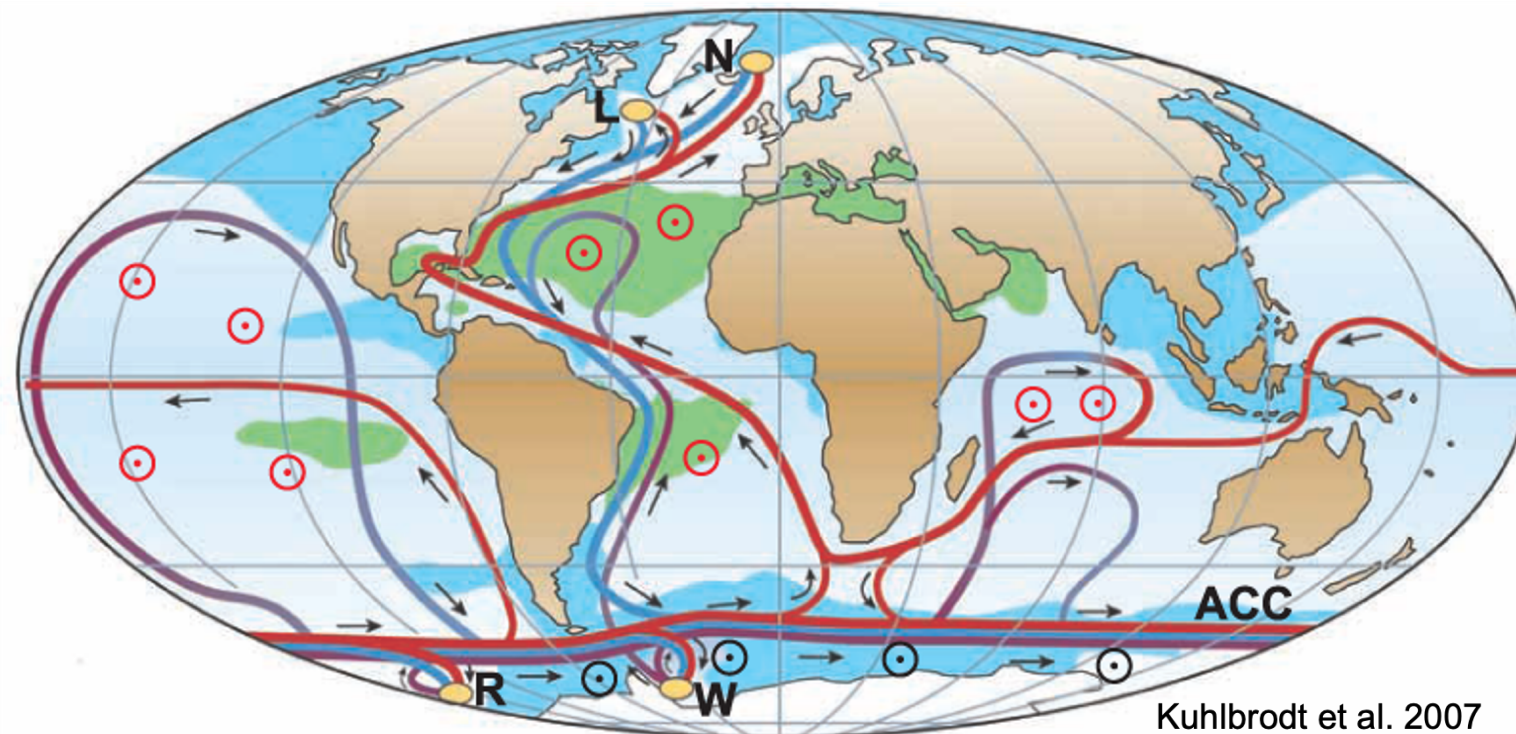


The Antarctic Ice Sheet and the AMOC: a story of interhemispheric transient responses

Riccardo Farneti & Zihan Song

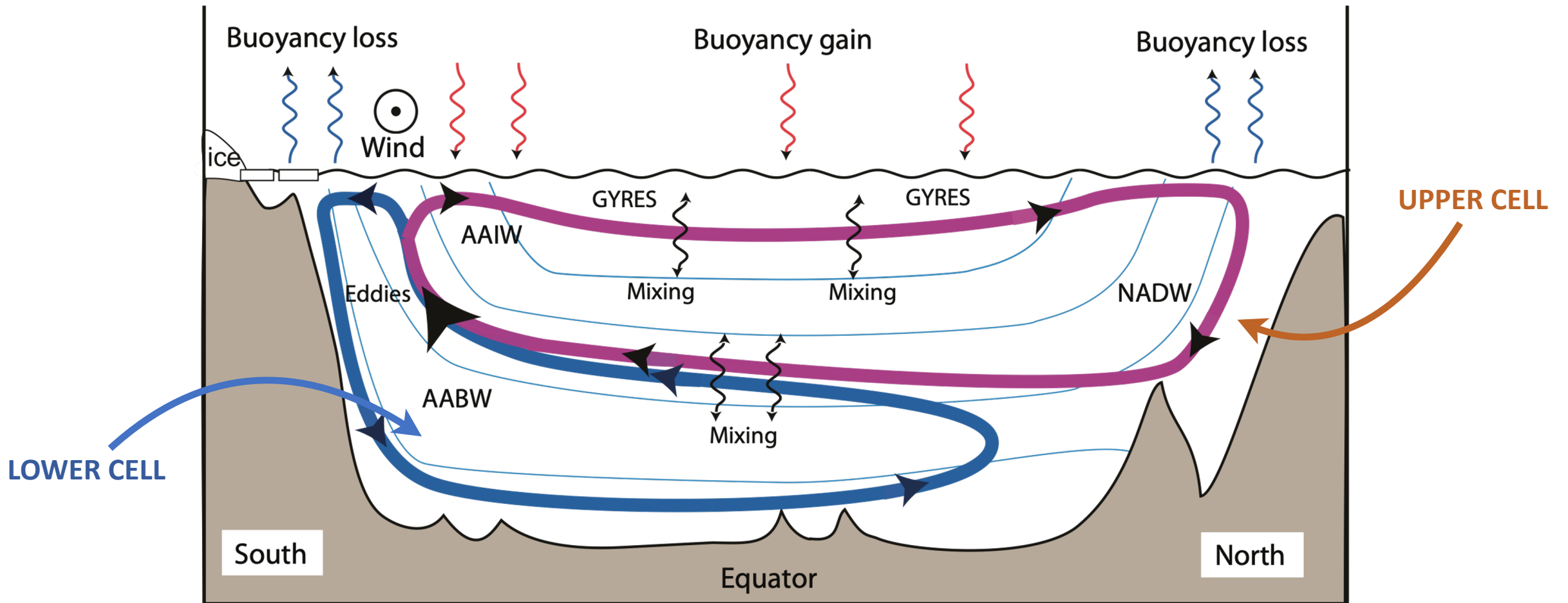


Kuhlbrodt et al. 2007

- | | | | | | |
|--|----------------------|--|-------------------------|----------|--------------|
| | Surface flow | | Wind-driven upwelling | L | Labrador Sea |
| | Deep flow | | Mixing-driven upwelling | N | Nordic Seas |
| | Bottom flow | | Salinity > 36 ‰ | W | Weddell Sea |
| | Deep Water Formation | | Salinity < 34 ‰ | R | Ross Sea |



First, some background: the AMOC

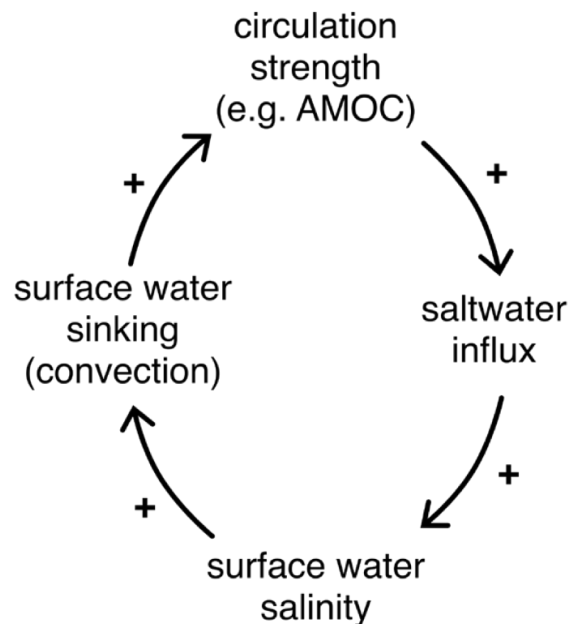


The Atlantic Meridional Overturning Circulation (AMOC)

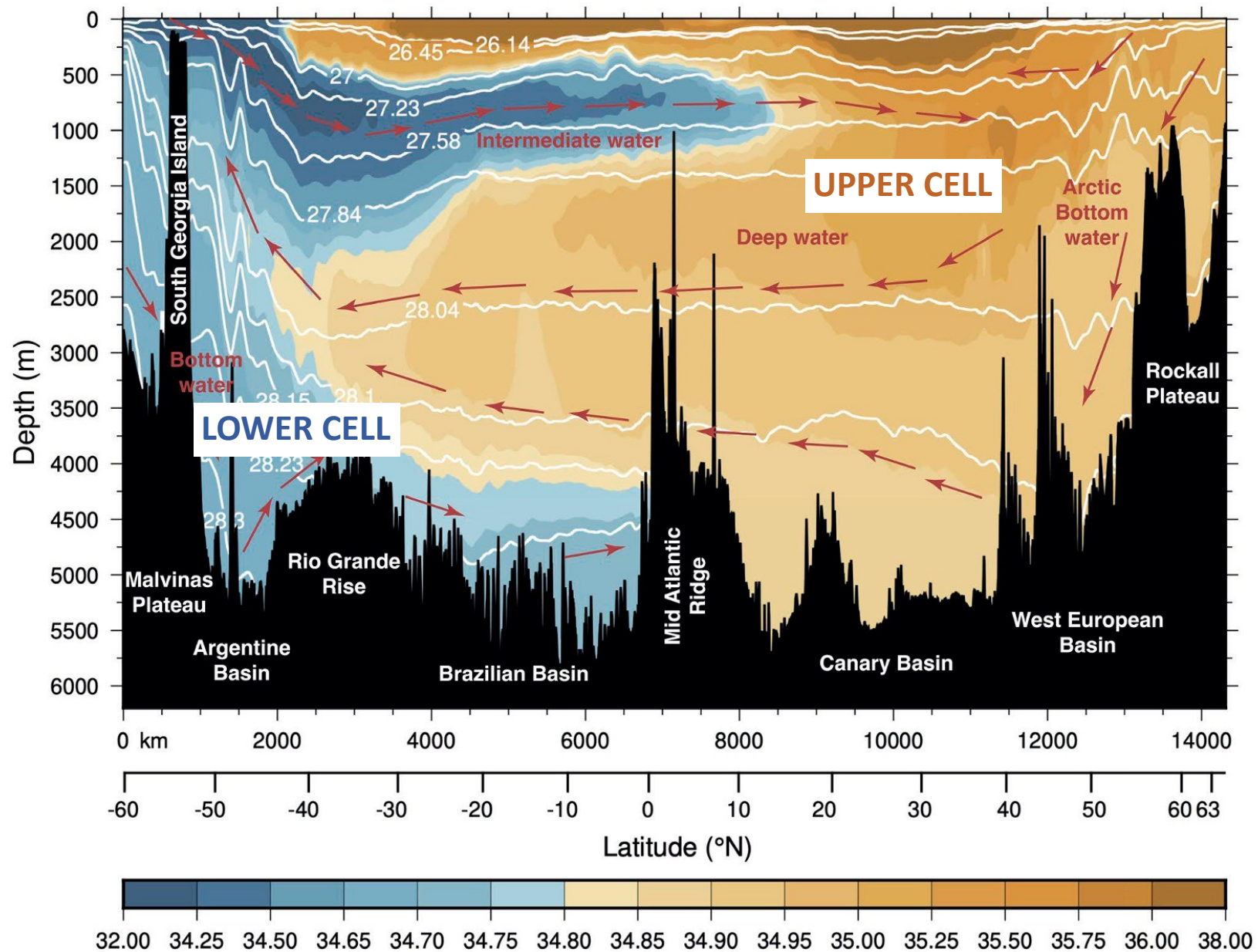
- It transports mass, heat, nutrients and regulates our climate
- It varies naturally on decadal and longer timescales
- It is also one of the main mechanisms for ocean heat and CO₂ uptake

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

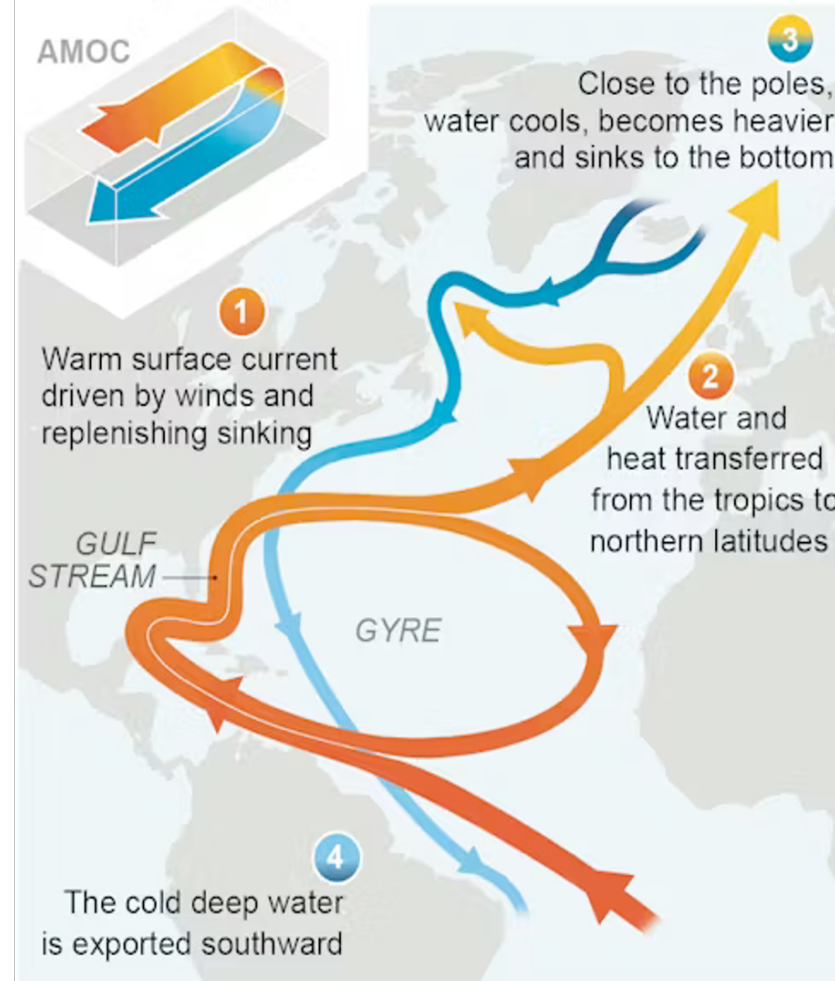


First, some background: What will happen to the AMOC?

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

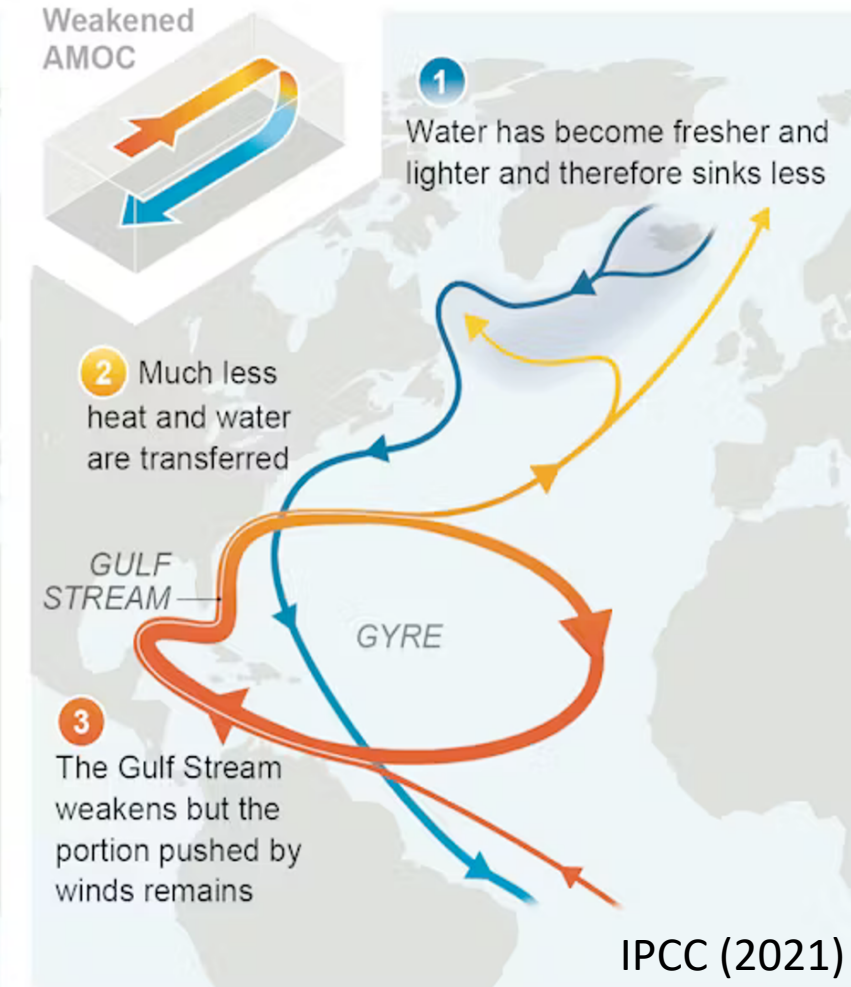
Today

The Gulf Stream is part of both the horizontal, subtropical gyre and the vertical, Atlantic Meridional Overturning Circulation (AMOC)



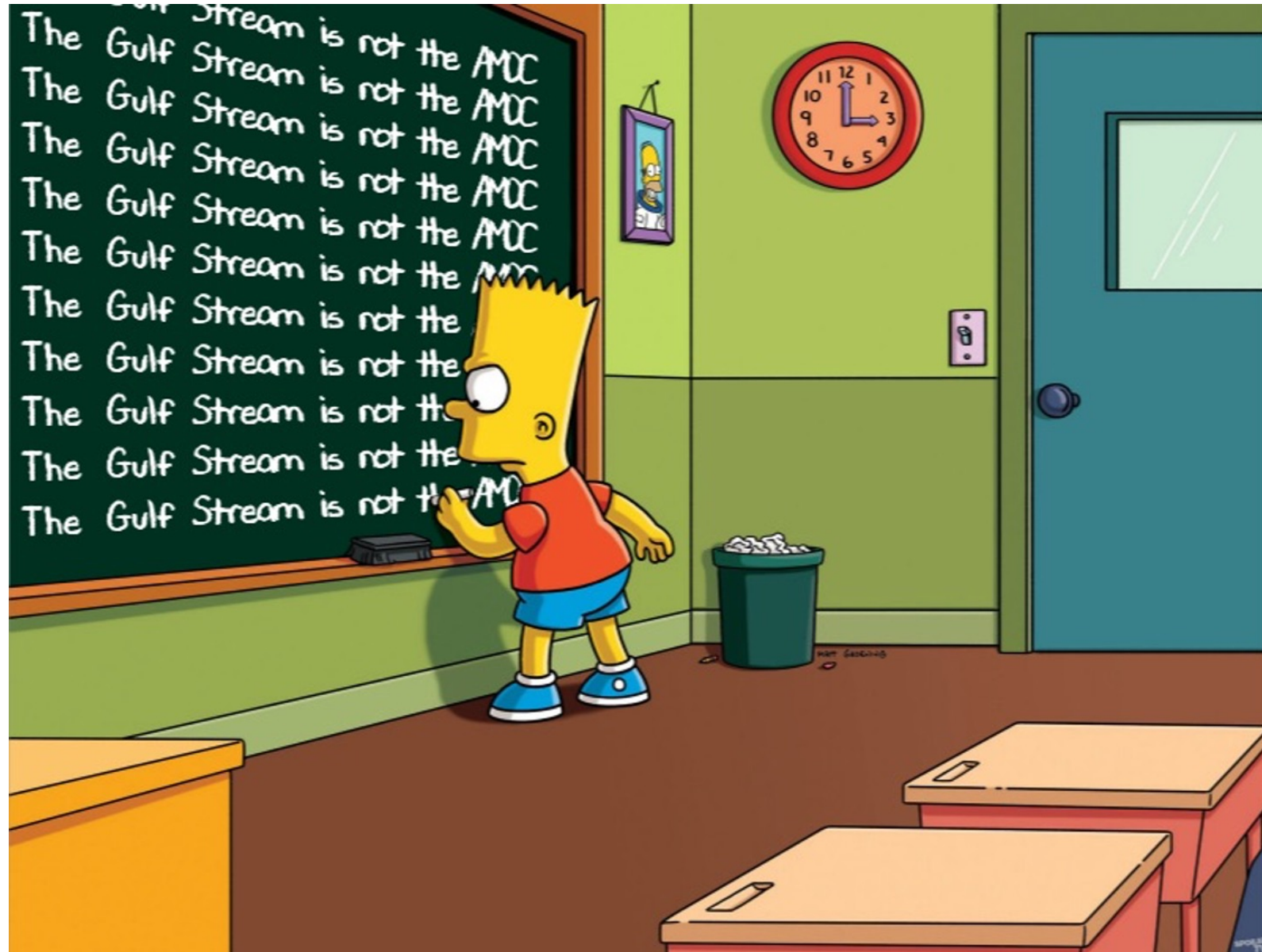
In a warmer world

Climate change weakens the AMOC, which slows the Gulf Stream down



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

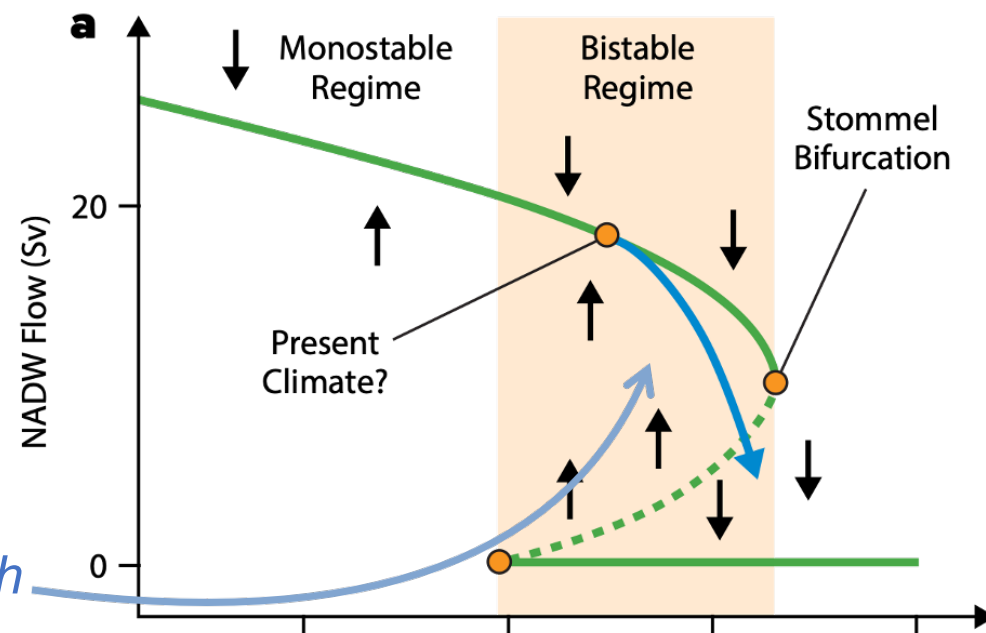
but not the Gulf Stream!
which is a Western Boundary
Current, subject to different
dynamics



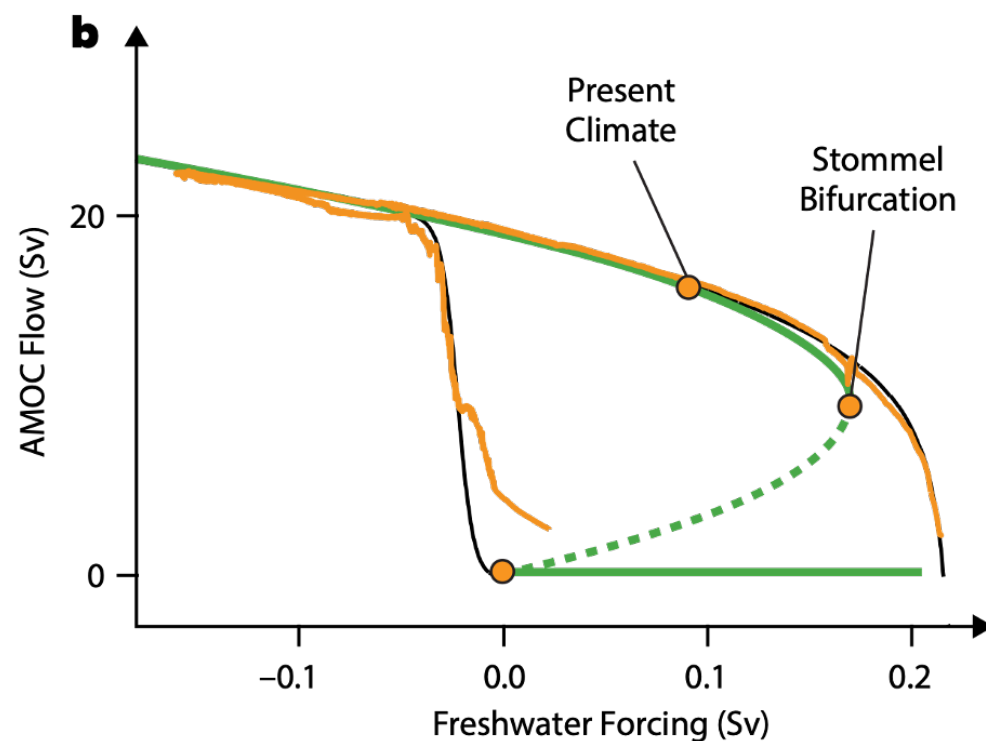
First, some background: multiple equilibria

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

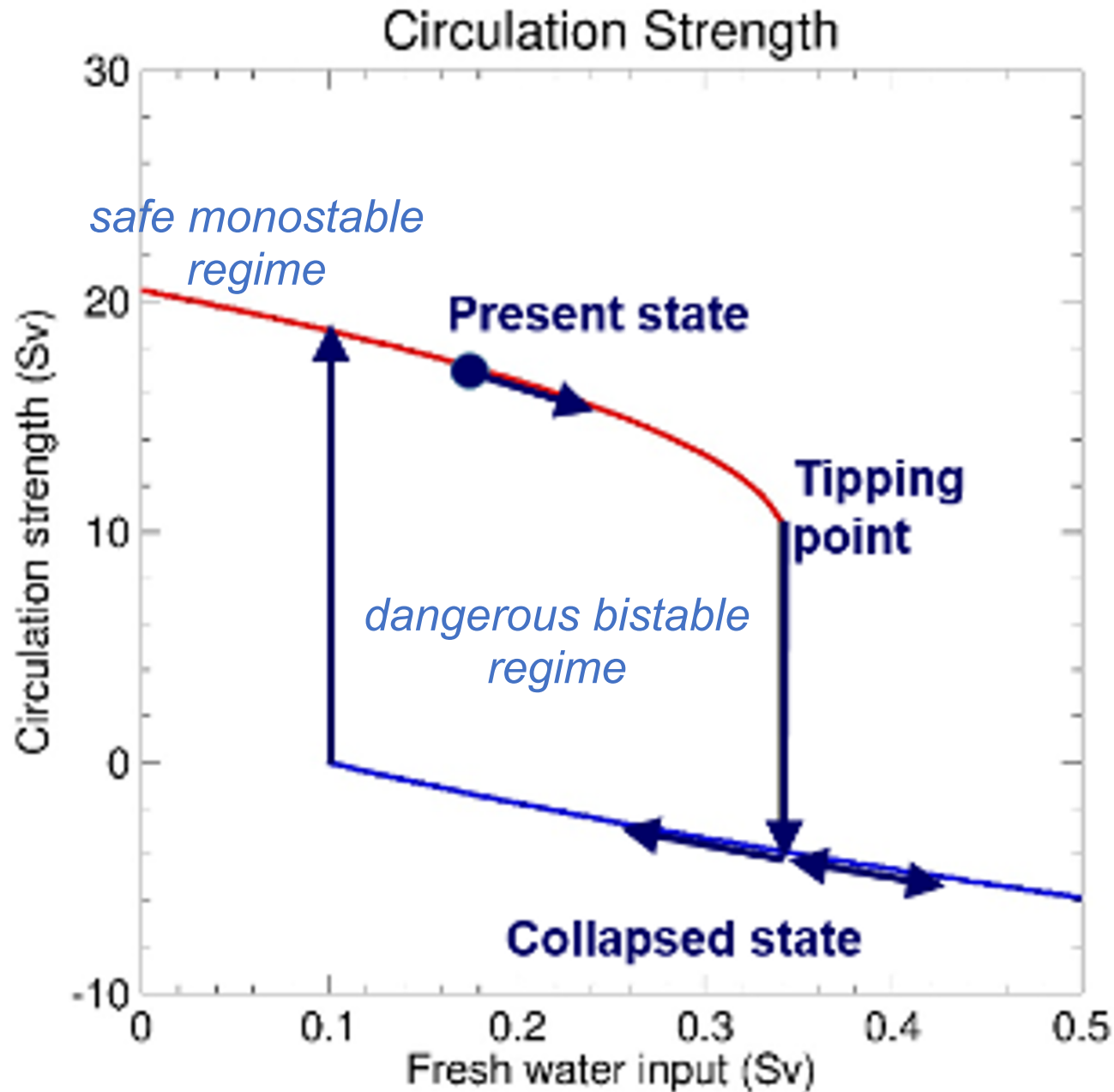
A possible climate change path



Simple and Complex models (*Rahmstorf, 1996*)



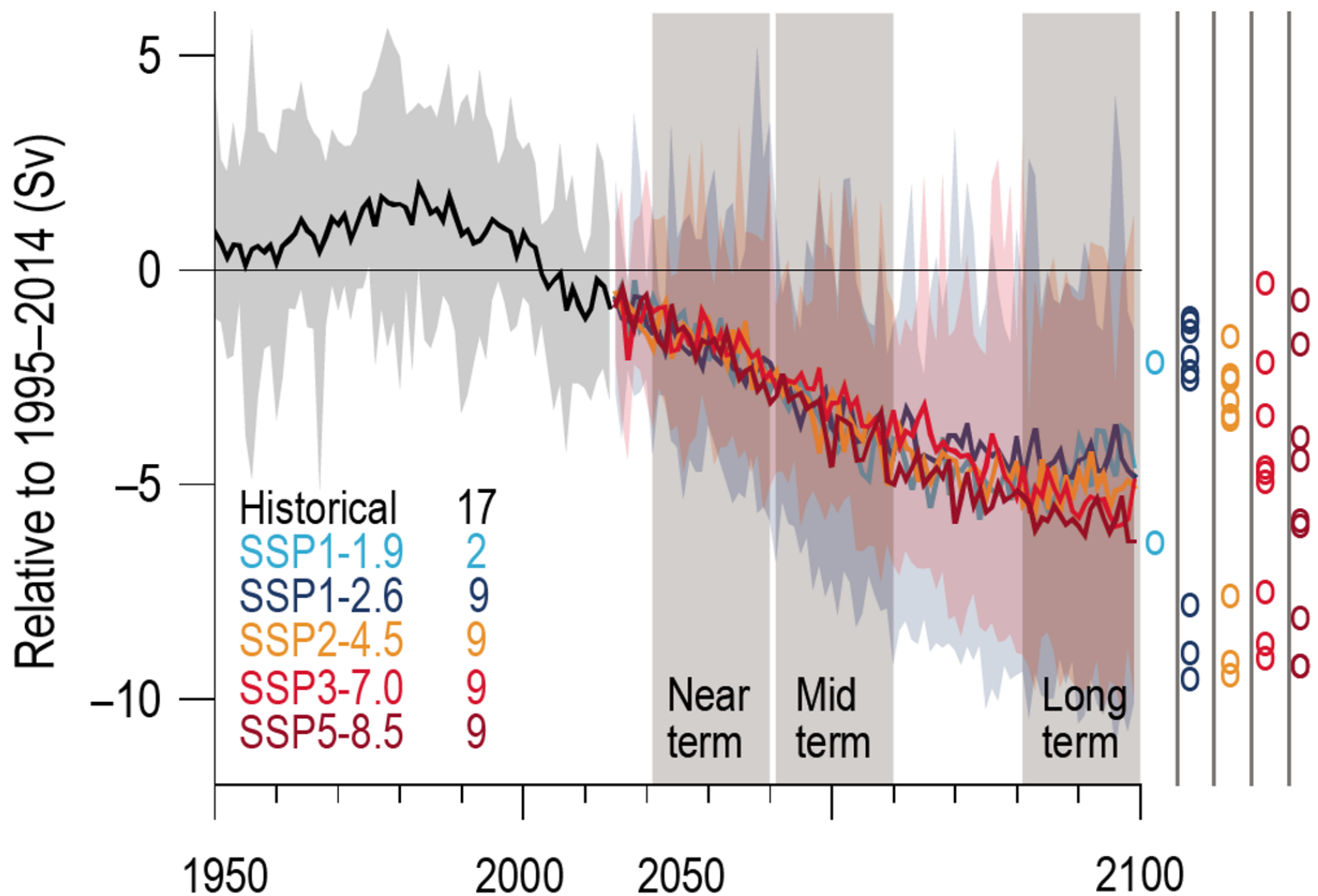
First, some background: and the question is 'where are we now?'



Tipping Point:
it happened in the past
(Dansgaard-Oeschger and
Heinrich events)

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

Atlantic meridional overturning circulation



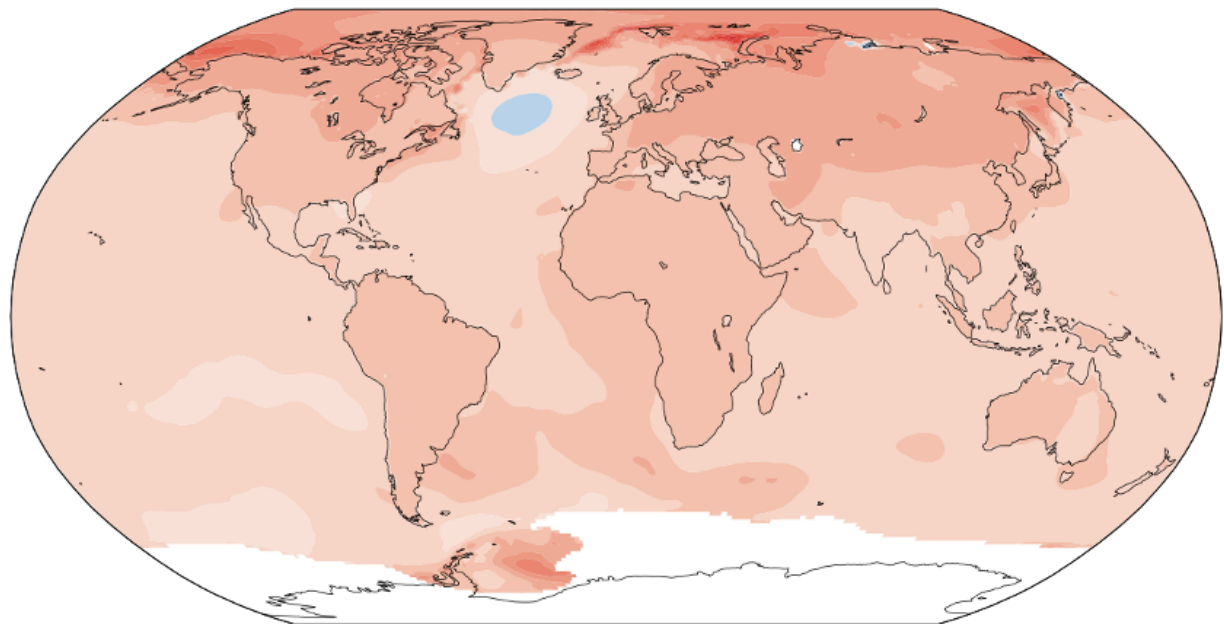
- In all scenarios, CMIP6 models project a modest weakening of the AMOC by the end of the century.
- In hosing experiments, the vast majority of models recover

HOWEVER:

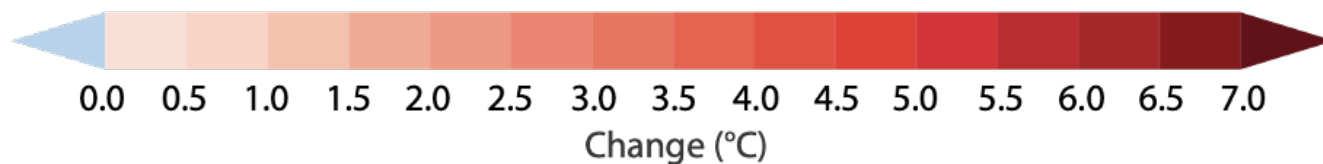
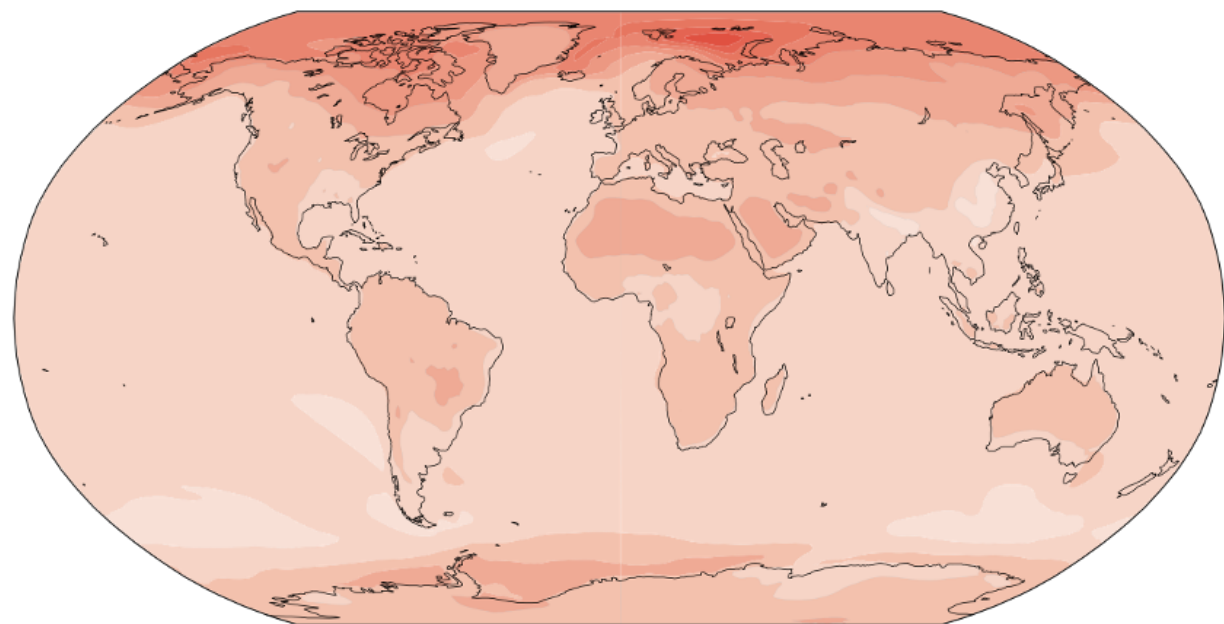
We know models might be *'too stable'*
We know models have large interior *'biases'* anchoring them in the monostable regime

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

Observed change per **1°C** global warming



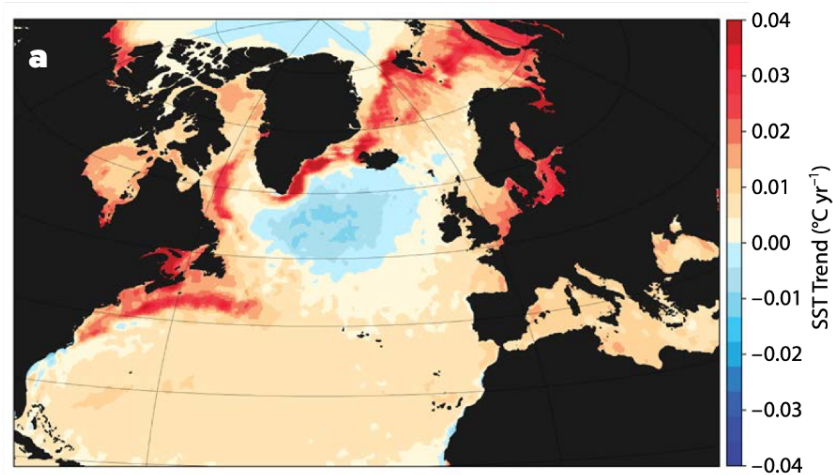
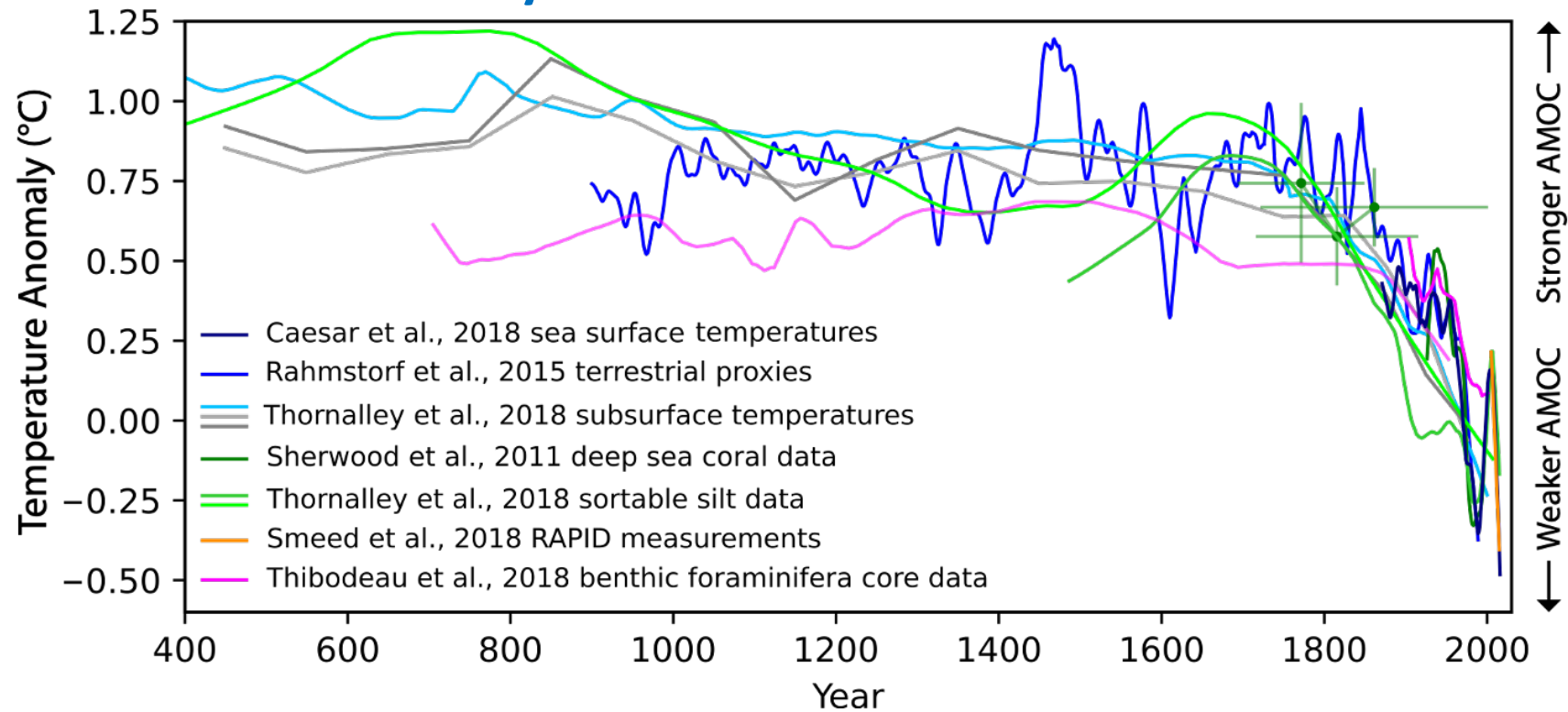
Simulated change at **1°C** global warming



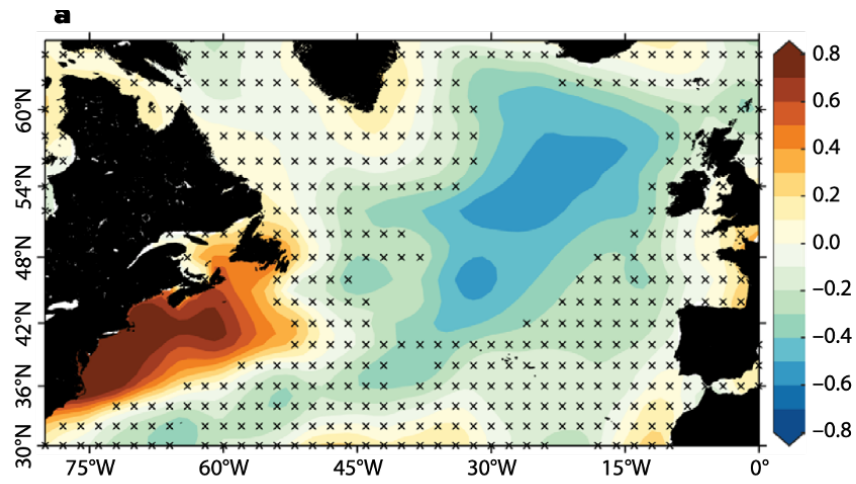
Observed and simulated surface temperature change for 1C global warming (IPCC, 2021)

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

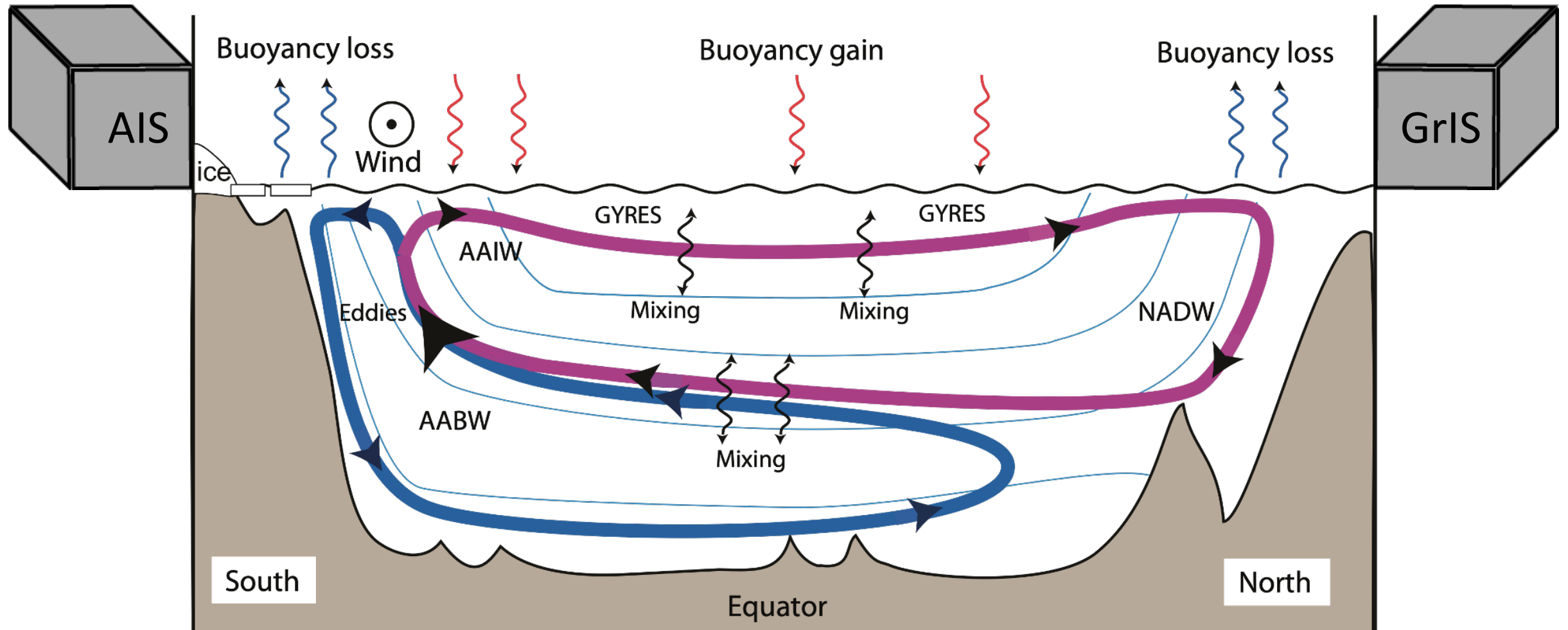


Fresh blob

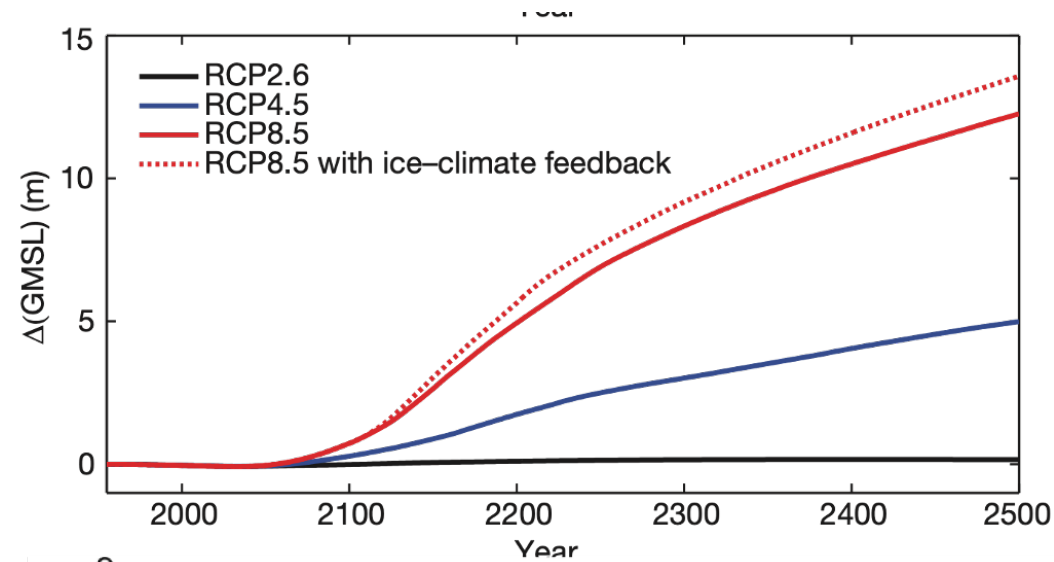
First, some background: so where lies the problem? (something big is missing!)

State-of-the-art Climate Models do not include interactive ice-sheets:

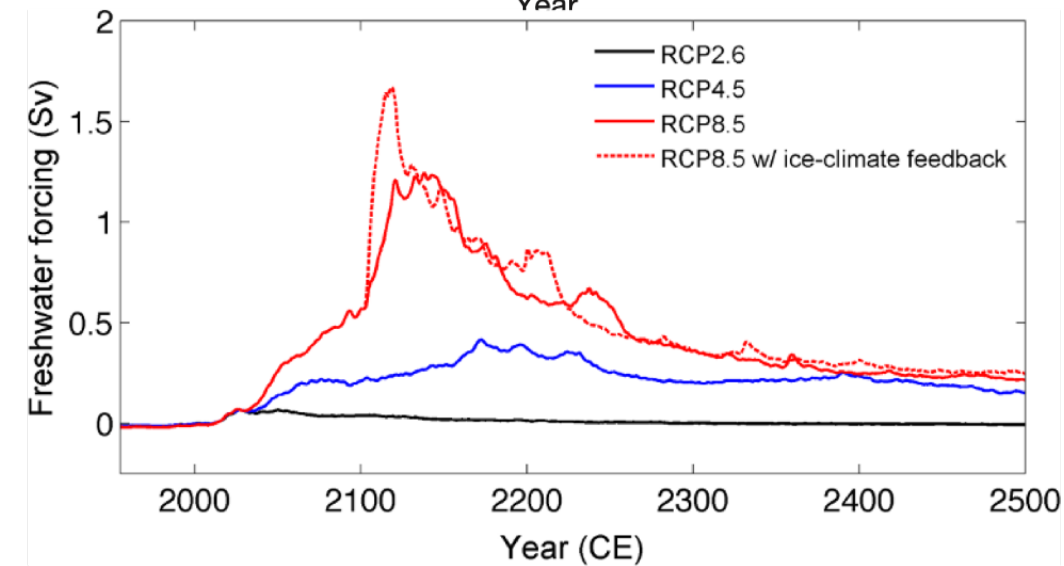
- Greenland Ice Sheet (GrIS)
- Antarctic Ice Sheet (AIS)



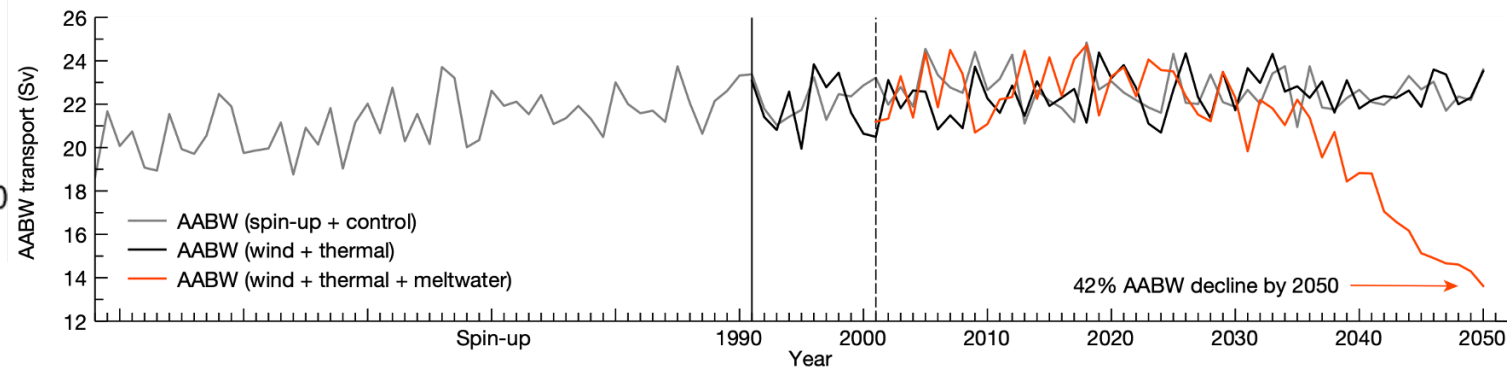
First, some background: Antarctic freshwater flux from IceSheet models



- 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 ($10^6 \text{ m}^3/\text{s}$) or $\sim 30000 \text{ Gt/yr}$
- 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)

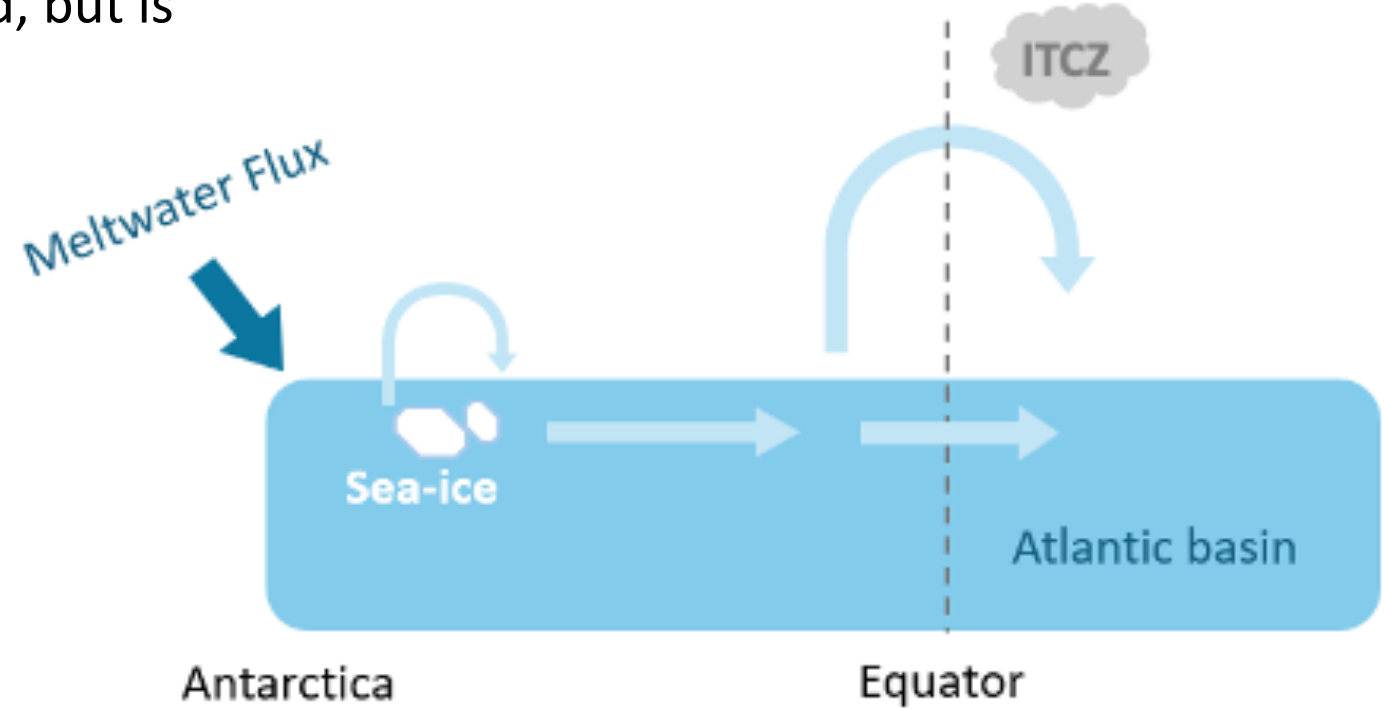
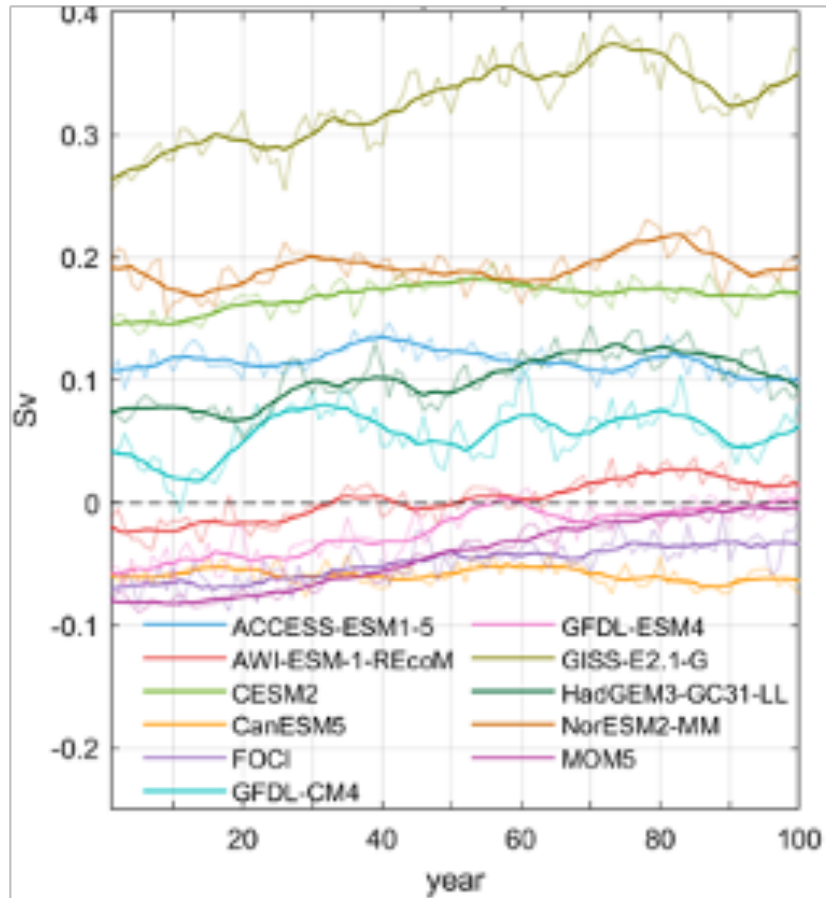


AABW decline in a model forced by 'climate change anomalies' and realistic Antarctic meltwater (Li et al., 2023)

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.
(*Song and Farneti, in preparation*)

Freshwater transport by AMOC at 34.5°S (FovS)



- ... Influencing the stability of the AMOC
(*Song and Farneti, in preparation*)



Southern Ocean Freshwater Input from Antarctica (SOFIA) initiative

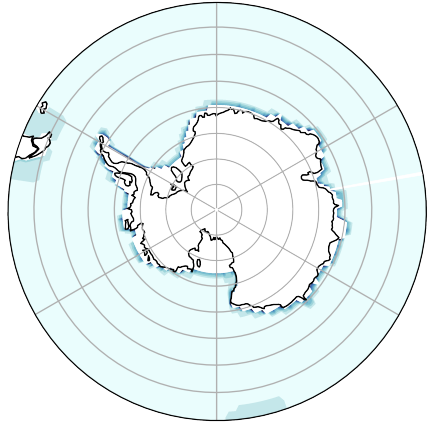
Southern Ocean
Freshwater Input
from Antarctica
(SOFIA) Initiative

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

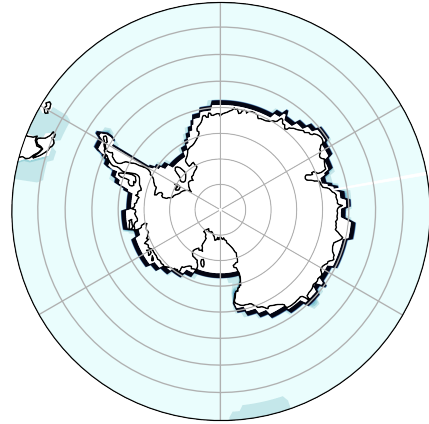


(Swart et al. 2023)

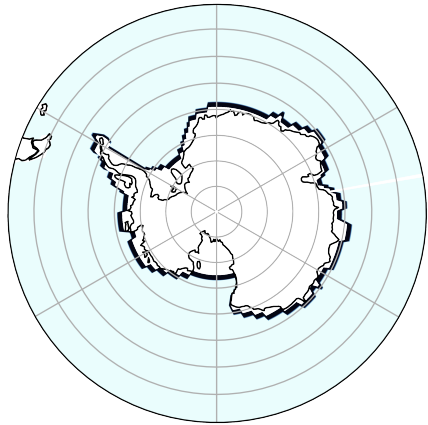
a) runoff



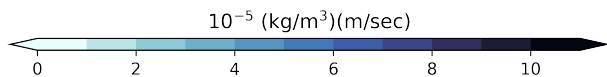
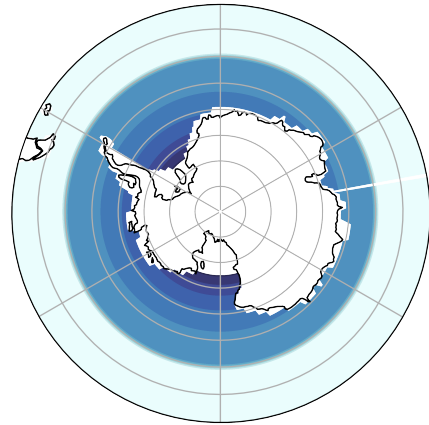
c) total runoff



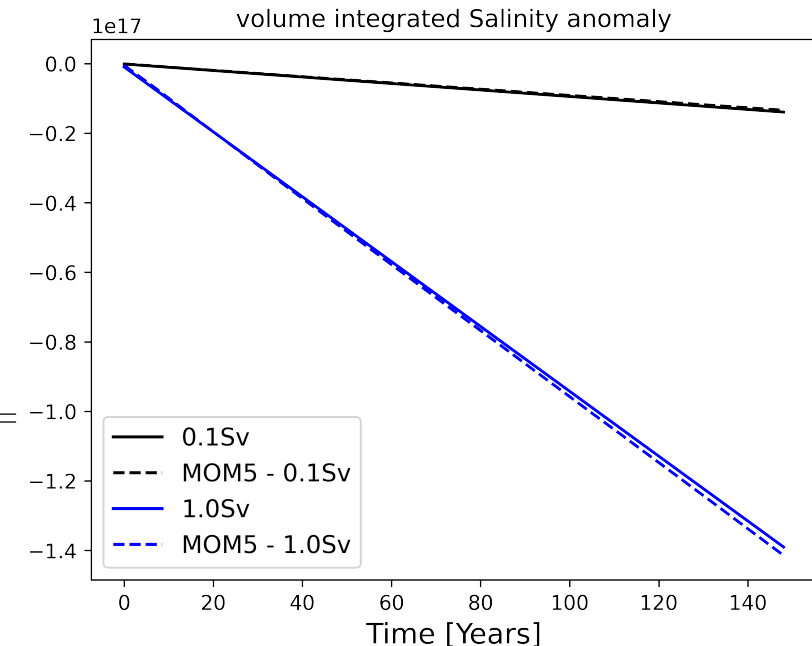
b) ideal runoff



d) ideal runoff (60S)

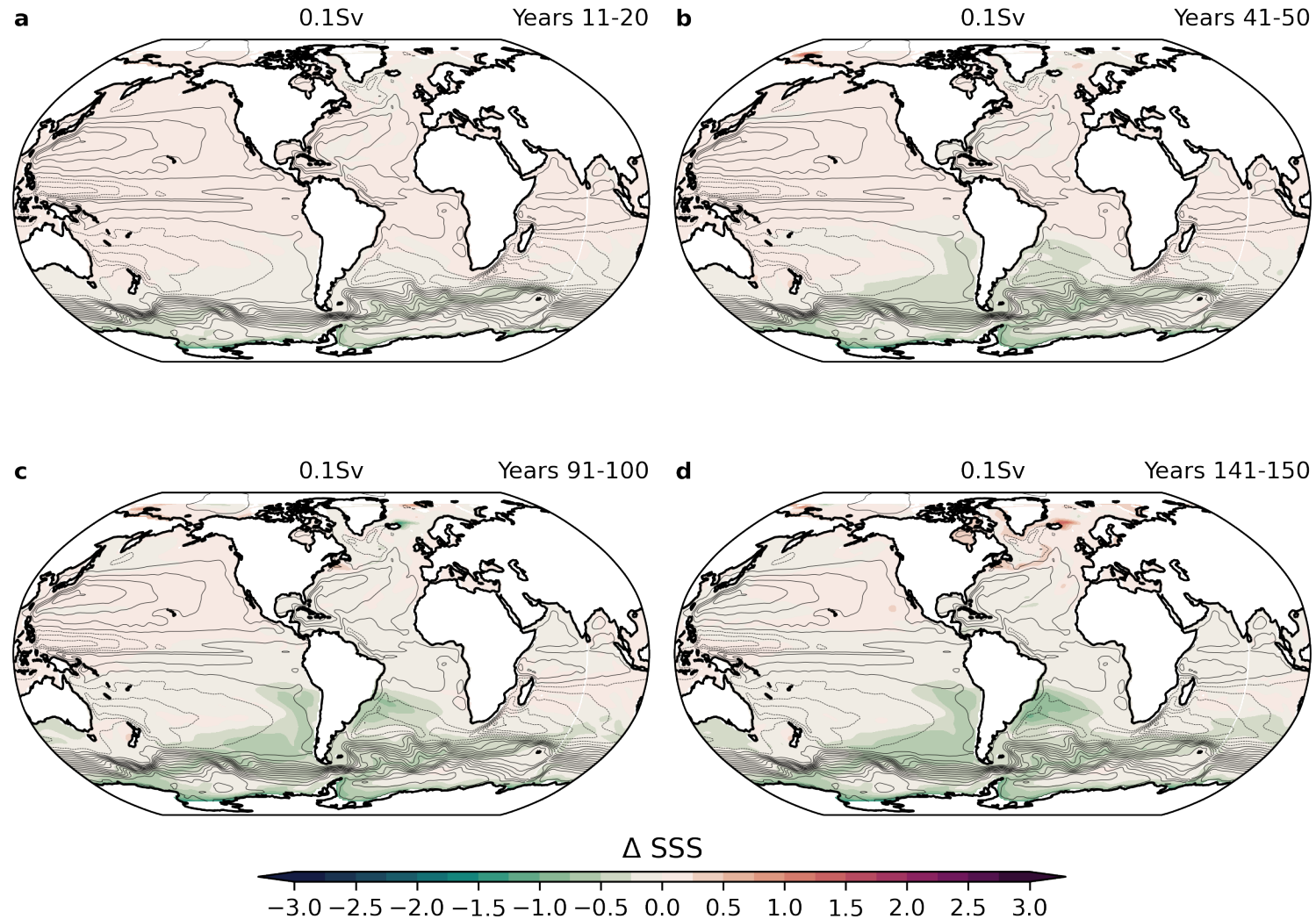


FW forcing (Sv)	FW forcing (~ Gt/yr)	coast/surface (years)	60S (years)
0.01	315	150	
0.02	630	150	
0.05	1575	150	
0.07	2205	150	
0.1	3150	150	150
0.15	4725	150	
0.2	6300	150	
0.3	9460	150	
0.4	12600	150	
0.5	15760	150	
0.6	18920	150	
0.7	22070	150	
0.8	25230	150	
0.9	28380	150	
1.0	31500	150	150



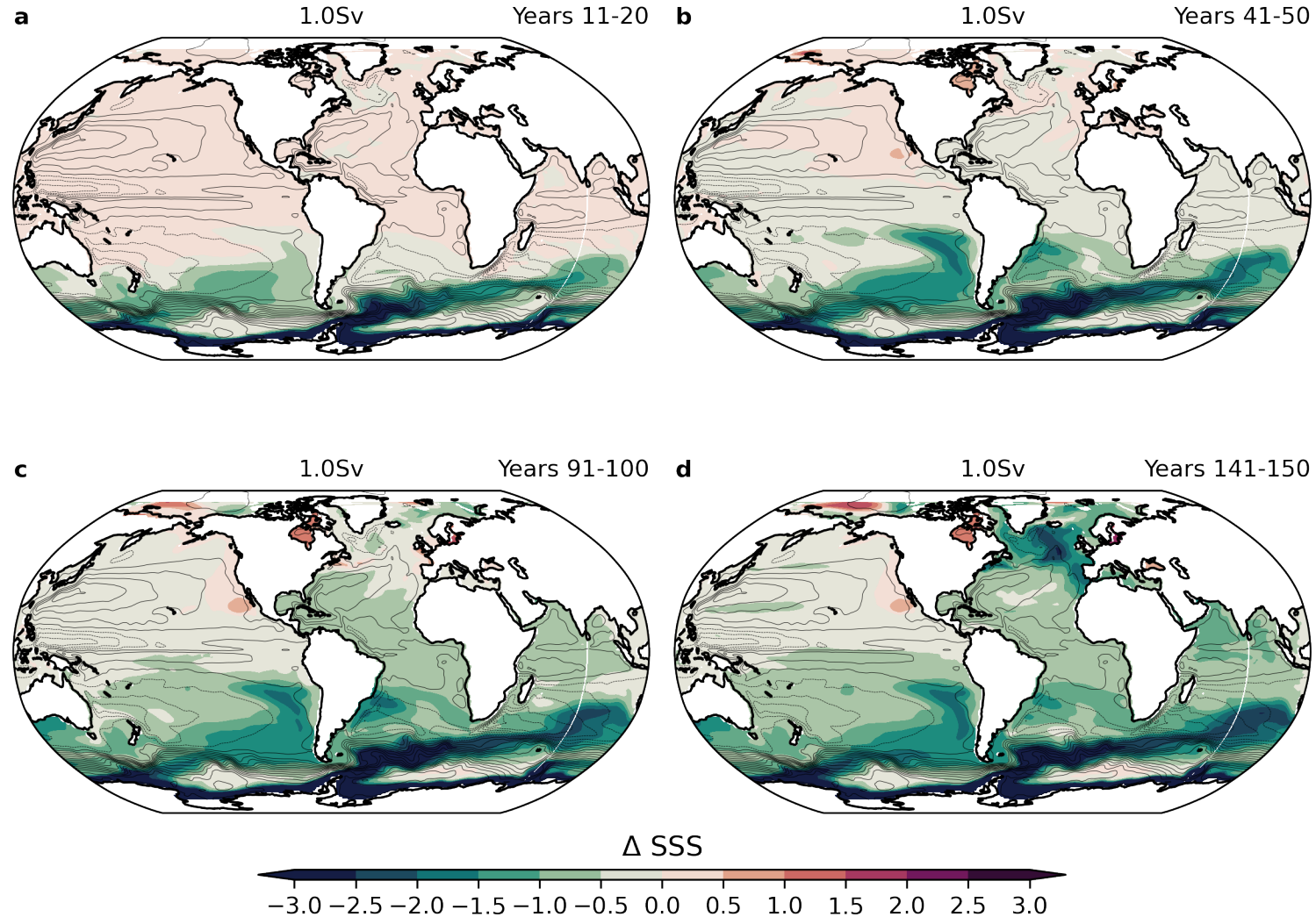
The surface response

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



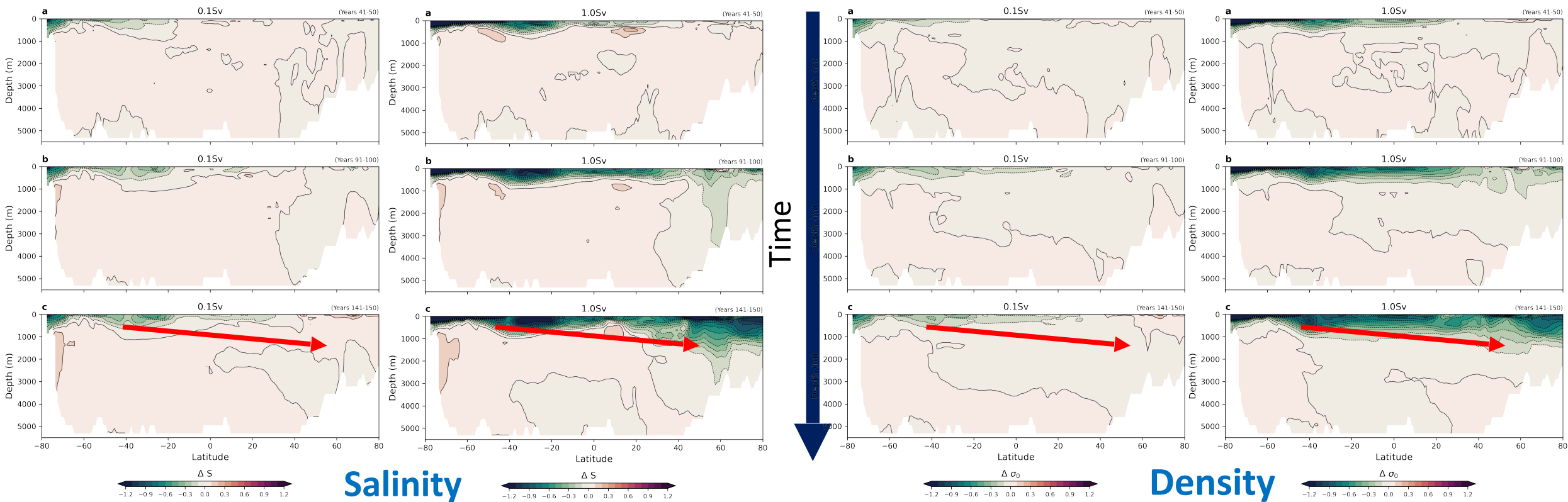
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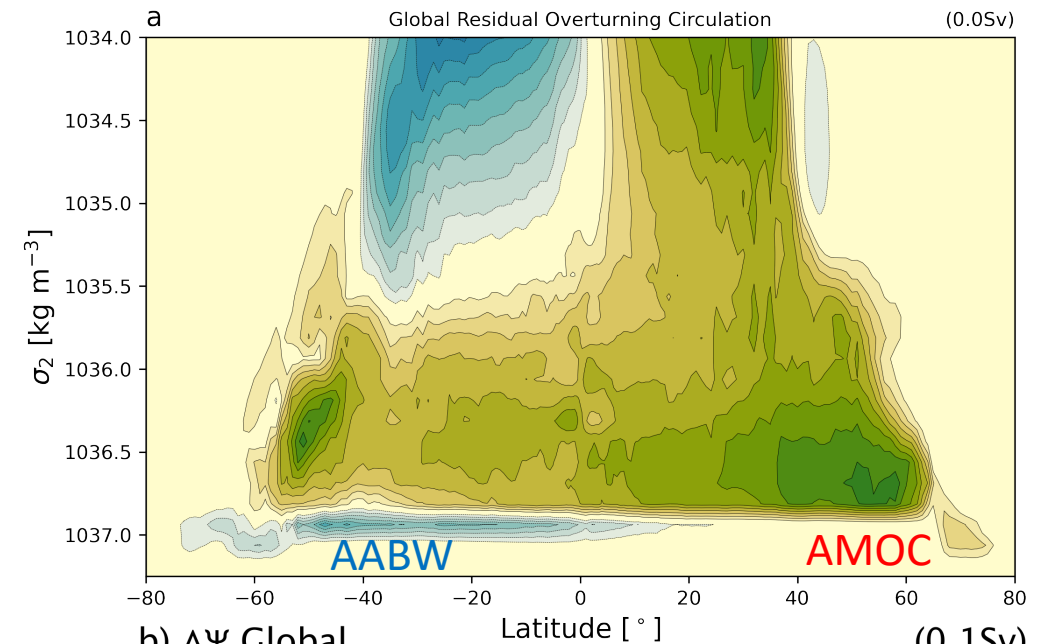


The Atlantic interior response

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

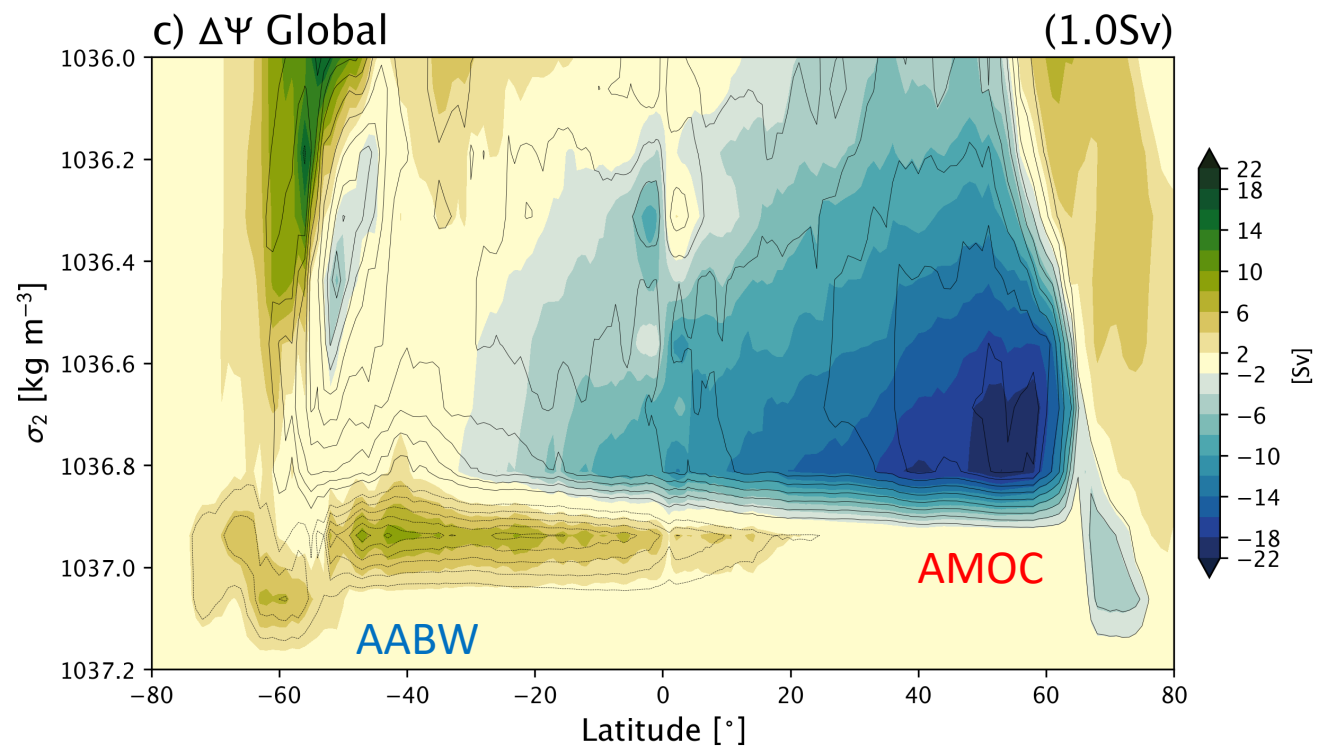
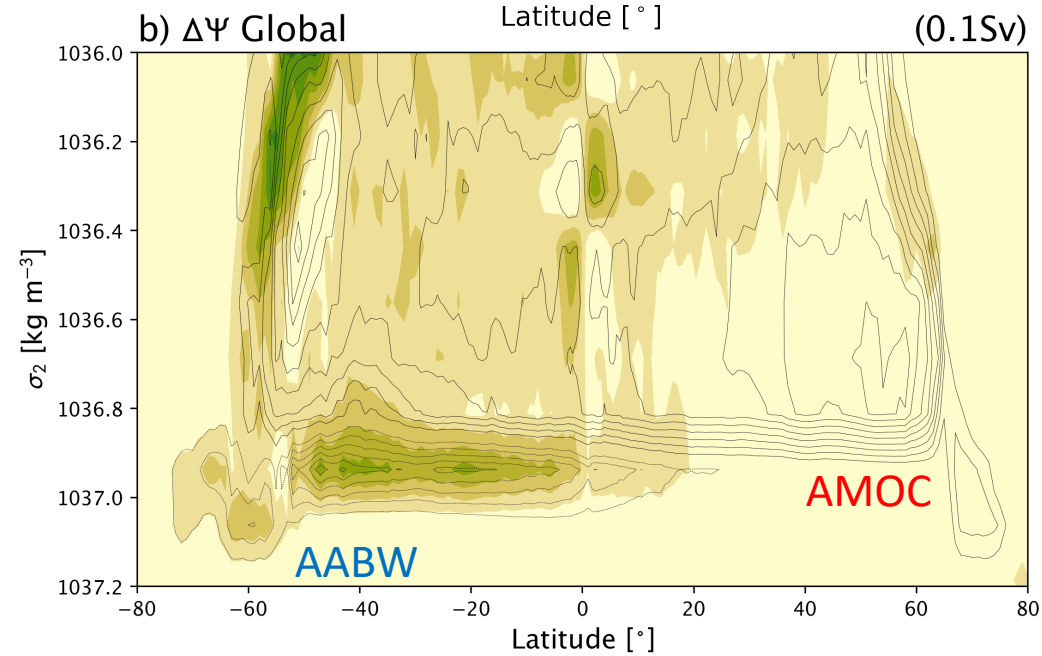


The Global MOC response (in density space)

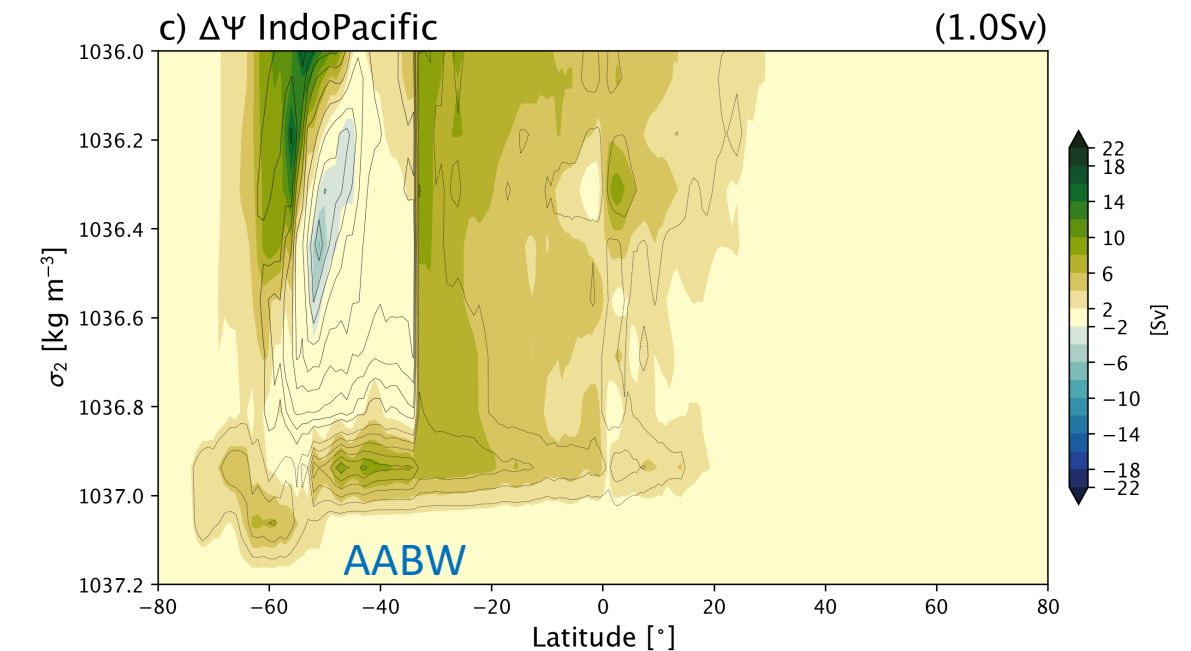
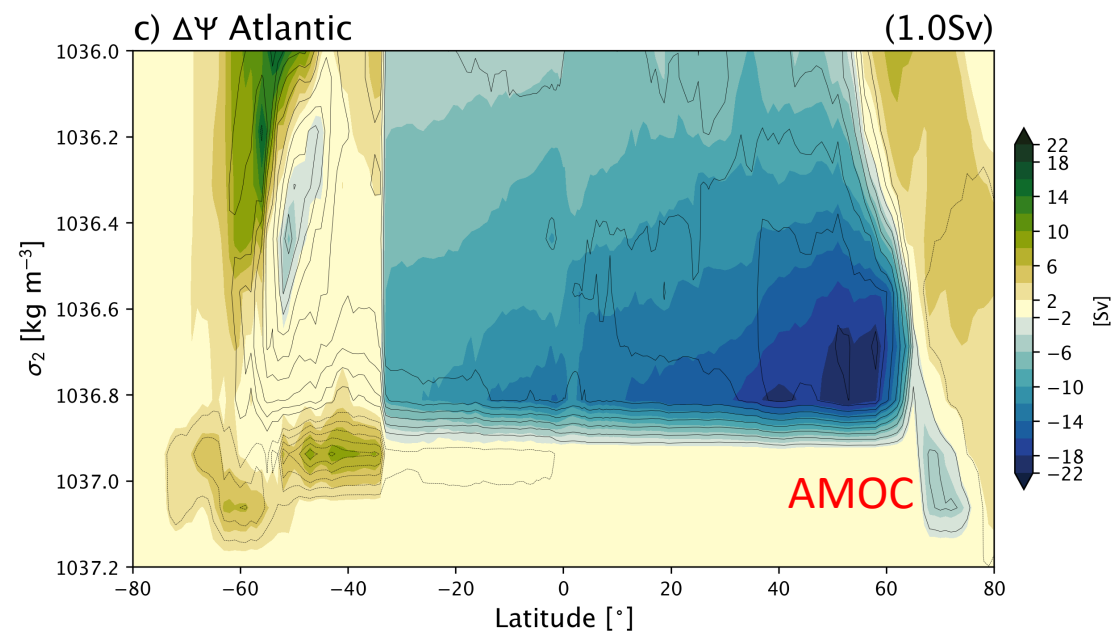
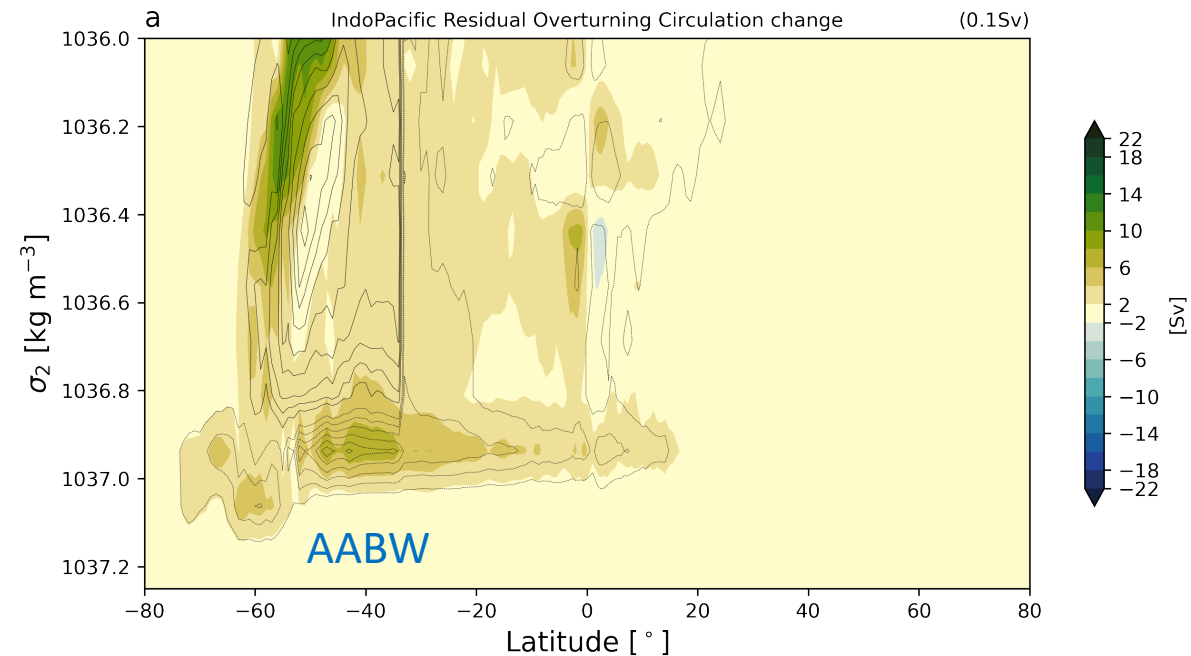
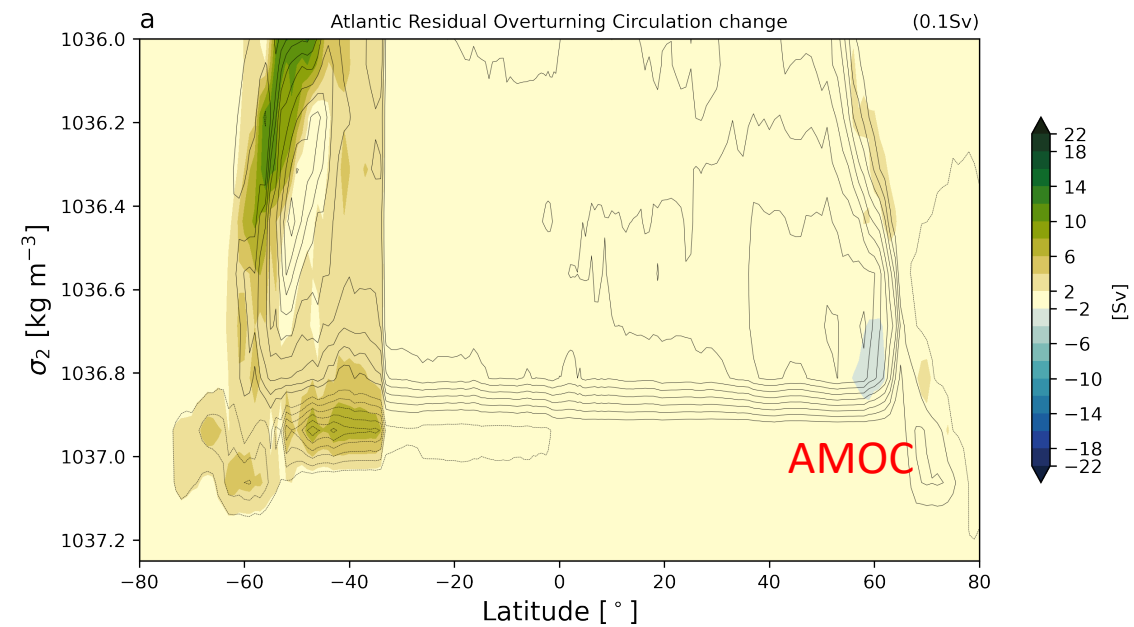


- **At the end of the experiments:**

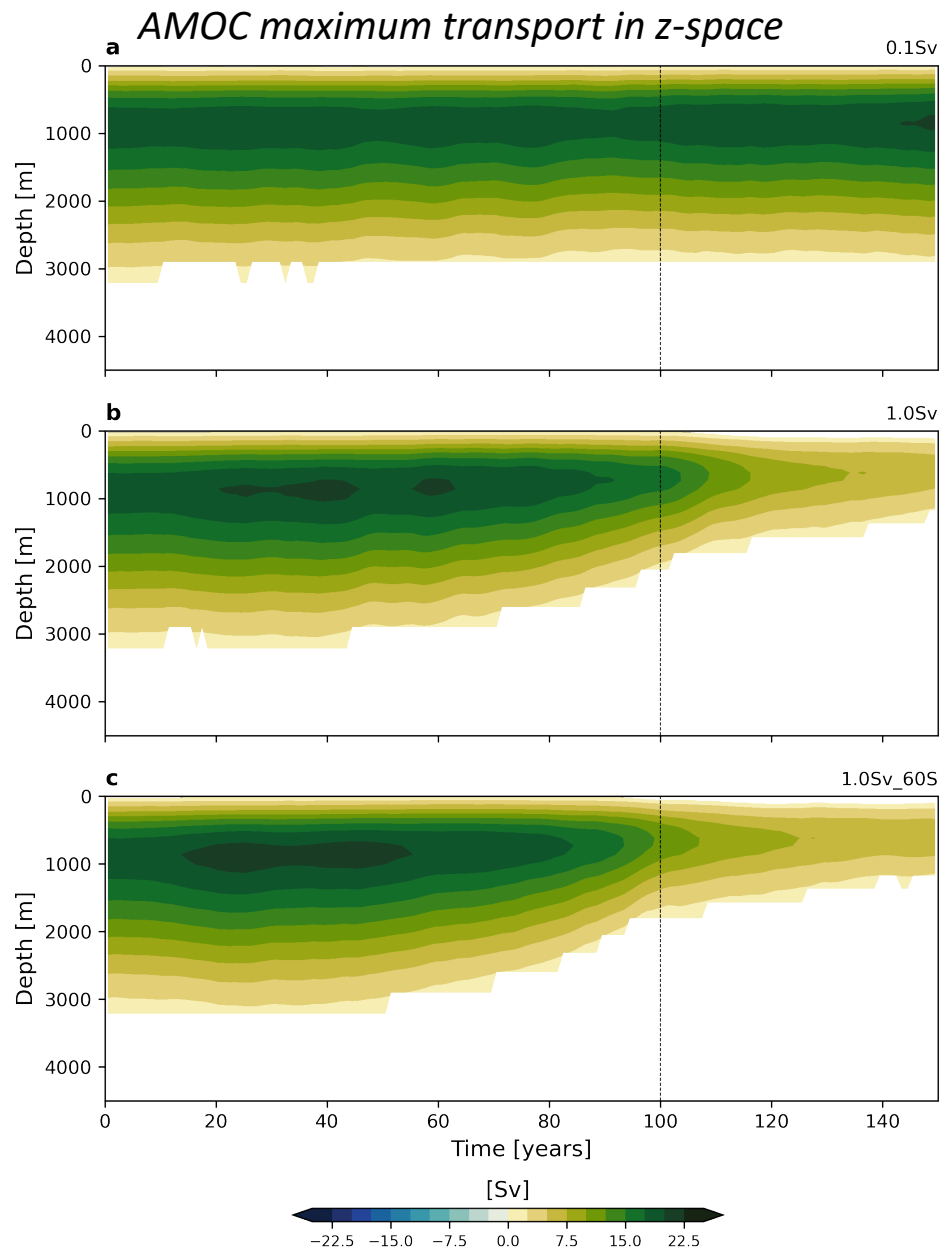
- **AABW** seems to be insensitive to strength of FW forcing and reduces considerably with small forcing
- **AMOC** weakens only for *large* FW forcing anomalies
- expansion of the Deep Cell into lighter waters



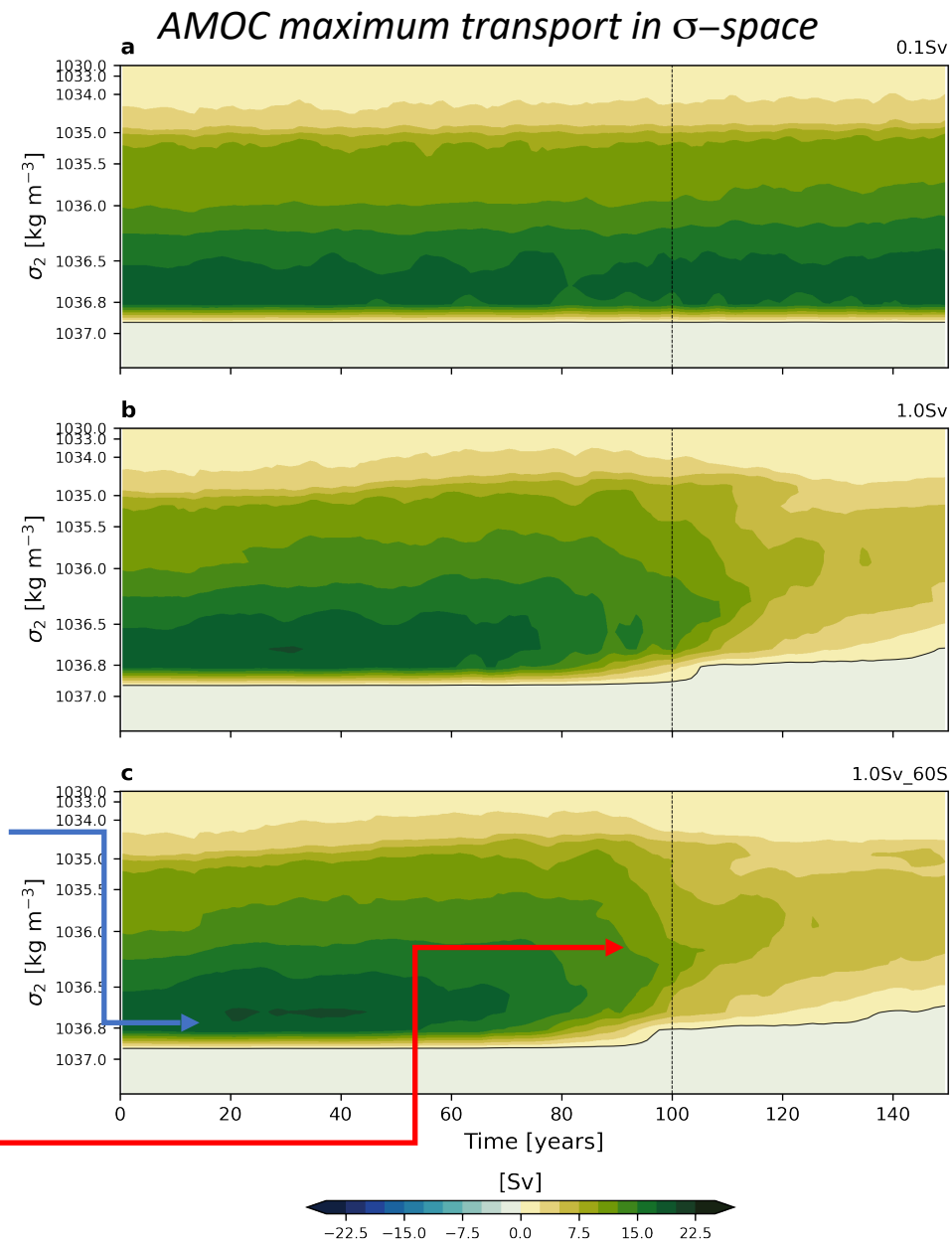
The Atlantic and IndoPacific MOC response (in density space)



The AMOC transient (time-dependent) response

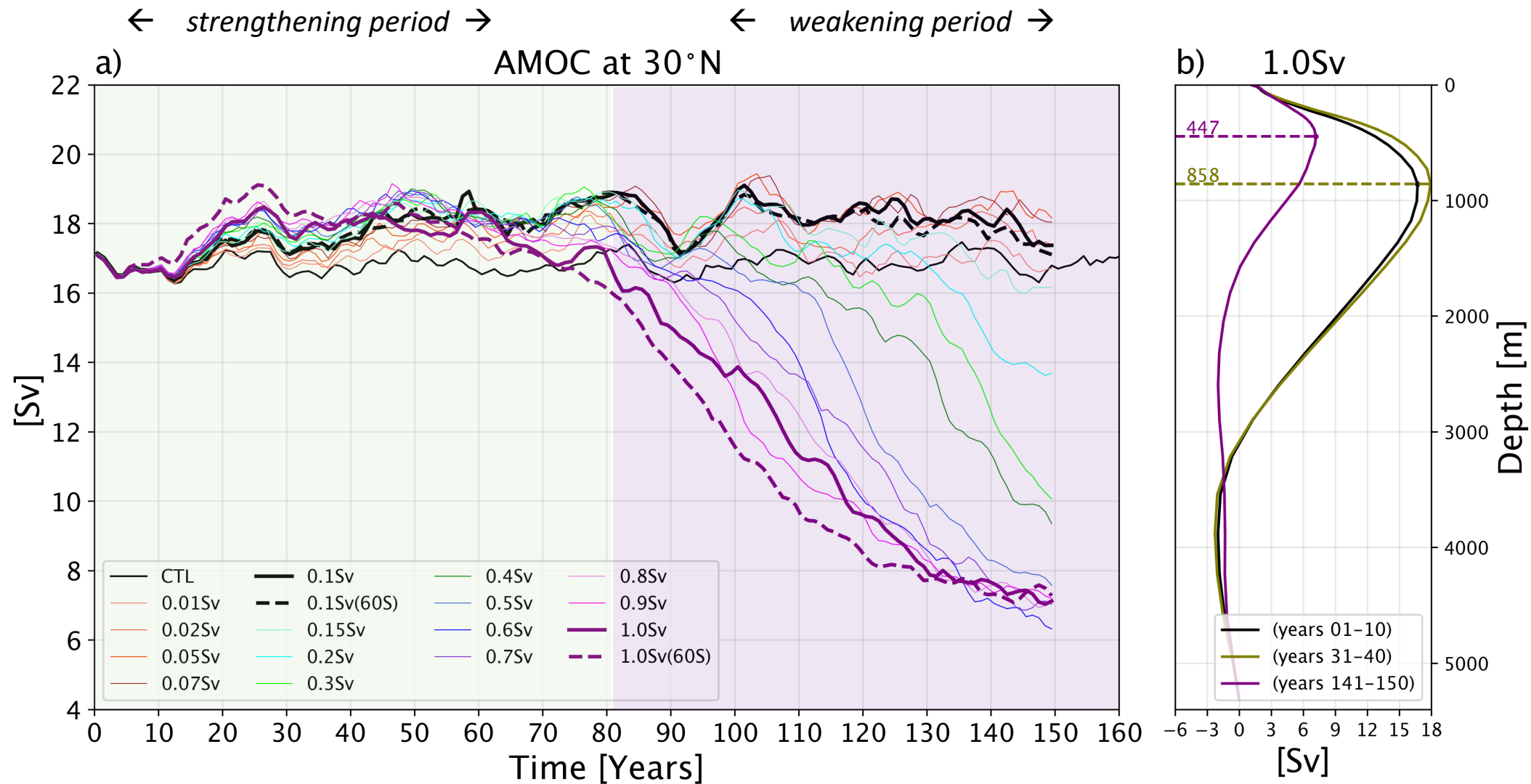


- **AMOC** gets progressively shallower (lighter waters)
- **initial strengthening**
- **followed by a substantial weakening**



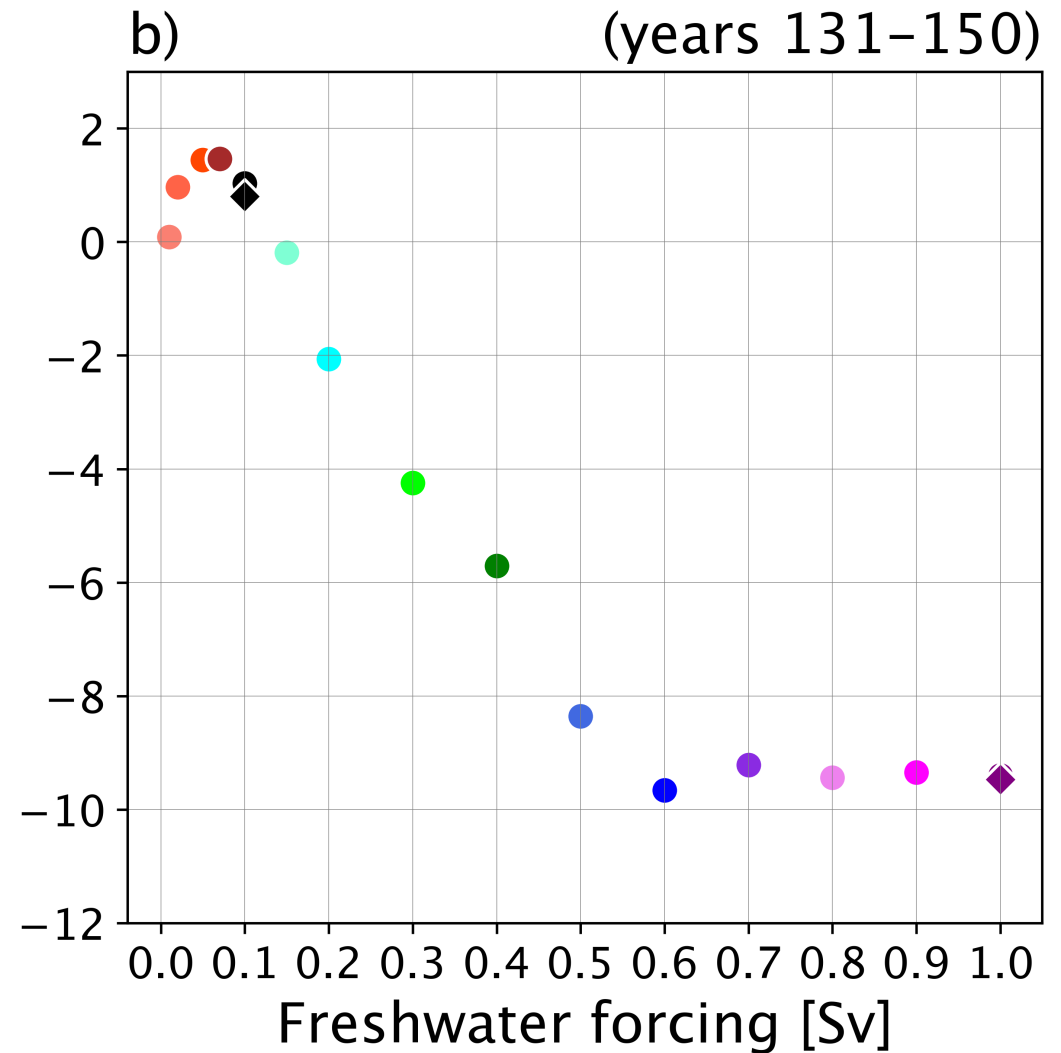
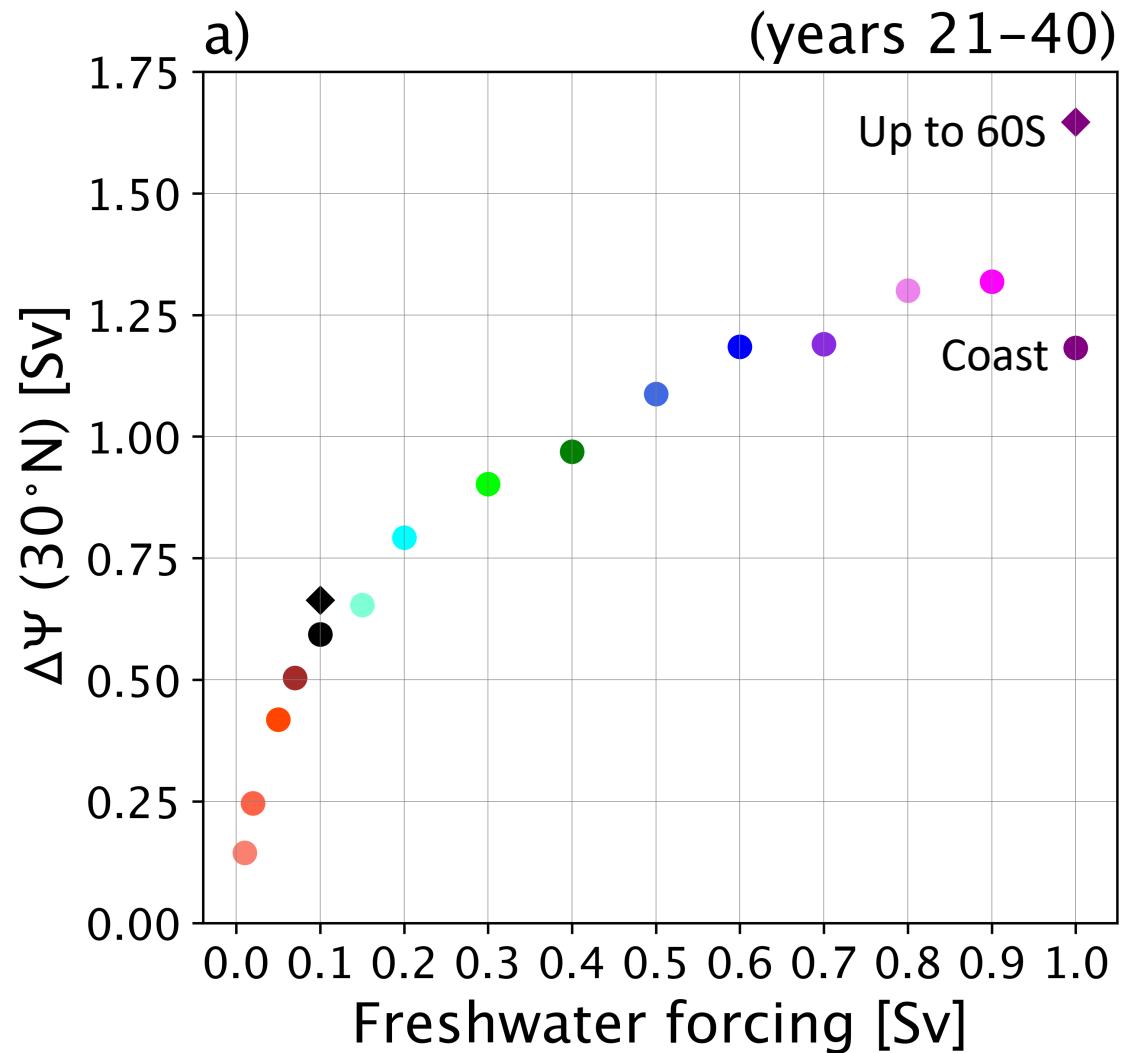
The AMOC transient response

- **AMOC** initially strengthens
- **AMOC** eventually weakens for $FW > 0.2\text{Sv}$
- period of both strengthening/weakening phases varies with FW forcing amplitude



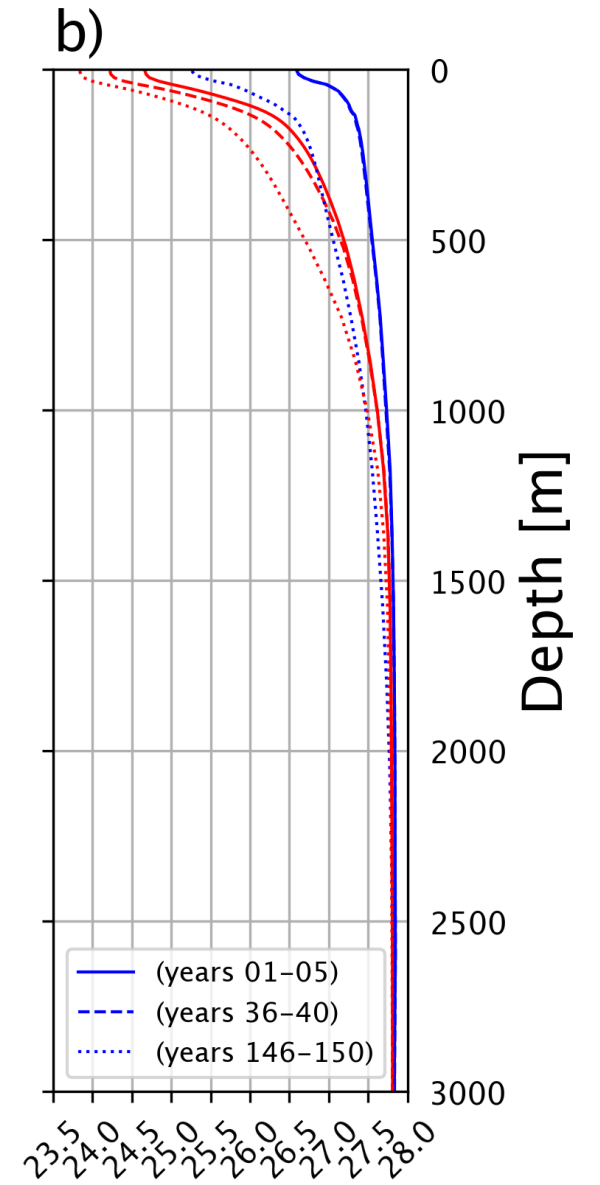
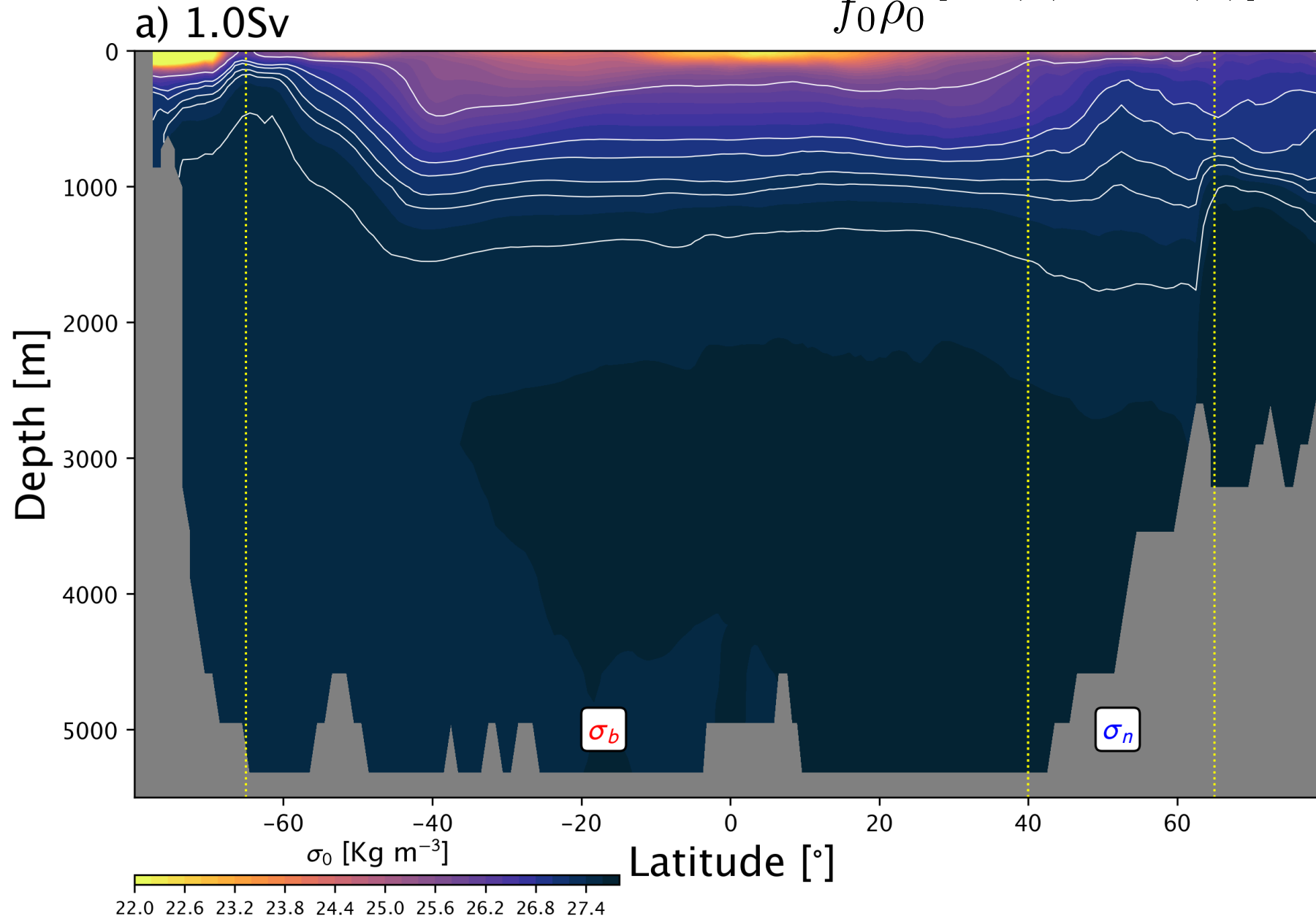
The AMOC transient response

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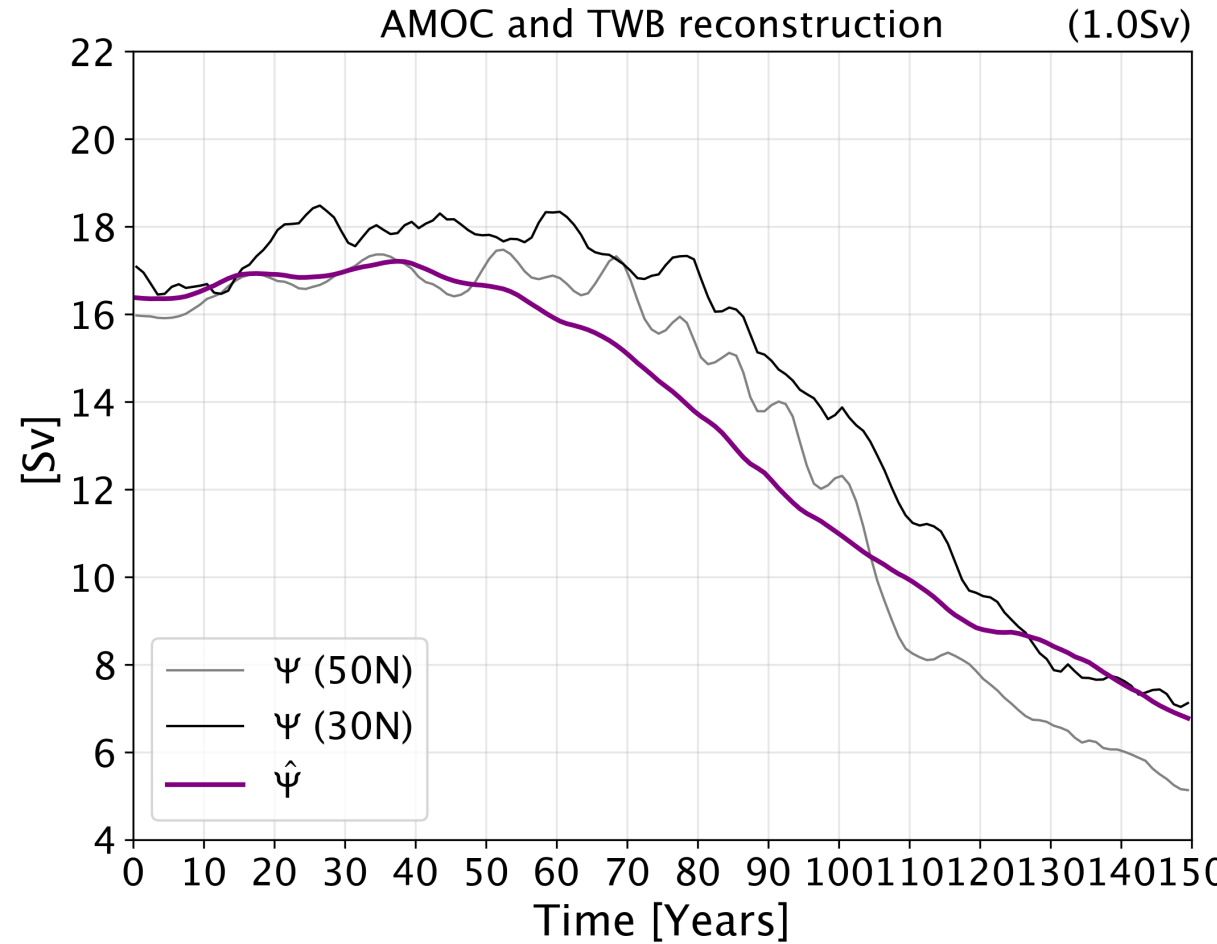
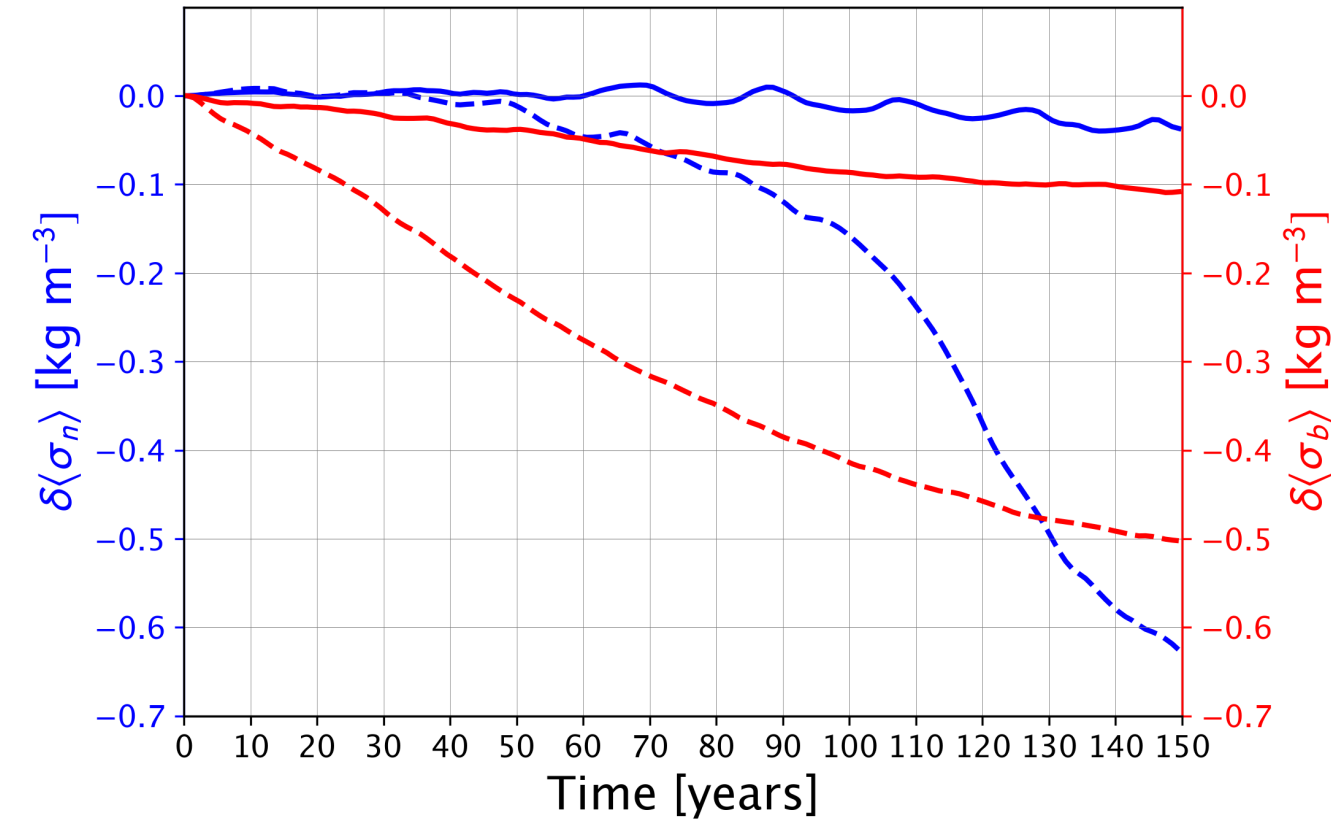
A Thermal Wind reconstruction

$$\Psi_{zz} = \frac{g}{f_0 \rho_0} [\sigma_n(z) - \sigma_b(z)]$$



A Thermal Wind reconstruction

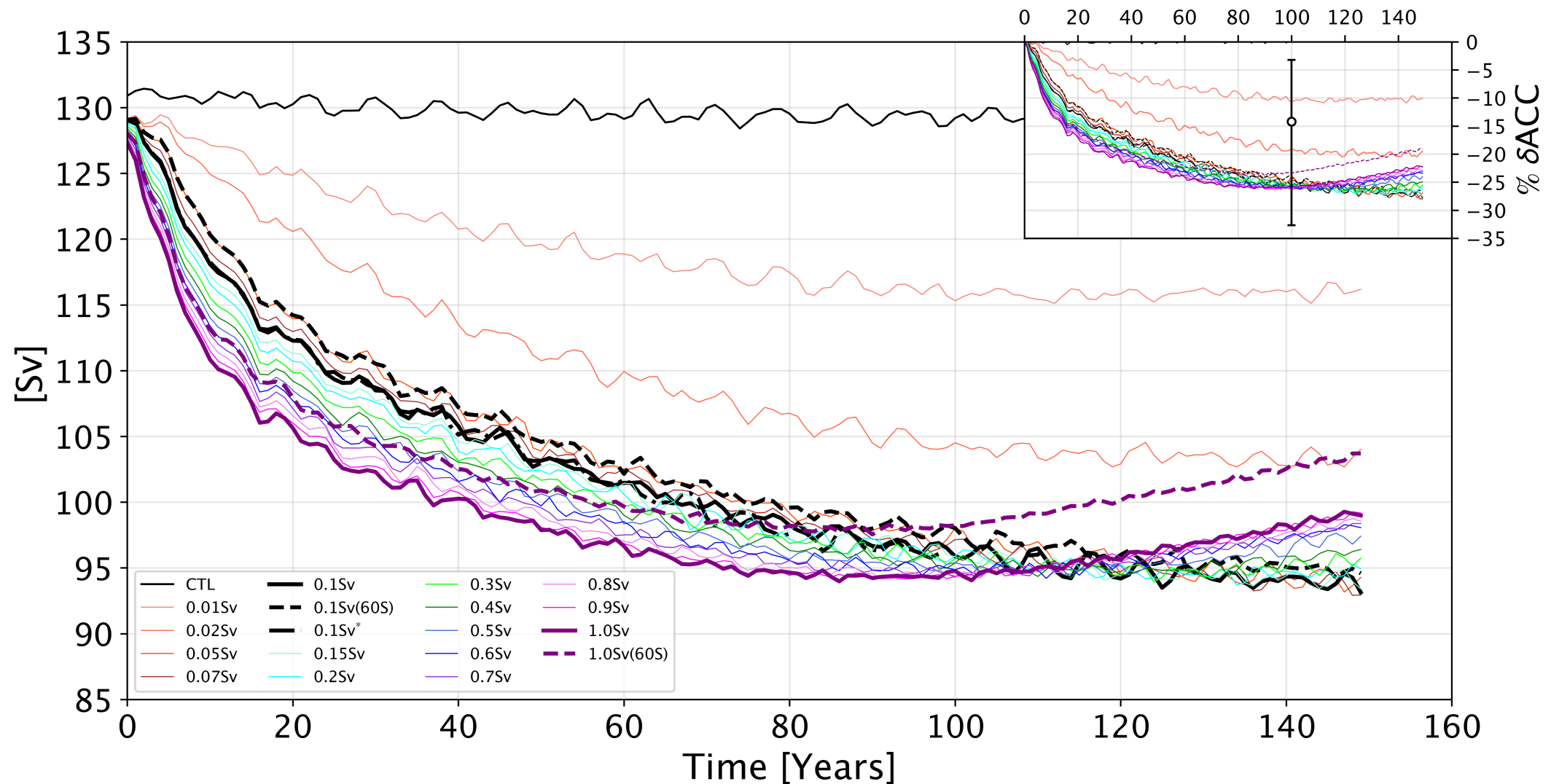
$$\Psi_{zz} = \frac{g}{f_0 \rho_0} [\sigma_n(z) - \sigma_b(z)]$$



- 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?

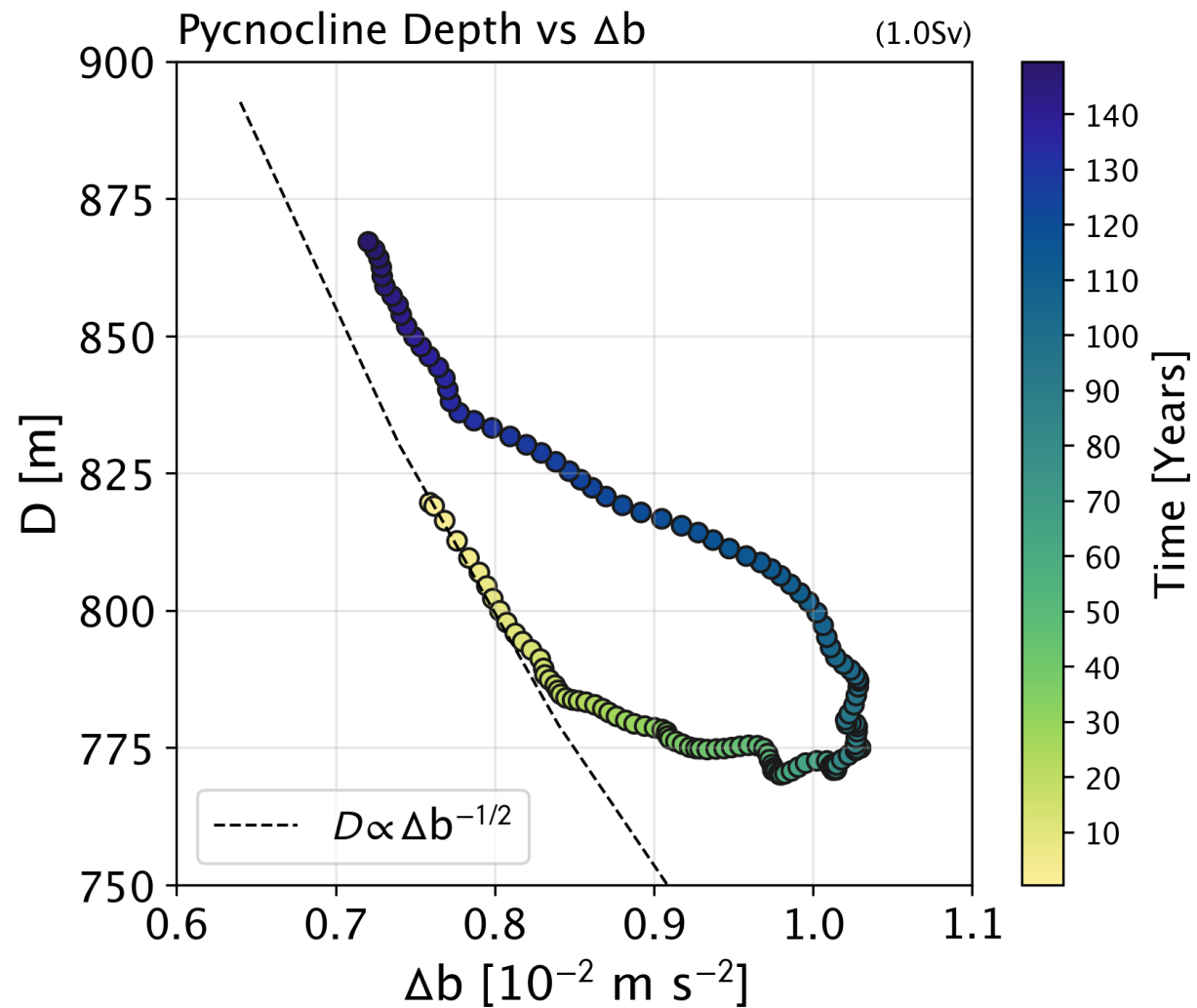
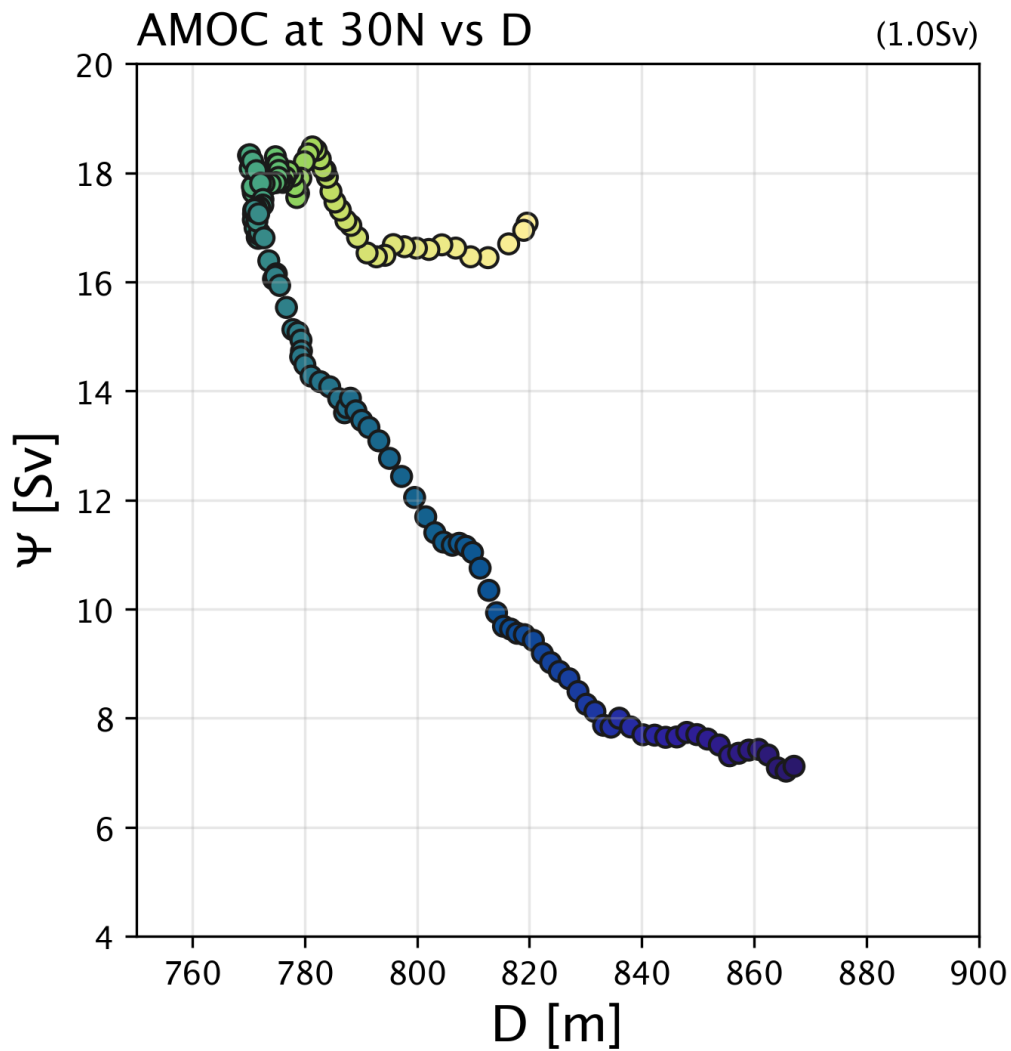
- ACC weakening initially scales linearly with FW forcing
- ACC weakening eventually saturates
- for FW forcing inducing AMOC weakening, the ACC partially recovers why?



What happens to the ACC? Pycnocline depth adjustment

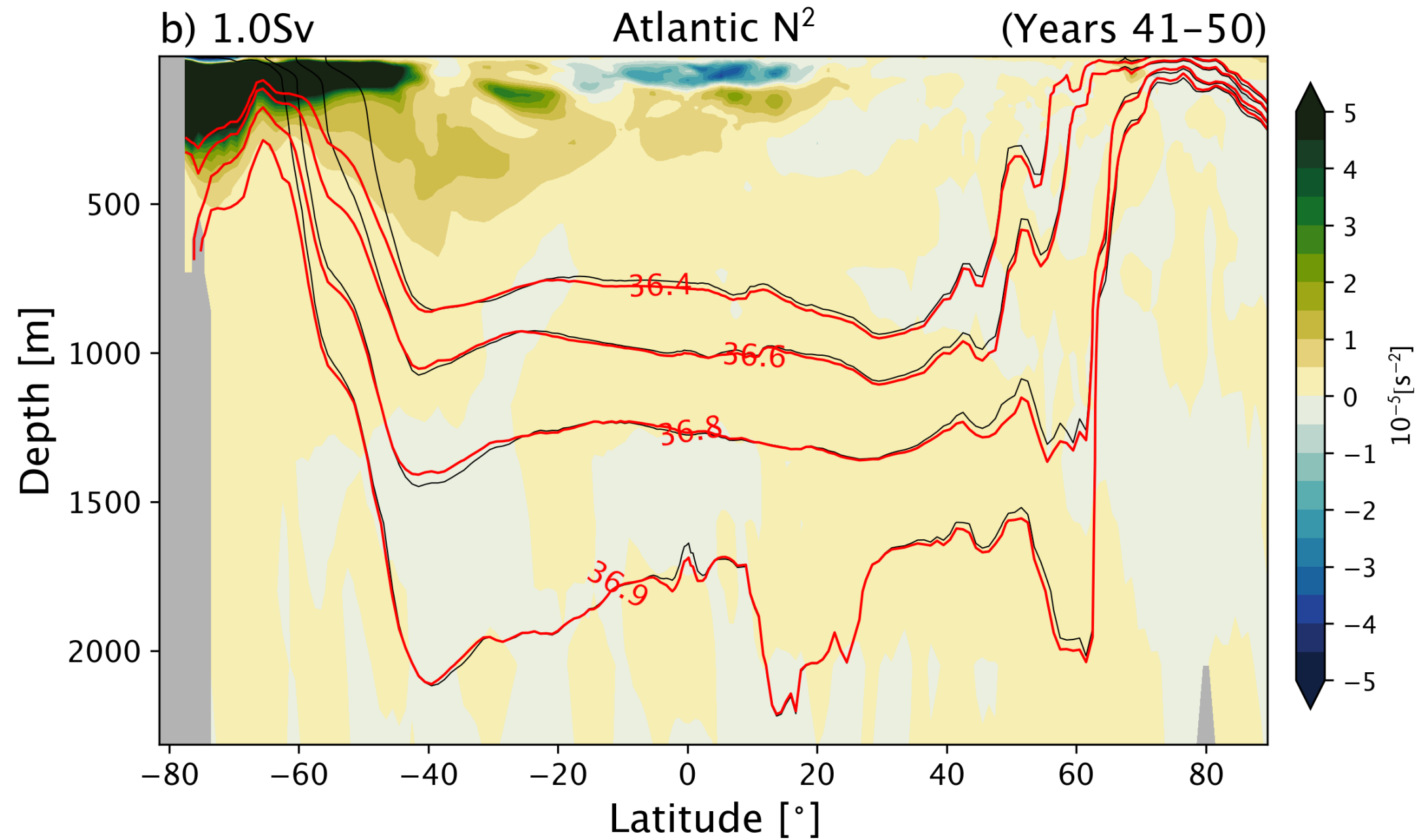
$$D = \frac{\int_{z=-H}^0 dz \Delta\sigma_2 z}{\int_{z=-H}^0 dz \Delta\sigma_2}$$

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

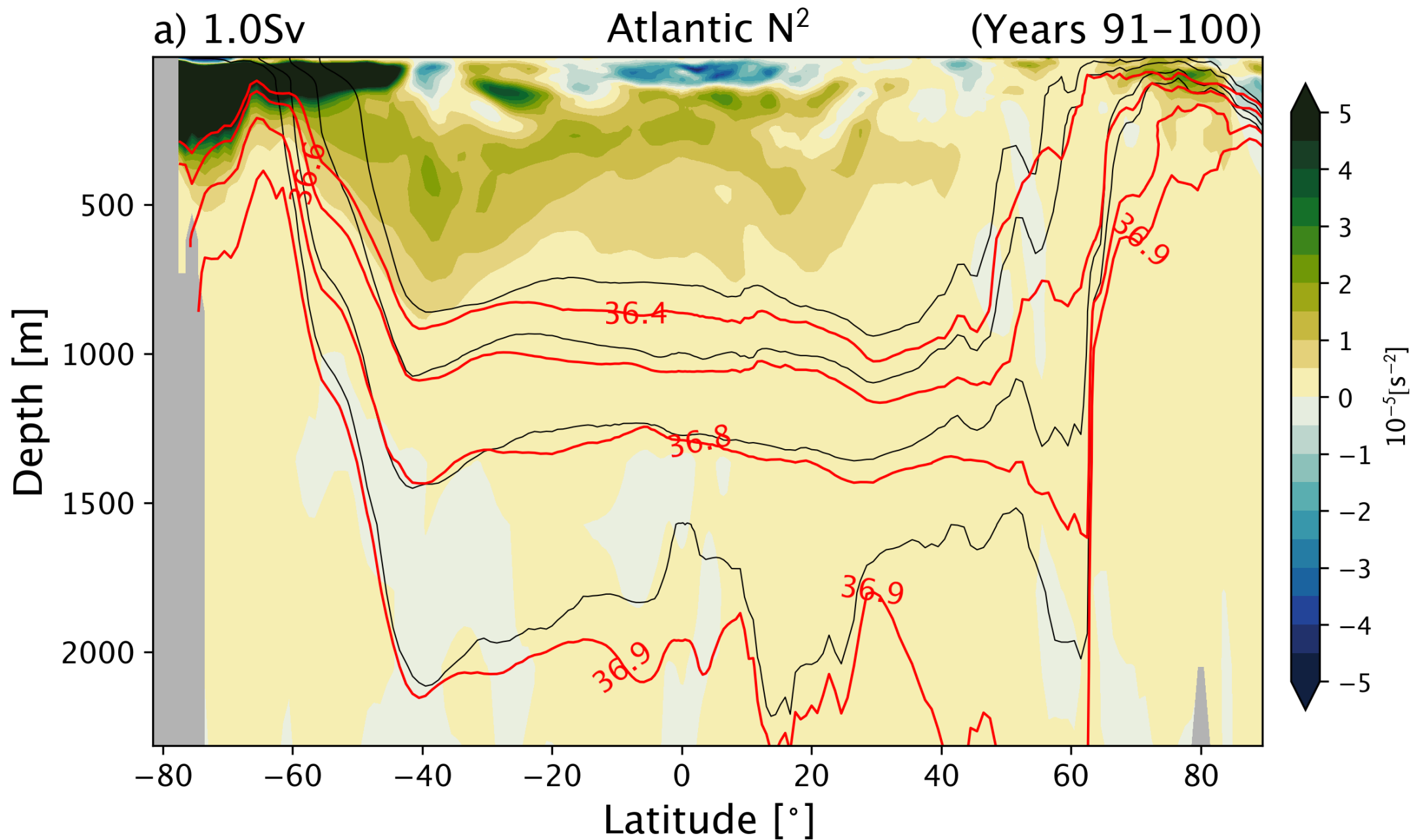


What happens to the ACC? Pycnocline depth adjustment

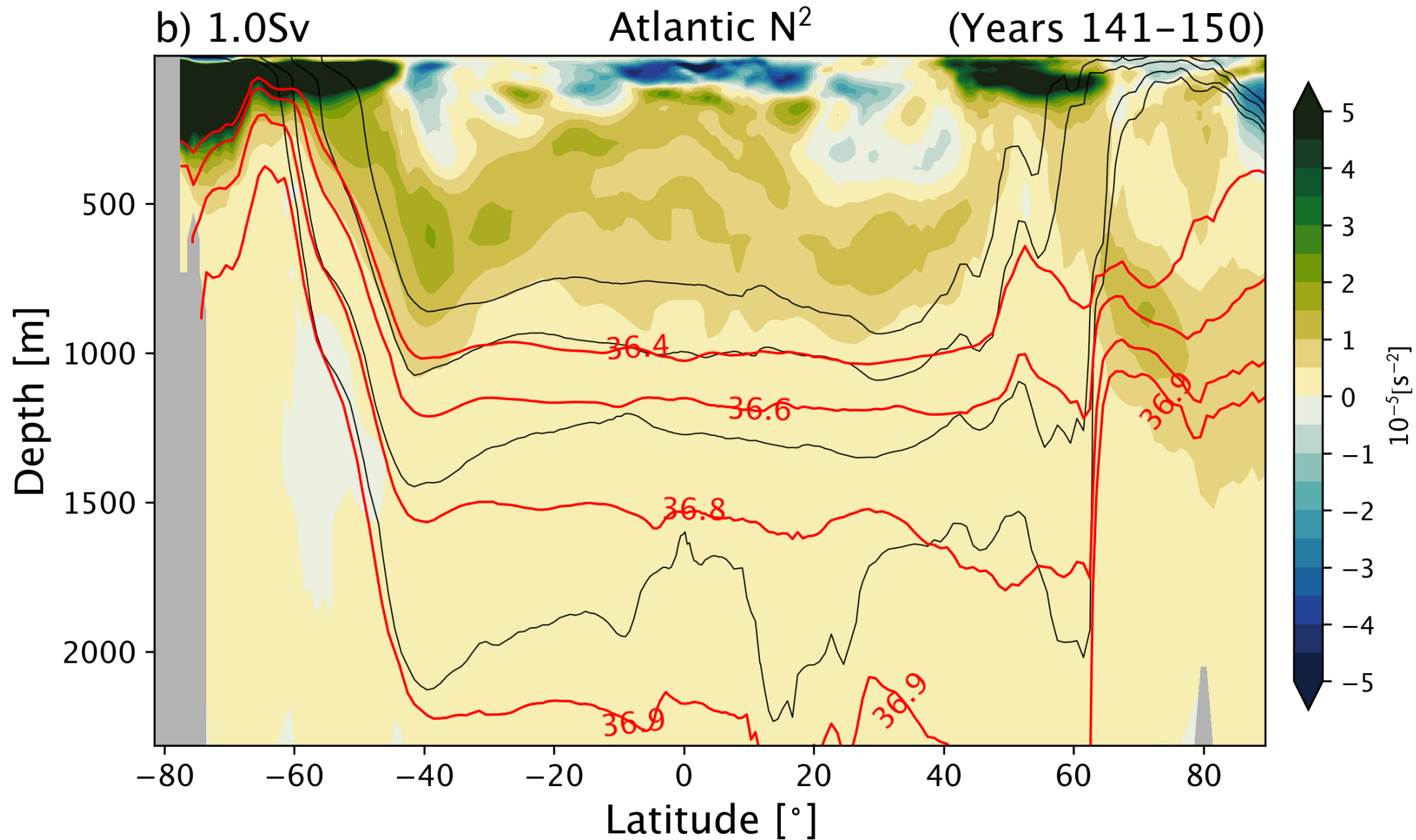
$$N^2 = -g\rho^{-1}\partial_z\rho = \partial_z b$$



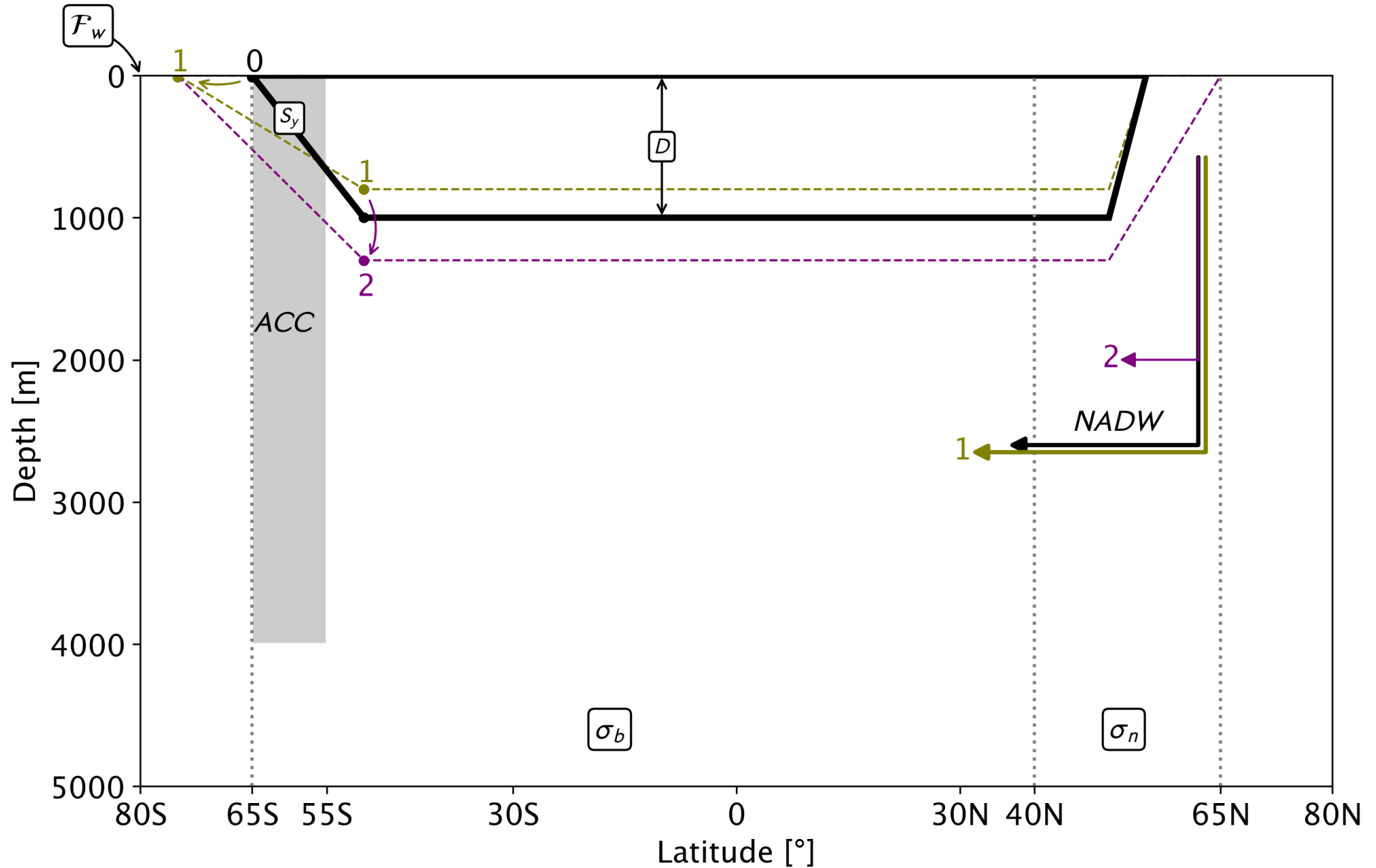
What happens to the ACC? Pycnocline depth adjustment



What happens to the ACC? Pycnocline depth adjustment



A final picture: AMOC, ACC, and interior stratification adjustment

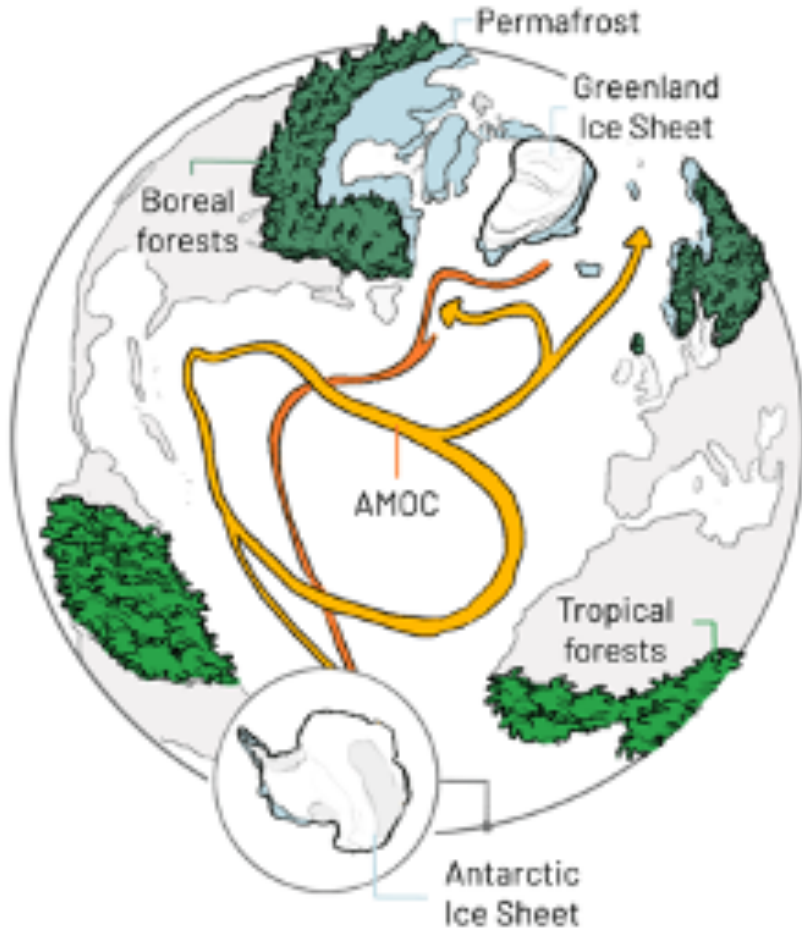


Some Conclusions

- 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 next?

- Add GIS discharge and test the simultaneous effects on the AMOC.



- Include future changes in surface fluxes: FAF-heat and FAF-water

