Points de bascule de la circulation océanique : risques, impacts et anticipations

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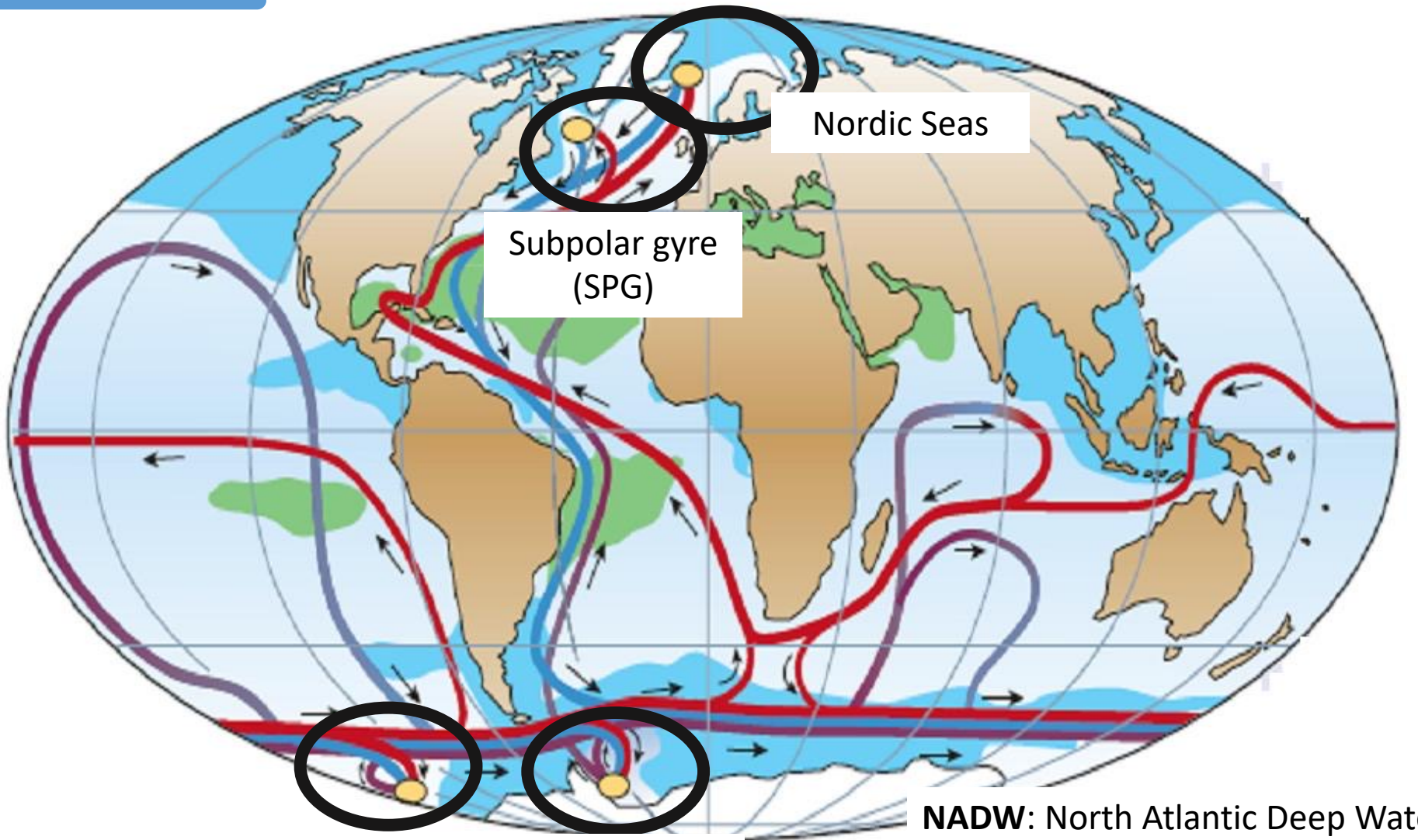
EPOC

Juliette Mignot, Marion Devilliers, Simon Michel, Giovanni Sgubin, Julie Deshayes,, Marie-Noelle Houssais, Christophe Herbaut, Sybren Drijfhout, Gerard McCarthy, Vincent Hanquiez, Pascale Braconnot, Pascale Delécluse, Hugues Goosse, Thierry Fichefet, Matt Collins, Pepijn Bakker, Kees van Leeuwen, Yulia Polkova…

The large-scale ocean circulation

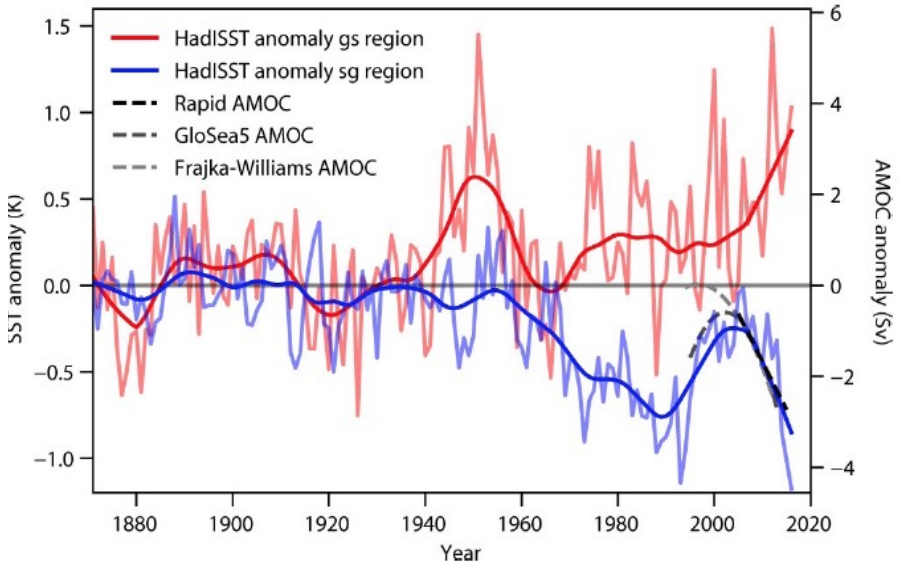


Rahmstorf 2002

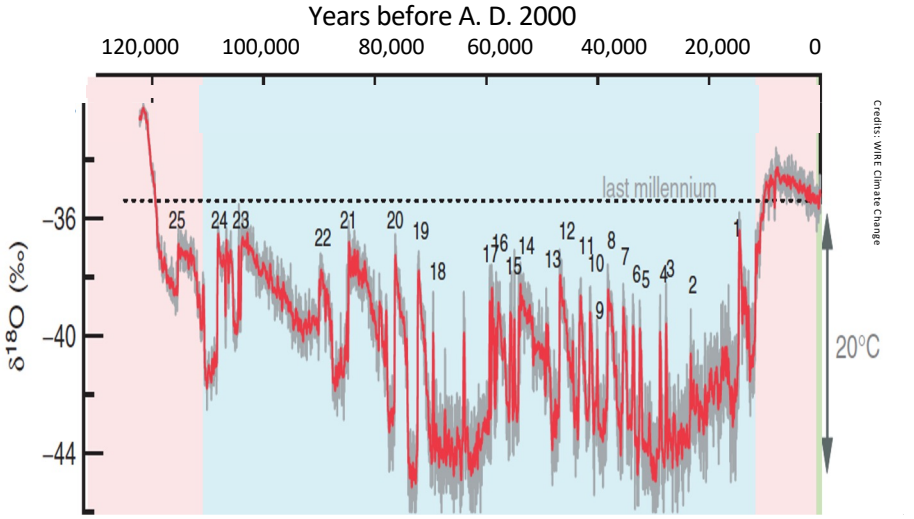
NADW: North Atlantic Deep Water
AABW: Antarctic Bottom Water

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 (cf. Caesar et al. 2018)
- Lessons from the past both in glacial and interglacial periods highlight that abrupt changes/tipping points are possible



Ice core reconstructions

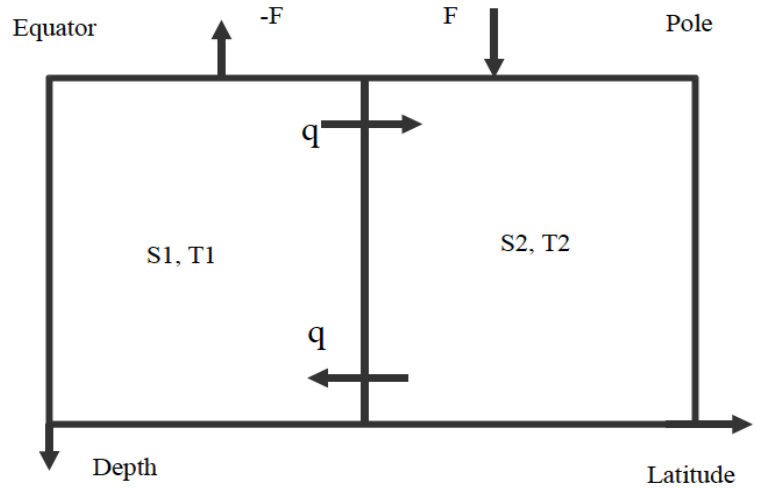


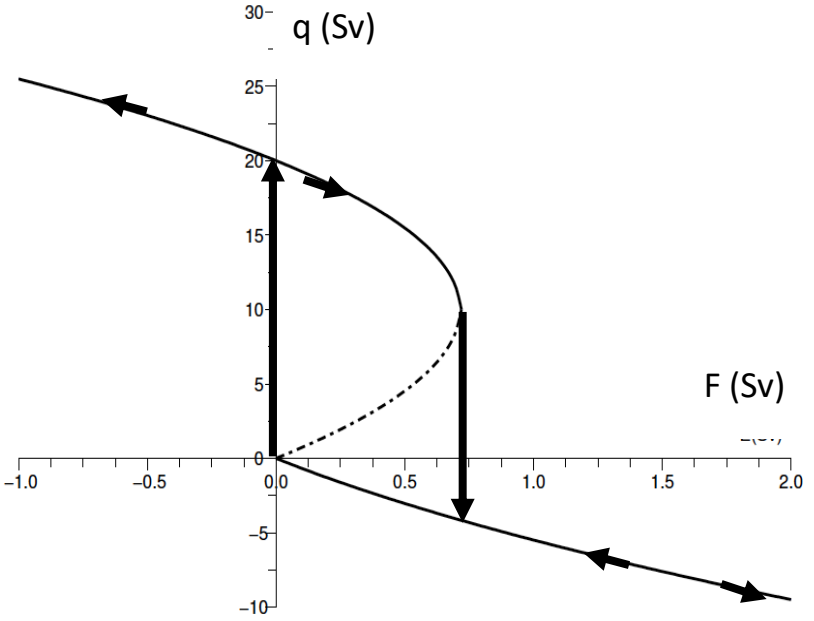
Masson-Delmotte et al. 2012

Non linearity of the Atlantic Overturning (AMOC)?

- Stommel (1961) early showed that the AMOC may exhibit strongly non-linear response to surface freshwater forcing
- His simple analytical model showed that the AMOC may have multiple solutions for a given freshwater forcing and hysteresis behavior
- Still true in higher resolution models (cf. Rahmstorf et al. 2005, Jackson et al 2018…)

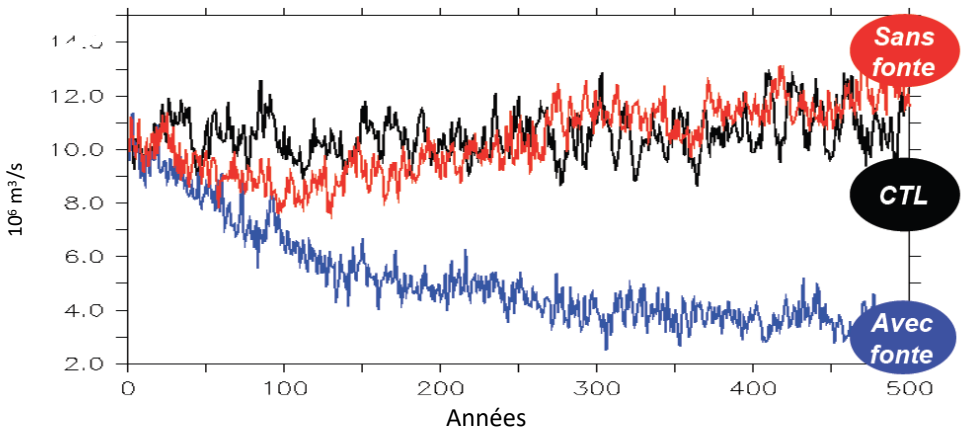
This is a steady state response! (potentially implying millennial scale)





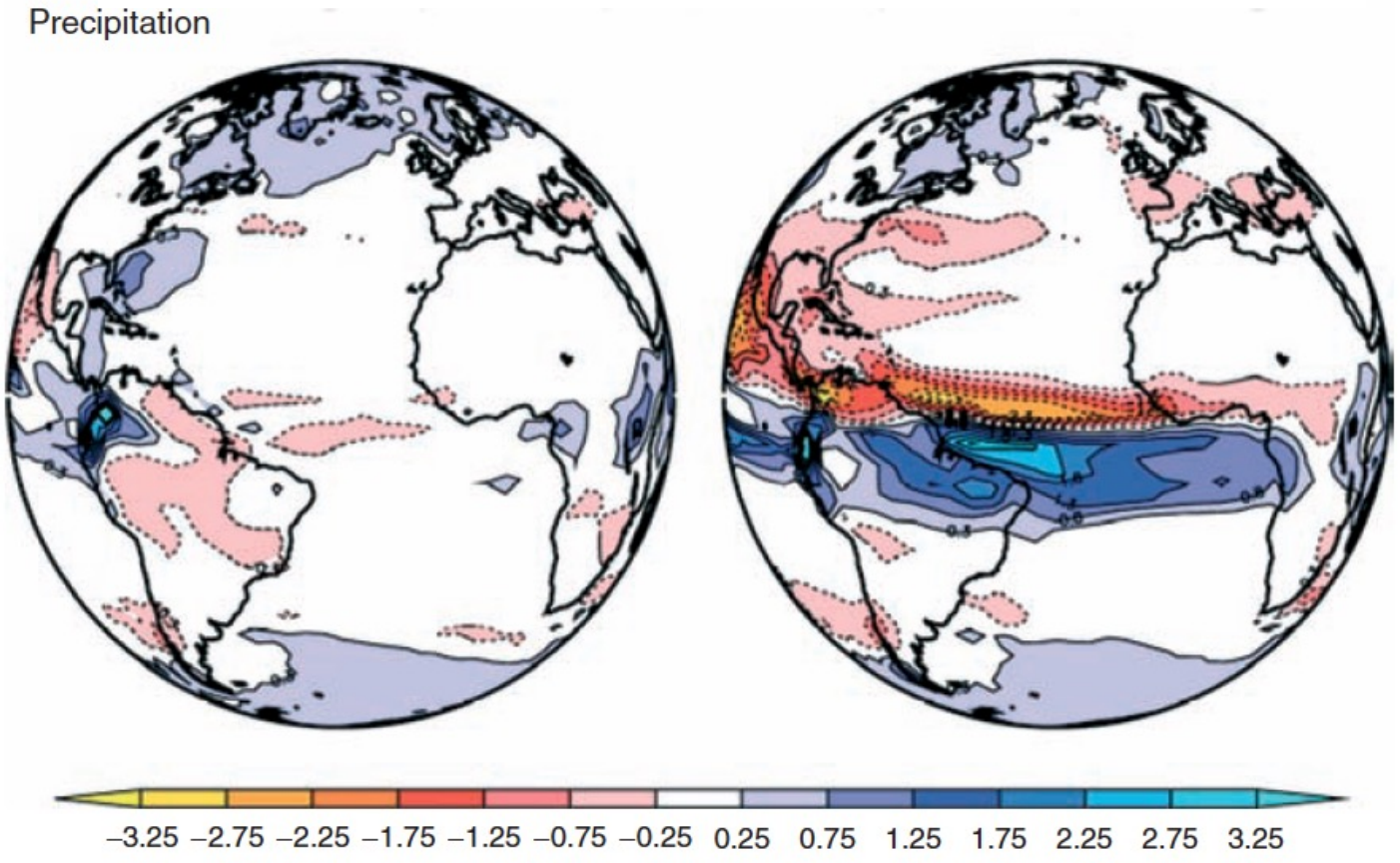
Can the AMOC collapse?

Swingedouw et al., *Clim. Dyn.*, 2007a, Masson-Delmotte et al., *WIRE*, 2012



Without melting

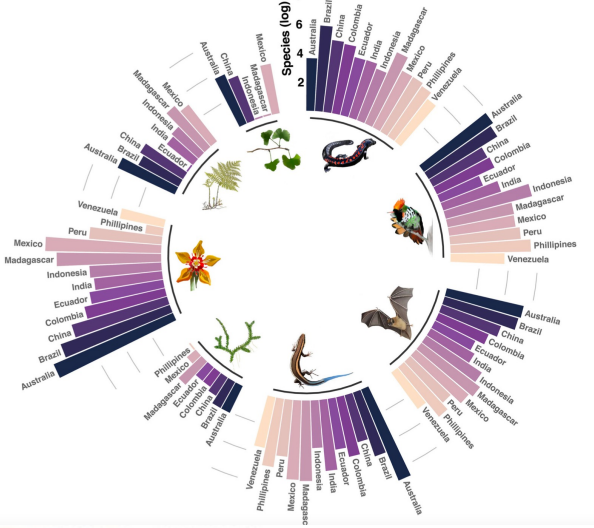
With melting



Large-scale impact of a substantial weakening in the Atlantic circulation

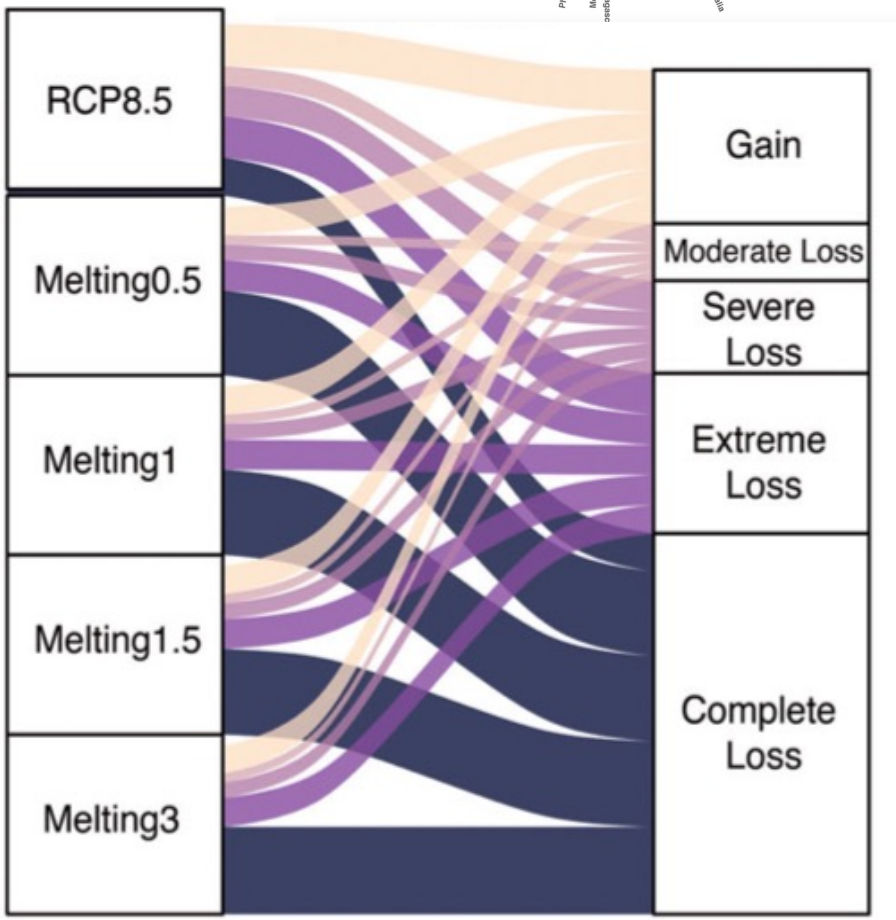
Fig. 6.10 from IPCC SROCC report, 2019

All cascading potential impacts not fully assessed yet?



- Impacts on biodiversity: a new example of cascading tipping points: Velasco et al. (2021), Ureta et al. (2022) both in *Communications Biology*

- A strong weakening of the AMOC can push a number of species to cross their own tipping point (due to changes in regional climate and seasonality) reducing biodiversity



Key questions

- Can the AMOC tip in the future and on what time frame?
- Have other circulations shown sign of potential rapid changes?
- How can we anticipate those tipping points?

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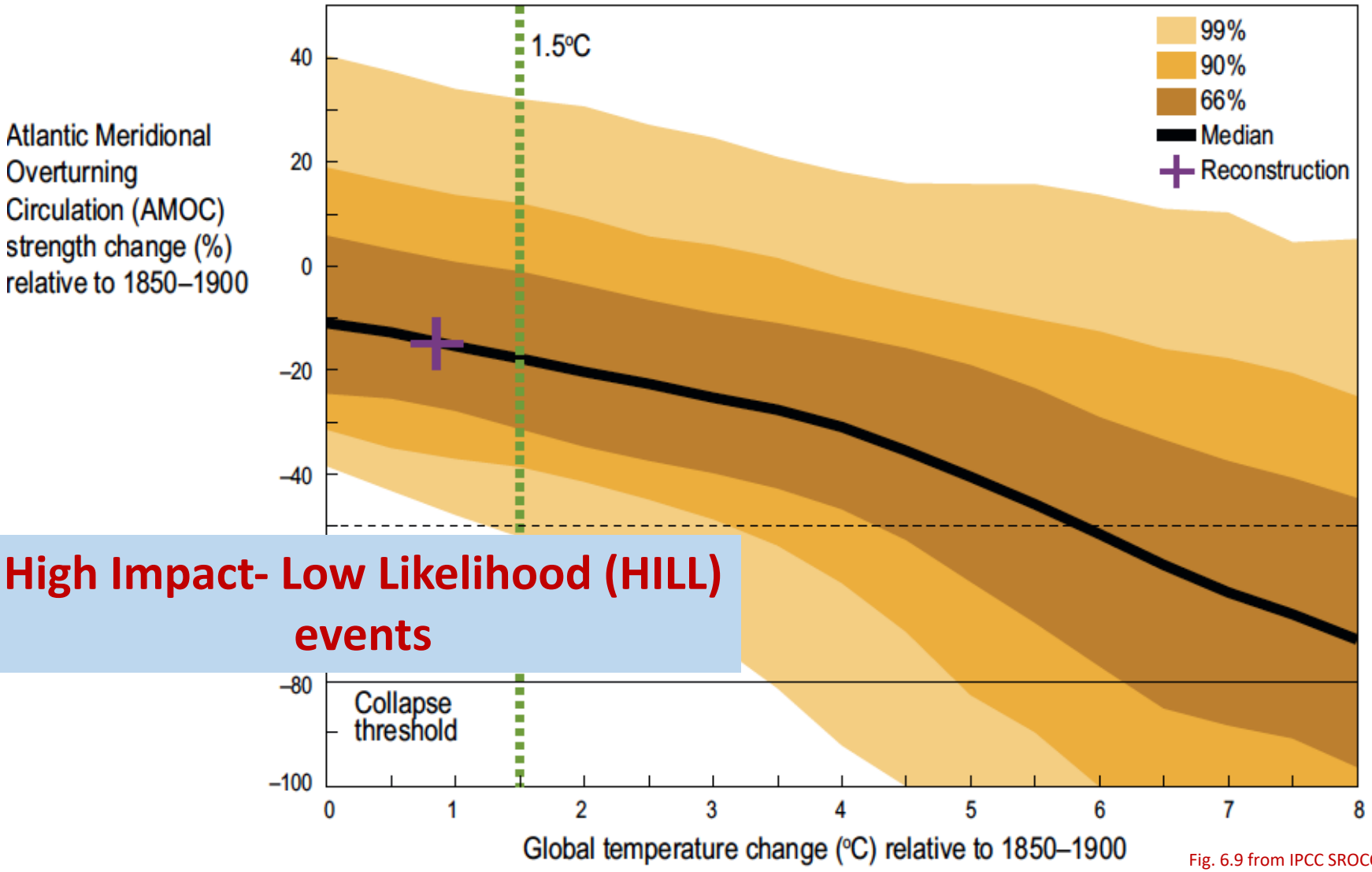
Risk of AMOC substantial weakening



High Impact- Low Likelihood (HILL) events

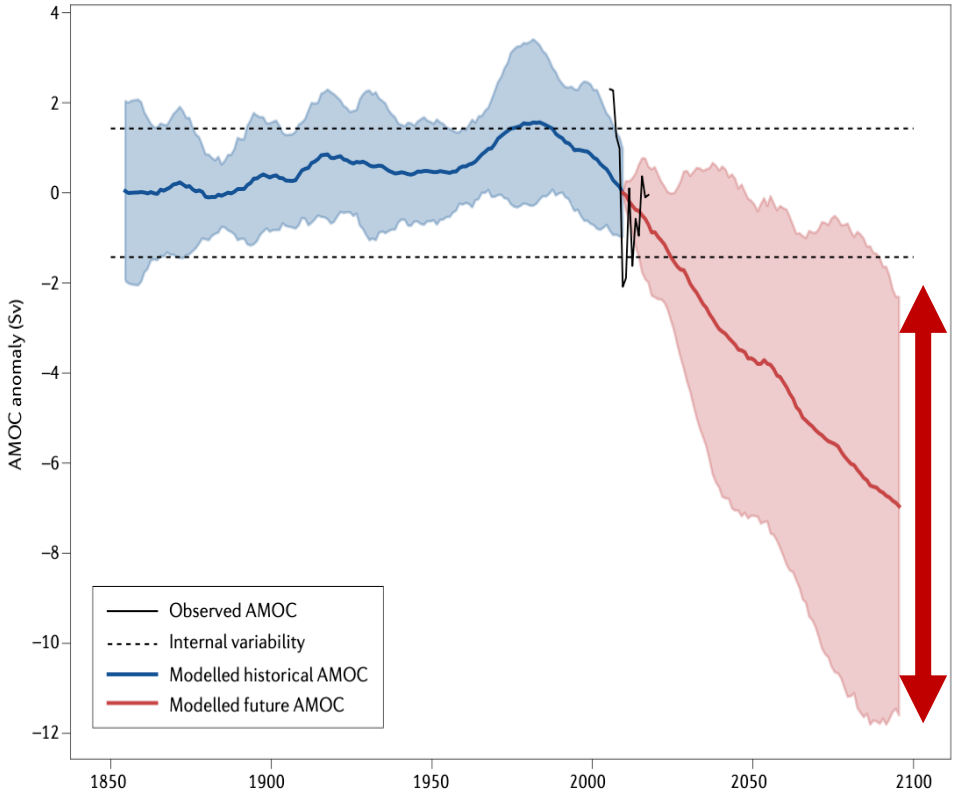
IPCC
INTERGOVERNMENTAL PANEL ON climate change

Fig. 6.9 from IPCC SROCC report, 2019

Projections of the AMOC in CMIP6 models

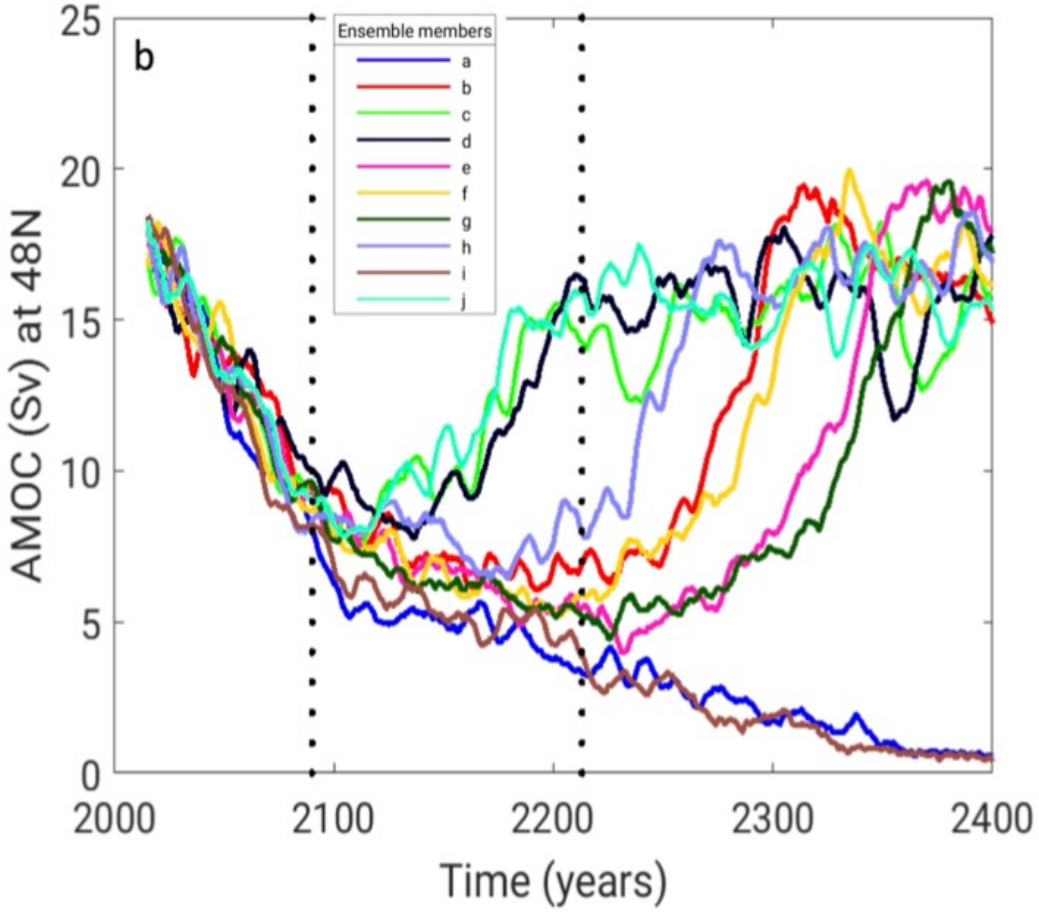
- IPCC 2021 statements:
  - "The AMOC is ***very likely* to weaken** over the 21st century for all emission scenarios.
  - There is ***medium confidence*** that there will **not be** an **abrupt collapse** before 2100 "

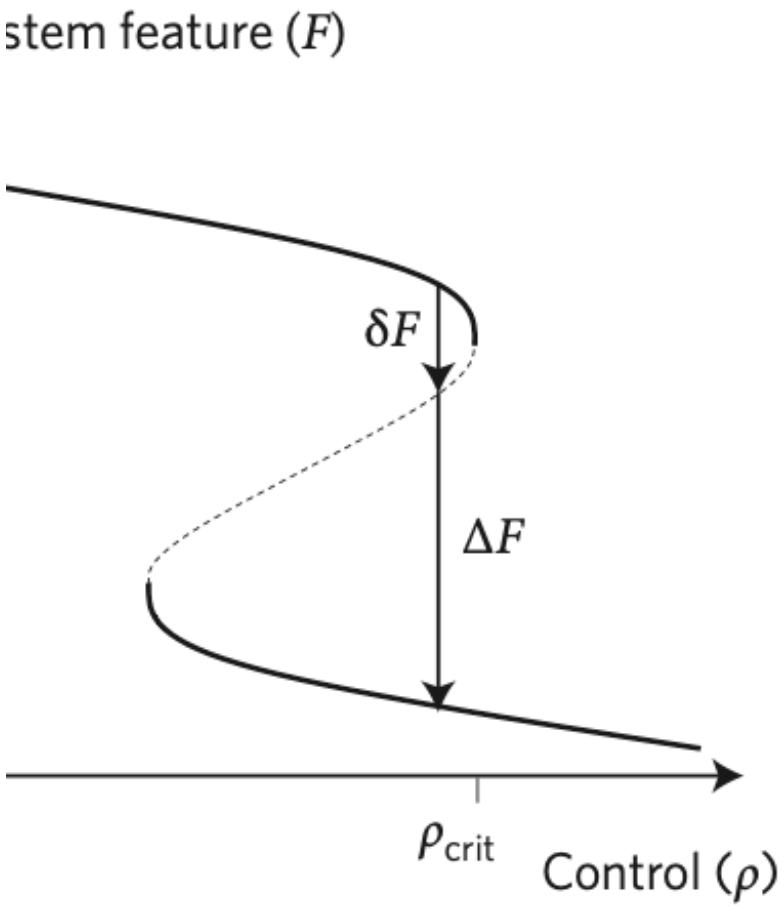
- Spread in the AMOC is explaining a large amount of CMIP6 uncertainty for some key climate variables (Bellomo et al., *Nat. Com.* 2021) like
  - the shift of the atmospheric jets,
  - the ITCZ position,
  - the level of warming in the North Atlantic region, *etc*.



Jackson et al., Nat. Clim. Ch. 2022

Long-term changes and noise induced bifurcation



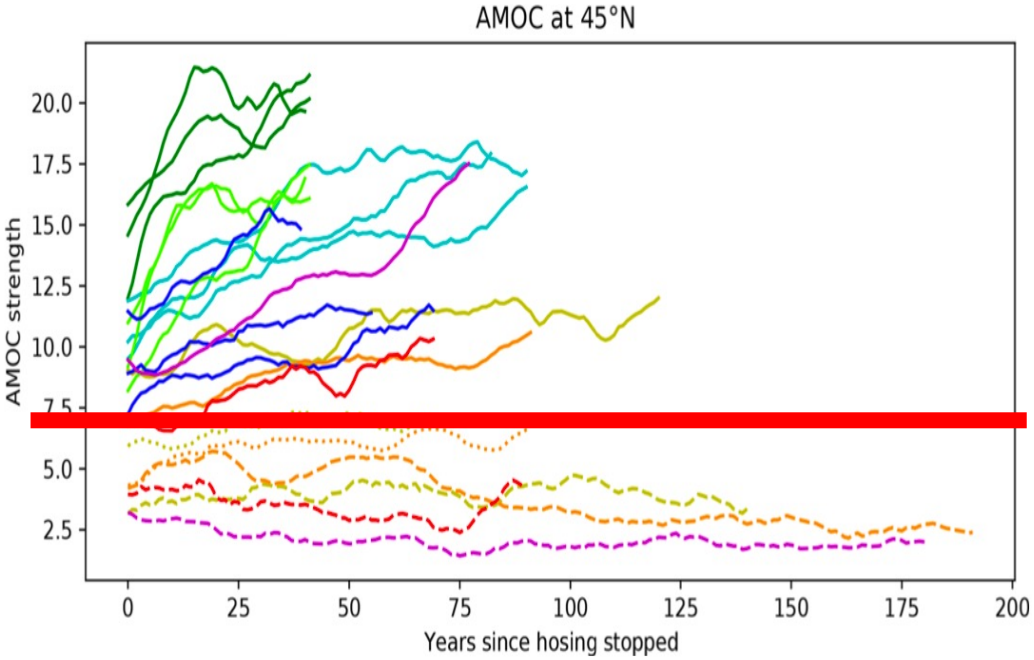


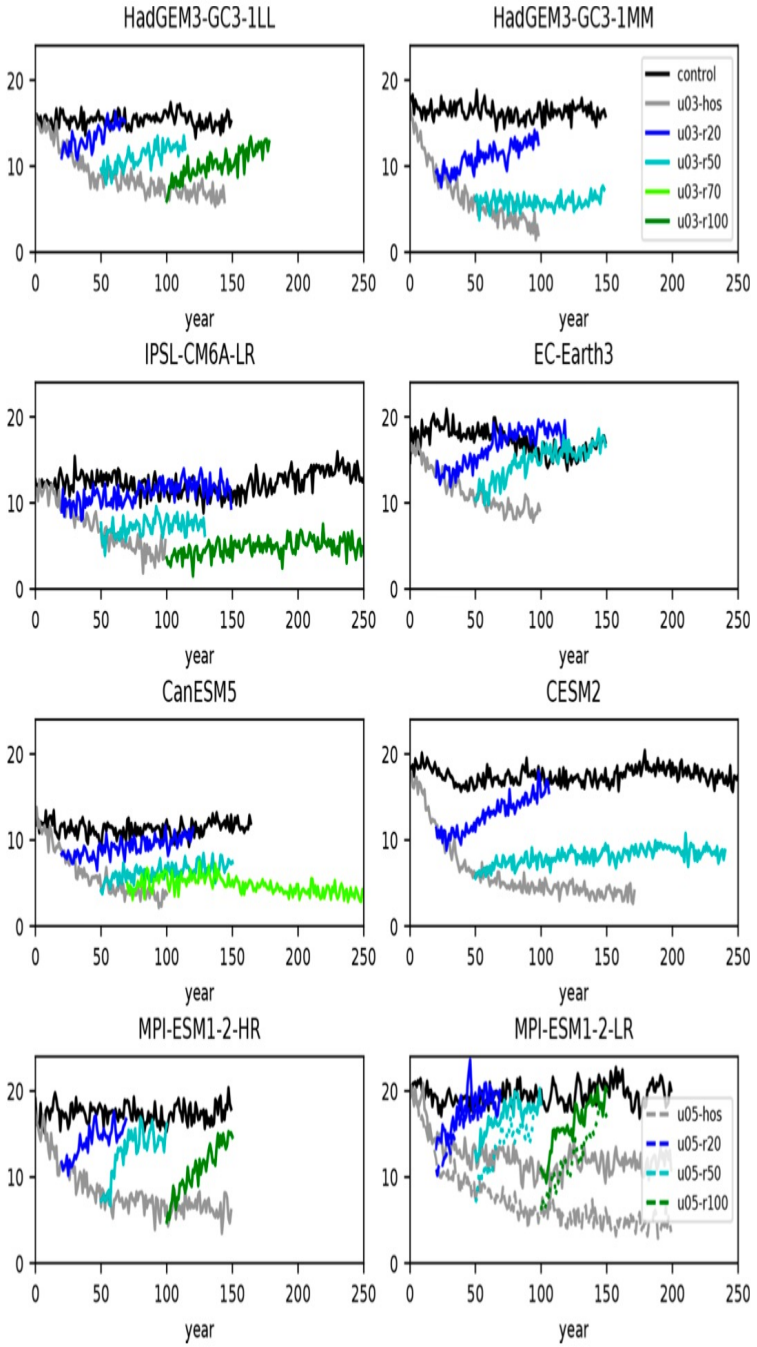
Romanou et al., *J. Climate* 2023

Lenton et al., *Nat. Clim. Ch.* 2011

Bi-stability of the AMOC in CMIP6 models

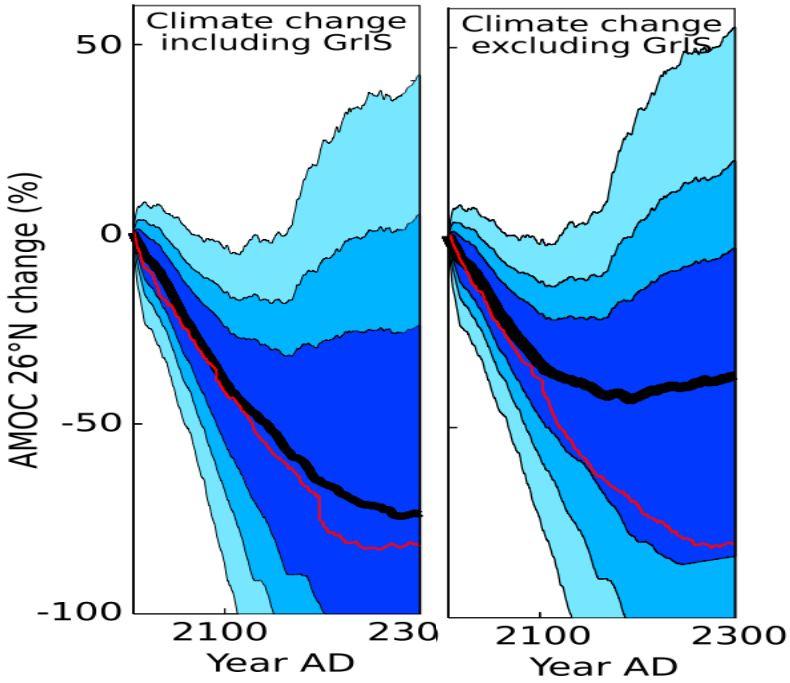
- Can the AMOC come back after a collapse
- Test using CMIP6 models through hosing experiments (Jackson et al. 2023)
- 4/8 models do show sign of irreversibility
- A Threshold in AMOC strength as a point of no return?



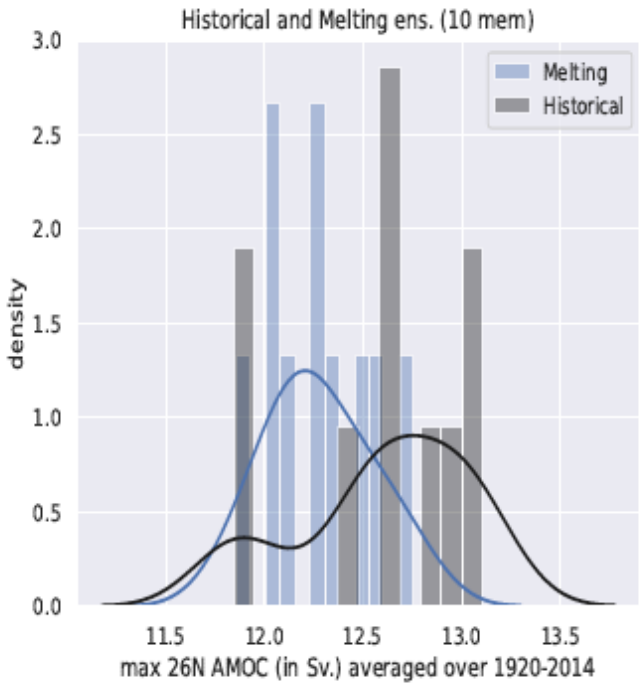


Jackson et al., *GMD*, 2023

What about Greenland melting?



- It further weakens the CMIP5 projected AMOC by up to 10% in 2100 and up to 25% in 2300 under RCP8.5 scenario (Bakker et al. 2016)
- **Has Greenland melting played a role in the recent AMOC weakening?**
- Using of 10 members of IPSL-CM6A-LR historical simulations including this melting since 1920 (**Melting ensemble**) or not (**Historical ensemble**) until 2014, Devilliers et al. (2021) showed that the AMOC weakens by 0.20 ± 0.39 Sv at 45°N

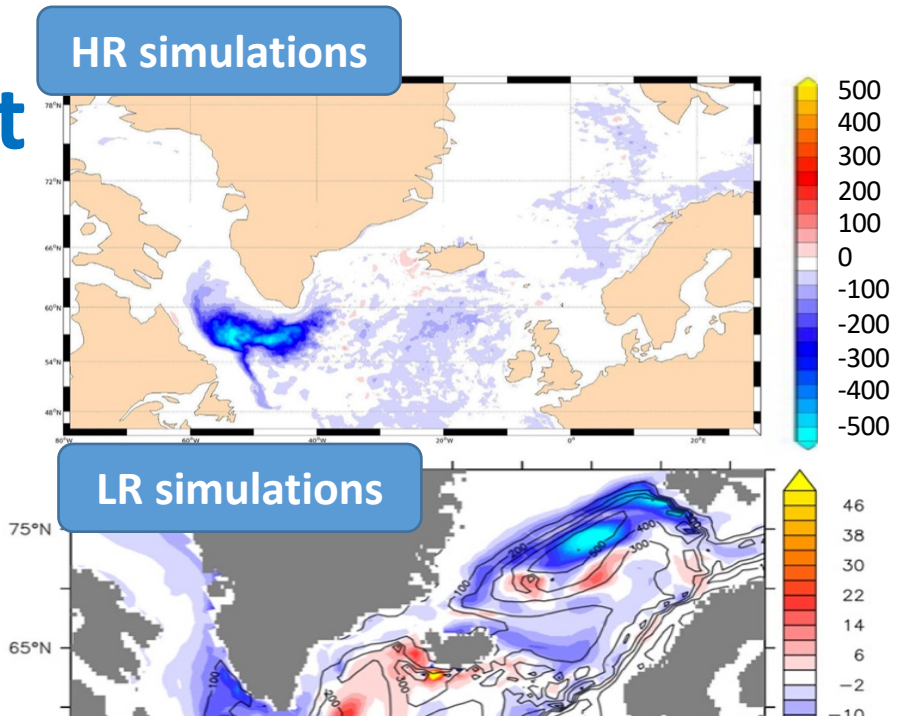


Devilliers et al. *Clim. Dyn*. 2021

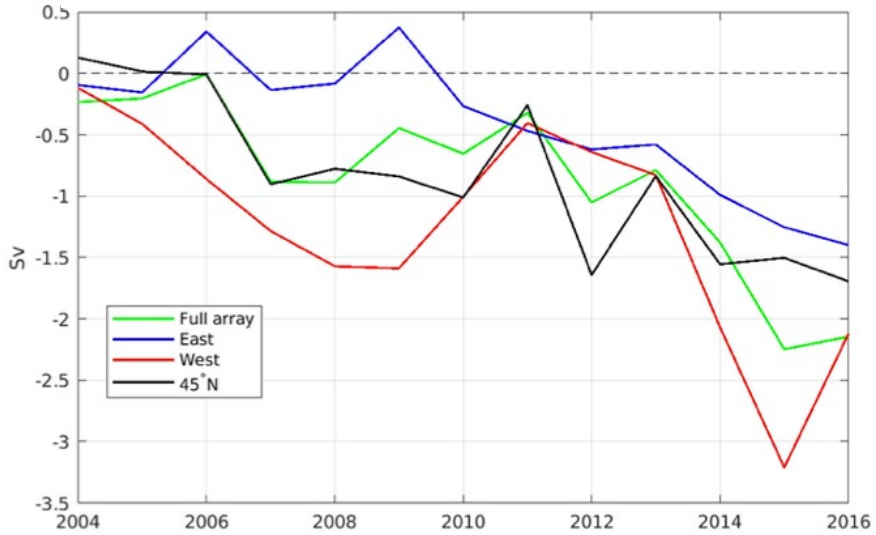
Impacts of oceanic resolution on GrIS impact

- We compare IPSL-CM6A Low Resolution (**LR, 50-60 km**) run with very High Resolution (**HR, 2-3 km**) simulations from an ocean-only model (Swingedouw et al., 2022)
- Higher impact of Greenland melting on the AMOC in the HR runs

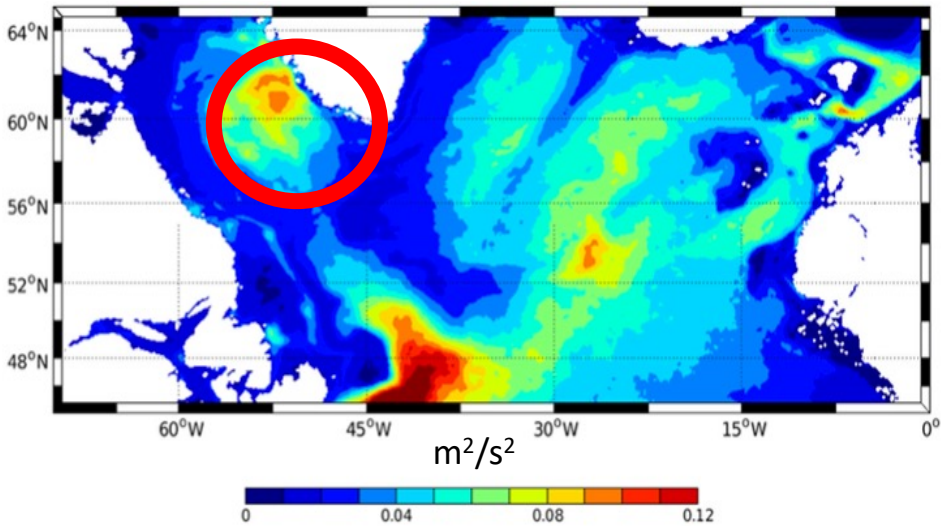
Mixed layer depth anomalies



AMOC anomalies in HR simulations

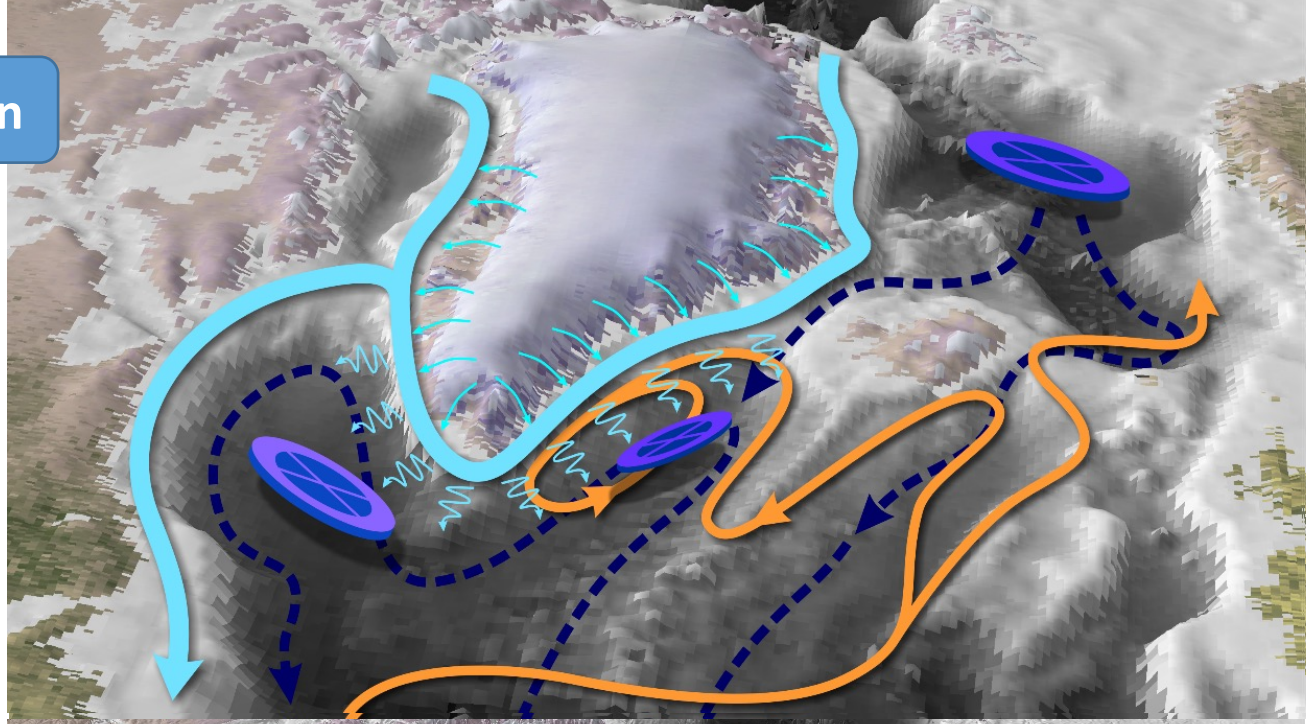


Eddy Kinetic energy in HR simulation

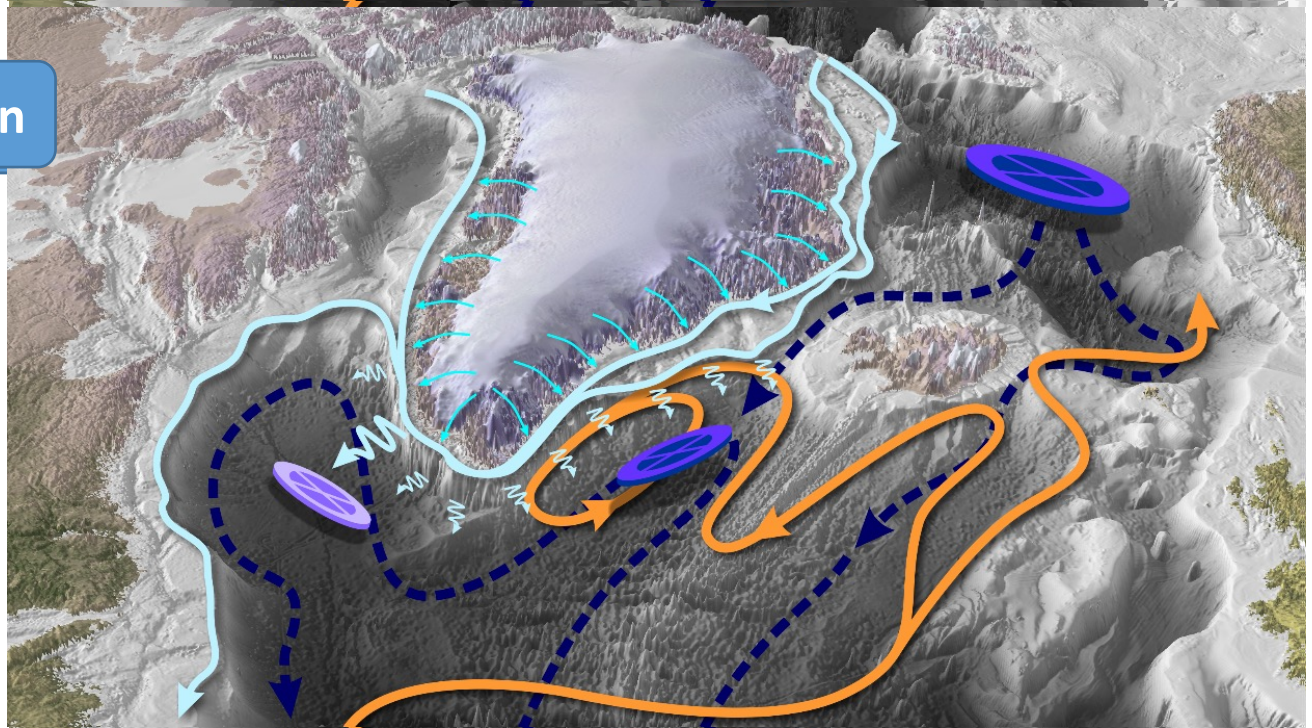


Swingedouw et al., *Frontiers*, 2022

Low Resolution



High Resolution



Scheme by Vincent Hanquiez

Key questions

- Can the AMOC tip in the future and on what time frame?
- **Have other circulations shown sign of potential rapid changes?**
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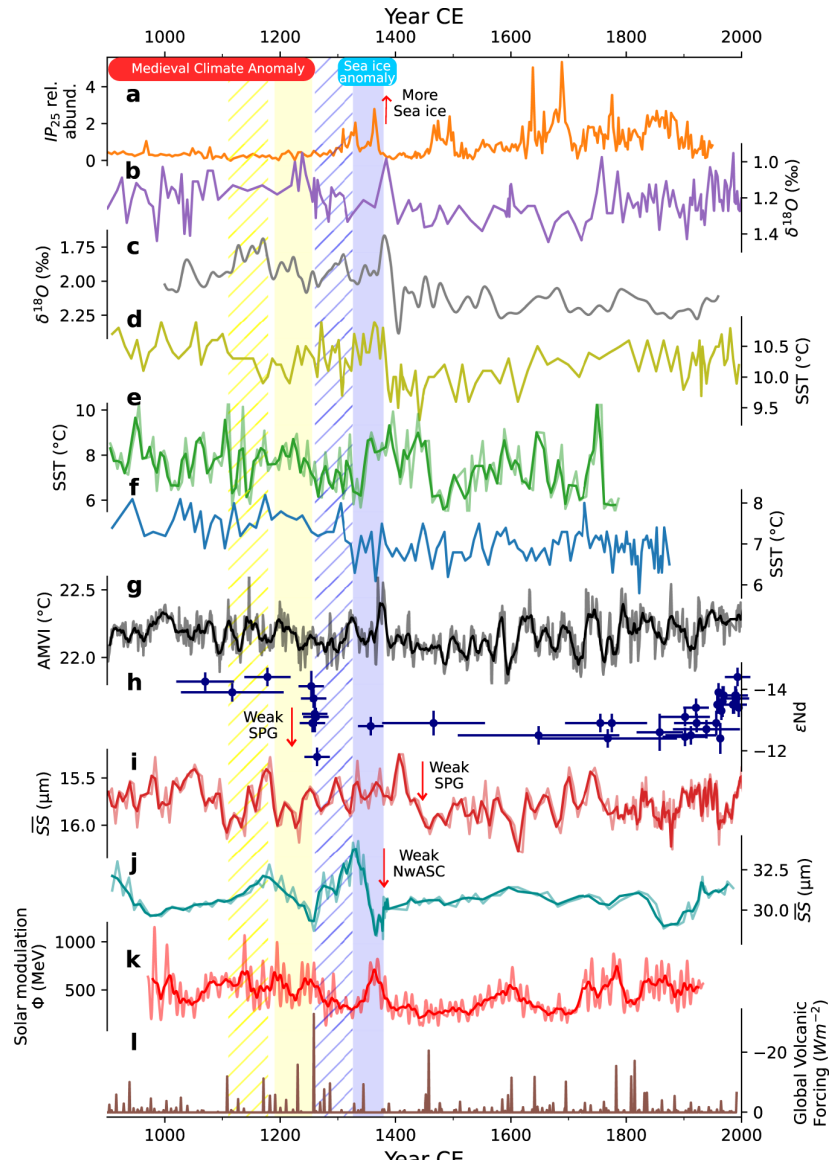
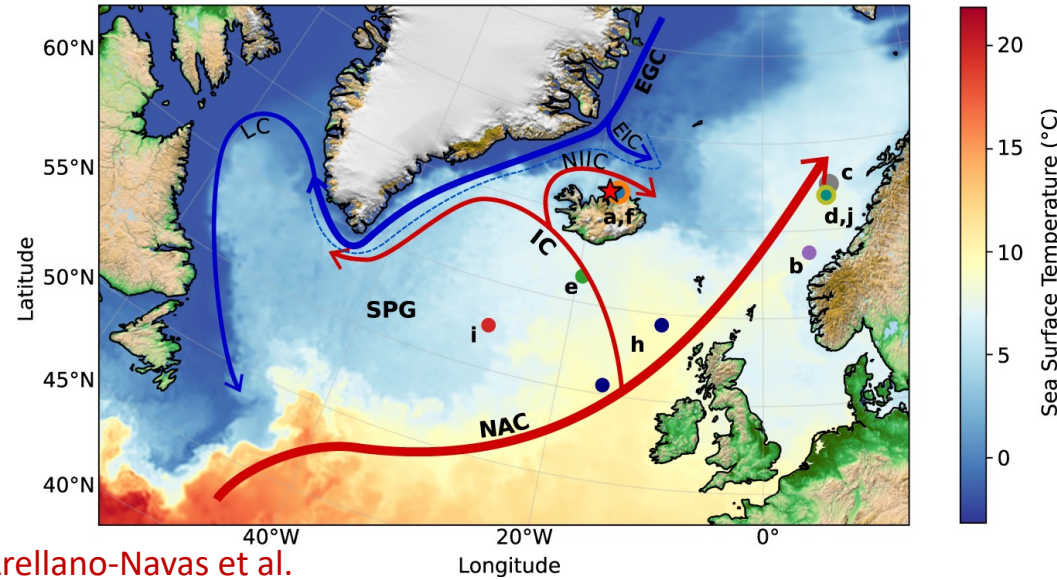
SPG and the Little Ice Age





Arellano-Navas et al. *Nat. Com.* 2023

- A large number of proxy records now show a rapid change in the SPG as a potential **key precursors of the onset of the Little Ice Age**

(e.g. Michel et al. 2022, Arellano-Navas et al. 2023)

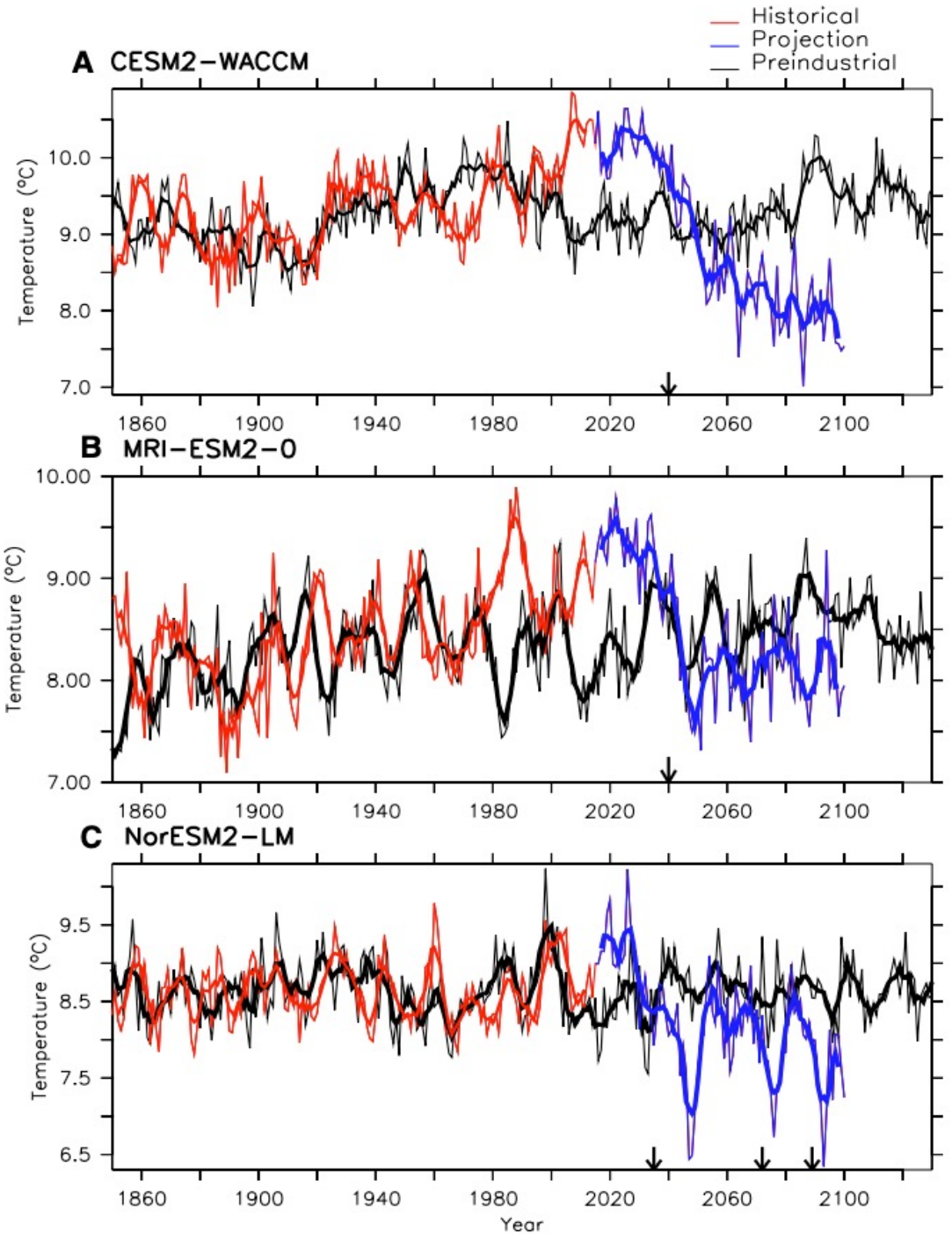
- However, the **exact timing and drivers are** still largely discussed (internal noise-induced change, volcanic eruptions…)

Possibility of Abrupt the North Atlantic in

- Some CMIP models do show abr cooling in the subpolar gyre (SP(

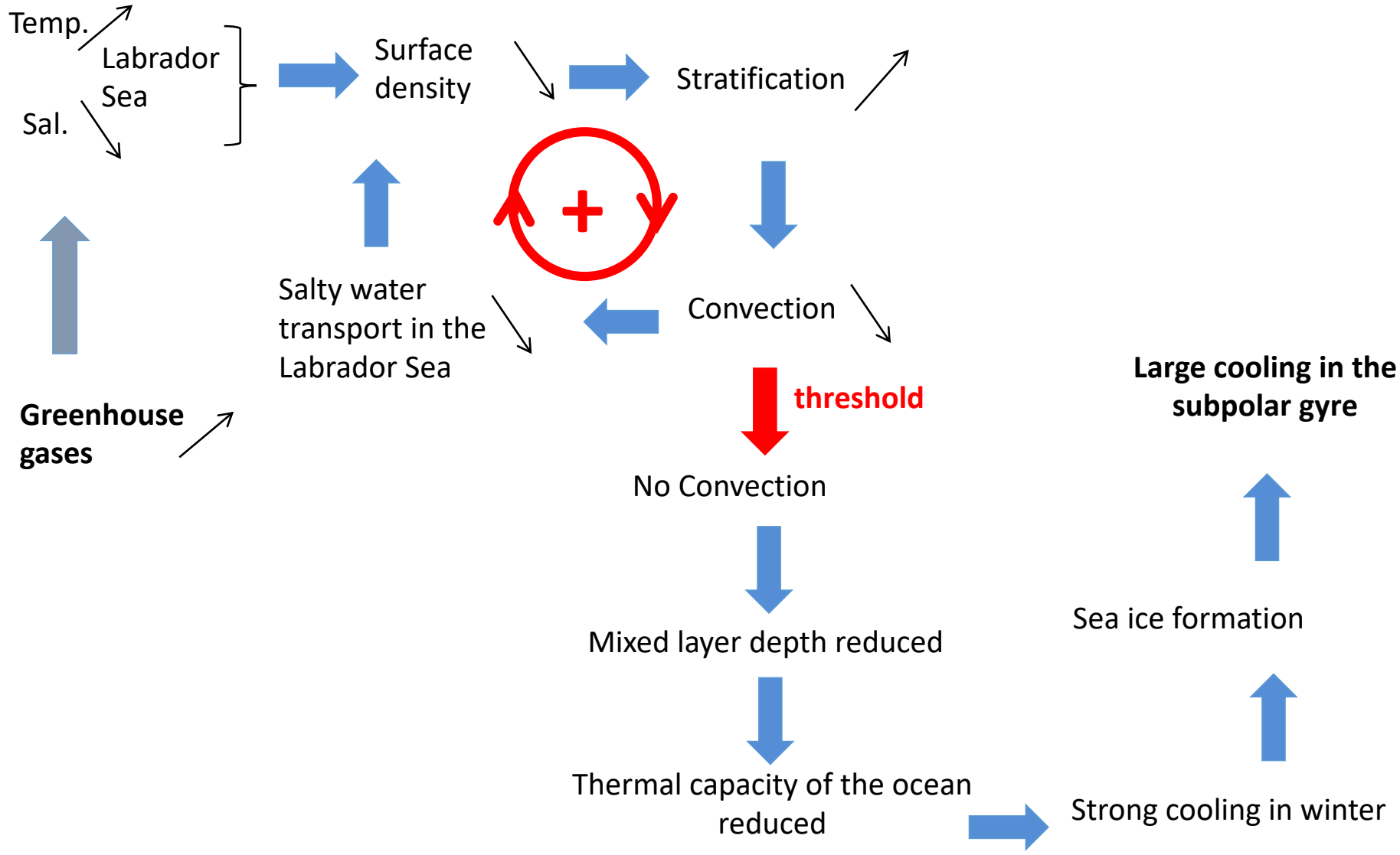
- Two different processes
  - Disruption of the AMOC (strong decrease of convection both in the Labrador and Nordic Seas)
  - Collapse of convection in the Labrador Sea : can occur in only one decade => **the SPG as a new tipping element**

- This was true in CMIP5 (Sgubin et al. 2017) and is still the case in CMIP6 for SPG collapse (Swingedouw et al. 2021)



Sgubin et al. 2017, Swingedouw et al. 2021

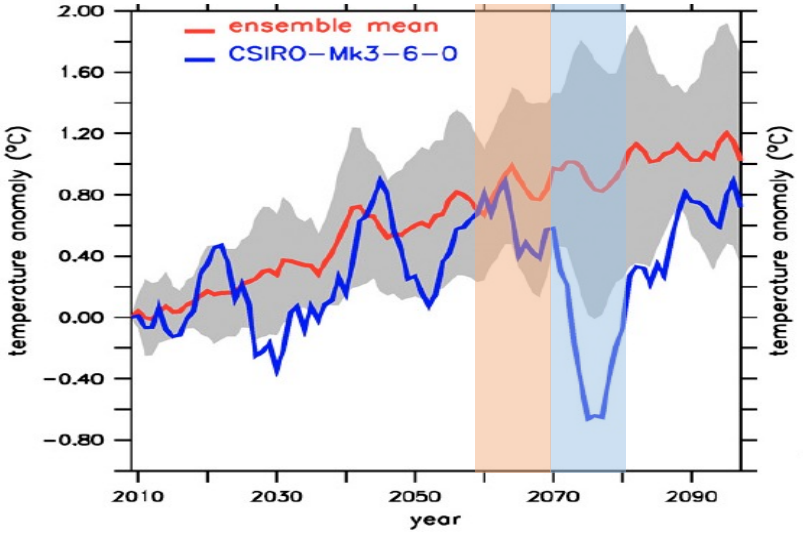
Mechanisms at play



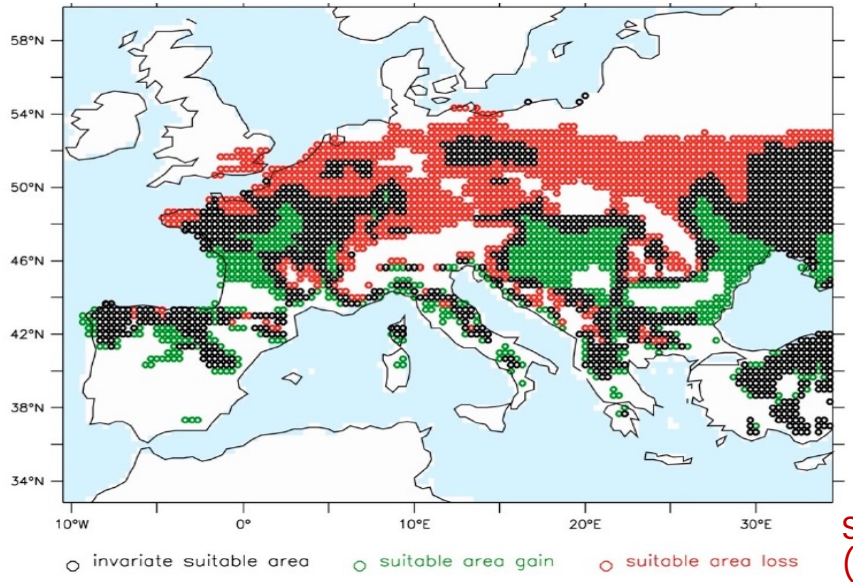
Impacts of abrupt decadal cooling

- Decadal climate variability can play a a key role for uncertainty at the regional scale (Hawkins et Sutton 2009)
- Such impacts can be very fast (<10 years)
- They might affect climate of Europe for at least a decade with various consequences on adaptation plans, e.g. agriculture.

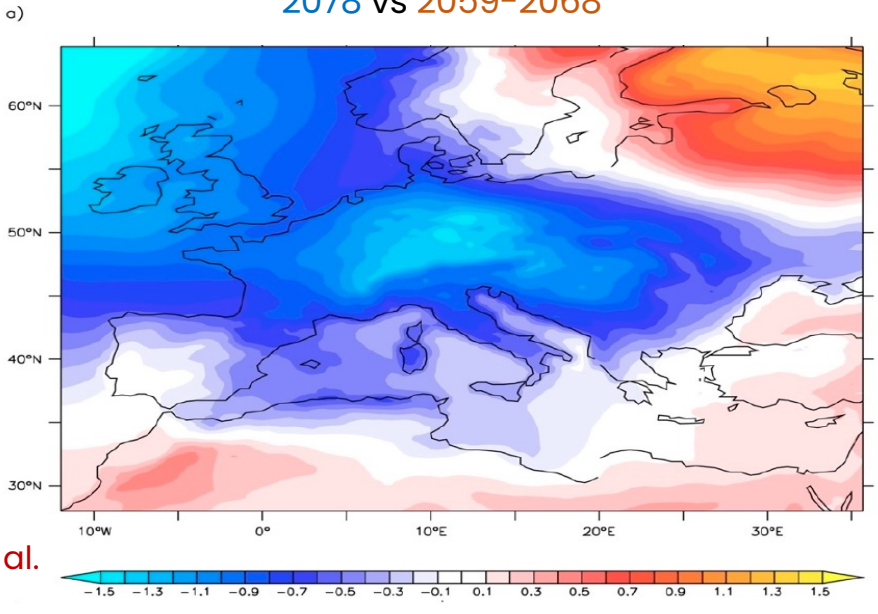
Temperature in the UK



Suitability of Chardonnay
2069-2078 vs 2059-2068



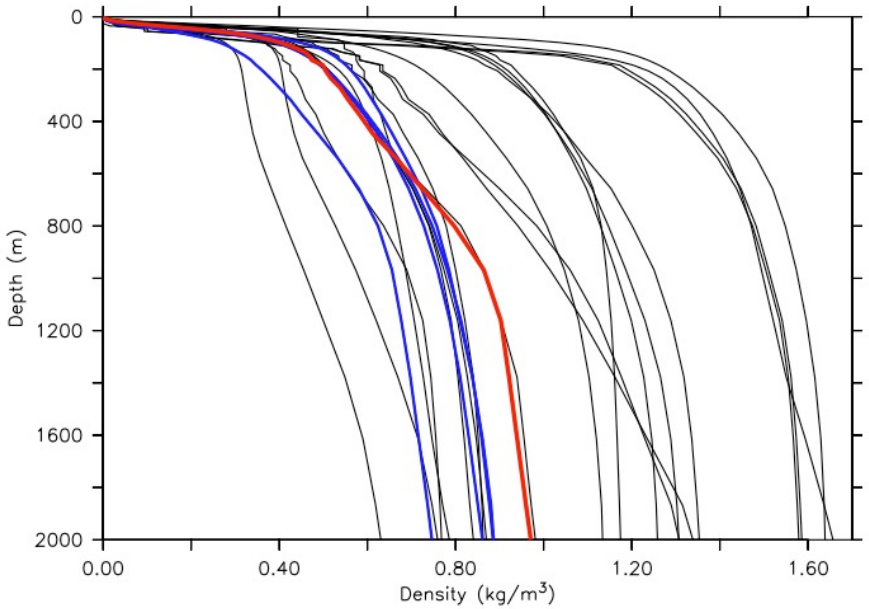
Temperature difference 2069-2078 vs 2059-2068

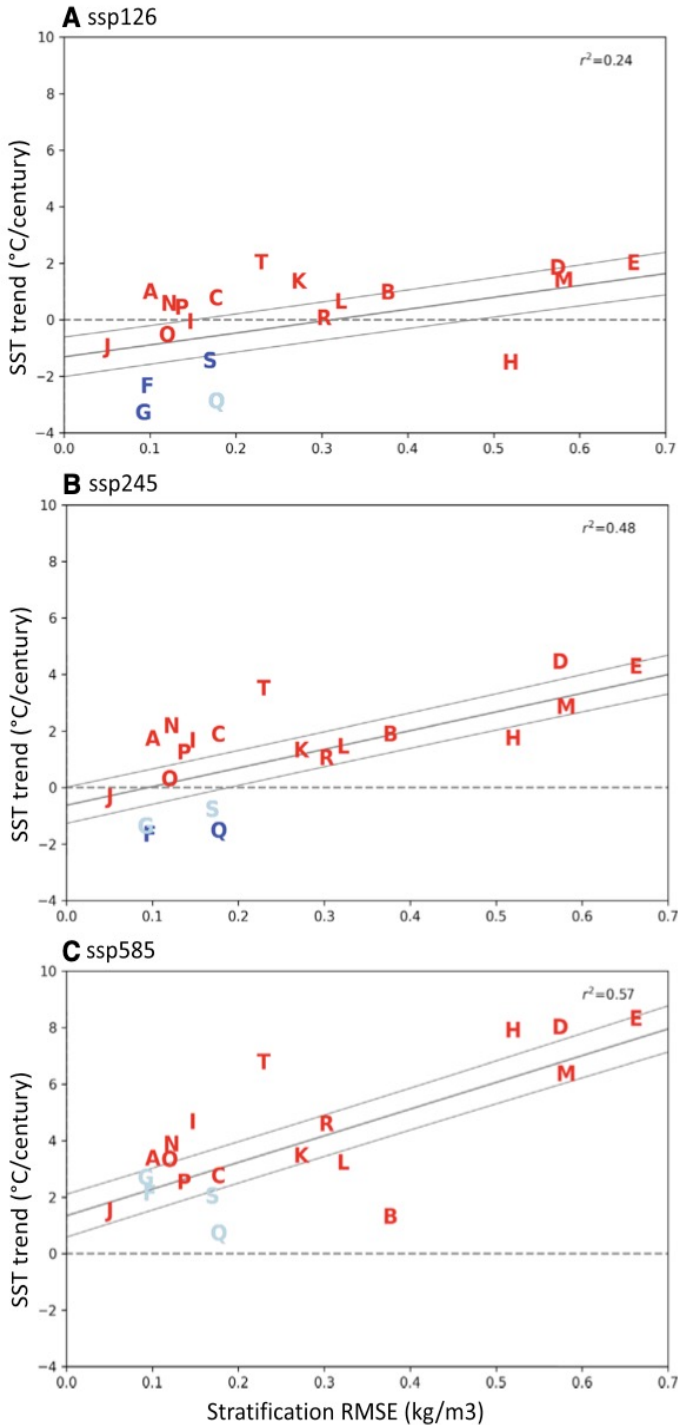


Sgubin et al. (2019)

SPG stratification as an observational constraint

- Stratification in the SPG is a key component of convection process
- Models showing abrupt changes are usually better than the ones showing none
- When using this as **an emergent constraint**, the probability for such a SPG rapid cooling before 2100 can be estimated between about **36% (CMIP6) to 45% (CMIP5)**





A: AWI-CM-1-1-MR
B: BCC-CSM2-MR
C: CAMS-CSM1-0
D: CanESM5
E: CanESM5-Can0E
F: CESM2
G: CESM2-WACM
H: CIESM
I: CNRM-CM6-1
J: GFDL-ESM4
K: INM-CM4-8
L: INM-CM5-0
M: IPSL-CM6A-LR
N: MCM-UA-1-0
O: MIROC6
P: MPI-ESM1-2-LR
Q: MRI-ESM2-0
R: NESM3
S: NorESM2-LM
T: UKESM1-0-LL

Z : Model showing an abrupt event for this scenario

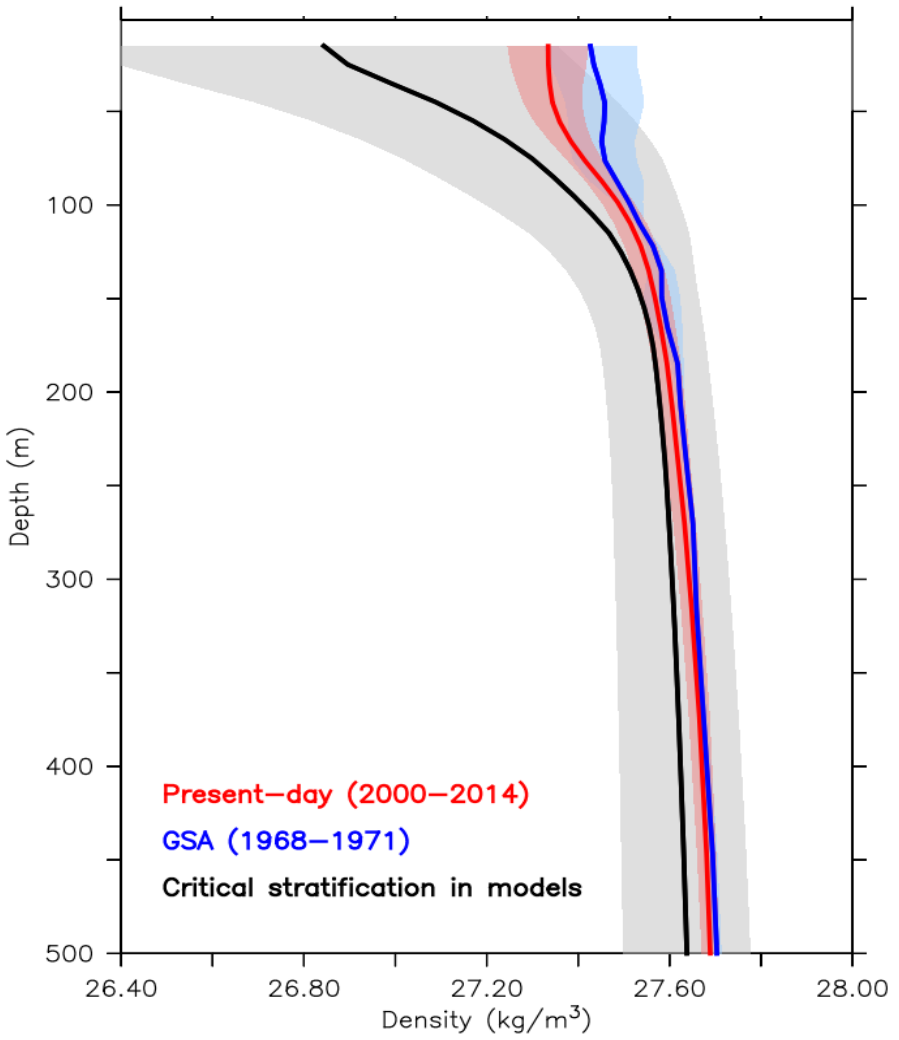
Z : Model showing an abrupt event but not for this scenario

Z : Model not showing any abrupt change in all scenarios

Proximity to a SPG tipping point?

- To analyse the proximity to tipping points, models can be useful as well, on top classical early warning statistical approach.
- For instance, since SPG stratification is crucial element of convection, and a useful emergent constraint for the evolution of centennial SST trend, it is interesting to define a **critical stratification**
- This is the stratification just before the large drop in SST
- When estimated in CMIP5 models, we can see that recent days are already in the envelop (66%) of the models just before their abrupt cooling…

Stratification in the SPG

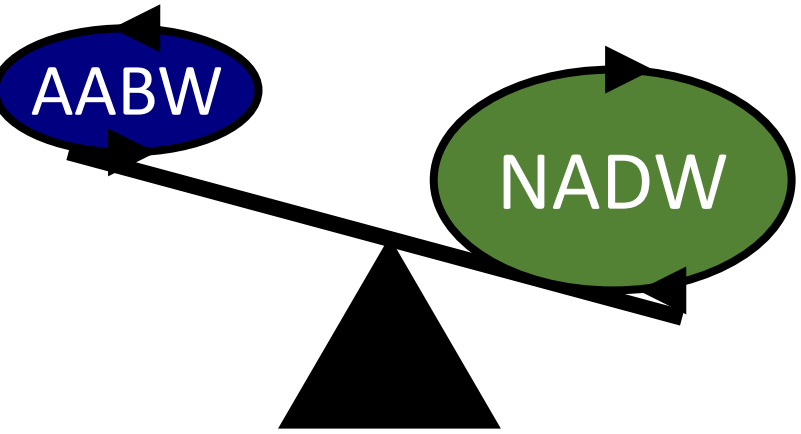


Swingedouw et al., *Surv. Geoph.*, 2020

What about the Southern Ocean?

- Meltwater from the Antarctic ice sheet can strongly reduce the AABW (Swingedouw et al. 2008)

- It can even impact the NADW formation through three main mechanisms (Swingedouw et al., 2009), but the seasaw remain moderate in amplitude



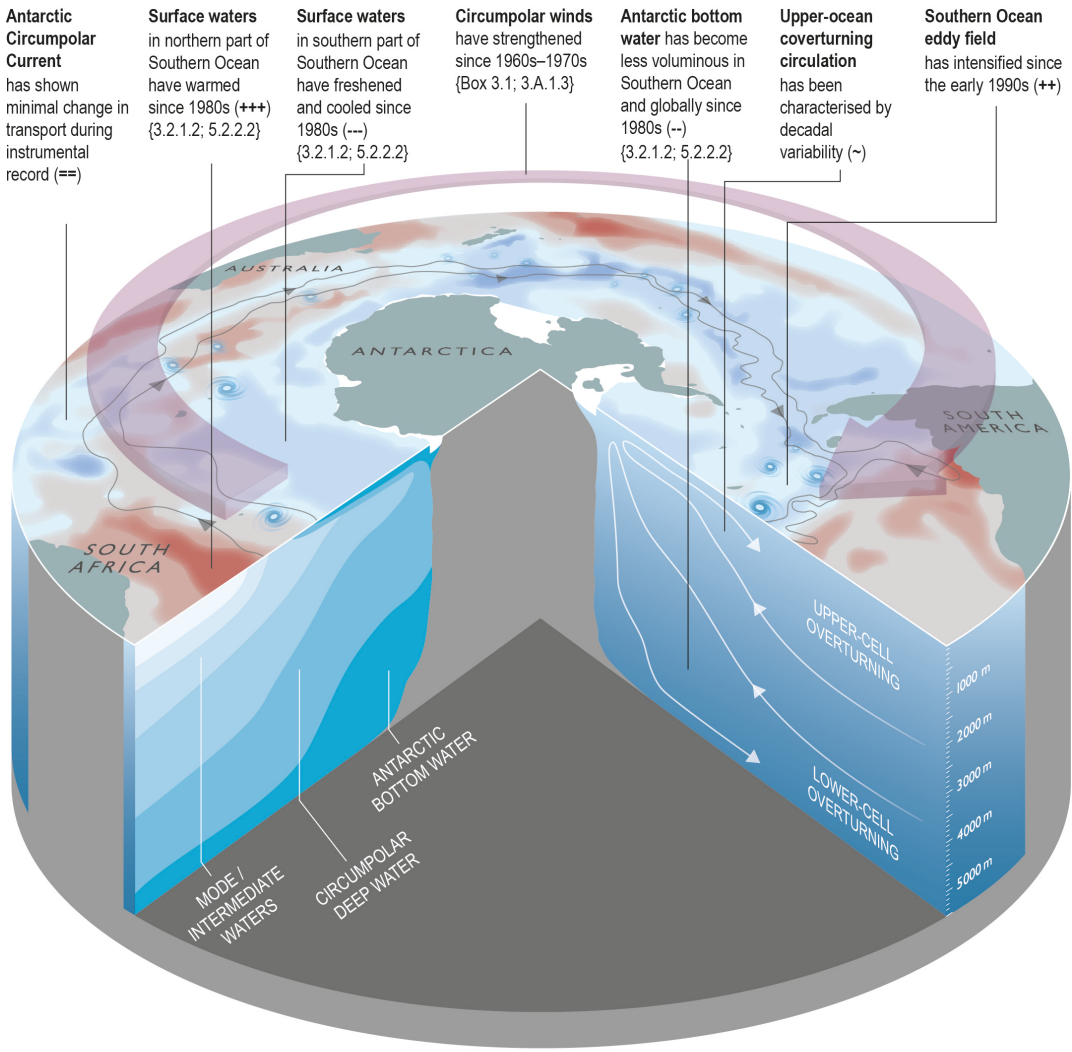
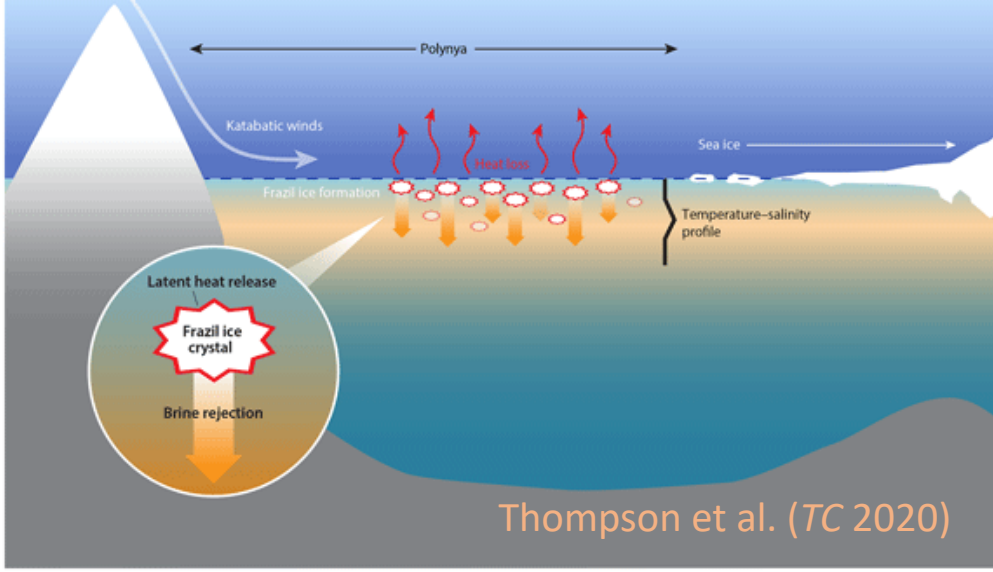
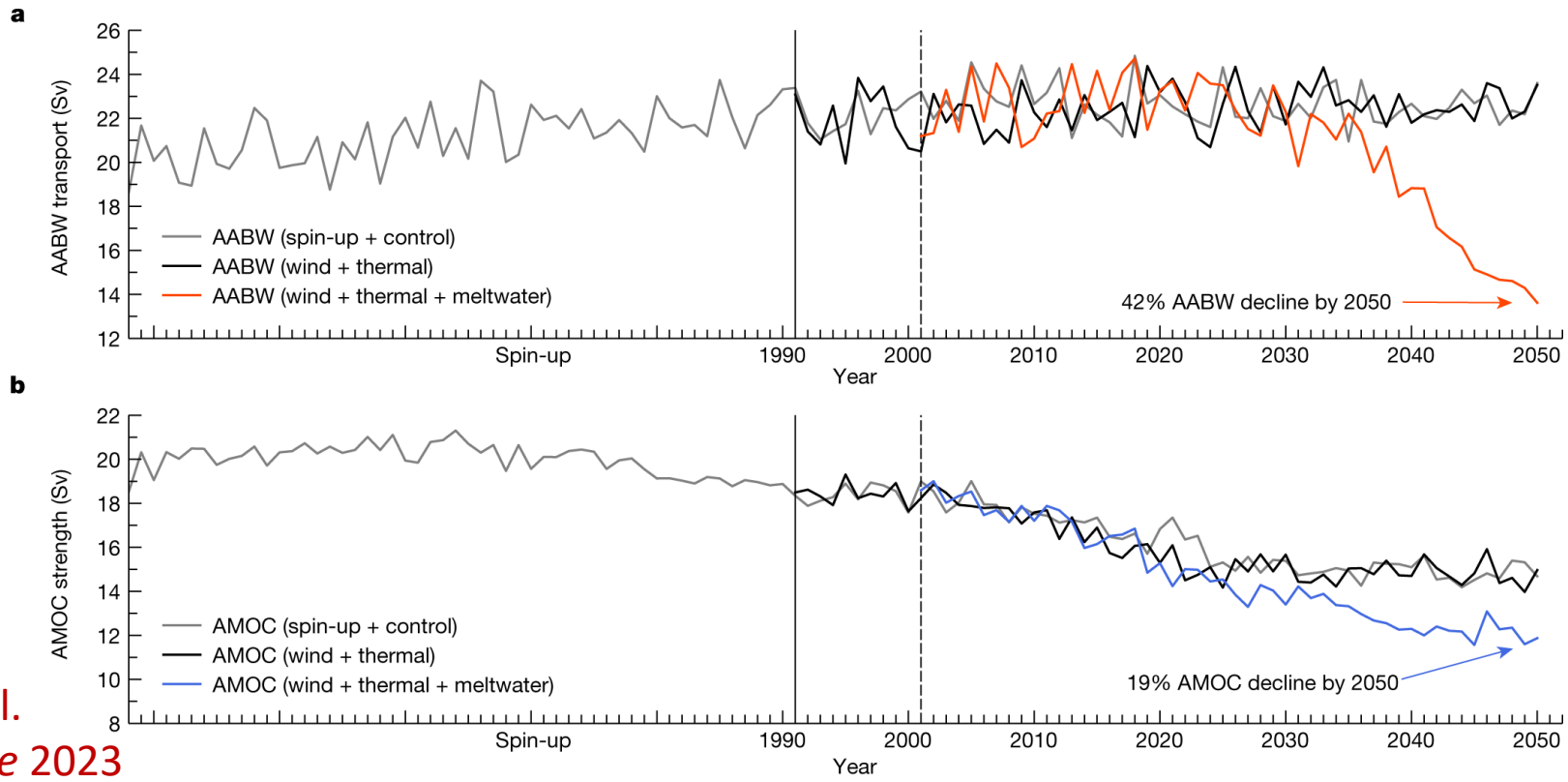


Fig. 3.7 IPCC SROCC 2019

A tipping point in the Southern Ocean?

Li et al. (2023) using a 0.1° ocean model (ACCES-OM2) show potential rapid change in AABW transport





Li et al. *Nature* 2023

Key questions

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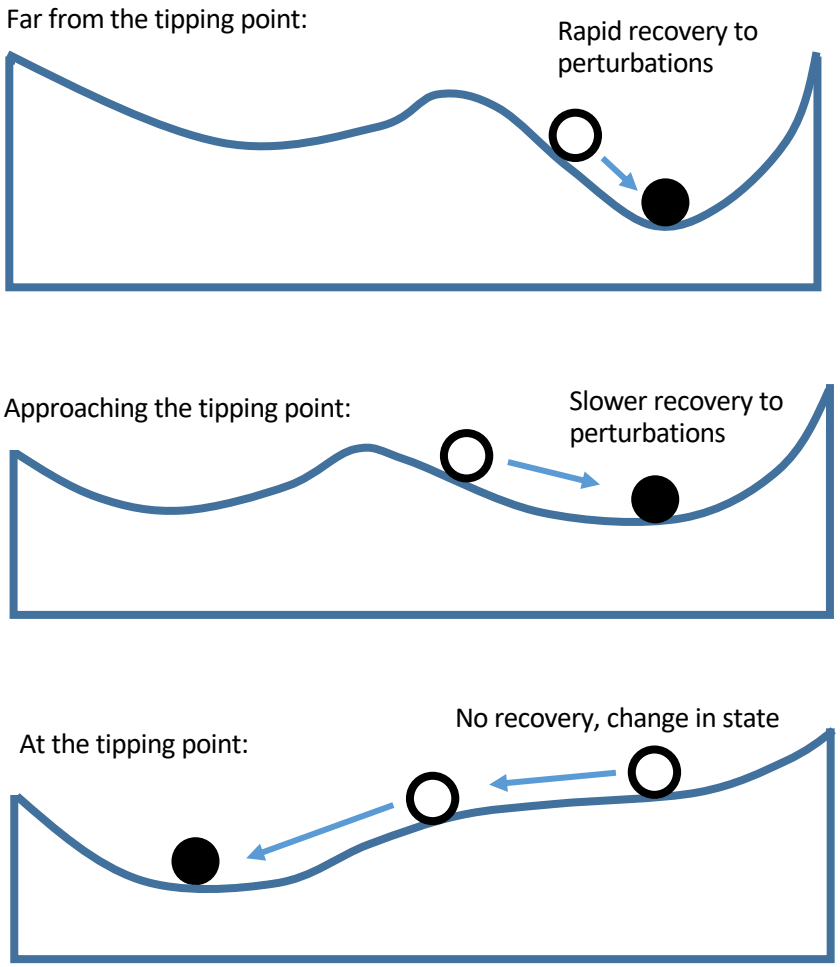
- **How can we anticipate those tipping points?**

How to have early warnings of a potential AMOC collapse?

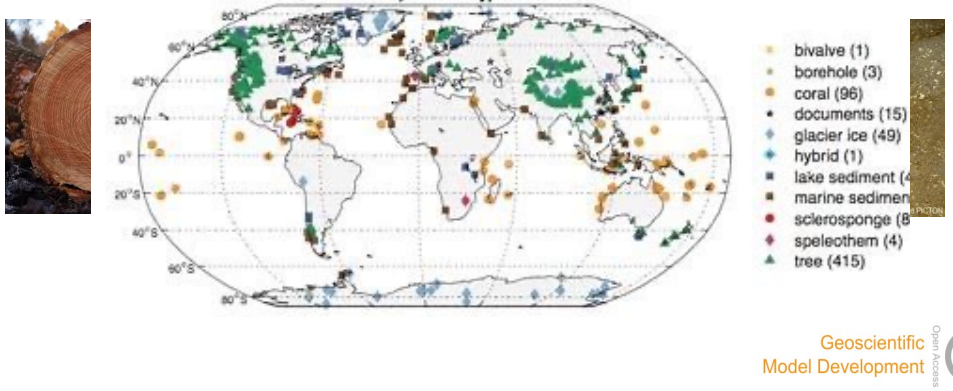
- Theory from dynamical system teaches us that approaching a tipping point, the system variability tend to increase
- Boulton et al. (2014) : we need **at least 250 years** to be able to apply to AMOC
- Bowers (2021) : we are approaching a tipping point (but using AMOC fingerprints **over only the last 150 years**)
- This might be a bit short, and the new EWS method of Boers (2021) has not been tested in “pseudo-proxy” approach

Change of temporal variability when approaching a tipping point



Adapted from: Lenton 2011

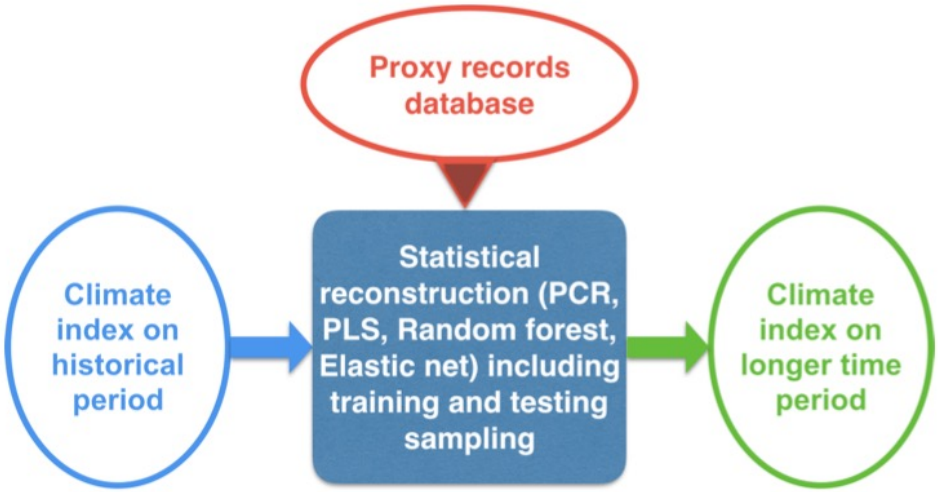
Proximity to an AMOC tipping point?



Geoscientific Model Development

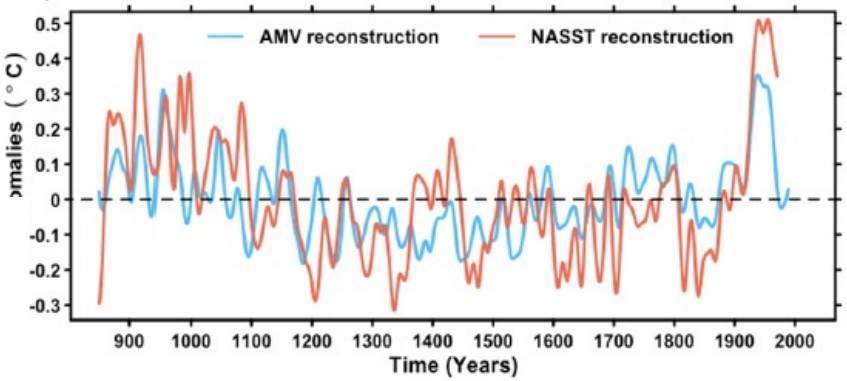
Reconstructing climatic modes of variability from proxy records using ClimIndRec version 1.0

Simon Michel[1], Didier Swingedouw[1], Marie Chavent[2], Pablo Ortega[3], Juliette Mignot[4], and Myriam Khodri[4]

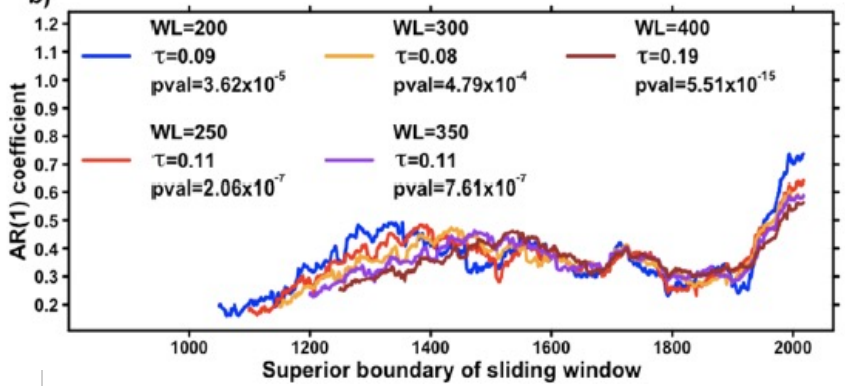


AMV reconstruction as a proxy of AMOC internal variability

a) Reconstruction of the North Atlantic SST



b) Bifurcation test



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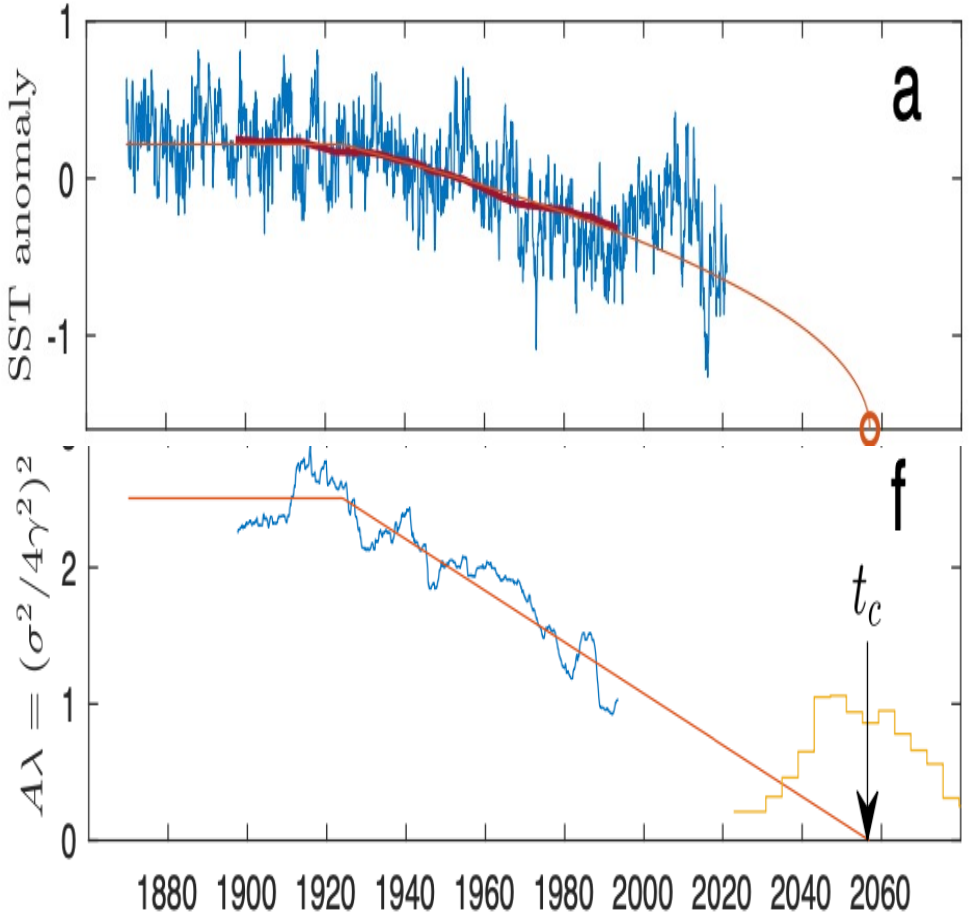
Michel et al., 2022

Time scale for a coming AMOC collapse?

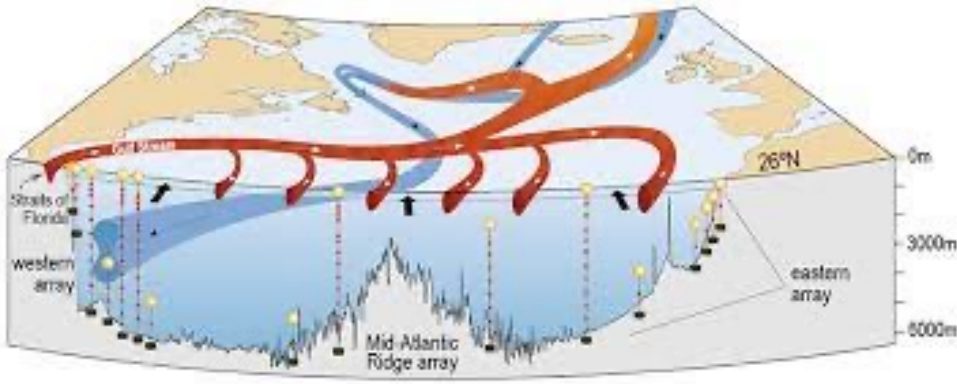
- Climate models might be too stable (Liu et al. 2017)
- And they underestimate key processes (Swingedouw et al. 2022)
- Can simple dynamical system theory help to assess time scale of response?
- Ditlevsen & Ditlevsen (2023) found a risk of AMOC collapse as early as the mid 21st century
- But the result remains sensitive to the AMOC index chosen and of the stochastic differential equation

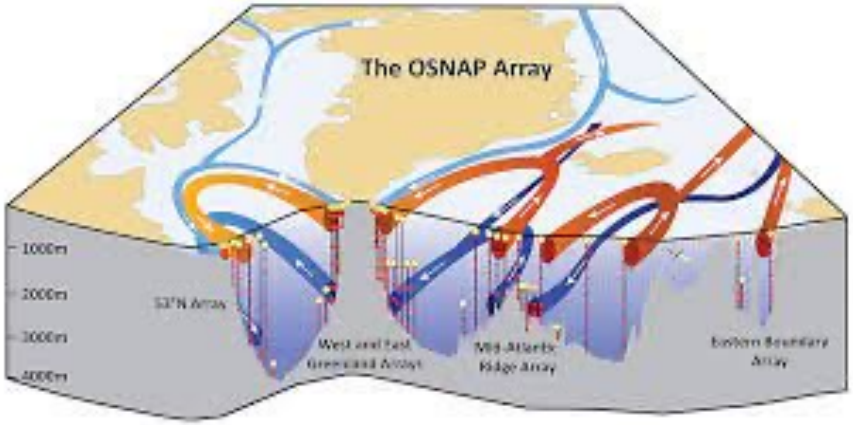


Ditlevsen & Ditlevsen (*Nat. Clim. Ch.* 2023)

Precursors of AMOC changes from observations

RAPID array might **precede** SST changes by around 5 years



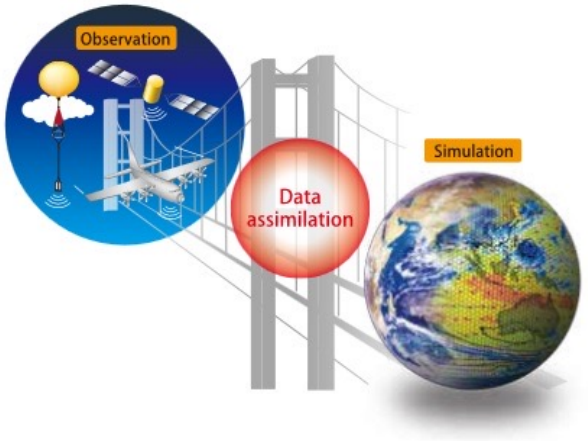


OSNAP array can further enlarge this time scale by a few years

Convective activity might provide a few more years, and can be assessed thanks to ARGO and satellites

Decadal predictions to gain insights on early warnings of abrupt changes

Initial conditions



External forcing

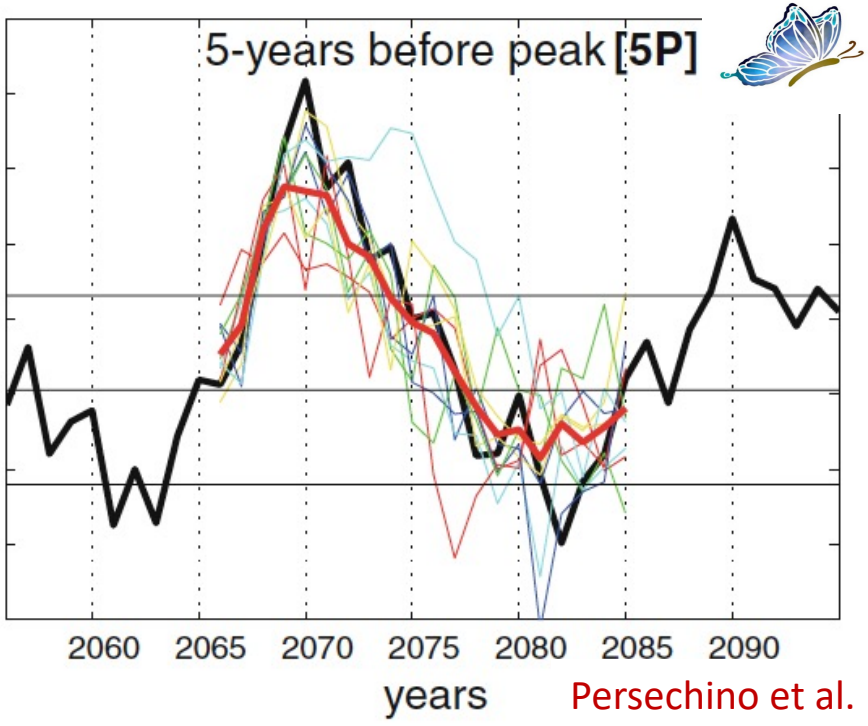
Weather forecast | **Seasonal prediction** | **Decadal prediction** | **Centennial projections** | **Glacial cycles**

day | week | month | year | decade | century | millennium

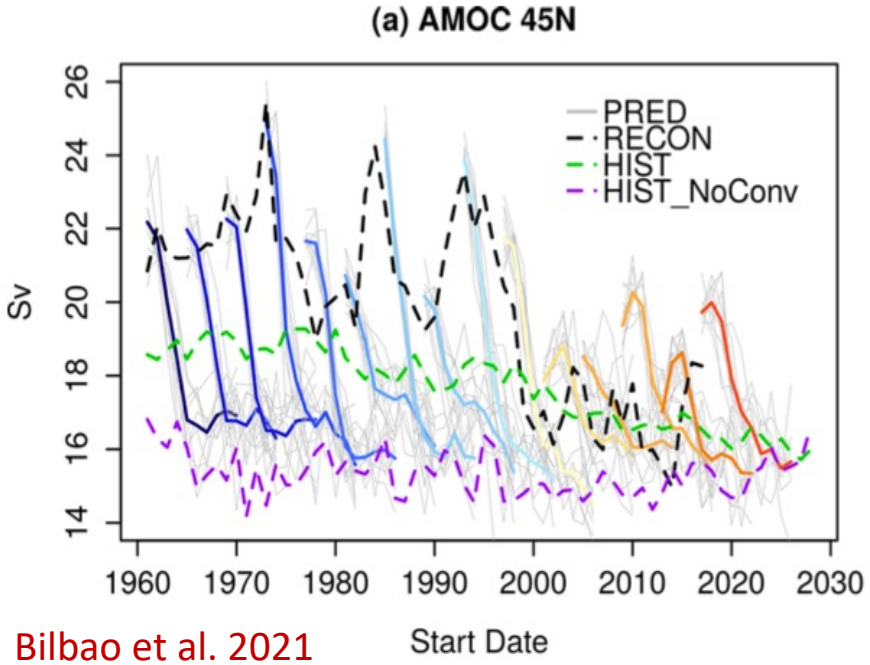
Time scale

How to properly initialise the AMOC?

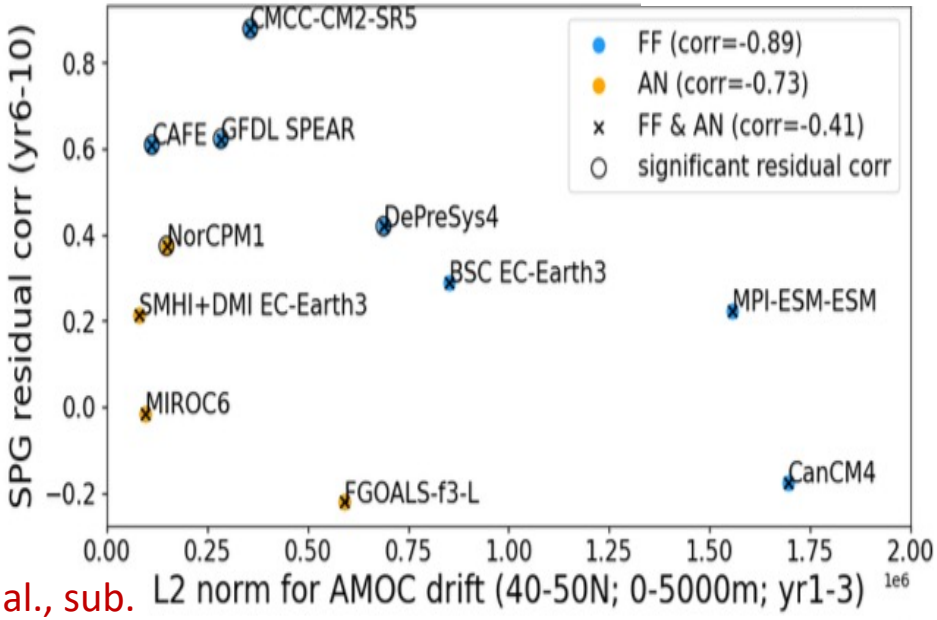
- The AMOC as a key source of decadal prediction (Persechino et al. 2013)
- The issue of the initial shock is crucial for tippping point predictions
- Solving it can also increase prediction skill of the SPG (Polkova et al. sub)



Persechino et al. 2013



Bilbao et al. 2021



et al., sub.

What are the research gaps?

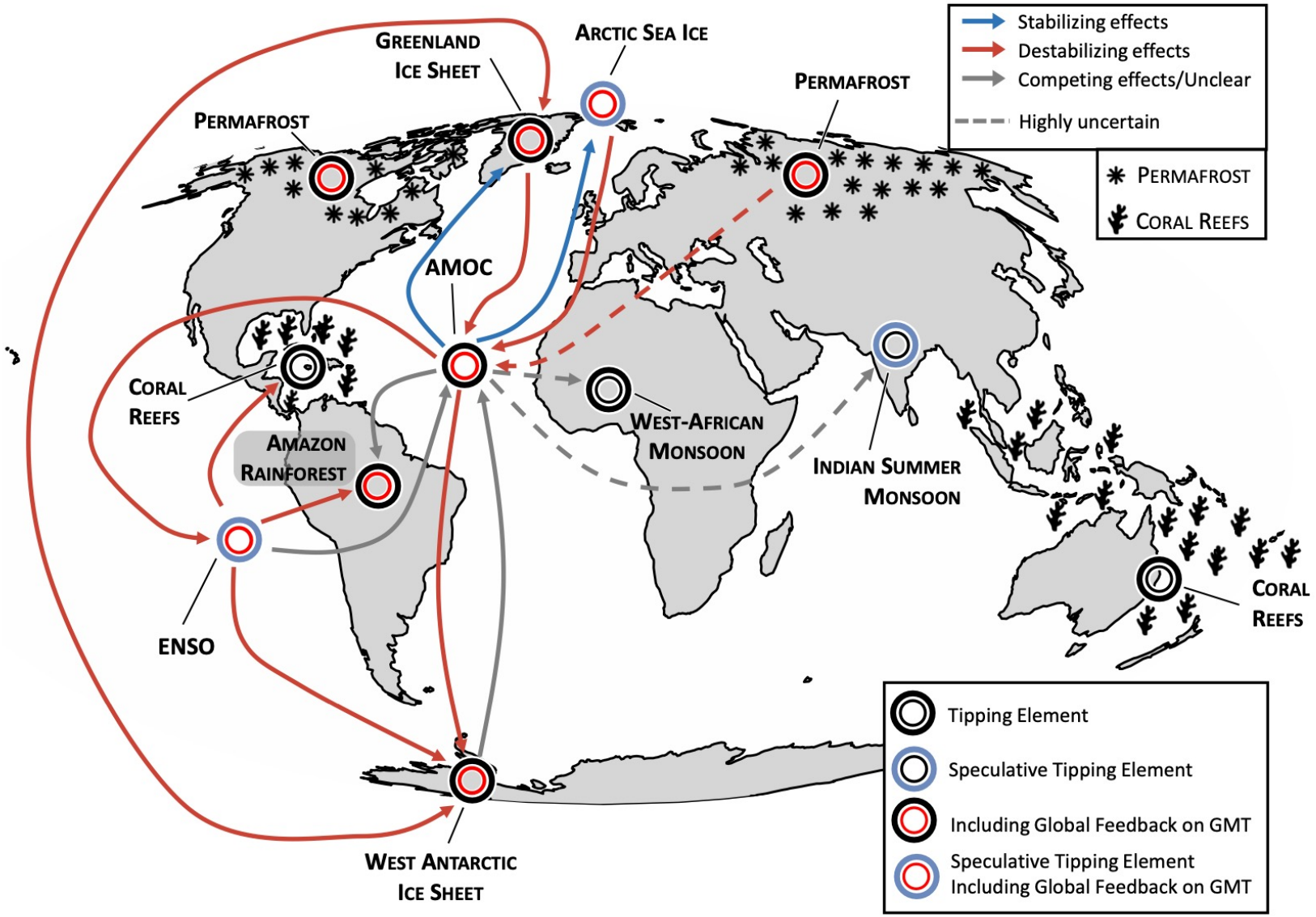
- **Observation systems** are needed for an efficient early warning system:
  - ✓ Continue on-going *in situ* arrays and monitoring systems
  - ✓ Include more oceanic observations below 2000m
- **Decadal prediction systems** still need further development to:
  - ✓ Diminish their offset to observations
  - ✓ Better include meso-scale processes (parametrization, zoom)
  - ✓ Understand the spread among models
- Need for better **reconstructions of the last few thousands of years** to have more insights on the approach of a tipping point

Key take-home messages

- Ocean circulation can shift abruptly in the Atlantic and Southern oceans
- It is difficult to assess the exact probability, but some models do show abrupt shifts to occurs in the coming decades
- We are not ready to anticipate such shifts correctly at the moment
- Observation of key precursors and decadal prediction systems can provide efficient early warnings of such potential abrupt changes
- Adaptation plans should include such High Impact – Low Likelihood (HILL) events

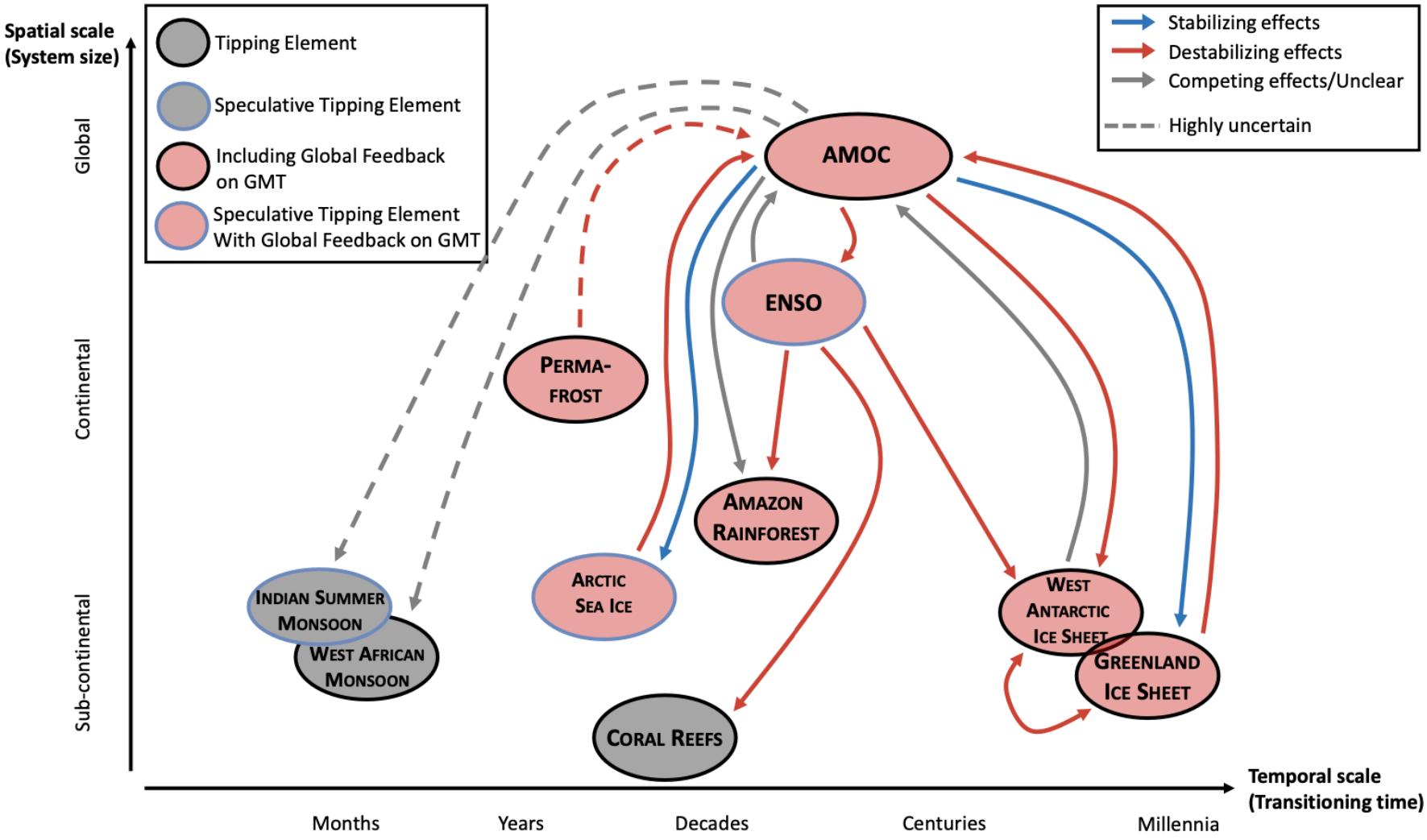
Thank you!

Cascades



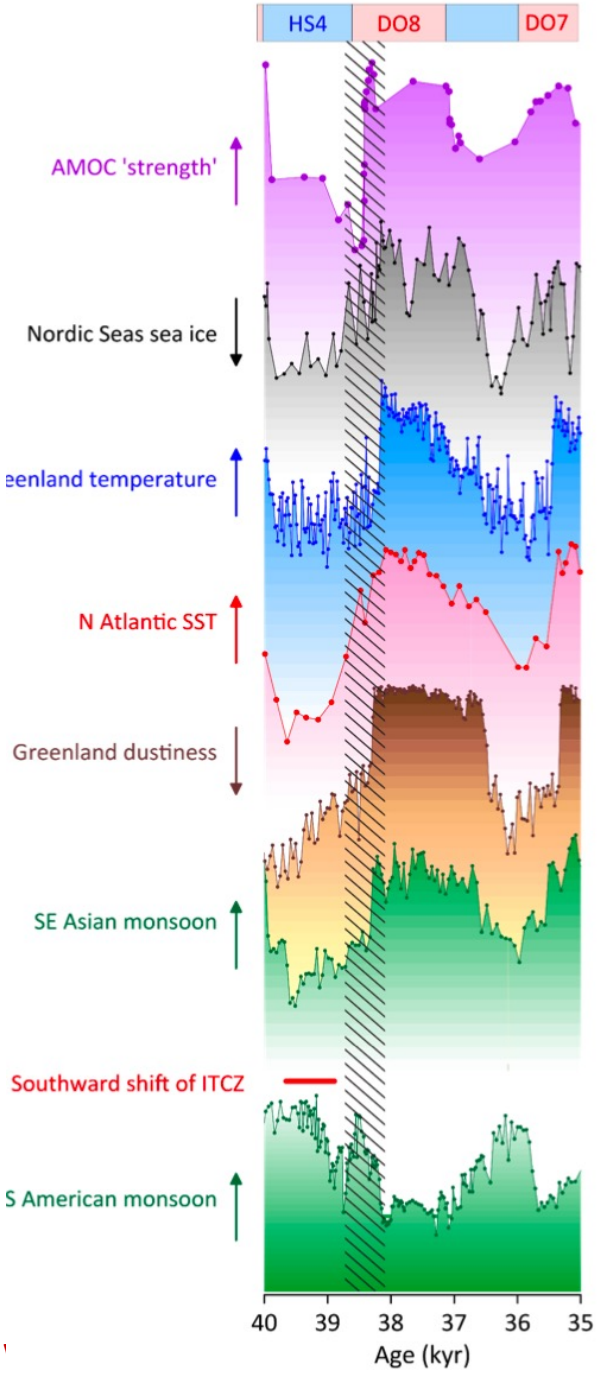
Wunderling et al., ESDD 2023

Cascades



Wunderling et al., ESDD 2023

Cascades


HS4
DO8
DO7
AMOC 'strength'
Nordic Seas sea ice
eenland temperature
N Atlantic SST
Greenland dustiness
SE Asian monsoon
Southward shift of ITCZ
S American monsoon
40
39
38
37
36
35
Age (kyr)