

# Ocean boundary pressure: Its significance and sensitivities

**Andrew Styles<sup>1</sup>, Emma Boland<sup>1</sup>, Chris Hughes<sup>2</sup>**

<sup>1</sup> British Antarctic Survey, UK

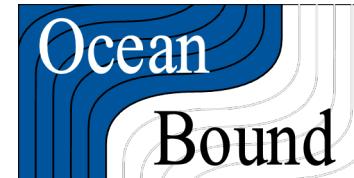
<sup>2</sup> University of Liverpool, UK

3<sup>rd</sup> September 2024



**British  
Antarctic Survey**

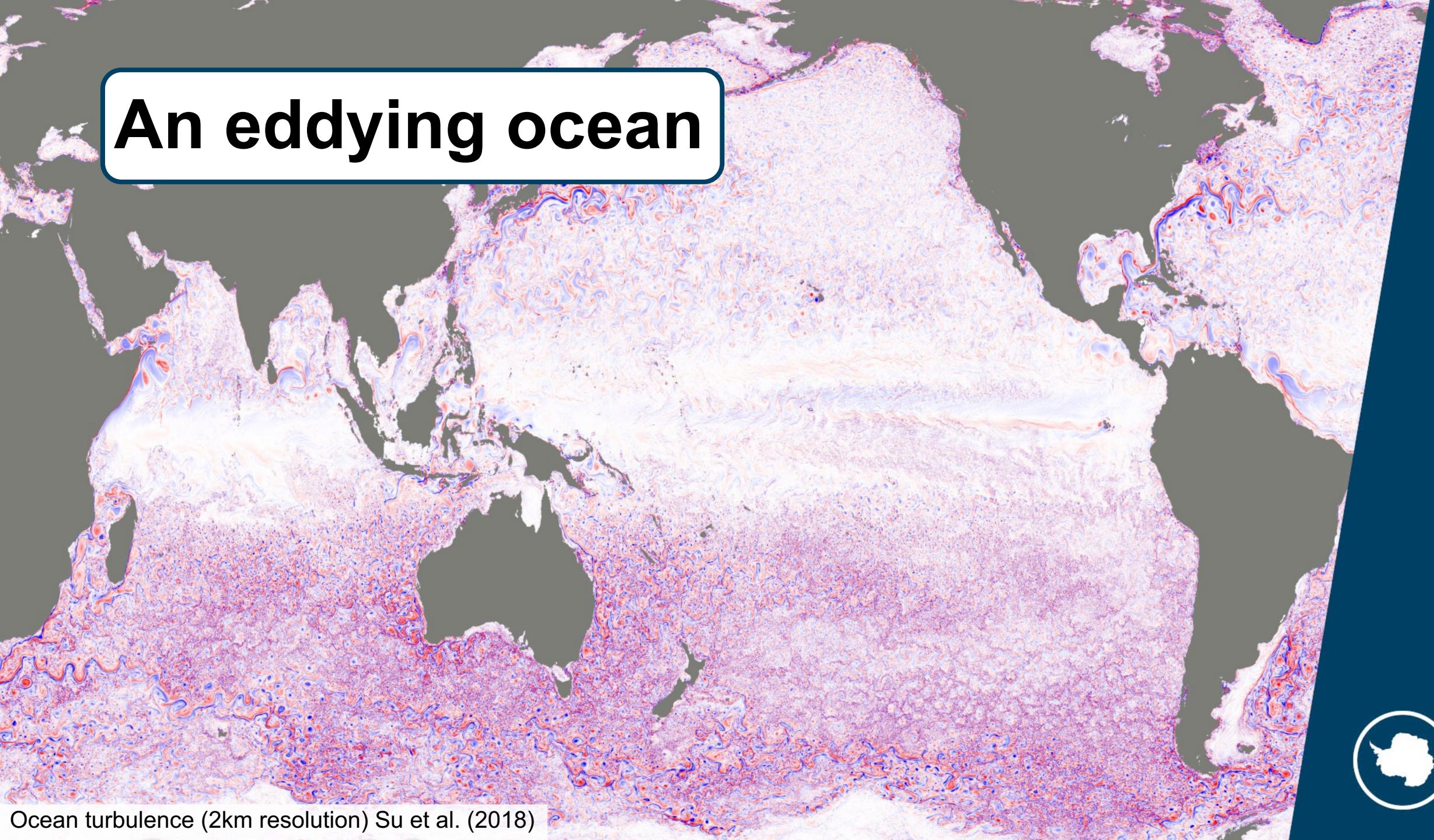
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FOR A SUSTAINABLE PLANET



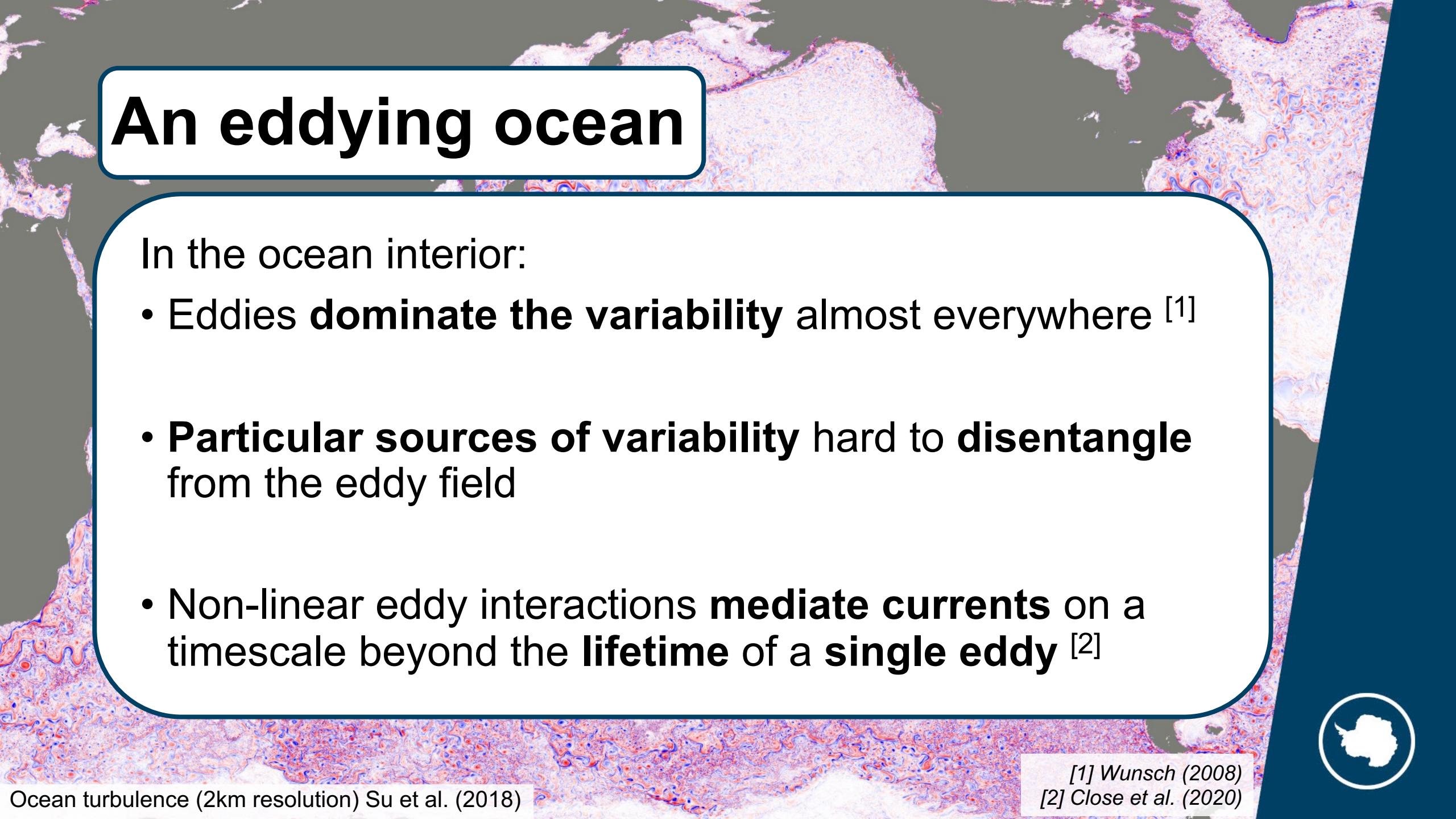
# An eddying ocean



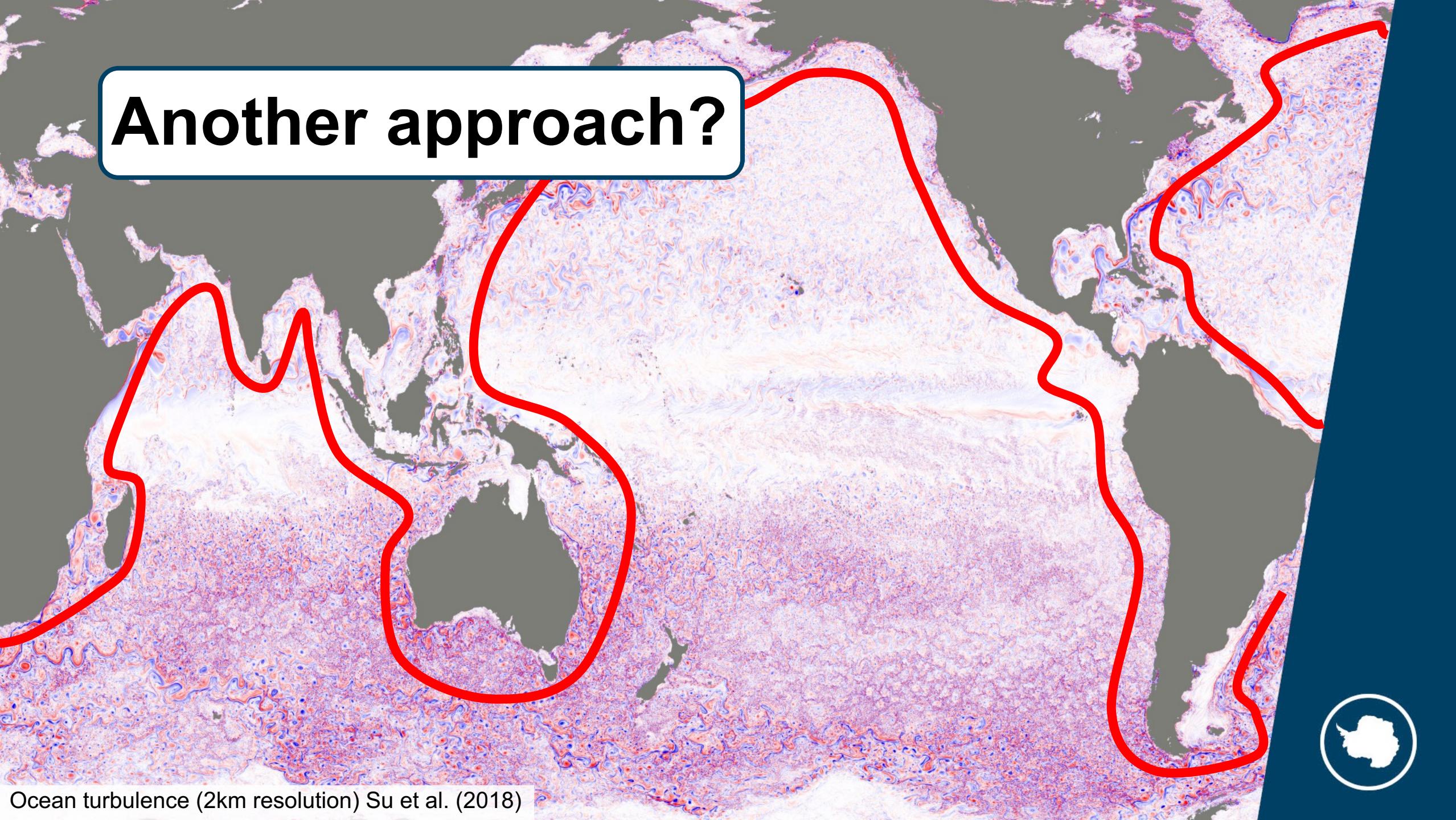
# An eddying ocean

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]



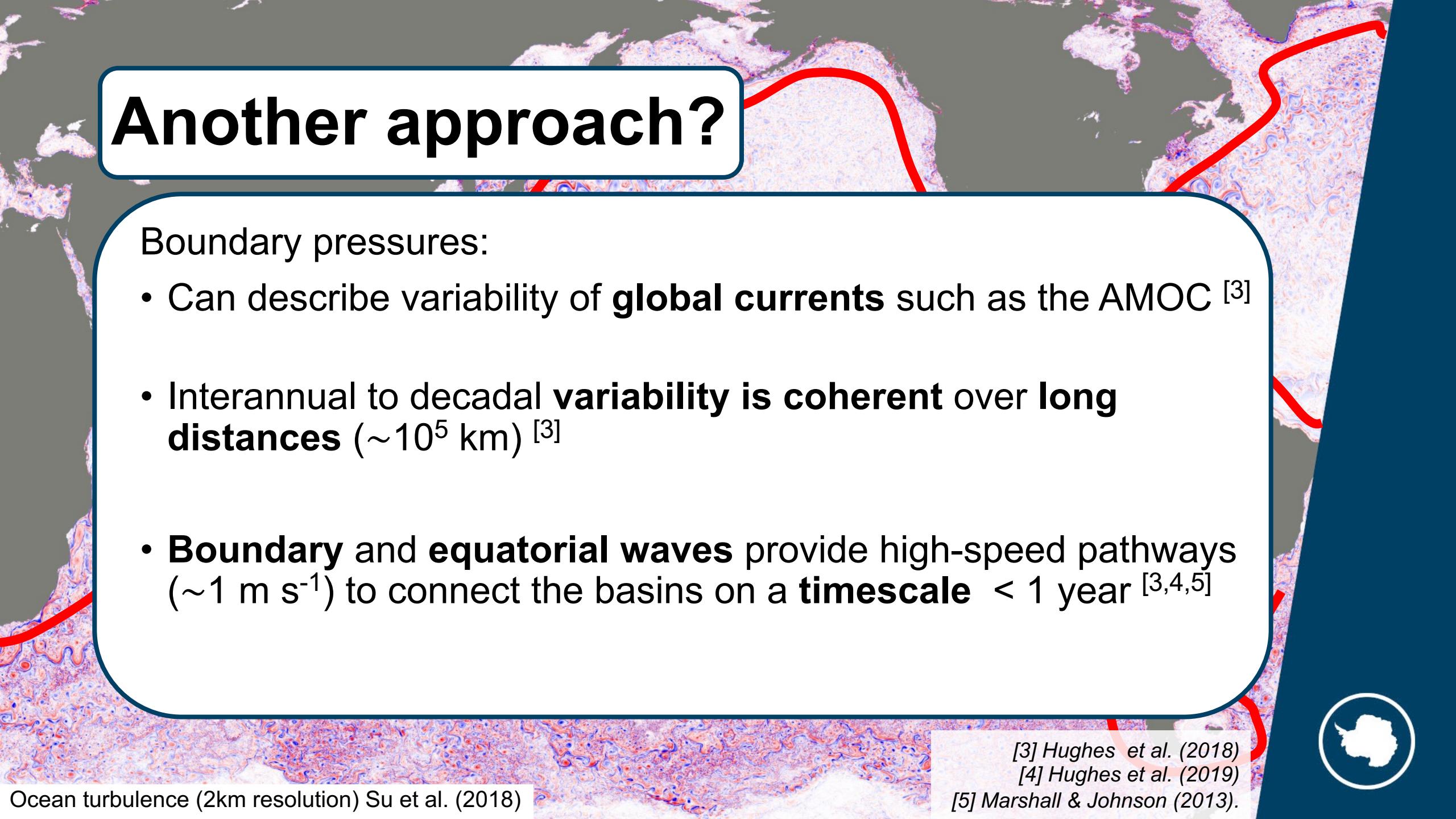
# Another approach?



# Another approach?

Boundary pressures:

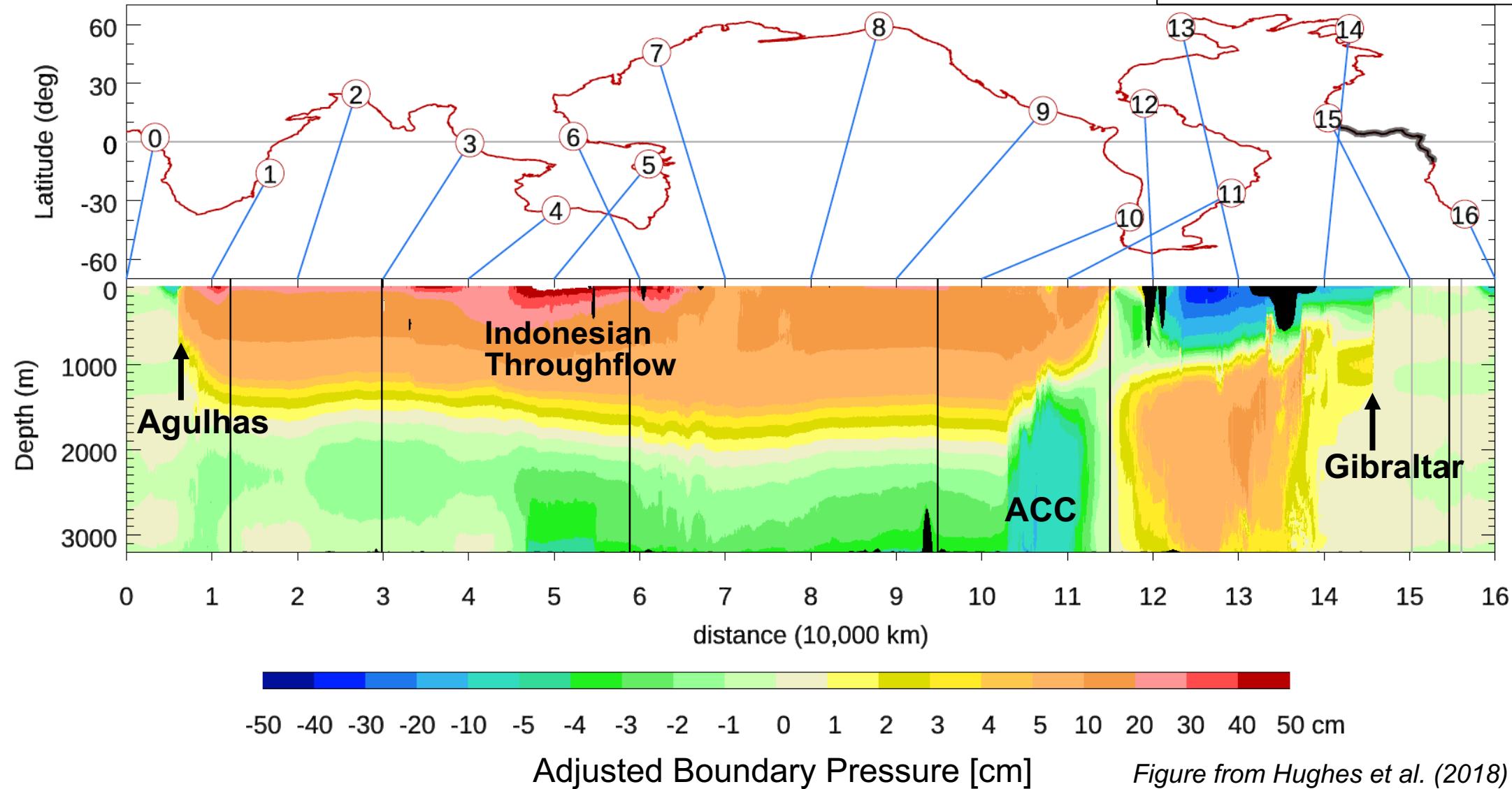
- Can describe variability of **global currents** such as the AMOC [3]
- Interannual to decadal **variability is coherent over long distances** ( $\sim 10^5$  km) [3]
- **Boundary and equatorial waves** provide high-speed pathways ( $\sim 1 \text{ m s}^{-1}$ ) to connect the basins on a **timescale**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



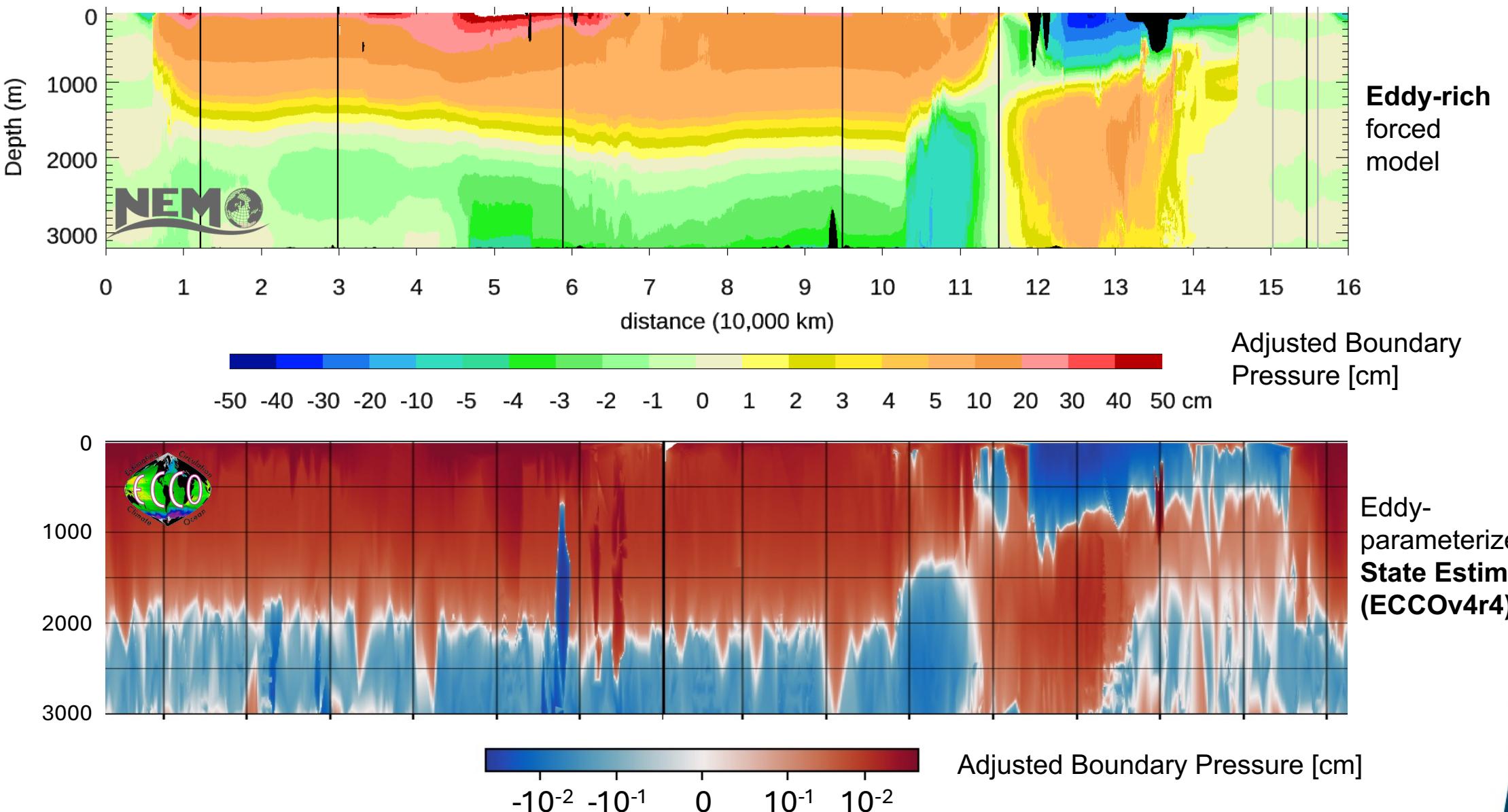
# Boundary Pressure Structure

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

Boundary pressure relative to East Atlantic

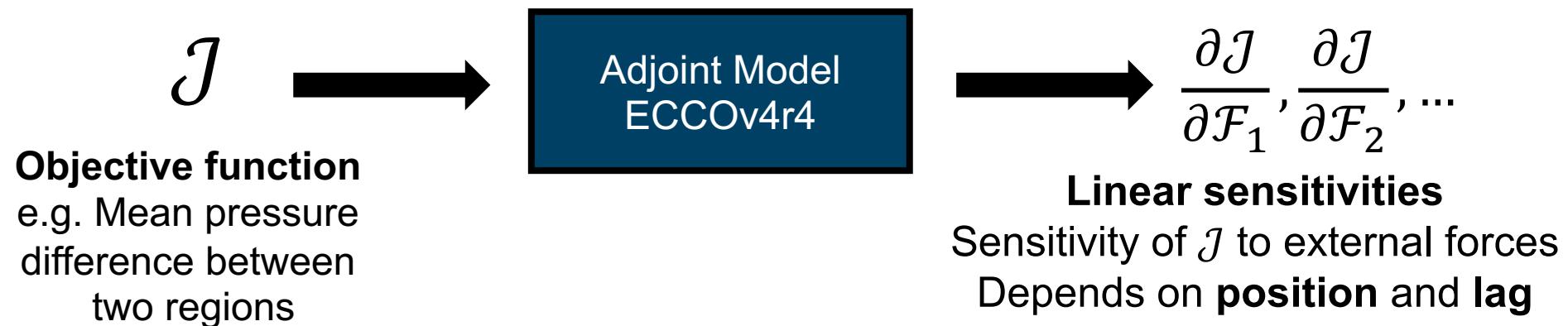


# Boundary Pressure Structure



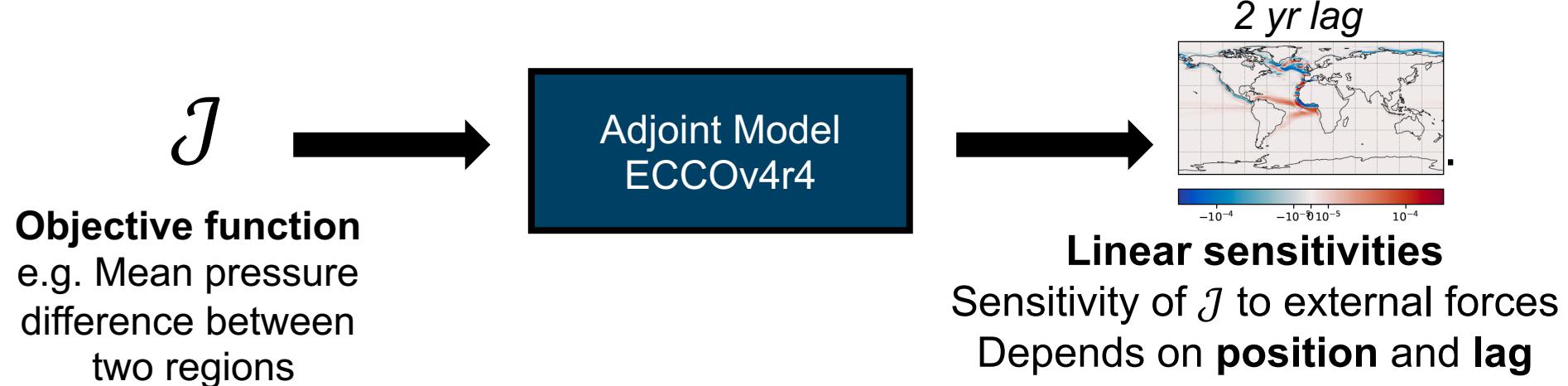
# Adjoint models

- **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**



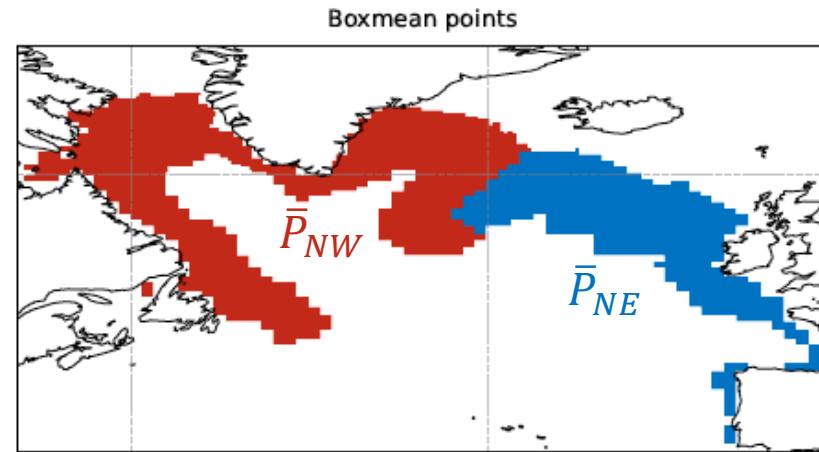
# Adjoint models

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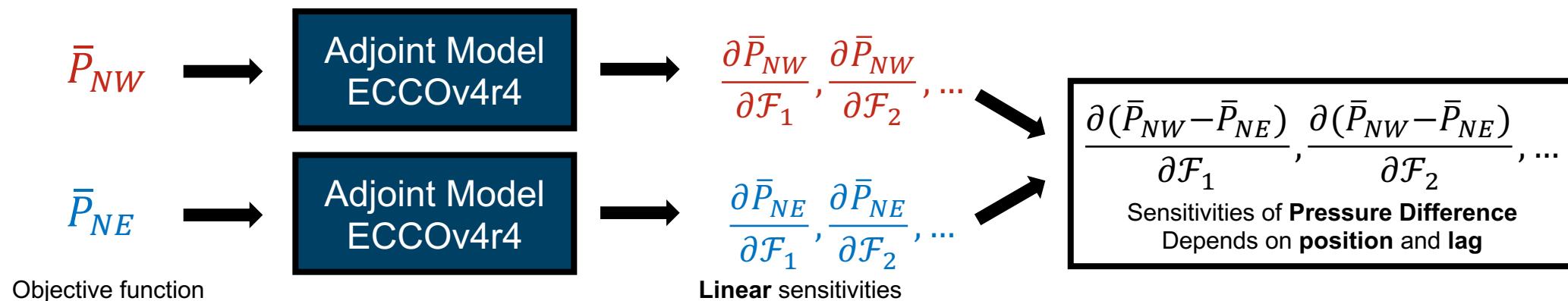


# Objective function for pressure difference

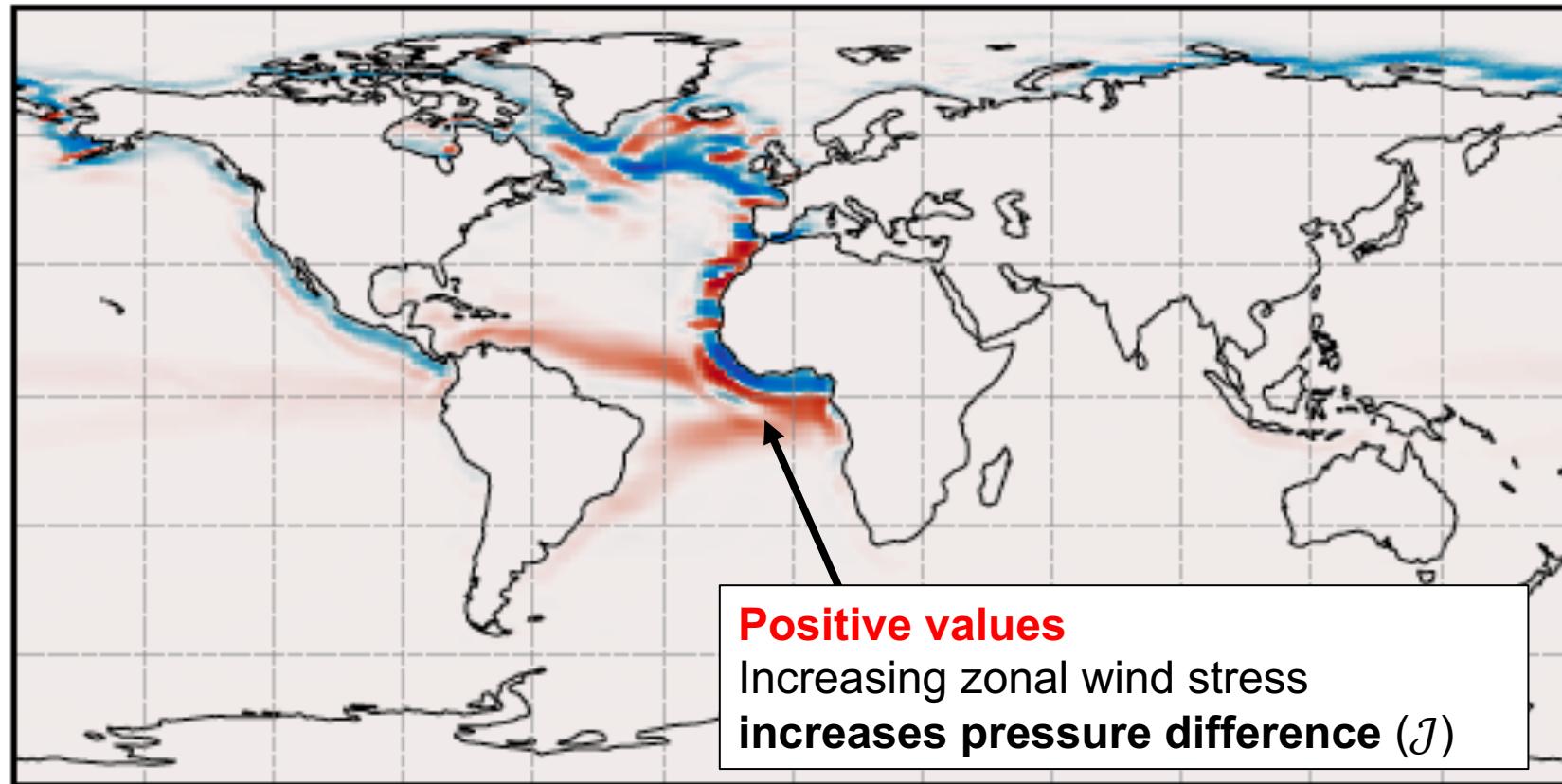
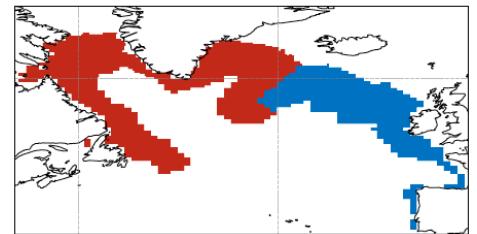
- Select 2 **clusters** of boundary grid points (e.g. figure)
- Select a time window (e.g. Jan  $\Rightarrow$  Dec 2008 )
- **Bottom pressure** within each cluster is spatially and then temporally averaged (e.g.  $\bar{P}_{NW}$ ,  $\bar{P}_{NE}$  )
- The adjoint model calculates the **linear sensitivities**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



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



# Sensitivity field: Zonal winds stress



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

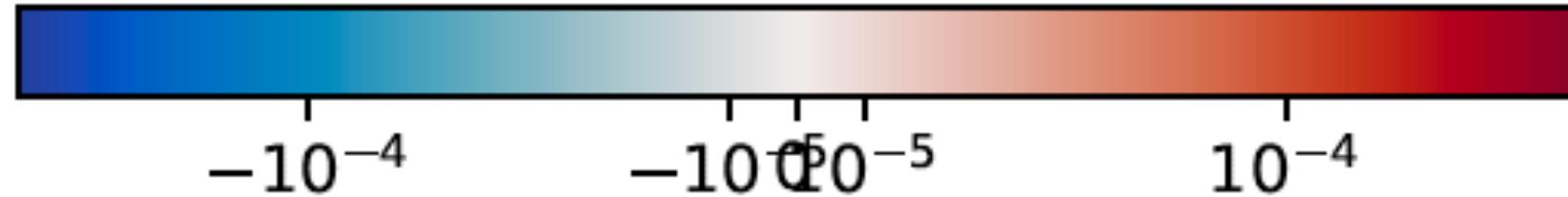
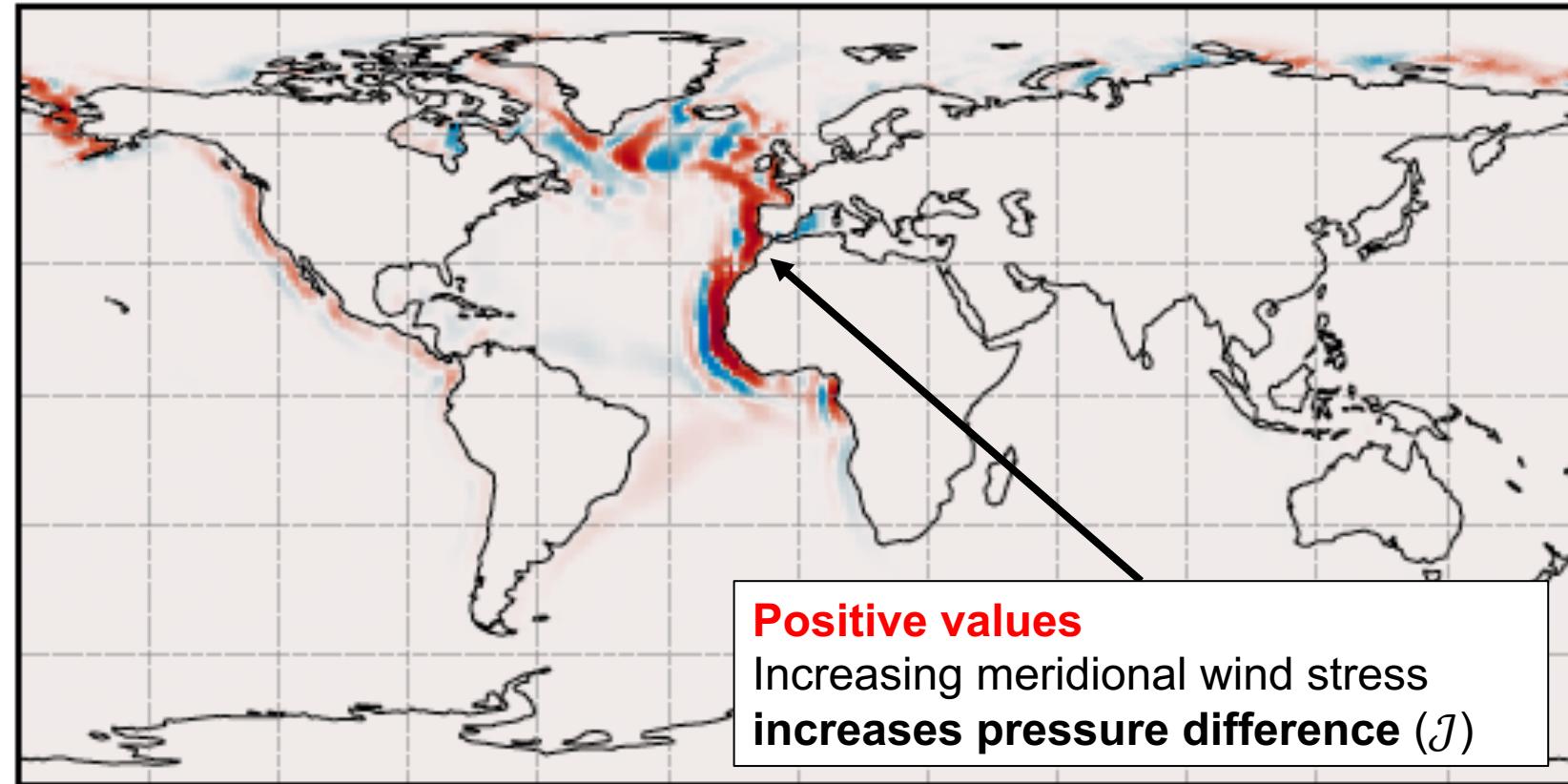
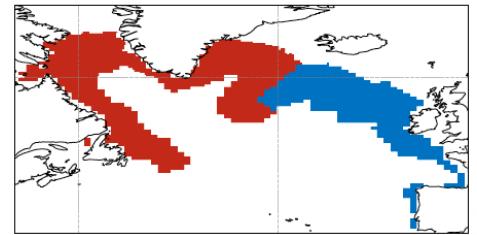
The shown  
sensitivity is for a  
value of lag where  
the pattern is  
**particularly strong**



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



# Sensitivity field: Meridional Wind Stress

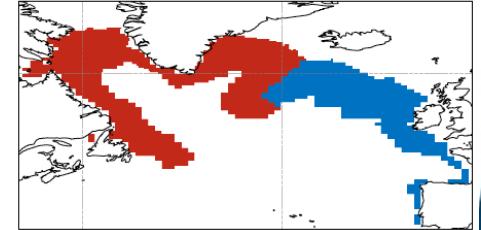


Remember that **sensitivity is a function of lag** also

The shown sensitivity is for a value of lag where the pattern is **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  $\mathcal{F}_i$

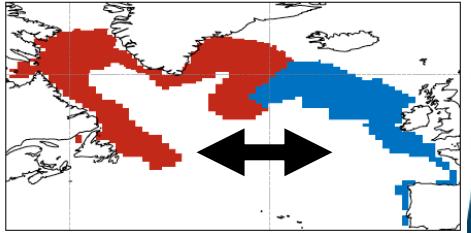
Approximate sensitivity of the pressure anomaly to forcing at time  $t + t'$

Forcing anomaly at time  $t + t'$

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



# 'All in' reconstruction



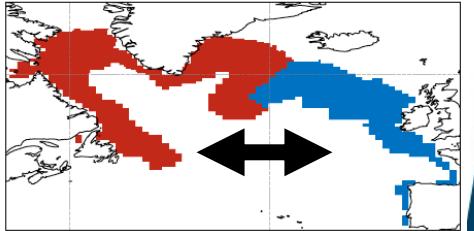
$$\mathcal{R}(t) = \sum_i \iint_A \int_{t_1}^{t_2} \mathcal{A}_i(\mathbf{x}, t') \Delta \mathcal{F}_i(\mathbf{x}, t + t') dt' dA$$

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

$P_{NW} - P_{NE}$  reconstruction

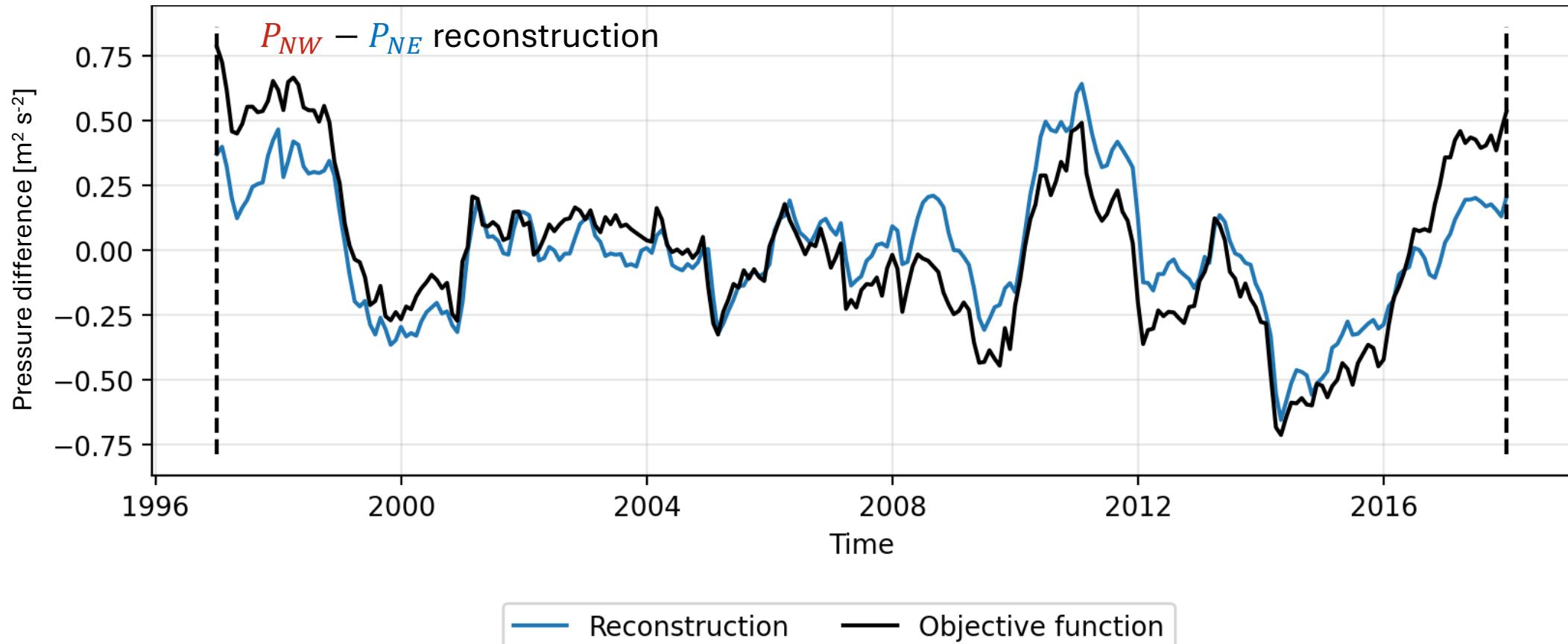


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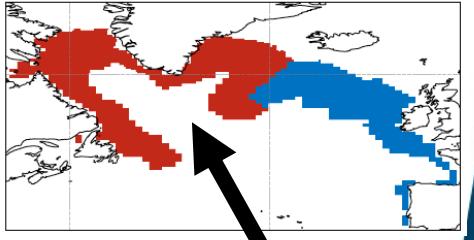


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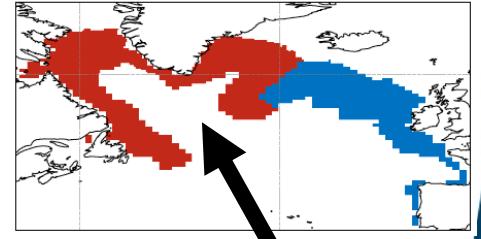
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Reconstruction using all forces (  $\forall i$  ) and all available lag (  $t_1 = -5\text{yrs}$ ,  $t_2 = 0$  )

$P_{NW}$  reconstruction

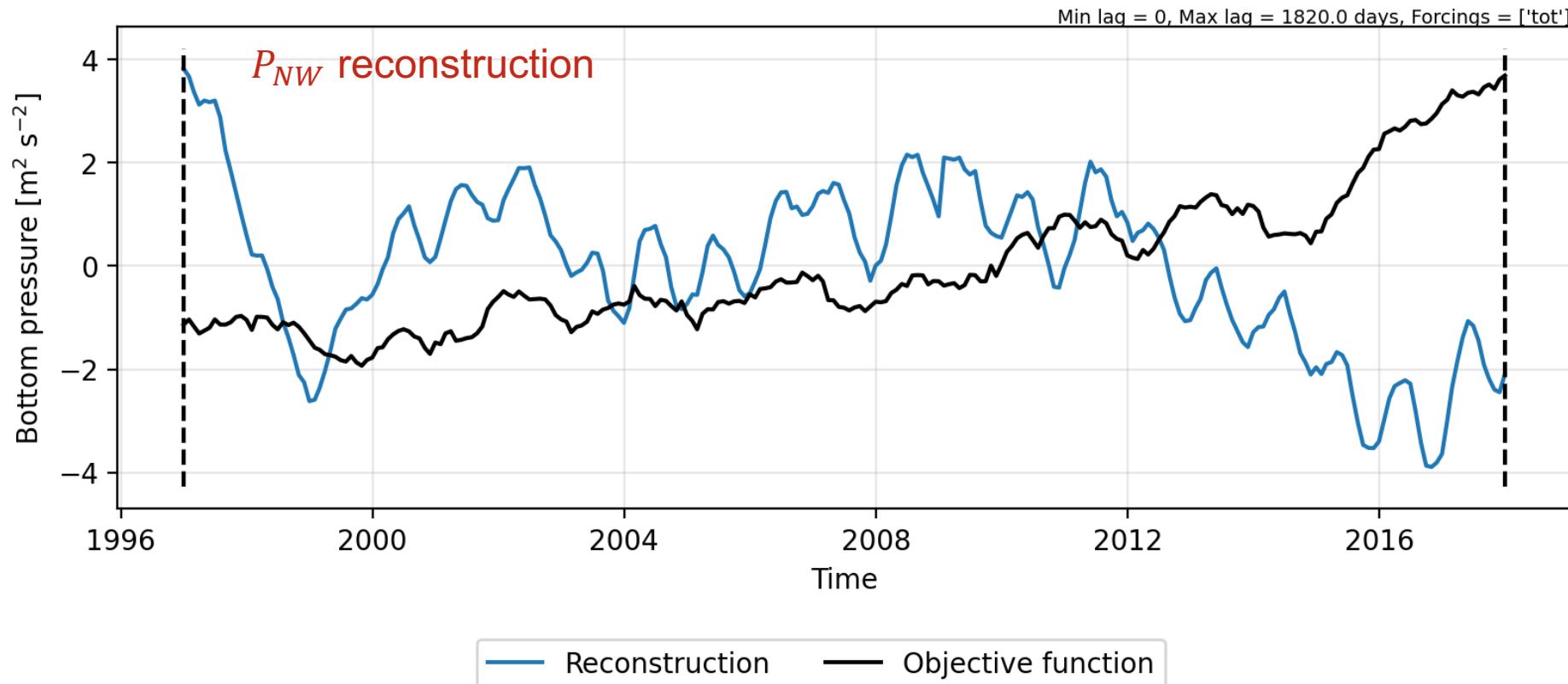


# 'All in' reconstruction

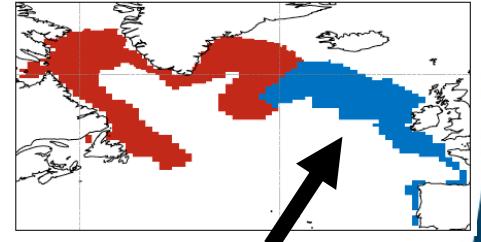


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Reconstruction using all forces (  $\forall i$  ) and all available lag (  $t_1 = -5\text{yrs}$ ,  $t_2 = 0$  )



# 'All in' reconstruction



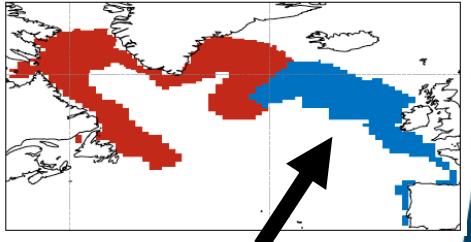
$$\mathcal{R}(t) = \sum_i \iint_A \int_{t_1}^{t_2} \mathcal{A}_i(\mathbf{x}, t') \Delta \mathcal{F}_i(\mathbf{x}, t + t') dt' dA$$

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

$P_{NE}$  reconstruction

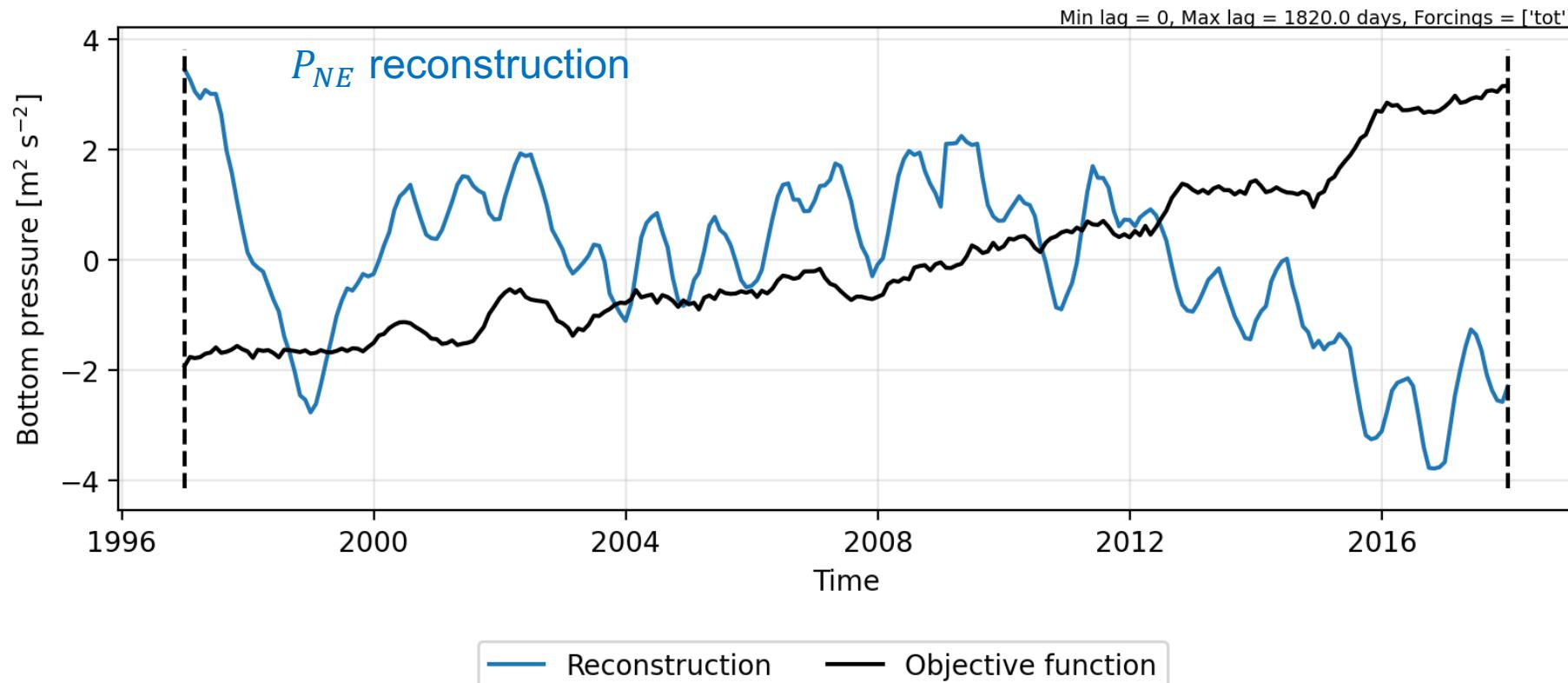


# 'All in' reconstruction



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

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**)

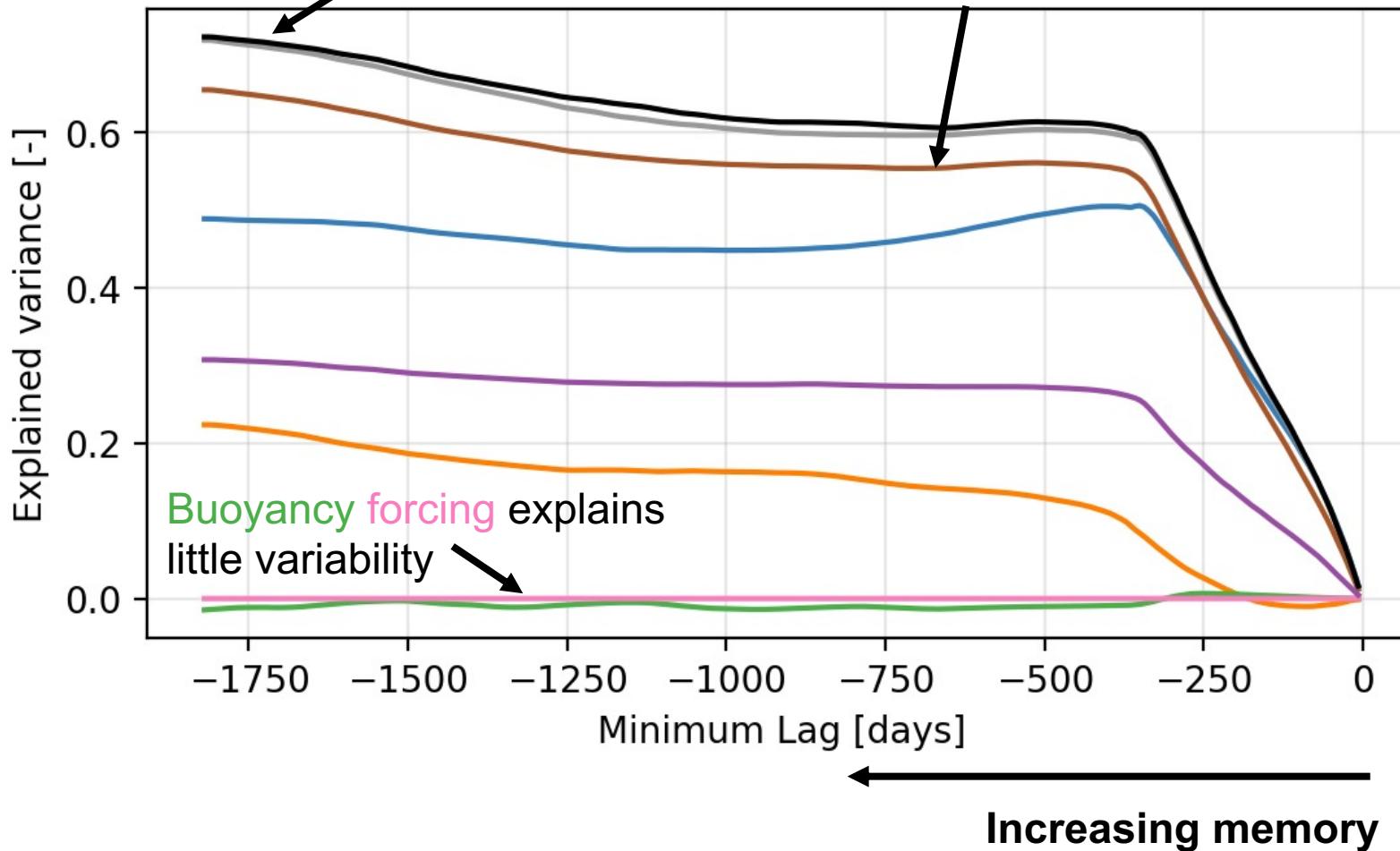
Identifying the optimal combination of forces and memory indicates the **relevant forces** and **timescales**.



# Explained variability

Approximately 72% of variability explained by reconstruction

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



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

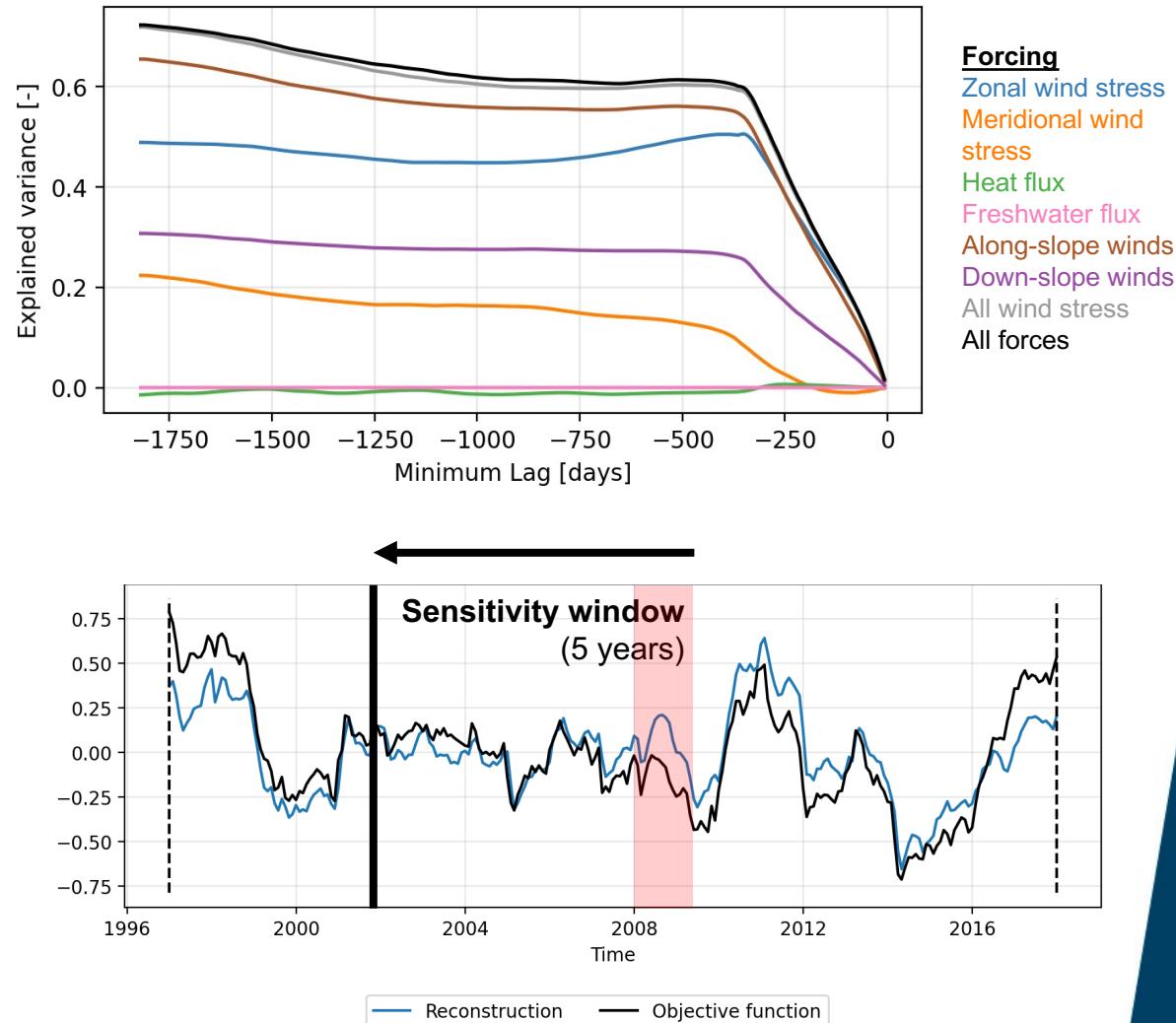
## Forcing

- 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



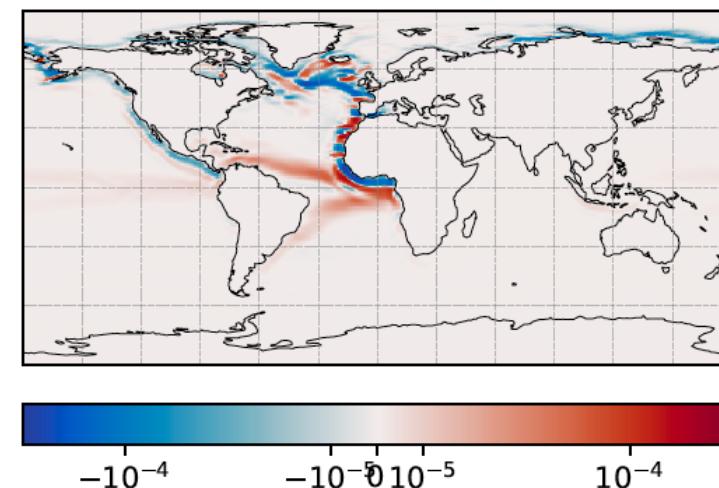
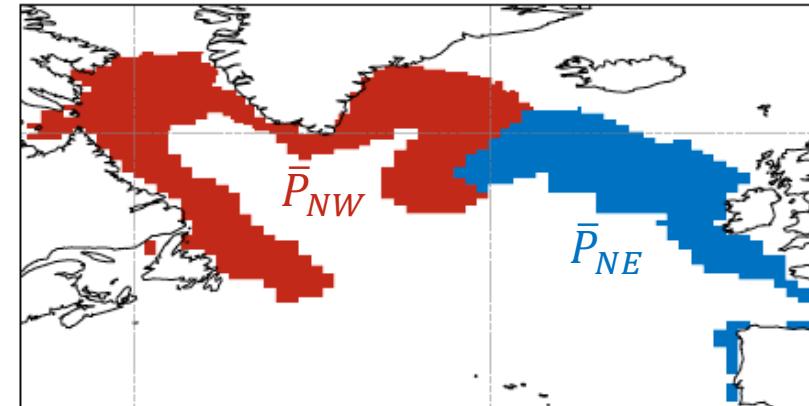
# Where is the remaining variability?

- 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. MOC) can be described by boundary pressure differences.
- In this case study, 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

”

- [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



# Explained variability of the MOC

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

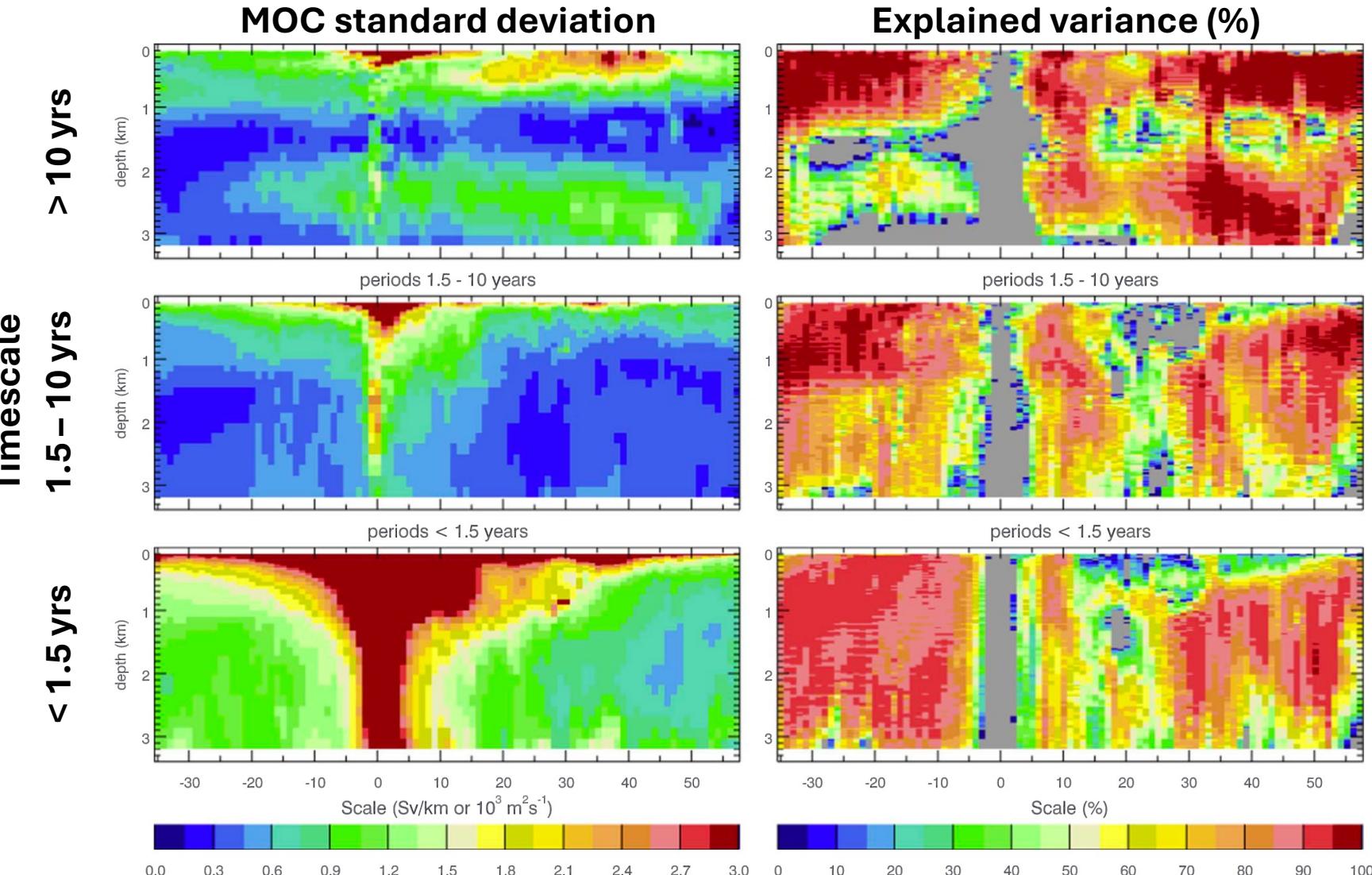


Figure 17 from Hughes et al. (2018)

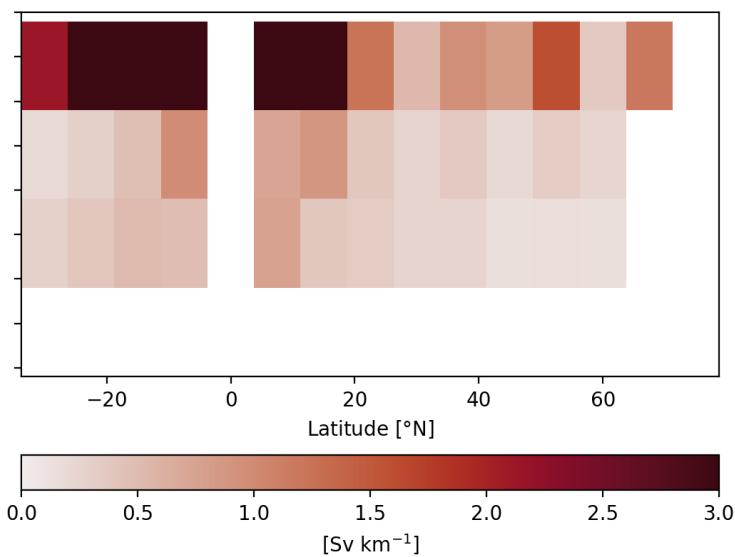
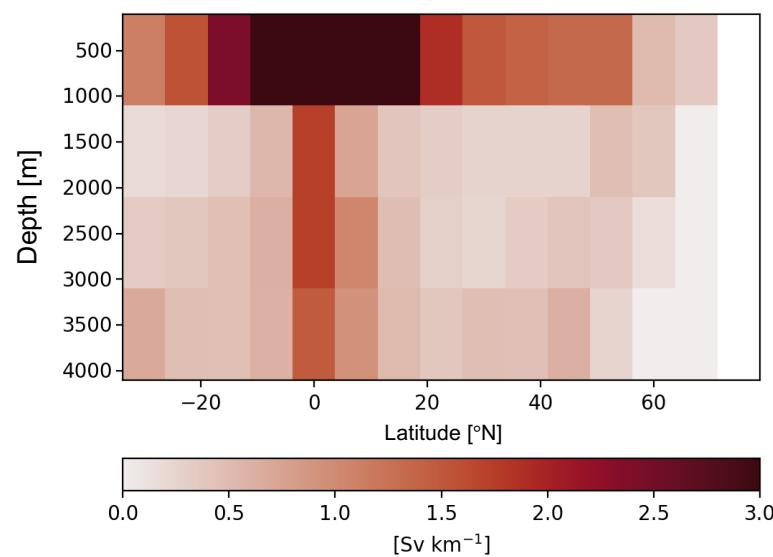
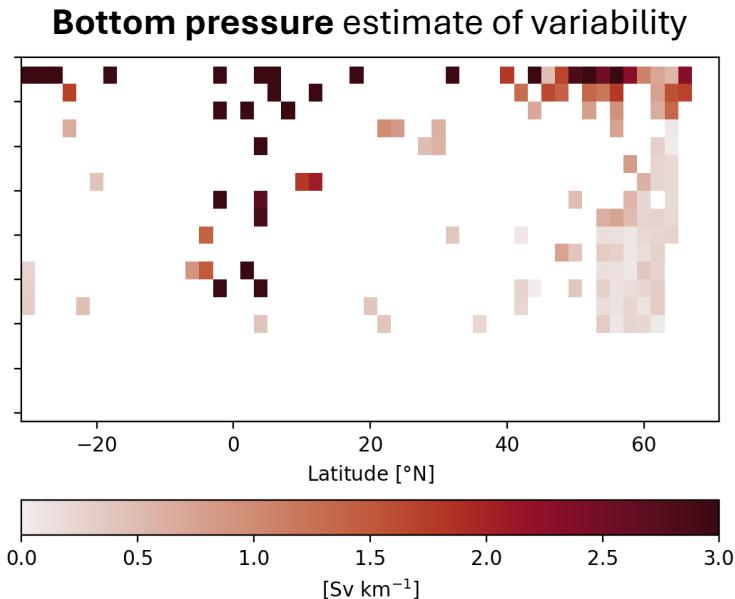
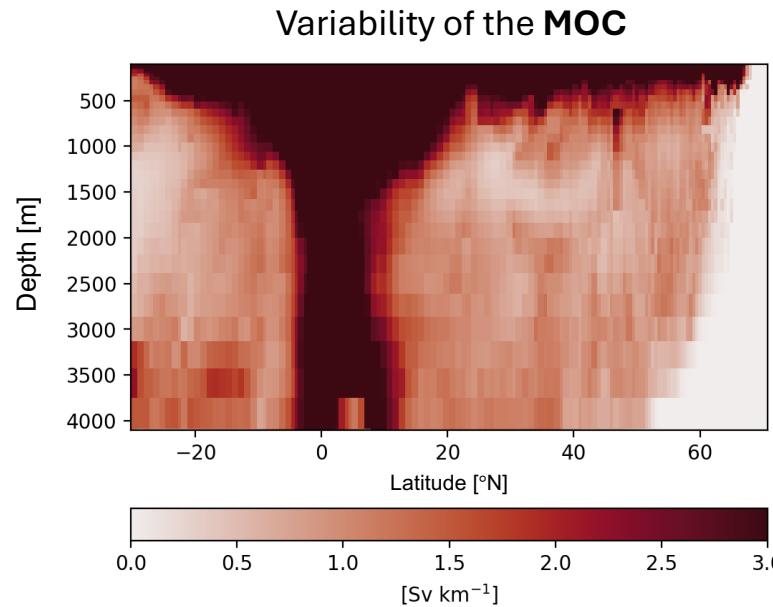
$$fT(z, y) = p_E - p_W$$

MOC calculation  
from **geostrophic**  
assumptions



# Explained variability of the MOC

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



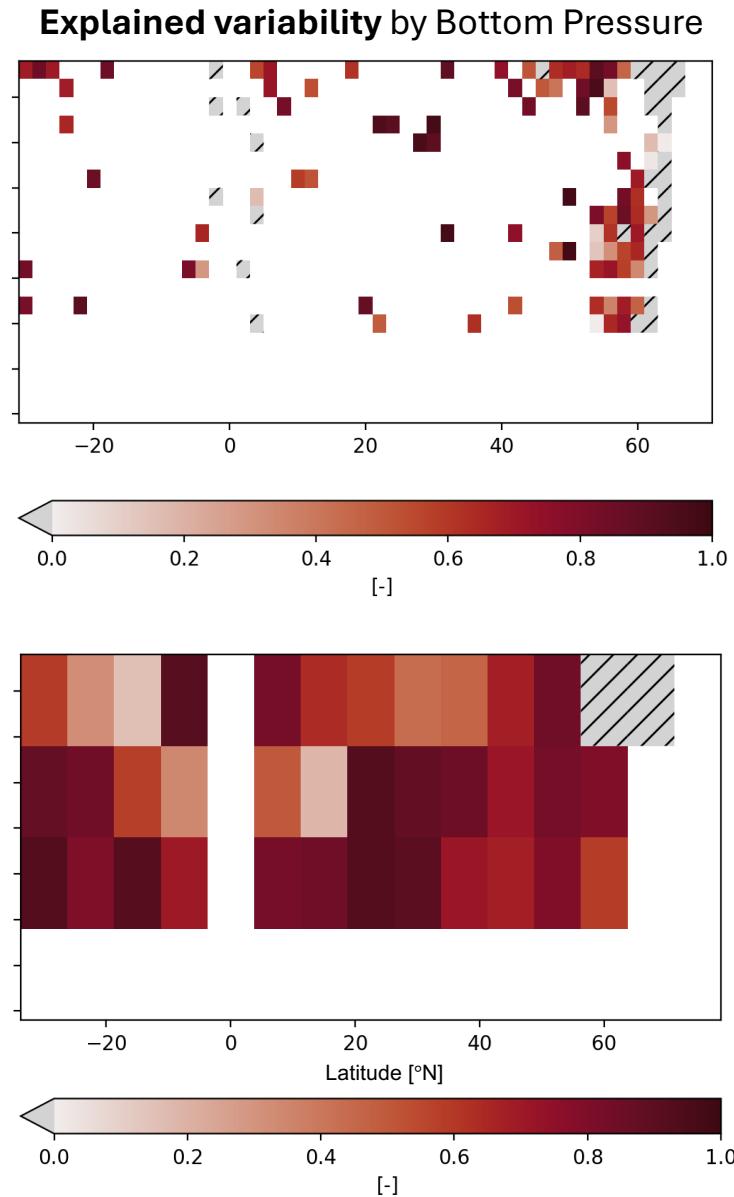
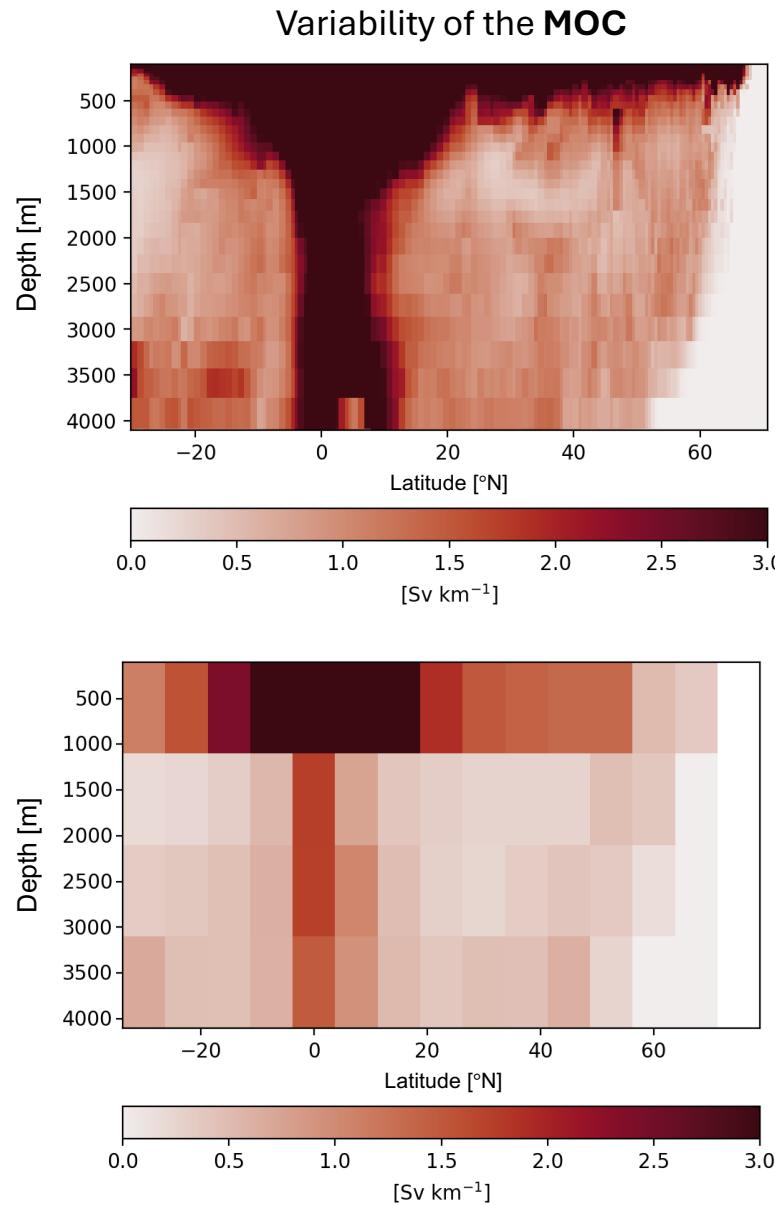
$$fT(z, \phi) = p_E - p_W$$

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# Explained variability of the MOC

**NEMO (ORCA12)**  
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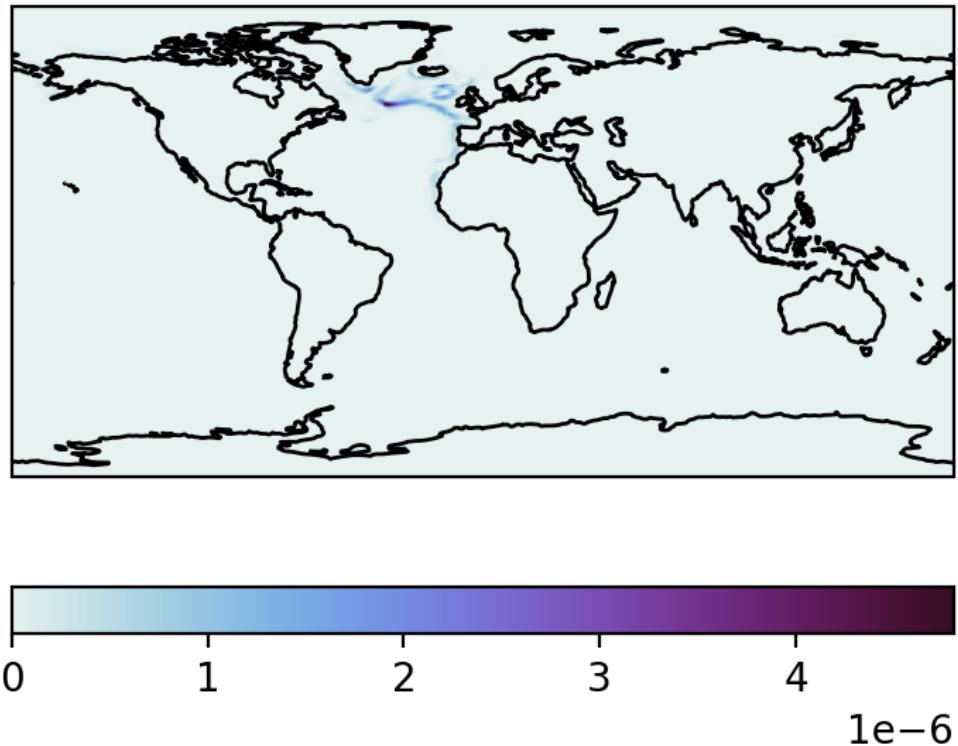
$$E(z, \phi) = 1 - \frac{\text{Var}(V - V_{OBP})}{\text{Var}(V)}$$

**Explained variability**

**Variability of the MOC**  
is well-explained by  
Bottom Pressure  
differences



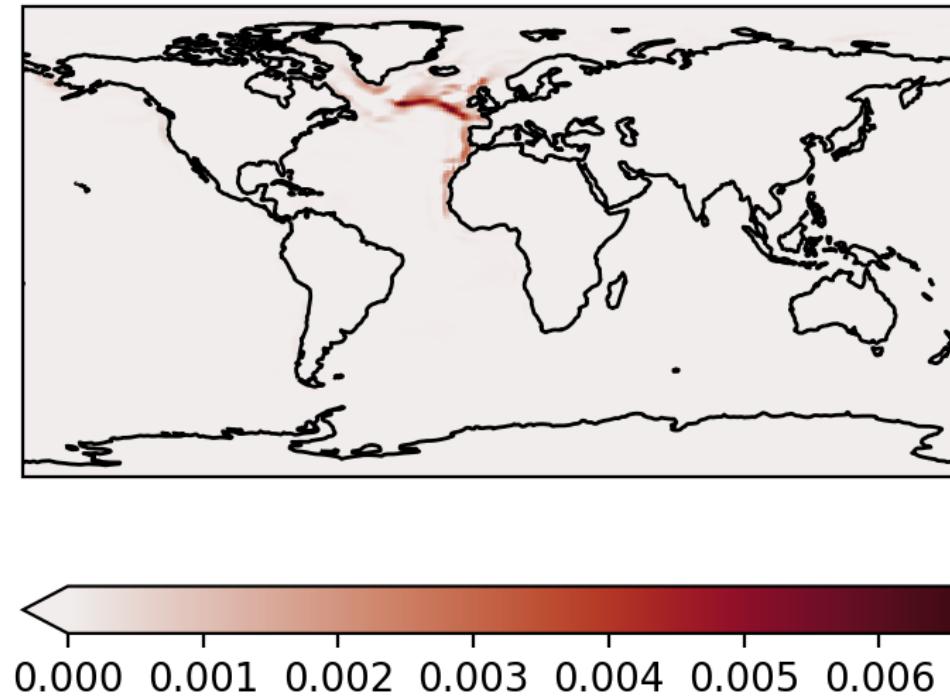
wnd: Constructed Variability



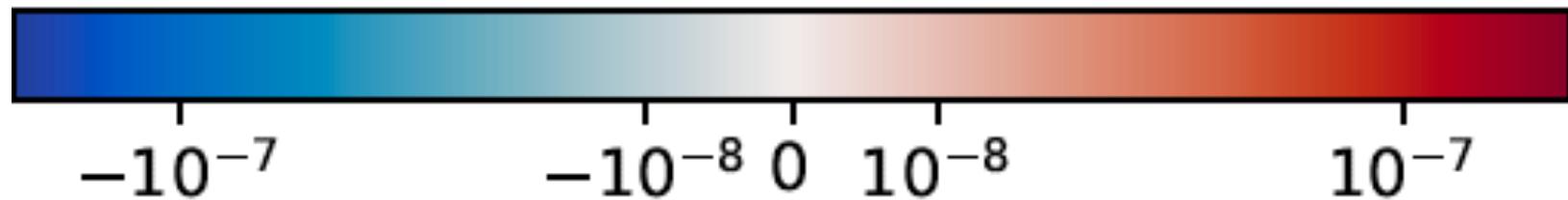
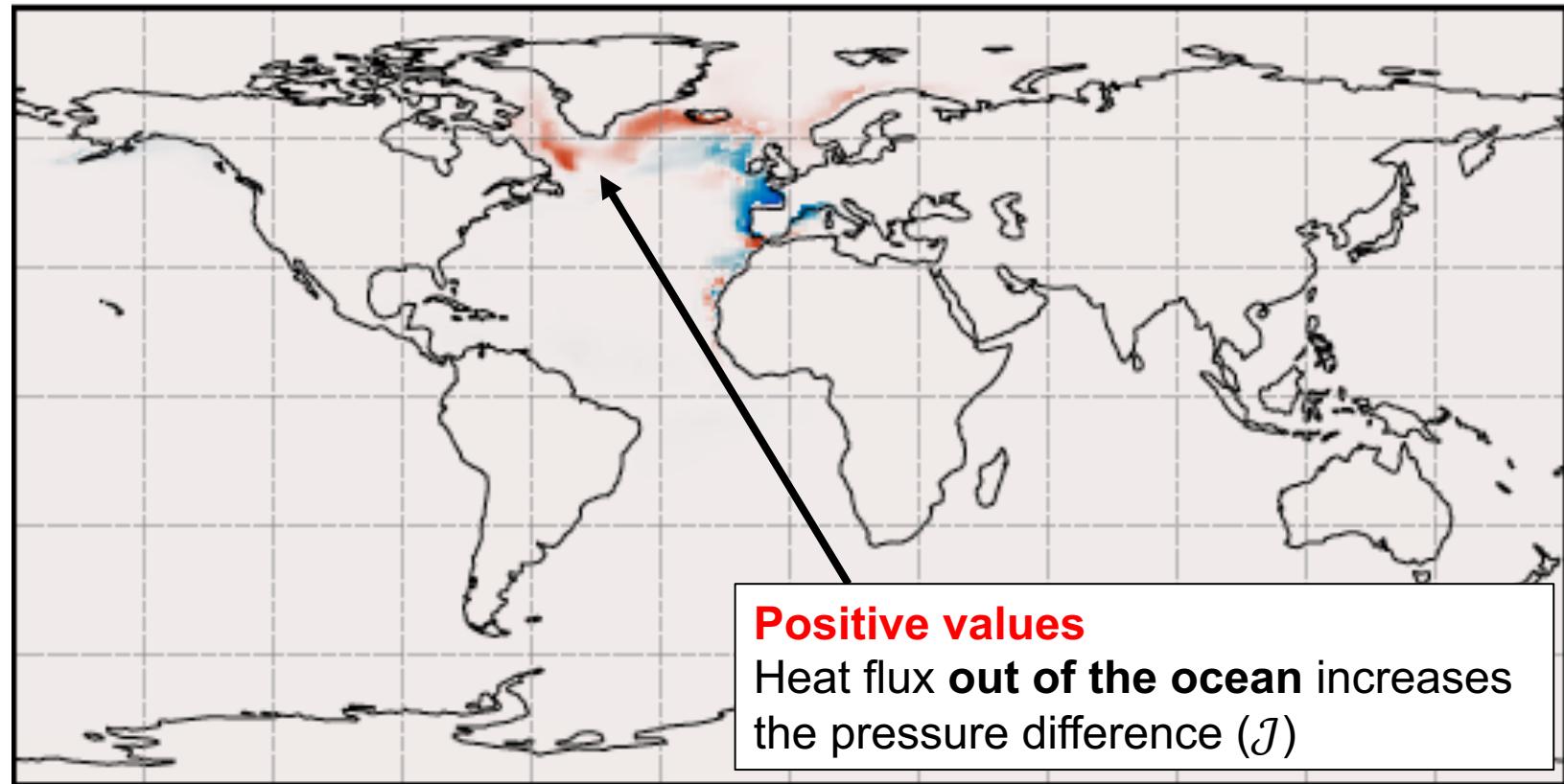
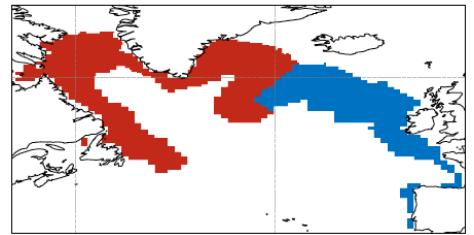
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$$E_i(\mathbf{x}, t) = 1 - \frac{Var(\mathcal{J} - \mathcal{R}(\mathbf{x}, t))}{Var(\mathcal{J})}$$

wnd: Explained Variability



# Sensitivity field: Heat flux



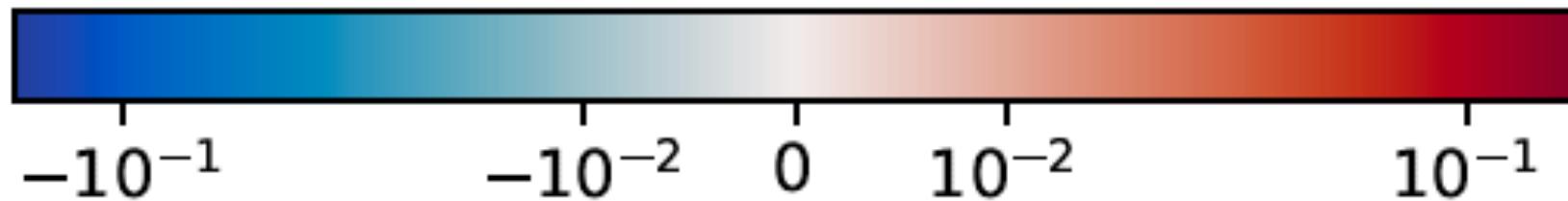
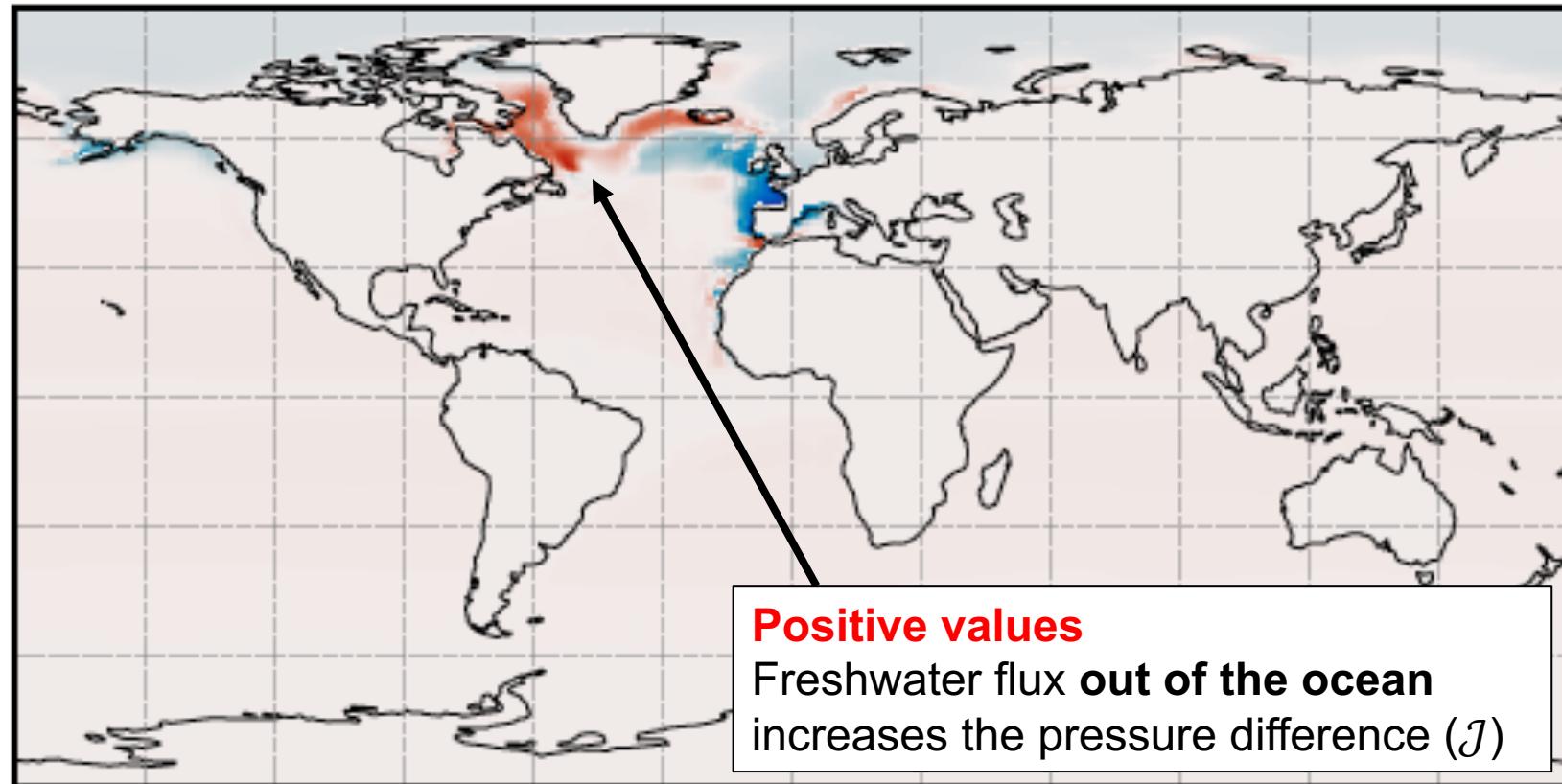
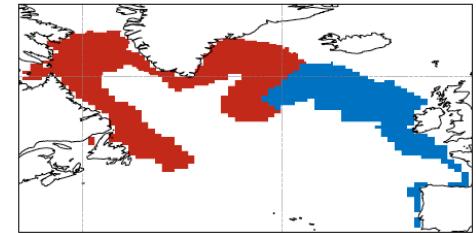
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function of lag**  
also

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

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



# Sensitivity field: Freshwater flux



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<sup>2</sup> s<sup>-2</sup>] / [ m<sup>-1</sup> ]

