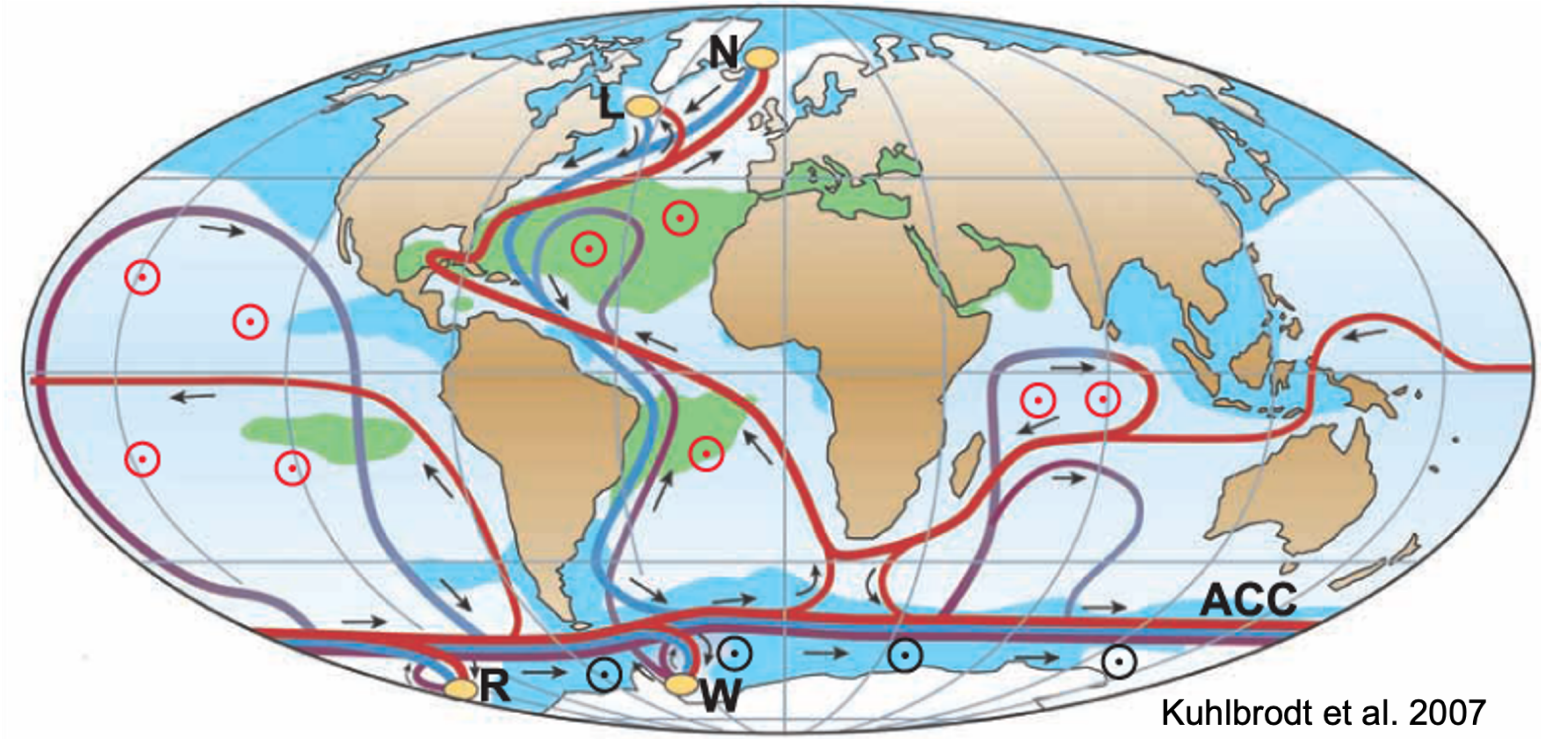
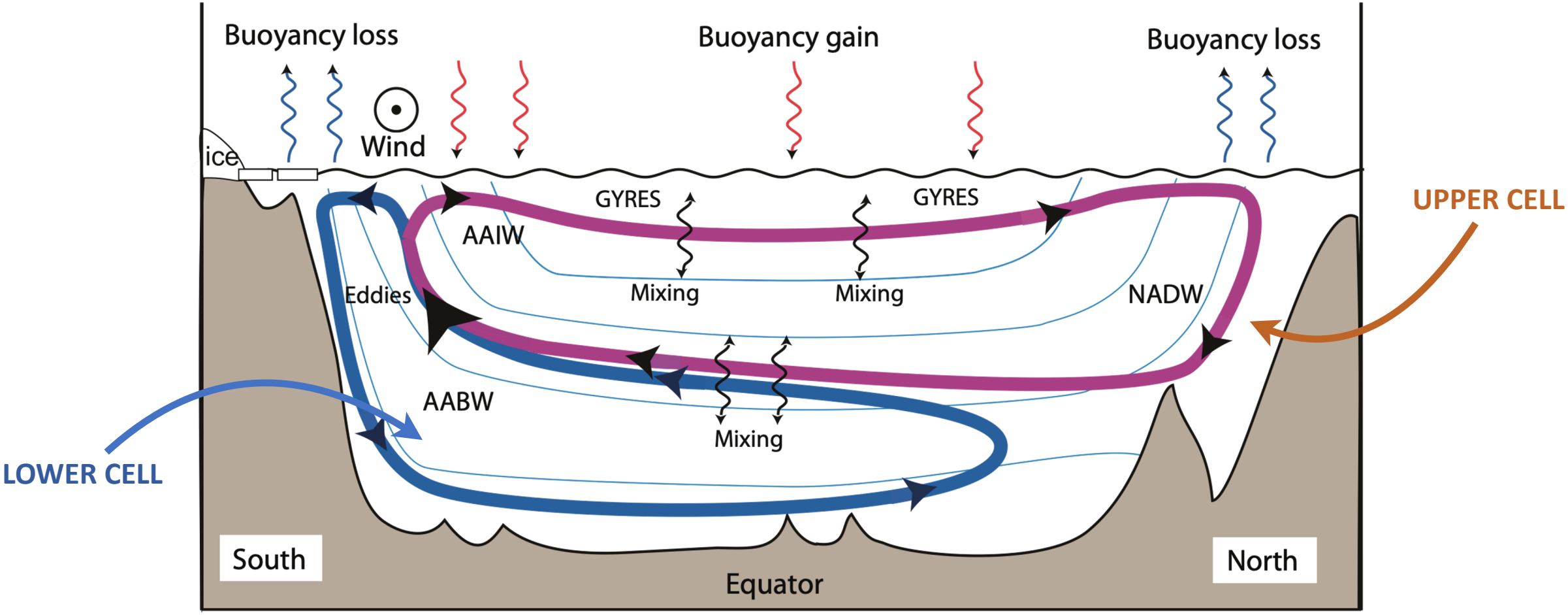
The Antarctic Ice Sheet and the AMOC: a '*what if*' story of interhemispheric transient responses

Riccardo Farneti & Zihan Song



First, some background: the AMOC

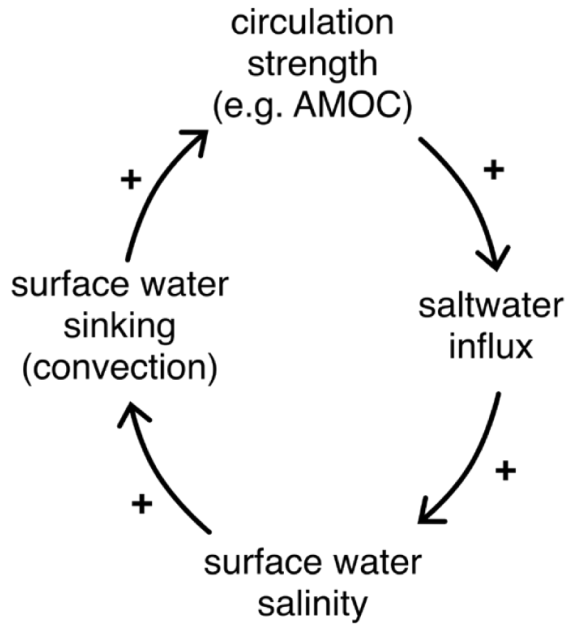


The Atlantic Meridional Overturning Circulation (AMOC)

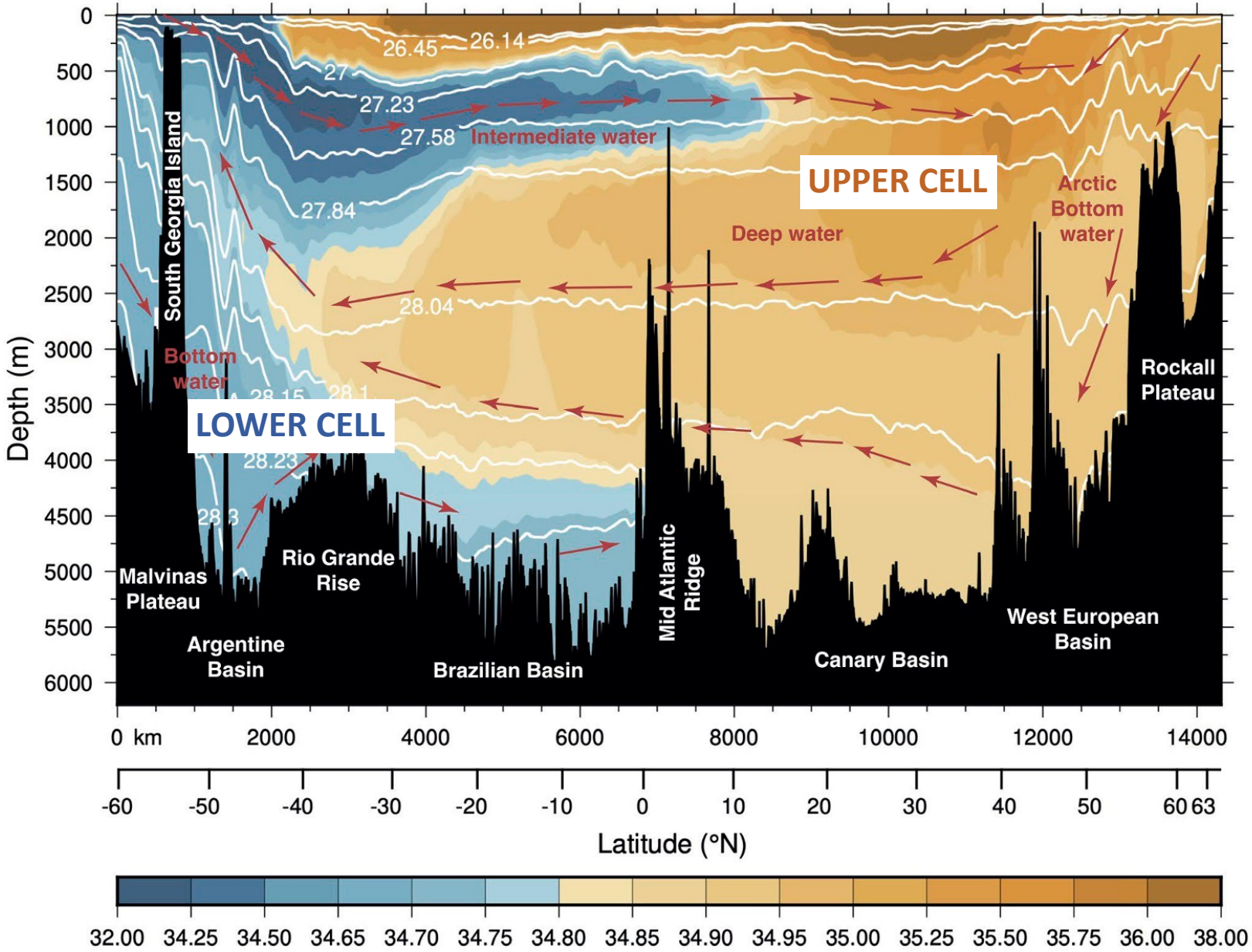
- It transports mass, heat, nutrients and regulates our climate
- It varies naturally on decadal and longer timescales
- It is also one of the main mechanisms for ocean heat and CO2 uptake

First, some background: the AMOC and Salinity

- You can trace both Upper Cell and Lower Cell through Salinity
- Salinity, as we will see, is crucial for the AMOC stability

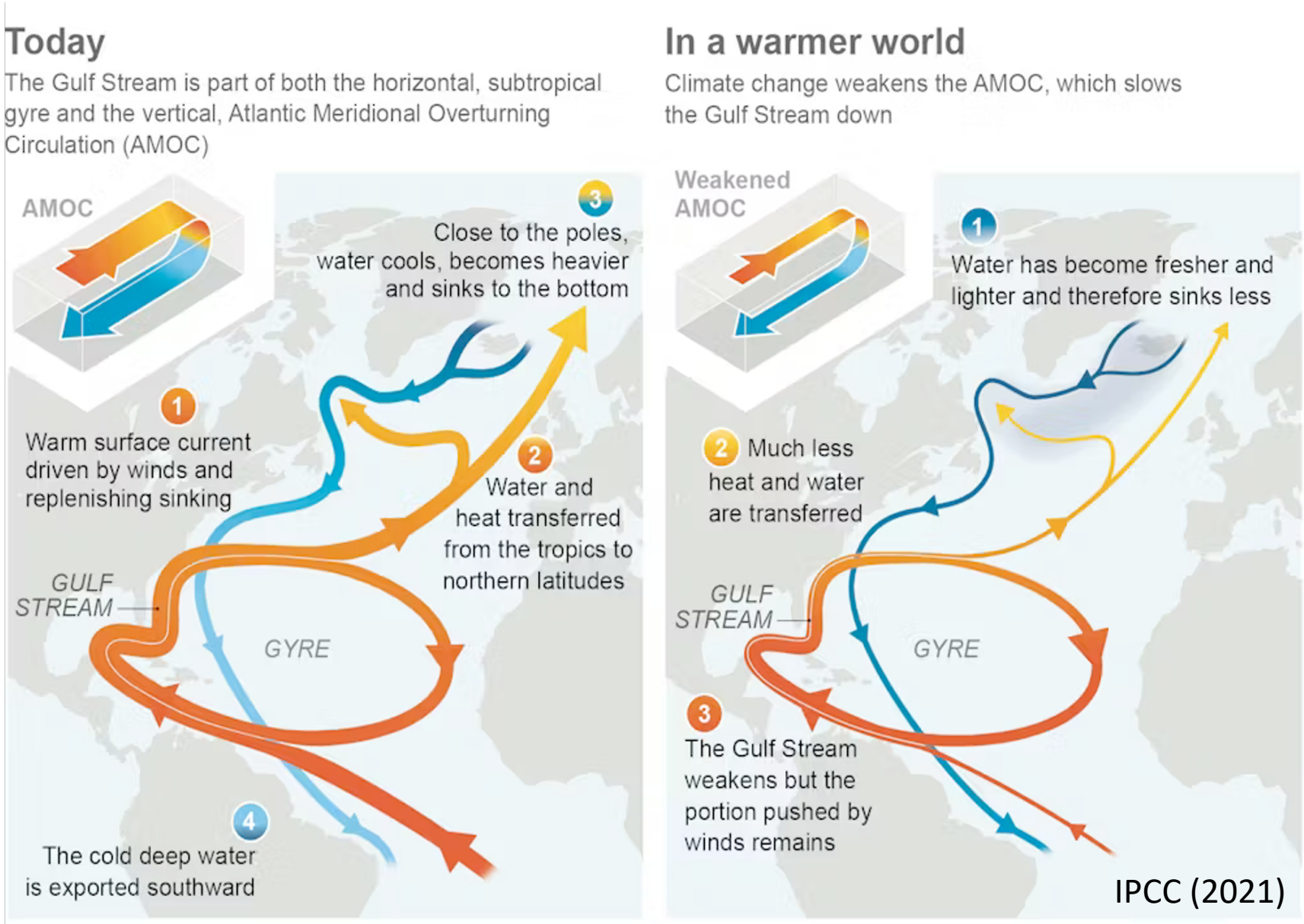


Salt-Advection feedback



First, some background: What will happen to the AMOC?

as the Climate warms
(and depending on possible future scenarios)
the AMOC is projected to weaken and, in some models and scenarios, collapse(?)

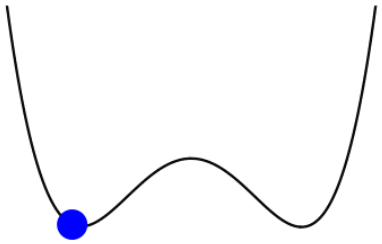


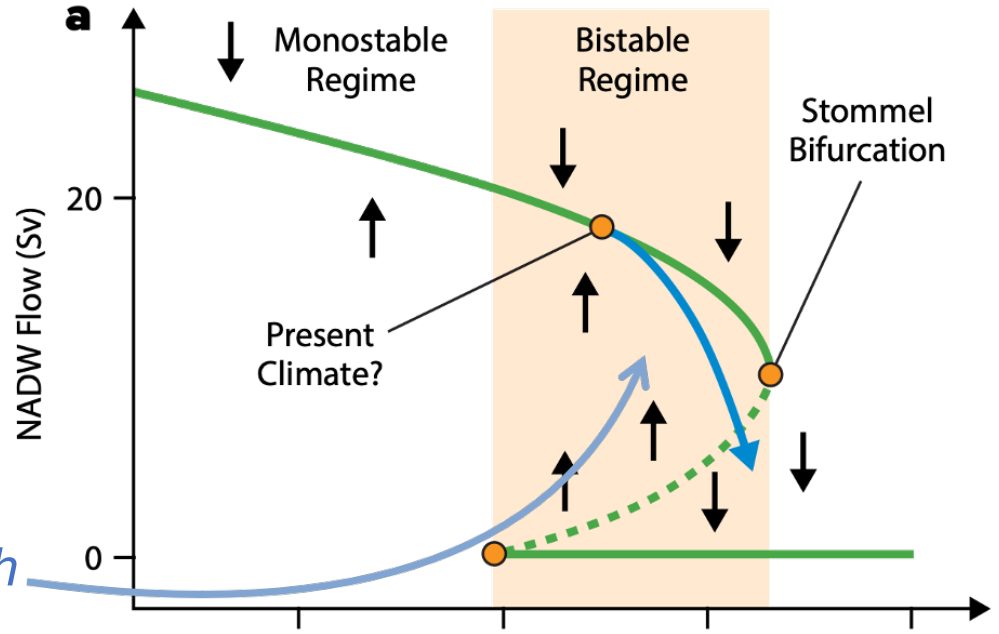
IPCC (2021)

First, some background: multiple equilibria

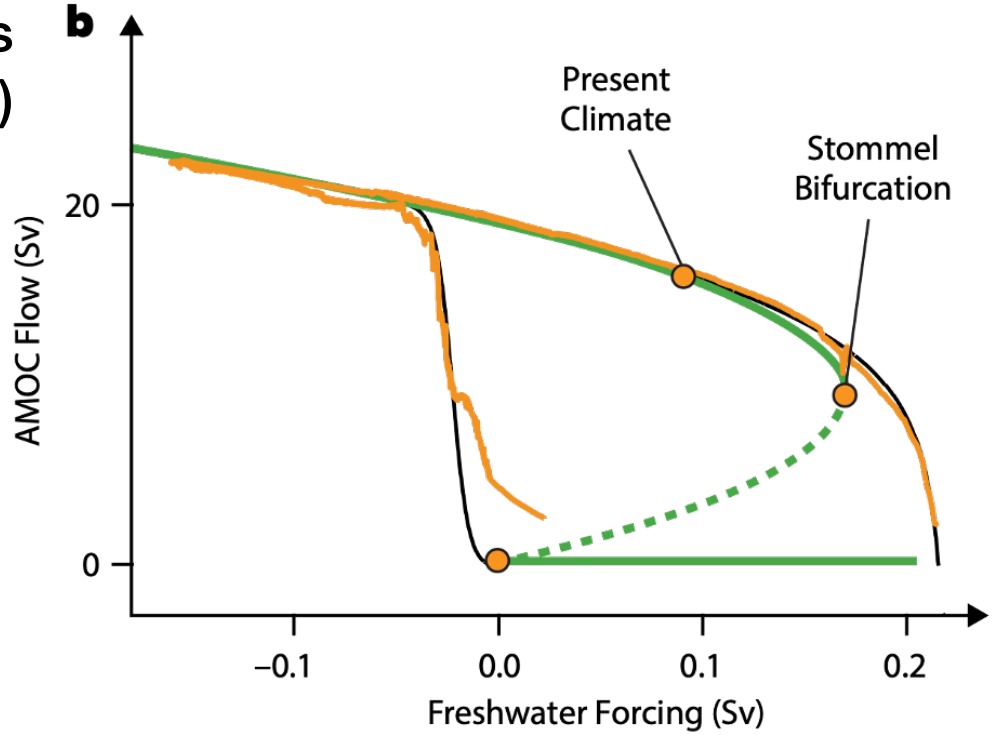
Theoretical Multiple equilibria and Hysteresis (*Stommel, 1961*)

A possible climate change path

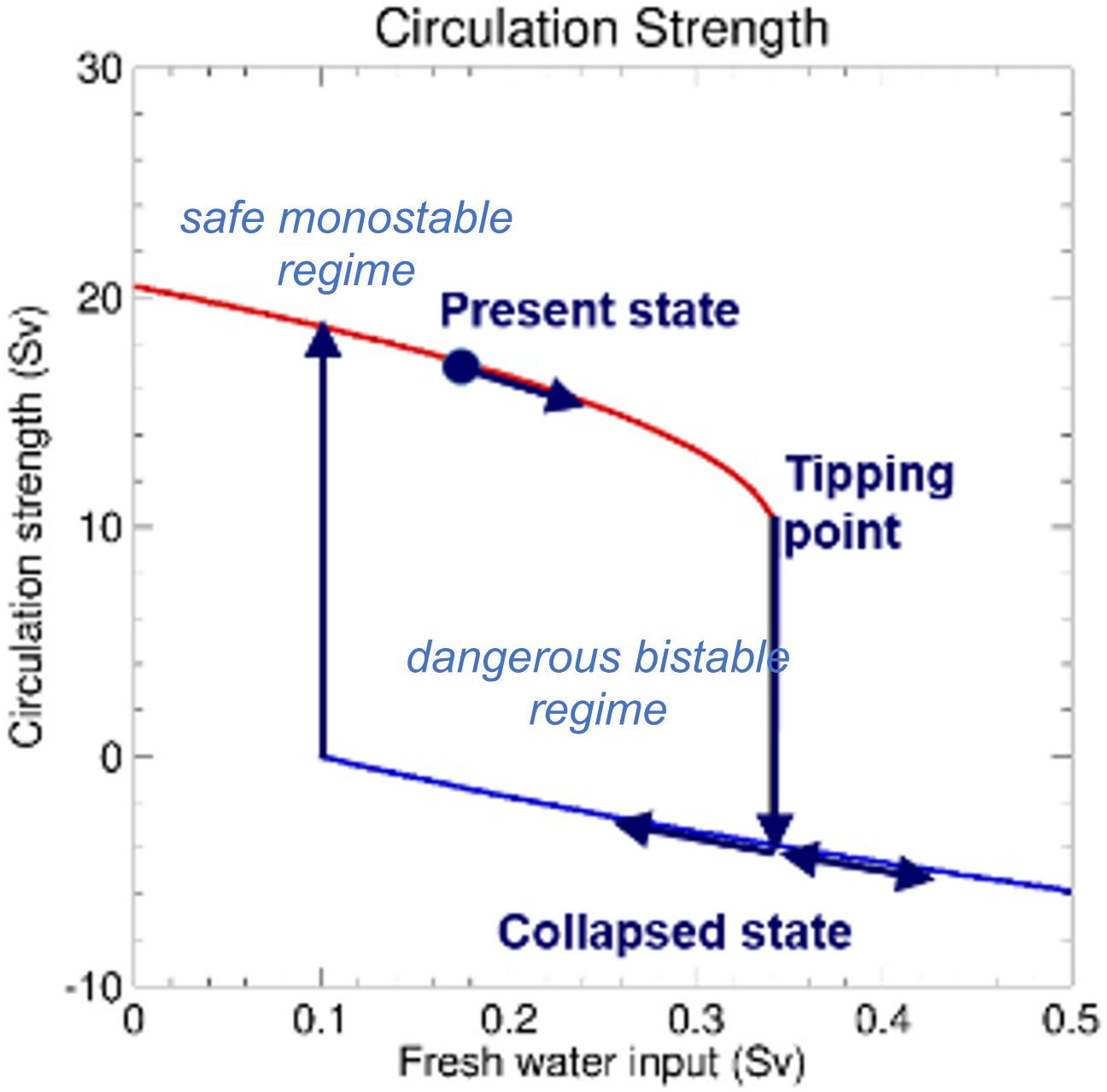




Simple and Complex models (*Rahmstorf, 1996*)



First, some background: and the question is '*where are we now*?'

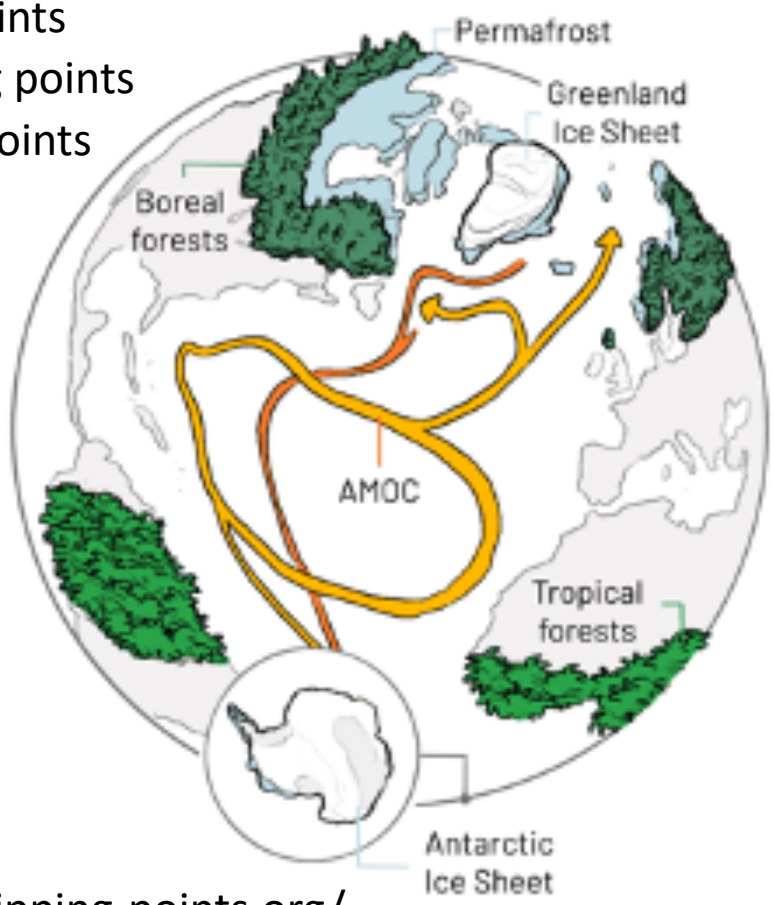


Tipping Points:

it happened in the past

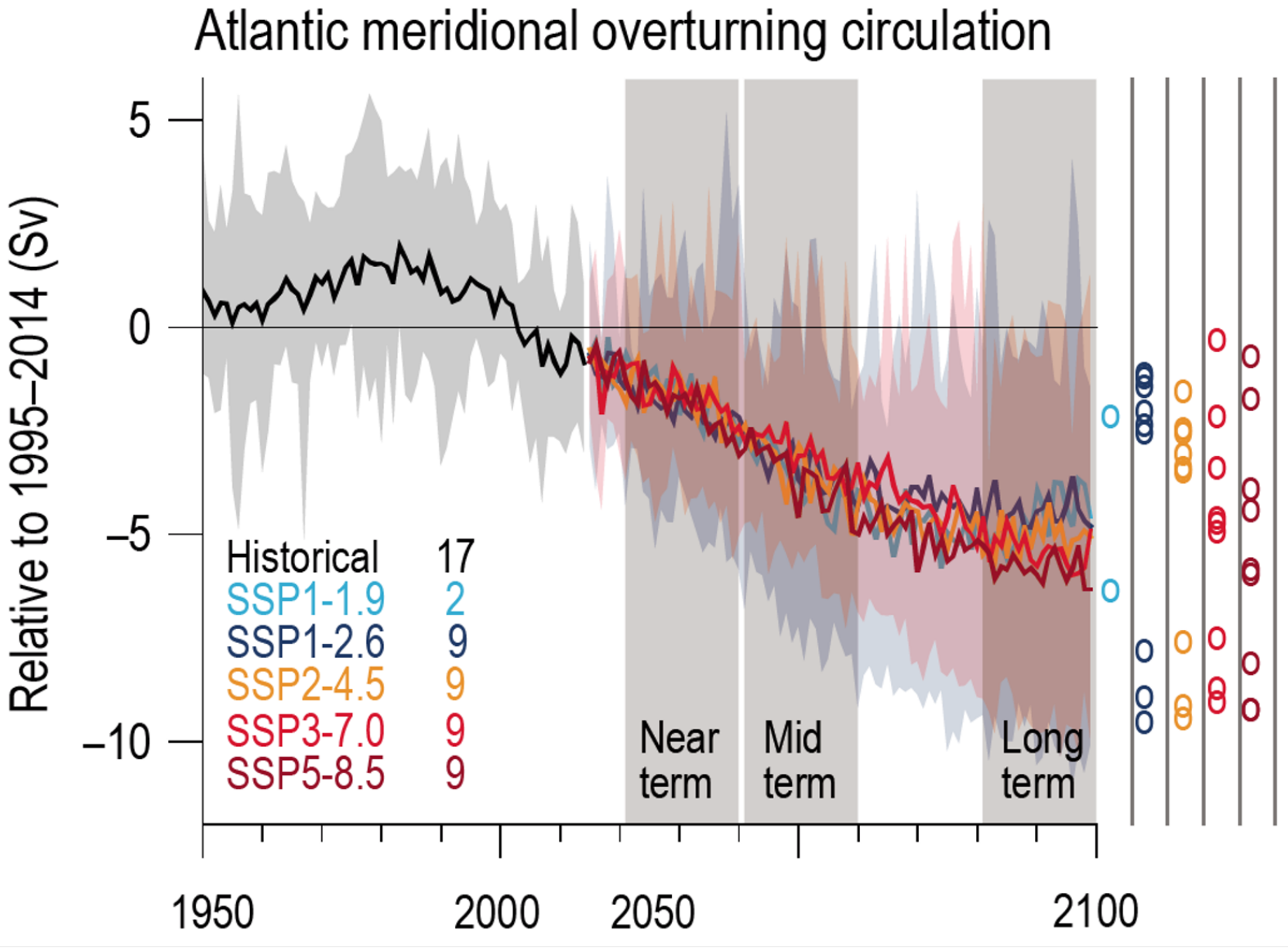
(Dansgaard-Oeschger and Heinrich events)

- Global Tipping points
- Cascading Tipping points
- Positive Tipping points



https://global-tipping-points.org/

First, some background: What do models say? and why we (probably) should not trust them



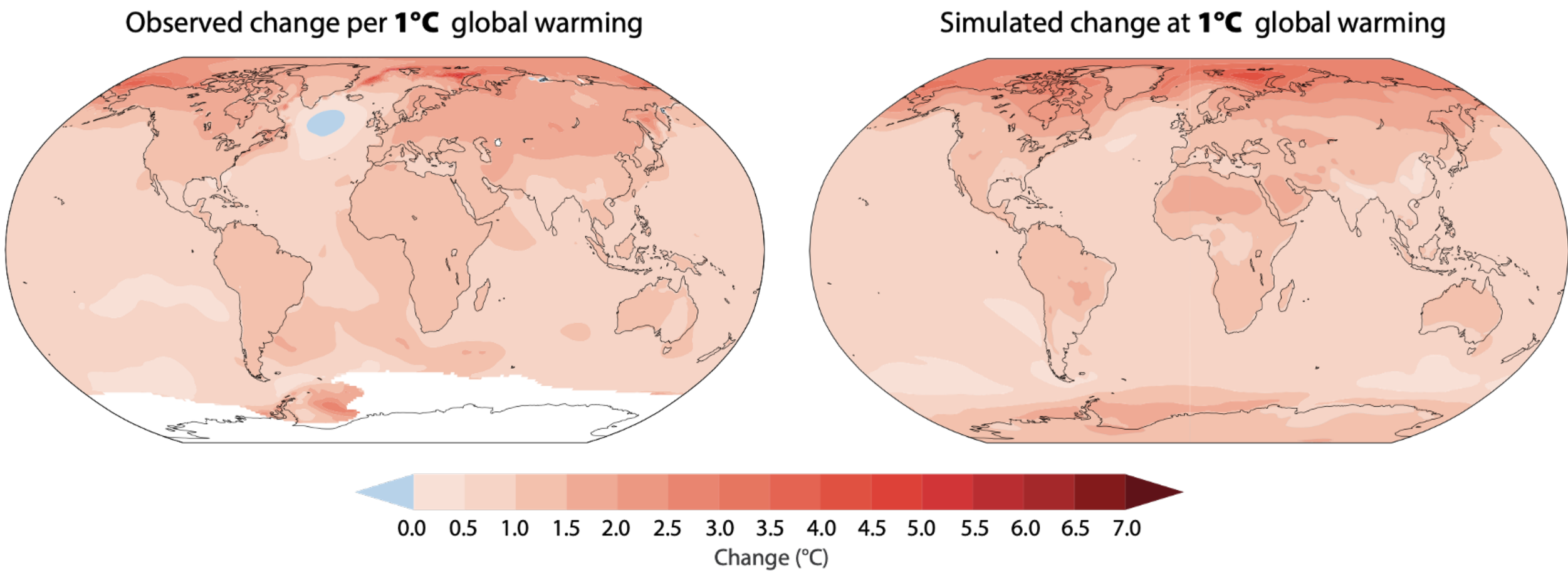
CMIP6 annual mean AMOC strength change in historical and scenario simulations

- In all scenarios, CMIP6 models project a modest weakening of the AMOC by the end of the century.
- In NH hosing experiments, the vast majority of models recover

HOWEVER:

- We know models might be '*too stable*' ($F_{ov} > 0$)
- We know models have large interior 'biases' anchoring them in the monostable regime

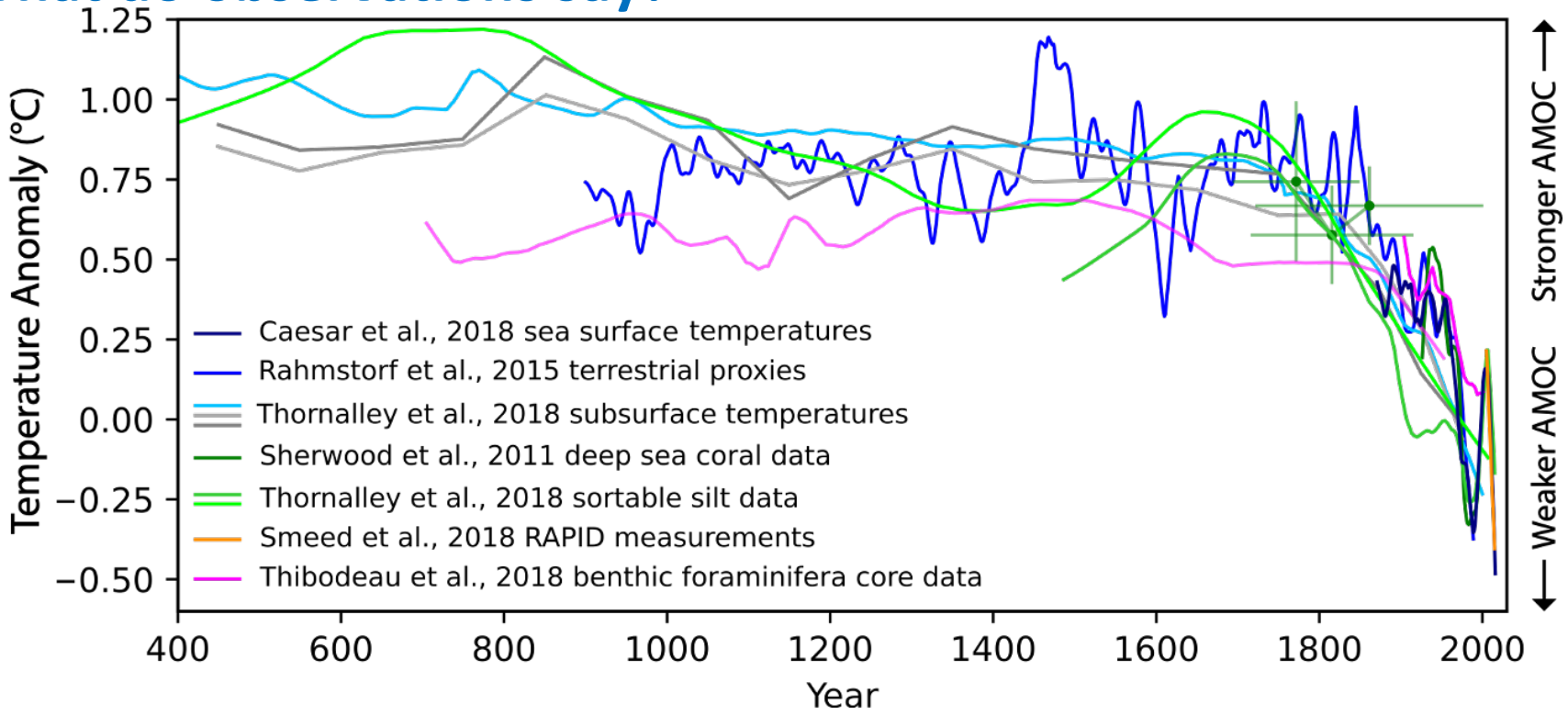
First, some background: What do models say? and why we (probably) should not trust them

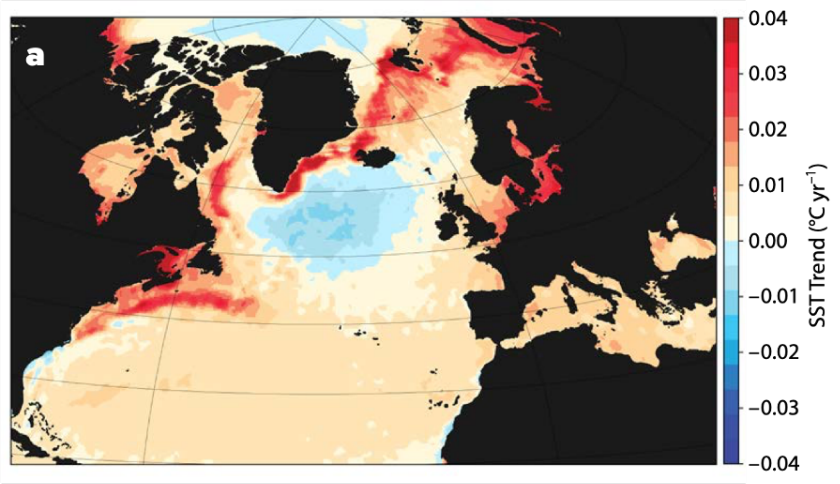


Observed and simulated surface temperature change for 1C global warming (IPCC, 2021)

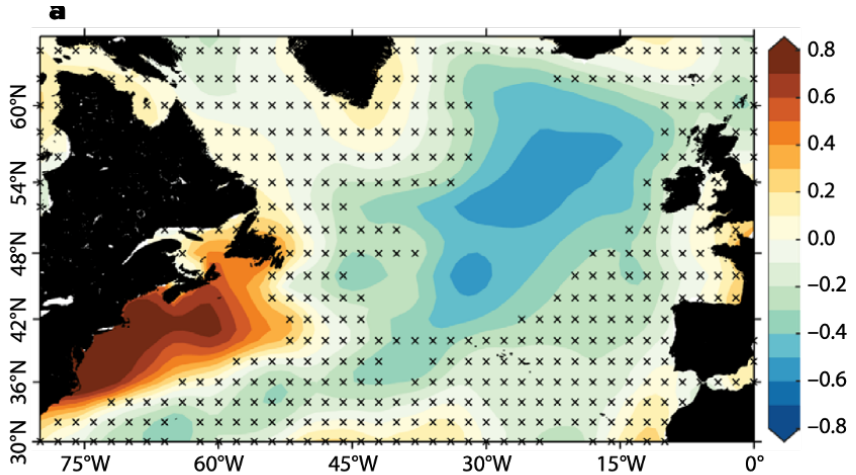
For example, CMIP6 models don't generate the observed '*cold blob*', a *fingerprint* for AMOC changes

First, some background: What do observations say?



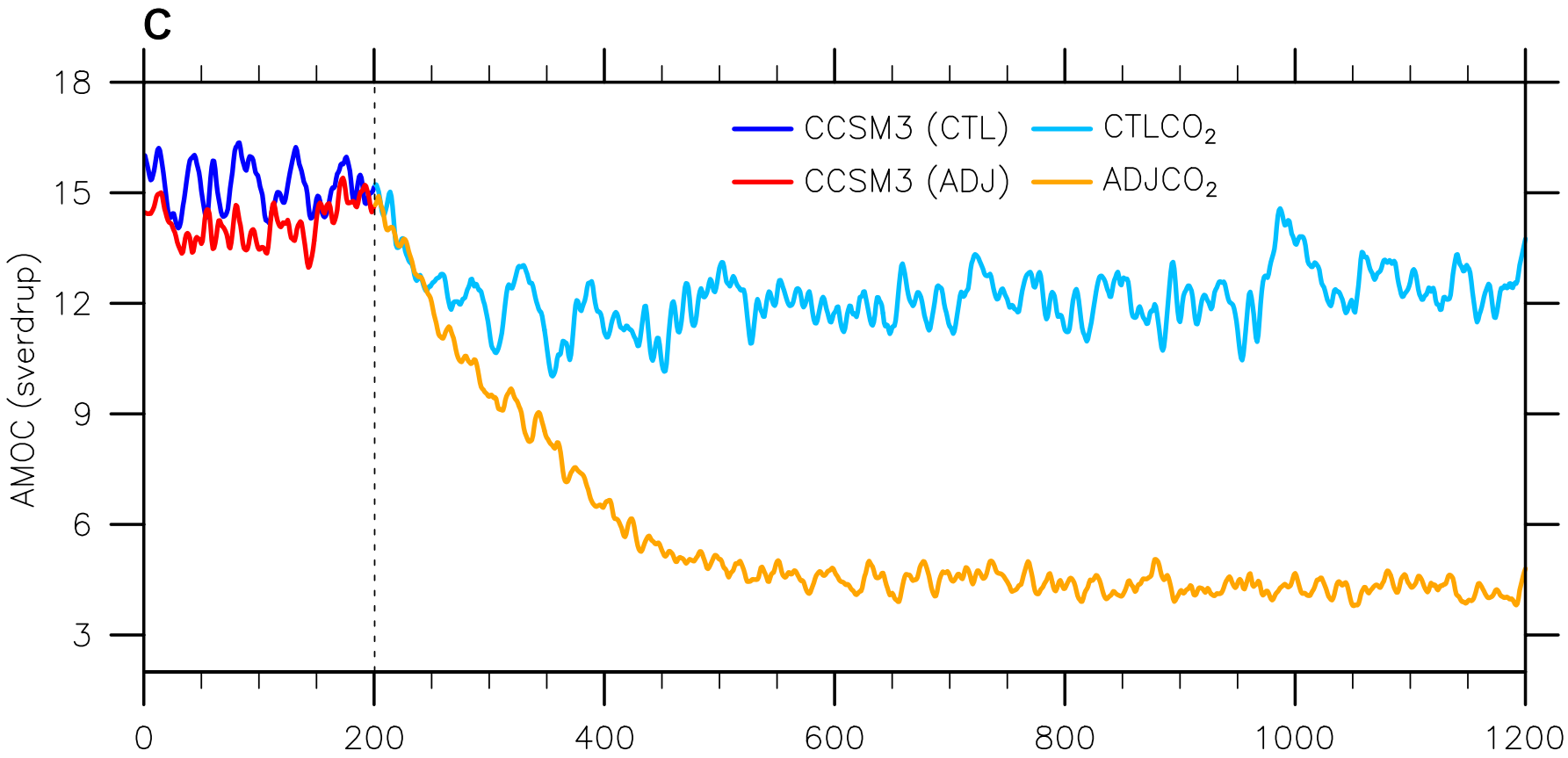


Cold blob



Fresh blob

First, some background: What if we correct our models?

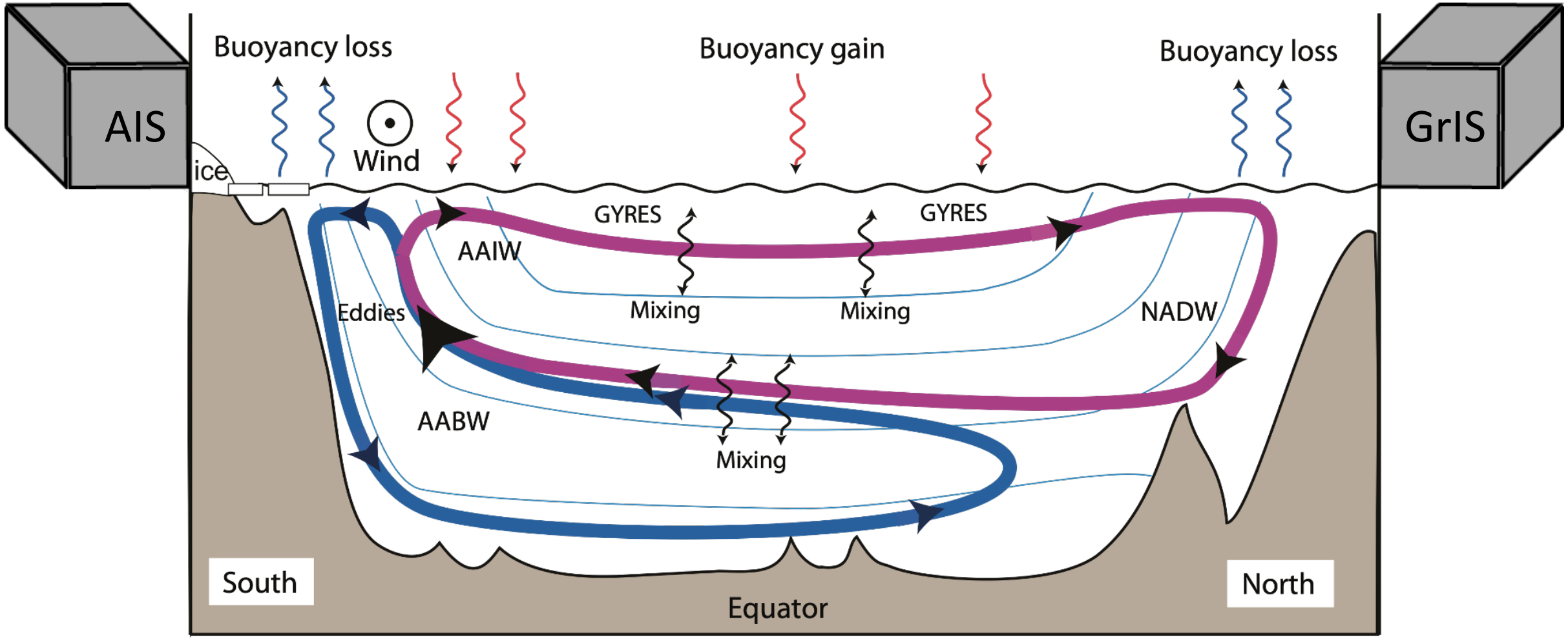


Liu et al. (2017)

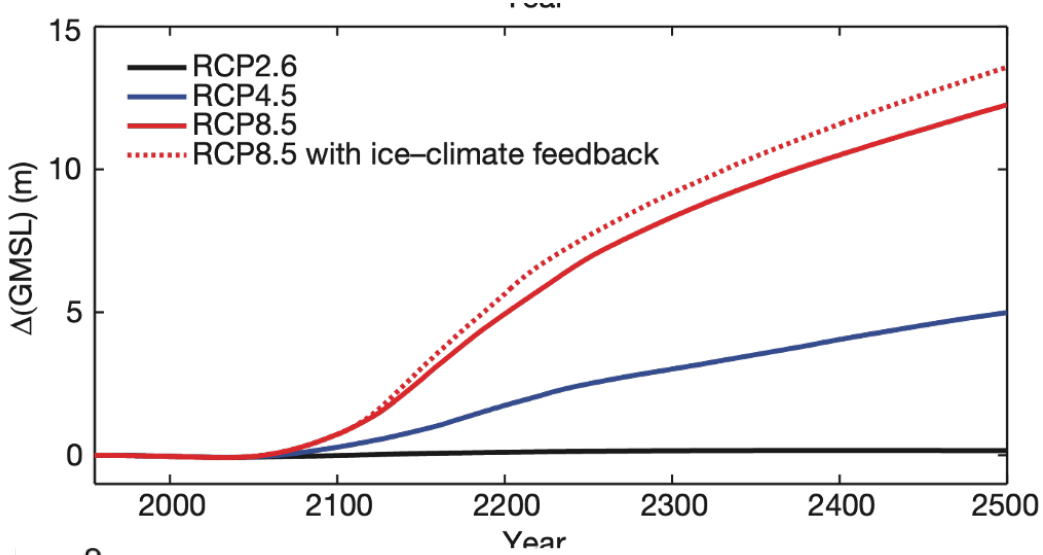
By adjusting the ocean (correcting for South Atlantic salinity biases) the AMOC collapses under a 2xCO2 concentration scenario

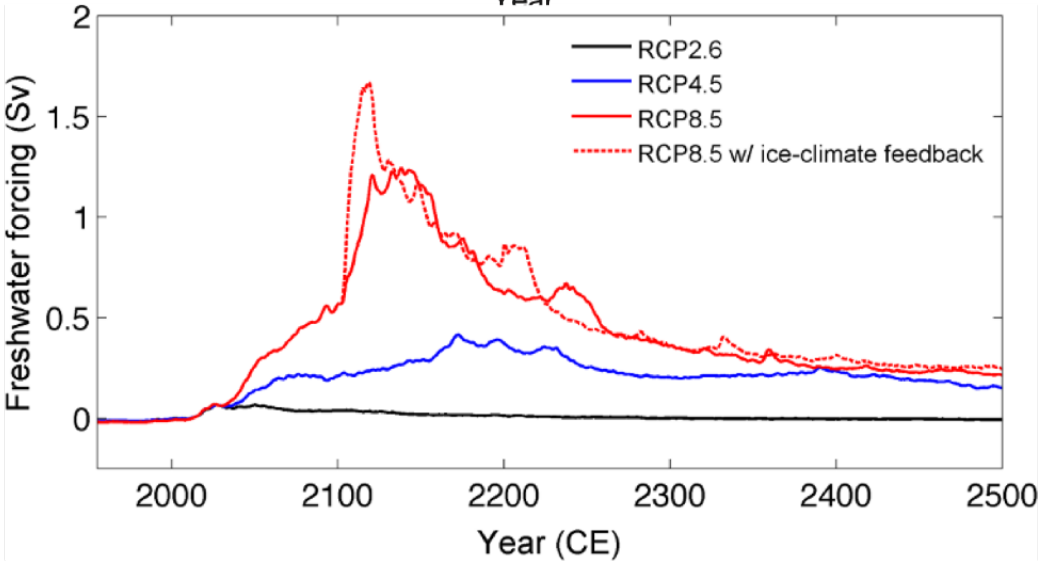
First, some background: so where lies the problem? (something big is missing!)

State-of-the-art Climate Models do not include interactive ice-sheets:
- Greenland Ice Sheet (GrIS)
- Antarctic Ice Sheet (AIS)



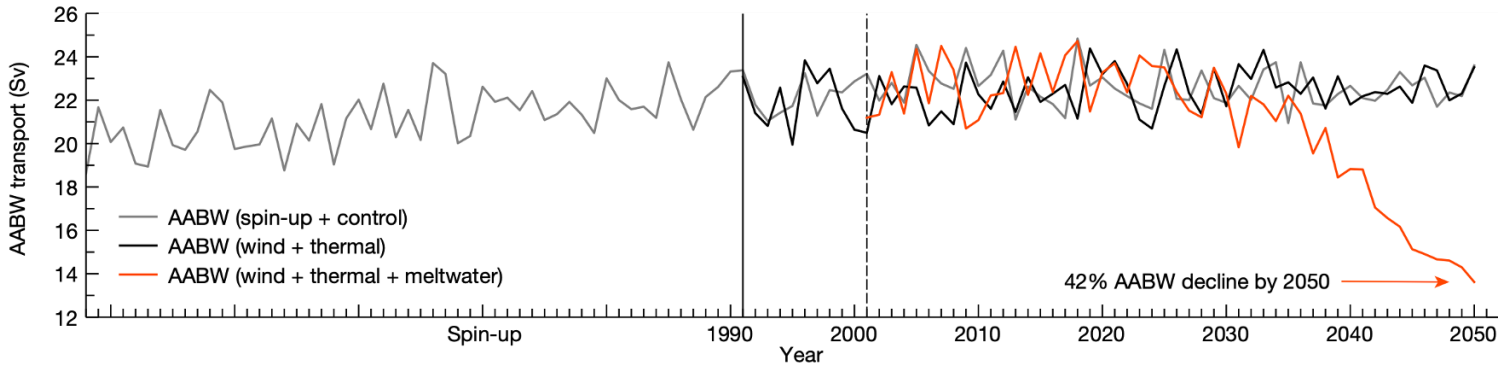
First, some background: Antarctic freshwater flux from IceSheet models





DeConto et al. (2016)

- AIS could contribute between 0.25 to 1m to sea level by 2100 (and more than 10m by 2500)
- The freshwater and iceberg flux following future scenarios could be up to 1 Sv (10^6 m^3/s) or ~30000 Gt/yr
- GrIS is presently losing more mass than AIS, but in the future AIS mass balance loss is projected to accelerate
- Many studies are showing that AIS freshwater discharges impact the Lower Cell (AABW production)

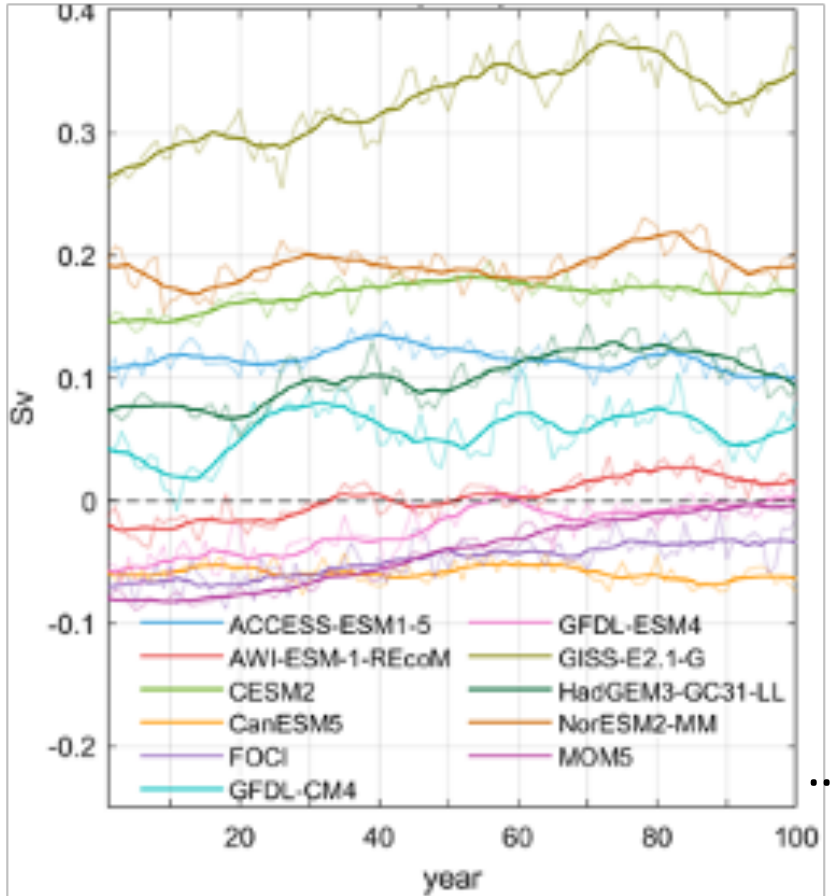


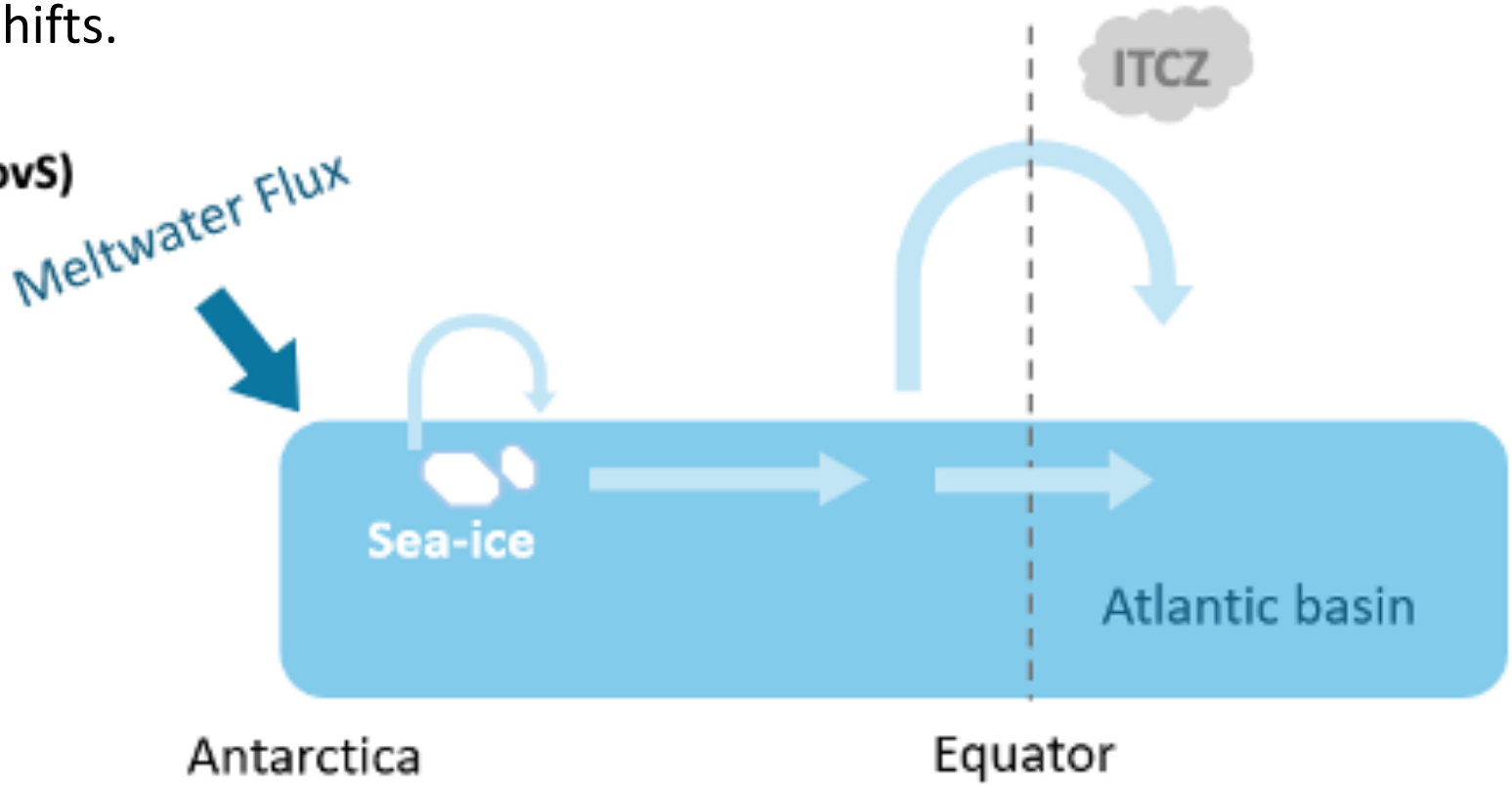
AABW decline in a model forced by 'climate change anomalies' and realistic Antarctic meltwater (Li et al., 2023)

Antarctic Ice Sheet melting results in additional freshwater into the Southern Ocean:

- The freshwater is not regionally trapped, but is transported globally through a) sea-ice processes, b) AMOC, and c) ITCZ shifts.
  —> SEE presentation by Zihan

Freshwater transport by AMOC at 34.5°S (FovS)





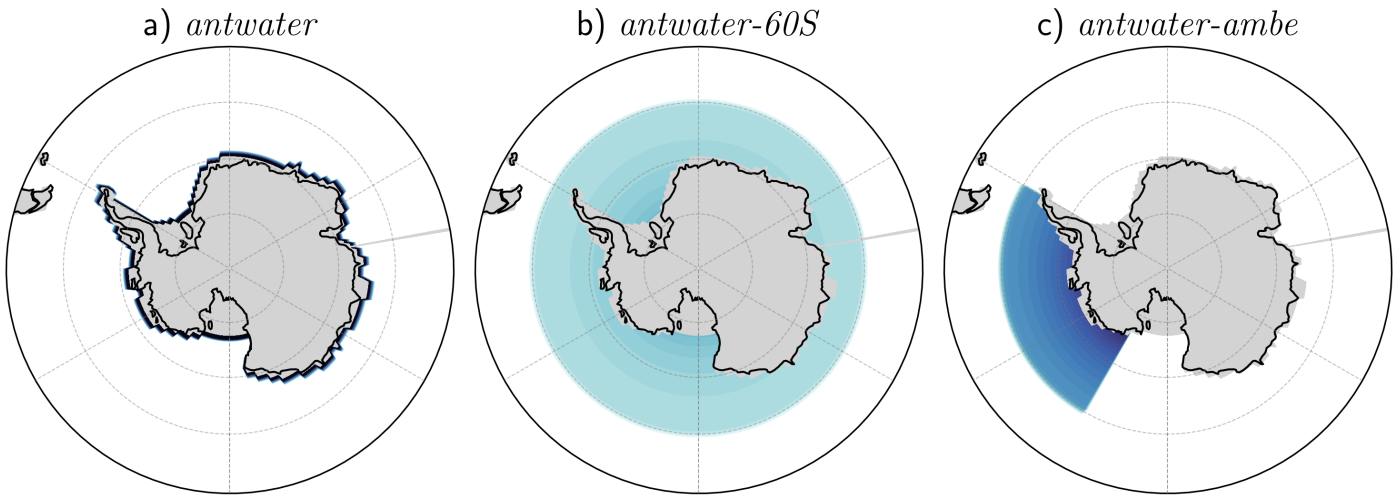
… Influencing the stability of the AMOC

Southern Ocean Freshwater Input from Antarctica (SOFIA) initiative

Southern Ocean Freshwater Input from Antarctica (SOFIA) Initiative

- 11 models from SOFIA antwater forcing (10 coupled models + **1 ocean-sea ice model**)

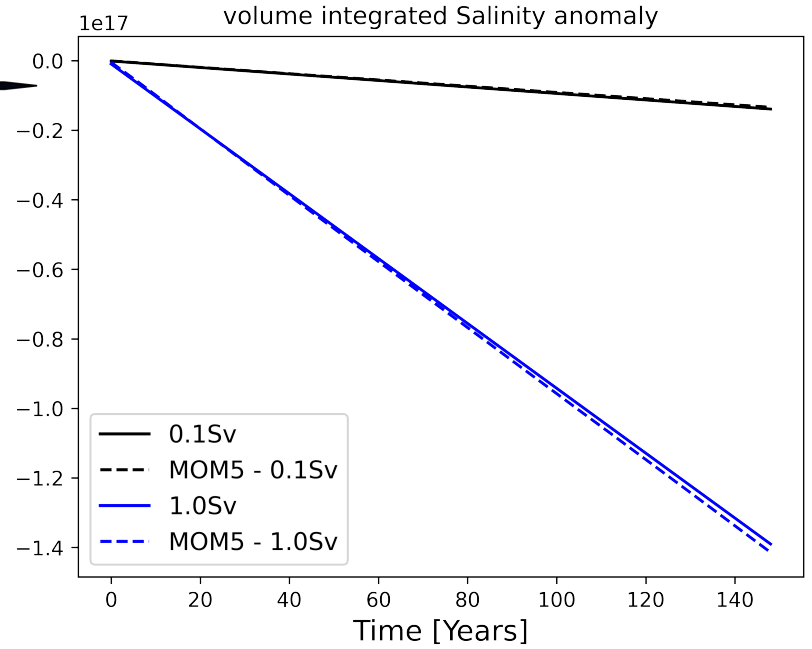
FW forcing (Sv)	FW forcing (∼ Gt/yr)	coast/surface (years)	60S (years)
0.01	315	150	
0.02	630	150	
0.05	1575	150	
0.07	2205	150	
0.1	3150	150	150
0.15	4725	150	
0.2	6300	150	
0.3	9460	150	
0.4	12600	150	
0.5	15760	150	
0.6	18920	150	
0.7	22070	150	
0.8	25230	150	
0.9	28380	150	
1.0	31500	150	150



(Swart et al. 2023)

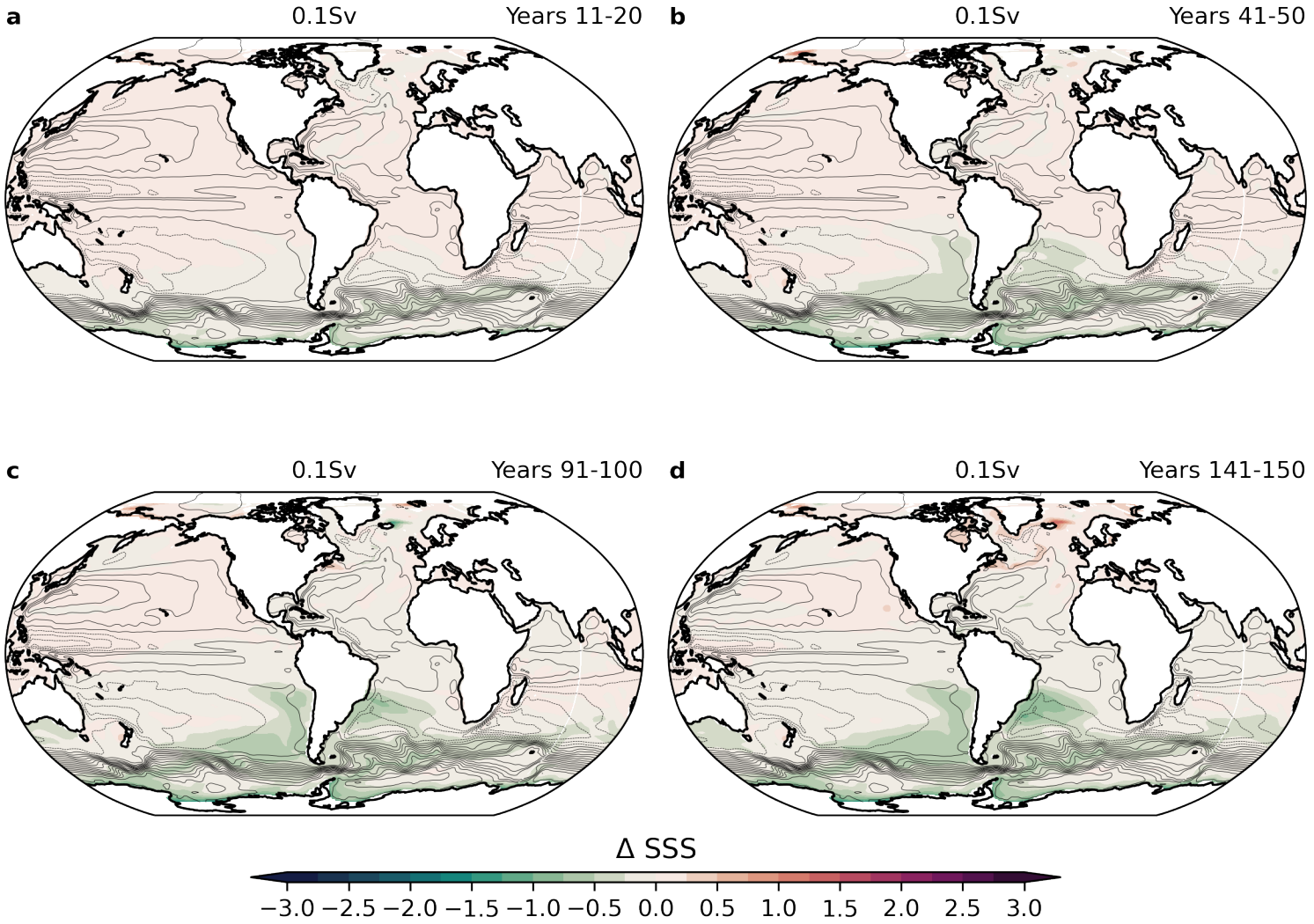
Very Idealized!

- constant in time
- at the surface
- spatially homogeneous



The surface response

- **SSS anomalies are advected northward, mainly following the barotropic circulation, and reach the NA after ~80/90 years, if the anomaly is *large* enough**



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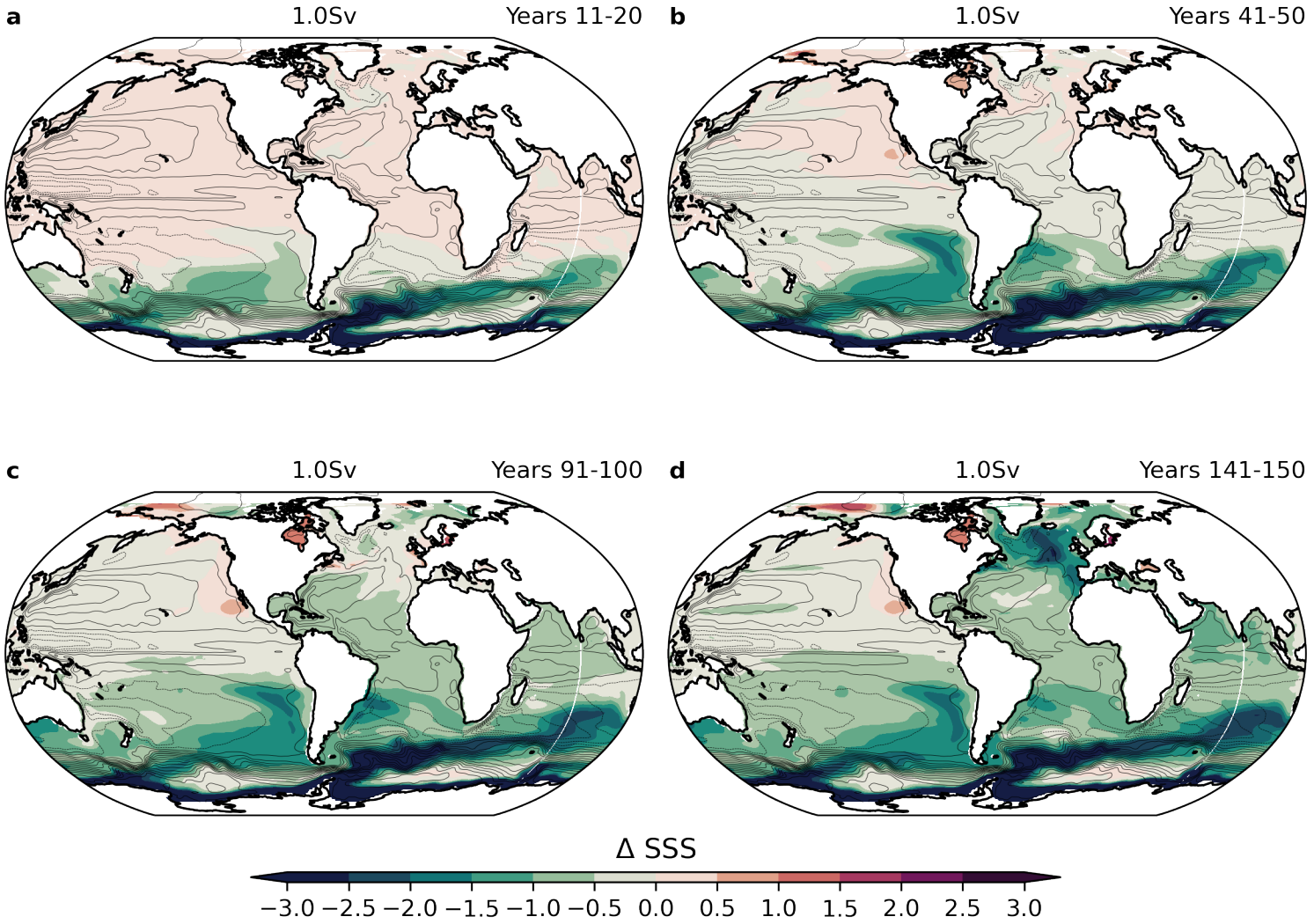
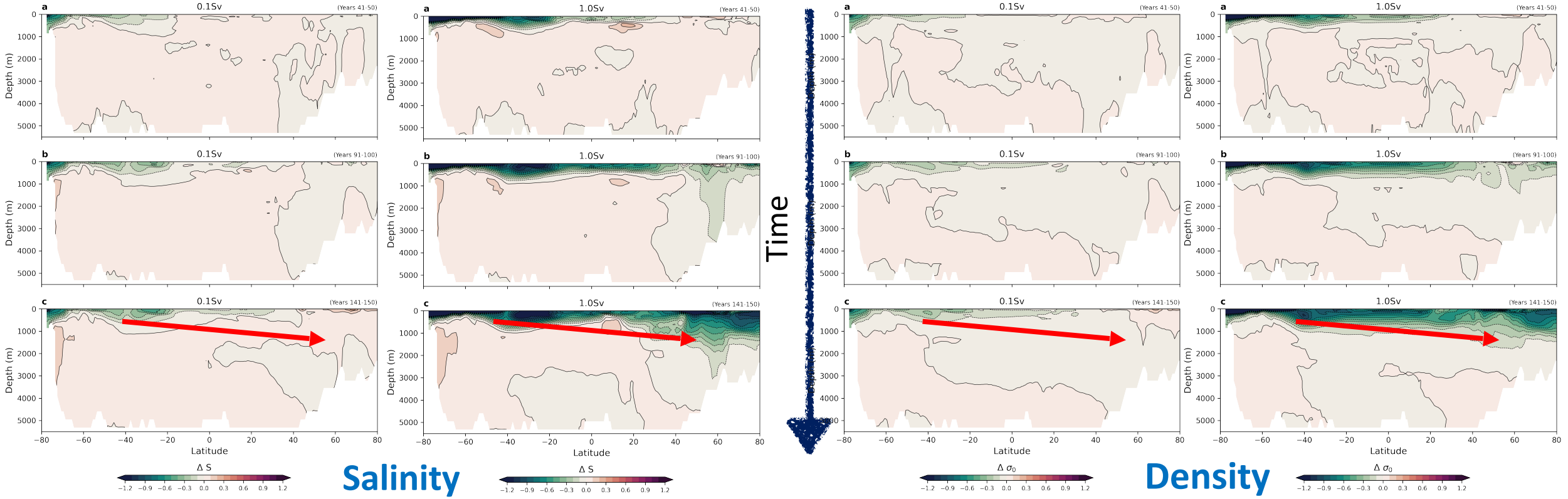
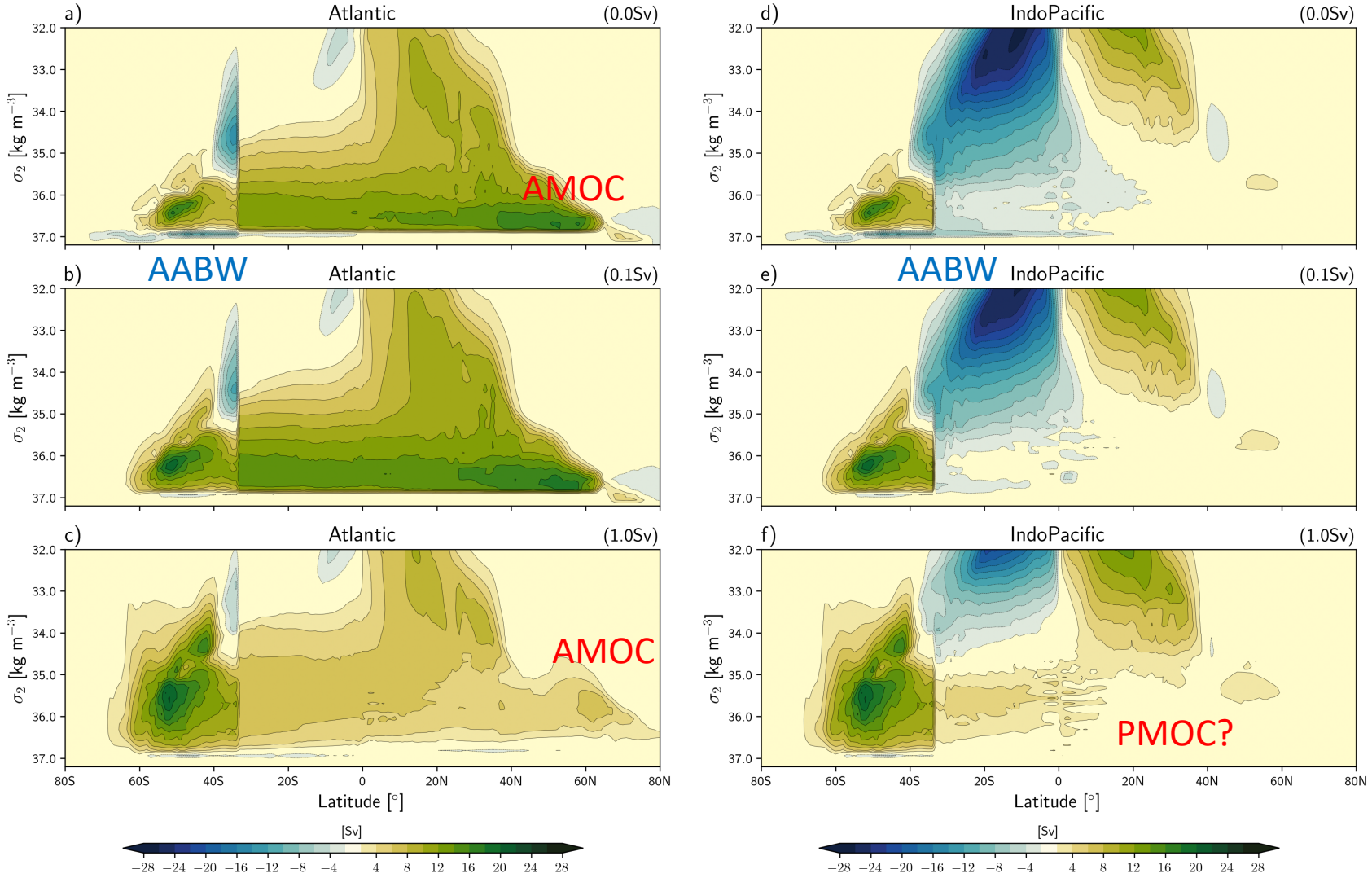


The Atlantic interior response

- **Salinity (Density) anomalies are advected northward, comparing positively with previous coupled-models results**

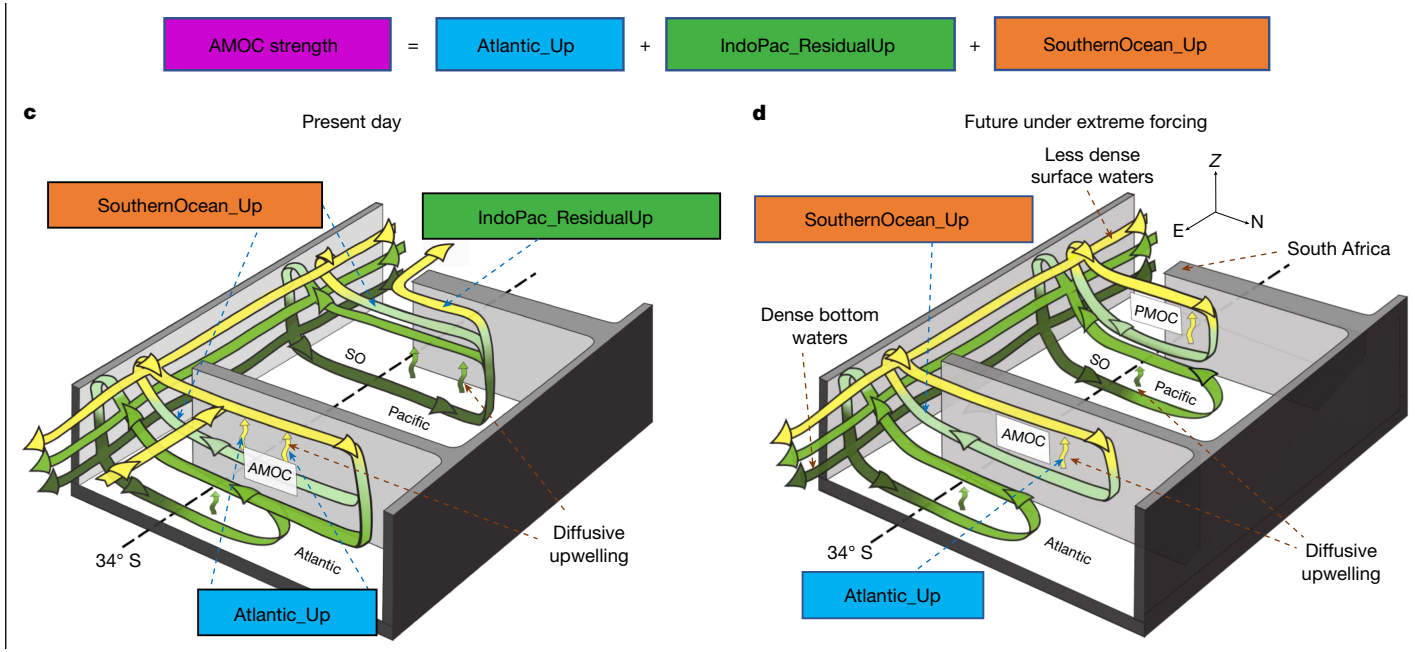


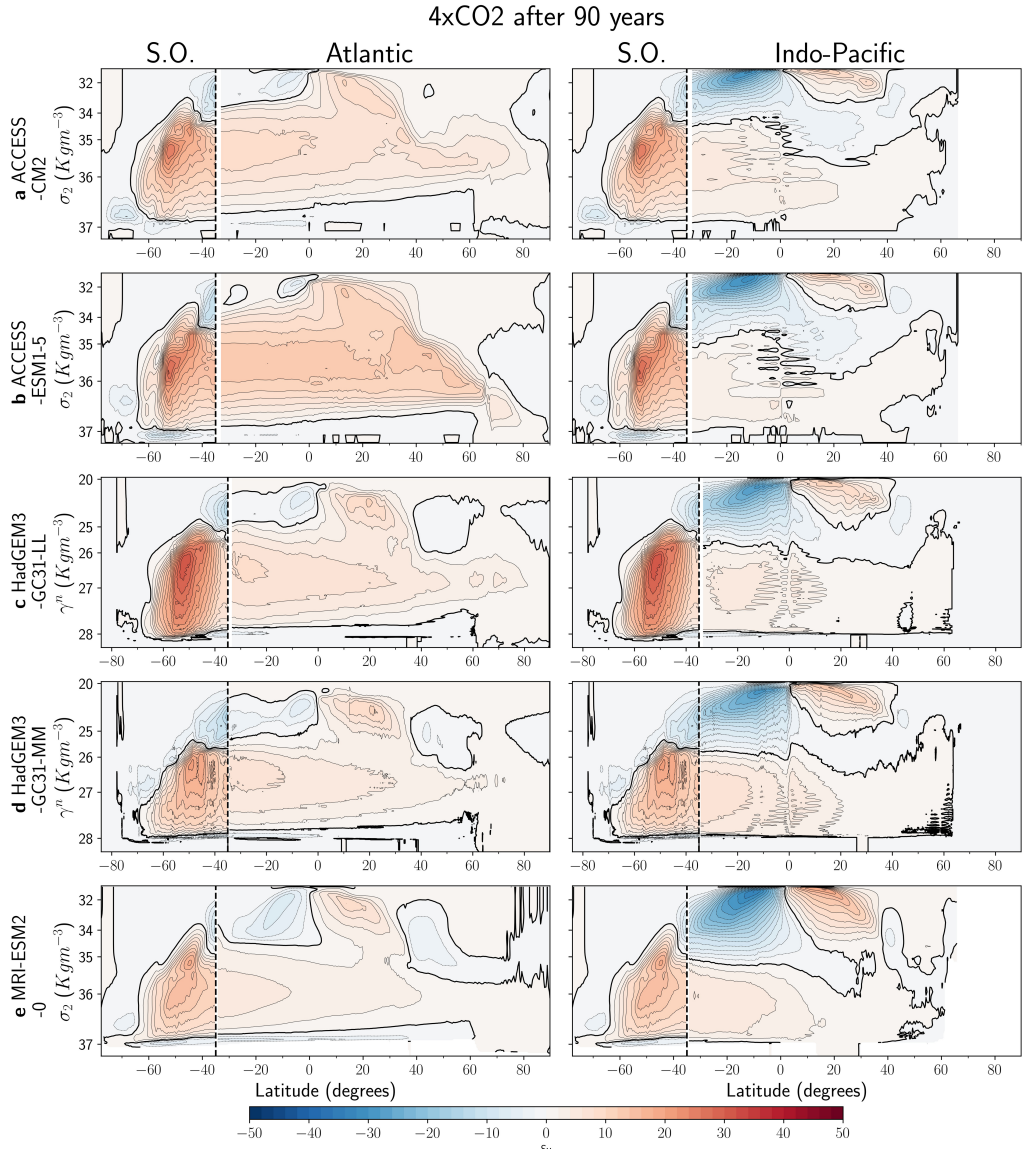
The MOC response (in density space)



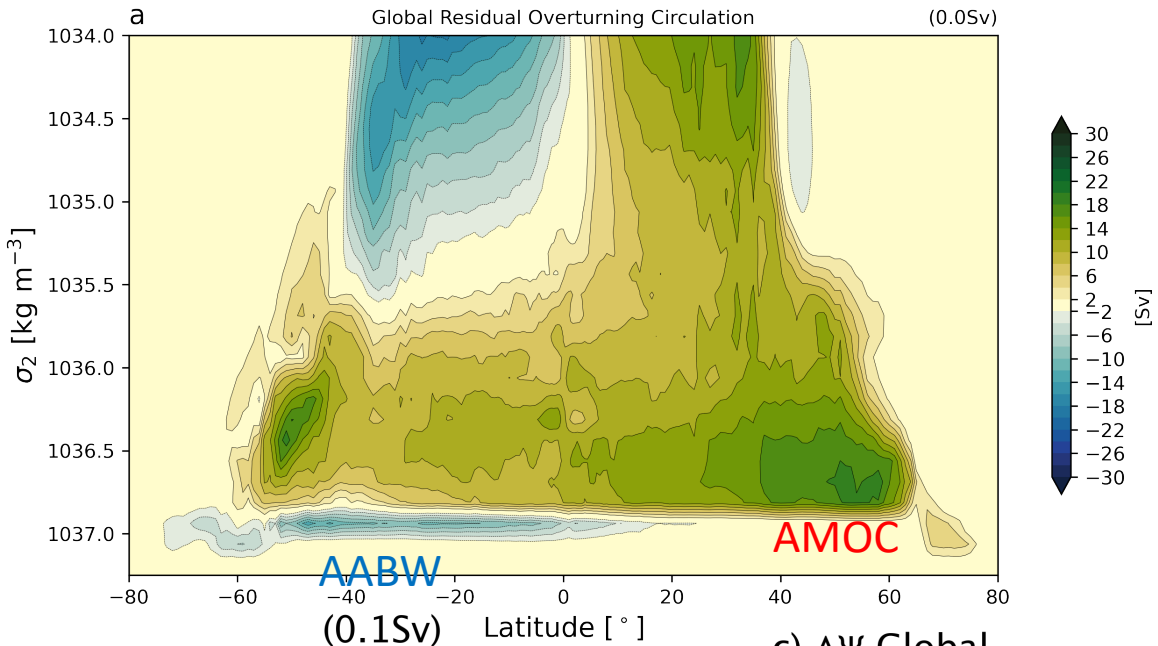
- **At the end of the experiments (150 years):**
  - **AABW seems to be insensitive to strength of FW forcing and reduces considerably with weak forcing**
  - **AMOC weakens only for *large* FW forcing anomalies**
  - **a convective cell in the Pacific?**

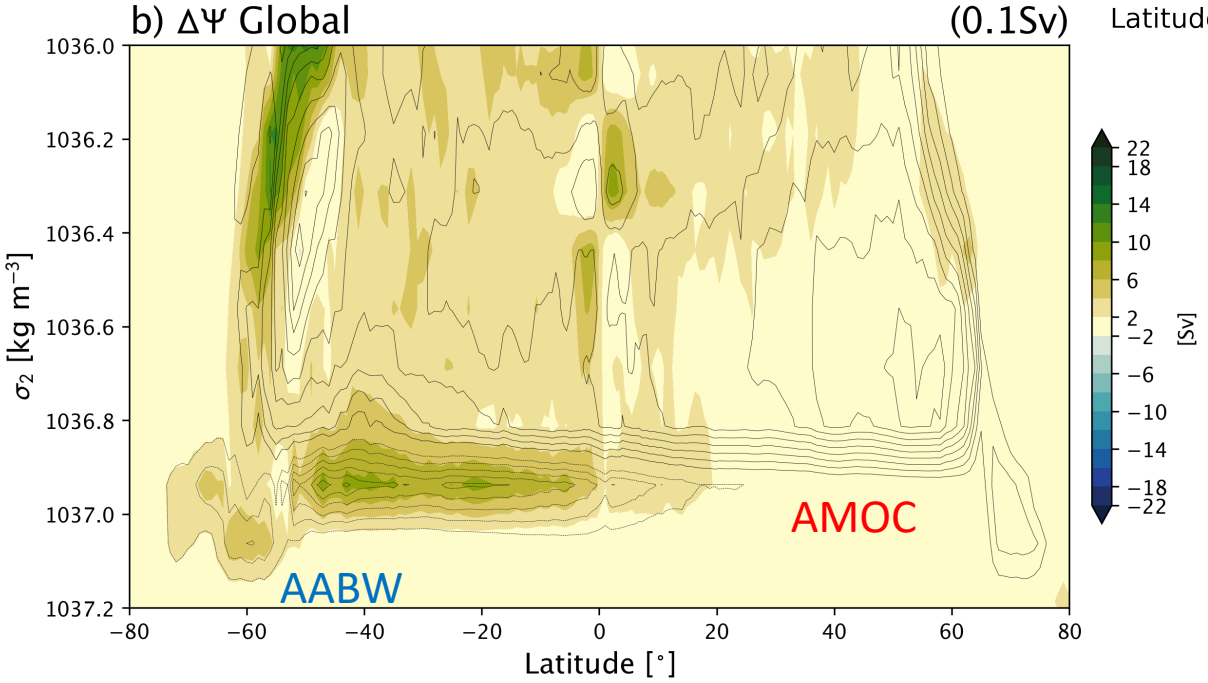
Baker et al. (2025) suggests an Atlantic-Pacific see-saw

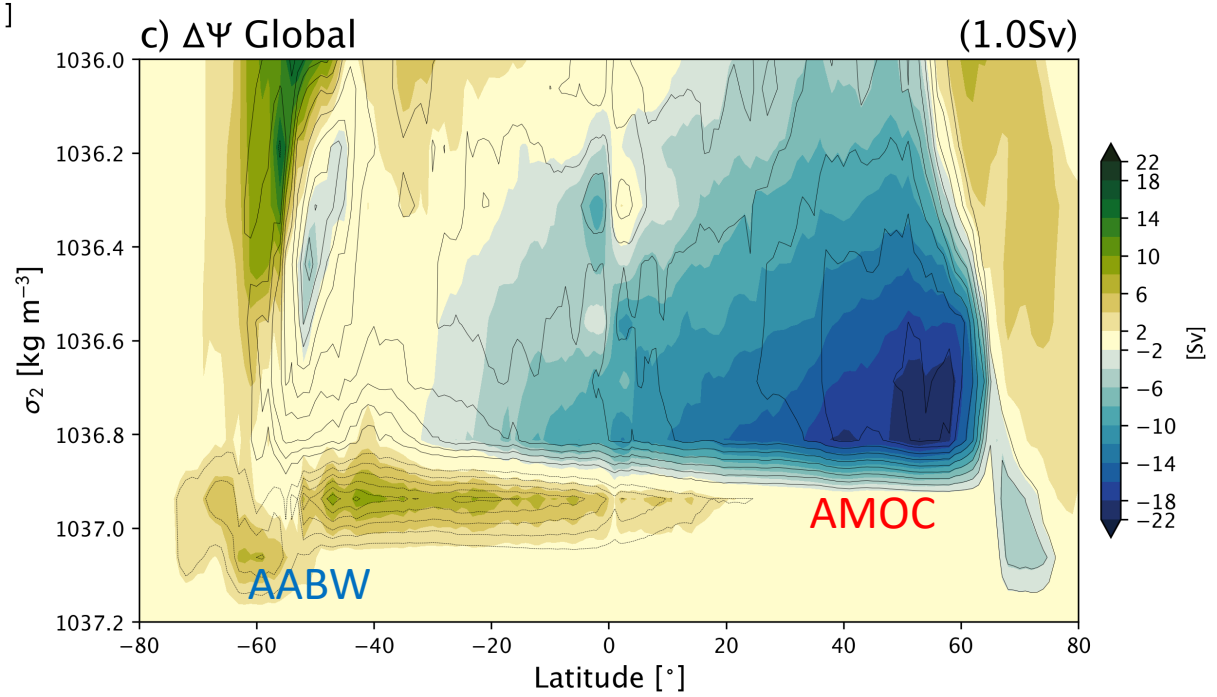




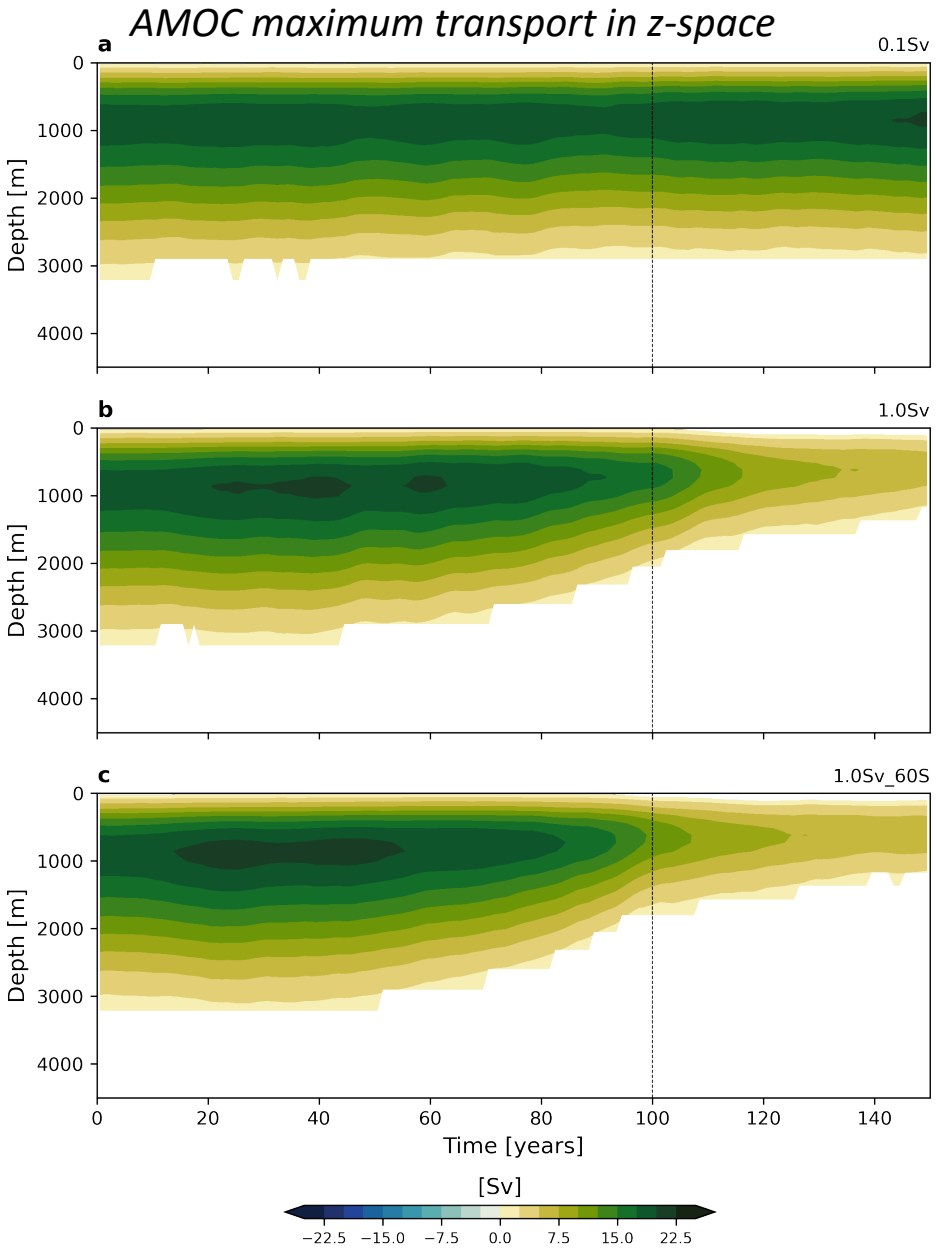
The Global MOC response (in density space)



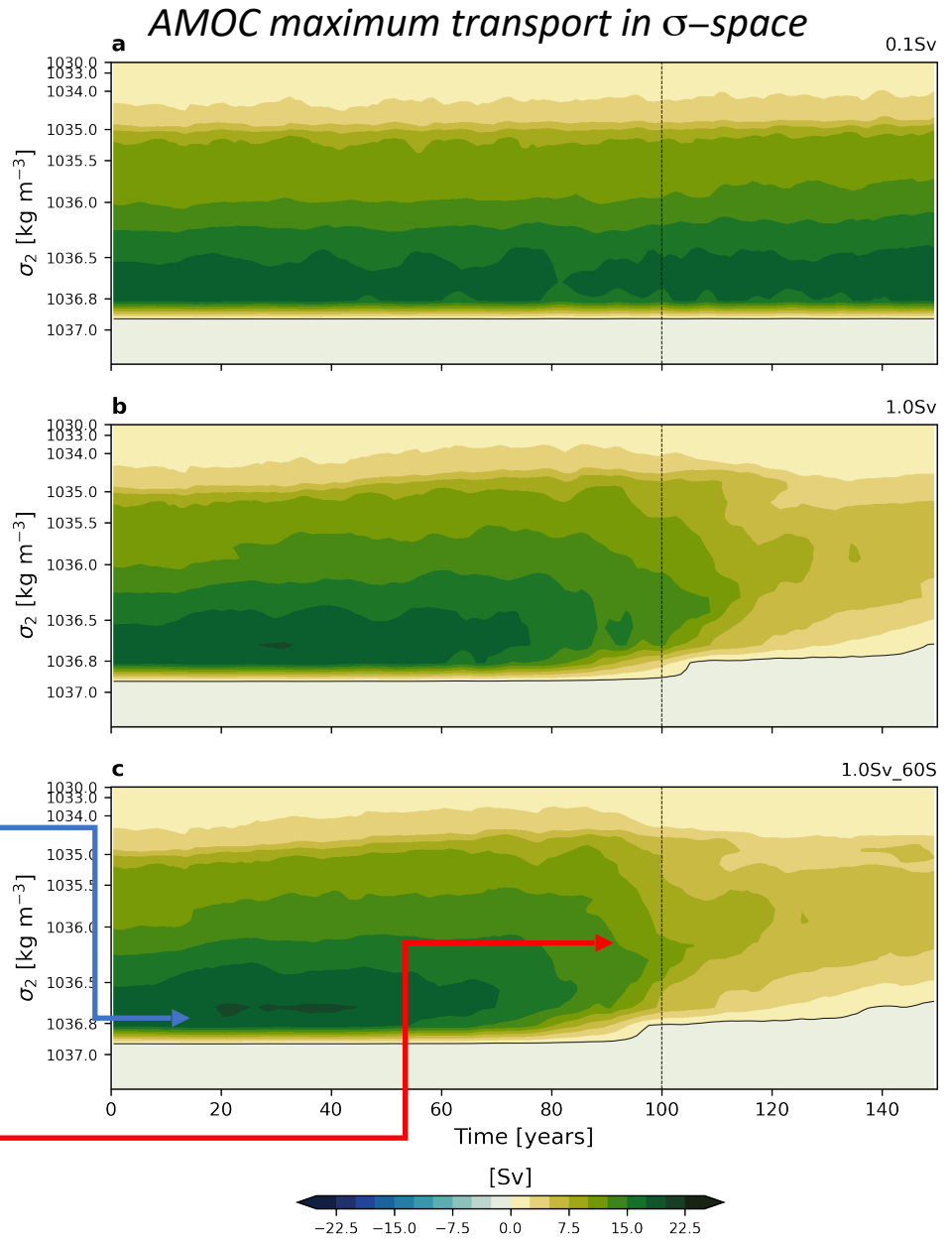




The AMOC transient (time-dependent) response

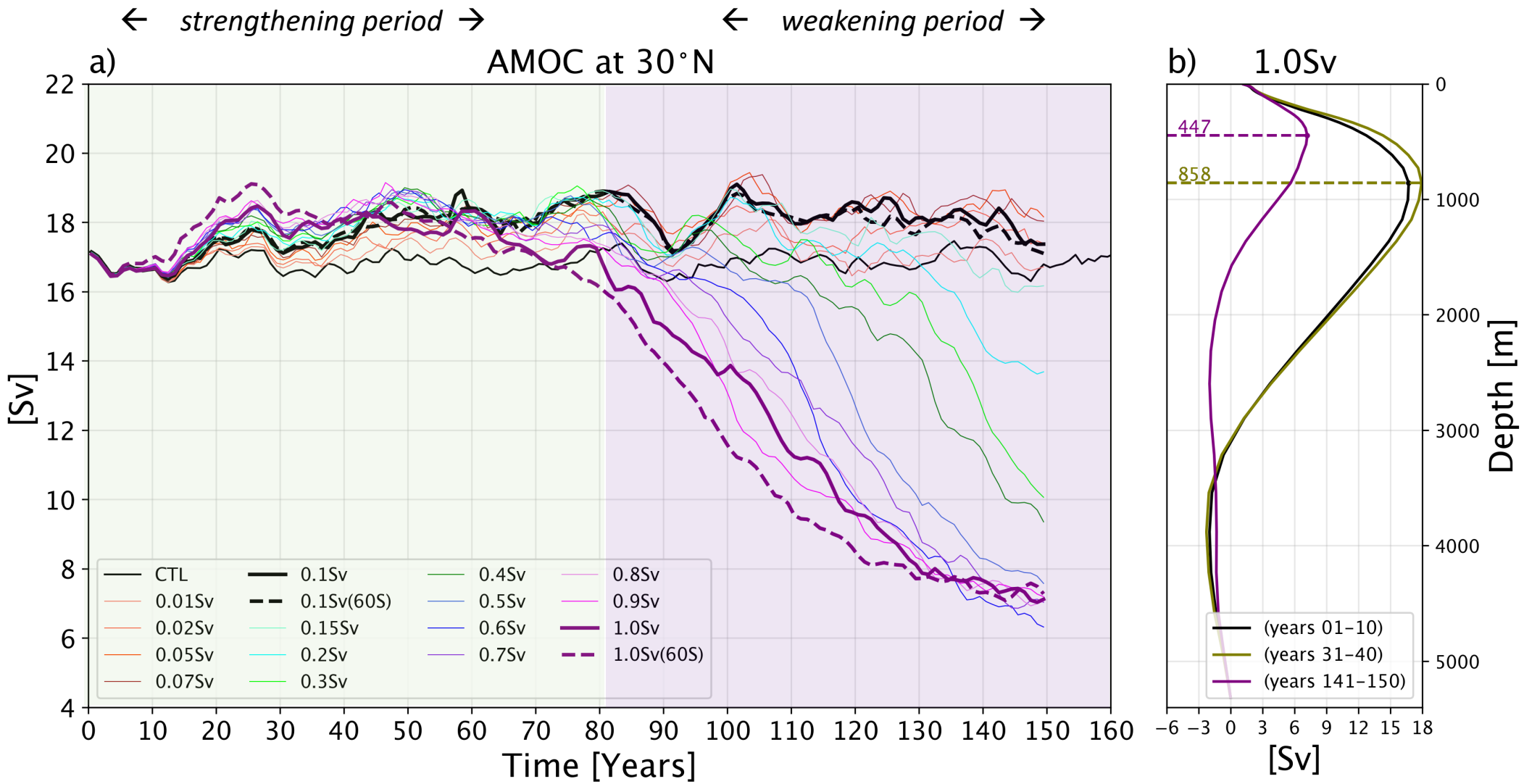


- **AMOC gets progressively shallower (large implications for heat transport)**
- **initial strengthening**
- **followed by a substantial weakening**



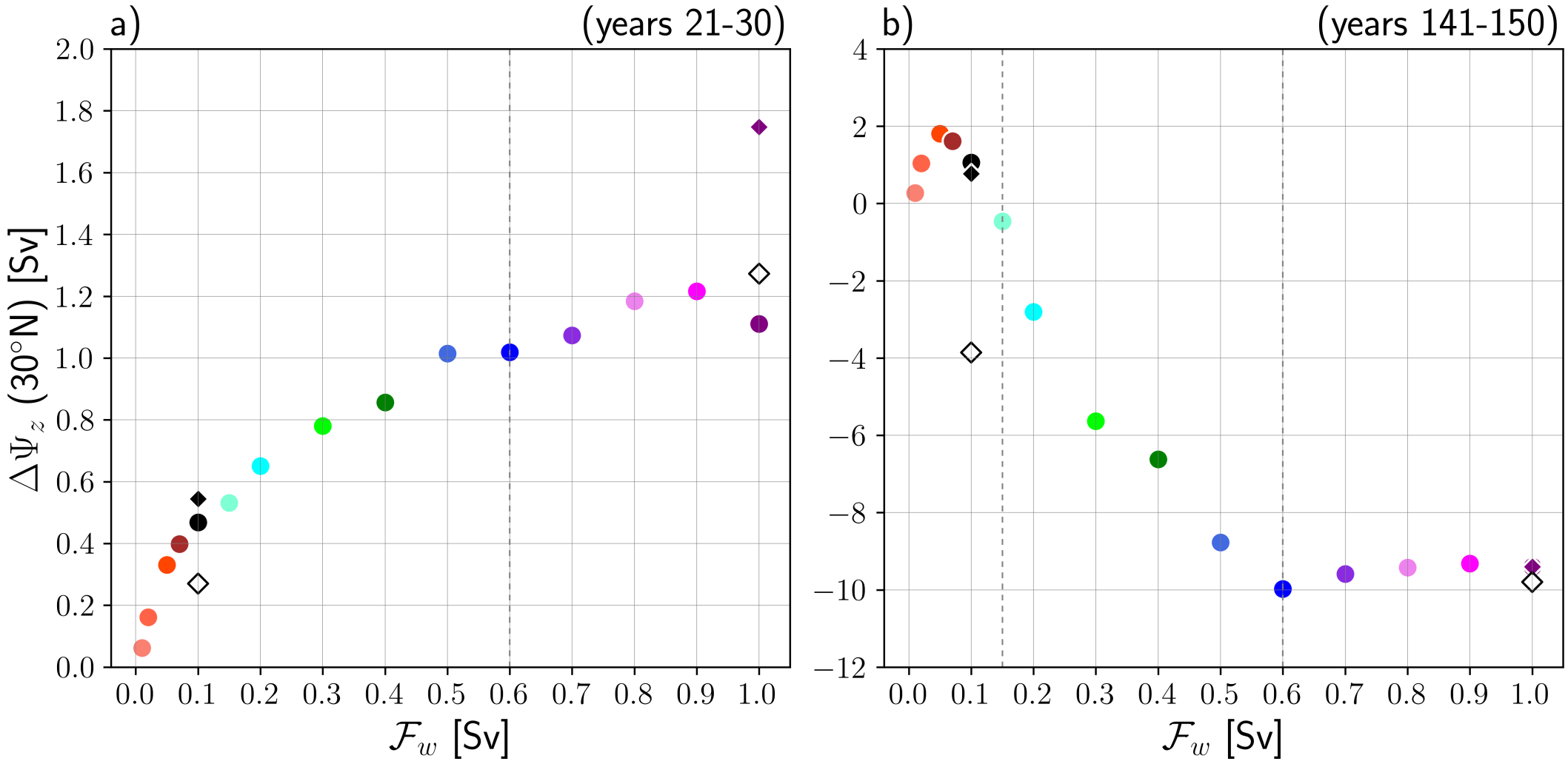
The AMOC transient response

- **AMOC initially strengthenes**
- **AMOC eventually weakens for FW>0.2Sv**
- **period of both strengthening/weakening phases varies with FW forcing amplitude**



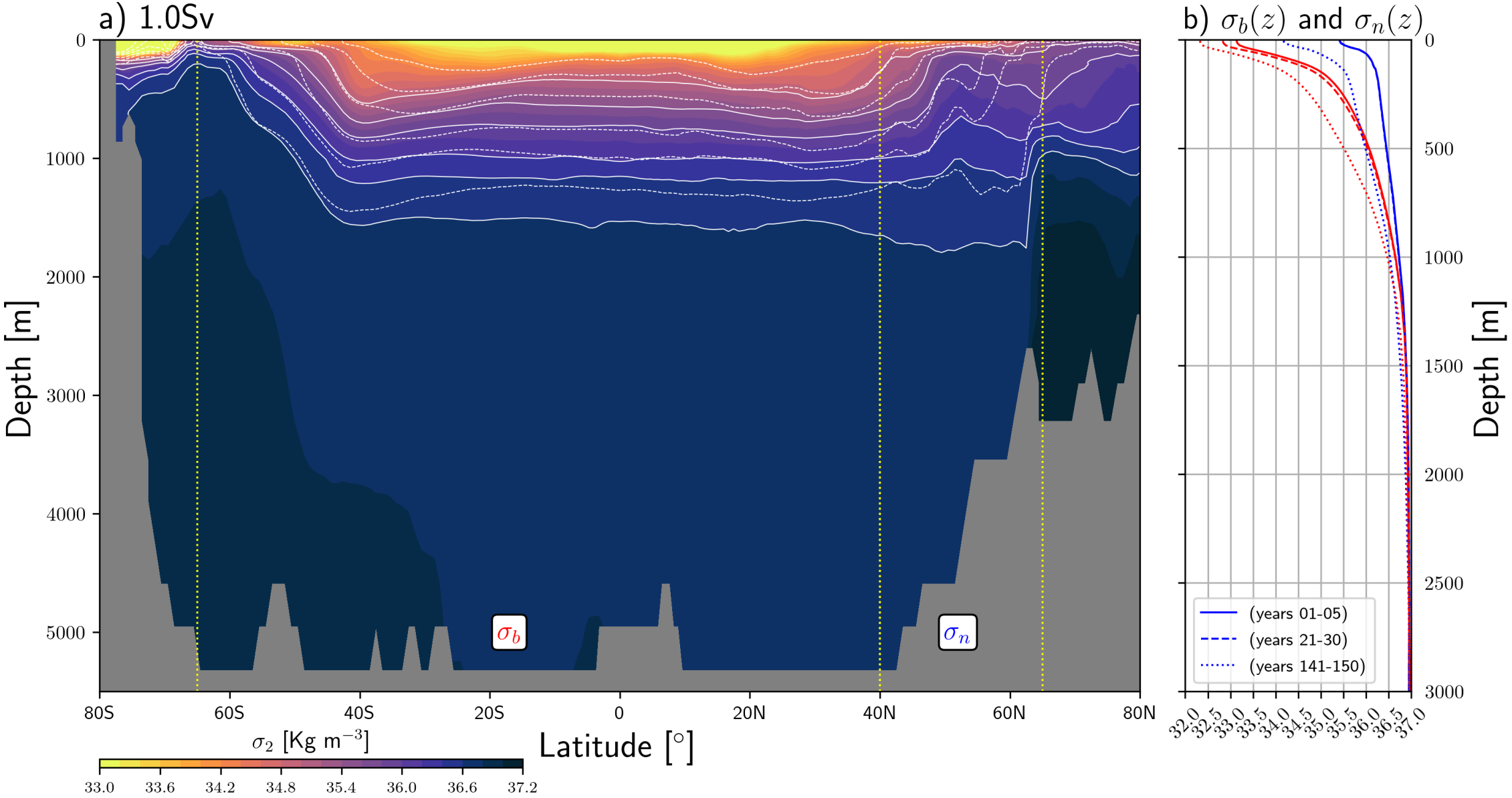
The AMOC transient response

- **AMOC initially strengthens**
- **AMOC eventually weakens for FW>0.15Sv**
- **period of both strengthening/weakening phases varies with FW forcing amplitude**



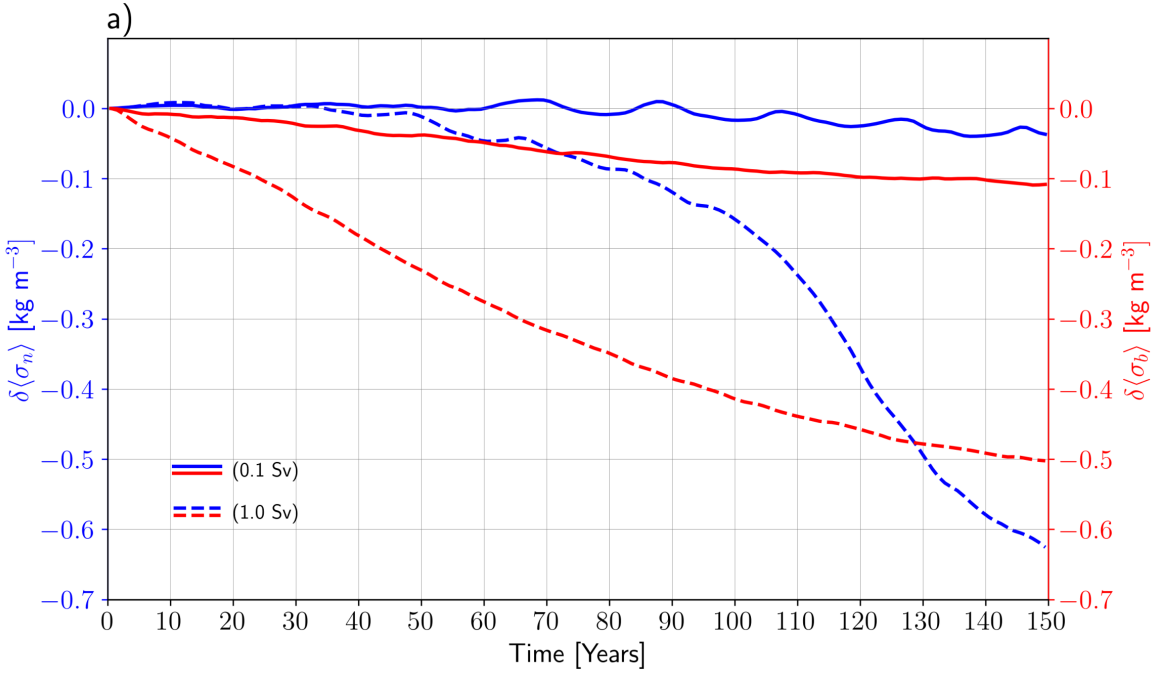
A (rotated) Thermal Wind reconstruction

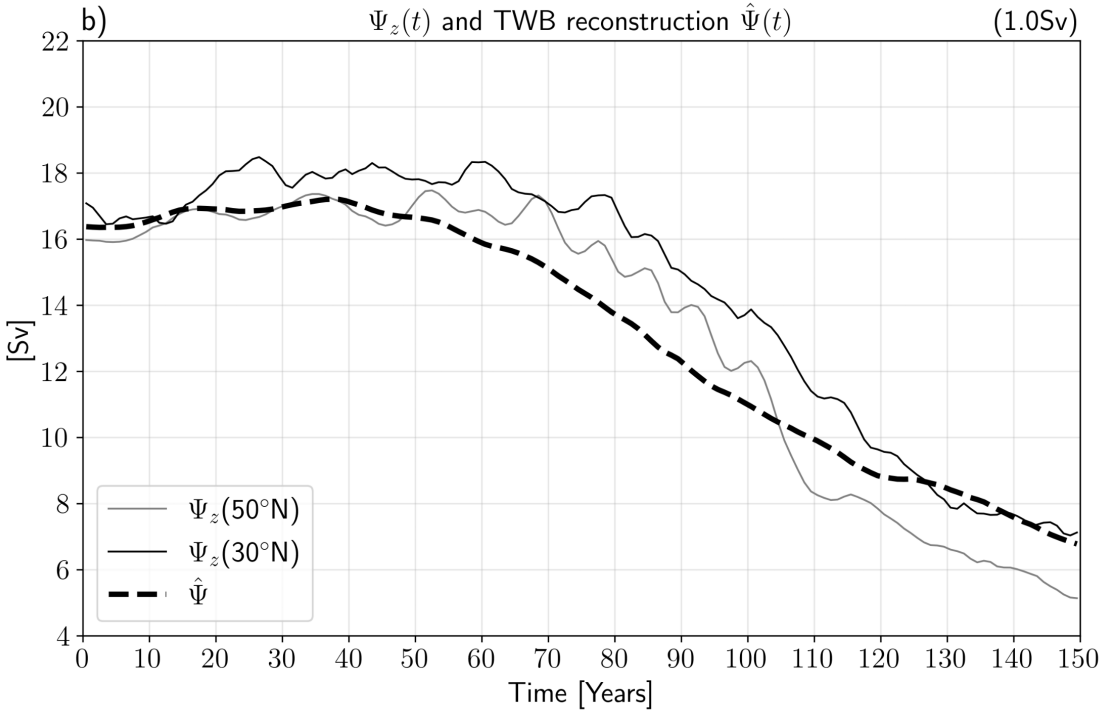
$$\partial_{zz}\hat{\Psi}(z) = -g(f_0\rho_0)^{-1}[\sigma_n(z) - \sigma_b(z)]$$



A Thermal Wind reconstruction

- **Meridional density differences between convective region and the basin can explain the transient AMOC evolution (e.g., *Jansen et al. 2018; Bonan et al. 2022*).**

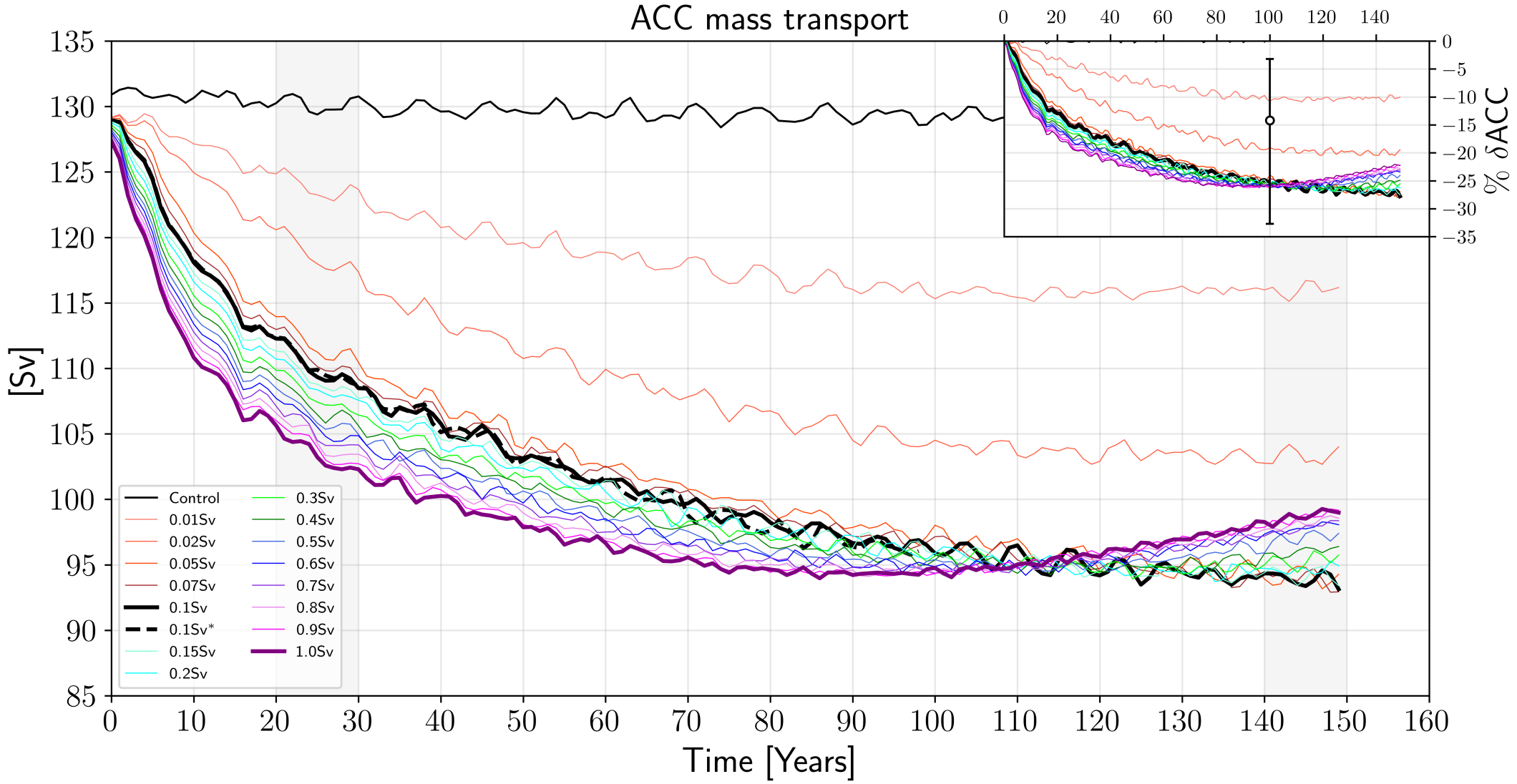




What happens to the ACC?

- **ACC weakening initially scales linearly with FW forcing**
- **ACC weakening eventually saturates**
- **for FW forcing inducing AMOC weakening, the ACC partially recovers …. why?**

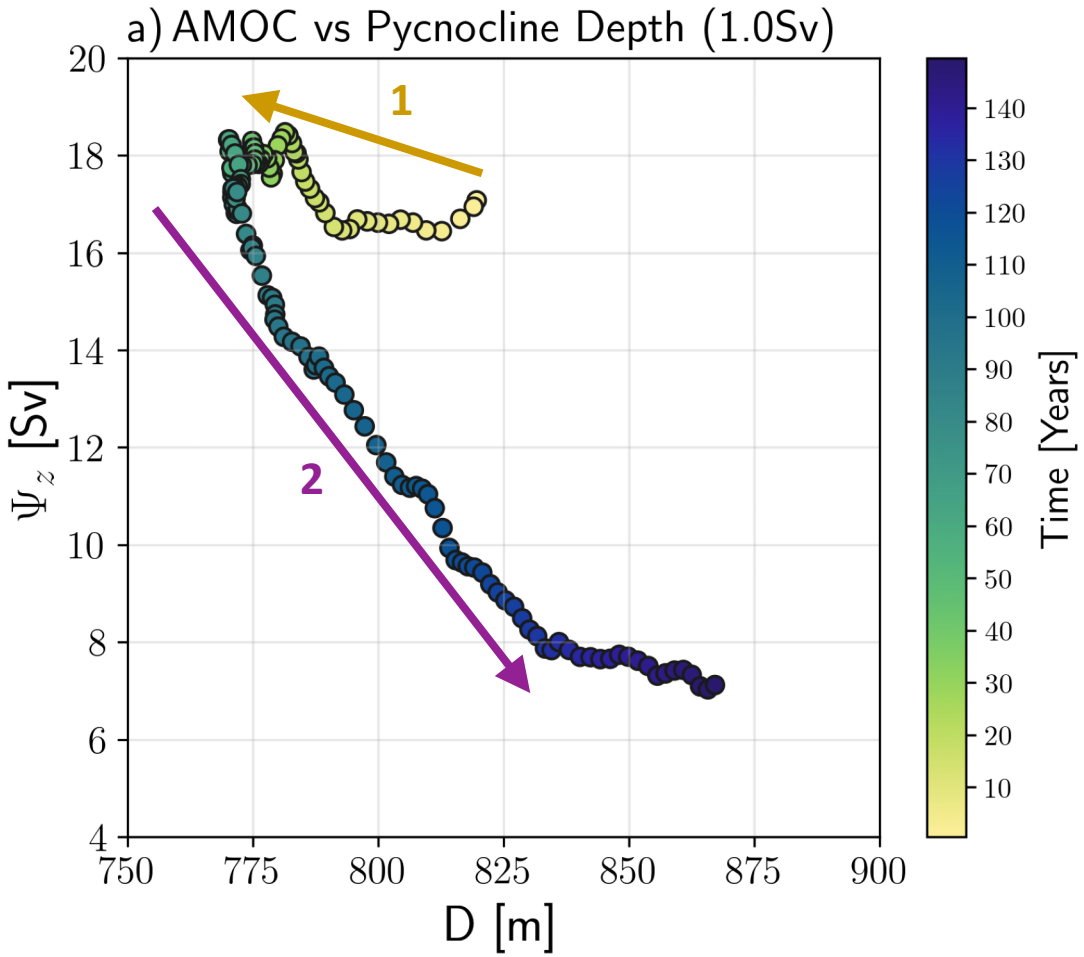
$$U \approx \frac{\Delta b}{fL} D$$

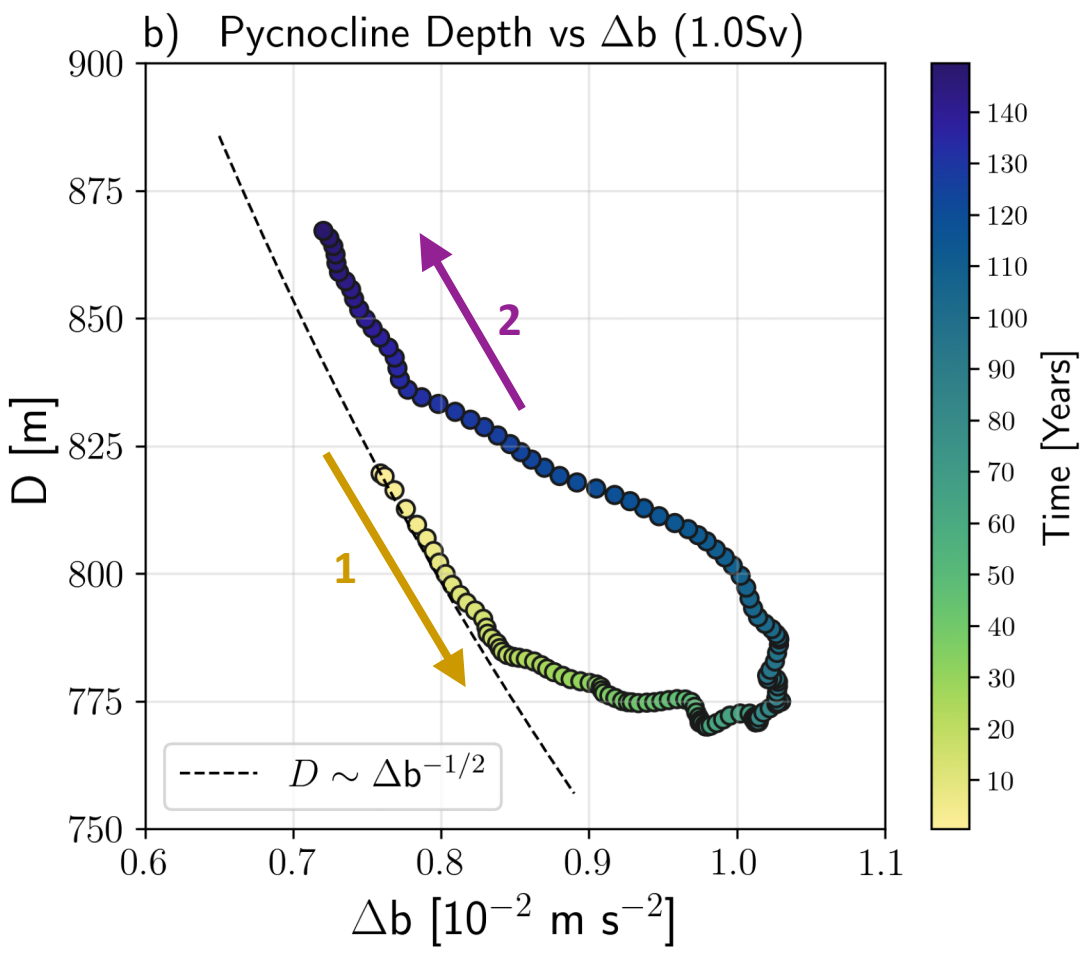


What happens to the ACC? Pycnocline depth adjustment

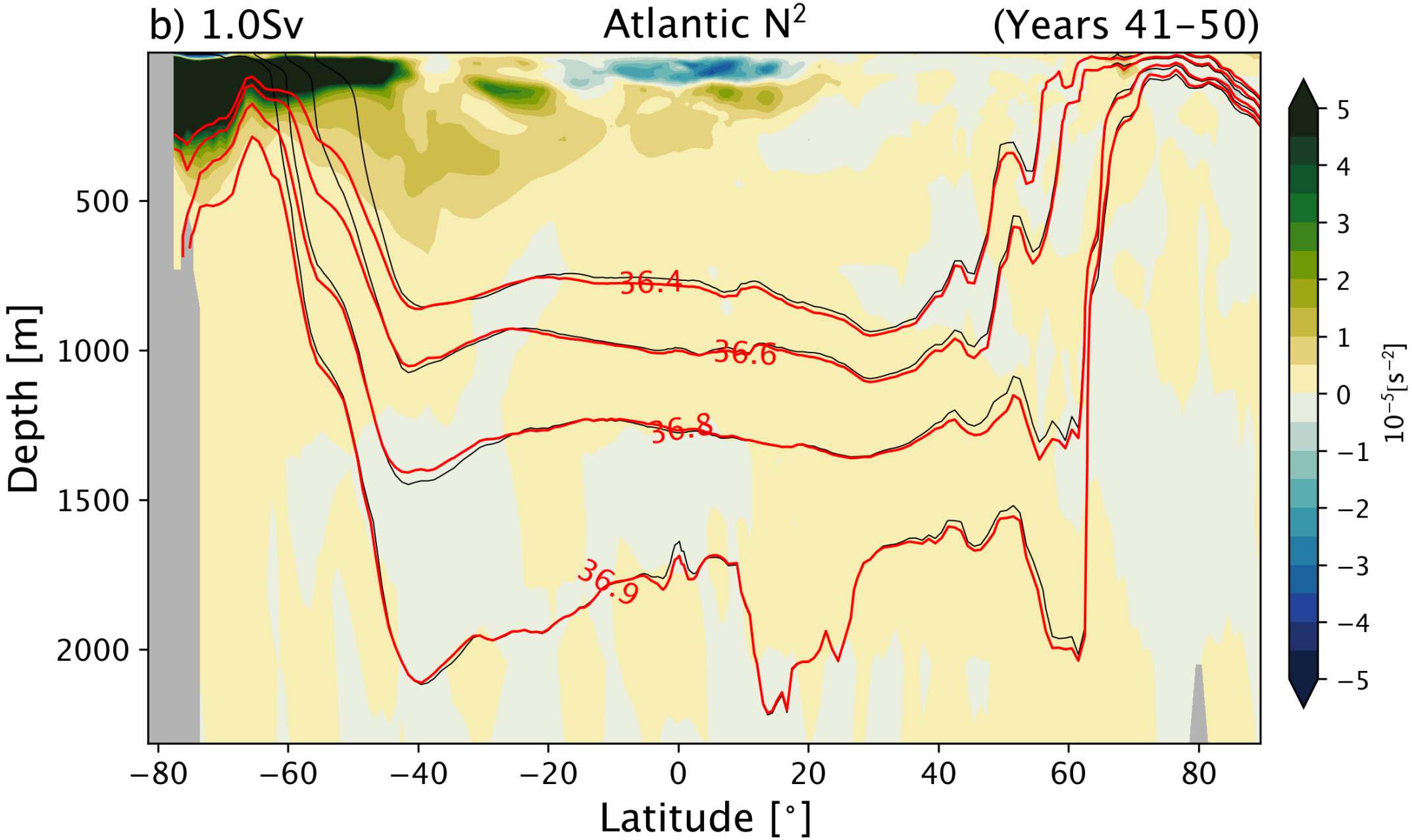
$$D = \frac{\int_{z=-H}^{0} dz \Delta\sigma_2 z}{\int_{z=-H}^{0} dz \Delta\sigma_2}$$

$$D \sim \left(\frac{W f^2 L}{\beta \Delta b}\right)^{1/2}; \; b = -g\rho^{-1}\rho$$





What happens to the ACC? Pycnocline depth adjustment $N^2 = -g\rho^{-1}\partial_z\rho = \partial_z b$



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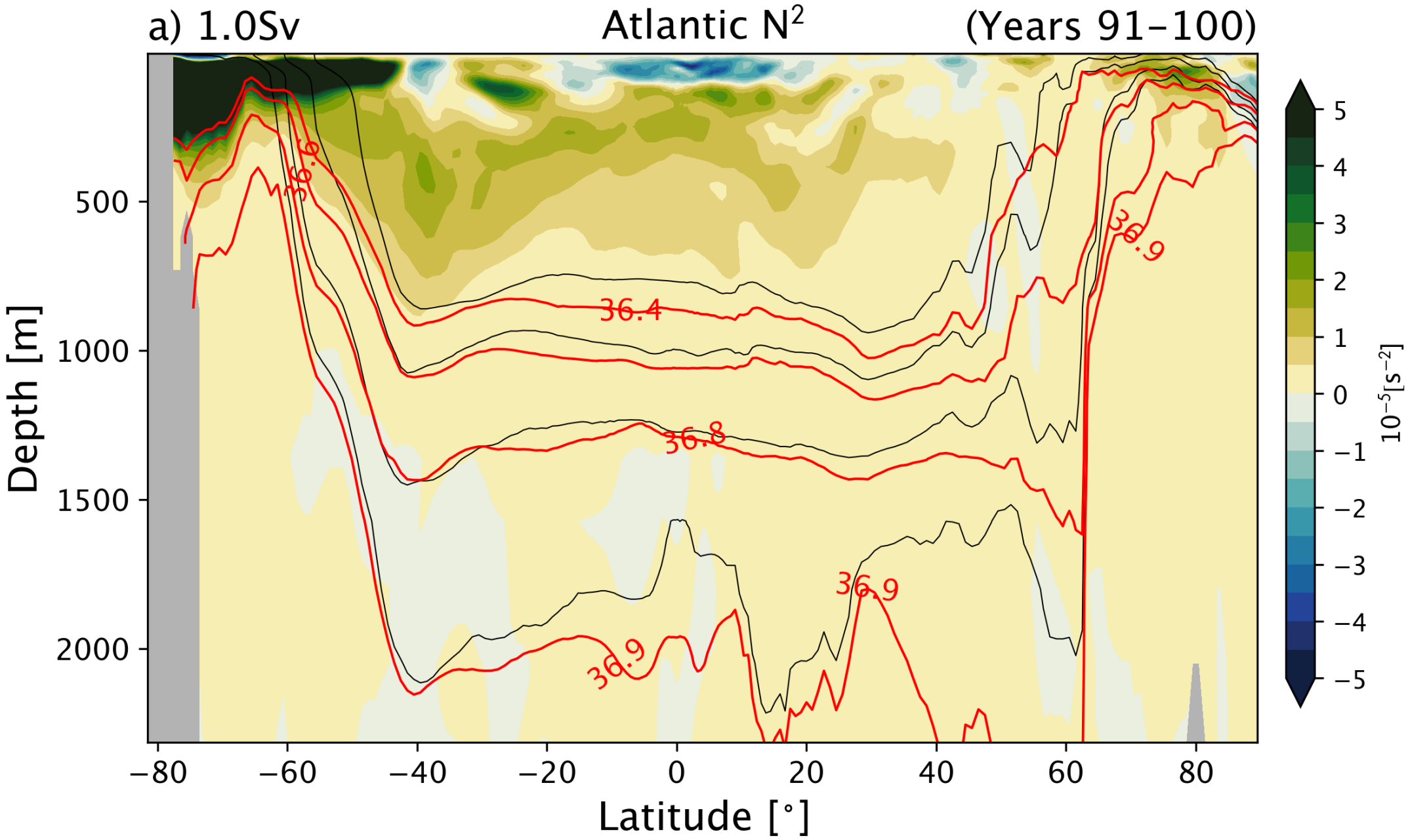
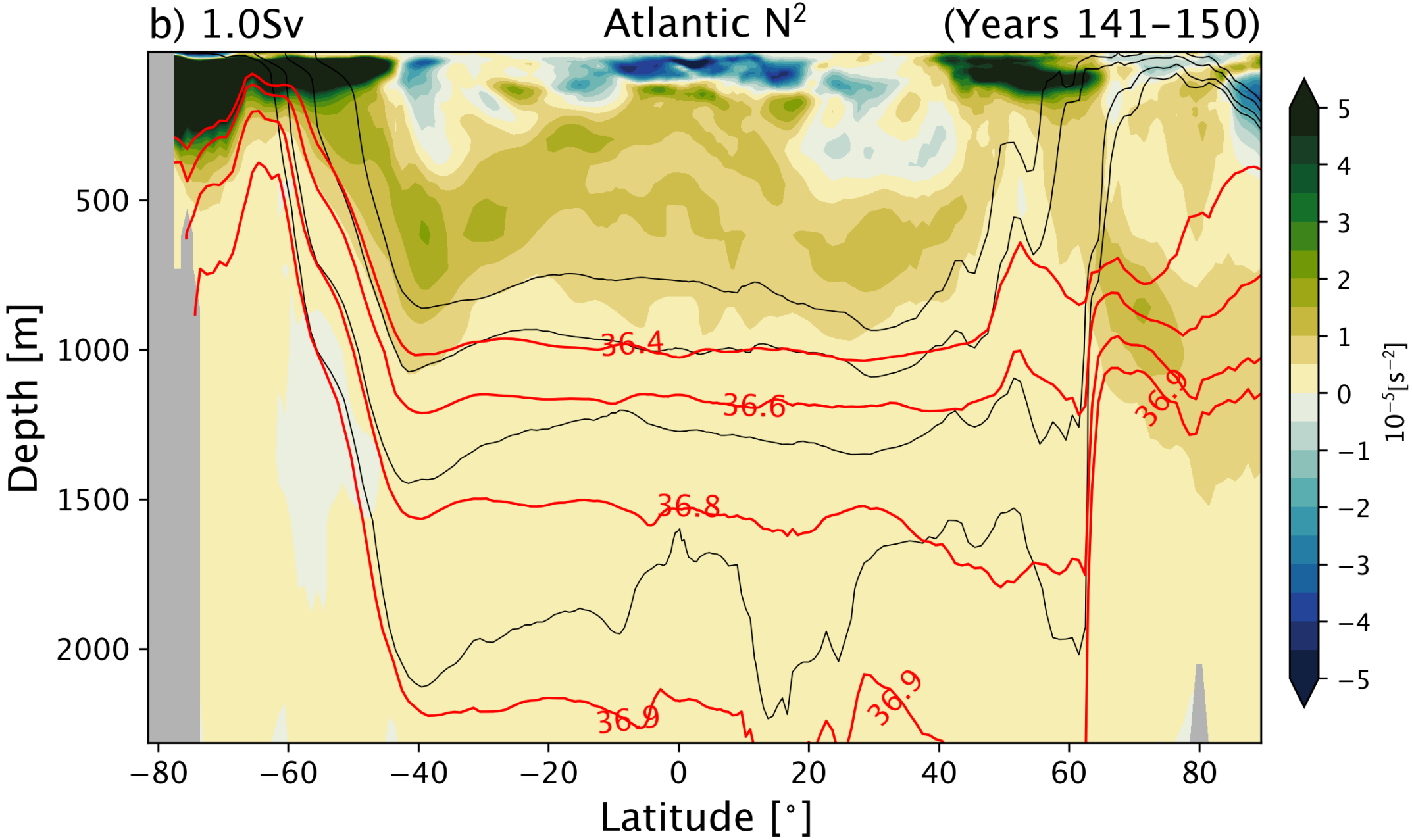
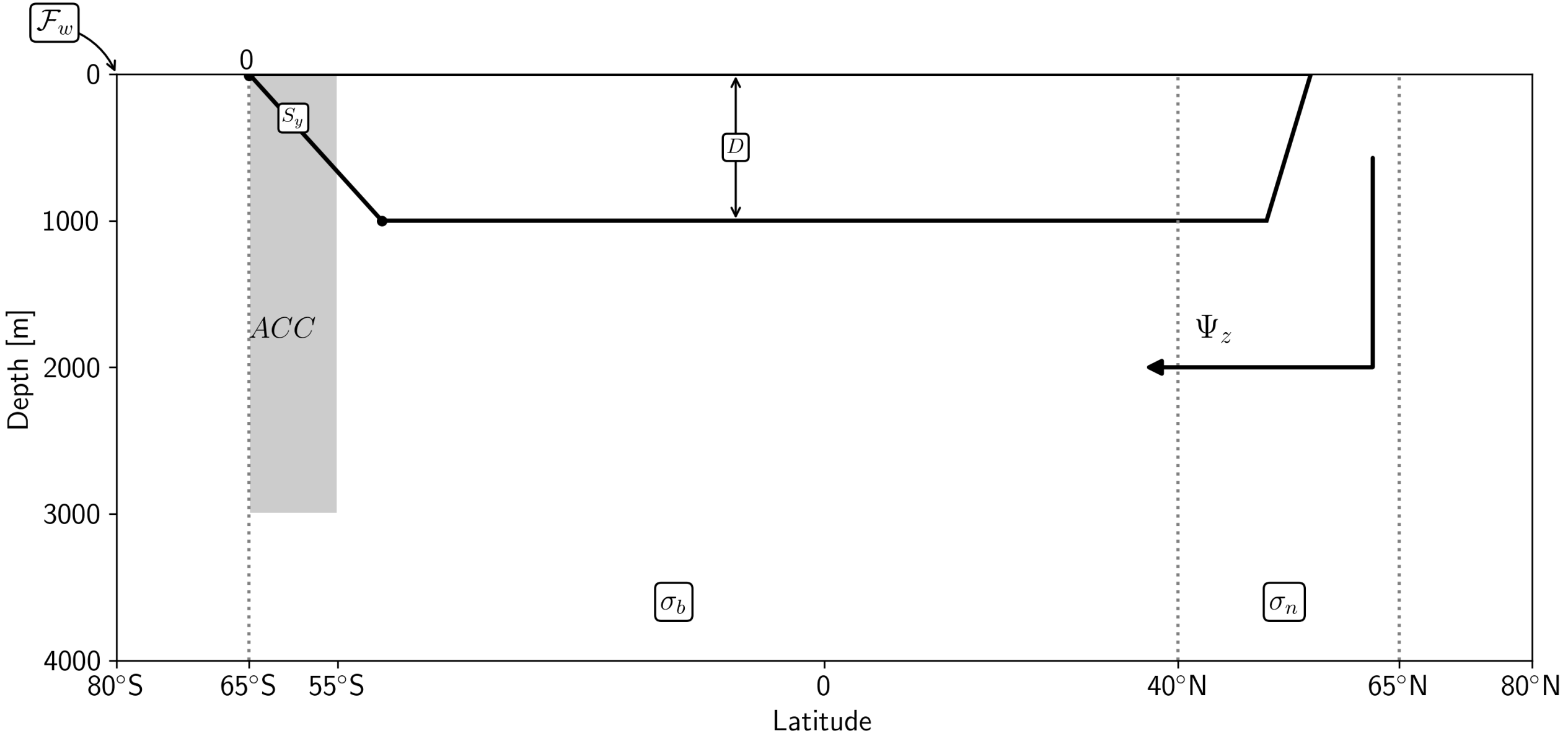


What happens to the ACC? Pycnocline depth adjustment



A final picture: AMOC, ACC, and interior stratification



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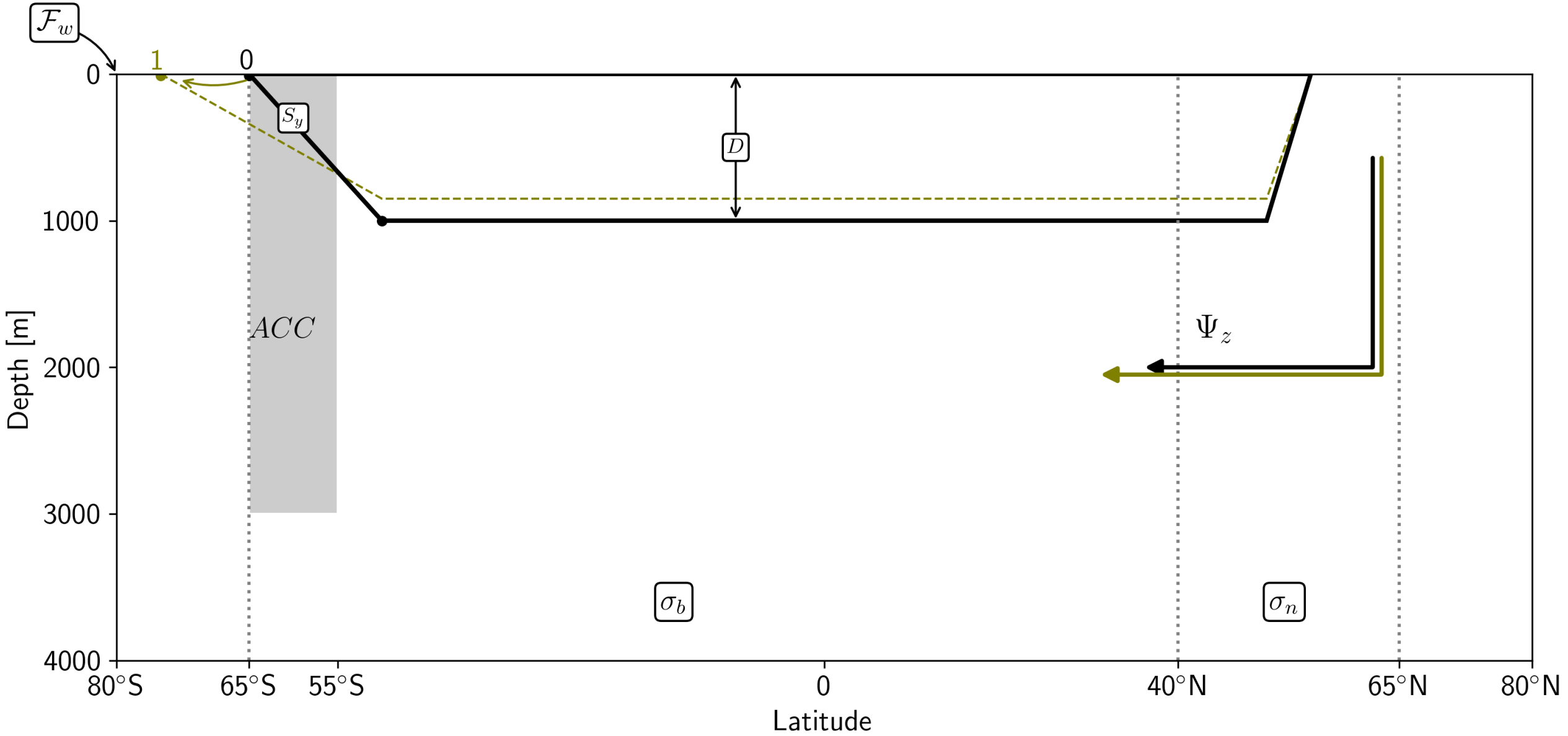
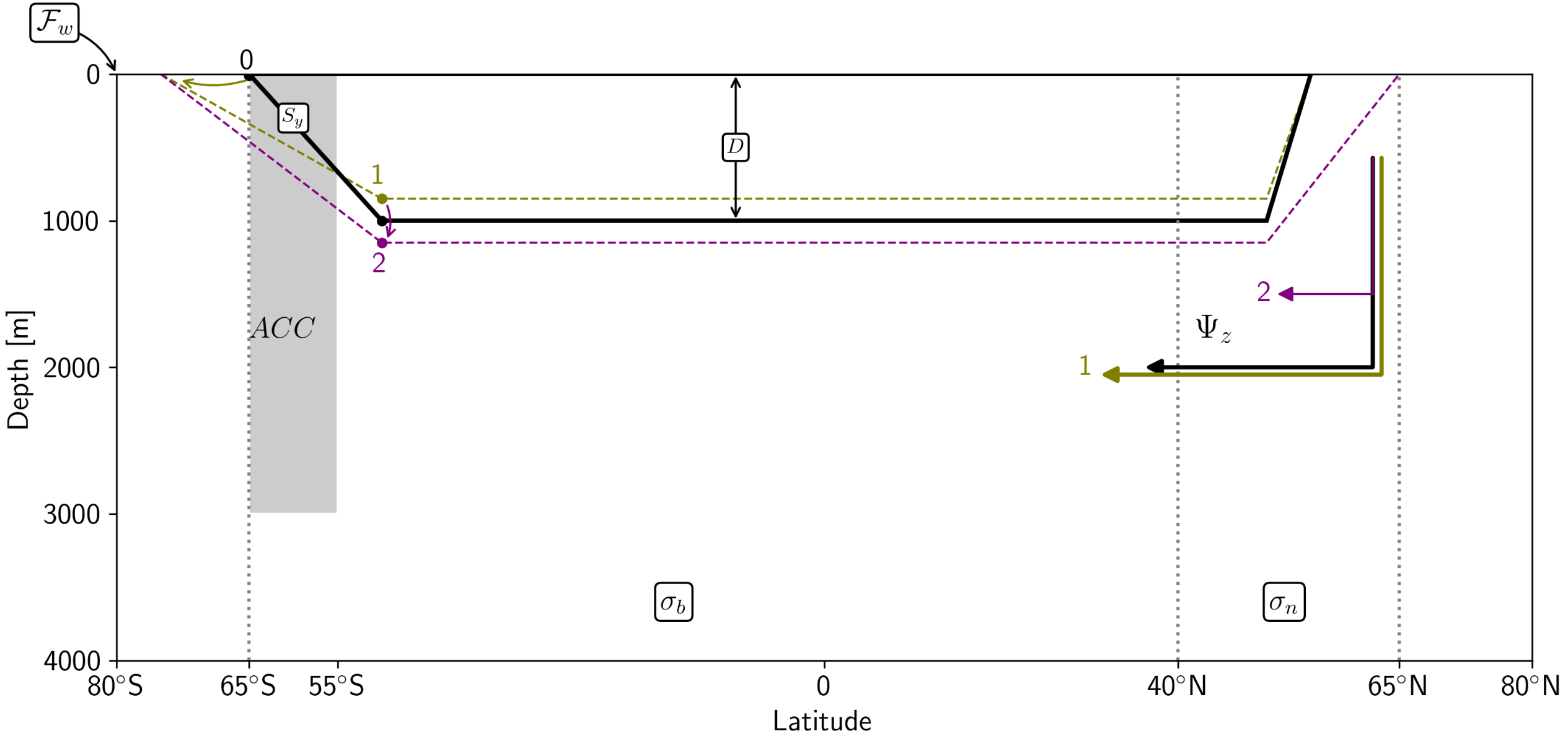
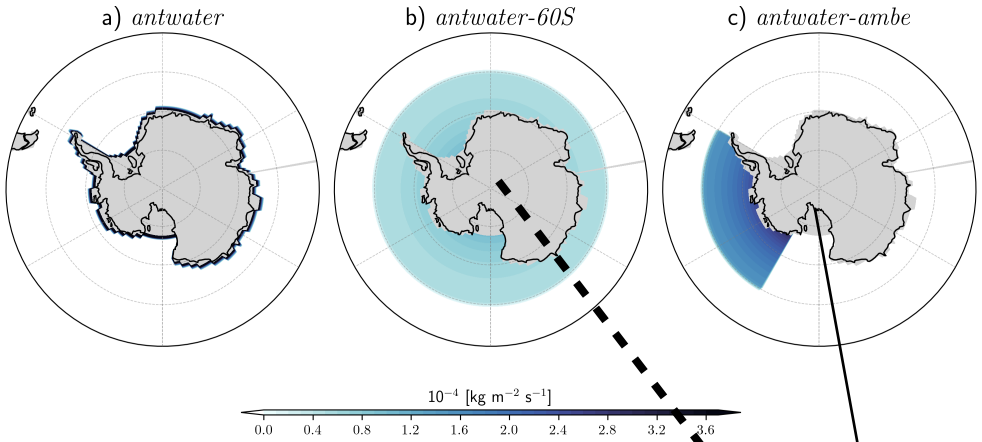


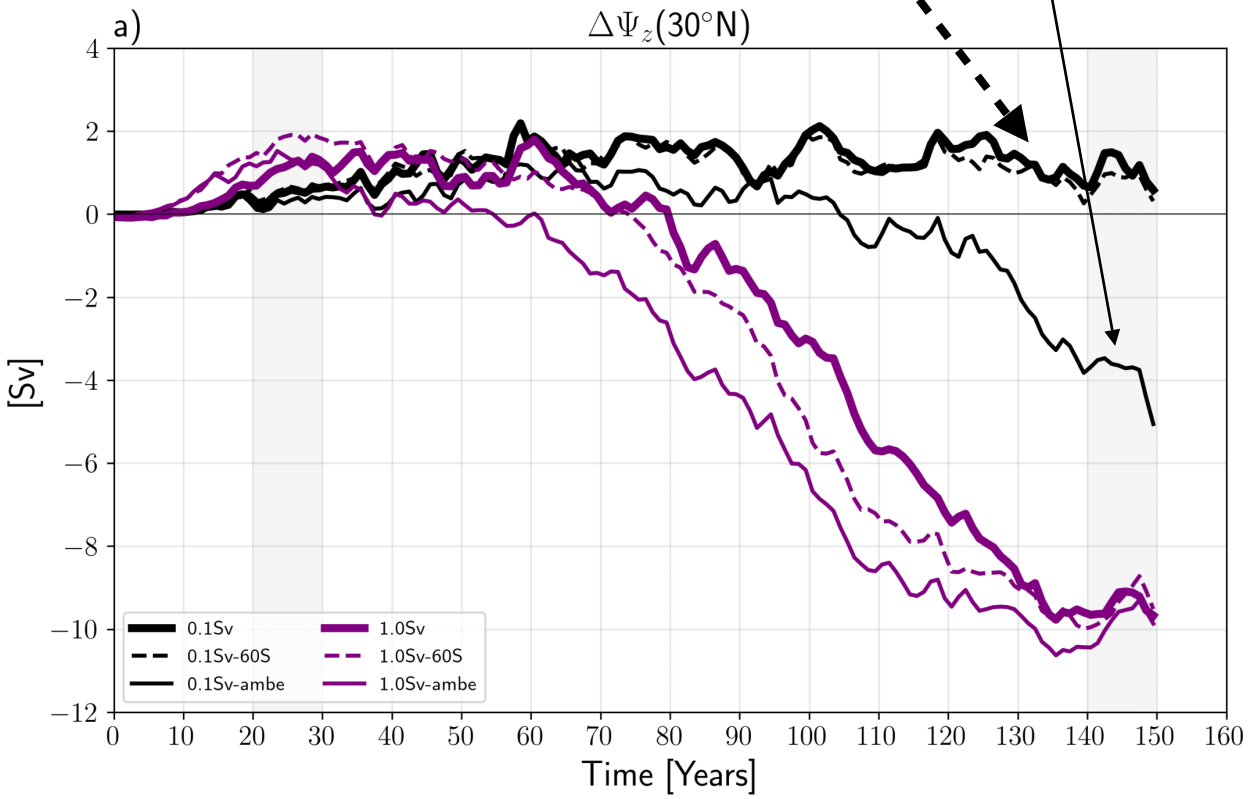
A final picture: AMOC, ACC, and interior stratification

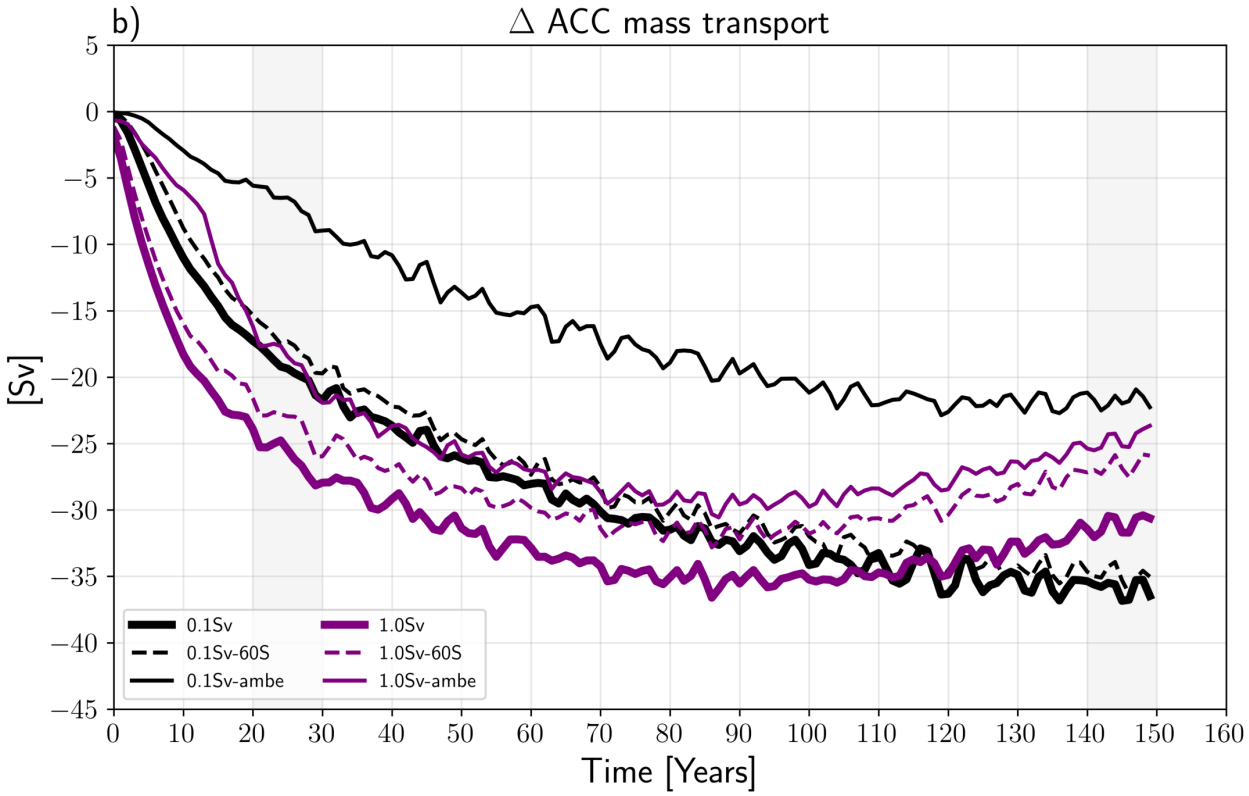


Where you discharge freshwater matters



- not so much for 60S
- Ambe more effectively advects anomalies into NA





Some Conclusions

- FW discharge from Antarctic Ice Sheet can be advected into the North Atlantic and **weaken the AMOC after about 80/90 years.**
- A plausible **FW forcing >0.2 Sv** is needed for inducing a significant weakening.
- However, the **initial response is a strengthening of the AMOC**, induced by the altered meridional density gradient in the basin (*thermal wind response*), which could partially offset the climate change-induced and GIS-induced weakening of the AMOC.
- **AABW production is significantly reduced** with 0.1Sv of FW discharge, and insensitive to larger forcing.
- Similarly, the **ACC weakens considerably** with all FW forcing, but can partially recover due to interior pycnocline adjustment.
- How ***large*** is ***large*** *enough*? …
- What happens in a coupled framework?