Boundary Pressure: A Unique Window into Atlantic Transport Variability

Andrew Styles[1], Emma Boland[1], Chris Hughes[2,3], Saranraj Gururaj[2], Dani Jones[4,1],

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23rd February 2026

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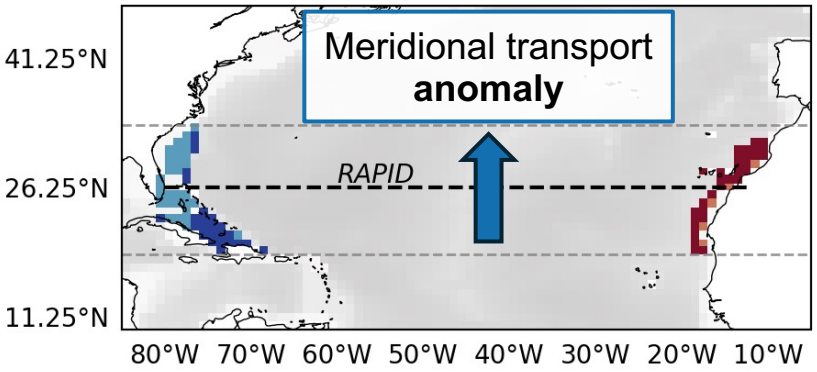
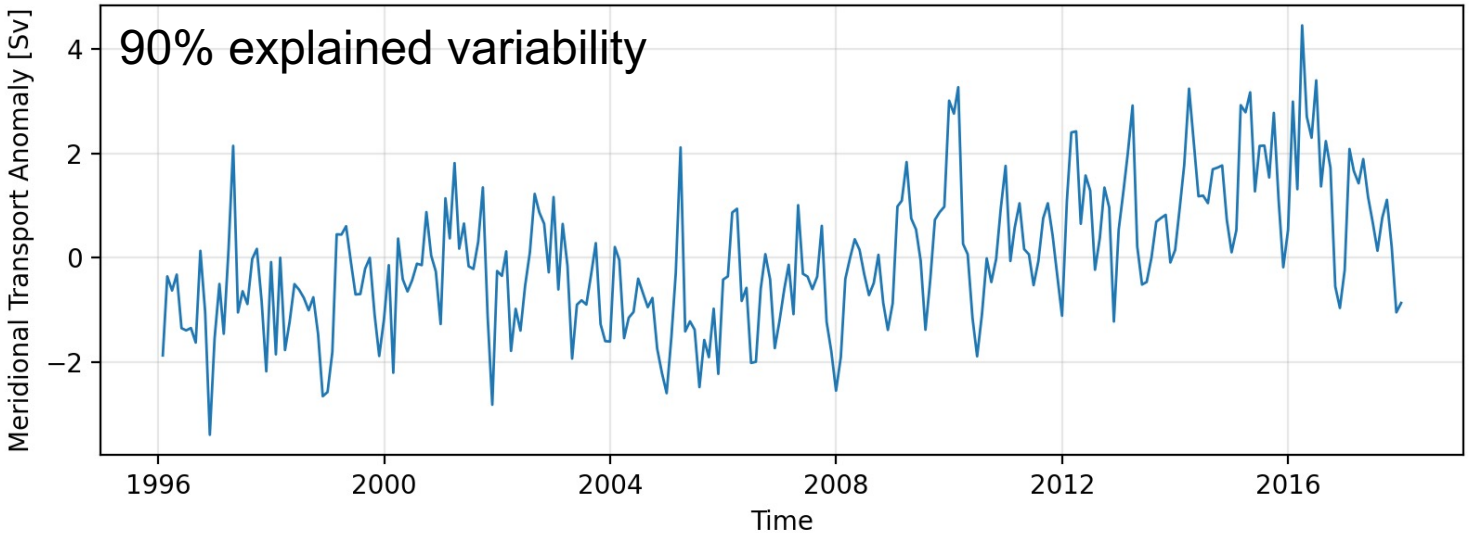
Transports and boundary pressures



The time series shows the basin-wide **transport anomaly**…



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**

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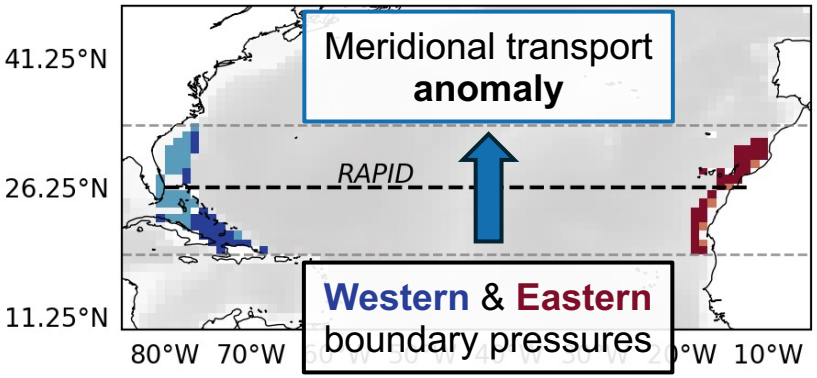

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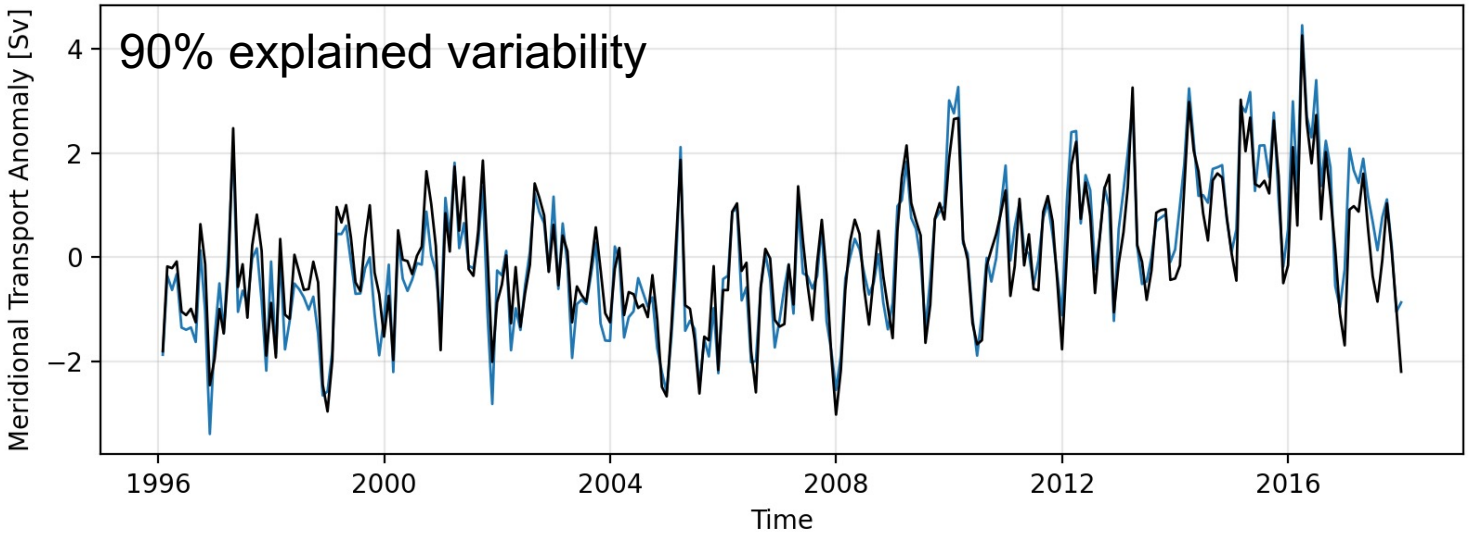
which can be estimated using **boundary pressures.**



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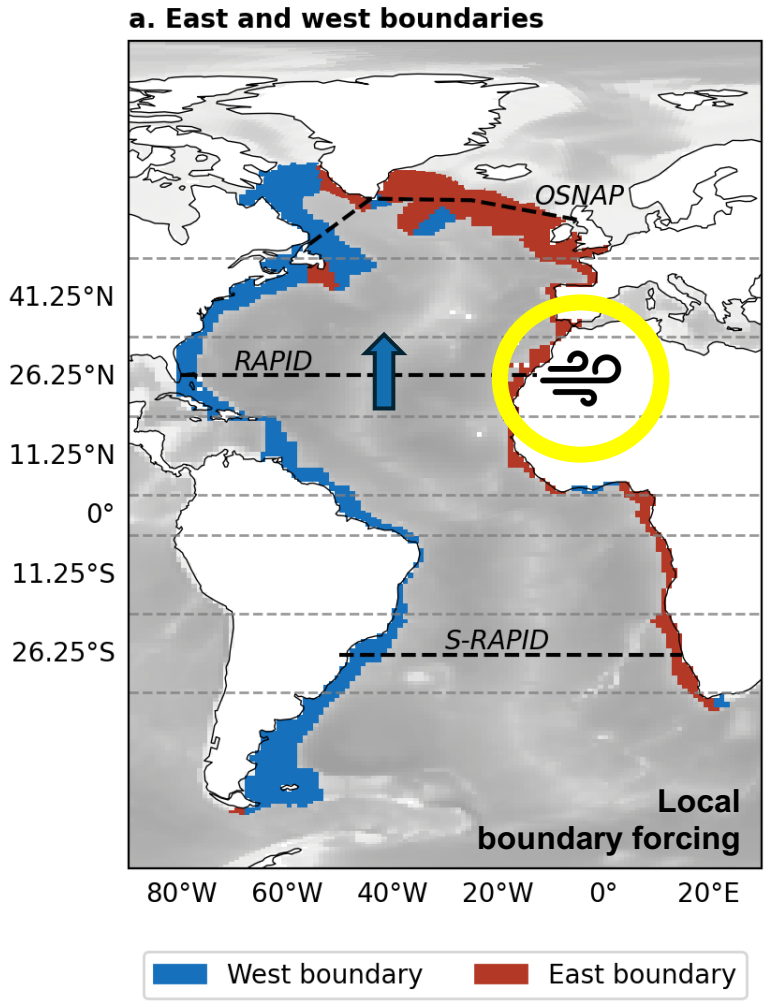
Key questions

If a significant component of Atlantic transport variability is described at the boundaries…

What drives this variability?

- Local forcing at the local boundary,



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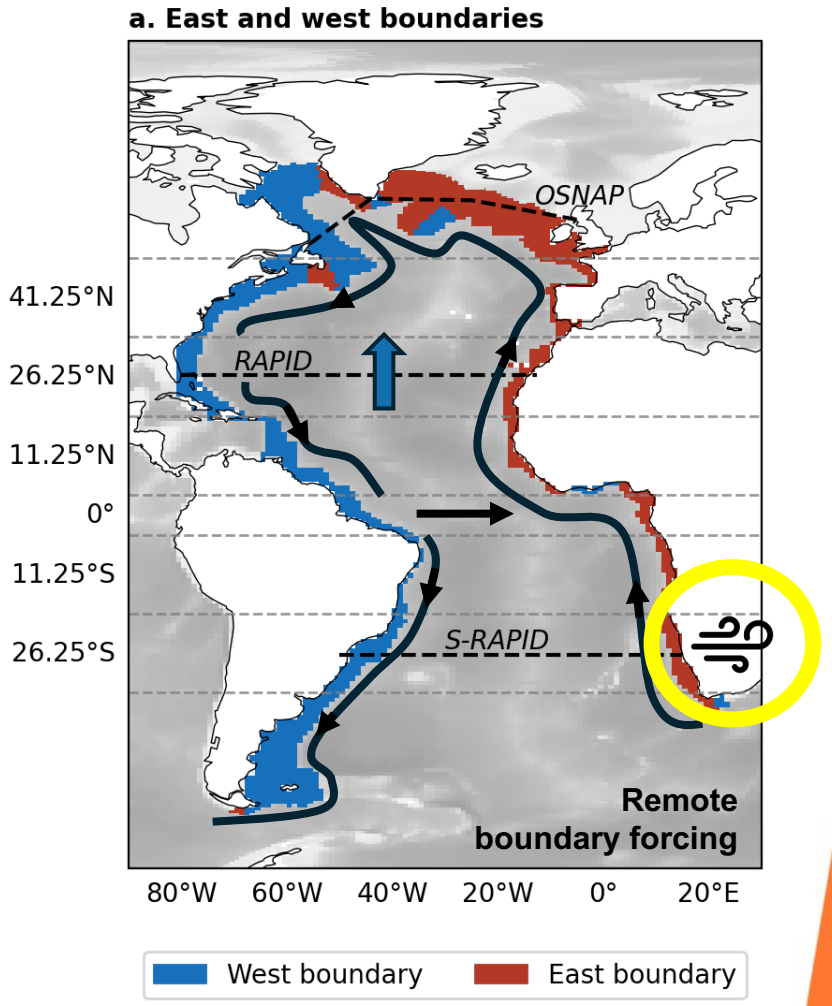

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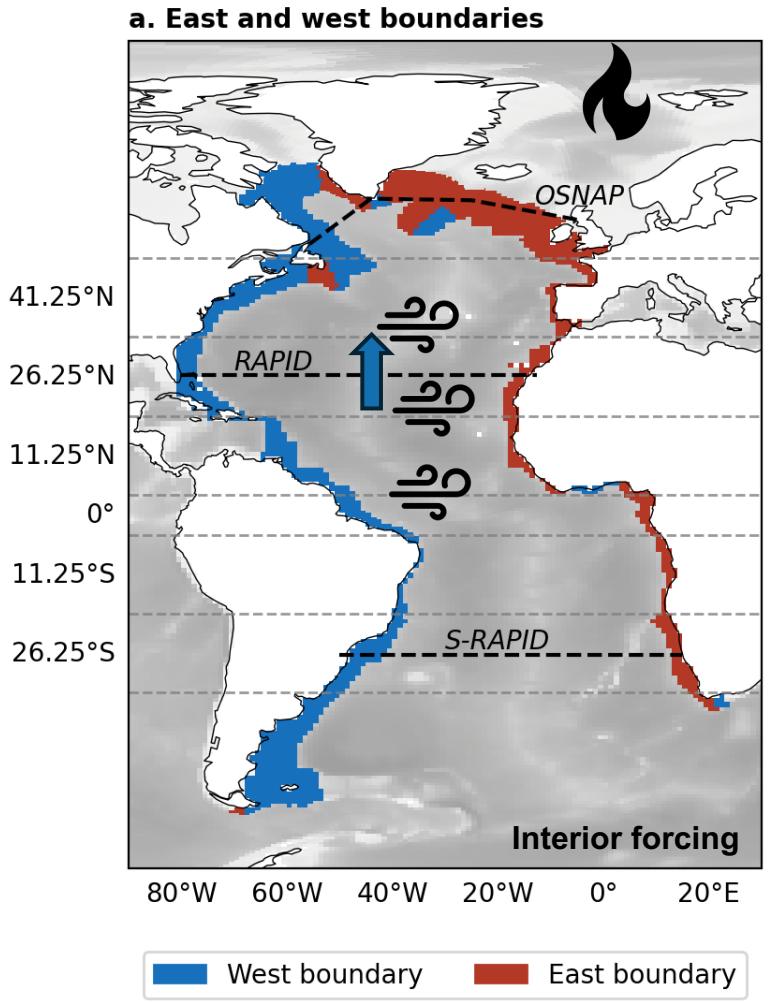

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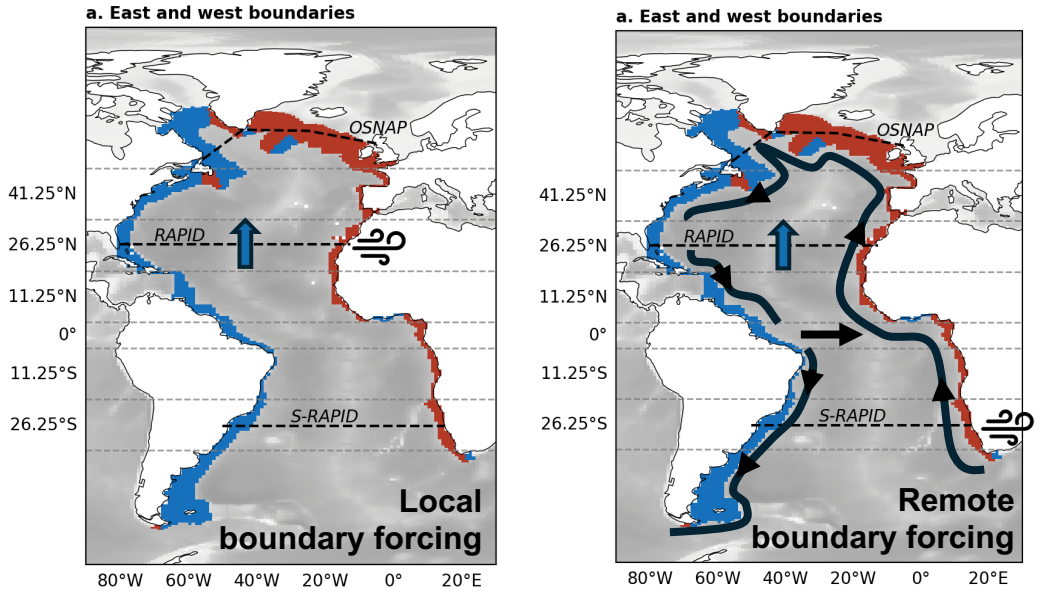

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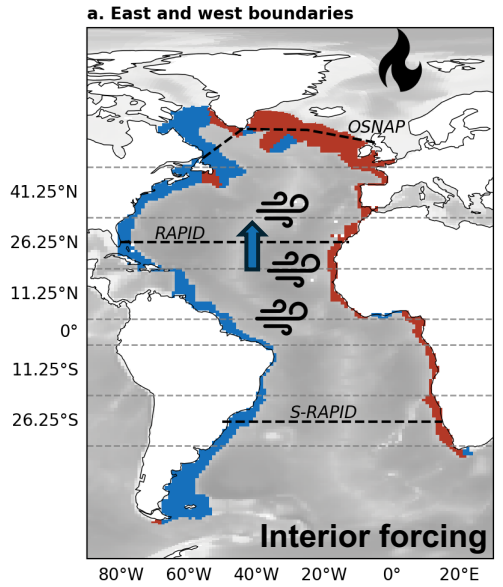

We investigate this using an **adjoint model.**

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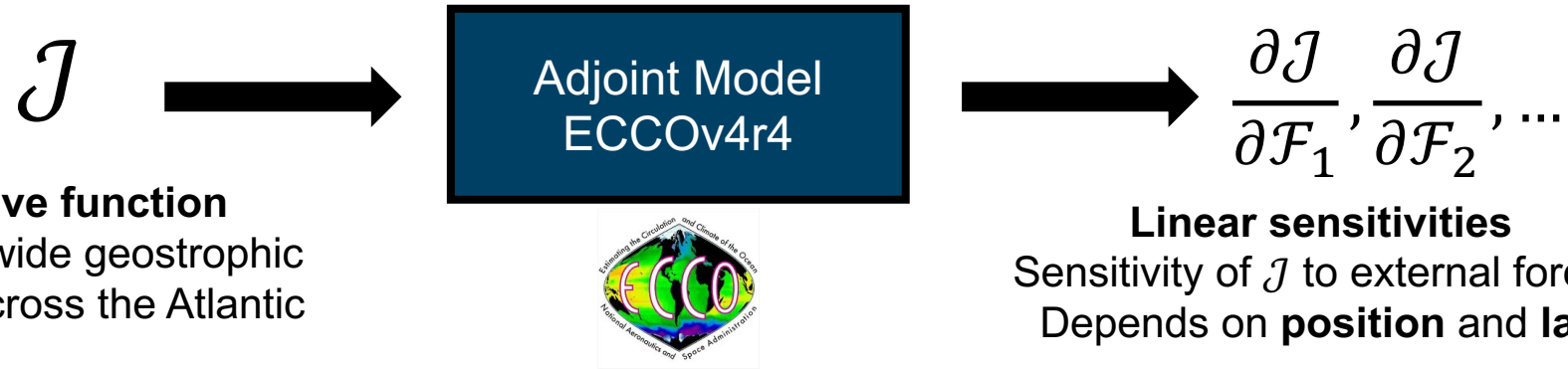
Adjoint models

- **Adjoint models** effectively run “backwards”.
- Relate an **ocean behaviour** to **physical drivers** in the past via algorithmic differentiation.
- Calculates the linear sensitivities of an **objective function**.



Objective function
e.g. Basin-wide geostrophic transport across the Atlantic

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

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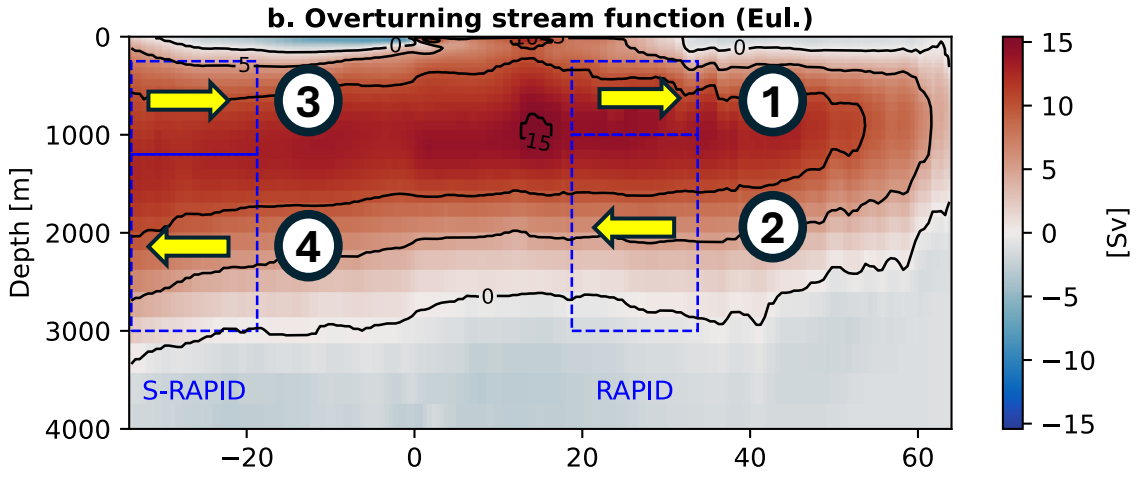
Objective functions

- Use the **annually-averaged basin-wide geostrophic transport** as our objective function.



- **Four subtropical subdomains** which target the upper and lower limbs of the time-averaged overturning.

- Focus on the **Northern Hemisphere** today.

	Subdomain	Latitude range	Depth range	Explained variability
★ 1	RAPID Upper	18.75-33.75°N	250-1000m	74%
★ 2	RAPID Lower	18.75-33.75°N	1000-3000m	90%
3	S-RAPID Upper	18.75-33.75°S	250-1200m	75%
4	S-RAPID Lower	18.75-33.75°S	1200-3000m	83%

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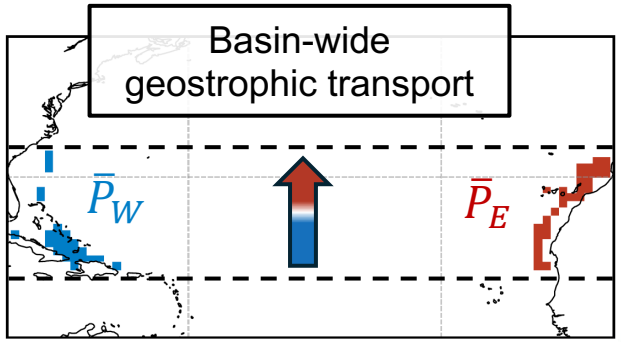
Example sensitivity field



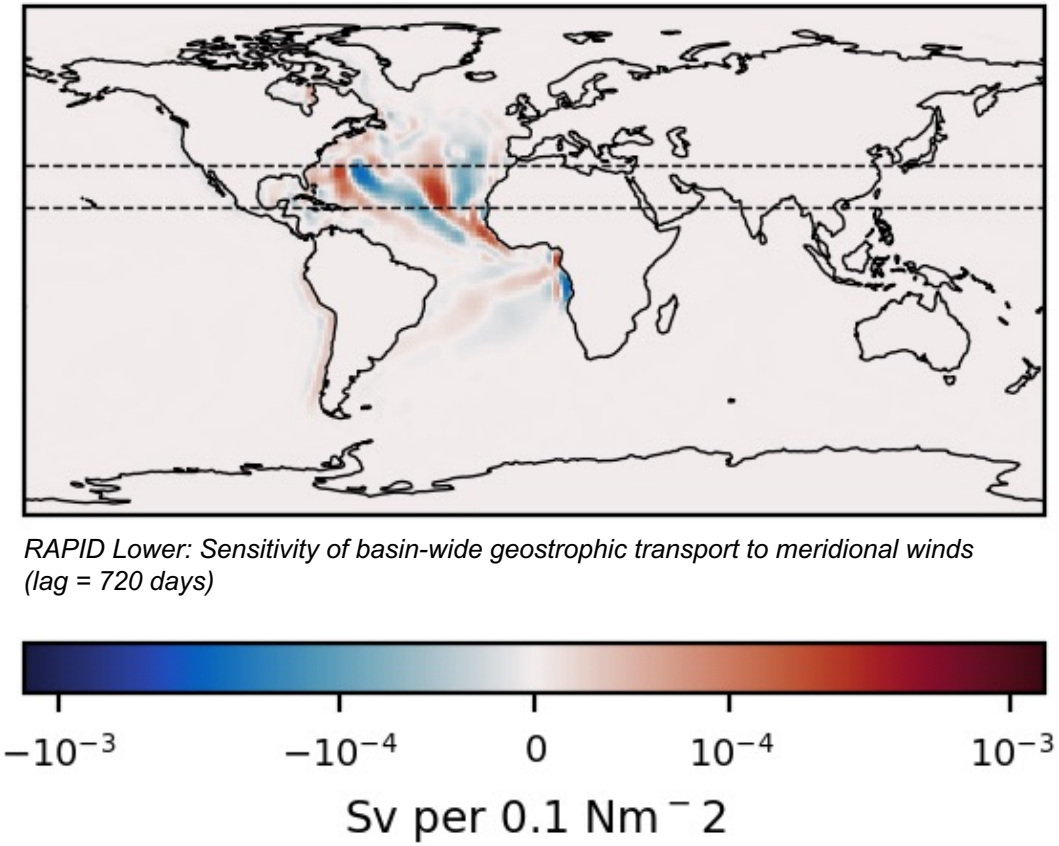
Sensitivity to meridional winds

Describes how meridional winds can increase basin-wide geostrophic transport.

If you…

- Increase meridional winds where the field is **positive,**
- Decrease meridional winds where the field is **negative,**

The basin-wide geostrophic transport should **increase linearly** after a time equal to the lag.



RAPID Lower: Sensitivity of basin-wide geostrophic transport to meridional winds (lag = 720 days)

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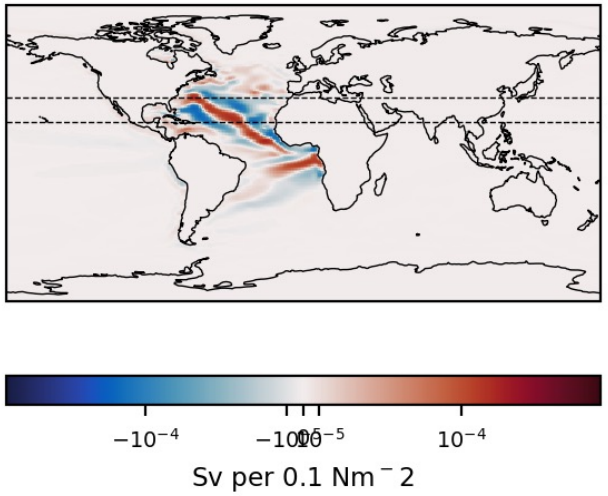
Available sensitivities

We calculate sensitivities to:

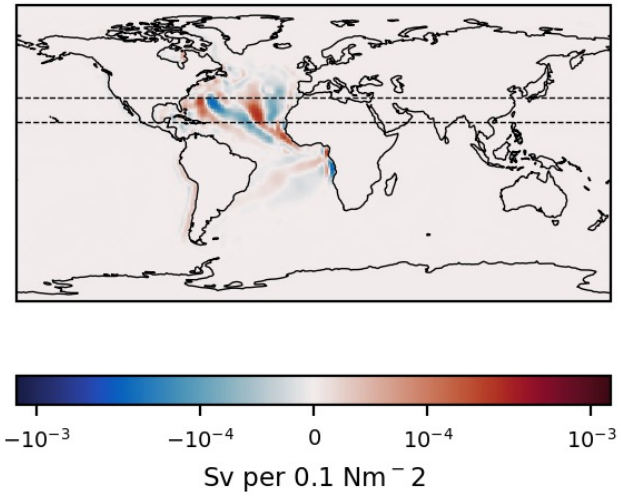
- Zonal wind stress
- Meridional wind stress
- Surface heat fluxes
- Surface freshwater fluxes*

**Sensitivities to freshwater fluxes are negligible in all cases.*

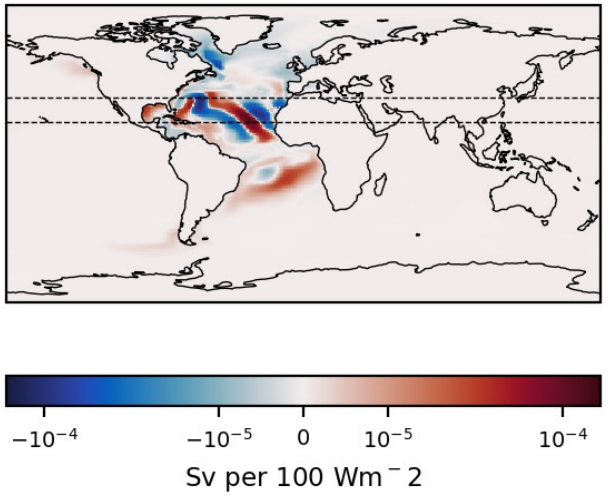
Sensitivity to **zonal wind stress**



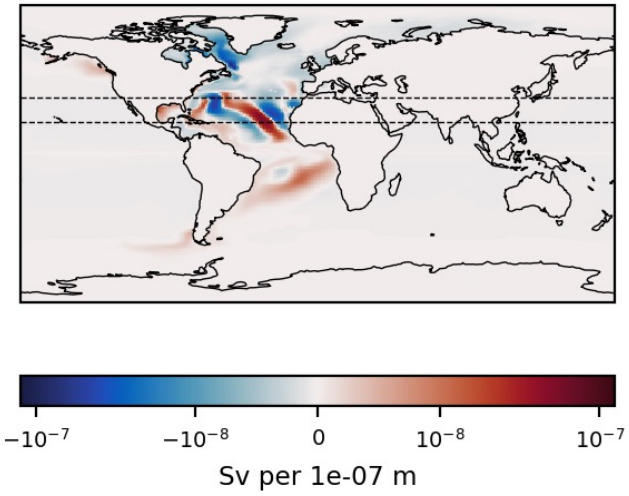
Sensitivity to **meridional wind stress**



Sensitivity to **heat fluxes**



Sensitivity to **freshwater fluxes**



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Reconstructions

Reconstructions are **a product of sensitivity fields and forcing anomalies** experienced by the model.

$$\mathcal{R}_{\mathcal{F}}(t\,) = \sum_{i \in \mathcal{F}} \iint_{\Omega} \int_{-t_m}^{0} \mathcal{A}_i(\boldsymbol{x}, t')\, \Delta\mathcal{F}_i(\boldsymbol{x}, t + t')\, dt'\, dA$$

Reconstruction of the basin-wide geostrophic transport anomaly at time t for a combination of forces $\mathcal{F}$

Linear sensitivity of the transport to i-th force with a lag of t'

Forcing anomaly at time $t + t'$

An optimal combination of forcing and memory **identifies the forces and timescales** which drive the transport variability.

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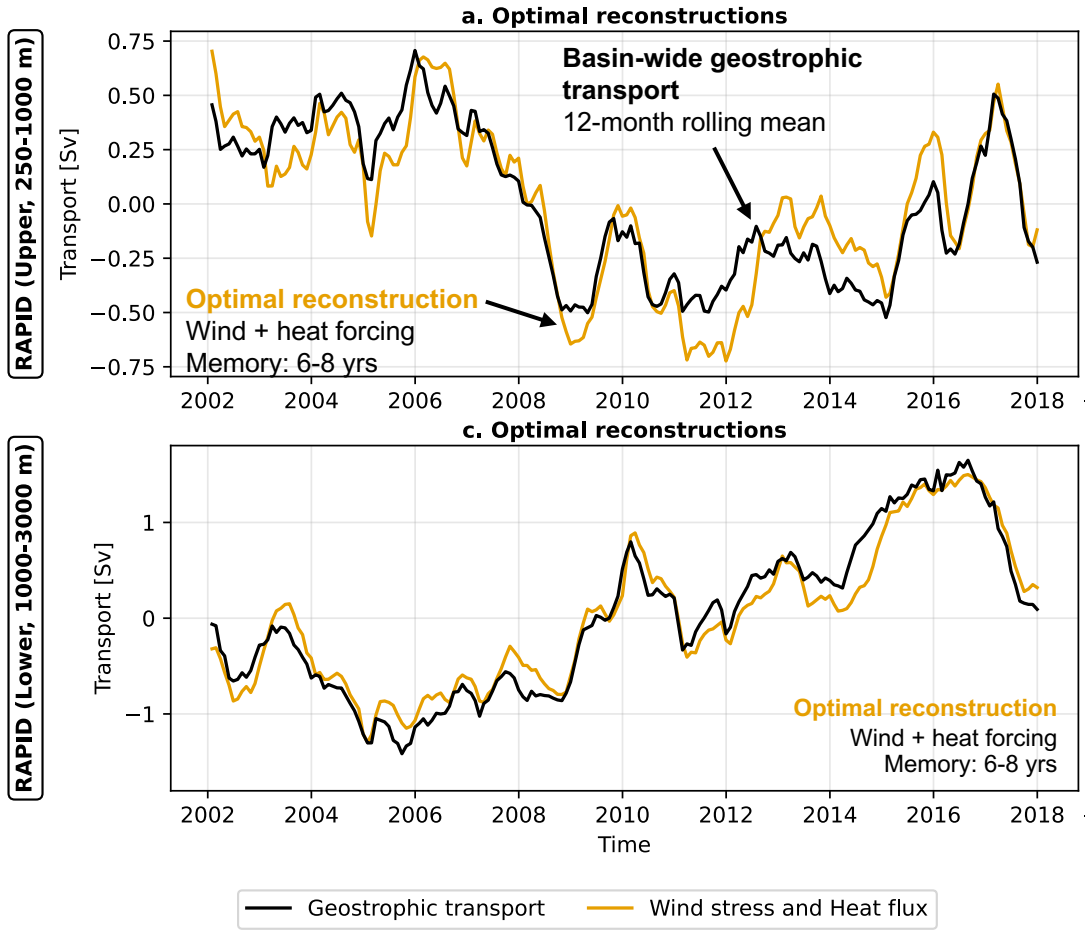
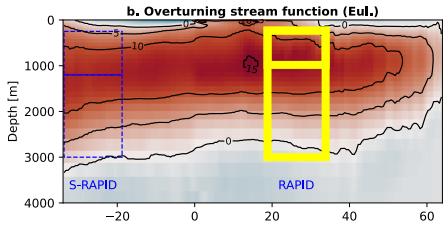
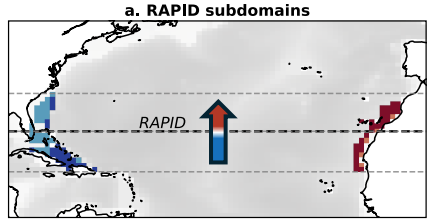
Reconstructions of RAPID transport

Upper depth range

Lower depth range







Depth range	Forcing	Explained variability	Minimum memory
RAPID Upper (250-1000m)	**Wind + Heat**	**79%**	**6 yrs**
RAPID Lower (1000-3000m)	**Wind + Heat**	**94%**	**6 yrs**

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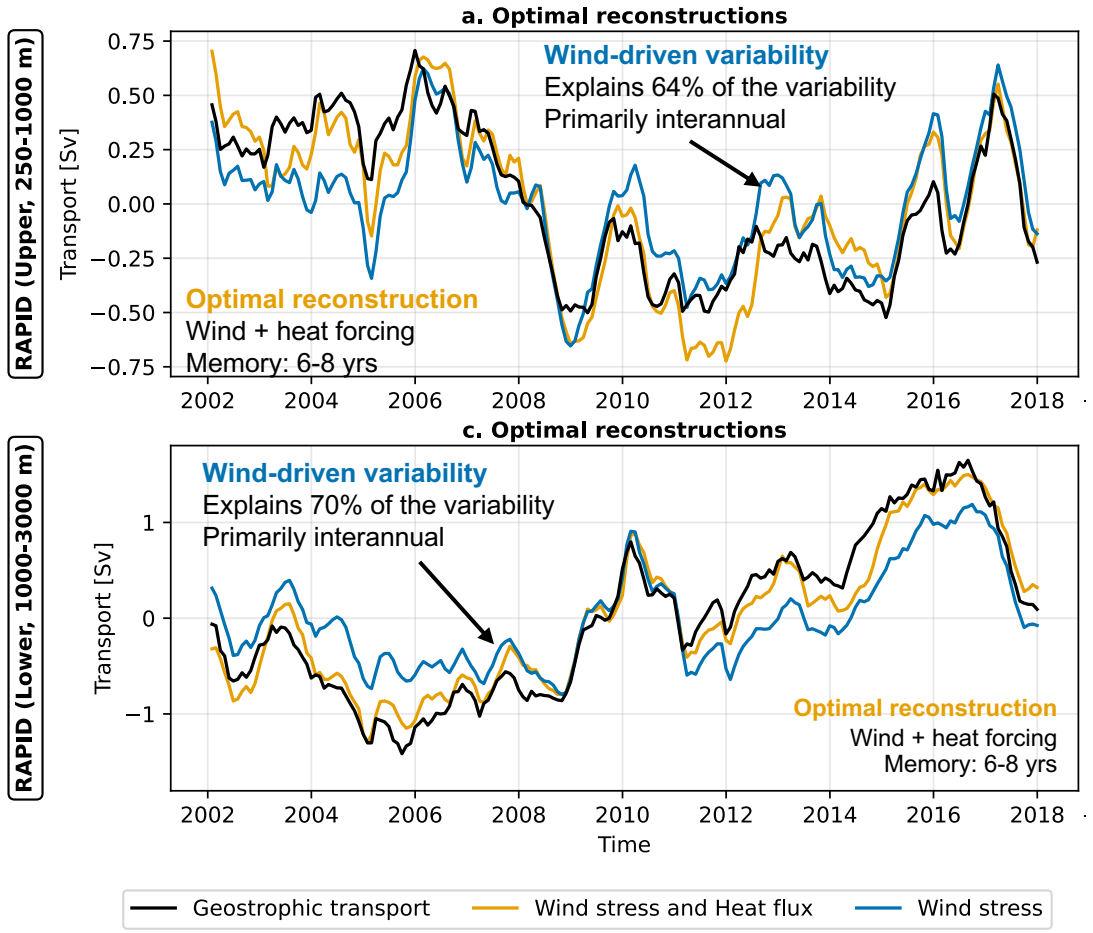
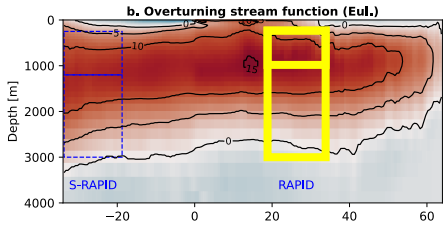
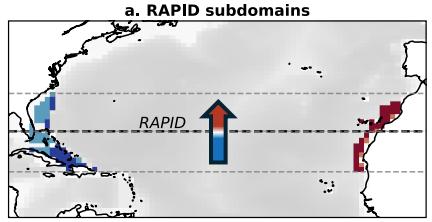
Reconstructions of RAPID transport

Upper depth range

Lower depth range







Depth range	Forcing	Explained variability	Minimum memory
RAPID Upper (250-1000m)	**Wind + Heat**	**79%**	**6 yrs**
	Wind	64%	8 yrs
RAPID Lower (1000-3000m)	**Wind + Heat**	**94%**	**6 yrs**
	Wind	70%	6 yrs

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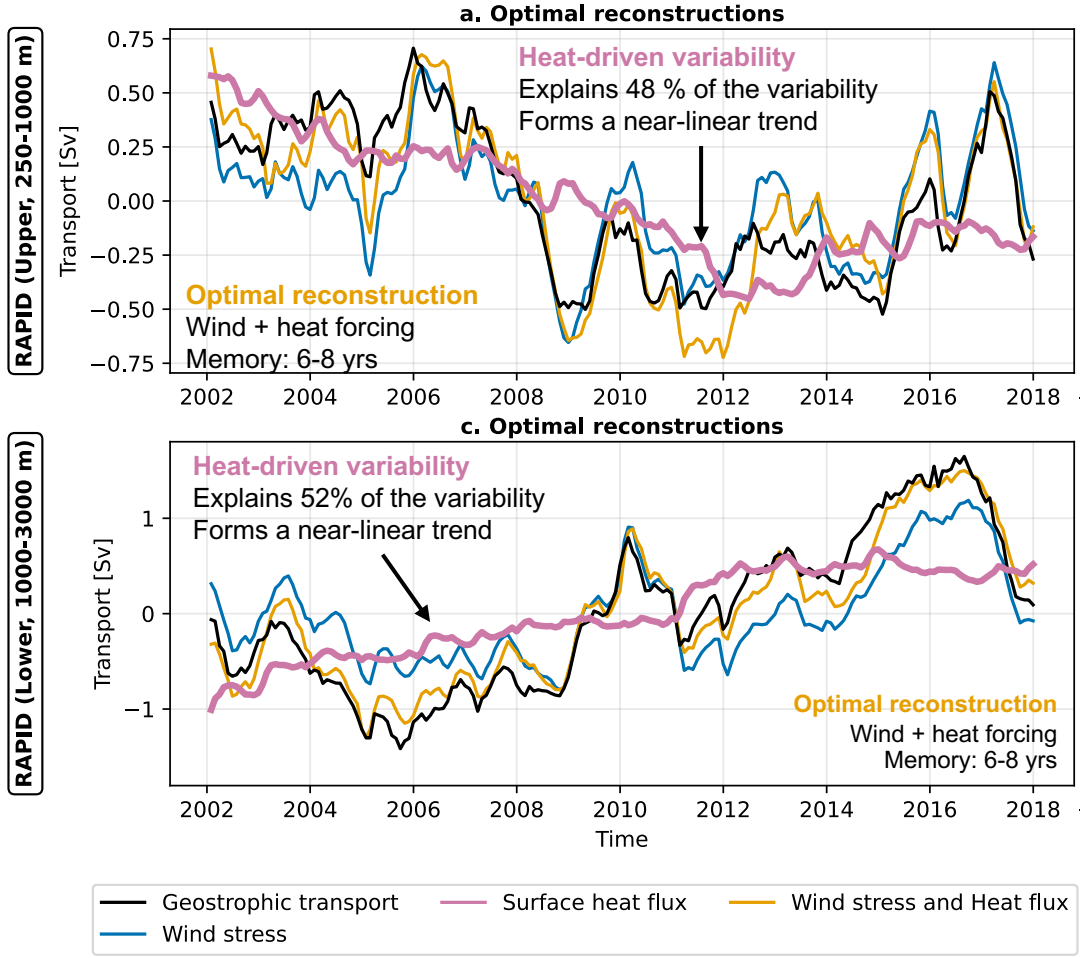
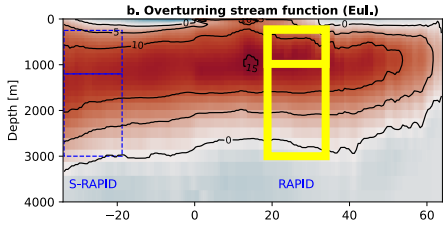
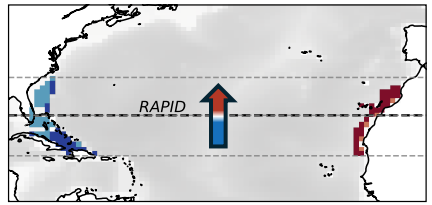
Reconstructions: RAPID transport

Upper depth range

Lower depth range







Depth range	Forcing	Explained variability	Minimum memory
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	Wind	64%	8 yrs
	Heat	48%	6 yrs
RAPID Lower (1000-3000m)	**Wind + Heat**	**94%**	**6 yrs**
	Wind	70%	6 yrs
	Heat	52%	8 yrs

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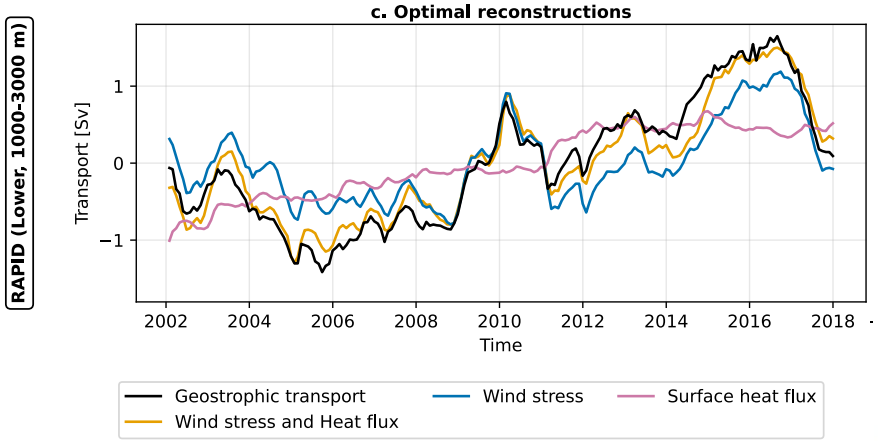
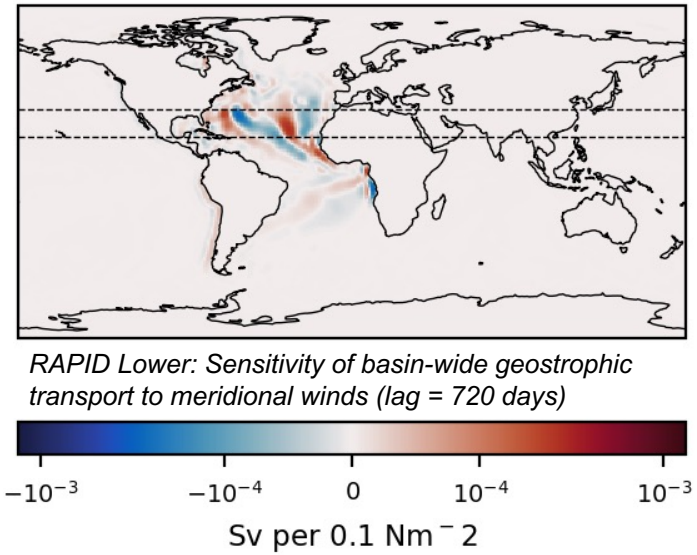
Summary

- There is a **robust relationship** between transport variability and boundary pressures.
- Adjoint sensitivities **explain 79-94%** of the basin-wide geostrophic transport variability.
- **Wind-driven variability is necessary** to describe the interannual variability of the basin-wide geostrophic transport.
- **Heat-driven variability can represent trends** in a 15-year time series of the transport.





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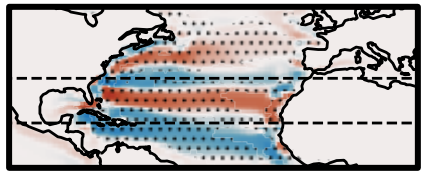
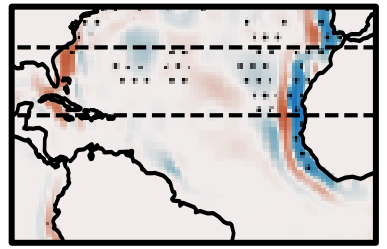
Our full investigation

- Calculate sensitivities and reconstructions of the basin-wide geostrophic transport for the subtropical **Southern Hemisphere.**
- Identify **a rogues' gallery** of wind and heat patterns which drive the transport variability.
- Identify cases where the **western boundary** is significantly **more sensitive than the eastern boundary.**
- Tested for **non-linear sensitivities** in a series of perturbation experiments.



RAPID Lower: Sensitivity to zonal winds



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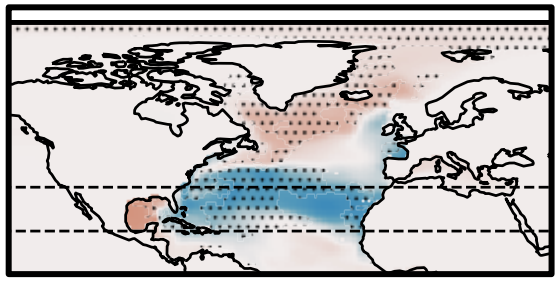

RAPID Upper: Sensitivity to heat flux

Atmospheric drivers of basin-wide geostrophic transport in the Atlantic

OCEANOGRAPHY

ADJOINT MODEL | AMOC | BOTTOM PRESSURE | GEOSTROPHIC TRANSPORT | SENSITIVITY | VARIABILITY

Andrew F Styles, Emma J.D. Boland, Chris W. Hughes, Saranraj Gururaj, Dani C Jones

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EXTRA SLIDES

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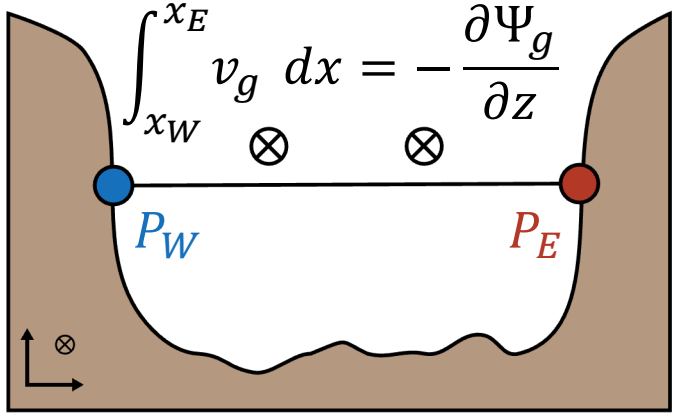
Basin-wide geostrophic transport

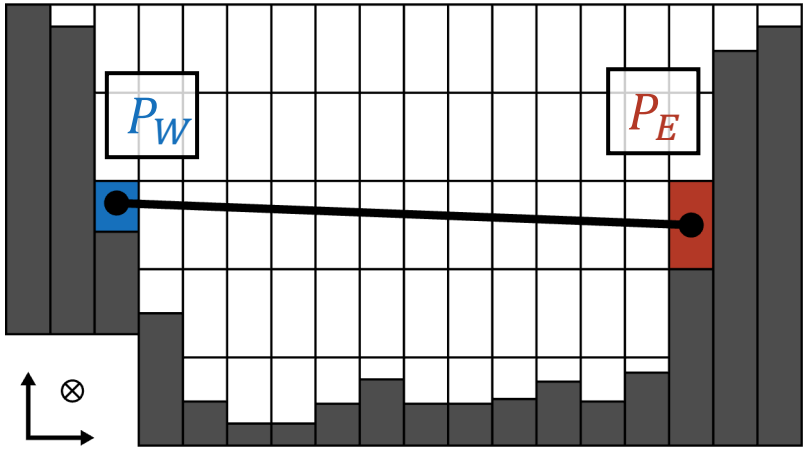
Basin-wide geostrophic transport is a product of **geostrophic balance**:

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



The above equation can be integrated zonally to relate the basin-wide transport to the across-basin pressure difference

$$\underbrace{-\frac{\partial \Psi_g}{\partial z}}_{\text{Basin-wide transport per unit depth}} = \frac{1}{\rho_0 f}\underbrace{(P_E - P_W)}_{\text{Across-basin pressure difference}}$$



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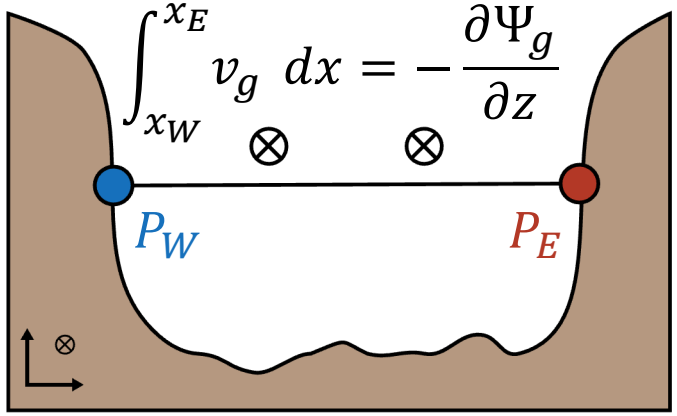
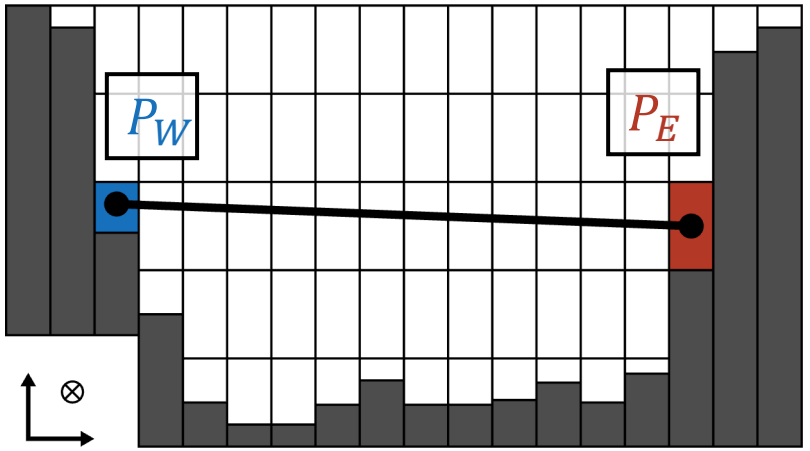
Basin-wide geostrophic transport

$$-\frac{\partial \Psi_g}{\partial z} = \frac{1}{\rho_0 f}(P_E - P_W)$$



Applying the above equation on a model grid can be problematic. Problems include:

- Unaligned grid points
- Noise in the vertical pressure profile
- Vertical sidewalls



Resolved by averaging **bottom pressures** over **fixed depth and latitude ranges**

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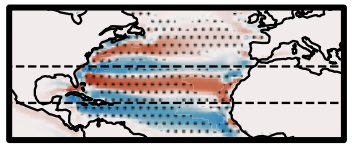
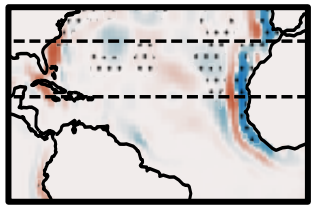
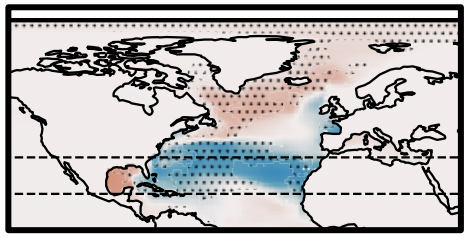
Summary of spatial features







Feature	RAPID Upper	RAPID Lower	S-RAPID Upper	S-RAPID Lower	Boundary affected
Zonal wind bands	✓	✓	✓	✓	**West**
Local along-slope winds	✓	✓	✓	✓	**Both**
Remote along-slope winds	✓	✓	✓	✓	**Both**
Local interior heat fluxes	✓	✗	✗	✗	**West**
Northern heat fluxes	✓	✓	✗	✗	**Both**

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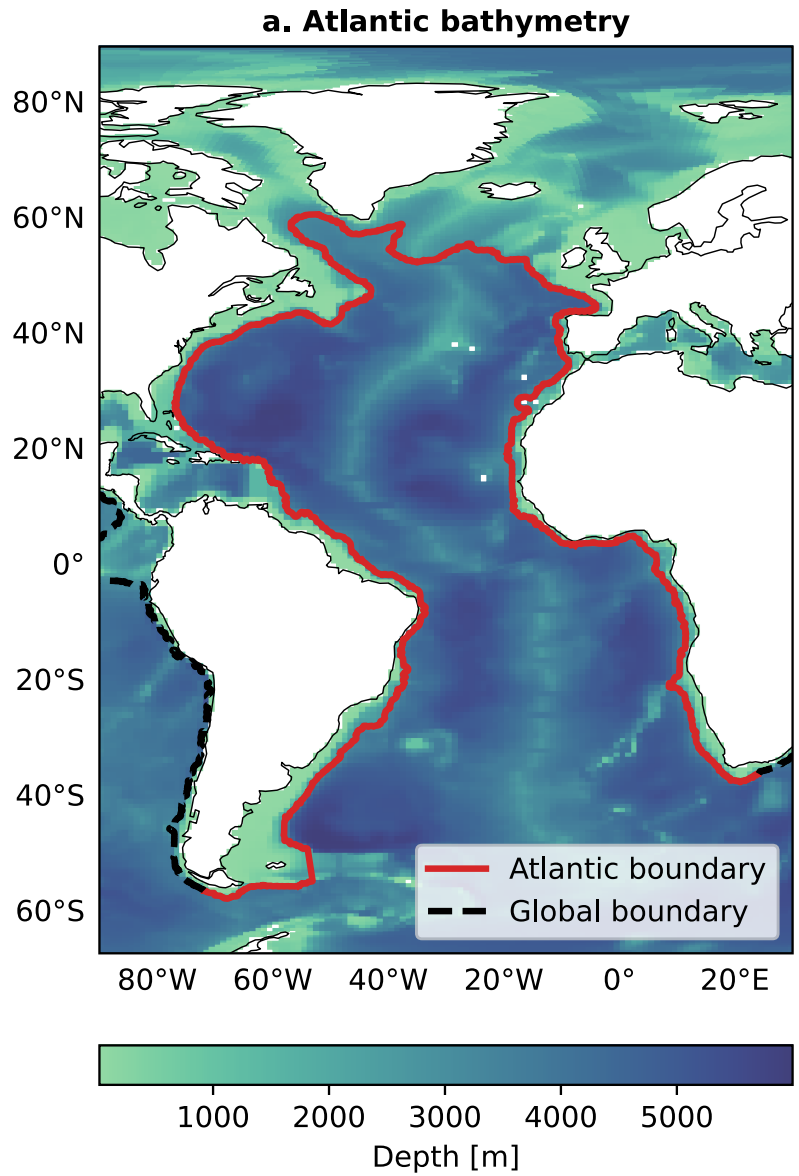

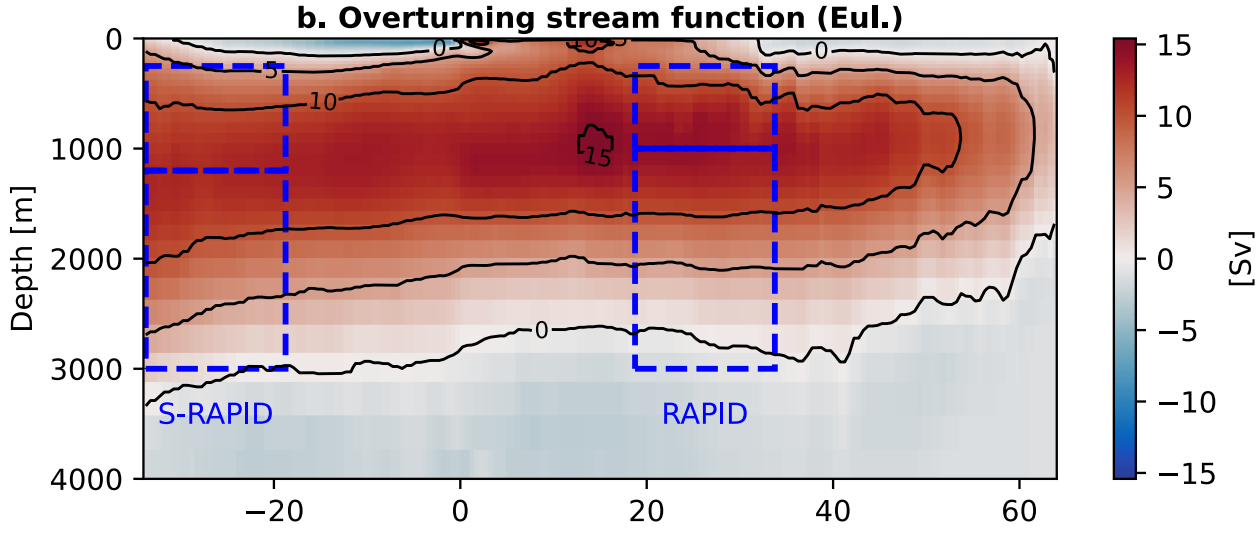

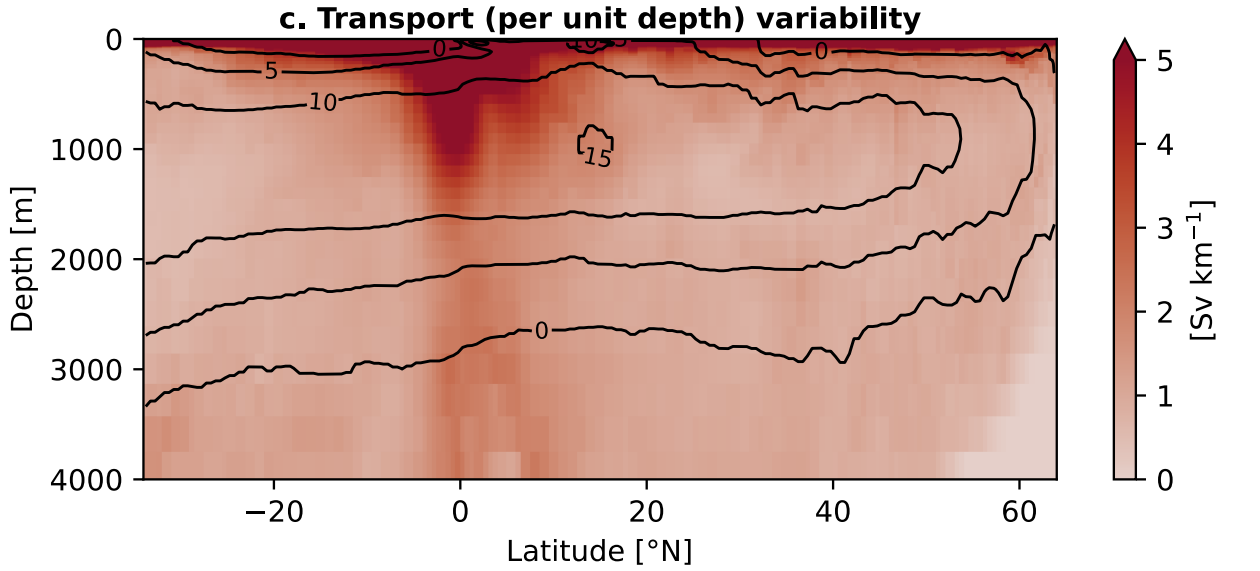

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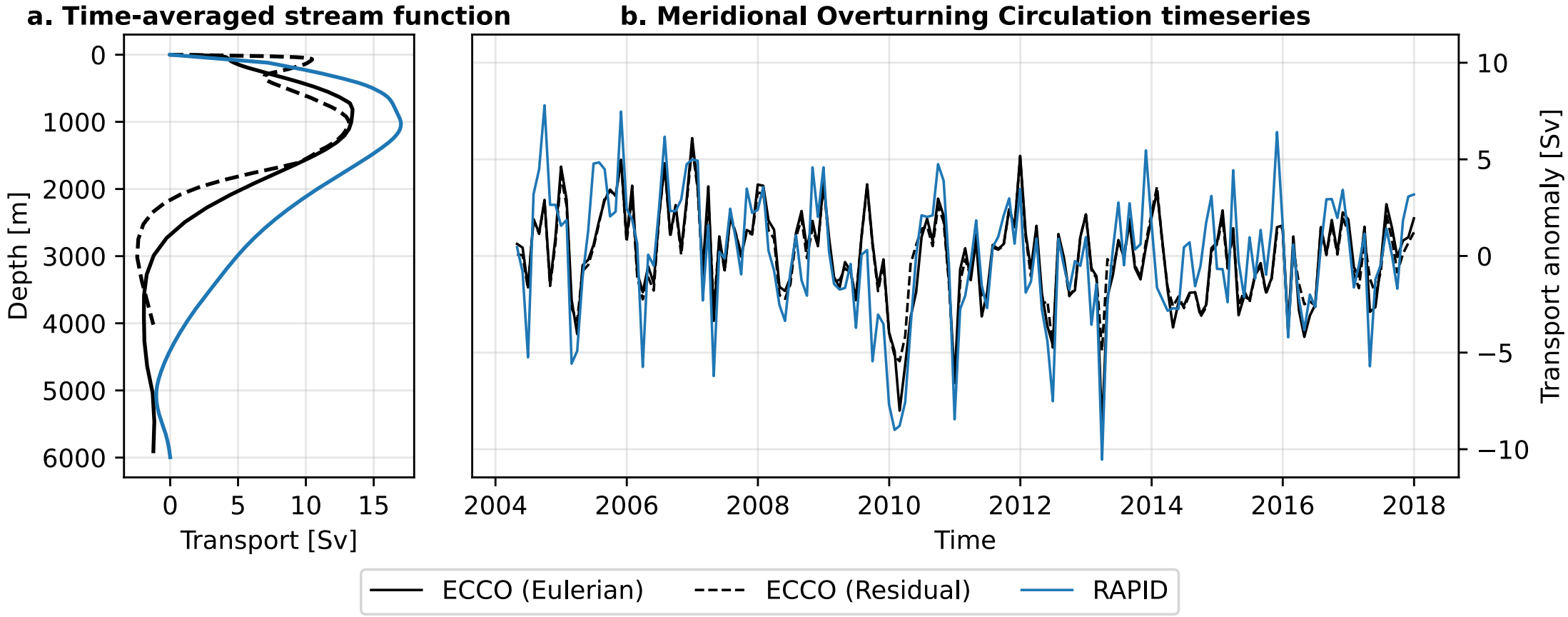

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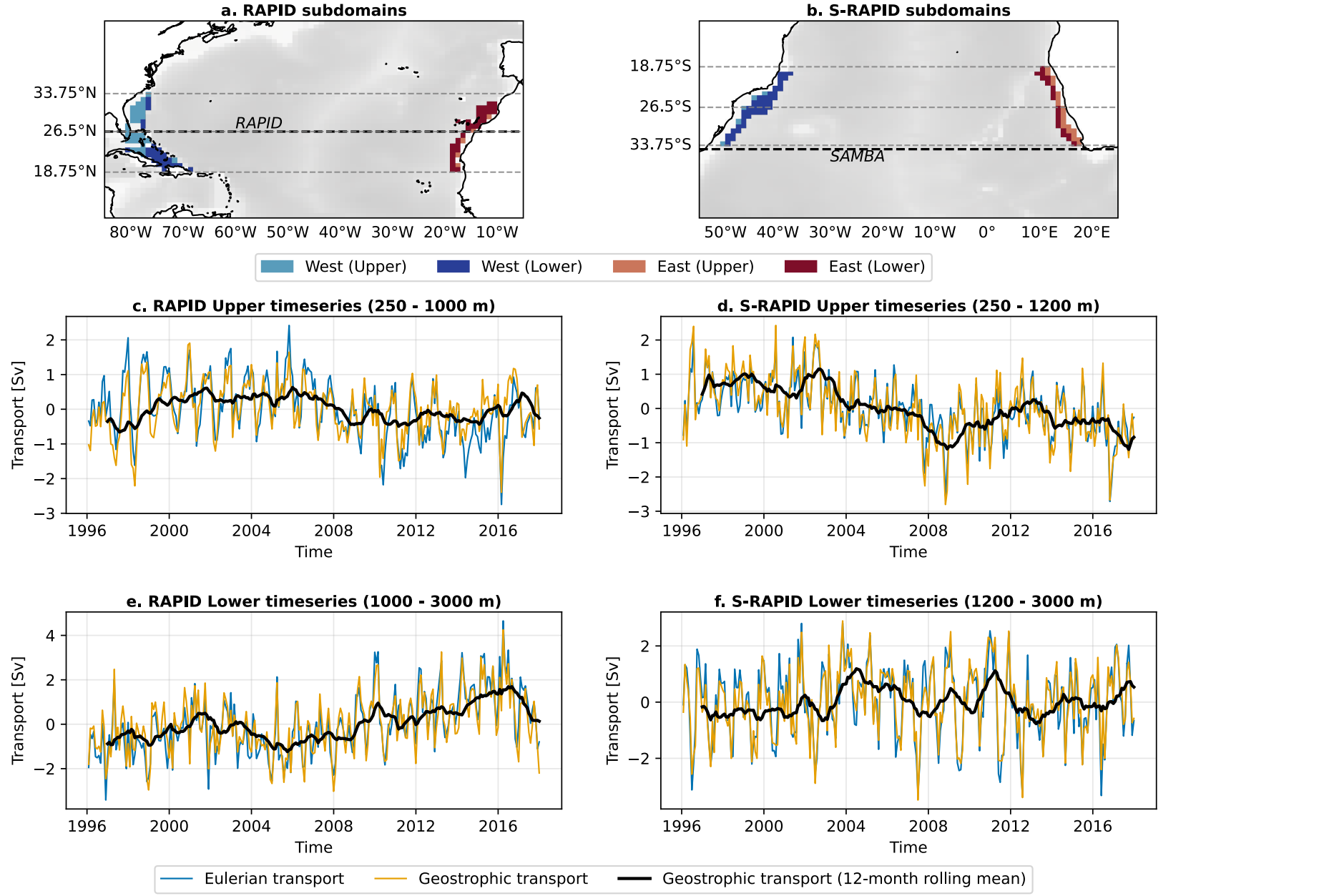

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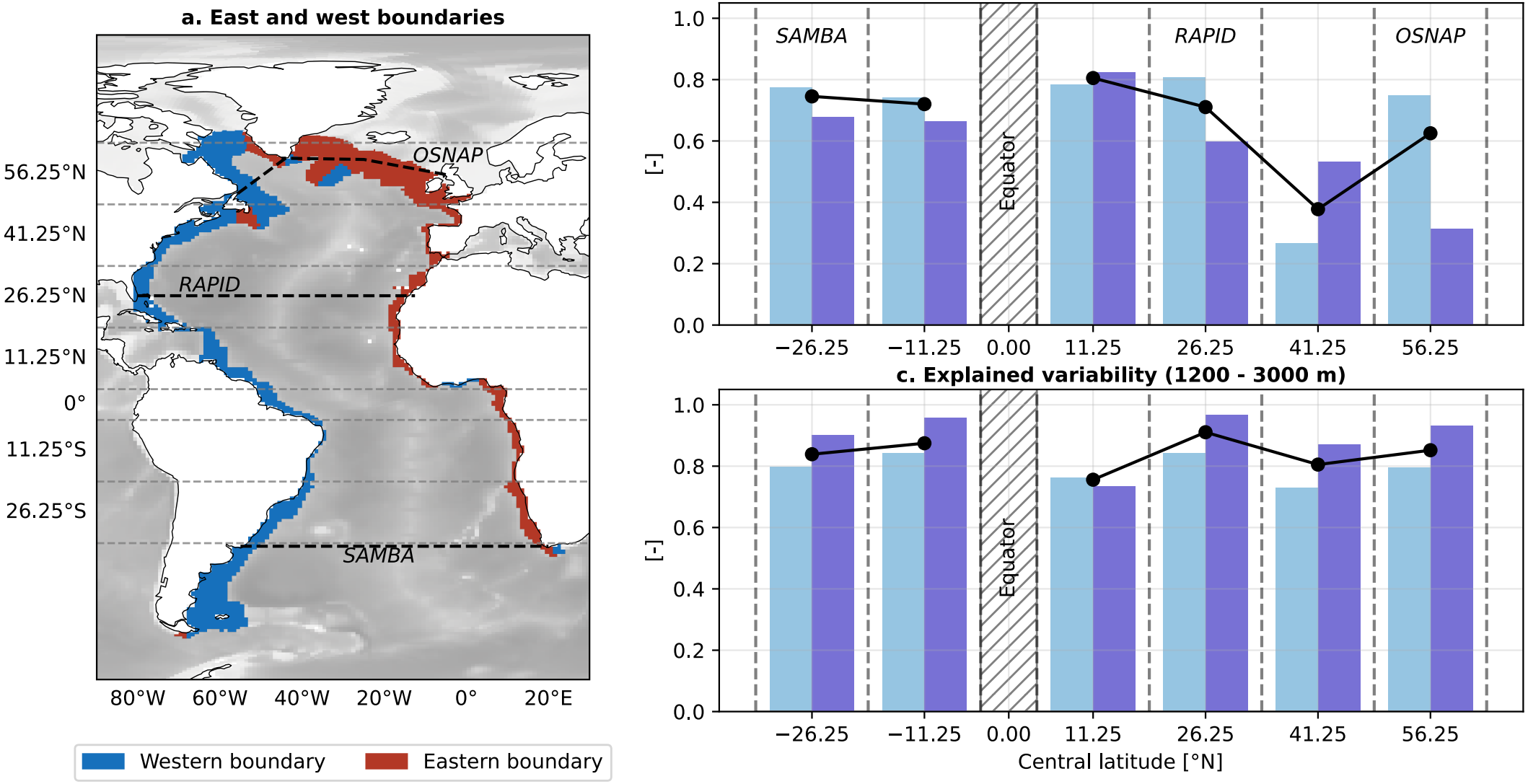

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Table 1. Table reviewing the target subdomains. Explained variability values describes the fraction of transport variability explained by the basin-wide geostrophic transport on several timescales: Unfiltered (all available timescales), subannual, and interannual. The highest explained variability for each subdomain is shown in bold.

			Explained variability		
Subdomain	**Latitude range**	**Depth range**	**Unfiltered**	**Subannual**	**Interannual**
RAPID Upper	18.75-33.75°N	250-1000 m	0.74	**0.83**	0.63
RAPID Lower	18.75-33.75°N	1000-3000 m	0.90	0.83	**0.96**
S-RAPID Upper	18.75-33.75°S	250-1200 m	0.75	**0.77**	0.68
S-RAPID Lower	18.75-33.75°S	1200-3000 m	0.83	0.80	**0.90**

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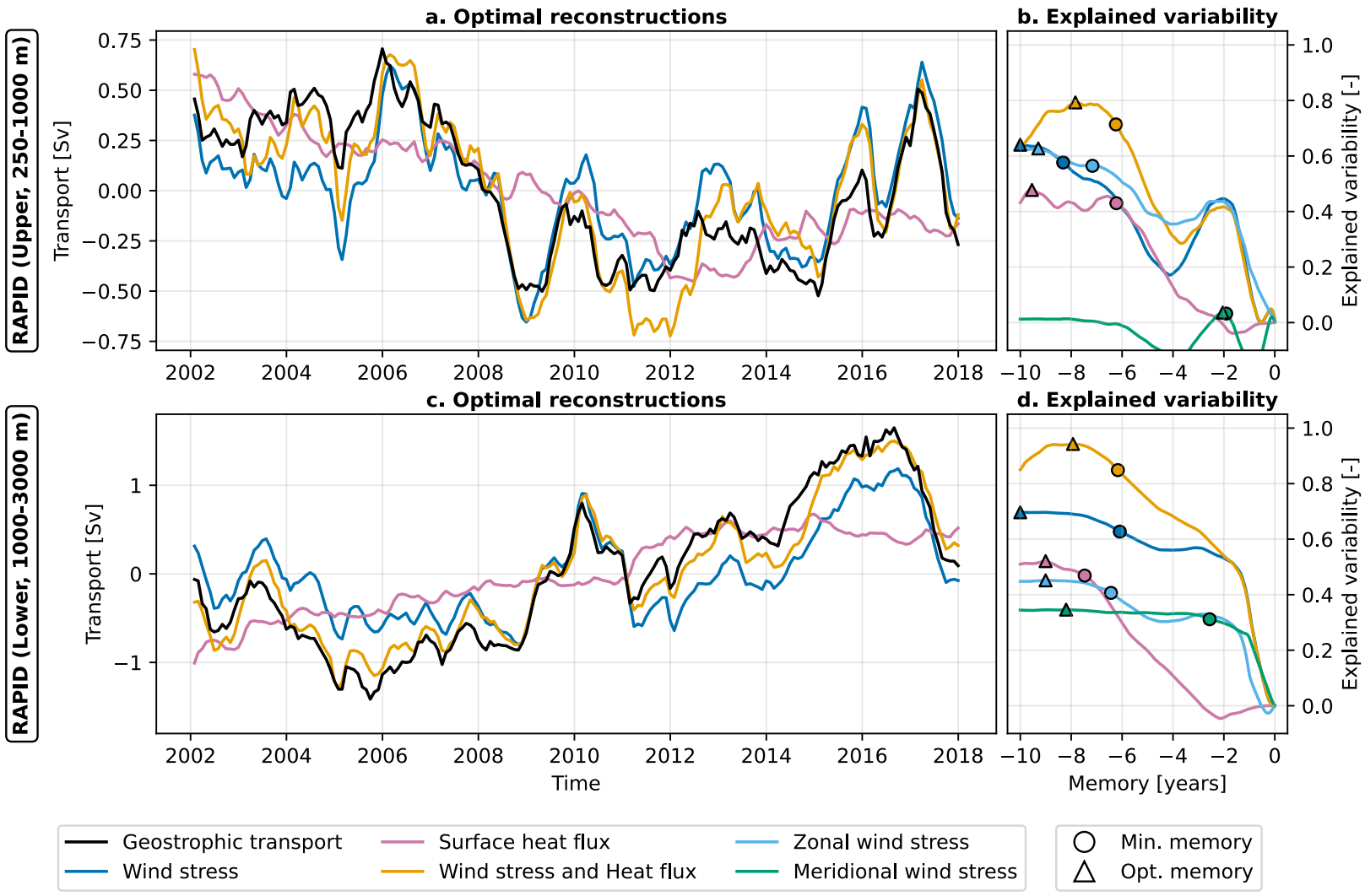
Table 2. Table summarizing the performance of the reconstructions. For each subdomain, the optimal reconstruction is shown in bold. Values in parentheses are the explained variabilities when the time series are detrended.

Experiment name	Forcing	Max. explained variability	Optimal memory in years	Minimum memory in years
RAPID (upper)	Wind stress	0.64 (0.80)	10.0 (6.7)	8.3 (5.1)
	Heat flux	0.48 (0.33)	9.5 (6.5)	6.2 (6.1)
	Wind stress + Heat flux	**0.79 (0.81)**	**7.8 (6.6)**	**6.2 (5.2)**
	Zonal wind stress	0.63 (0.71)	9.3 (7.0)	7.2 (5.5)
	Meridional wind stress	0.04 (0.24)	2.0 (5.7)	1.9 (4.9)
RAPID (lower)	Wind stress	0.70 (0.76)	10.0 (7.4)	6.1 (4.9)
	Heat flux	0.52 (0.10)	9.0 (7.0)	7.5 (6.8)
	Wind stress + Heat flux	**0.94 (0.87)**	**7.9 (7.4)**	**6.2 (6.1)**
	Zonal wind stress	0.45 (0.56)	9.0 (7.4)	6.4 (5.7)
	Meridional wind stress	0.35 (0.34)	8.2 (6.4)	2.6 (2.3)
S-RAPID (upper)	Wind stress	0.77 (0.93)	4.0 (6.8)	2.4 (2.9)
	Heat flux	0.19 (0.05)	10.0 (8.3)	9.7 (8.1)
	Wind stress + Heat flux	**0.86 (0.94)**	**10.0 (6.6)**	**7.3 (3.0)**
	Zonal wind stress	0.53 (0.80)	8.6 (8.8)	4.0 (3.8)
	Meridional wind stress	0.52 (0.59)	9.3 (9.2)	1.3 (4.0)
S-RAPID (lower)	**Wind stress**	**0.88 (0.88)**	**7.2 (7.2)**	**4.0 (3.8)**
	Heat flux	0.00 (0.02)	0.00 (8.5)	0.00 (8.3)
	Wind stress + Heat flux	0.85 (0.90)	7.5 (7.6)	4.2 (3.9)
	Zonal wind stress	0.81 (0.81)	6.6 (6.7)	3.9 (4.2)
	Meridional wind stress	0.43 (0.51)	7.4 (7.3)	5.2 (2.1)



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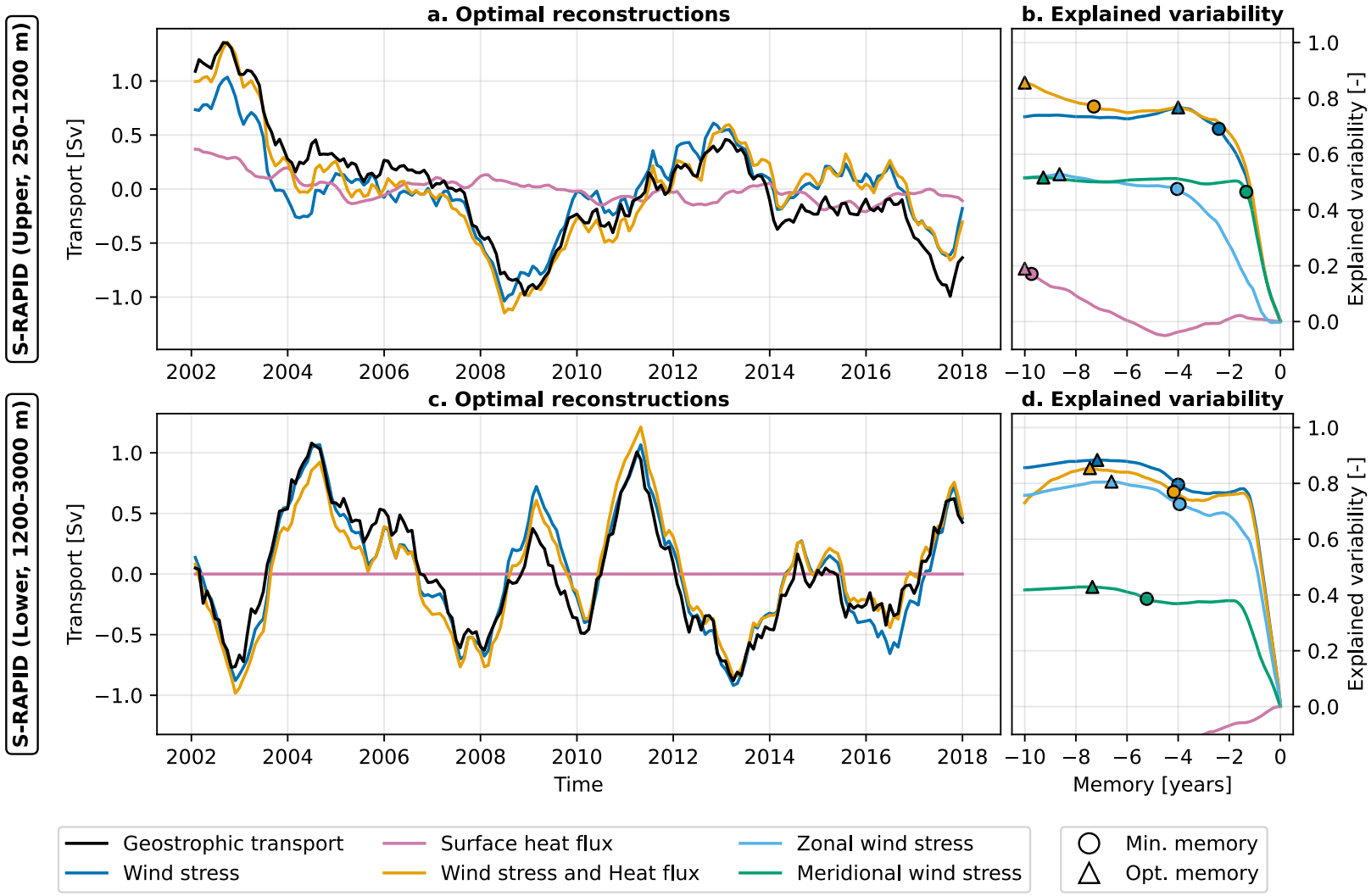

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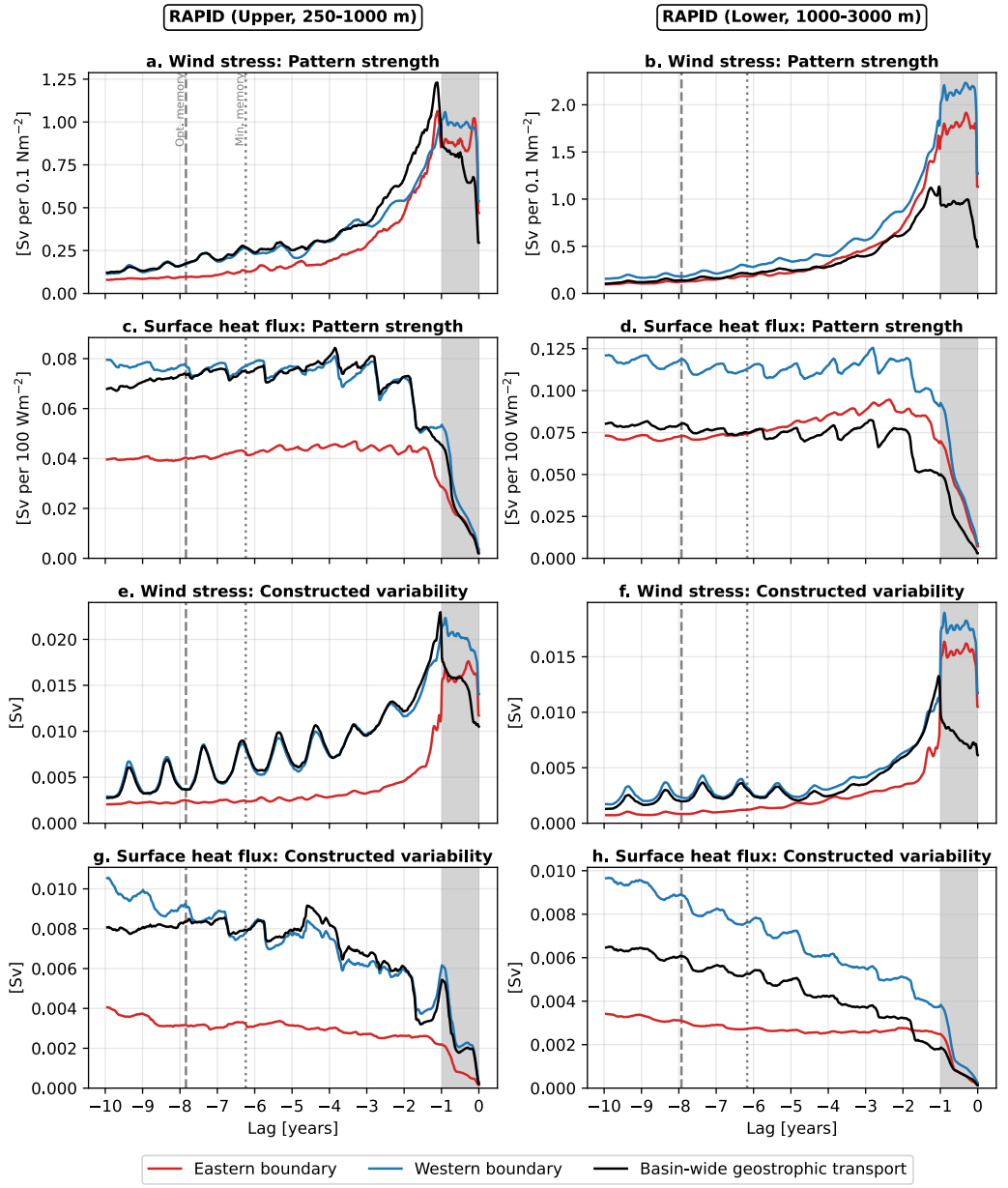

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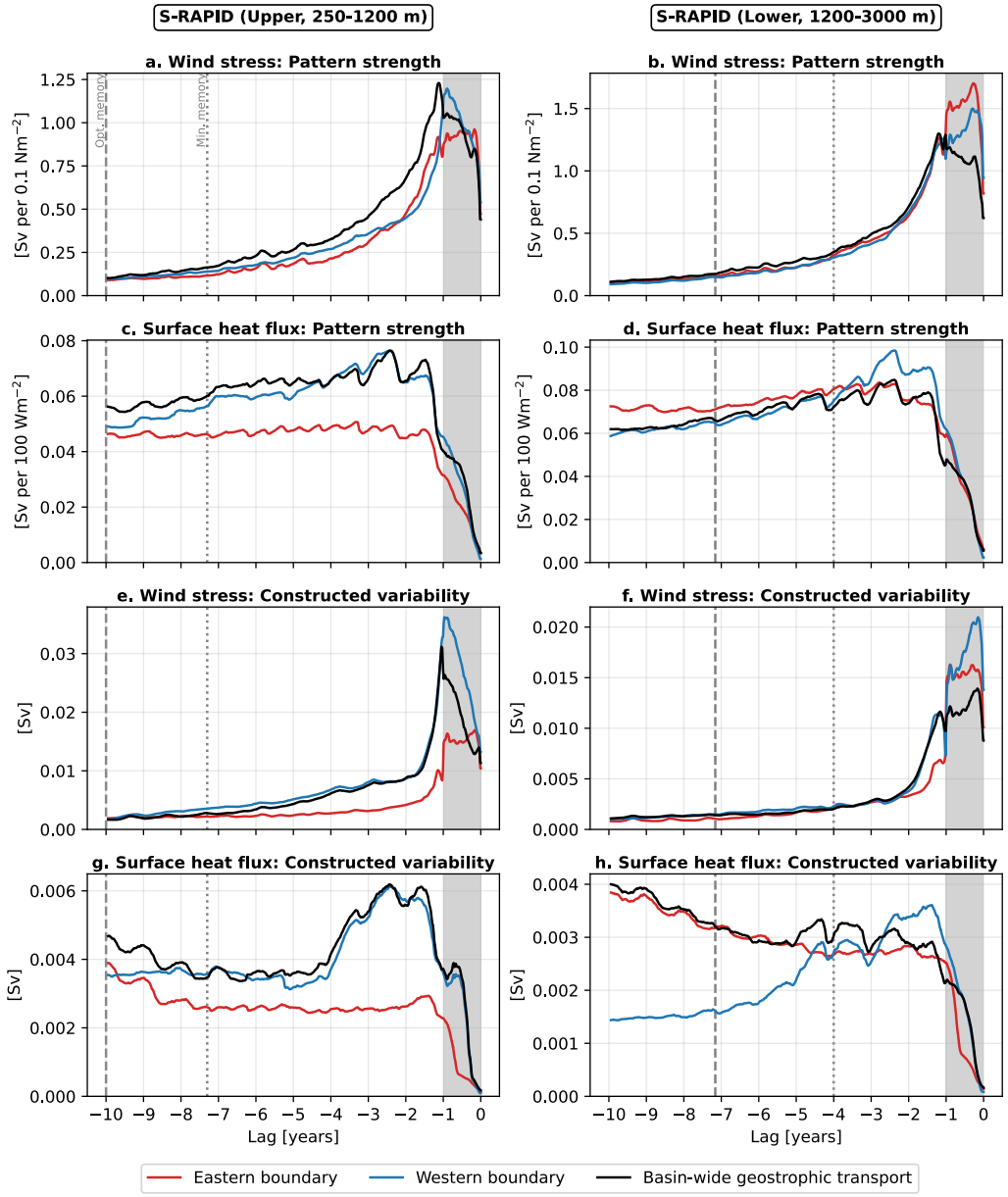

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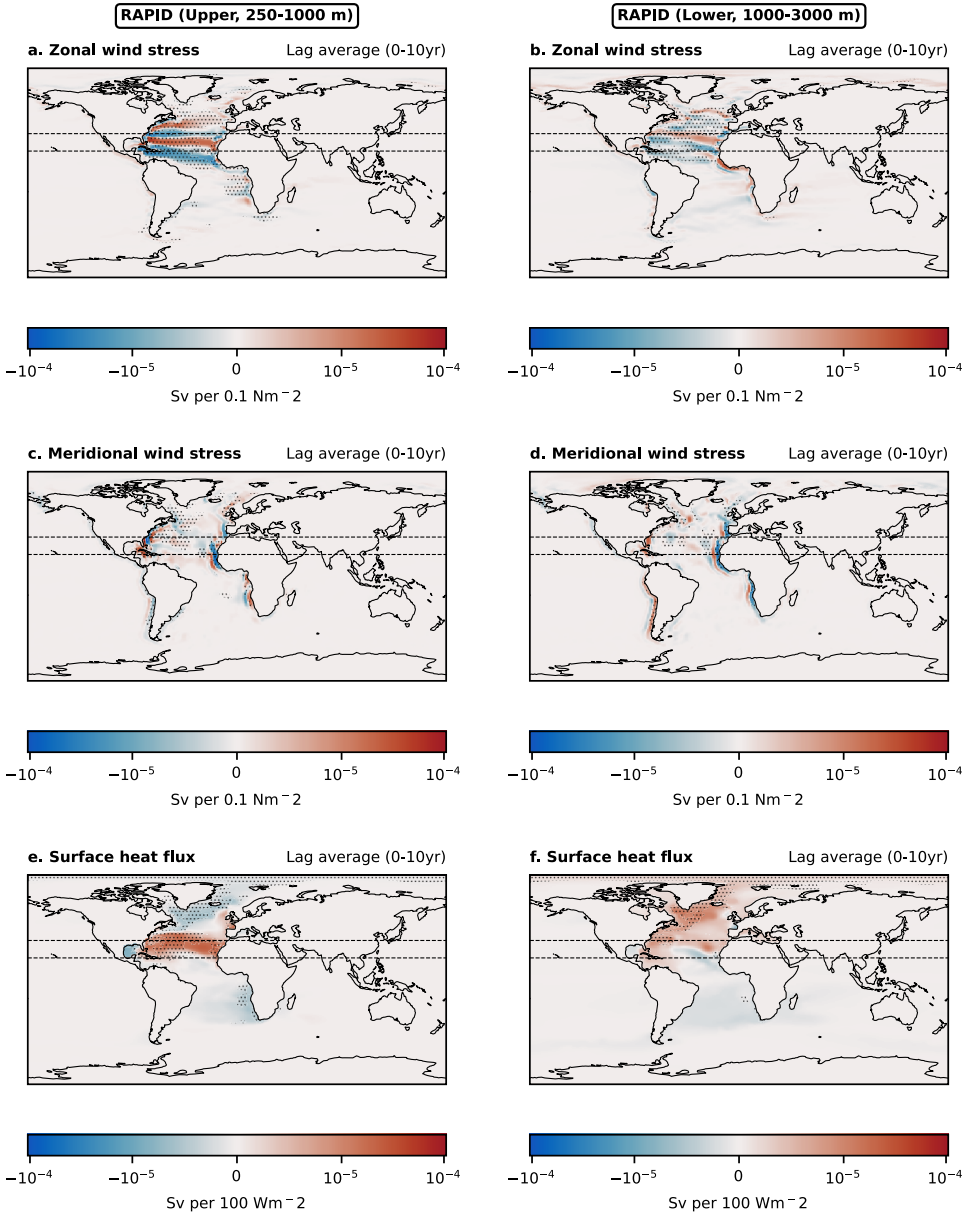

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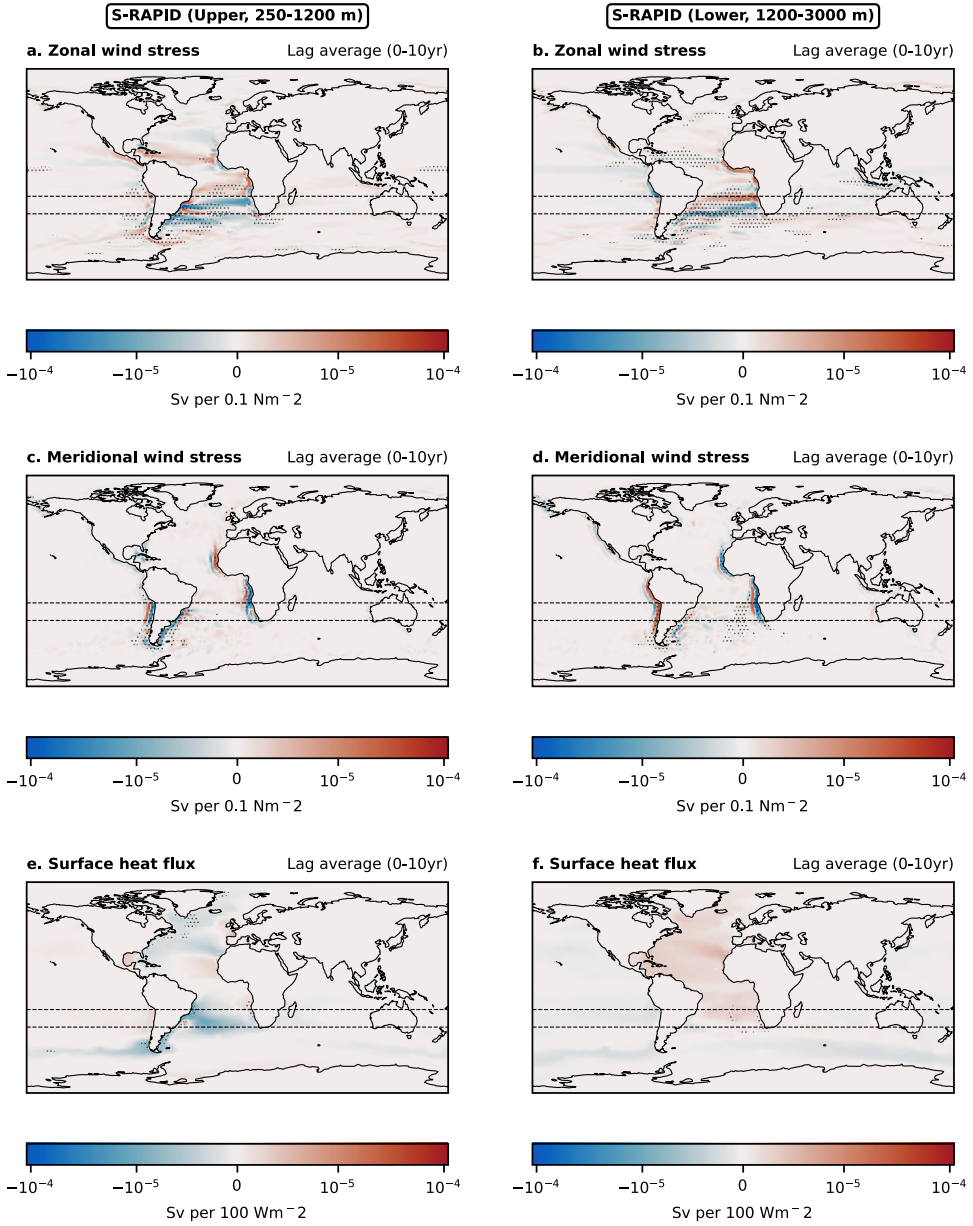

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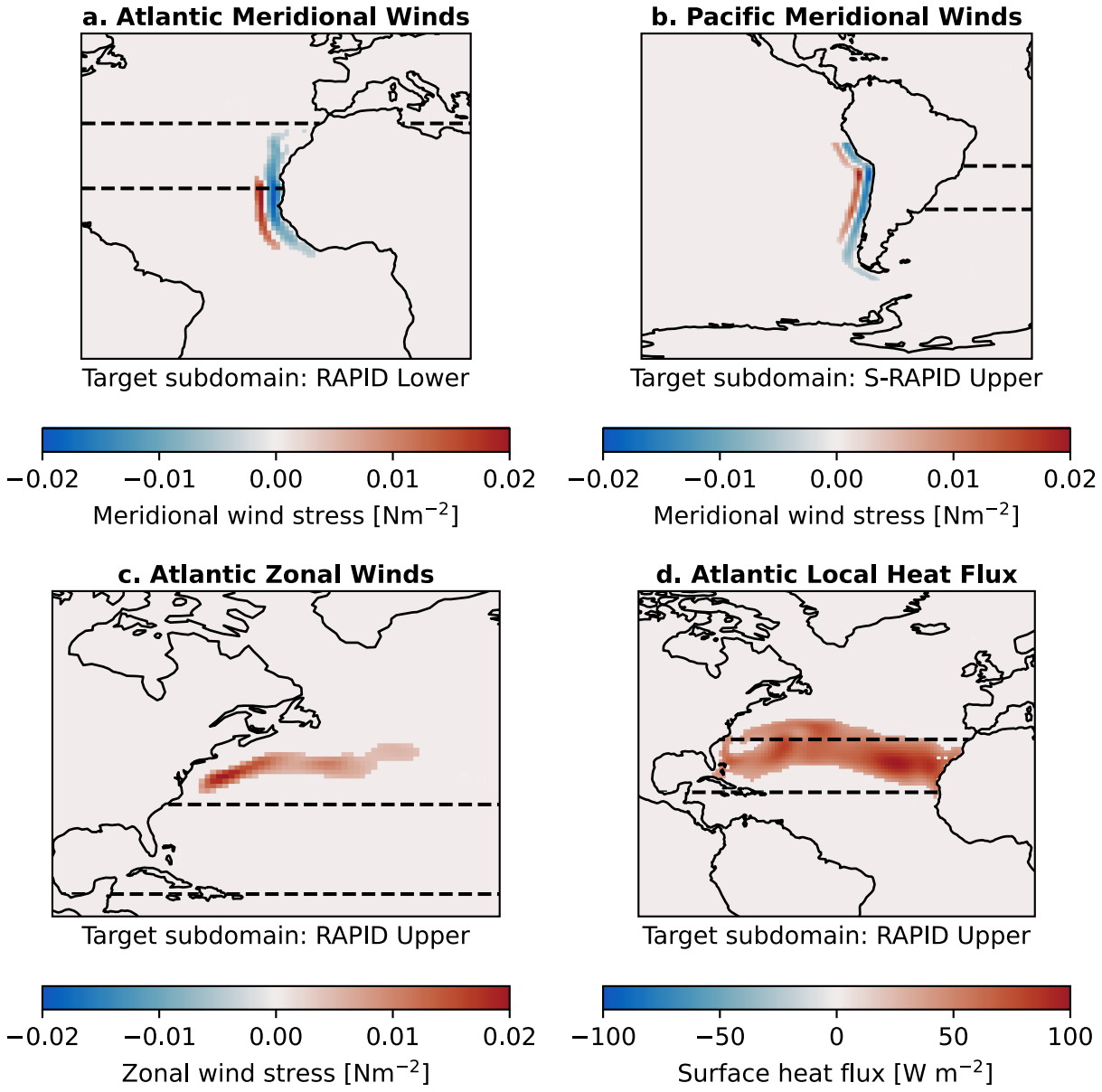

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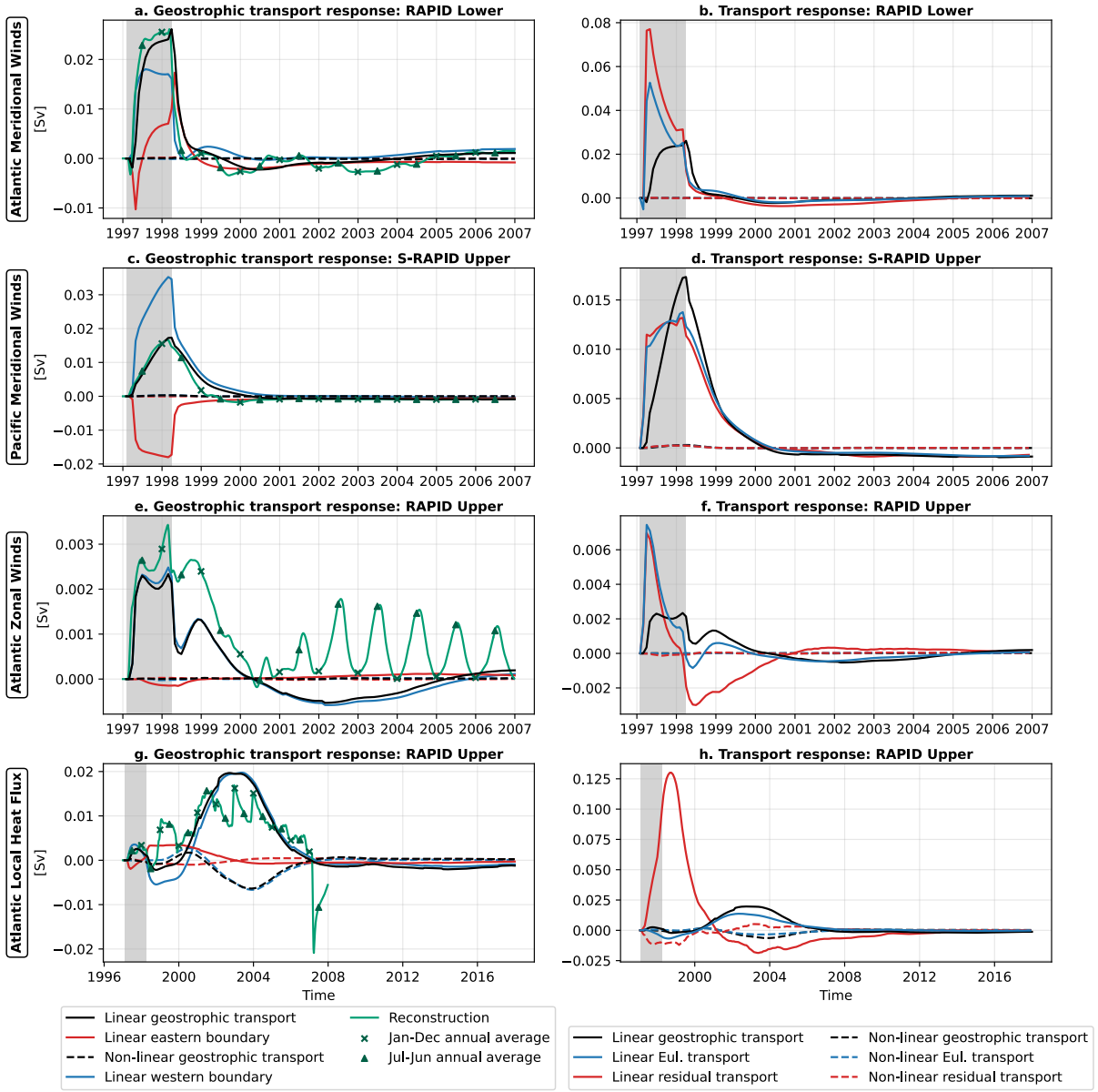

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