Ocean boundary pressure:
Its significance and sensitivities

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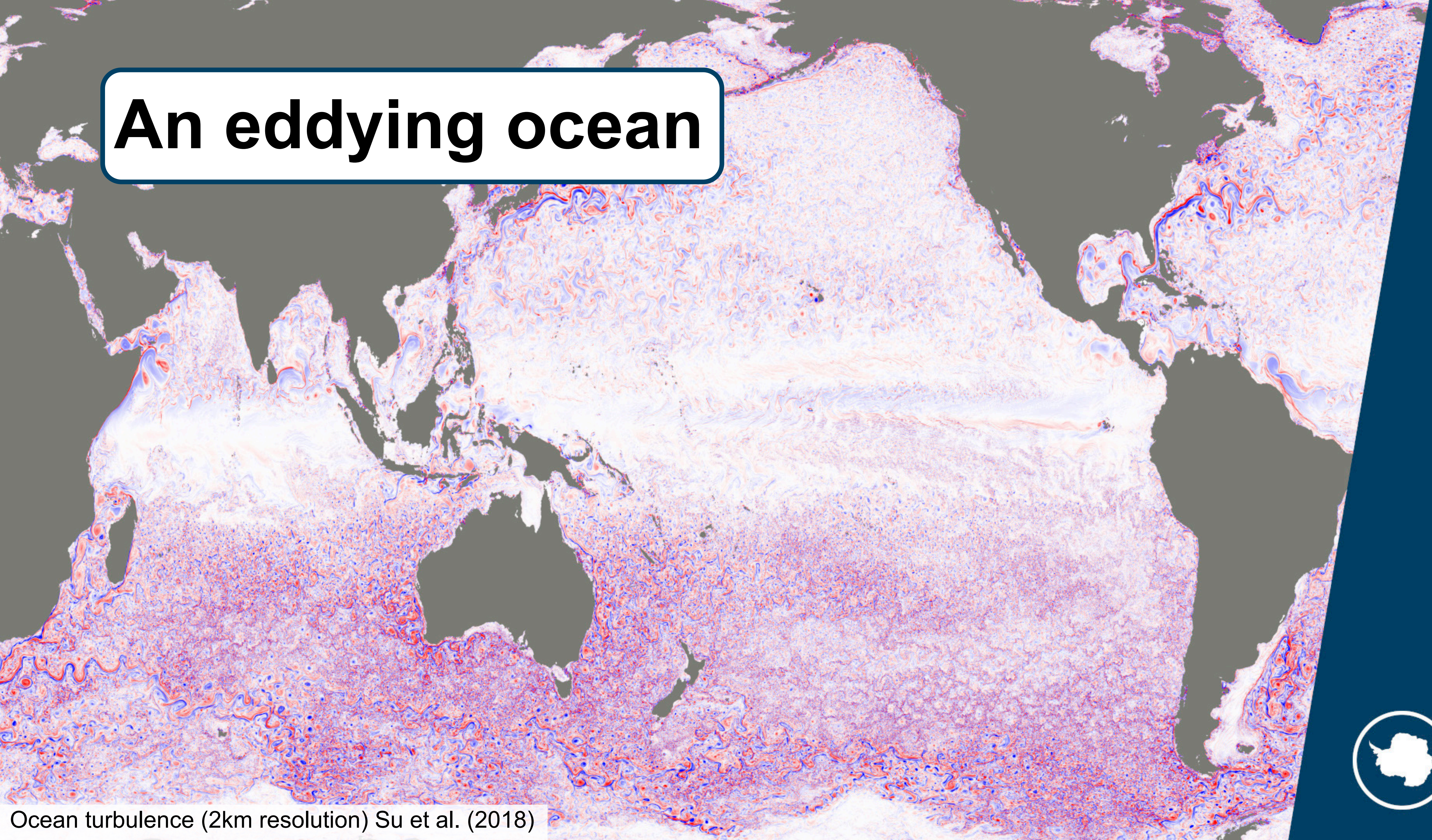
21st October 2024 – TACOMA meeting

An eddying ocean

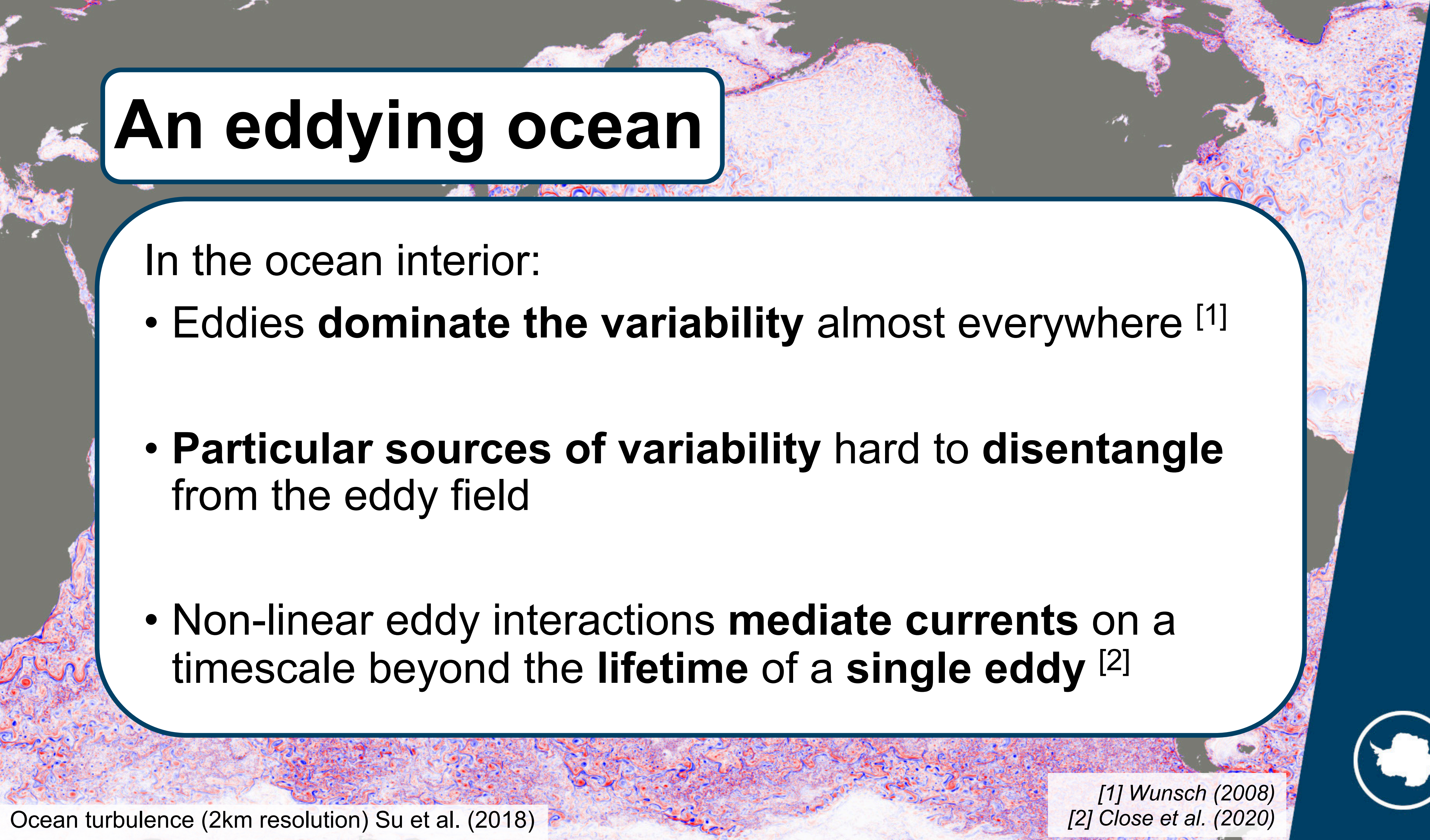


Ocean turbulence (2km resolution) Su et al. (2018)

An eddying ocean

In the ocean interior:

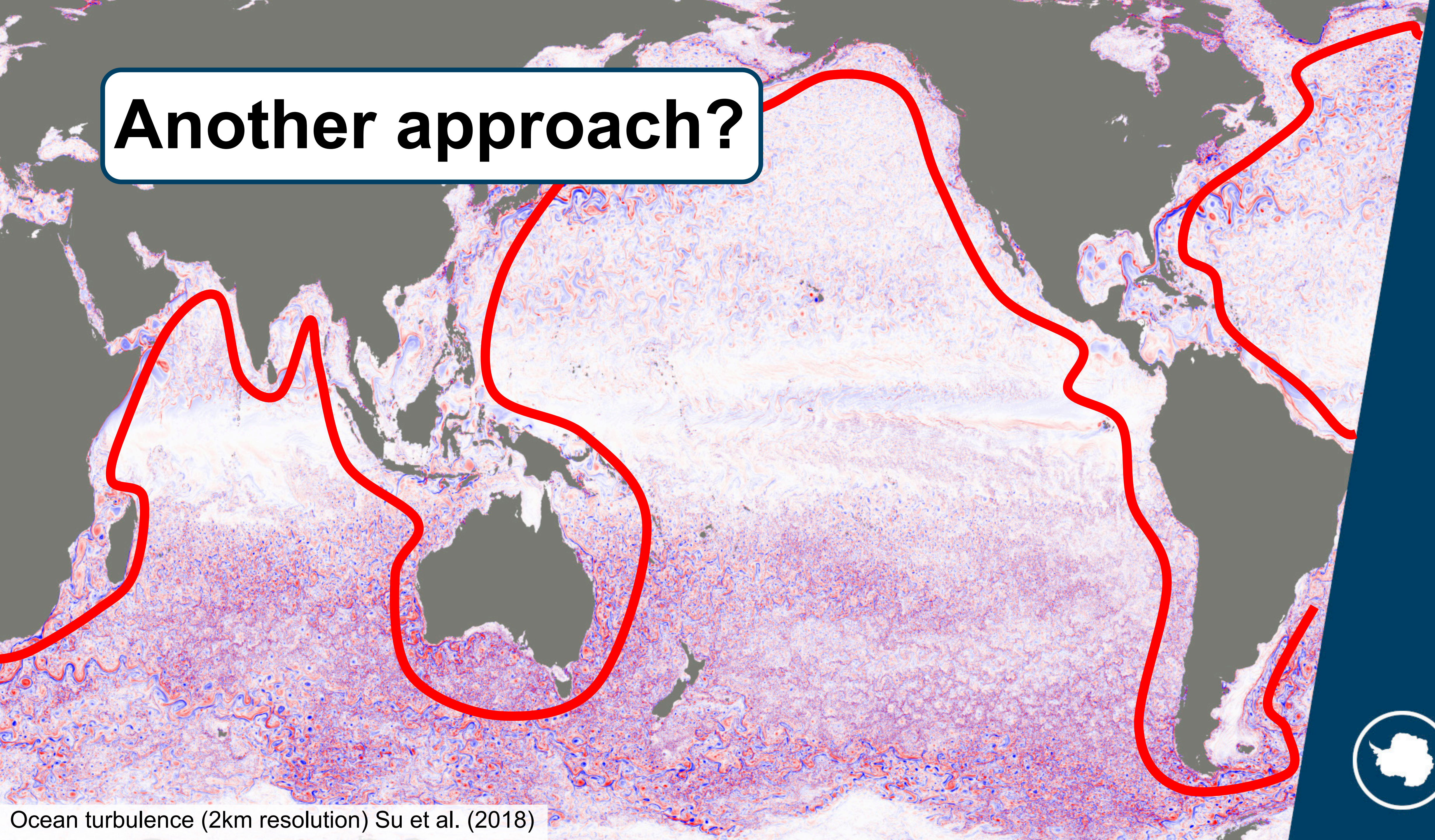
- Eddies **dominate the variability** almost everywhere [1]
- **Particular sources of variability** hard to **disentangle** from the eddy field
- Non-linear eddy interactions **mediate currents** on a timescale beyond the **lifetime** of a **single eddy** [2]



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

[1] Wunsch (2008)
[2] Close et al. (2020)

Another approach?

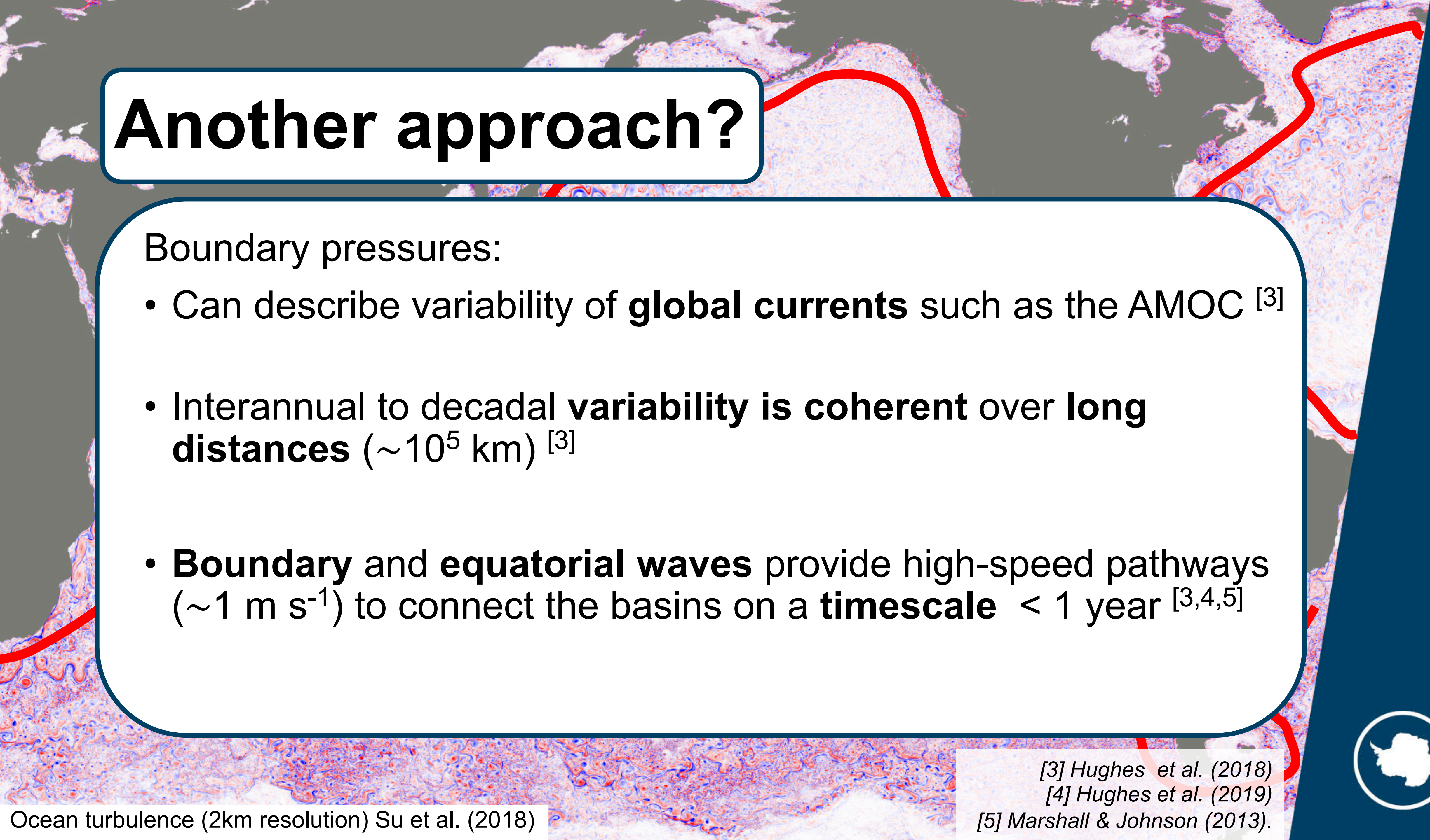


Ocean turbulence (2km resolution) Su et al. (2018)

Another approach?

Boundary pressures:

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



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

[3] Hughes et al. (2018)
[4] Hughes et al. (2019)
[5] Marshall & Johnson (2013).

Boundary Pressure Structure

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

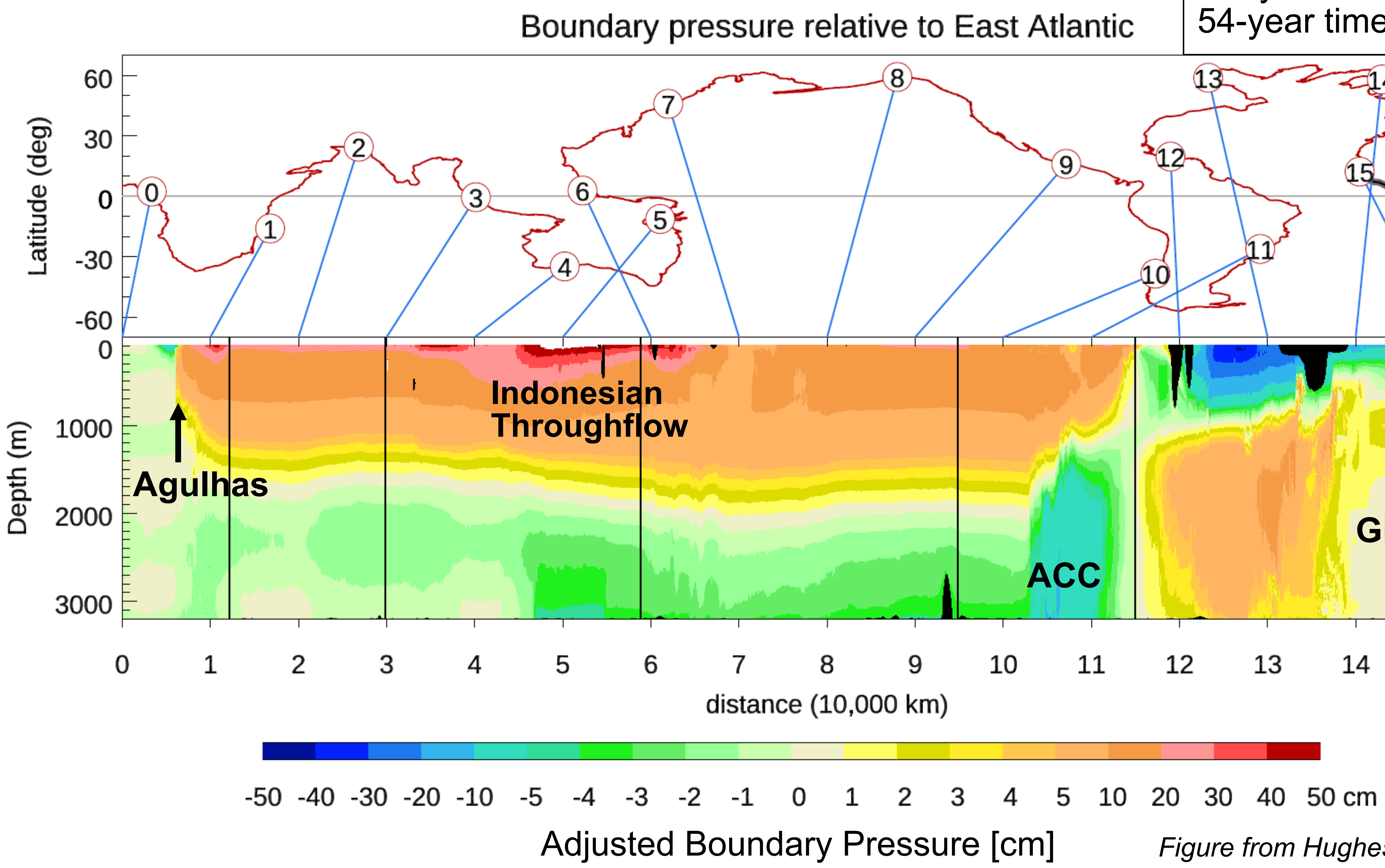
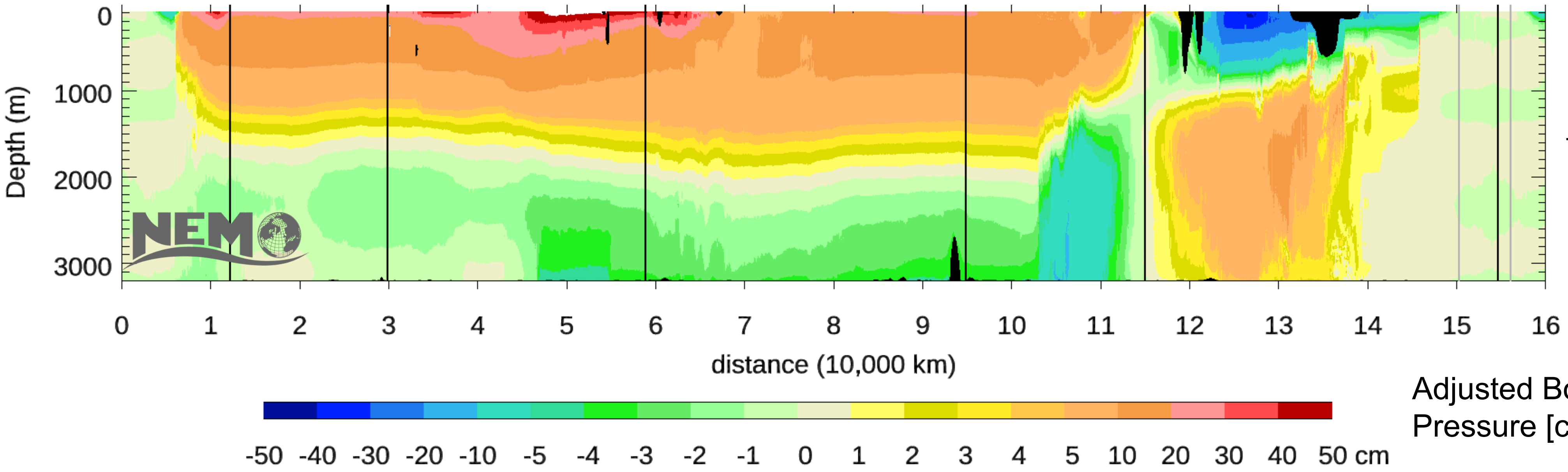
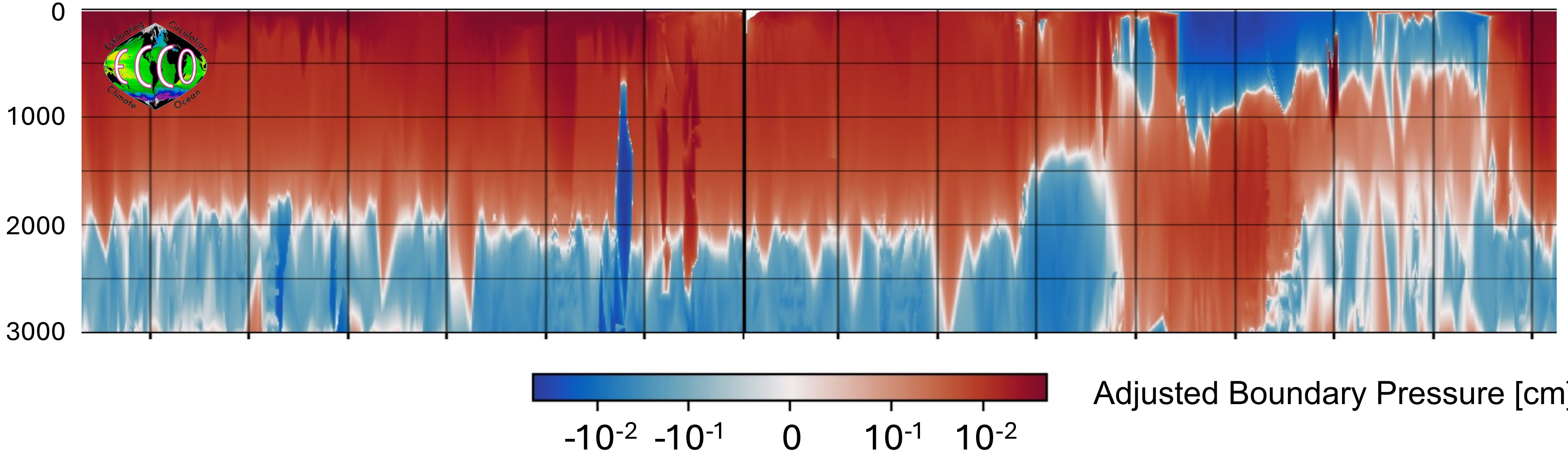


Figure from Hughes et al. (2018)

Boundary Pressure Structure



Eddy-rich forced model



Eddy-parameterized **State Estimate (ECCOv4r4)**

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**

$\mathcal{J}$ → Adjoint Model ECCOv4r4 → $\frac{\partial \mathcal{J}}{\partial \mathcal{F}_1}, \frac{\partial \mathcal{J}}{\partial \mathcal{F}_2}, \ldots$

Objective function
e.g. Mean pressure difference between two regions

Linear sensitivities
Sensitivity of $\mathcal{J}$ to external forces
Depends on **position** and **lag**

Adjoint models

- **Adjoint models** effectively run “backwards”
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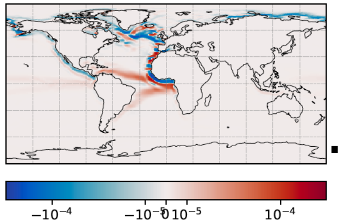
$\mathcal{J}$ → Adjoint Model ECCOv4r4 → *2 yr lag*

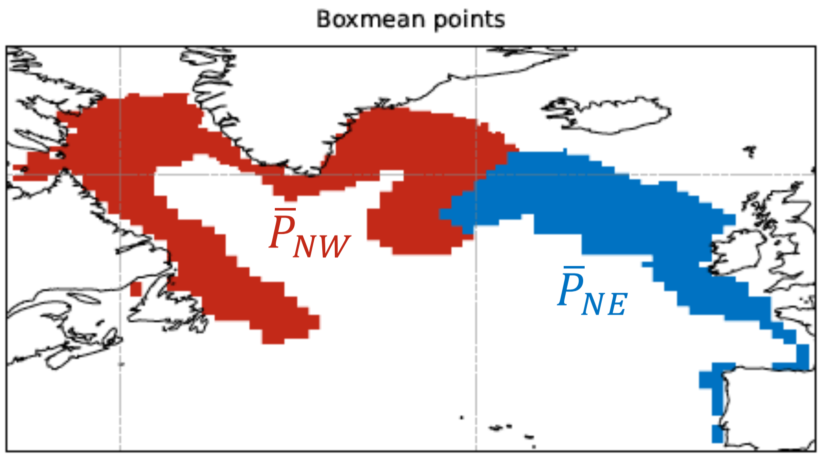


Objective function
e.g. Mean pressure difference between two regions

Linear sensitivities
Sensitivity of $\mathcal{J}$ to external forces
Depends on **position** and **lag**

Objective function for pressure difference

- Select 2 **clusters** of boundary grid points (e.g. figure)
- Select a time window (e.g. Jan ⇒ 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

$\bar{P}_{NW}$ → Adjoint Model ECCOv4r4 → $\frac{\partial \bar{P}_{NW}}{\partial \mathcal{F}_1}, \frac{\partial \bar{P}_{NW}}{\partial \mathcal{F}_2}, \ldots$

$\bar{P}_{NE}$ → Adjoint Model ECCOv4r4 → $\frac{\partial \bar{P}_{NE}}{\partial \mathcal{F}_1}, \frac{\partial \bar{P}_{NE}}{\partial \mathcal{F}_2}, \ldots$

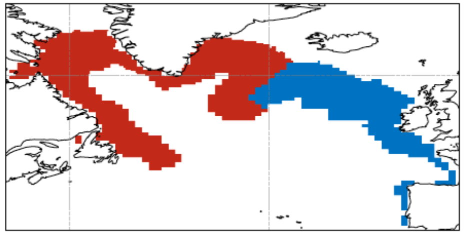
Objective function

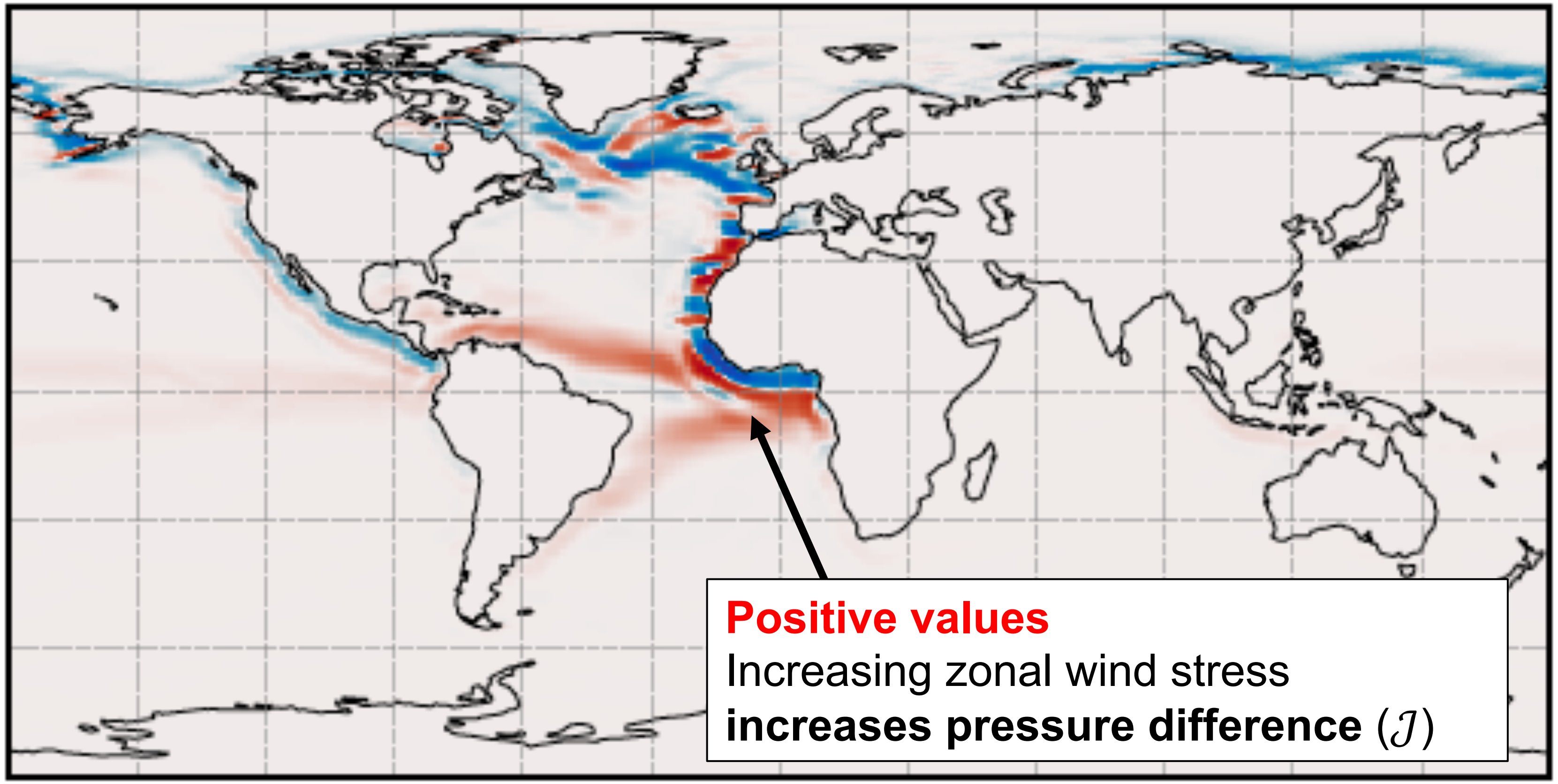
Linear sensitivities

$$\frac{\partial(\bar{P}_{NW}-\bar{P}_{NE})}{\partial \mathcal{F}_1}, \frac{\partial(\bar{P}_{NW}-\bar{P}_{NE})}{\partial \mathcal{F}_2}, \ldots$$

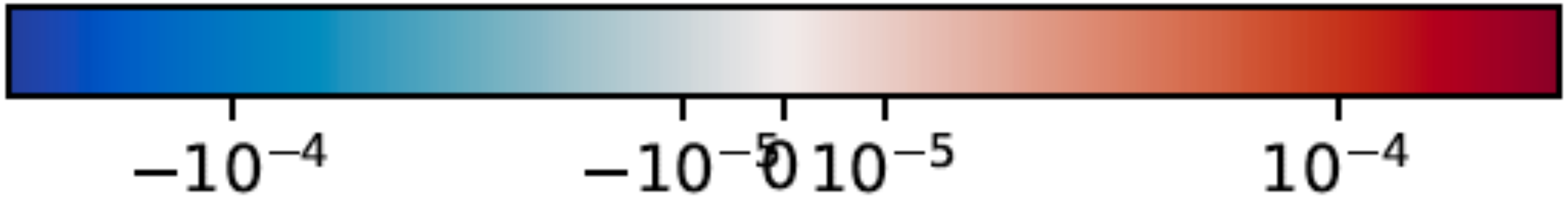
Sensitivities of **Pressure Difference**
Depends on **position** and **lag**

Sensitivity field: Zonal winds stress





Positive values
Increasing zonal wind stress
increases pressure difference ($\mathcal{J}$)

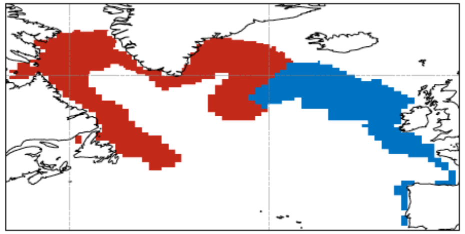


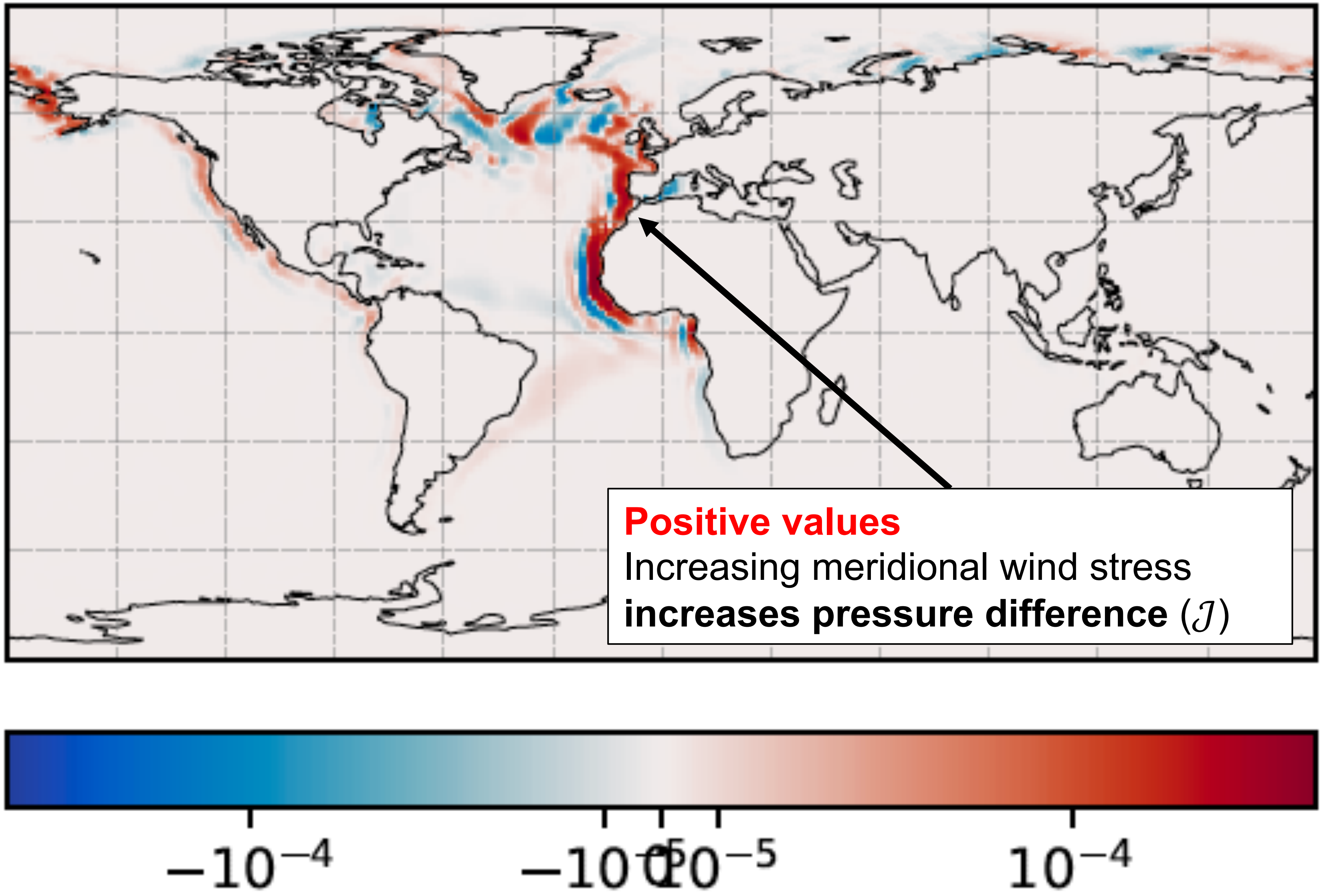
[m^2 s^{-2}] / [N m^{-2}]

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

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

Sensitivity field: Meridional Wind Stress





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

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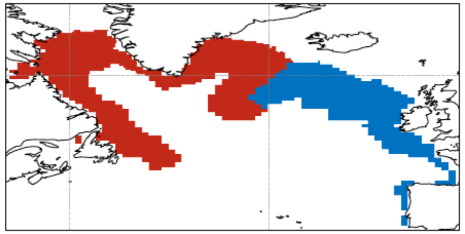
Reconstructions



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

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

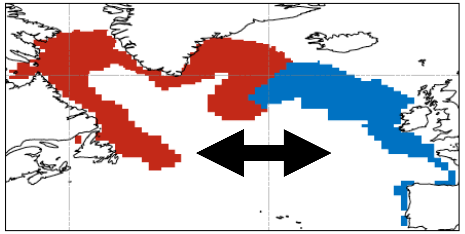
Reconstruction of the pressure anomaly at time t for the force $\mathcal{F}_i$

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

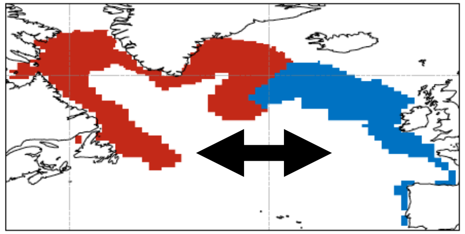


$$\mathcal{R}(t) = \sum_i \iint_A \int_{t_1}^{t_2} \mathcal{A}_i(\boldsymbol{x}, t')\, \Delta\mathcal{F}_i(\boldsymbol{x}, t + t')\, dt'\, dA$$

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

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

‘All in’ reconstruction



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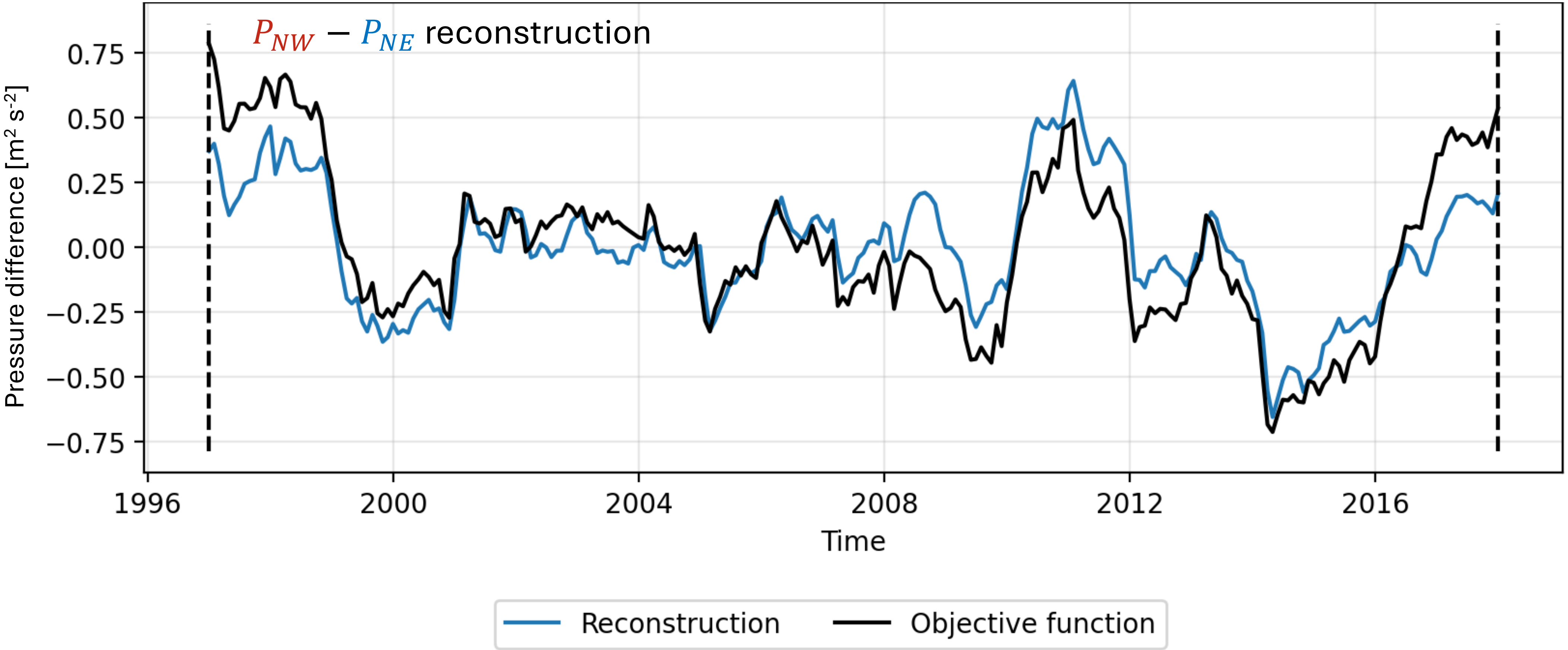
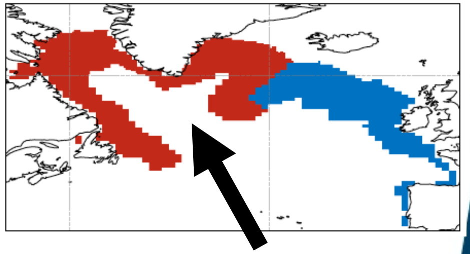


‘All in’ reconstruction



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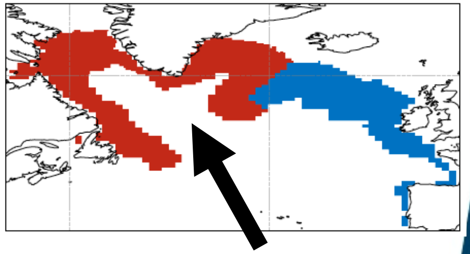
Reconstruction using all forces ($\forall i$) and all available lag ($t_1 = -5$yrs, t_2 = 0)

P_{NW} reconstruction

‘All in’ reconstruction



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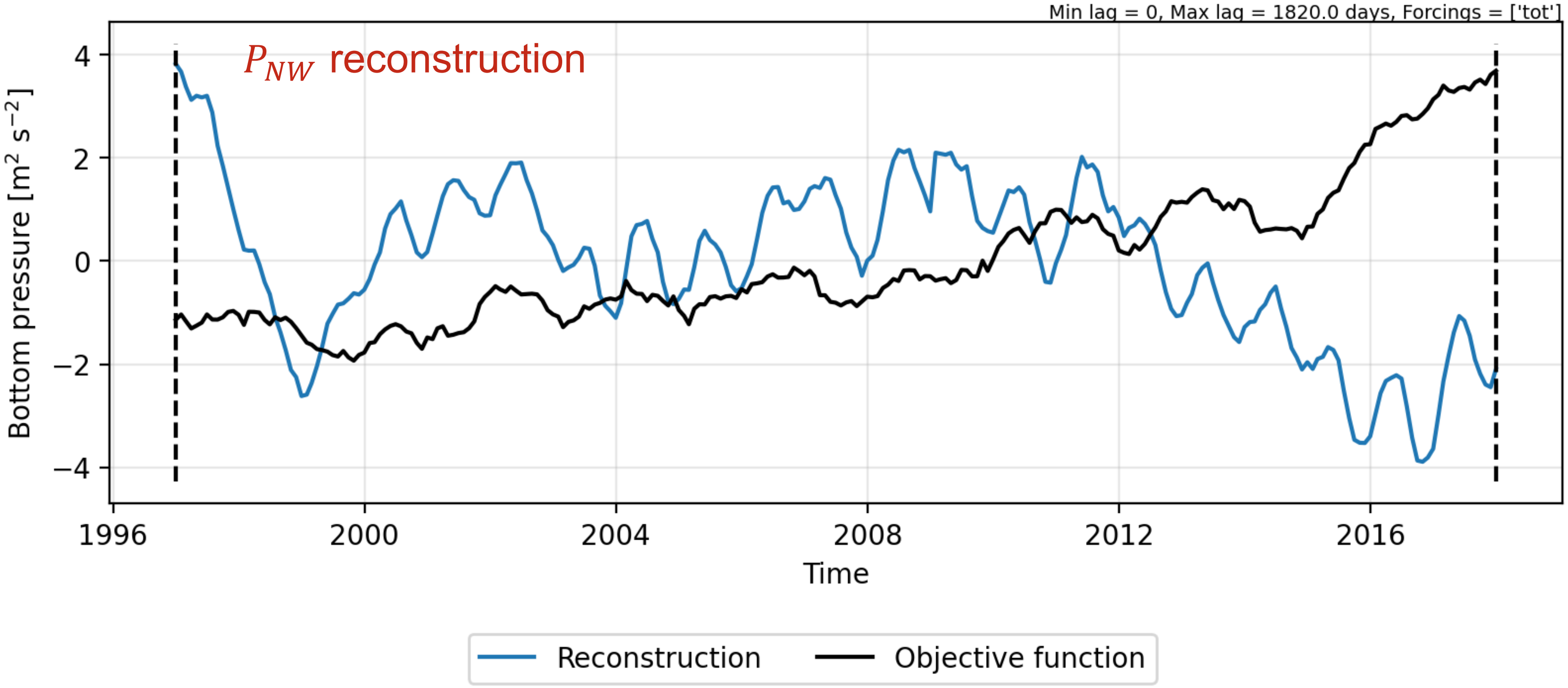
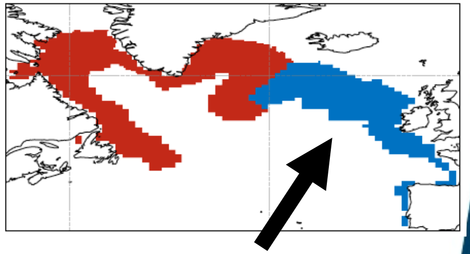
Reconstruction using all forces ($\forall i$) and all available lag ($t_1 = -5$yrs, $t_2 = 0$)



‘All in’ reconstruction

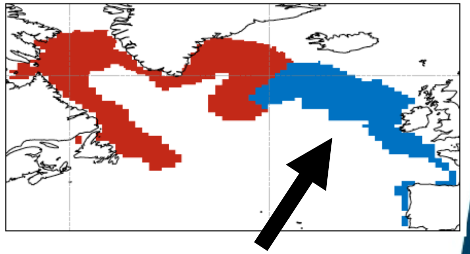


$$\mathcal{R}(t) = \sum_i \iint_A \int_{t_1}^{t_2} \mathcal{A}_i(\boldsymbol{x}, t')\, \Delta\mathcal{F}_i(\boldsymbol{x}, t + t')\, dt'\, dA$$

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

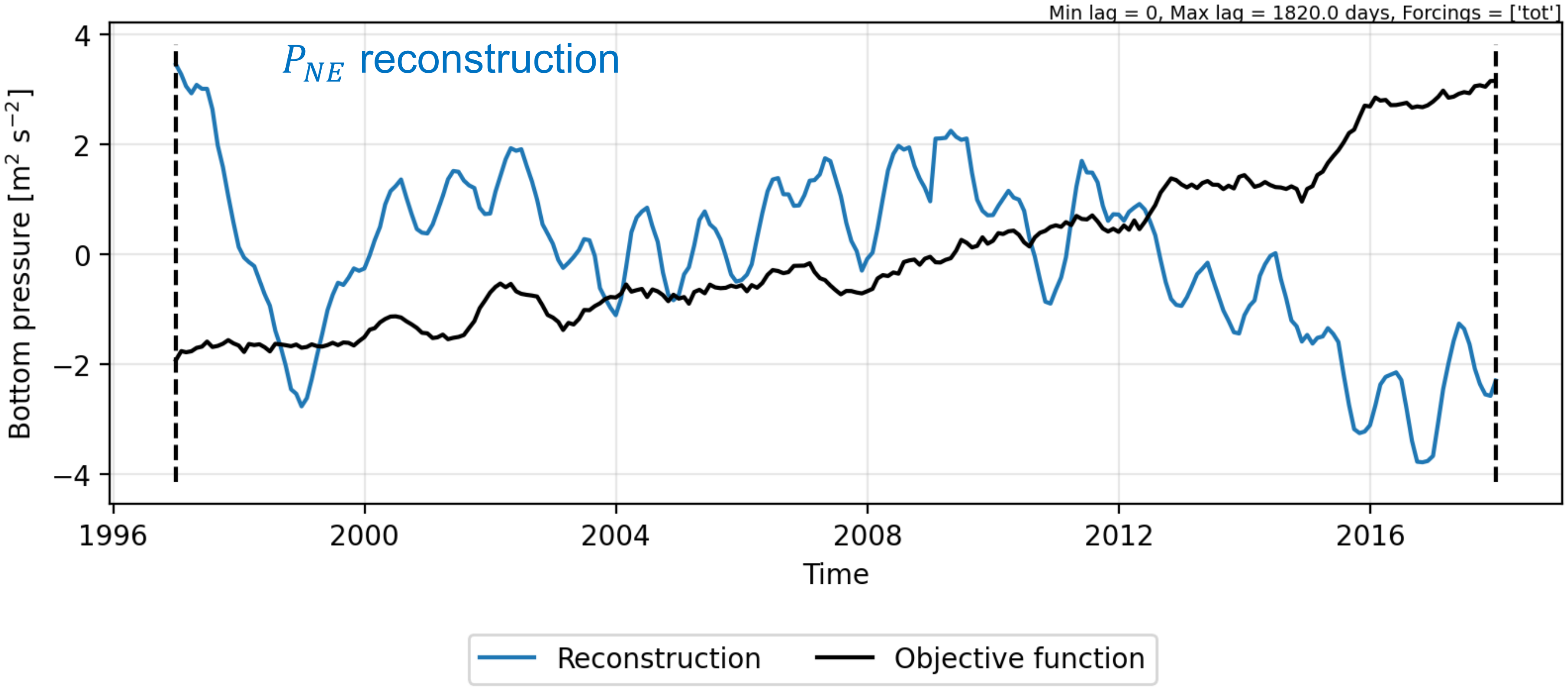
P_{NE} reconstruction

‘All in’ reconstruction



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

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



Explained variability

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

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

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**)

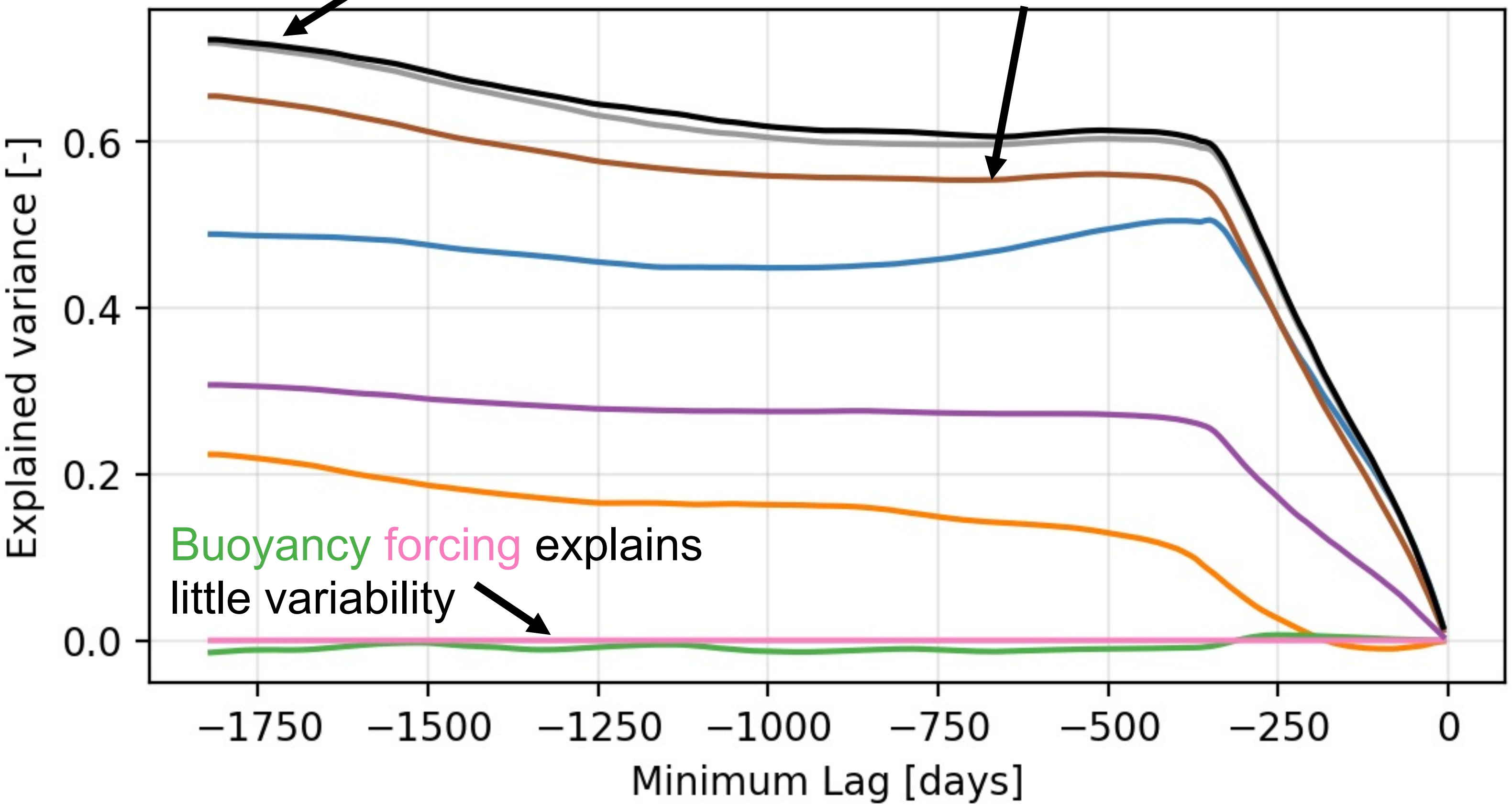
Identifying the optimal combination of forces and memory indicates the **relevant forces** and **timescales**.

Explained variability

Approximately 72% of variability explained by reconstruction

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

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



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

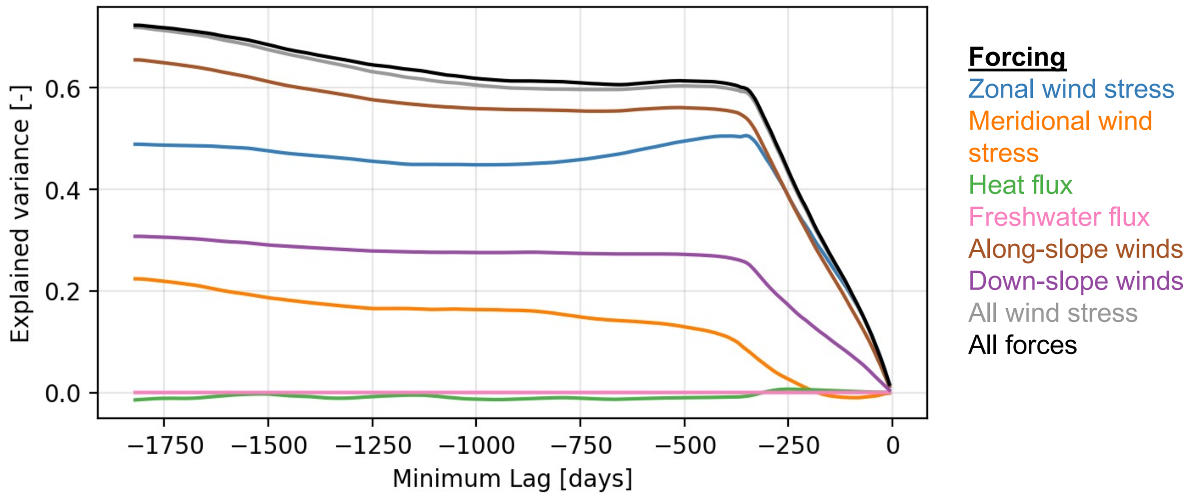
Increasing memory

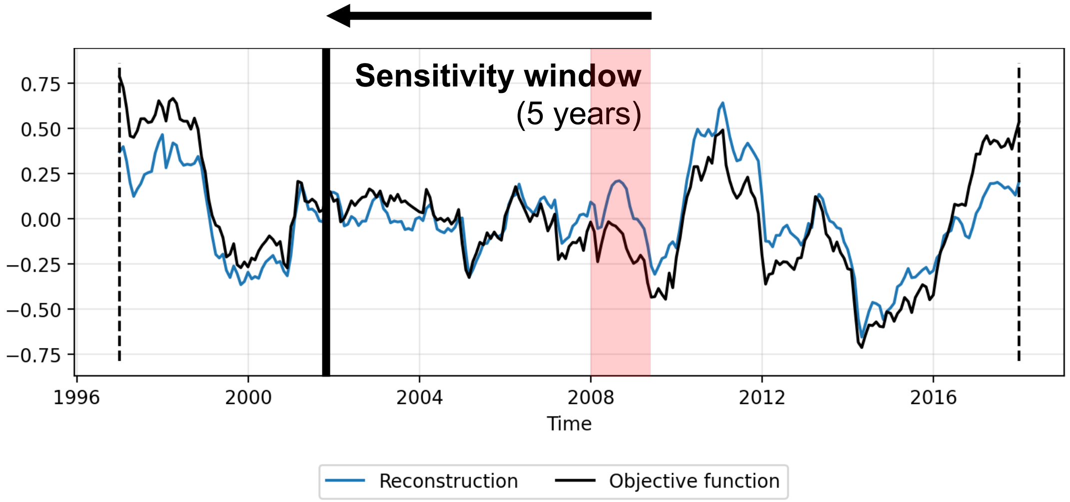
Where is the remaining variability?

- **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**

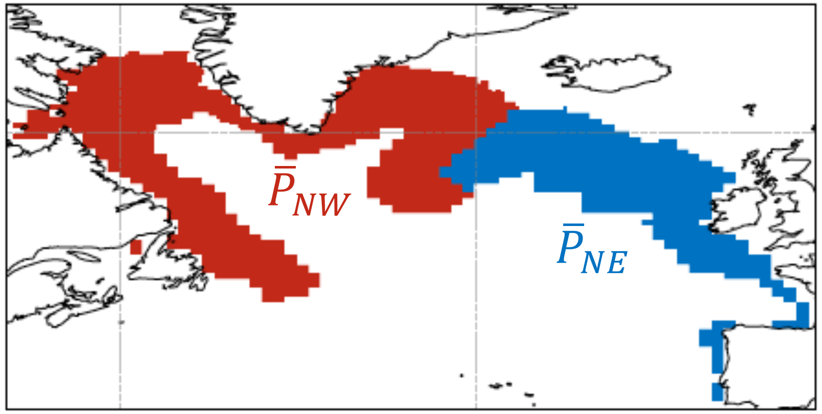
- **Assuming** sensitivities are **stationary** may also produce errors → Calculate **sensitivities** centered on a **different time**

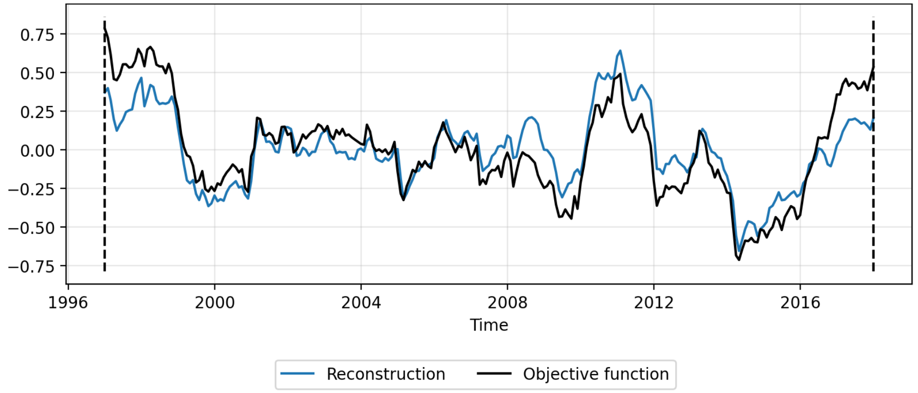
Conclusions

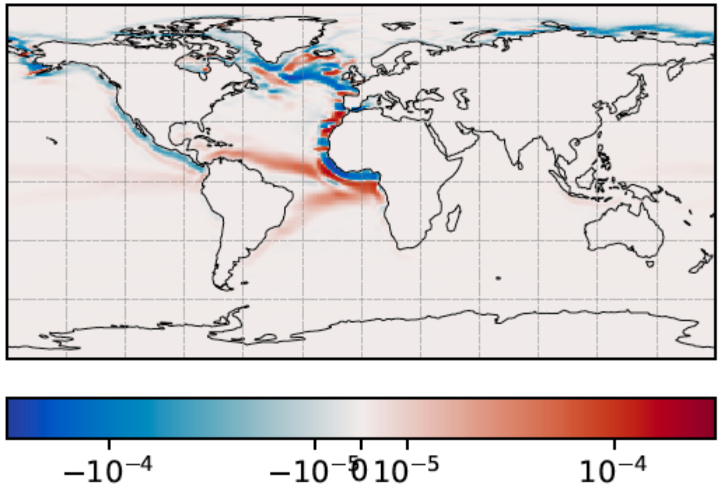
- **Components of variability** in large scale circulations (e.g. MOC) can be described by boundary pressure differences.

- In this case study, we can reconstruct **72%** of the **pressure difference variability** in the North Atlantic

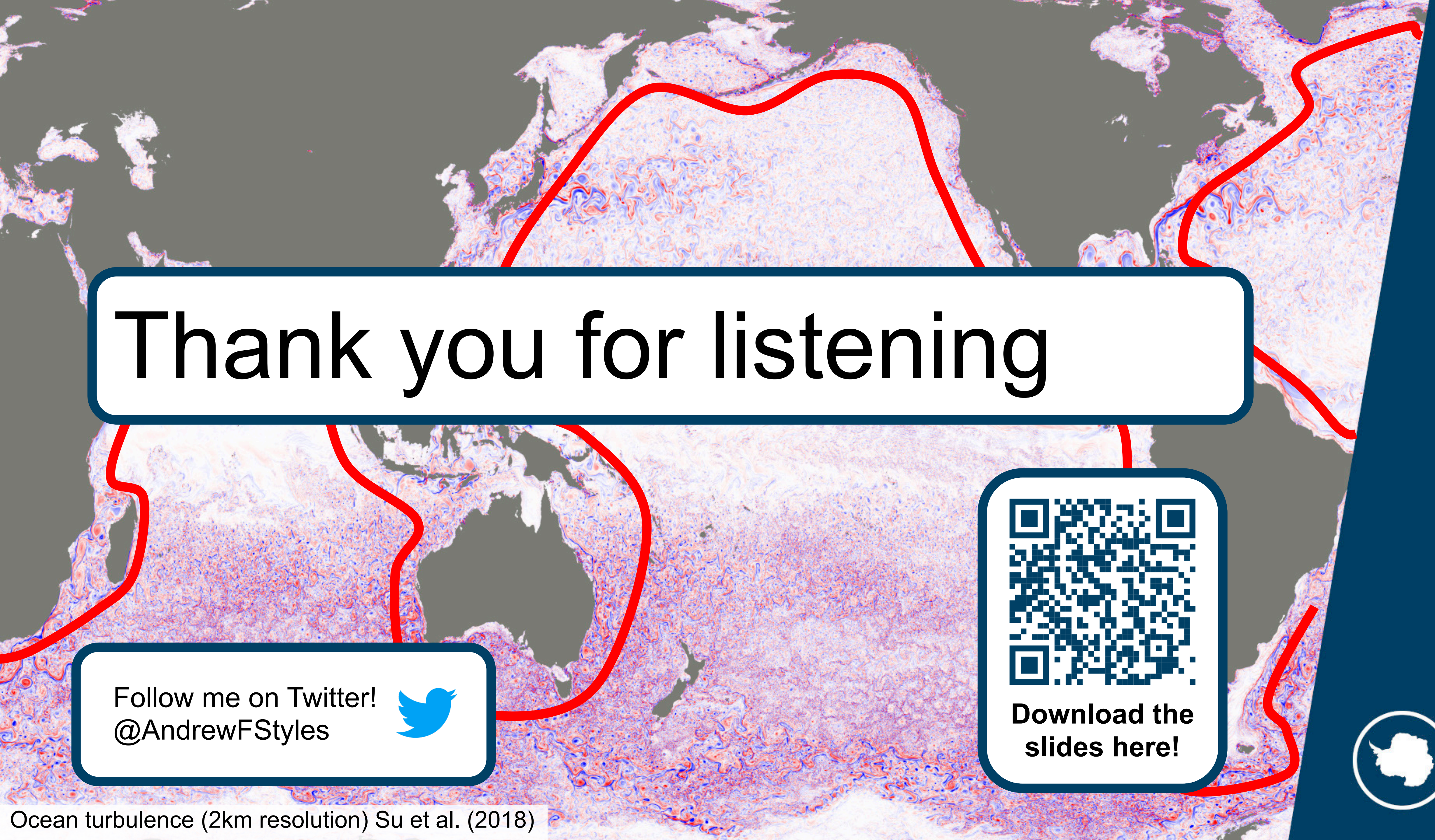
- Most of the explained variability originates from **along-slope winds**







Thank you for listening



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

References

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Extra Slides

Explained variability of the MOC

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

Timescale

> 10 yrs

1.5 – 10 yrs

< 1.5 yrs

MOC standard deviation | Explained variance (%)

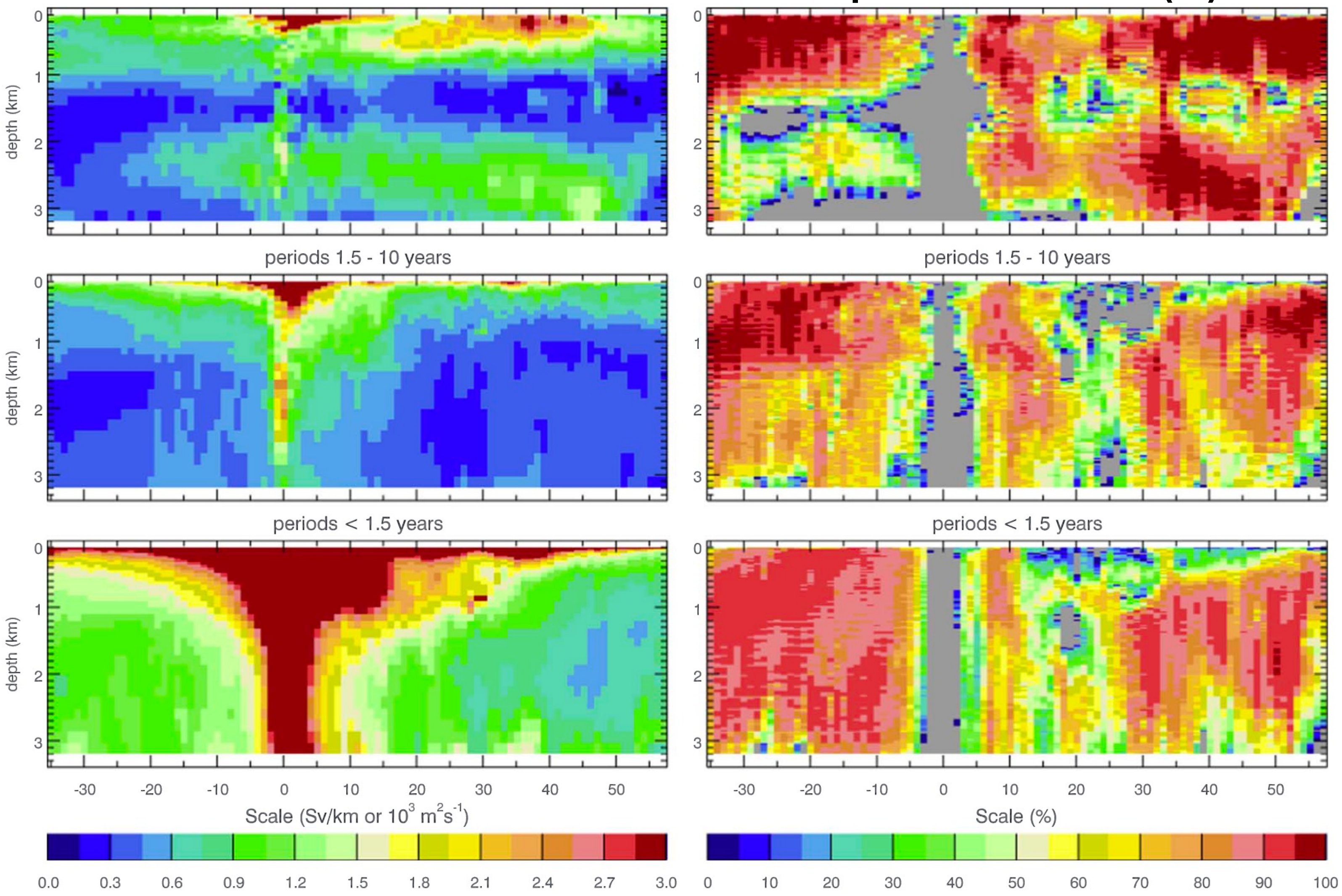


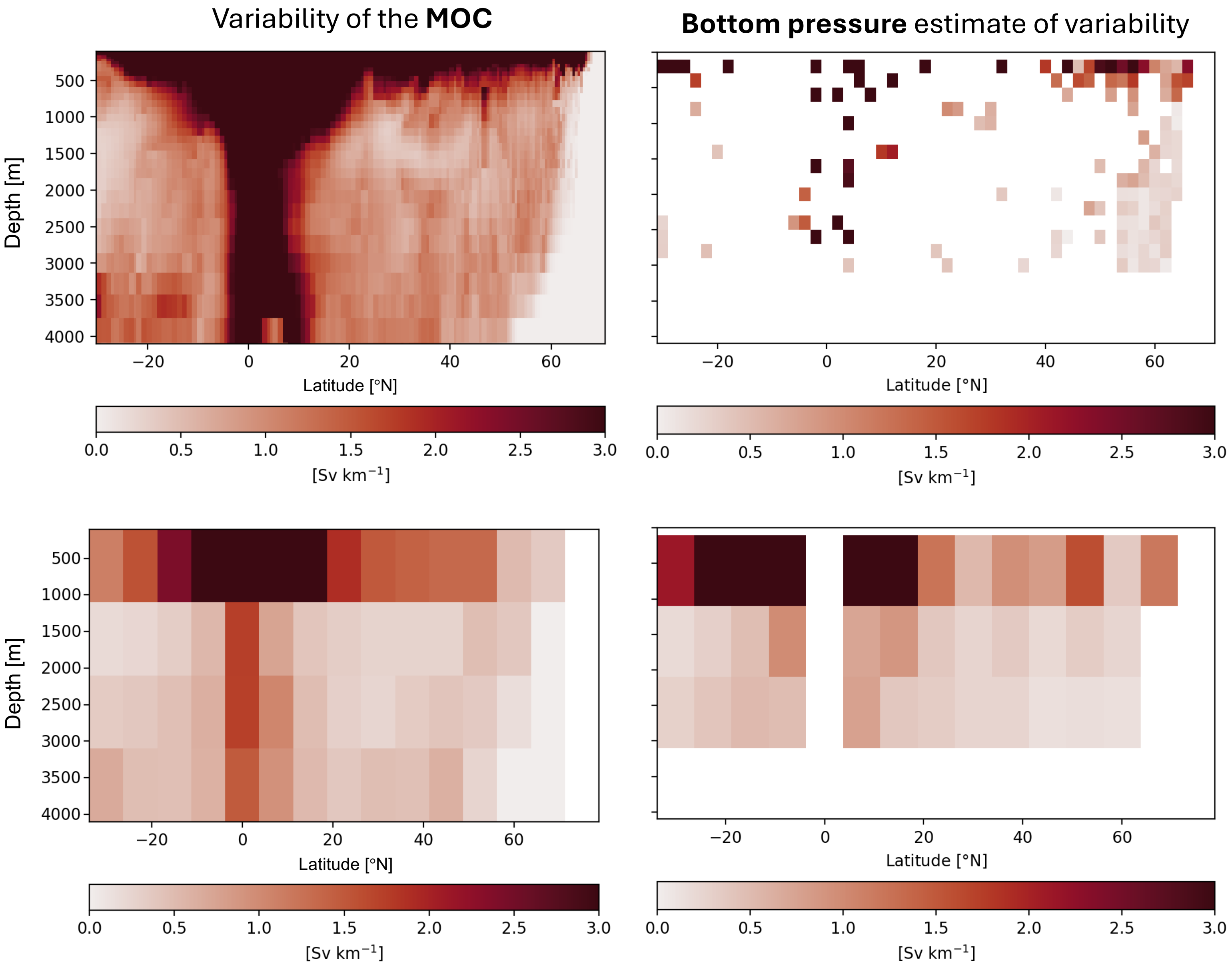
Figure 17 from Hughes et al. (2018)

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

MOC calculation from **geostrophic assumptions**

Explained variability of the MOC

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



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

MOC calculation from **geostrophic assumptions**

Explained variability of the MOC

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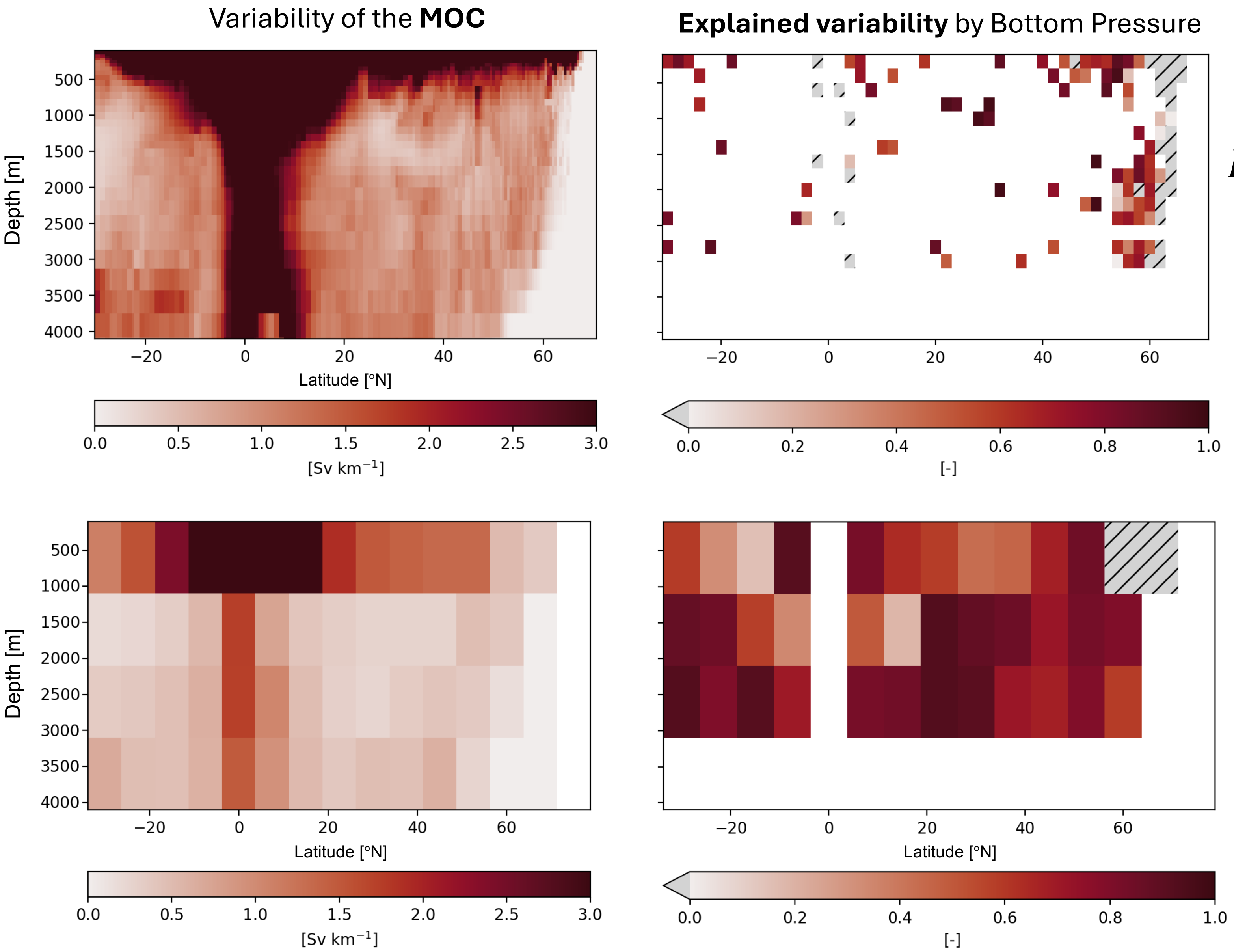
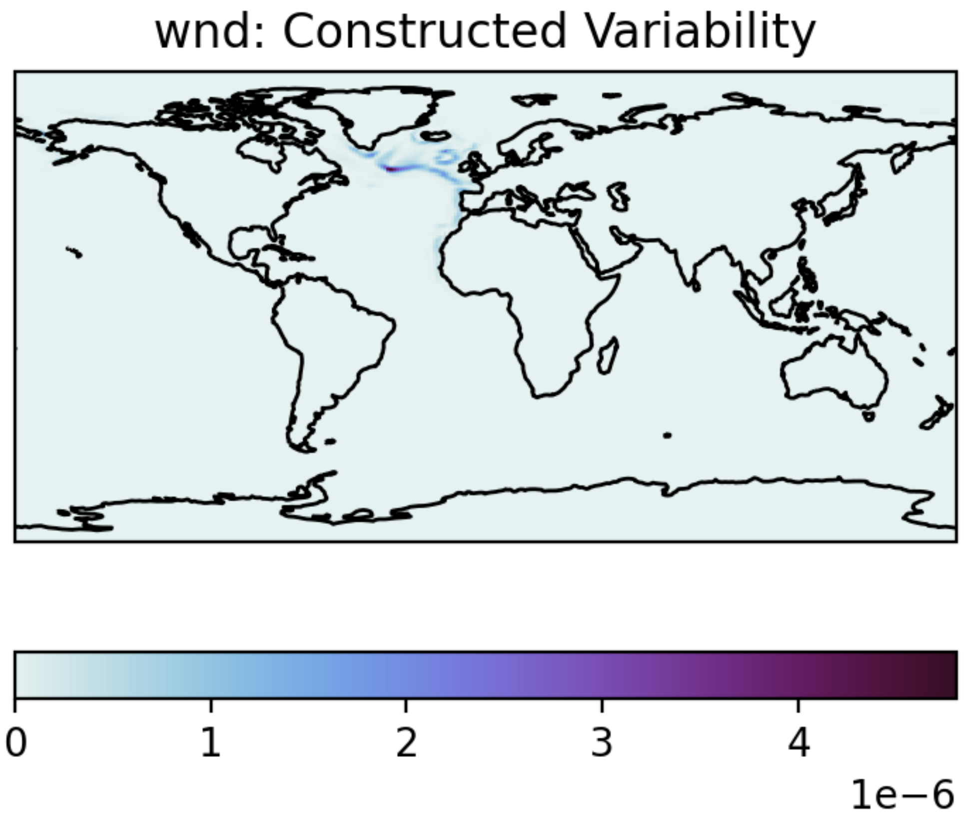
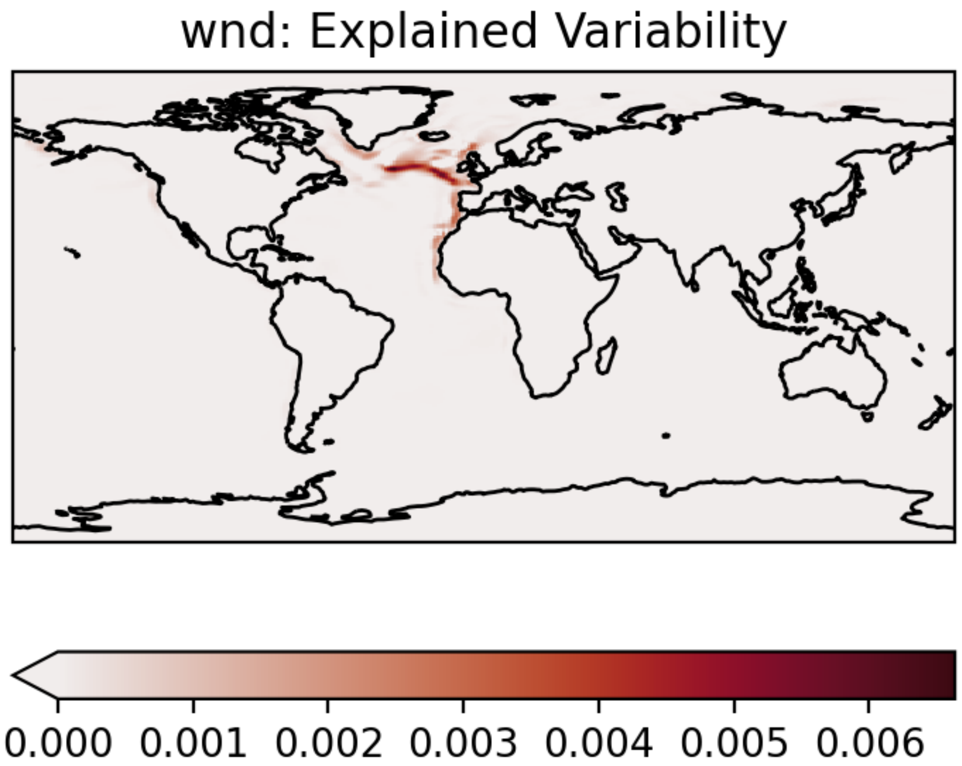


$$E(z,\phi) = 1 - \frac{\mathrm{Var}(V - V_{OBP})}{\mathrm{Var}(V)}$$

Explained variability

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

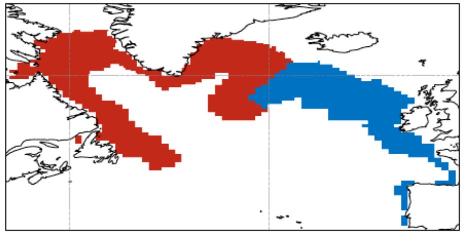


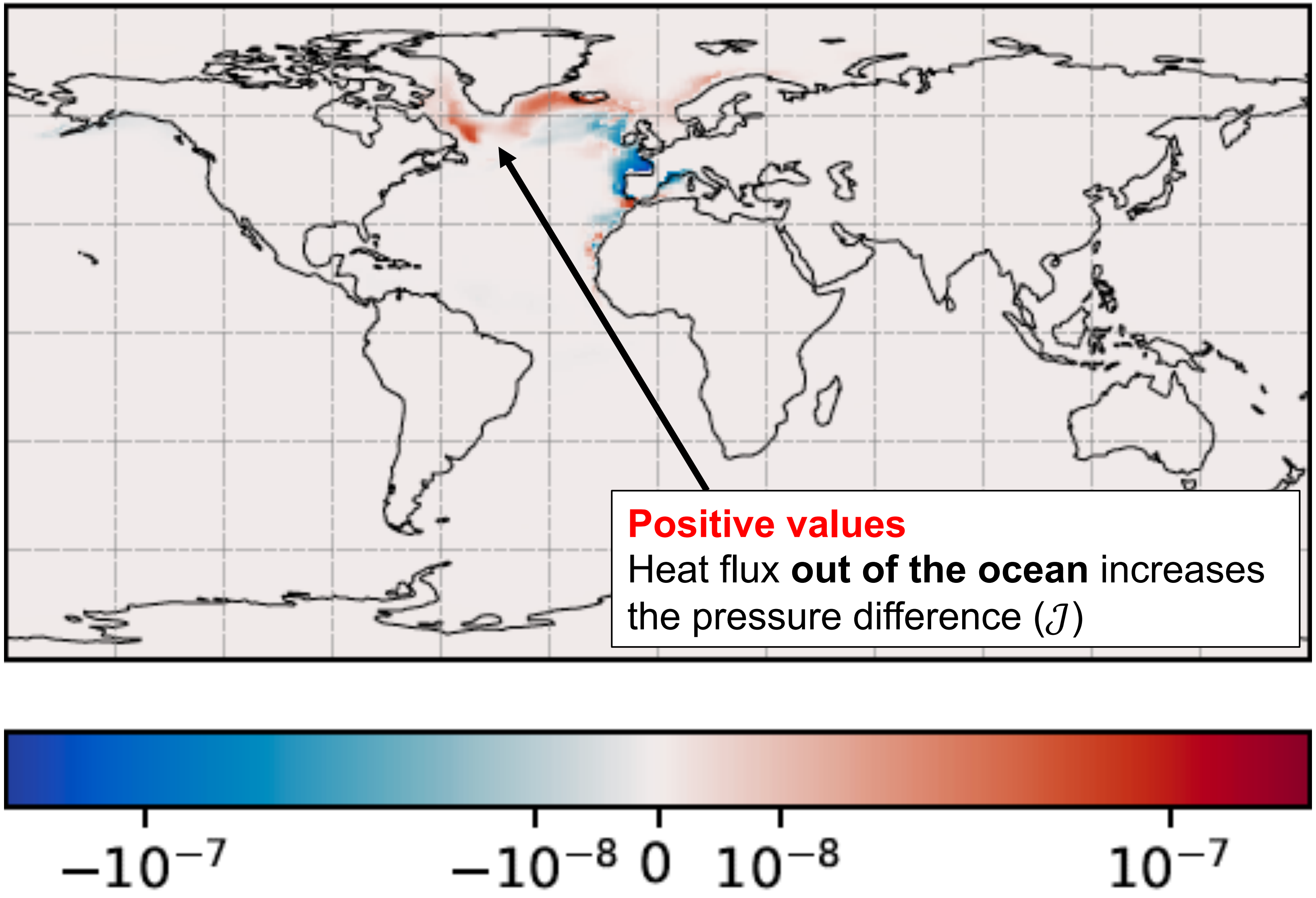


$$\mathcal{R}_i(\boldsymbol{x}, t) = \int_{t_1}^{t_2} \mathcal{A}_i(\boldsymbol{x}, t')\, \Delta\mathcal{F}_i(\boldsymbol{x}, t + t')\, dt'$$

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

Sensitivity field: Heat flux



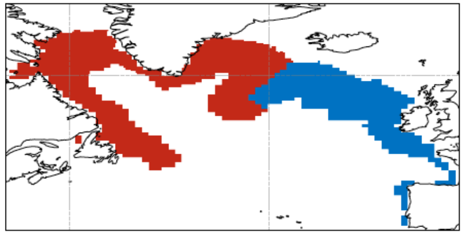


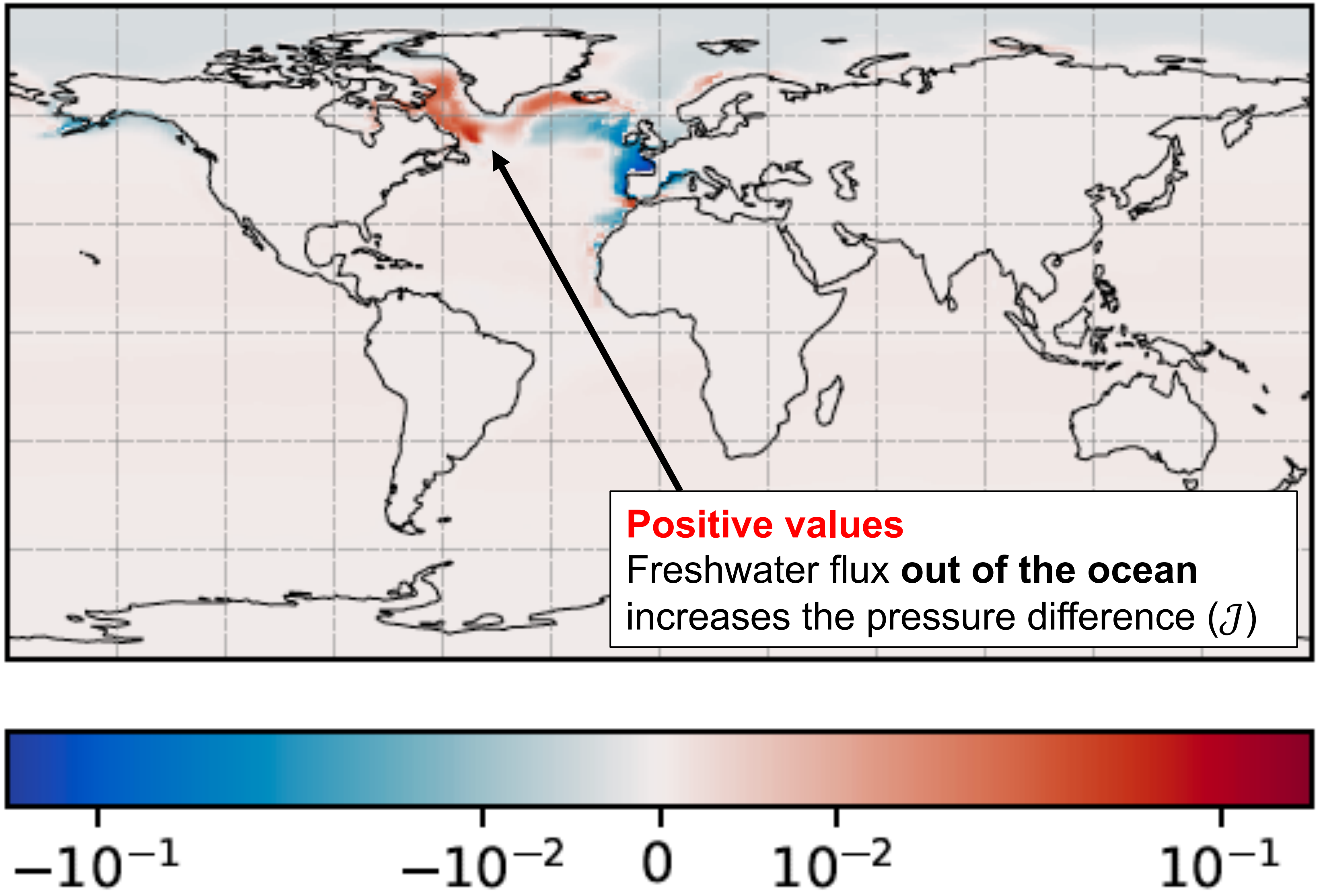
[m^2 s^{-2}] / [W m^{-2}]

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

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

Sensitivity field: Freshwater flux





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

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

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