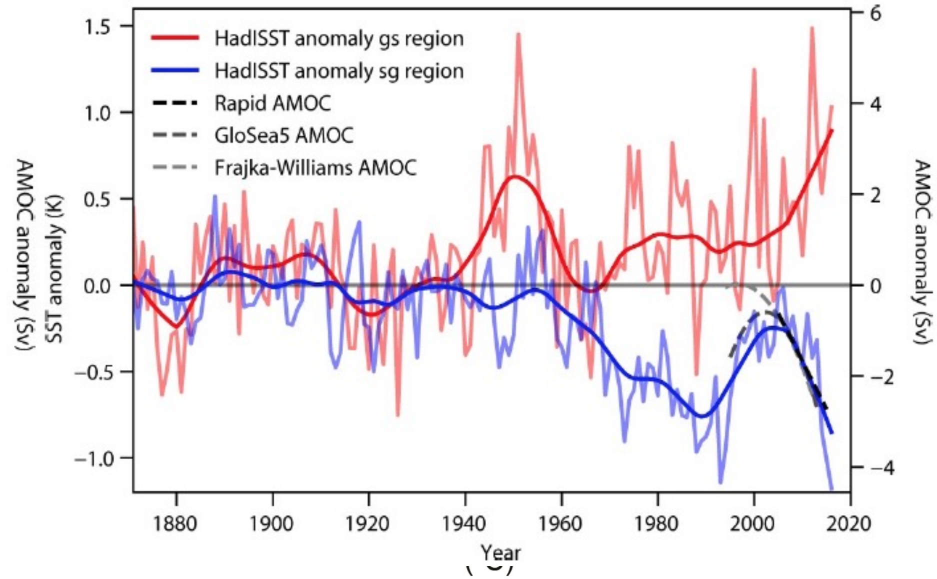
Salty tales of the AMOC from the Holocene to the Anthropocene

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…

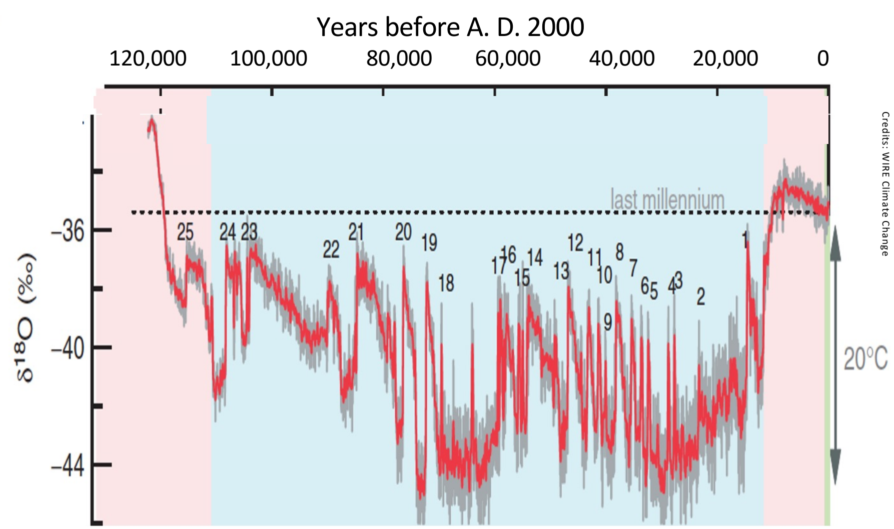
Where are we now?

- 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 15% Caesar et al. 2018)
- Lessons from the past both in glacial and interglacial periods highlight that abrupt changes/tipping points are possible



Credits: CNRS

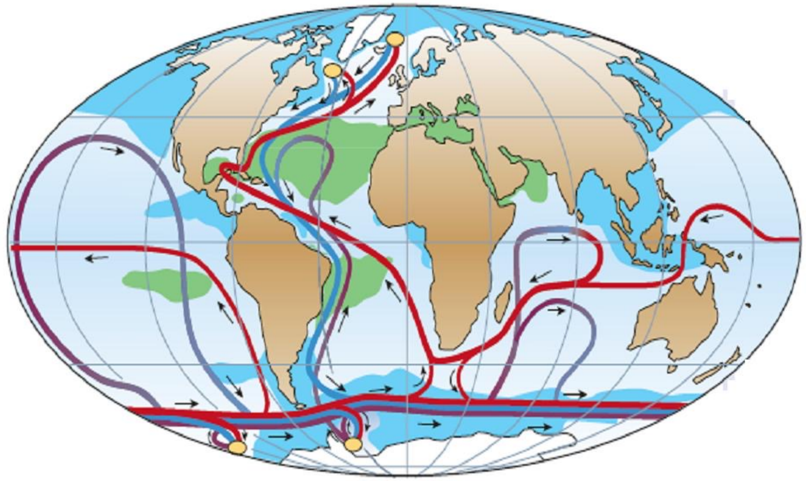
Ice core reconstructions



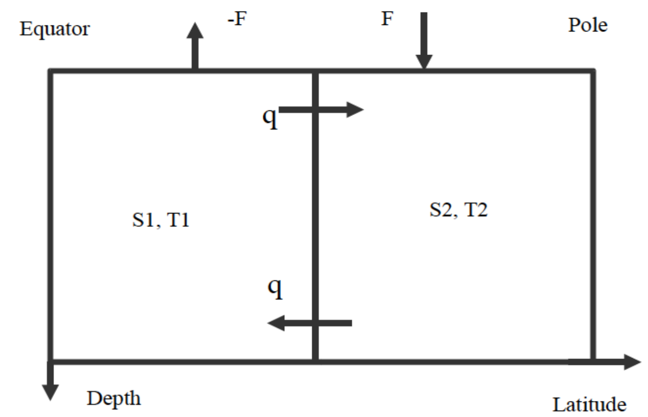
Credits: WIRE Climate Change

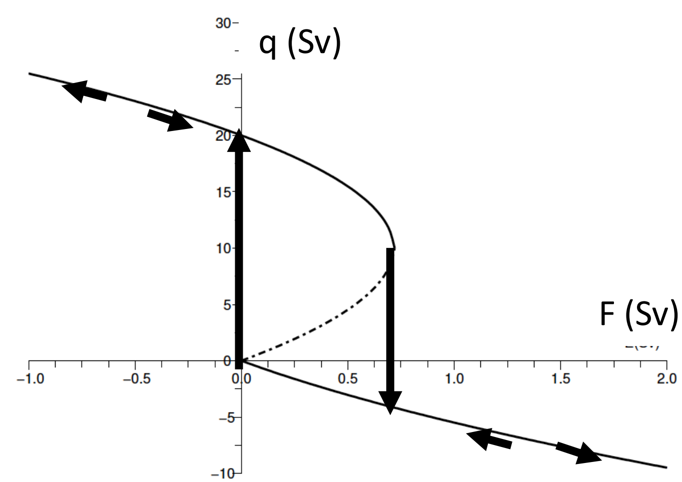
Masson-Delmotte et al. 2012

Non linearity of the Atlantic Overturning (AMOC)?



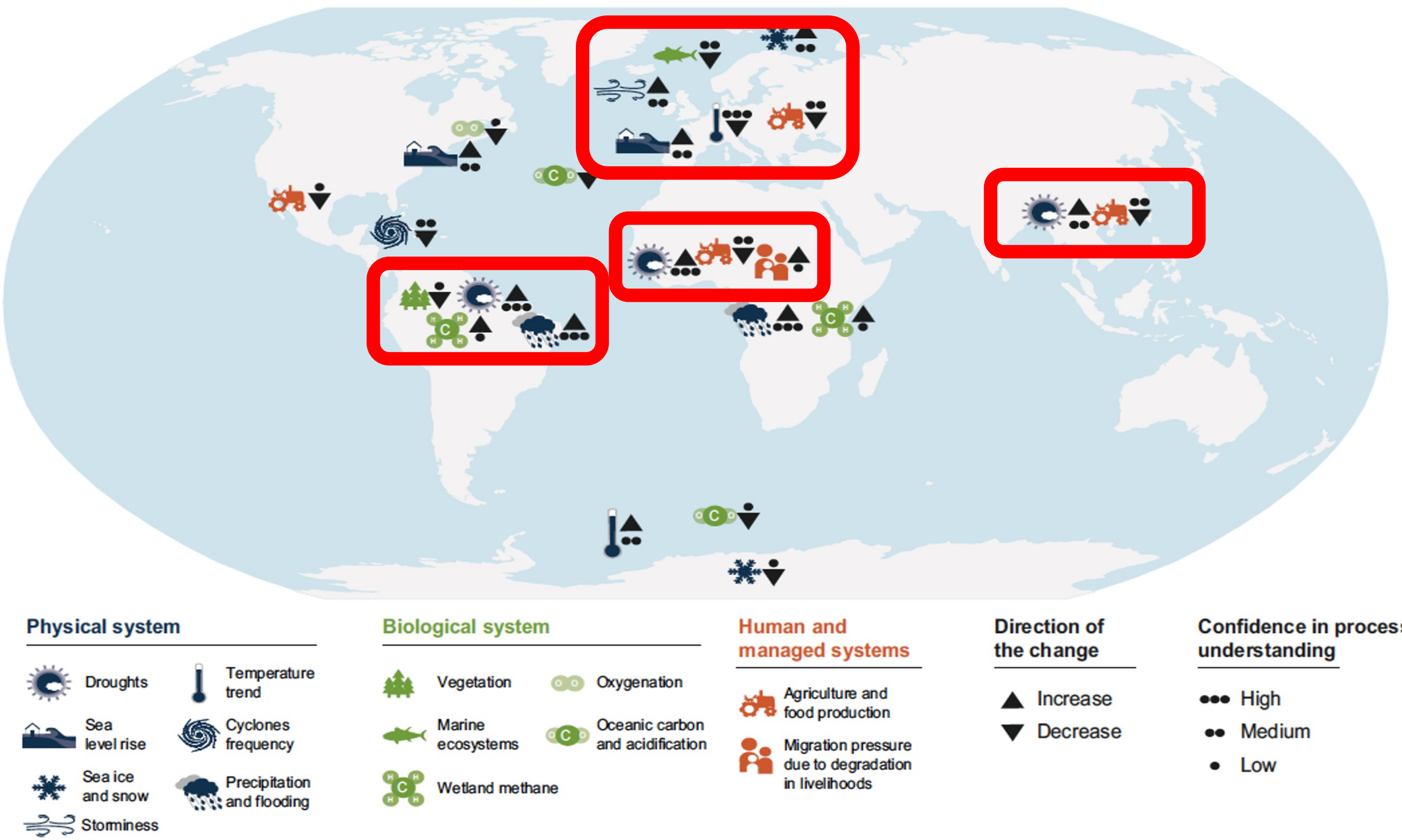
- Stommel (1961) early showed that the AMOC may exhibit strongly non-linear response to surface freshwater forcing
- His simple analytical model showed that the AMOC may have multiple solutions for a given freshwater forcing and hysteresis behavior
- Still true in higher resolution models (cf. Rahmstorf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





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

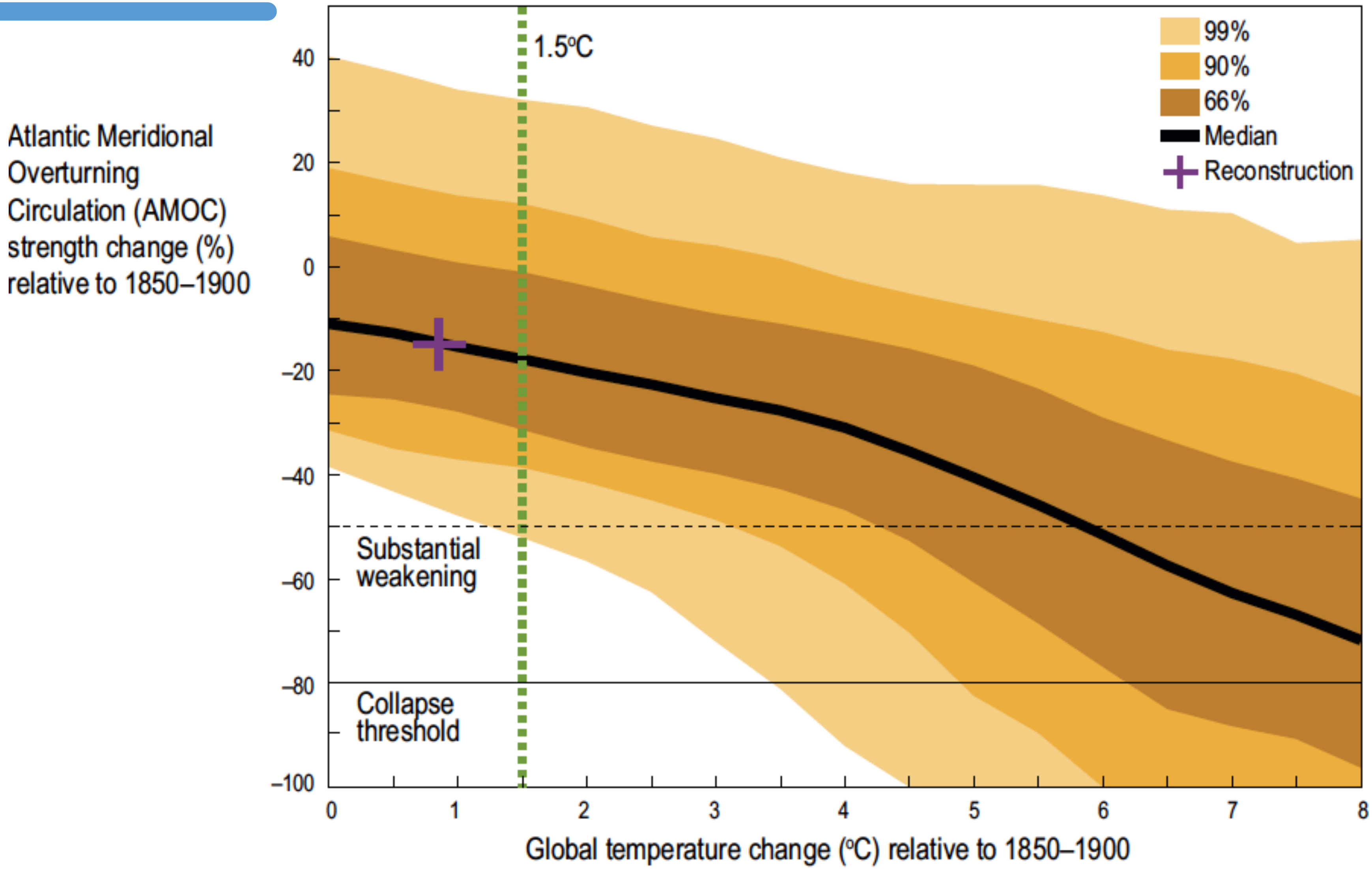
Large-scale impact of a substantial weakening in the Atlantic circulation



IPCC
INTERGOVERNMENTAL PANEL ON climate change

Fig. 6.10 from IPCC SROCC report, 2019

Risk of AMOC substantial weakening



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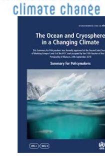
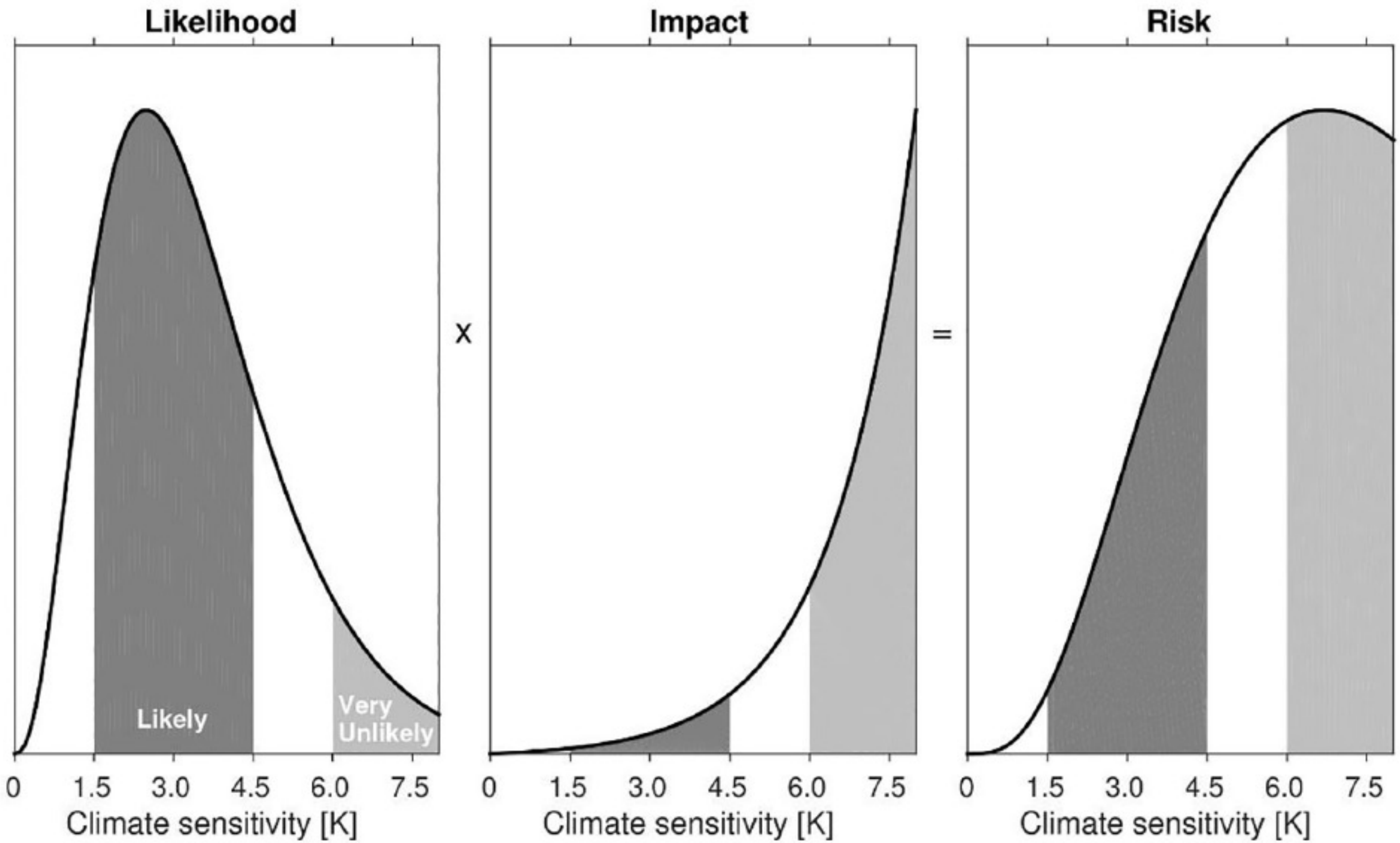


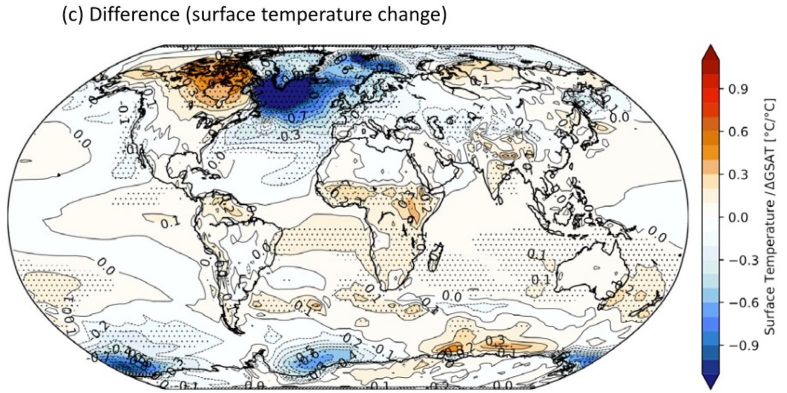
Fig. 6.9 from IPCC SROCC report, 2019

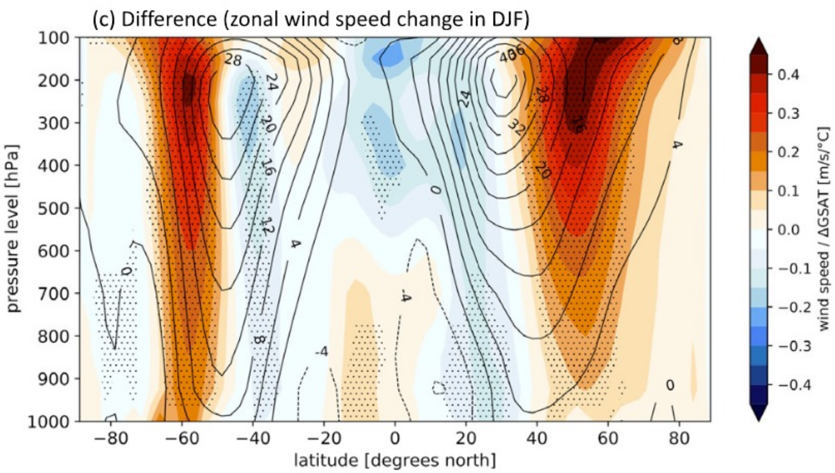
Low probability-high impact event

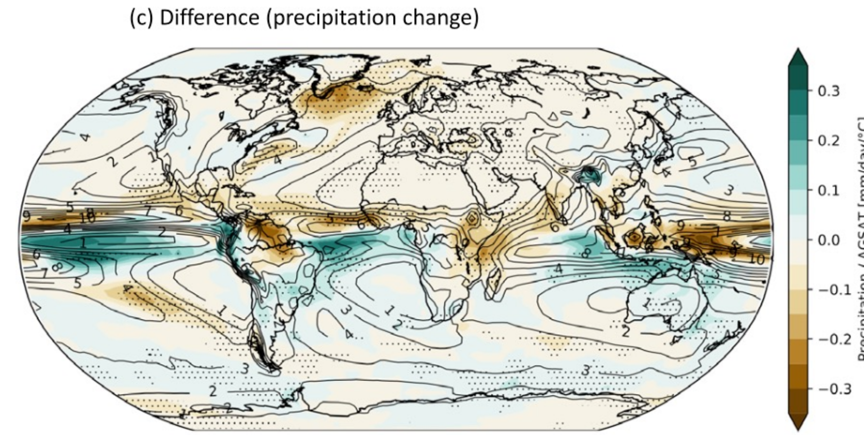


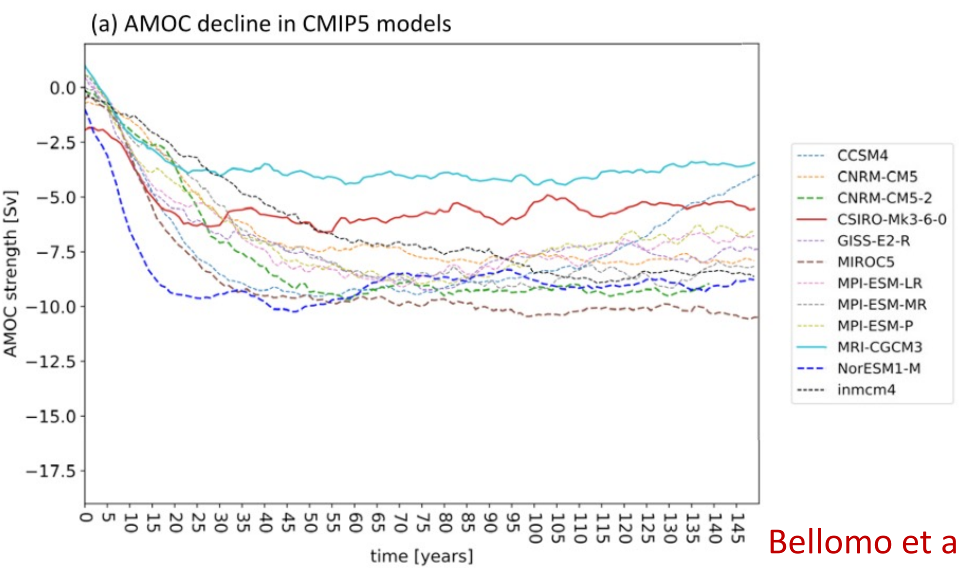
Sutton 2018

Still so much AMOC uncertainty in CMIP6

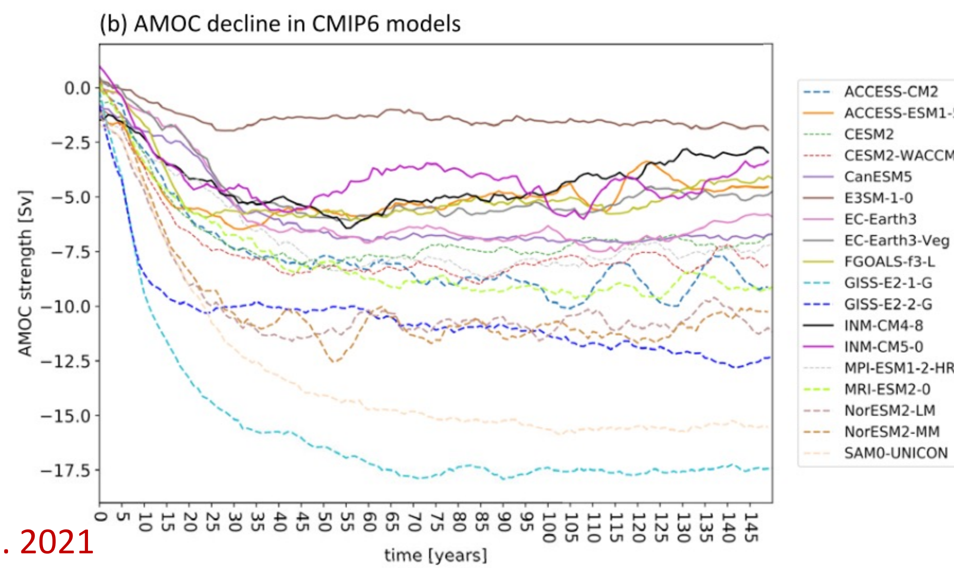






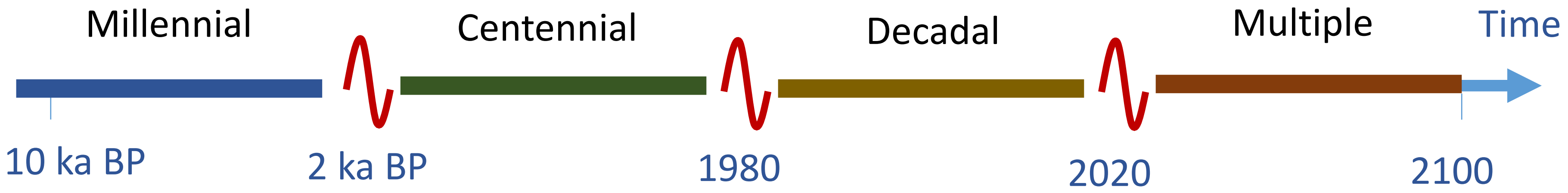


Bellomo et al. 2021



Key questions

- **How has evolved the millennial AMOC since the beginning of the Holocene? And what might be the main drivers?**
- **Is the AMOC moving towards a tipping and what is causing its weakening over the recent period (if any)?**
- **Is the impact of GrIS melting now well represented?**
- **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…

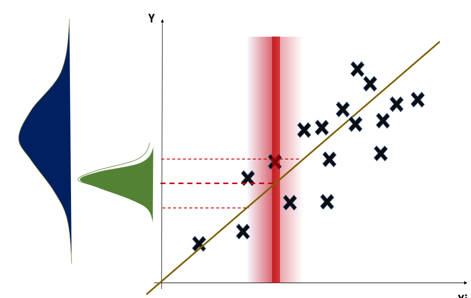
  - Instrumental ones since about 1850

  - Paleo data and pseudo-proxy approaches

- Database from climate Model Intercomparison Projects (CMIP)

WCRP CMIP6
World Climate Research Programme

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



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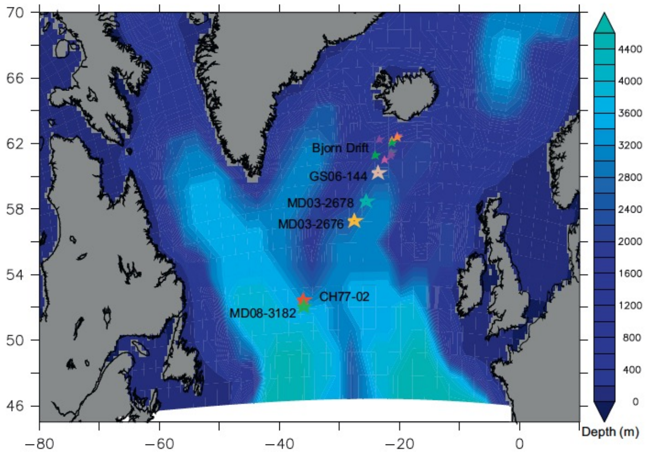
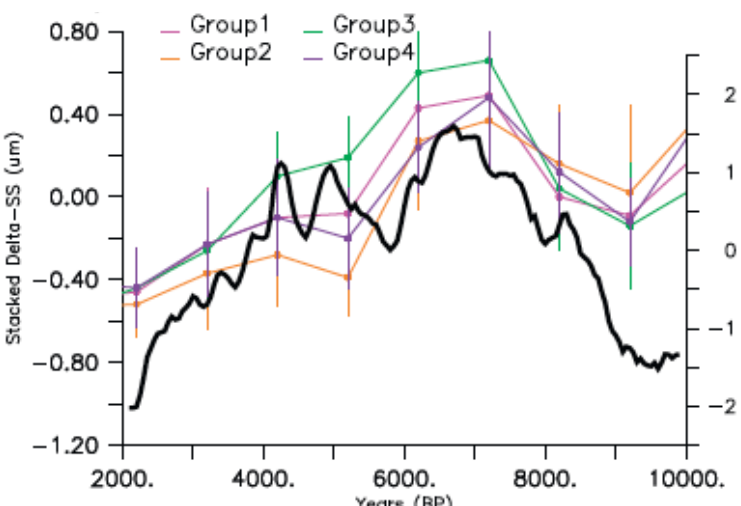
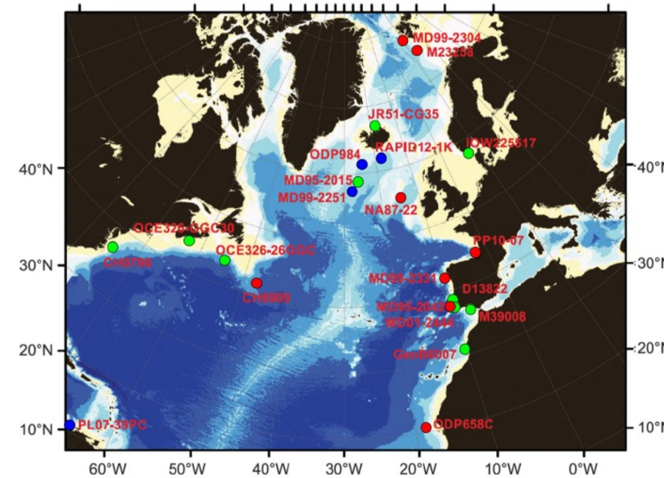
A new AMOC reconstruction over the Holocene

- Use of 22 sediment cores with SST proxy records (Eynaud et al. 2017)
- Use of EOF analysis to find consistent variability (Ayache et al.2018)





Ayache et al. (2018)

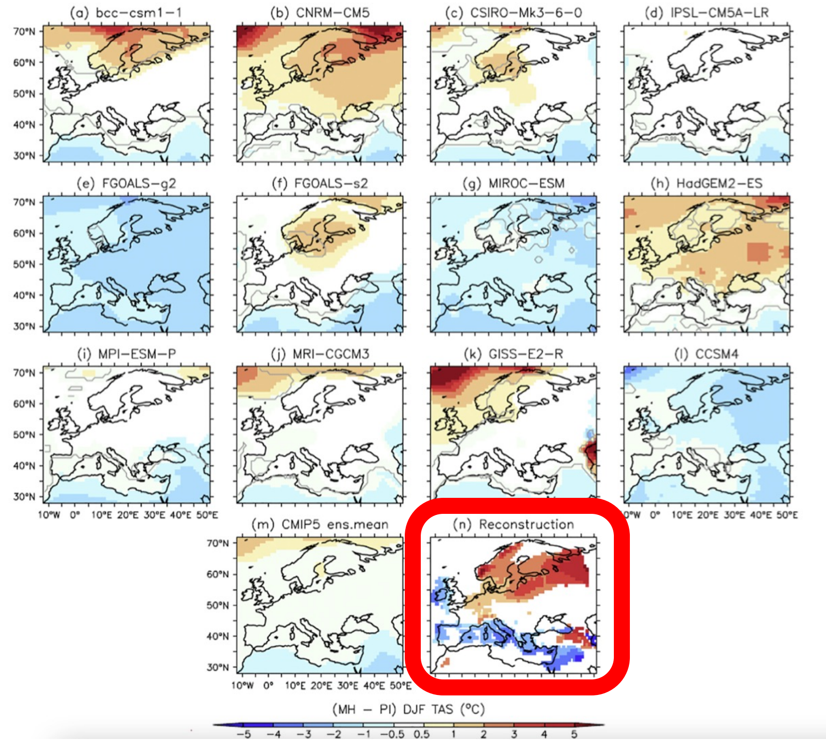


Eynaud et al. (2017)

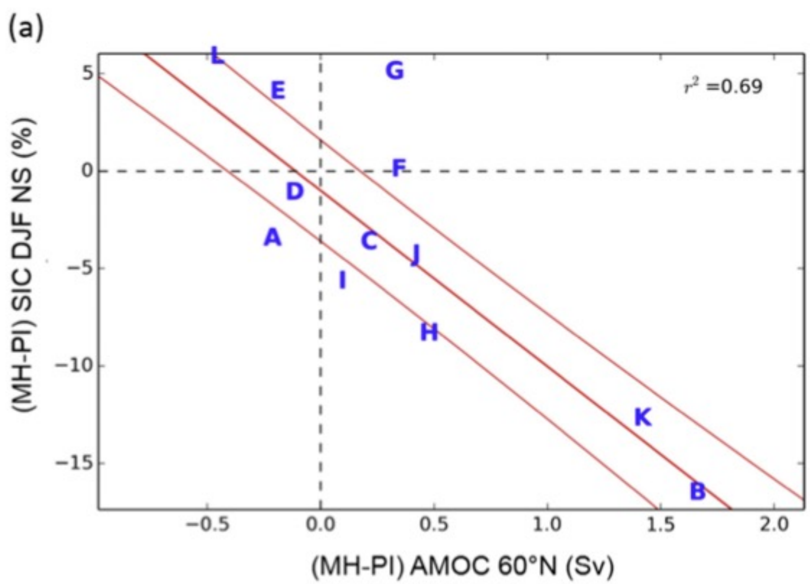
- Validation using pseudo-proxy (does the method work in the model "world"?)
- Validation using independent of deep ocean circulation, glaciers' evolution…
- Calibration in Sverdrup using NH hemisphere reconstruction (Jomelli et al., *Nat. Com.*, 2022)

What is causing the maximum at the mid-Holocene?

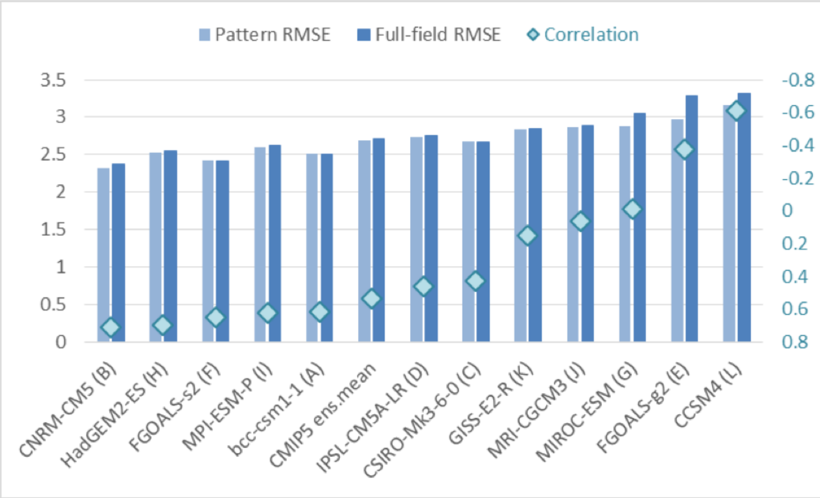
A stronger AMOC at the mid-Holocene?



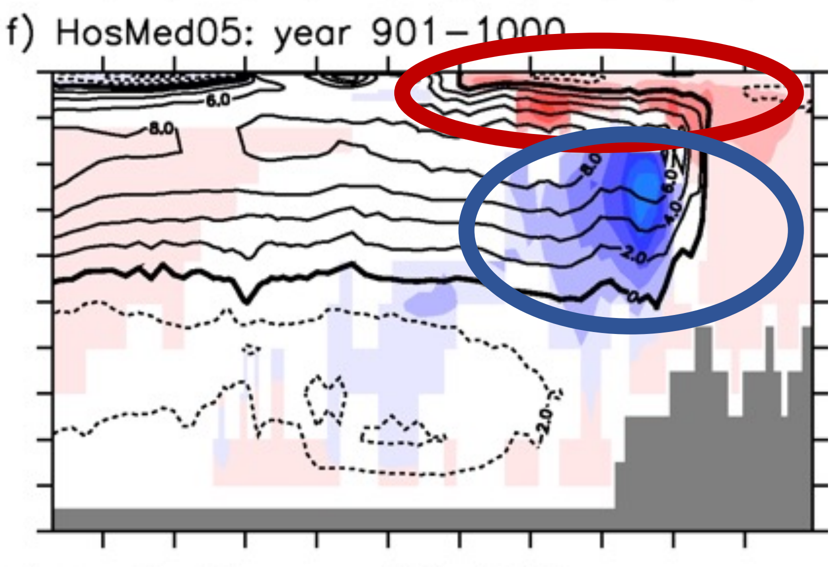
- Born et al. (2011): this is because less sea ice is formed and transported in the SPG at 6 ka BP
- Gainusa-Bogdan et al. (2021): the spread in AMOC response might explain the spread in T2M response over Europe In PMIP
- **An emergent constraint?**

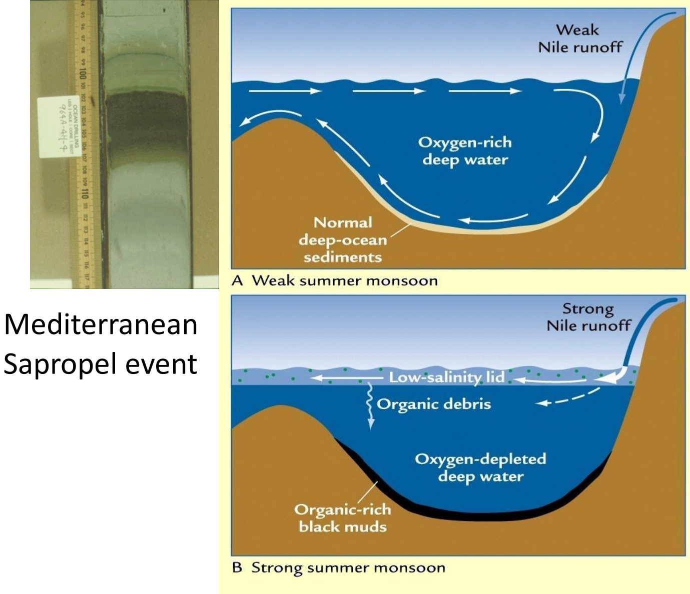


➢ « Best models » are the ones with largest AMOC enhancement

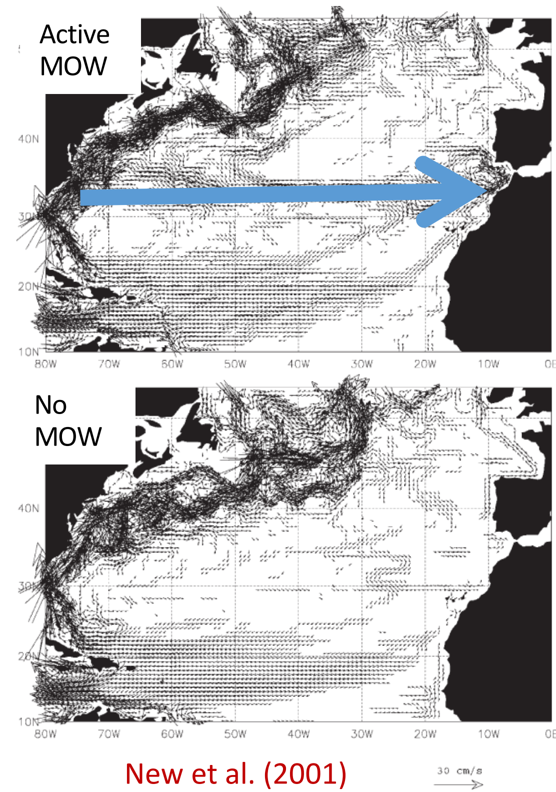


A new mechanism to explain the weakening of the AMOC from 6 ka





Mediterranean Sapropel event



1) No MOW: direct impact on density distribution in the ocean

⇒ Lower zonal density gradient at depth (≈500-1500m)

⇒ Thermal wind relationship: **weakened AMOC at depth**

2) No MOW: impact on subtropical gyre geometry

⇒ Increased subtropical surface water transport in the North Atlantic

⇒ Increased surface salinity and convection in the North Atlantic

⇒ **Increased AMOC and subpolar gyre**

Swingedouw et al. (*Clim. Dyn.*, 2019)

New et al. (2001)

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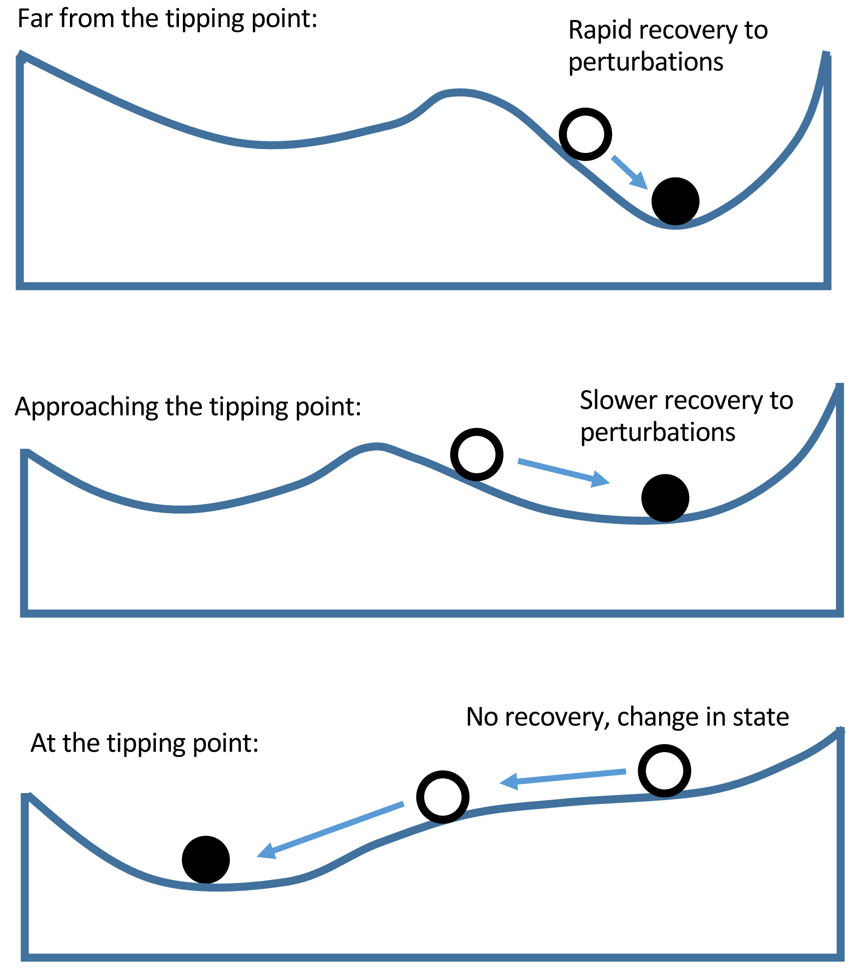
How to have early warnings of a potential abrupt change?

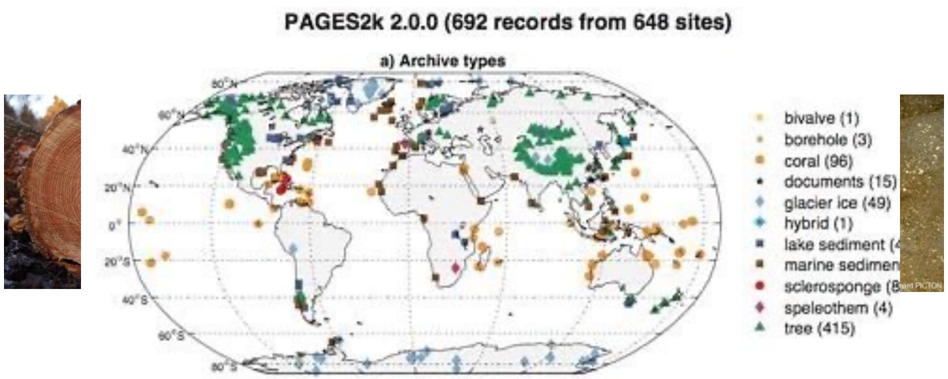
- Theory from dynamical system teaches us that approaching a tipping point, the system variability tend to increase
- Boulton et al. (2014) : we need **at least 250 years** to be able to apply to AMOC
- Bowers et al. (2021) : we are approaching a tipping point (but using AMOC fingerprints **over only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

Change of temporal variability when approaching a tipping point



Adapted from: Lenton 2011

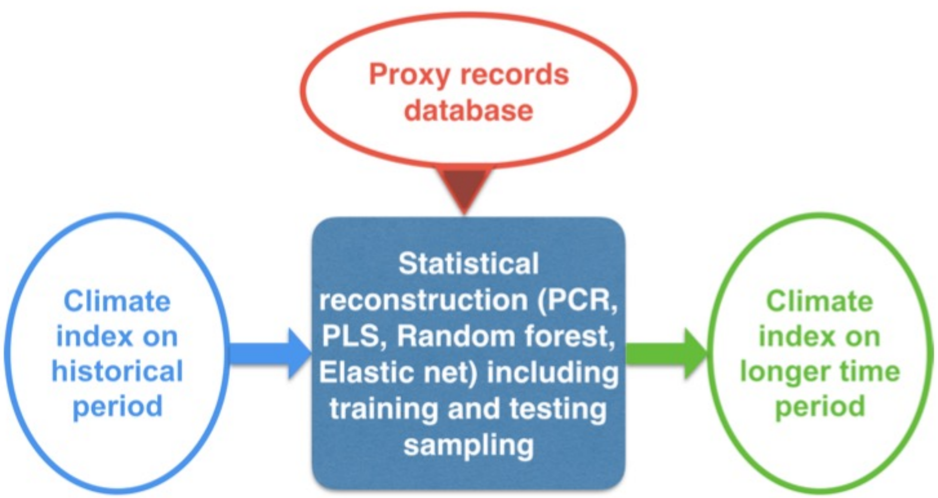
Proximity to an AMOC tipping point?



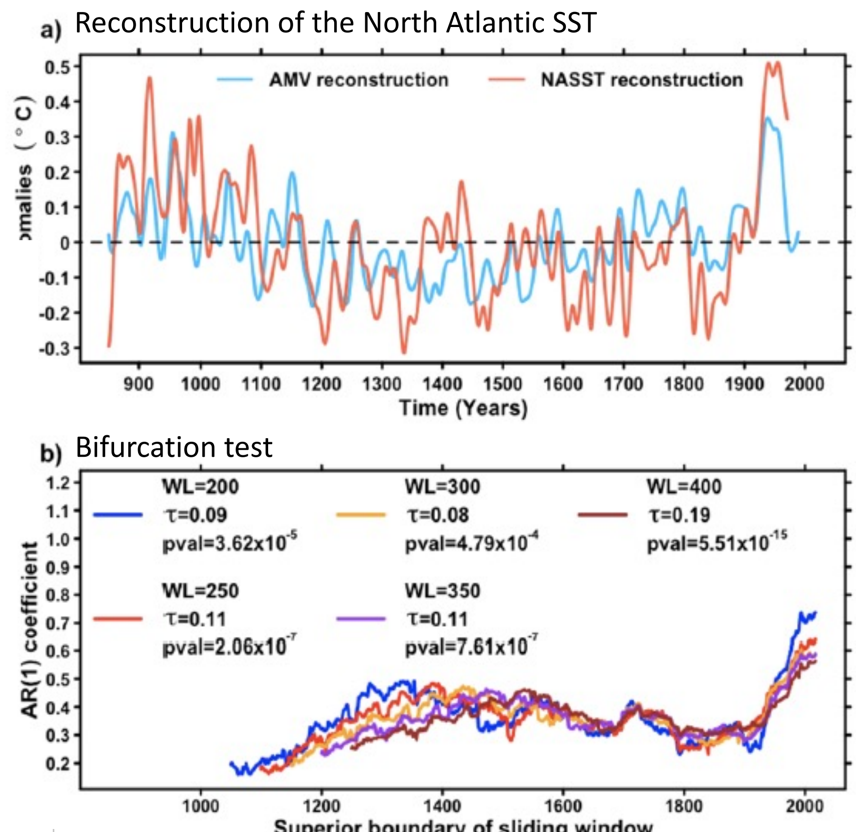
Geoscientific Model Development

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]



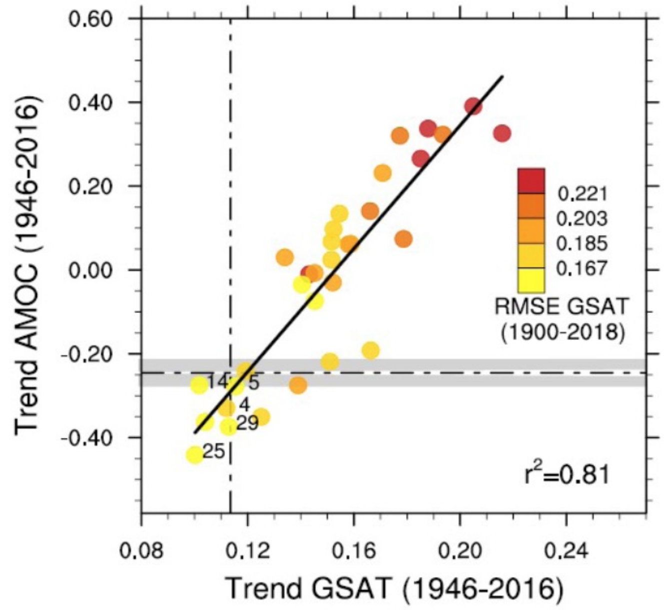
AMV reconstruction as a proxy of AMOC internal variability



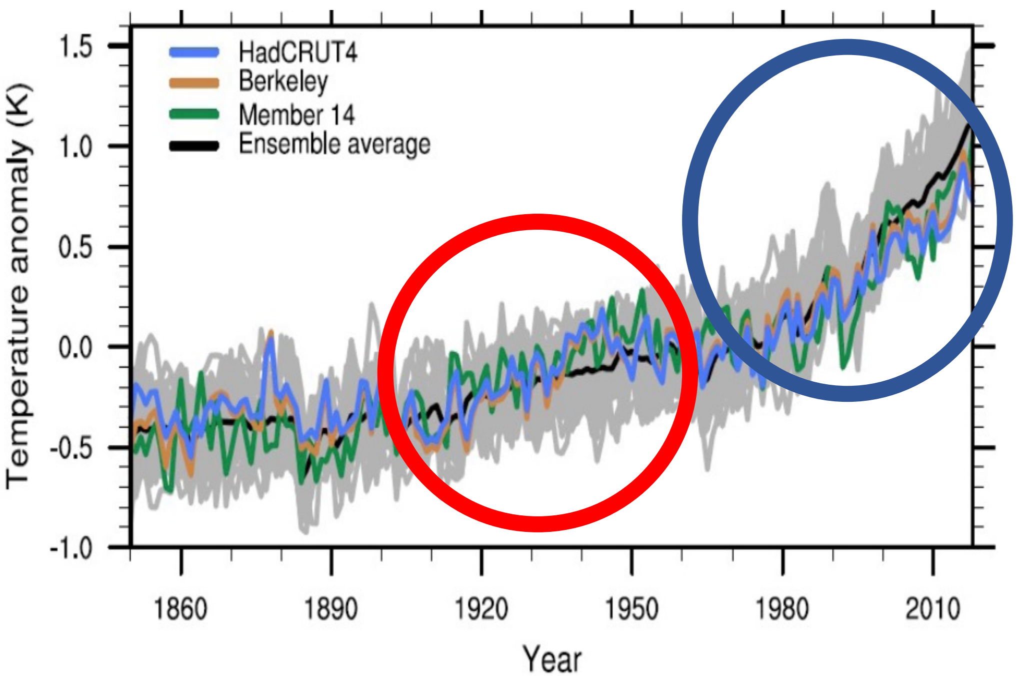
Michel et al., in rev..

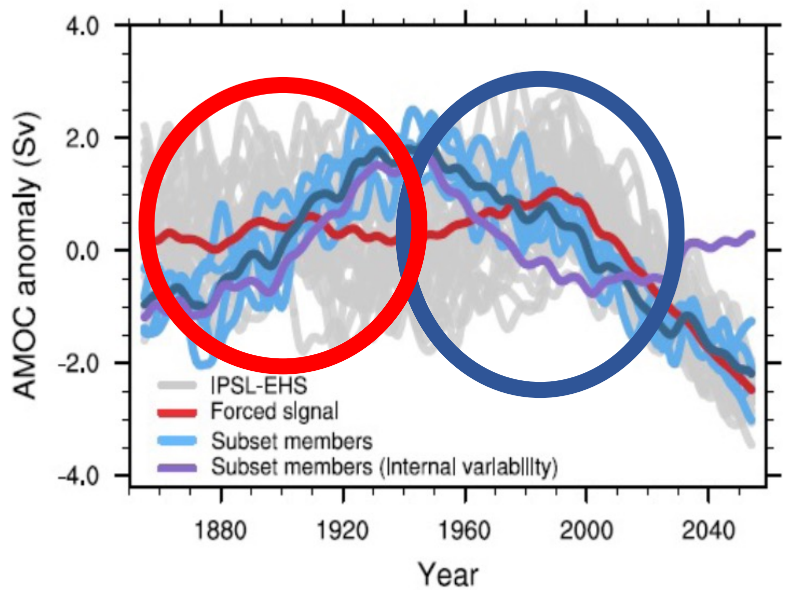
AMOC internal variability and climate sensitivity

- What is causing the AMOC weakening?
- Can it affect climate sensitivity estimates over the last century?



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

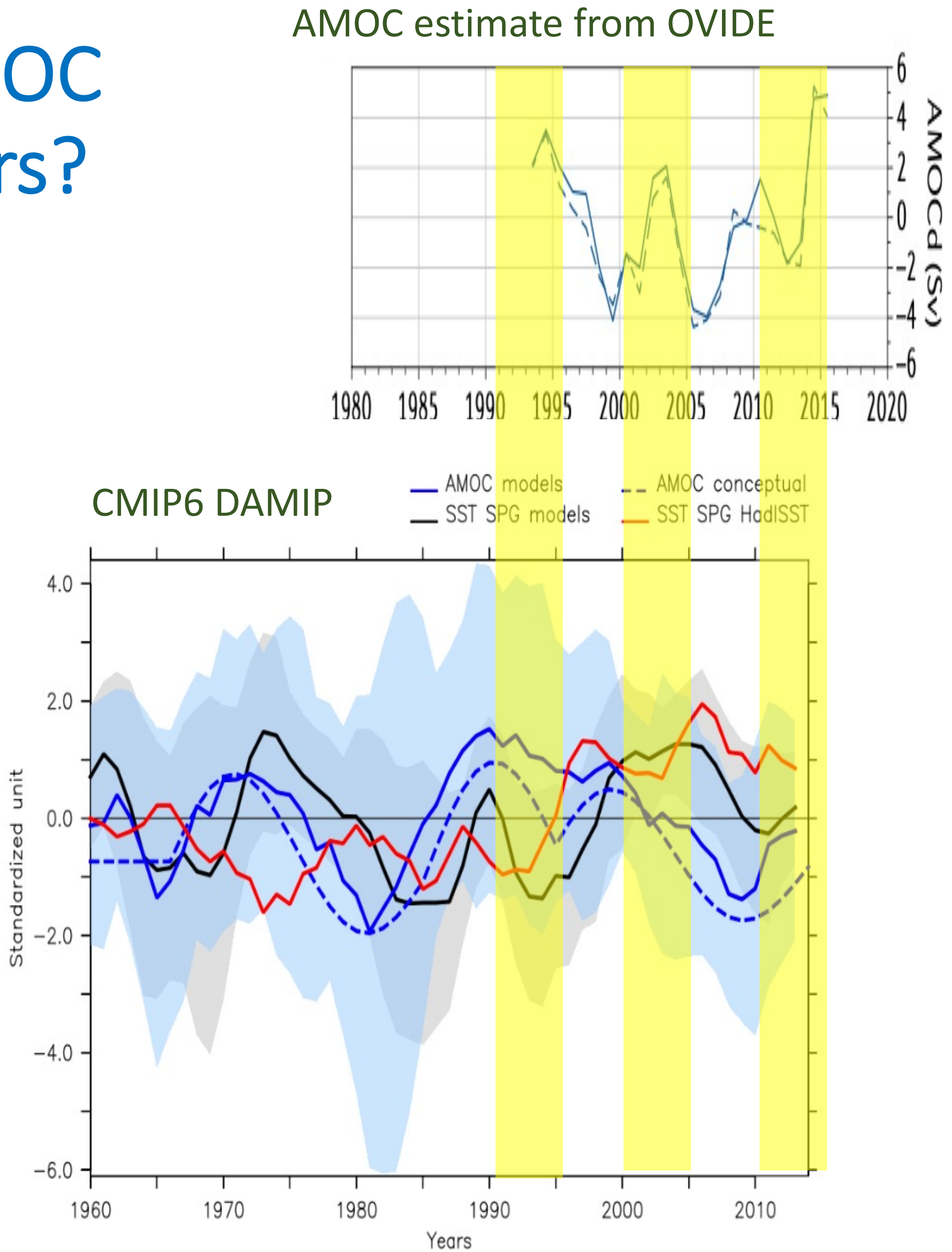




Bonnet et al., *Nat Com.*, 2021

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 timesclae (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 eruption response (cf. Swingedouw et al., 2015).
- Still at play in CMIP6 Detection-Attribution ensemble (Borchert et al., *GRL*, 2021)

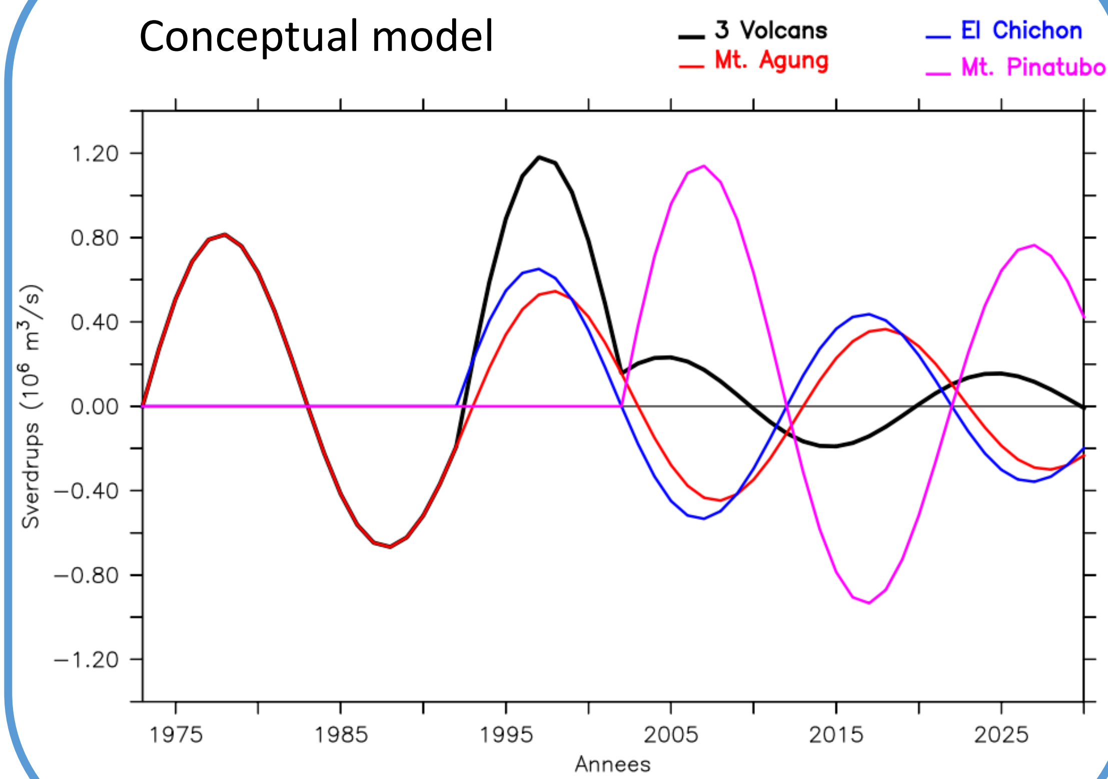


EUCP European Climate Prediction system

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., *Nat. Com.*, 2015)
- It fits well with Great Salinity anomalies timing since the late 1960s
- It is partly validated using paleo-data (but not with all of them… thus, more is requested to further validate this hypothesis)

AMOC response to volcanoes



ANR Greenland

SPECS

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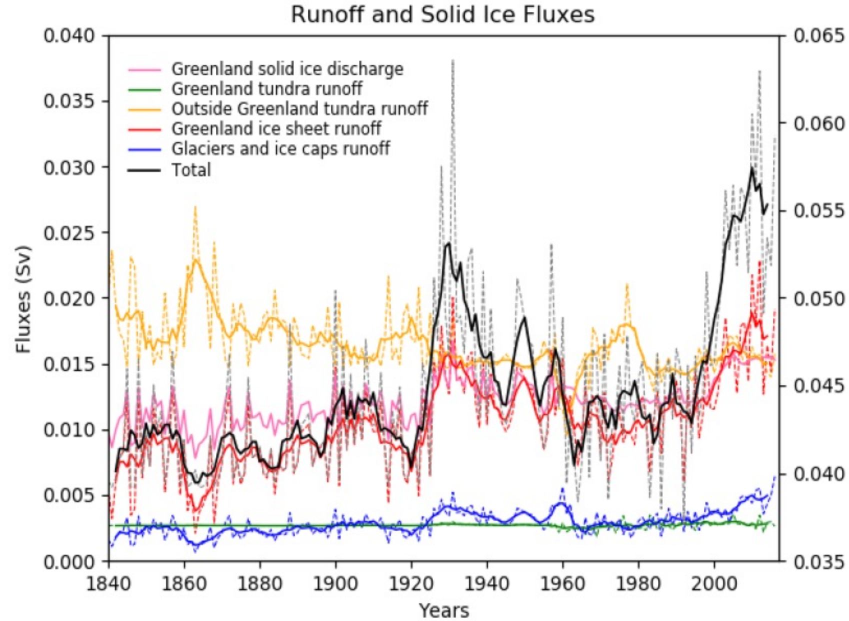
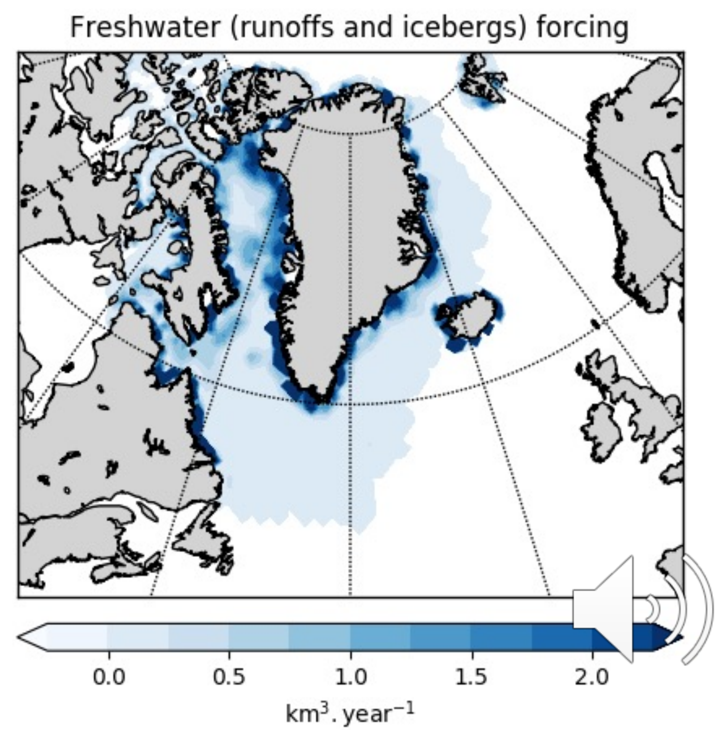
What about GrIS melting?

- Use of Bamber et al. (2018) recent reconstruction
- Extension 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**)
- Comparison with historical simulations from IPSL-CM6A-LR starting from same initial conditions (**Historical ensemble**)

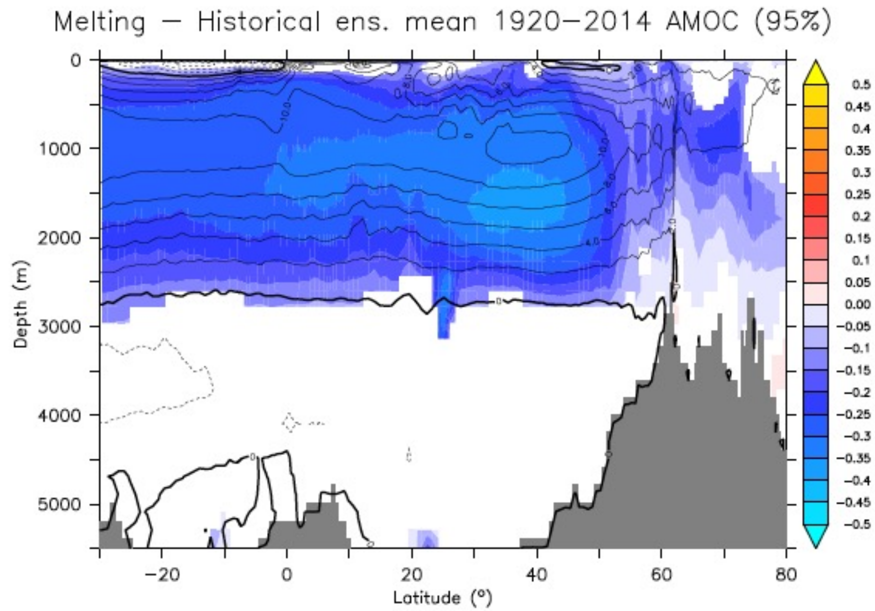




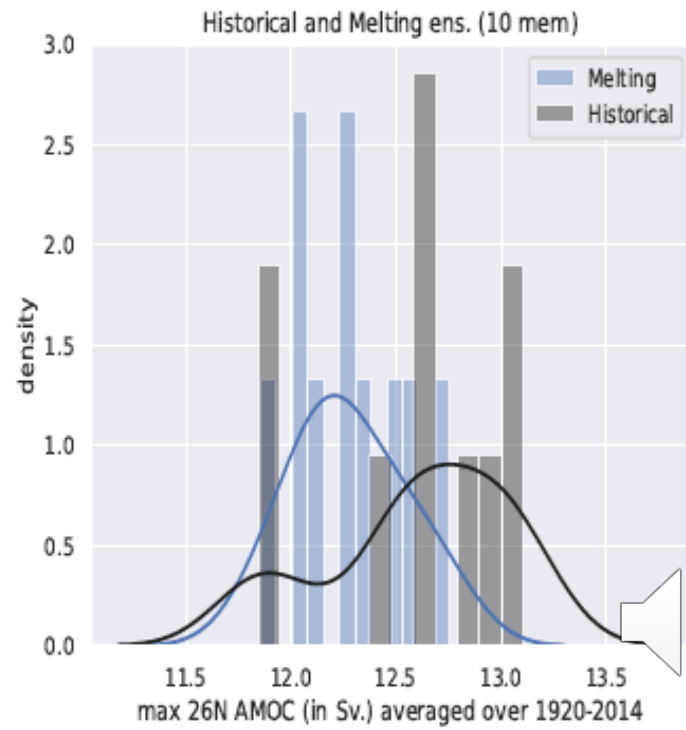
Devilliers et al. 2021

BLUE ACTION

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)



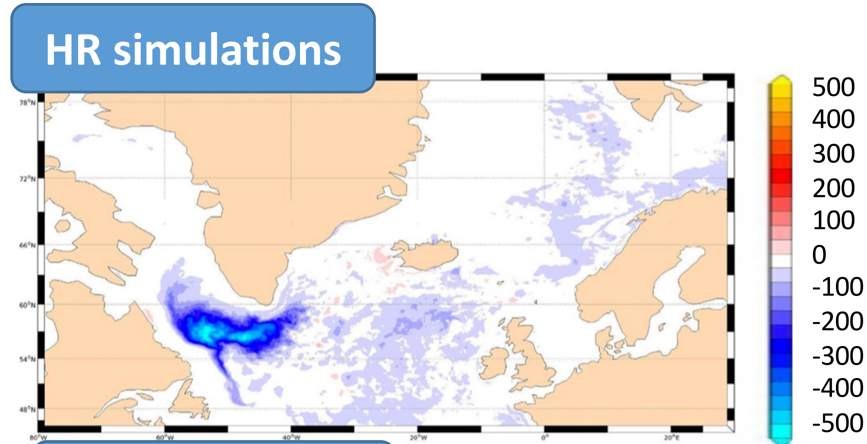
Devilliers et al. 2021

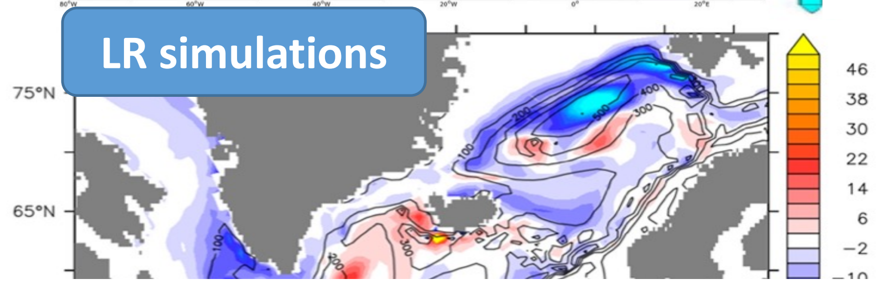
BLUE ACTION

Impacts of oceanic resolution on GrIS impact

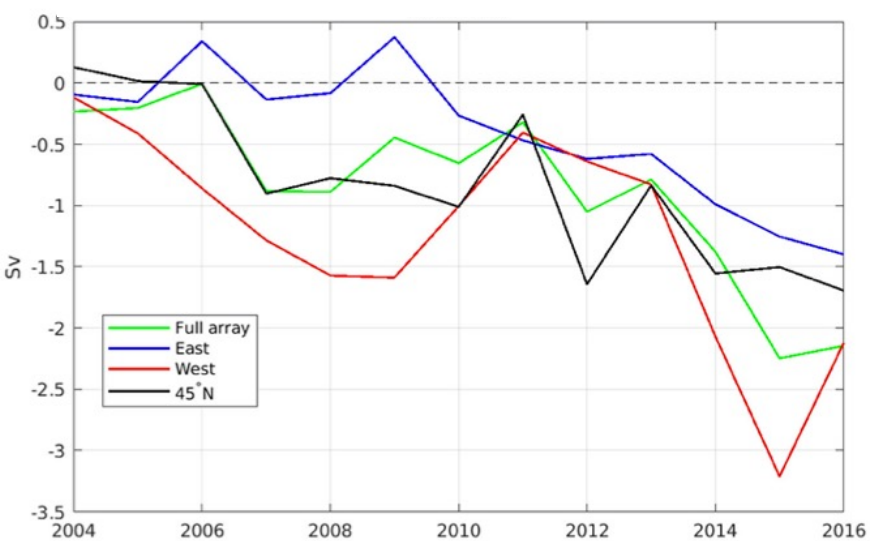
- We compare IPSL-CM6A Low Resolution (**LR, 50-60 km**) run with very High Resolution (**HR, 2-3 km**) simulations from an ocean-only model (Swingedouw et al., Frontiers, 2022
- Higher impact of Greenland melting on the AMOC in the HR runs

Mixed layer depth anomalies

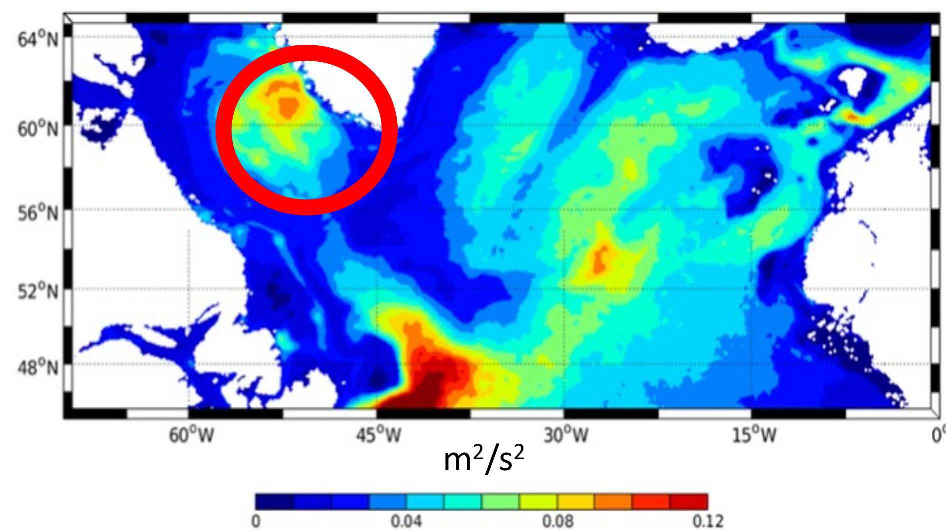




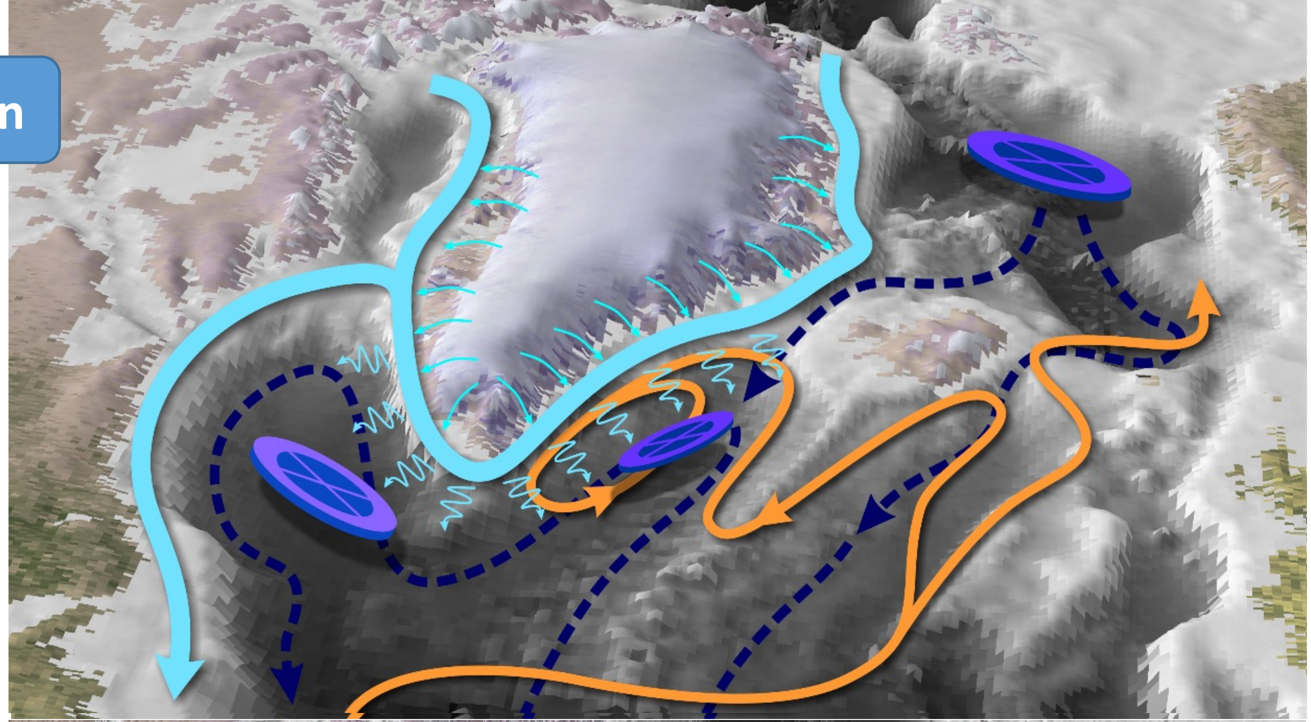
AMOC anomalies in HR simulations



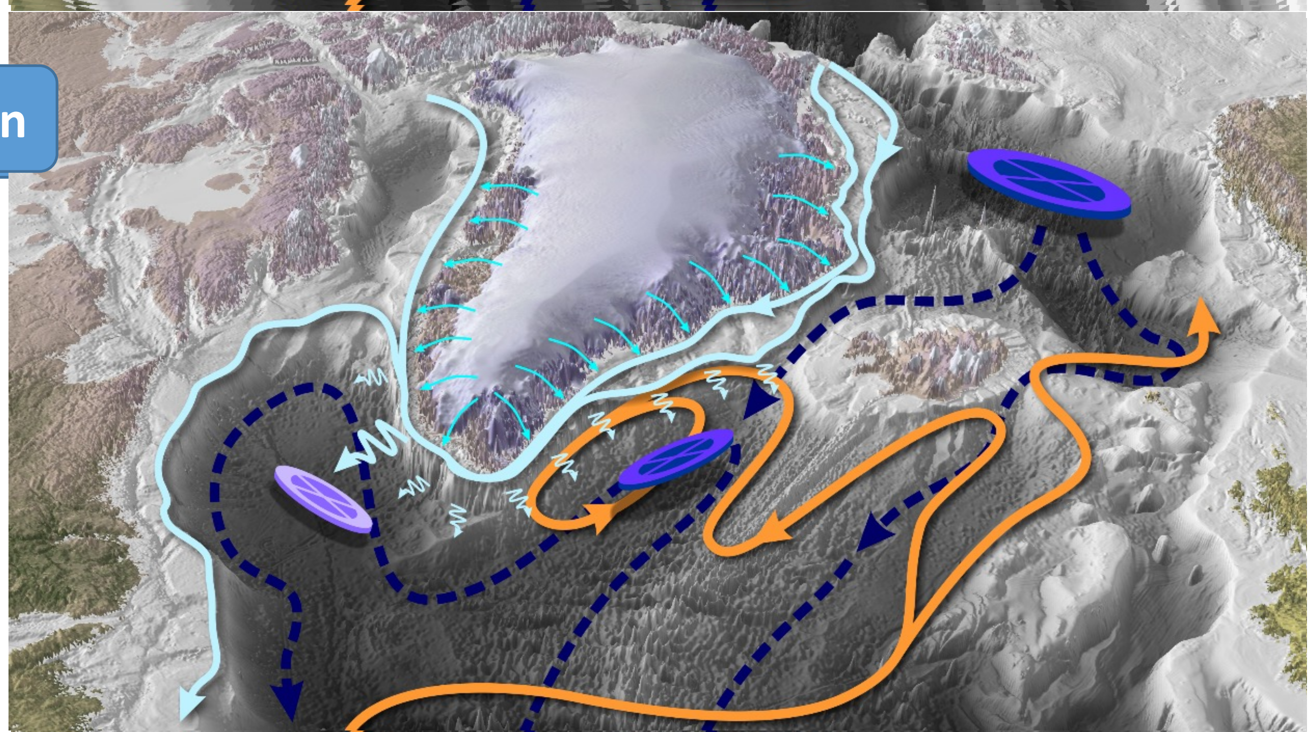
Eddy Kinetic energy in HR simulation



Low Resolution



High Resolution



Courtesy of
Vincent Hanquiez

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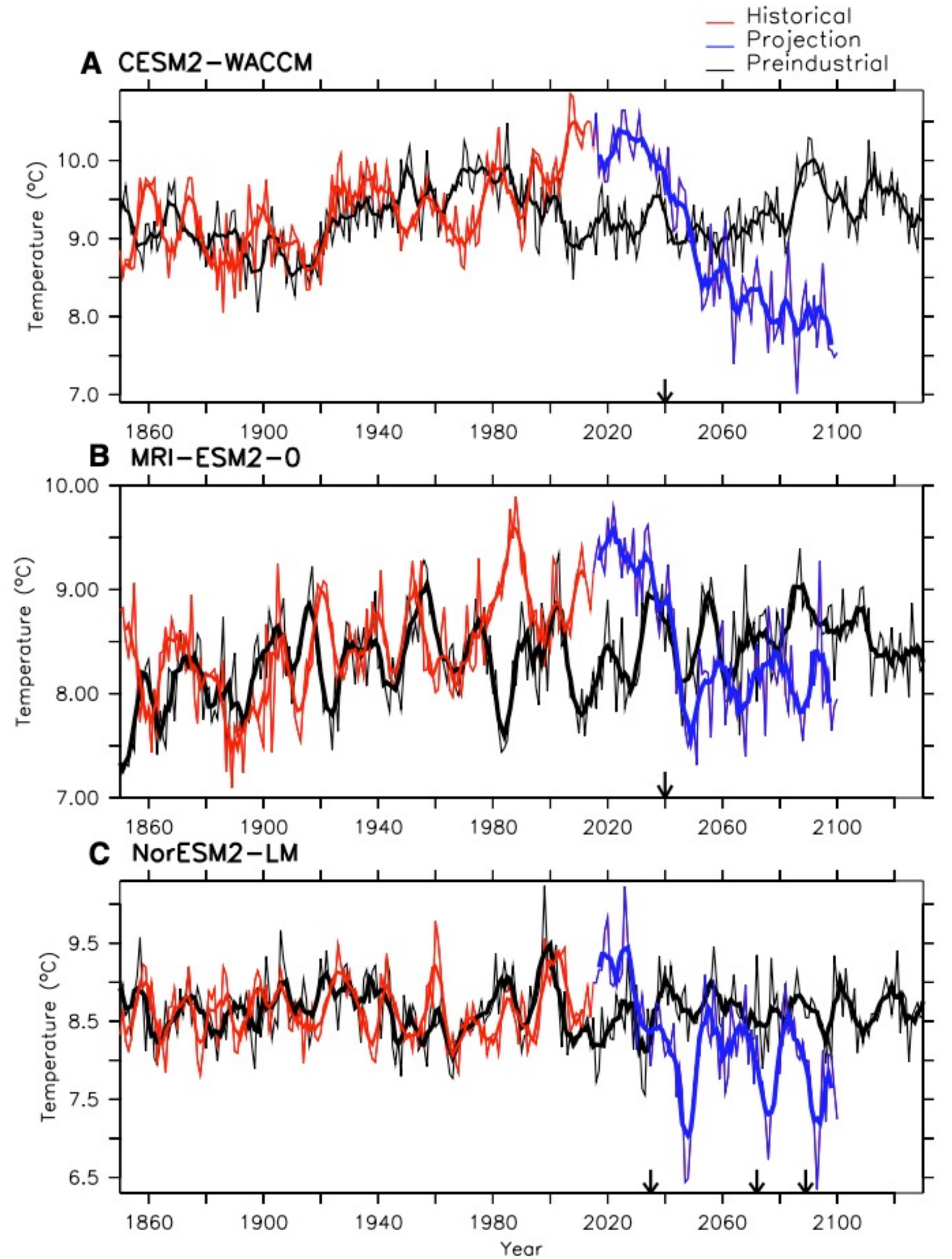
Possibility of Abrupt C North Atlantic in clima

- Some CMIP models do show abrur cooling in the subpolar gyre (SPG)

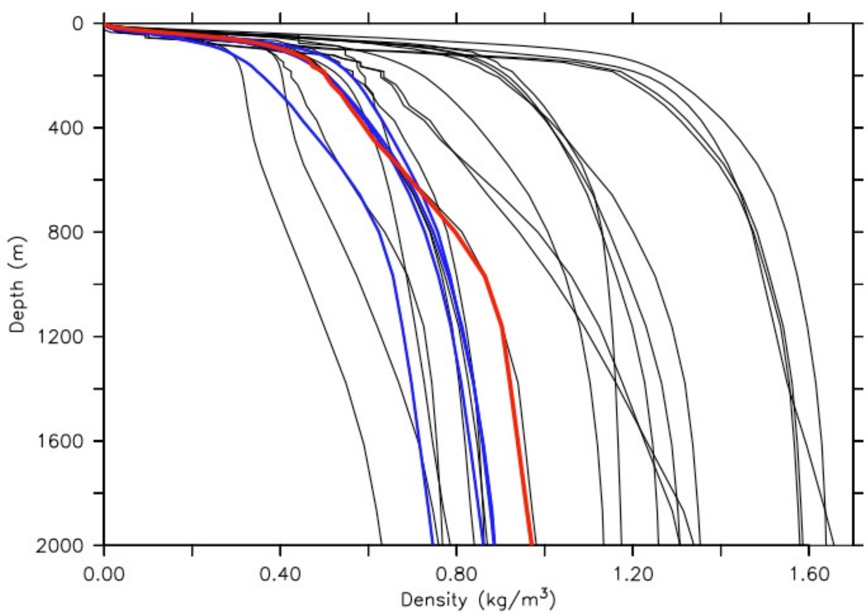
- Two different processes
  - Disruption of the AMOC (strong decrease of convection both in the Labrador and Nordic Seas)
  - Collapse of convection in the Labrador Sea : can occur in only one decade => **the SPG as a new tipping element**
- This was true in CMIP5 (Sgubin et al. 2017) and is still the case in CMIP6 for SPG collapse (Swingedouw et al. 2021)

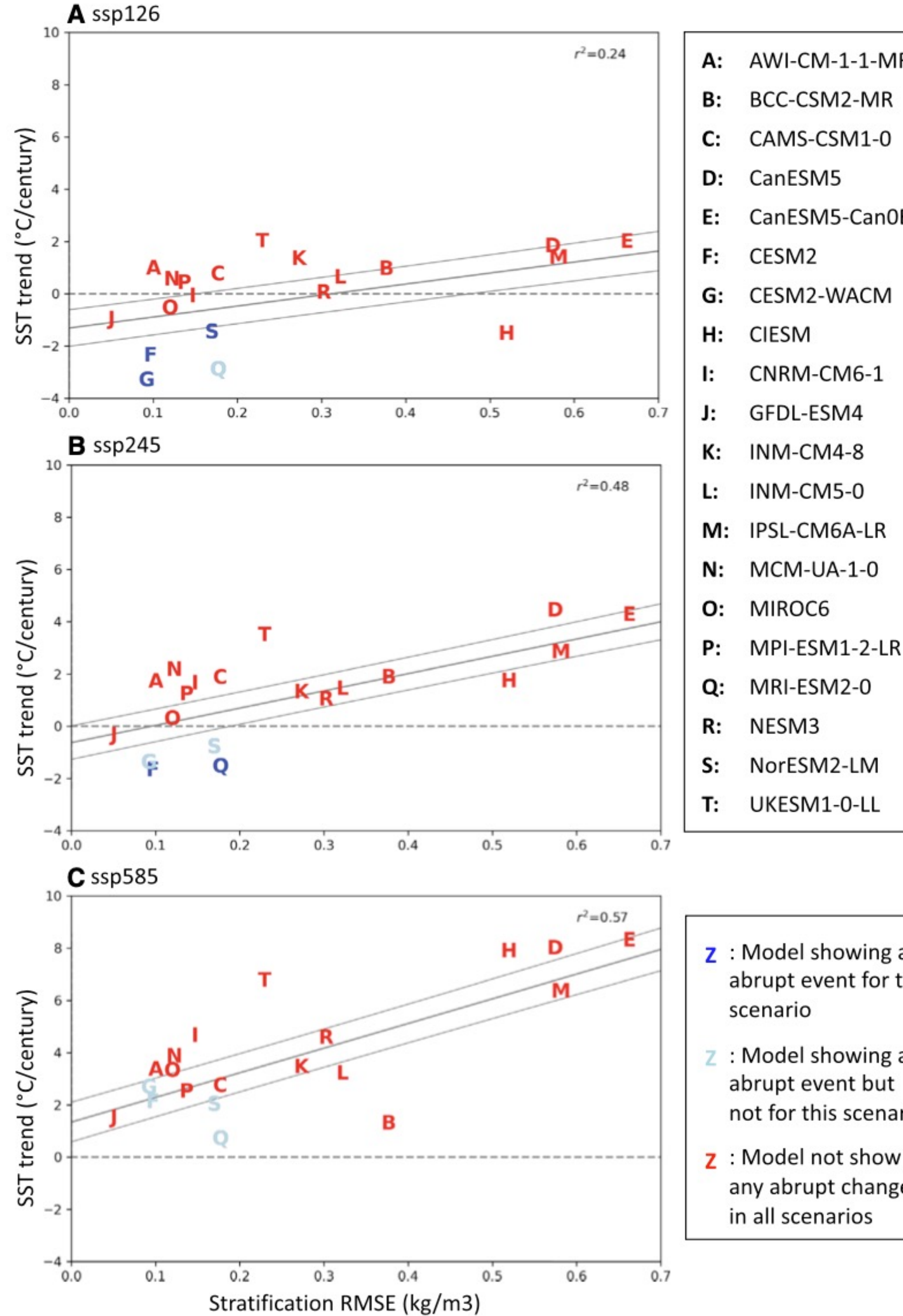


Sgubin et al. 2017, Swingedouw et al. 2021

SPG stratification as an Emergent constraint

- Stratification in the SPG is a key component of convection process
- Models showing abrupt changes are, on average, better than the ones showing no abrupt change
- 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)**

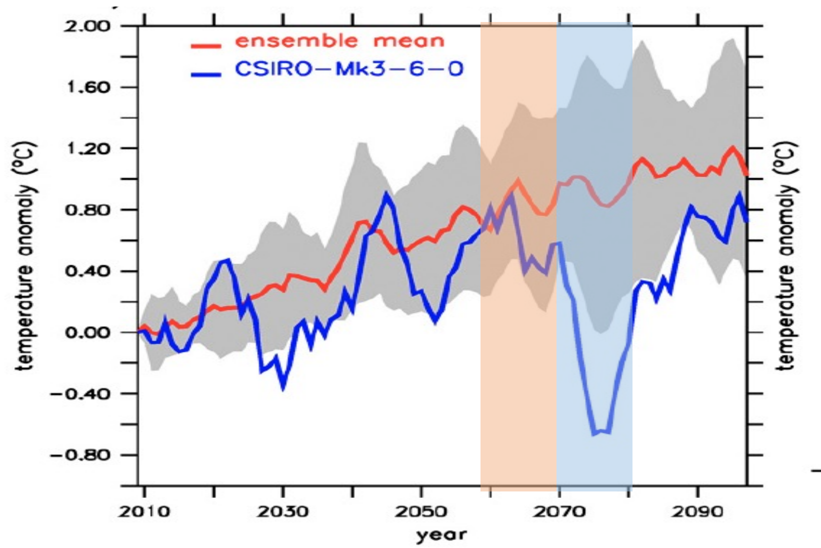




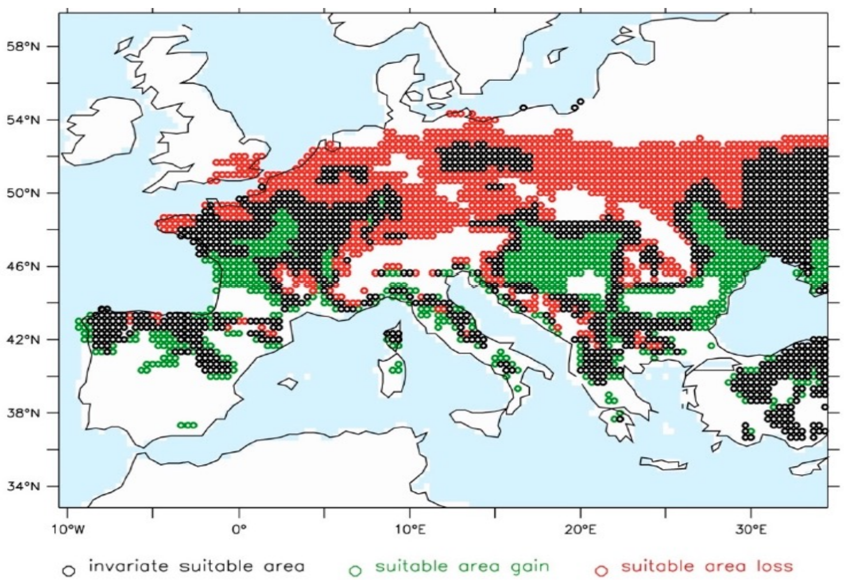
Impacts of abrupt decadal cooling

- 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

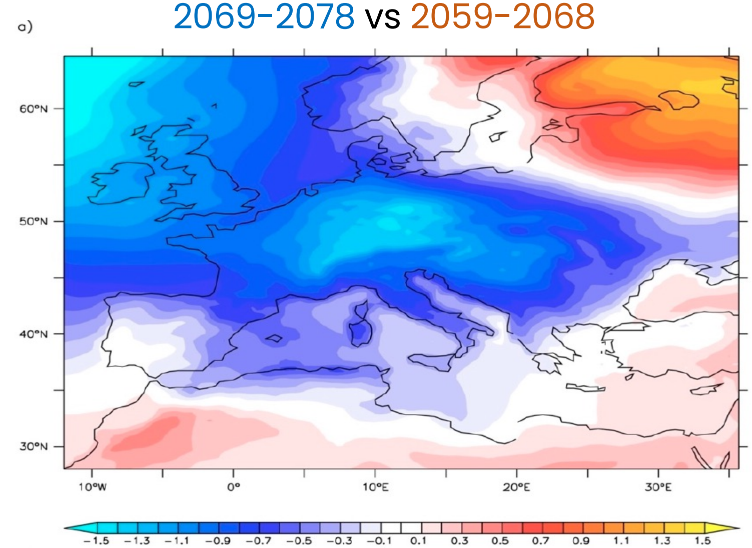


Suitability of Chardonnay
2069-2078 vs 2059-2068



Sgubin et al. (2019)

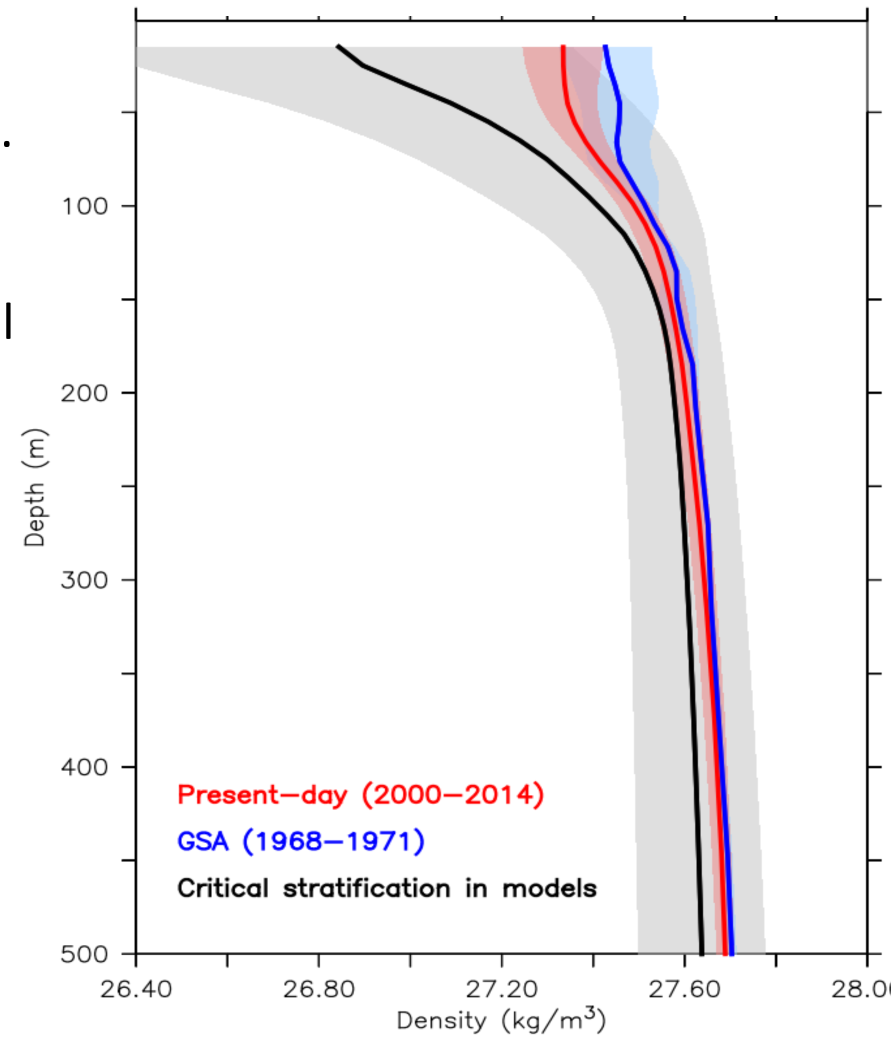
Temperature difference
2069-2078 vs 2059-2068



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
  - Avoid drift when launched from the observed ocean
- Need for further **reconstructions of the last few thousands of years** to have better insights on “natural variability” and 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

- The AMOC have largely shaped climate variability over the Holocene
- 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!