

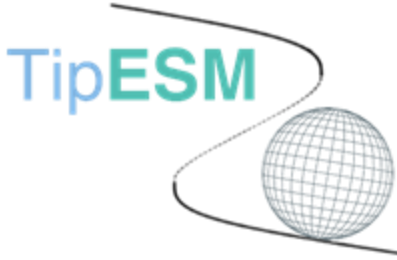
On-going and future changes of the AMOC: what can we learn from combining models and various sources of observations?



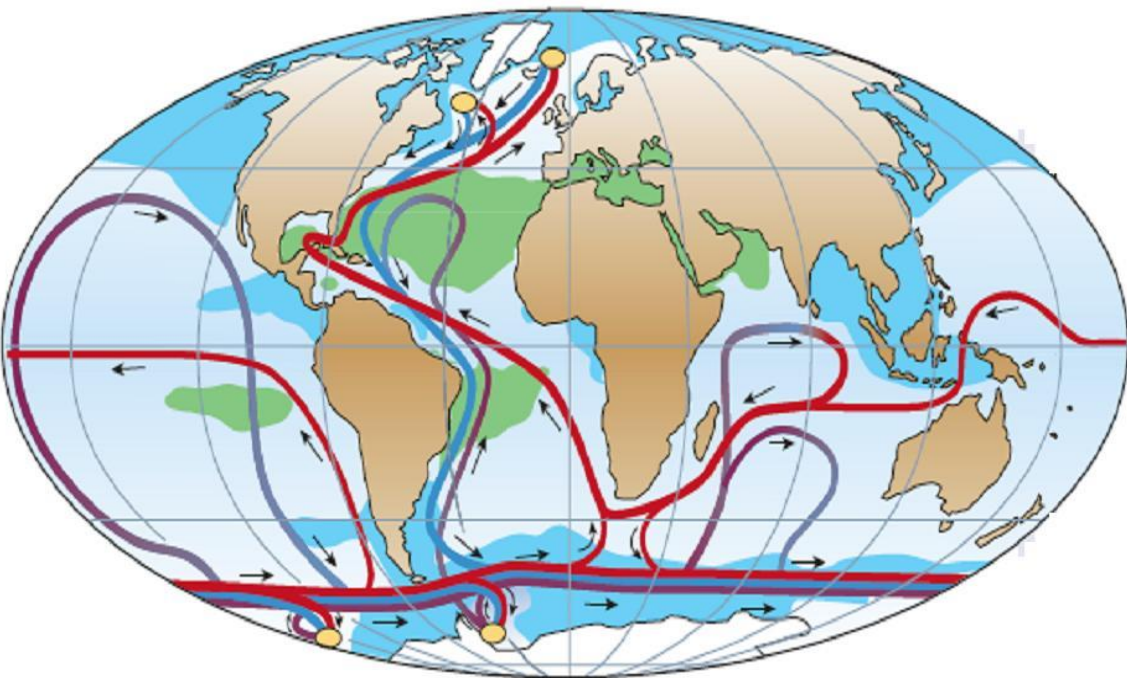
Didier Swingedouw, Amen Al-Yaari, Valentin Portmann...



Meridional overturning circulations (MOC)



Present-day large scale ocean circulation



Effect of a substantial (>50%) Atlantic MOC weakening



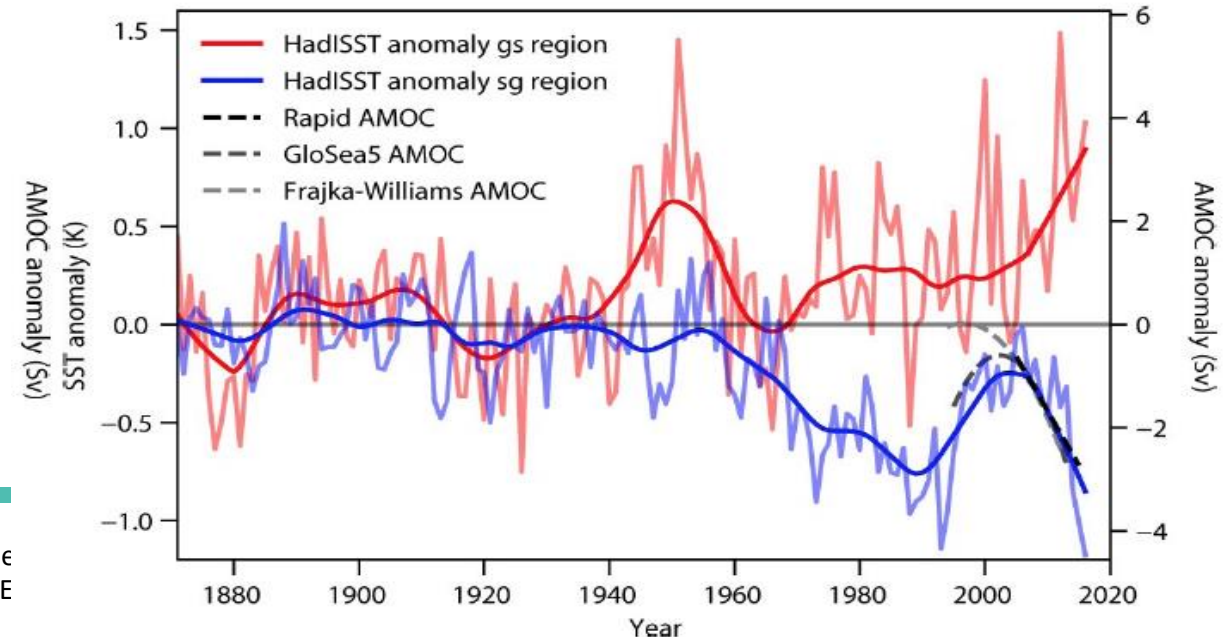
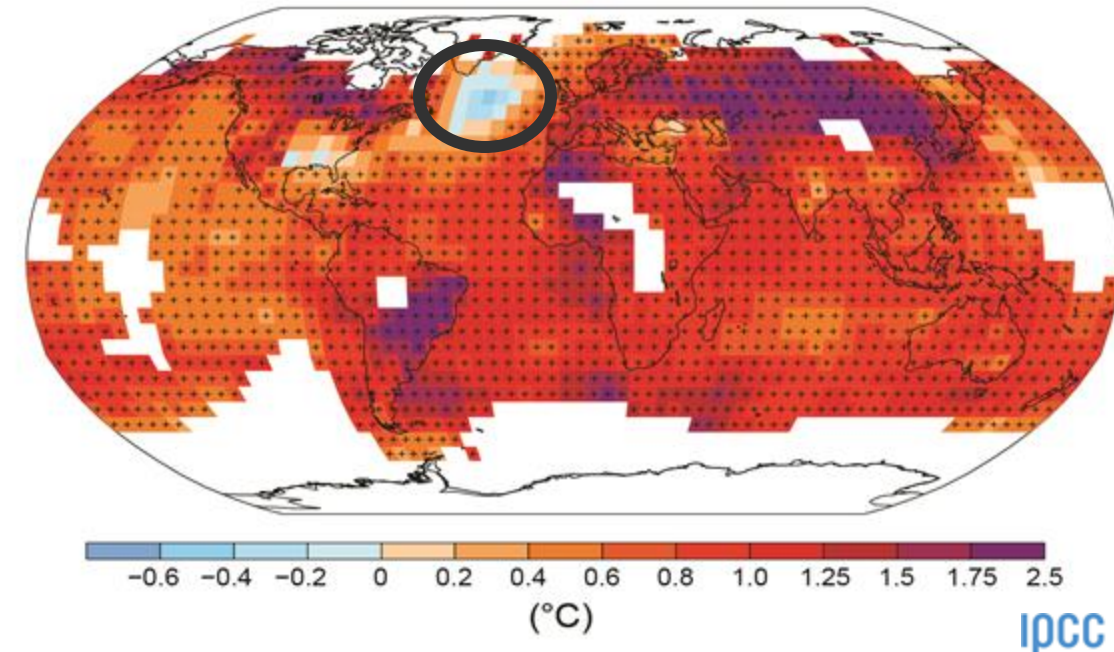
Physical system	Biological system	Human and managed systems	Direction of the change	Confidence in process understanding
<ul style="list-style-type: none"> Droughts Temperature trend Sea level rise Cyclones frequency Sea ice and snow Precipitation and flooding Storminess 	<ul style="list-style-type: none"> Vegetation Marine ecosystems Wetland methane Oxygenation Oceanic carbon and acidification 	<ul style="list-style-type: none"> Agriculture and food production Migration pressure due to degradation in livelihoods 	<ul style="list-style-type: none"> Increase Decrease 	<ul style="list-style-type: none"> High Medium Low

Rahmstorf et al. 2002

Where are we now?

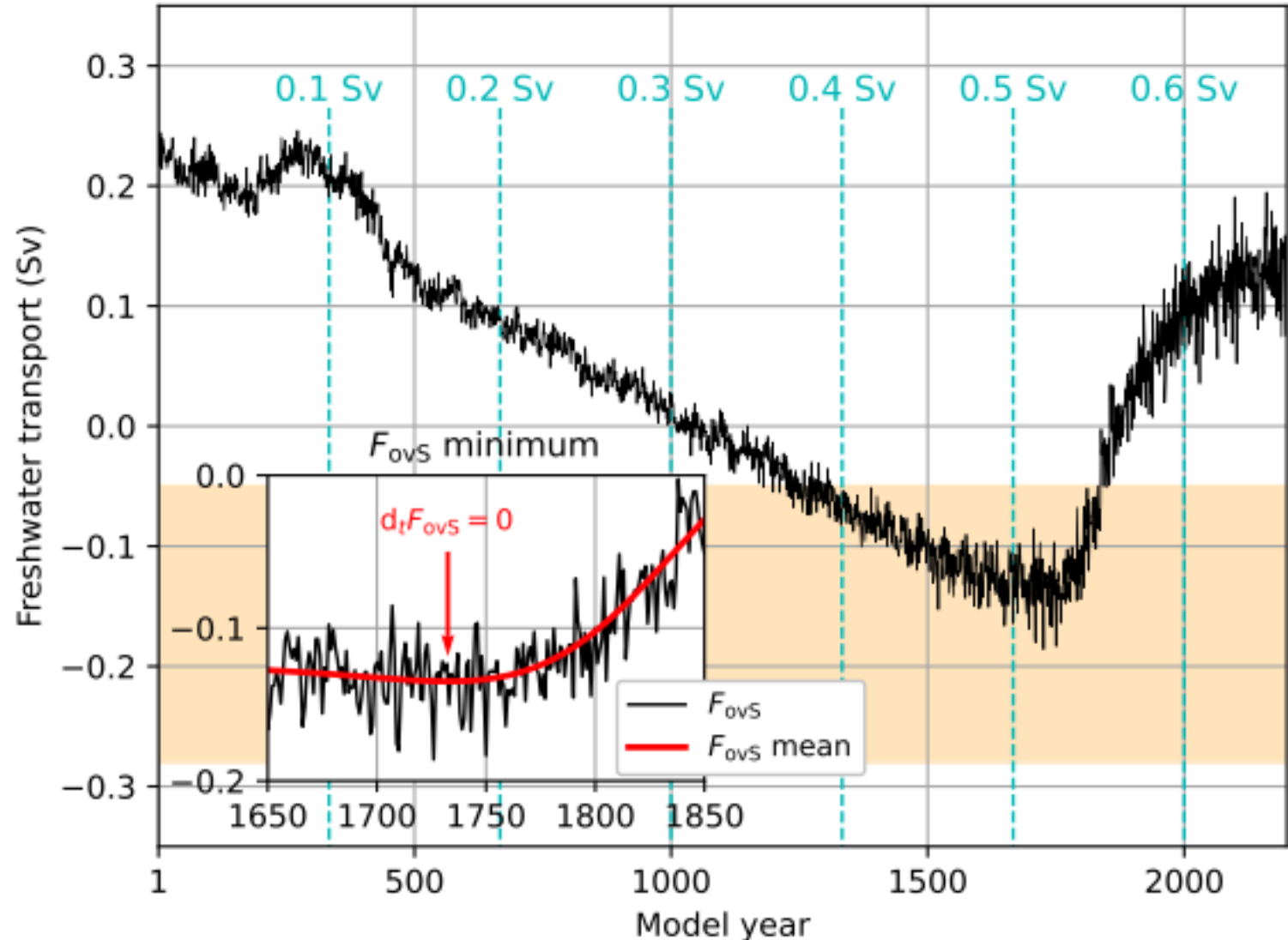
- There is an observed cooling and freshening of the subpolar gyre (SPG) over the last century (IPCC SROCC 2019)
- This could be a fingerprint of an on-going weakening of the Atlantic ocean circulation (by about 3 Sv or 15%, cf. Caesar et al. 2018)
- This is confirmed by other variables (e.g. SSS Zhu et al. 2023), but not all, so that this remains debated (e.g. Terhaar et al. 2024)

Observed change in surface temperature 1901–2012



Proximity to a collapse threshold?

Salinity advection by the overturning at 34°S (F_{ov})



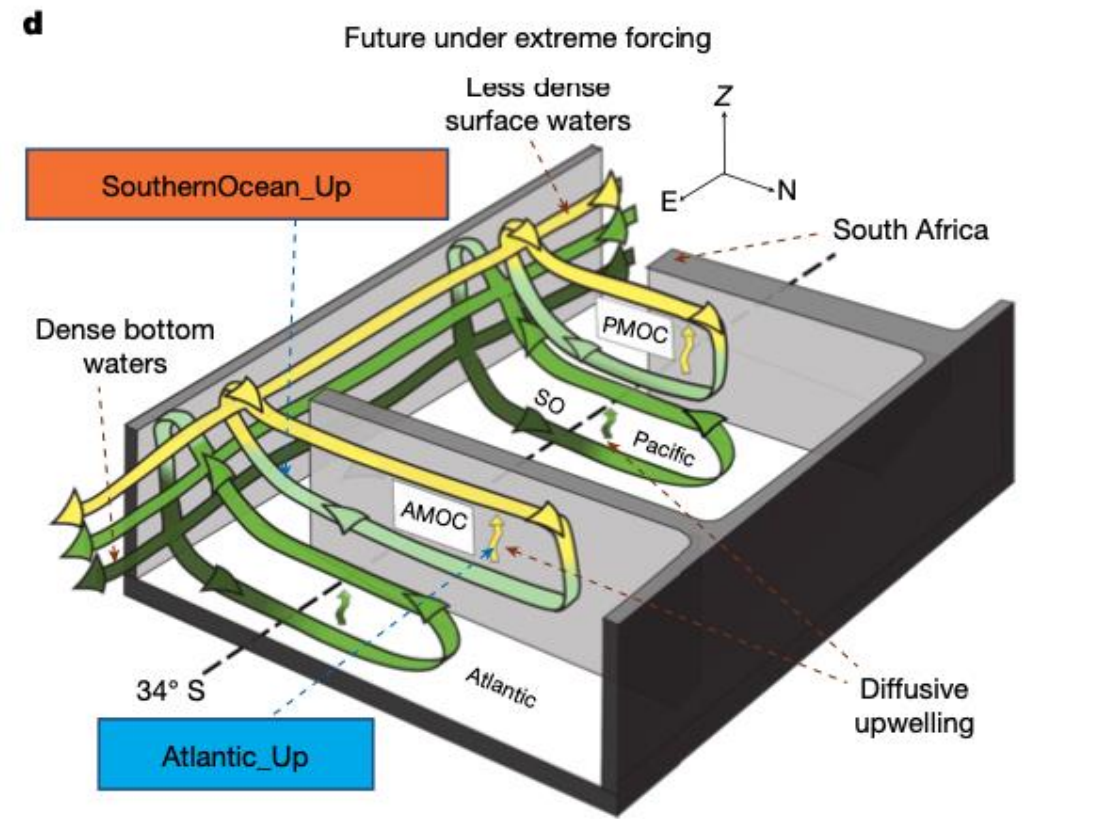
- Since pioneering work from Henry **Stommel (1961)**, it has been confirmed in various type of models that the AMOC might be bistable
- How close are we from a potential tipping point threshold remain unclear due to model diversity (e.g. **Jackson et al. 2023**)

AMOC collapse in future?

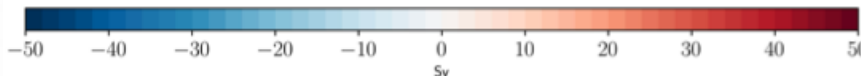
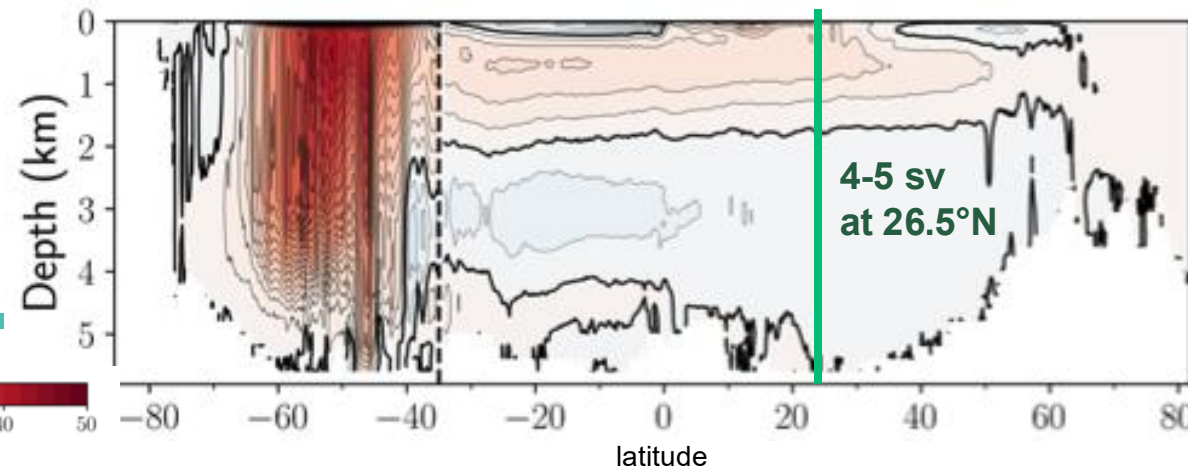
- “it does not collapse in the model experiments considered here. Instead, the AMOC levels off at a weaker strength that varies widely across models” (Baker et al. 2025)
- The key new question might not be “is the AMOC will collapse?”

but

- “by how much and how fast will the AMOC be reduced in the coming centuries”?



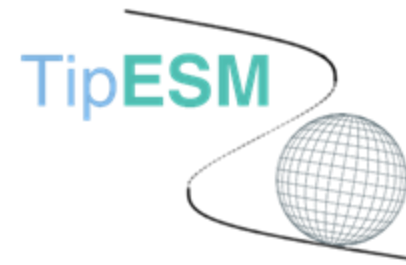
AMOC streamfunction in HadGEM3-GC31-MM at 4xCO₂



Two crucial questions

1. What can explain any recent AMOC changes?
2. What will be the rate of future AMOC weakening? (can we go beyond multi-model ensemble mean?)

Internal variability of the AMOC

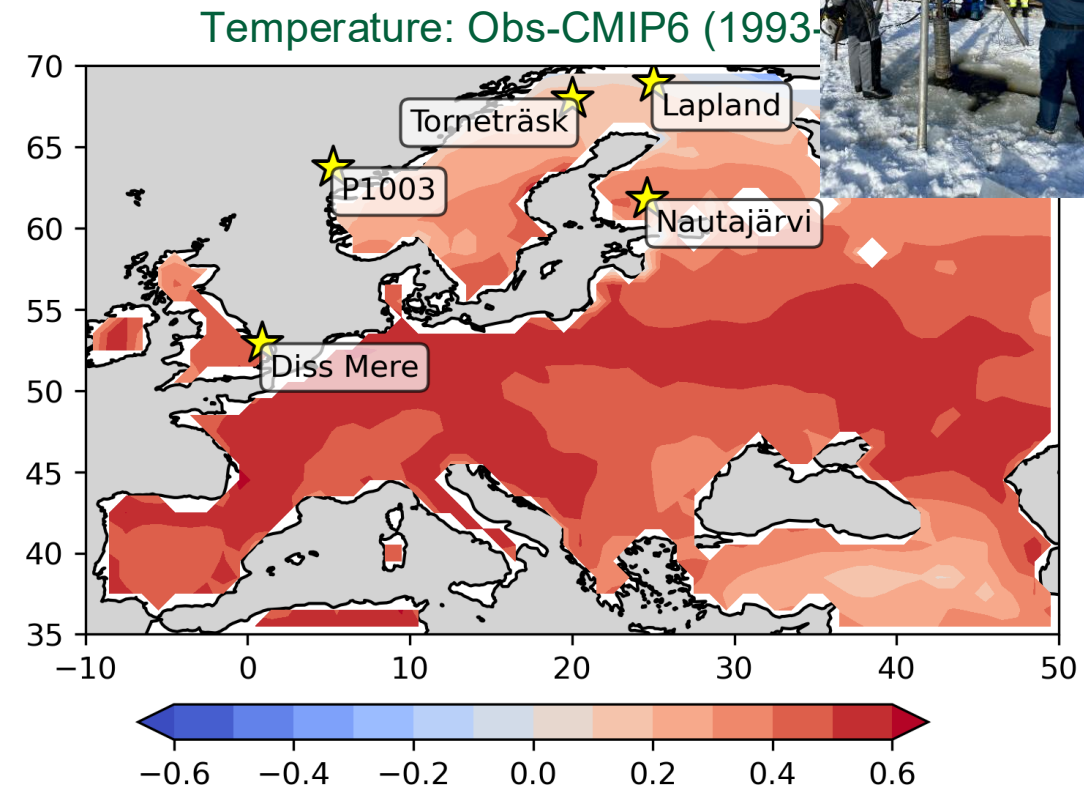


- There are a few models showing multi-centennial variability in the AMOC ([Mehling et al. 2024](#))
- The question of the realism of such a variability mode necessitates paleo-data
- Warming over Europe is larger than simulated ([Van Oldenborgh et al. 2009](#))

Materials and methods

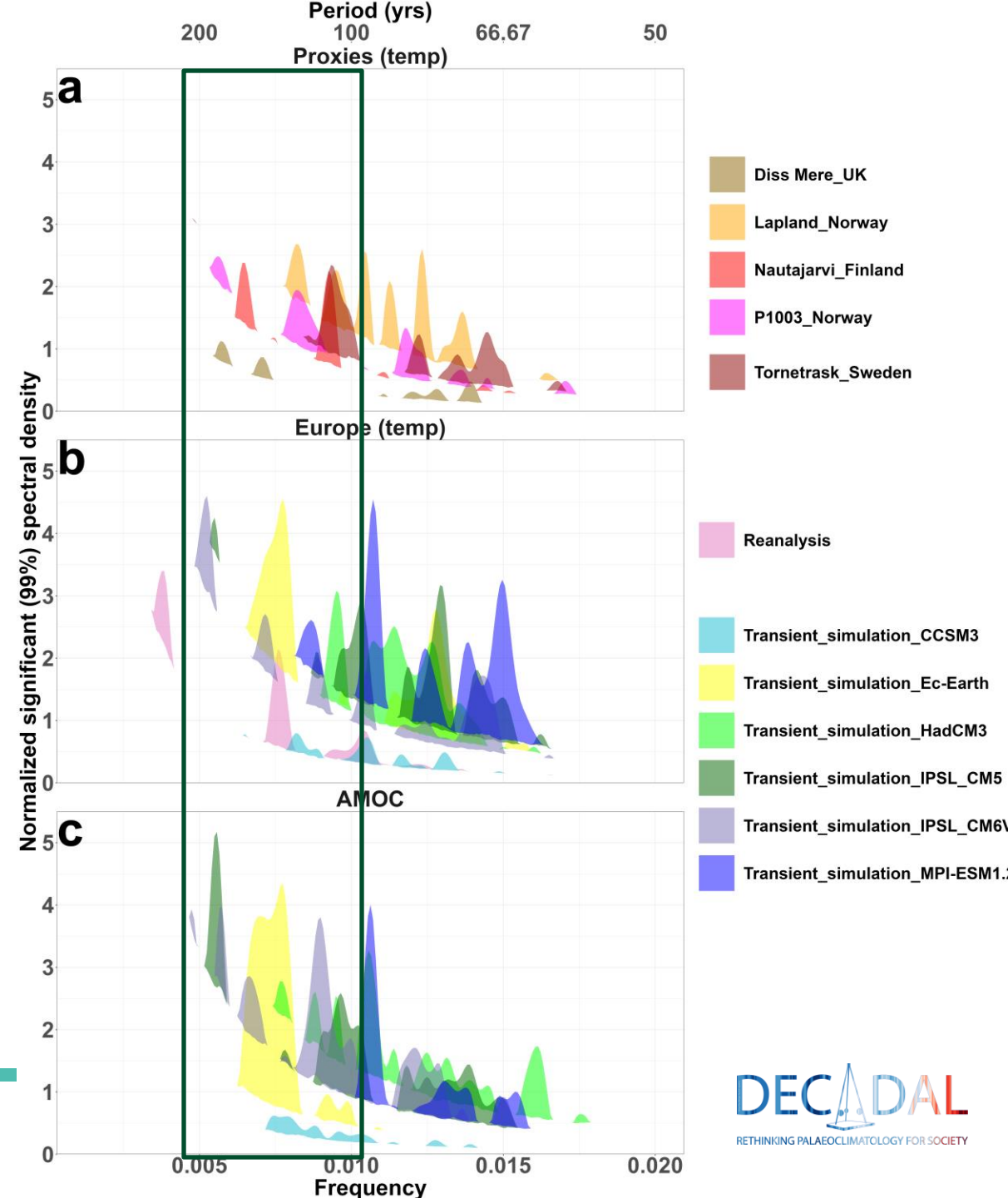
We use the few high resolution reconstructions available

- Varved sediments over Europe (annual resolution)
- Reanalysis over the Holocene ([Erbe et al. 2022](#))
- Various transient simulations from CMIP models



Multi-centennial variability over the Holocene

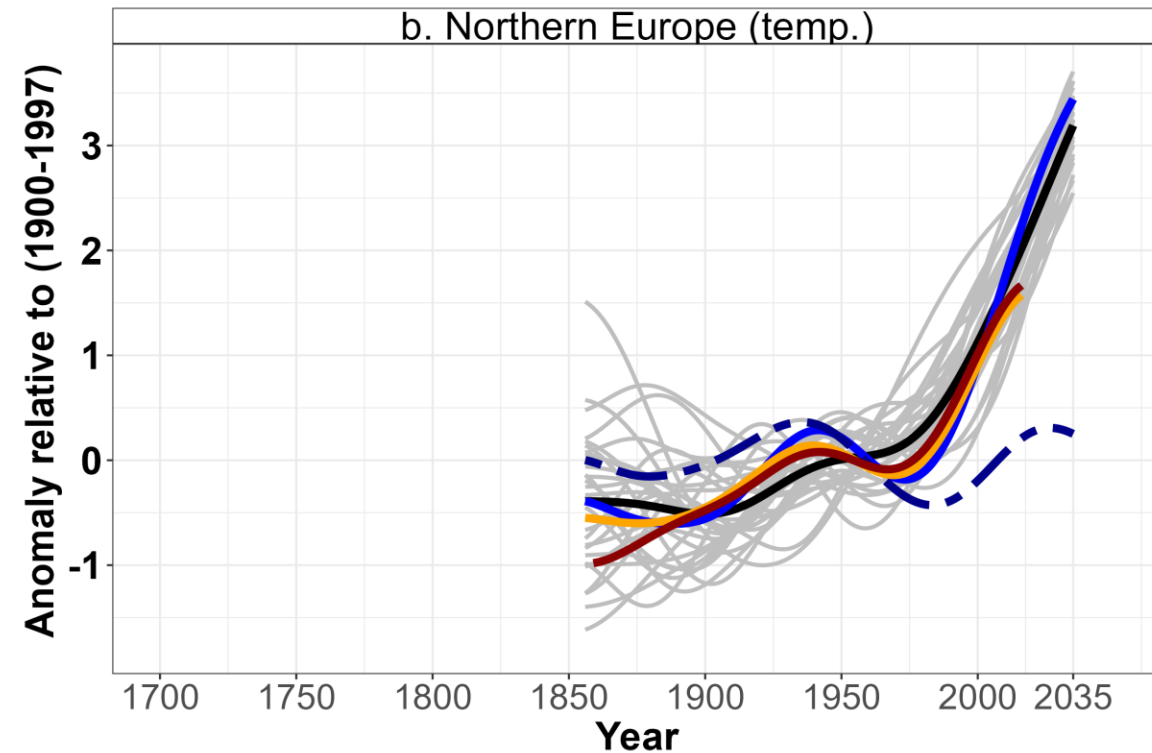
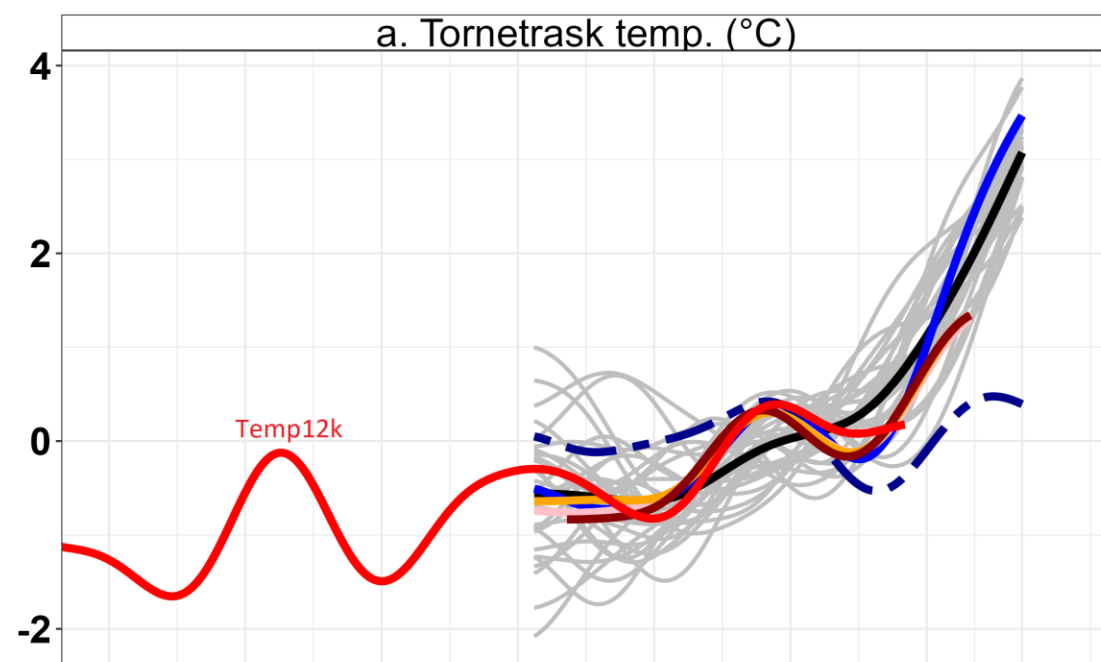
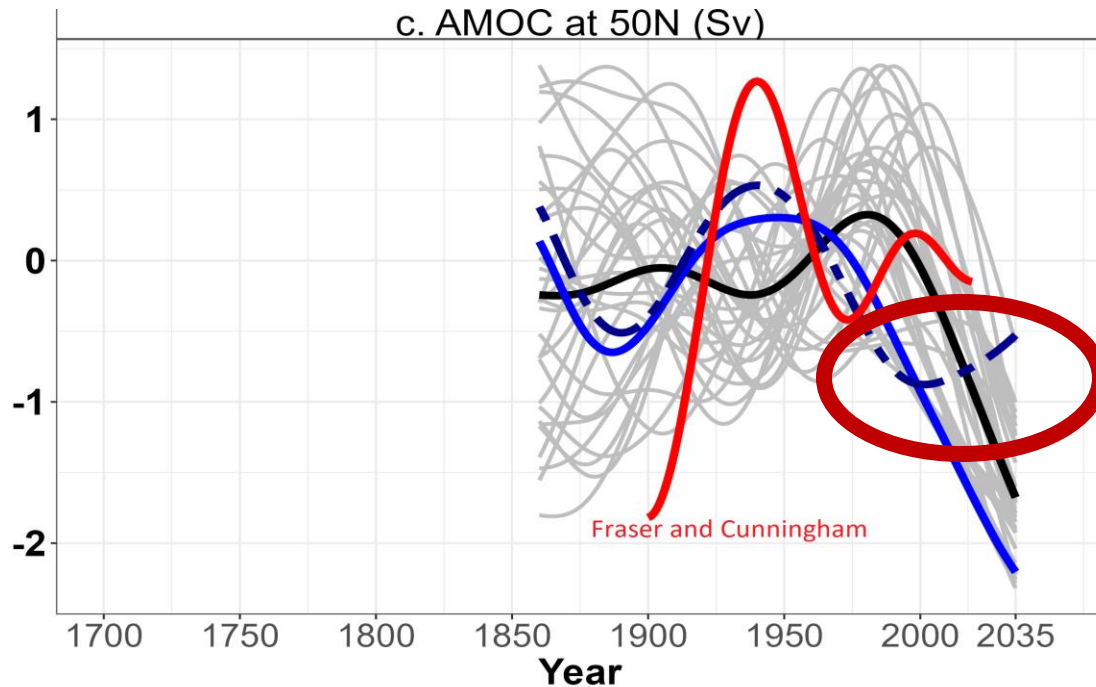
- Variability at the **multi-centennial time scale** can be found both in proxy records, reanalysis and transient simulations over the last 6 ka.
- It seems to be closely linked with a multi-centennial **variability mode of the AMOC** in a number of models related to Arctic-North Atlantic interactions ([Jiang et al. 2021](#))



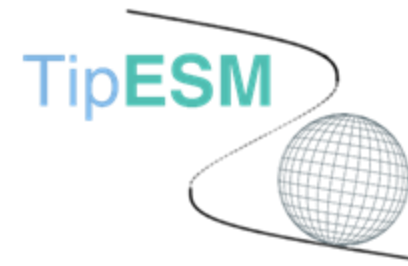
Phase of the multi-centennial variability over the recent period?

- · - : Internal variability (member 8-forced)

- IPSL-EHS_members
- IPSL-EHS ensemble mean (forced signal)
- Member 8
- Internal variability (member8 - forced)
- Hadley Center (HadCRUT5)
- Berkeley earth surface temp. (BEST)
- Dyn. consistent ens. of temp. (DCENT)
- Reconstruction



Contribution to the recent and coming warming (2000-2035 trend)

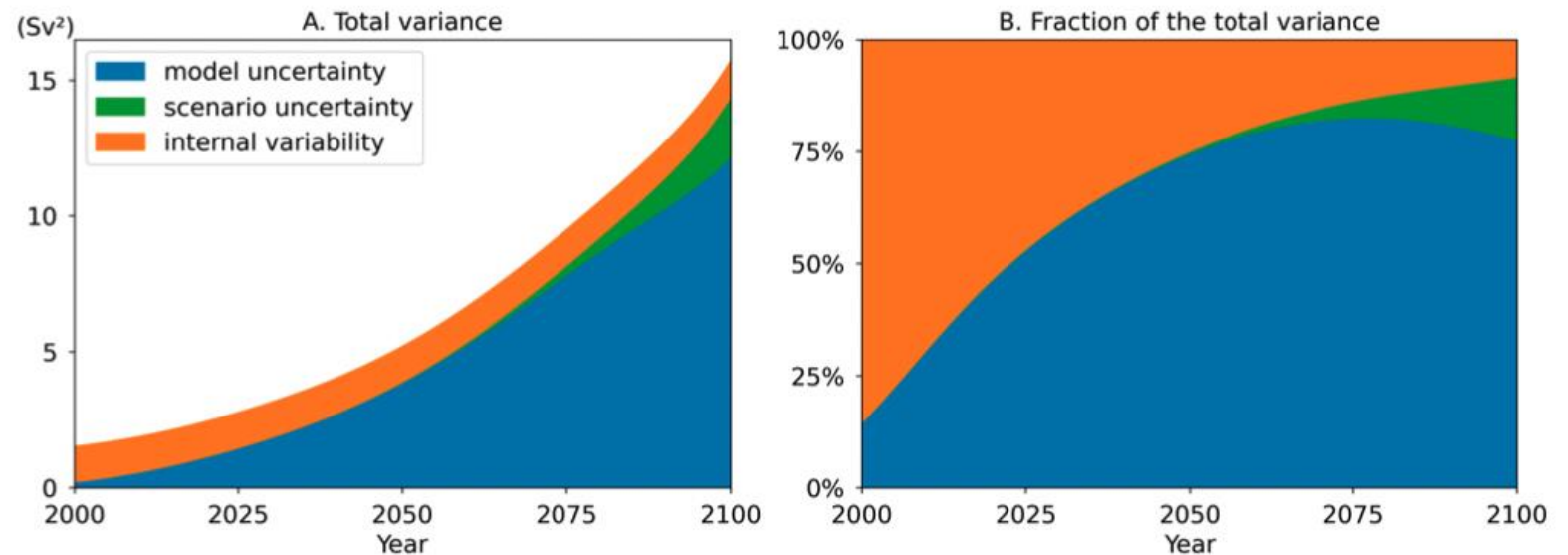
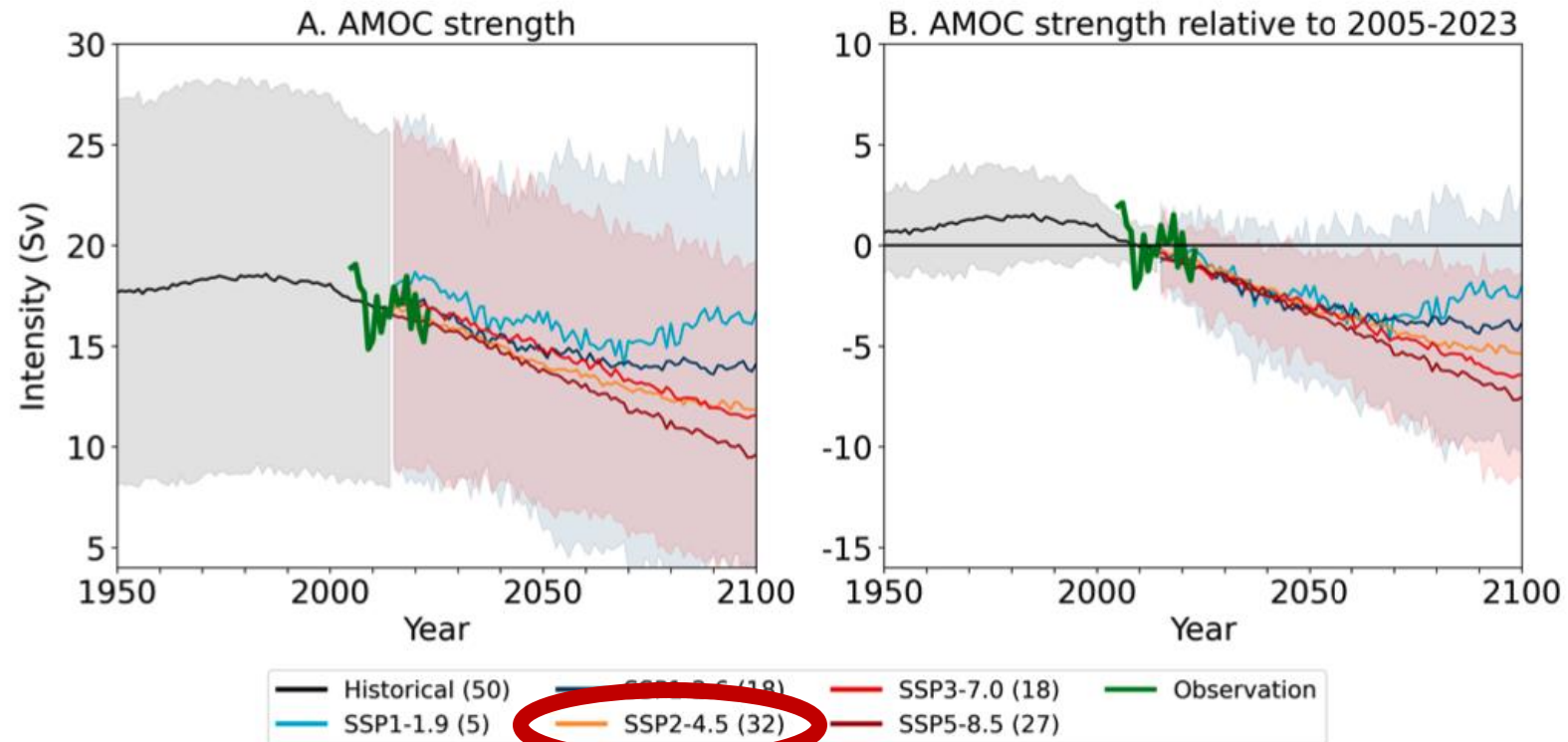


Rate of increase (2000-2035 in °C/decade)	Lapland	Northern Europe	Europe	Global
Forced	0.54*	0.57*	0.48*	0.44*
Internal	0.20	0.33*	0.28*	0.13*
Internal constrained by observations	0.20	0.30	0.24	0.12
Increase in the forced warming	37%	53%	50%	27%

AMOC Projections

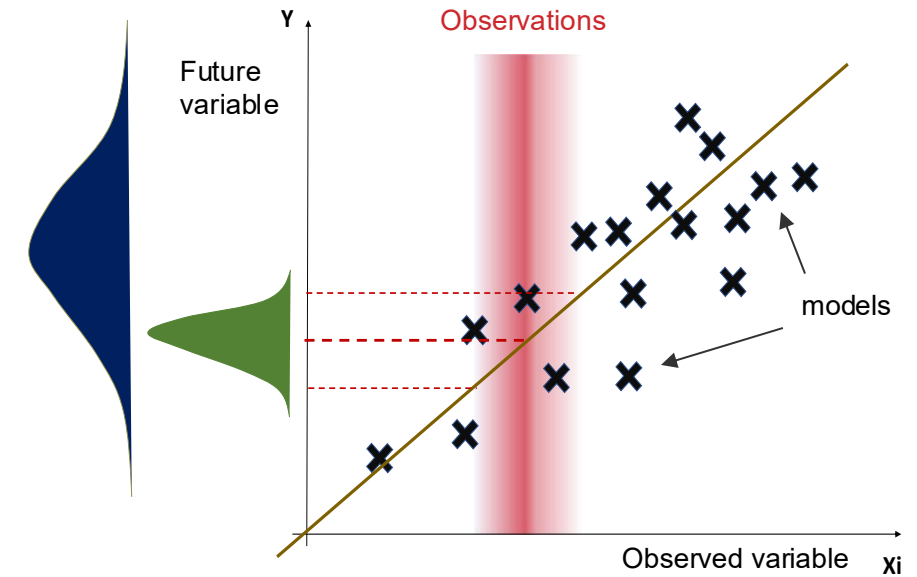
- CMIP6 models suggest a **$32 \pm 37\%$ (90% probability)** reduction in AMOC strength by 2100 (SSP2-4.5 scenario, **3 to 72%** depending on the model!)

- This large uncertainty is dominated by internal variability at the decadal scale and **model uncertainty** for the end of the century

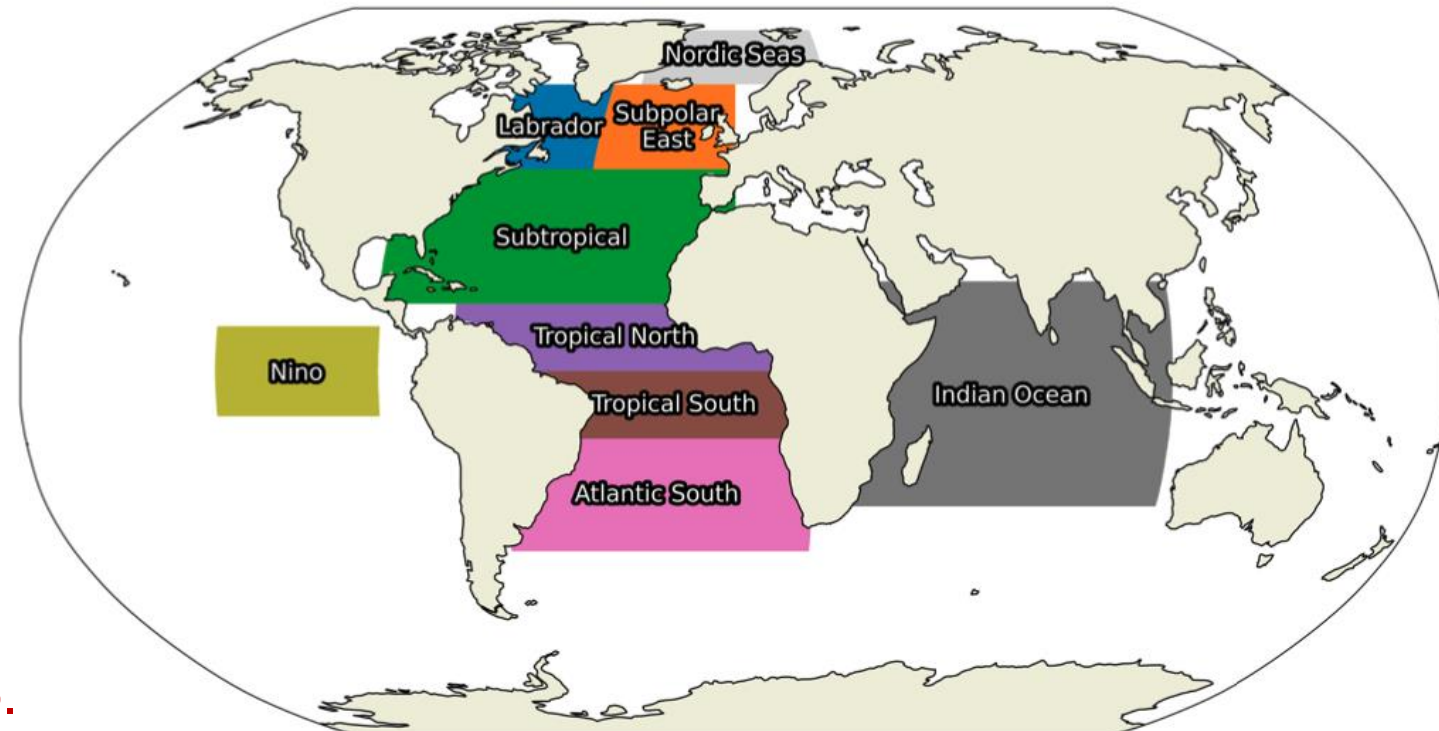


Observational constraints

- Use of 4 methods of observational constraint approaches
 - Weighted average
 - Random forest
 - Linear regression
 - Ridge regression
- Use of one variable (mean AMOC) or **multiple variables** to explain the spread
- Check robustness of the methods using leave-one-out method

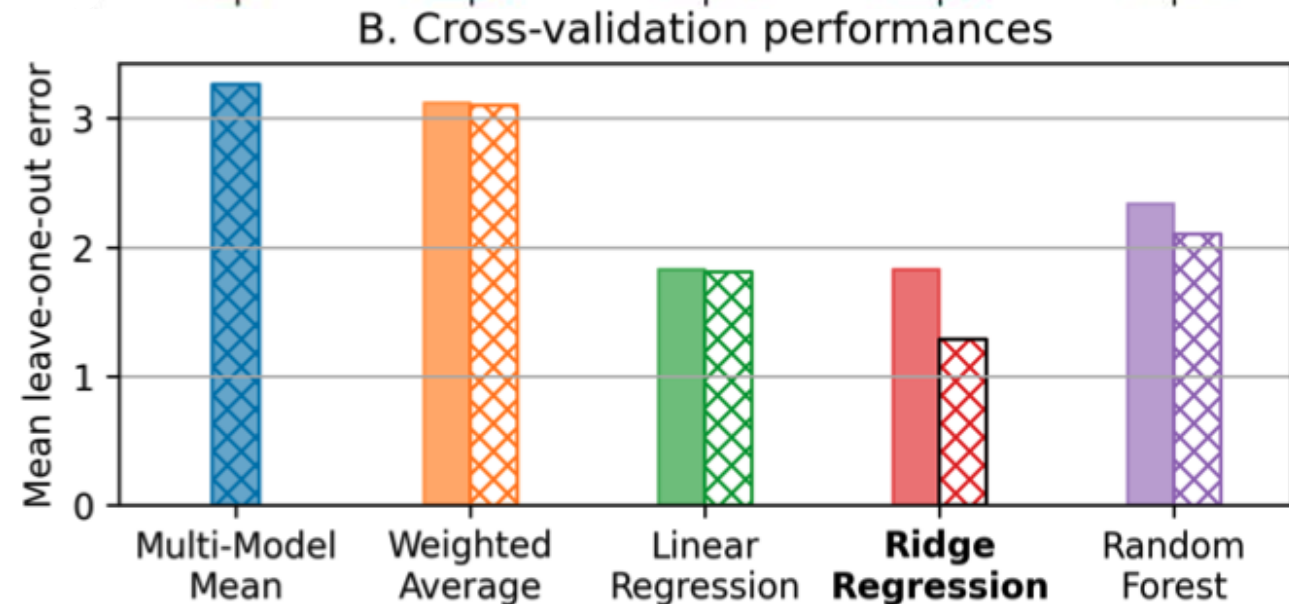
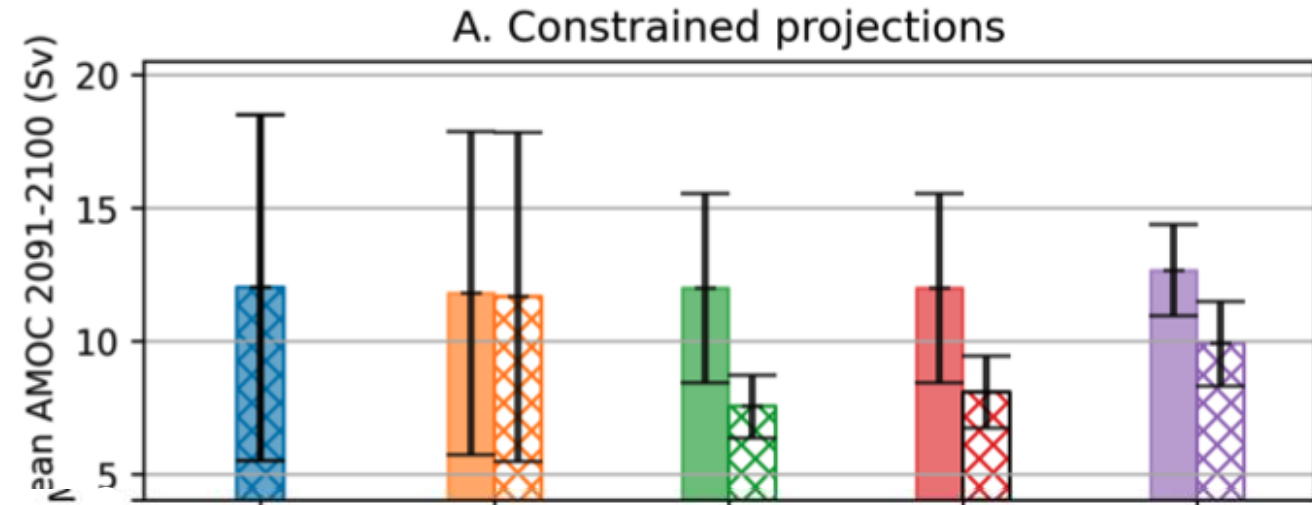
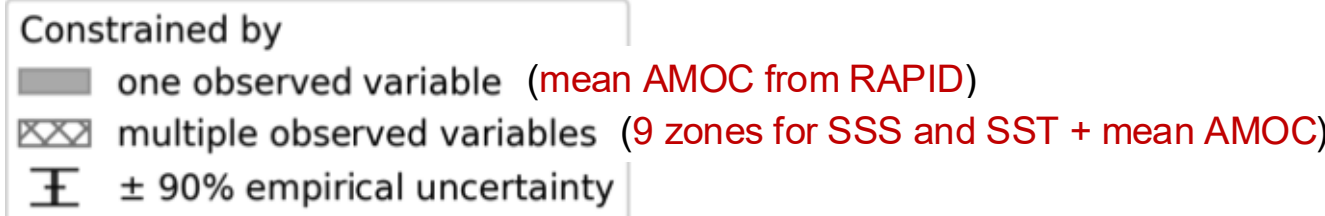


Chosen regions in SSS and SST as predictors of the AMOC spread

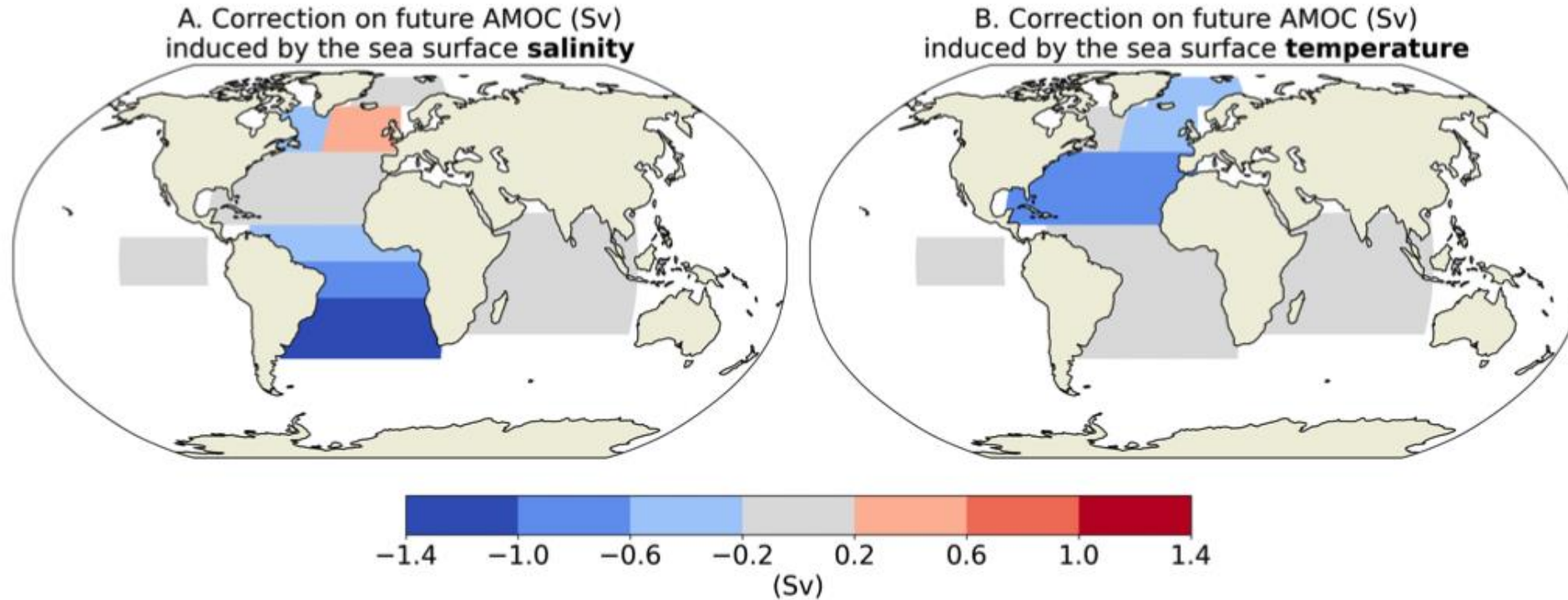


AMOC future

- Constraining by multiple variables is leading to weaker future AMOC
- The best method in terms of leave-one-out is **the ridge regression with multiple predictor variables**
- It provides a guess of the AMOC slowdown of **$54 \pm 8\%$** (90% probability), i.e. a **70% stronger weakening** than the multi-model mean



Main factors explaining the change in the mean



$$\hat{f}(x_0) = \hat{\mu}_Y - \hat{\beta}^T (\hat{\mu}_X - x_0)$$

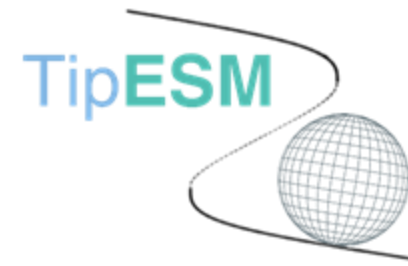
Observation-constrained estimate

Multi-Model Mean

Regression coefficient

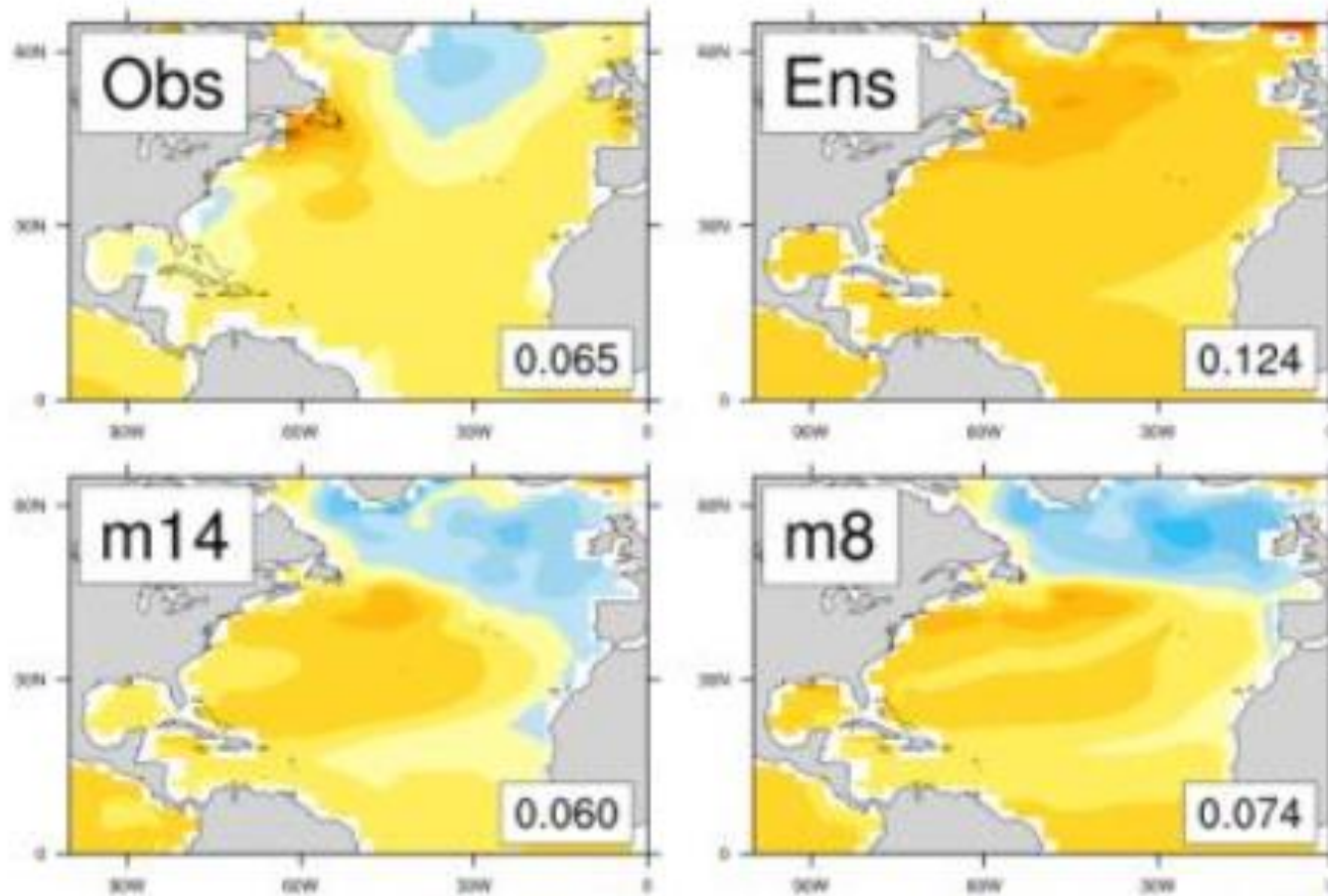
(mean bias)

Conclusions



- An internal **multi-centennial** variability mode of the AMOC might be able to explain **variability observed in the few high-resolution proxy** data available over Europe
- The phase of this variability is able to explain a potential **AMOC weakening in the second half of the 20th century**, as well as a recovery in the recent decades, **explaining the additional warming observed over Europe** compared to forced signal
- Multi-variate observational constraints suggest a potentially **larger AMOC weakening(70% more)** than suggested by simple ensemble mean of CMIP6 models
- This might be mainly related to **large SSS bias in the South Atlantic**, possibly related with a biased salt advection positive feedback at 34°S in models making **some models too stable** to perturbation

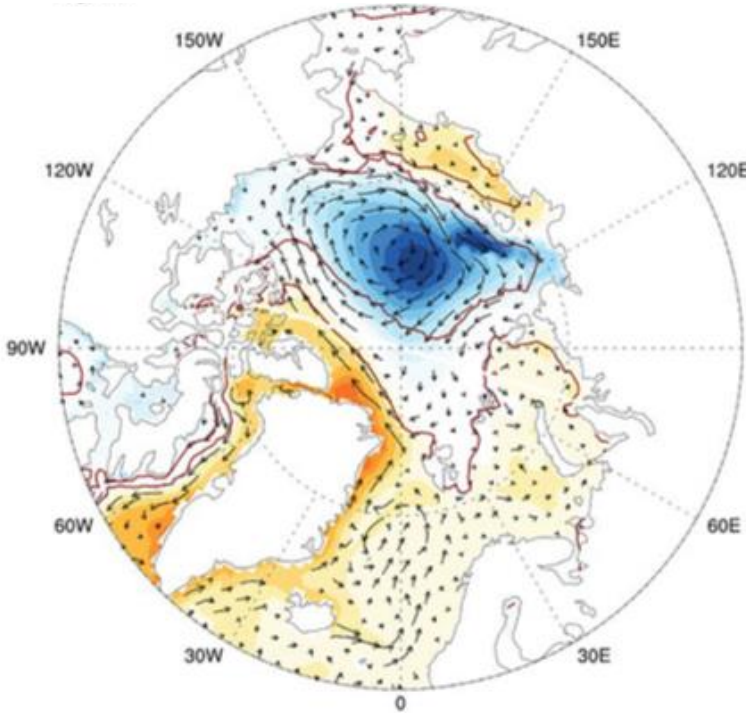
SST trends over the North Atlantic in the IPSL-EHS (K decade⁻¹) over the 1940–2018 period



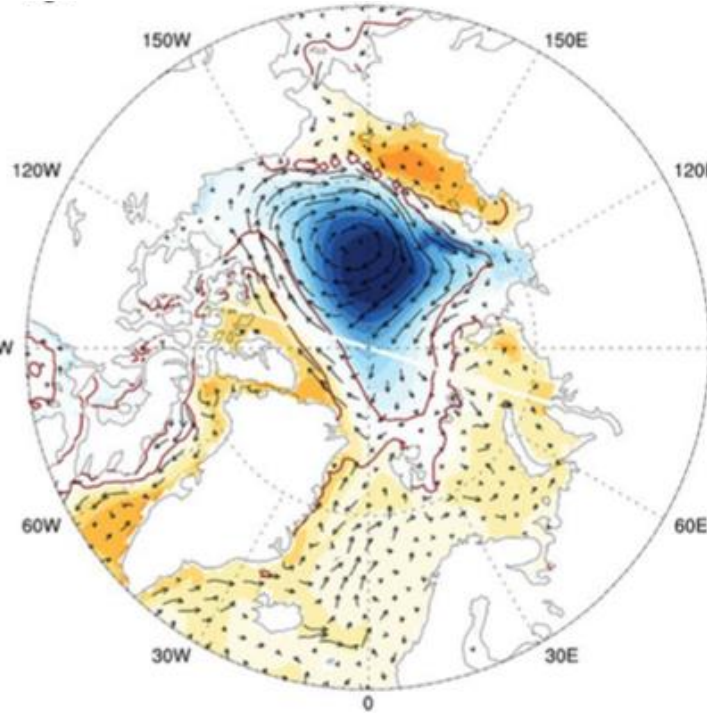
Link with observed freshening of the Arctic?

Regression of the SSS and currents over the AMOC in IPSL-CM6A-LR model (Jiang et al. 2021)

20 years before AMOC maximum



In phase with AMOC maximum



10 years after AMOC maximum

