Tipping points in the North Atlantic Ocean circulation

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Tipping elements of the Earth System

TipESM

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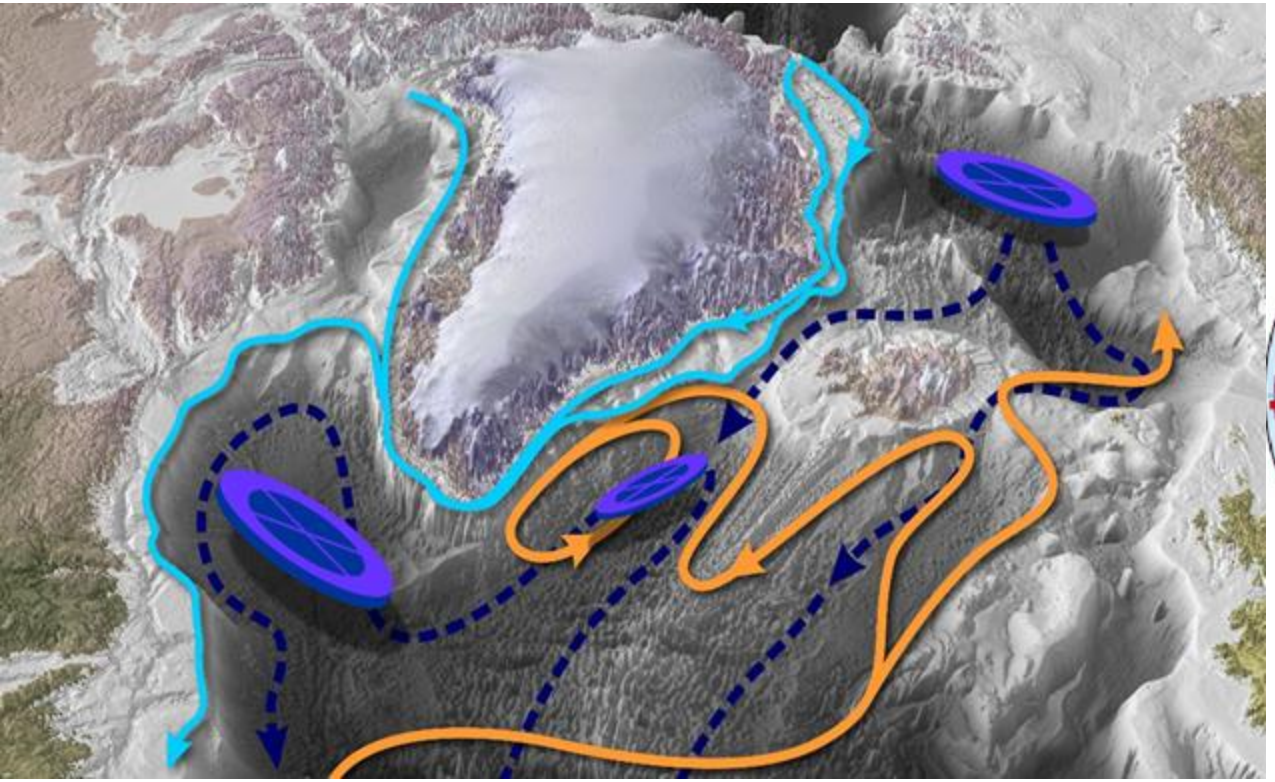
Armstrong McKay et al., Science (2022)

Large-scale oceanic currents

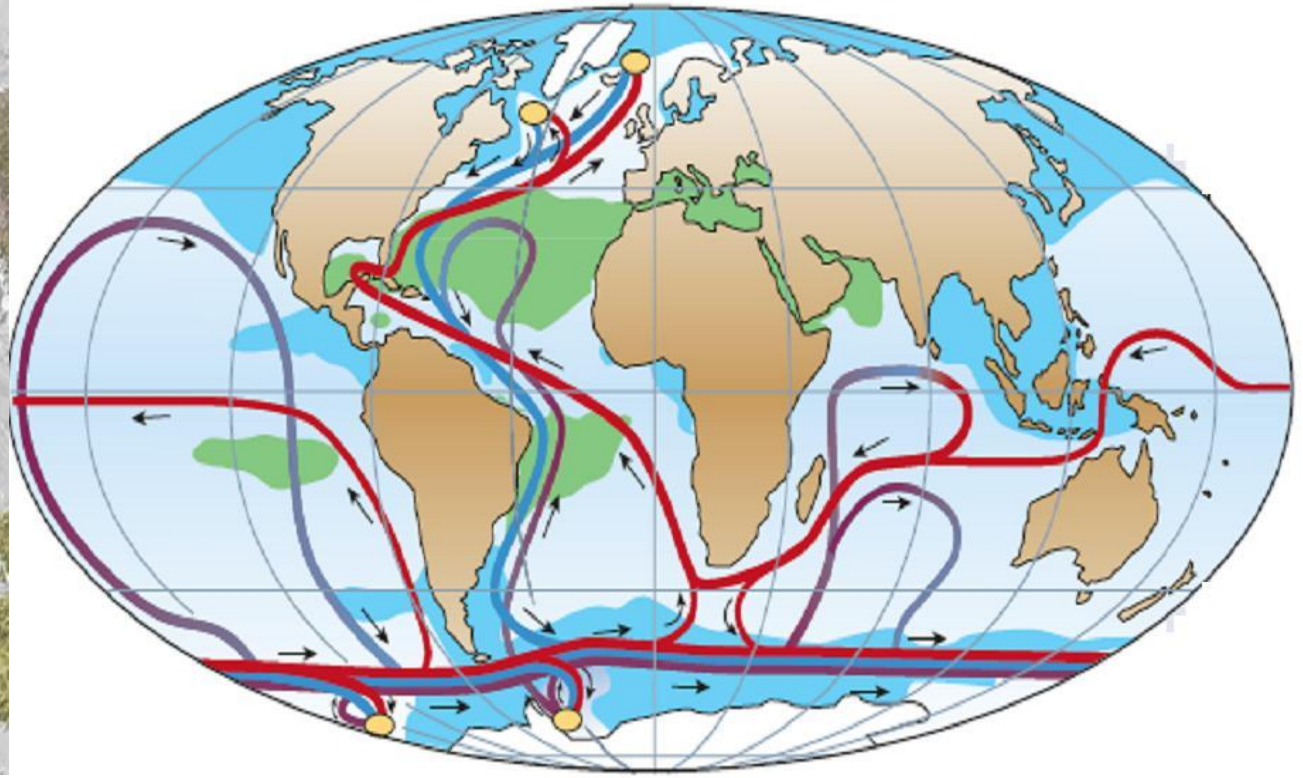
TipESM

Norh Atlantic Subpolar Gyre (SPG)



Swingedouw et al. 2022

Atlantic Meridional Overtunring Circulation (AMOC)



Rahmstorf et al. 2002

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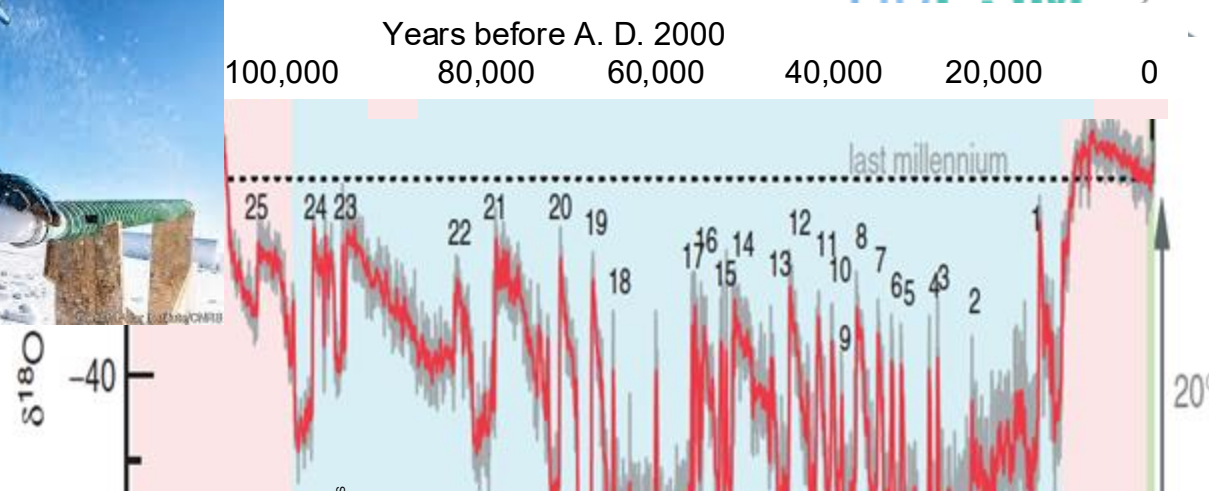
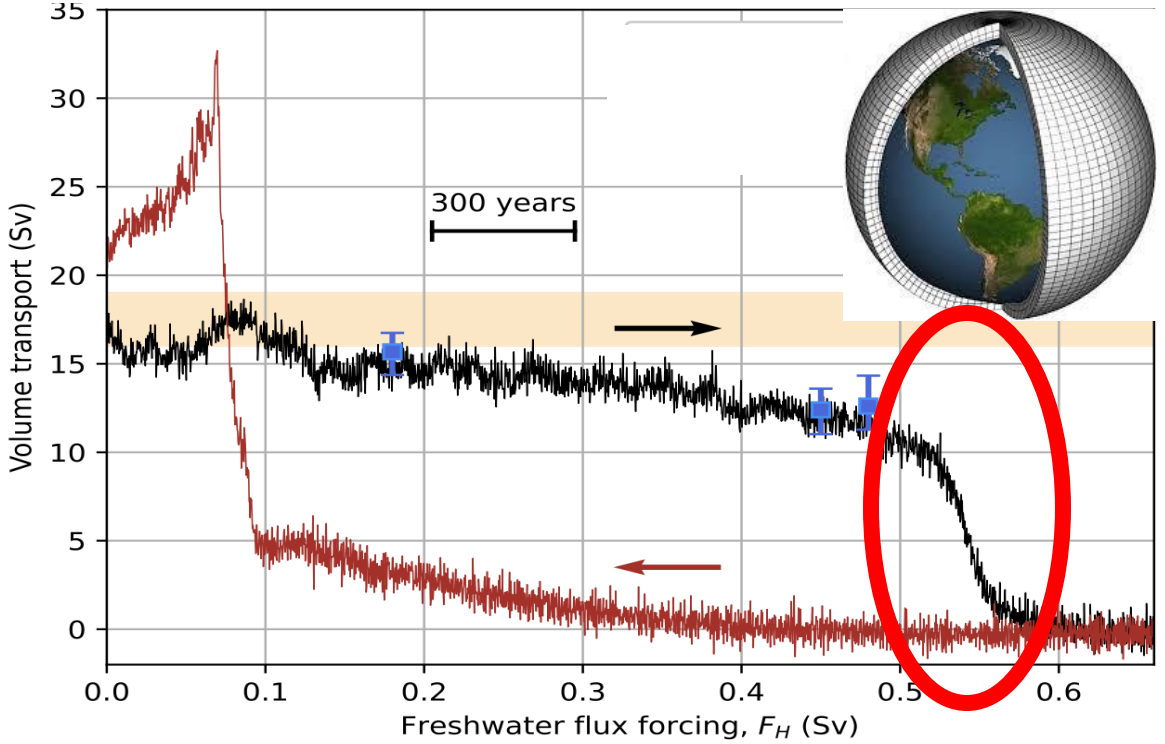
AMOC dynamics



- Lessons from the past highlight that **abrupt AMOC changes** are possible

- AMOC response to freshwater release is highly non-linear: **tipping point behavior** and hysteresis in a wide range of models



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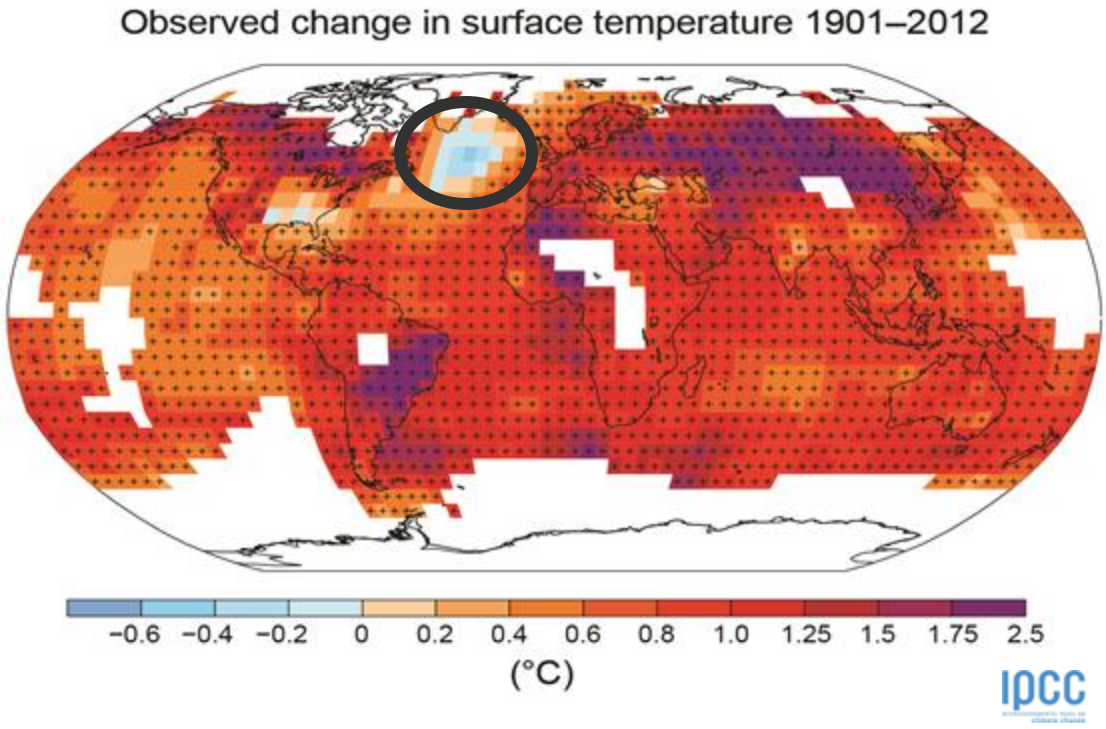
Van Westen et al. Sc. Adv. (2024)

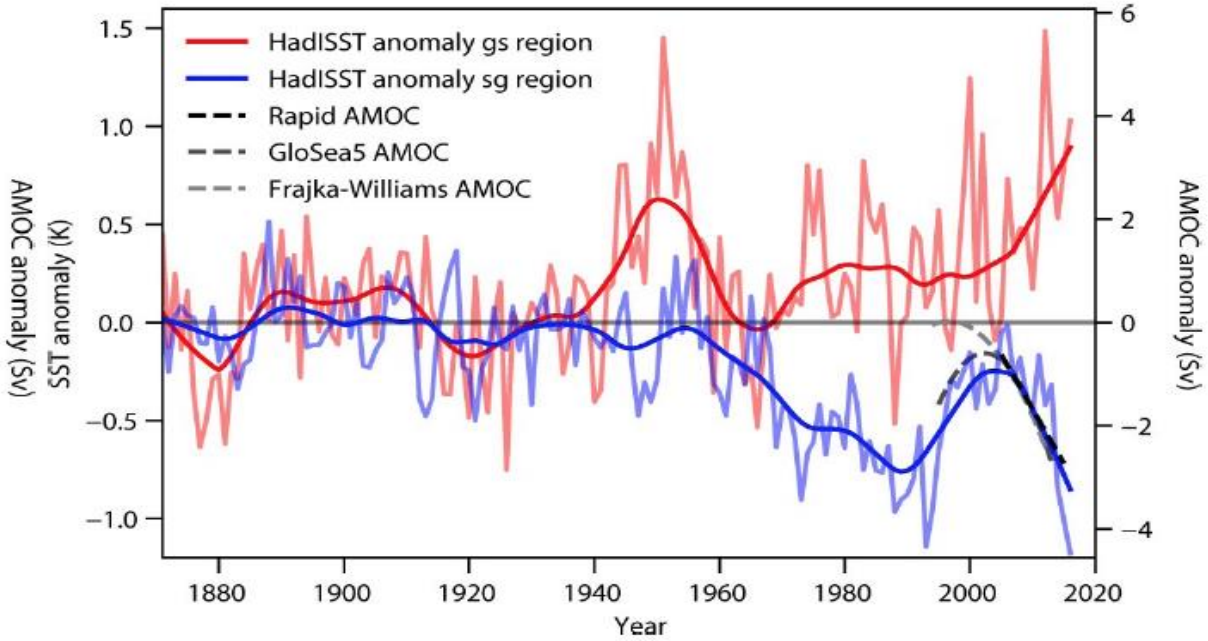
Impact of a substantial (>50%) AMOC weakening

Fig. 6.10 from IPCC SROCC report 2019

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 a number of other variables, but it is unclear if this weakening (if any) is anthropogenic or natural





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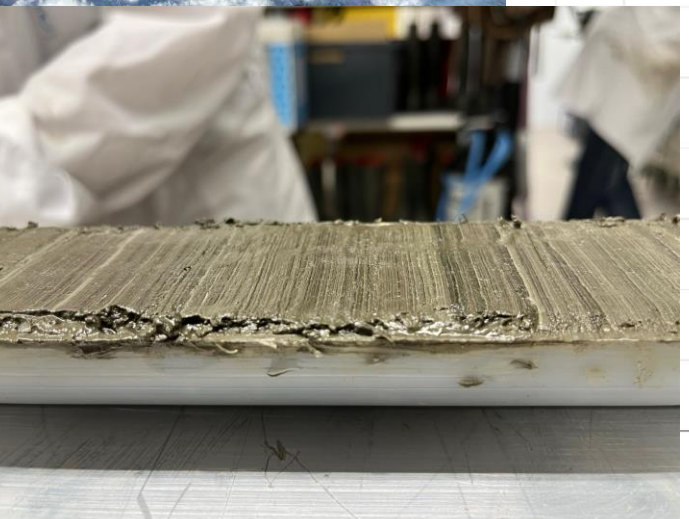
Can the weakening from the 1950s be caused by internal variability?

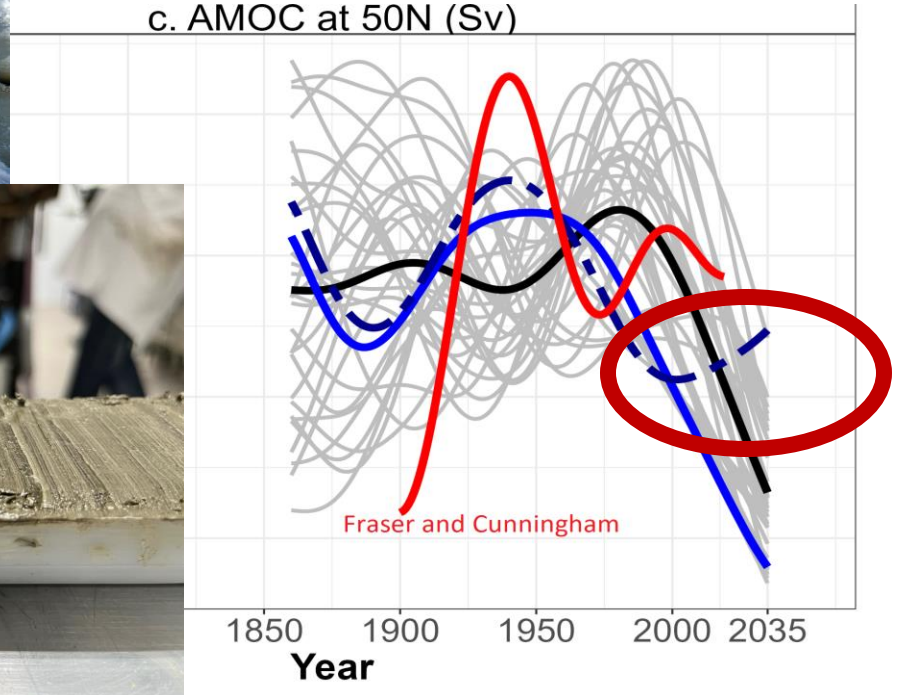


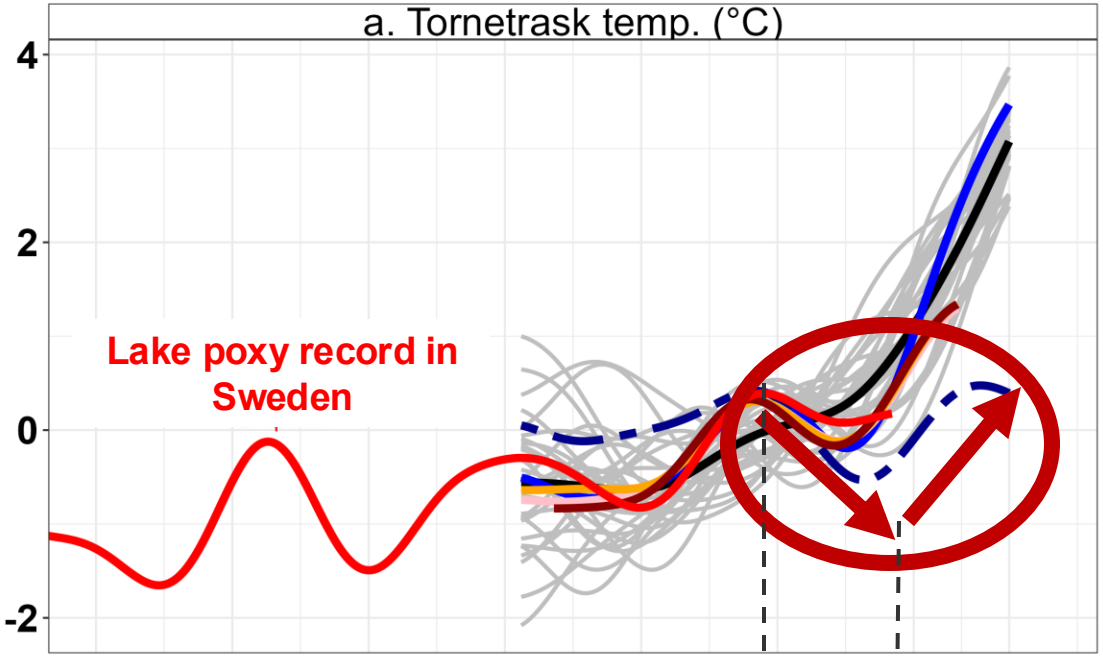
Observations

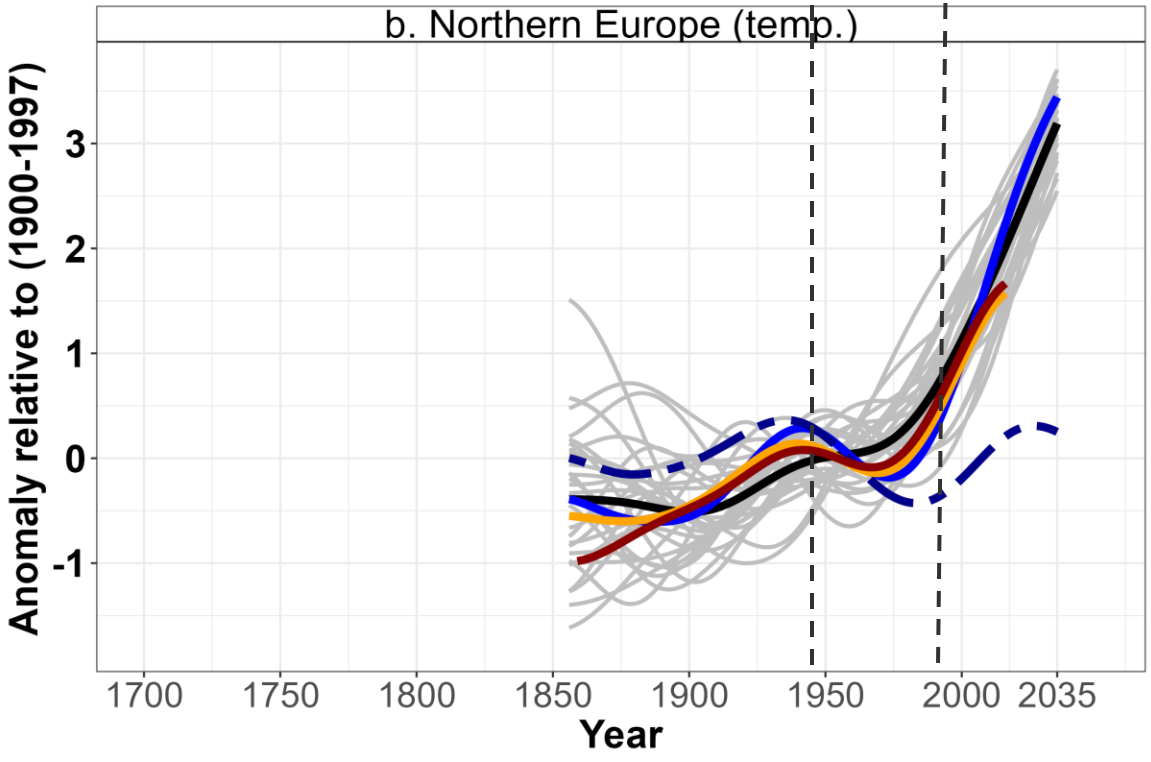
Forced signal

Internal variability

Forced +internal







What about the future?

Approved Version Summary for Policymakers IPCC AR6 WGI

C.3.4 The Atlantic Meridional Overturning Circulation is *very likely* to weaken over the 21st century for all emission scenarios. While there is *high confidence* in the 21st century decline, there is only *low confidence* in the magnitude of the trend. There is *medium confidence* that there will not be an abrupt collapse before 2100.

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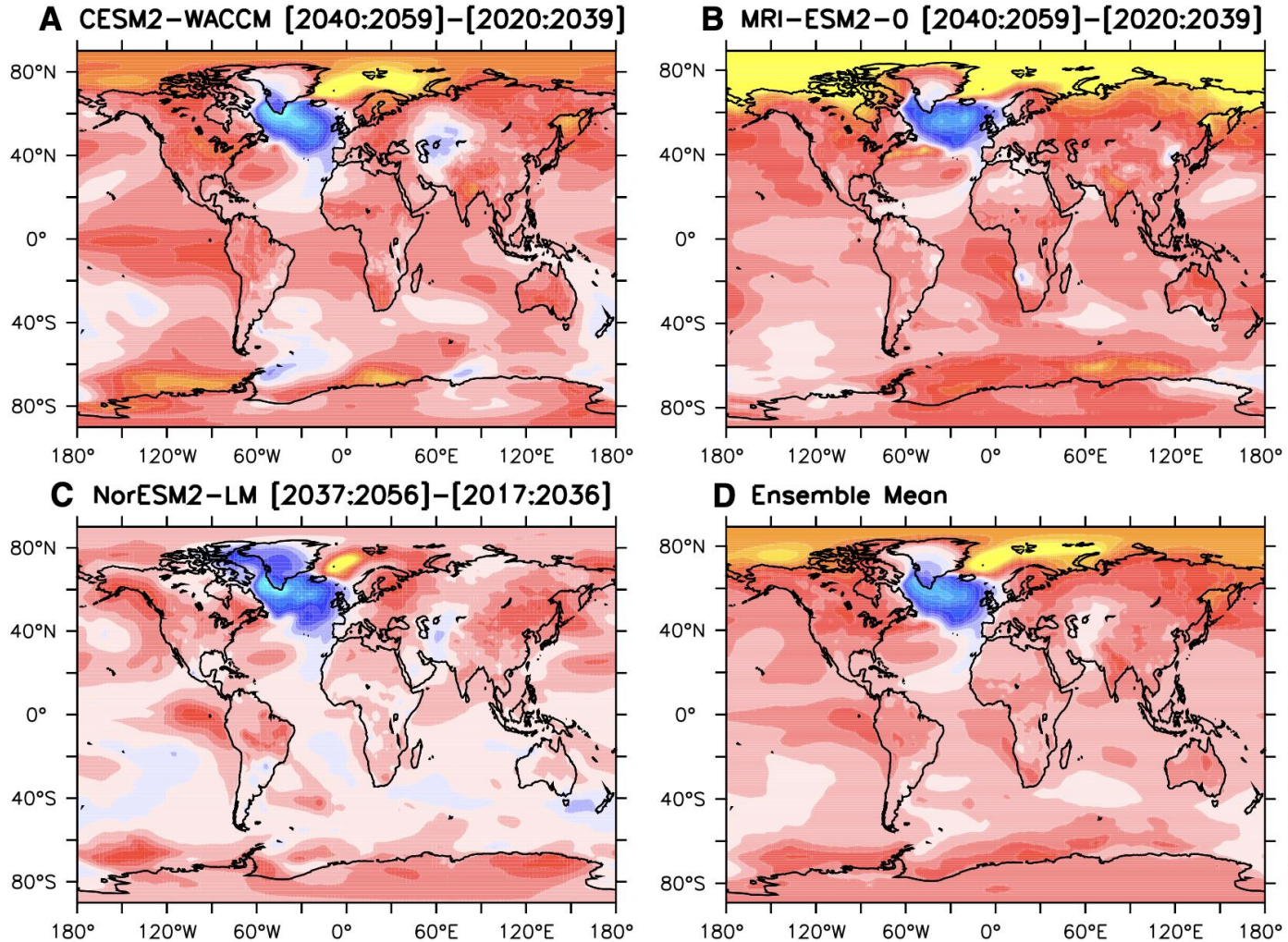
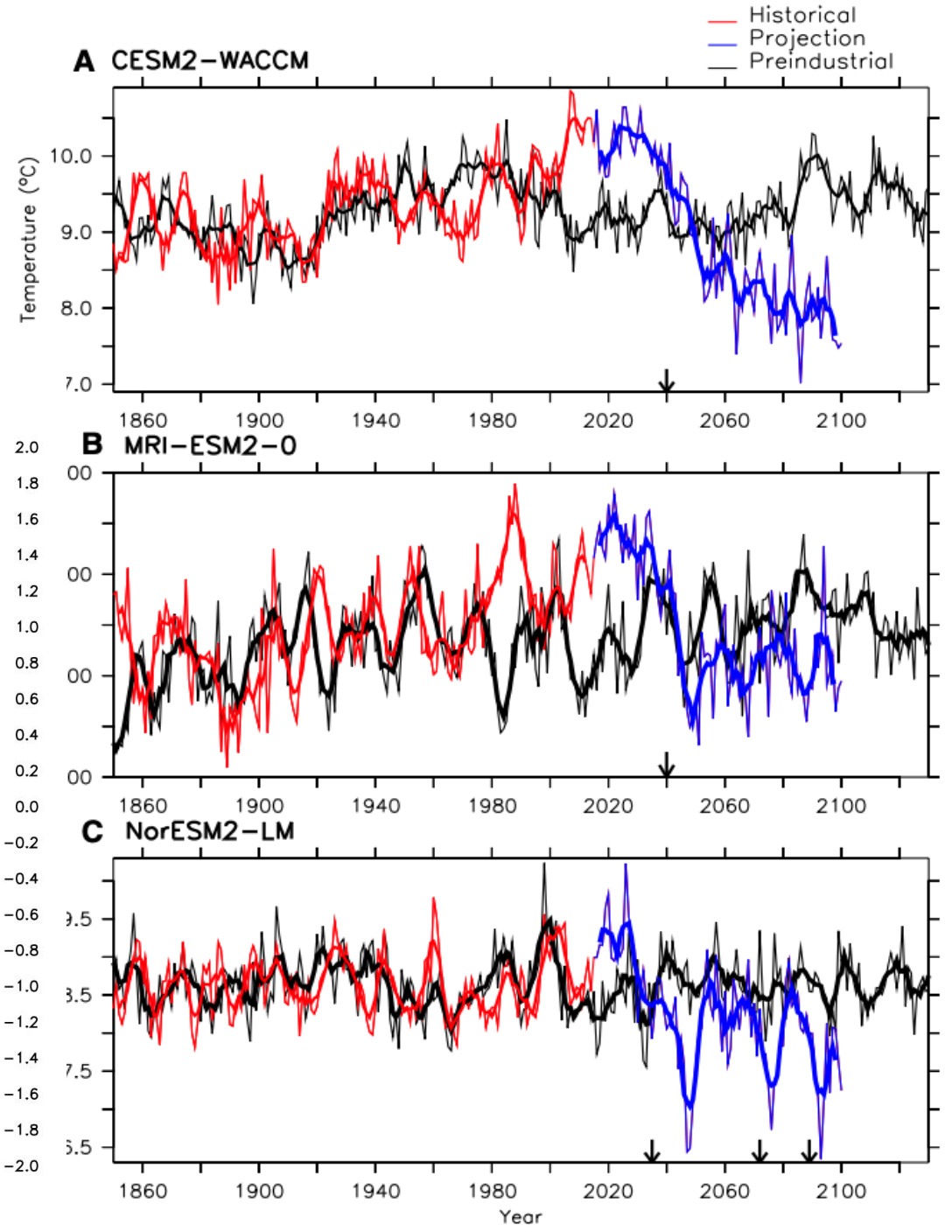
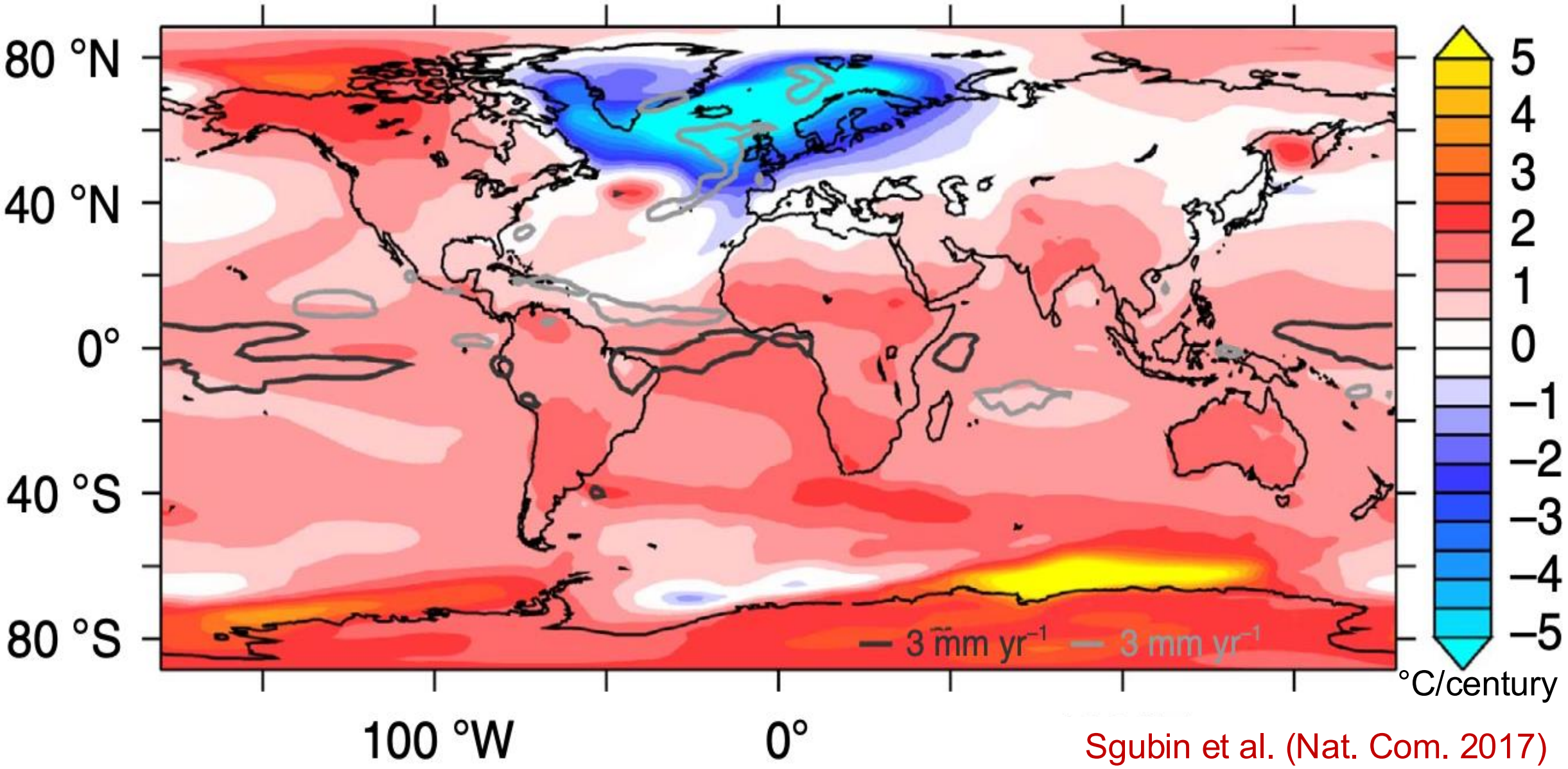
ipcc 2021
INTERGOVERNMENTAL PANEL ON climate change

Possibility of Abrupt (10 years) SPG collapse in the near future





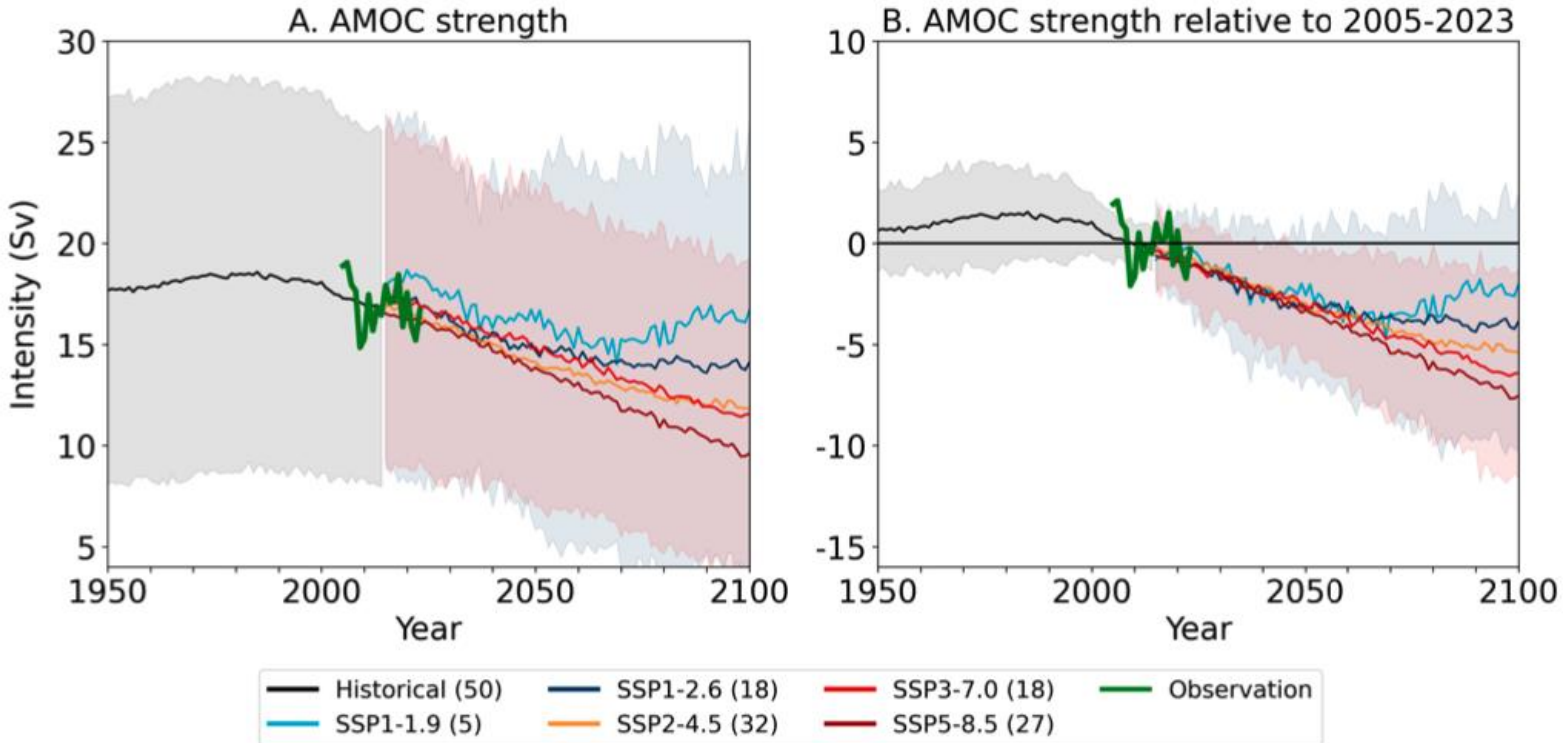
AMOC disruption in 2100 in CMIP5 models

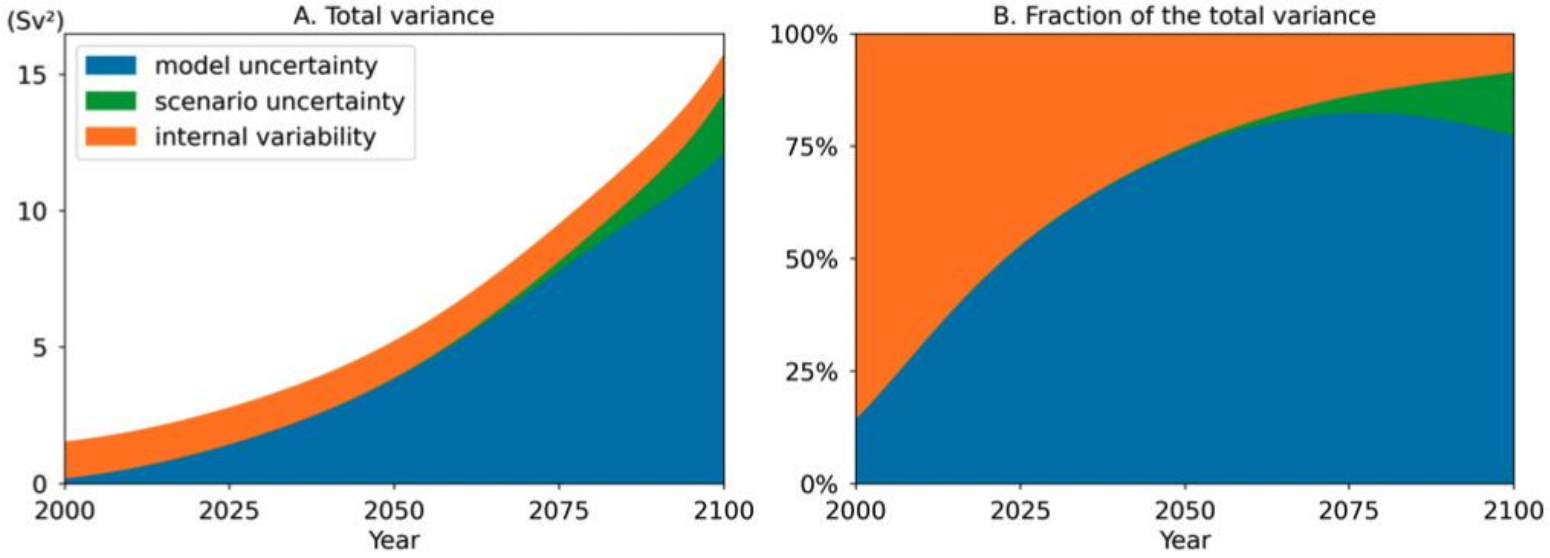


Sgubin et al. (Nat. Com. 2017)

AMOC Projections

- Models suggest a **32 ± 37%** reduction in AMOC by 2100 (**3 to 72%** depending on the model!)
- In 2100, this is dominated by **model uncertainty**





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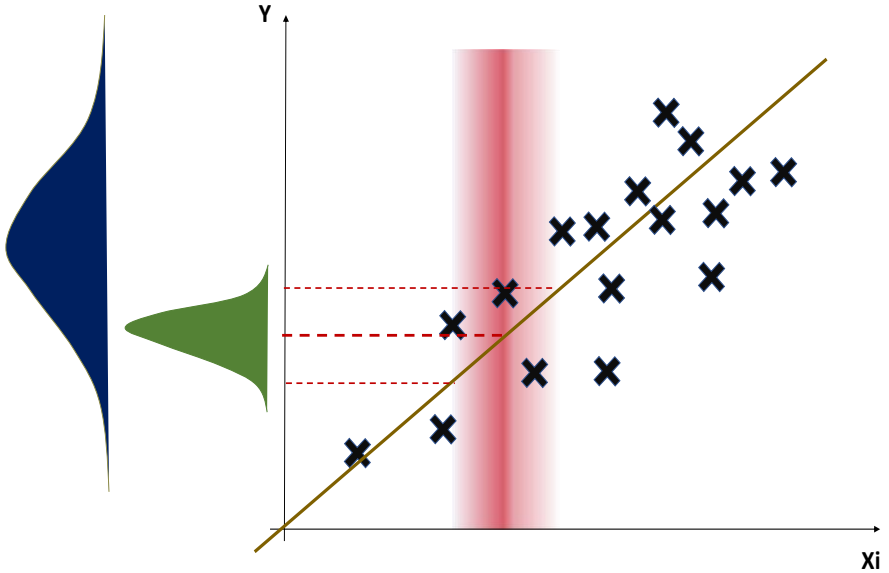
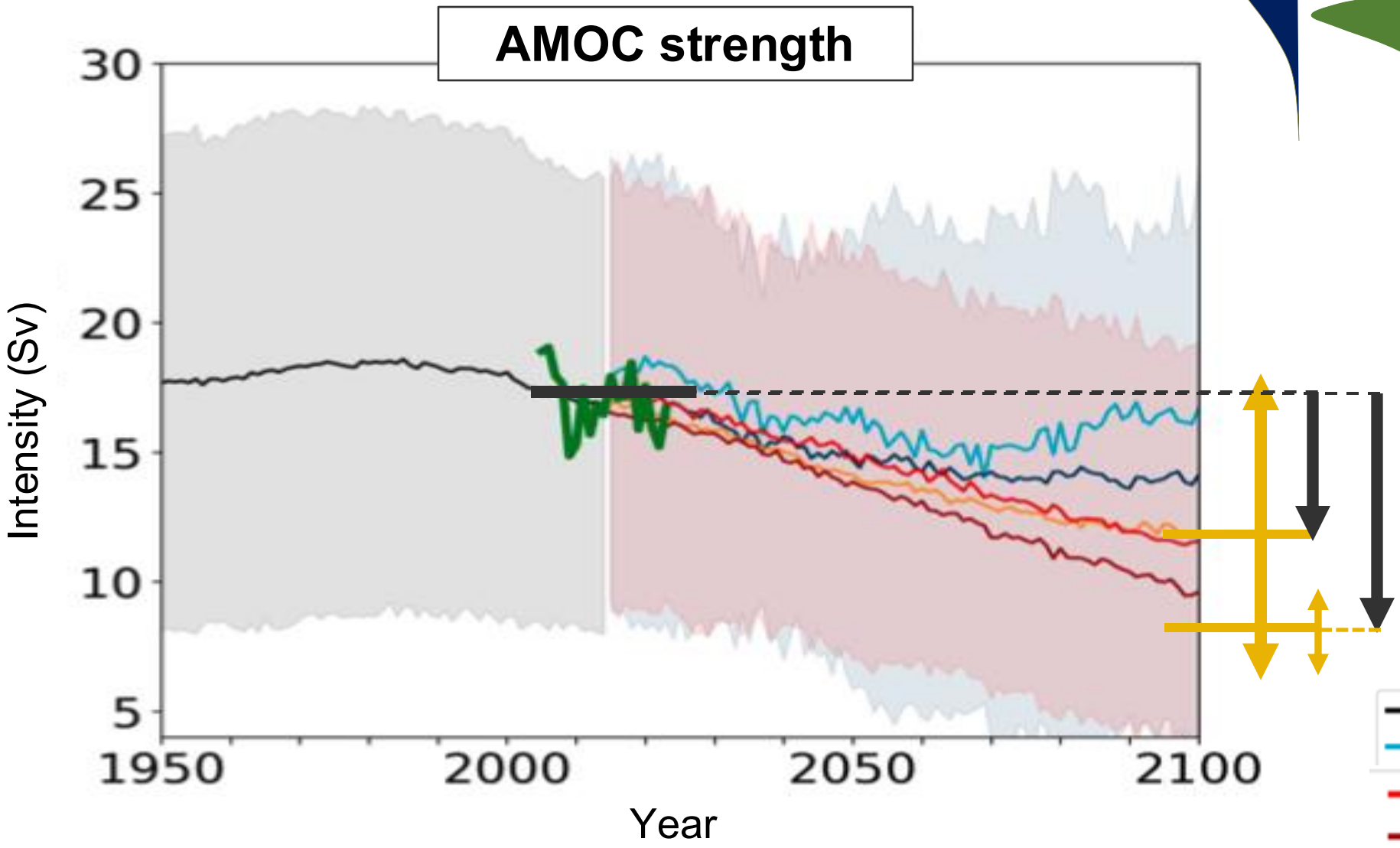
Portmann et al., sub.

Observational constraints





54% weakening when constrained by surface ocean properties

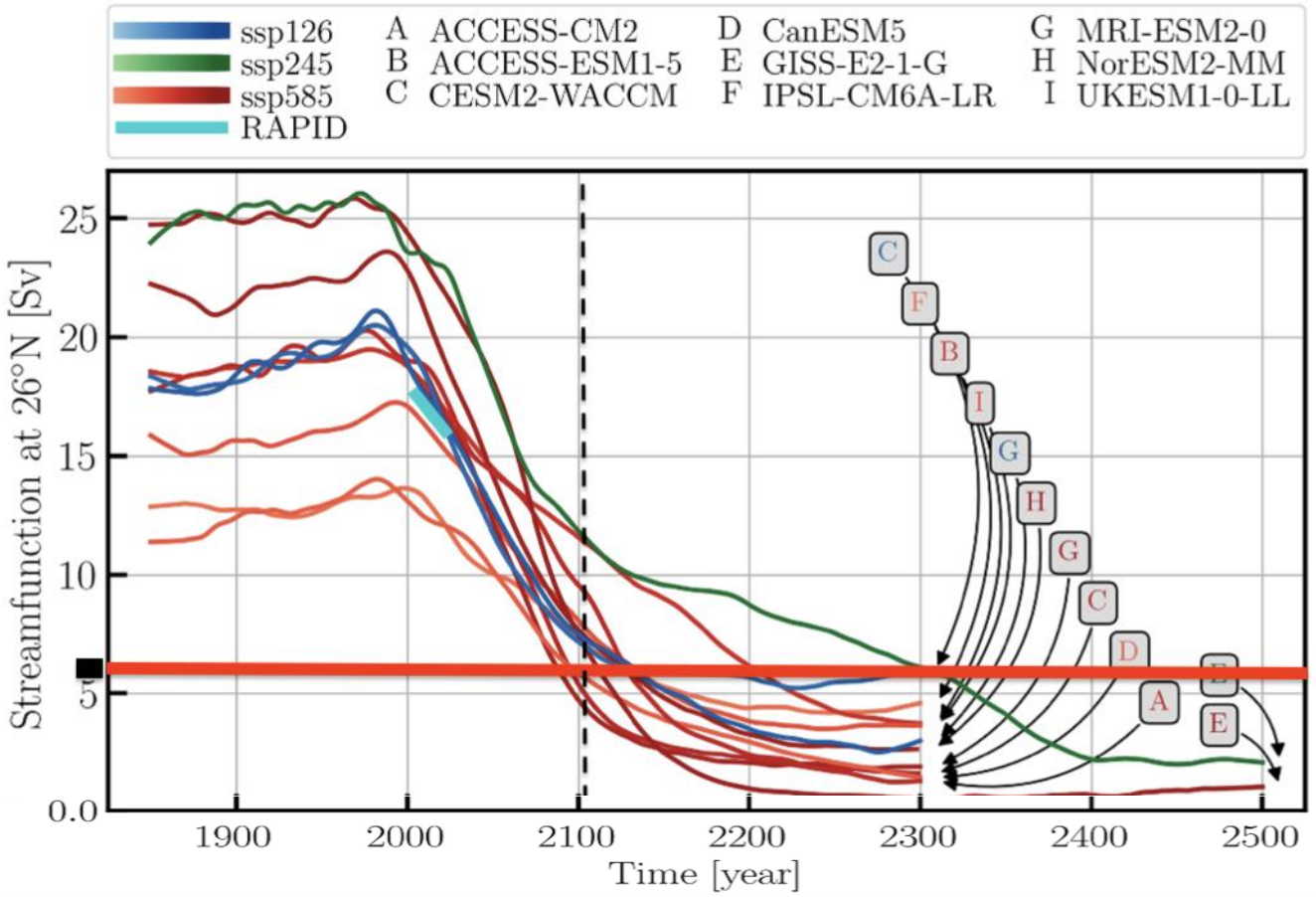
Historical (50)
SSP1-2.6 (18)
SSP1-1.9 (5)
SSP2-4.5 (32)
SSP3-7.0 (18)
Observation
SSP5-8.5 (27)

AMOC collapse beyond 2100?

TipESM

- A large number of simulations that goes beyond 2100 do show an AMOC collapse
- This is especially true in high emission scenario
- But can be found in a few models for medium and very moderate emission scenario

AMOC strength in shutdown simulations



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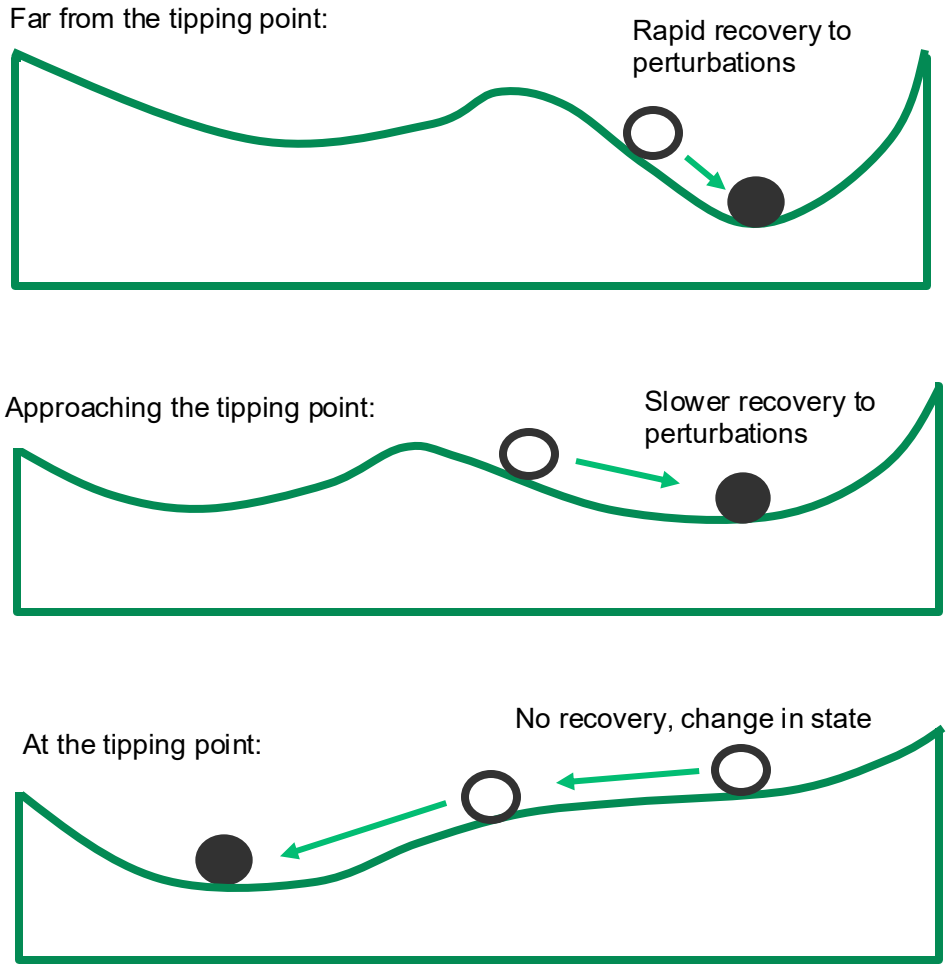
Drijfhout et al., ERL, 2025

Early warnings of tipping points

TipESM

Change of temporal variability when approaching a tipping point

- **Dynamical system theory** teaches us that approaching a tipping point, the variability of the system tends to increase
- Change in **variance** or **autocorrelation** can be used to quantify such changes (also related to resilience loss)
- However, **real system is far more complex** than theoretical models from dynamical system theory
- Need of **multiple early warning** to gain in robustness



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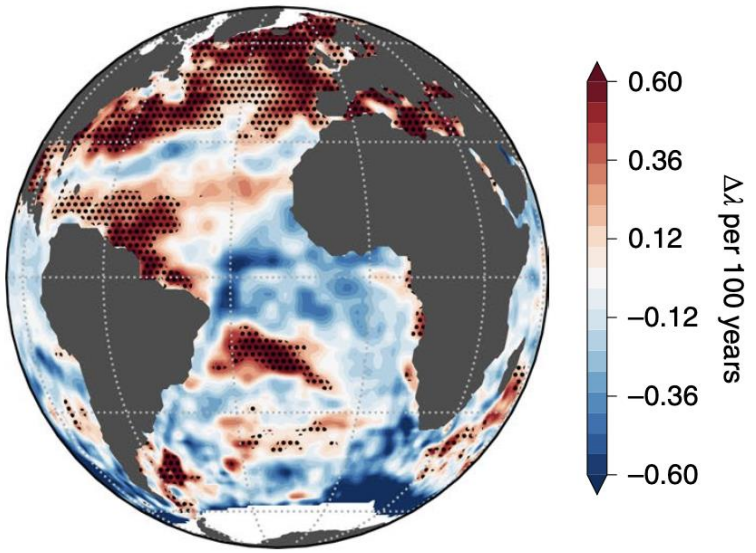
Adapted from: Lenton (2011)

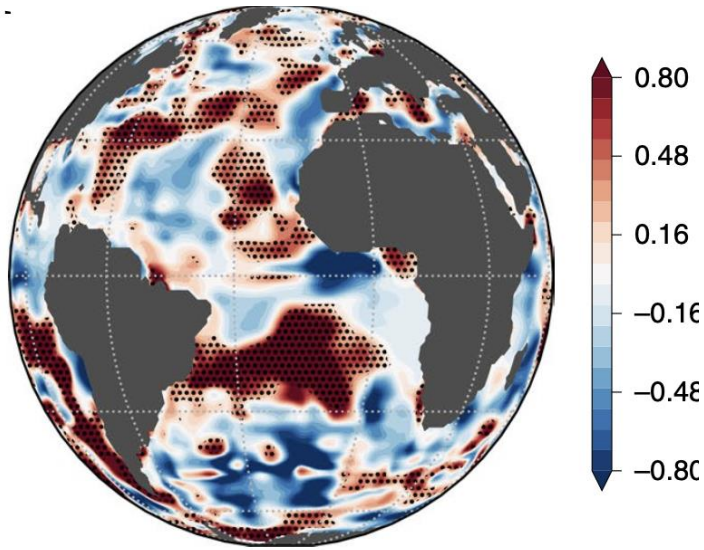
Proximity to an Atlantic circulation tipping point?

Significant changes in ocean surface variability since 1850

Sea Surface Temperature

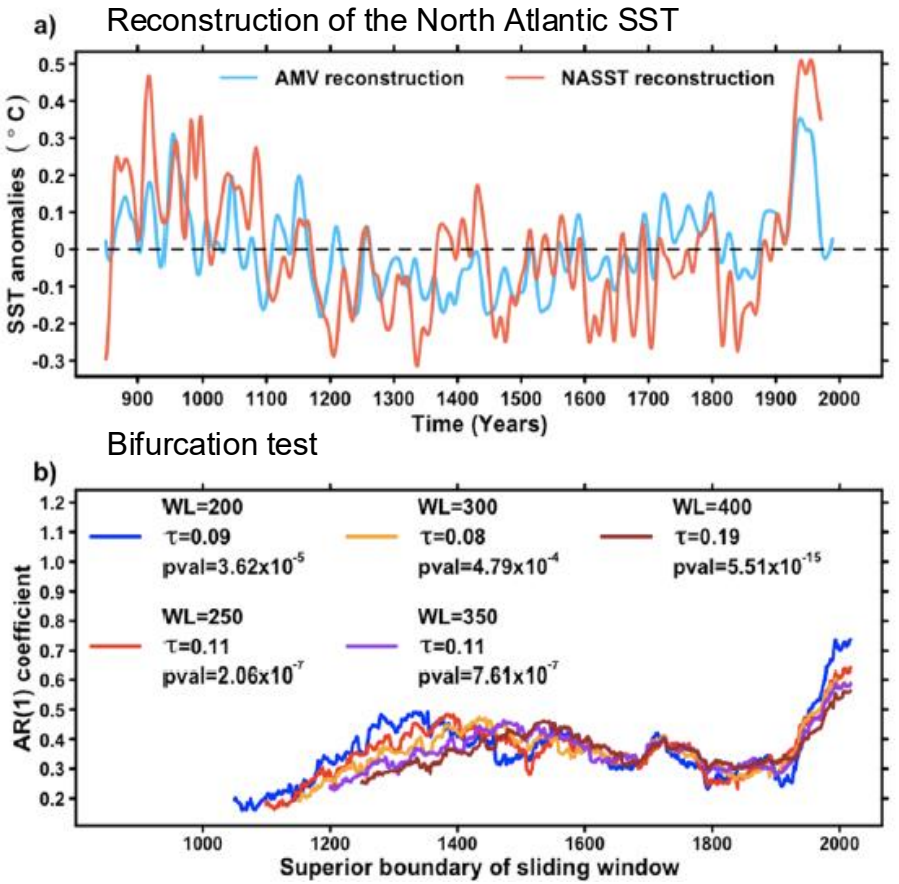


Sea Surface Salinity



Boers et al., Nat. Clim. Ch. (2021)

AMV reconstruction as a proxy of Atlantic internal variability



Michel et al., Nat. Com. (2022)

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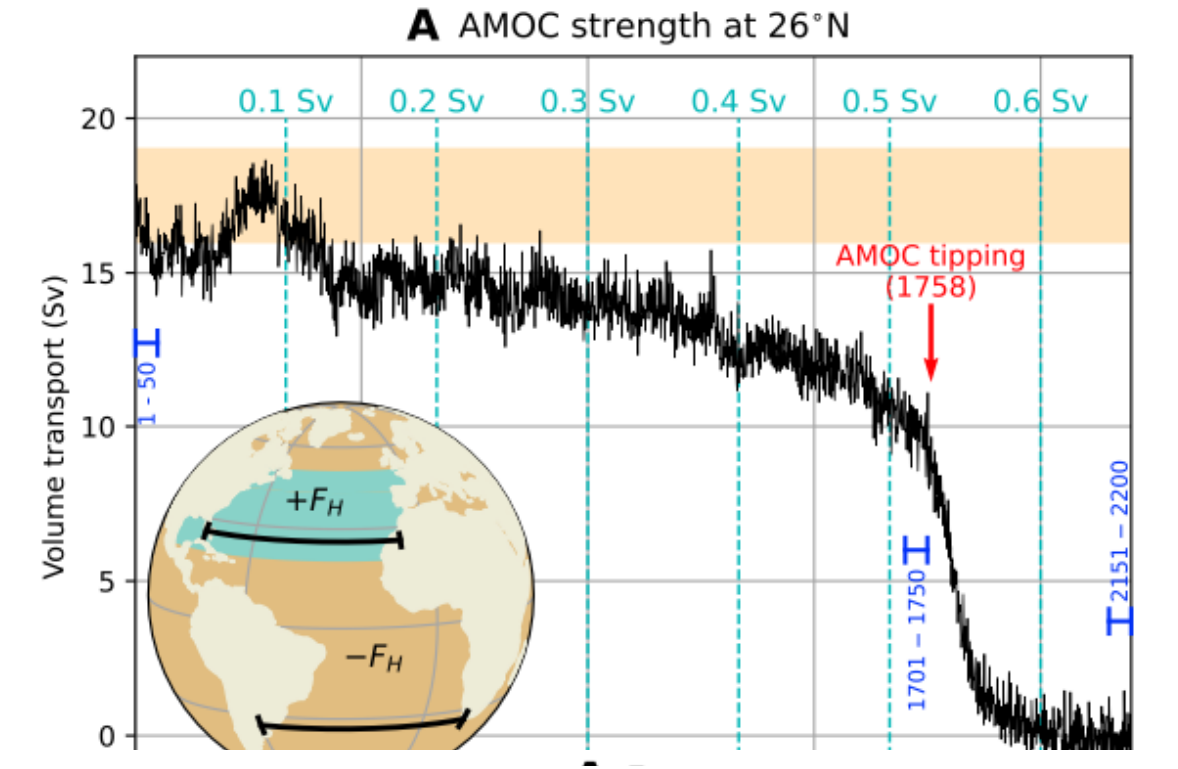
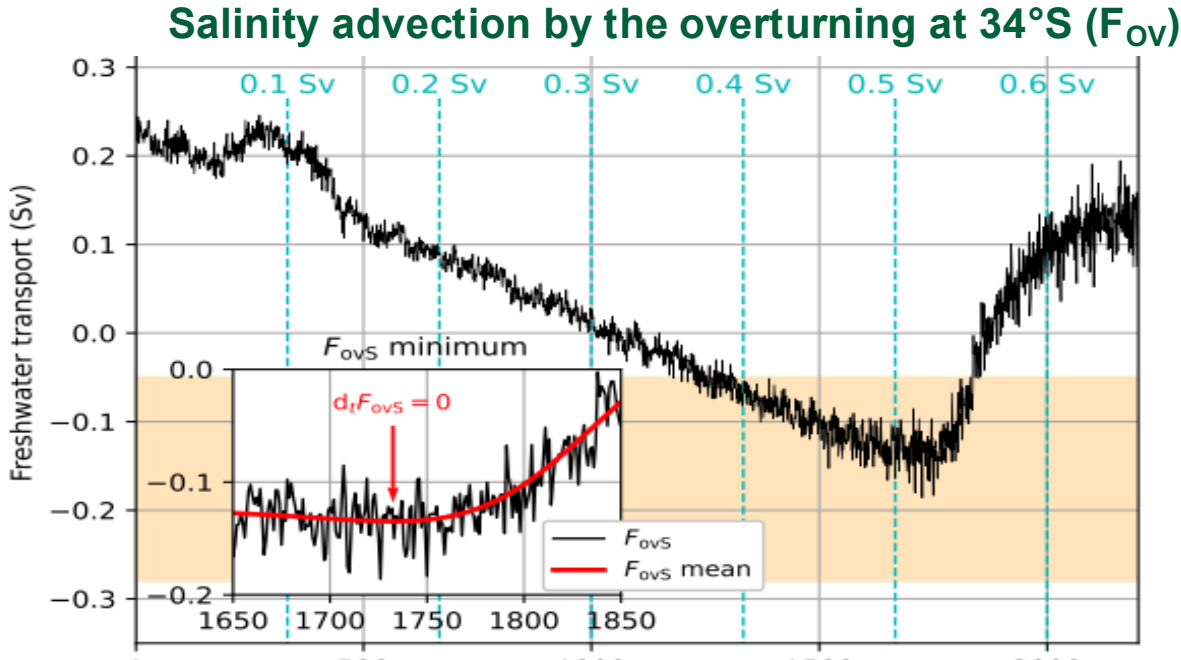
Proximity to an AMOC tipping point?

- Early warning based on **physical understanding** of the are very useful to gain in robustness
- Bistability has been related to **freshwater transport at 34°S** due salt advection feedback
- A change in the variation of this transport can be a good precursor of an AMOC collapse
- if correctly observed





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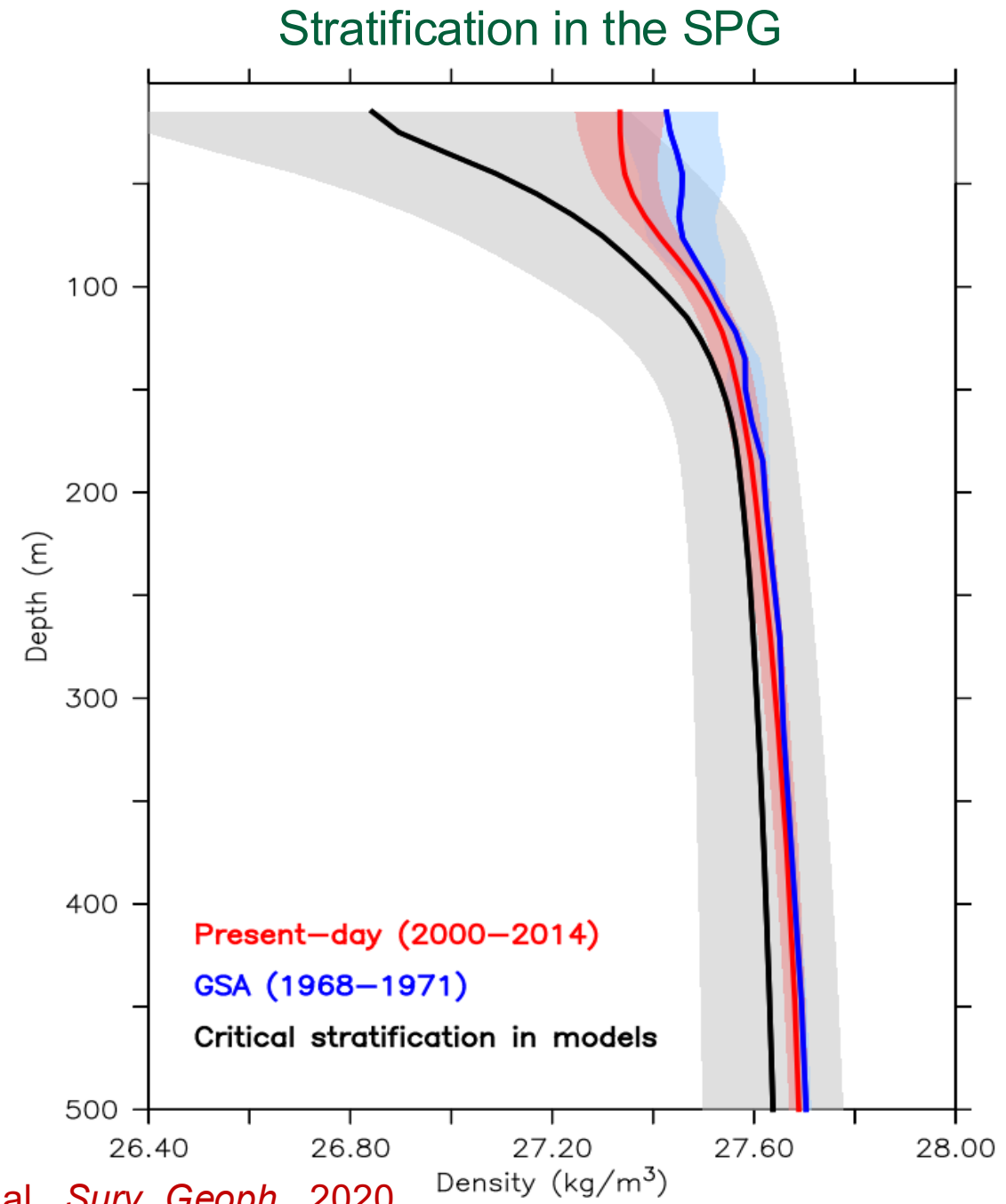
Van Westen et al. Sc. Adv. (2024)

Proximity to a SPG tipping point?

- **Stratification** stands for variations of density with depth
- This is a key prerequisite for deep water formation through convection processes
- **Critical stratification** can be defined beyond which no convection is possible leading to SPG collapse, which constitute useful early warning
- when correctly observed



Swingedouw et al., *Surv. Geoph.*, 2020

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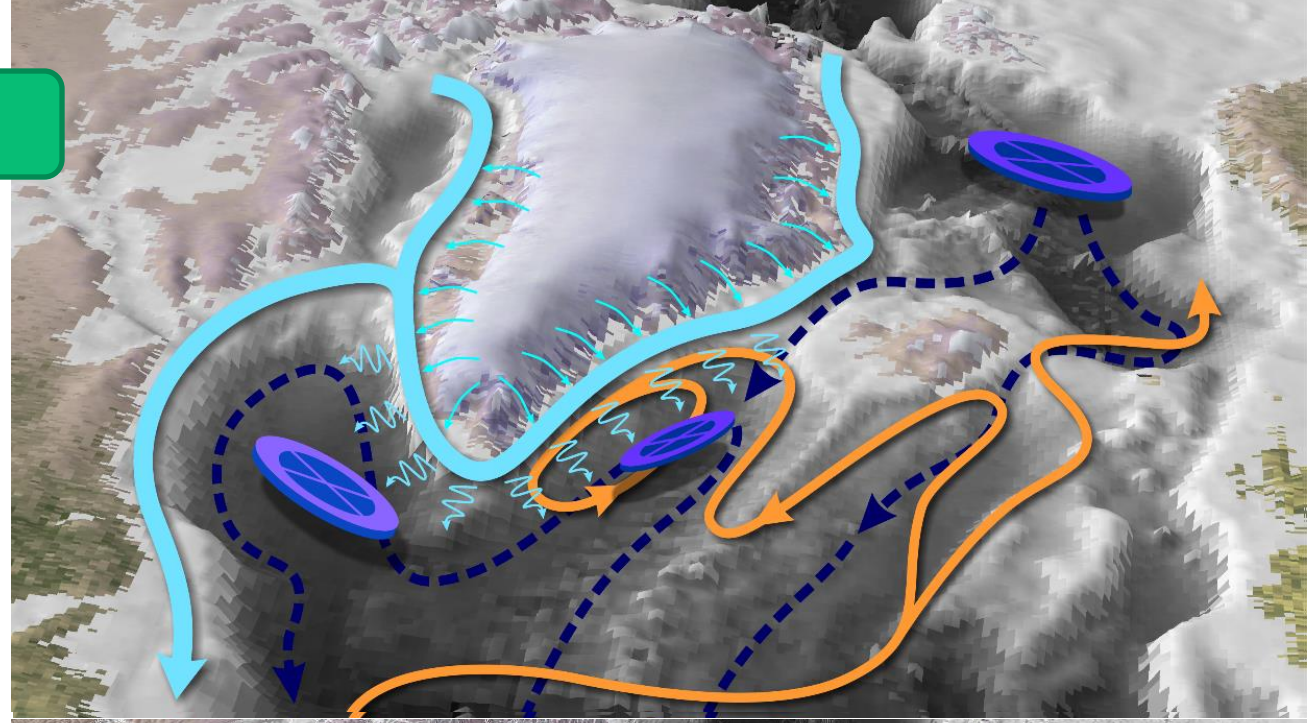
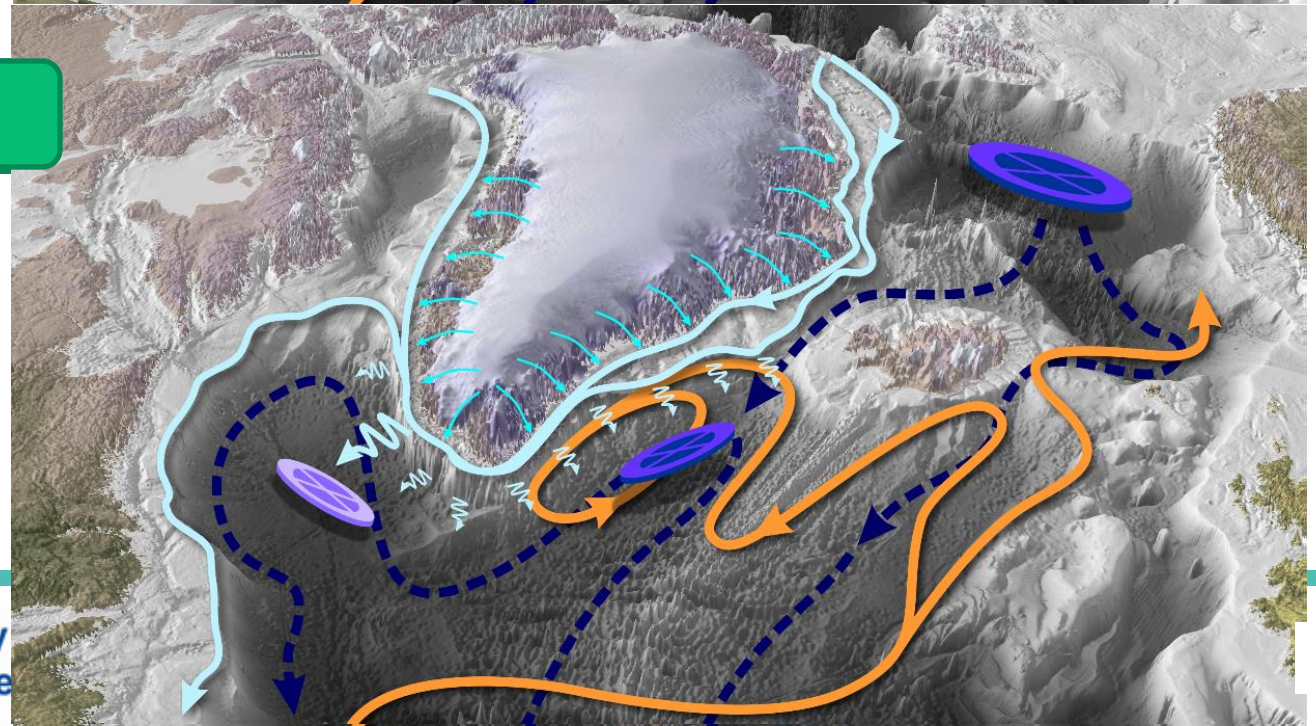
BLUE ACTION

Low Resolution



High Resolution



TipESM

What about Greenland melting and spatial resolution of models?

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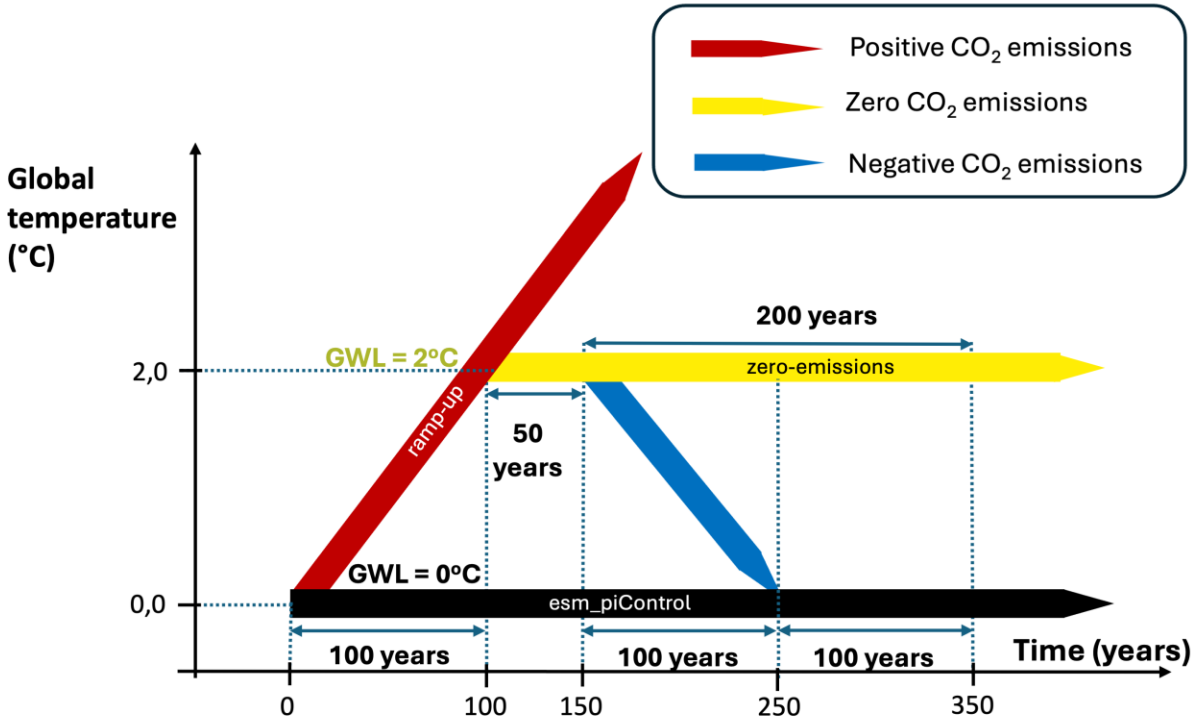
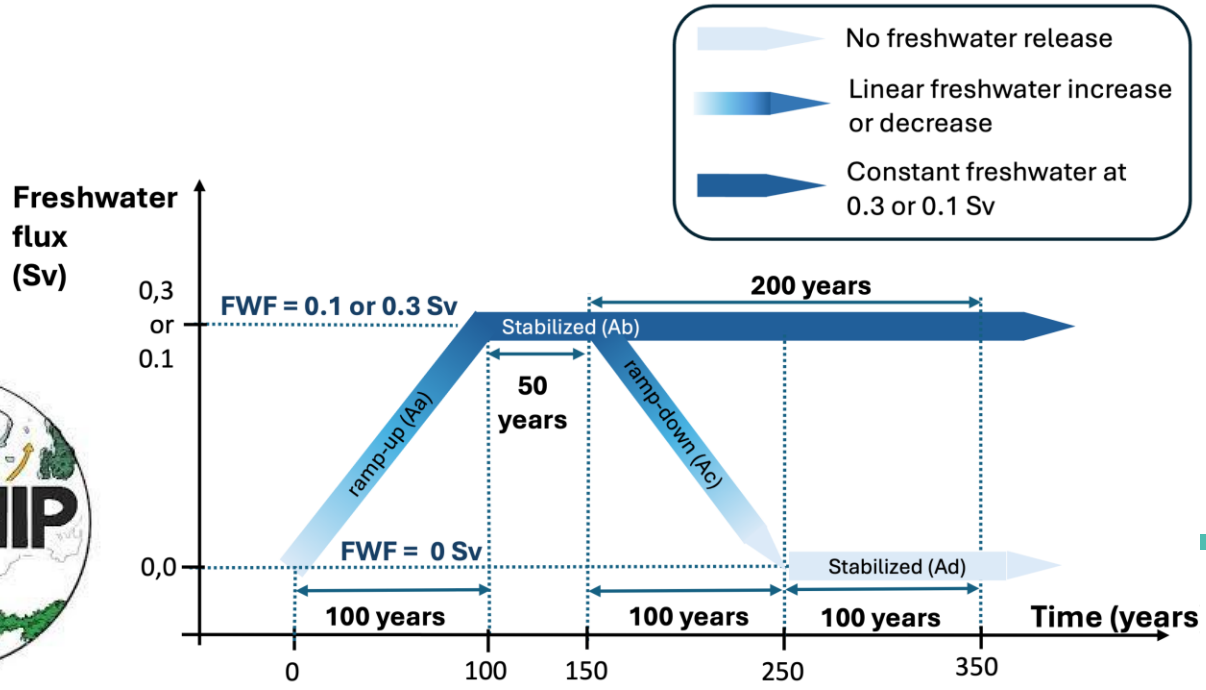
Swingedouw et al.,*Frontiers in climate* (2022)

Beyond 2100: can the AMOC change be irreversible?

- Since the AMOC is following an hysteresis with freshwater forcing, its collapse might be **irreversible**

- TIPMIP is a new project at the **international scale** aiming at estimating irreversiberlity of the AMOC using new climate models





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Conclusions

- AMOC **is very likely to weaken in the future** and might already be doing so
- A number of models is showing that **it might collapse after 2100**
- A sub-part of the AMOC, **the subpolar gyre system** might collapse more rapidly in just 10 years, before 2100
- Lots of early warning are flashing red
- A number of **processes missing in climate models** might make the AMOC more unstable (e.g. Greenland melting, eddies…)
- HOWEVER, the exact likelihood of any potential collapse is **poorly quantitatively estimated** and uncertainty remains very strong (model dependant results)

=> There is a **need** to prepare storylines for adaptation **in case** of such instabilities

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Credit: Steffen Olsen