Boundary Pressure: A Unique Window into Atlantic Transport Variability

Andrew Styles[1], Emma Boland[1], Chris Hughes[2], Saranraj Gururaj[2], Dani Jones[3]

[1]British Antarctic Survey, UK

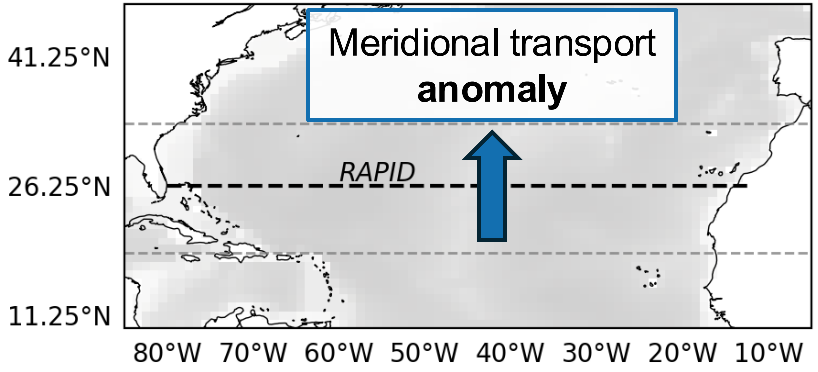
[2]Univeristy of Liverpool, UK

[3]University of Michigan, USA

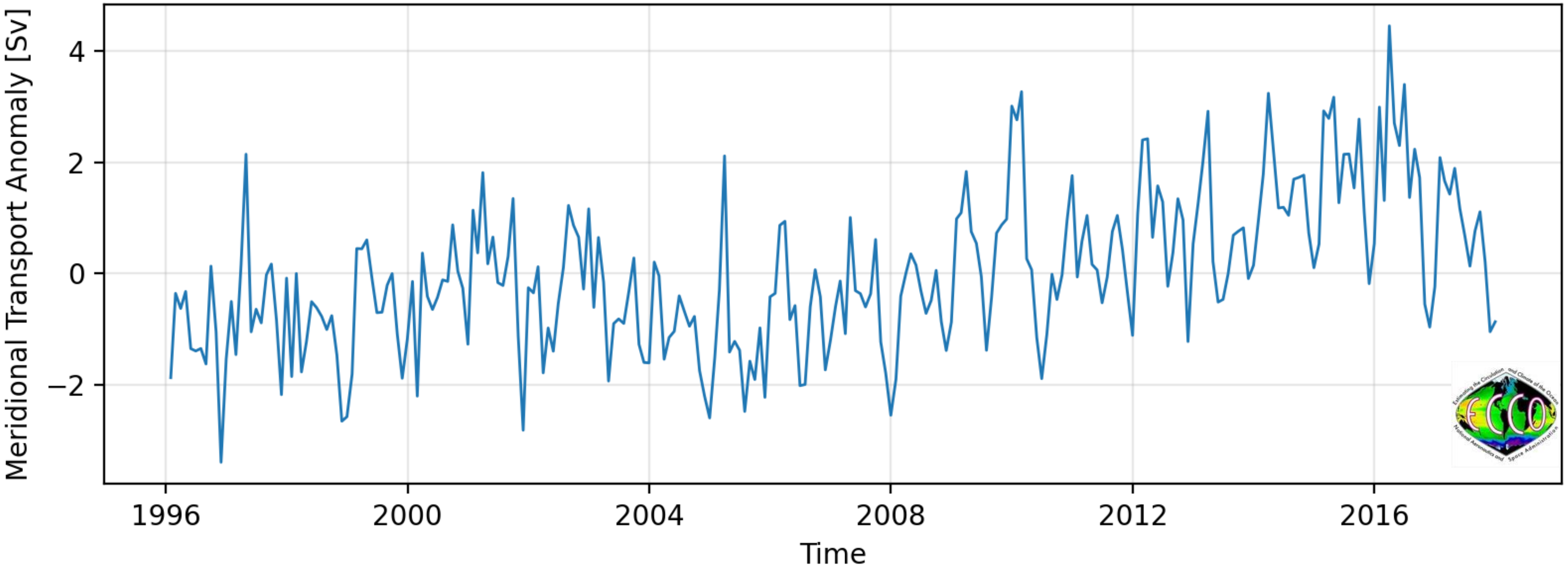
Supplementary material

29th April 2025

Transports and pressures



The timeseries shows the basin-wide **transport anomaly**…



Meridional transport **anomaly**

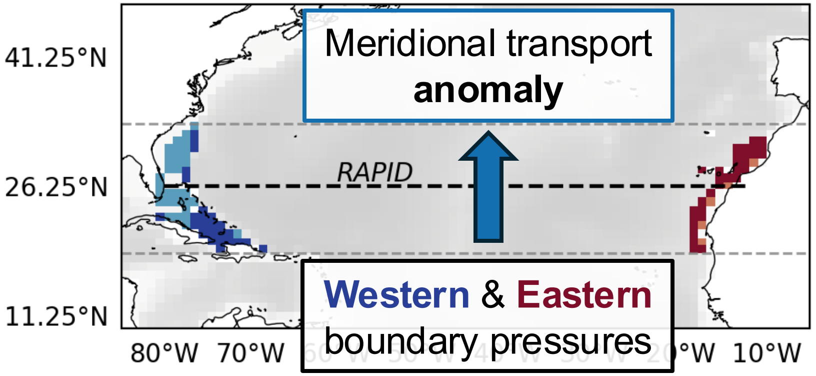
Depth interval: 1000-3000m

Latitude band: 18.75-33.75°N

Transports through the depth interval are averaged across the latitude band.

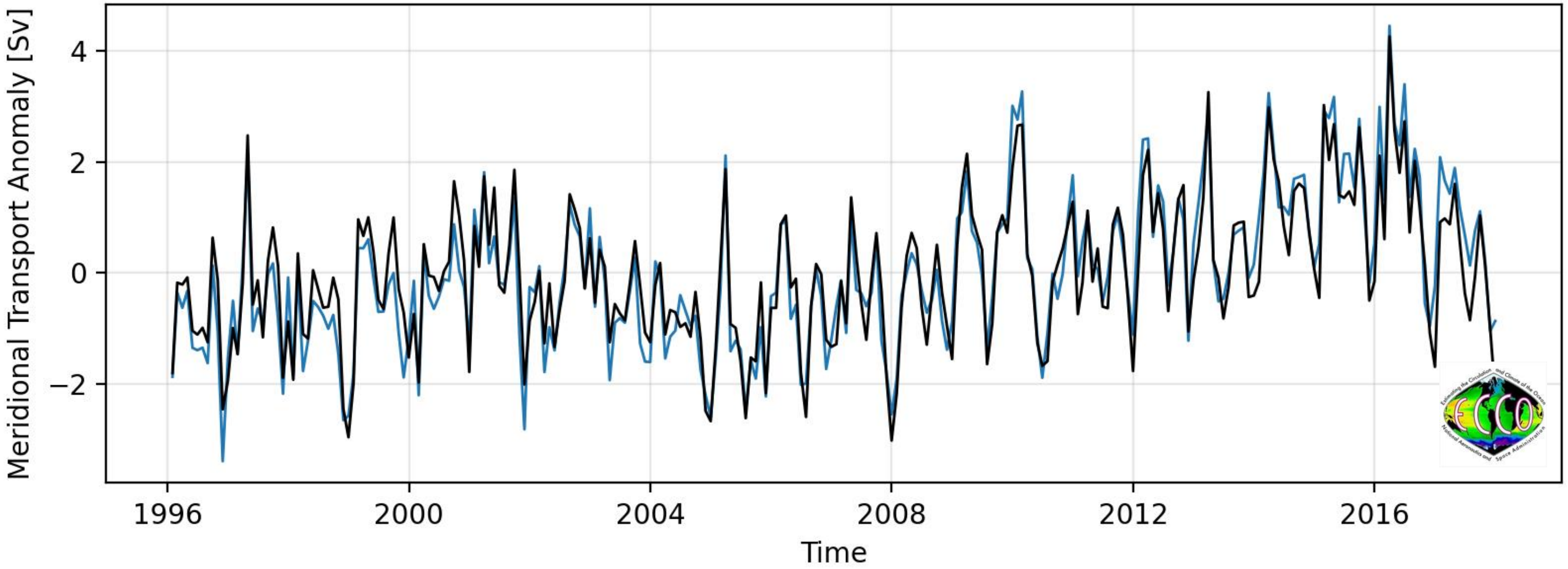
Calculated using the **ECCO state estimate**

Transports and pressures



The timeseries shows the basin-wide **transport anomaly**…

which can be estimated using **boundary pressures**



Meridional transport **anomaly**

Boundary pressure estimate

Depth interval: 1000-3000m

Latitude band: 18.75-33.75°N

Transports through the depth interval are averaged across the latitude band.

Calculated using the **ECCO state estimate**

Method behind the estimate

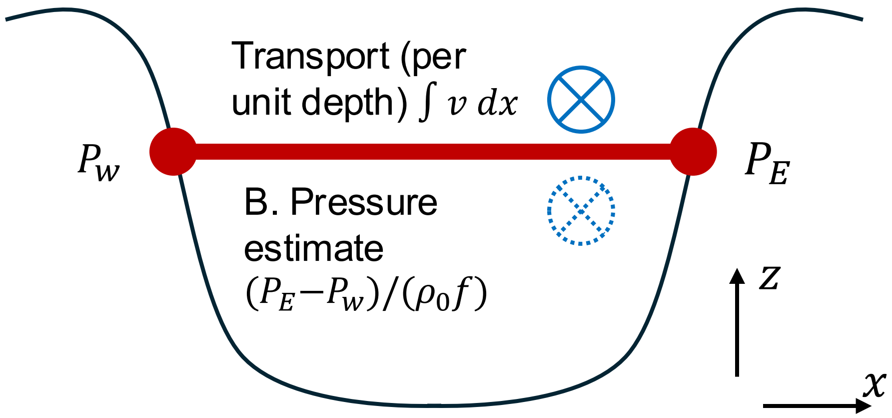
We assume **geostrophic balance**:

$$v = \frac{1}{\rho_0 f}\frac{\partial P}{\partial x}$$

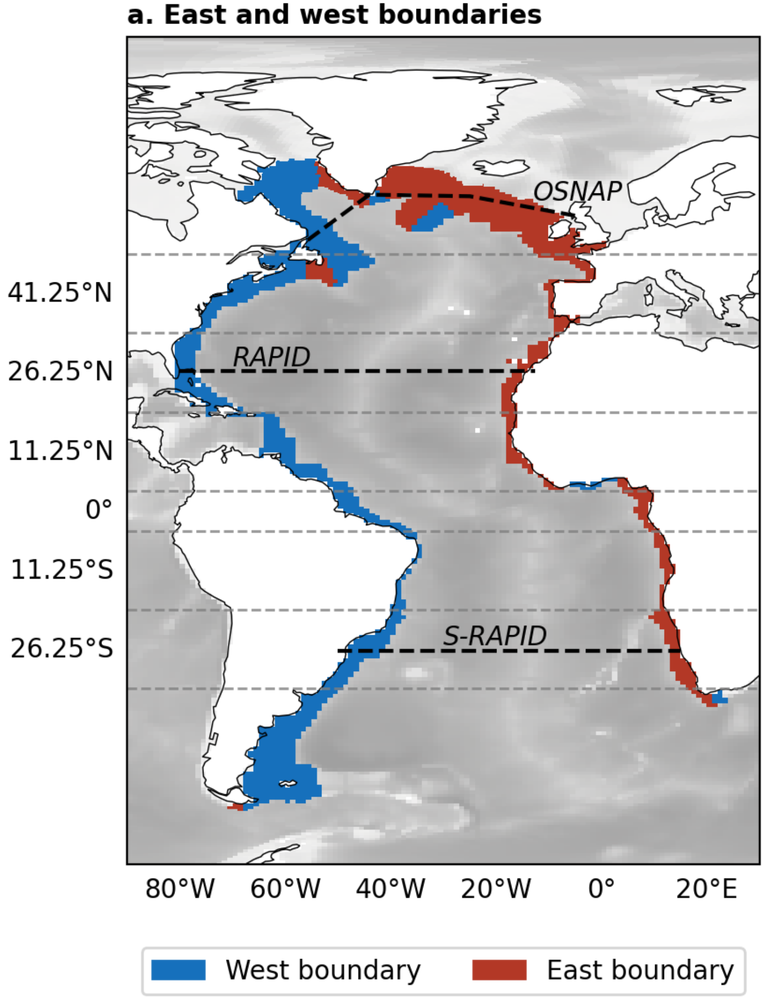
and **zonally integrate** across the basin,

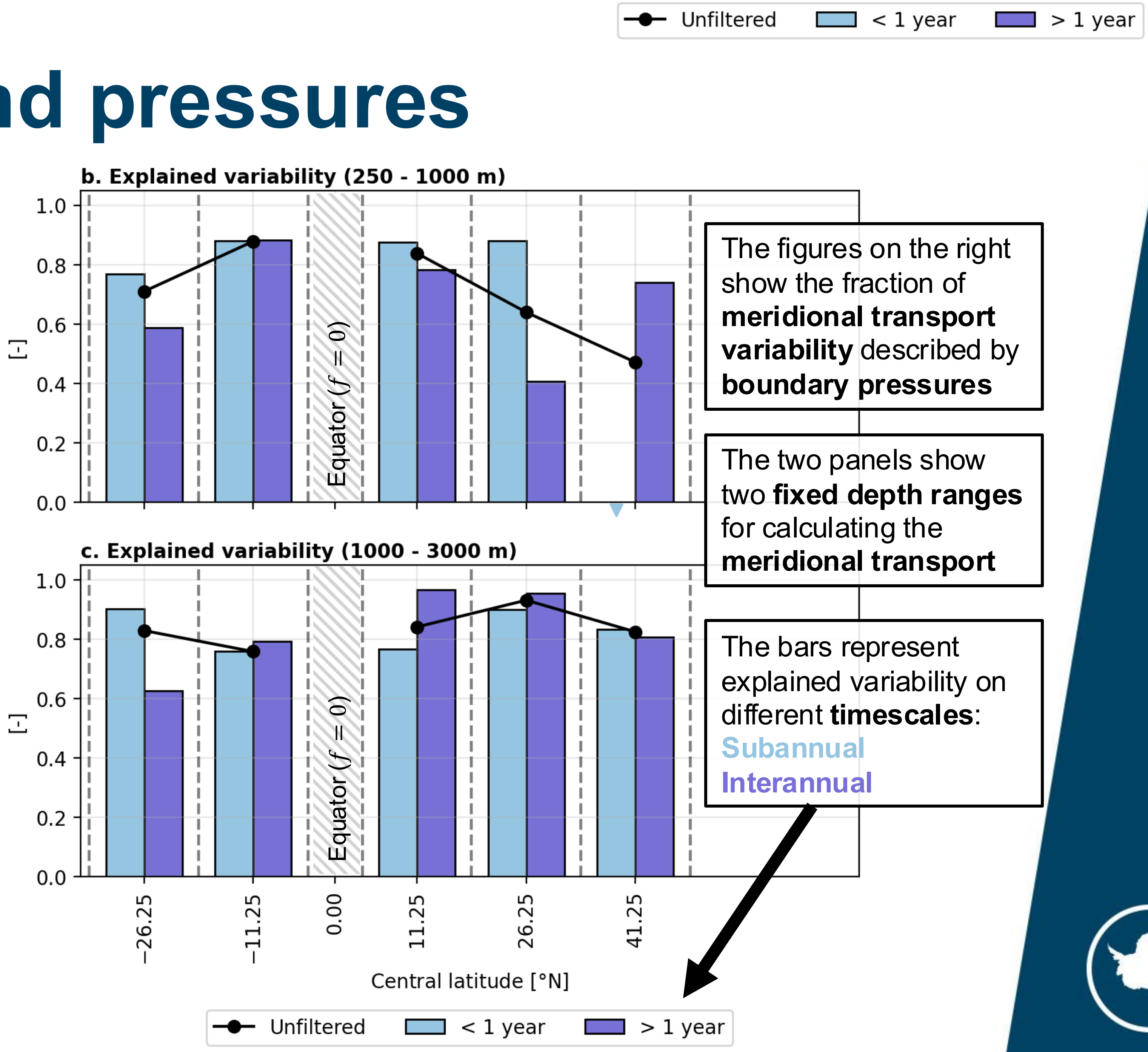
$$\int_{x_W}^{x_E} v \; dx = \frac{1}{\rho_0 f}(P_E - P_W)$$

We now have an estimate for the **meridional transport** per unit depth



Transports and pressures

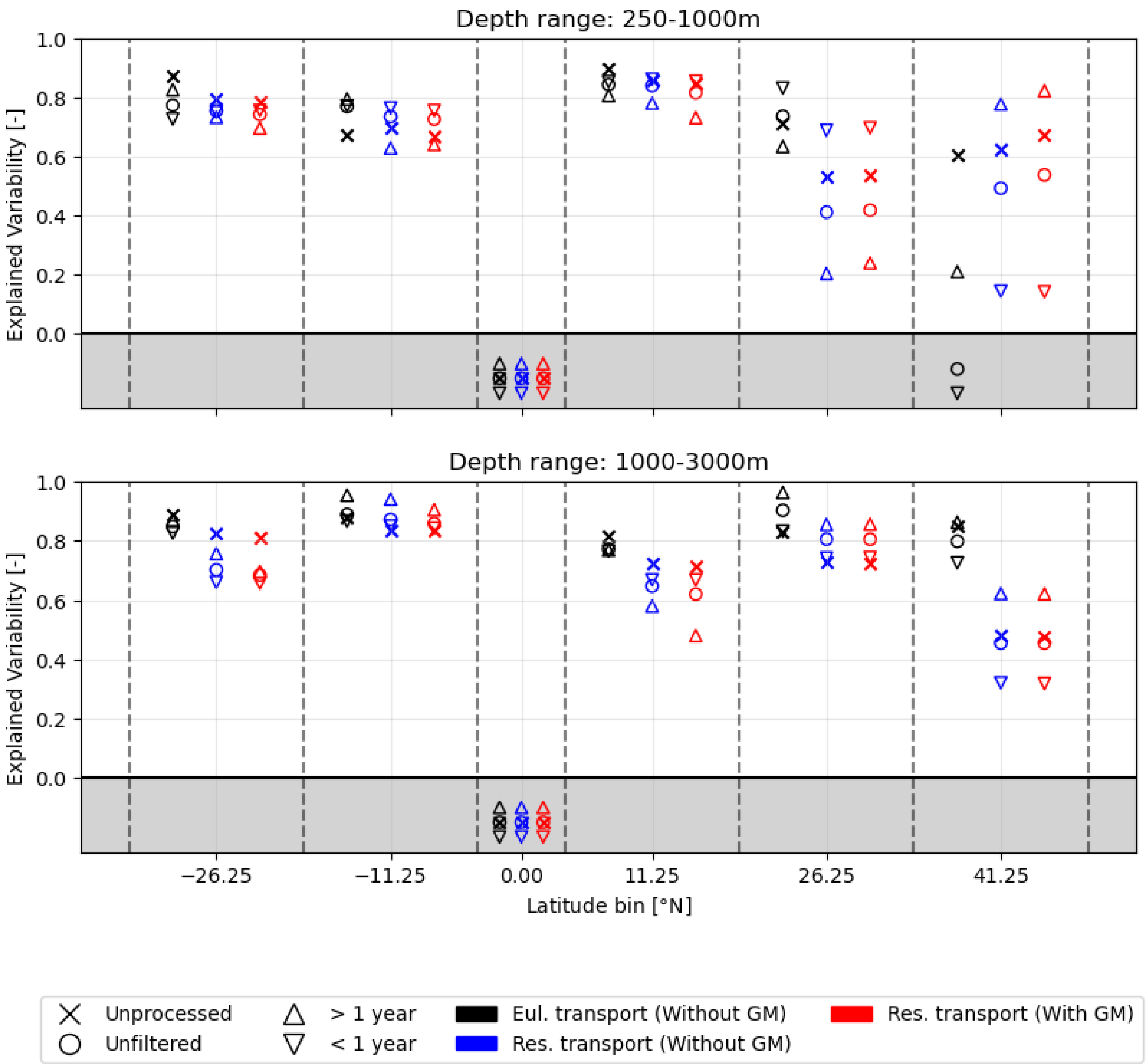




The figures on the right show the fraction of **meridional transport variability** described by **boundary pressures**

The two panels show two **fixed depth ranges** for calculating the **meridional transport**

The bars represent explained variability on different **timescales**:
Subannual
Interannual



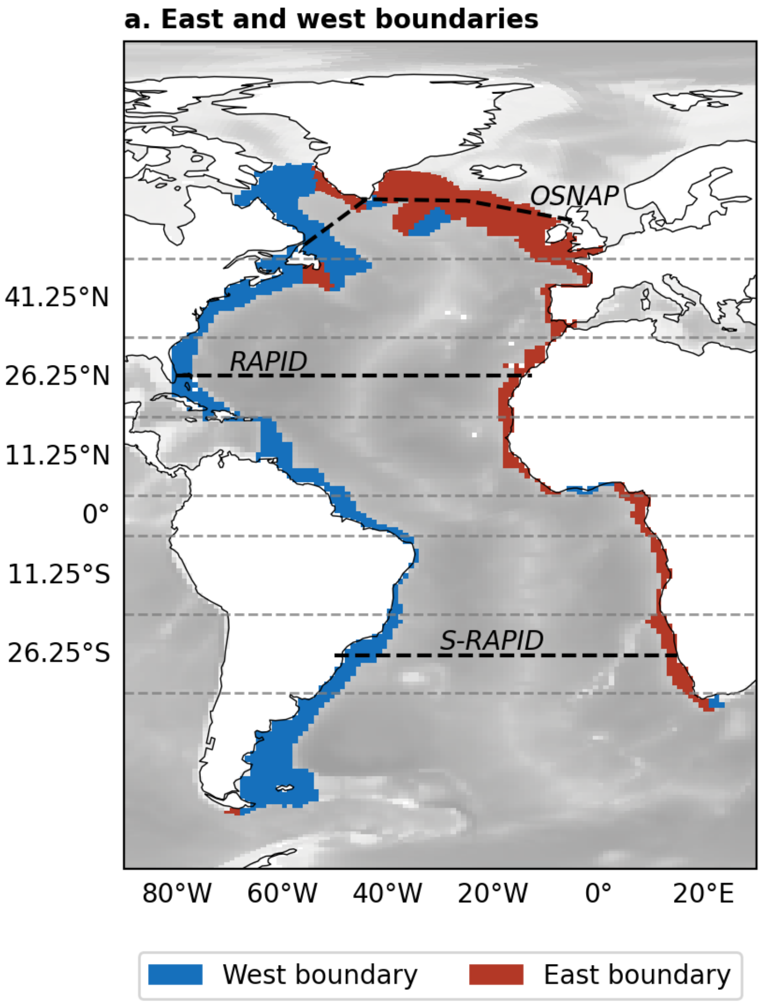
The relationship between **meridional transport** and **boundary pressure** has been tested with various combinations of:

- Latitude
- Transport definition
- Postprocessing
- Timescale

The key question

If a significant component of Atlantic **transport variability** is constrained by **boundary pressures**…

What controls the boundary pressures?



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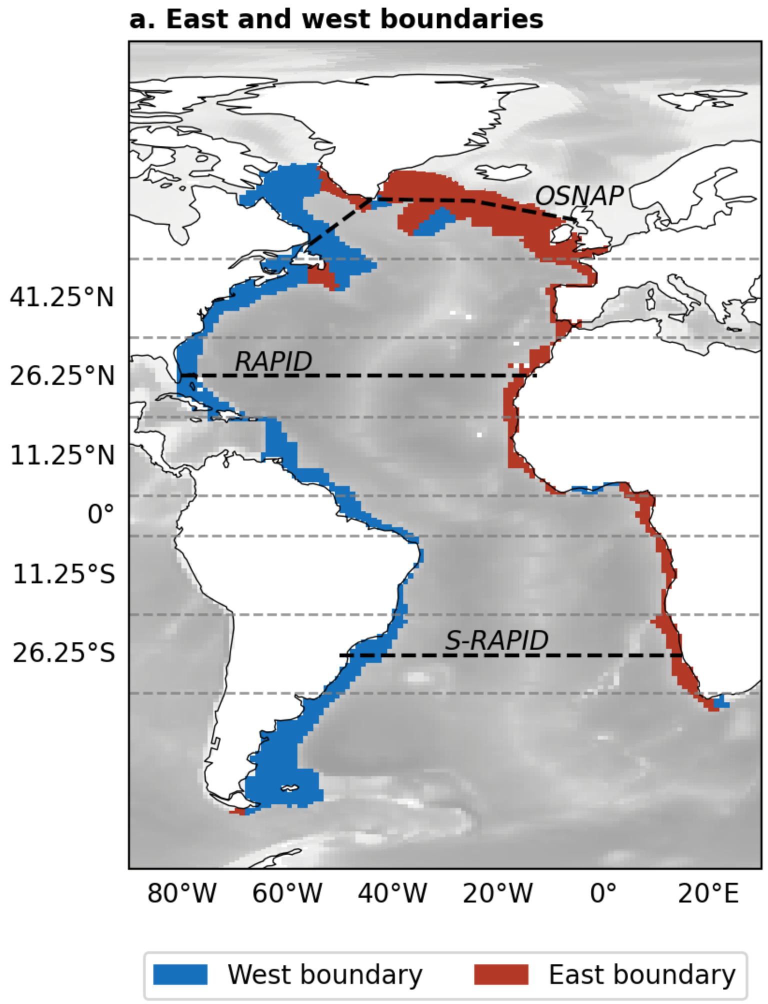
If a significant component of Atlantic **transport variability** is constrained by **boundary pressures**…

How should we observe the Atlantic?

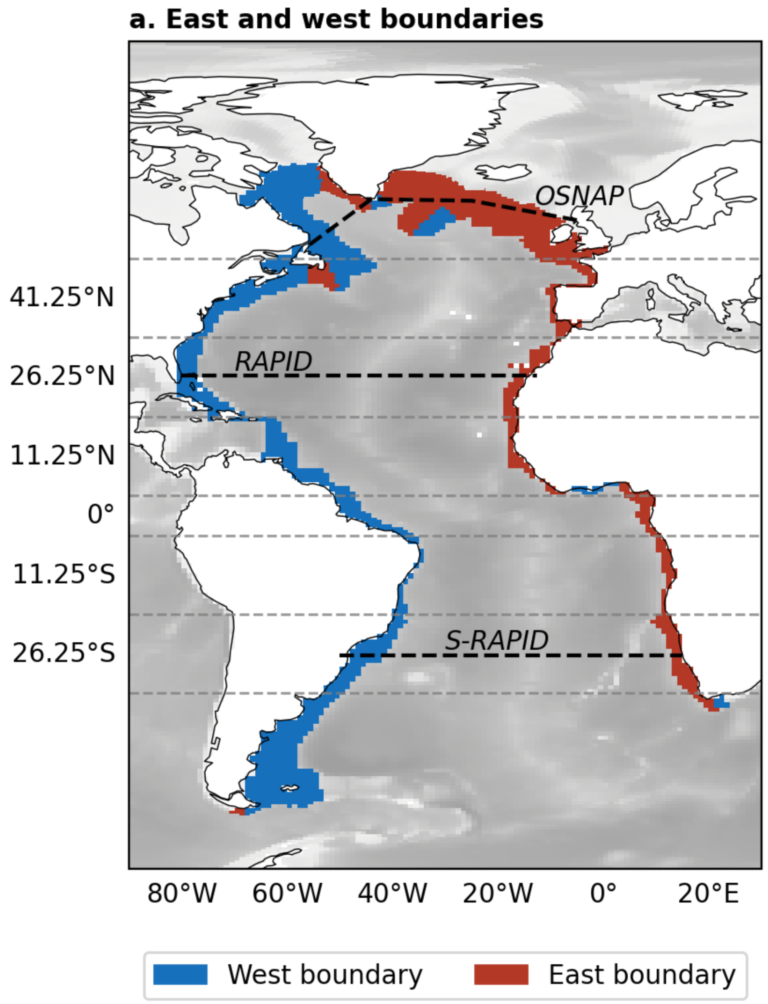


The key questions

If a significant component of Atlantic **transport variability** is constrained by **boundary pressures**…

How should we observe the Atlantic?

- Extend coverage of the **interior** at **specific latitudes**?
- Extend coverage of the **boundaries** at **all latitudes**?

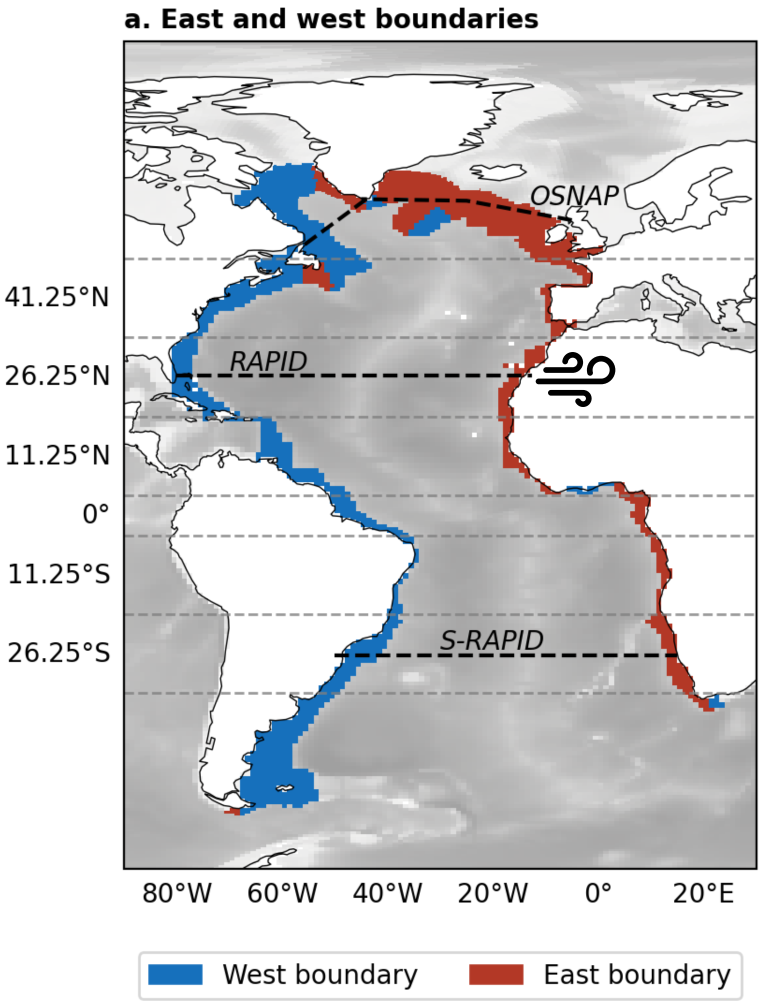


The key questions

If a significant component of Atlantic **transport variability** is constrained by **boundary pressures**…

What controls the boundary pressures?

- Is it forcing **at the boundary**?

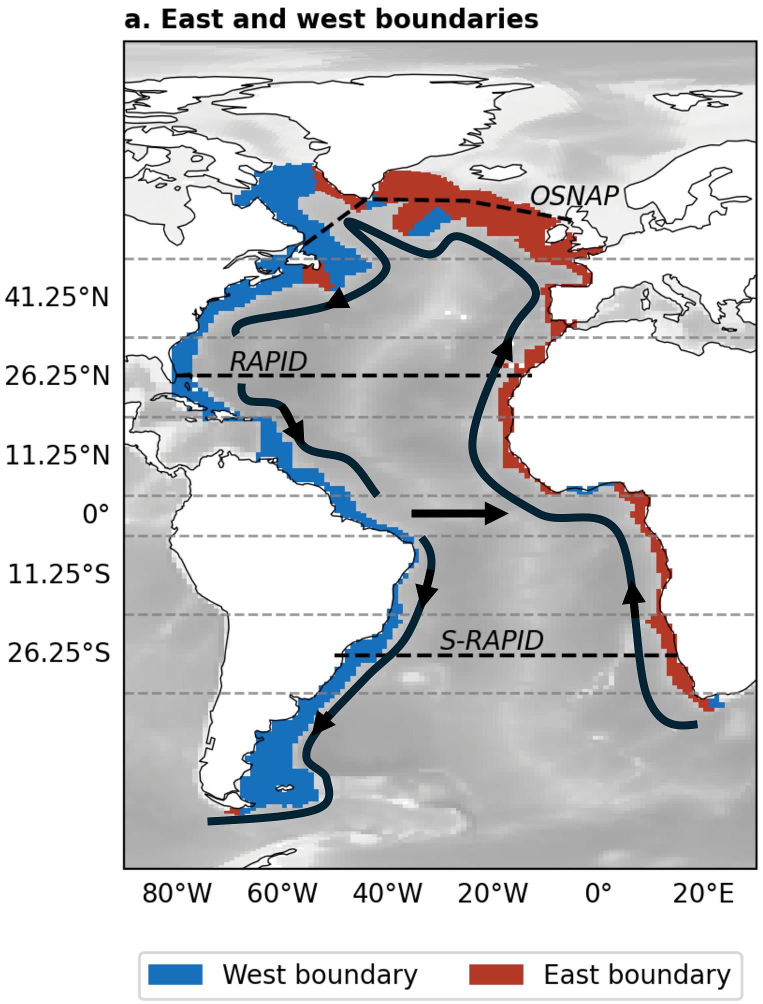


The key questions

If a significant component of Atlantic **transport variability** is constrained by **boundary pressures**…

What controls the boundary pressures?

- Is it forcing **at the boundary**?
- Are **boundary waves** significant?



The key questions

If a significant component of Atlantic **transport variability** is constrained by **boundary pressures**…

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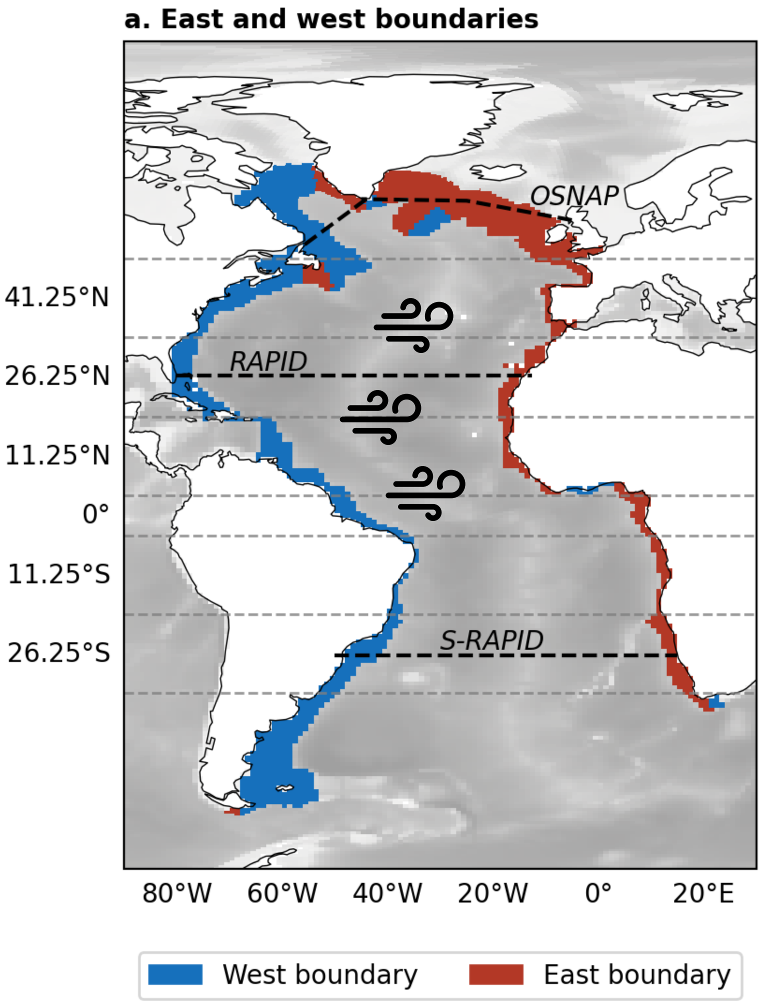
- Is it forcing **at the boundary**?
- Are **boundary waves** significant?
- Is forcing in the **basin interior** important?



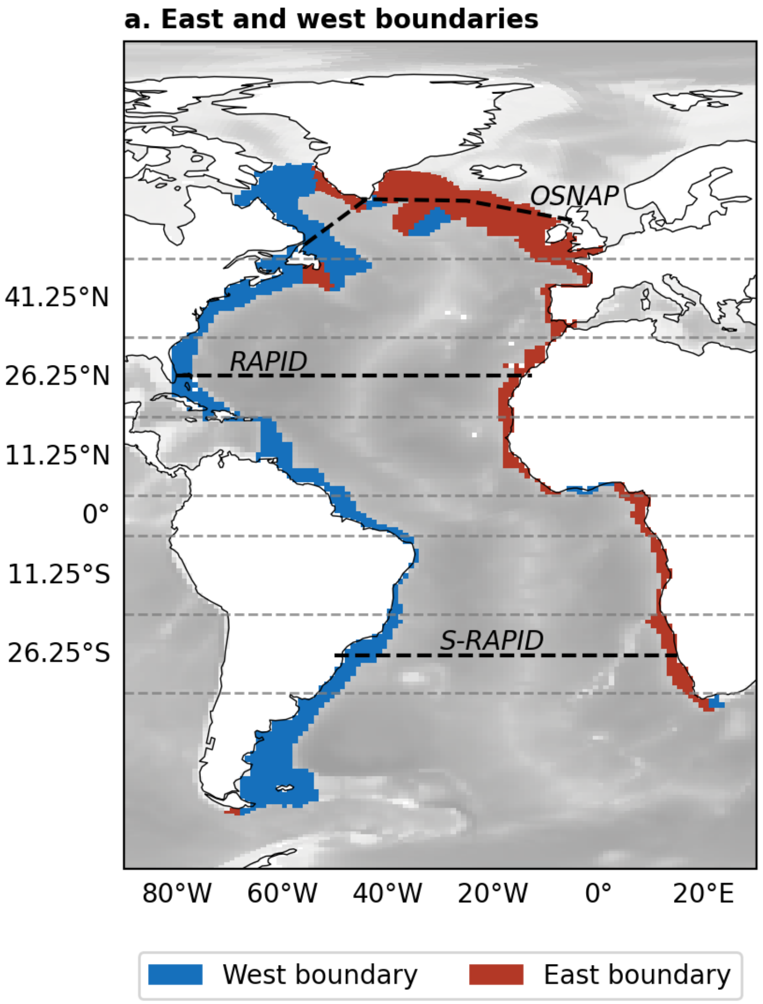
The key questions

If a significant component of Atlantic **transport variability** is constrained by **boundary pressures**…

What controls the boundary pressures?

- Is it forcing **at the boundary**?
- Are **boundary waves** significant?
- Is forcing in the **basin interior** important?

We are investigating this using an **adjoint model**



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**

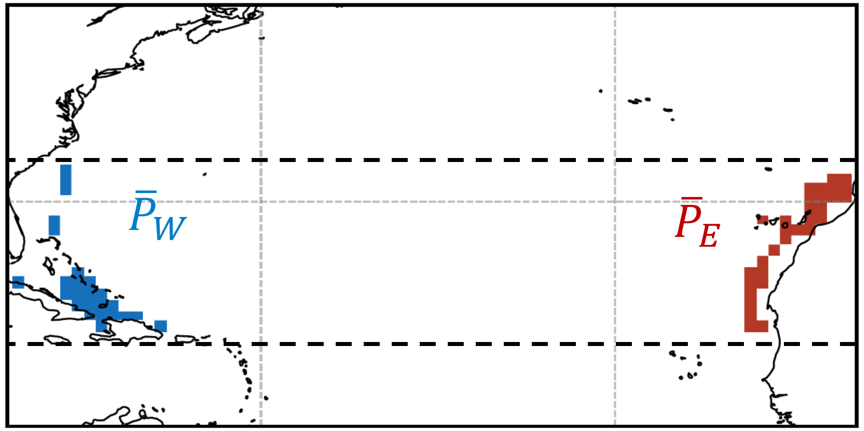
$\mathcal{J}$ → Adjoint Model ECCOv4r4 → $\frac{\partial \mathcal{J}}{\partial \mathcal{F}_1}, \frac{\partial \mathcal{J}}{\partial \mathcal{F}_2}, \ldots$

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

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

Objective function for pressure difference

- Select 2 **clusters** of boundary grid points (e.g. figure)
- Select a **time window** (e.g. Jan ⇒ Dec 2013)
- **Bottom pressure** within each cluster is spatially and then temporally averaged (e.g. $\bar{P}_W, \bar{P}_E$)
- The adjoint model calculates the **linear sensitivities** of each mean pressure to:



Example clusters in the Atlantic. Both clusters contain boundary grid points with 1000 and 3000 m depth

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

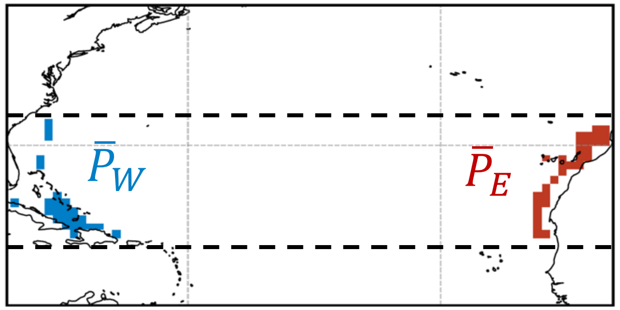
$\bar{P}_E$ → Adjoint Model ECCOv4r4 → $\frac{\partial \bar{P}_E}{\partial \mathcal{F}_1}, \frac{\partial \bar{P}_E}{\partial \mathcal{F}_2}, \ldots$

Objective function

Linear sensitivities

$$\frac{\partial(\bar{P}_E - \bar{P}_W)}{\partial \mathcal{F}_1}, \frac{\partial(\bar{P}_E - \bar{P}_W)}{\partial \mathcal{F}_2}, \ldots$$

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



$$\mathcal{J} = \bar{P}_E - \bar{P}_W$$

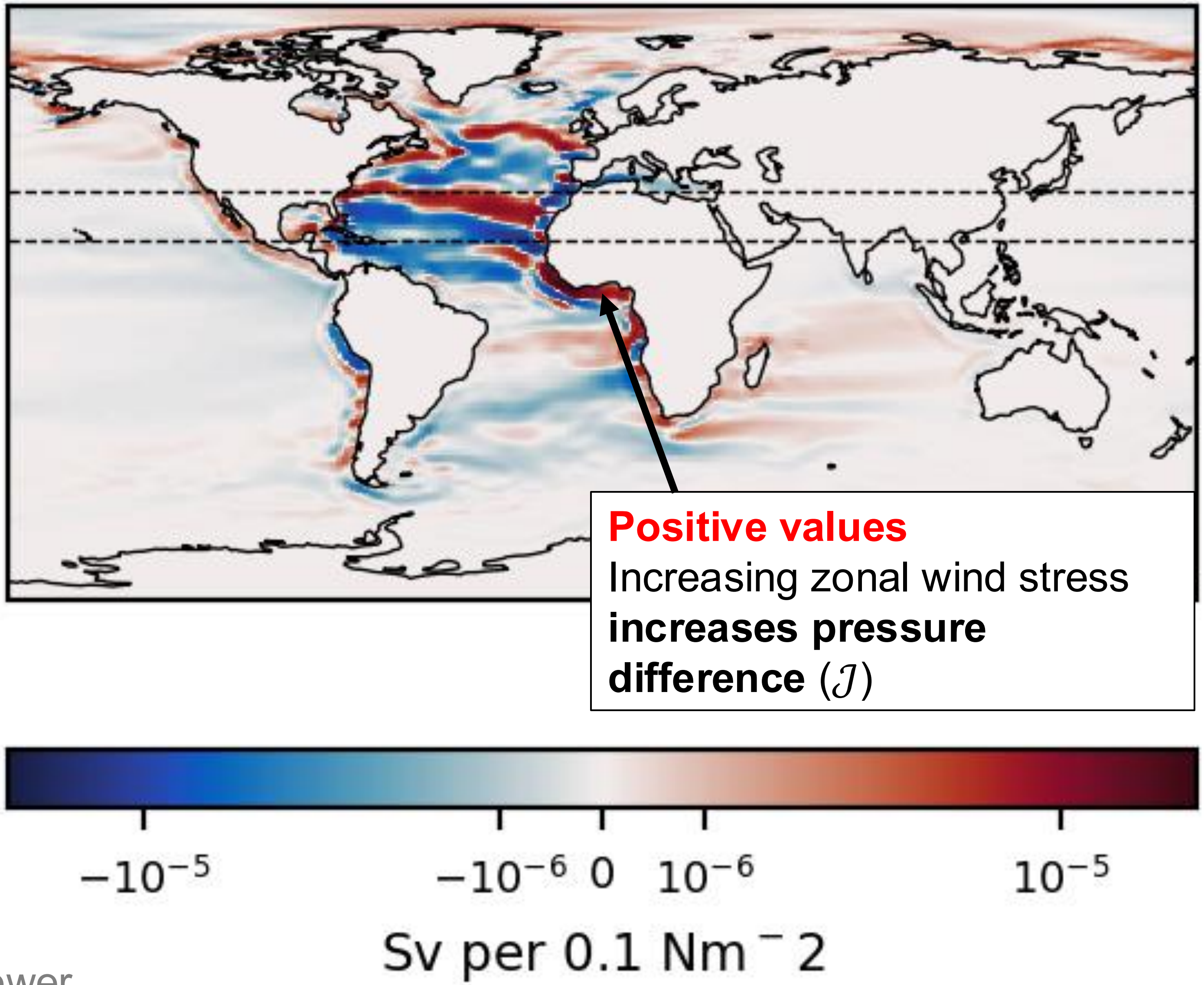
Results: RAPID Lower

18.75-33.75°N

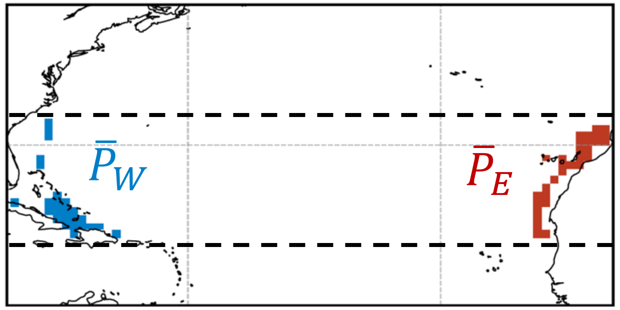
1000-3000 m depth

As featured in presentation

Sensitivity field: Zonal wind stress



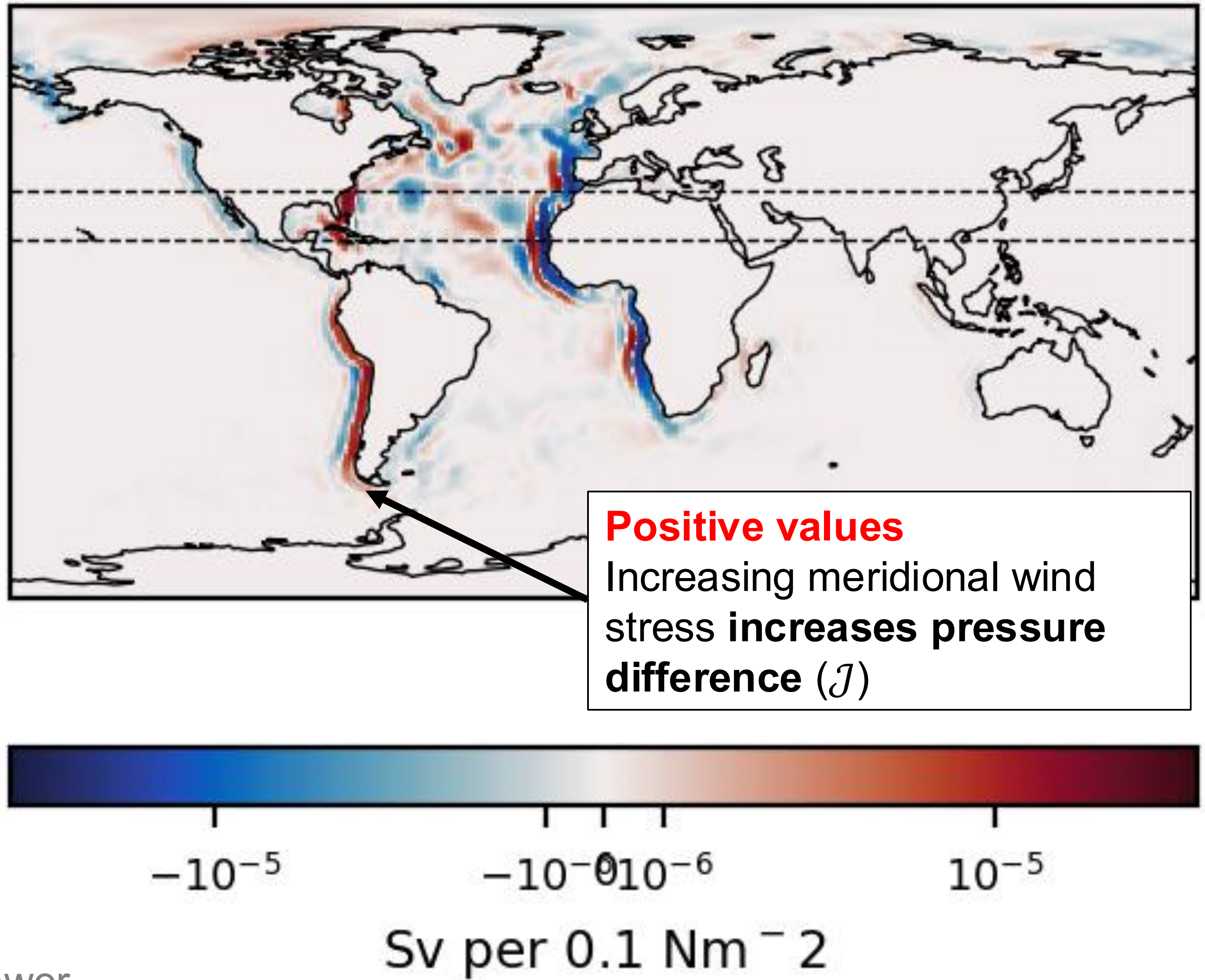
Sensitivity of pressure difference surrounding 26.5°N between 1000 and 3000m depth



$$\mathcal{J} = \overline{P}_E - \overline{P}_W$$

The shown sensitivity is **averaged** over all available lags (0-10 yrs)

Sensitivity field: Meridional wind stress



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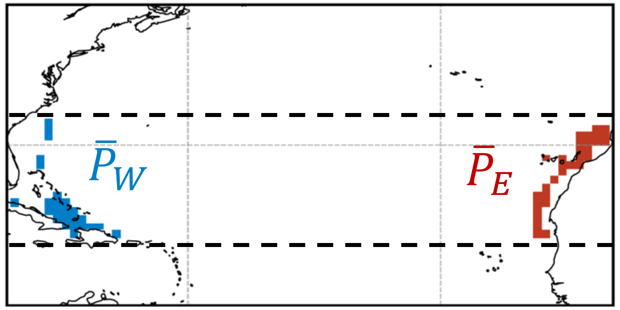

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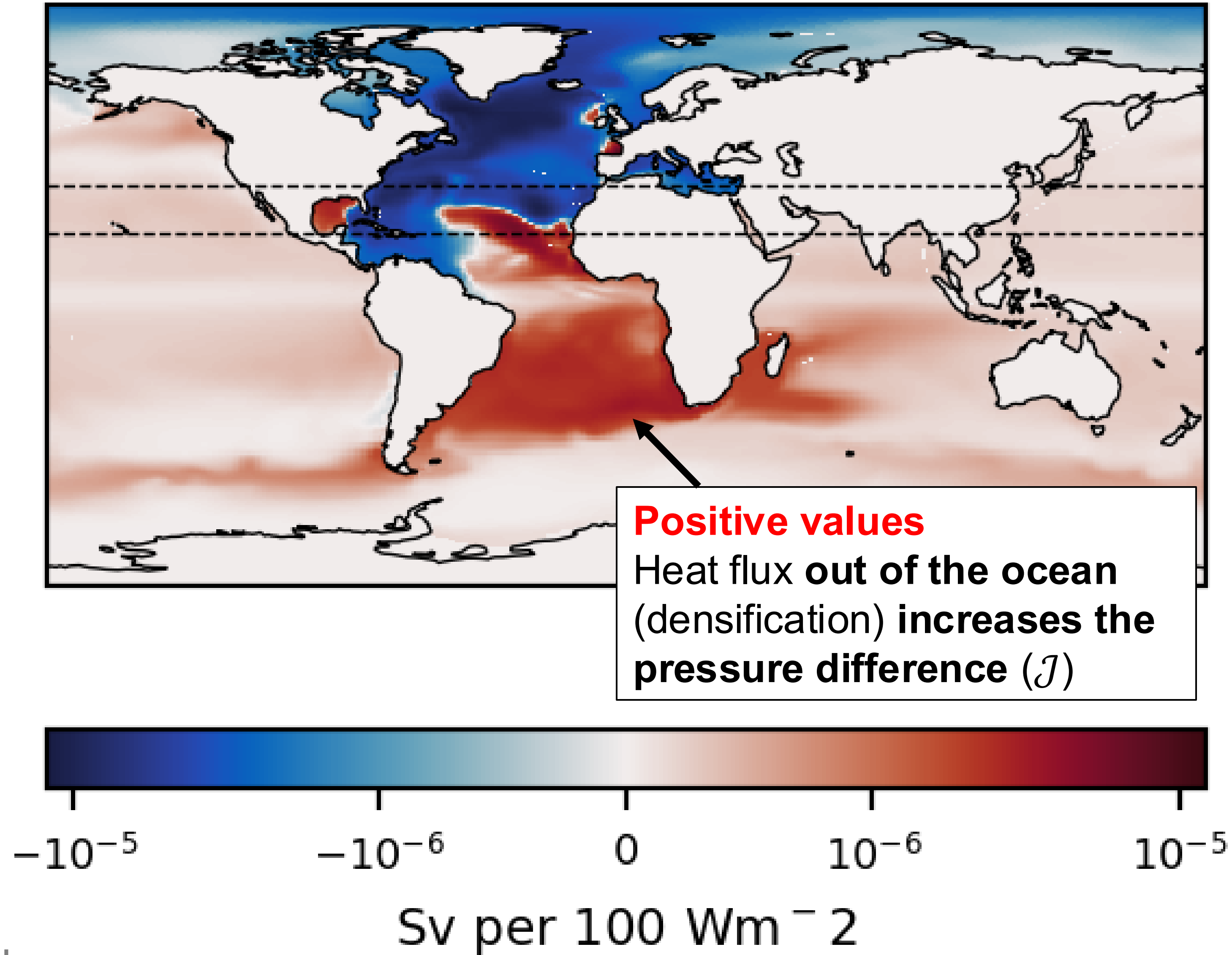
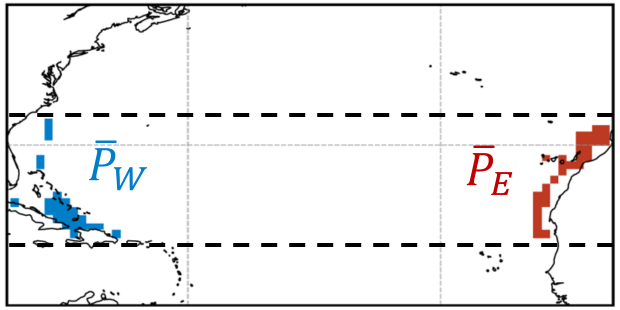
Sensitivity field: Heat flux



Positive values
Heat flux **out of the ocean** (densification) **increases the pressure difference** ($\mathcal{J}$)

Sensitivity of pressure difference surrounding 26.5°N between 1000 and 3000m depth



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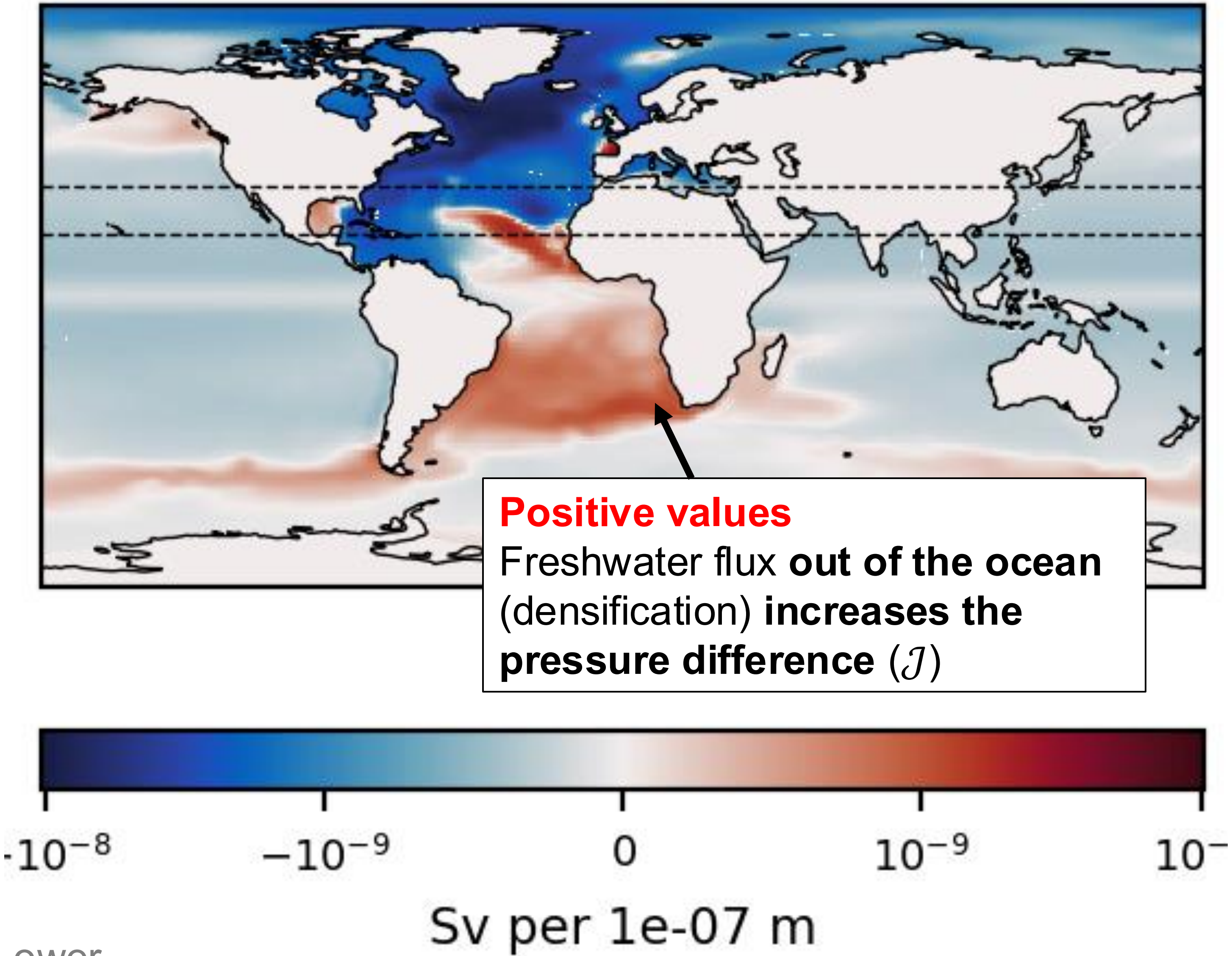
RAPID Lower

Sensitivity field: Freshwater flux



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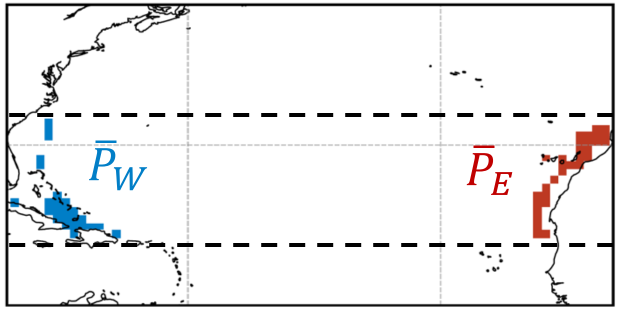

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The shown sensitivity is **averaged** over all available lags (0-10 yrs)

RAPID Lower

Reconstructions

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

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

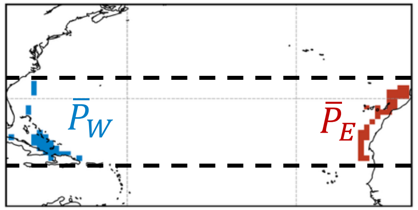
Reconstruction of the pressure anomaly at time t for the force $\mathcal{F}_i$

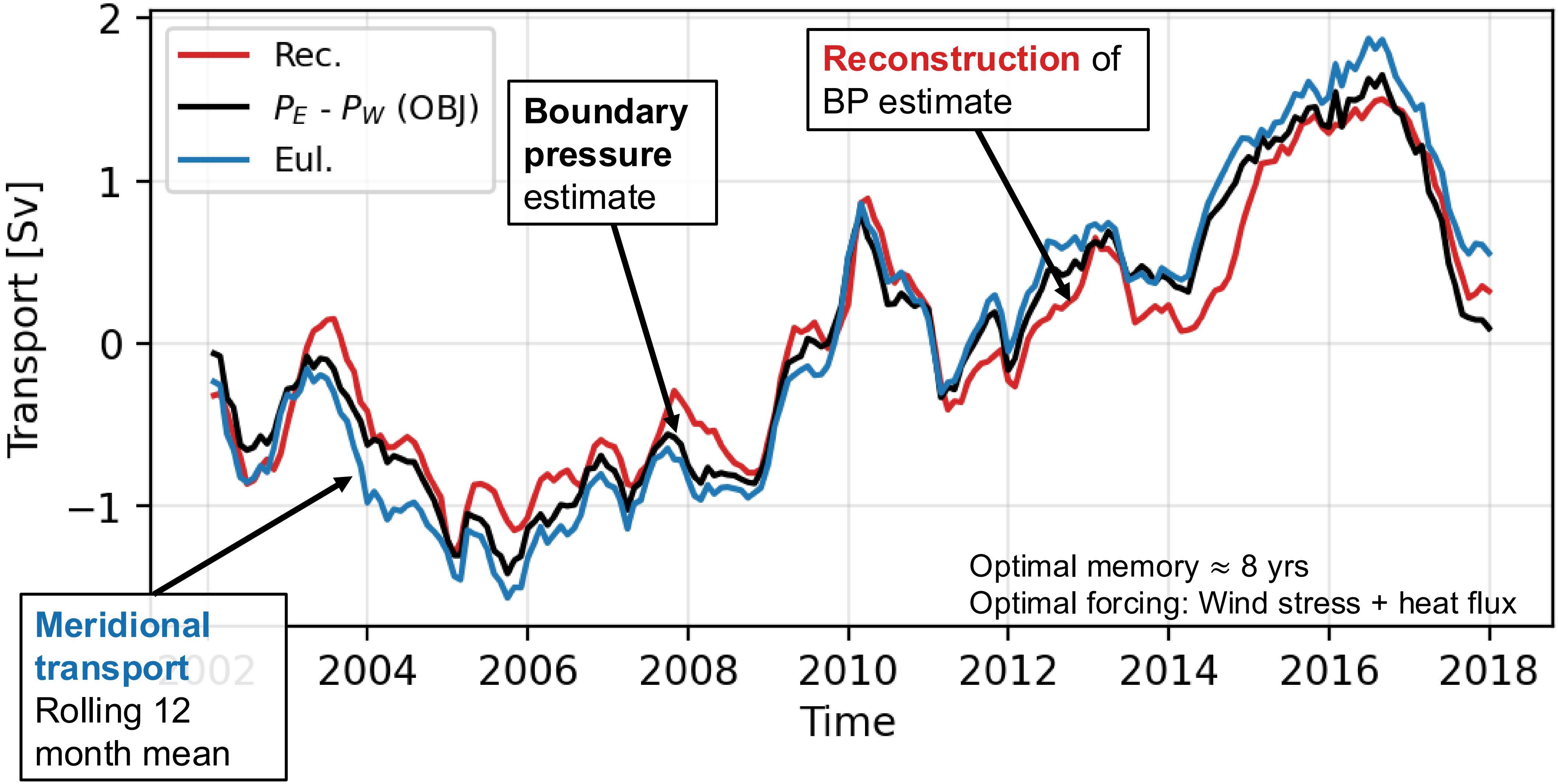
Approximate sensitivity of the pressure anomaly to forcing at time $t + t'$

Forcing anomaly at time $t + t'$

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

Optimal Reconstruction



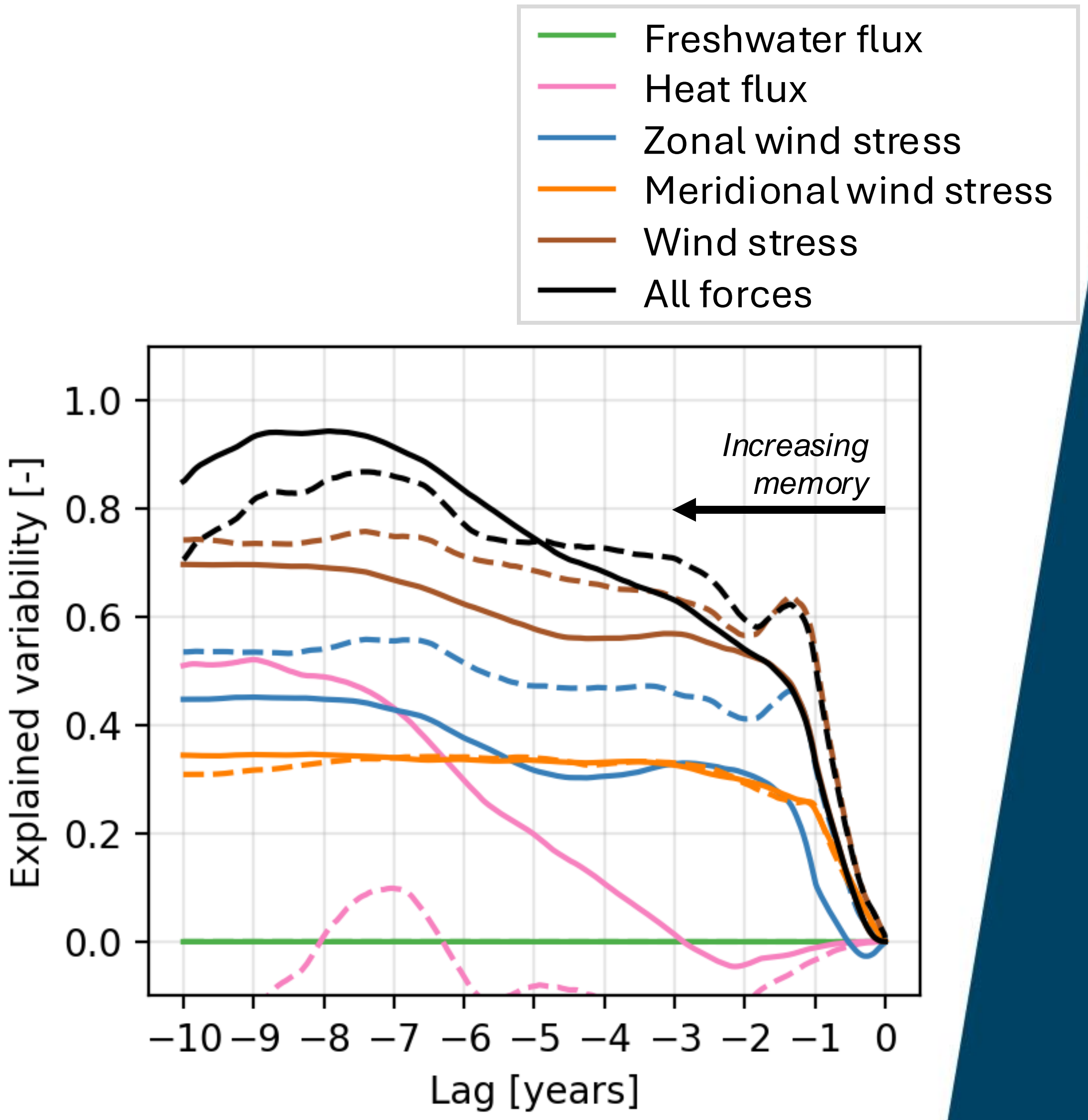


RAPID Lower

Explained variability

A reconstruction can be modified to include different **forces** and different amounts of lag (**memory**)

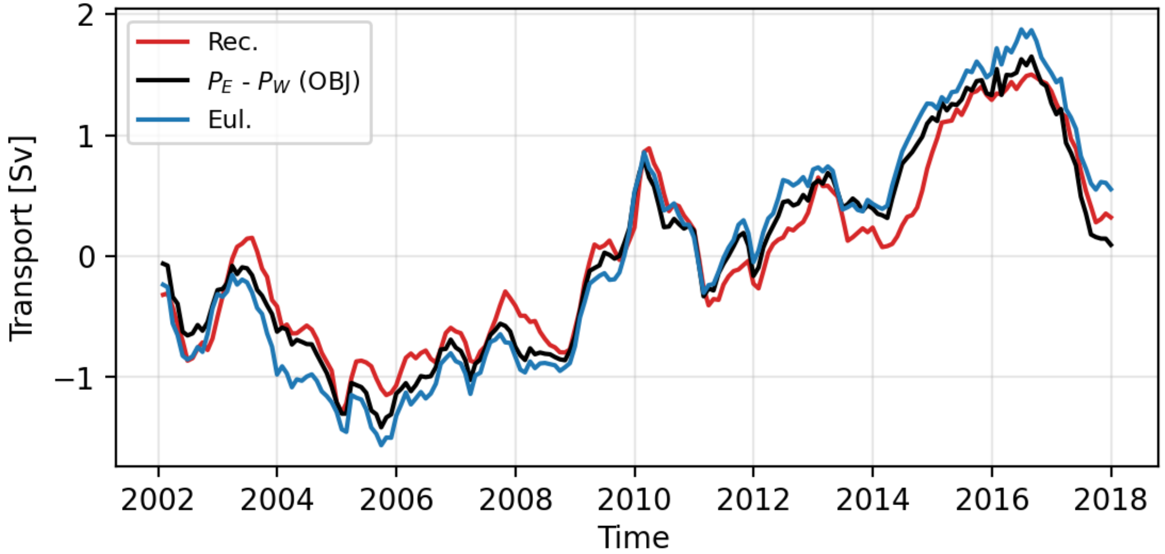
Identifying the optimal combination of forces and memory indicates the **relevant forces** and **timescales**



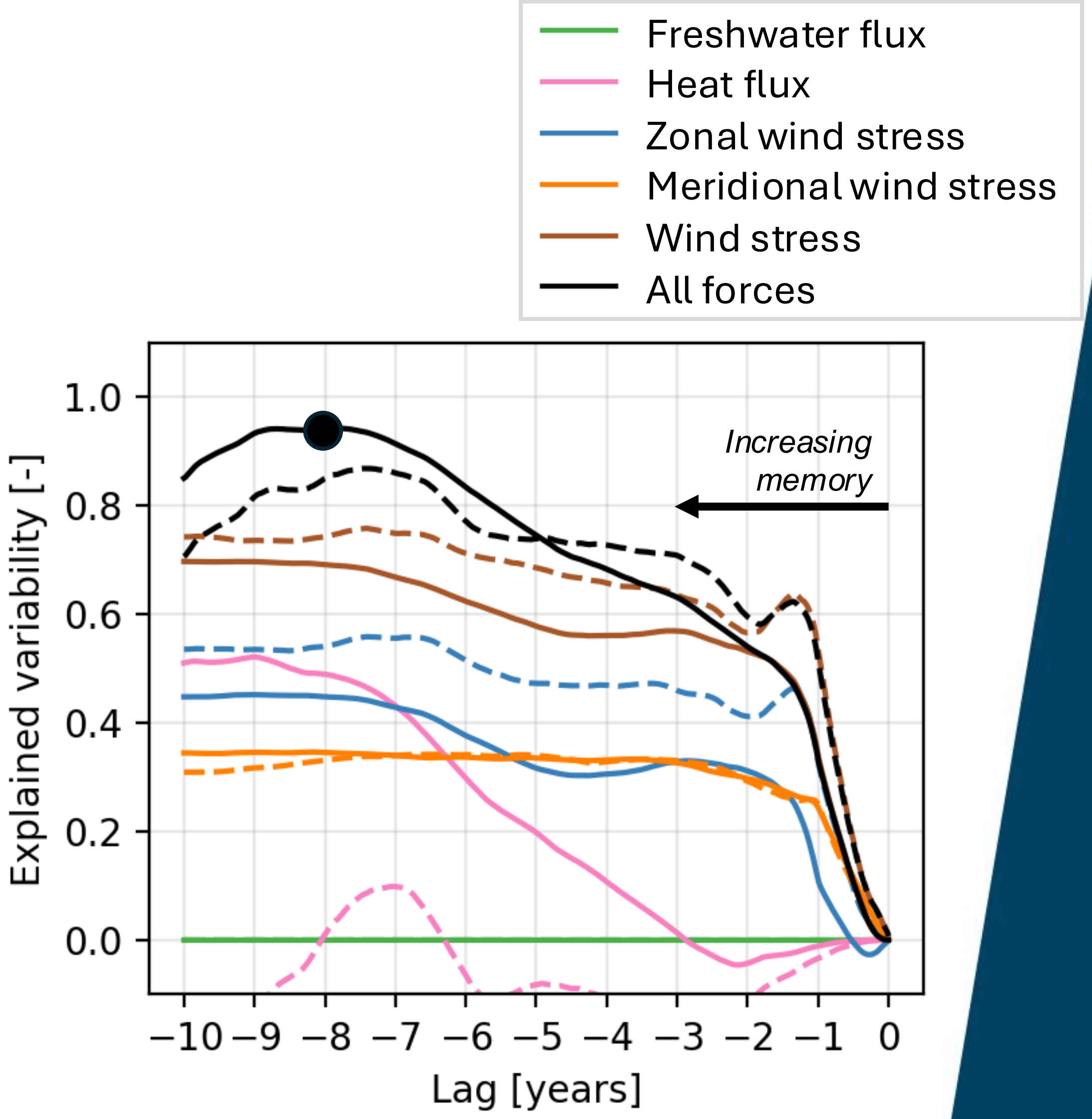
Explained variability of the reconstruction as a function of memory. Dashed lines represent the explained variability once the timeseries has been ***detrended***

Explained variability

Optimal reconstruction: Wind and Heat flux



The **optimal reconstruction** explains **90%** of the variability and needs a memory of **7-8 years.**



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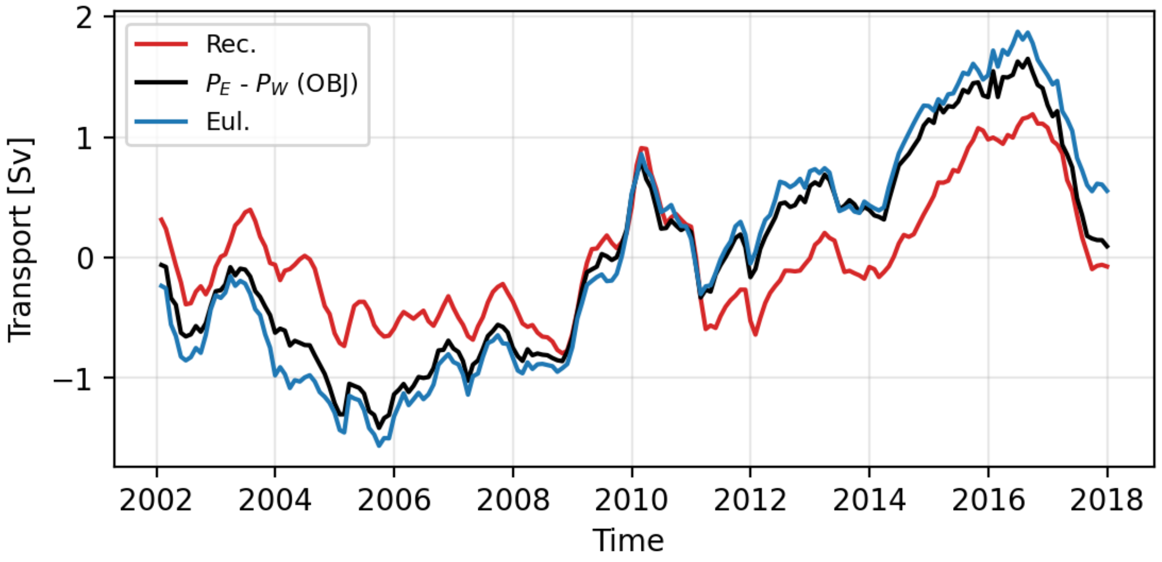
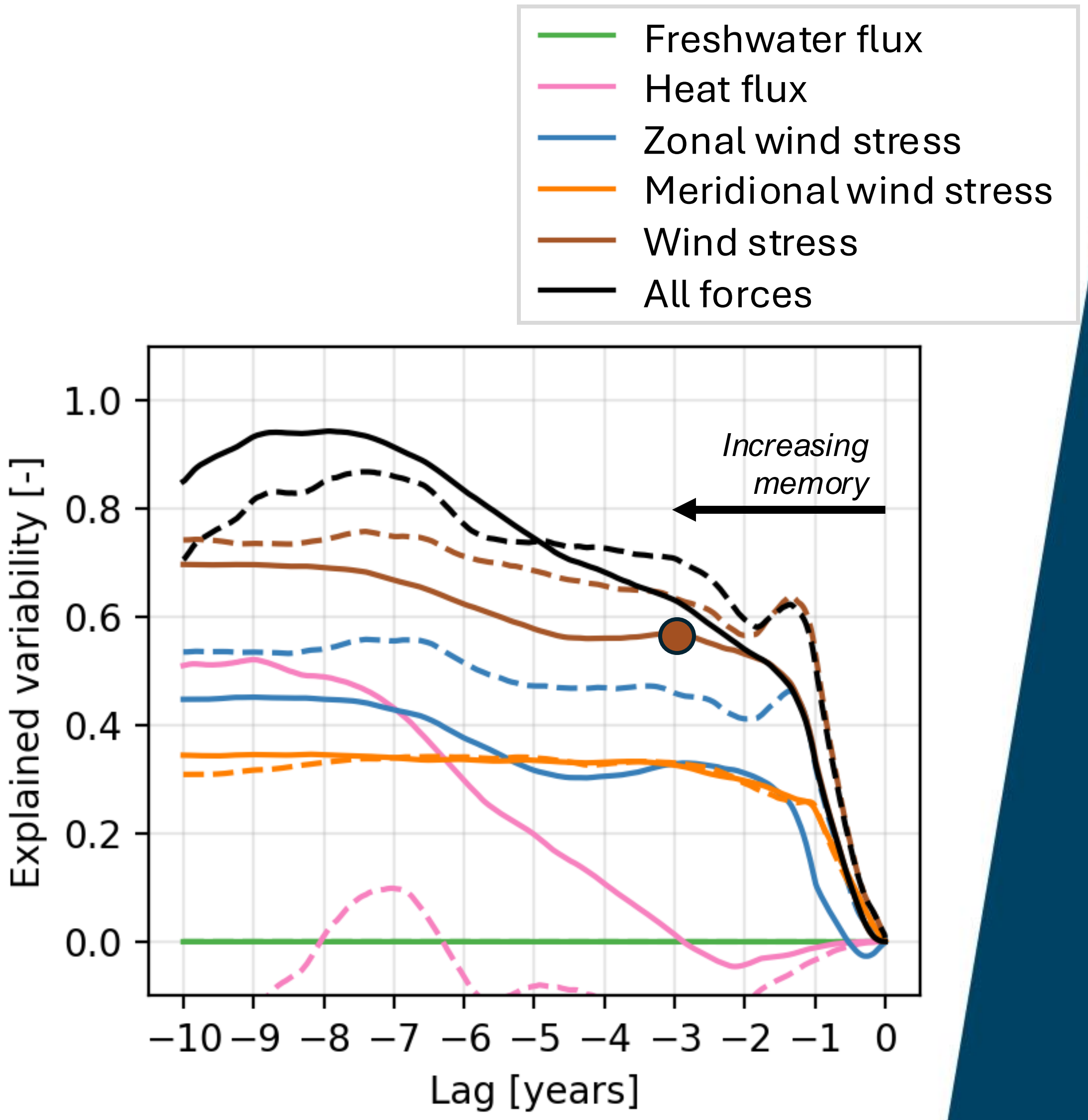
RAPID Lower

Explained variability

Optimal reconstruction: **Wind** only



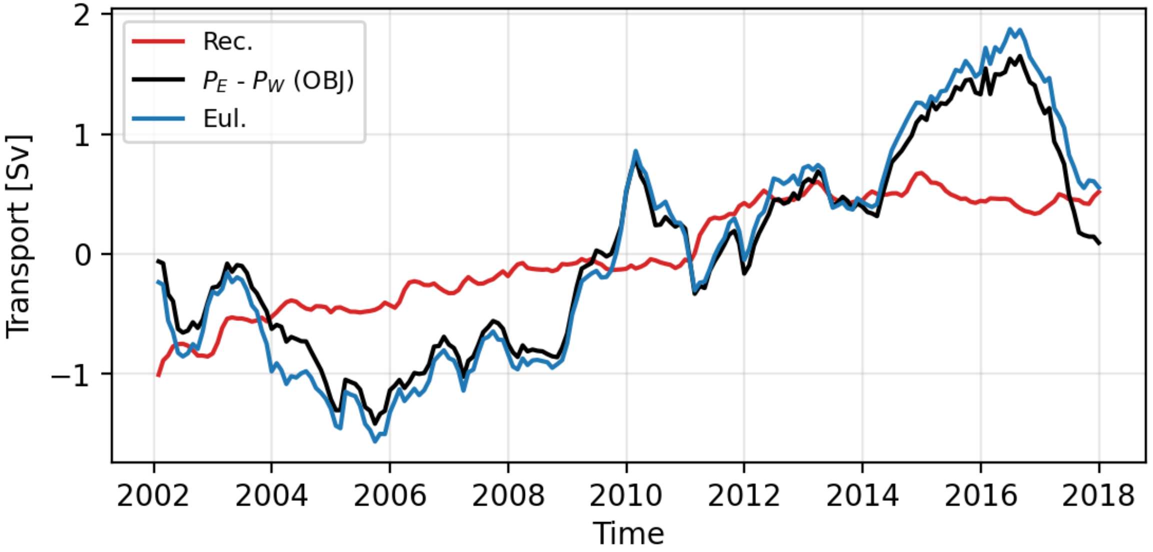
A **wind-based** reconstruction explains **60-70%** of the variability and needs a minimum memory of **3 years.**



Explained variability of the reconstruction as a function of memory. Dashed lines represent the explained variability once the timeseries has been ***detrended***

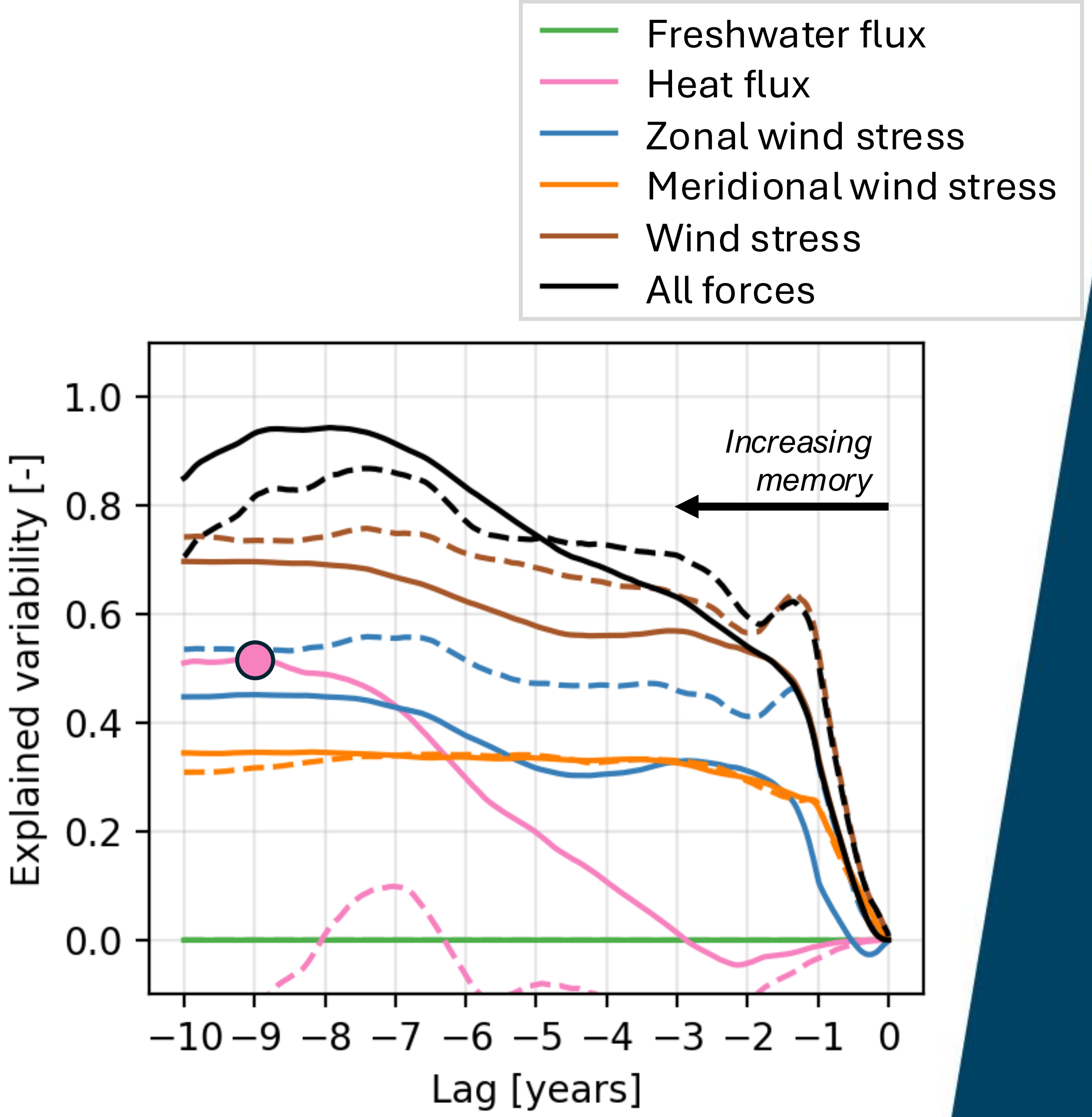
Explained variability

Optimal reconstruction: Heat flux only



A **heat-based** reconstruction explains **50%** of the variability and needs a minimum memory of **7 years**

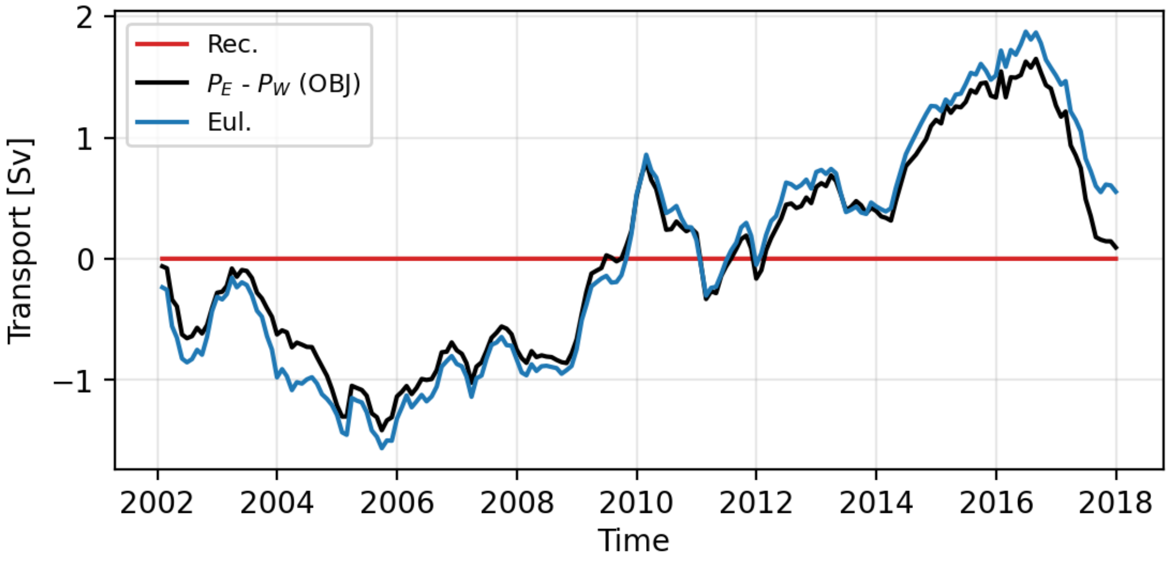
Heat fluxes are mostly reconstructing **the trend**



Explained variability of the reconstruction as a function of memory. Dashed lines represent the explained variability once the timeseries has been ***detrended***

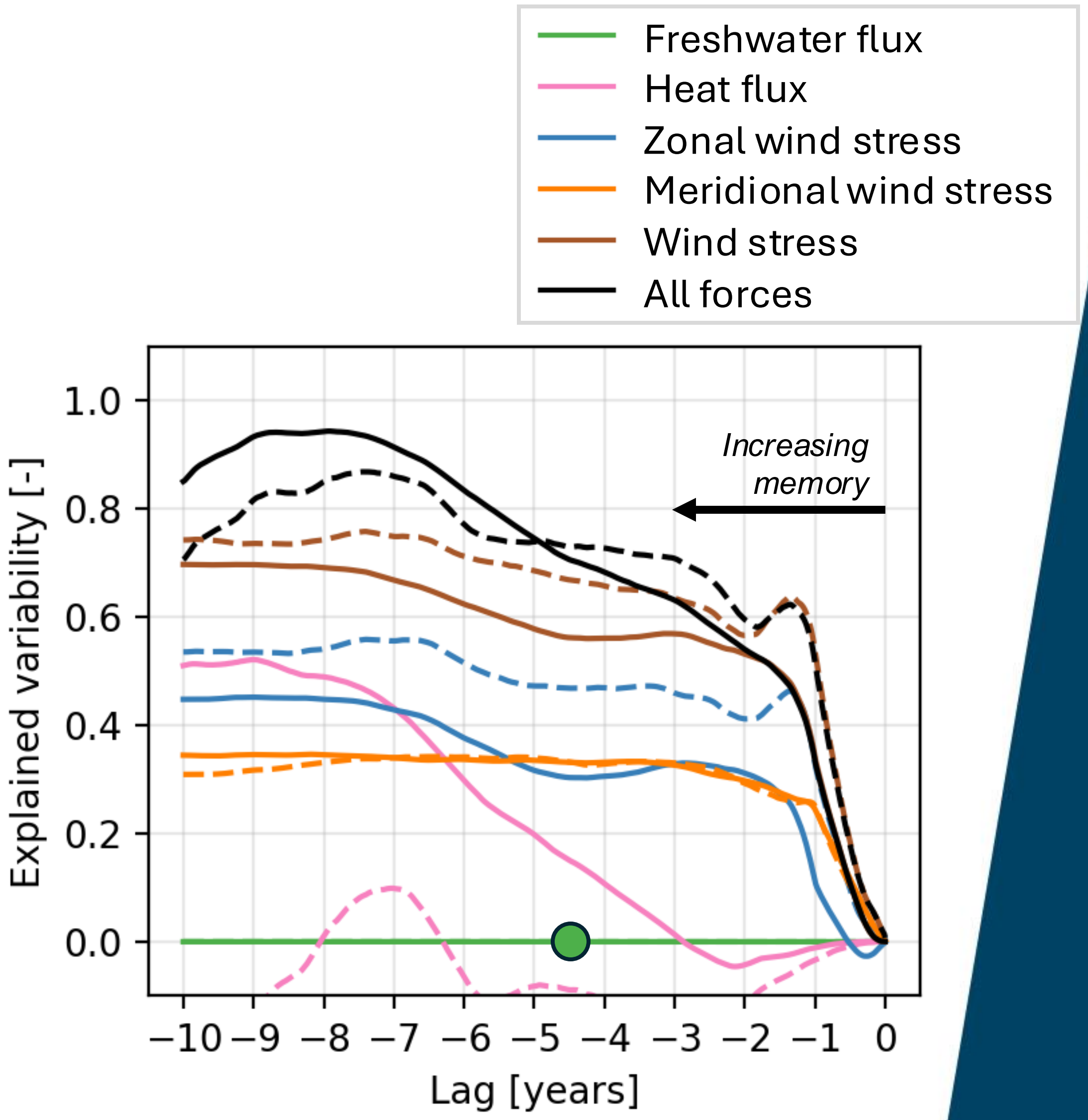
Explained variability

Optimal reconstruction: Freshwater flux only



Freshwater fluxes do not contribute to the reconstruction at all.

A **longer memory** may be required



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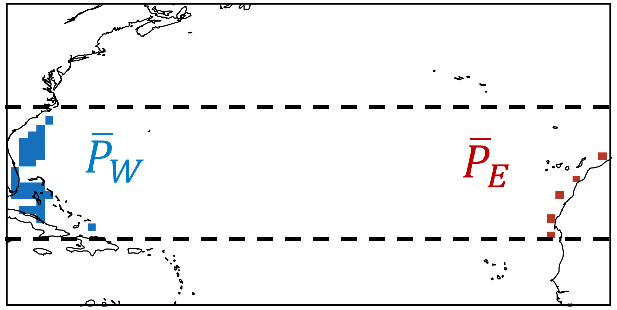


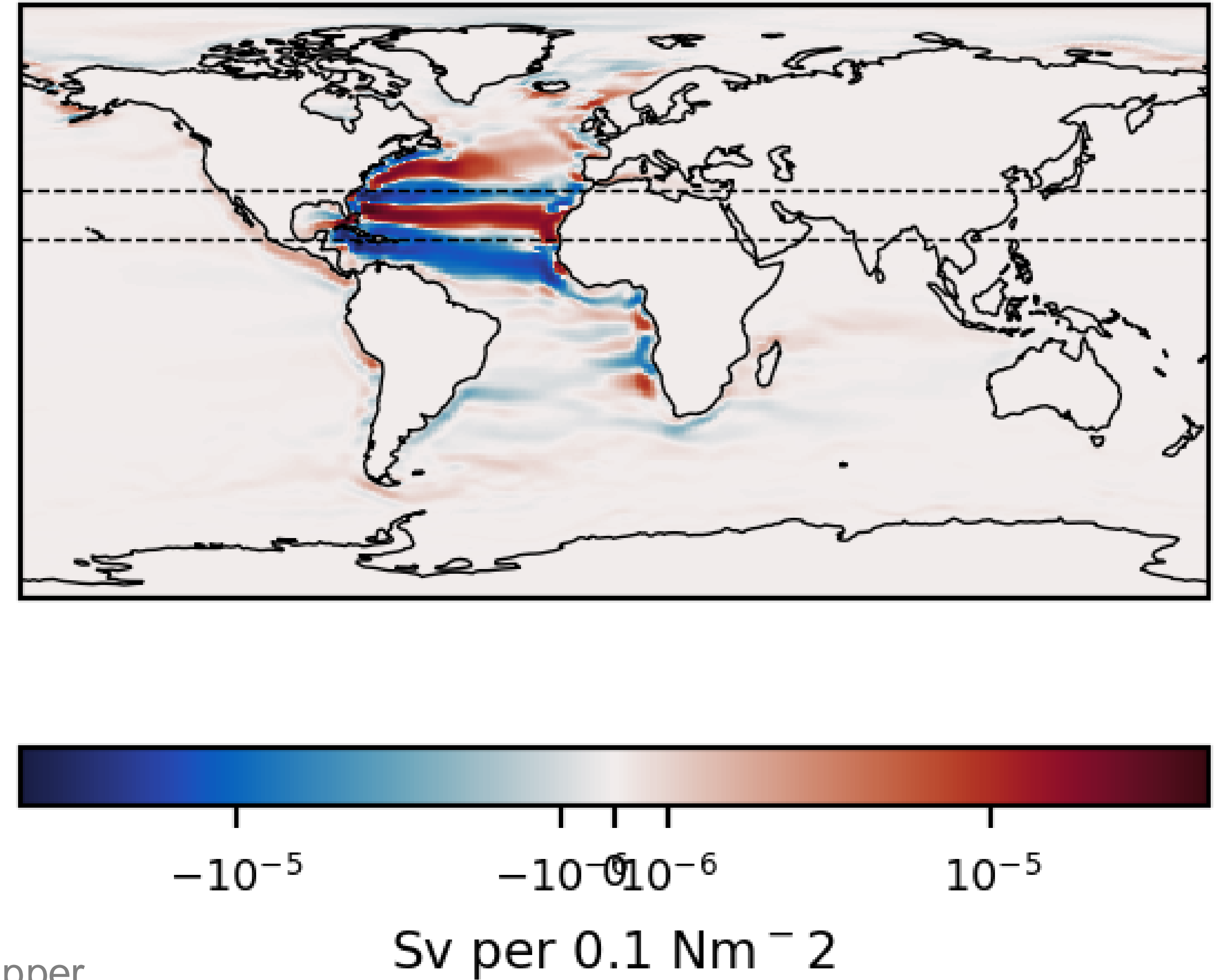
$$\mathcal{J} = \bar{P}_E - \bar{P}_W$$

Results: RAPID Upper

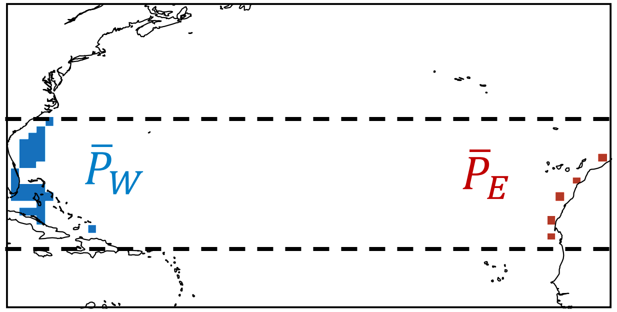
18.75-33.75°N

250-1000 m depth

Sensitivity field: Zonal wind stress



Sensitivity of pressure difference surrounding 26.5°N between 250 and 1000m depth

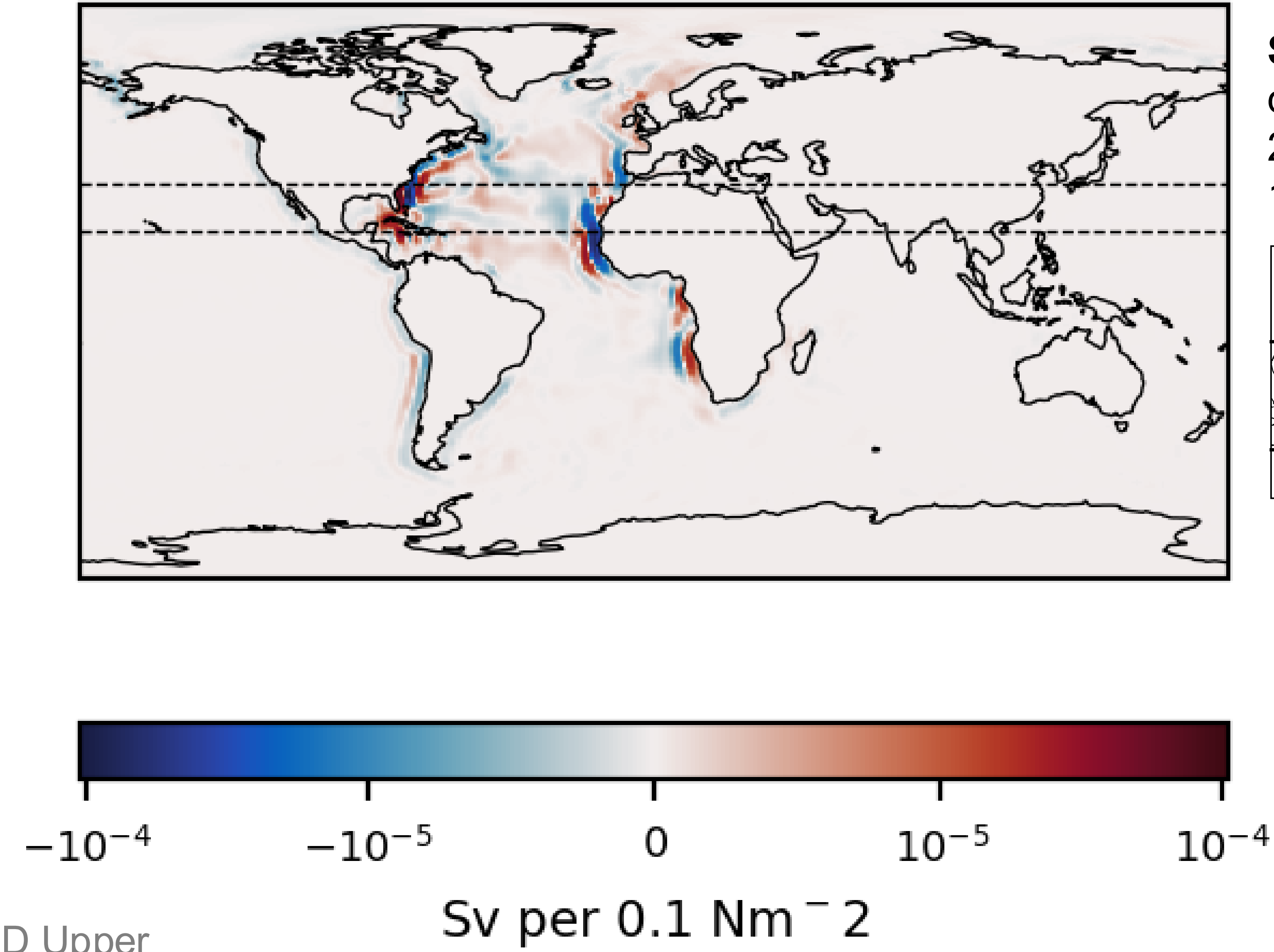


$$\mathcal{J} = \bar{P}_E - \bar{P}_W$$

The shown sensitivity is **averaged** over all available lags (0-10 yrs)

RAPID Upper

Sensitivity field: Meridional wind stress



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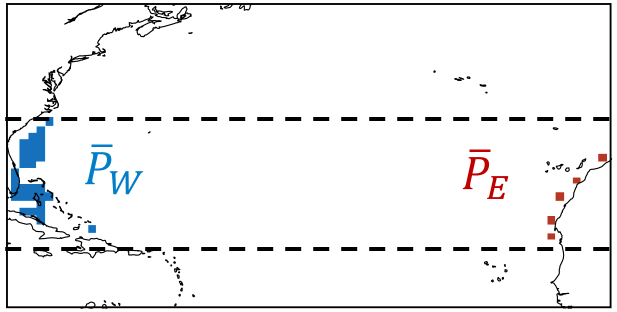

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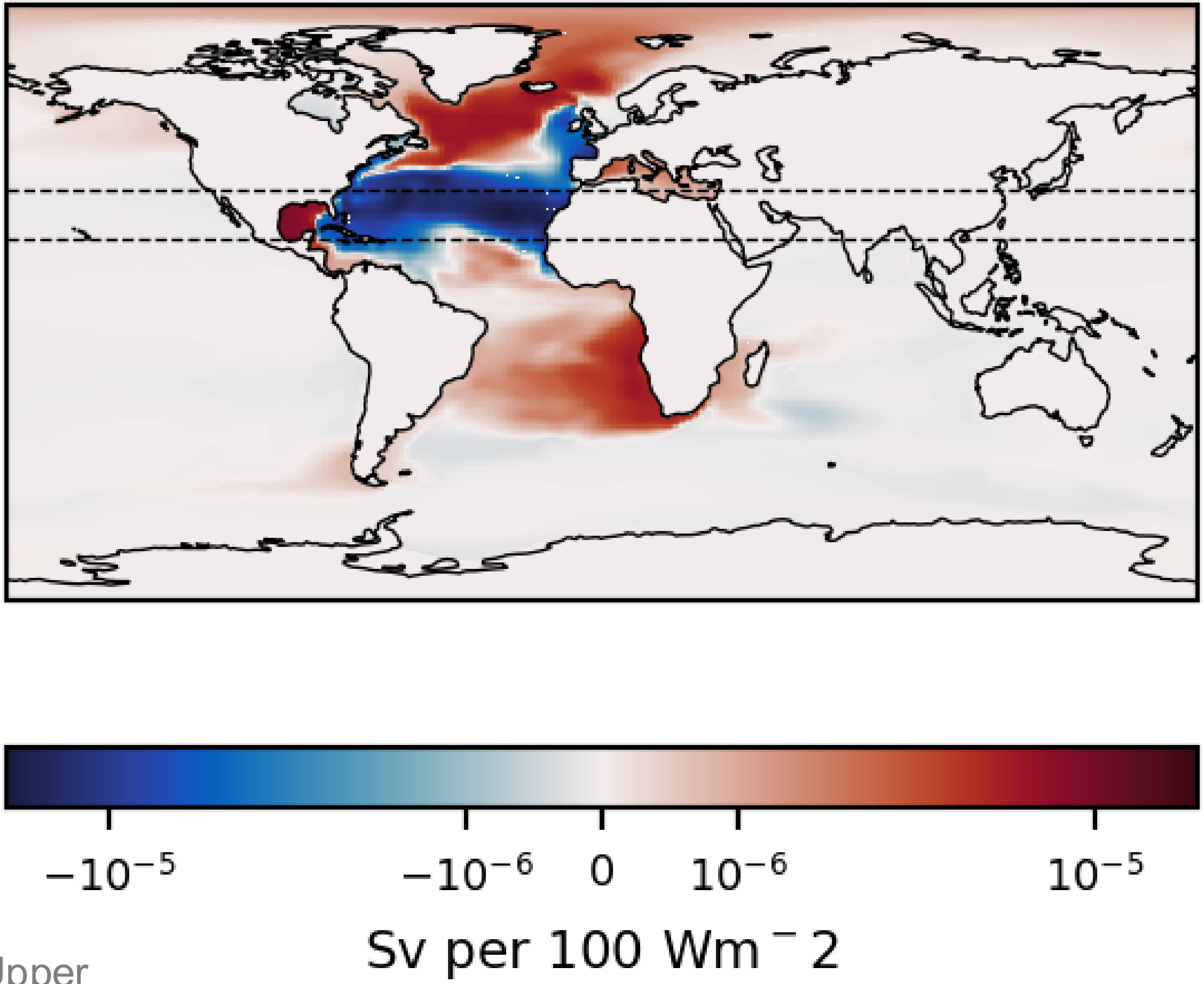
RAPID Upper

Sensitivity field: Heat flux



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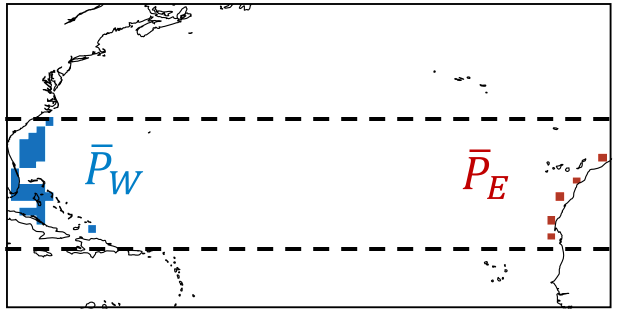
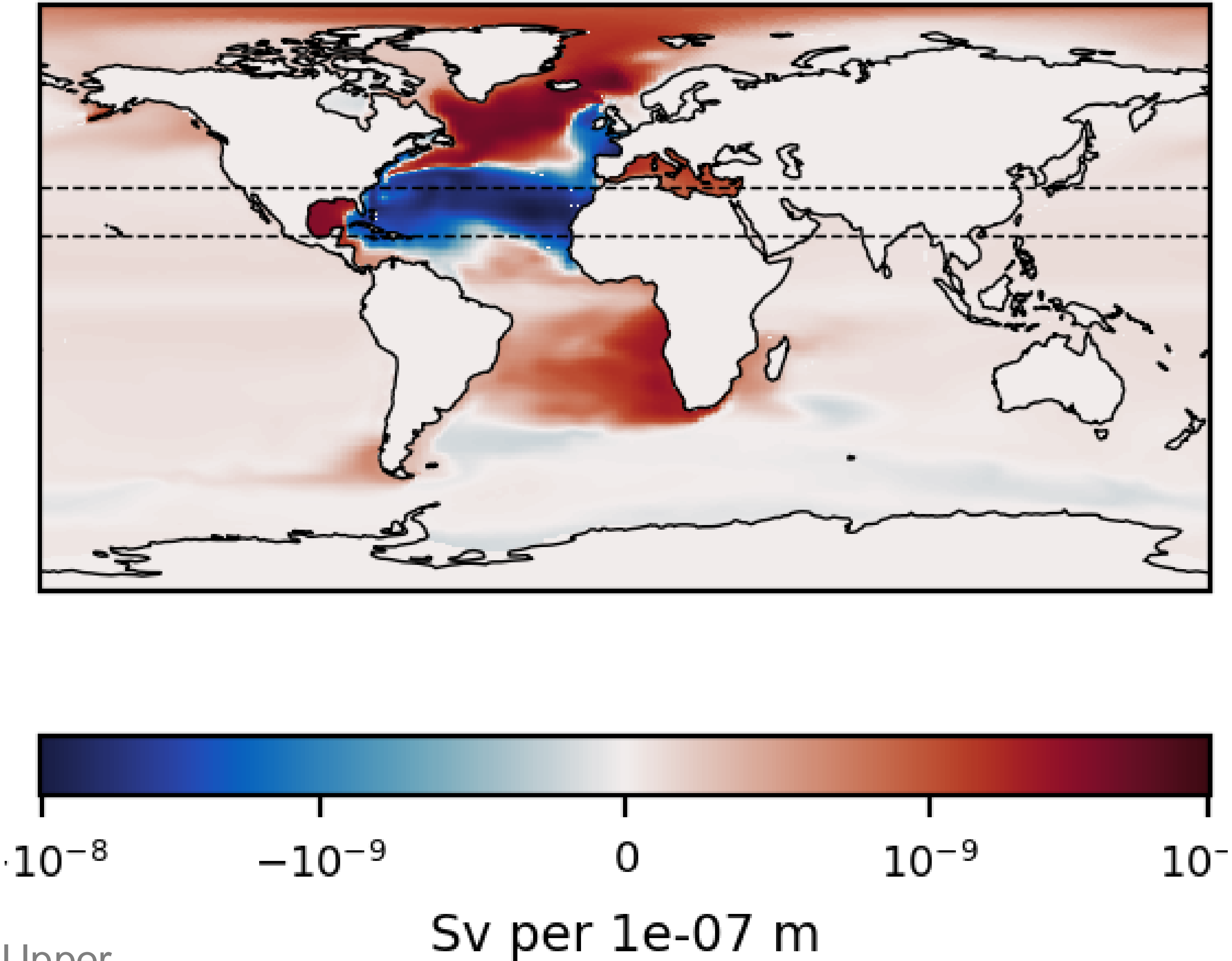


$$\mathcal{J} = \bar{P}_E - \bar{P}_W$$

The shown sensitivity is **averaged** over all available lags (0-10 yrs)

Sensitivity field: Freshwater flux



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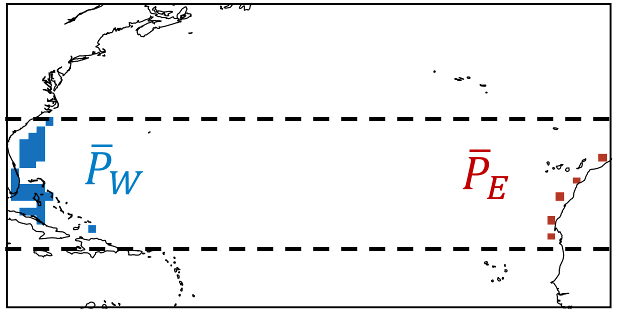

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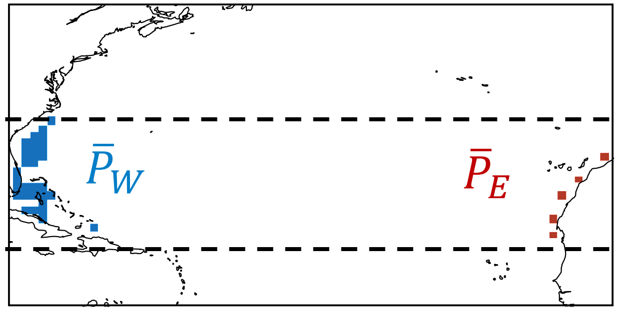
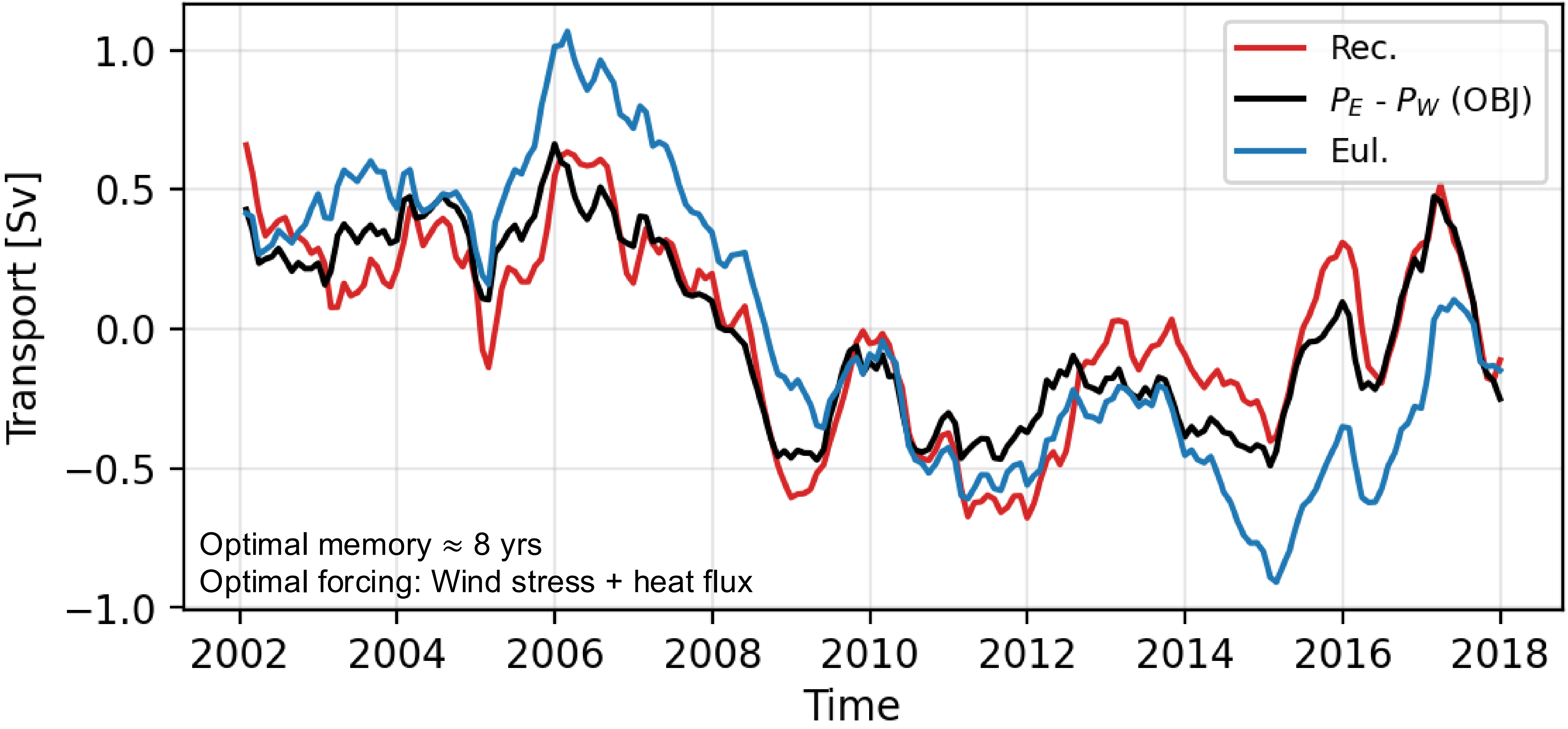
RAPID Upper

Optimal Reconstruction

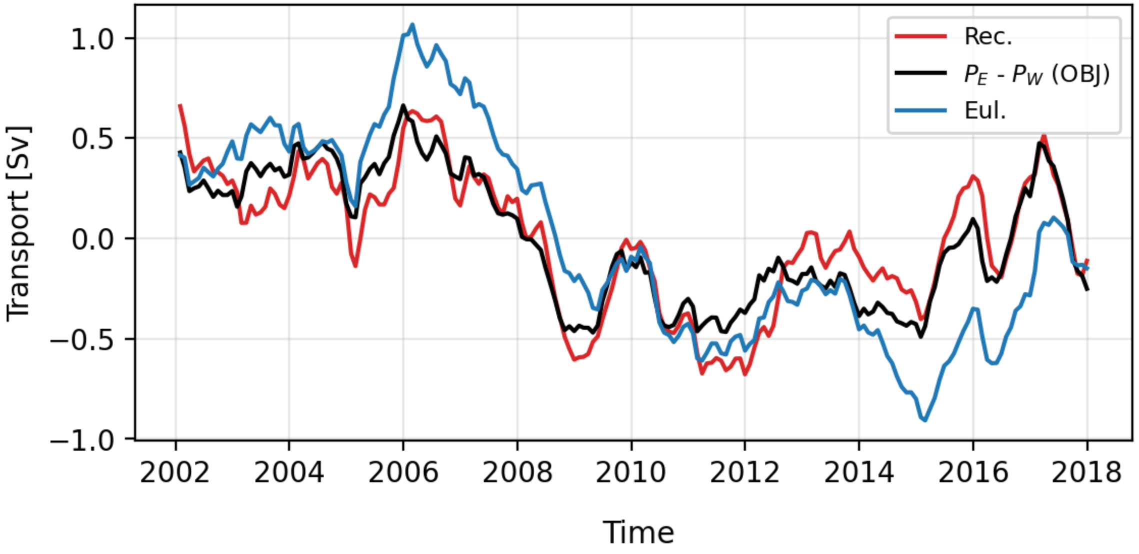




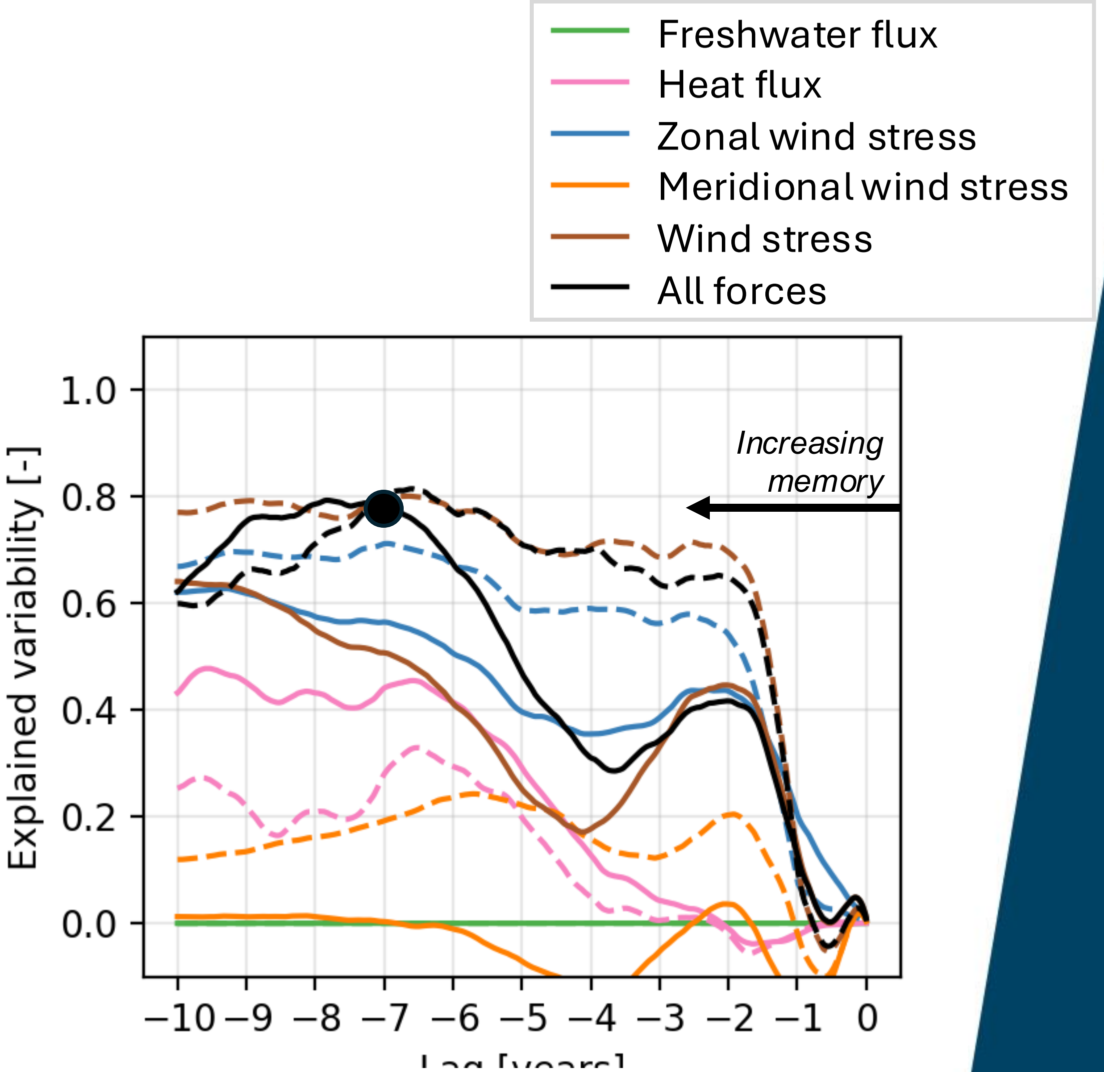
RAPID Upper

Explained variability

Optimal reconstruction: Wind and Heat flux



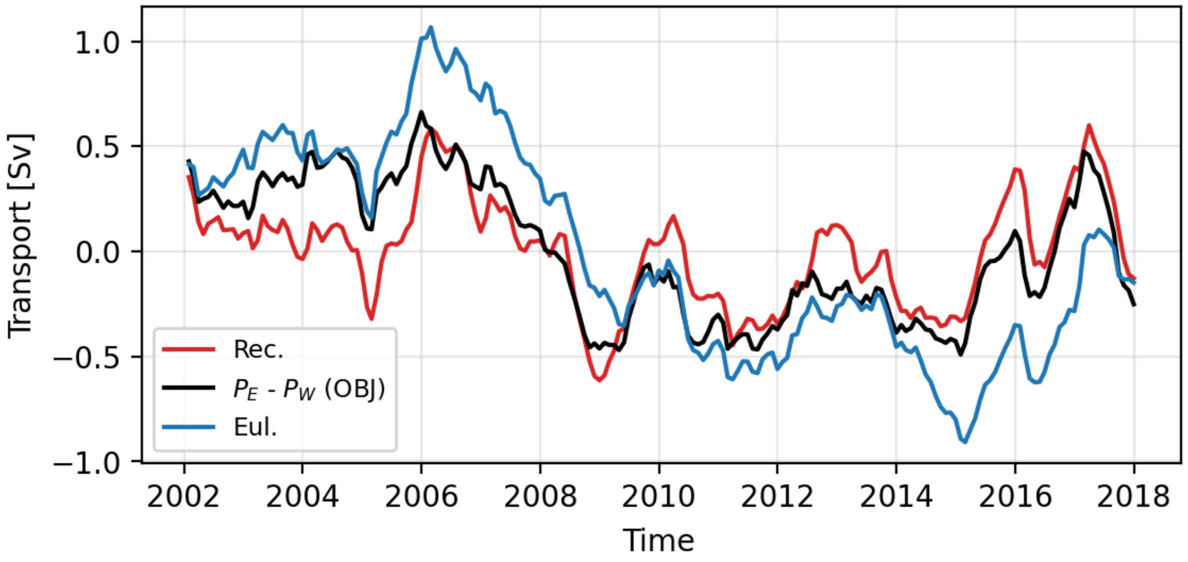
The **optimal reconstruction** explains **80%** of the variability and needs a memory of **7-8 years.**

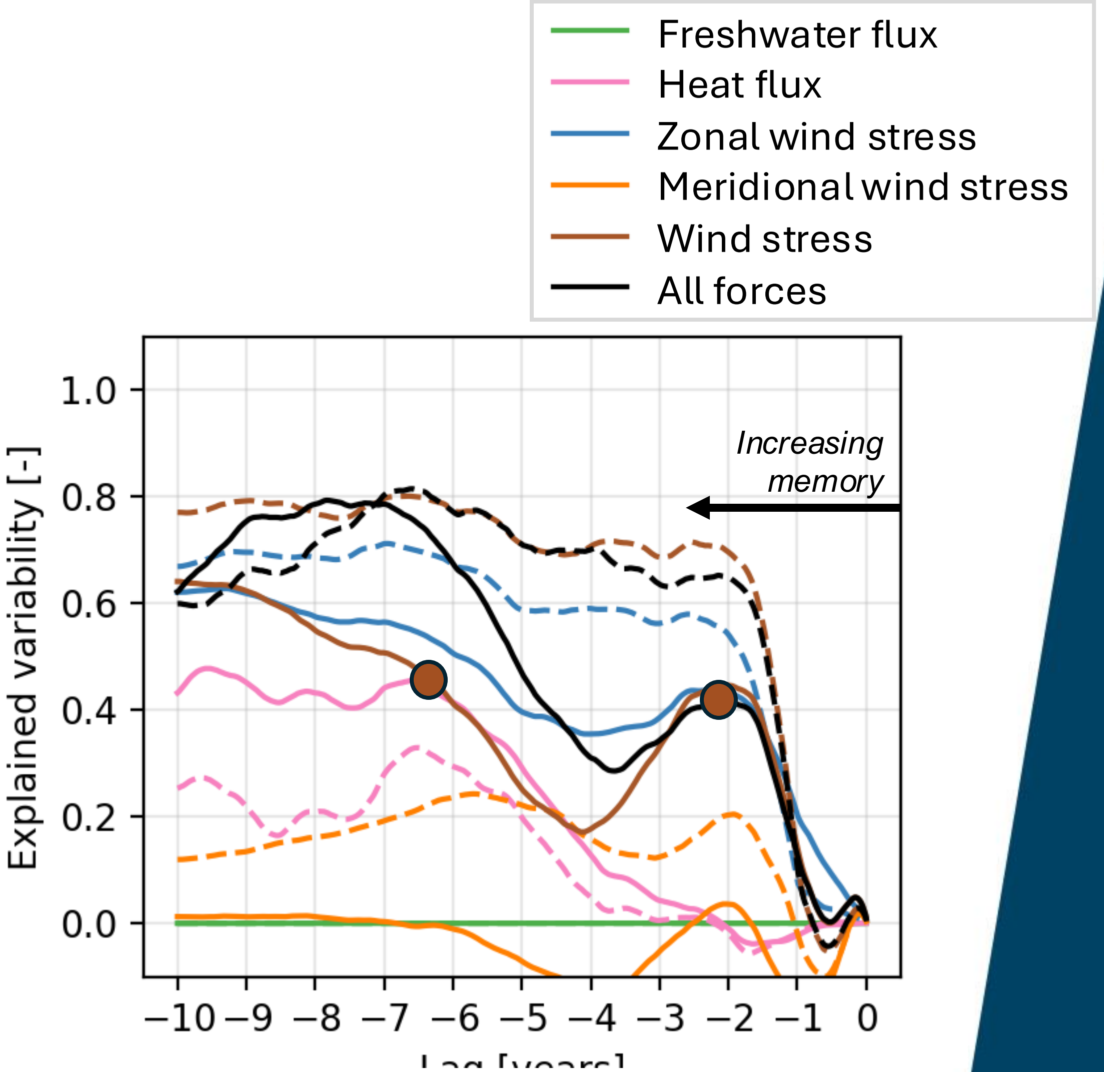


Explained variability of the reconstruction as a function of memory. Dashed lines represent the explained variability once the timeseries has been ***detrended***

Explained variability

Optimal reconstruction: Winds only



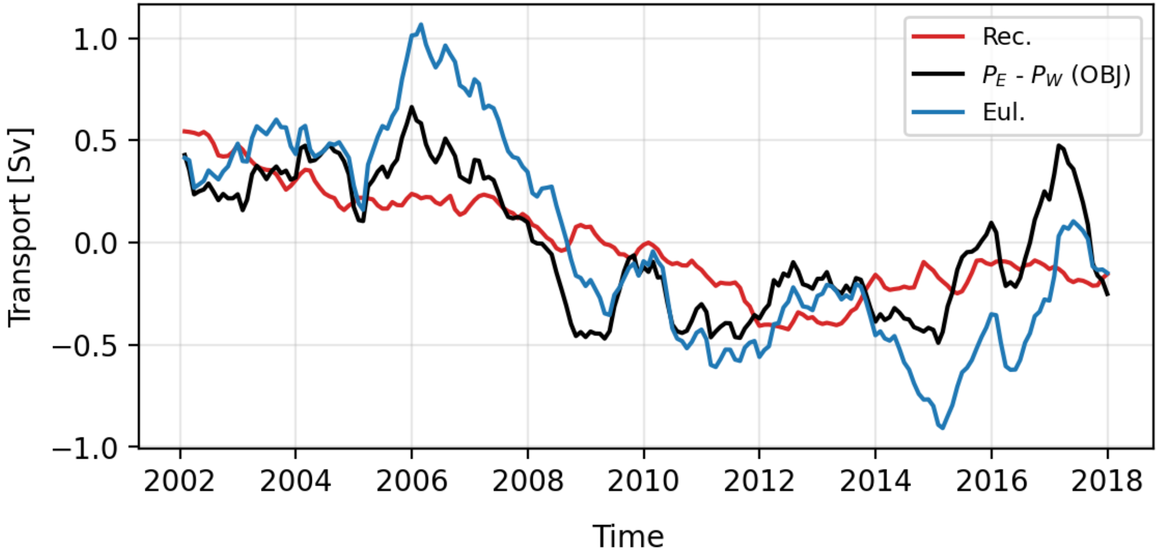


A **wind-based** reconstruction explains **40-60%** of the variability and needs a minimum memory of **2-3 years** or **6 years**

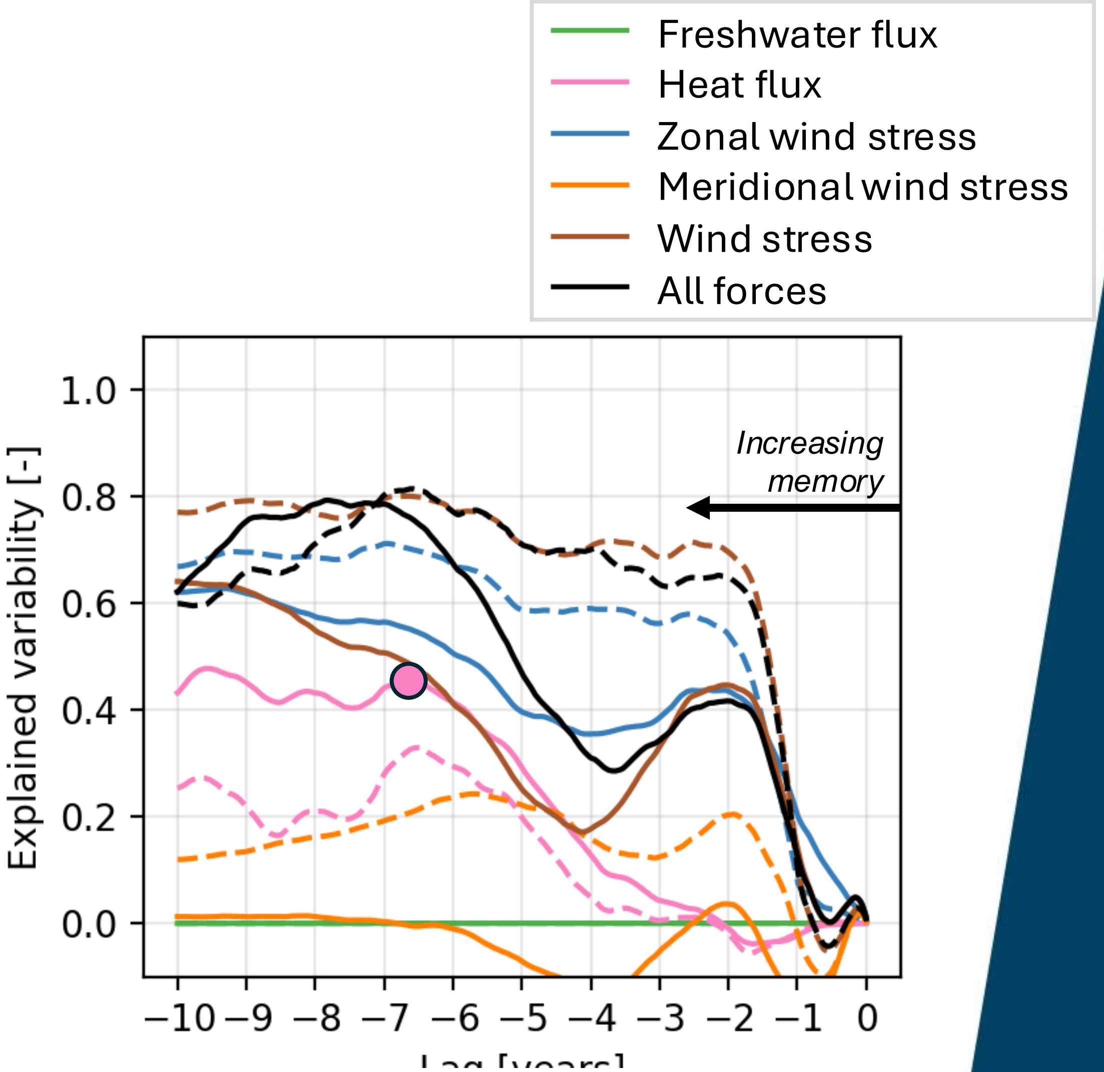
Explained variability of the reconstruction as a function of memory. Dashed lines represent the explained variability once the timeseries has been ***detrended***

Explained variability

Optimal reconstruction: Heat flux only



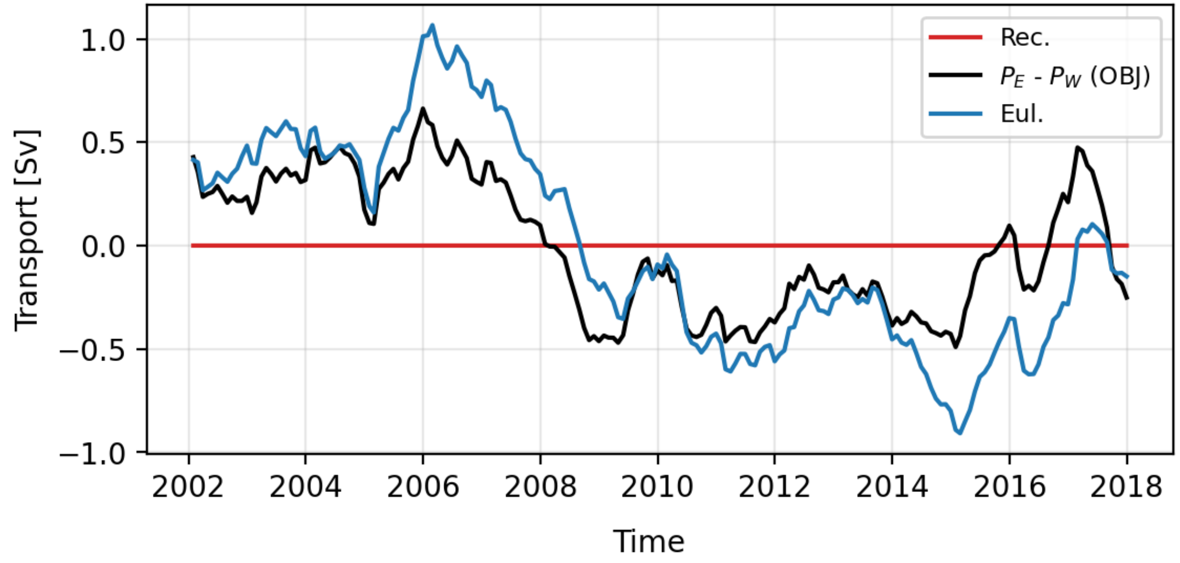
A heat-based reconstruction explains approximately **40% of the variability** and requires a minimum memory of **6-7 years**

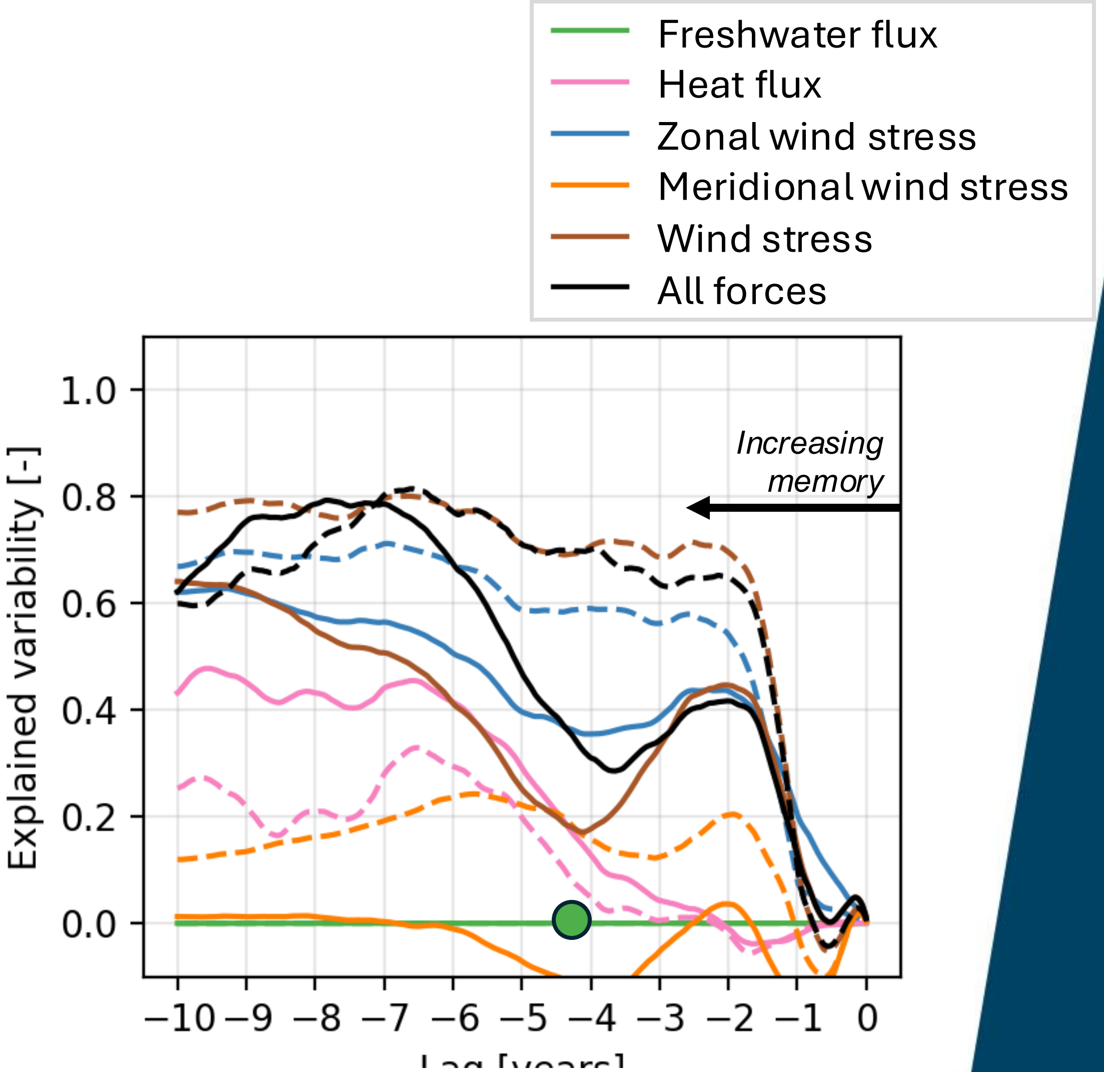


Explained variability of the reconstruction as a function of memory. Dashed lines represent the explained variability once the timeseries has been ***detrended***

Explained variability

Optimal reconstruction: **Freshwater flux** only

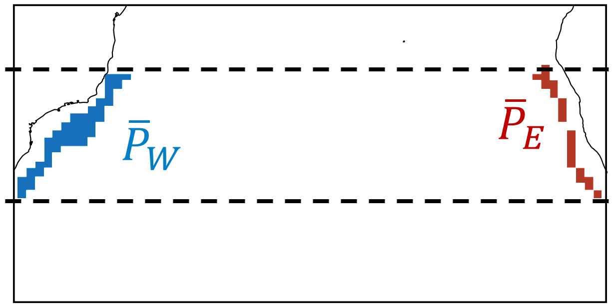




Explained variability of the reconstruction as a function of memory. Dashed lines represent the explained variability once the timeseries has been ***detrended***

Freshwater fluxes do not contribute to the reconstruction at all.

A **longer memory** may be required



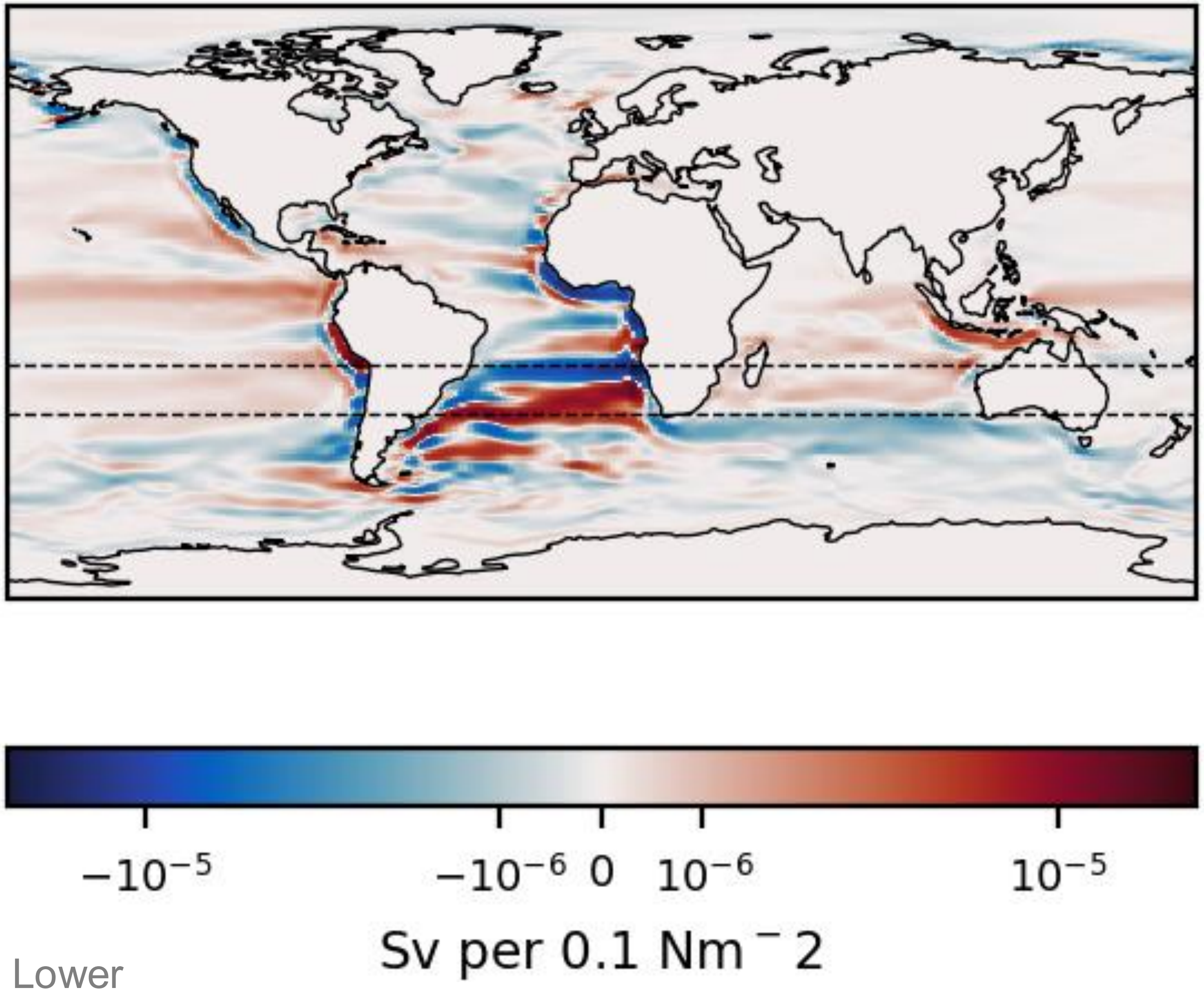
$$\mathcal{J} = \bar{P}_E - \bar{P}_W$$

Results: S-RAPID Lower

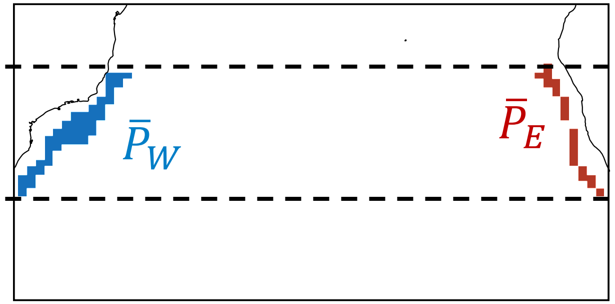
18.75-33.75°S

1200-3000 m depth

Sensitivity field: Zonal wind stress



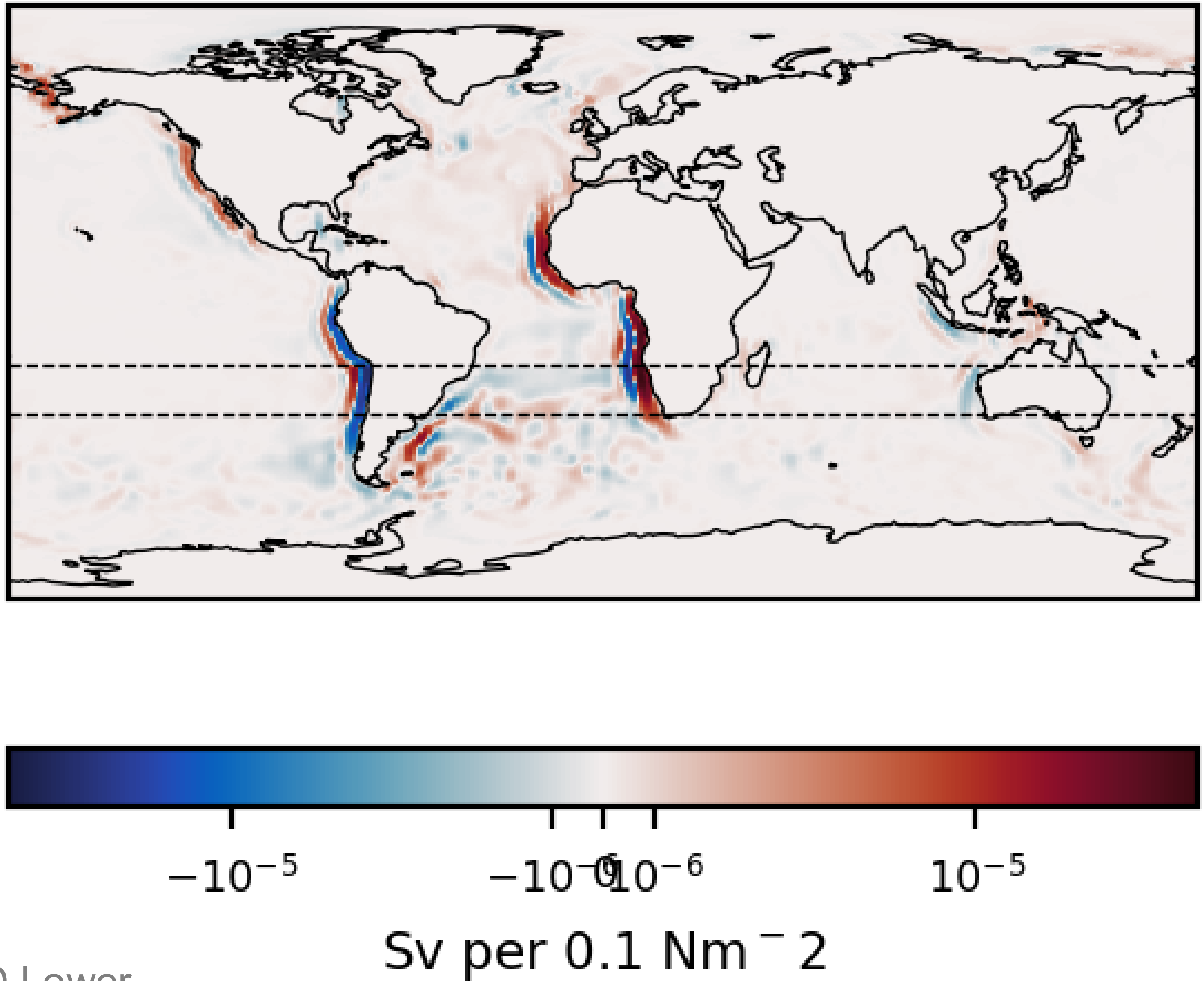
Sensitivity of pressure difference surrounding 26.5°S between 1200 and 3000m depth



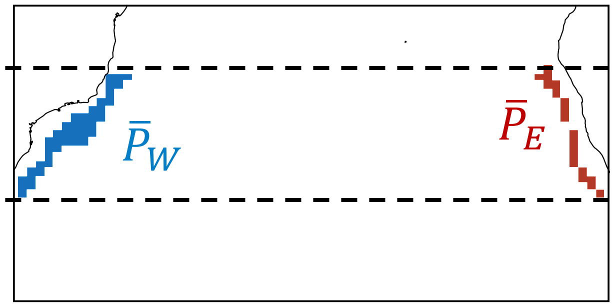
$$\mathcal{J} = \bar{P}_E - \bar{P}_W$$

The shown sensitivity is **averaged** over all available lags (0-10 yrs)

Sensitivity field: Meridional wind stress



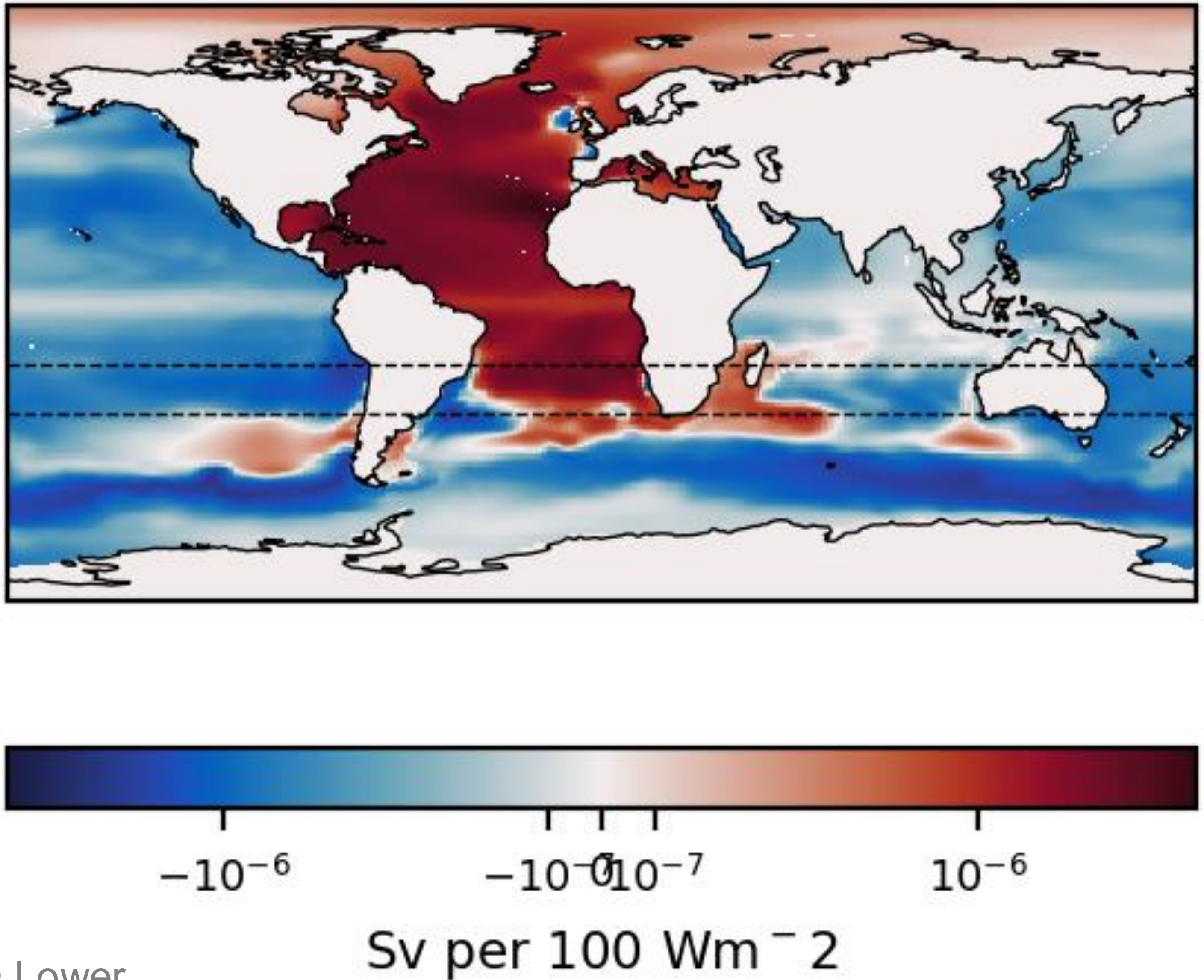
Sensitivity of pressure difference surrounding 26.5°S between 1200 and 3000m depth



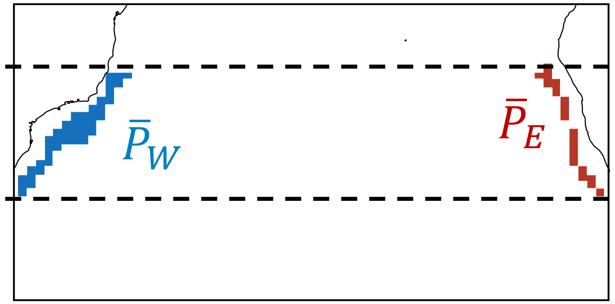
$$\mathcal{J} = \bar{P}_E - \bar{P}_W$$

The shown sensitivity is **averaged** over all available lags (0-10 yrs)

Sensitivity field: Heat flux



Sensitivity of pressure difference surrounding 26.5°S between 1200 and 3000m depth

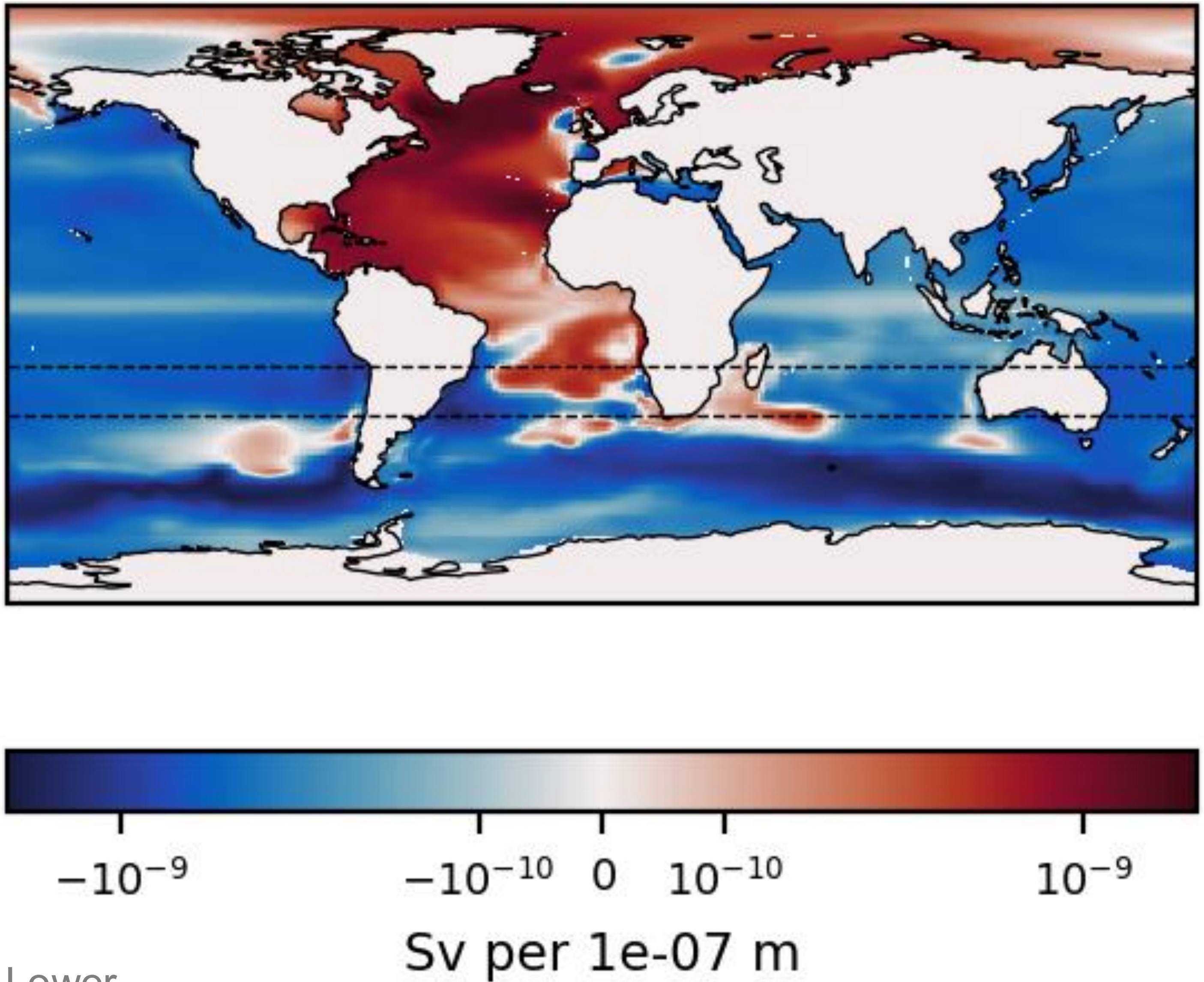


$$\mathcal{J} = \bar{P}_E - \bar{P}_W$$

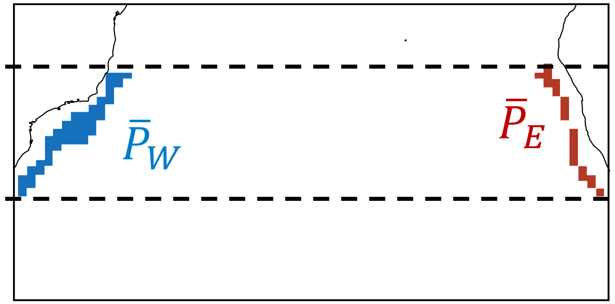
The shown sensitivity is **averaged** over all available lags (0-10 yrs)

S-RAPID Lower

Sensitivity field: Freshwater flux



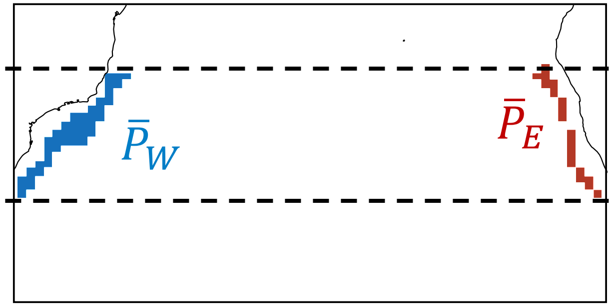
Sensitivity of pressure difference surrounding 26.5°S between 1200 and 3000m depth

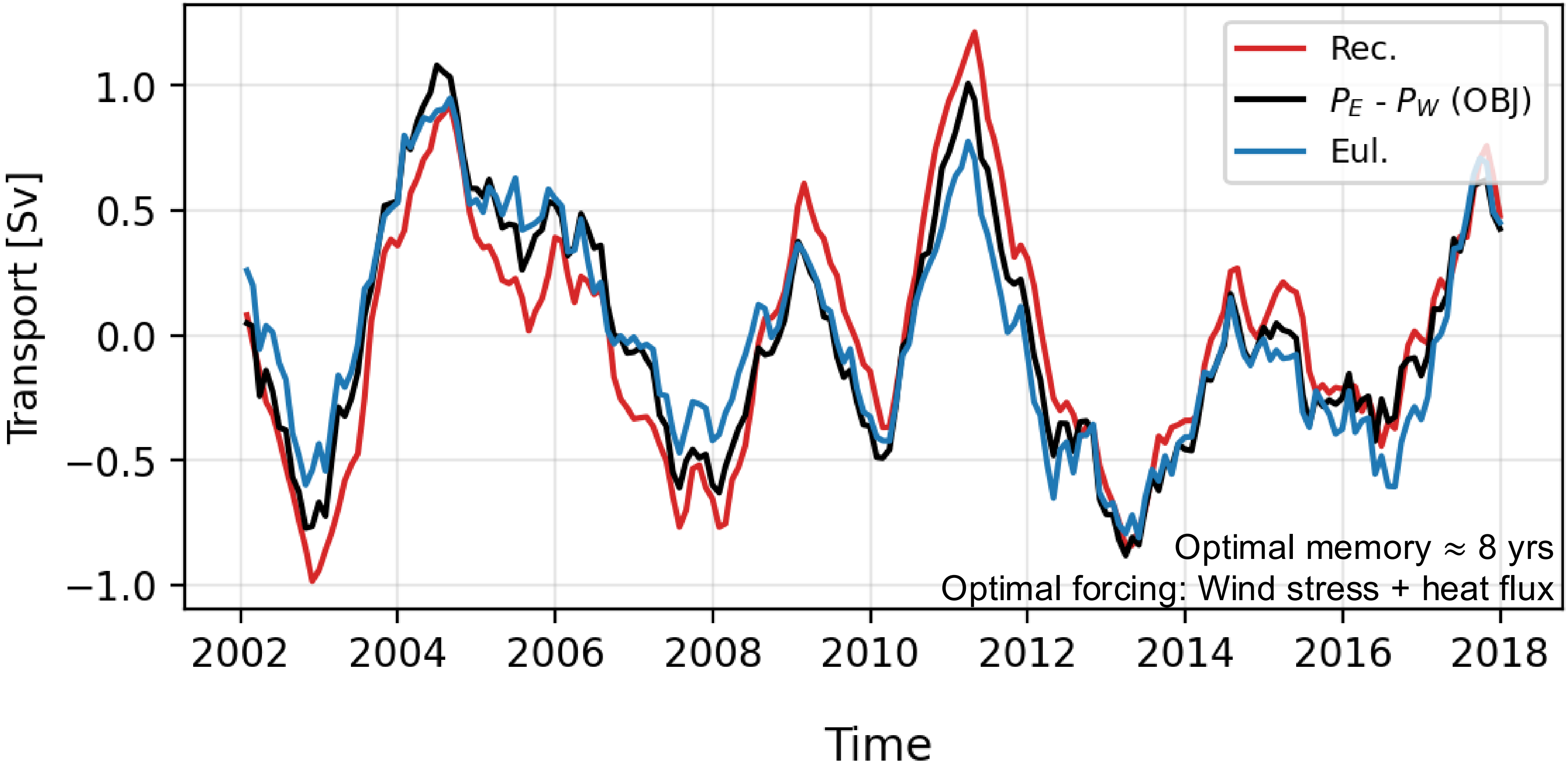


$$\mathcal{J} = \bar{P}_E - \bar{P}_W$$

The shown sensitivity is **averaged** over all available lags (0-10 yrs)

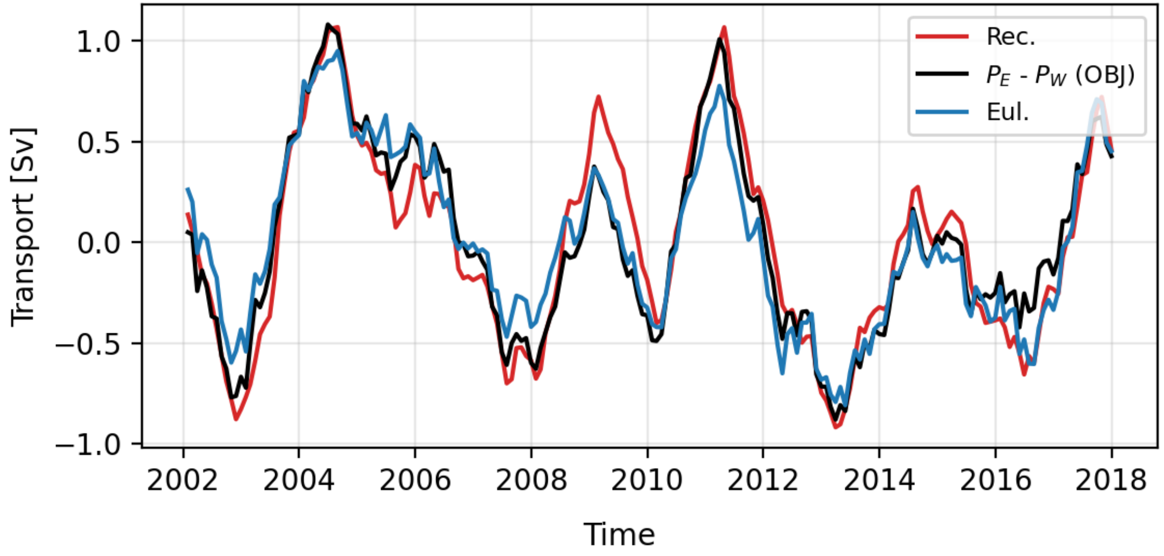
Optimal Reconstruction



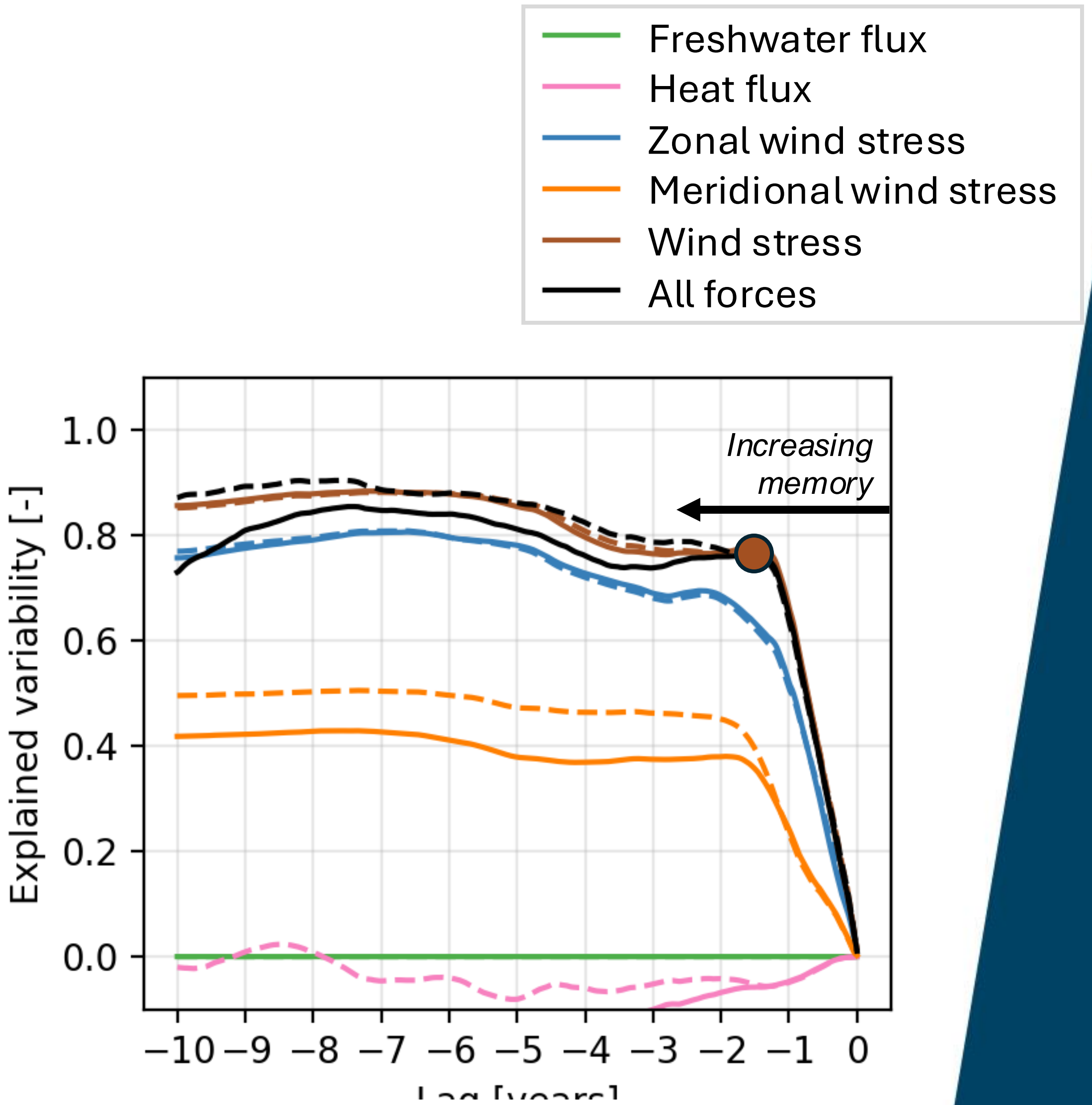


Explained variability

Optimal reconstruction: **Winds** only

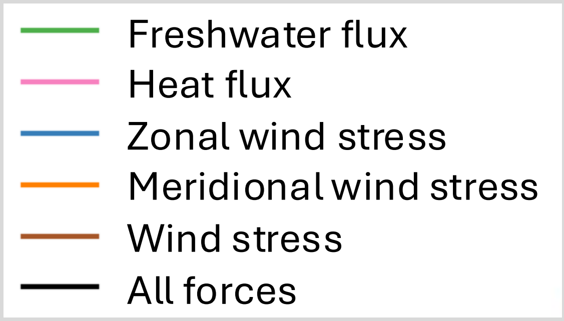


The **optimal reconstruction** is **wind-based** and explains **90%** of the variability. A **minimum memory** of **1-2 years** accomplishes 80% explained variability

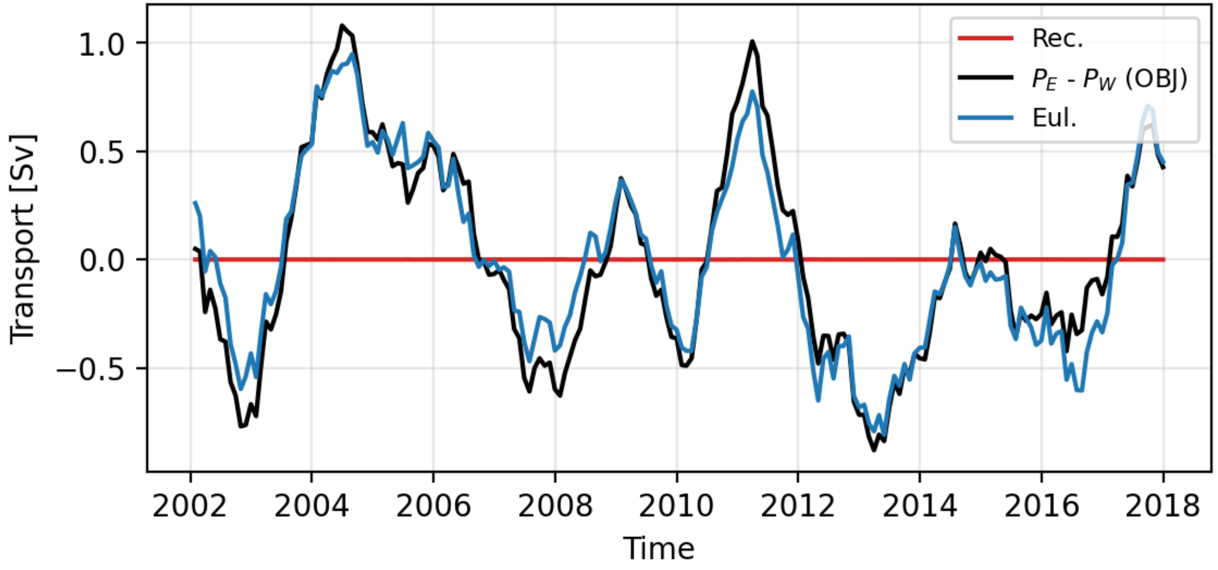


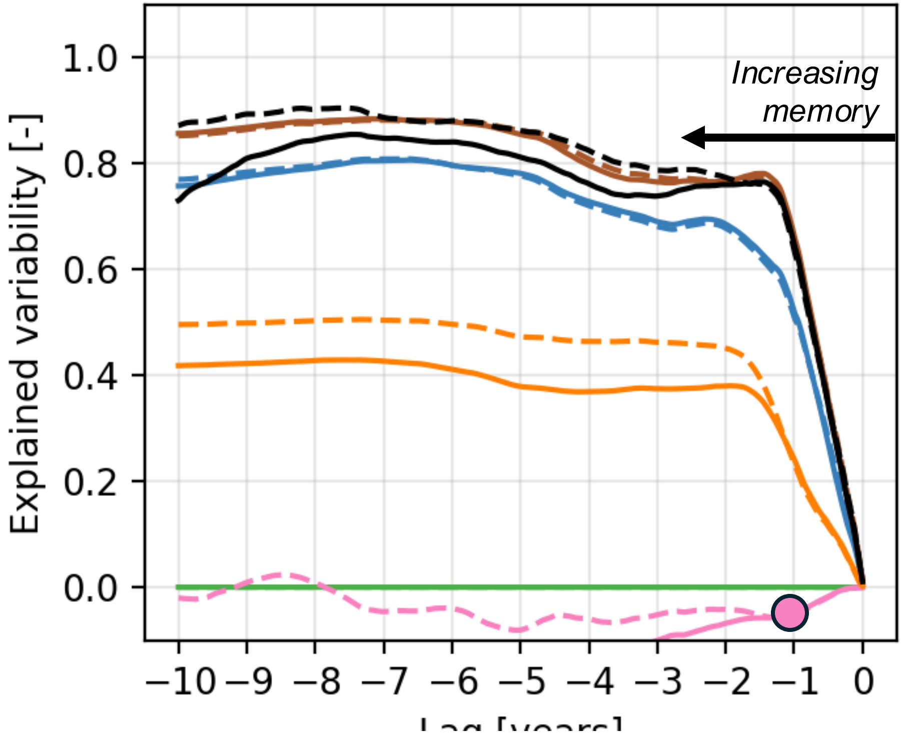
Explained variability of the reconstruction as a function of memory. Dashed lines represent the explained variability once the timeseries has been ***detrended***

Explained variability



Optimal reconstruction: **Heat flux** only



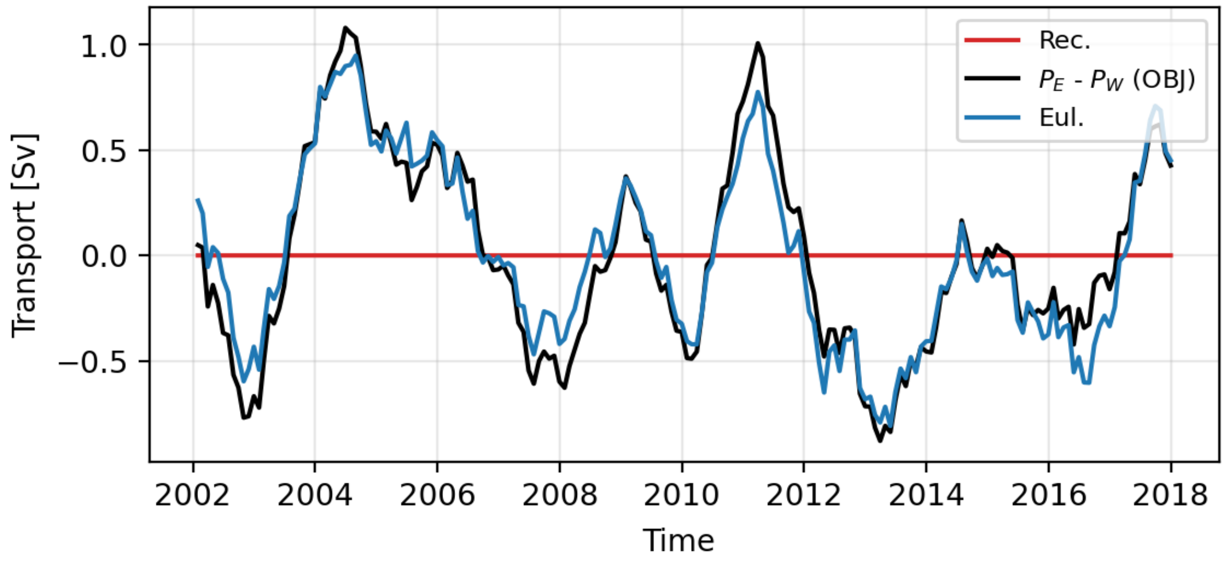


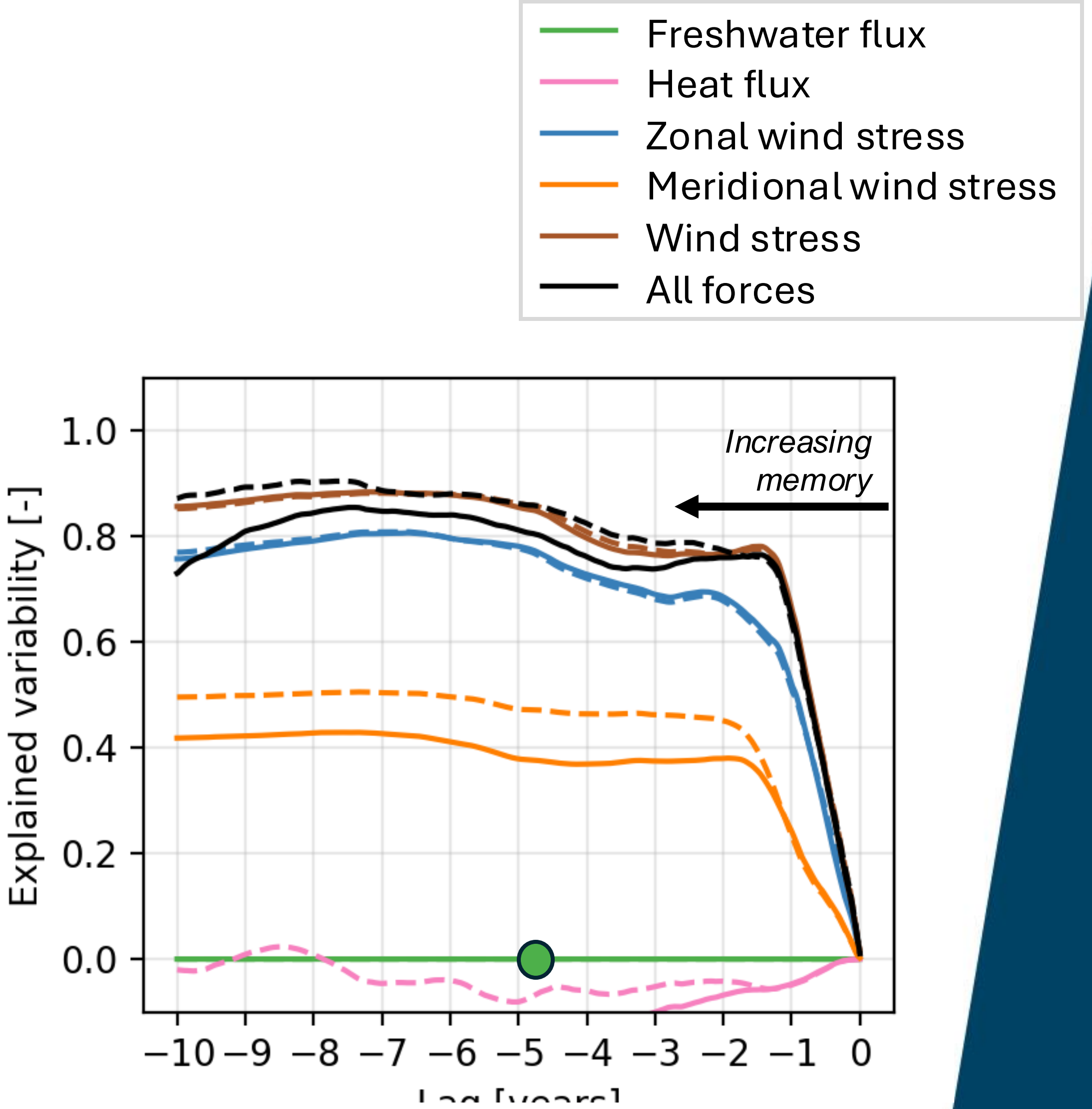
A **heat-based** reconstruction is **negligible in magnitude**

Explained variability of the reconstruction as a function of memory. Dashed lines represent the explained variability once the timeseries has been ***detrended***

Explained variability

Optimal reconstruction: Freshwater flux only

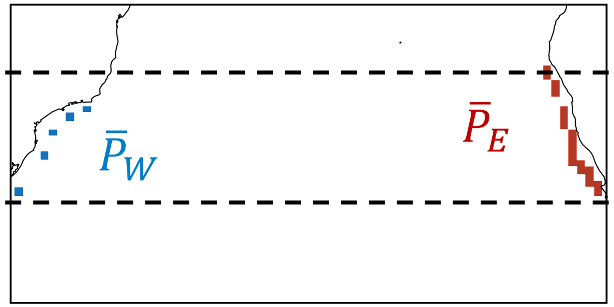




*Explained variability of the reconstruction as a function of memory. Dashed lines represent the explained variability once the timeseries has been **detrended***

Freshwater fluxes do not contribute to the reconstruction at all.

A **longer memory** may be required



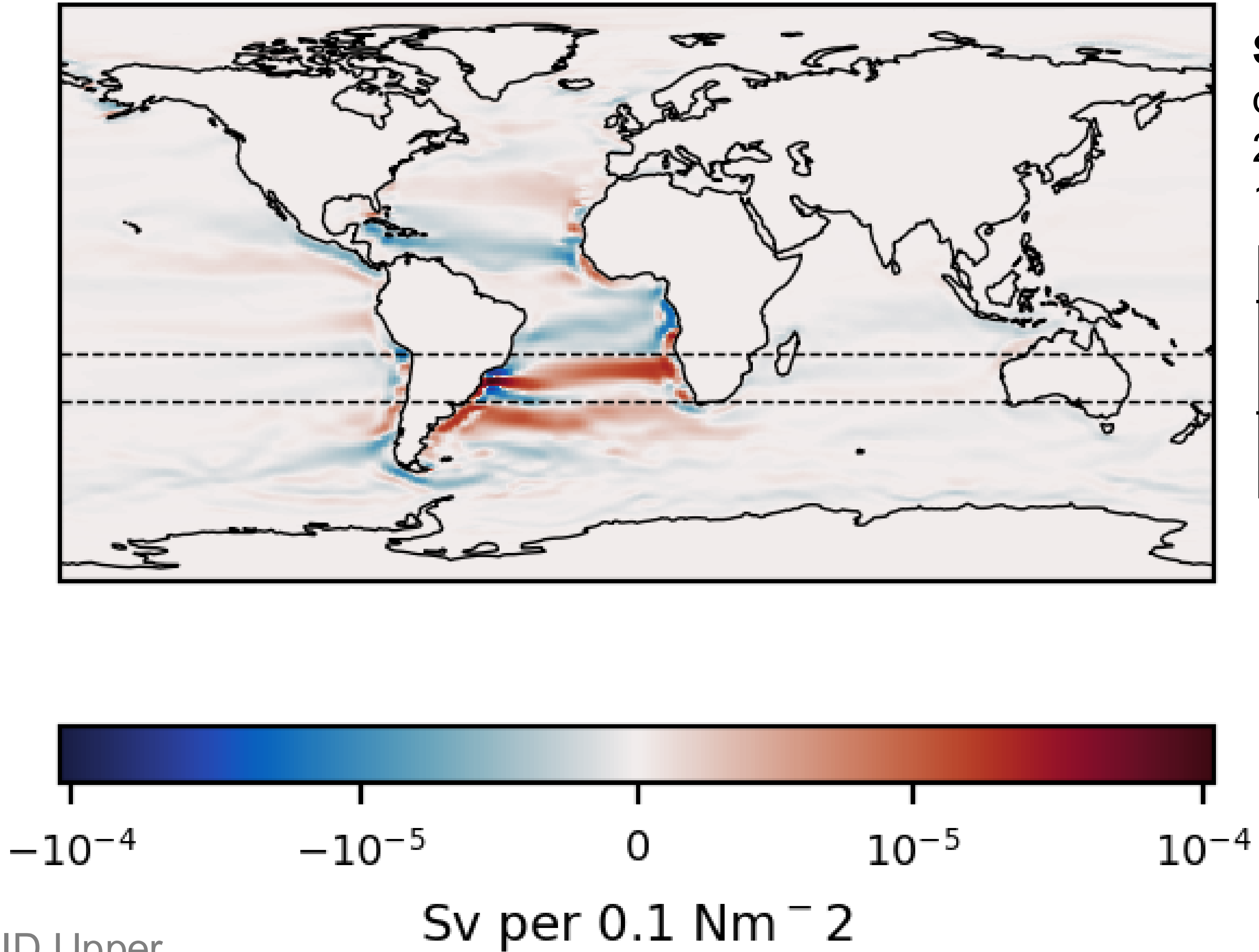
$$\mathcal{J} = \overline{P}_E - \overline{P}_W$$

Results: S-RAPID Upper

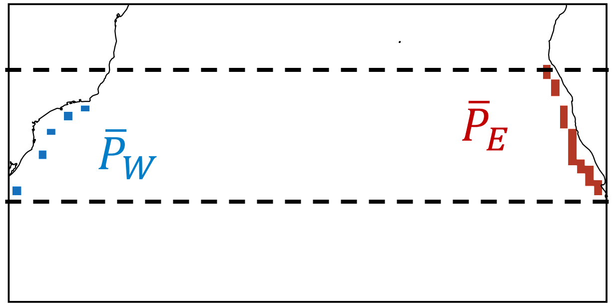
18.75-33.75°S

250-1200 m depth

Sensitivity field: Zonal wind stress



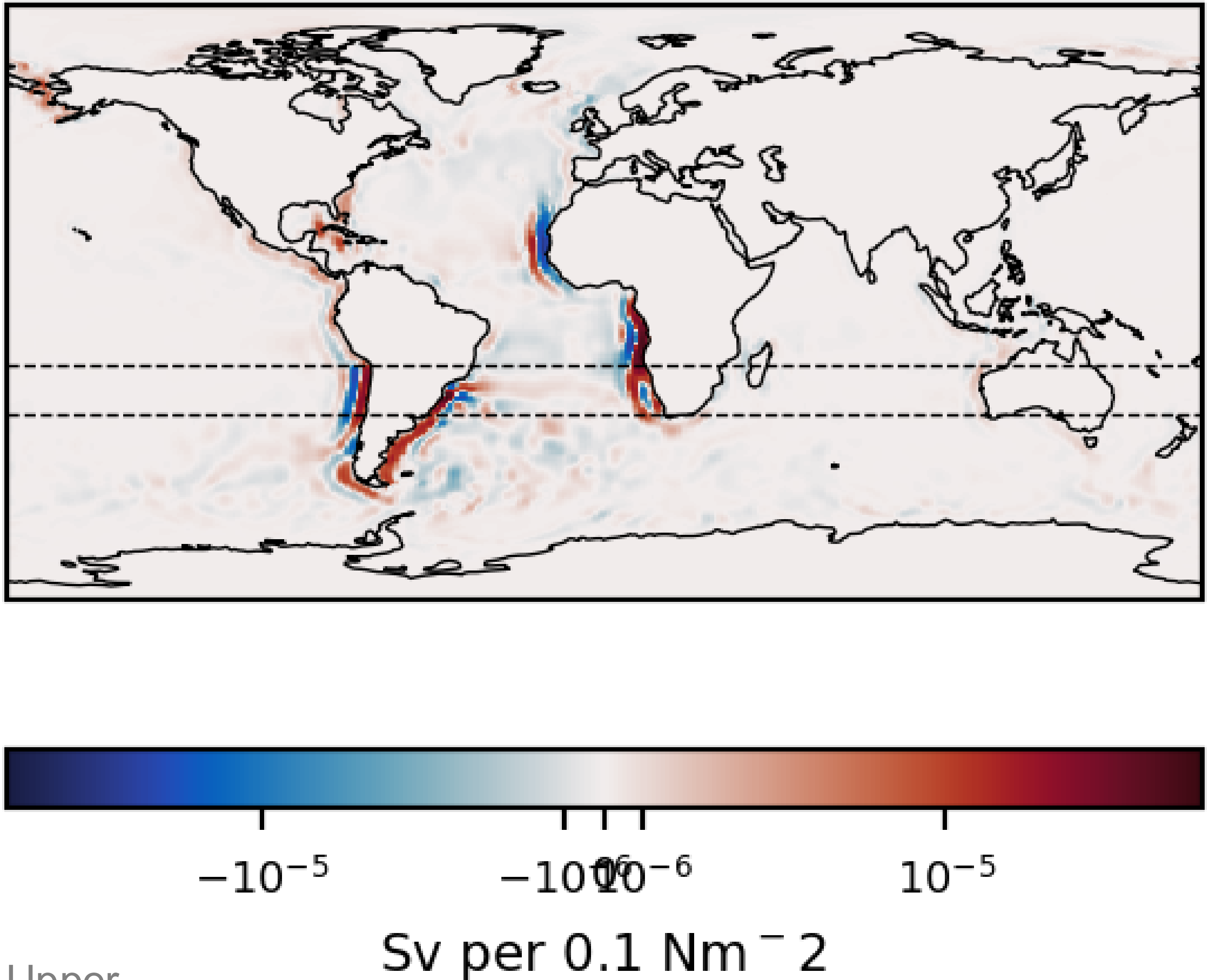
Sensitivity of pressure difference surrounding 26.5°S between 250 and 1200m depth



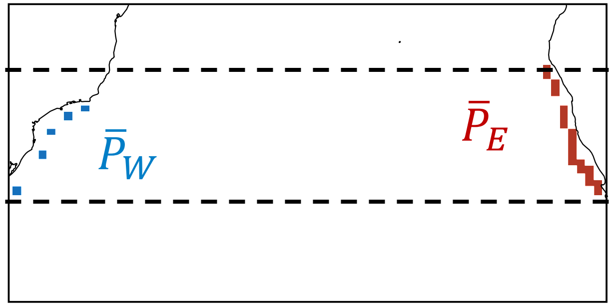
$$\mathcal{J} = \bar{P}_E - \bar{P}_W$$

The shown sensitivity is **averaged** over all available lags (0-10 yrs)

Sensitivity field: Meridional wind stress



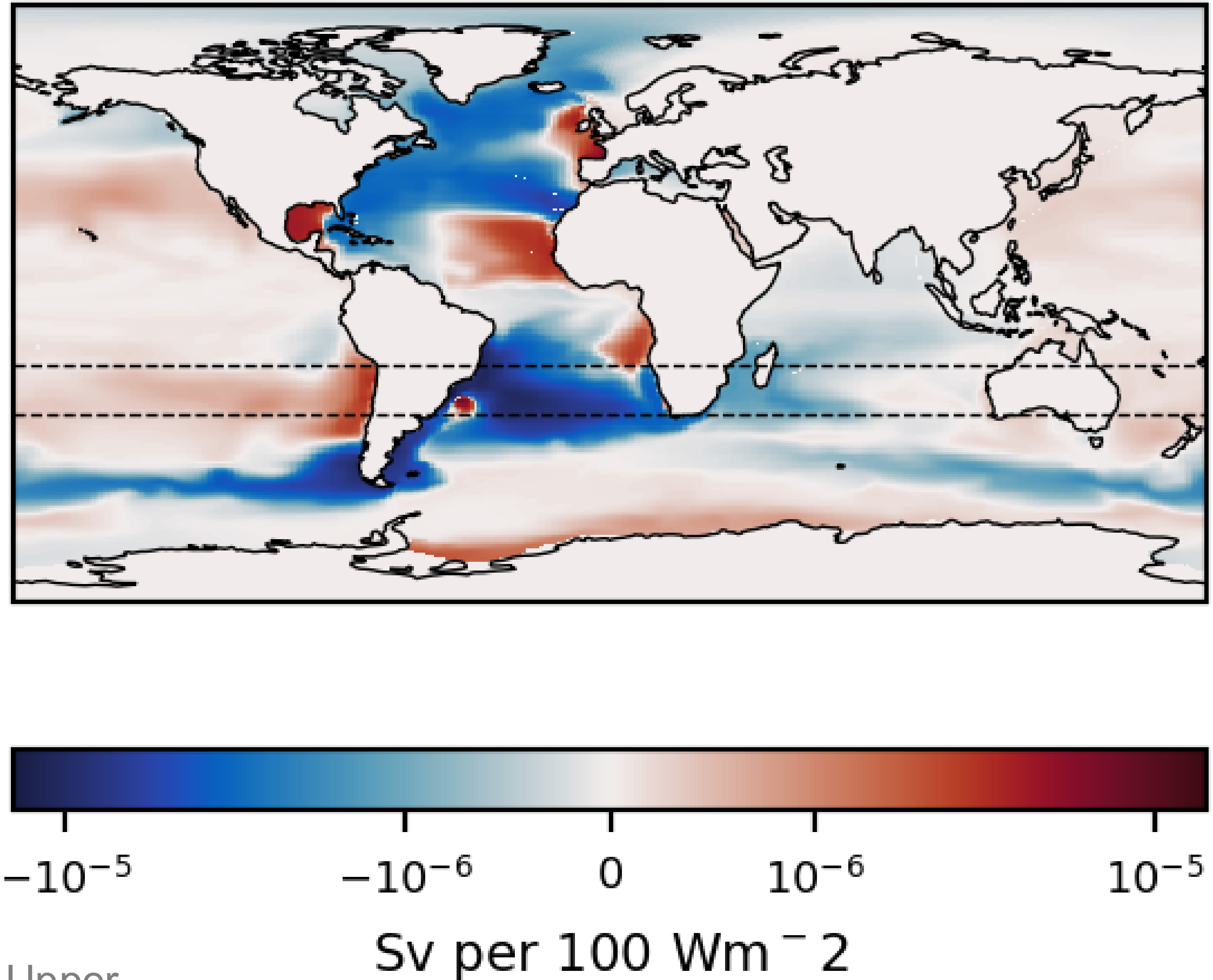
Sensitivity of pressure difference surrounding 26.5°S between 250 and 1200m depth



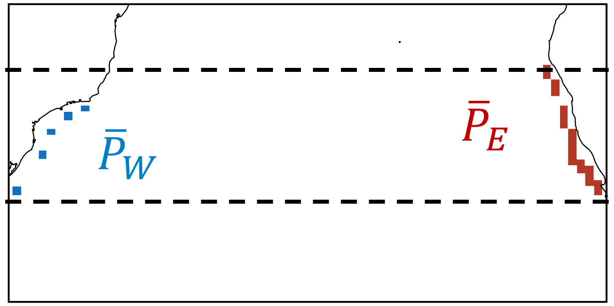
$$\mathcal{J} = \bar{P}_E - \bar{P}_W$$

The shown sensitivity is **averaged** over all available lags (0-10 yrs)

Sensitivity field: Heat flux



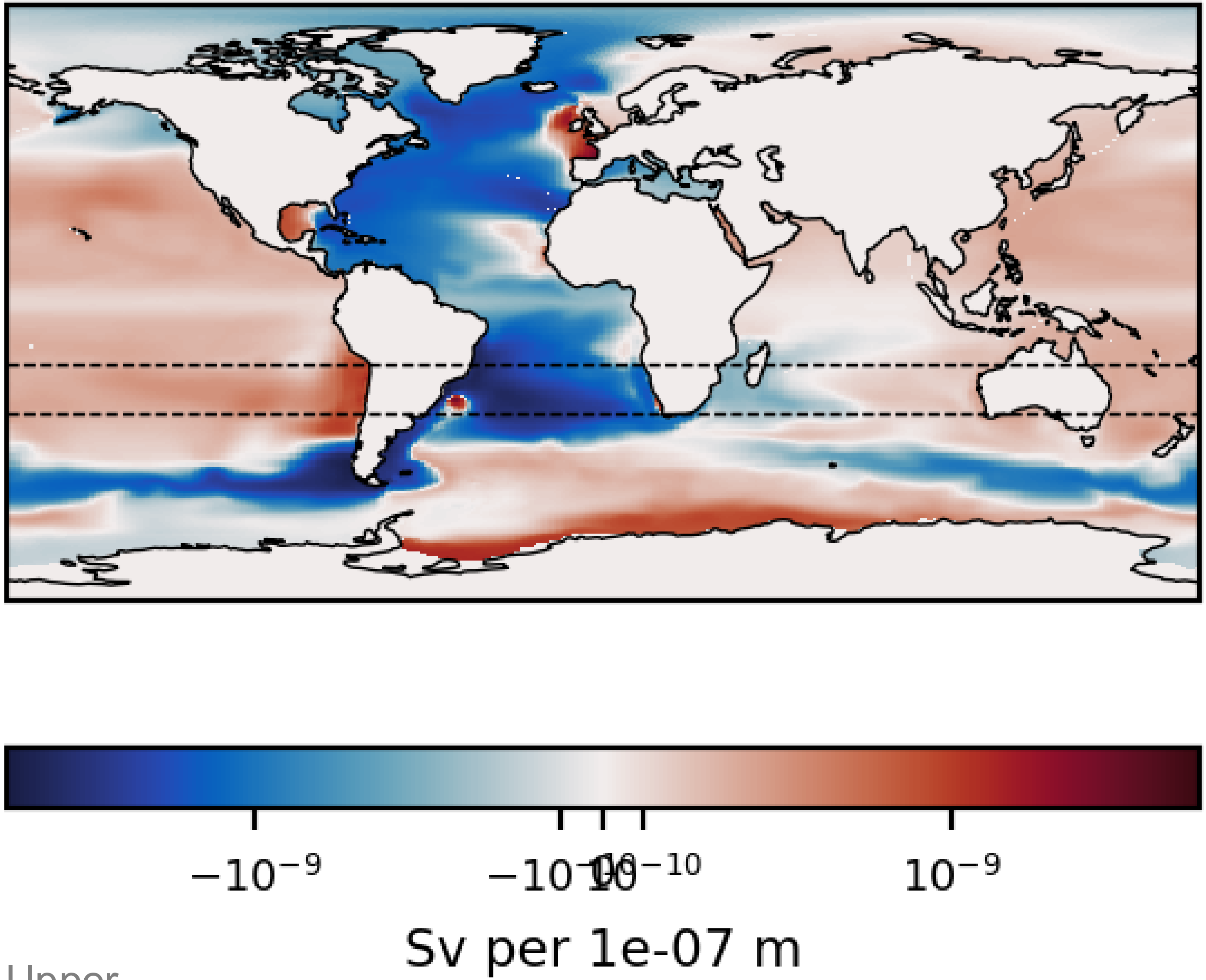
Sensitivity of pressure difference surrounding 26.5°S between 250 and 1200m depth



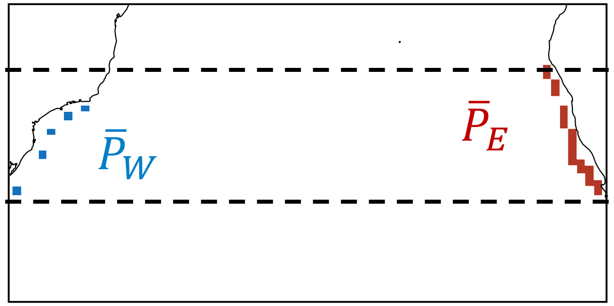
$$\mathcal{J} = \bar{P}_E - \bar{P}_W$$

The shown sensitivity is **averaged** over all available lags (0-10 yrs)

Sensitivity field: Freshwater flux



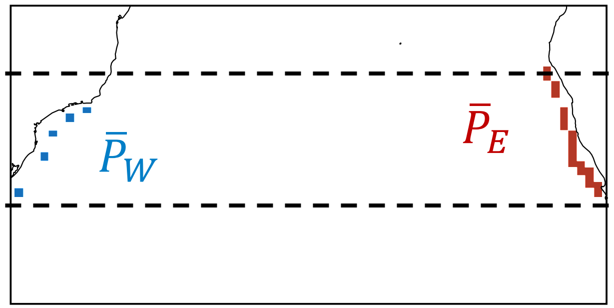
Sensitivity of pressure difference surrounding 26.5°S between 250 and 1200m depth

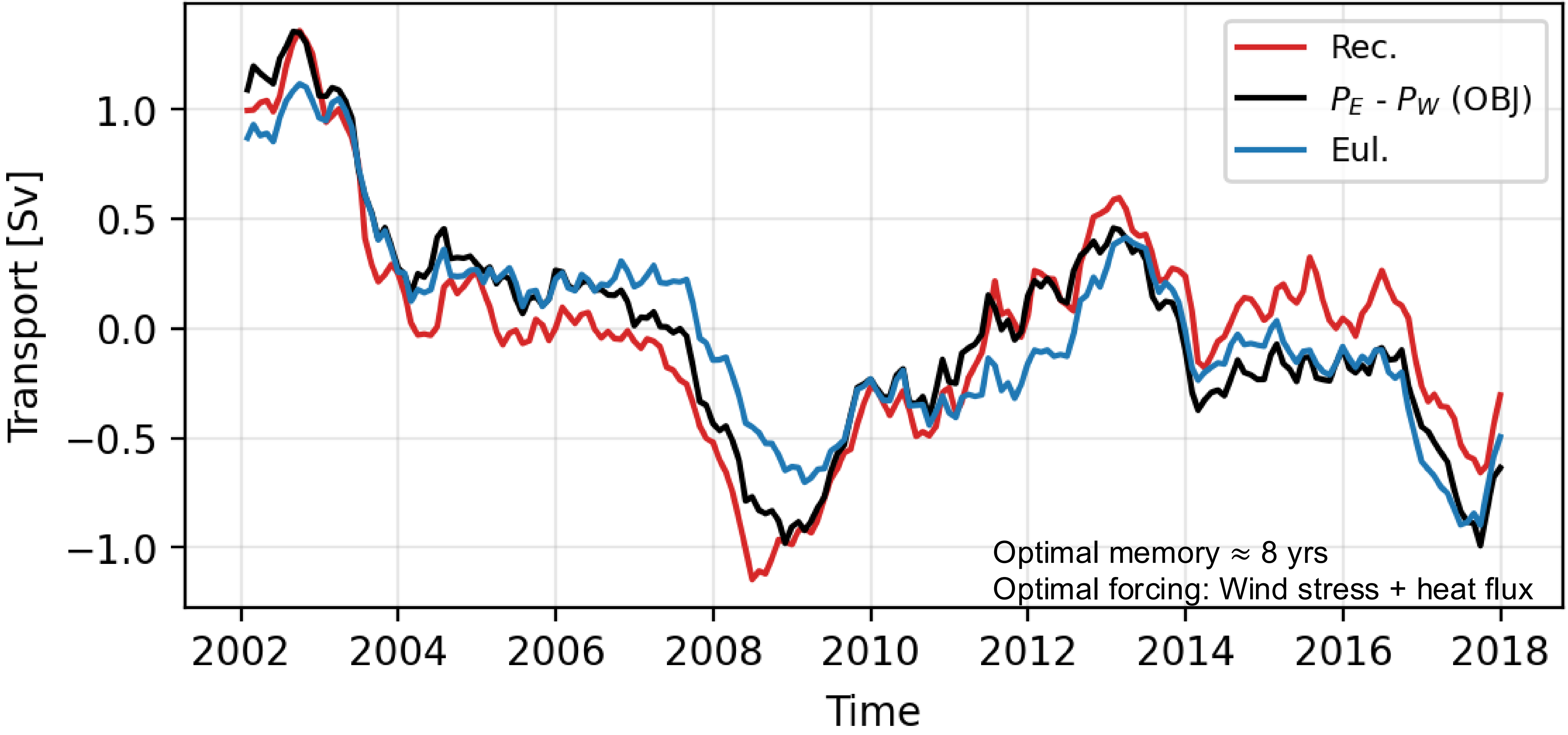


$$\mathcal{J} = \bar{P}_E - \bar{P}_W$$

The shown sensitivity is **averaged** over all available lags (0-10 yrs)

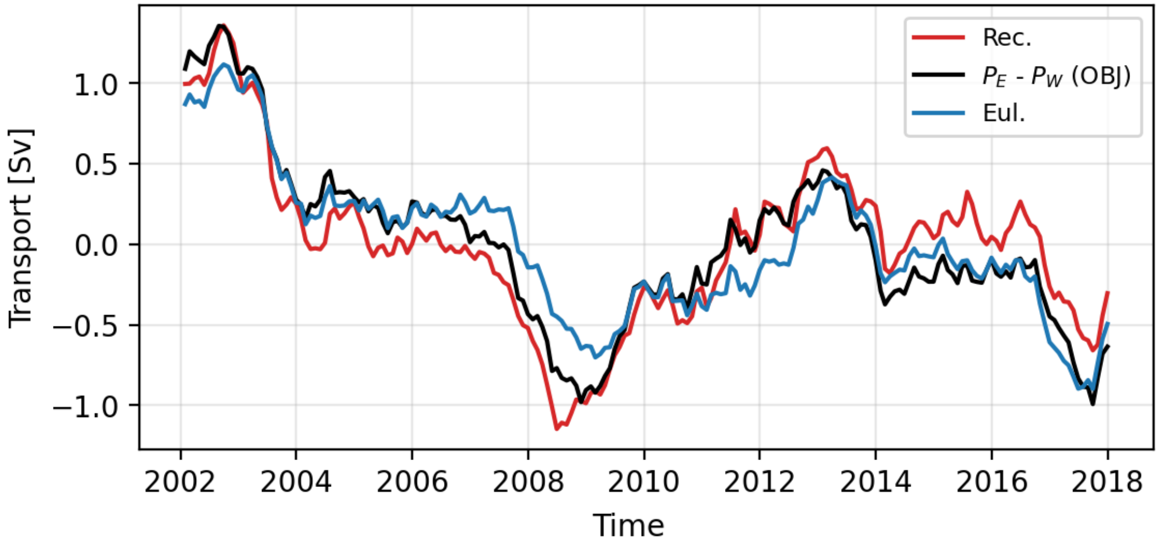
Optimal Reconstruction





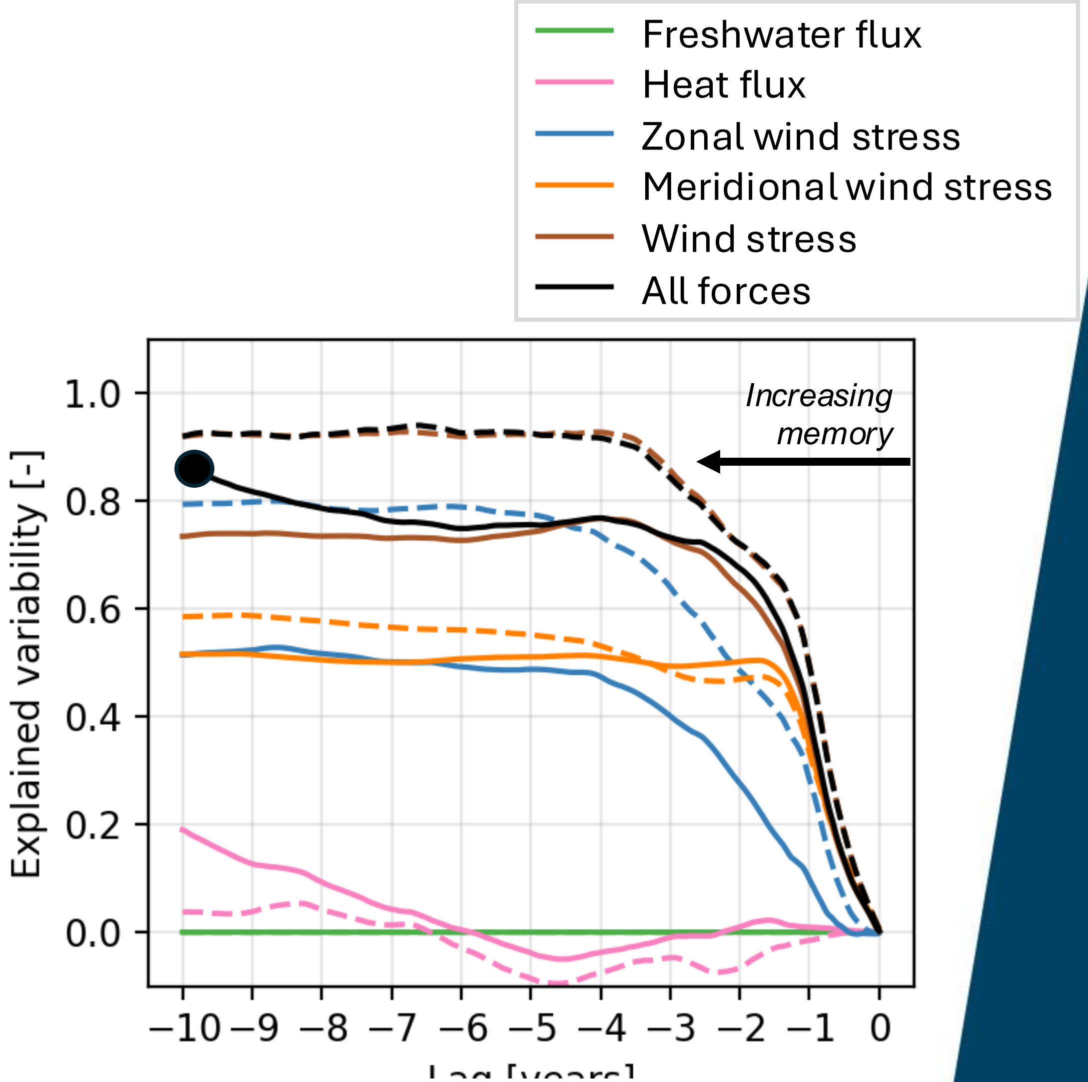
Explained variability

Optimal reconstruction: Wind and Heat flux



The **optimal reconstruction** explains **85%** of the variability with an optimal memory of **10 years** (max. available value).

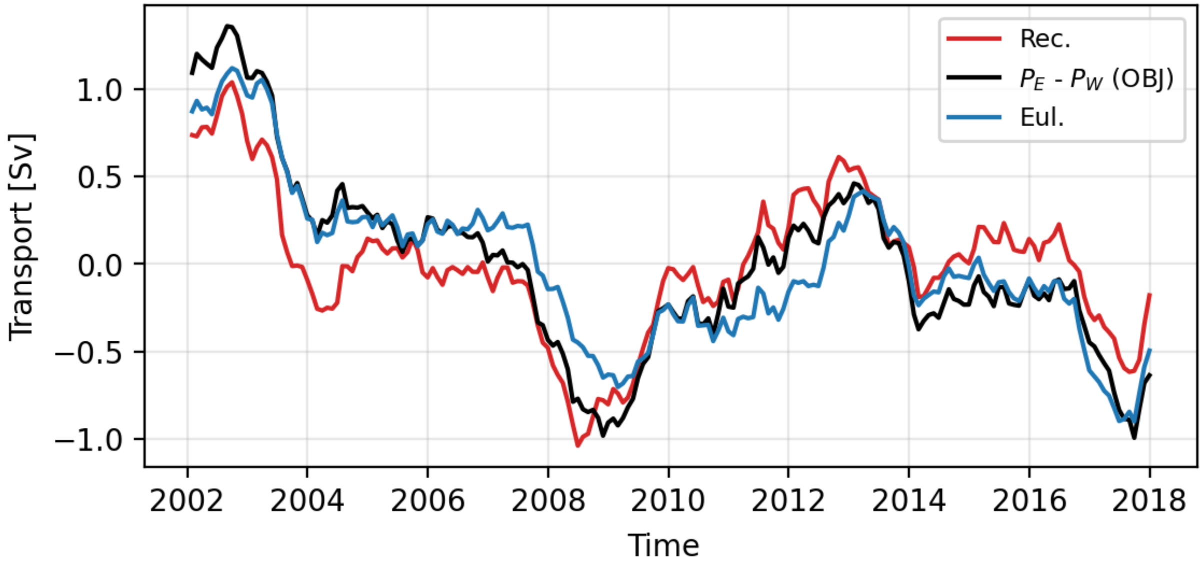
A **minimum memory** of **4 years** explains **75%** of the variability

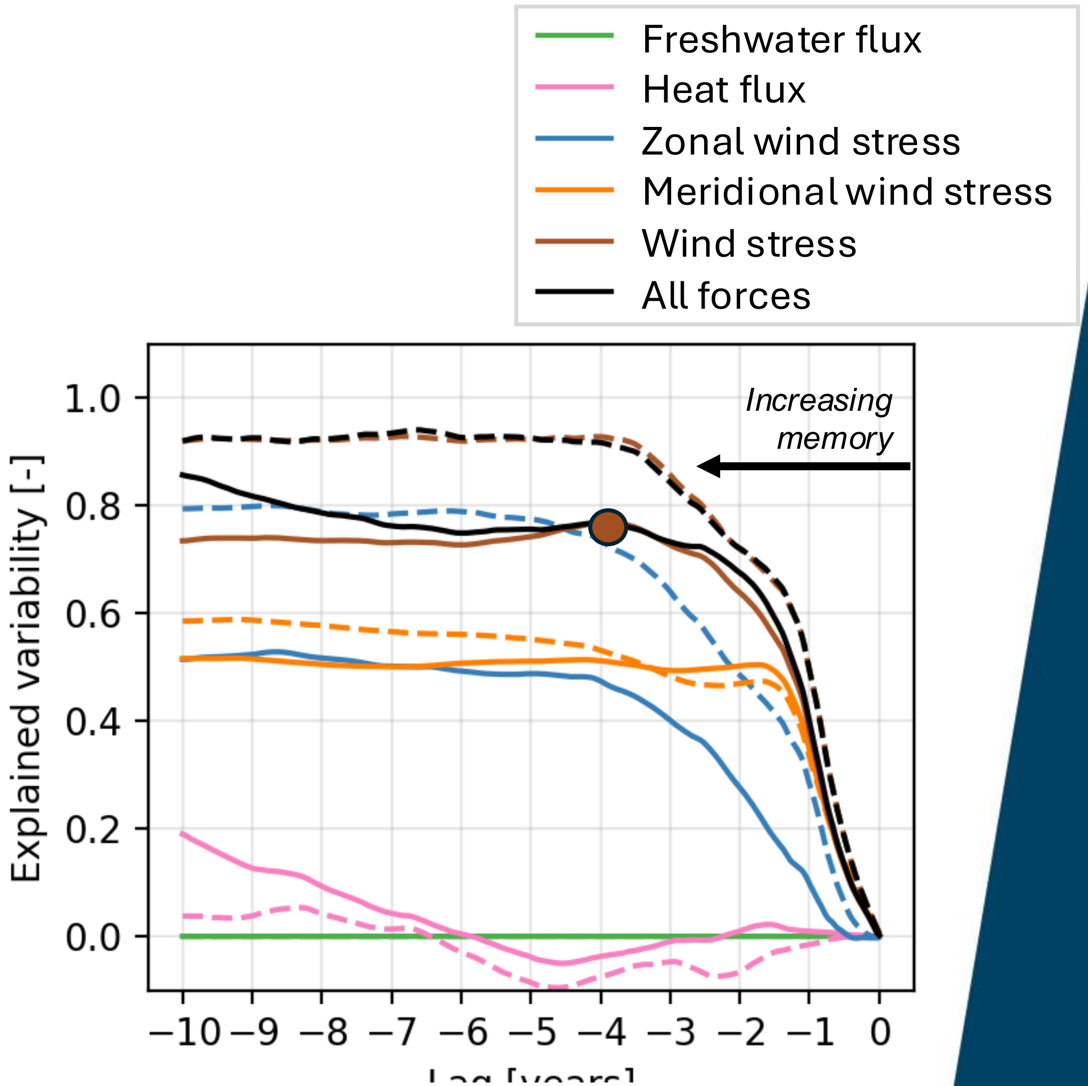


Explained variability of the reconstruction as a function of memory. Dashed lines represent the explained variability once the timeseries has been ***detrended***

Explained variability

Optimal reconstruction: Winds only



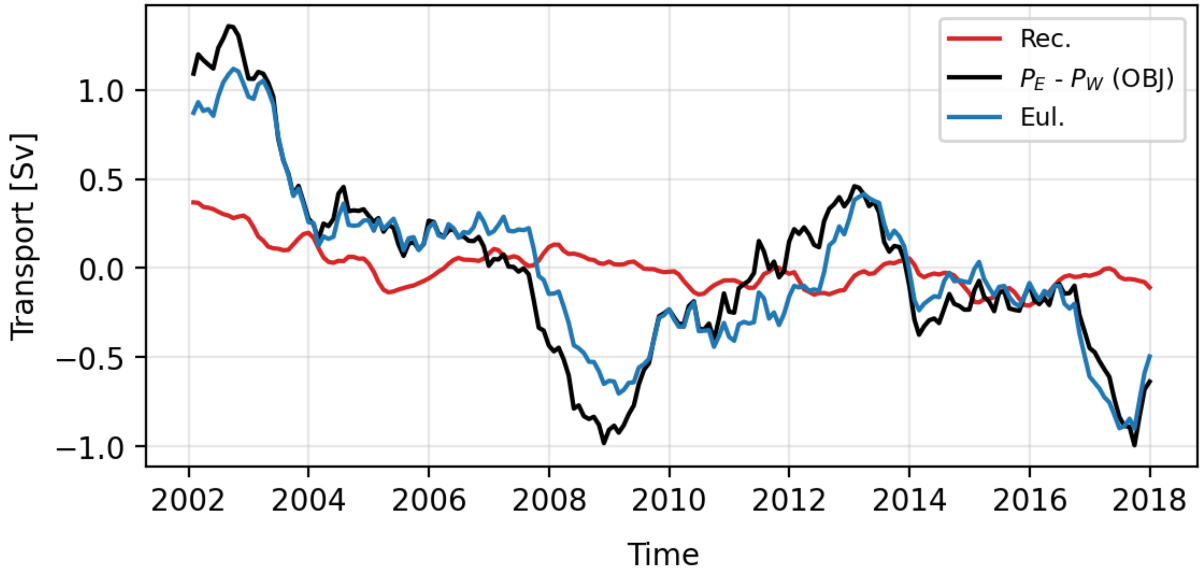


A **wind-based** reconstruction explains 75% of the variability. With as minimum memory of **3-4 years**

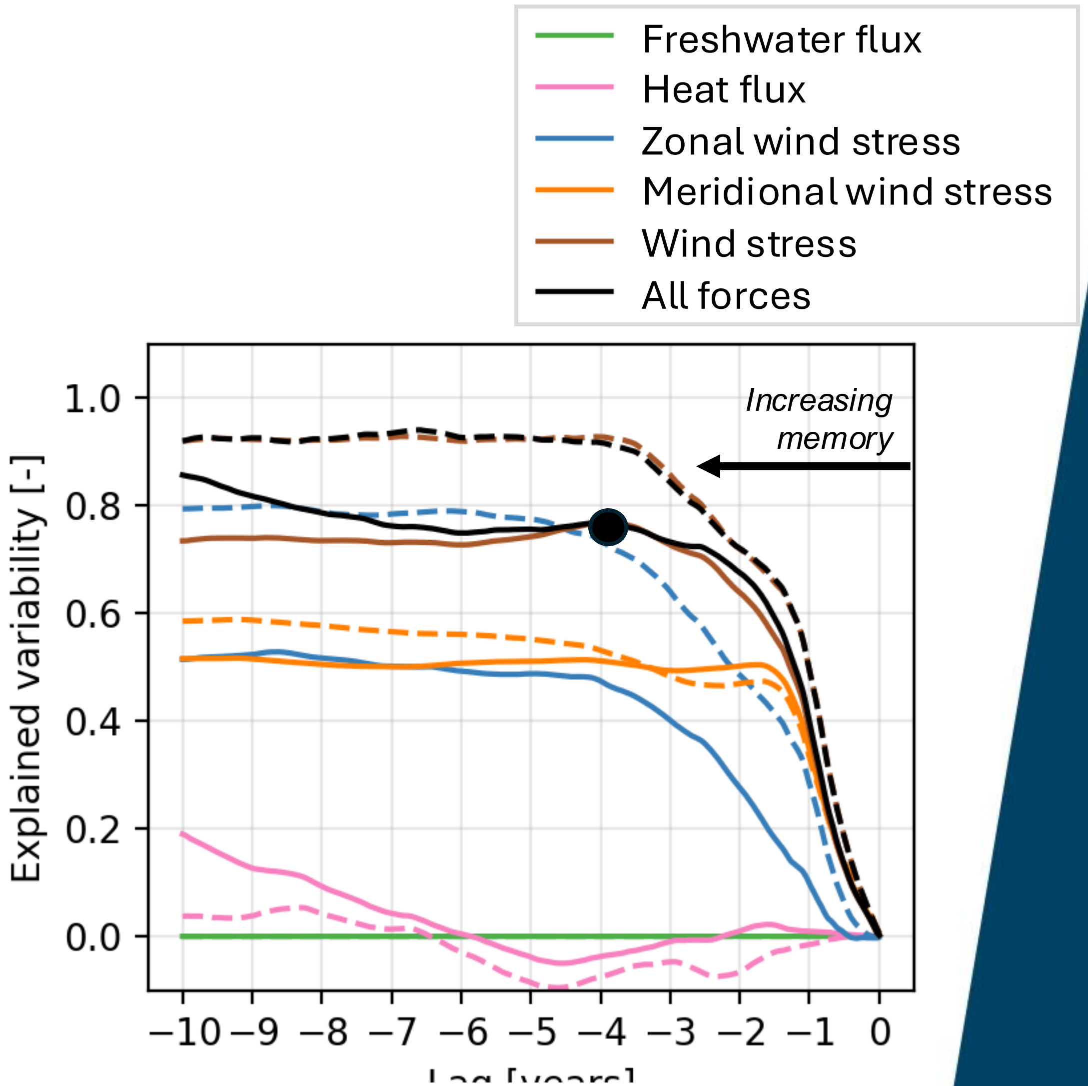
Explained variability of the reconstruction as a function of memory. Dashed lines represent the explained variability once the timeseries has been ***detrended***

Explained variability

Optimal reconstruction: Heat flux only



A **heat-based** reconstruction can explain **20%** of the variability and requires a memory of **10 years** (max available value)



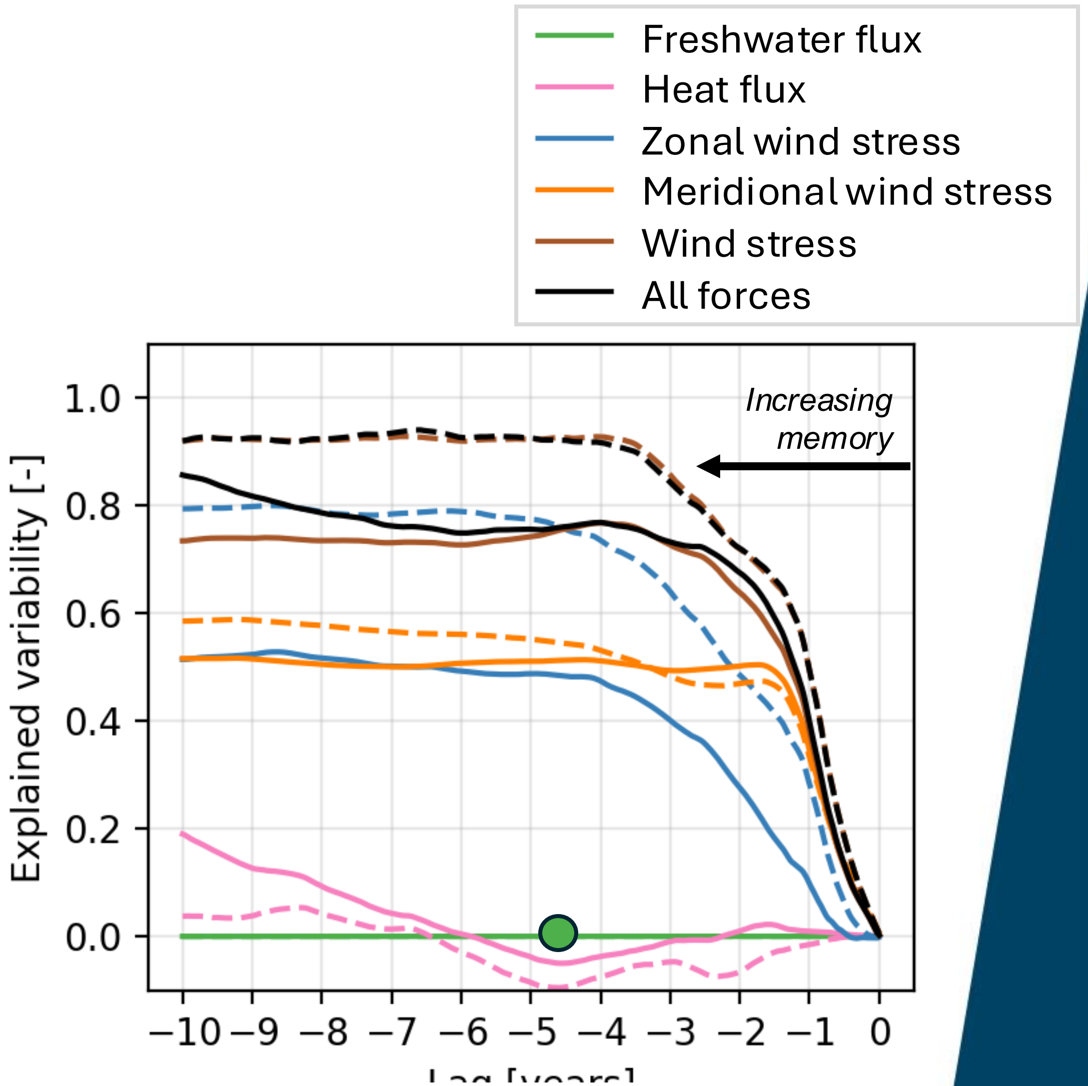
*Explained variability of the reconstruction as a function of memory. Dashed lines represent the explained variability once the timeseries has been **detrended***

Explained variability

Optimal reconstruction: **Freshwater flux** only

Freshwater fluxes do not contribute to the reconstruction at all.

A **longer memory** may be required



Explained variability of the reconstruction as a function of memory. Dashed lines represent the explained variability once the timeseries has been ***detrended***

Summary

- There is a robust relationship between **transport variability** and **boundary pressures**
- **Wind forcing** drives year-to-year variability of transport on a **3-year timescale**
- In the **Northern Hemisphere**, **heat fluxes** drive a trend in the transport on a **7-year timescale**
- In the **Southern Hemisphere**, the transport variability is almost entirely **wind-driven**