

Likelihood and impacts of a collapse of the SPG in CMIP models: can we have any confidence in them?

Didier Swingedouw

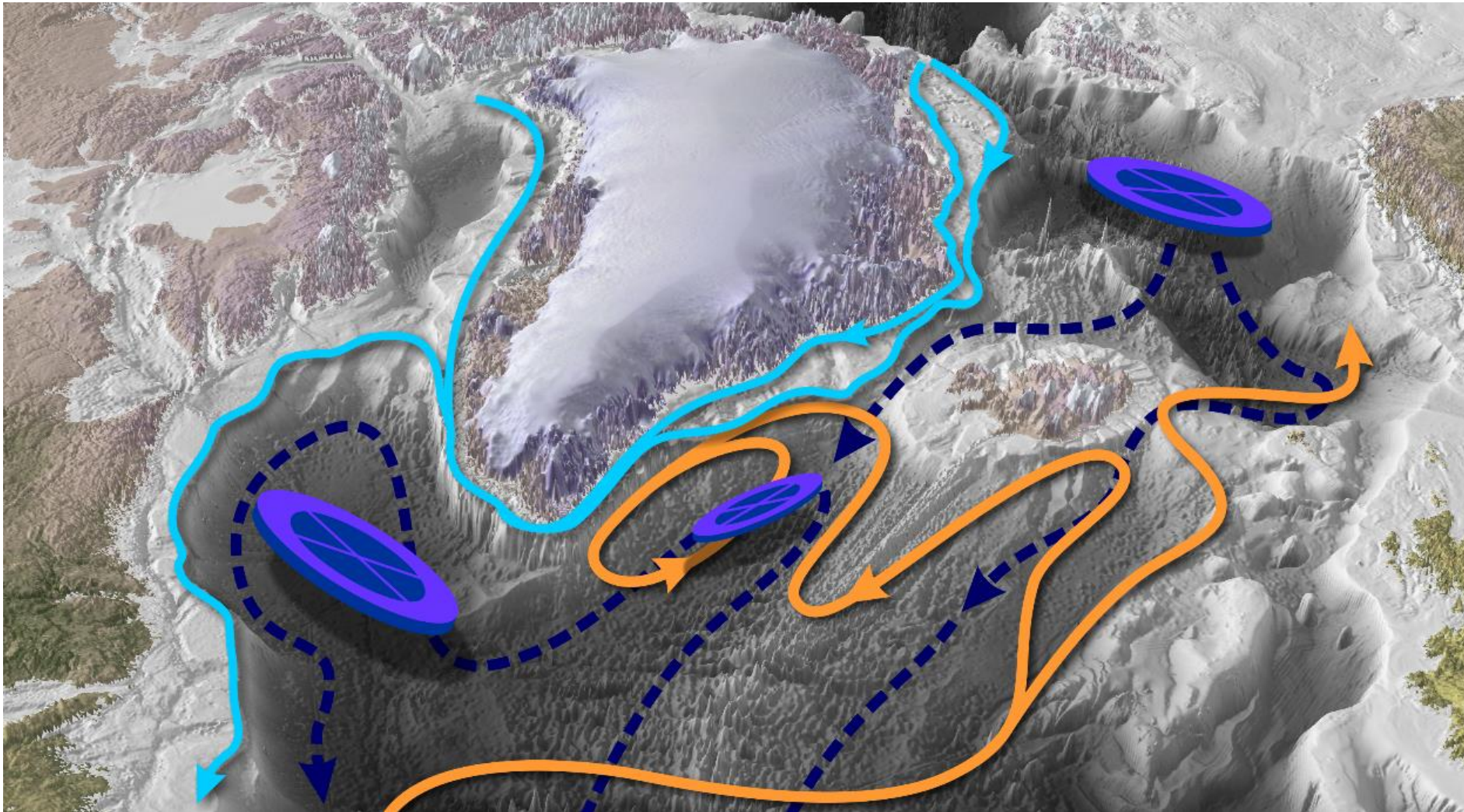
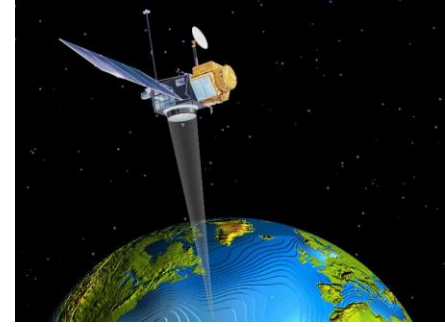
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EPOC

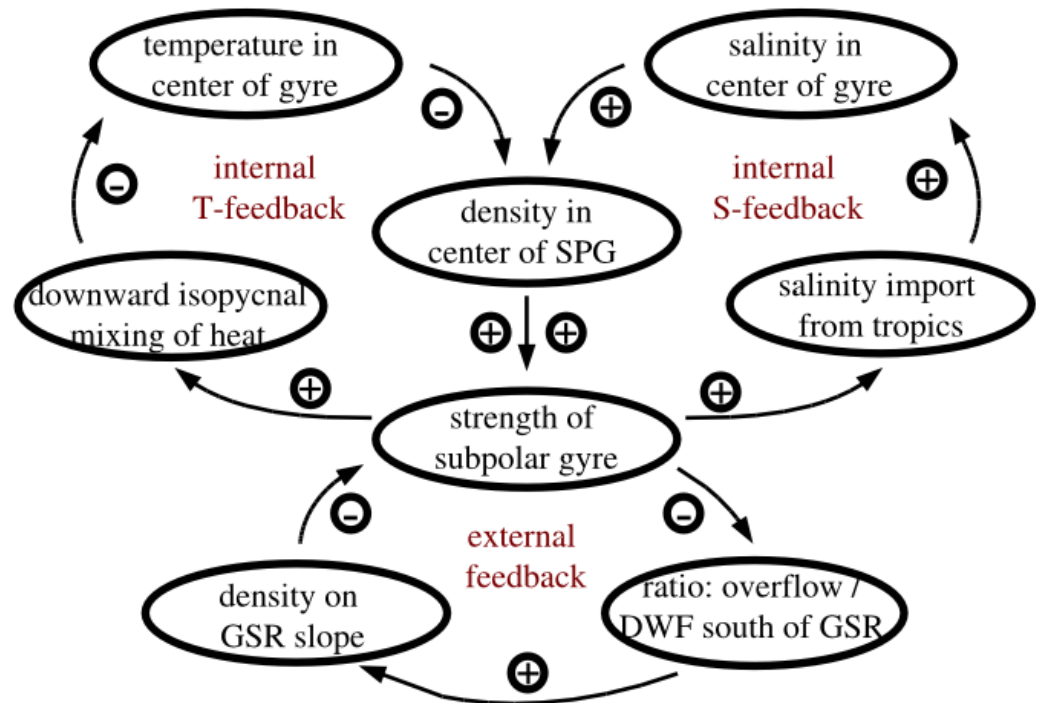
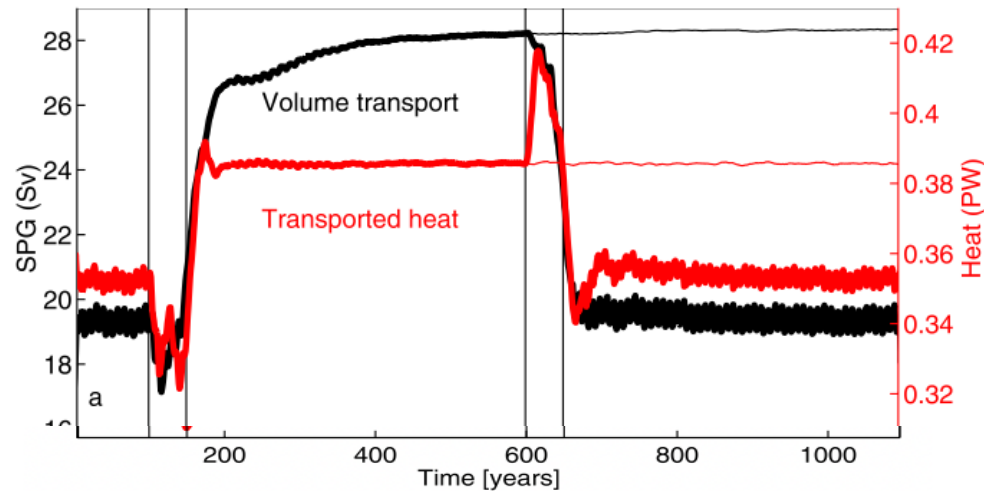
Giovanni Sgubin, Simon Michel, Sybren Drijfhout, Juliette Mignot, Marion Devilliers, Julie Deshayes,, Marie-Noelle Houssais, Christophe Herbaut, Vincent Hanquiez,, Kees van Leeuwen, Lucas Almeida...

The subpolar gyre



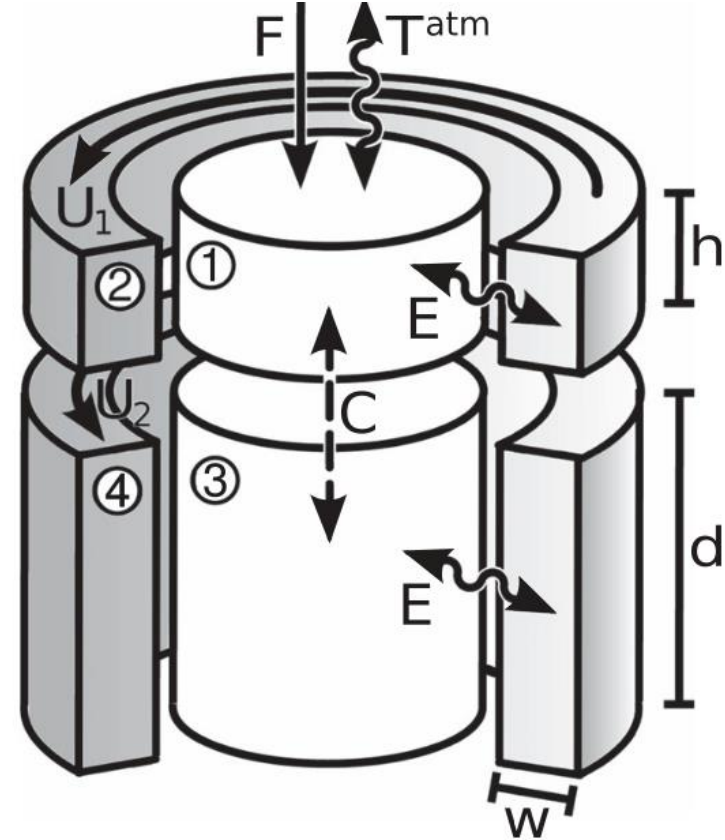
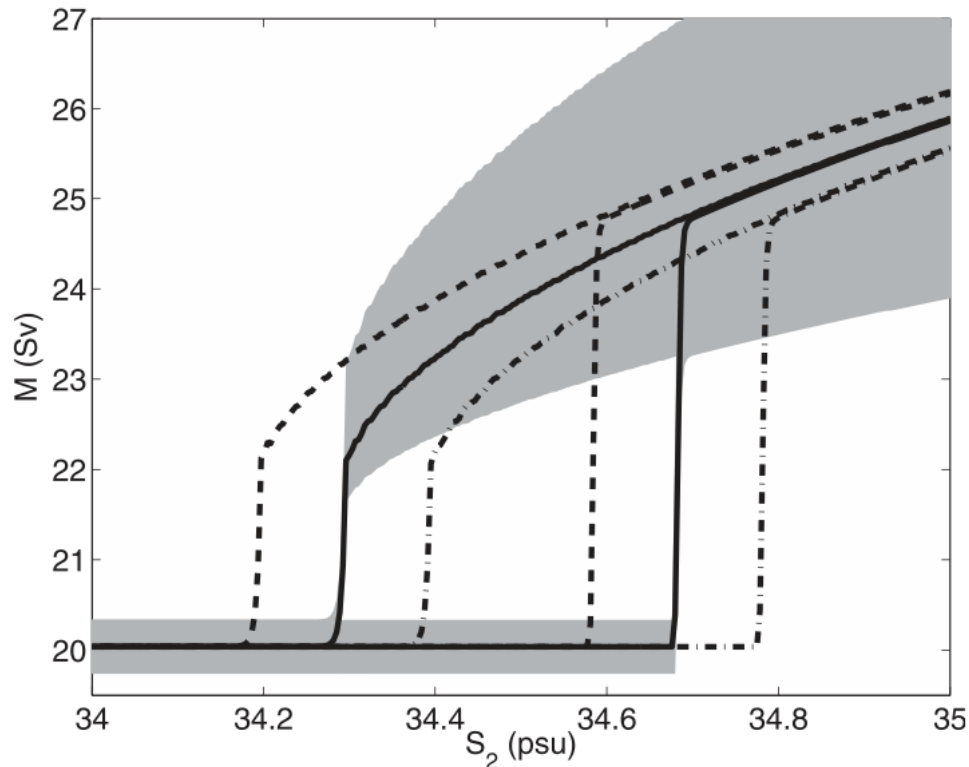
A bistable system?

- **Leverman and Born (2007)** using CLIMBER-3 α (MOM-3 ocean at 3.75° resolution) did find a rapid change and apparent bistability in SPG strength
- *“Addition of 0.05 Sv of anomalous freshwater for 50 years to the Nordic Seas switches the circulation into a stronger state.”*
- *“Application of a negative anomaly of 0.1 Sv for 50 years switches the system back to the initial state.”*

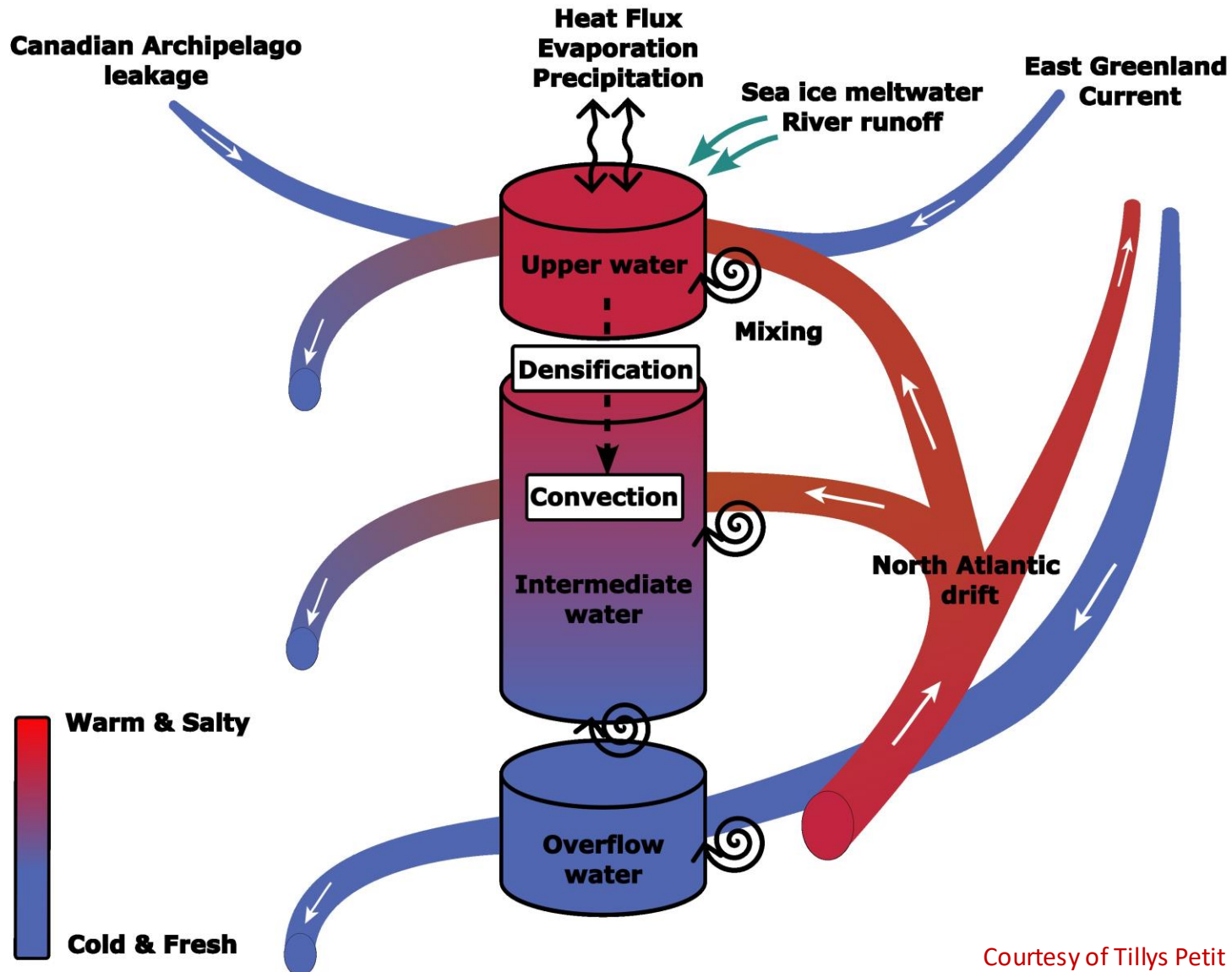


A bistable system?

- **Born & Stocker (2014)** proposed an idealised SPG model, highlighting potential hysteresis for the SPG



A complex 3-dimensional dynamics



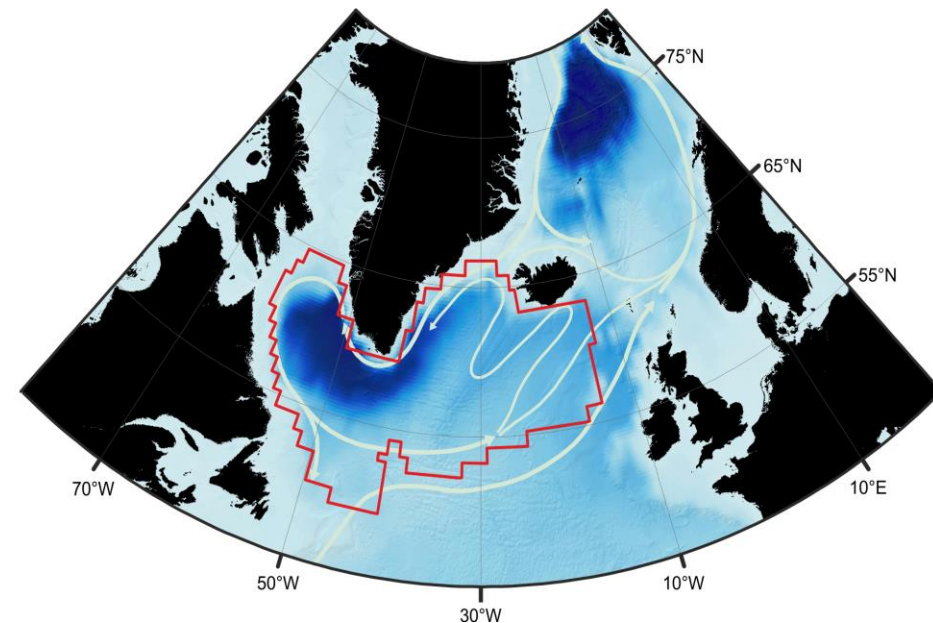
Possibility of Abrupt Changes in the North Atlantic in CMIP5 models



Detection algorithm:

- Following Drijfhout et al. (2015), we computed 10-year differences in time series for different regions
- We search for differences in historical simulations or projections larger than 3 times the standard deviation computed in piControl

Up to **9 CMIP5 models** do show abrupt (<10 years) cooling in the subpolar gyre (SPG)



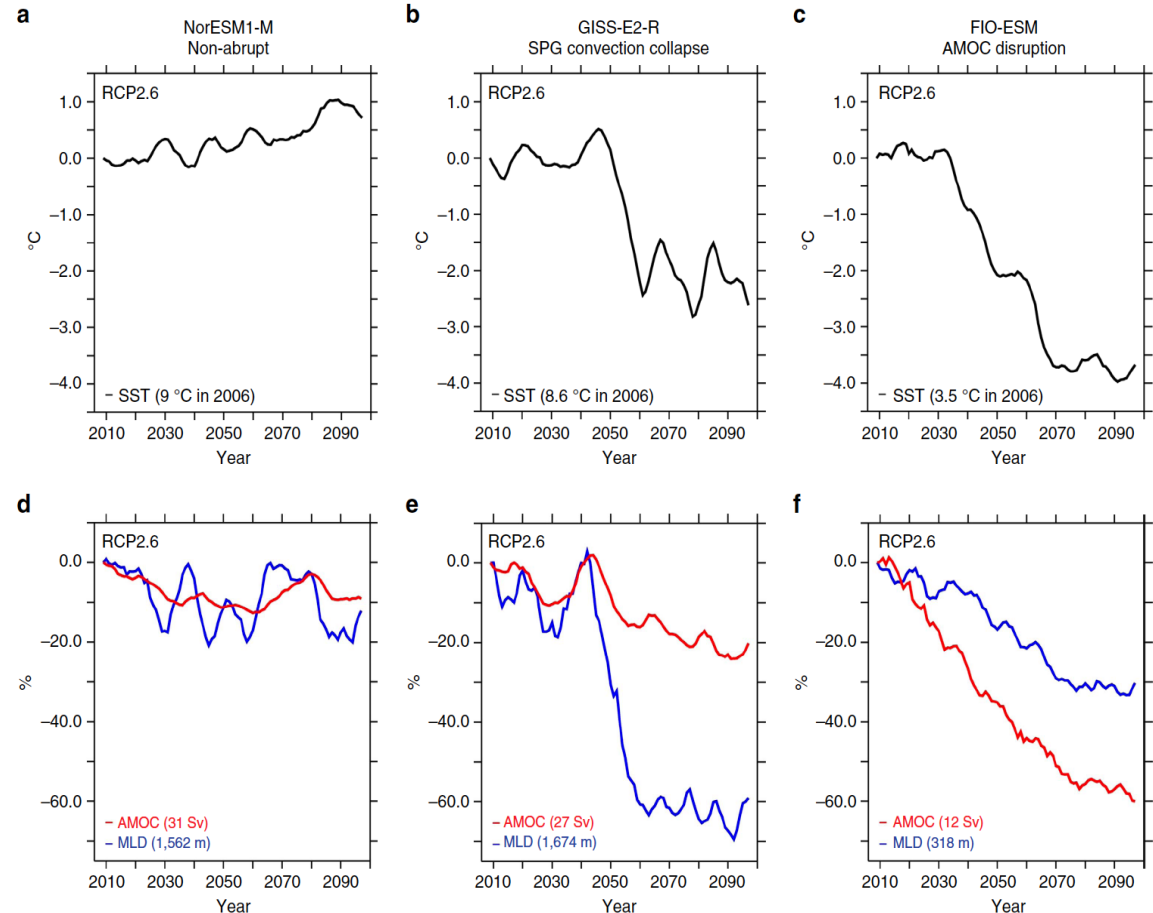
Possibility of Abrupt Changes in the North Atlantic in models



Changes in the subpolar gyre

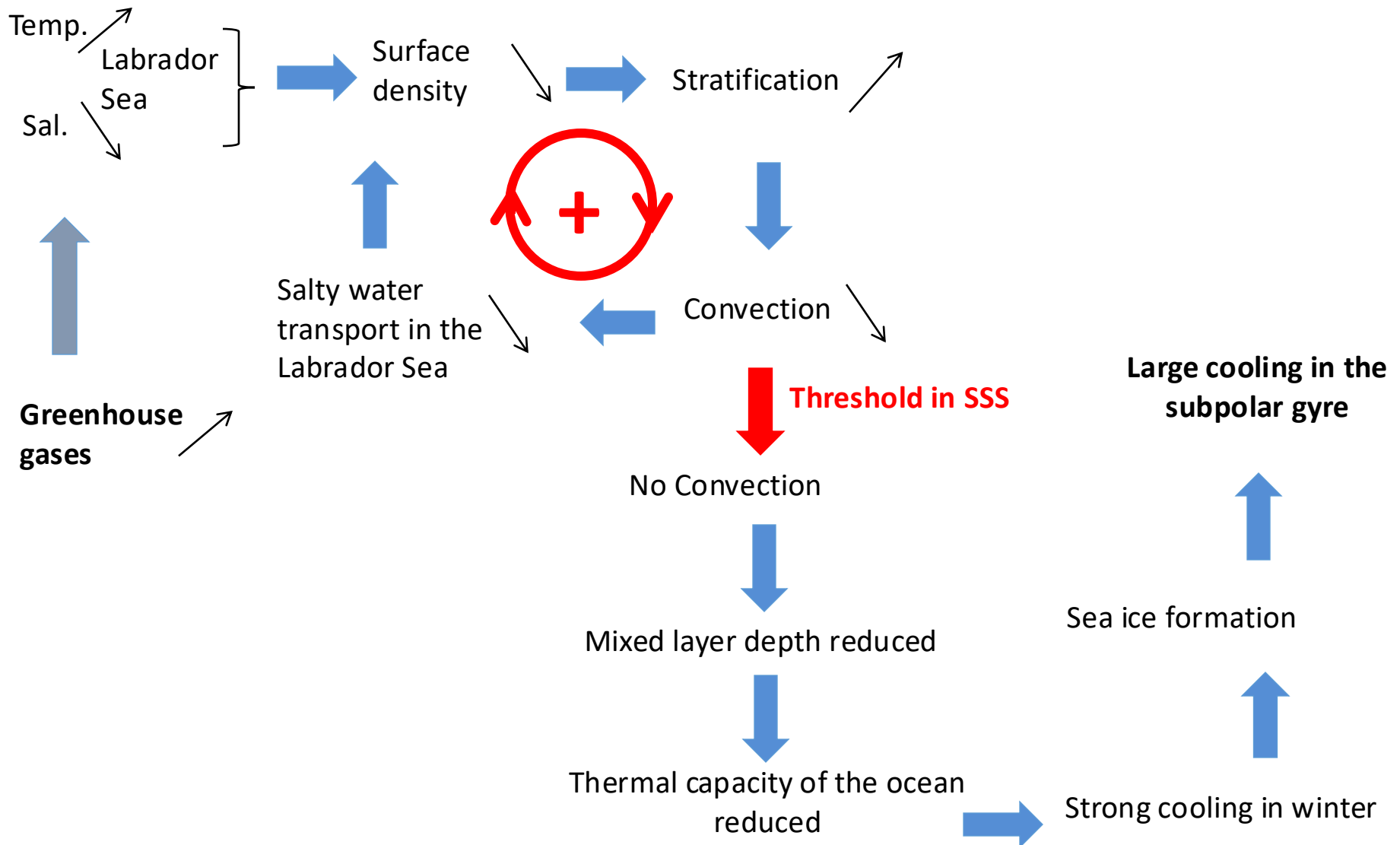
Two different processes

- Disruption of the AMOC (strong decrease of convection both in the SPG and Nordic Seas)
- Collapse of convection mainly in the subpolar gyre can occur in only one decade => **the SPG as a new tipping element in CMIP models**

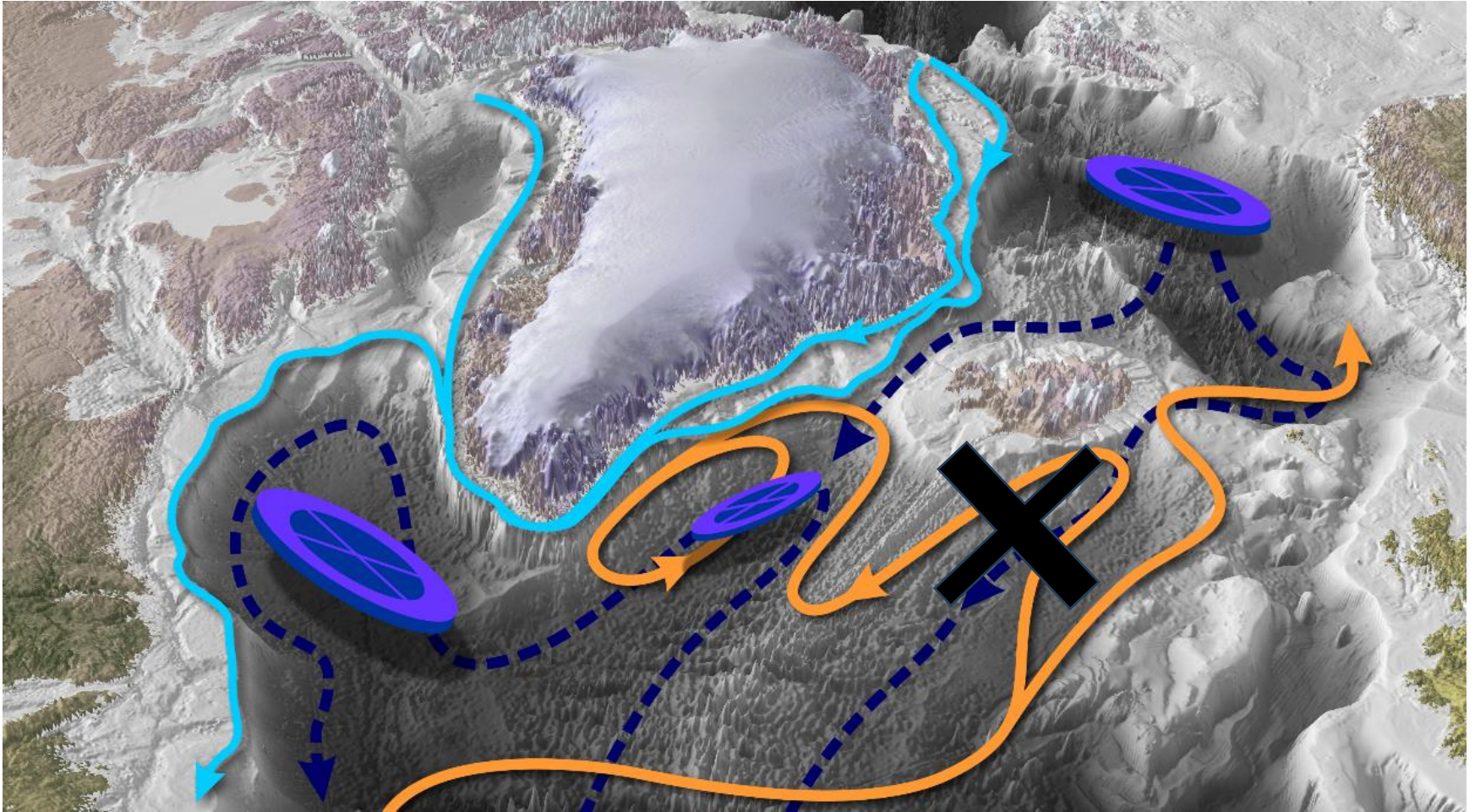


Credits: Nature Communications

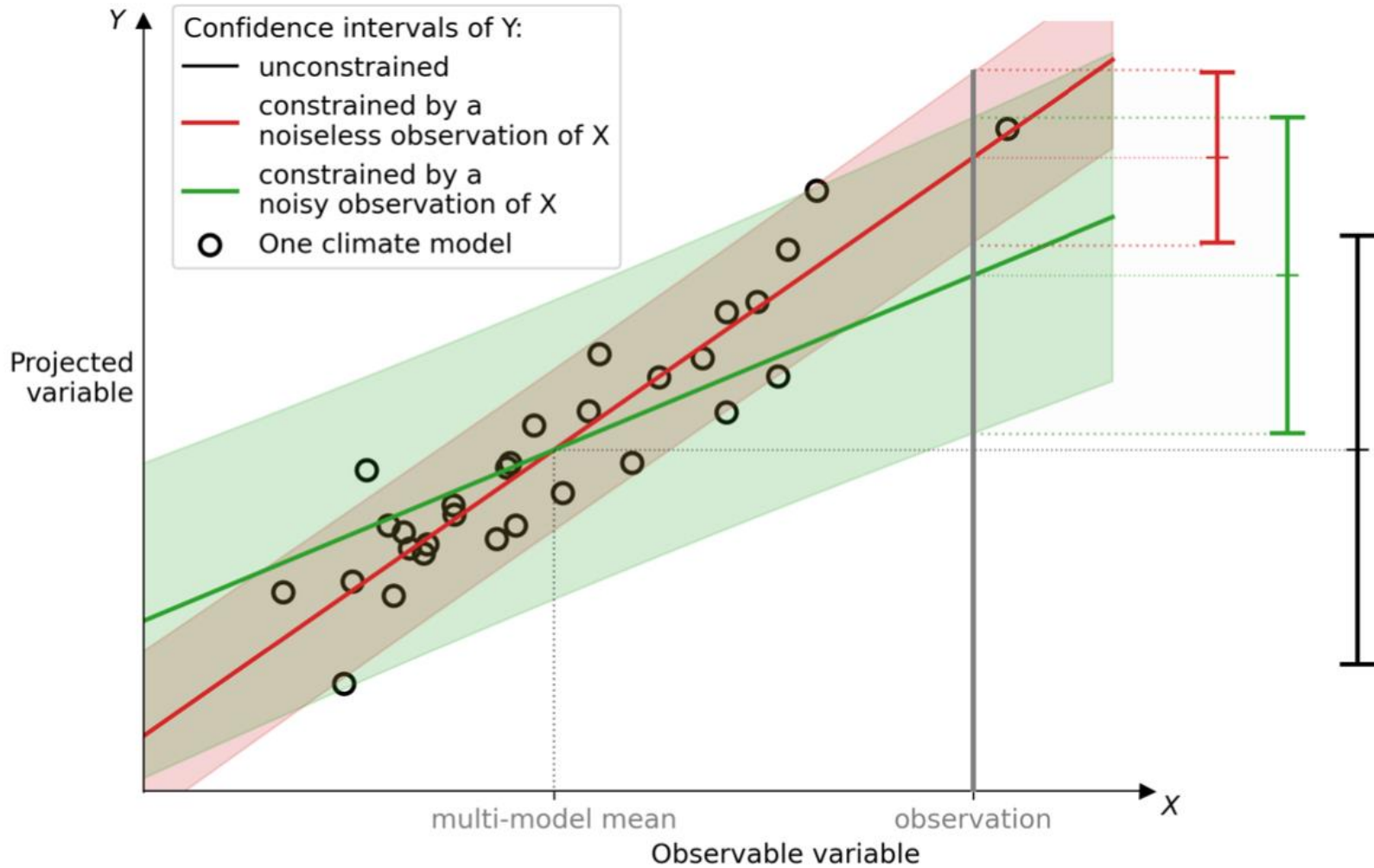
Mechanisms at play for SPG collapse



Positive salt advection feedback

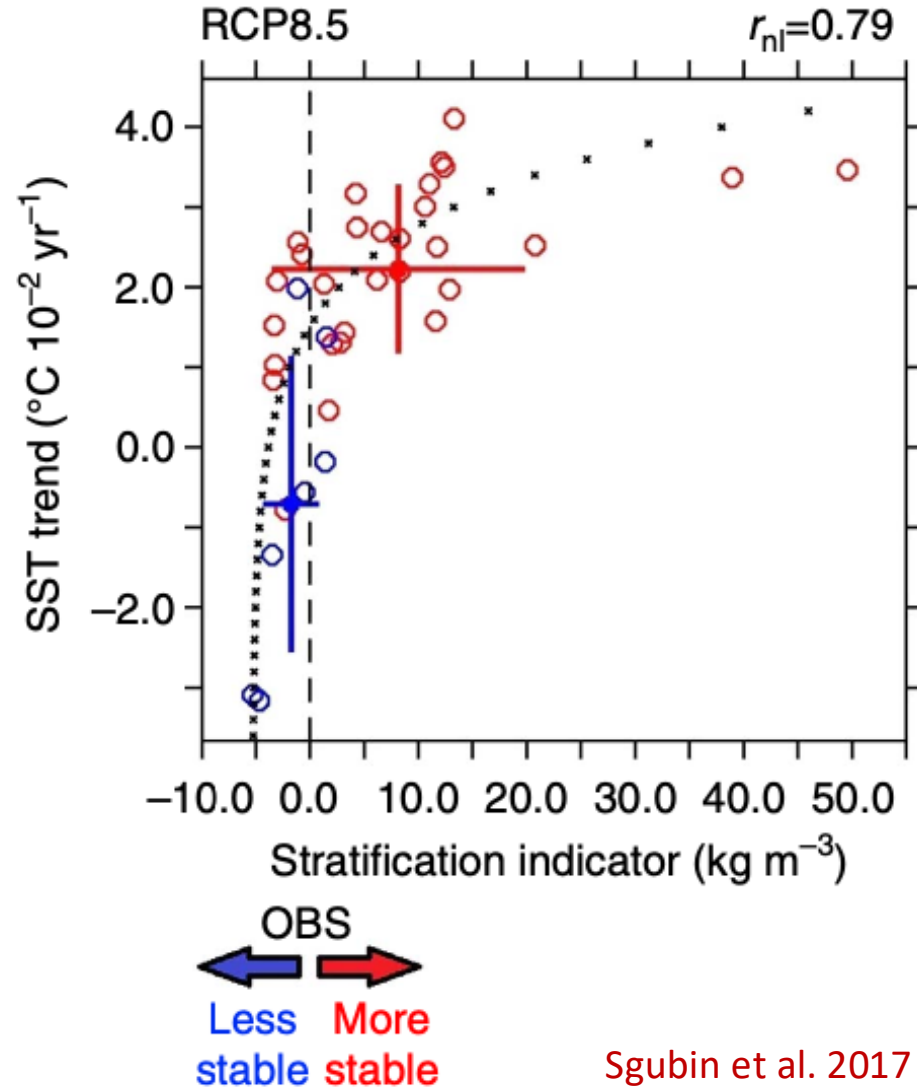


Observational constraints



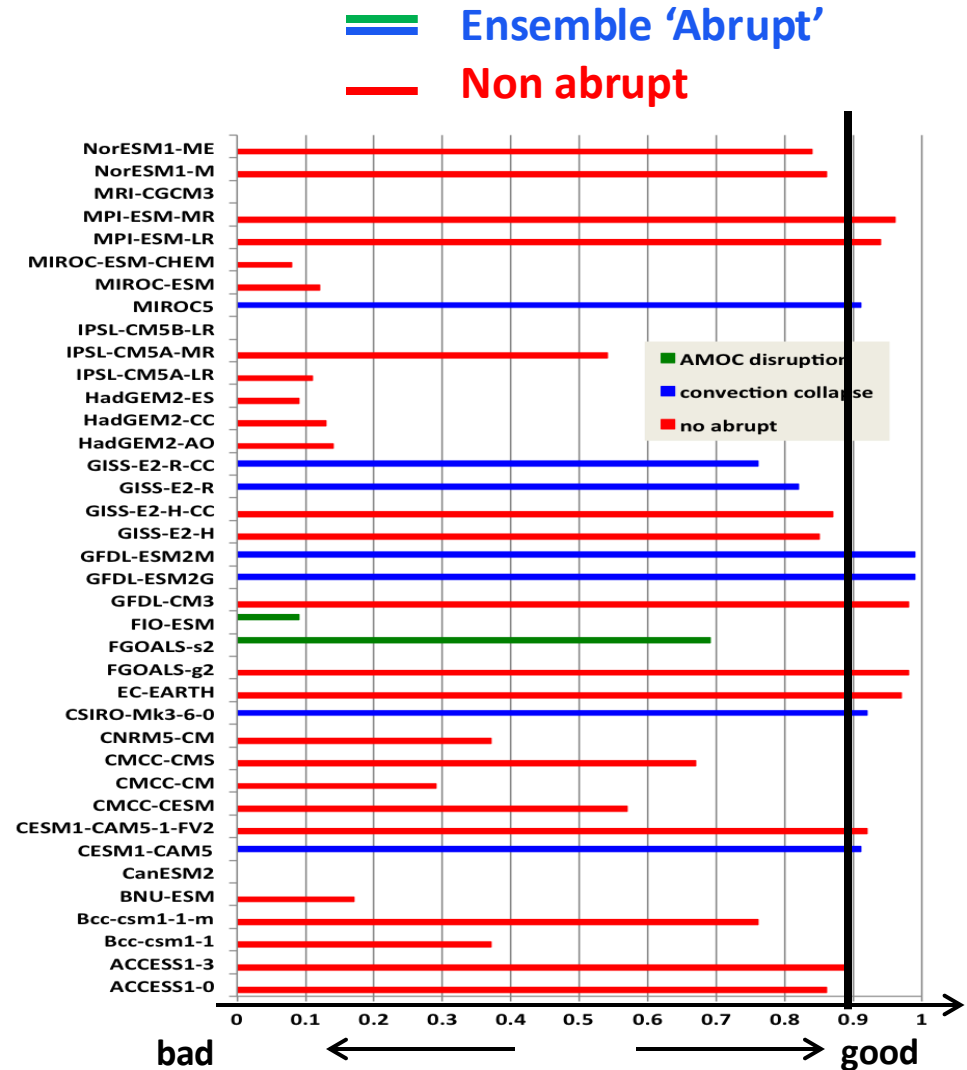
Observational constraints for the SPG

- Stratification is a key variable for the ocean dynamics
- It has influence on the thermodynamics (water mass formation) and the dynamics but is also deeply influenced by the dynamics (theory of the pycnocline)
- As such it can be a very interesting variable to evaluate quality of climate models
- We used it as an observational constrain since it also showed relatively good linkages to explain model spread



Observational constraints for the SPG

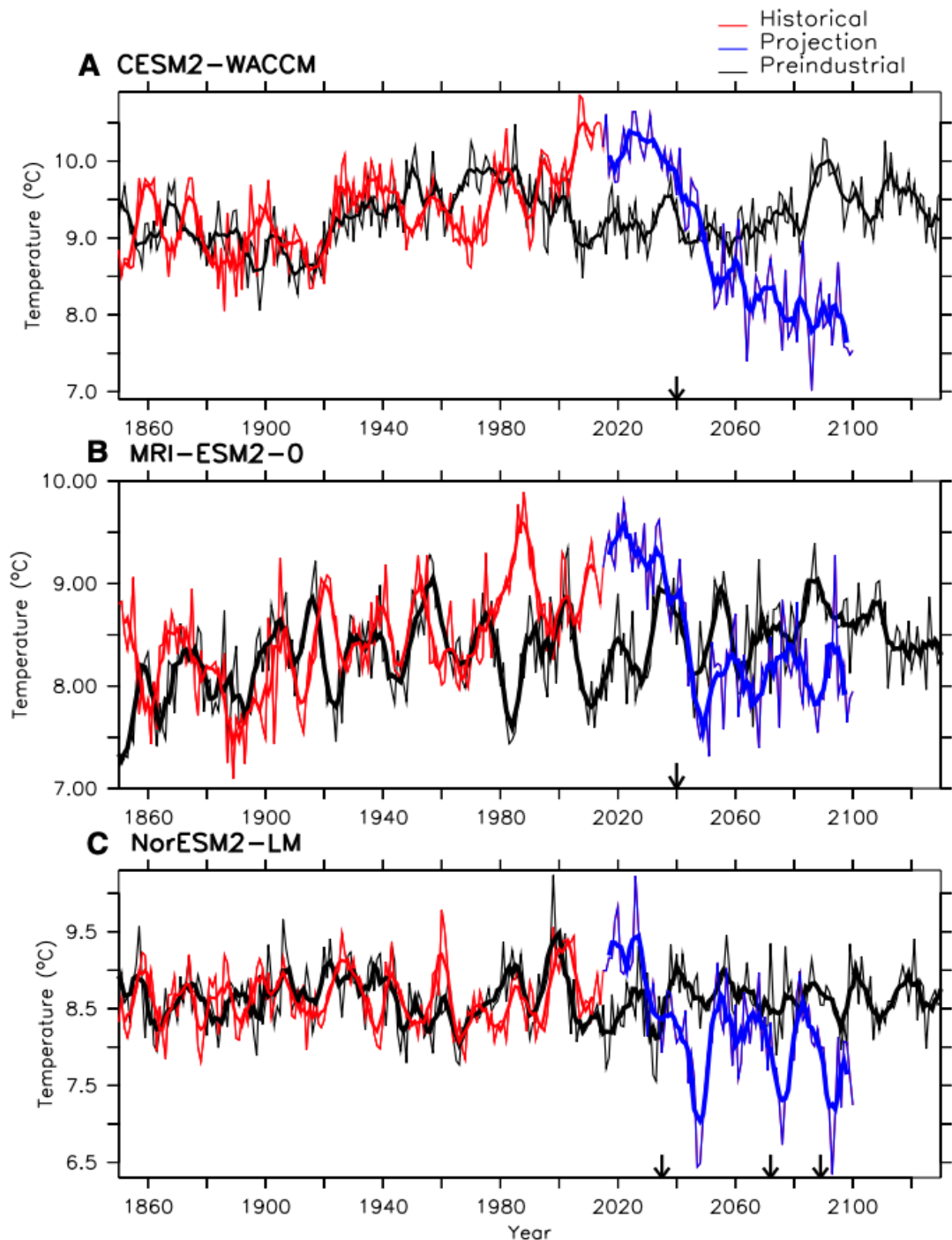
- The 7 models showing only an SPG collapse (removing the 2 ones showing an AMOC collapse) are among the best in terms of stratification representation
- With a subjective threshold, we find that 5 among the 11 best models do show an abrupt SPG collapse
- This represents about **45%** of these 11 best models



Model skill score in stratification

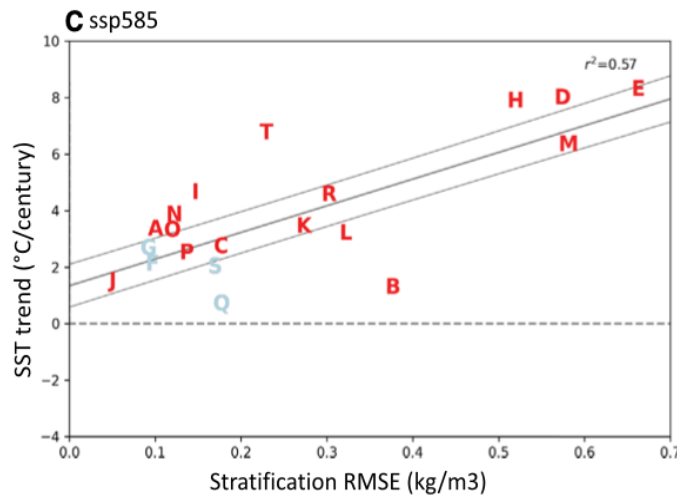
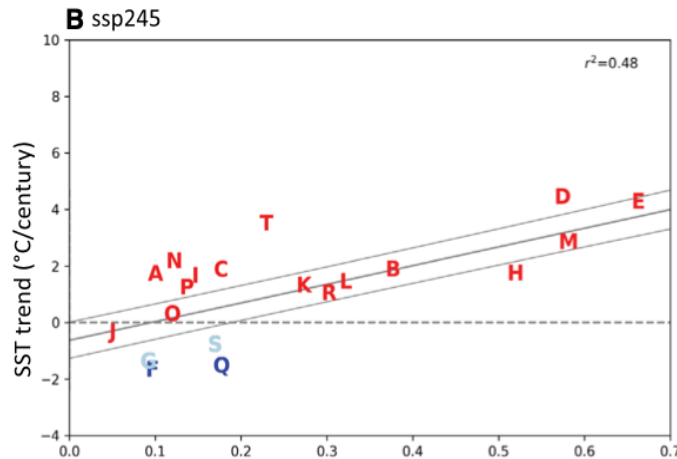
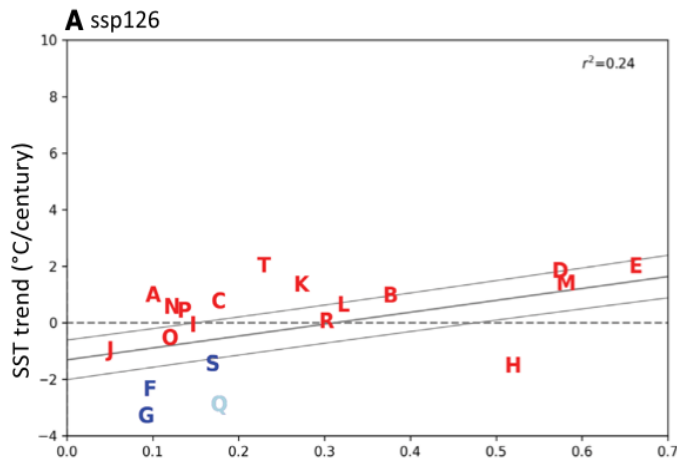
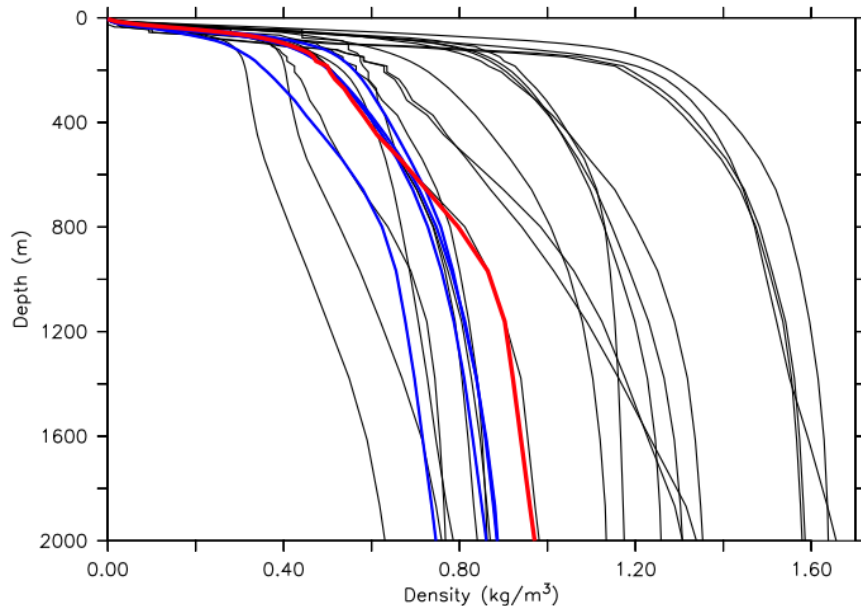
Possibility of Abrupt Changes in the SPG in CMIP6

- We use the same detection algorithm
- There is still SPG collapse in a few CMIP6 models (Swingedouw et al. 2021)
- But with far less models though (4 in total over 32)



SPG stratification as an observational constraint

- CMIP6 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)**



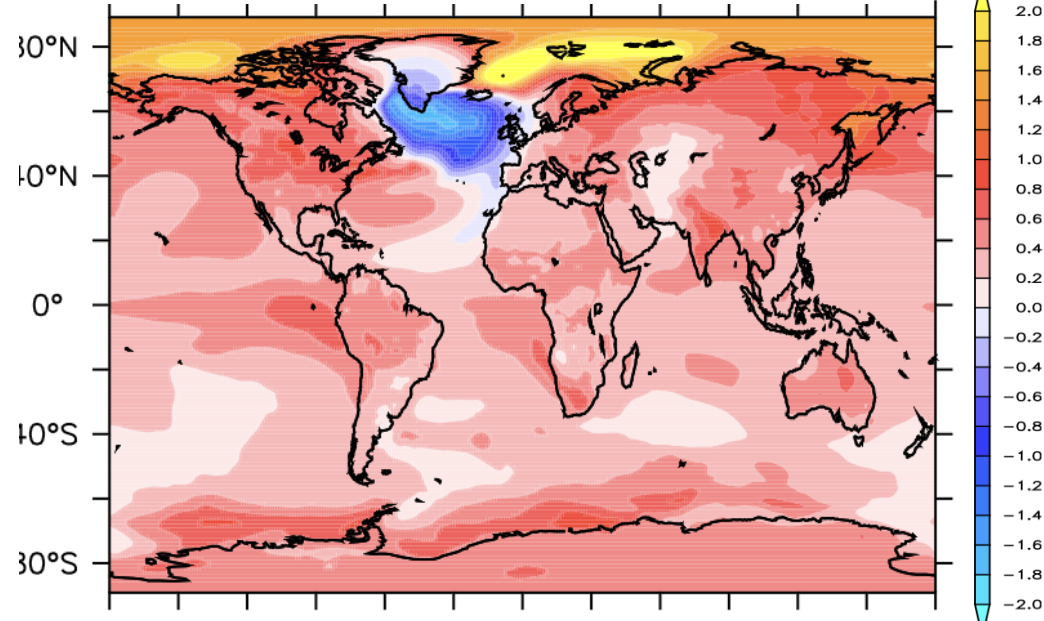
- A:** AWI-CM-1-1-MR
- B:** BCC-CSM2-MR
- C:** CAMS-CSM1-0
- D:** CanESM5
- E:** CanESM5-CanOE
- F:** CESM2
- G:** CESM2-WACM
- H:** CIESM
- I:** CNRM-CM6-1
- J:** GFDL-ESM4
- K:** INM-CM4-8
- L:** INM-CM5-0
- M:** IPSL-CM6A-LR
- N:** MCM-UA-1-0
- O:** MIROC6
- P:** MPI-ESM1-2-LR
- Q:** MRI-ESM2-0
-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

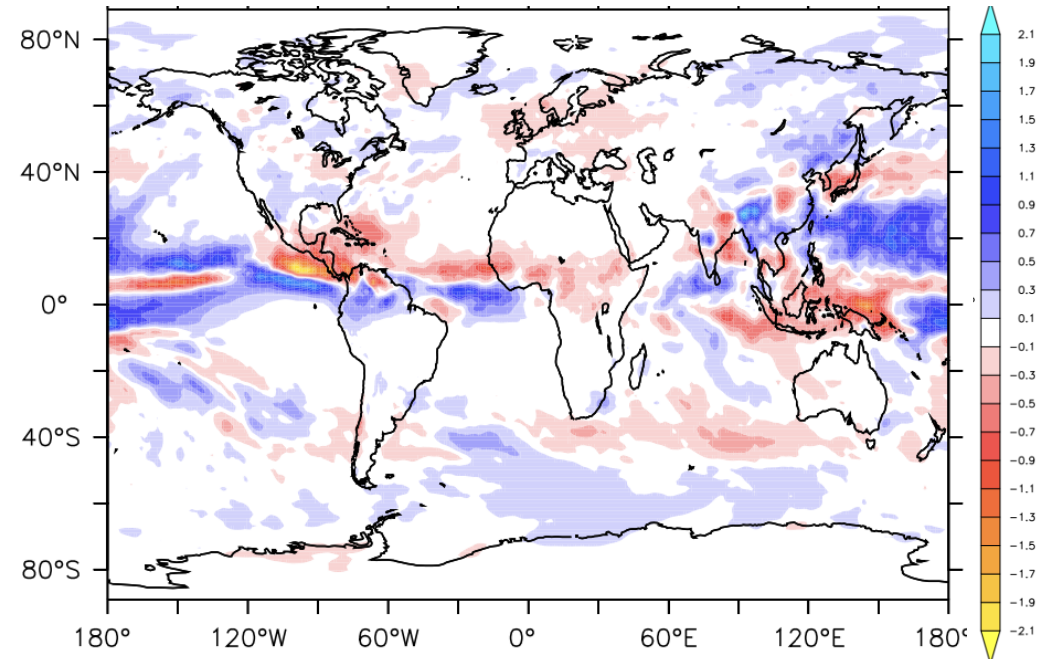
Climatic impacts

- We compute the average 20 years after the events minus 20 years before in CMIP6 models to obtain a composite based on 4 model simulations
- We do find a clear signal a cooling in the SPG also over western Europe, with a clear removal of warming trend
- There is also a southward shift of the ITCZ and more complex response in the Pacific and Indian oceans

Composite of temperature changes



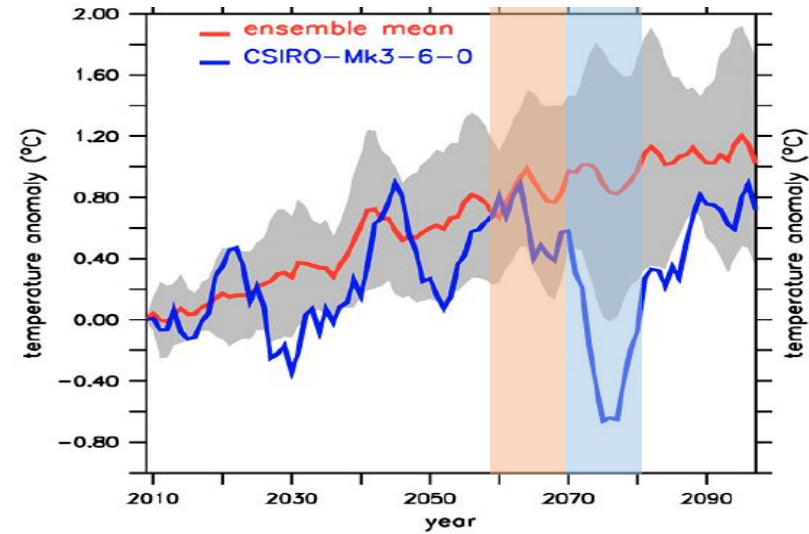
Composite of JJA precipitation changes



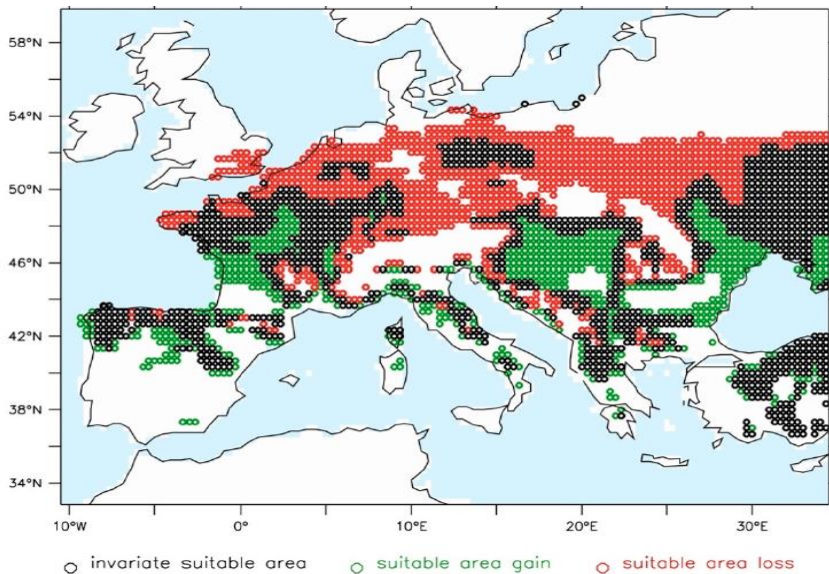
Impacts of abrupt decadal cooling

- The impact of these fast (<10 years) events can affect climate of Europe for at least a decade (one CORDEX simulation)
- Adaptation polycies are poorly accounting for such events
- The exemple of viticulture is enlightening in this respect

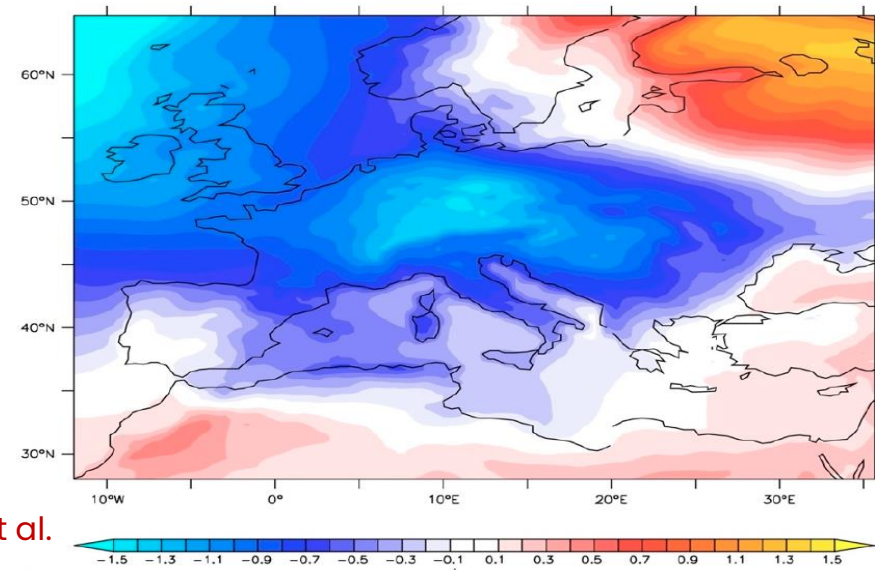
Temperature in the UK



Suitability of Chardonnay
2069-2078 vs 2059-2068



Temperature difference 2069-2078 vs 2059-2068



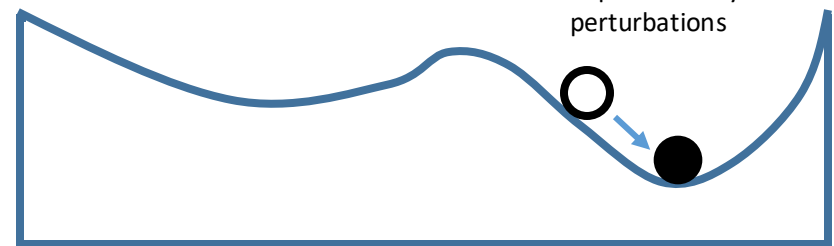
Sgubin et al.
(2019)

How to have early warnings of a potential AMOC collapse?

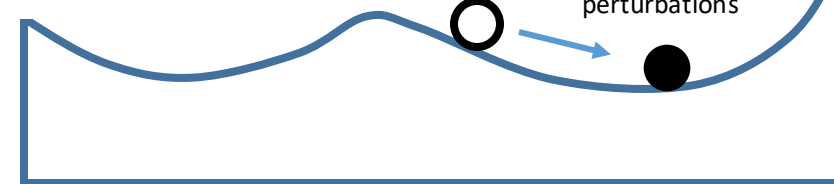
- Theory from dynamical system teaches us that approaching a tipping point, the system variability tend to increase
- **However**, a long enough time series is necessary to be able to correctly evaluate “normal” internal variability from the system.
- Boulton et al. (2014): we need **at least 250 years** to be able to apply this to the AMOC

Change of temporal variability when approaching a tipping point

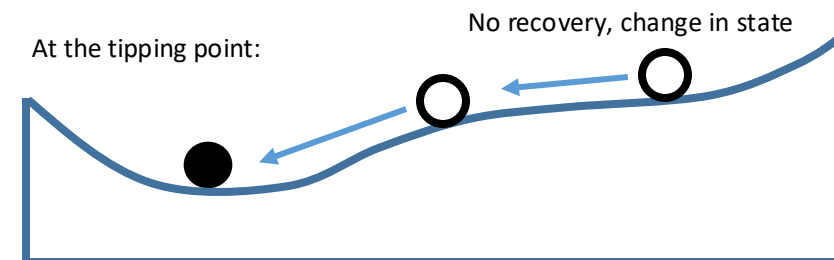
Far from the tipping point:



Approaching the tipping point:

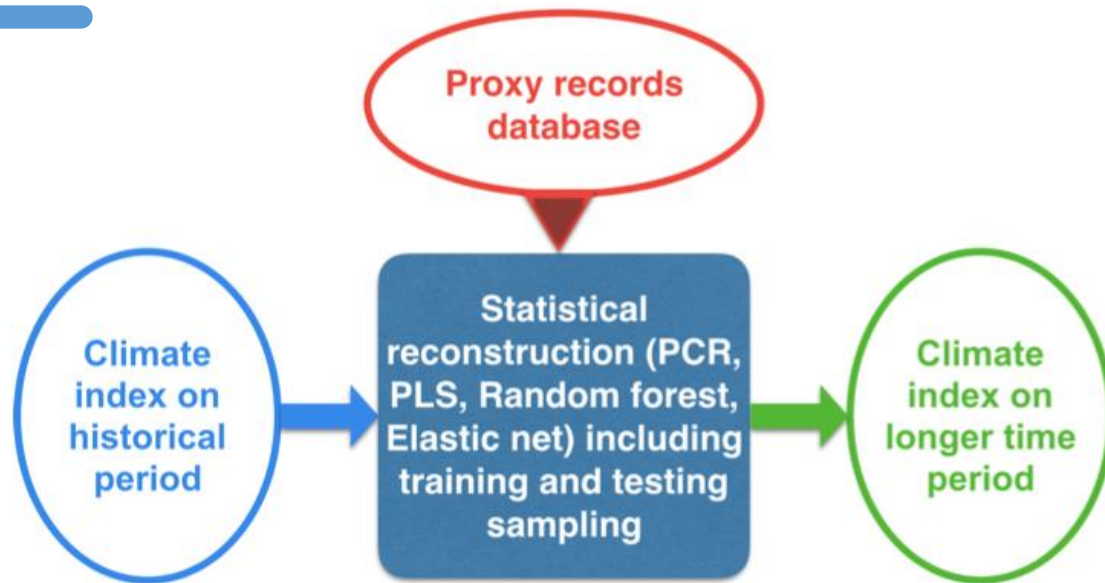


At the tipping point:



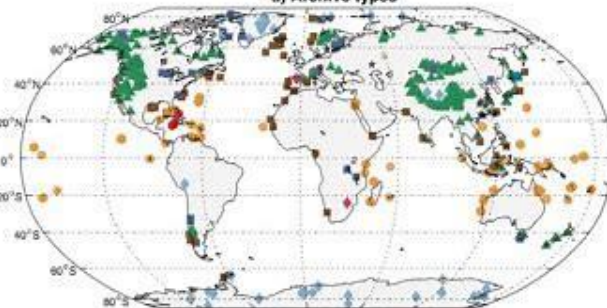
Reconstructing climatic modes of variability from proxy records using ClimIndRec version 1.0

Simon Michel¹, Didier Swingedouw¹, Marie Chavent², Pablo Ortega³, Juliette Mignot⁴, and Myriam Khodri⁴



PAGES2k 2.0.0 (692 records from 648 sites)

a) Archive types

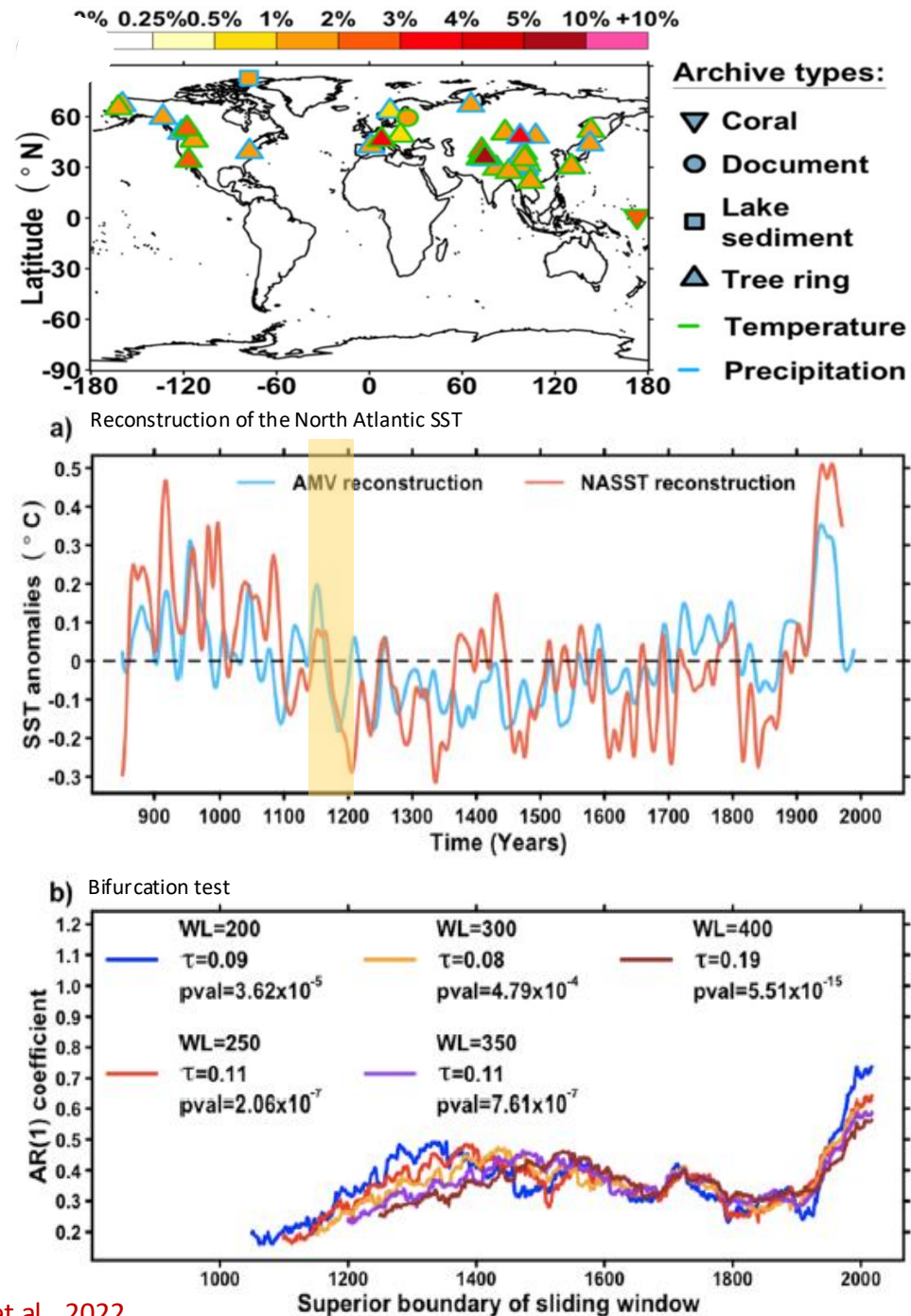


- bivalve (1)
- borehole (3)
- coral (96)
- documents (15)
- glacier ice (49)
- hybrid (1)
- lake sediment (4)
- marine sedimen
- sclerosponge (8)
- speleothem (4)
- ▲ tree (415)



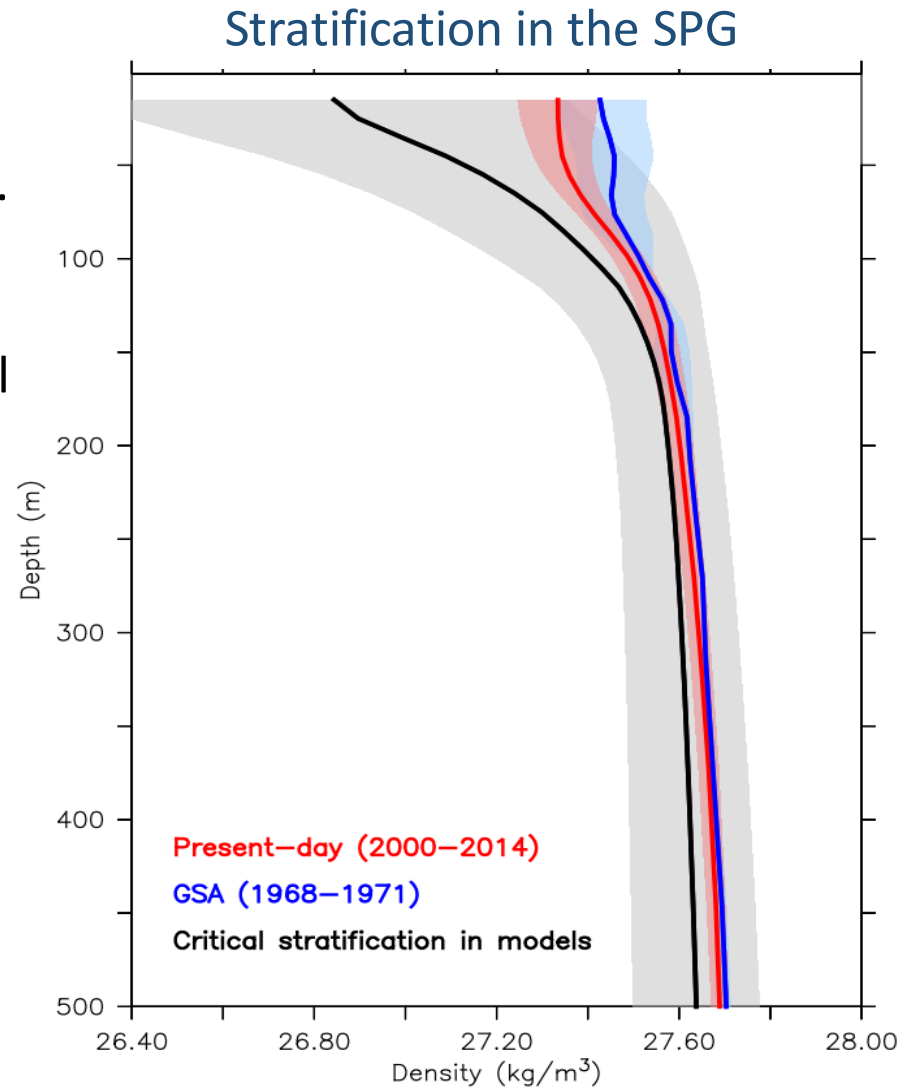
Early warning indicators for SPG changes

- 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](#))
- These reconstructions seems to show that North Atlantic system might be approaching a tipping point
- However, it is still unclear if this is concerning the SPG or the whole AMOC (e.g. [Chafik & Lozier 2025](#)), as well as the exact time scale implied



Proximity to a SPG tipping point?

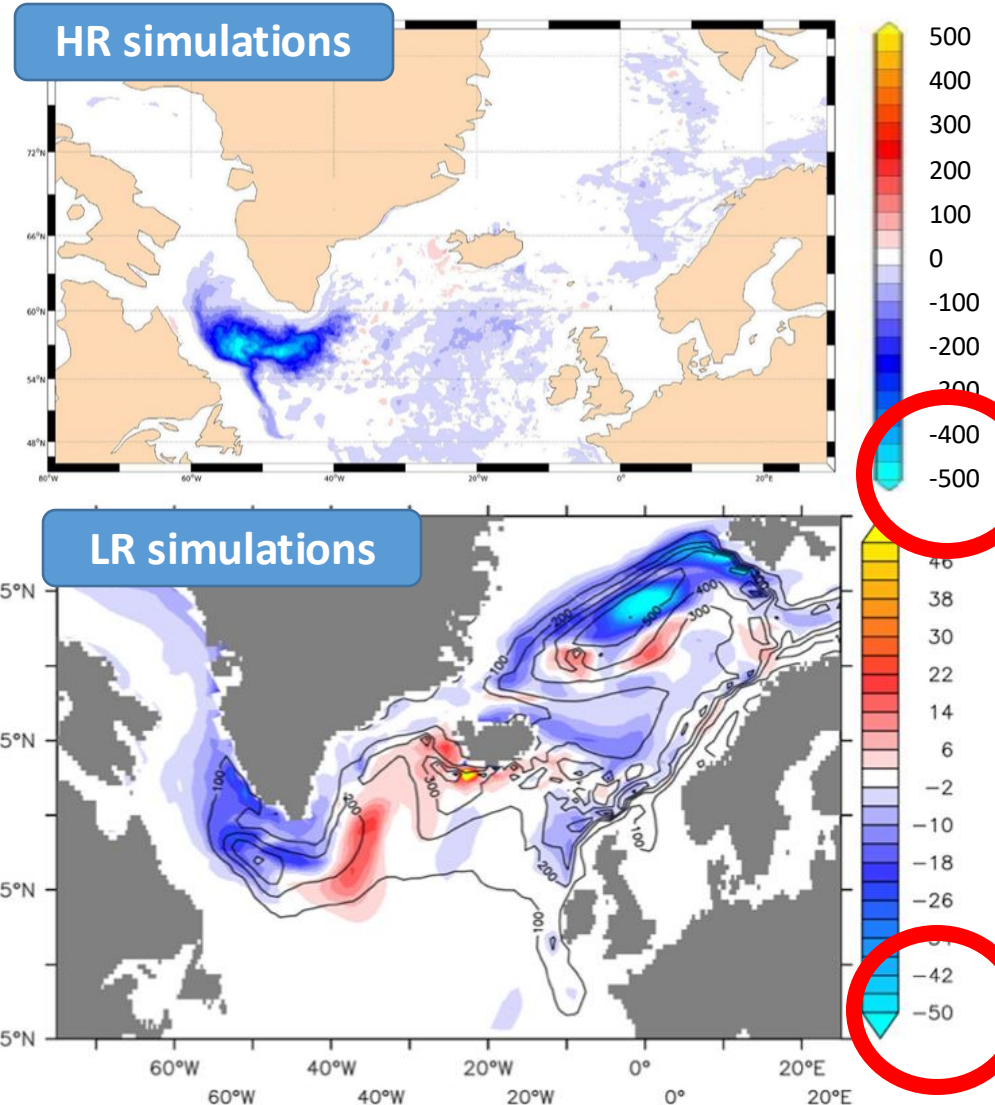
- To analyse the proximity to tipping points, models can be useful as well, on top of classical early warning statistical approach.
- For instance, since SPG stratification is crucial element of convection, and a useful emergent constraint for the evolution of centennial SST trend, it is interesting 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...



What about the impact of Greenland melting?

Mixed layer depth anomalies

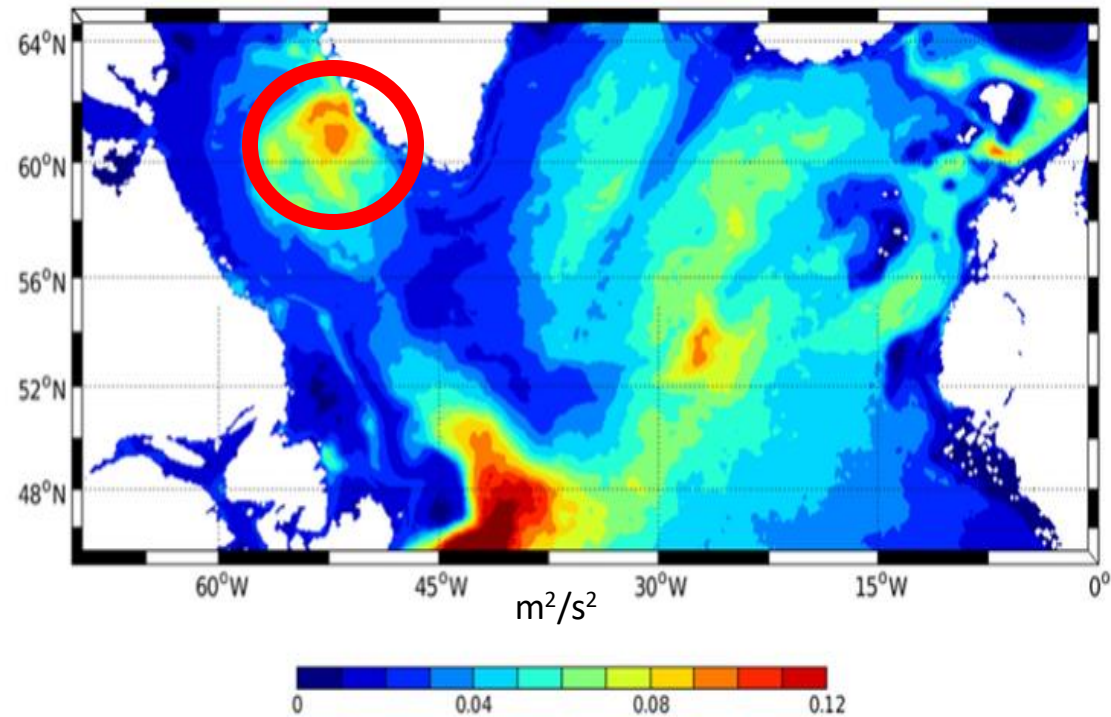
- We compare IPSL-CM6A Low Resolution (LR, 50-60 km) run with very High Resolution (HR, 2-3 km) simulations from an ocean-only model over the historical period
- Similar impact of observed Greenland melting on salinity, but **one of order of magnitude larger in HR!**
- The same is true for mixed layer depth: one order of magnitude stronger weakening of Labrador Sea convective activity in HR simulations



What can explain the differences ?

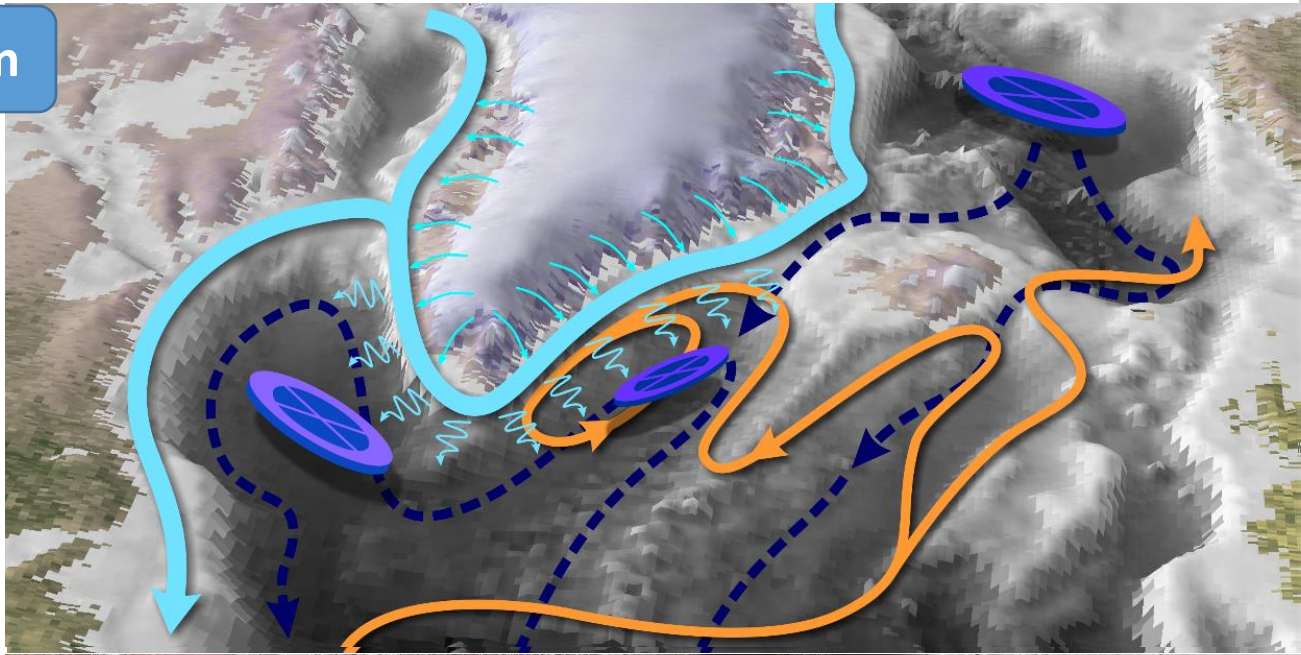
- The currents around Greenland are fine-scale (a few tenths of kilometers) and are too wide in the LR simulations
- There is a hotspot of eddy formation just west of the Greenland tip, bringing directly the melt water collected around Greenland into the Labrador Sea center

Eddy Kinetic energy in HR simulation

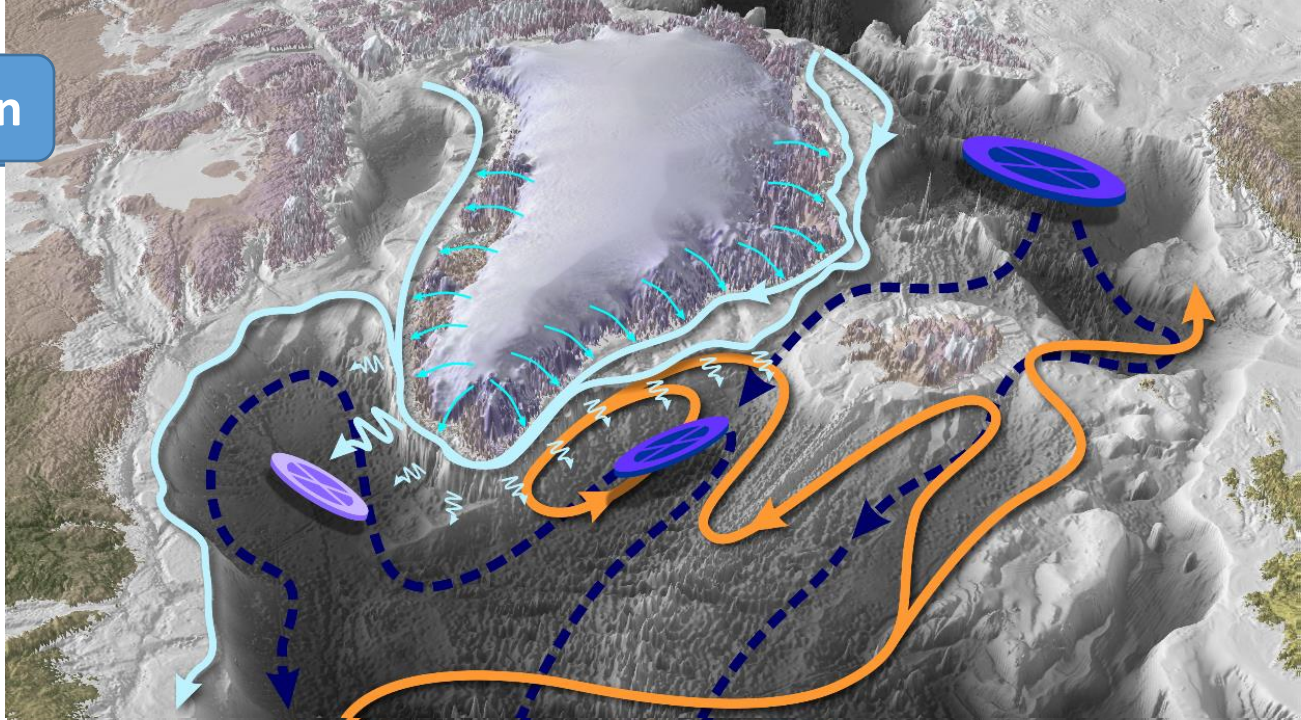


What about Greenland melting and resolution of models?

Low Resolution



High Resolution



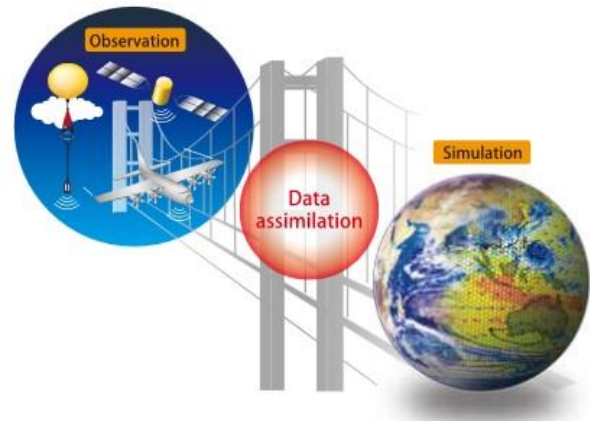
Swingedouw et al., *Frontiers in climate*, 2022

Scheme by
Vincent
Hanquiez

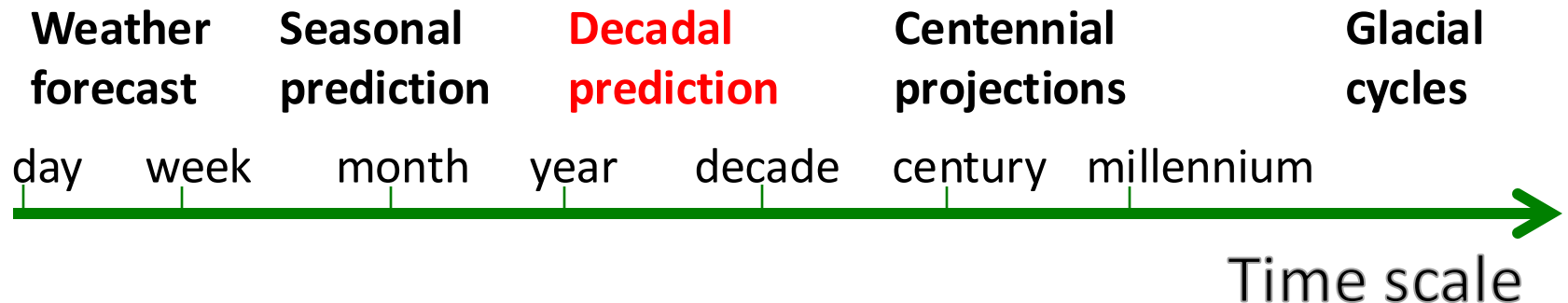
Decadal predictions to gain insights on early warnings of abrupt changes

Initial conditions

e.g. Gu et al.,
Nat. Com. 2024



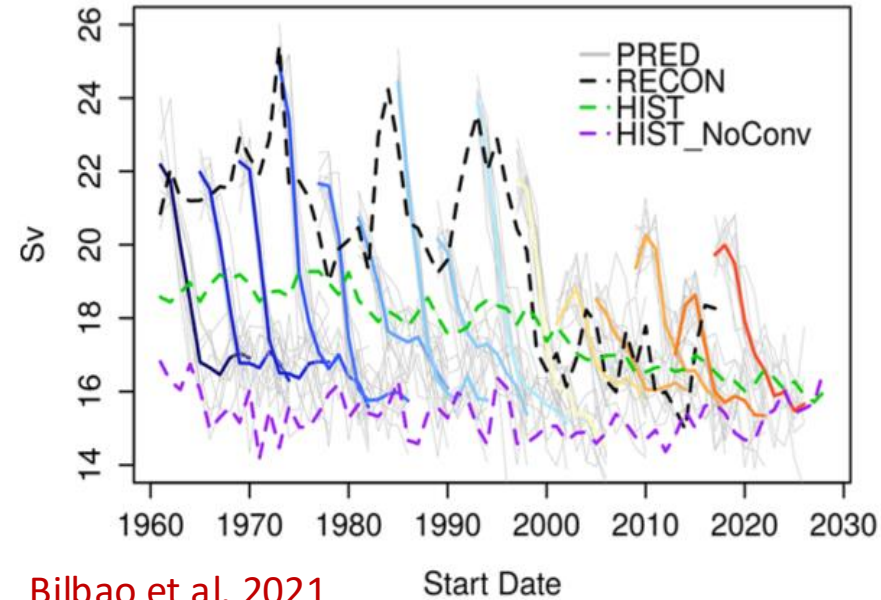
External forcing



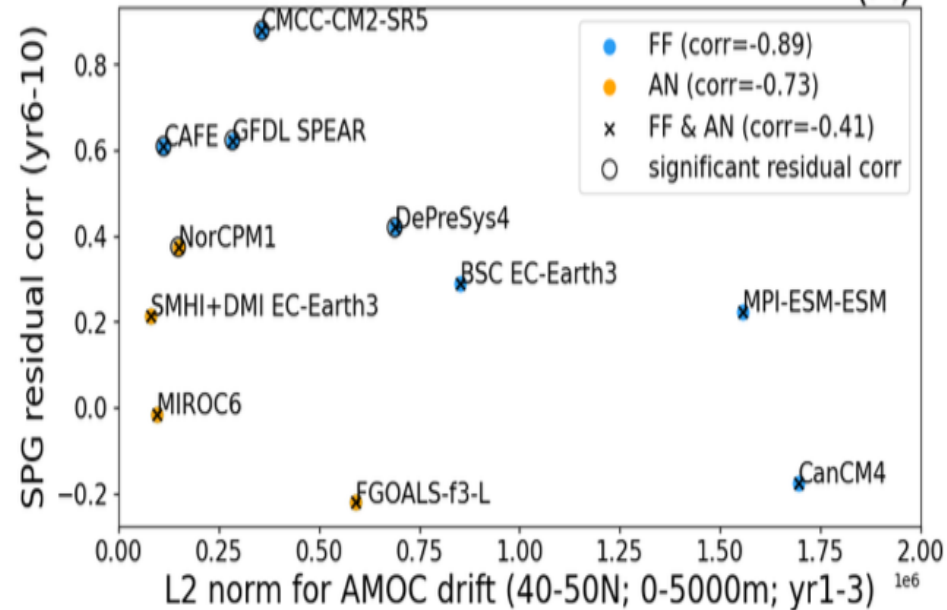
How to properly initialise the North Atlantic?

- The issue of the initial shock is crucial for tipping point predictions
- Solving it can also increase prediction skill of the SPG SST (Polkova et al. 2014)

(a) AMOC 45N



(A)

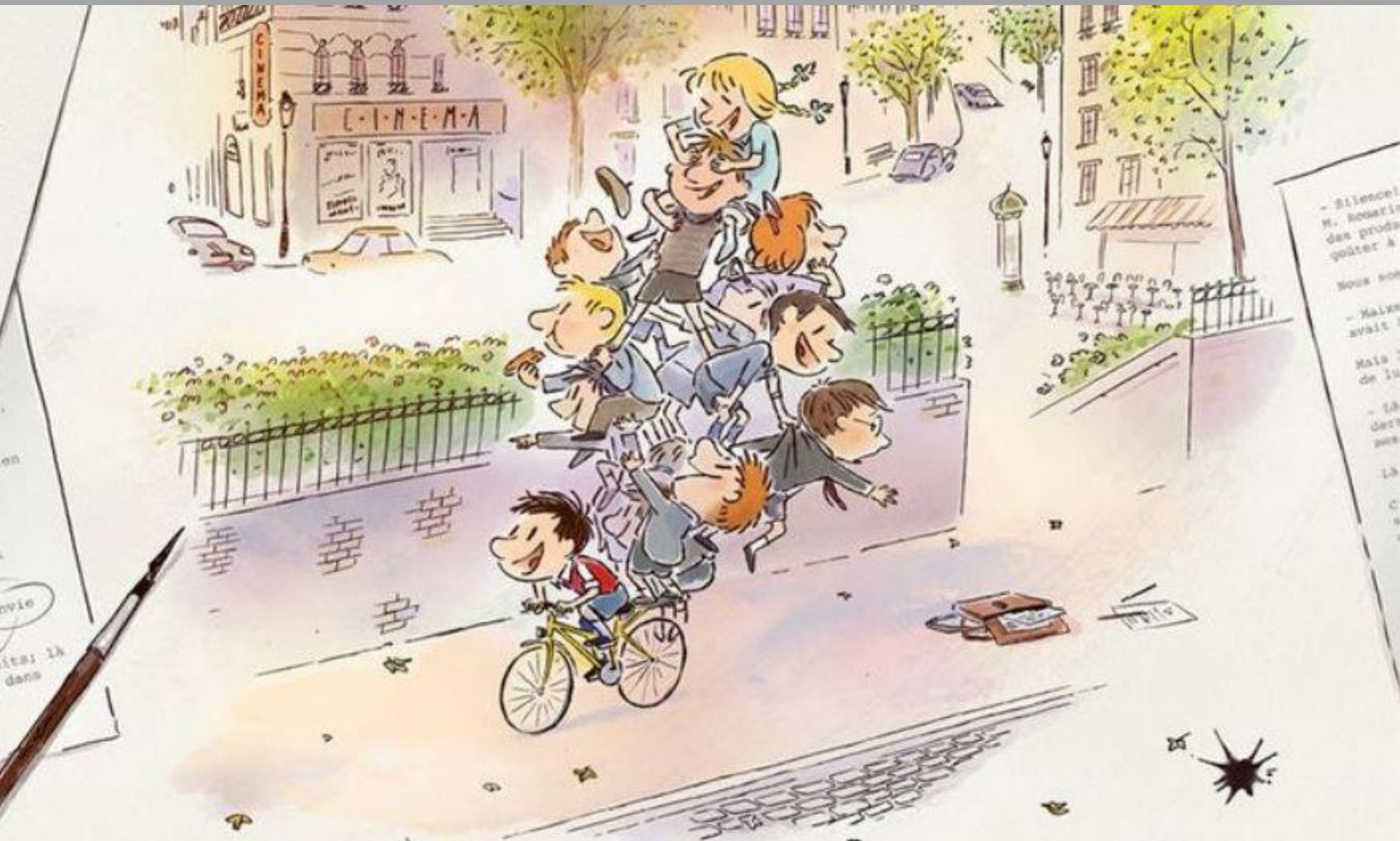


Polkova et al., 2024

Conclusions

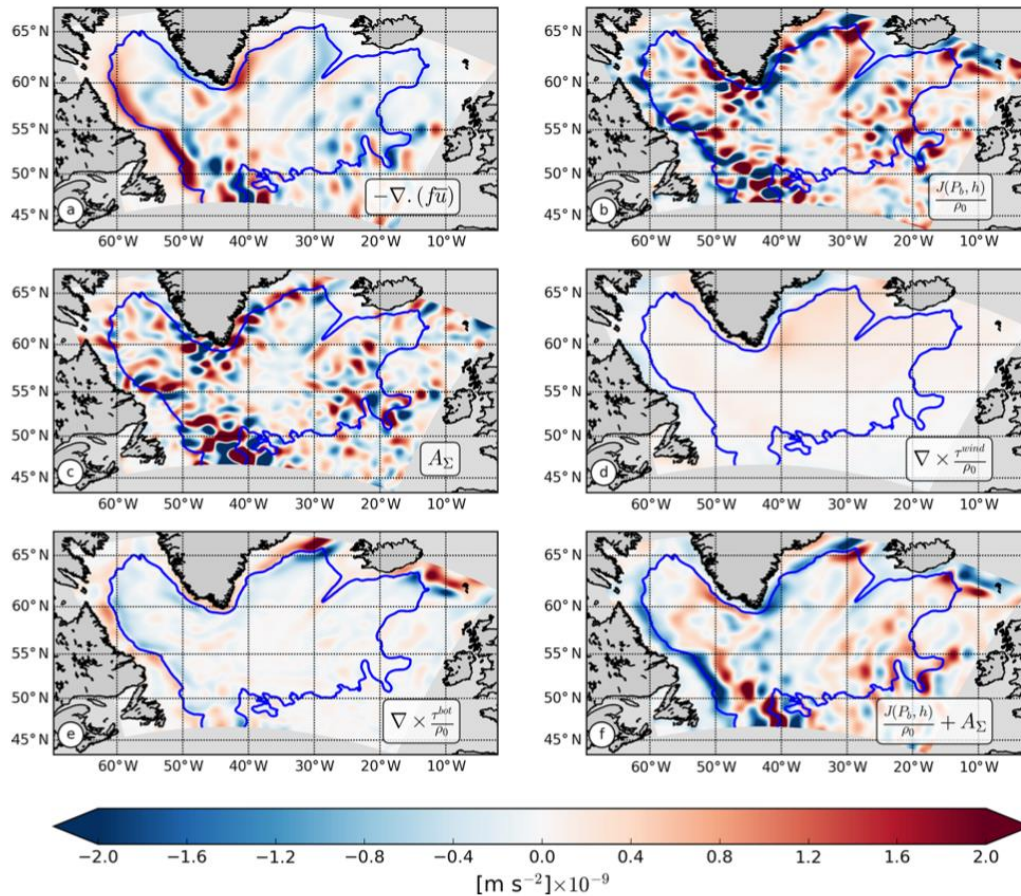
- **Exact physical mechanisms at play are still debated**
- **Observation systems** are needed for an efficient early warning system
- Need for further **reconstructions of the last few thousands of years** to have better insights on the approach of a tipping point
- **Decadal prediction systems** still need further development to:
 - Diminish their offset to observations
 - Better include meso-scale processes
- Assessment of the impact of **such low probability - high impact scenario in adaptation plans** are poorly accounted for up to now

Thank you!



TipESM is funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

A complex vorticity budget



$$\begin{aligned}
 \underbrace{\frac{\partial \Omega}{\partial t}}_{\text{rate}} = & - \underbrace{\nabla \cdot (f\bar{u})}_{\text{planet. vort. adv}} + \underbrace{\frac{J(P_b, h)}{\rho_0}}_{\text{BPT}} + \underbrace{k \cdot \nabla \times \frac{\tau_{wind}}{\rho_0}}_{\text{wind curl}} \\
 & - \underbrace{k \cdot \nabla \times \frac{\tau_{bot}}{\rho_0}}_{\text{BDC}} + \underbrace{D_\Sigma}_{\text{horiz. diffusion}} + \underbrace{A_\Sigma}_{\text{NLA}},
 \end{aligned}$$

Climatic impacts

- CMIP5 models that do not show an SPG collapse have a very moderated warming hole
- Models highlighting a SPG collapse have large warming

