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A Multi-Data Set Analysis of the Freshwater Transport by the Atlantic Meridional Overturning Circulation at Nominally 34.5ºS

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7th July 2026

Outline

- **Introduction**
- **Objectives**
- **Data**
- **Methods**
- **Results & Discussion**
- **Conclusions**

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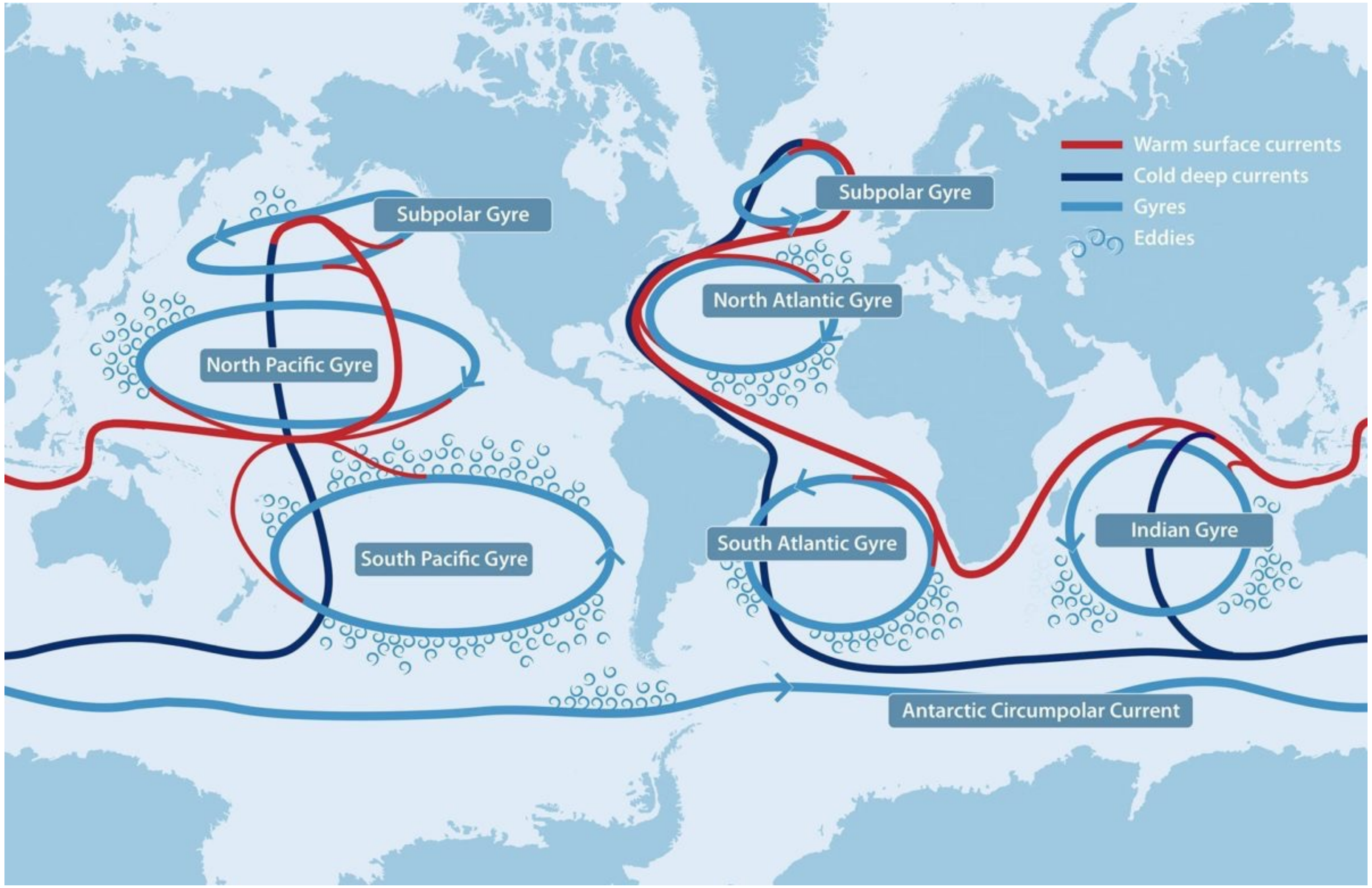
The Meridional Overturning Circulation (MOC)



(Illustration by Natalie Renier, © Woods Hole Oceanographic Institution)

Climate Change:

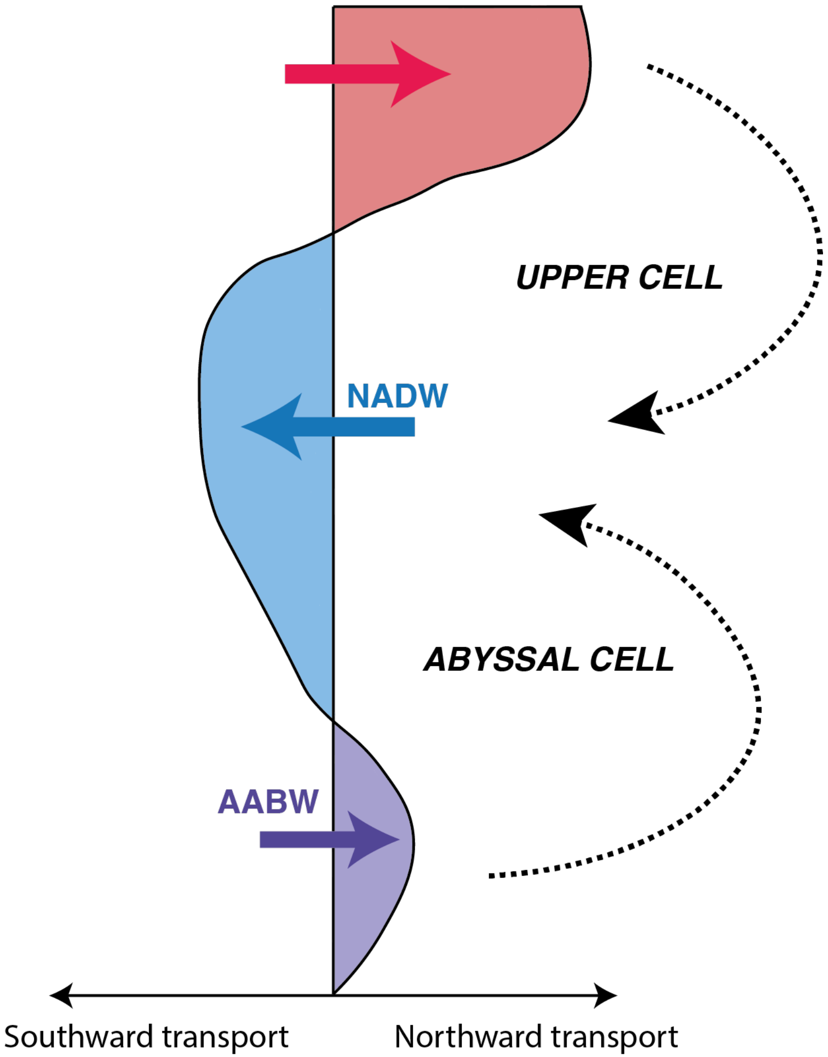
- Rising Sea Surface Temperature (SST)
- Melting Polar Ice Sheets

Results & implications:

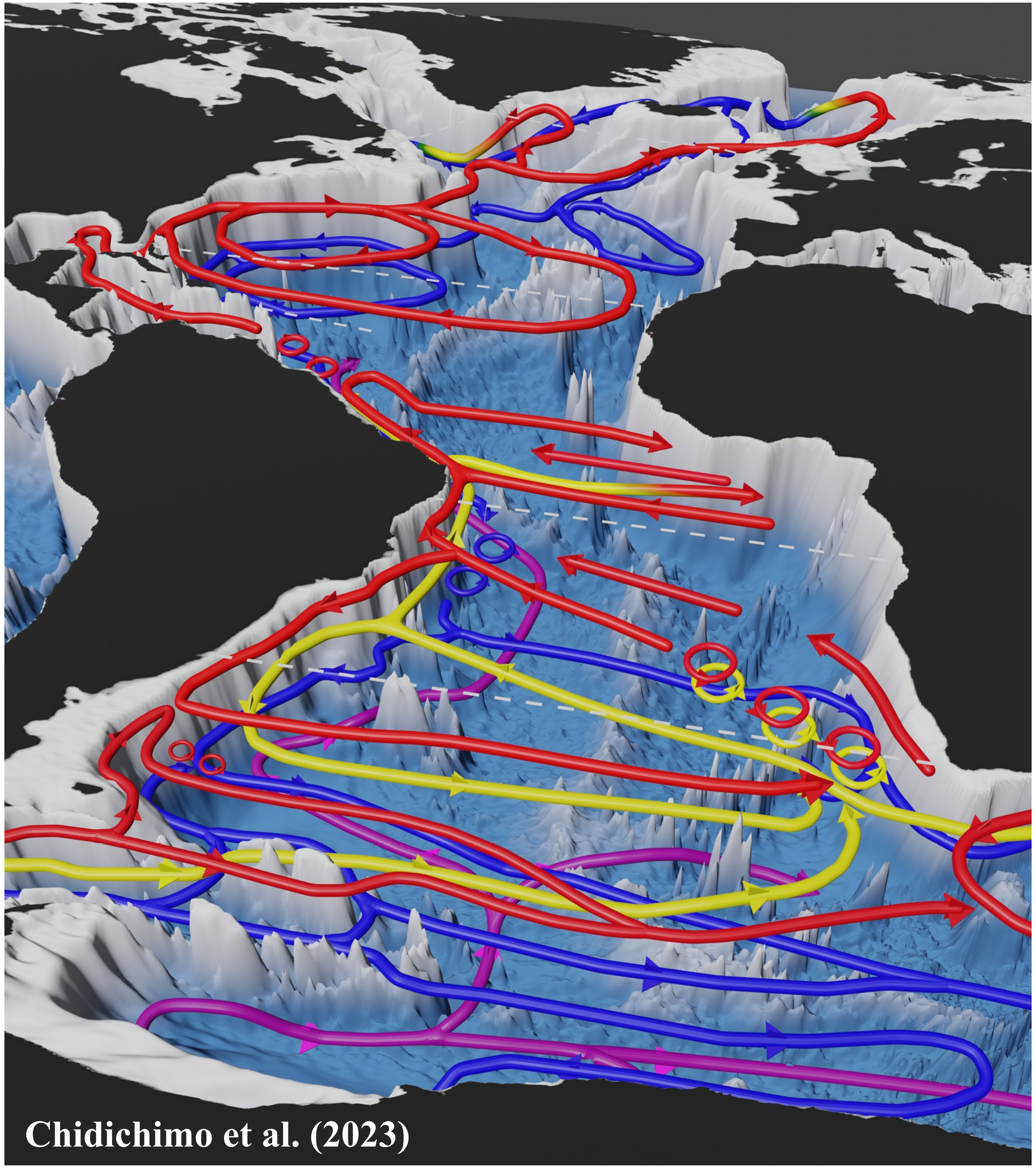
- Intensified near-surface stratification (especially North Atlantic and Antarctic Oceans)
- Slowing or potential collapse of MOC.

Introduction: AMOC definition

Atlantic Meridional Overturning Circulation (AMOC)



Adapted from Kersalé et al. (2020)



Chidichimo et al. (2023)

Introduction: **AMOC stability**

1. What is the M_{ov}?

- Freshwater transport by the AMOC at 34.5ºS in the South Atlantic: **is an indicator of AMOC stability** **(Rahmstorf, 1996).**
- Computed as the zonally averaged vertical circulation of the salt at a specific zonal section at 34.5ºS in Sv:

$$M_{ov} = -\frac{1}{S_0}\int_{-B}^{0} \rho\, \overline{v^*}(z)\langle S'(z)\rangle dz$$

$\boxed{M_{ov} > 0}$ → monostable AMOC regime

$\boxed{M_{ov} < 0}$ → bistable AMOC regime

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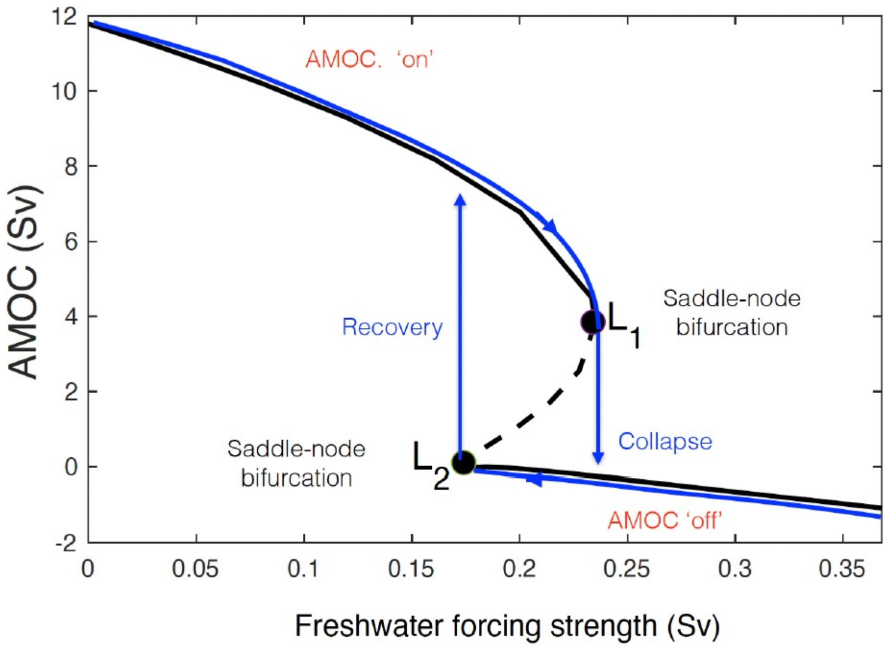


Dijkstra et al. (2026)

2. Monostable vs bistable AMOC:

- **Monostable:** the system has only one stable equilibrium state.
- **Bistable:** the system has two stable equilibrium states.

If AMOC weakens beyond a certain tipping point (L1), it may collapse into the weak state and won't recover unless the freshwater forcing is significantly reversed past another tipping point (L2).

MOC variability and climate change

Role of Climate & Ocean Models offer the opportunity to:

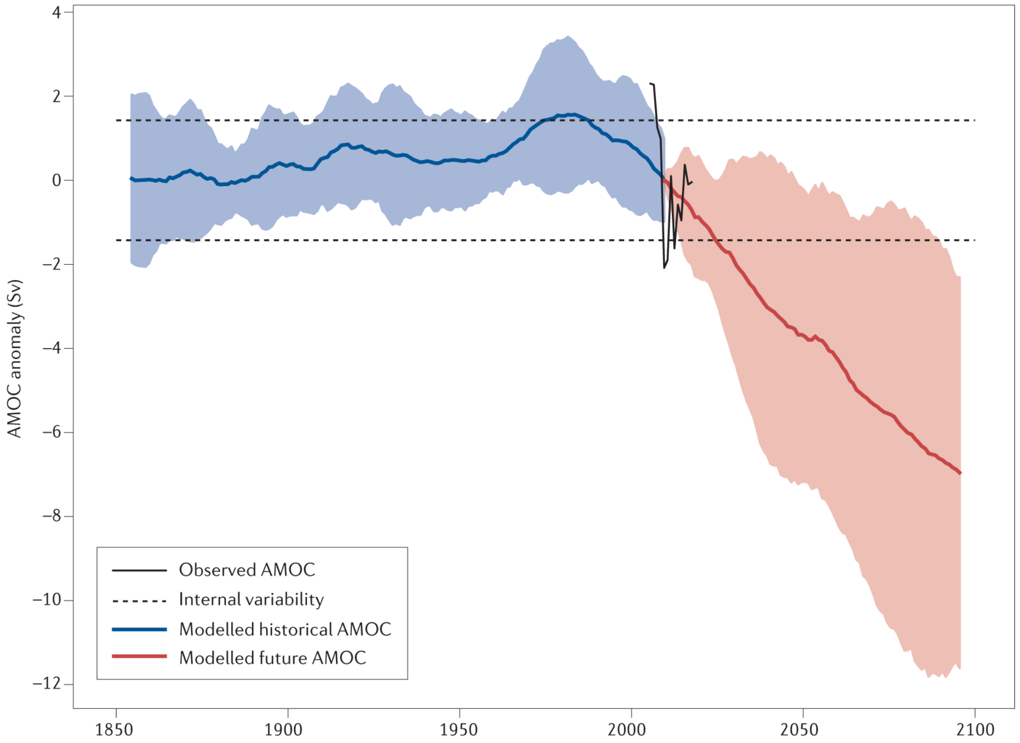
- Better understand the MOC.
- Provide projections for its future evolution.

Projected MOC decline:

- CMIP model ensambles show a consistent **decline of MOC** strength in the **21st century** due to **anthropogenic climate change**.
- **Limitations:** model biases due to misrepresentation of key processes (e.g., mesoscale eddies, boundary currents, mixing in overflows, etc.)

Climate implications of MOC decline:

- Could disrupt the global distribution of ocean properties that sustain marine ecosystems, the carbon cycle, and other key processes.



Jackson et al. (2022)

An accurate estimate of the MOC variability is crucial and can be computed using multiple sources.

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A Multi-Data Set Analysis of the Freshwater Transport by the AMOC at Nominally 34.5ºS: **Objectives**

- The main goal of this chapter is to present a multi-data set analysis of the M_{ov} at nominally 34.5ºS in the Atlantic Ocean, using AX18-XBT data collected from April 2002 to October 2019.
- To examine the consistency between observed and simulated multidecadal variability of the South Atlantic meridional fluxes using two datasets derived from Argo floats, Ocean General Circulation Models (OGCMs), and Coupled General Circulation Models (CGCMs), and to diagnose the causes of the differences in the sign of M_{ov}.
- To analyze the seasonal variability and how the fluxes covary on longer timescales.

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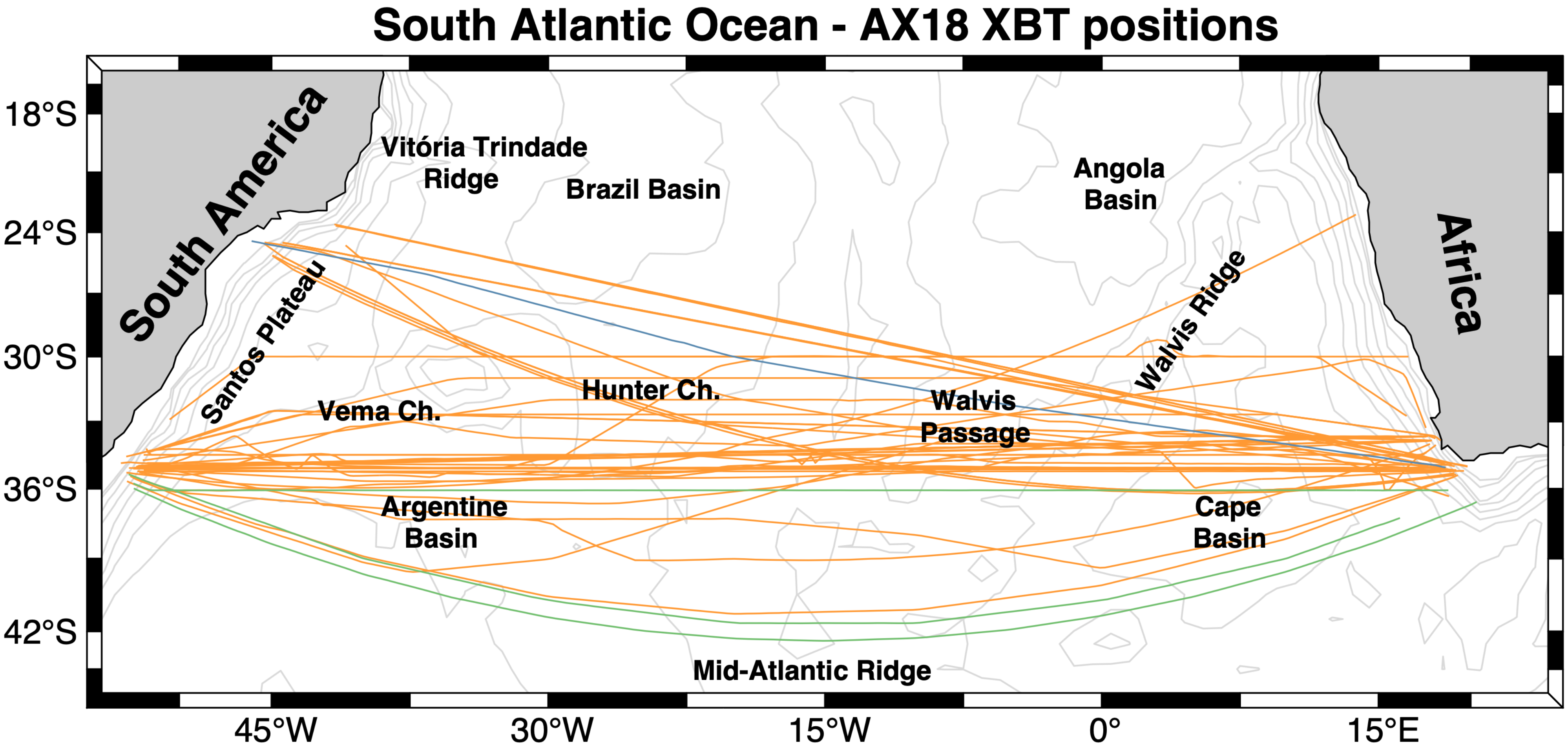
49 realizations of AX18-XBT transect from April 2002 – October 2019



A Multi-Data Set Analysis of the Freshwater Transport by the AMOC at Nominally 34.5ºS: **Data**

Our **product derived from XBT** data are complemented with data from:

- **Argo Altimetry product (Argo Alt.)**
- **Roemmich-Gilson (RG) Argo Climatology,** using YoMaHa dataset to reference velocities at 1000 m depth
- **OFES** (Ocean general circulation model For the Earth Simulator)
- **GLORYS12V1** (Global Ocean Physics Reanalysis)
- Modular Ocean Model version 6: **MOM6-MERRA2** and **MOM6-JRA**
- Historical simulations of **32 CMIP6 models** (Phase 6 of the Coupled Model Intercomparison Project)

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M_{ov}, MOC, and MHT calculations

- The M_{ov} is computed as the zonally averaged vertical circulation of the salt at a specific zonal section at 34.5ºS in Sv (1 Sv = 10^9 kg/s):

$$M_{ov} = -\frac{1}{S_0}\int_{-B}^{0} \rho\, \overline{v^*}(z)\langle S'(z)\rangle dz$$

$\boxed{M_{ov} > 0}$ → monostable AMOC regime

$\boxed{M_{ov} < 0}$ → bistable AMOC regime

$\boldsymbol{S_o}$**:** is the area-weighted section salinity average
$\boldsymbol{z}$**:** depth
$\boldsymbol{-B}$**:** depth of the ocean bottom
$\boldsymbol{\rho}$: ocean density
$\boldsymbol{\overline{v^*}(z)}$**:** meridional baroclinic ocean velocity and overbar denotes zonal integral
$\boldsymbol{\langle S'(z)\rangle}$**:** denotes the area-weighted zonally averaged deviations from the salinity average, S_o

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- The intensity of the overturning, MOC, is defined as the maximum value in the overturning stream function in the upper cell. Thus, the strength of the MOC can be expressed as:

$$MOC = \int_{-M}^{0}\int_{x_{west}}^{x_{east}} \rho\, v\,(x, z)\, dx\, dz$$

Integrated over depth ($\boldsymbol{z}$) and across the section from west ($\boldsymbol{x_{west}}$) to east ($\boldsymbol{x_{east}}$)
$\boldsymbol{\rho}$**:** seawater dentisy
$\boldsymbol{v}$: absolute meridional velocities
$\boldsymbol{-M}$**:** depth of the maximum overturning streamfunction

M_{ov}, MOC, and MHT calculations

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- The MHT is computed at a zonal section at latitude 34.5ºS, in Petawatts (PW):

$$MHT = \int_{-B}^{0}\int_{x_{west}}^{x_{east}} \rho\, c_p\, \theta(x,z)\, v(x,z)\, dx\, dz$$

$\boldsymbol{\rho}$**:** seawater dentisy
$\boldsymbol{c_p}$: heat capacity of the seawater
$\boldsymbol{\theta}$: potential temperature
$\boldsymbol{v}$: absolute meridional velocities
$\boldsymbol{-B}$**:** depth of the ocean bottom

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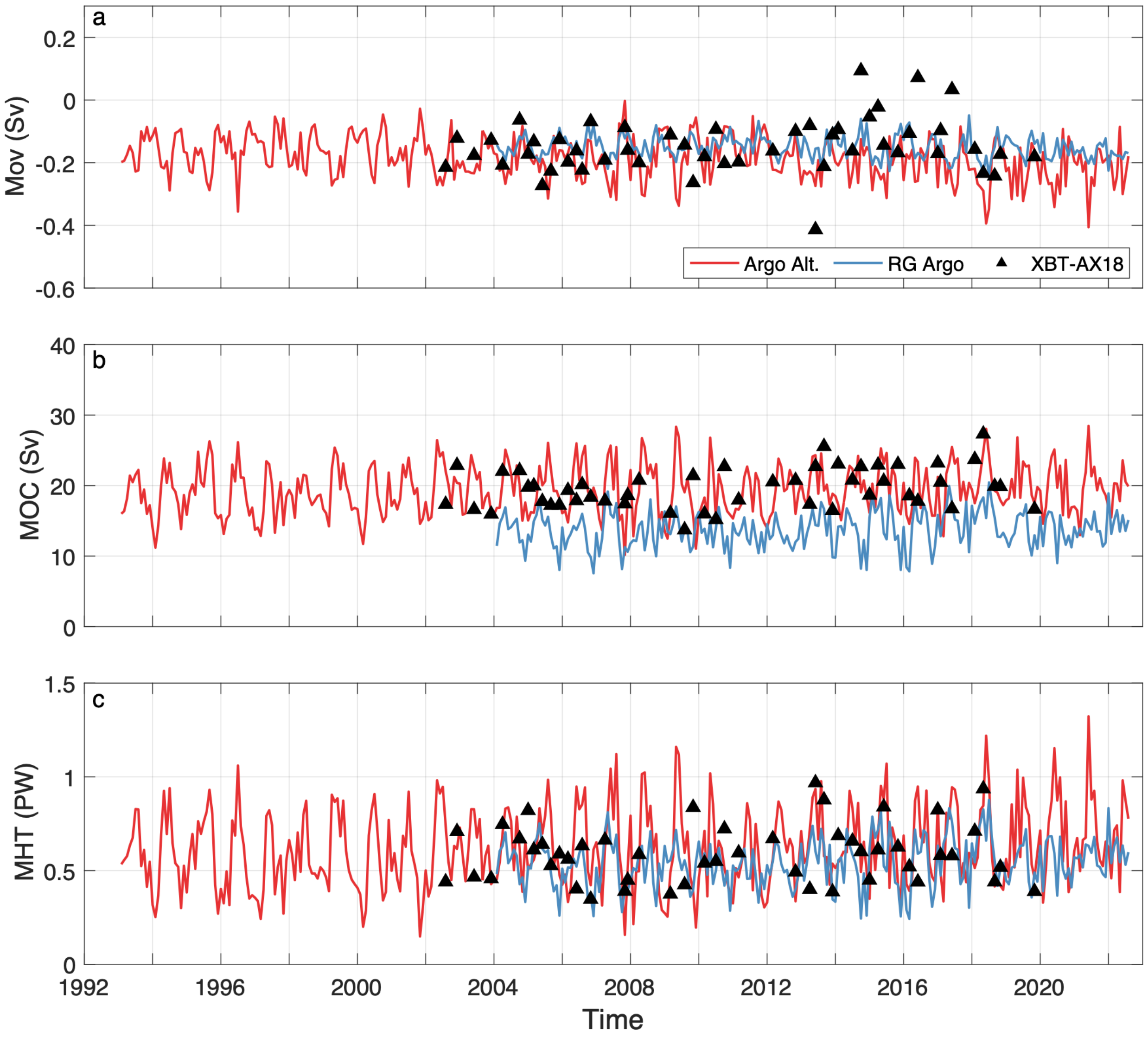
Interannual variability of M_{ov}, MOC and MHT in the South Atlantic at 34.5ºS

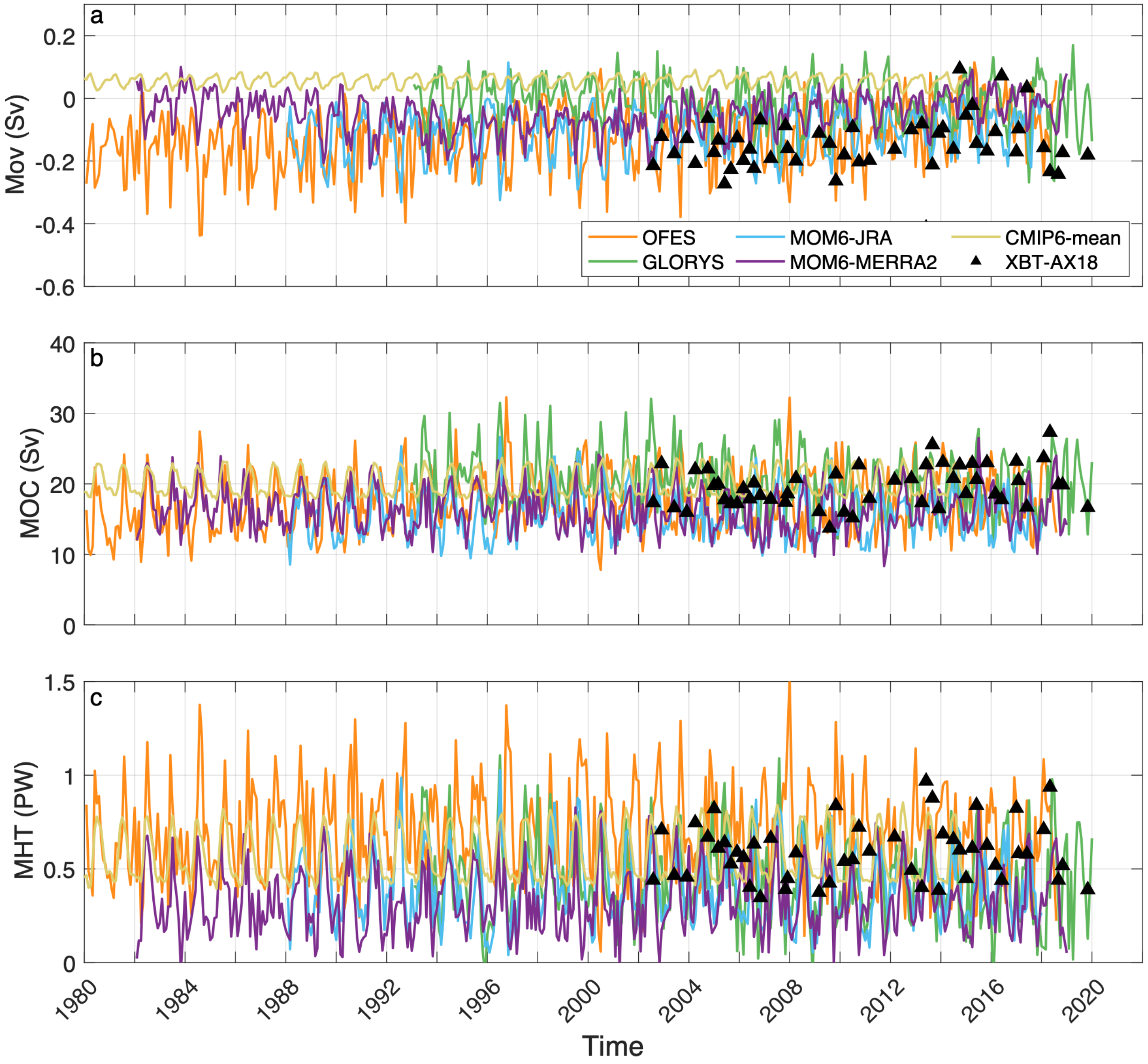


- Observations suggest a bistable AMOC (M_{ov}<0)

- Weaker MOC with RG Argo can be explained by:
    - Absence of Argo data in regions shallower than 2,000 m near the east and west coasts.
    - The uneven distribution of Argo data in space and time.

- Argo Alt. combines T-S profiles from Argo floats with monthly satellite altimetry SLA, reducing underestimation of MOC.

Interannual variability of M_{ov}, MOC and MHT in the South Atlantic at 34.5ºS



- The estimation of the M_{ov} is very sensitive to the data used.

- The time series of M_{ov} from OGCMs have predominantly negative values.

- We have estimated a positive multi-model M_{ov} mean from the CMIP6-mean (yellow).

Mean of M_{ov}, MOC and MHT in the South Atlantic at 34.5ºS

Mean meridional transports		**AX18-XBT**	**Argo Alt.**	**RG Argo**	**OFES**	**GLORYS**	**MOM6-JRA**	**MOM6-MERRA2**	**CMIP6-mean**
M_{ov} (Sv)	Full record length	-0.15±0.09	-0.19±0.07	-0.15±0.04	-0.13±0.10	-0.02±0.08	-0.11±0.08	-0.05±0.06	0.04±0.14
	2004-2014	-0.16±0.09	-0.18±0.06	-0.14±0.03	-0.11±0.09	-0.03±0.08	-0.09±0.07	-0.03±0.05	0.06±0.15
MOC (Sv)	Full record length	19.6±2.9	19.3±3.5	13.8±2.5	17.4±4.0	19.4±3.8	15.8±3.3	16.4±3.1	19.6±5.2
	2004-2014	19.3±2.7	19.3±3.6	13.3±2.3	17.6±4.1	19.9±3.7	15.4±3.1	16.2±3.2	20.1±5.2
MHT (PW)	Full record length	0.59±0.16	0.62±0.21	0.54±0.13	0.58±0.38	0.45±0.22	0.41±0.19	0.33±0.18	0.54±0.28
	2004-2014	0.59±0.16	0.62±0.21	0.52±0.12	0.57±0.39	0.45±0.21	0.40±0.18	0.35±0.17	0.58±0.28

- There are **no significant differences between the two periods** considered in this study.

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- There are **no significant differences between the two periods** considered in this study.
- Observations and OGCMs suggest a **bistable AMOC regime** ($M_{ov}<0$).
- Only CMIP6-mean present a **positive M_{ov} mean** with a large standard deviation.

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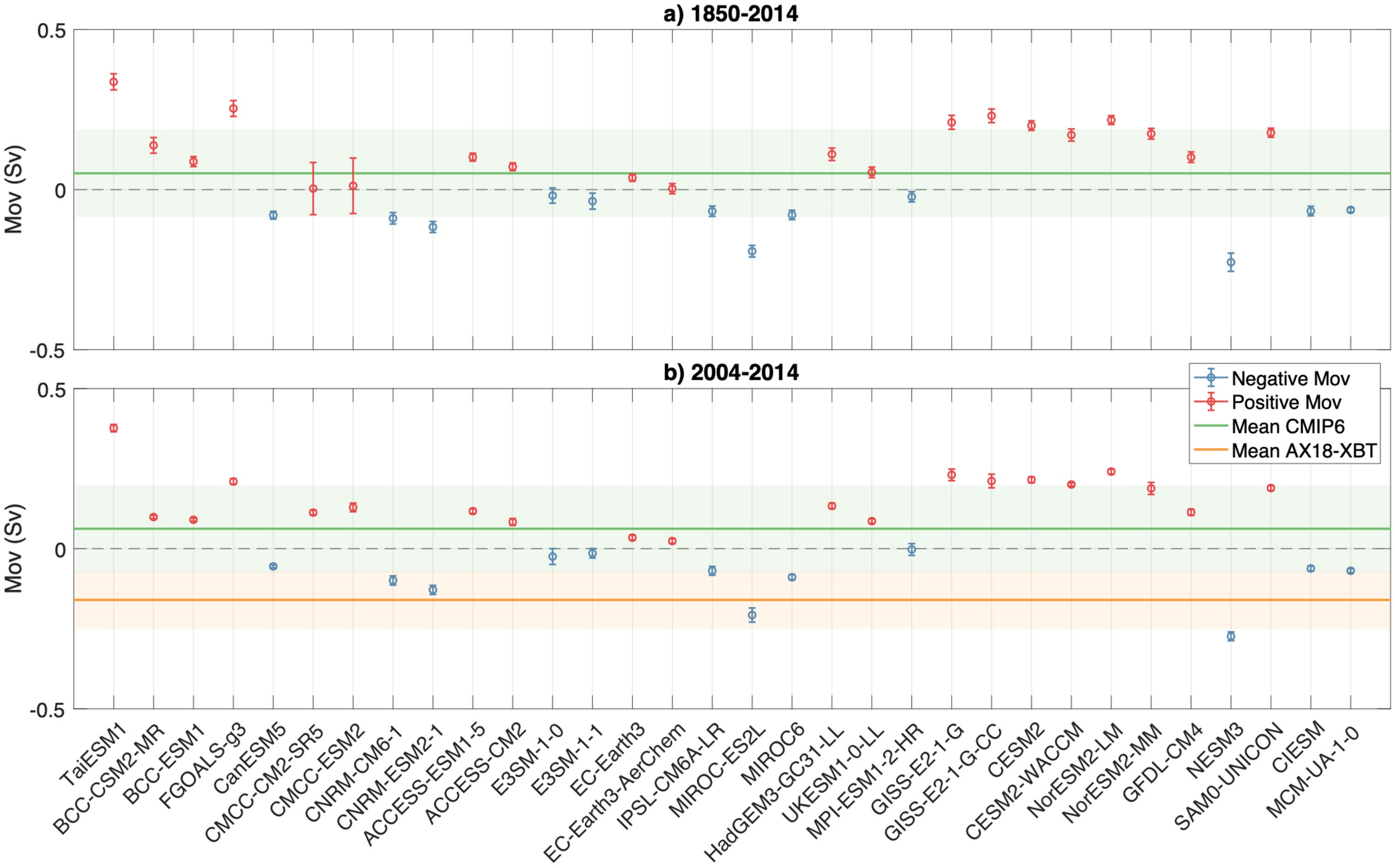
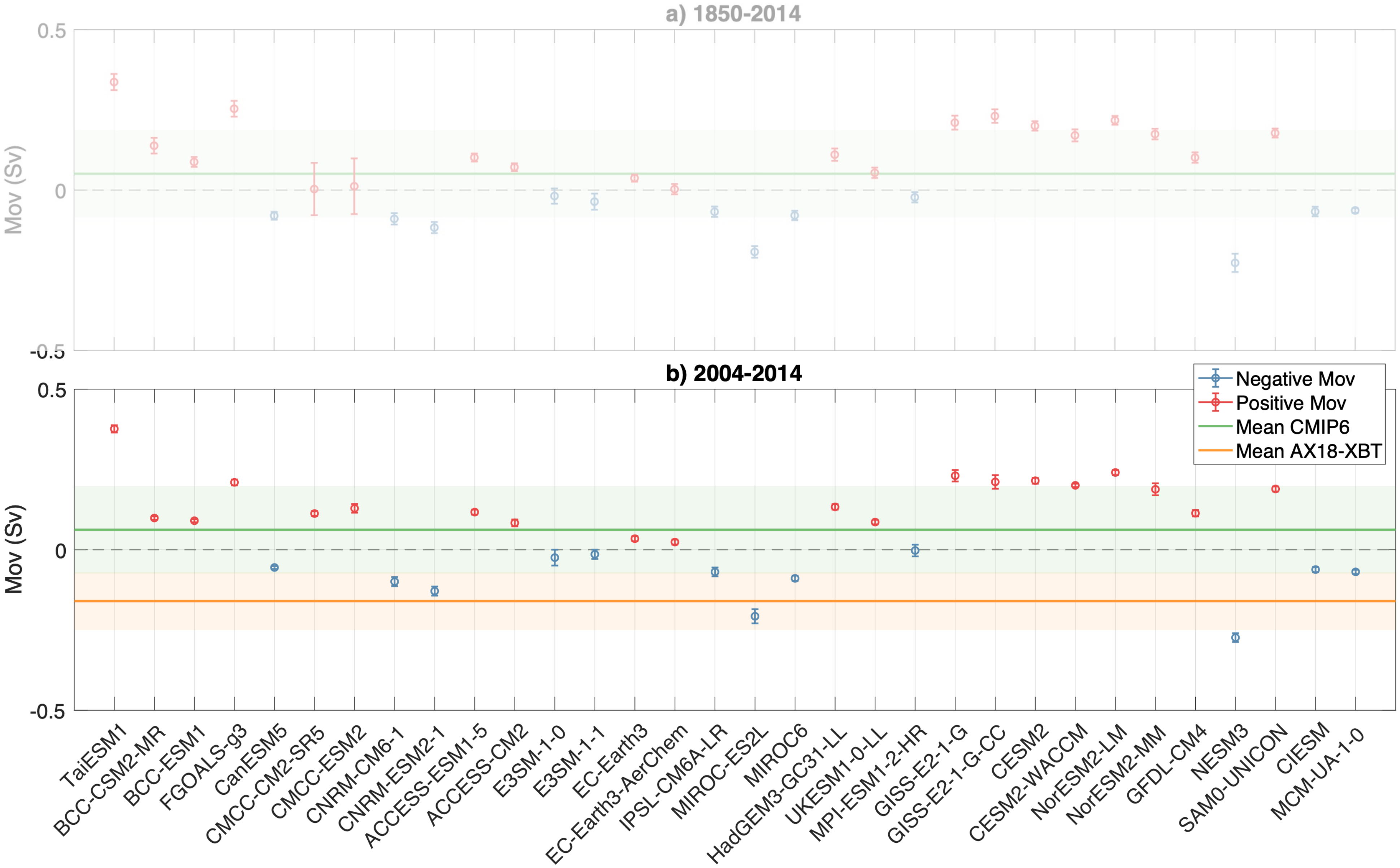
- Observations and OGCMs suggest a **bistable AMOC regime** (M_{ov}<0).
- Only CMIP6-mean present a **positive M_{ov} mean** with a large standard deviation.
- MOC≈19 Sv & MHT≈0.60 PW estimates are consistent with earlier studies.
- Weaker MOC values from RG Argo.

M_{ov} in CGCMs data



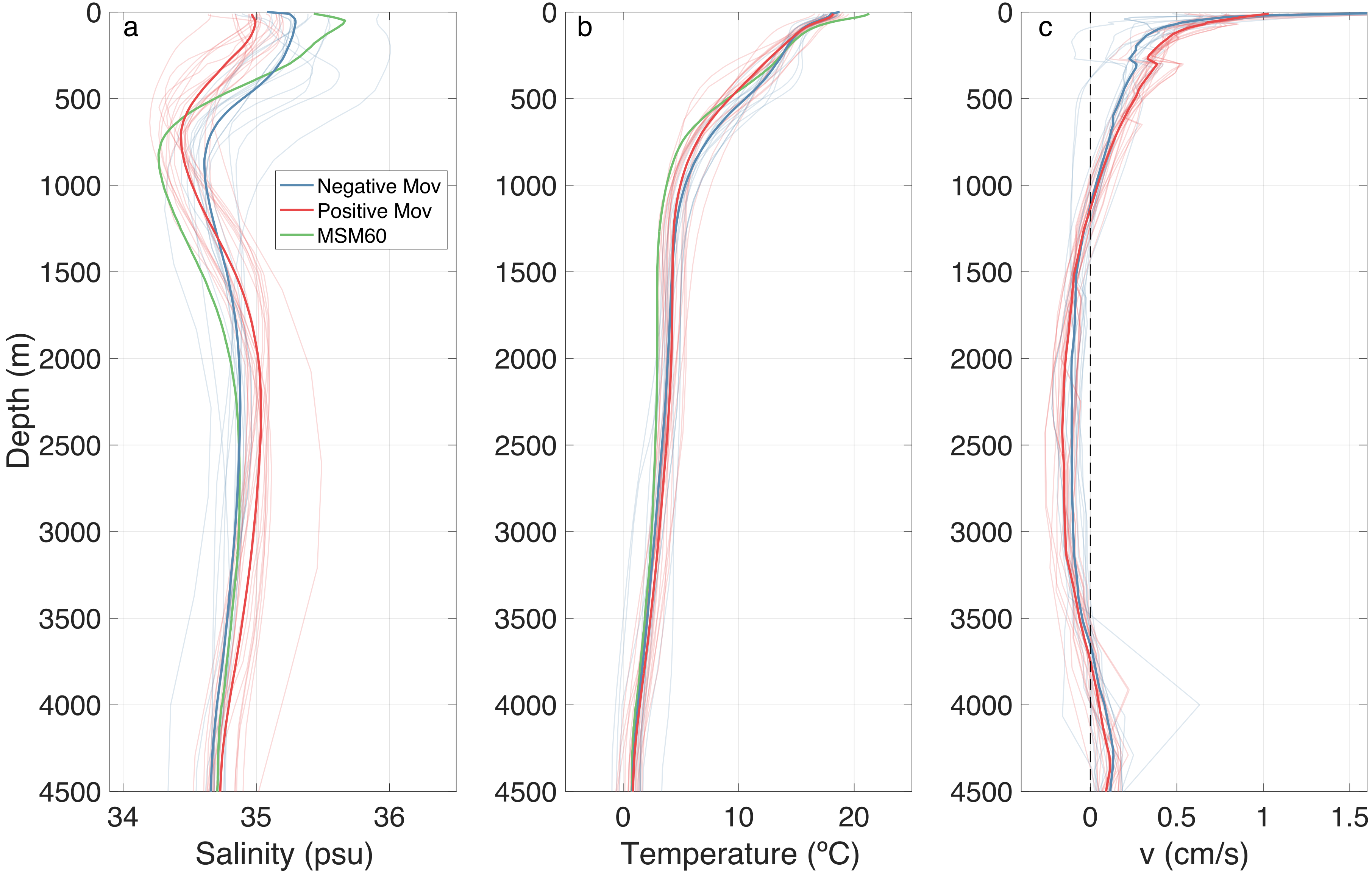
Only 12 out of 32 CMIP6 models have a negative mean of M_{ov} (in both periods)

M_{ov} in CGCMs data



Only 7 out of 32 CMIP6 models show a mean not significantly different from XBT (2004-2014)

Vertical profiles of salinity, temperature and velocity



Our results show differences **in salinity and velocity** profiles, but **only the salinity** profiles exhibit a **clear separation** between models with positive and negative M_{ov} mean.

Correlation between the South Atlantic meridional fluxes

Data	M_{ov}/MOC (Sv/Sv)		M_{ov}/MHT (Sv/PW)		MHT/MOC (PW/Sv)	
	Slope	R^2	Slope	R^2	Slope	R^2
AX18-XBT	-0.0050 ± 0.0043	0.03	-0.2310 ± 0.0733	0.17	0.0407 ± 0.0053	0.56
Argo Alt.	-0.0149 ± 0.0007	0.59	-0.2750 ± 0.0087	0.74	0.0557 ± 0.0013	0.85
RG Argo	-0.0123 ± 0.0005	0.76	-0.4383 ± 0.0141	0.82	0.0484 ± 0.0009	0.93
OFES	-0.0174 ± 0.0002	0.52	-0.3527 ± 0.0111	0.69	0.0604 ± 0.0003	0.87
GLORYS	-0.0106 ± 0.0009	0.30	-0.3061 ± 0.0126	0.65	0.0483 ± 0.0015	0.76
MOM6-JRA	-0.0195 ± 0.0006	0.74	-0.3245 ± 0.0095	0.76	0.0560 ± 0.0009	0.92
MOM6-MERRA2	-0.0124 ± 0.0007	0.38	-0.2914 ± 0.0110	0.61	0.0525 ± 0.0011	0.83
CMIP6-mean	-0.0091 ± 0.0002	0.57	-0.1265 ± 0.0022	0.63	0.0738 ± 0.0004	0.94

- **XBT: lower R^2 values** may be attributed to the small sample size of the dataset, as well as to the inherent limitations.
- **Numerical models: higher R^2 values →** are based on physical equations and incorporate various datasets and parameterizations, allowing them to capture complex interactions and processes that might not be fully captured by the XBT data.

This results in a stronger linear relationship when using numerical models.

Correlation between the South Atlantic meridional fluxes

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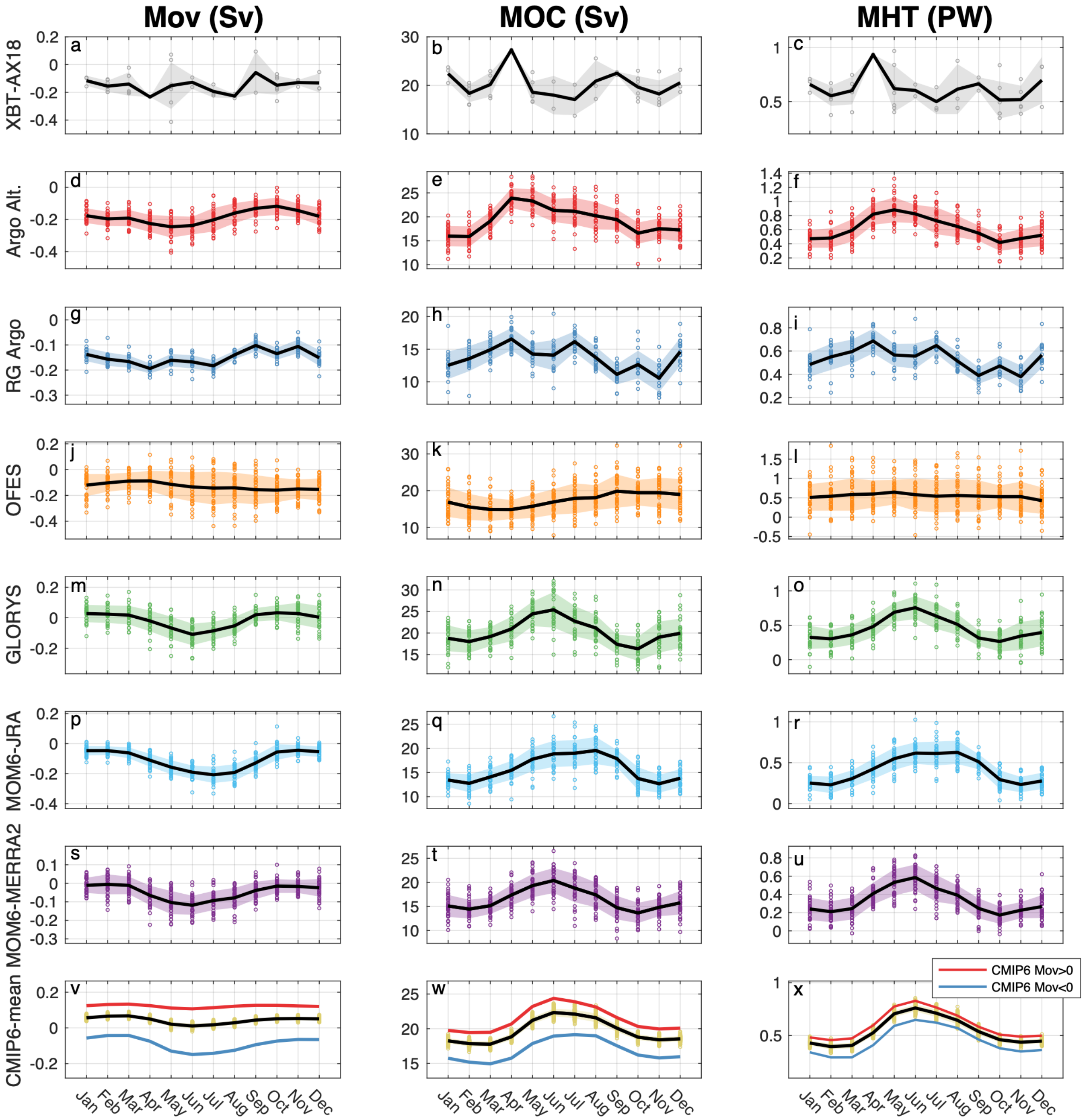
- M_{ov}/MOC and M_{ov}/MHT are positively correlated in magnitude and MHT/MOC positively correlated in all datasets.
- Modest linear relationship between MOC and M_{ov} (3-76%),
- A stronger linear dependence between MHT and M_{ov} (17-82%),
- And an even stronger linear relationship between MOC and MHT (56-94%).

A Multi-Data Set Analysis of the Freshwater Transport by the AMOC at Nominally 34.5ºS: **Results & Discussion**

Seasonal variability of the meridional fluxes



- Only XBT and OFES datasets don’t show a seasonal variability.

- From April to August:
  - ✓ Stronger negative M_{ov}.
  - ✓ Stronger positive MOC and MHT.

- CMIP6 $M_{ov} > 0$ (red) have stronger MOC and MHT values during all months.

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Conclusions

1. Observations, ocean models, and some coupled climate models suggest a **bistable MOC regime ($M_{ov} < 0$).**
2. M_{ov} is **positively correlated in magnitude to MOC and MHT**, while **MOC is positively correlated to MHT**, showing seasonal variations with **stronger values from April to August** at 34.5ºS.
3. This study suggests that **salinity biases in CMIP6 models** may be responsible for the opposite sign of M_{ov}.
4. We emphasize the need to **refine CMIP6 models** to improve the representation of ocean circulation and water column properties.

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Thanks for your attention!