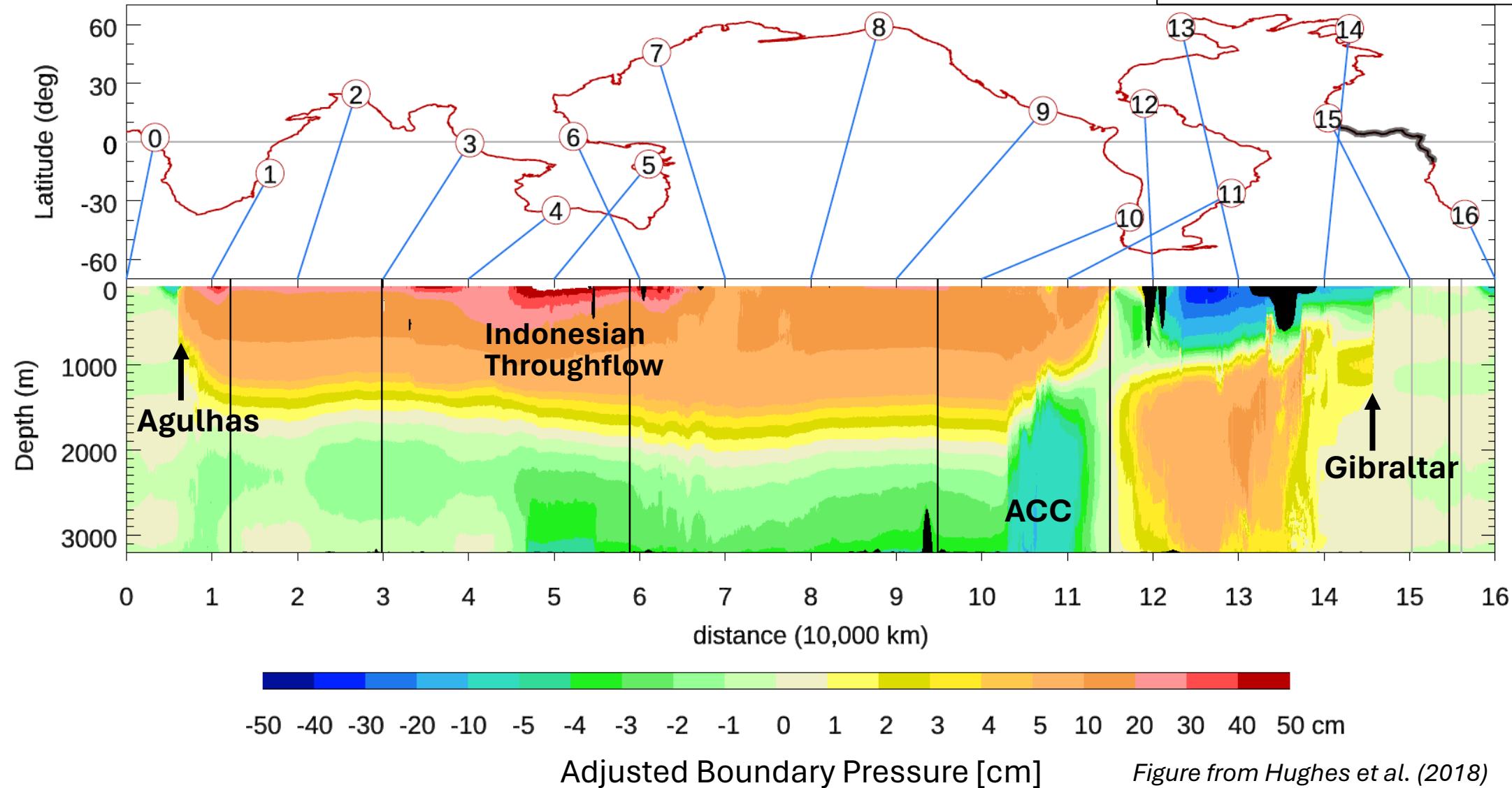
MOC calculation
from **geostrophic**
assumptions



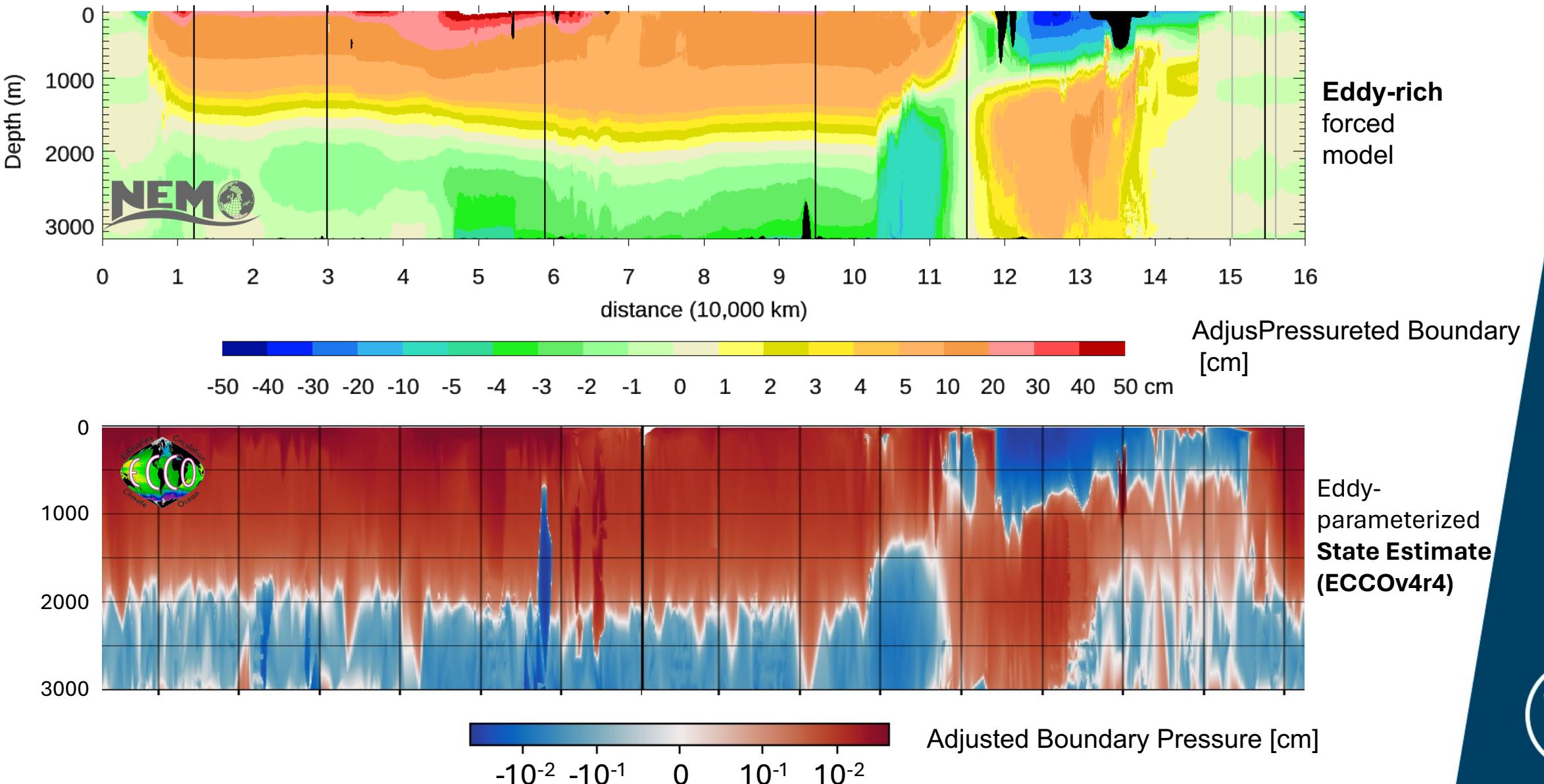
Boundary Pressure Structure

NEMO (ORCA12)
Eddy-rich forced model
54-year time-average

Boundary pressure relative to East Atlantic

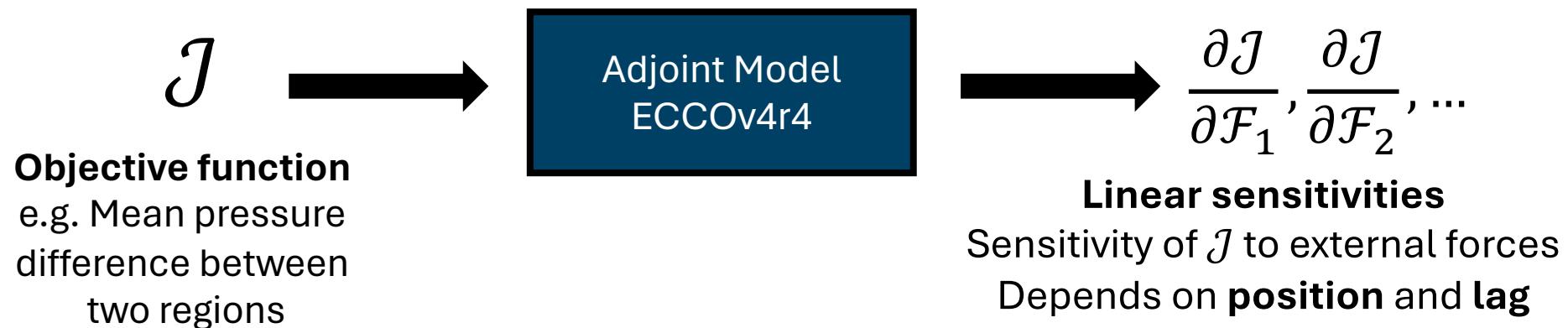


Boundary Pressure Structure



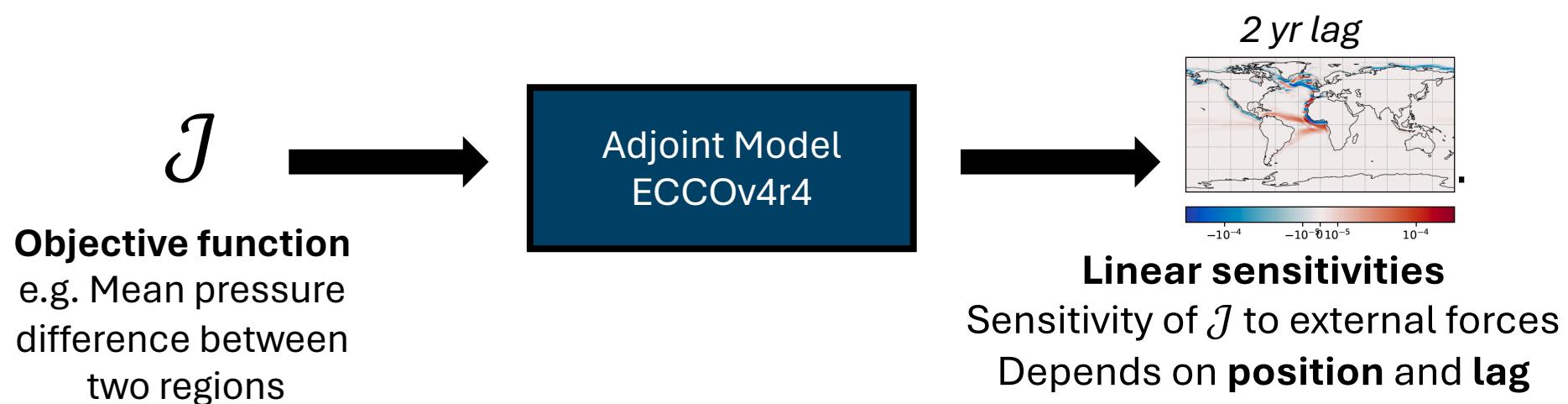
Adjoint models

- **Adjoint models** effectively run “backwards”
- Relate **ocean behaviors** to **physical causes** in the past via automatic differentiation
- Identify the linear sensitivities of an **objective function**



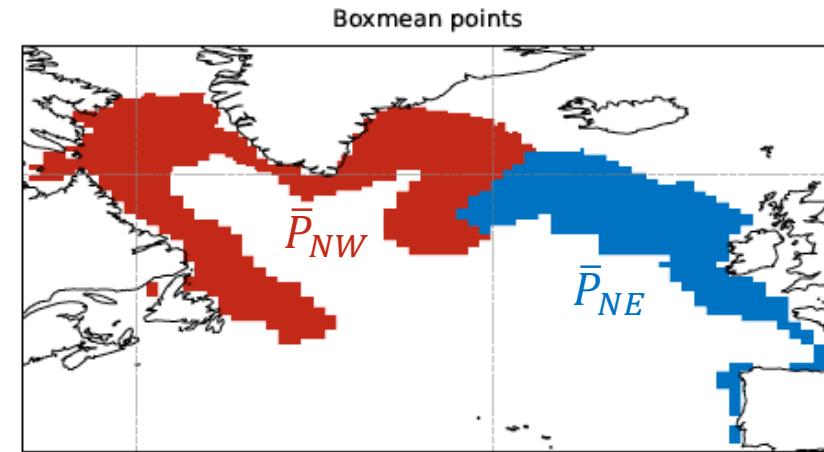
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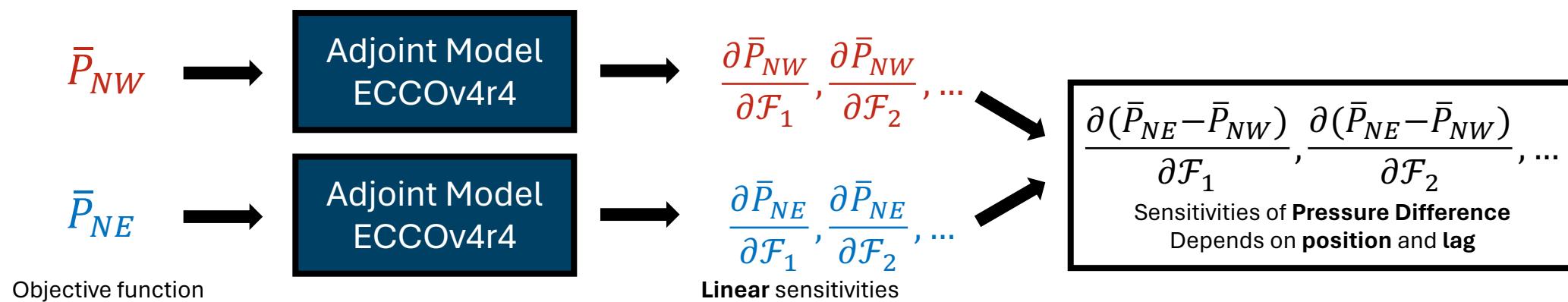


Objective function for pressure difference

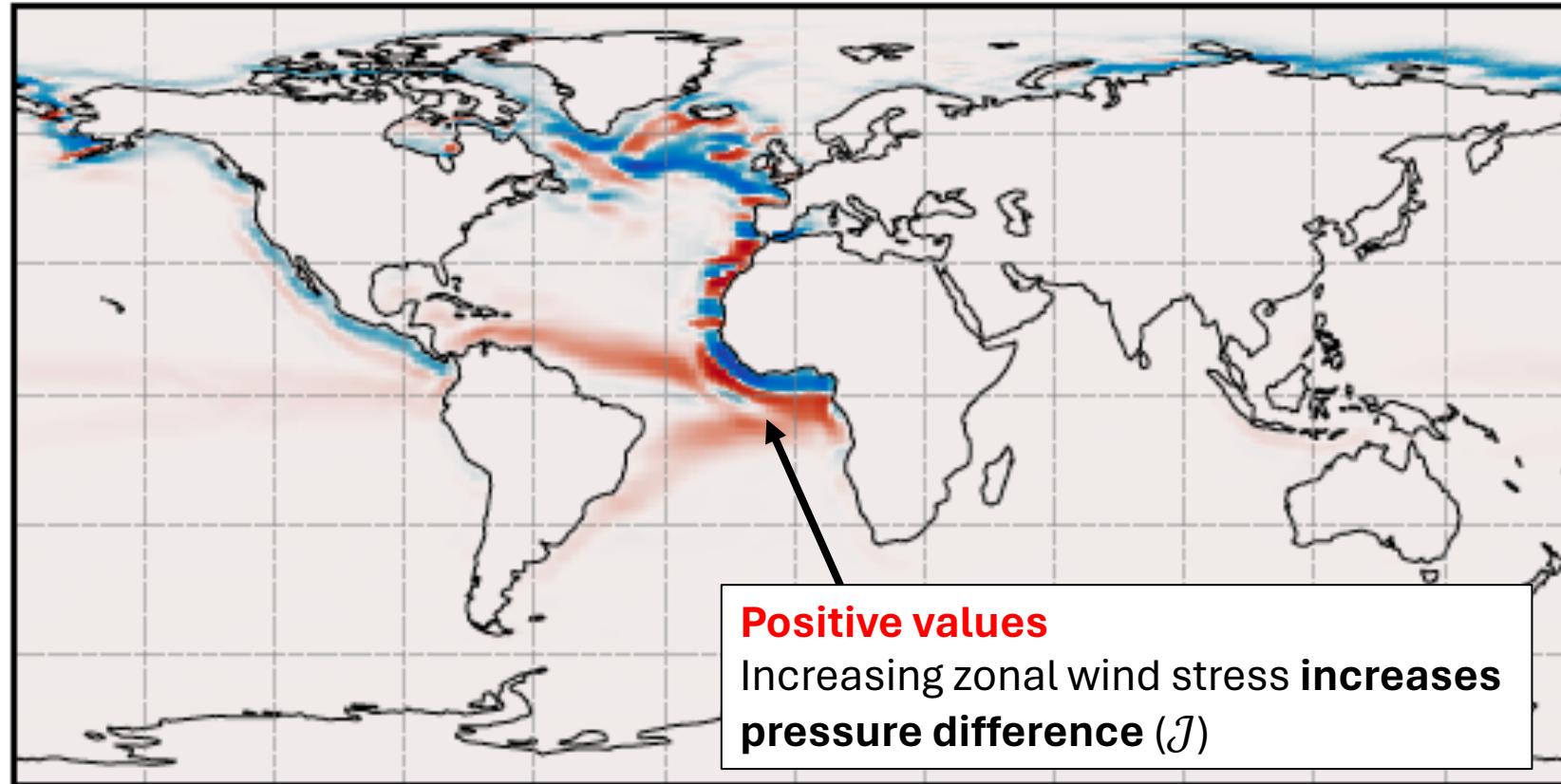
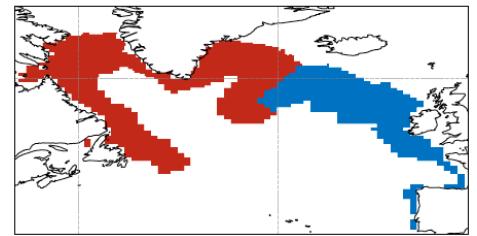
- Select 2 **clusters** of boundary grid points (e.g. figure)
- Select a time window (e.g. Jan \Rightarrow Dec 2008)
- **Bottom pressure** within each cluster is spatially and then temporally averaged (e.g. \bar{P}_{NW} , \bar{P}_{NE})
- The adjoint model calculates the **linear sensitivities** of each mean pressure to:



Example clusters in the NW Atlantic (Red) and NE Atlantic (Blue). Both clusters contain grid points with depths ≤ 3000 m within the approximate global 3000 m isobath



Sensitivity field: Zonal winds stress



Remember that
**sensitivity is a
function of lag also**

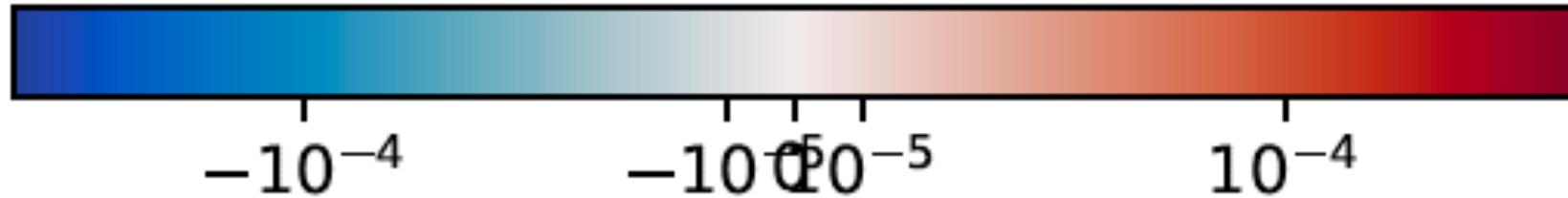
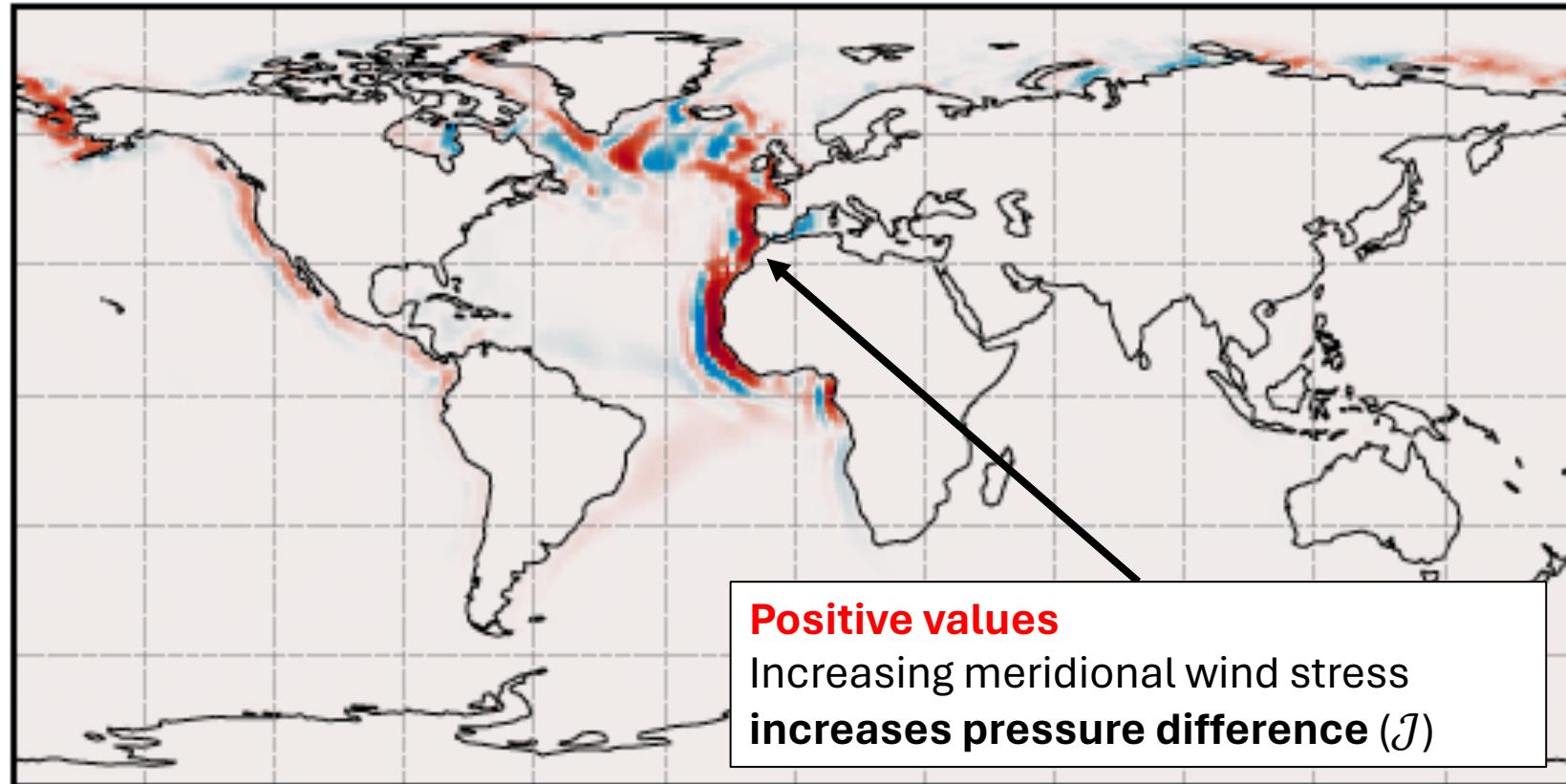
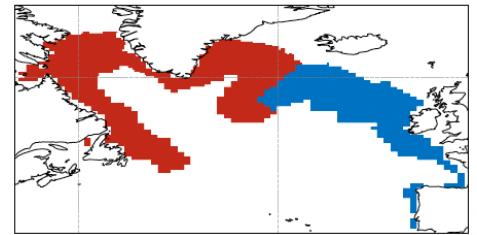
The shown
sensitivity is for a
value of lag where
the pattern is
particularly strong



$[m^2 s^{-2}] / [N m^{-2}]$



Sensitivity field: Meridional Wind Stress

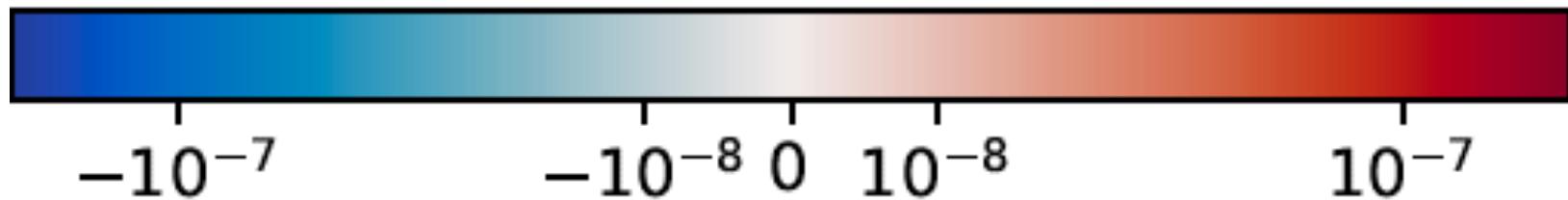
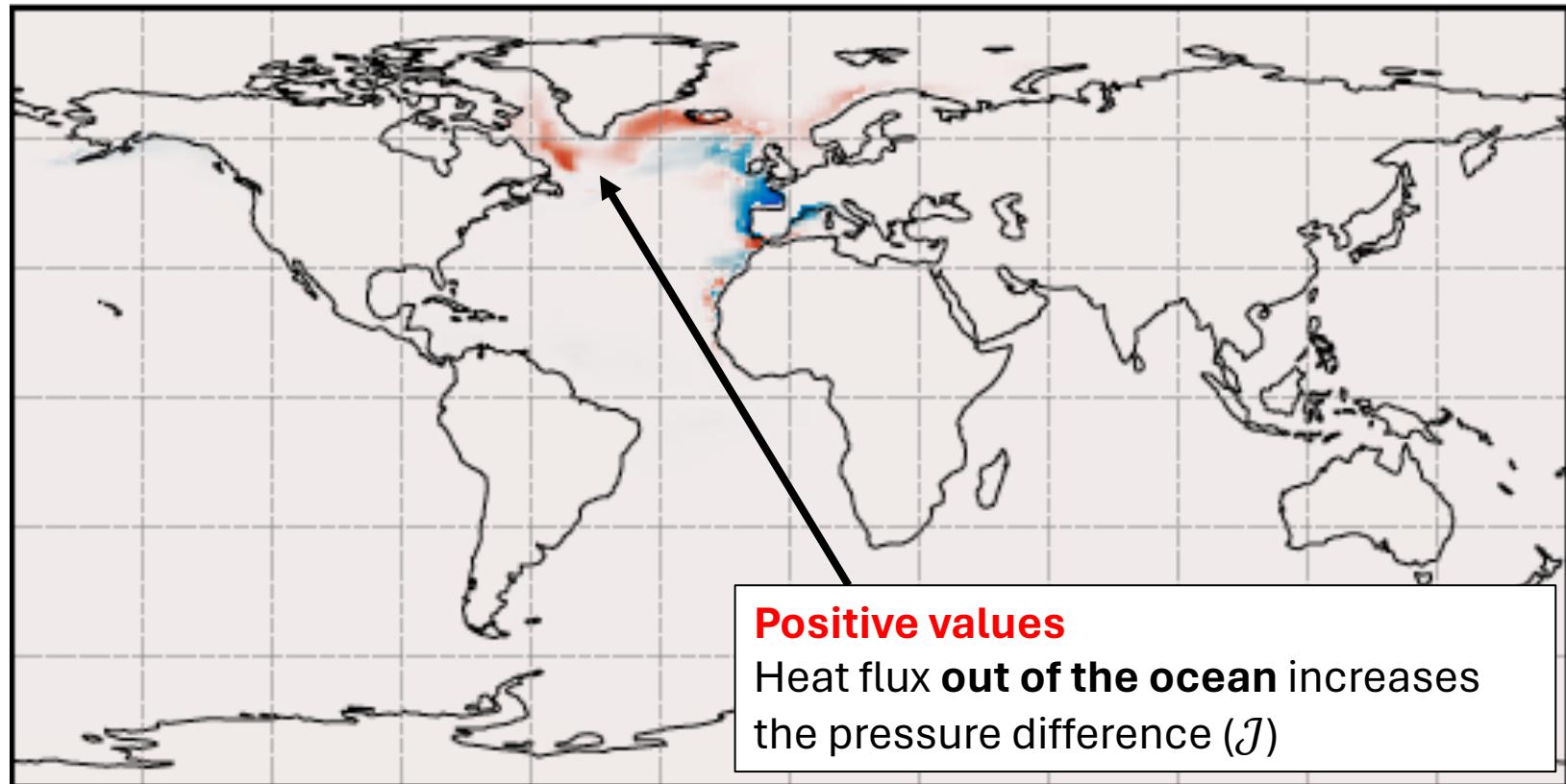
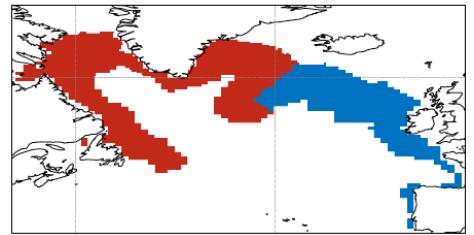


Remember that
**sensitivity is a
function of lag also**

The shown
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Sensitivity field: Heat flux

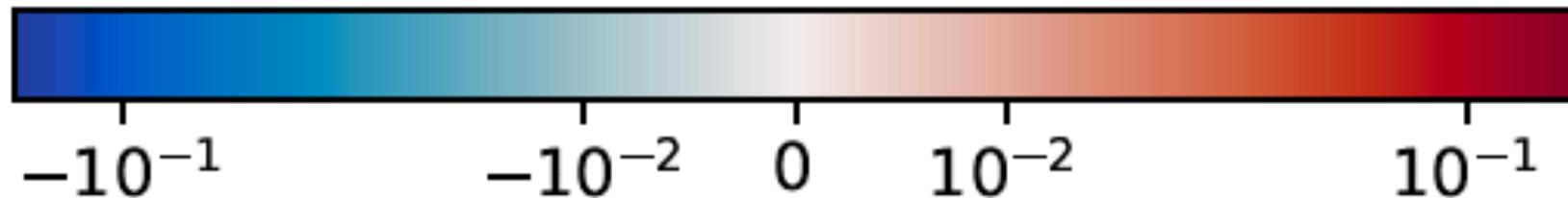
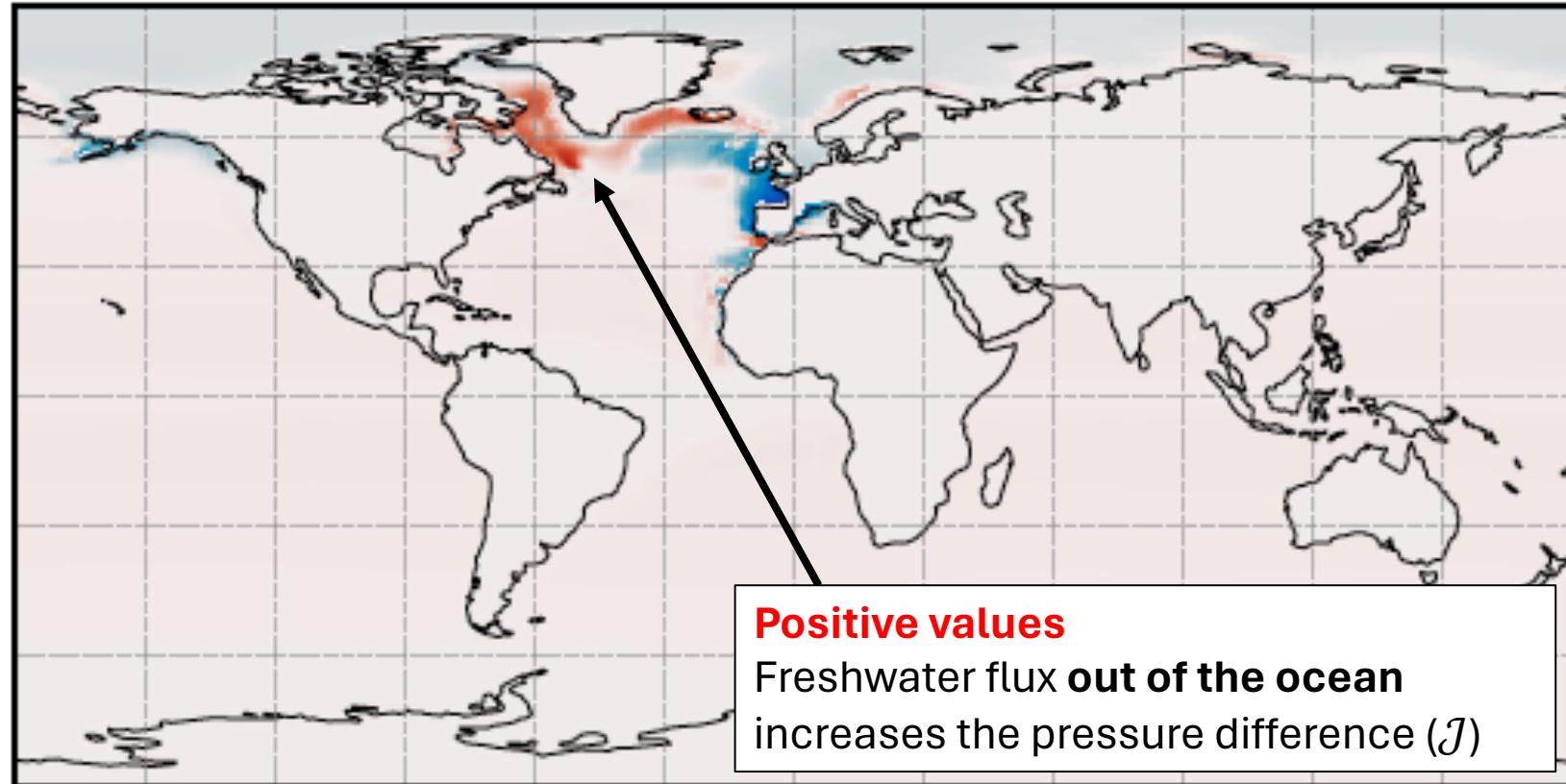
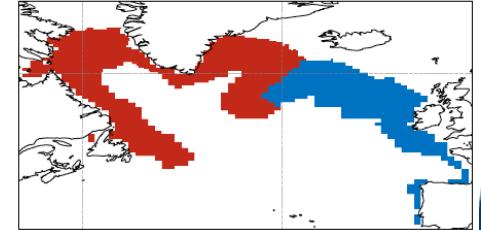


Remember that
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Sensitivity field: Freshwater flux



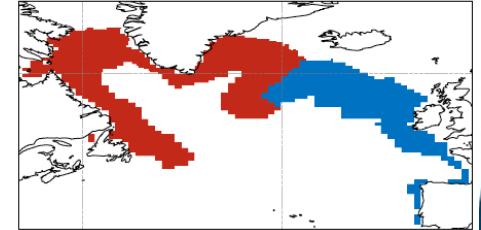
$[m^2 s^{-2}] / [m^{-1}]$

Remember that
**sensitivity is a
function of lag also**

The shown
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particularly strong



Reconstructions



- The **sensitivity fields** can be **convoluted** with forcing anomalies (relative to climatology) to **reconstruct** a pressure anomaly time series

$$\mathcal{R}_i(t) = \iint_A \int_{t_1}^{t_2} \mathcal{A}_i(x, t') \Delta \mathcal{F}_i(x, t + t') dt' dA$$

Reconstruction of the pressure anomaly at time t for the force \mathcal{F}_i

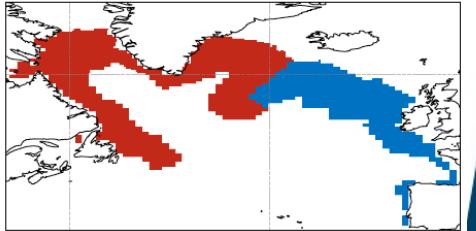
Approximate sensitivity of the pressure anomaly to forcing at time $t + t'$

Forcing anomaly at time $t + t'$

- In this reconstruction we assume the **sensitivity is stationary** (does not depend on absolute time)

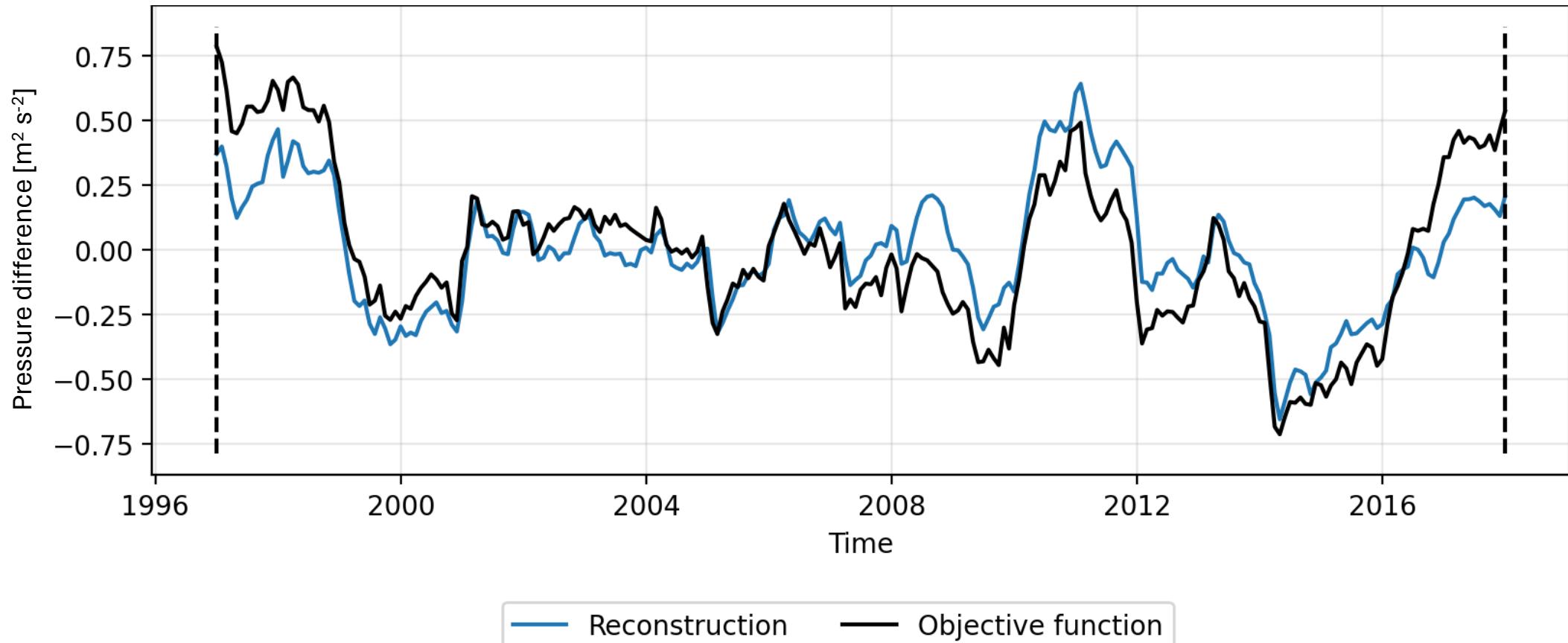


'All in' reconstruction



$$\mathcal{R}(t) = \sum_i \iint_A \int_{t_1}^{t_2} \mathcal{A}_i(\mathbf{x}, t') \Delta \mathcal{F}_i(\mathbf{x}, t + t') dt' dA$$

Reconstruction using all forces ($\forall i$) and all available lag ($t_1 = -5\text{yrs}$, $t_2 = 0$)



Explained variability

Explained variability describes how much of the desired variability is captured by a reconstruction

$$E_i = 1 - \frac{\text{Var}(\mathcal{J} - \mathcal{R}_i)}{\text{Var}(\mathcal{J})}$$

If $E = 1$ the variability is reconstructed perfectly
If $E < 0$ the reconstruction is worse than assuming a constant value

A reconstruction can be modified by including **different forces** and different amounts of lag (**memory**)

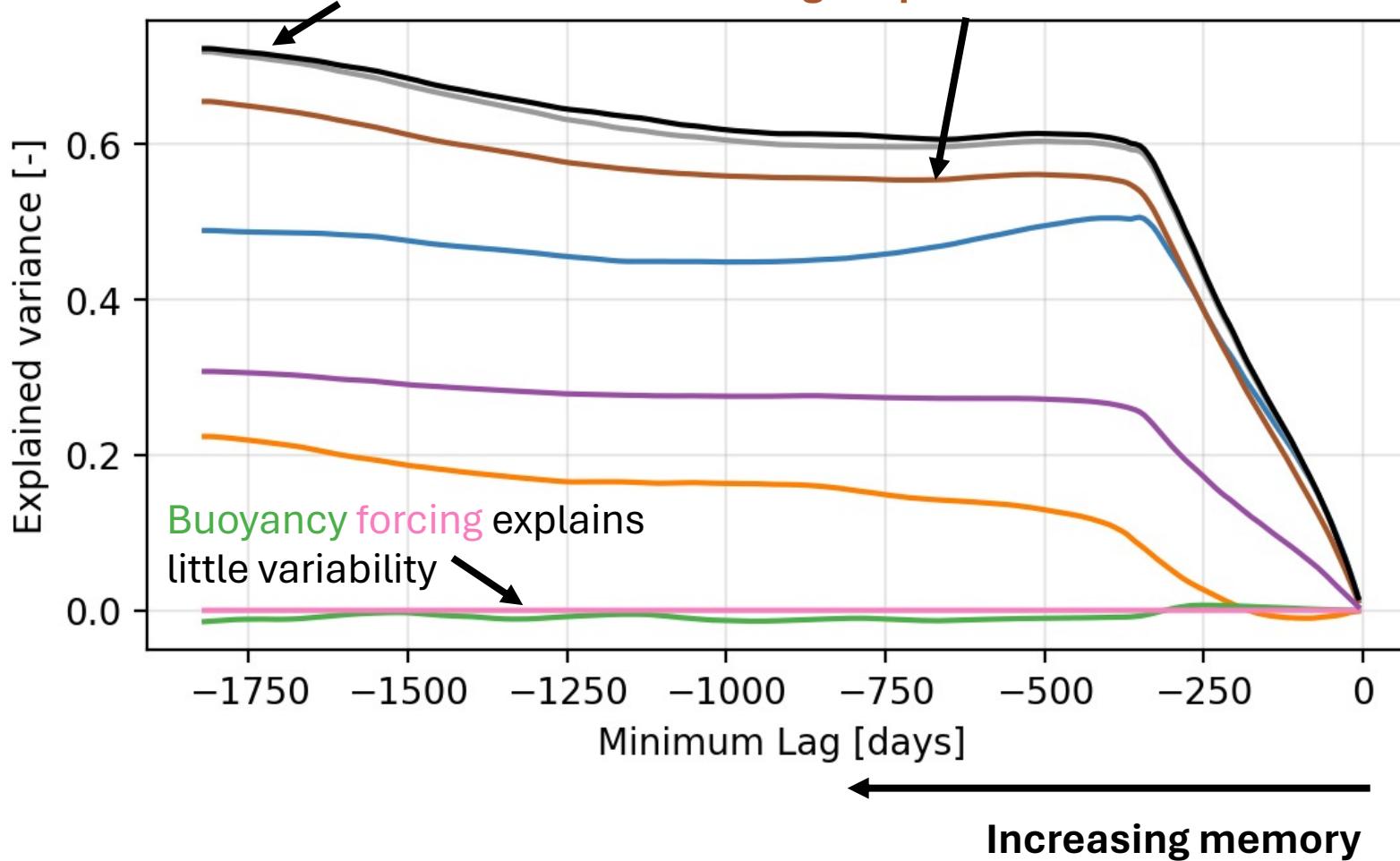
Identifying the optimal combination of forces and memory indicates the **relevant forces** and **timescales**.



Explained variability

Approximately 72% of variability explained by reconstruction

Most of the explained variability originates from **along-slope winds**



$$E_i = 1 - \frac{\text{Var}(\mathcal{J} - \mathcal{R}_i)}{\text{Var}(\mathcal{J})}$$

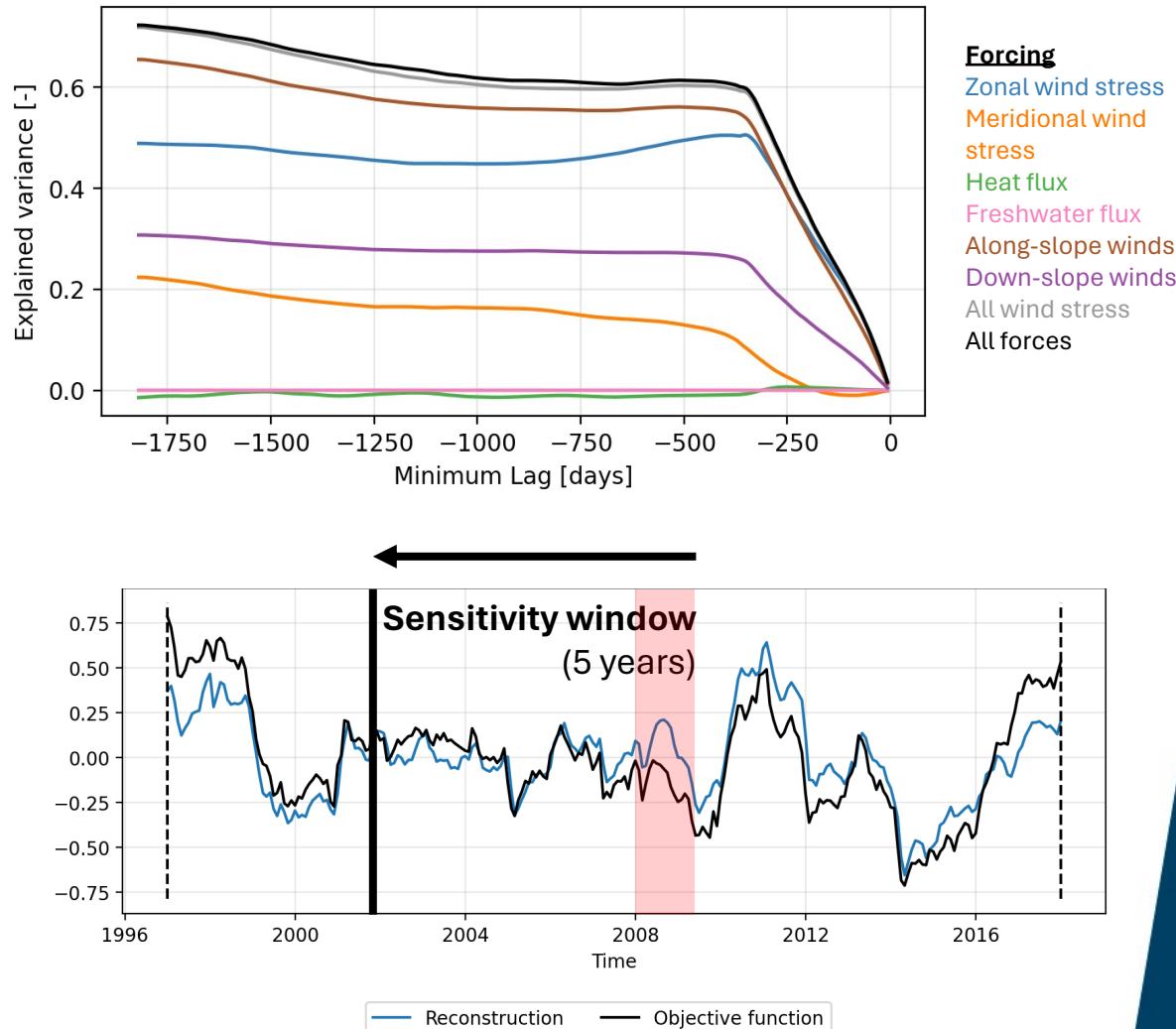
Forcing

- Zonal wind stress
- Meridional wind stress
- Heat flux
- Freshwater flux
- Along-slope winds
- Down-slope winds
- All wind stress
- All forces



Where is the remaining variability?

- **Longer lags** may be necessary (> 5 -year memory)
- **Non-linear sensitivities** of the pressure difference may also be significant
- **Assuming** sensitivities are **stationary** may also produce errors



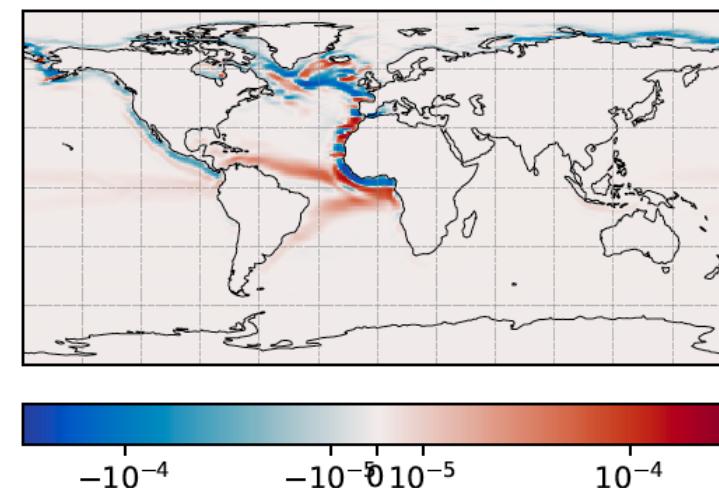
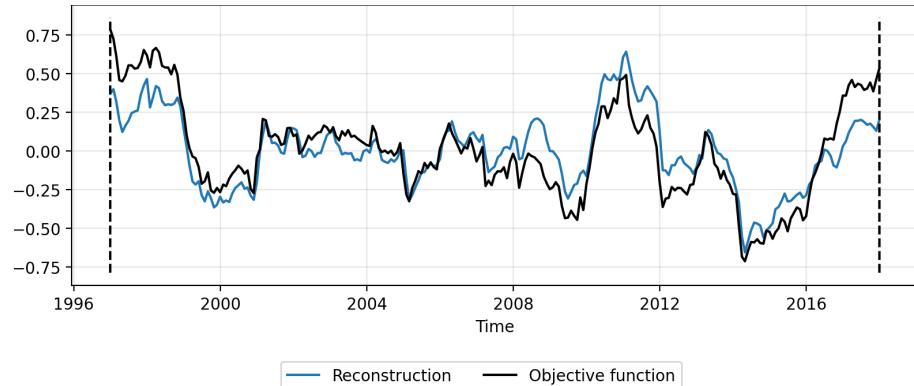
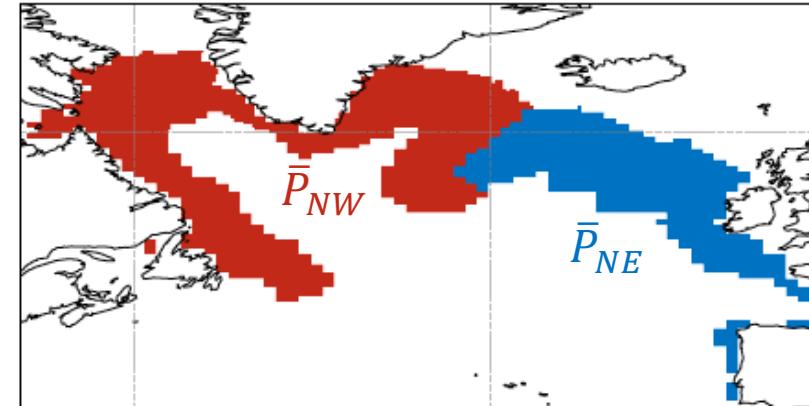
Where is the remaining variability?

- Longer lags may be necessary (> 5-year memory) → Extend adjoint runs to 10-20 years
- Non-linear sensitivities of the pressure difference may also be significant → Perform forward perturbation experiments
- Assuming sensitivities are stationary may also produce errors → Calculate sensitivities centered on a different time



Conclusions

- Components of variability in large scale circulations (e.g. AMOC) can be described by boundary pressures.
- Using an adjoint model, we can reconstruct **72% of the pressure difference variability** in the North Atlantic
- Most of the explained variability originates from **along-slope winds**



Thank you for listening

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slides here!



References

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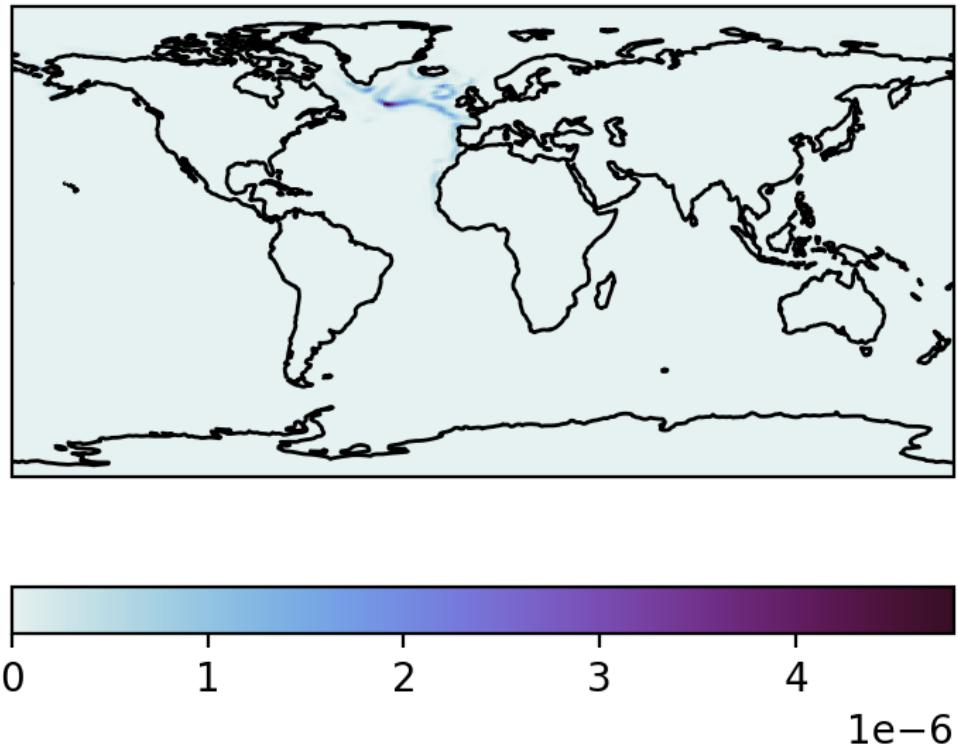
- [1] Wunsch, C. (2008). Mass and volume transport variability in an eddy-filled ocean. *Nature Geoscience*, 1(3), 165–168. <https://doi.org/10.1038/ngeo126>
- [2] Close, S., Penduff, T., Speich, S., & Molines, J.-M. (2020). A means of estimating the intrinsic and atmospherically-forced contributions to sea surface height variability applied to altimetric observations. *Progress in Oceanography*, 184, 102314. <https://doi.org/10.1016/j.pocean.2020.102314>
- [3] Hughes, C. W., Williams, J., Blaker, A., Coward, A., & Stepanov, V. (2018). A window on the deep ocean: The special value of ocean bottom pressure for monitoring the large-scale, deep-ocean circulation. *Progress in Oceanography*, 161, 19–46. <https://doi.org/10.1016/j.pocean.2018.01.011>
- [4] Hughes, C. W., Fukumori, I., Griffies, S. M., Huthnance, J. M., Minobe, S., Spence, P., Thompson, K. R., & Wise, A. (2019). Sea Level and the Role of Coastal Trapped Waves in Mediating the Influence of the Open Ocean on the Coast. *Surveys in Geophysics*, 40(6), 1467–1492. <https://doi.org/10.1007/s10712-019-09535-x>
- [5] Marshall, D. P., & Johnson, H. L. (2013). Propagation of Meridional Circulation Anomalies along Western and Eastern Boundaries. *Journal of Physical Oceanography*, 43(12), 2699-2717. <https://doi.org/10.1175/JPO-D-13-0134.1>



Extra Slides



wnd: Constructed Variability



$$\mathcal{R}_i(\mathbf{x}, t) = \int_{t_1}^{t_2} \mathcal{A}_i(\mathbf{x}, t') \Delta \mathcal{F}_i(\mathbf{x}, t + t') dt'$$

$$E_i(\mathbf{x}, t) = 1 - \frac{Var(\mathcal{J} - \mathcal{R}(\mathbf{x}, t))}{Var(\mathcal{J})}$$

wnd: Explained Variability

