Atlantic overturning inferred from air-sea heat fluxes indicates no decline since the 1960s

Swiss Polar Day
5th September 2025

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Climate and Environmental Physics
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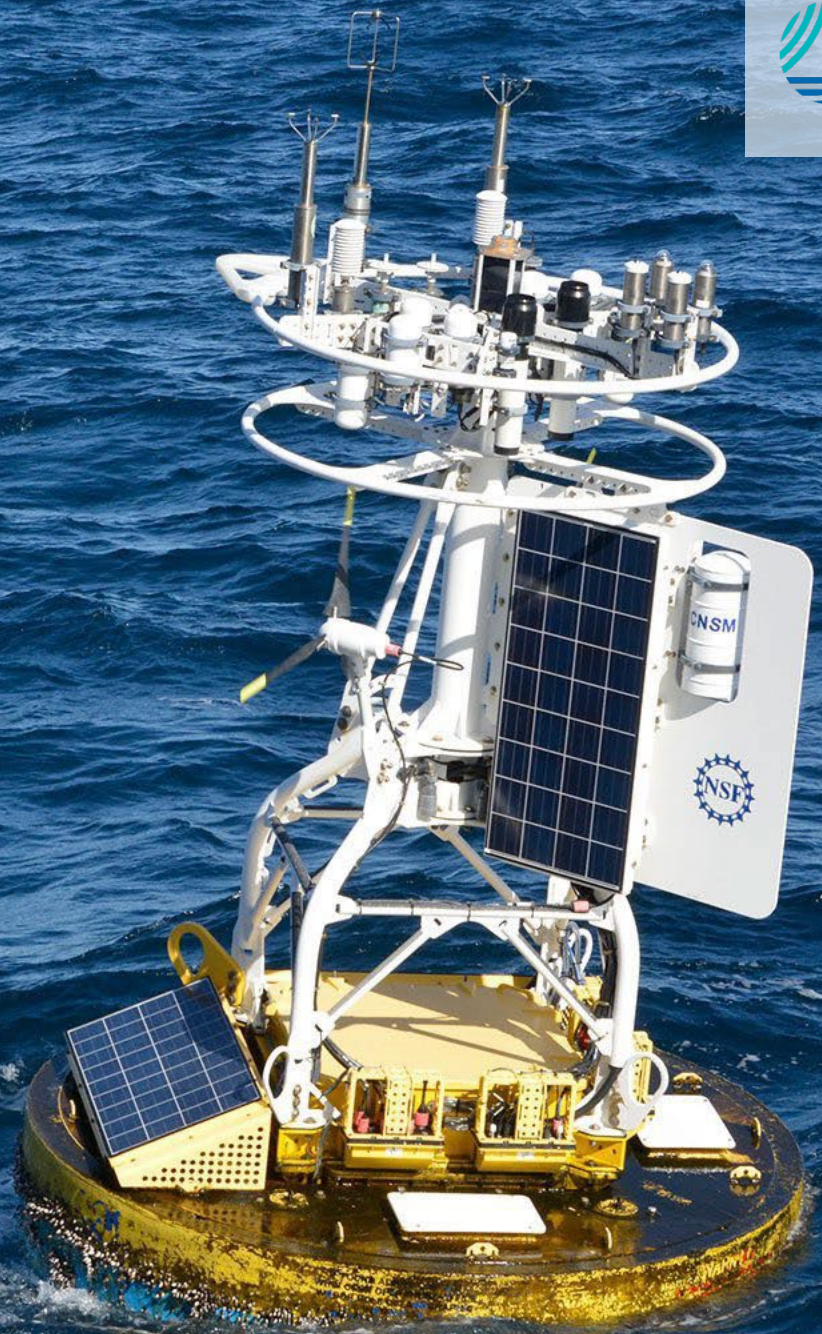
Linus Vogt & Nicholas Foukal



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LOCEAN

The Atlantic Meridional Overturning Circulation (AMOC) transports warm water northward at the surface and colder water southward below the surface

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NASA/Goddard Space Flight Center Scientific Visualization Studio

Zooming into the North Atlantic, the AMOC is a much more complex system of intertwined currents

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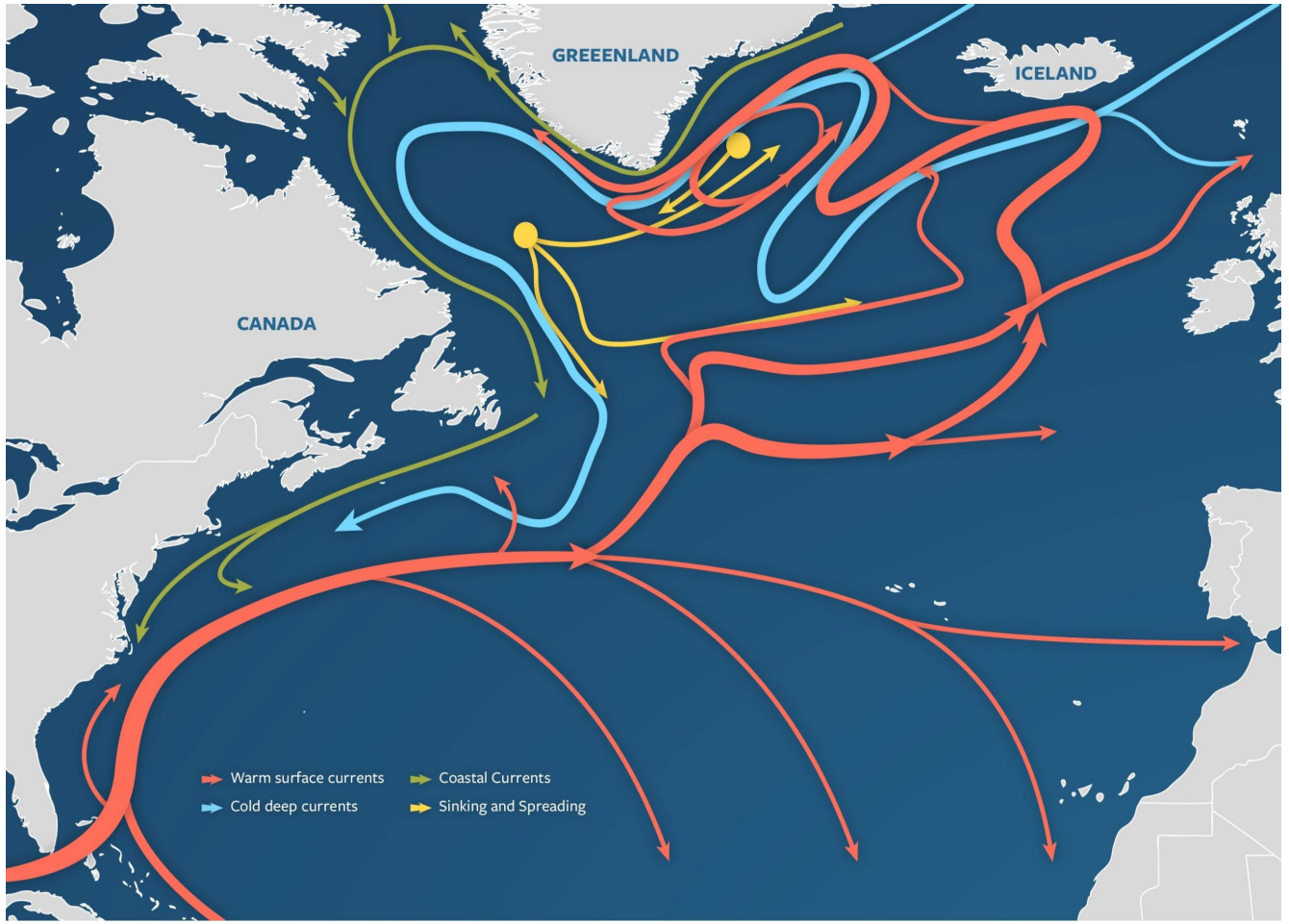

Eric S. Taylor, © Woods Hole Oceanographic Institution

Overall, the AMOC creates a net northward heat transport that warms the atmosphere over and around the North Atlantic Ocean

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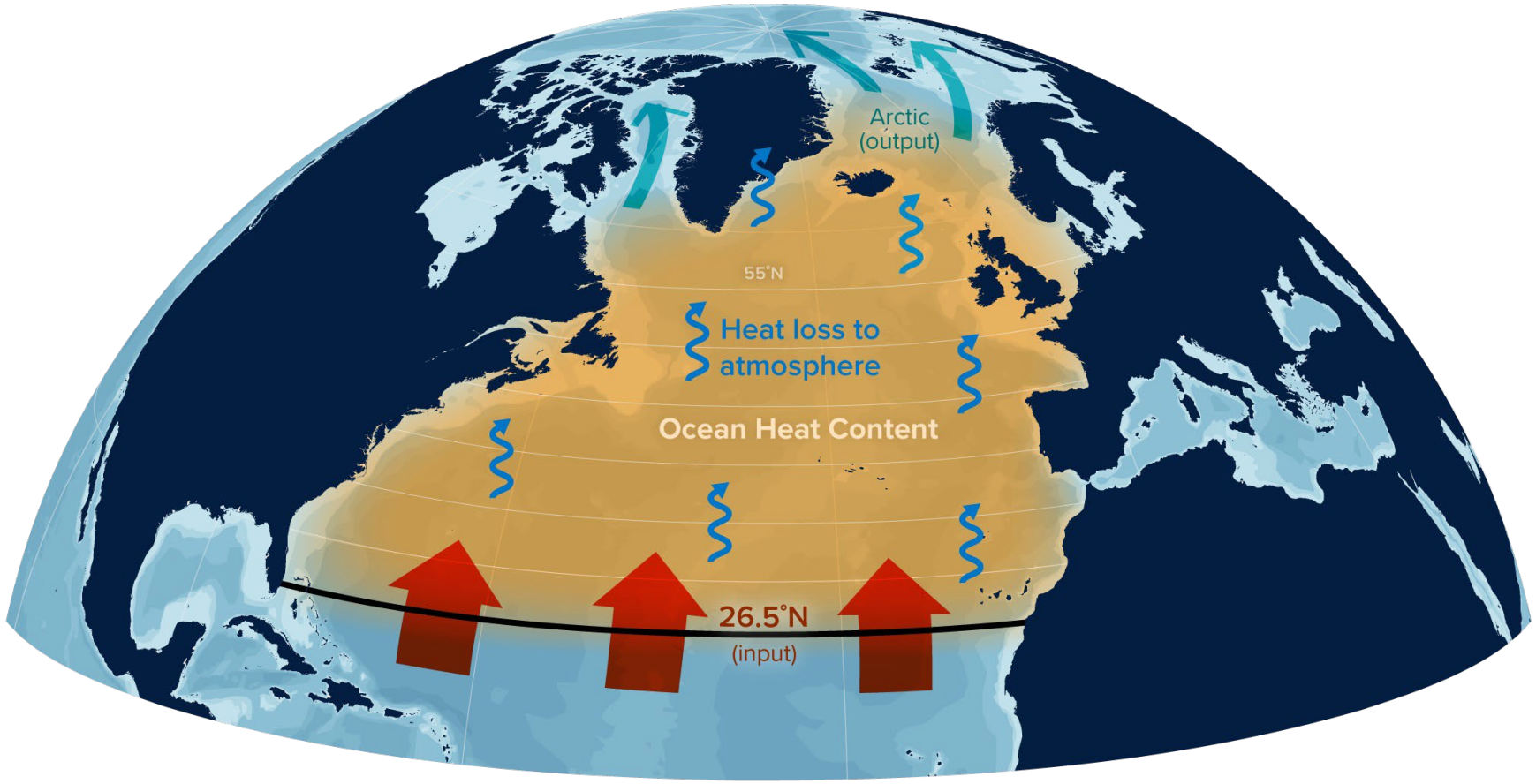

Terhaar et al. (2025) © Woods Hole Oceanographic Institution

The Atlantic Meridional Overturning Circulation is crucial for the warm European climate, and its collapse would lead to substantial cooling

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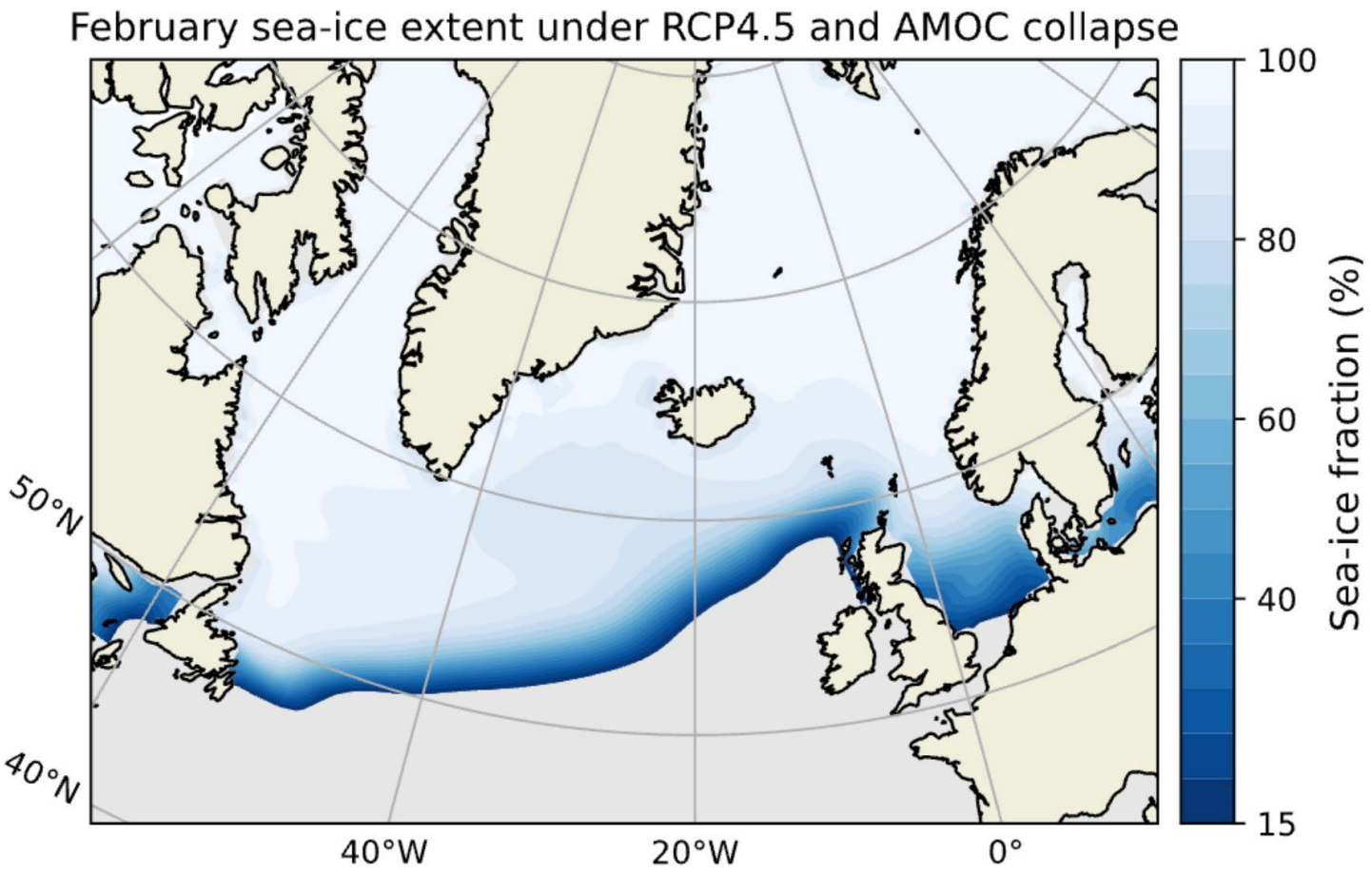

Van Westen et al. (2025)

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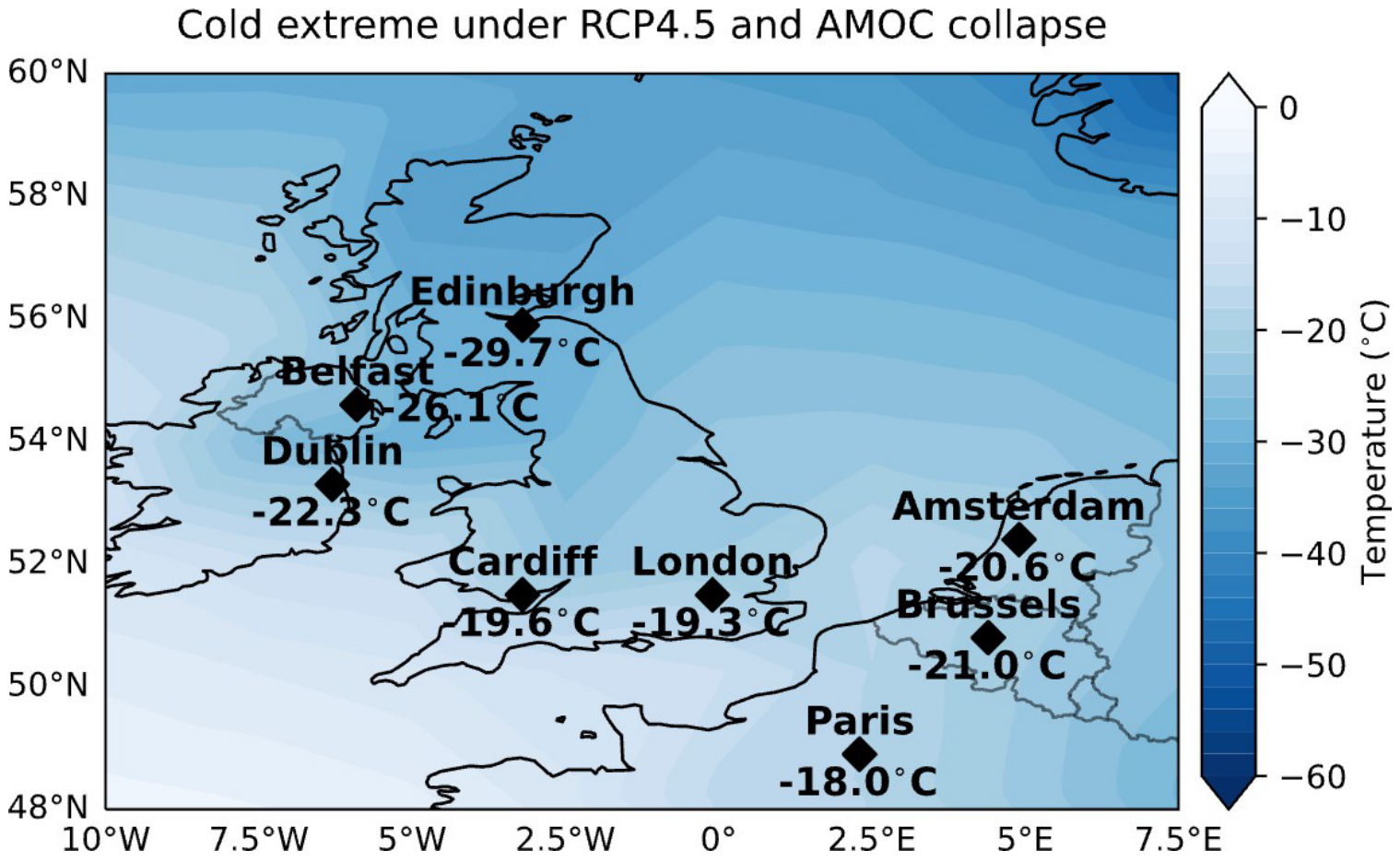

Cold extremes – defined as temperatures that could occur once every 10 years – under AMOC collapse and around 2C of warming ("RCP4.5").

Van Westen et al. (2025)

The AMOC can be observed with observational arrays like the RAPID array

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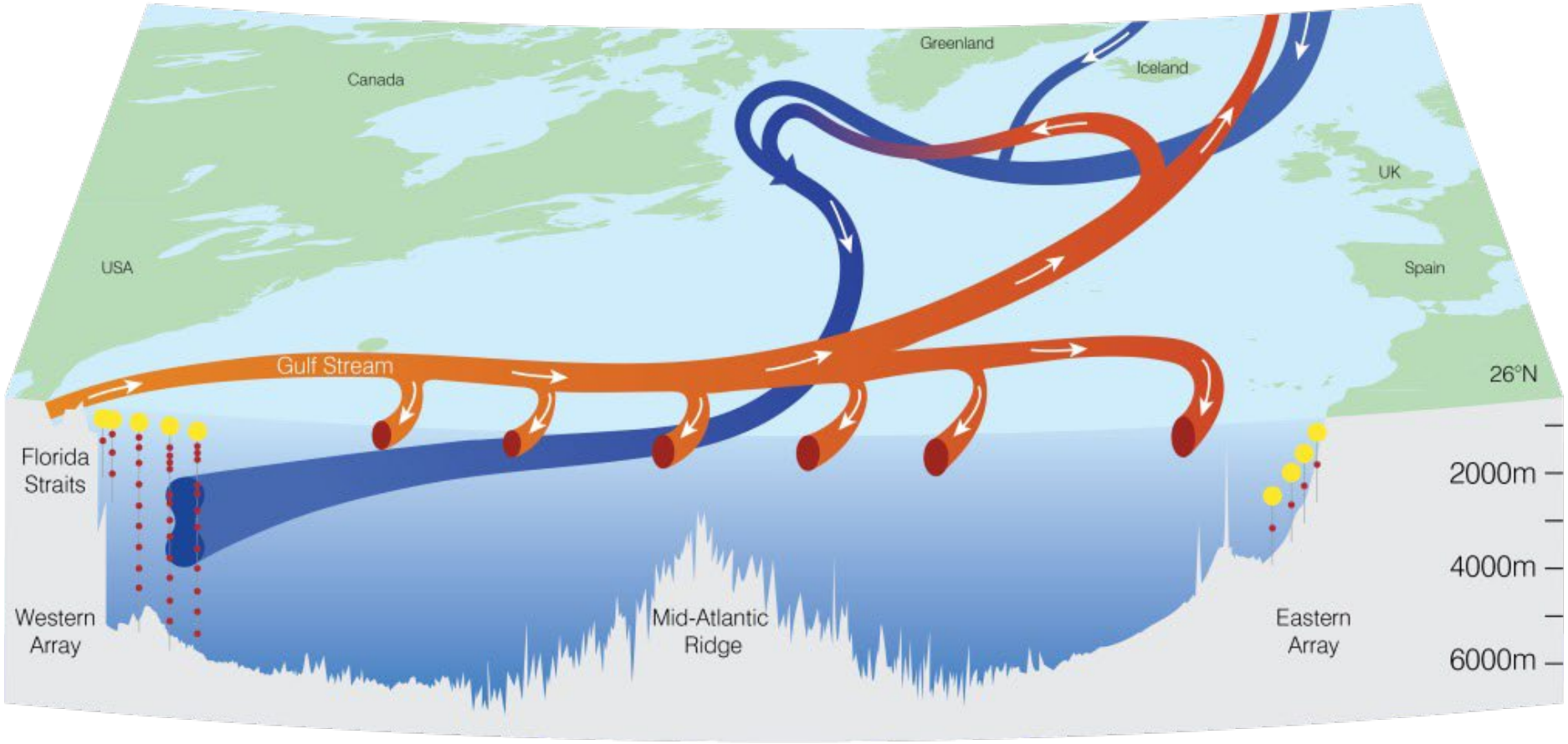

https://rapid.ac.uk/

No continuous direct observations of the AMOC exist before the RAPID array was set up in 2004

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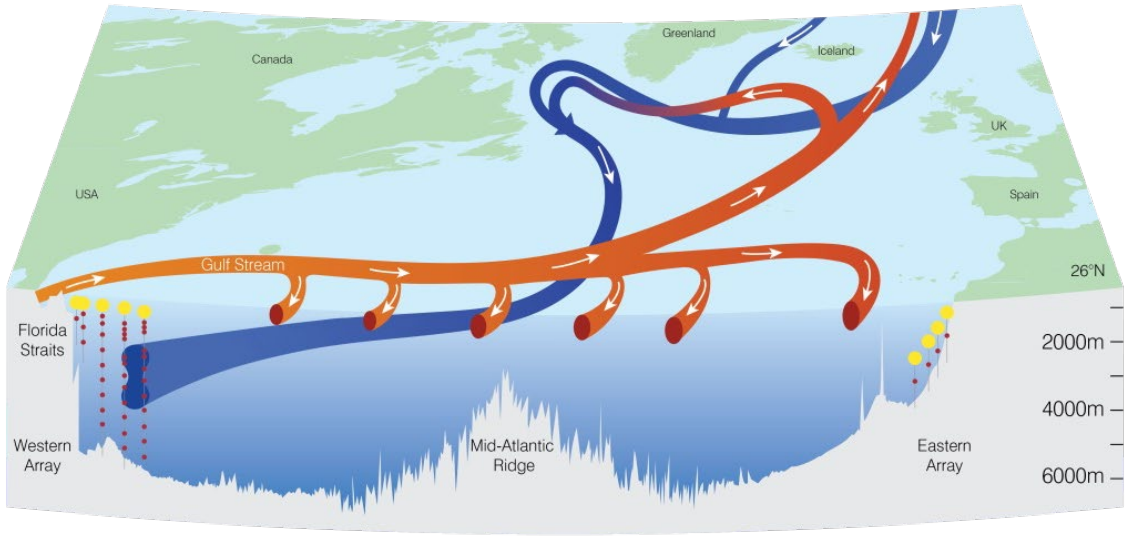

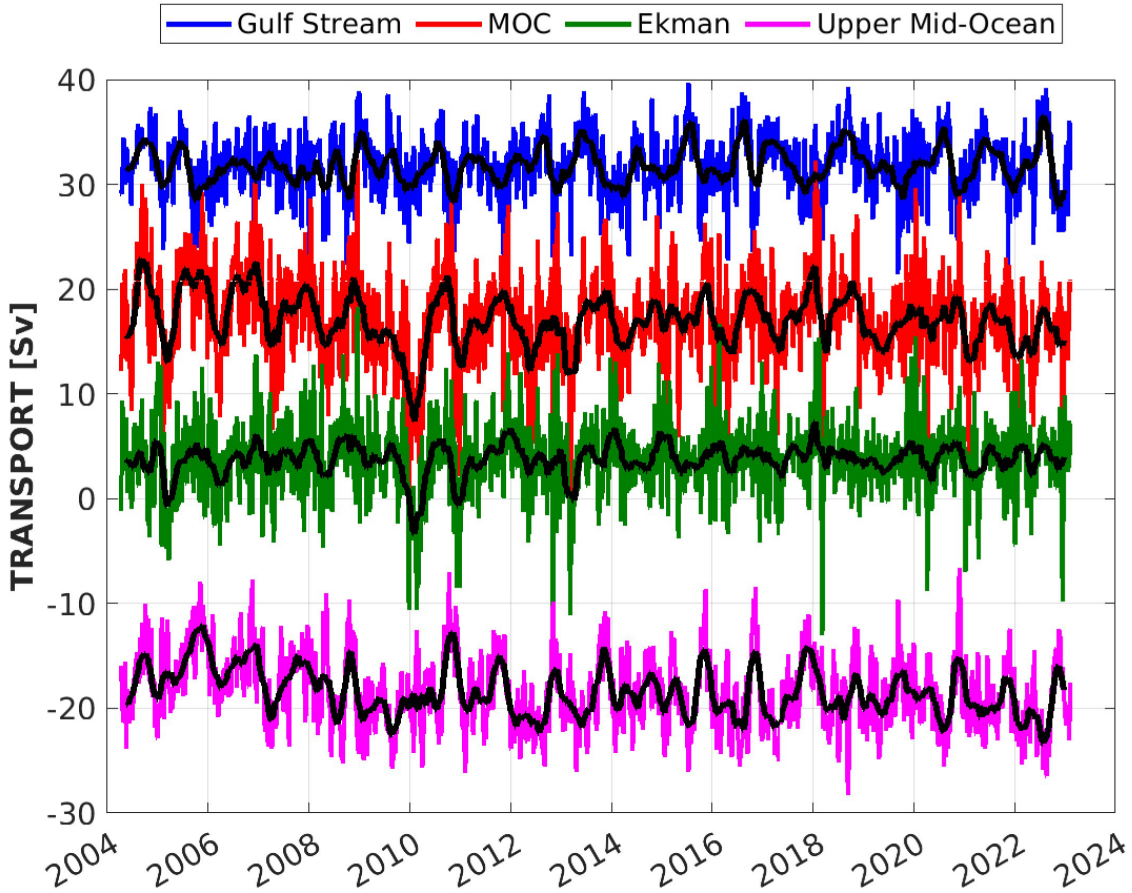

https://rapid.ac.uk/

A reduction of the AMOC leads to less northward transport of heat, a potential cooling, less heat transport to the Arctic, and less heat loss to the atmosphere

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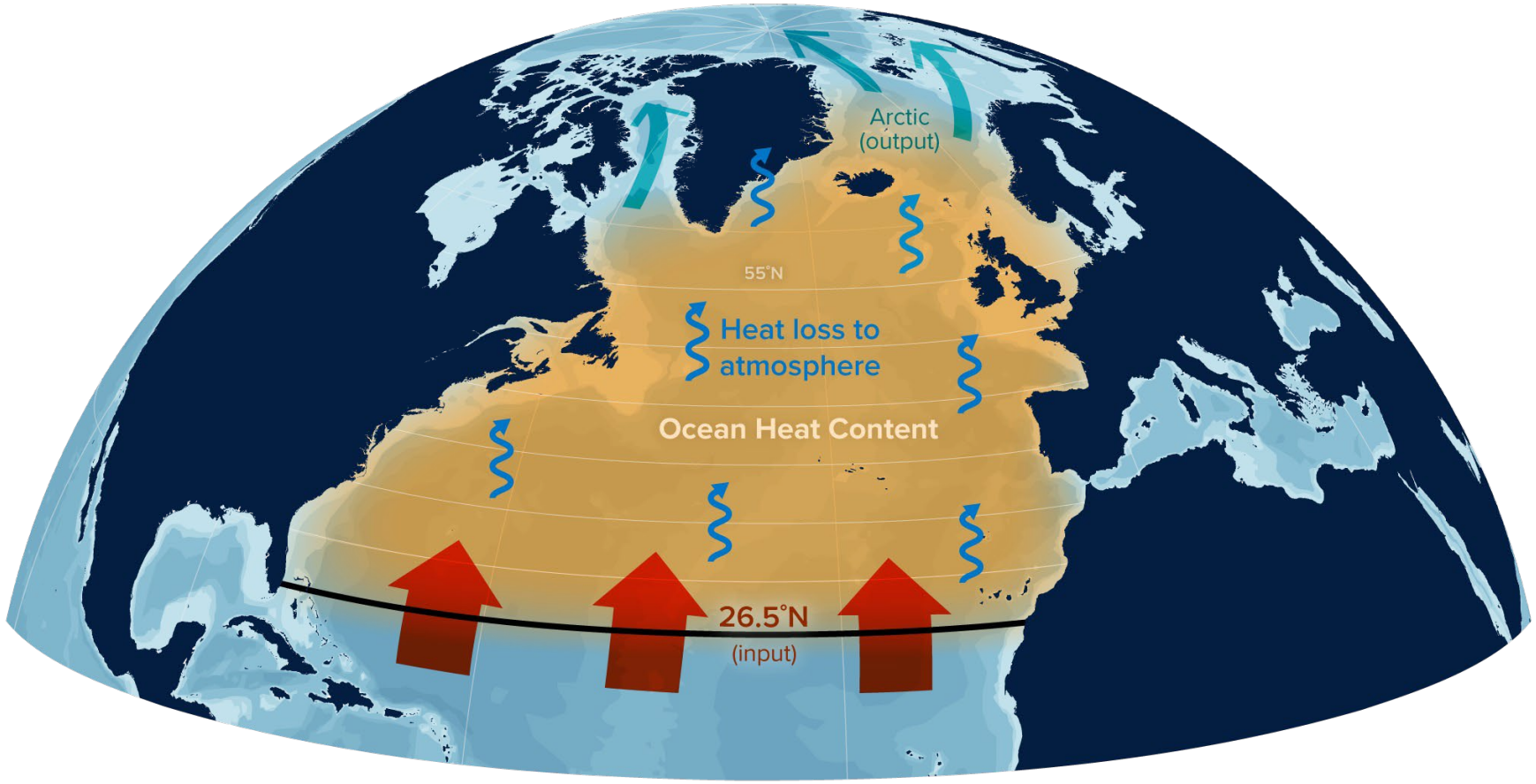

Terhaar et al. (2025) © Woods Hole Oceanographic Institution

The most prominent proxy of the AMOC is the ‘cold blob’ in the North Atlantic Ocean

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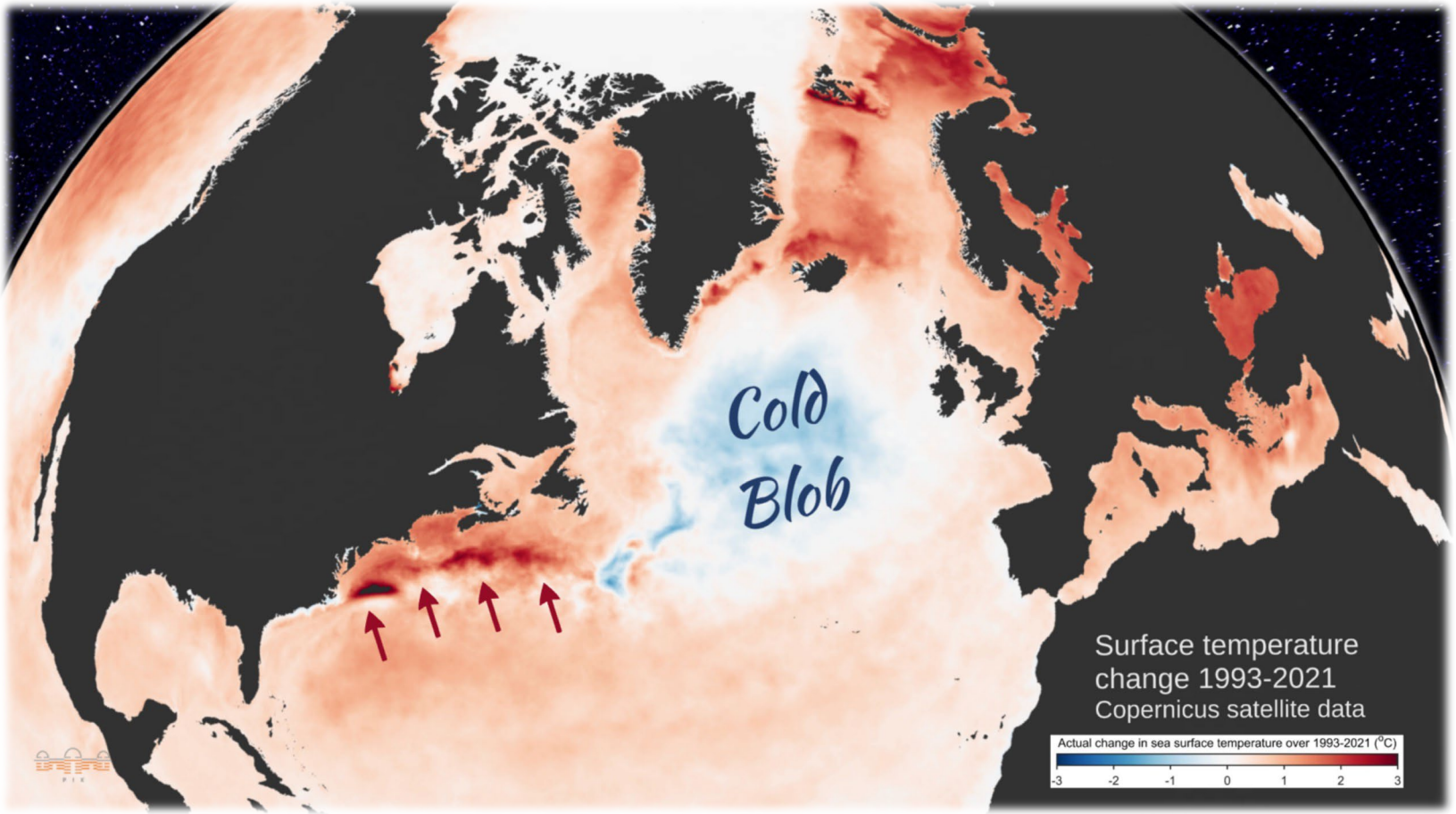

AMOC index

SSTs in the subpolar gyre - global SSTs

Map: Ruijian Gou

Models allow to relate the SST anomalies to the AMOC strength

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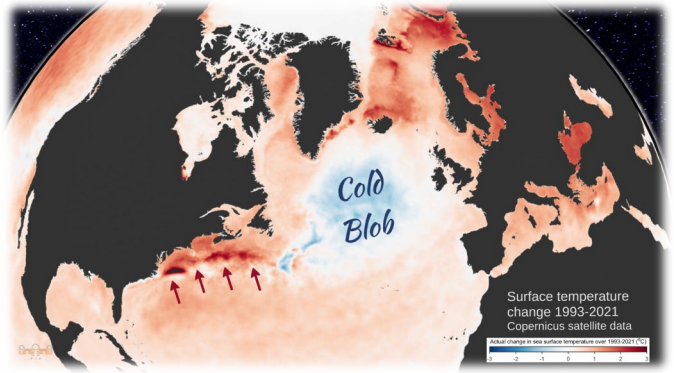
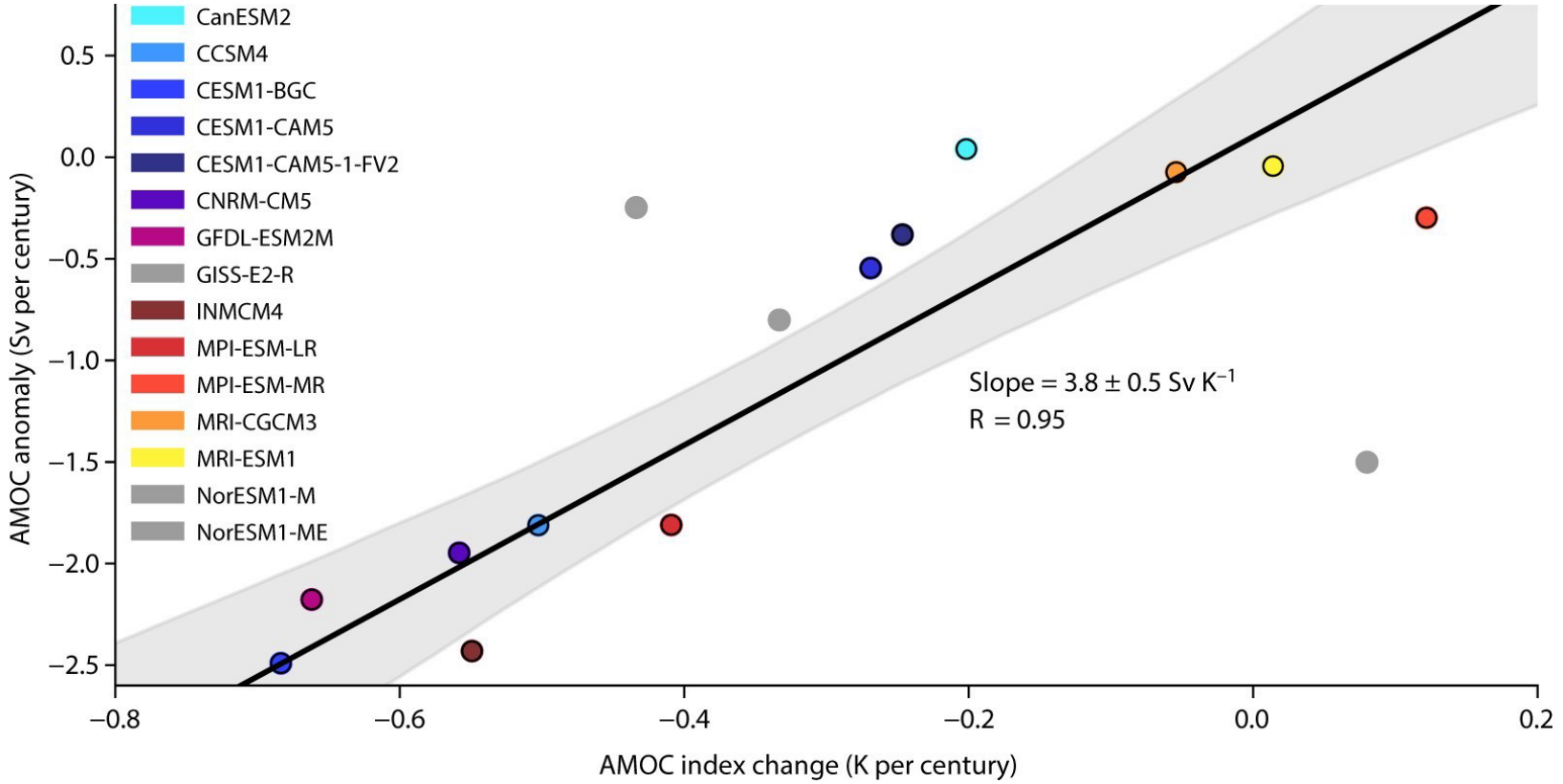


AMOC index = SSTs in the subpolar gyre - global SSTs



Caesar et al. (2018)

This SST-based reconstructions suggests a decline in the AMOC since the 1950s

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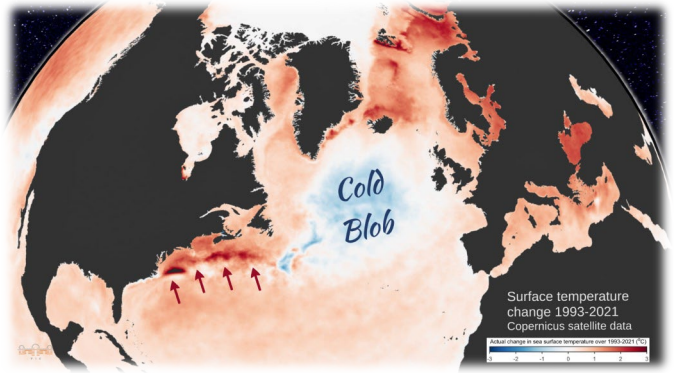

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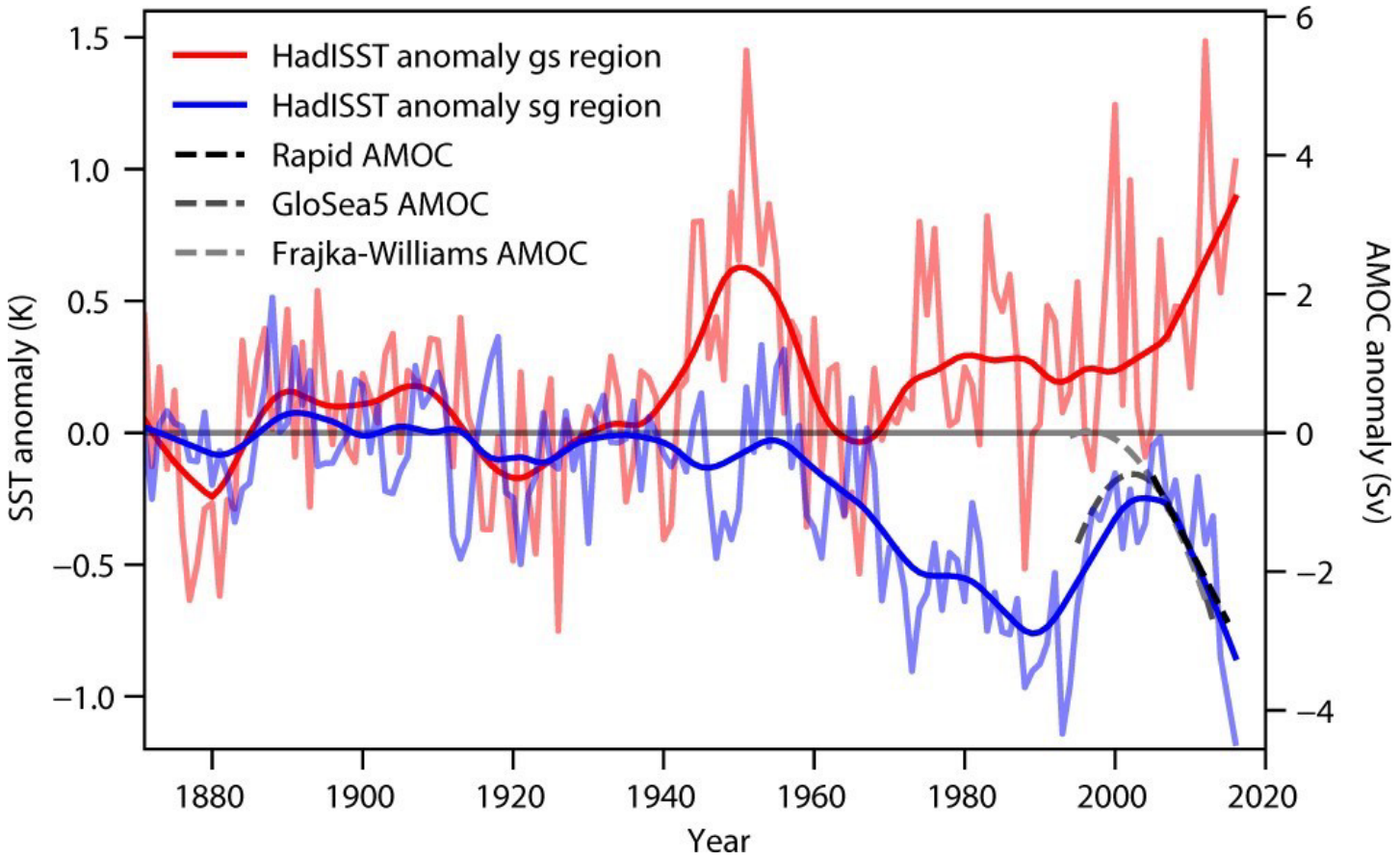

Caesar et al. (2018)

When repeating the analysis with most recent CMIP6 models, the results differ from the CMIP5 models selected by Caesar et al. (2018)

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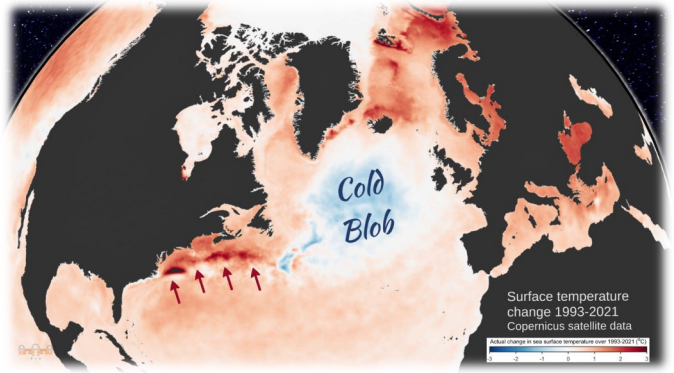
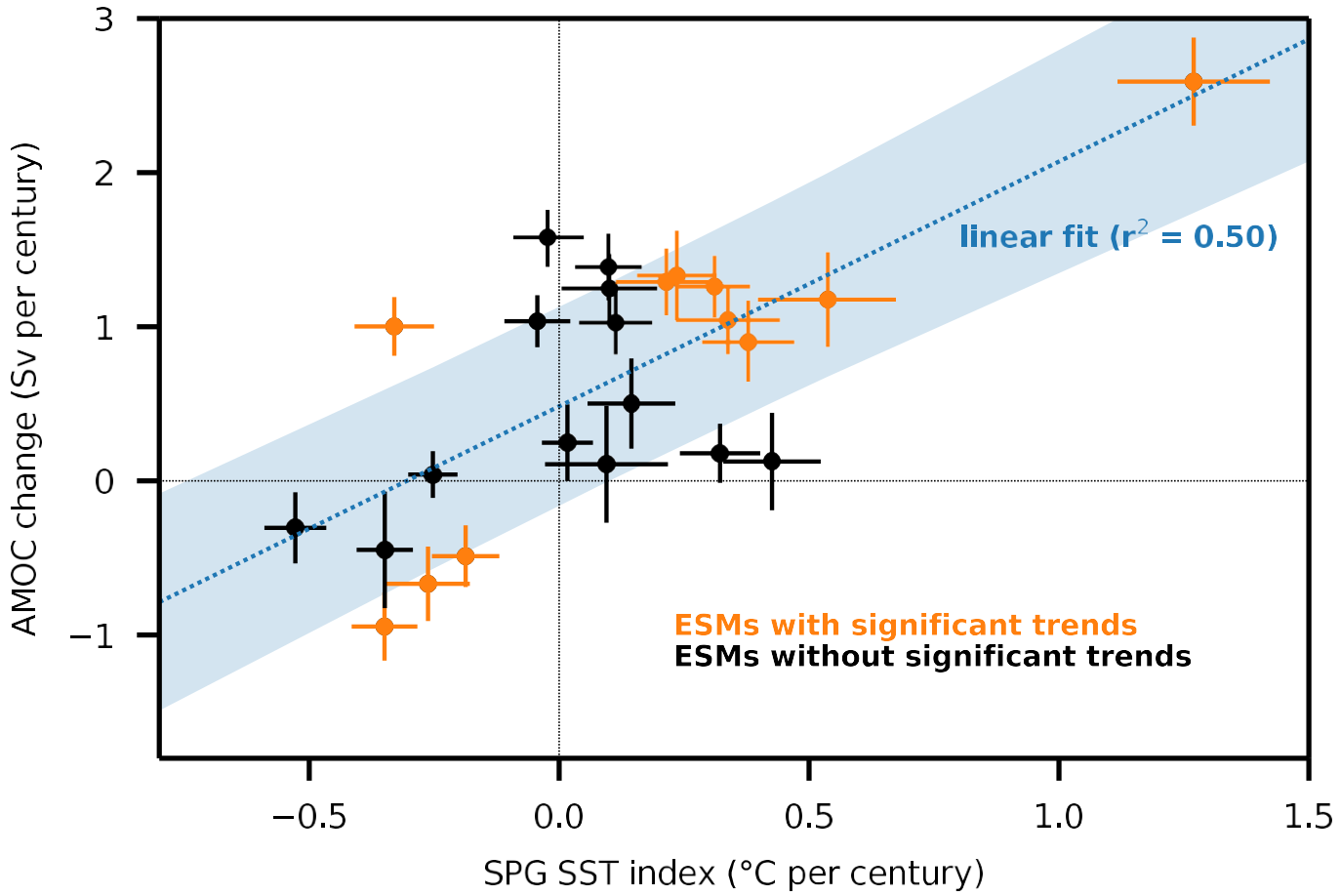


- 24 CMIP6 models; $r^2 = 0.50$



Terhaar et al. (2025)

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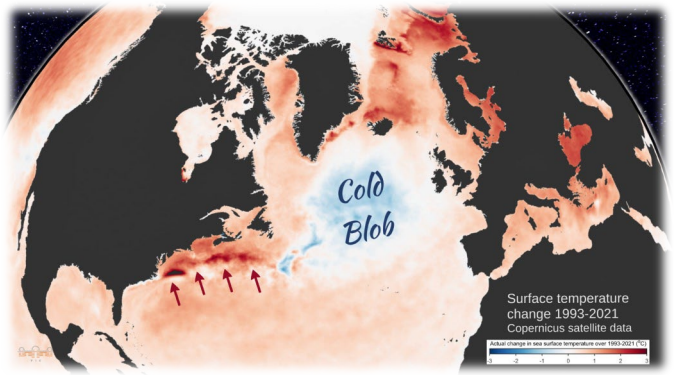
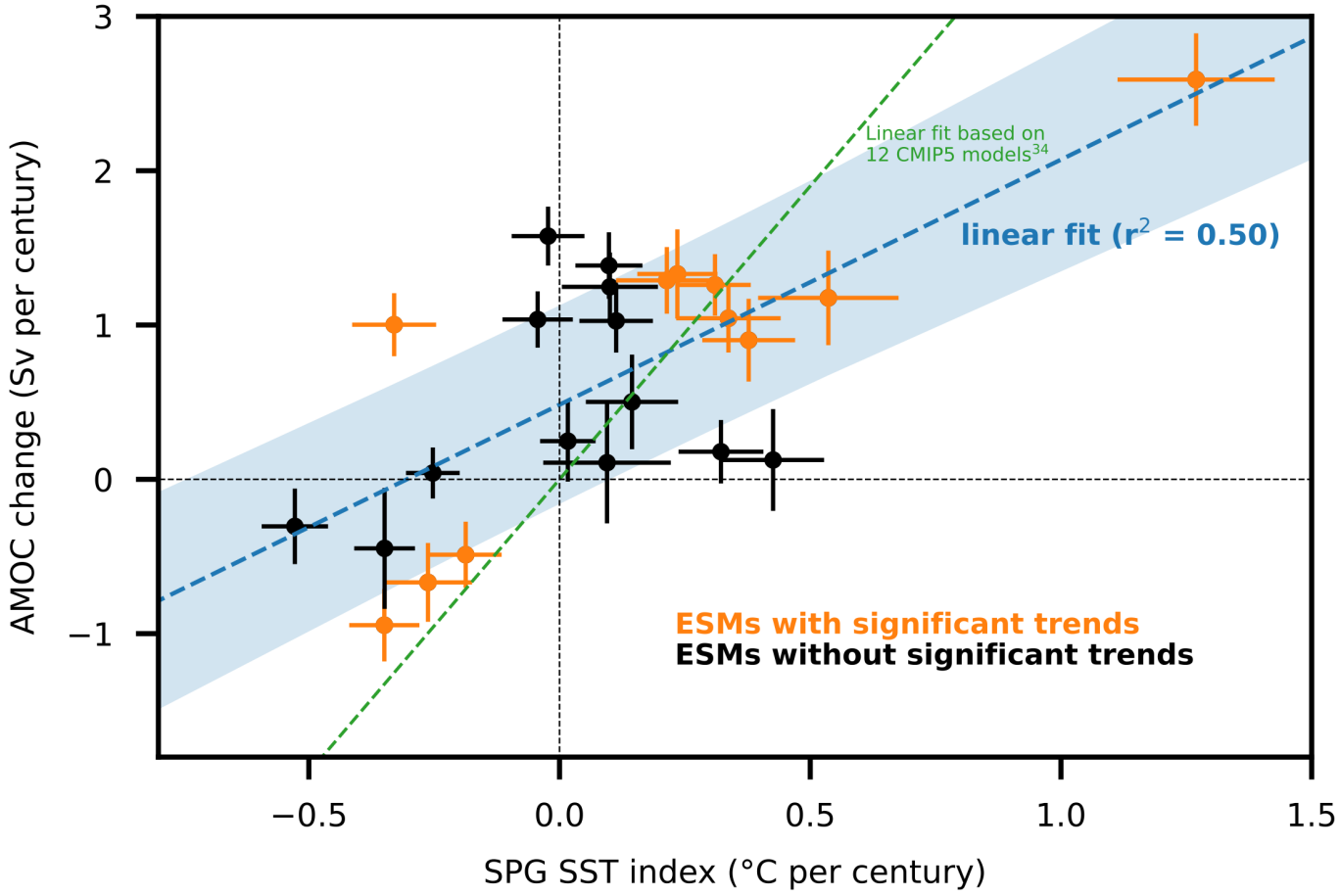


- 24 CMIP6 models; $r^2 = 0.50$
- Slope is weaker in CMIP6 models (1.6 Sv K^{-1}) than in CMIP5 models (3.8 Sv K^{-1})



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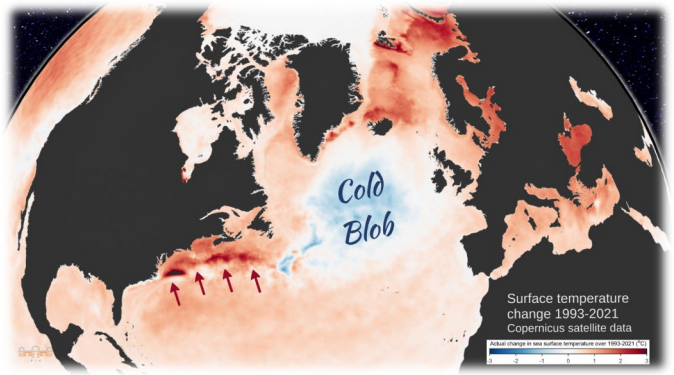

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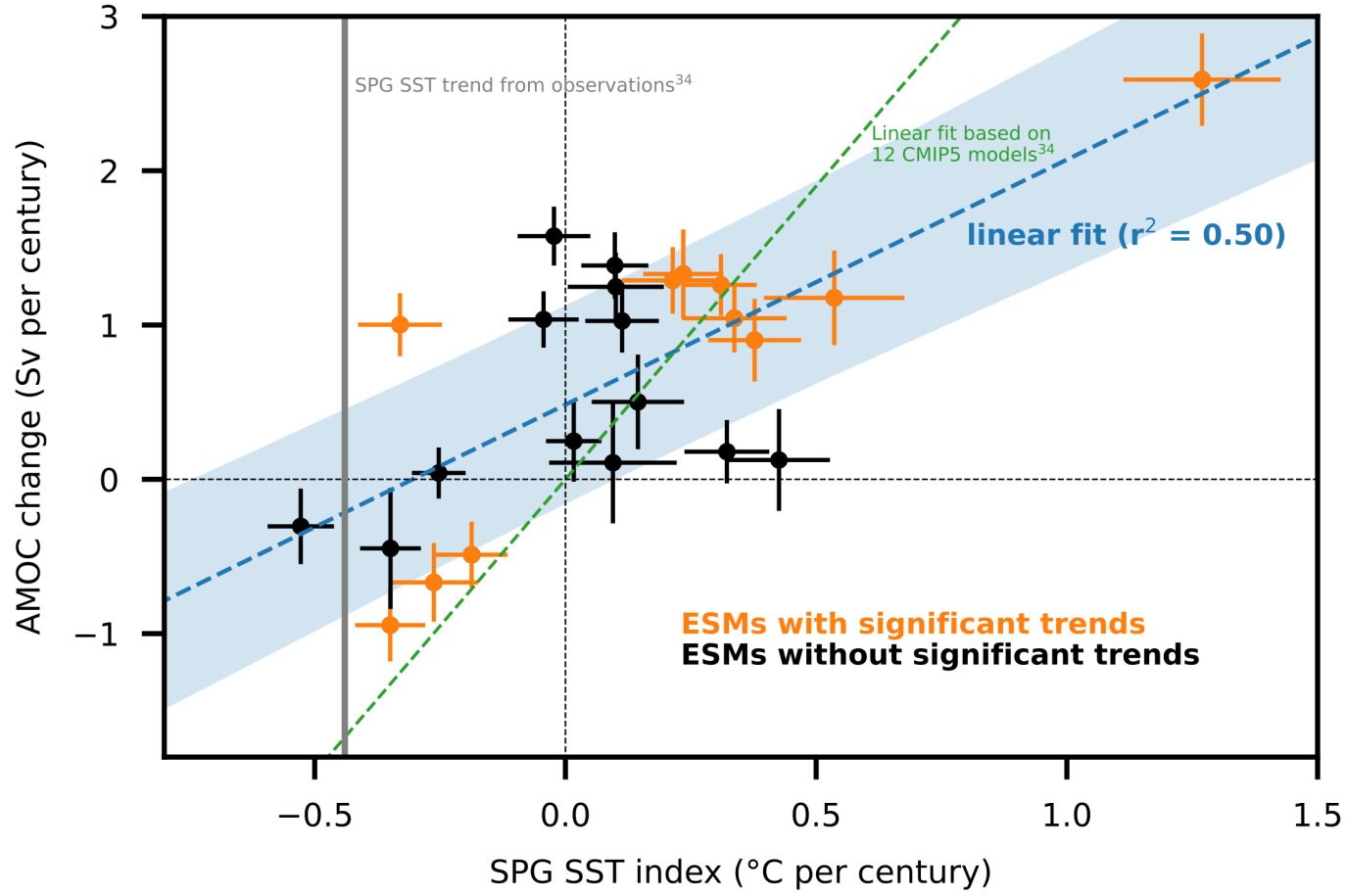
- Slope is weaker in CMIP6 models (1.6 Sv K^{-1}) than in CMIP5 models (3.8 Sv K^{-1})
- Linear trend in AMOC using CMIP6 SST relationship is -0.2 ± 0.7 Sv $century^{-1}$ (Caesar et al. (2018) inferred a 1.7 Sv $century^{-1}$ decline)



Terhaar et al. (2025)

Other studies with more models also suggested that the relationship is not as high as previously thought

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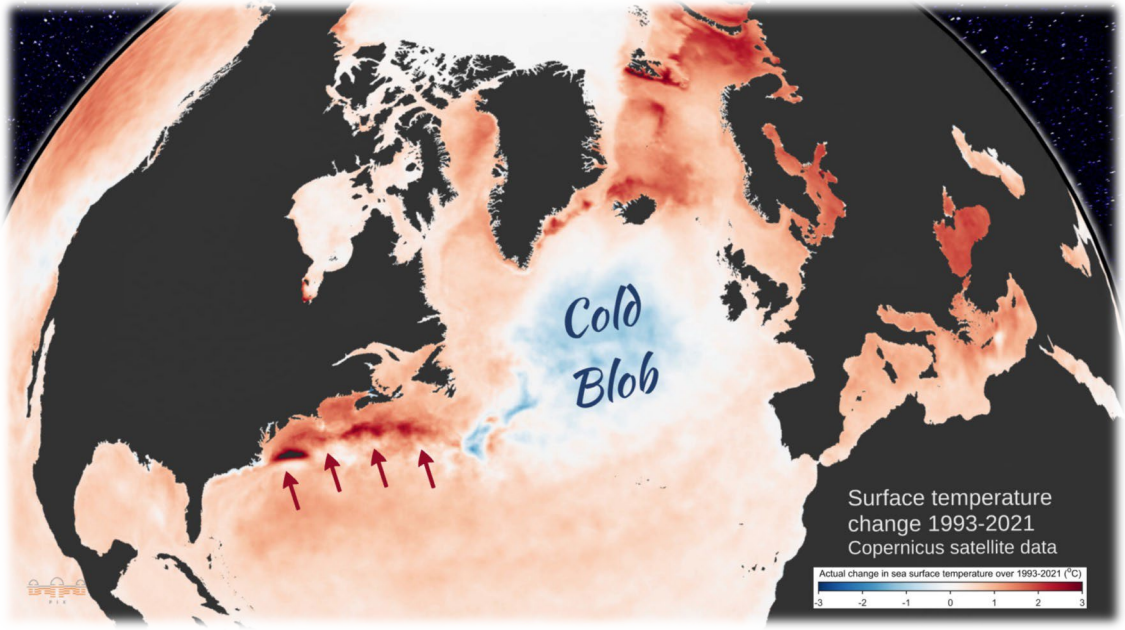

- Rahmstorf et al. (2015)
  - 1 CMIP5 model (MPI-ESM-MR)
  - r^2=0.81 after 10 year smoothing and detrending
- Caesar et al. (2018)
  - 15 CMIP5 models; 3 not considered due to unrealistic AMOCs
  - r^2=0.89 for linear trends
  - Time-varying AMOC reconstructed based on relationship calculated with long-term trends
- Olson et al. (2017)
  - 13 CMIP5 models
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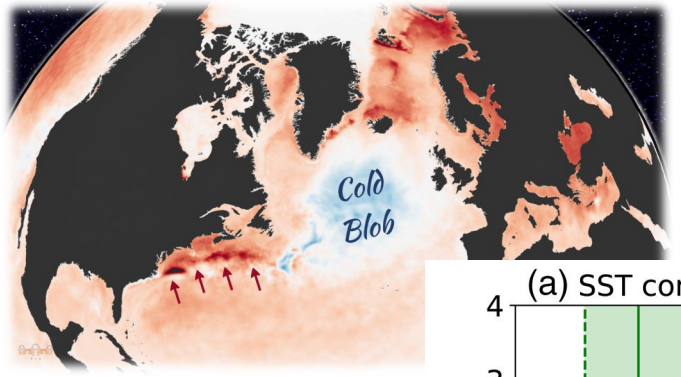

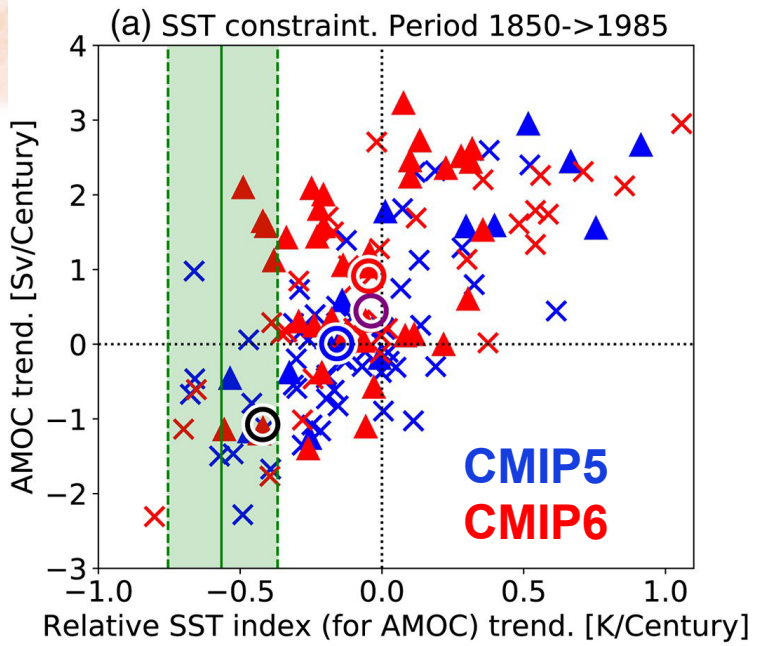

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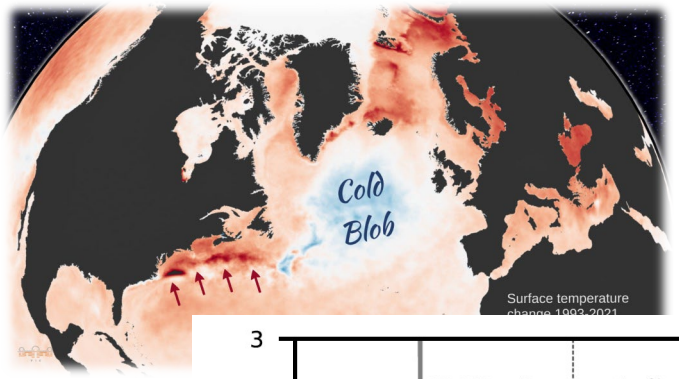

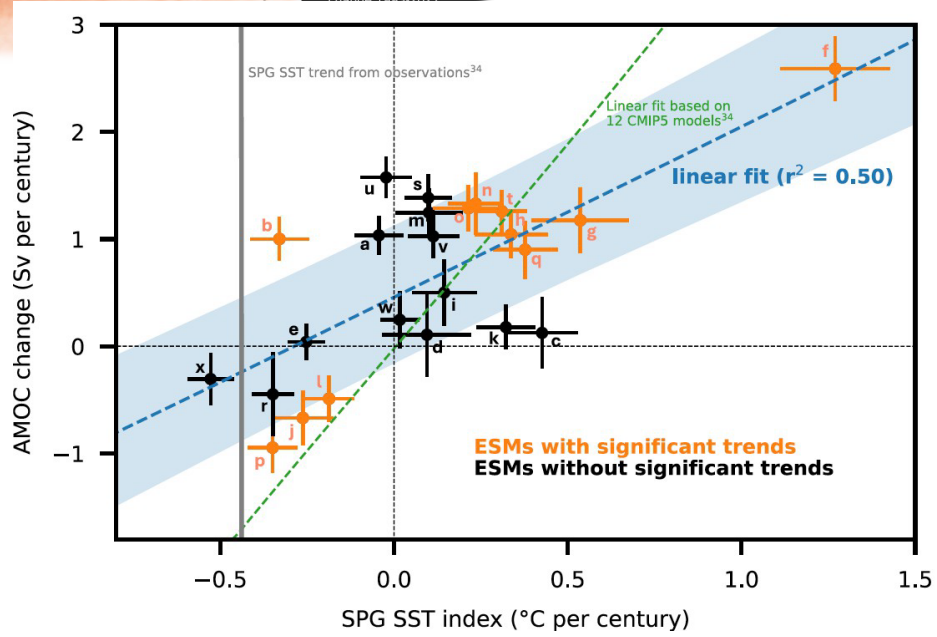

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Terhaar et al. (2025)

Trends are most likely not the best metric to understand the long-term evolution of the AMOC

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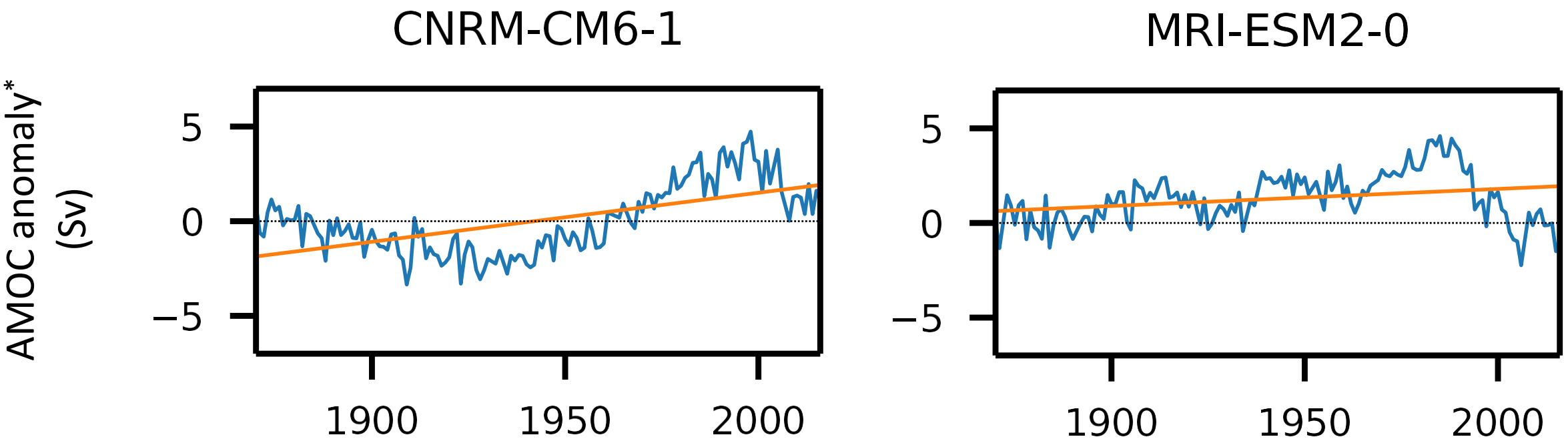

*Anomalies are calculated with respect to a linear fit over the pre-industrial Control simulation

Terhaar et al. (2025)

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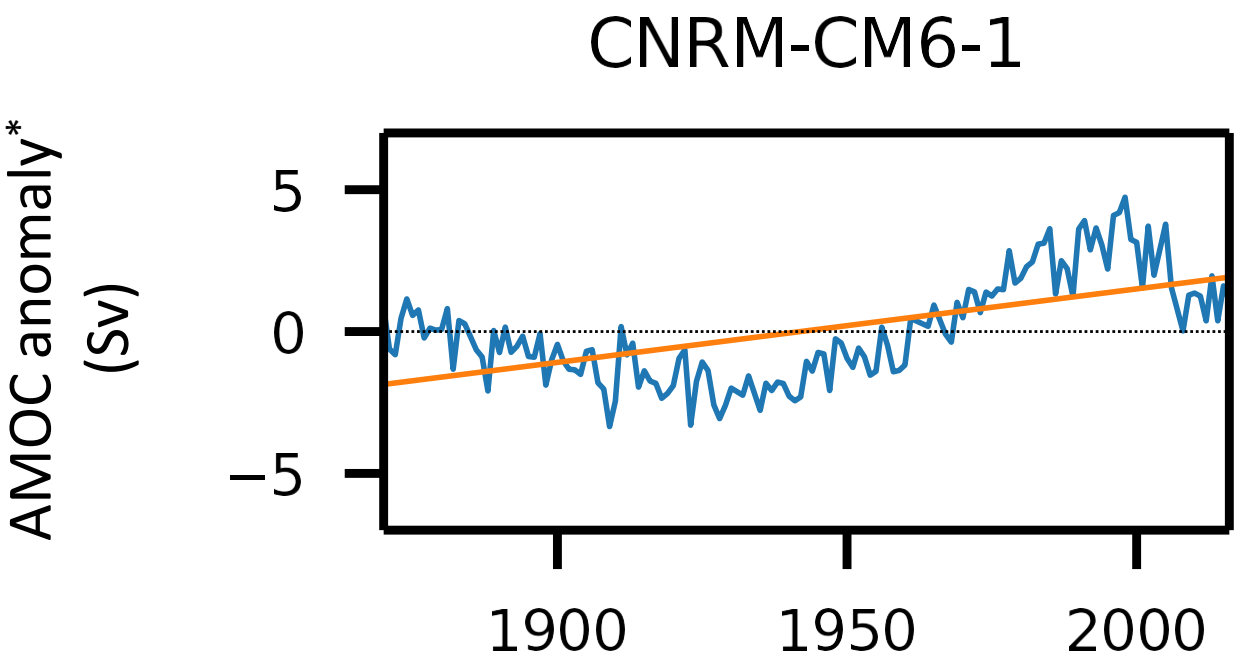

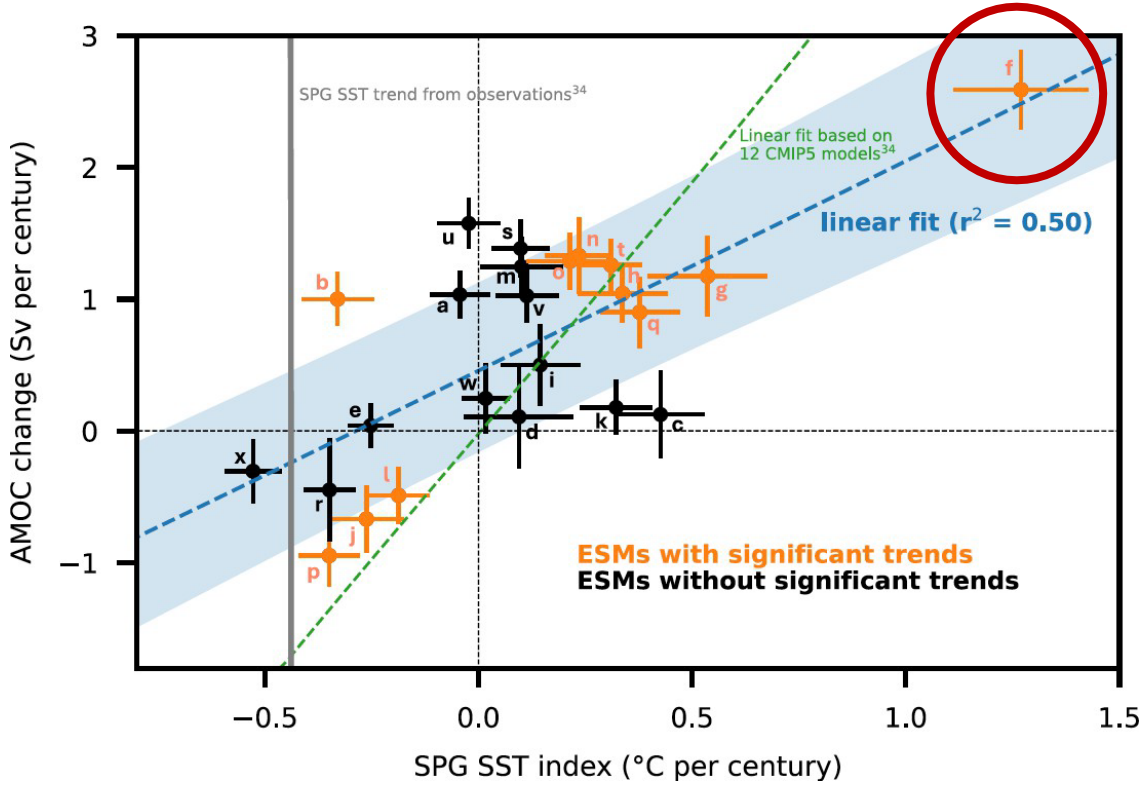

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Terhaar et al. (2025)

There are only weak correlations between the AMOC index and the AMOC on any timescales

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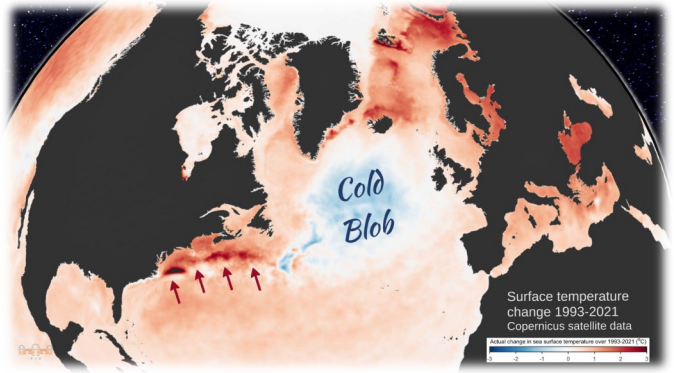

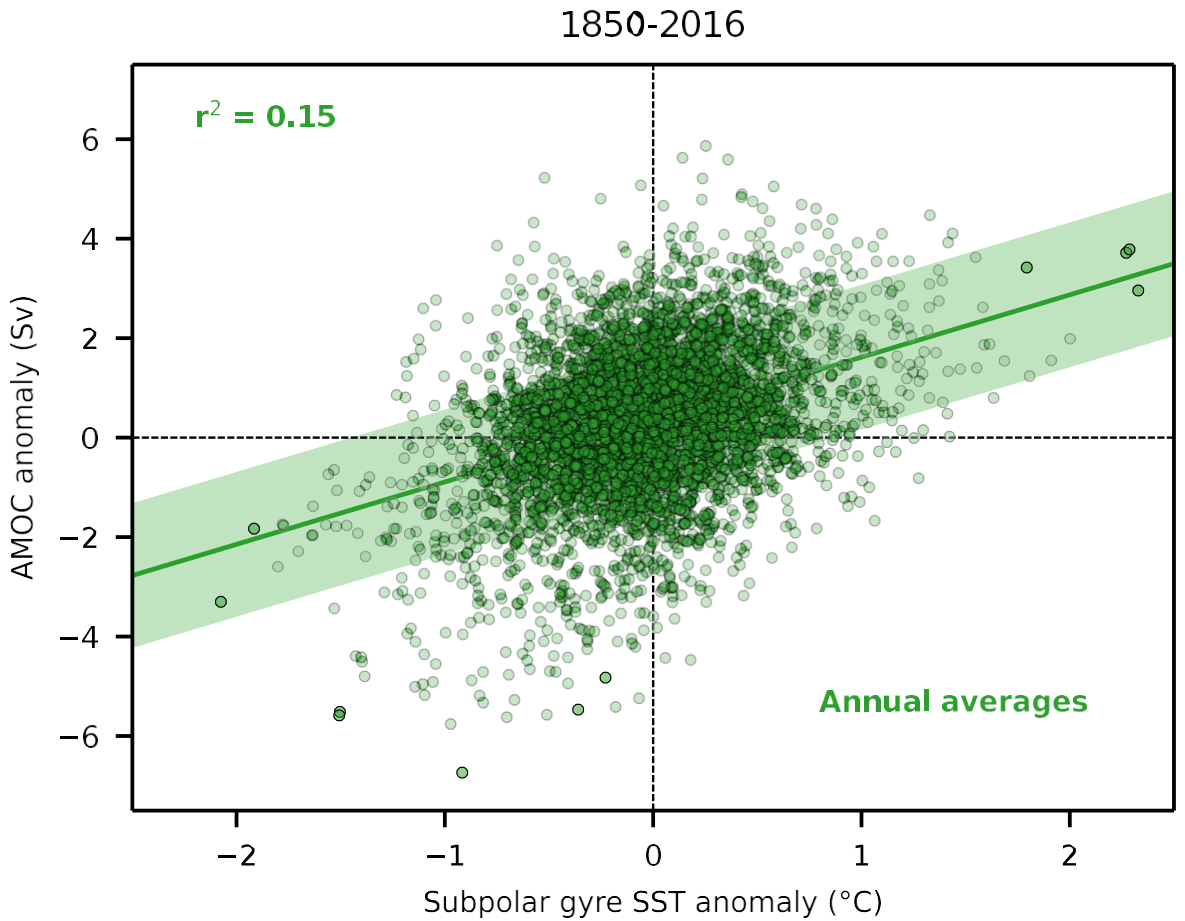

Terhaar et al. (2025)

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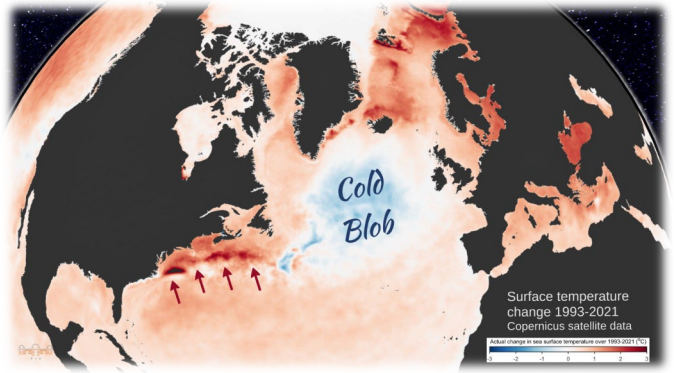

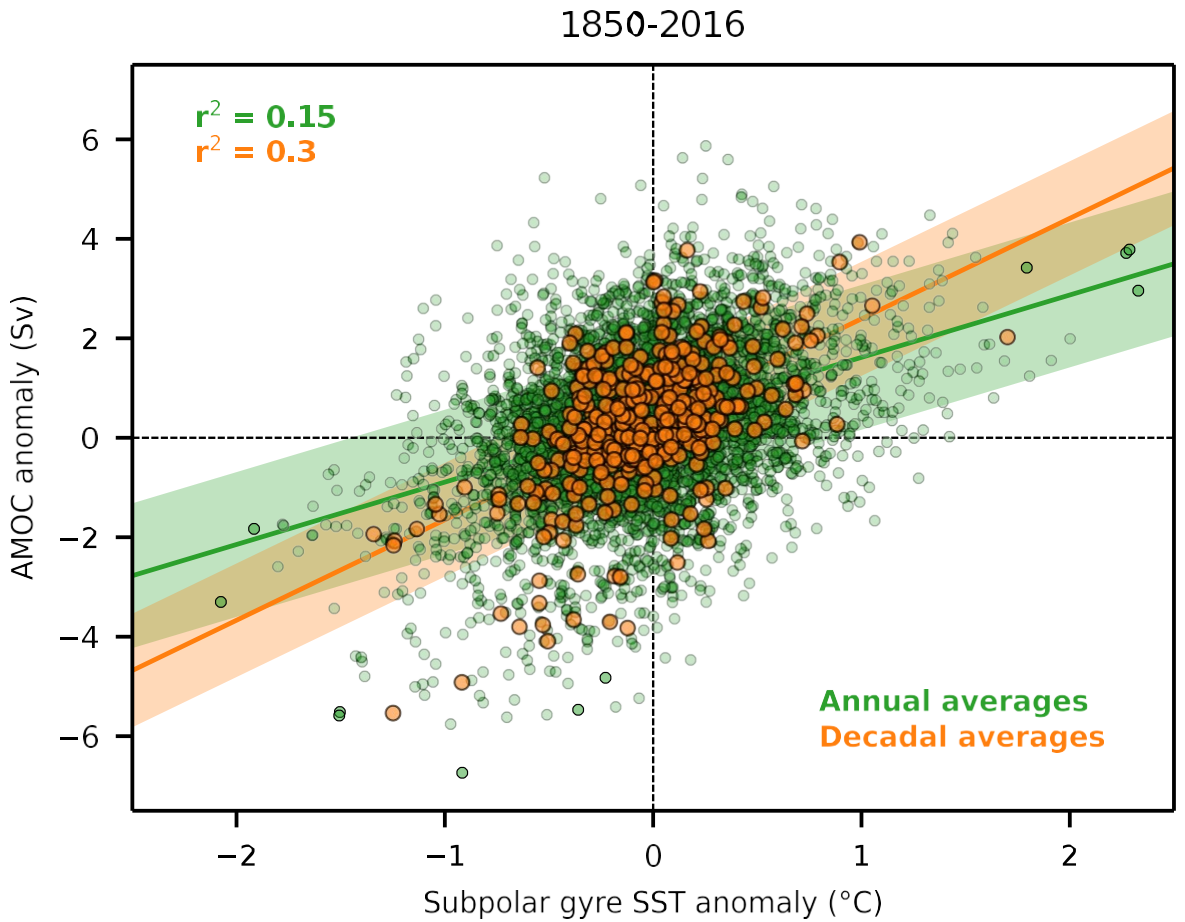

Terhaar et al. (2025)

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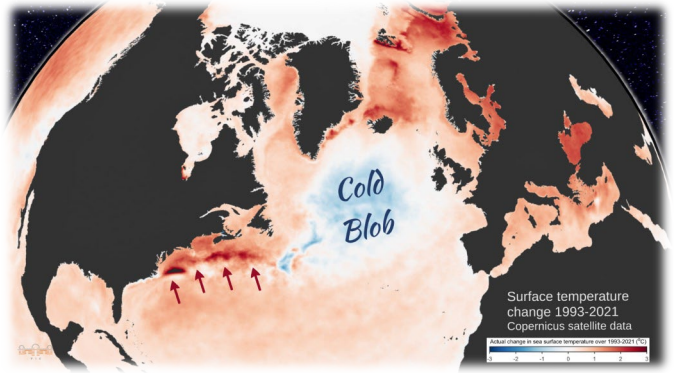

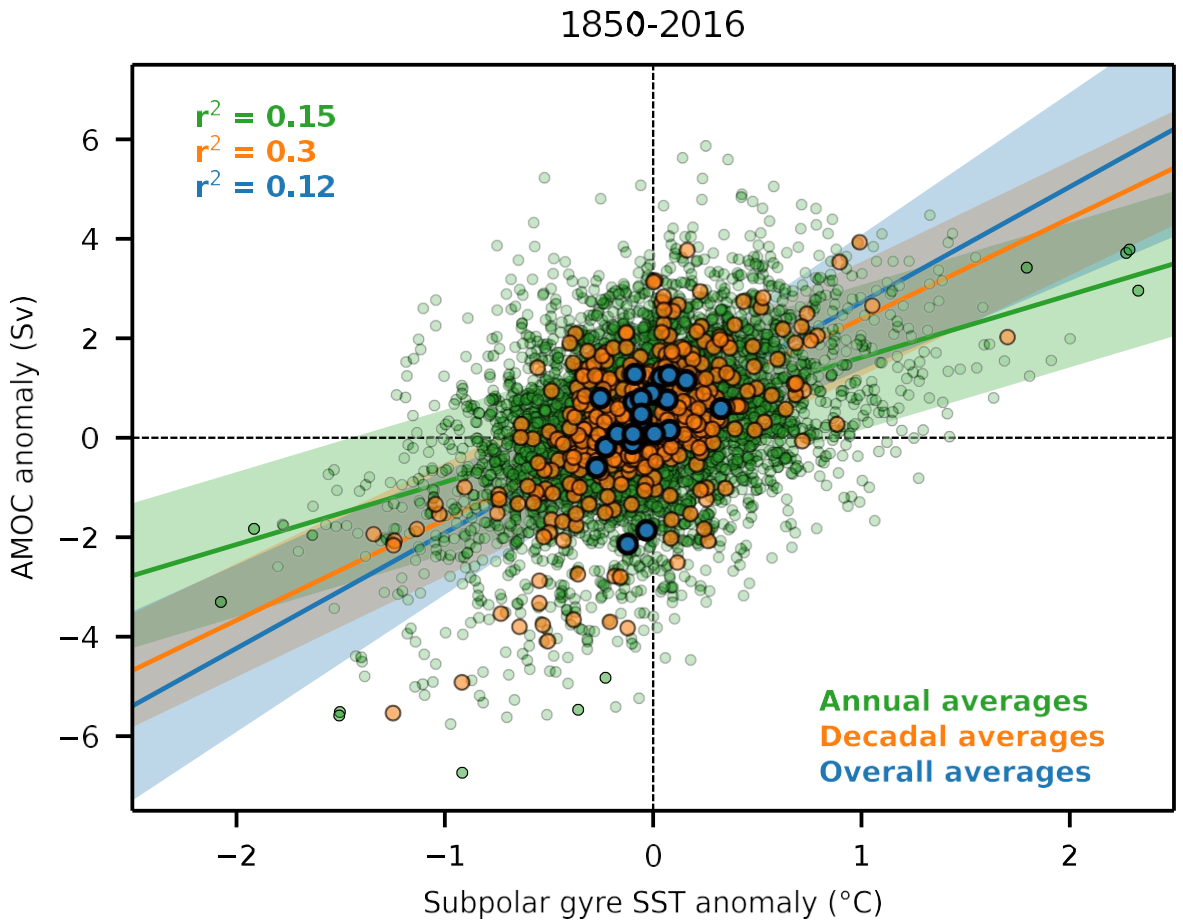

Terhaar et al. (2025)

Back to the beginning – the heat budget of the North Atlantic

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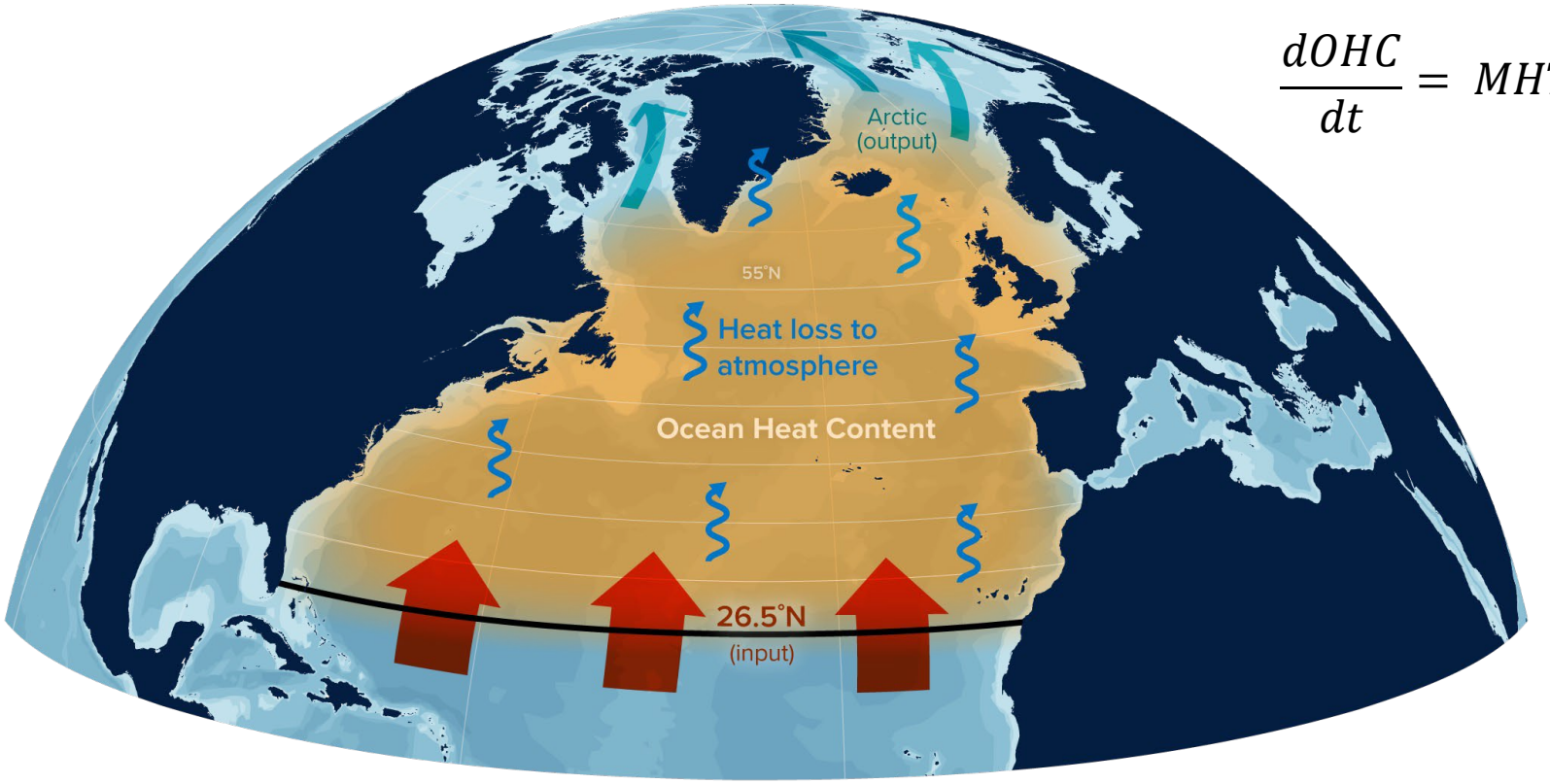

Heat budget of the North Atlantic:

$$\frac{dOHC}{dt} = MHT_{!"\#\$\%} - MHT_{\&"'\$\%} + + Q_{()\$}\, d\theta\, d\lambda$$

Terhaar et al. (2025)

The most important factors in the heat budget are the anomalies of the northward heat transport and the air-sea heat flux

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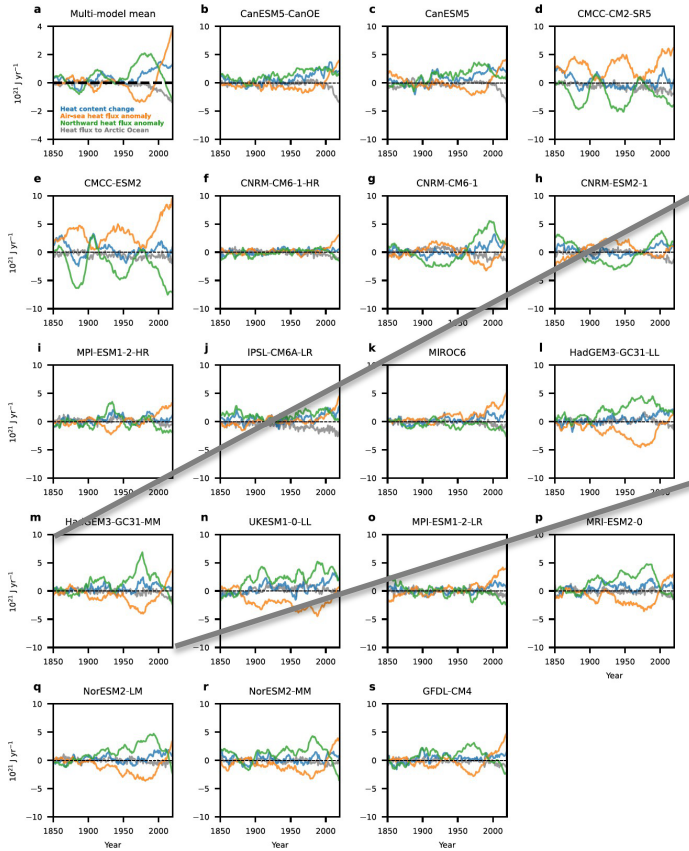
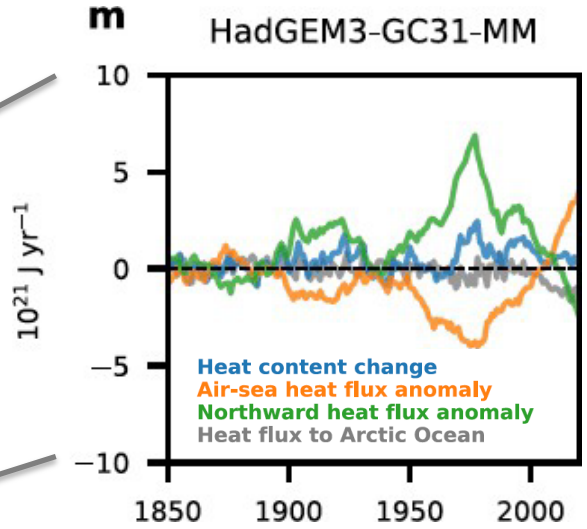
Heat budget terms for CMIP6 historical runs (18 models)





$$\frac{dOHC}{dt} = MHT_{South} - MHT_{North} + + Q_{net}\, d\theta\, d\lambda$$

Terhaar et al. (2025)

The heat budget of the North Atlantic in a box

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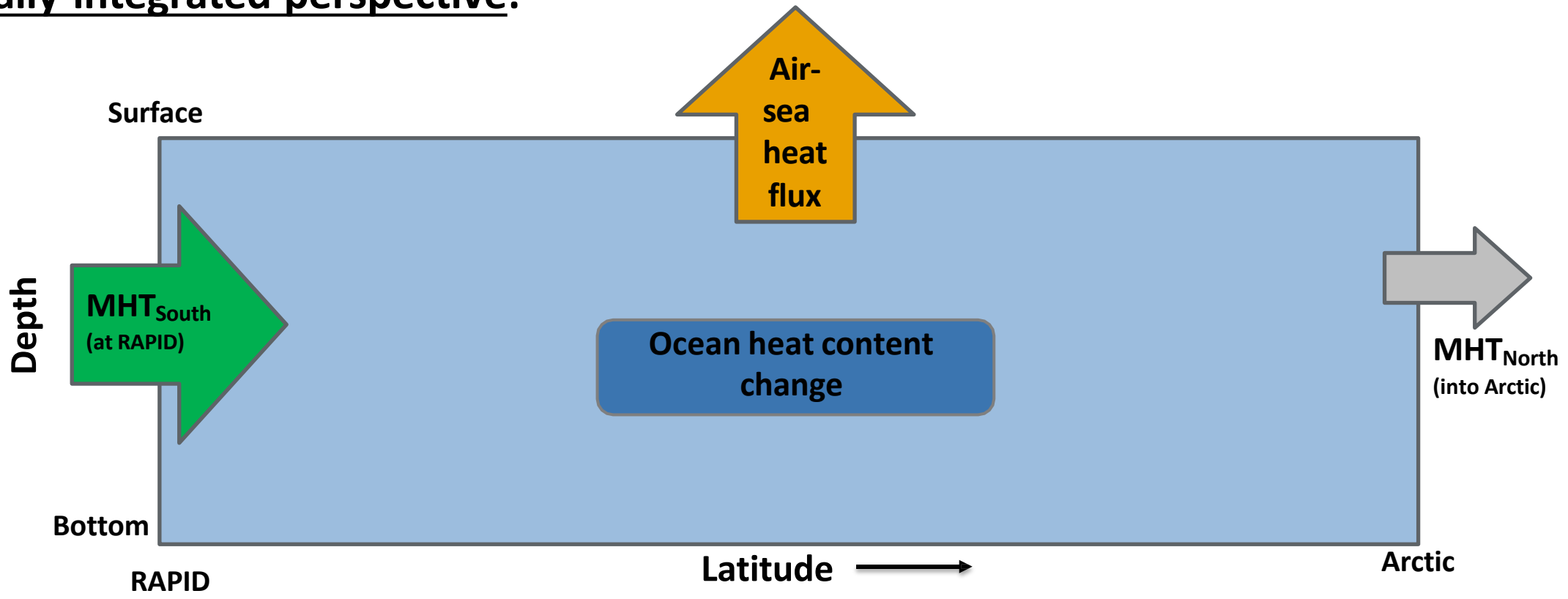
Zonally-integrated perspective:



Terhaar et al. (2025)

More northward heat transport is compensated by more heat loss to the atmosphere

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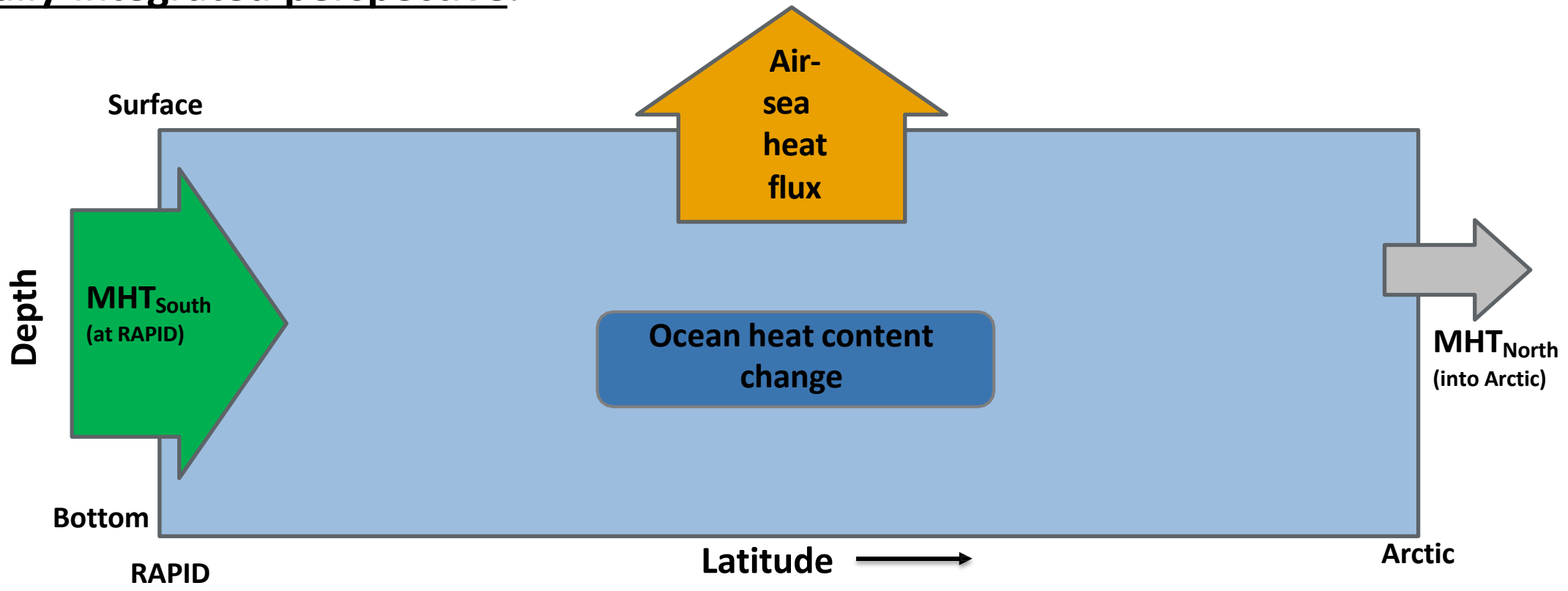

Terhaar et al. (2025)

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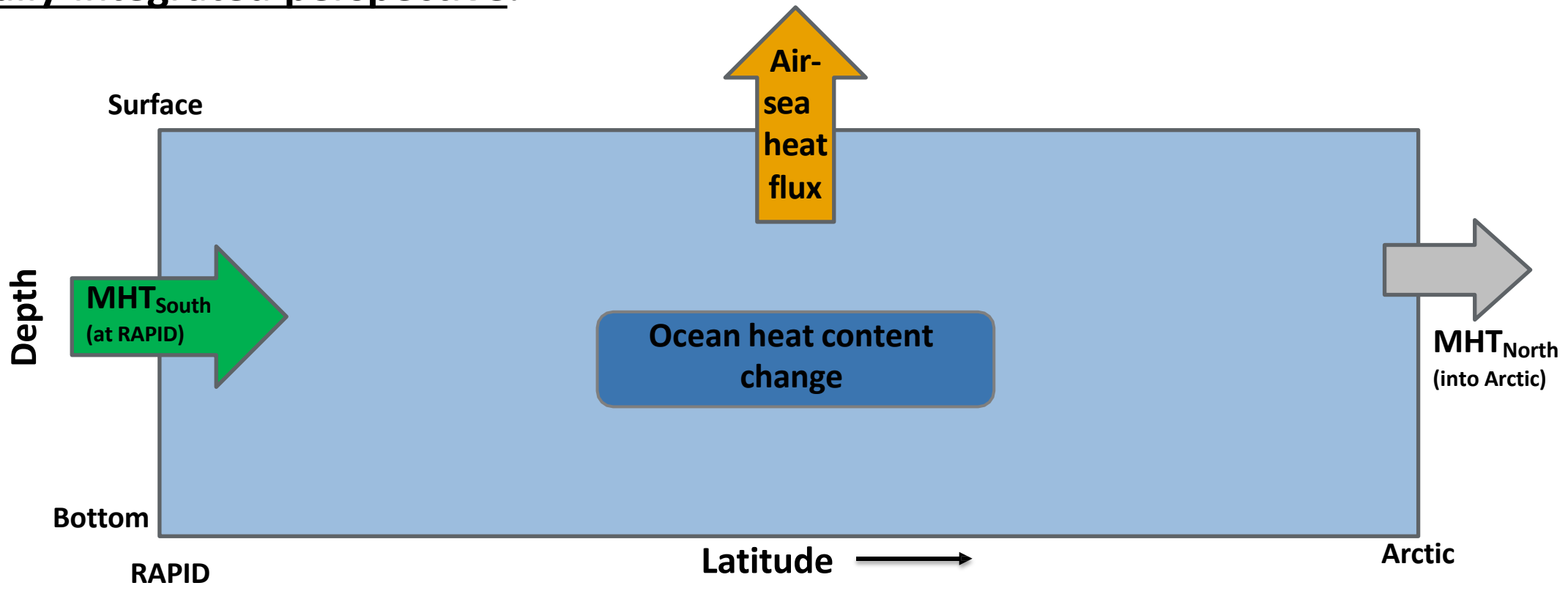

Terhaar et al. (2025)

The relationship is confirmed on decadal and centennial timescales by CMIP6 models

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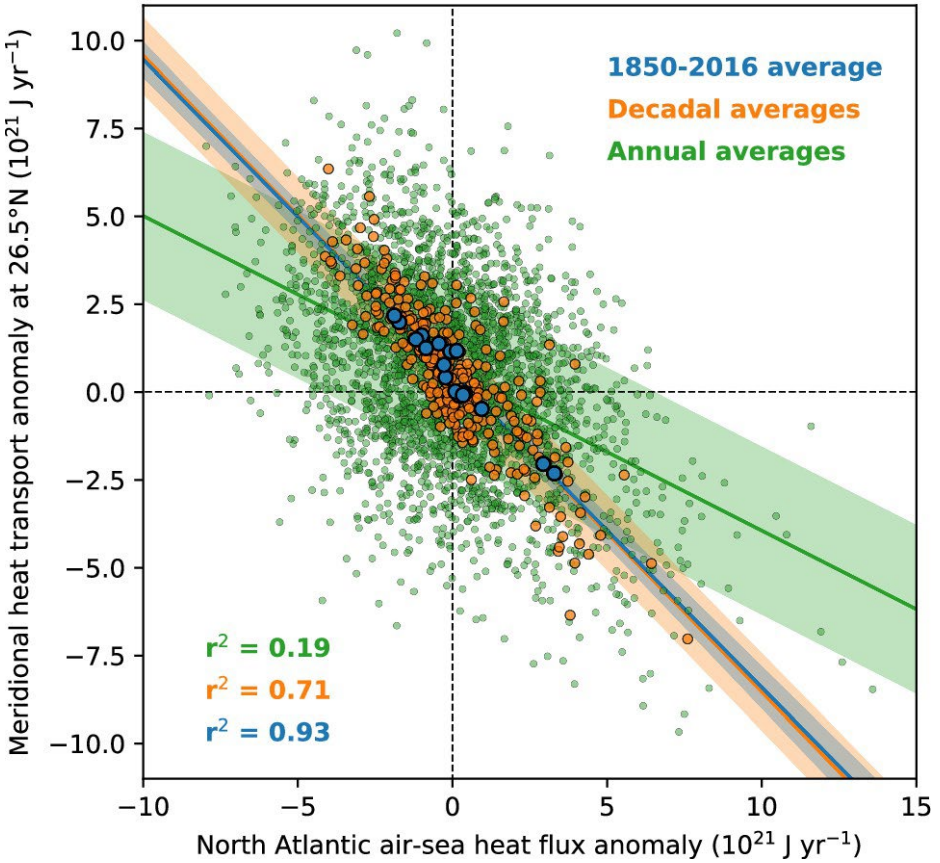

Terhaar et al. (2025)

The AMOC variability controls the northward heat transport variability

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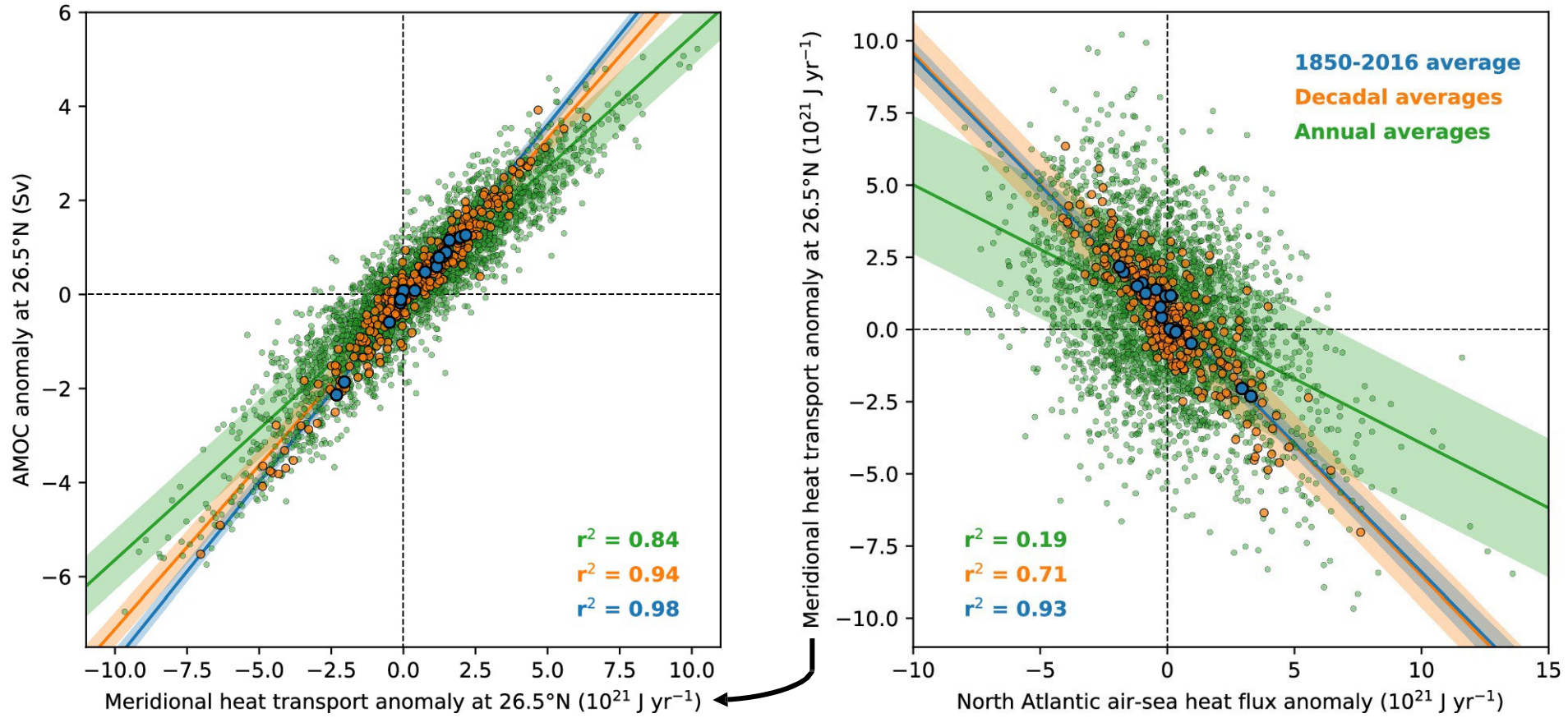

Terhaar et al. (2025)

Overall, the AMOC variability and the air-sea heat flux anomaly in the North Atlantic are thus strongly linked to each other

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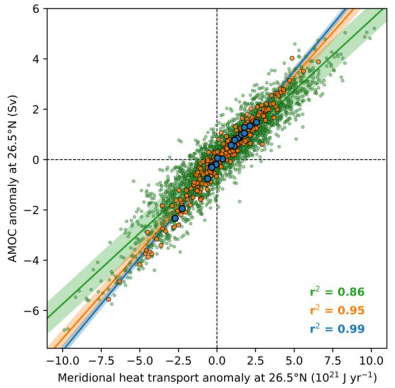

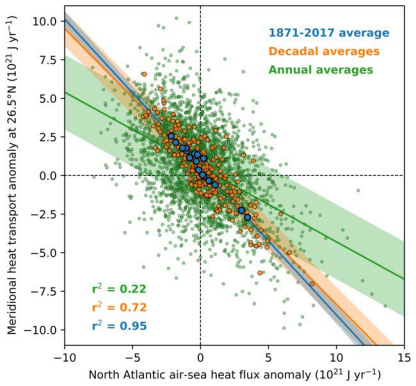

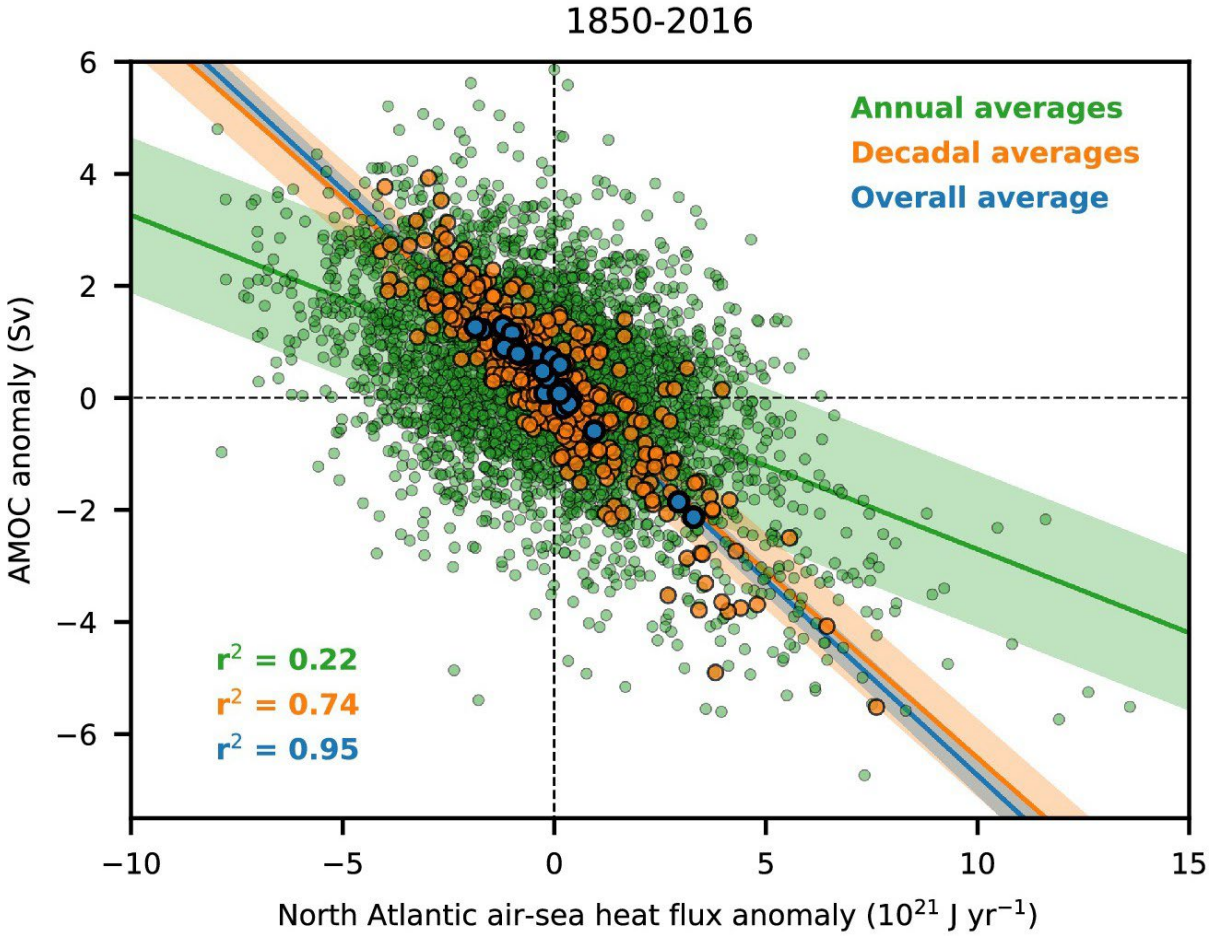

Terhaar et al. (2025)

ESMs can be used as a testbed for the capability of air-sea heat fluxes to reconstruct the AMOC

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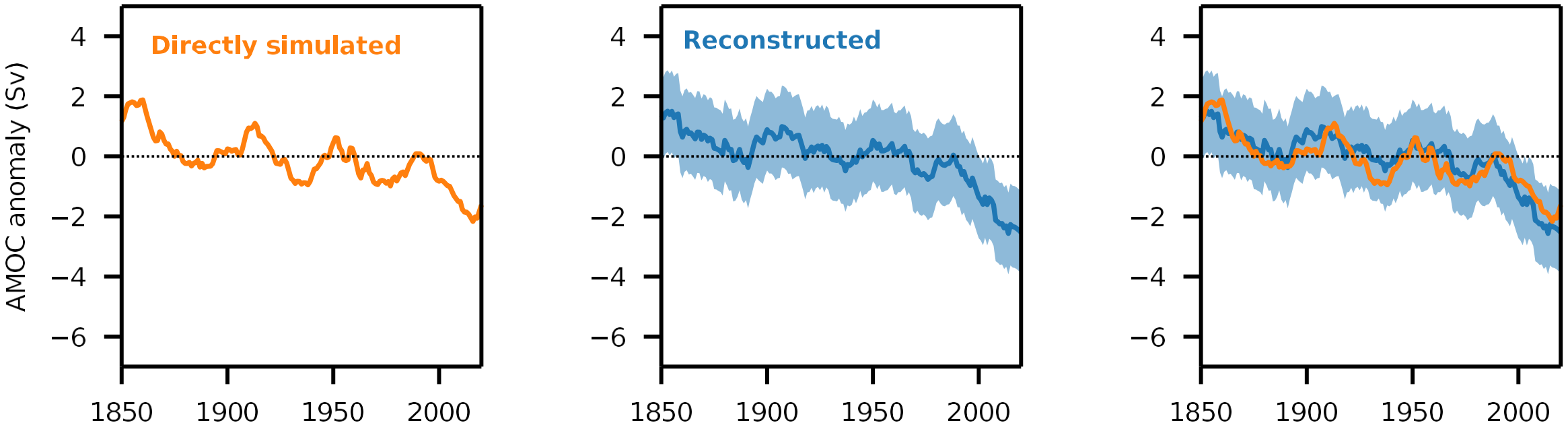

MPI-ESM1-2-LR

Terhaar et al. (2025)

Testing the new AMOC index with a wide range of ESMs demonstrate its robustness

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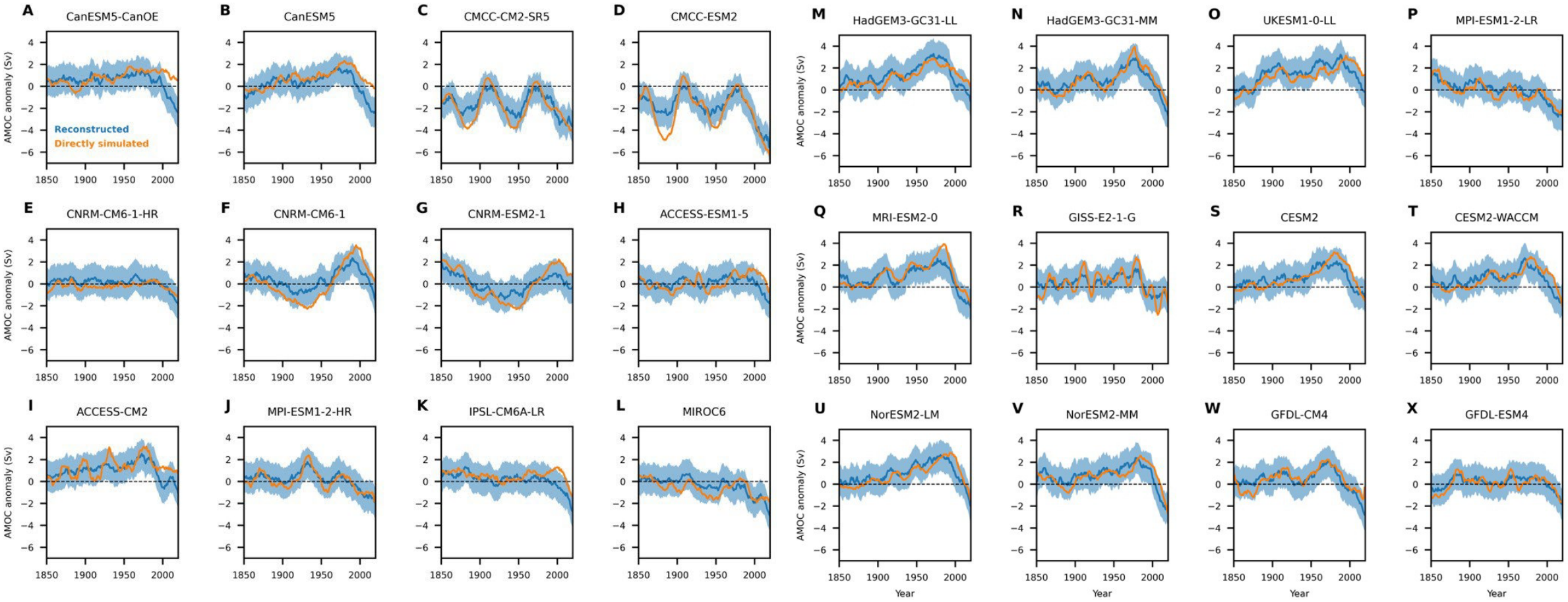

Terhaar et al. (2025)

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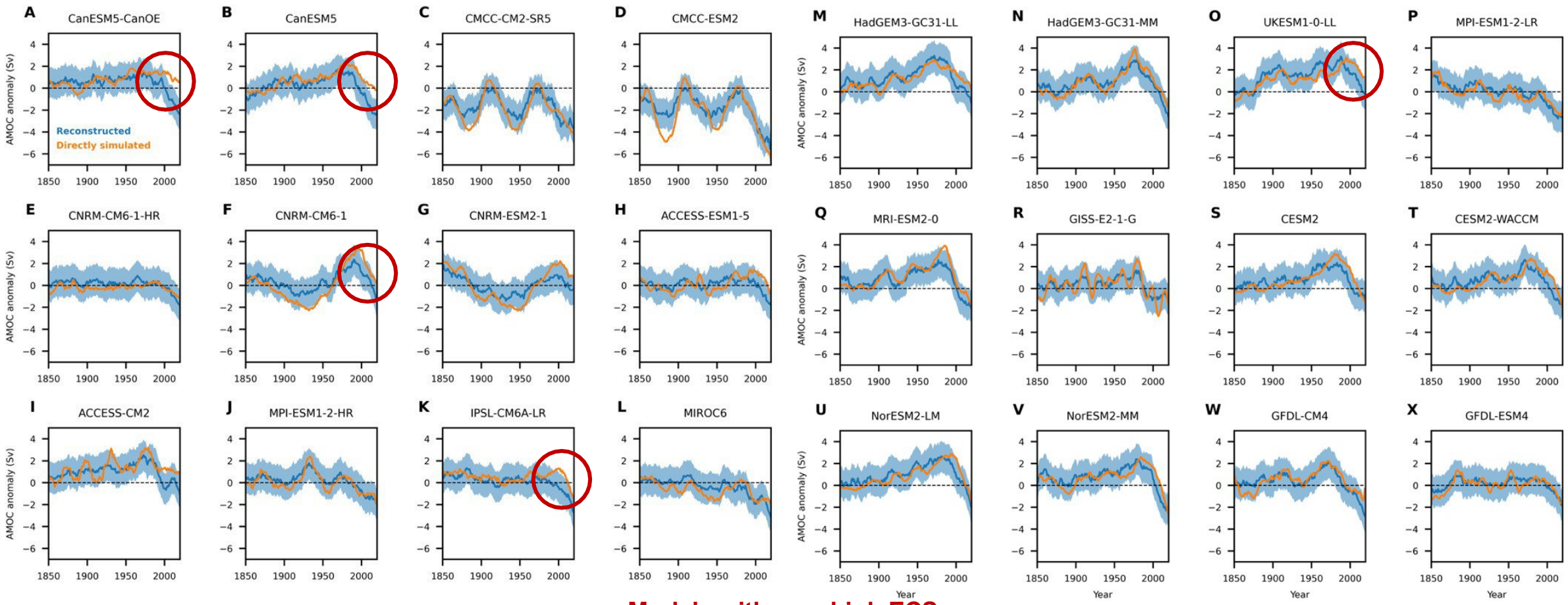

Models with very high ECS

Terhaar et al. (2025)

Additional air-sea heat flux from atmospheric warming would result in a decline in the reconstructed AMOC – our estimate is thus conservative

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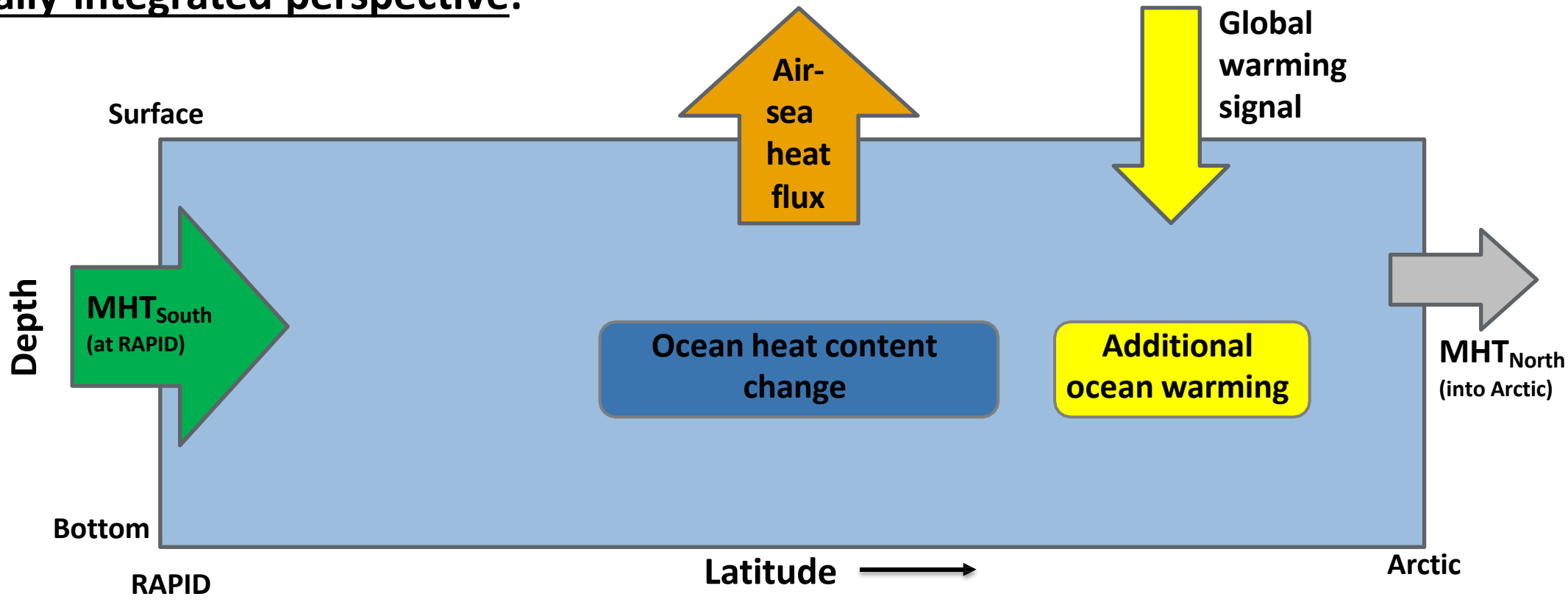
Zonally-integrated perspective:



Terhaar et al. (2025)

The link also holds in the future, although additional warming moves the relationship to the right

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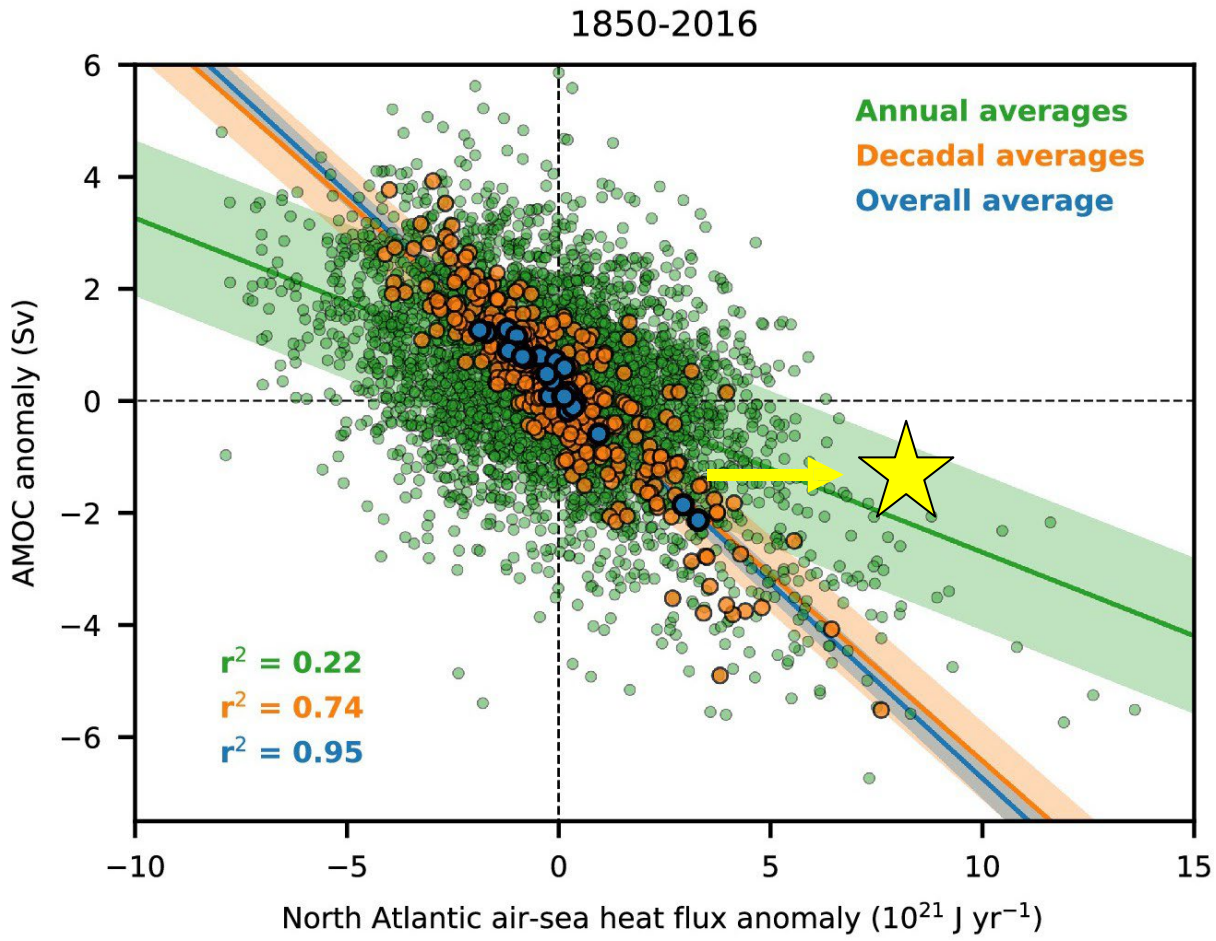

Air-sea heat flux change without associated change in the AMOC

Terhaar et al. (2025)

The link also holds in the future, although additional warming moves the relationship to the right

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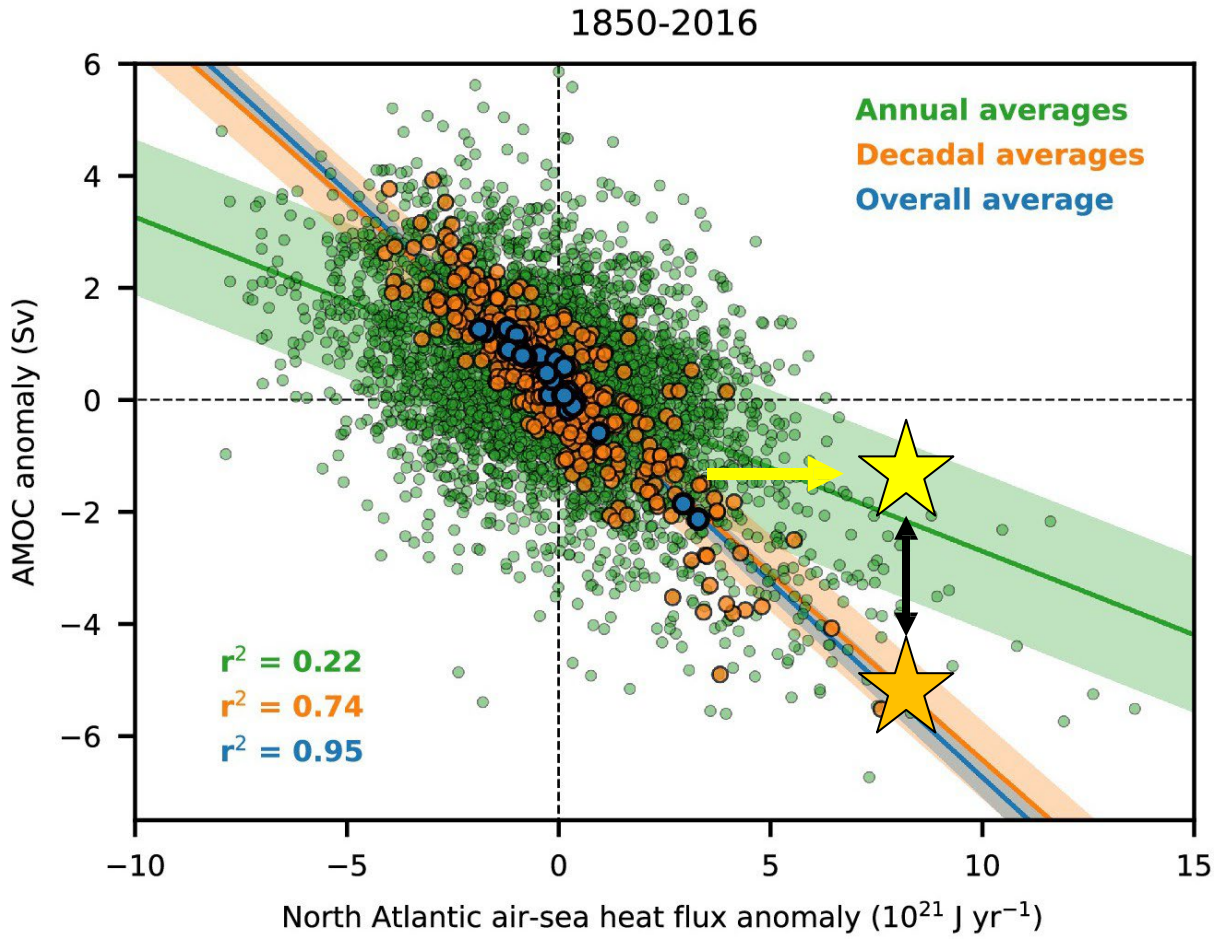

Air-sea heat flux change without associated change in the AMOC

AMOC deduced from air-sea heat flux changes

Terhaar et al. (2025)

The link also holds in the future, although additional warming moves the relationship to the right

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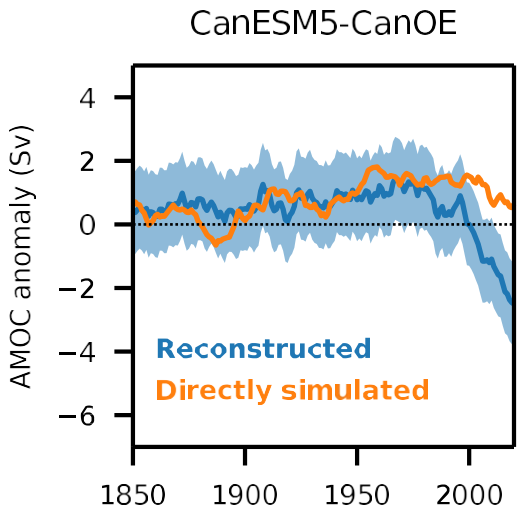

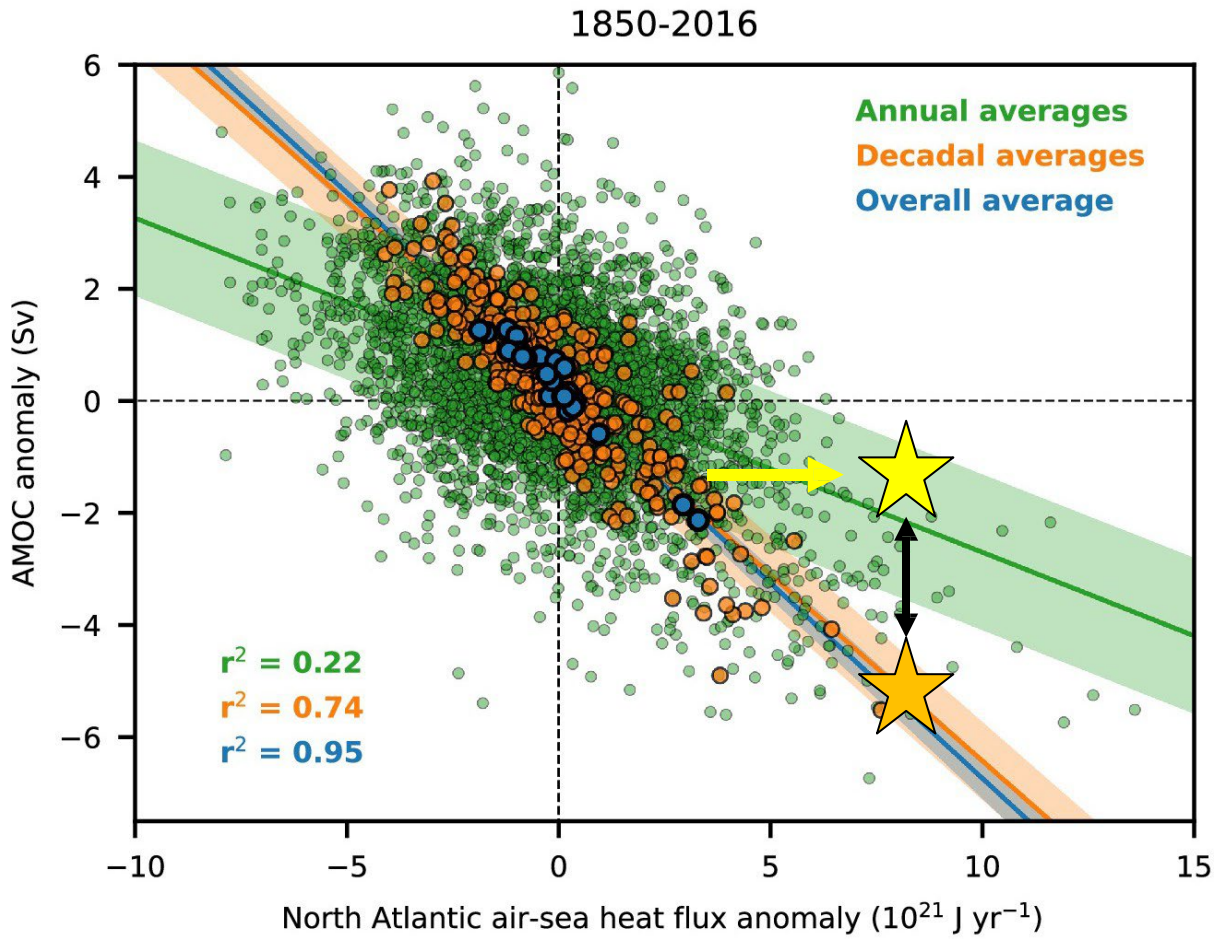

Air-sea heat flux change without associated change in the AMOC

AMOC deduced from air-sea heat flux changes

Terhaar et al. (2025)

After these tests, we now reconstructed the AMOC with air-sea heat fluxes from atmospheric reanalysis products

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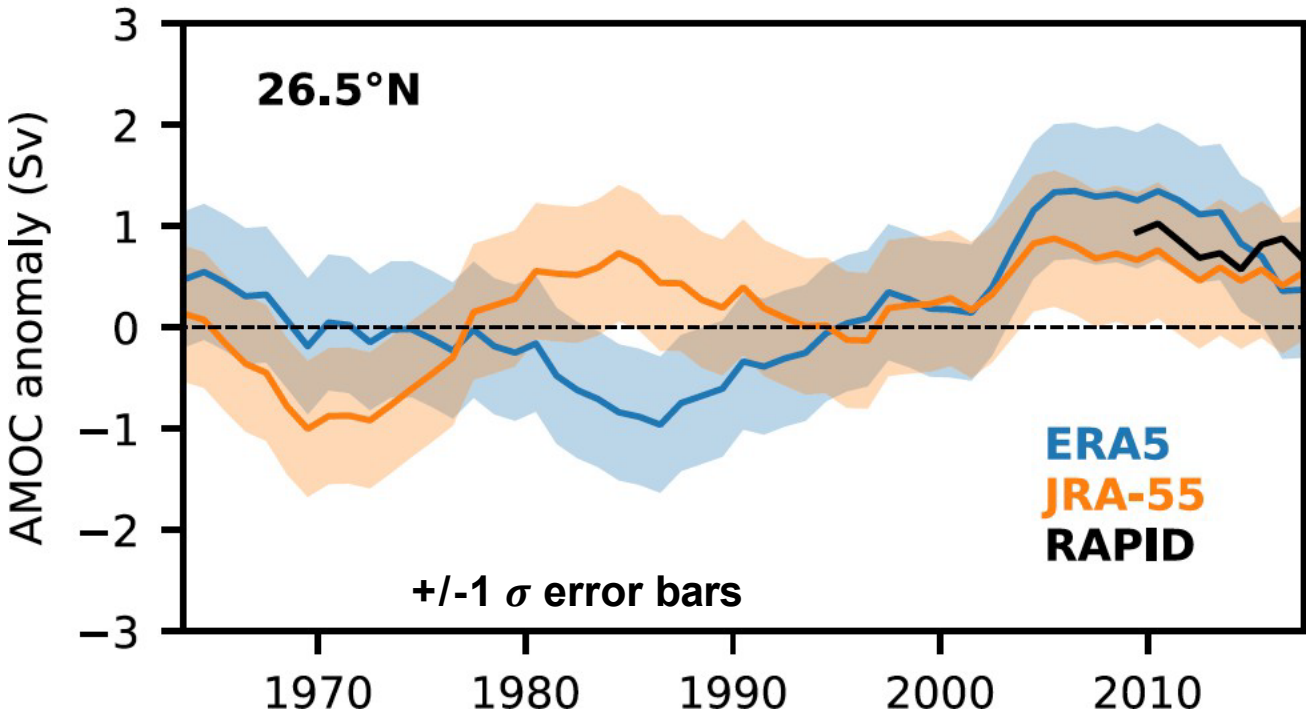

- Reanalysis Q_{net}:
  - ERA5: 1940-2022
  - JRA-55: 1958-2022
  - 10 year means => reconstruction goes from 1963-2017
- Error bars are +/- 1 standard deviation based on the linear fit between AMOC and surface heat fluxes
- No uncertainty of heat flux data incorporated into these error bars
- Time series agree with one another within +/- 2σ range.
- Total uncertainty (uncertainty from linear fit + measurement uncertainty) can be estimated by the range of values given by both reconstructions
- A slight positive trend in both time series

Terhaar, Vogt, and Foukal, 2025

Terhaar et al. (2025)

As this approach is based on a heat budget, we can reconstruct the AMOC at various latitudes

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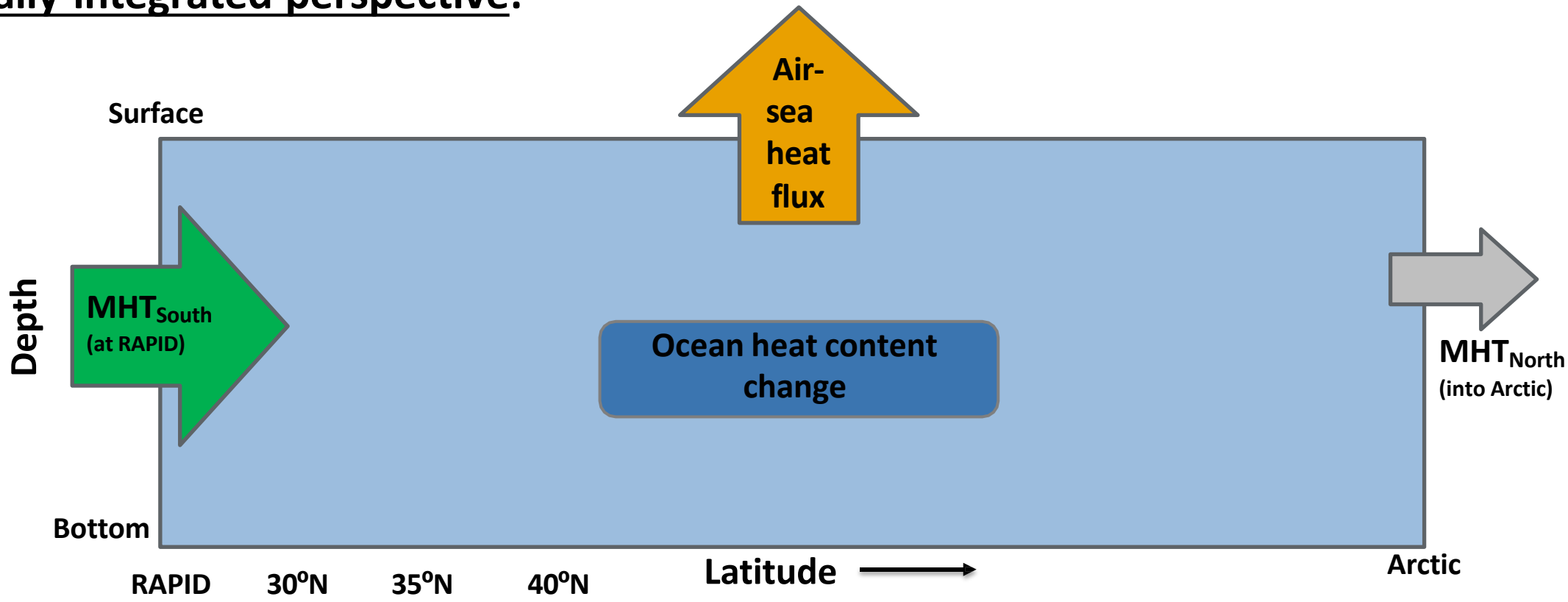
Zonally-integrated perspective:



Terhaar et al. (2025)

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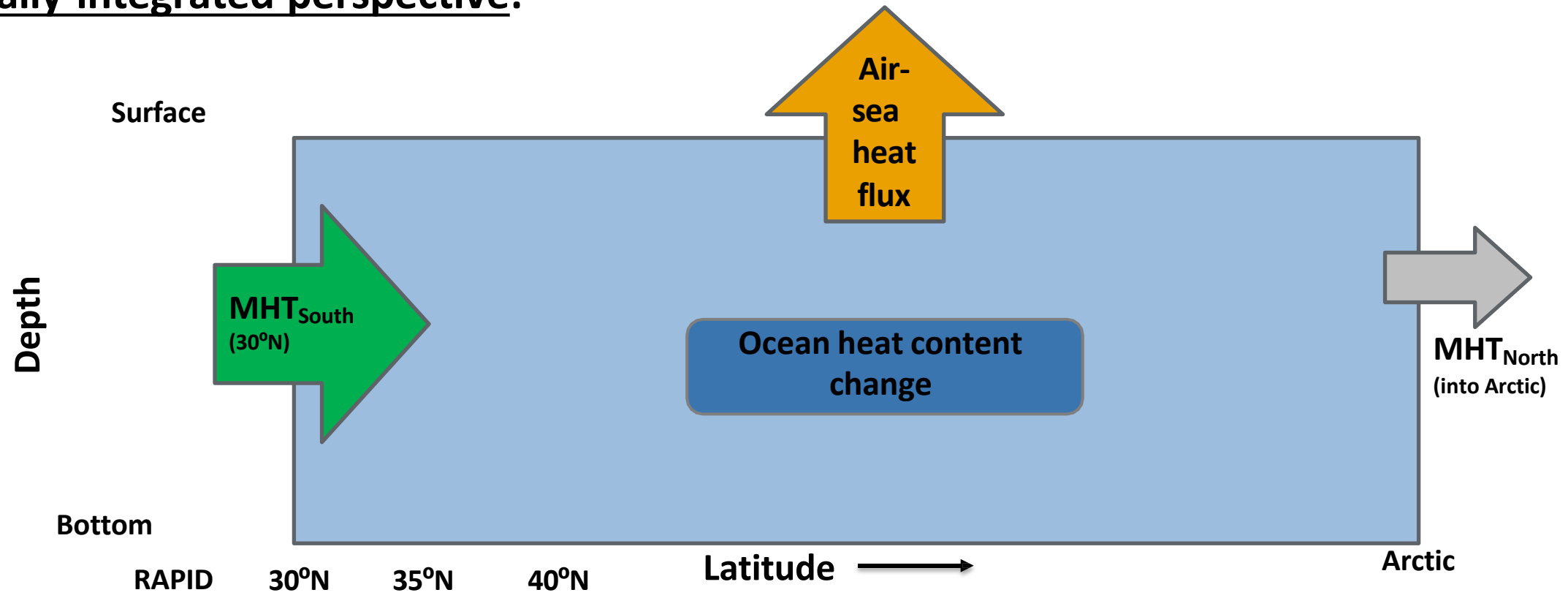

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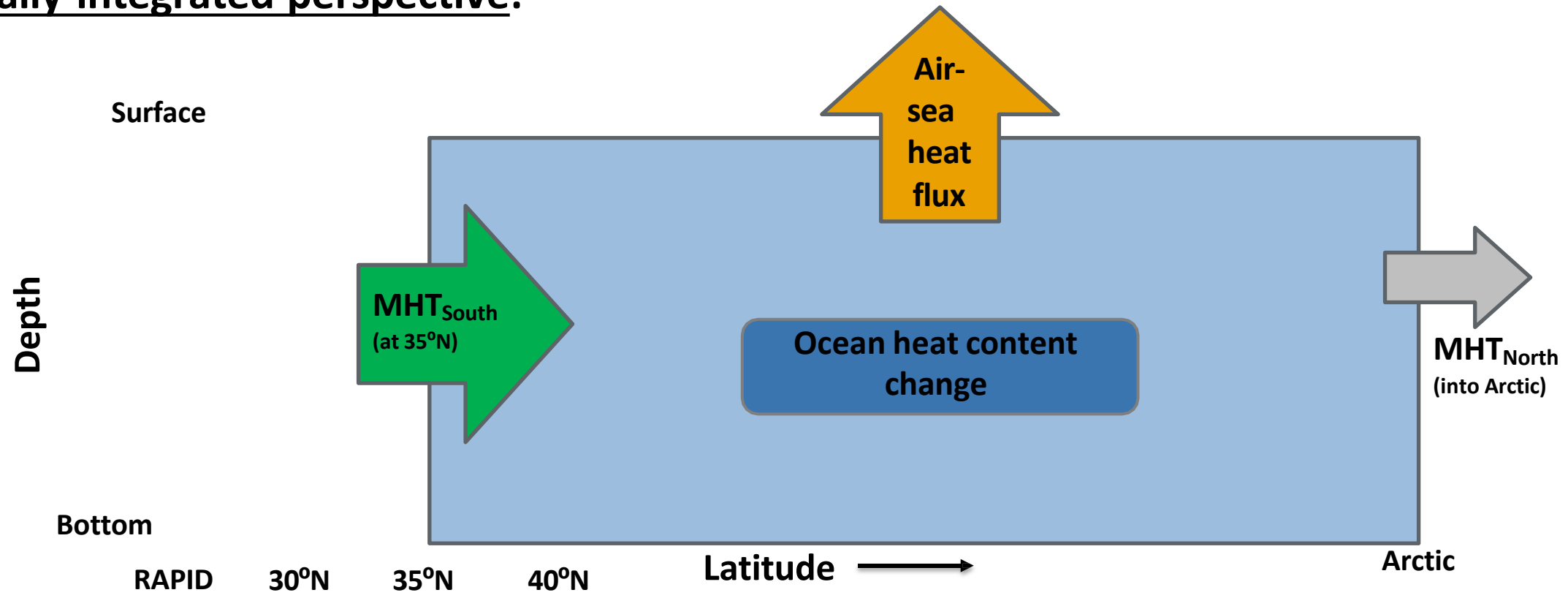

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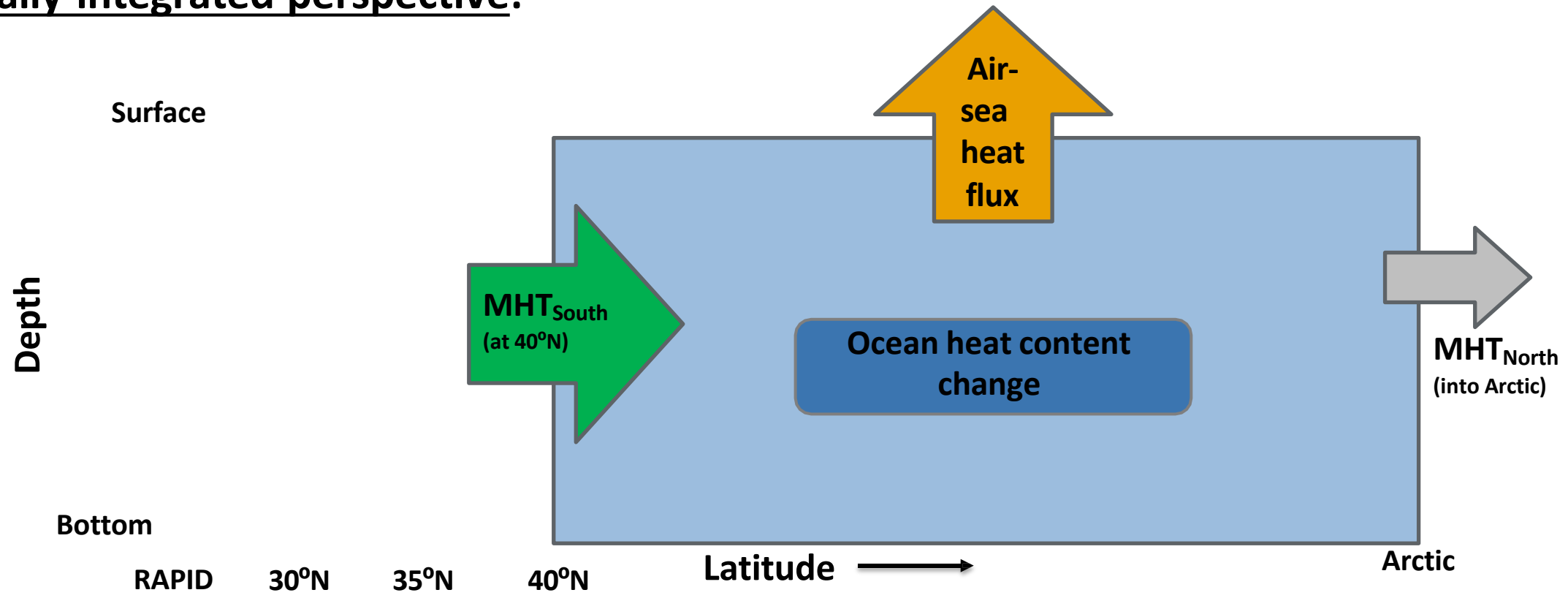

Terhaar et al. (2025)

The AMOC at the different latitudes is not necessarily correlated

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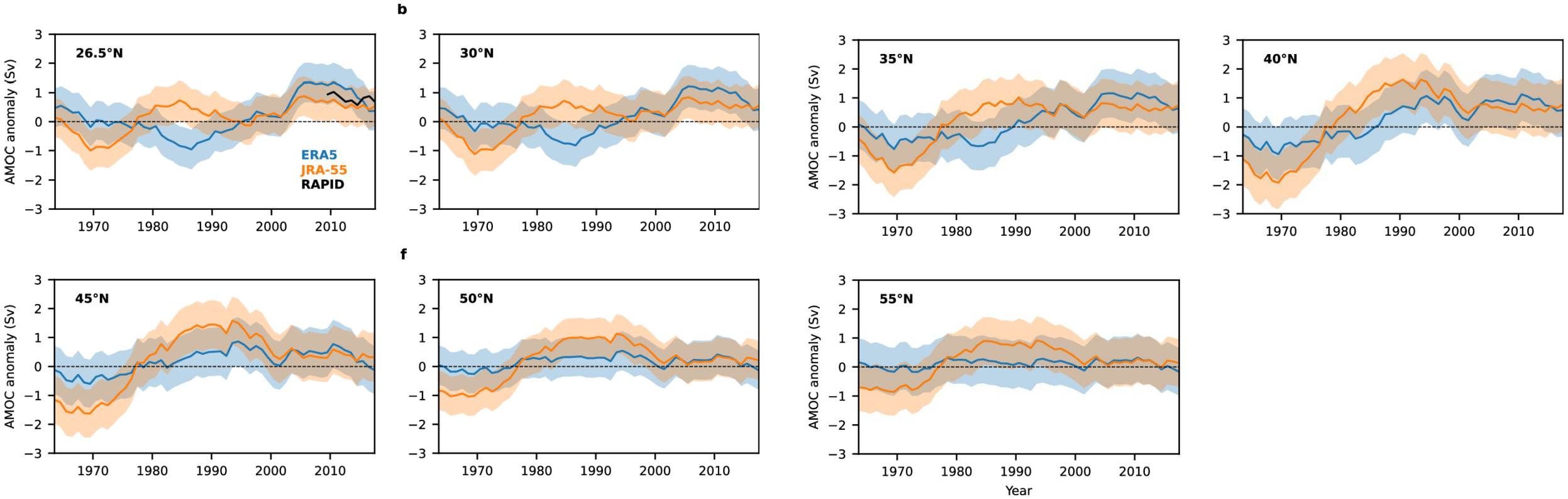

Terhaar et al. (2025)

Air-sea heat fluxes from reanalysis products do not match ocean heat content changes, but they work well in the North Atlantic

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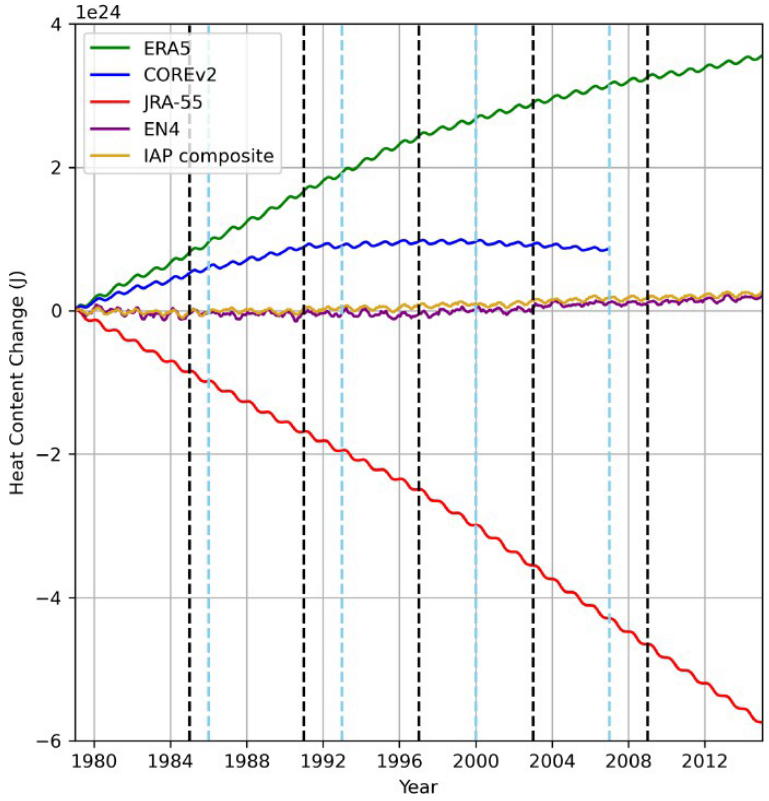
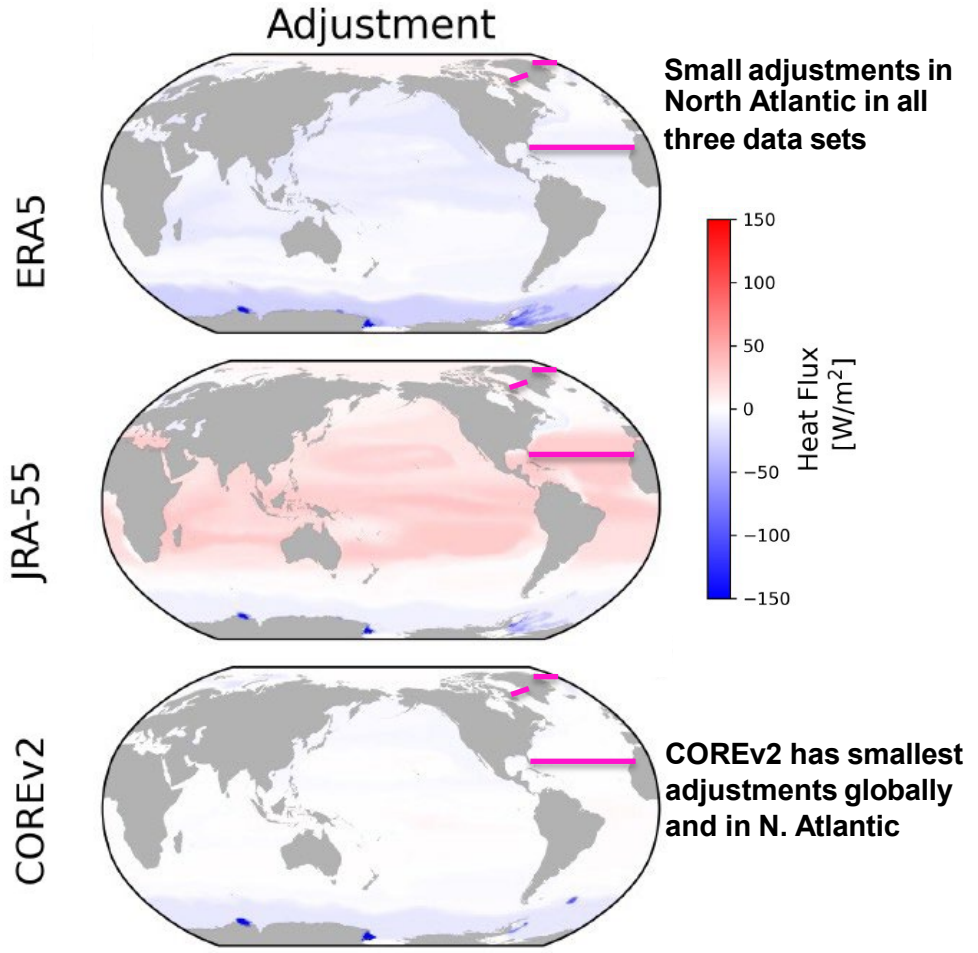
Time-integrated global air-sea heat fluxes without adjustments





Small adjustments in North Atlantic in all three data sets

COREv2 has smallest adjustments globally and in N. Atlantic

Sohail and Zika (2025)

Take home messages

1) Sea surface temperatures in the North Atlantic appear to be a very uncertain proxy for the AMOC

2) Air-sea heat flux anomalies allow reconstructing the AMOC on decadal and centennial timescales at various latitudes.

3) The AMOC appears to me more stable and potentially more robust to external forcing than previously thought.

4) Air-sea heat fluxes may provide a complimentary and relatively cheap way to detect AMOC changes in the future.