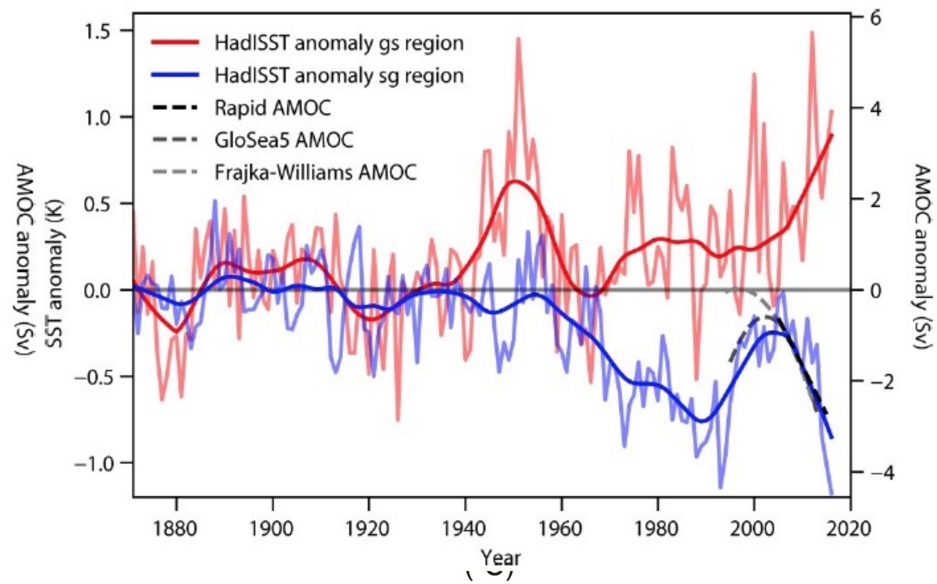
On-Going Changes and Possible Fate of the North Atlantic Ocean Circulation and Its Impacts on Climate and Biodiversity

Didier Swingedouw

Juliette Mignot, Mohamed Ayache, Marion Devilliers, Simon Michel Giovanni Sgubin, Julie Deshayes, Rémy Bonnet, Leonard Borchert, Vincent Jomelli, Marie-Noelle Houssais, Christophe Herbaut, Olivier Boucher, Pablo Ortega, Sybren Drijfhout, Samuel Diabaté, Gerard McCarthy, Vincent hanquiez…

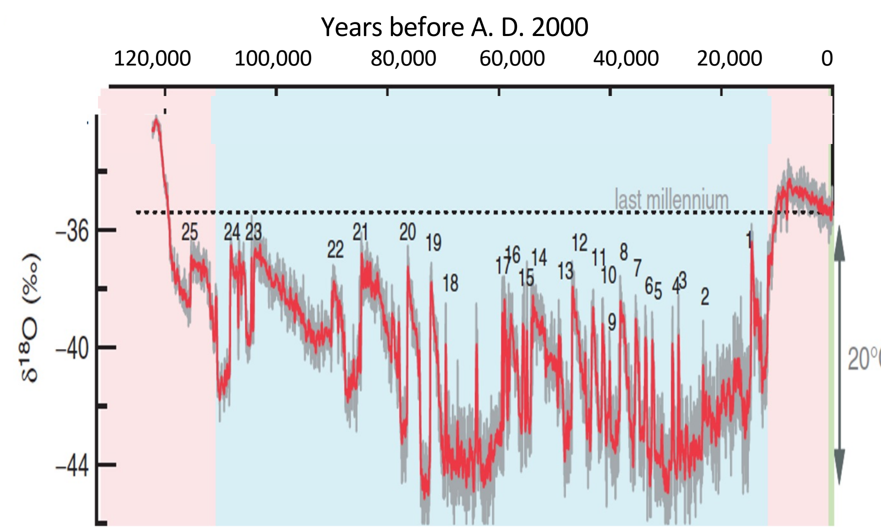
Where are we now?

- 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)
- Lessons from the past both in glacial and interglacial periods highlight that abrupt changes/tipping points are possible



Credits: CNRS

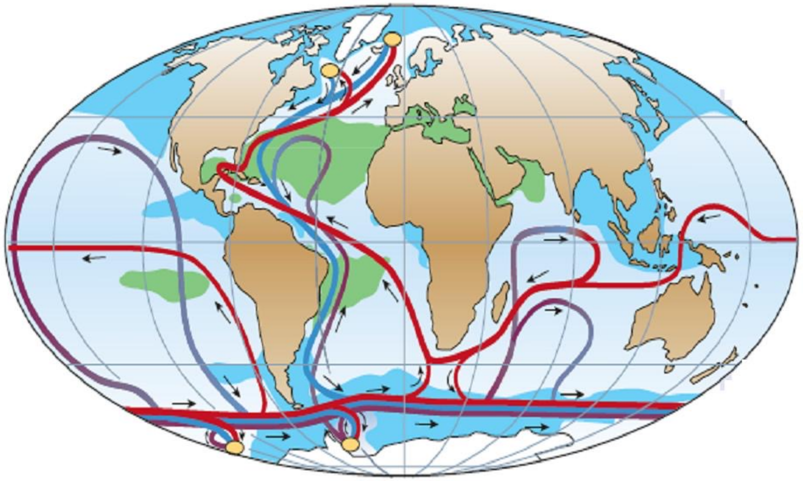
Ice core reconstructions



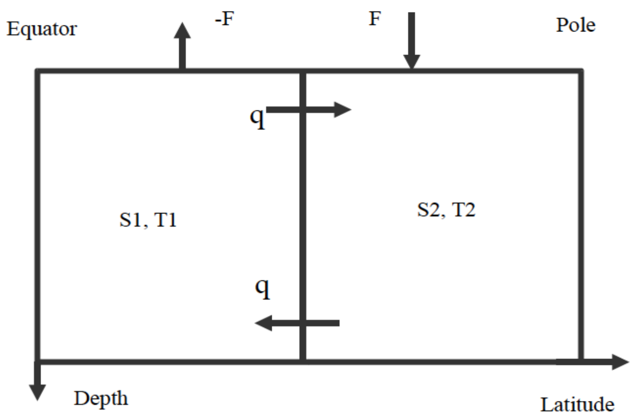
Credits: WIRE Climate Change

Masson-Delmotte et al. 2012

Non linearity of the Atlantic Overturning (AMOC)?

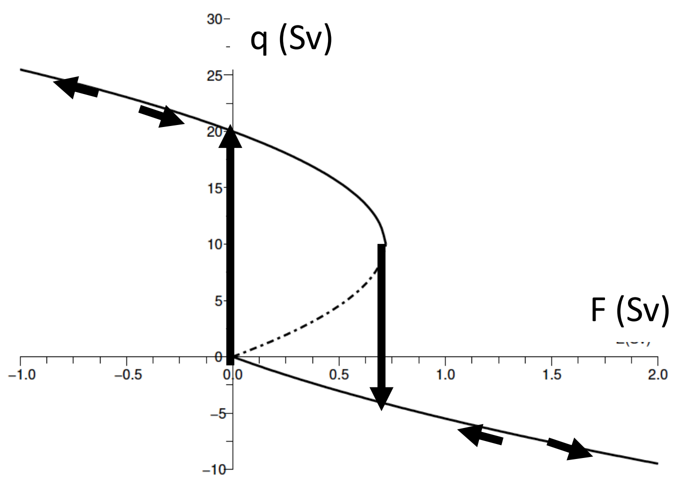


- Stommel (1961) early showed that the AMOC may exhibit strongly non-linear response to surface freshwater forcing



- 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)

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

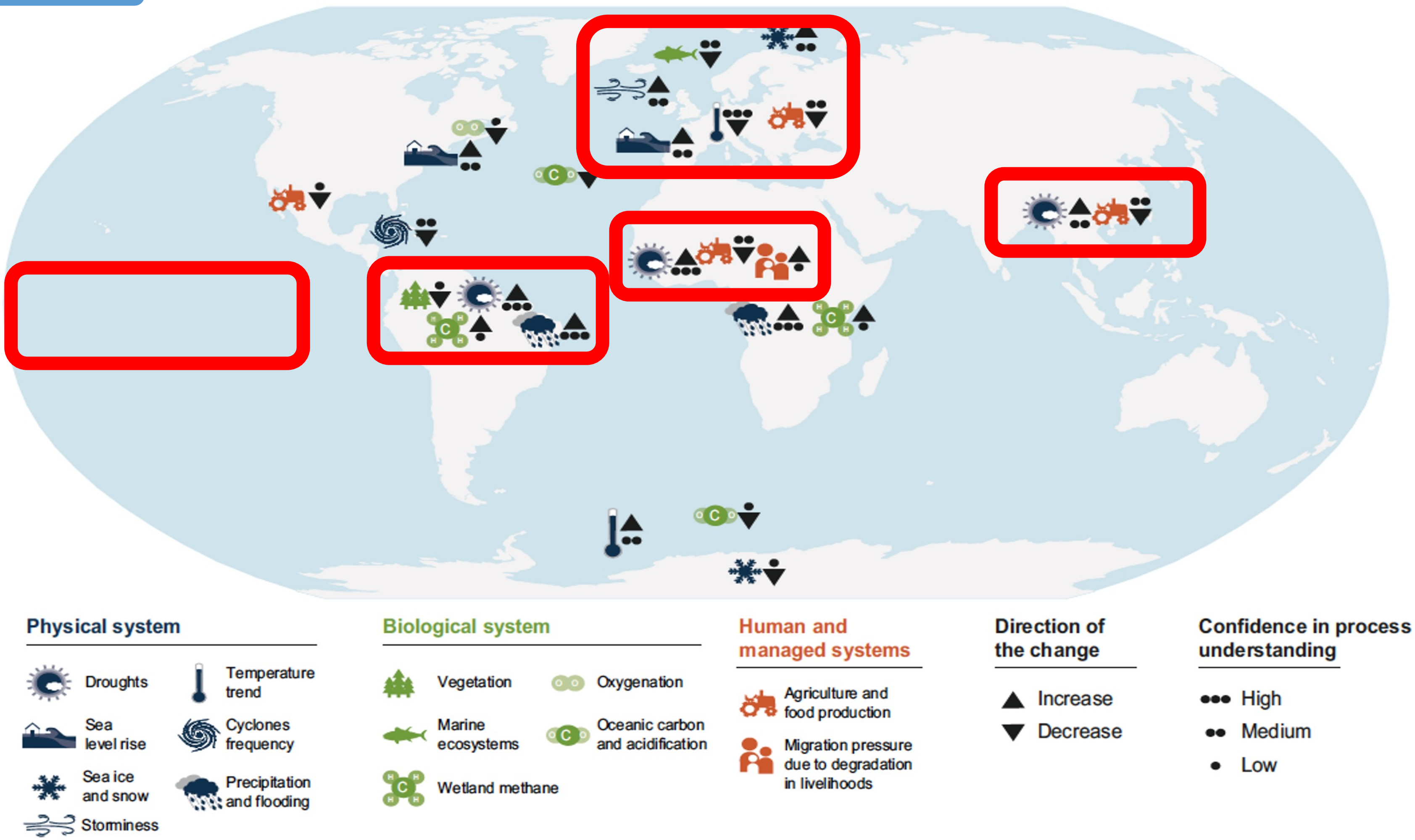


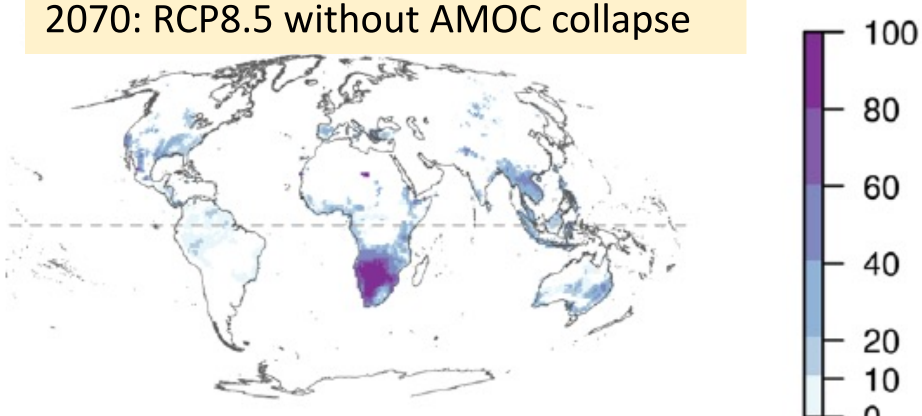
Fig. 6.10 from IPCC SROCC report, 2019

Even more potential impacts not assessed yet?

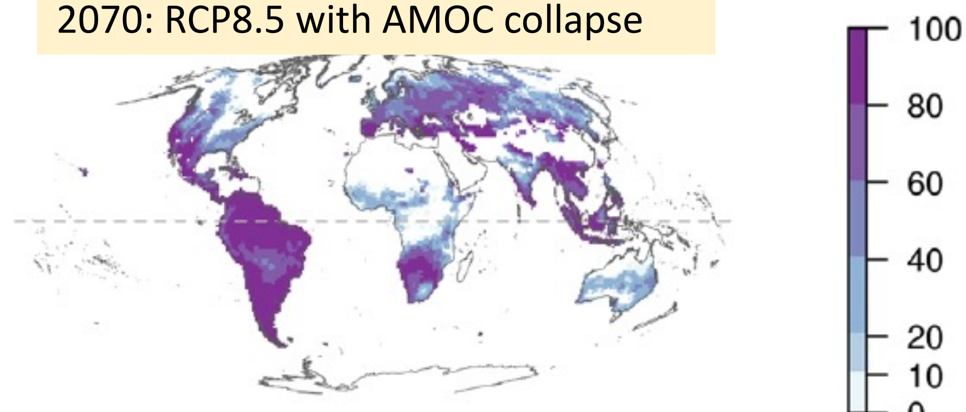
- Impacts on biodiversity: a new example of cascading tipping points: Velasco et al. (2021, Communications Biology)
- Amphibians are indicators of ecosystems' health because of their high sensitivity to novel climate conditions
- A strong weakening of the AMOC can push these animals to cross their own tipping point…

Percentage of amphibian species loss

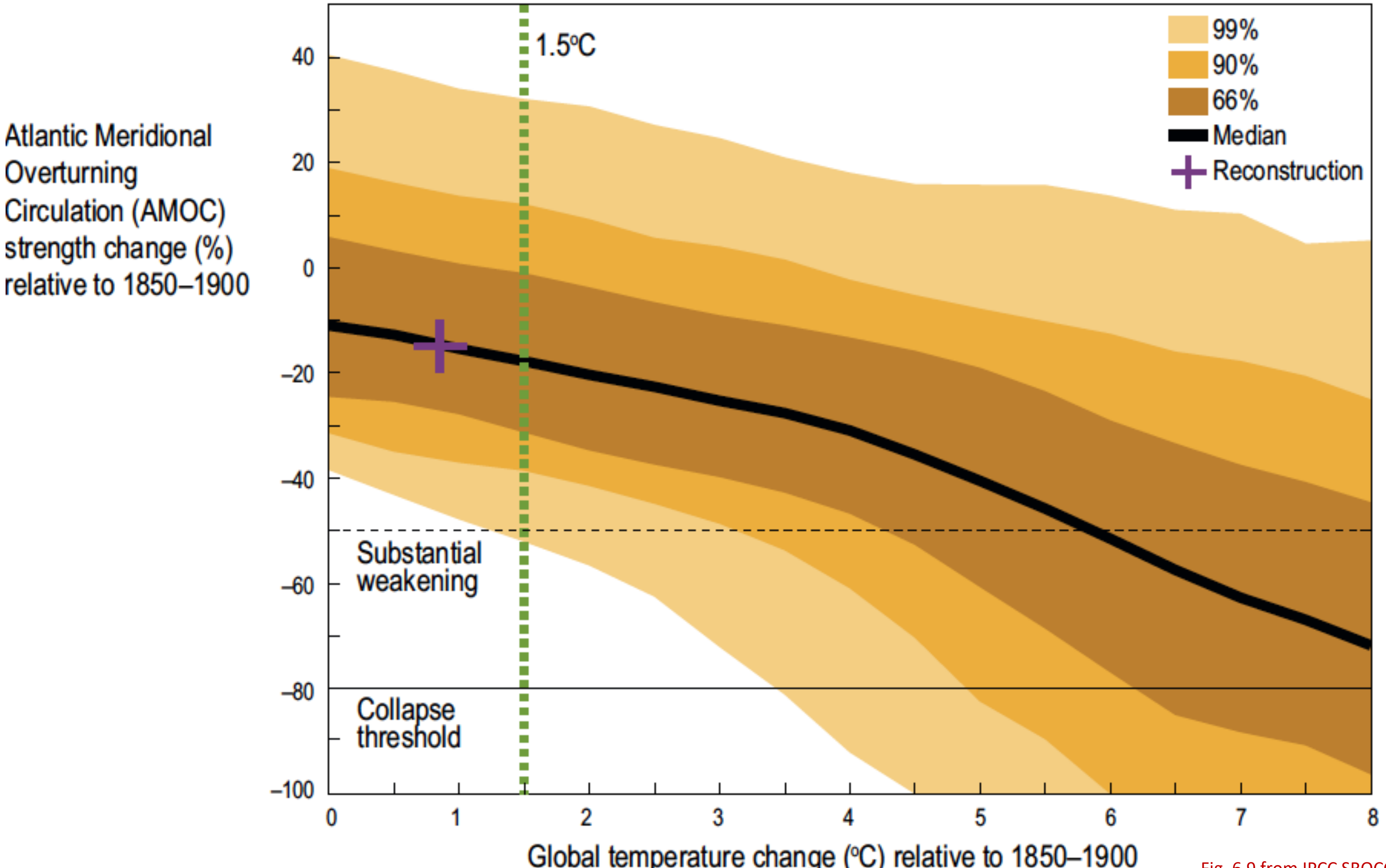
2070: RCP8.5 without AMOC collapse



2070: RCP8.5 with AMOC collapse



Risk of AMOC substantial weakening



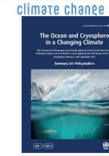
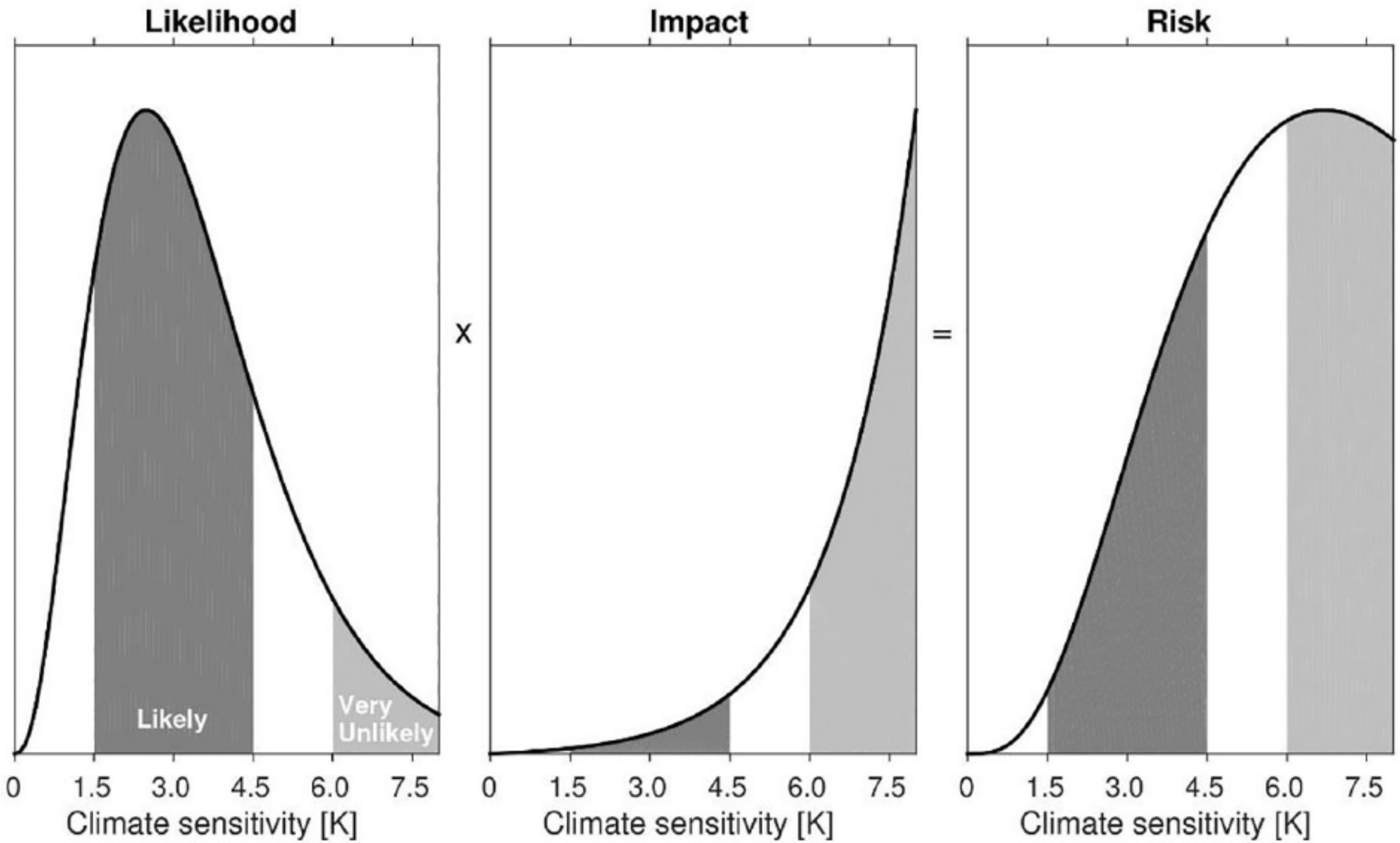


Fig. 6.9 from IPCC SROCC report, 2019

Low probability-high impact event



Sutton 2018

Key questions

- What is causing its weakening over the recent period (if any)?
- Is the impact of GrIS melting well represented in climate models?
- Is the AMOC moving towards a tipping and what kind of changes might occur in the near future?

Materials and methods

- Data are more convincing than models from a scientific point of view…

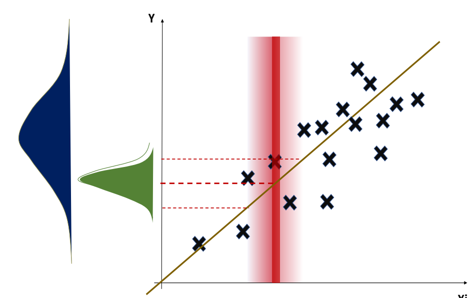
  - ➢ Instrumental ones since about 1850

  - ➢ Paleo data and pseudo-proxy approaches

- Database from climate Model Intercomparison Projects (CMIP)

WCRP World Climate Research Programme CMIP6

- Emergent constraint approaches: combining models and observations to improve projections



Key questions

- What is causing the AMOC changes over the last century (if any)?
- Is the impact of GrIS melting well represented in climate models?
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Attribution of recent changes in the North Atlantic

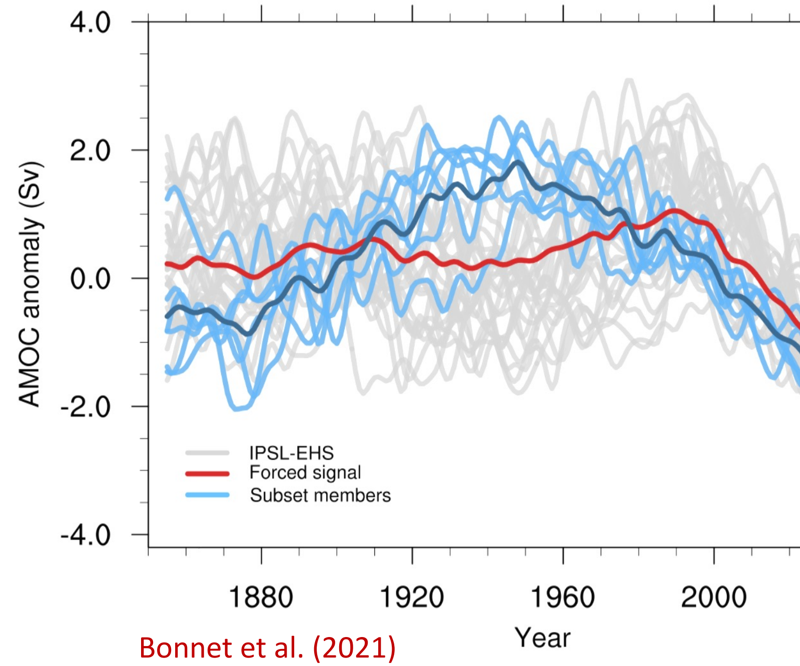
- External forcing is driving an increase (aerosols from about 1950-1990) and then a weakening (GHG from the 2000s) of the AMOC in the **ensemble mean** of CMIP6 models (Menary et al. 2020)

- **What drives the observed cooling in the subpolar gyre?**

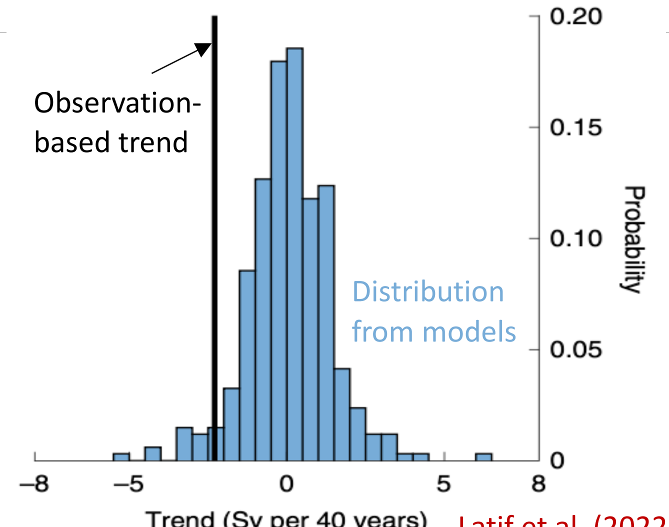
- Some models say: anthropogenic forcing (e.g. Chemke et al. 2022)

- Others say it is mainly internal variability (e.g. Bonnet et al. 2021)

- At least, the recent cooling in the North Atlantic subpolar gyre is not inconsistent with internal variability (Latif et al. 2022)



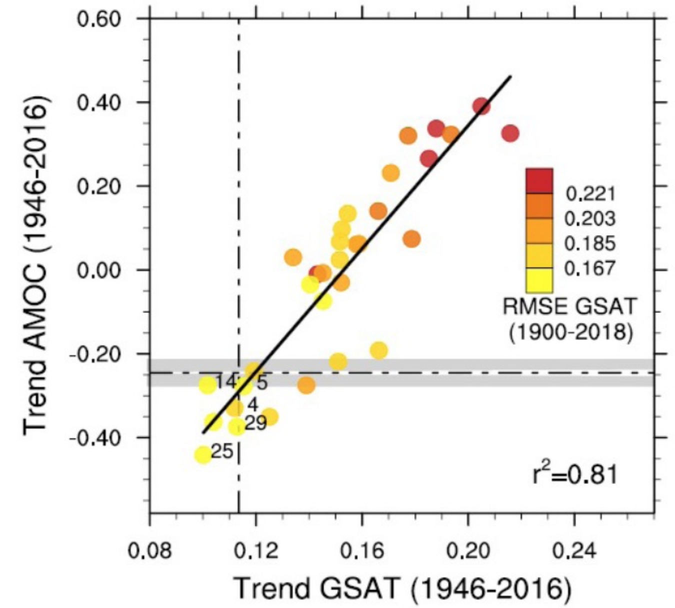
Bonnet et al. (2021)



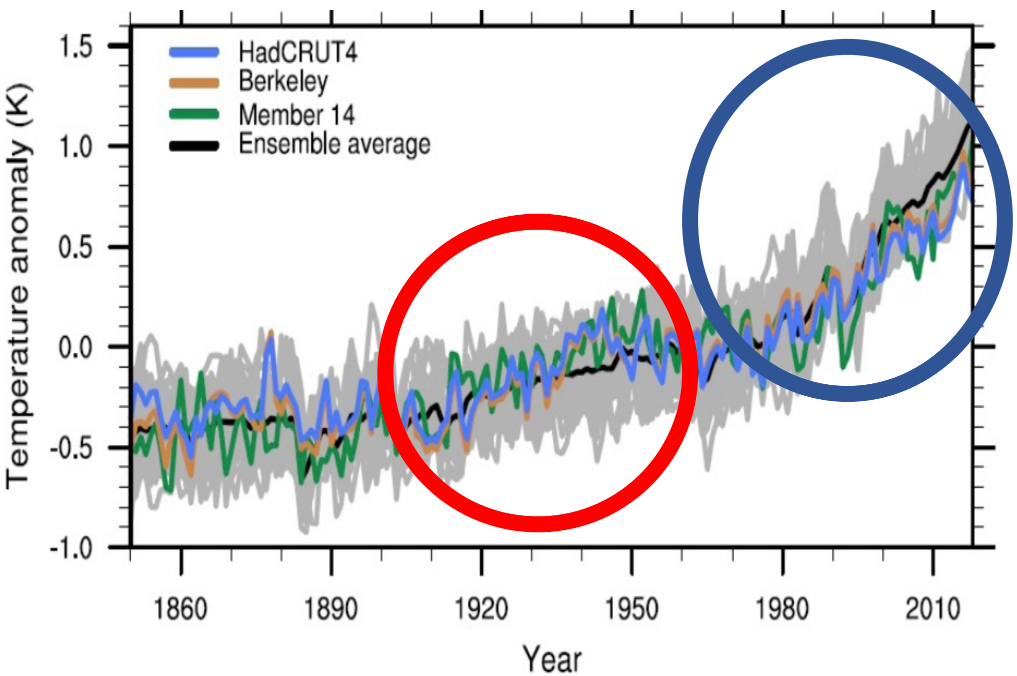
Latif et al. (2022)

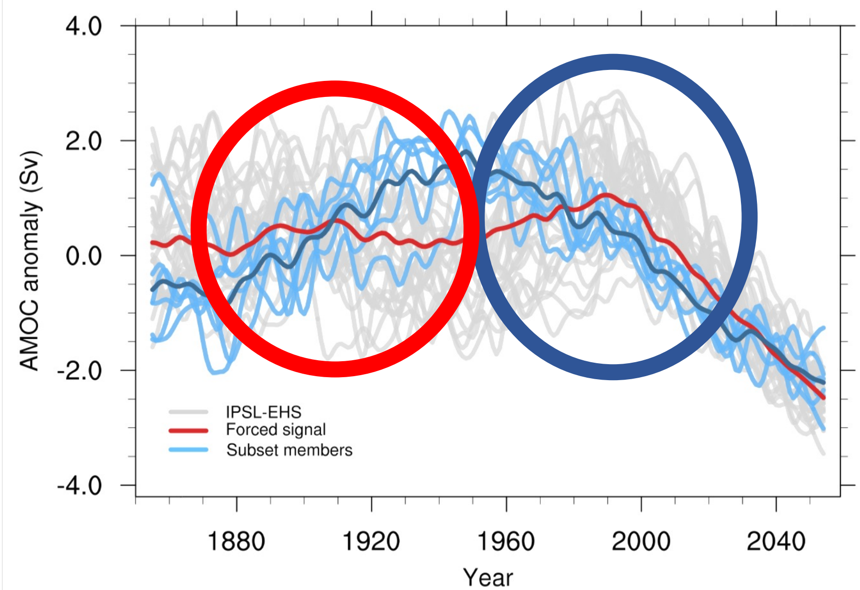
AMOC internal variability and climate sensitivity

- Can the AMOC weakening affect climate sensitivity (level of warming for a given amount of GHG) estimates over the last century?



Global near-surface temperature (GSAT) in IPSL-CM6A large ensemble



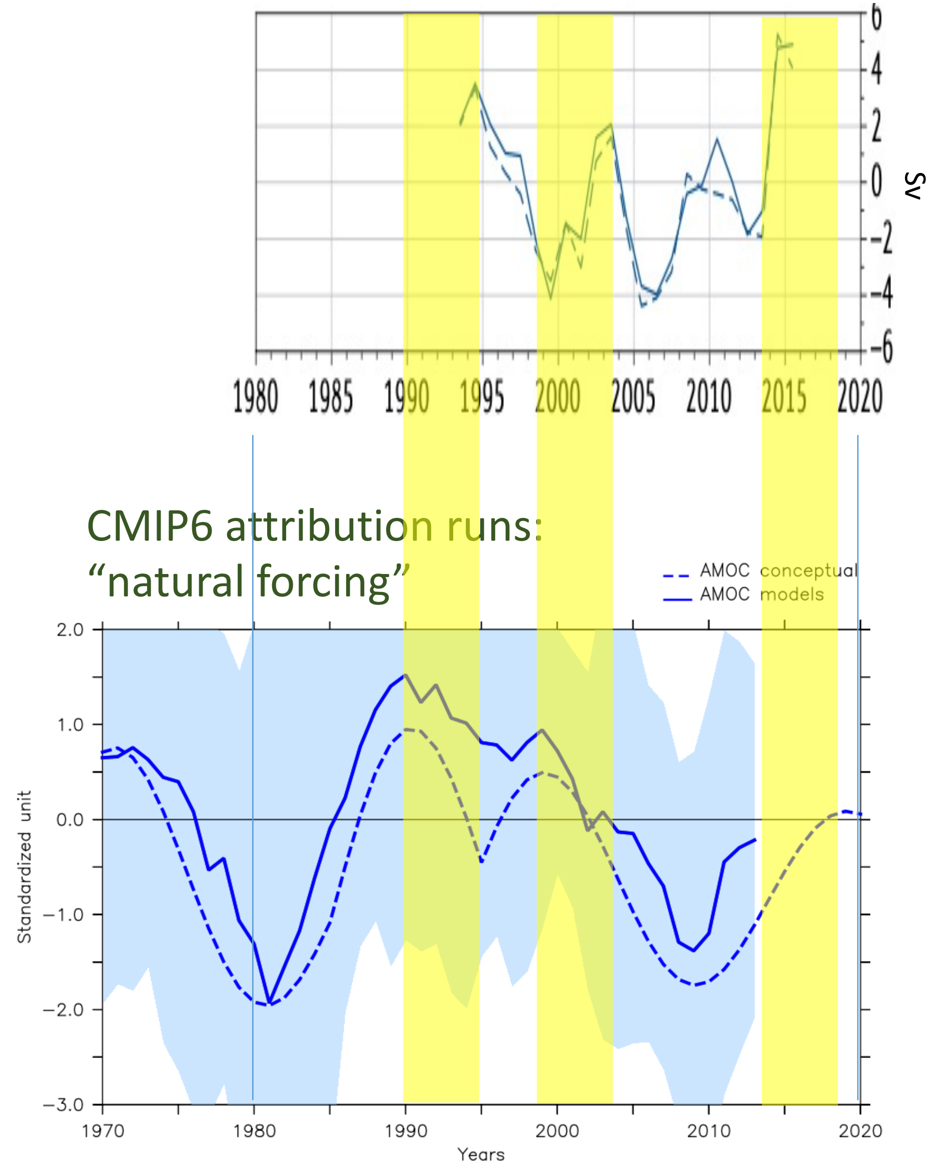


Bonnet et al., *Nat Com.*, 2021

What about the AMOC over the last 30 years?

- We now have 30 years with *in situ* observation-based estimates of the AMOC (cf. Jackson et al. 2022)
- **No AMOC trend** on this timescale (Worthington et al. 2021), which is **also coherent** with Caesar et al. (2018, 2021) estimates
- Variability **forced by the NAO**, but also consistent with a response to **volcanic eruptions** (cf. Swingedouw et al. 2015)
- Still at play in CMIP6 Detection-Attribution ensemble (Borchert et al. 2021)

AMOC estimate from OVIDE

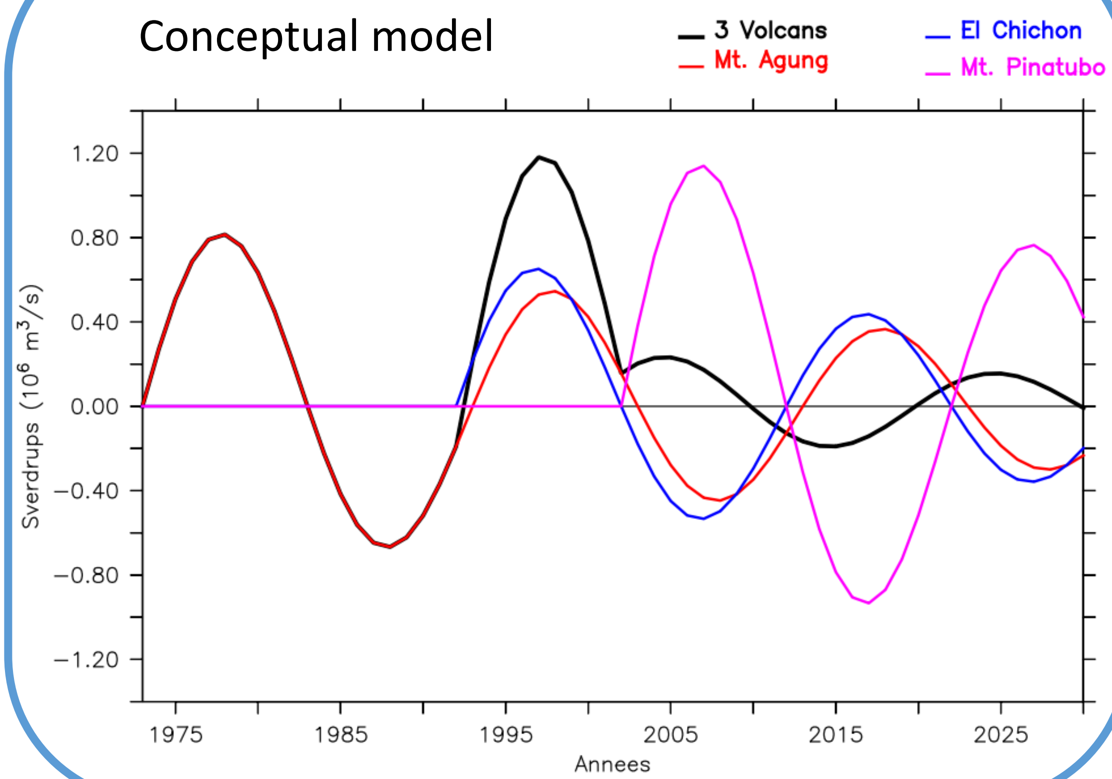


European Climate Prediction system

How can we explain recent AMOC variations?

- Volcanic eruptions might be part of the AMOC variability on top that forced by the NAO (Swingedouw et al. 2015)
- It fits well with Great Salinity Anomalies timing since the late 1960s
- It is also (partly) validated using paleo-data

AMOC response to volcanoes



AGENCE NATIONALE DE LA RECHERCHE ANR Greenland

SPECS

Key questions

- What is causing the AMOC changes over the last century (if any)?
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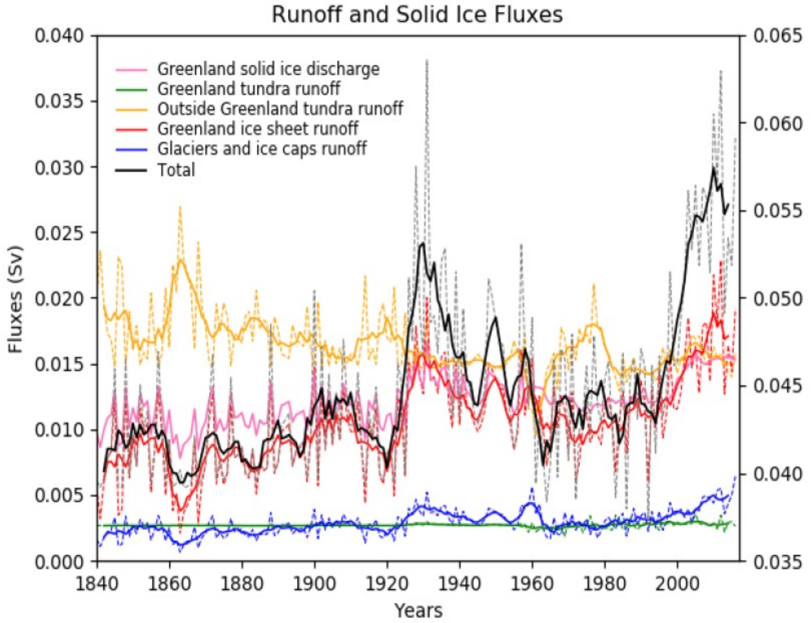
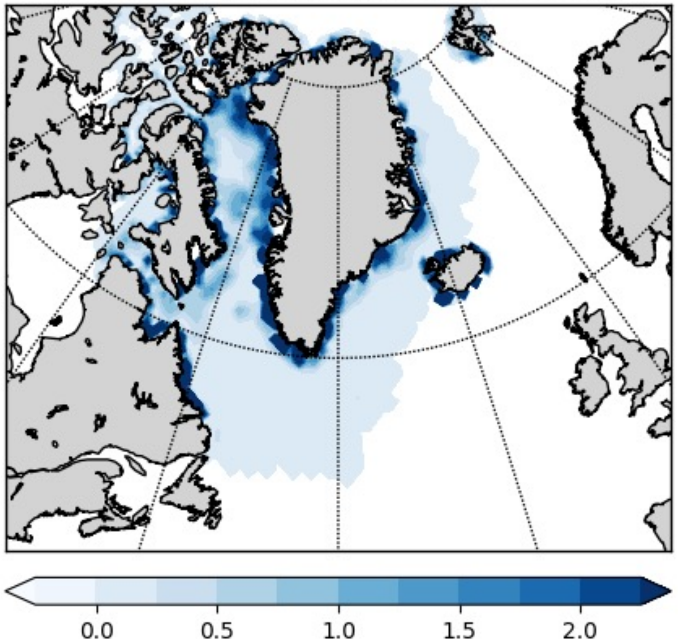
What about GrIS melting?



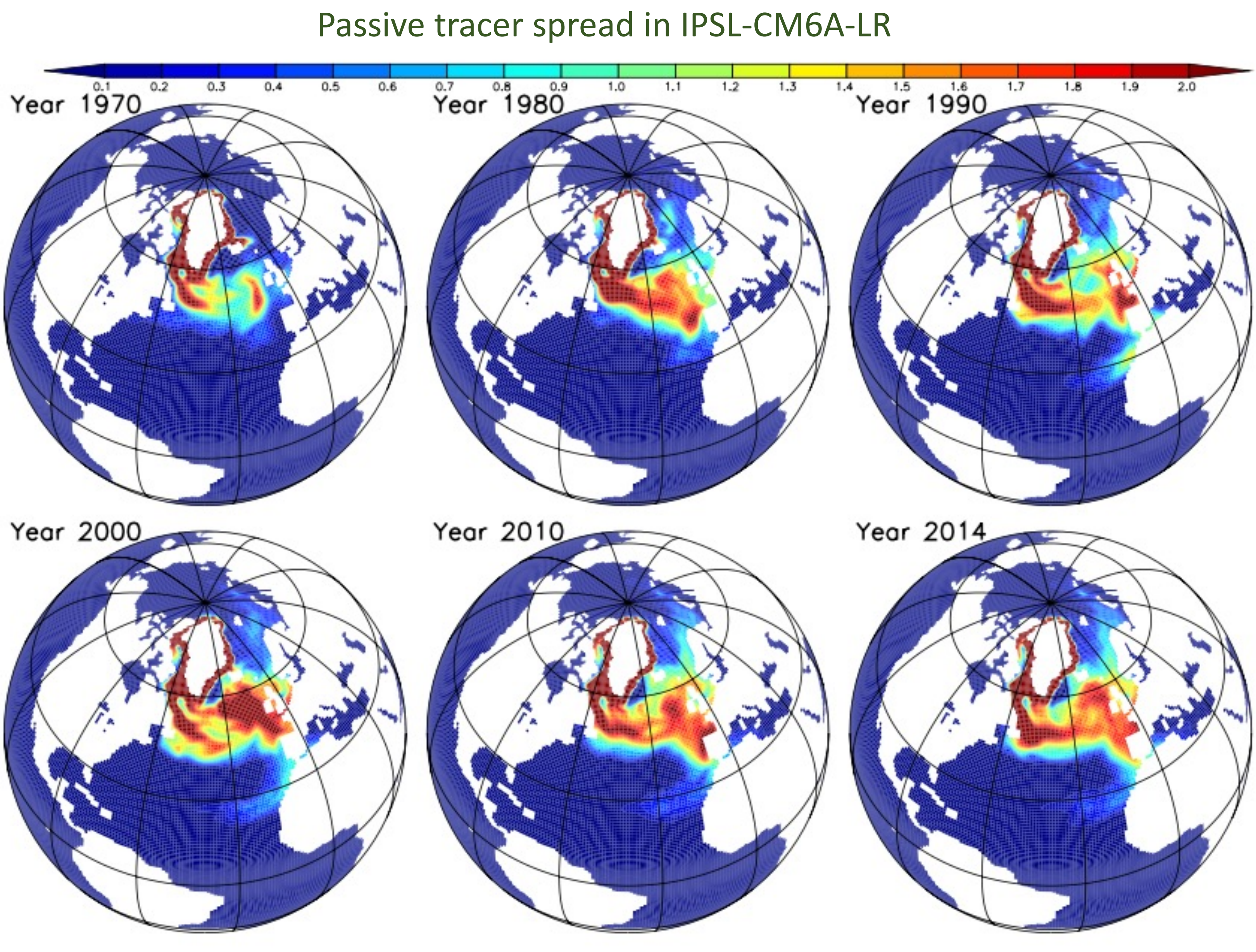
- **Has Greenland melting played a role in the recent AMOC weakening?**
- Use of Bamber et al. (2018) recent reconstruction extended back to 1840 following Box and Colgan (2013)
- Overwrite runoff and calving in the the Greenland region by those observation-based fluxes
- Use of 10 members of IPSL-CM6A-LR historical simulations including this melting since 1920 (**Melting ensemble**) or not (**Historical ensemble**)



Devilliers et al. 2021

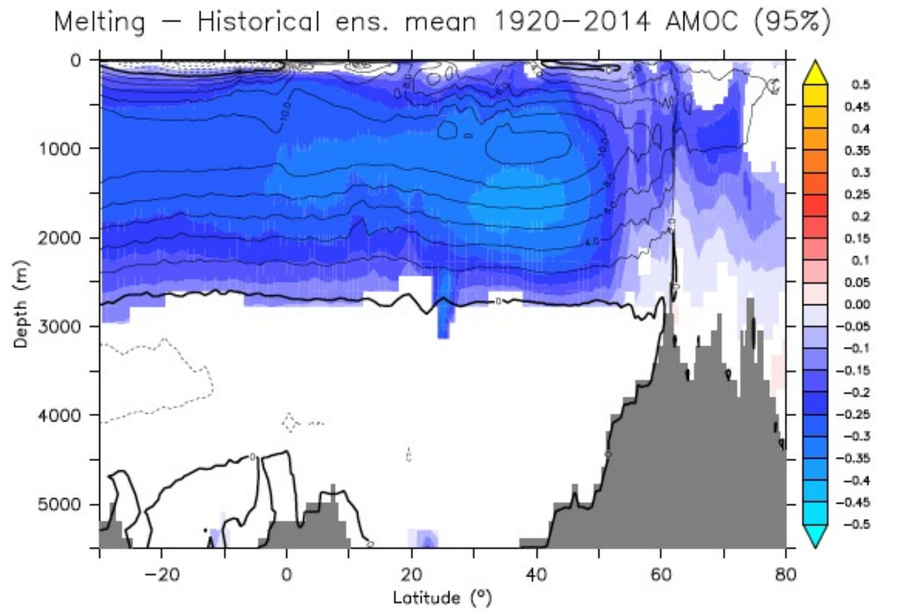
BLUE ACTION

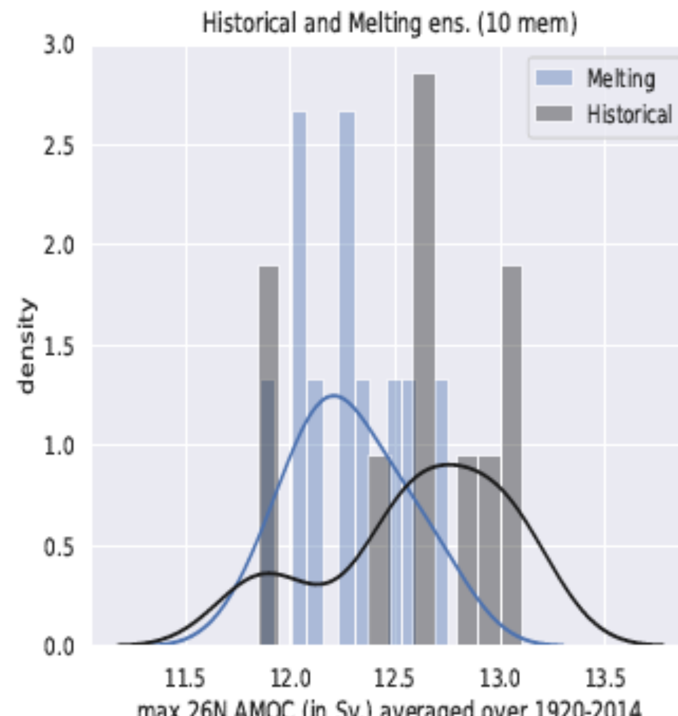
Propagation of the freshwater perturbation



Impacts on the AMOC

- The AMOC is slightly affected by the freshwater trends
- It weakens by 0.20 ± 0.39 Sv at 45°N
- Far less than the 3 ± 1 Sv estimated by Caesar et al. (2018)





Devilliers et al. 2021

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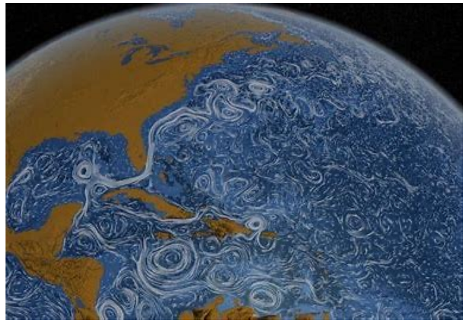
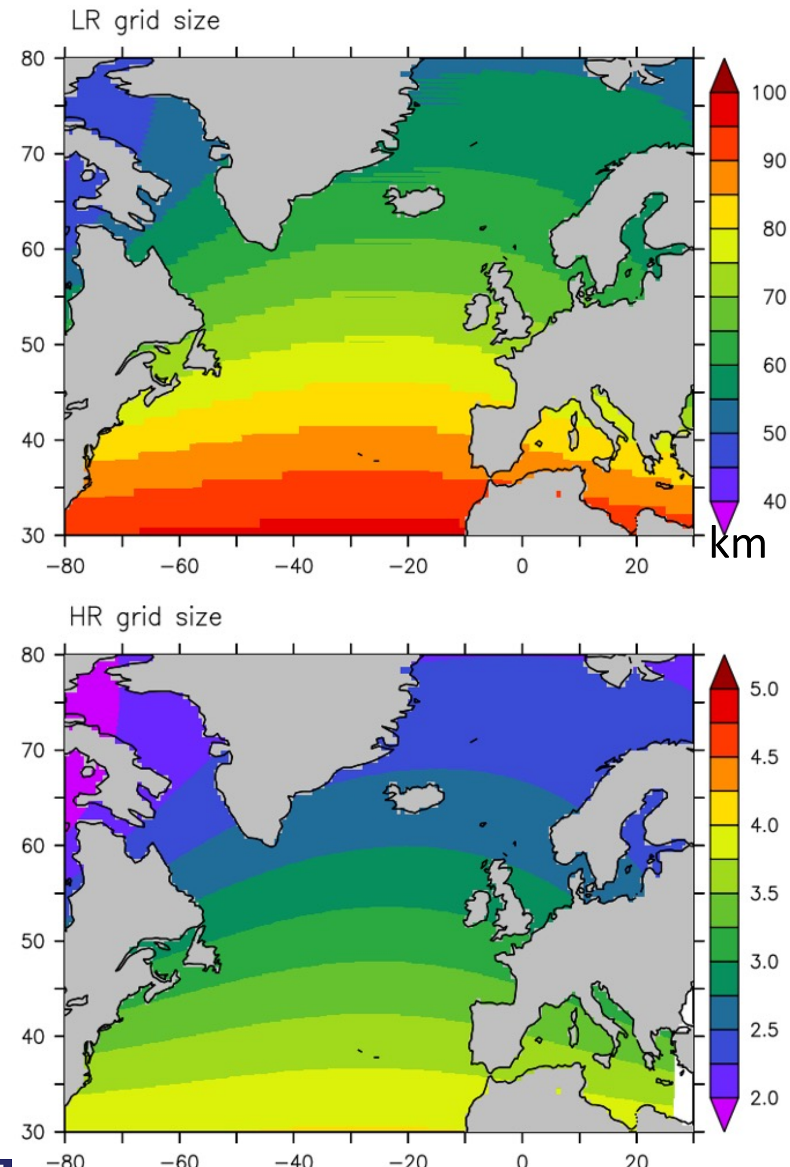
Can horizontal oceanic resolution play a role?



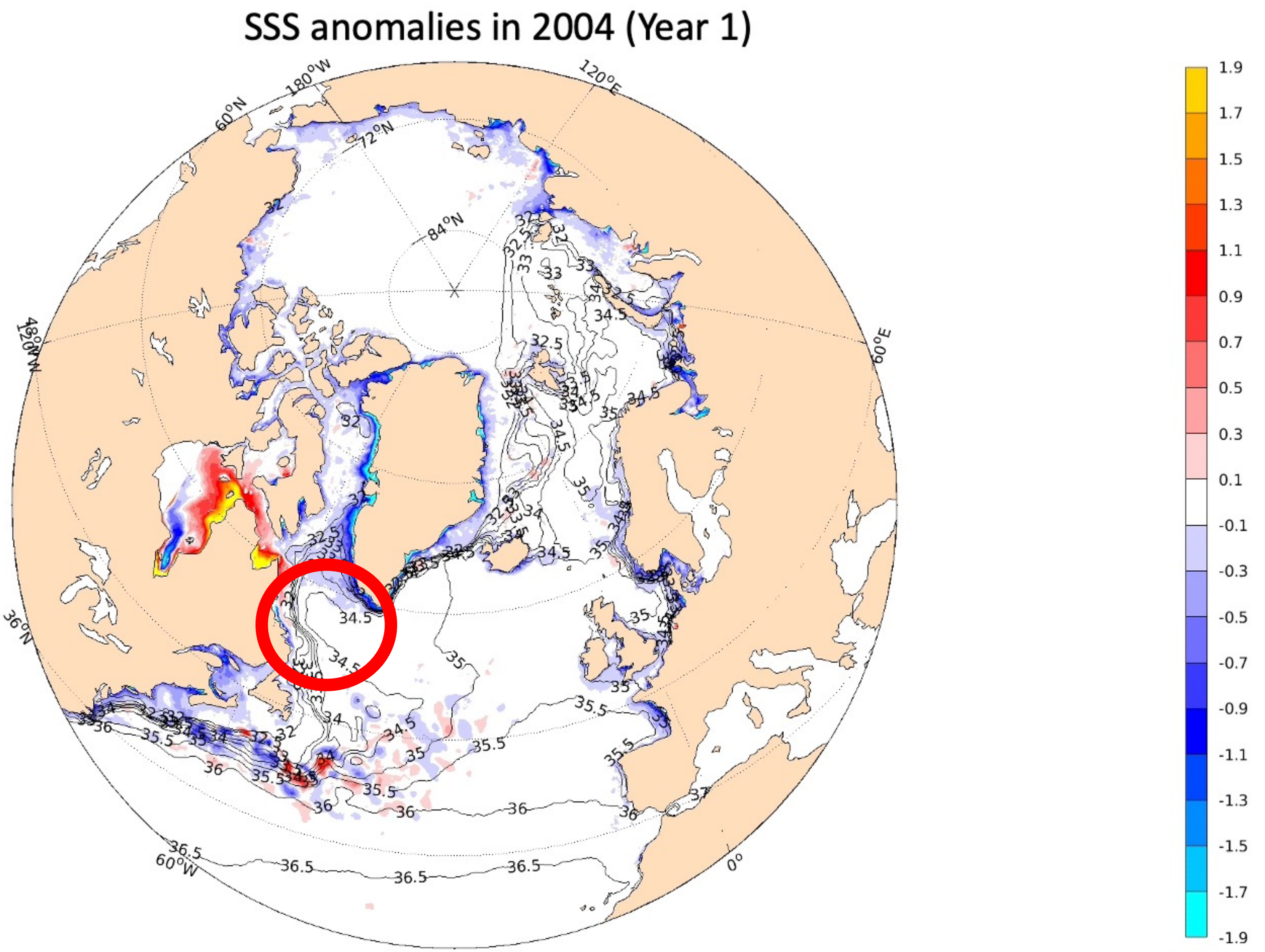
- A High Resolution (**HR**) model (2-3 km in the North Atlantic) ocean-only model is also integrated from 2004
- There is no salinity restoring at all in this model (to avoid removing the freshwater perturbation signal)
- Twin simulations, one (named **Melting**) with observed GrIS melting and the other (named **Control**) without
- Only 13 years of simulation due to high CPU cost (but planning to continue them)



Swingedouw et al. 2022

BLUE ACTION

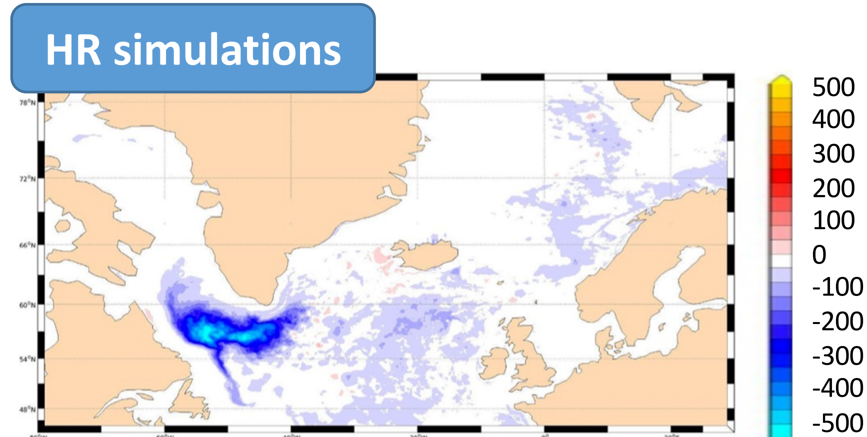
Propagation of the perturbation in HR simulations

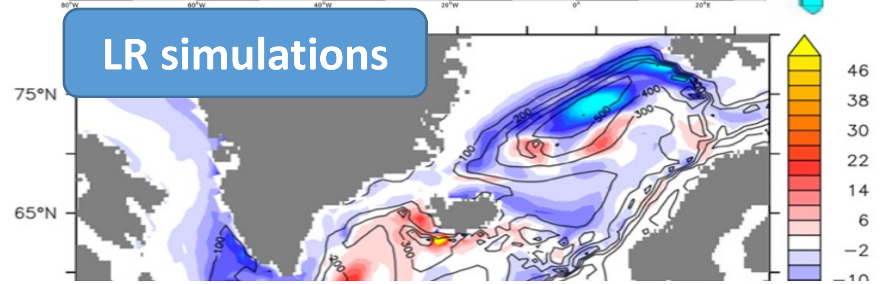


Impacts of oceanic resolution on GrIS impact

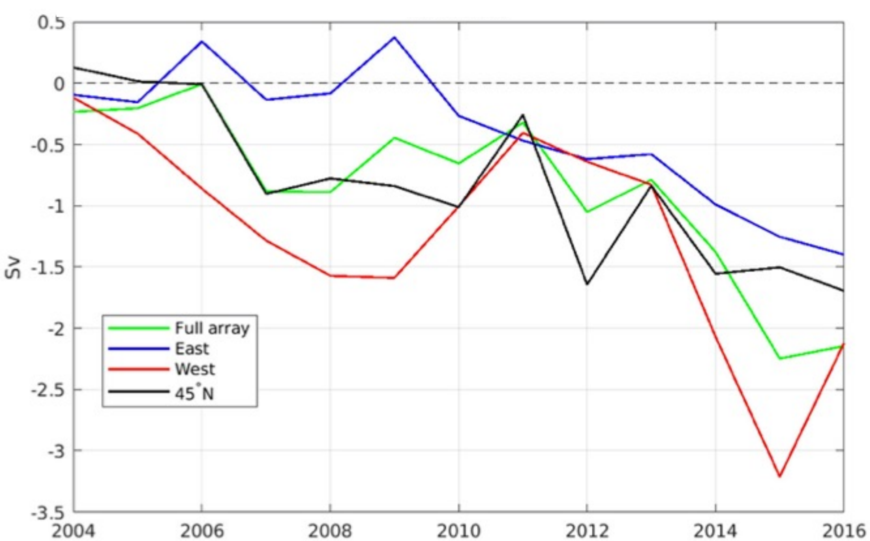
- We compare IPSL-CM6A Low Resolution (**LR, 50-60 km**) run with very High Resolution (**HR, 2-3 km**) simulations from an ocean-only model (Swingedouw et al., Frontiers, 2022
- Higher impact of Greenland melting on the AMOC in the HR runs

Mixed layer depth anomalies

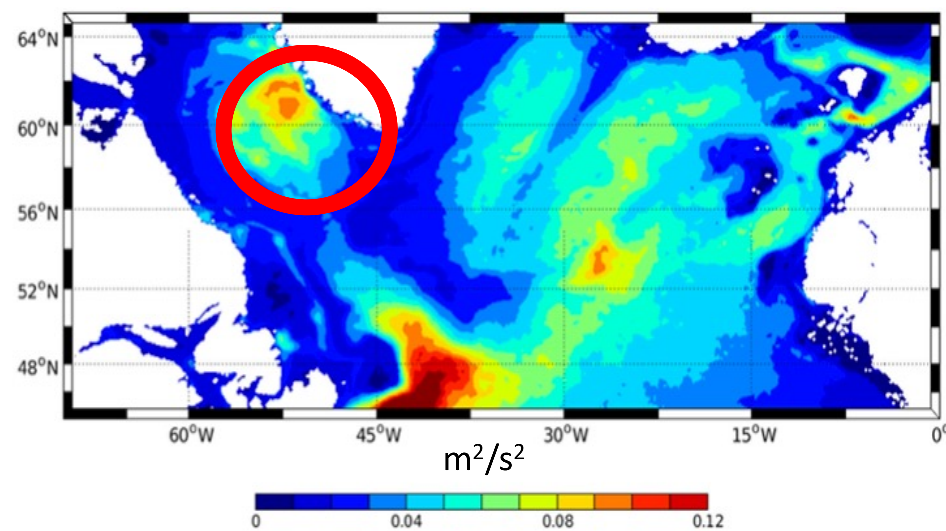




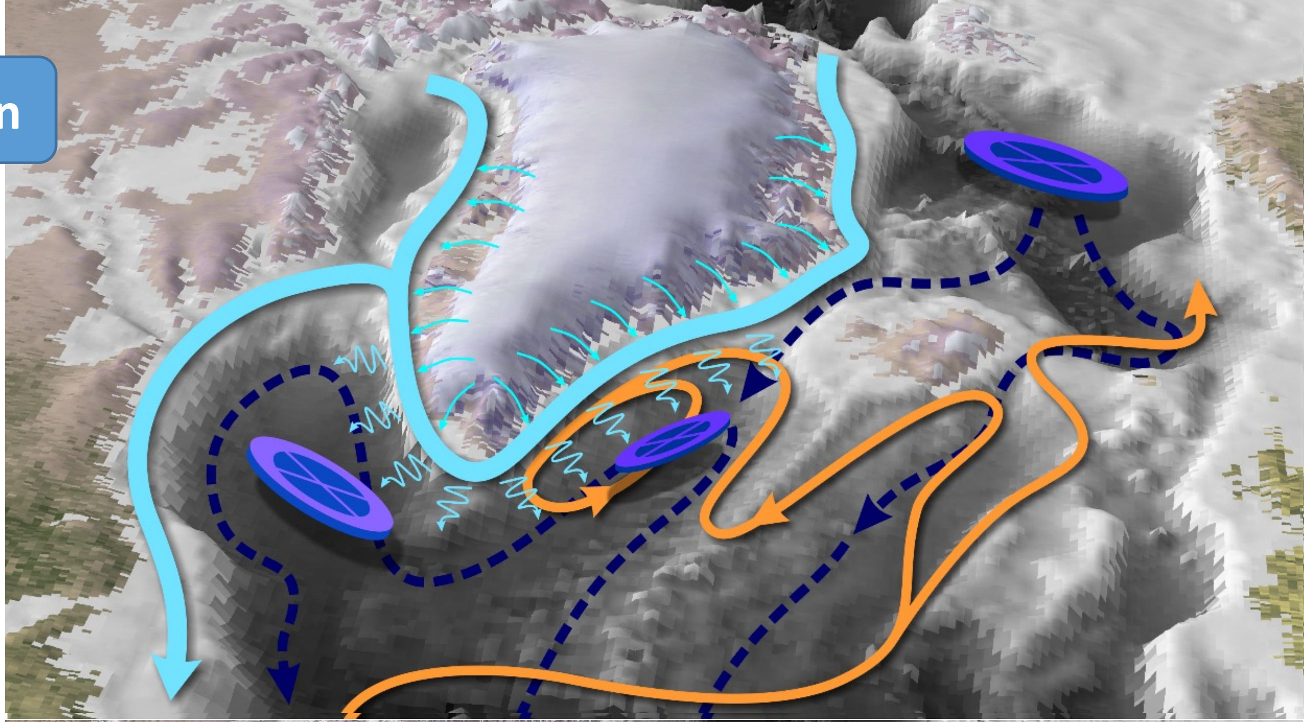
AMOC anomalies in HR simulations



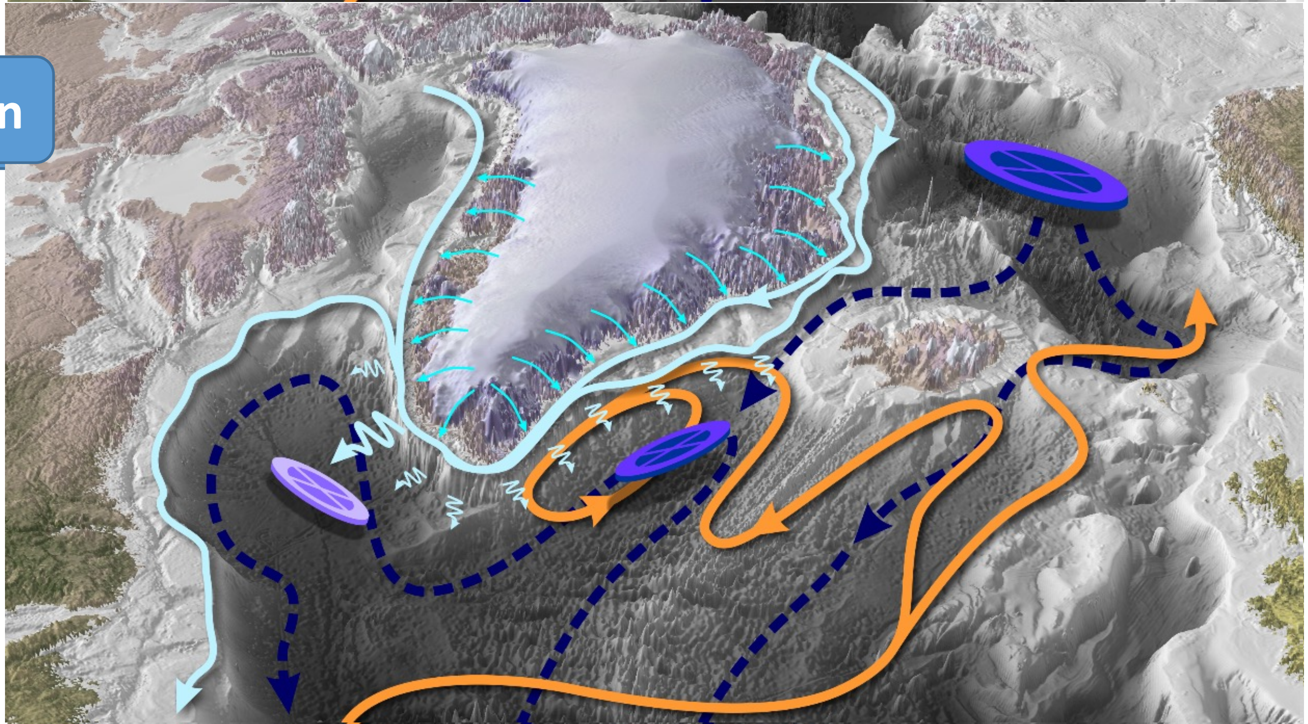
Eddy Kinetic energy in HR simulation



Low Resolution



High Resolution



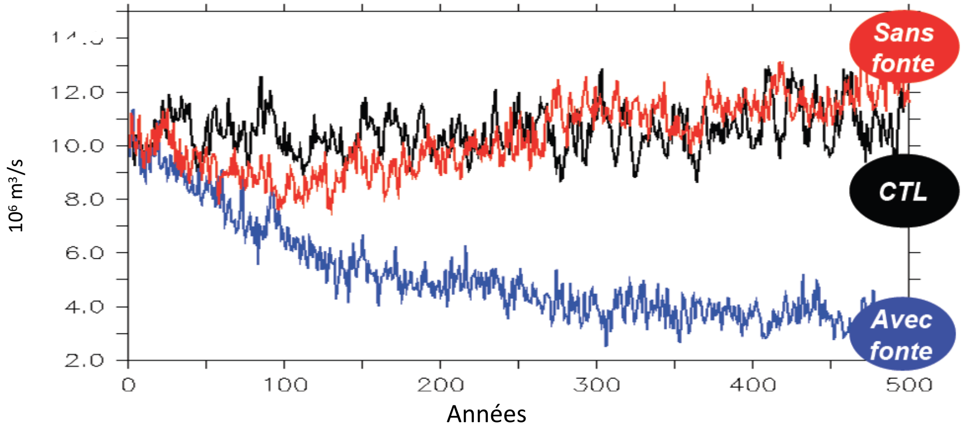
Courtesy of
Vincent Hanquiez

Key questions

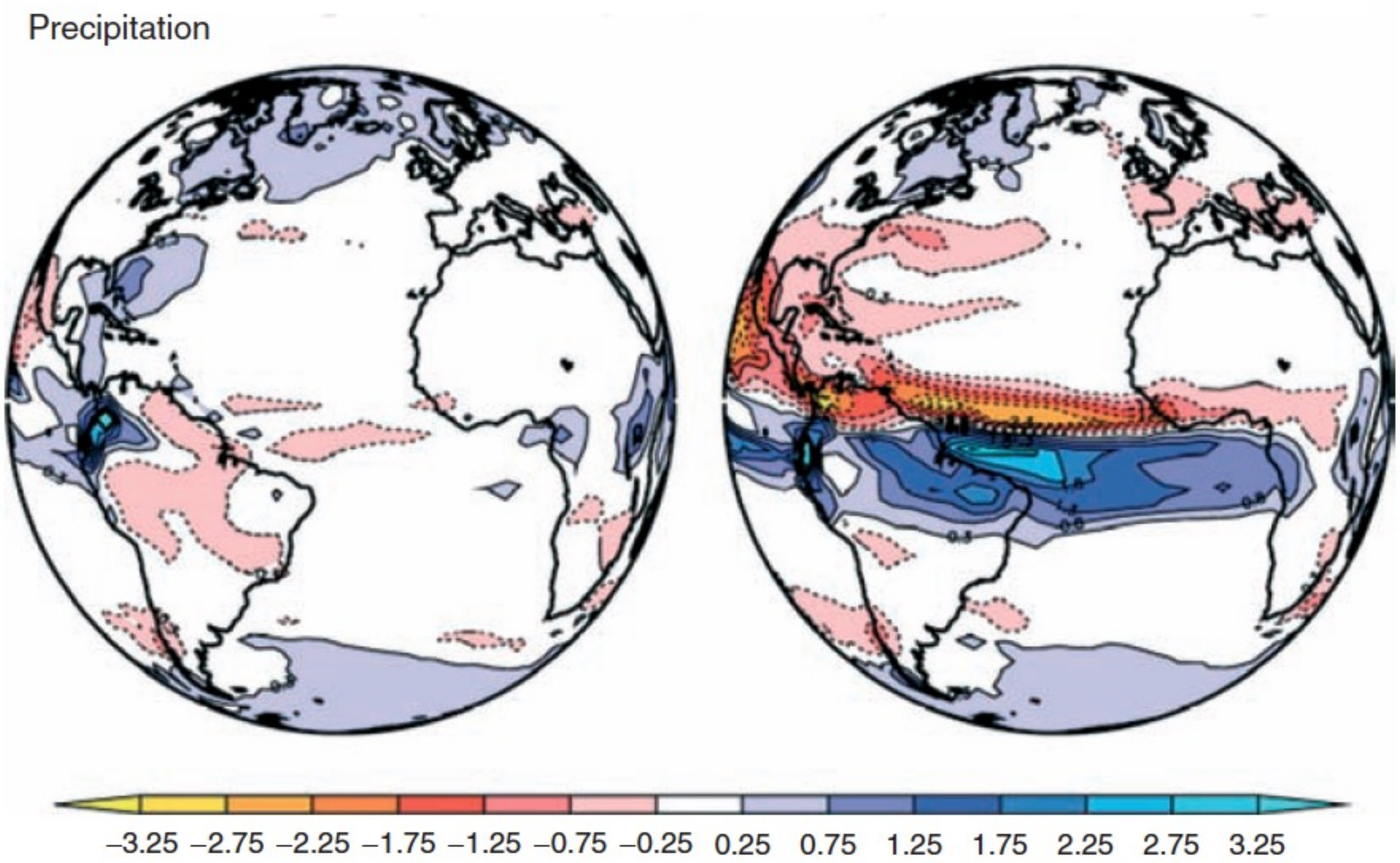
- What is causing the AMOC changes over the last century (if any)?
- Is the impact of GrIS melting well represented in climate models?
- Is the AMOC moving towards a tipping and what kind of changes might occur in the near future?

Can the AMOC collapse?

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

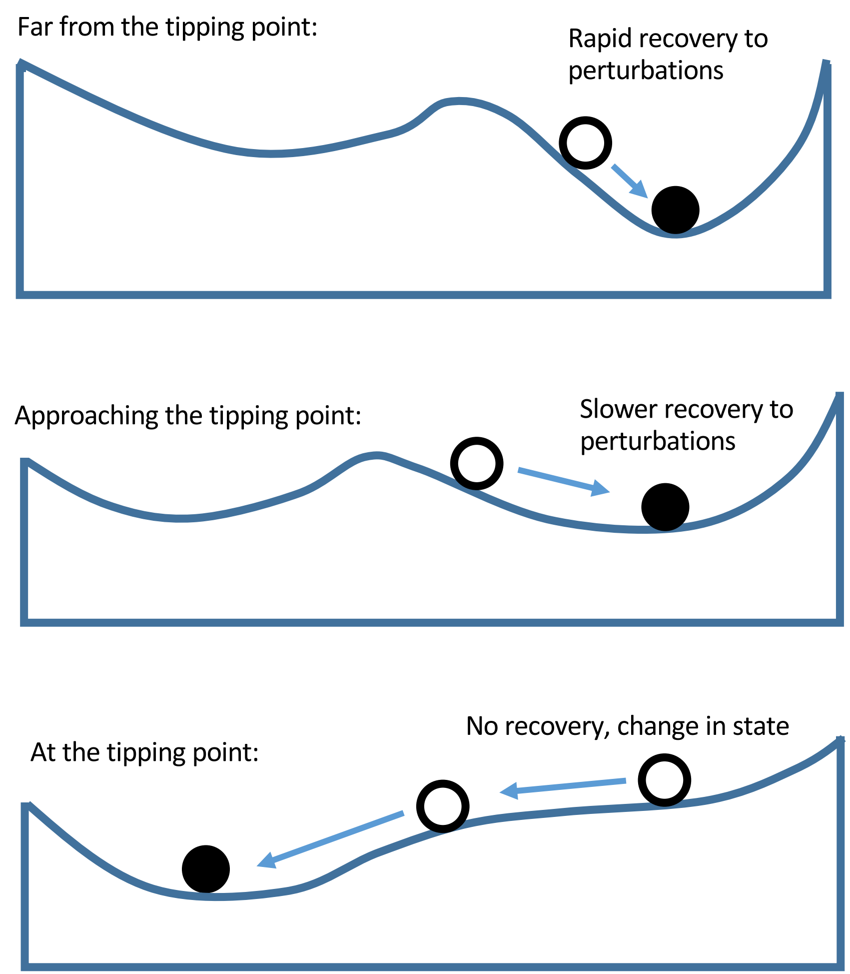


Without melting **With melting**



How to have early warnings of a potential AMOC collapse?

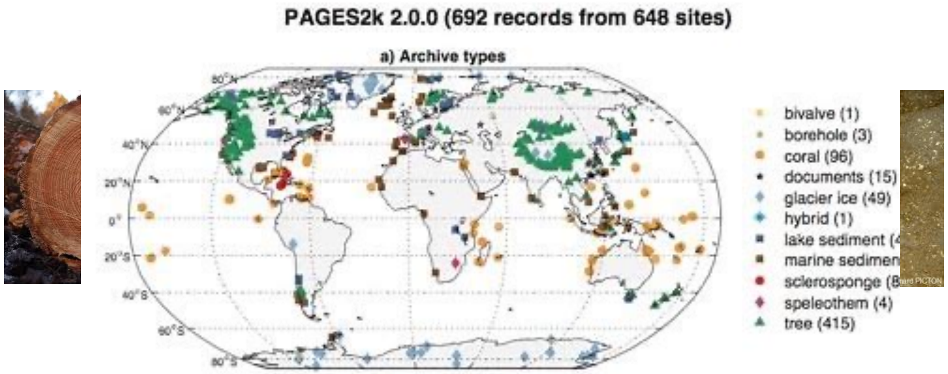
Change of temporal variability when approaching a tipping point



- 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

Adapted from: Lenton 2011

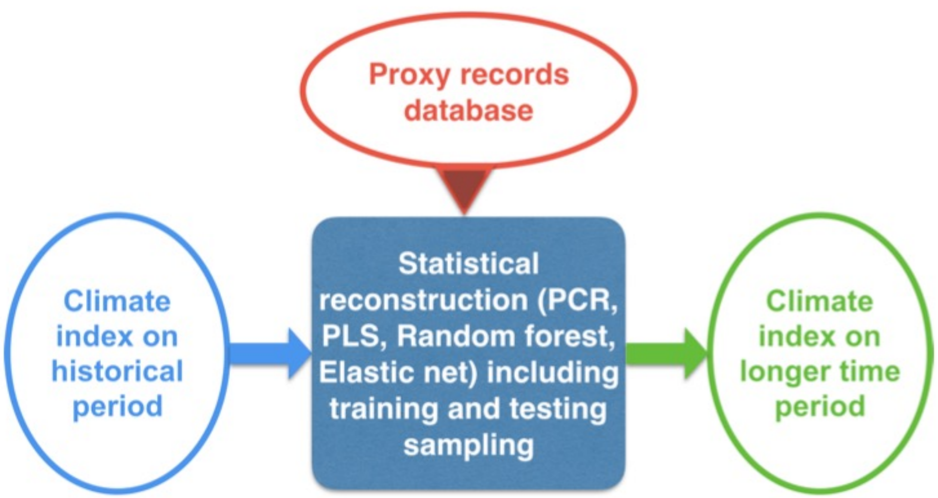
Proximity to an AMOC tipping point?



Geoscientific Model Development

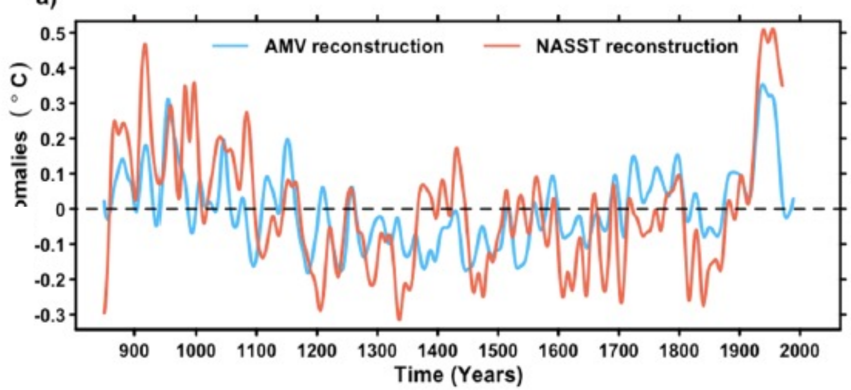
Reconstructing climatic modes of variability from proxy records using ClimIndRec version 1.0

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

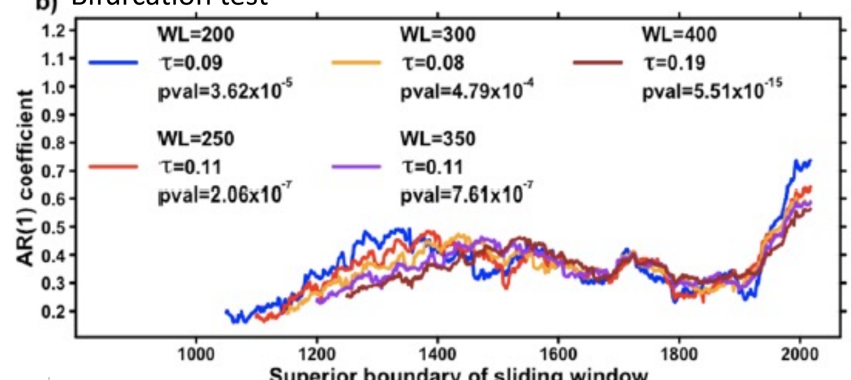


AMV reconstruction as a proxy of AMOC internal variability

a) Reconstruction of the North Atlantic SST



b) Bifurcation test

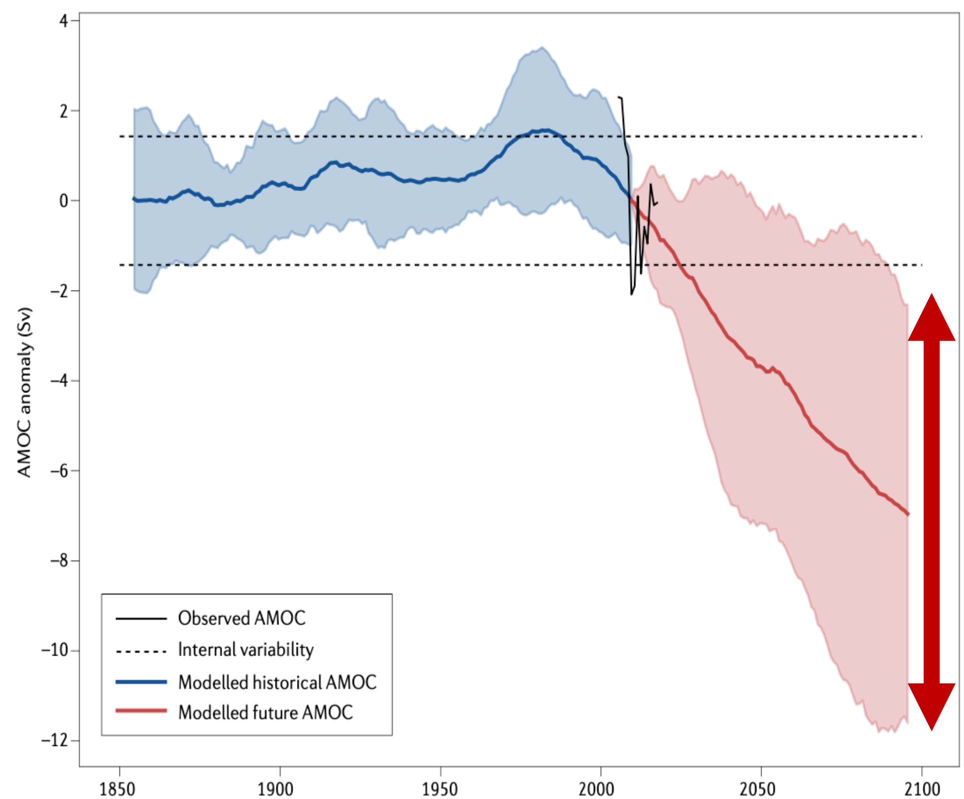


Michel et al., in rev..

Projections of the AMOC in CMIP6 models

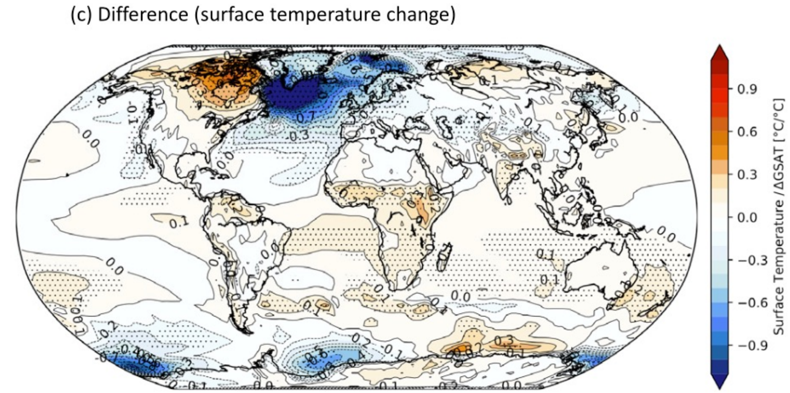
- Weijer et al. (2020) estimated, using CMIP6, an AMOC weakening of about 6 to 8 Sv (34–45%) by 2100 (when compared to historical period)

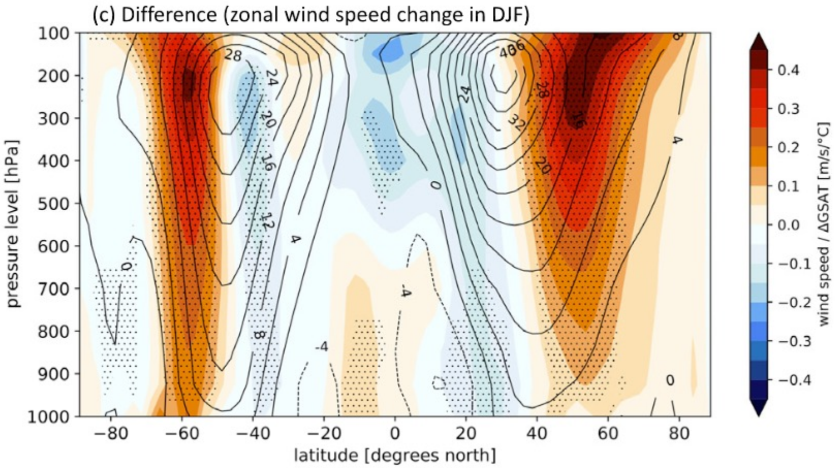
- IPCC 2021 statements:
  - “The AMOC is ***very likely* to weaken** over the 21st century for all emission scenarios.
  - While there is *high confidence* in the 21st century decline, there is only ***low confidence* in the magnitude** of the trend.
  - There is ***medium confidence*** that there will not be an **abrupt collapse** before 2100 ”

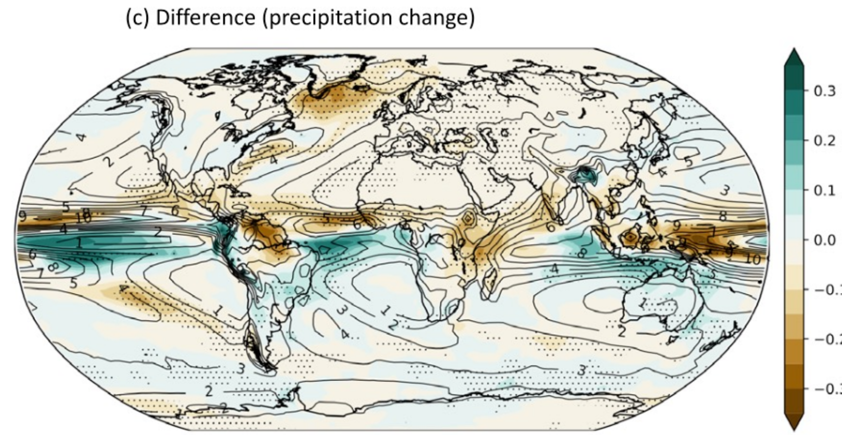


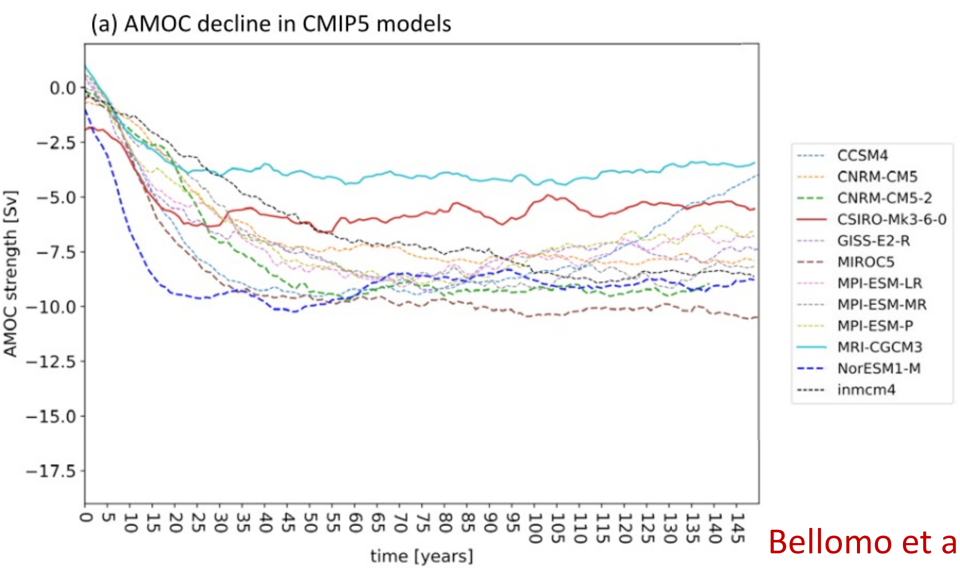
Jackson et al. 2022

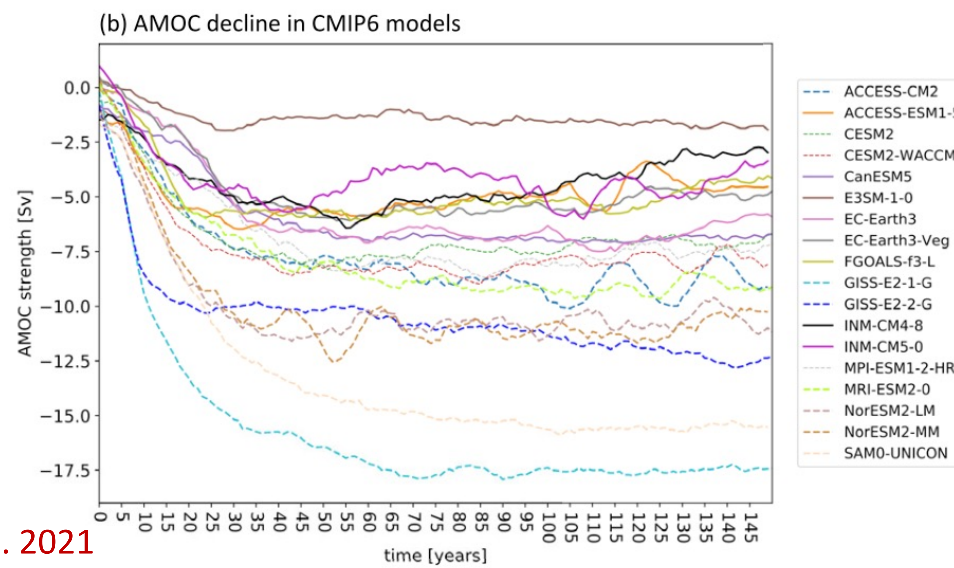
Still so much AMOC uncertainty in CMIP6











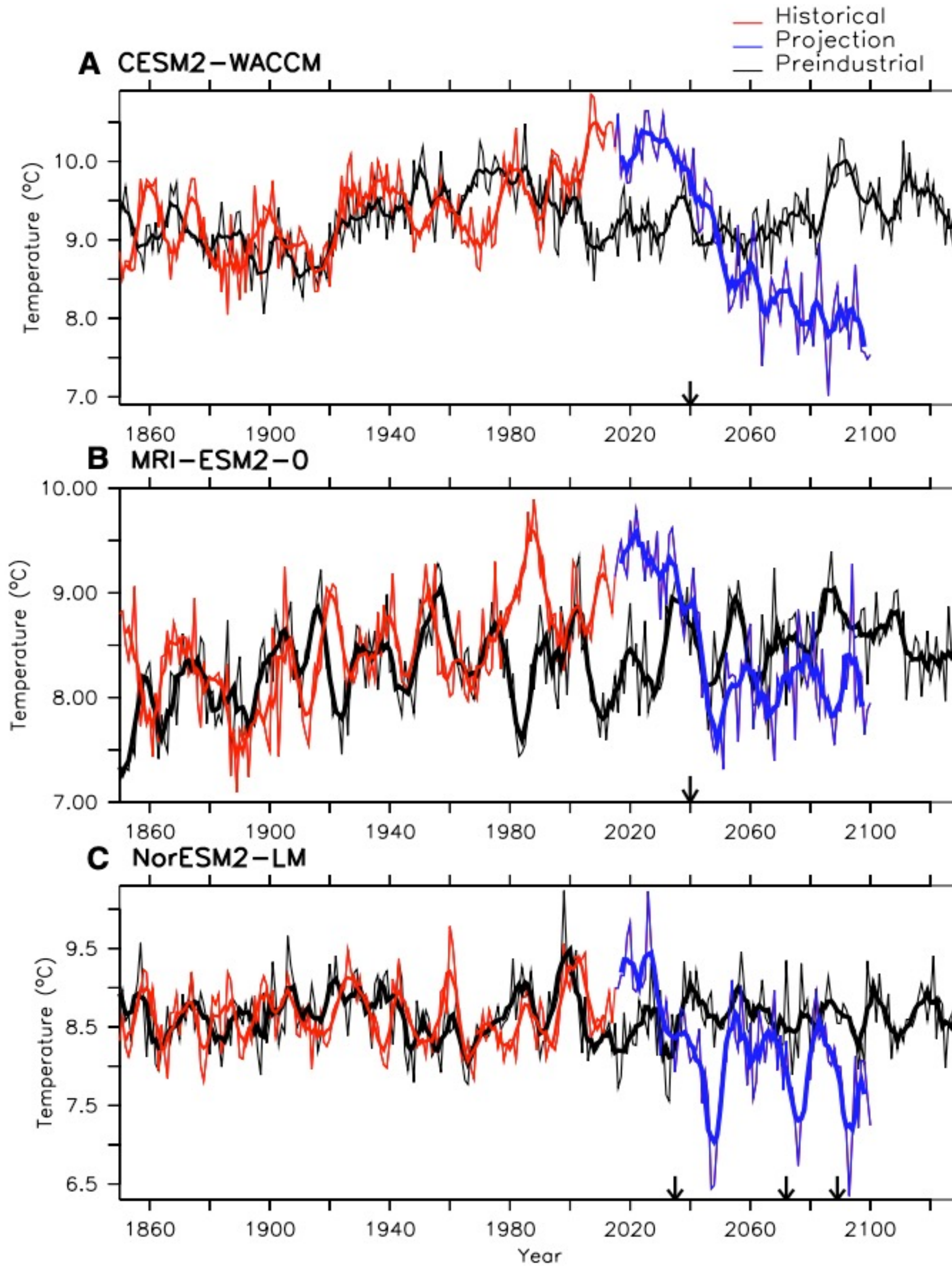
Bellomo et al. 2021

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**

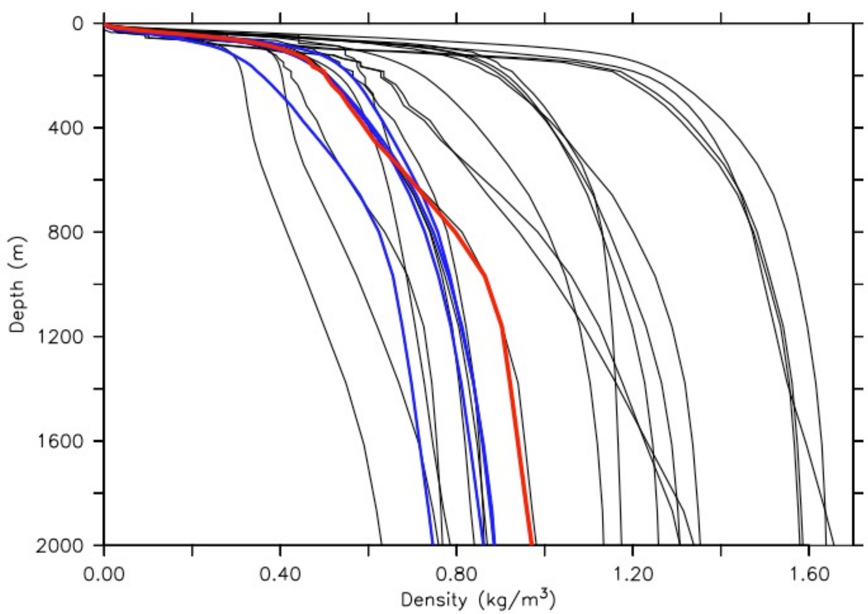
- This was true in CMIP5 (Sgubin et al. 2017) and is still the case in CMIP6 for SPG collapse (Swingedouw et al. 2021)

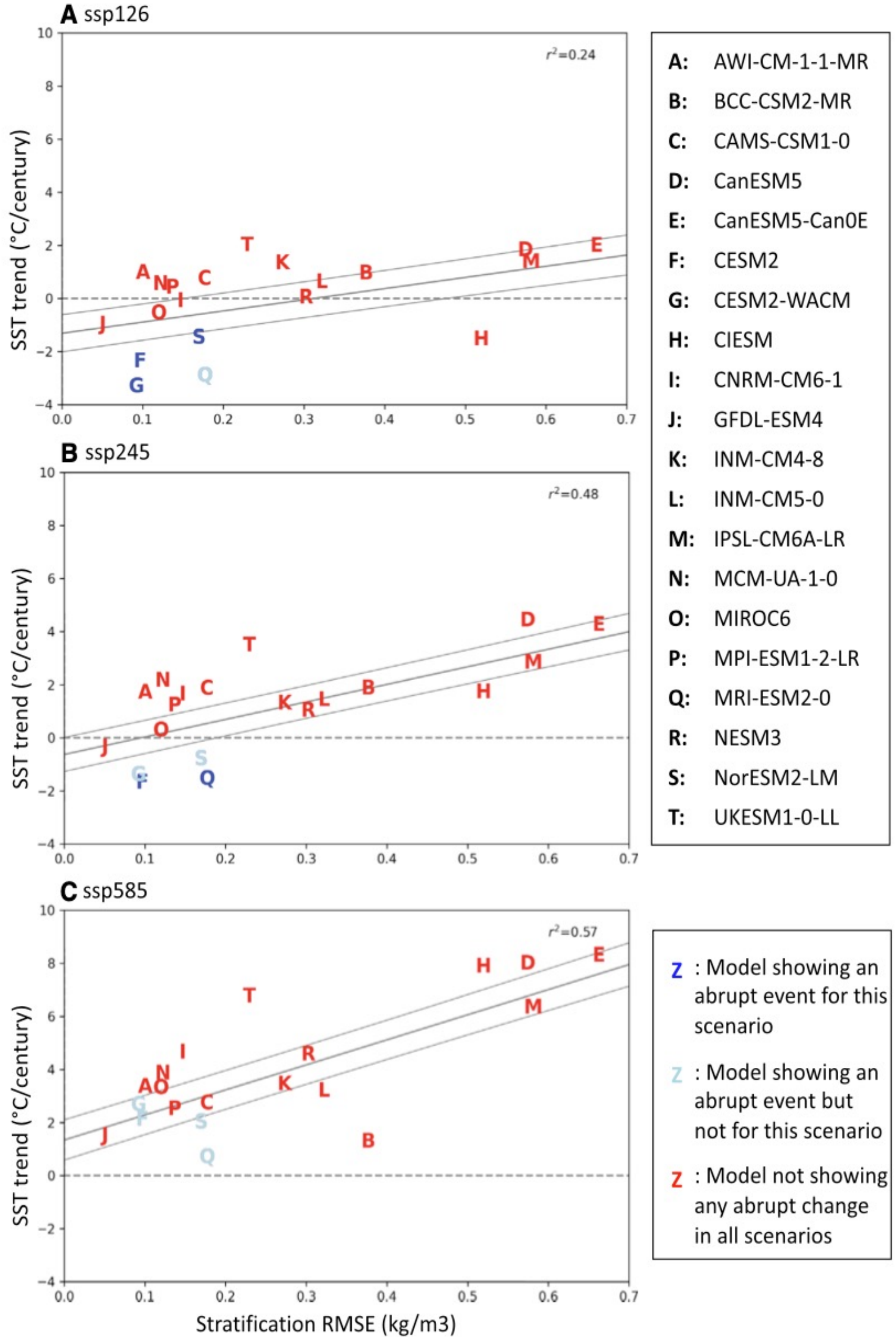


Sgubin et al. 2017, Swingedouw et al. 2021

SPG stratification as an Emergent 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)**

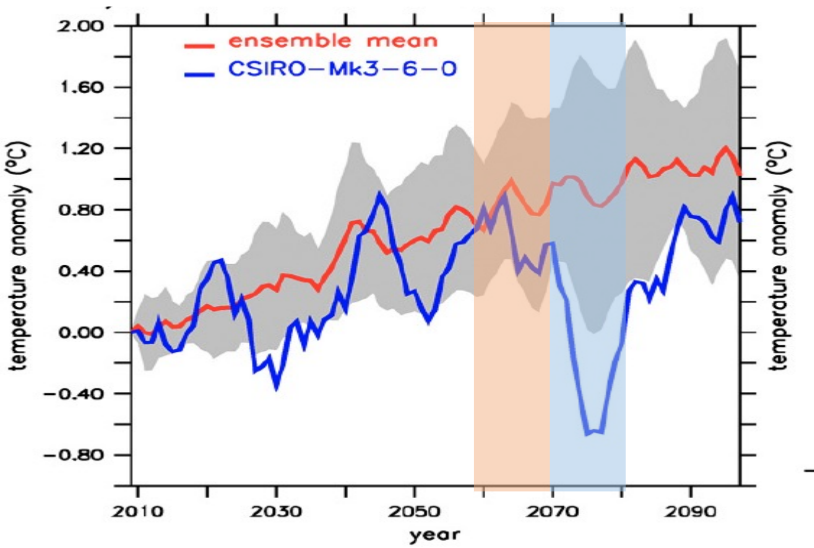




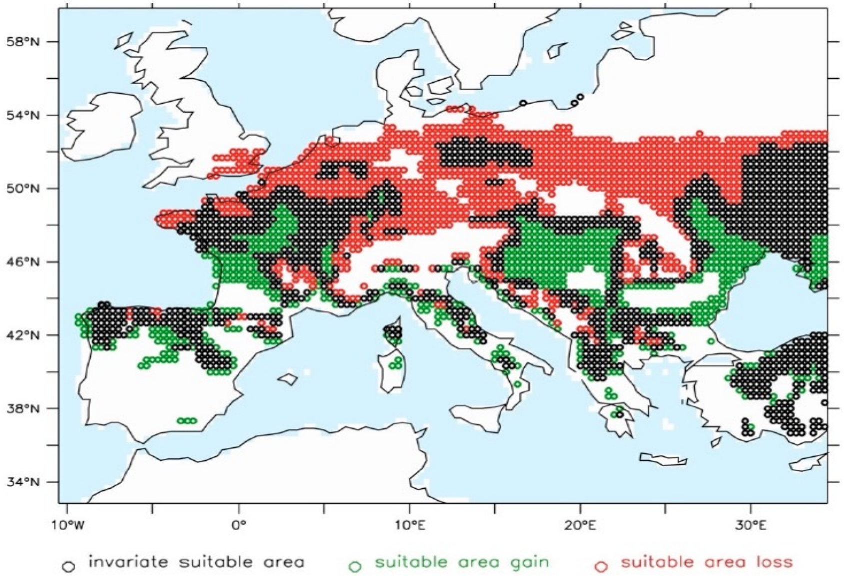
Impacts of abrupt decadal cooling

- 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.

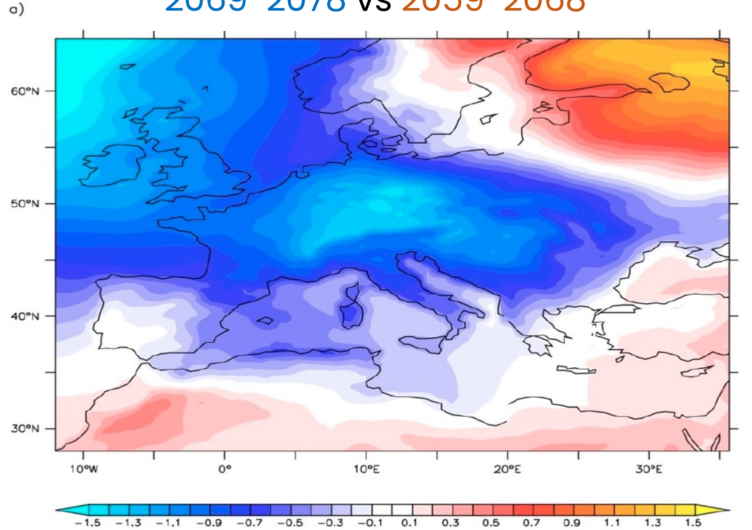
Temperature in the UK



Suitability of Chardonnay
2069-2078 vs 2059-2068



Temperature difference
2069-2078 vs 2059-2068

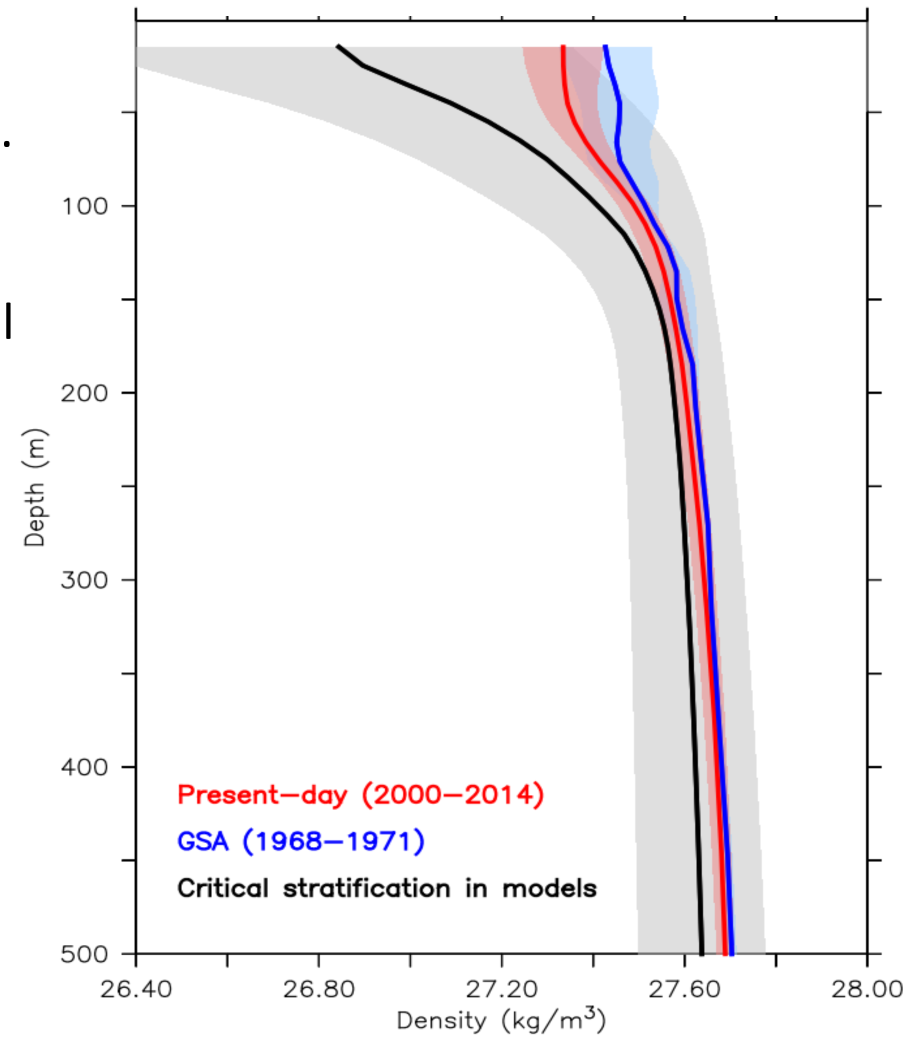


Sgubin et al. (2019)

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 in the envelop (66%) of the models just before theit abrupt cooling…

Stratification in the SPG



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

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

What are the research gaps?

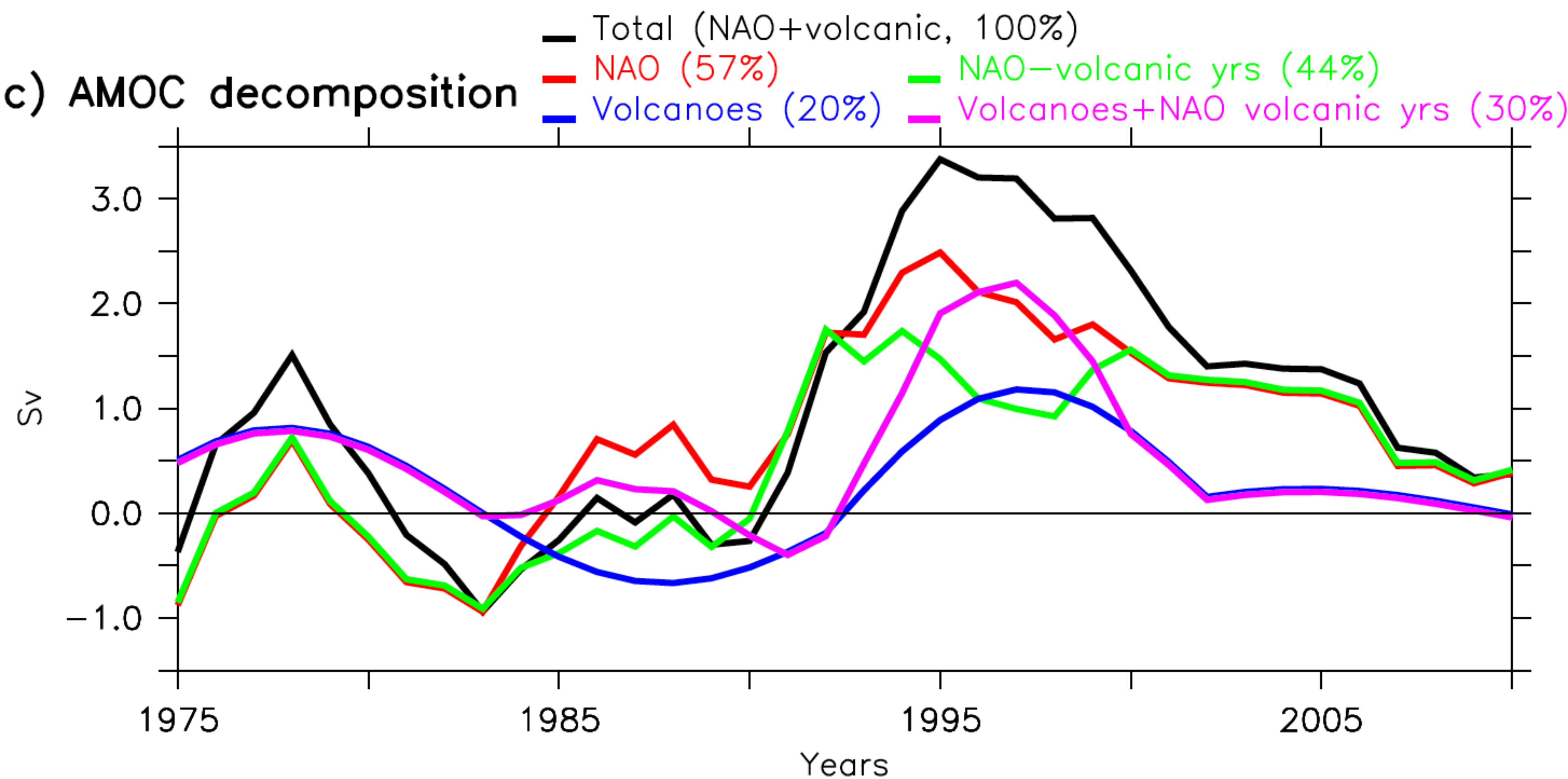
- **Observation systems** are needed for an efficient early warning system
  - Continue on-going *in situ* arrays and monitoring systems
  - Include more oceanic observations below 2000m
- **Decadal prediction systems** still need further development to:
  - Diminish their offset to observations
  - Better include meso-scale processes
- Need for further **reconstructions of the last few thousands of years** to have better insights on the approach of a tipping point
- Assessment of the impact of **such low probability - high impact scenario in adaptation plans** are poorly accounted for up to now

Key take-home messages

- On-going changes in the AMOC and SPG are not clearly attributed yet
- There is a possibility of Abrupt Changes in the North-Atlantic/Arctic in IPCC-type climate models
- It might take about a century for the AMOC and a decade for the SPG
- Both events have global impacts (marine life, Sahel precipitation, European climate, storms, agriculture, Asian monsoon shift…)
- Decadal prediction systems need to be further developed to have efficient early warnings of such potential abrupt changes
- Adaptation plans should include such low probability – high impact scenarios


Thank you!

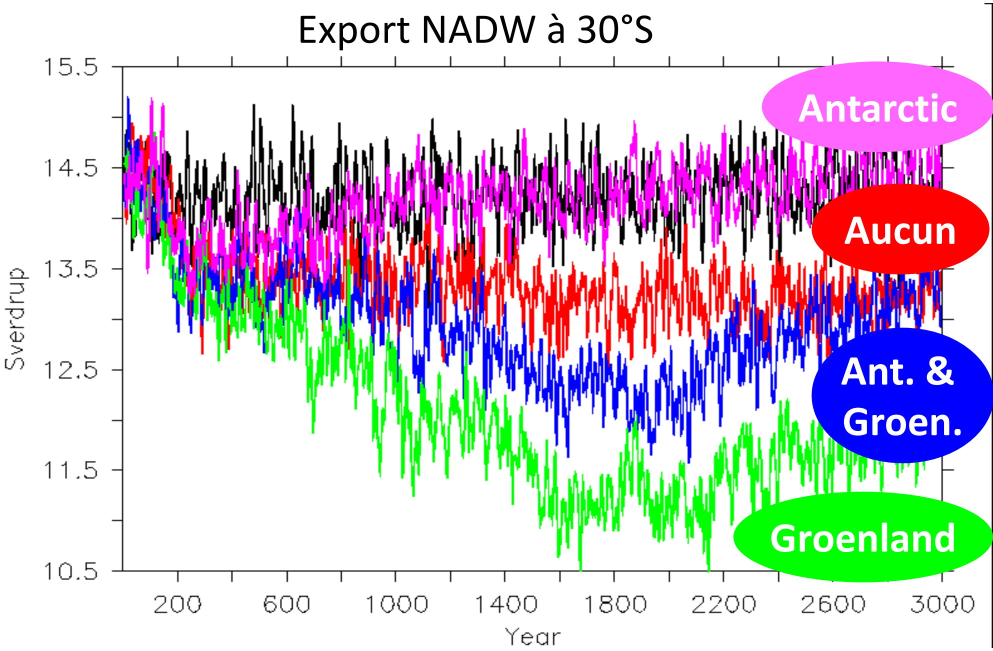
Attribution of the role of volcanic eruptions



Swingedouw et al. 2015

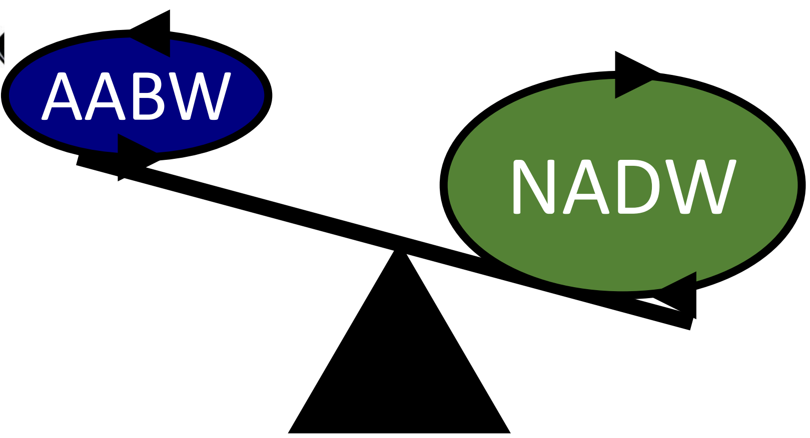
Et le sud ?

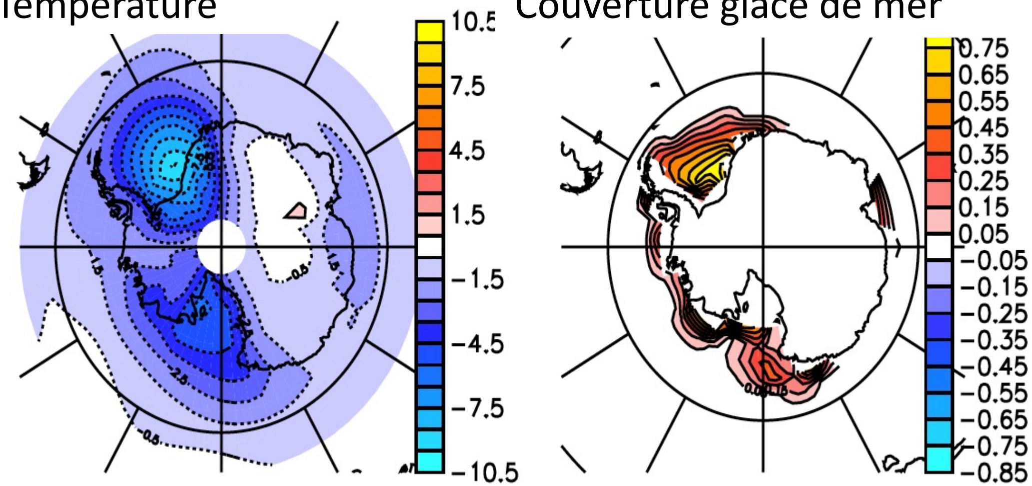
- Un effet de la fonte de l'Antarctique pour la THC à $4XCO_2$
- Des mécanismes complexes et oppos concernant la sensibilité de la THC (Swingedouw et al. 2009)



Swingedouw et al. 2008

- Impact climatique important au sud





The future of the Meridional Overturning Circulation and its impacts on climate

Didier Swingedouw

Juliette Mignot, Mohamed Ayache, Marion Devilliers, Simon Michel Giovanni Sgubin, Alina Gainusa-Bogdan, Rémy Bonnet, Leonard Borchert, Vincent Jomelli, Marie-Noelle Houssais, Christophe Herbaut, Olivier Boucher, Pablo Ortega, Sybren Drijfhout, Samuel Diabaté, Gerard McCarthy, Vincent hanquiez…