Mediterranean Sea

Surface and Intermediate Water Changes Triggering the Future Collapse of Deep Water Formation in the NorthWestern Mediterranean

Iván M. Parras-Berrocal , Rubén Vázquez , William Cabos , Dimitry V. Sein , Oscar Álvarez , Miguel Bruno , and Alfredo Izquierdo

Generalities :

LIW spreads westward at 150–600 m flowing through the Sicily strait and into the Tyrrhenian Sea, reaching the north western Mediterranean approximately a decade after its formation (Millot, 2005).

The LIW contributes to the Mediterranean outflow to the Atlantic Ocean, forming the main thermohaline circulation cell of the Mediterranean (Lascaratos et al., 1993; Robinson et al., 2001; Vargas-Yáñez et al., 2012).

Winter deep convection takes place in the Northwestern Mediterranean Sea (NWMed; Durrieu de Madron et al., 2013; Marshall &Schott, 1999; MEDOC-MEDOC Group, 1970), triggered by cold and dry regional winds of Mistral (northwester-ly) and Tramontane (northerly; Leaman & Schott, 1991; Somot et al., 2018).

These winds episodes induce intense surface buoyancy loss associated to a rapid surface cooling and strong evaporation (Schott & Leaman, 1991;Seyfried et al., 2017).

In the Gulf of Lions (GoL), the regional cyclonic circulation of MAW and of the underlying LIW (warmer and saltier) drives a doming of isopycnals that reduces the stratification locally and favors deep convection (Houpert et al., 2016; Rhein, 1995).

Surface and Intermediate Water Changes Triggering the Future Collapse of Deep Water Formation in the NorthWestern Mediterranean ; Iván M. Parras-Berrocal et al.

Abstract : Deep water formation (DWF) in the North Western Mediterranean (NWMed) is a key feature of Mediterranean overturning circulation. DWF changes under global warming may have an impact on the Mediterranean biogeochemistry and marine ecosystem. Here we analyze the deep convection in the Gulf ofLions (GoL) in a changing climate using a regional climate system model with a horizontal resolution high enough to represent DWF.

We find that under the RCP8.5 scenario the NWMed DWF collapses by 2040–2050, leading to a 92% shoaling in the winter mixed layer by the end of the century.

The collapse is related to a strengthening of the vertical stratification in the GoL caused by changes in properties of Modified Atlantic Water and Levantine Intermediate Water, being their relative contribution to the increase of the stratification 57.8% and 42.2%, respectively.

The stratification changes also alter the Mediterranean overturning circulation and the exchange with the Atlantic.

Keypoints :

- The North Western Mediterranean deep water formation (DWF) collapse by mid-21st century under the RCP8.5 scenario.
- The collapse is mostly drivenby changes in the properties of the Modified Atlantic Water and Levantine Intermediate Water.
- The DWF collapse is associated to changes in fluxes through the Straitof Gibraltar

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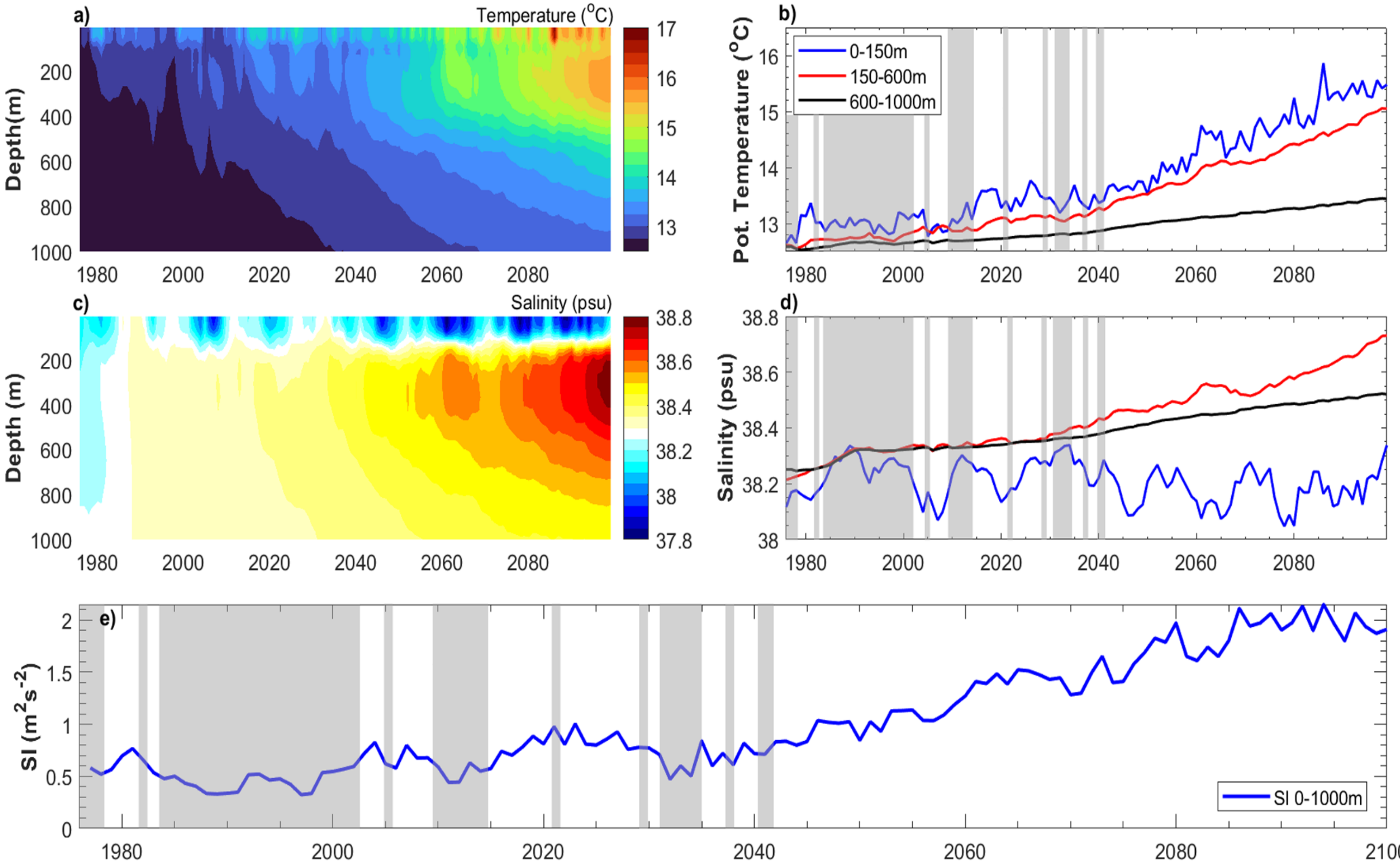
DWF collapse by mid-21st century under the RCP8.5 scenario.



$$SI = \int_0^h N^2 \, z dz$$

Figure 3. ROM RCP8.5 time series (1976–2099) of 0–1000 m (a) potential temperature (oC) and (c) salinity (psu). Yearly means of (b) potential temperature (oC) and (d) salinity (psu) averaged for the layers 0–150 m (blue), 150–600 m (red), 600–1000 m (black). (e) stratification index (SI) for 0–1000 m (blue). All time series correspond to winter months (December-January-February-March) whereas SI was computed in December of preceding year in the Gulf of Lions area. Gray bars indicate Deep water formation episodes (MLD_{max} > 1000 m).

Surface and Intermediate Water Changes Triggering the Future Collapse of Deep Water Formation in the NorthWestern Mediterranean ; Iván M. Parras-Berrocal et al.

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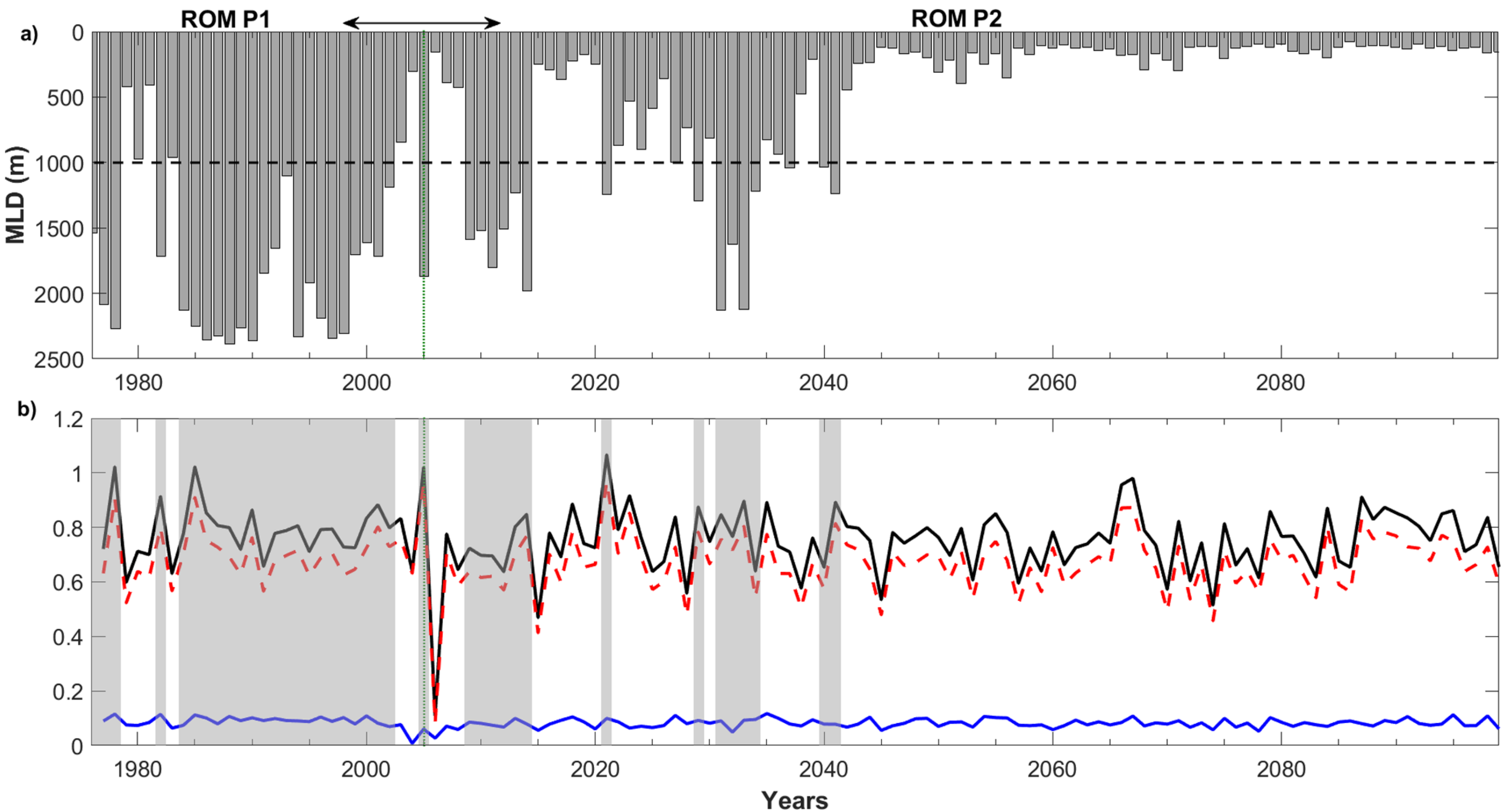


Figure 2. Time series (1976–2099) of ROM_P1 and ROM_P2 simulations of (a) yearly MLD_{max} (m) and (b) winter integrated buoyancy loss (BL) ($m^2 s^{-2}$) averaged over the Gulf of Lions. The black line corresponds to the total BL, the red dashed and the blue lines are the heat-related and the freshwater-related terms, respectively. Gray bars indicate Deep water formation episodes (MLD_{max} > 1000 m).

Atlantic Ocean

(but not only)

Is the AMOC collapsing ?

AMOC = **Atlantic meridional overturning circulation**

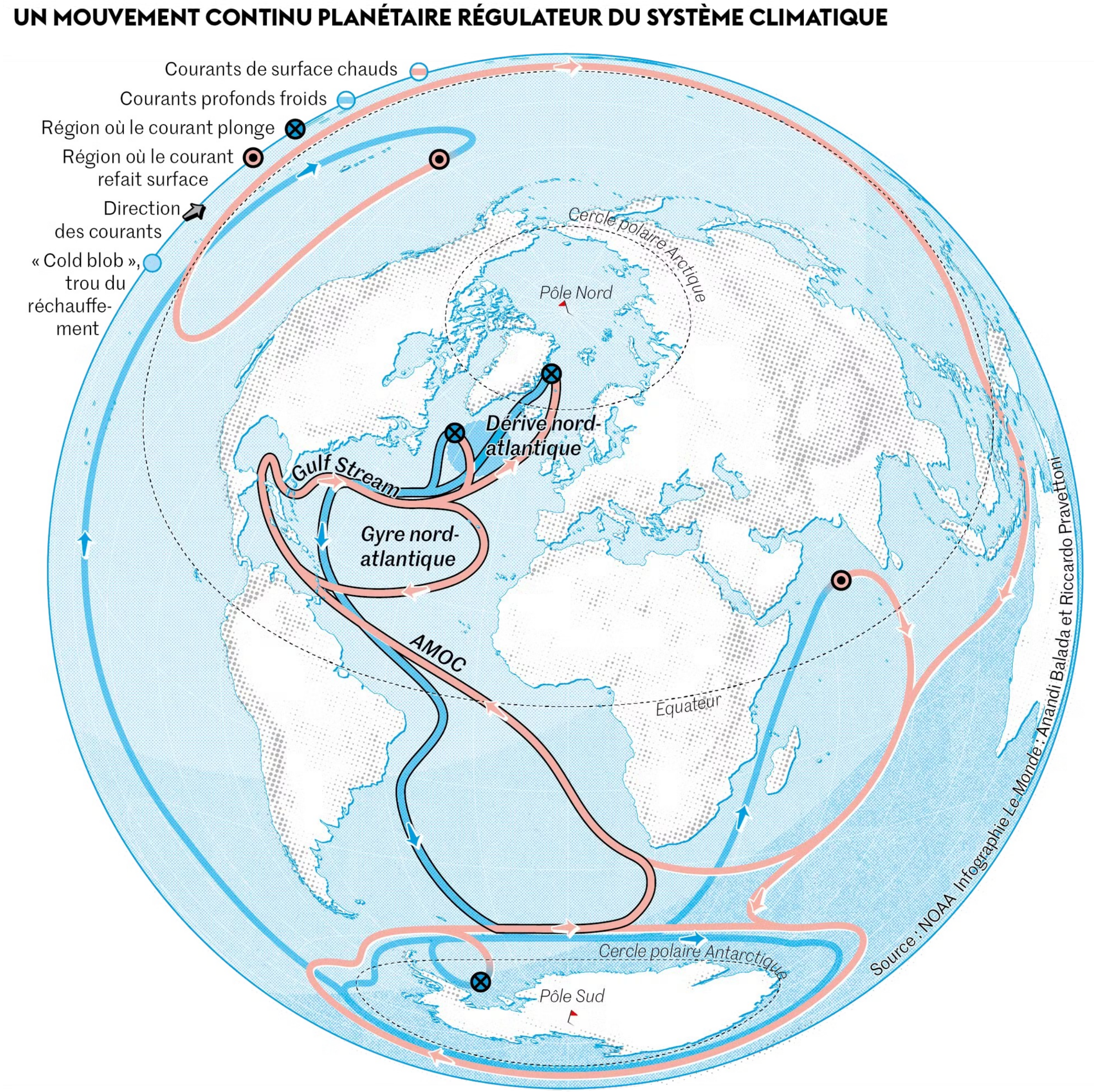
Warning of a forthcoming collapse of the Atlantic meridional overturning circulation.

Ditlevsen, P., Ditlevsen, S., Nat Commun 14, 4254 (2023).
https://doi.org/10.1038/s41467-023-39810-w

Niels Bohr Institute,
University of Copenhagen
Copenhagen, Denmark

50 times the energy of humanity

AMOC includes Gulf stream



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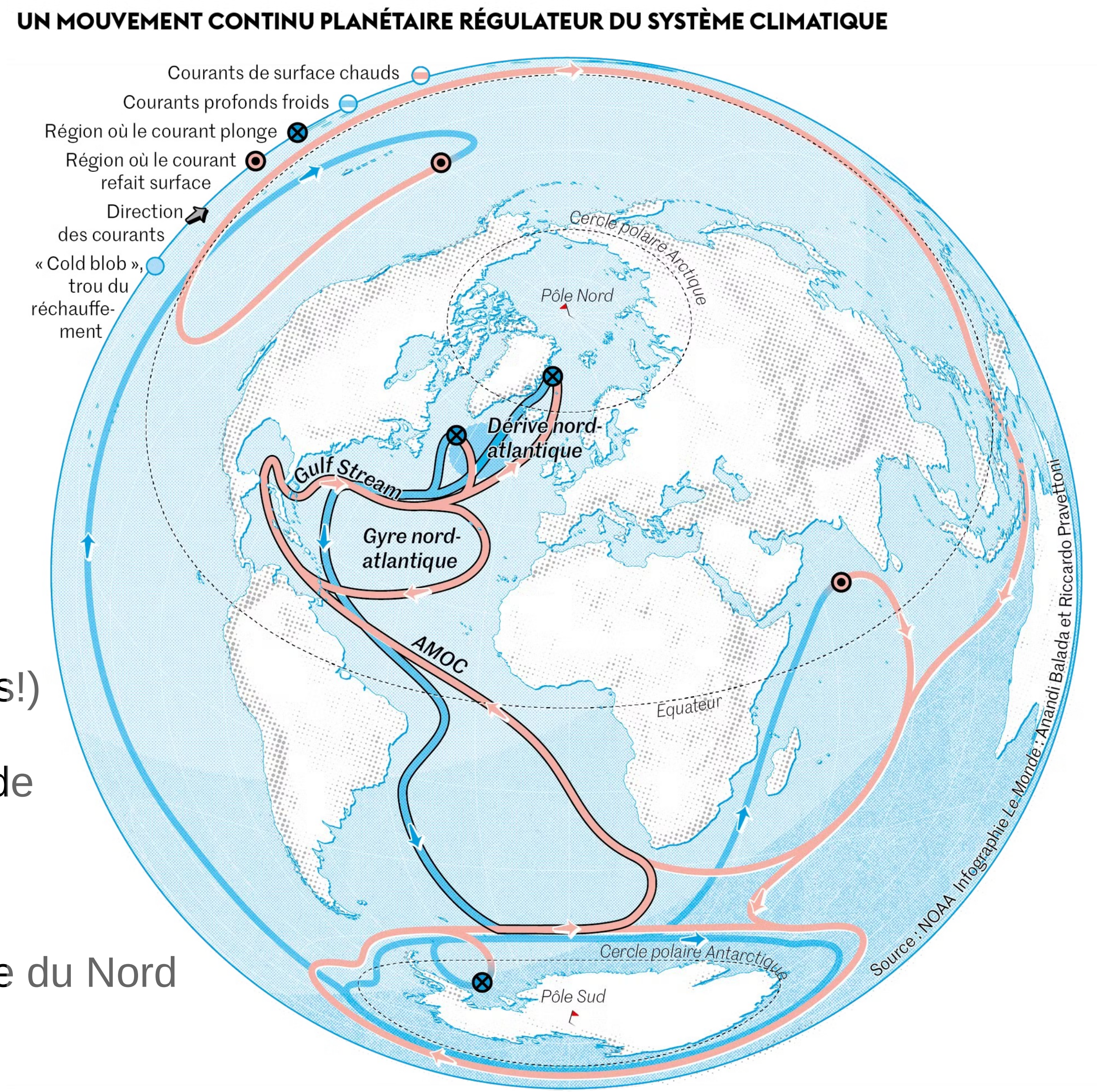
Niels Bohr Institute,
University of Copenhagen
Copenhagen, Denmark·

Film
« Le Jour d'après » (R. Emmerich)
conséquences catastrophiques d'une perturbation de la circulation de l'océan Atlantique, conduisant à une nouvelle ère glaciaire.
scénario totalement irréaliste (amplitude du refroidissement + échelle de temps : en quelques jours!)

Mais… inquiétude/ ralentissement de l'AMOC

climat doux en Europe
Régule la température de l'Amérique du Nord

- .



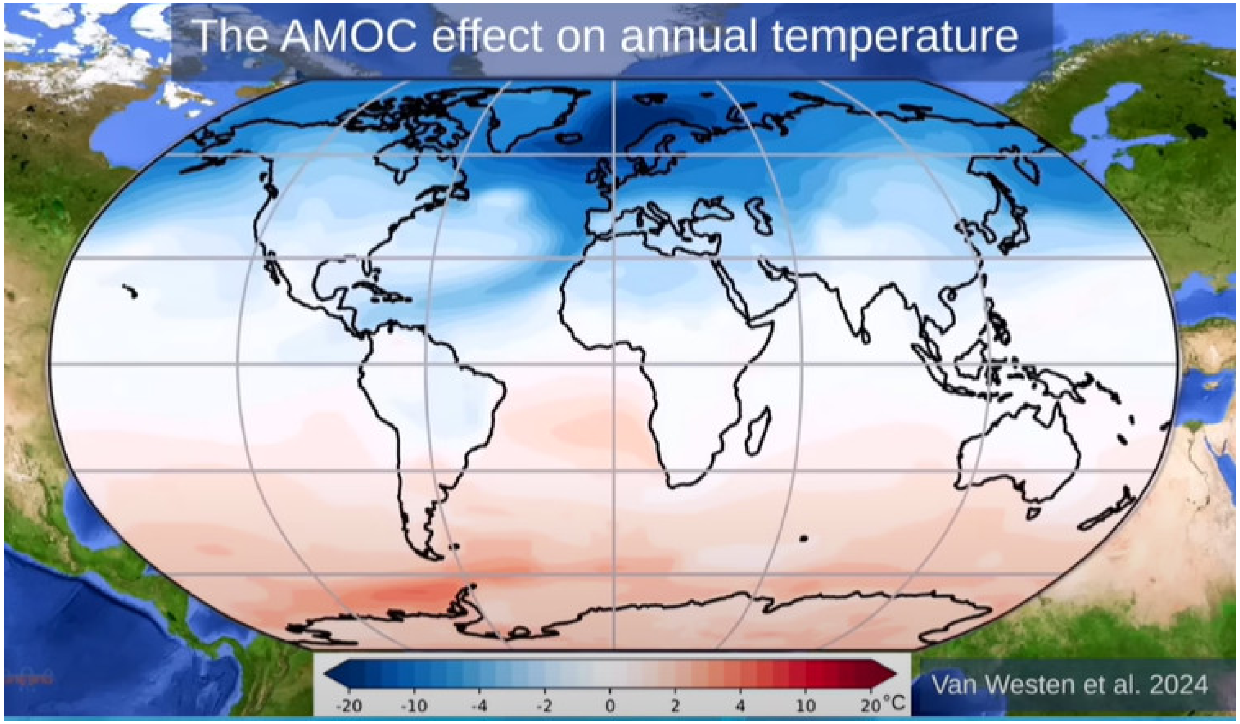
North Atlantic :
excess warming along Northern America
+ cold blob (down to 2000 m) in middle Northern Atlantic

Prof. Stefan Rahmstorf

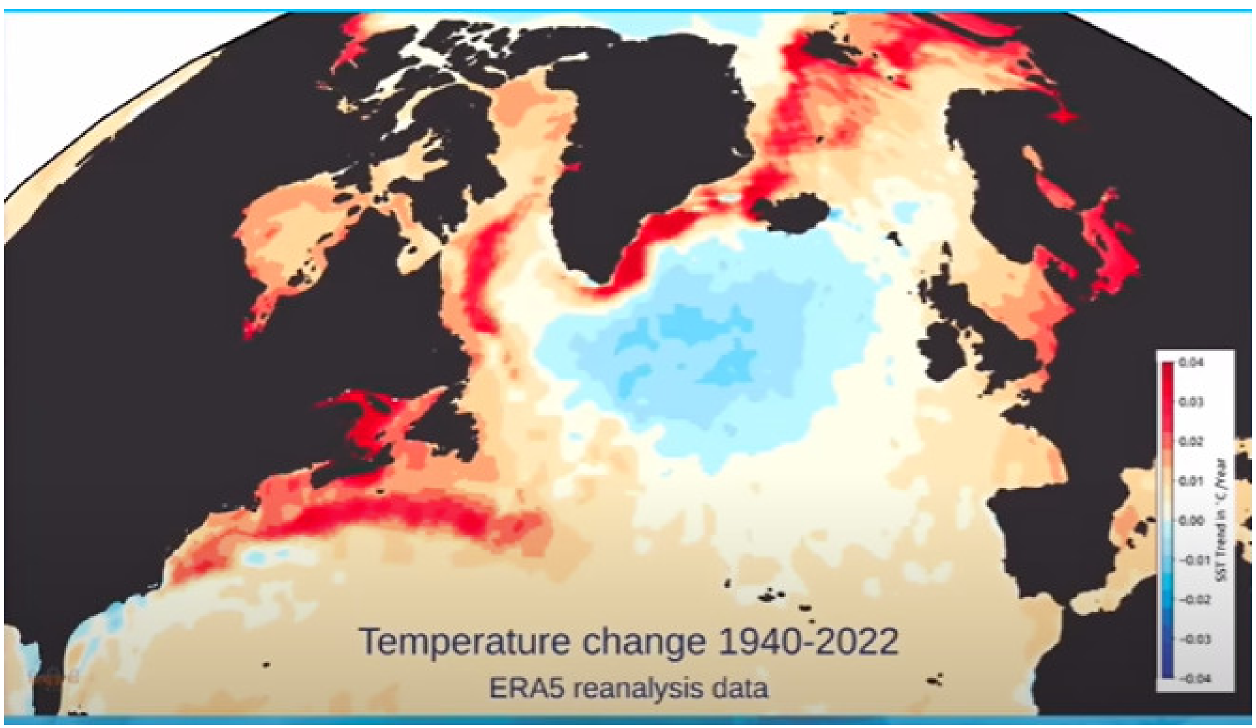
Postdam institute

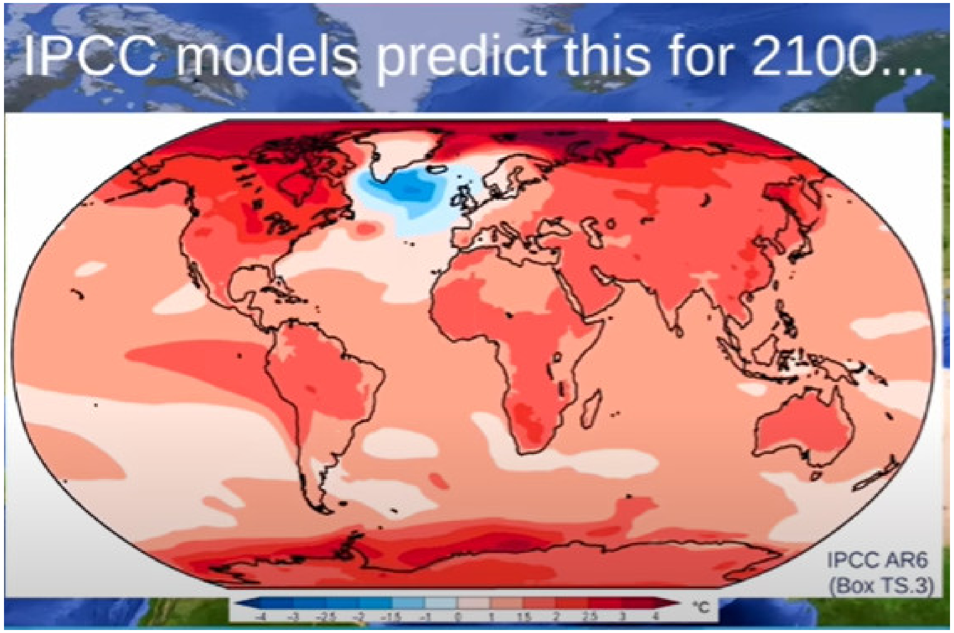
Is the AMOC shutting down ?

https://youtu.be/mm_YZ2juQL4

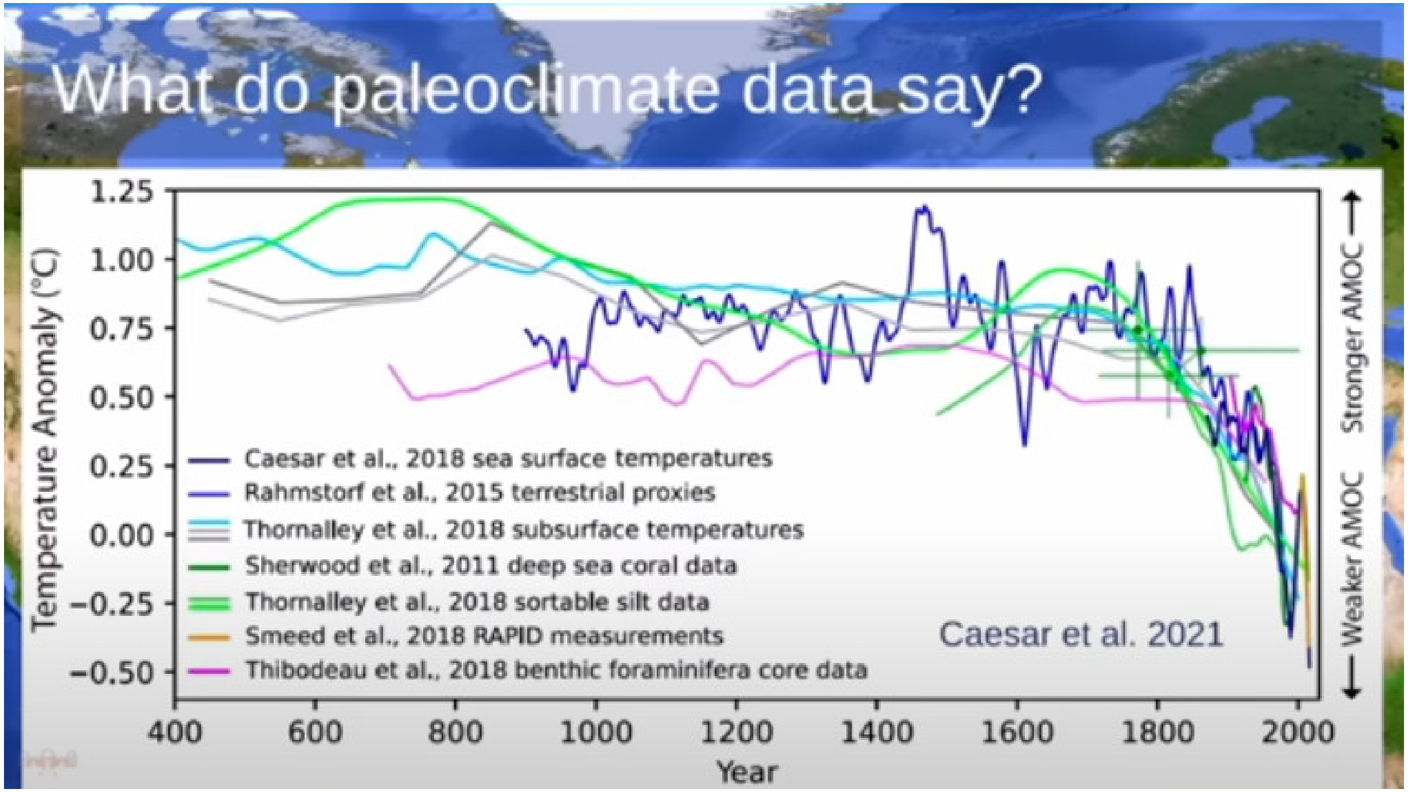


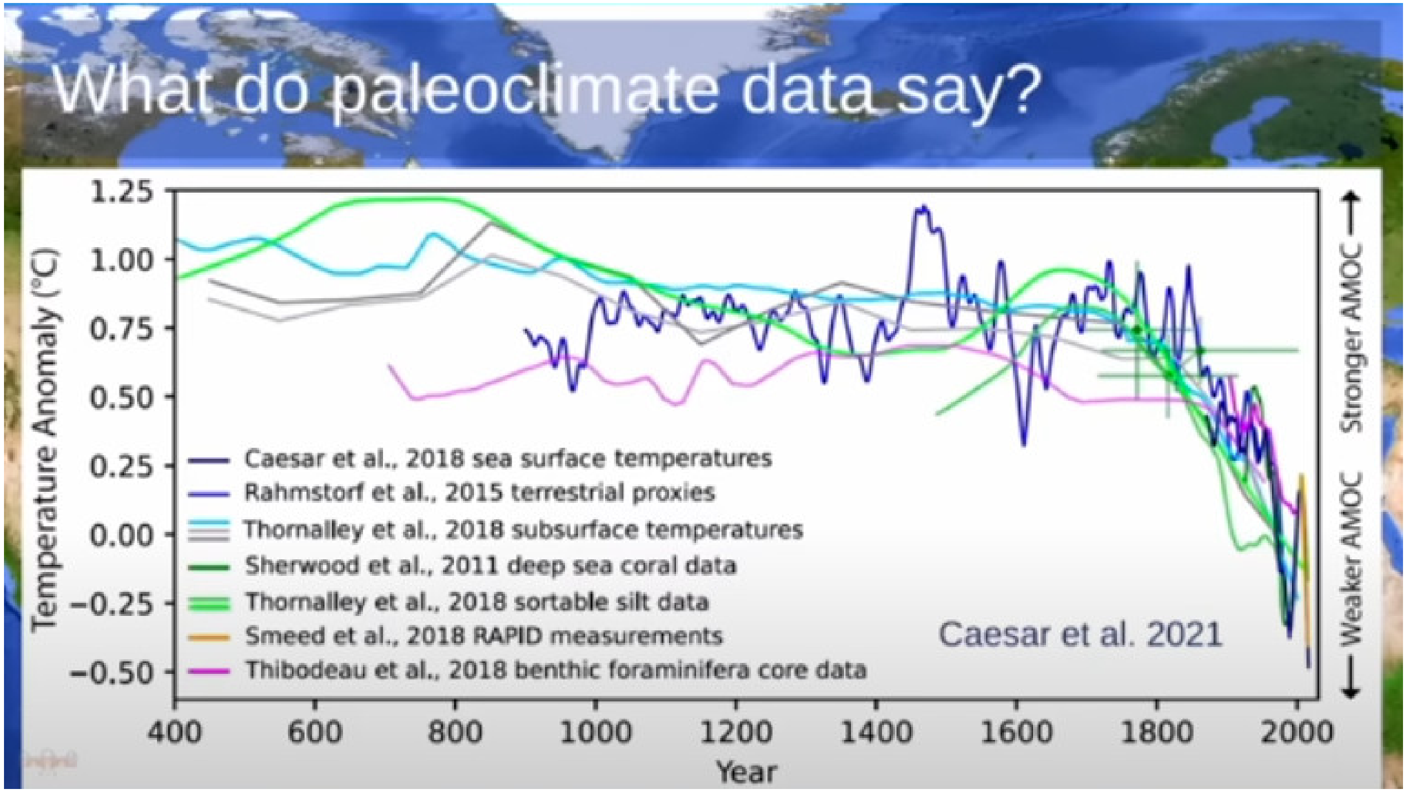
When stopping just the AMOC (no global warming)



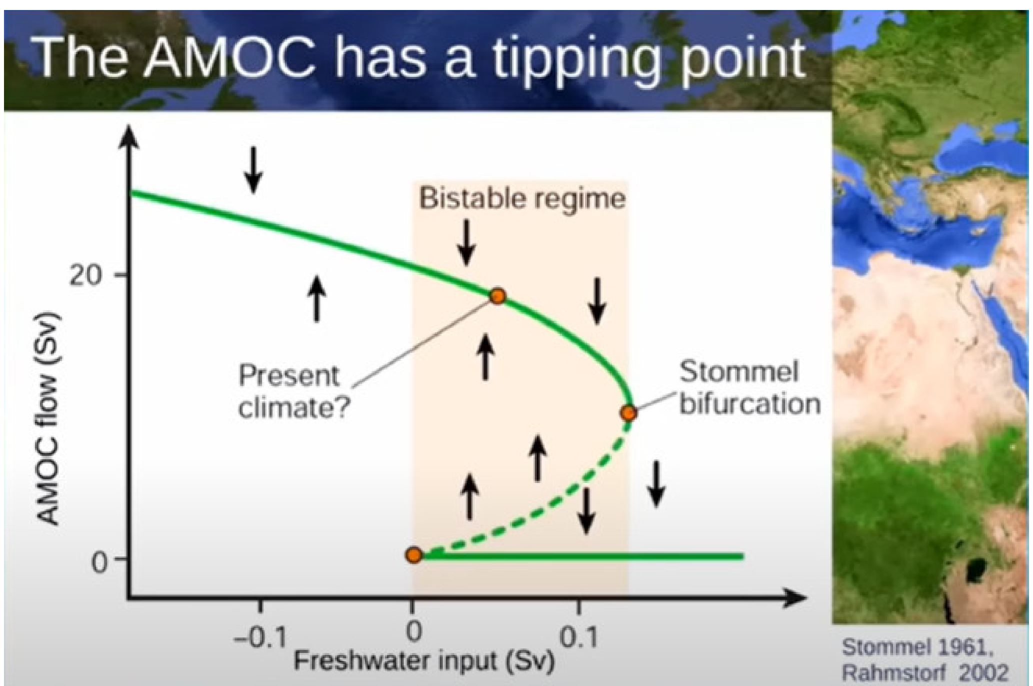


IPCC models underestimate
the NA cold blob





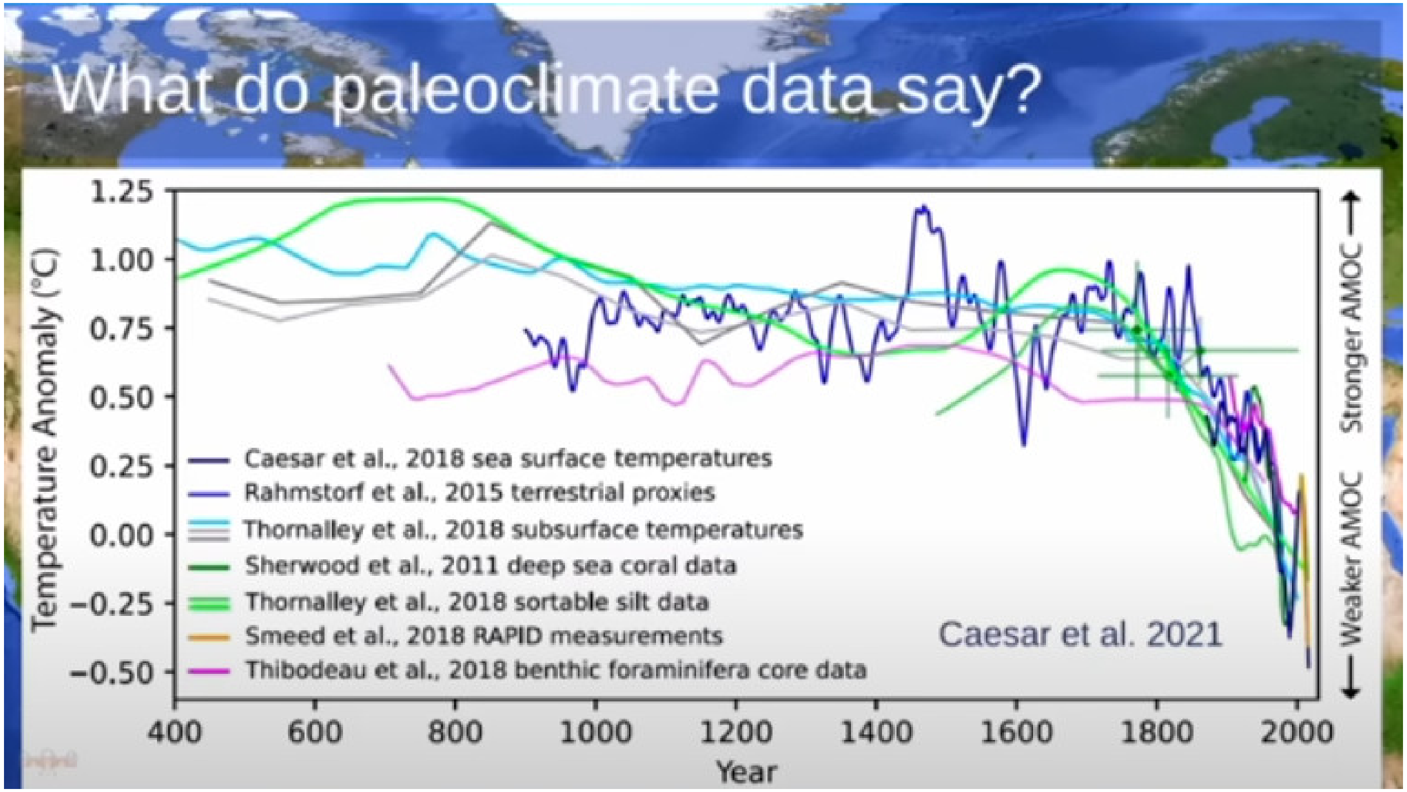
Caesar (2021) paleoclimate data show stability until 1800s, and then AMOC decline

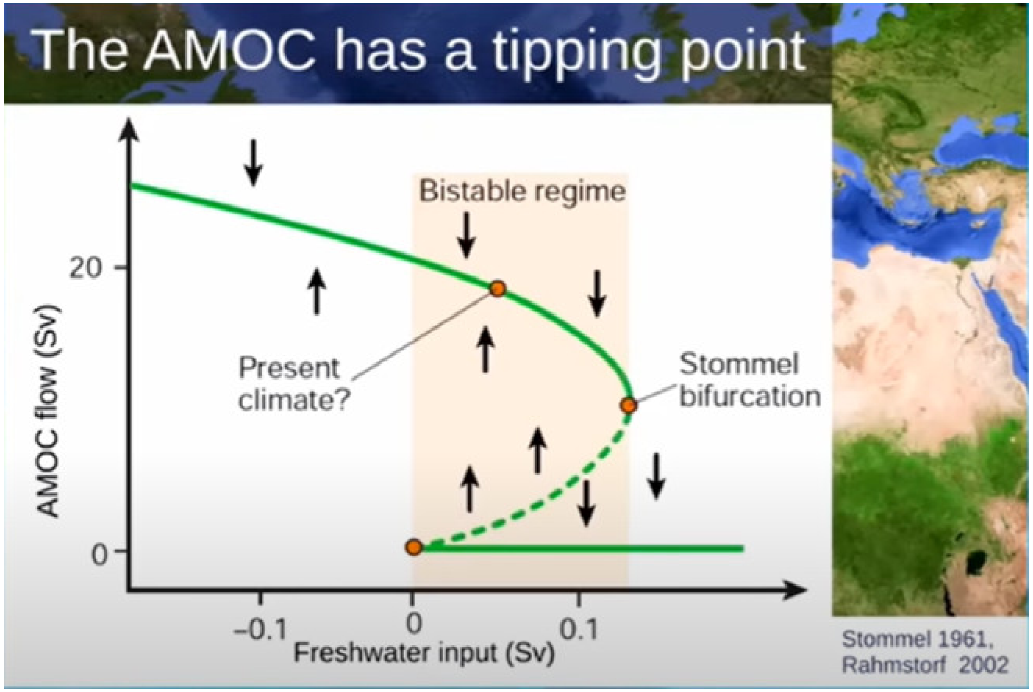


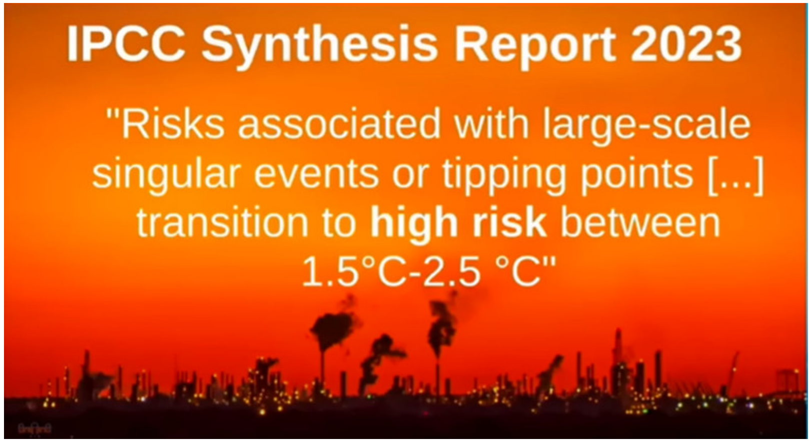
But this process has a tipping point

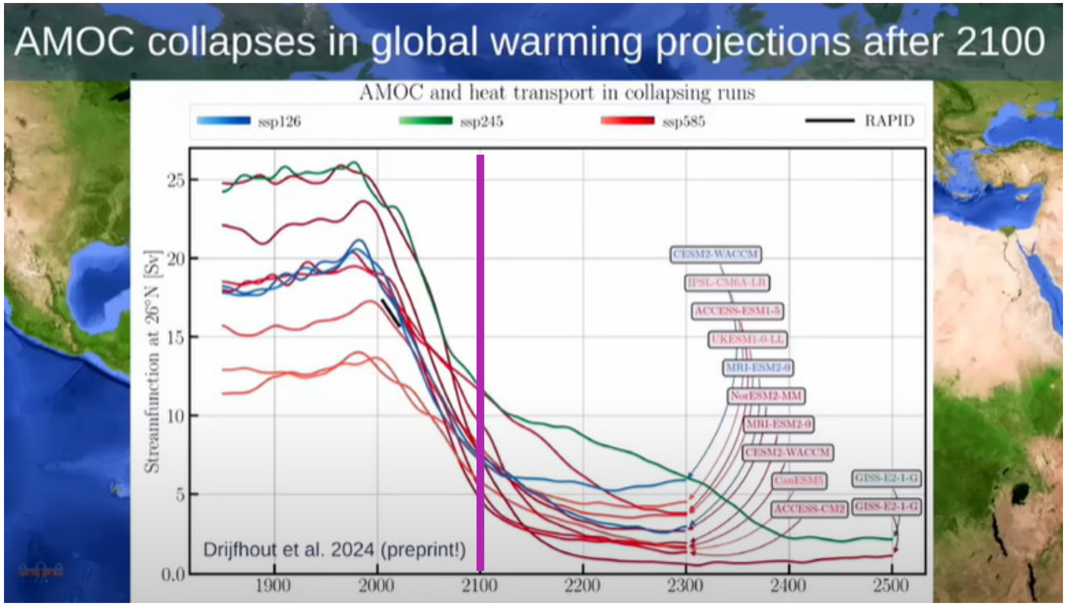
AMOC flow becomes weaker but also contains and transport less salty water to the North, hence reinforces the weakness of AMOC etc...

positive retro feedback -> amplifying effect, never ending hence BIG RISK

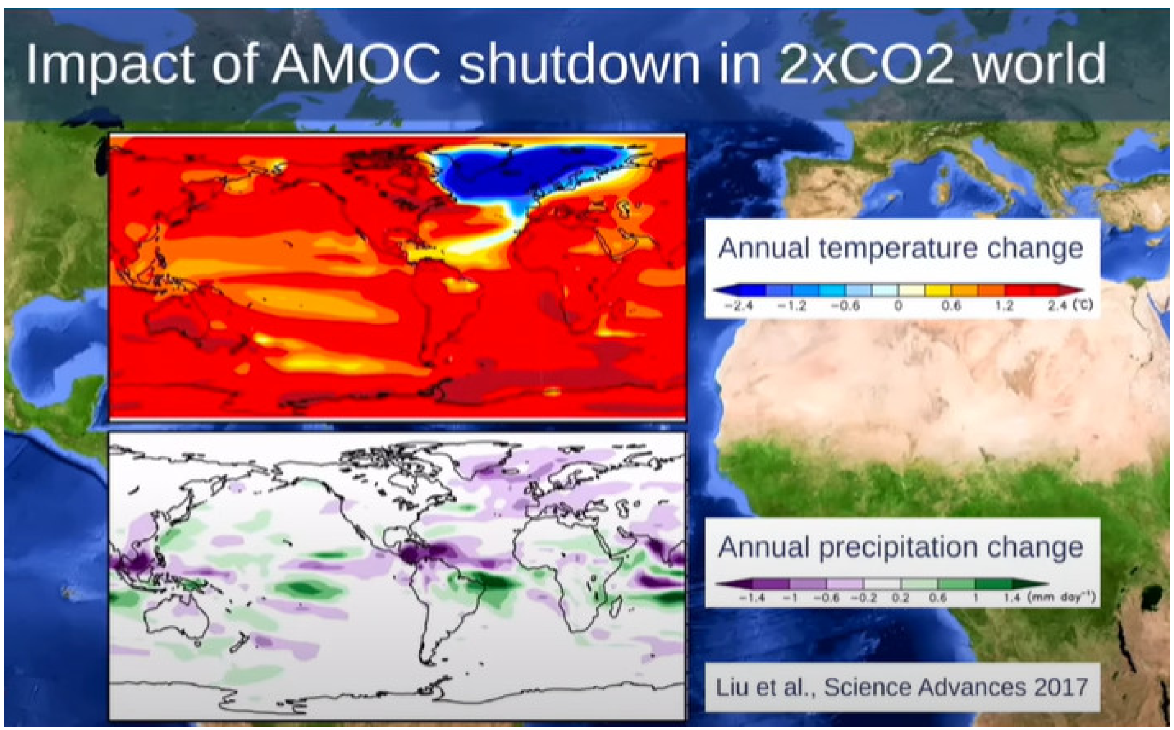

What do paleoclimate data say?
1.25
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
Temperature Anomaly (°C)
Caesar et al., 2018 sea surface temperatures
Rahmstorf et al., 2015 terrestrial proxies
Thornalley et al., 2018 subsurface temperatures
Sherwood et al., 2011 deep sea coral data
Thornalley et al., 2018 sortable silt data
Smeed et al., 2018 RAPID measurements
Thibodeau et al., 2018 benthic foraminifera core data
Caesar et al. 2021
400
600
800
1000
1200
1400
1600
1800
2000
Year
Stronger AMOC
Weaker AMOC


The AMOC has a tipping point
Bistable regime
20
0
AMOC flow (Sv)
Present
climate?
Stommel
bifurcation
−0.1
0
0.1
Freshwater input (Sv)
Stommel 1961,
Rahmstorf 2002


IPCC Synthesis Report 2023
"Risks associated with large-scale
singular events or tipping points [...]
transition to **high risk** between
1.5°C-2.5 °C"



8 models out of 10 predict that
AMOC collapses by 2100



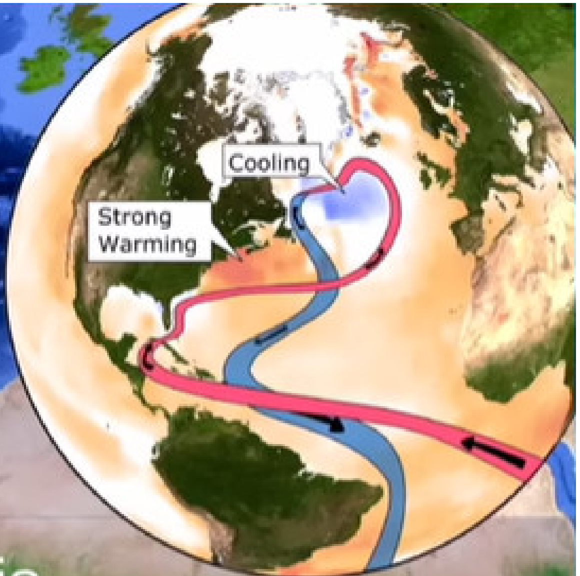
in average it looks good for
northern FranceGermany

but in fact it is an annual mean
while there will be weather fluctuations
and huge drastic temperature shifts

drier in Northern Europe
rain shift south in the Tropics

Conclusions

- The AMOC is weakening
- The AMOC has a tipping point
- It is still uncertain how close it is
- Recent studies: too close for comfort!



Lettre ouverte adressée aux dirigeants du Conseil nordique des ministres, par 44 scientifiques du climat, publiée fin octobre 2024

Mise en garde contre
le risque d'un effondrement de l'AMOC,
aux effets « irréversibles » et
« dévastateurs »,

en particulier pour les pays nordiques,
mais également
pour l'ensemble du monde.

Risque d'événements singuliers
à grande échelle ou de
points de basculement

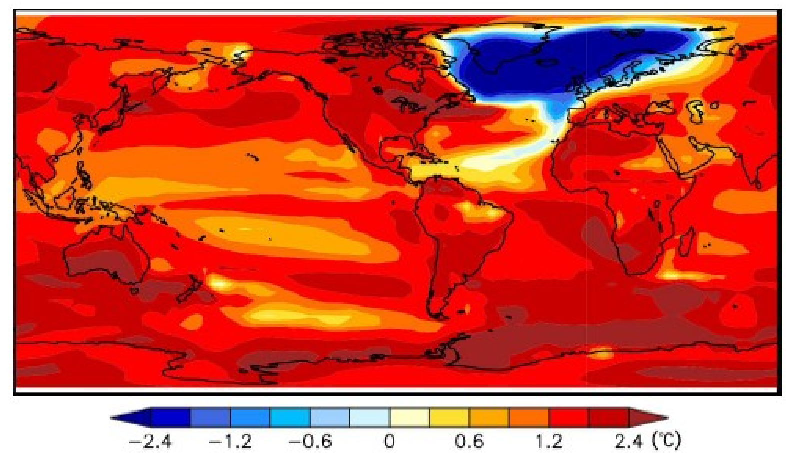
Figure
Anomalie de température
en cas de collapse de l'AMOC

Extrêmes
<-2.4 °C dans le Nord Atlantique
> + 2.4°C autres endroits

Open Letter by Climate Scientists to the Nordic Council of Ministers

Reykjavik, October 2024

We, the undersigned, are scientists working in the field of climate research and feel it is urgent to draw the attention of the Nordic Council of Ministers to the serious risk of a major ocean circulation change in the Atlantic. A string of scientific studies in the past few years suggests that this risk has so far been greatly underestimated. Such an ocean circulation change would have devastating and irreversible impacts especially for Nordic countries, but also for other parts of the world.



Annual mean temperature change in an idealised future CO2 doubling scenario in which the AMOC has fully collapsed. Source: Science[1].

Science increasingly confirms that the Arctic region is a "ground zero" for tipping point risks and climate regulation across the planet. In this region, the Greenland Ice Sheet, the Barents sea ice, the boreal permafrost systems, the subpolar gyre deep-water formation and the Atlantic Meridional Overturning Circulation (AMOC) are all vulnerable to major, interconnected nonlinear changes[2]. The AMOC, the dominant mechanism of northward heat transport in the North Atlantic, determines life conditions for all people in the Arctic region and beyond and is increasingly at risk of passing a tipping point.

Tipping point risks are real and can occur within the 1.5-2°C climate range of the Paris Agreement[3]. The world is currently heading well beyond this range (> 2.5°C). In the Synthesis report of the IPCC (2023) it is stated with high confidence that the likelihood of abrupt or

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IPCC report of 2023 regarding the risk of « tipping point»

“ medium confidence that the AMOC will not collapse abruptly before 2100,

but if it were to occur, it would very likely cause abrupt shifts in regional weather patterns, and large impacts on ecosystems and human activities.”

Recent research since the last IPCC report does suggest that the IPCC has underestimated this risk

and that the passing of this tipping point is a serious possibility already in the next few decades.

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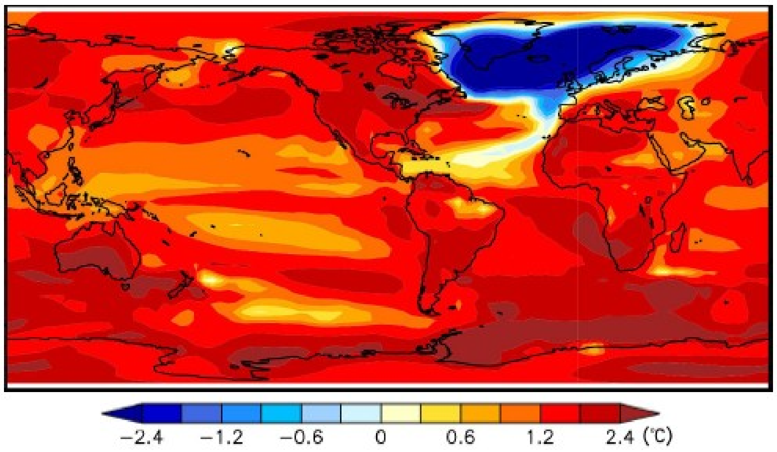

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Warning of a forthcoming collapse of the Atlantic meridional overturning circulation.

Ditlevsen, P., Ditlevsen, S., Nat Commun 14, 4254 (2023).
https://doi.org/10.1038/s41467-023-39810-w

Abstract :
The Atlantic meridional overturning circulation (AMOC) is a major tipping element in the climate system and a future collapse would have severe impacts on the climate in the North Atlantic region.

In recent years weakening in circulation has been reported, but assessments by the Intergovernmental Panel on Climate Change (IPCC), based on the Climate Model Intercomparison Project (CMIP) model simulations suggest that a full collapse is unlikely within the 21st century.

Tipping to an undesired state in the climate is, however, a growing concern with increasing greenhouse gas concentrations.

Predictions based on observations rely on **detecting early-warning signals, primarily an increase in variance (loss of resilience) and increased autocorrelation (critical slowing down), which have recently been reported for the AMOC.**

Here we provide statistical significance and data-driven estimators for the time of tipping :

We estimate a collapse of the AMOC to occur around mid-century under the current scenario of future emissions.

- .

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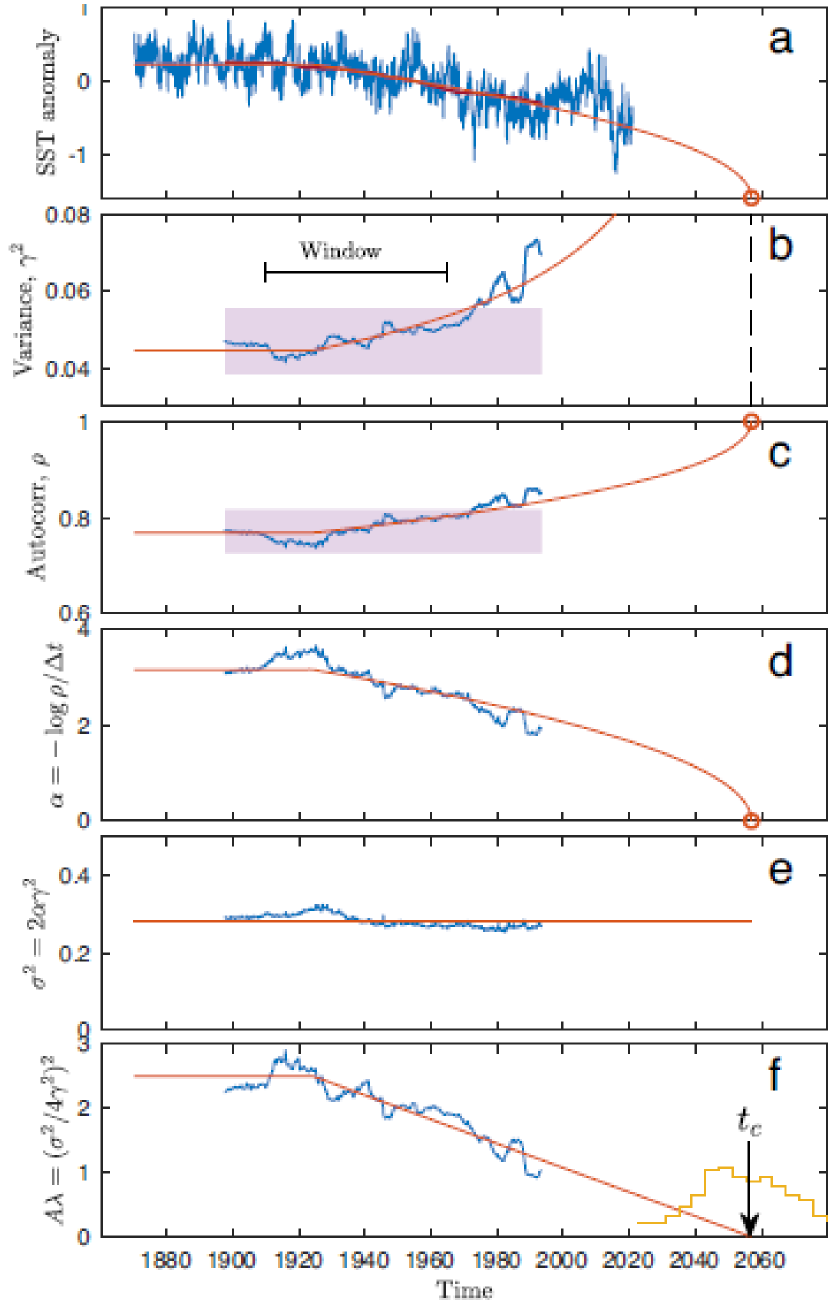

Fig. 5 | Detection of early-warning signals and prediction of tipping time. a Sea surface temperature (SST) anomaly (identical to Fig. 1e) together with the best estimate model of the steady state approaching a critical transition. b, c Variance and autocorrelation calculated within running 50-year windows, similar to Fig. 4c, d. The two-standard error level (indicated by the purple band) is obtained using the model to estimate the time varying α (d) and σ^2 (e) from the data. f Best estimate for t_c. The yellow histogram is the probability density for t_c obtained by maximum likelihood estimates (see Supplementary Information S1 and S2).

Physics-based early warning signal shows that AMOC is on tipping course.

van Westen, R. M., Kliphuis, M. A. & Dijkstra, H. A.
Science Advances (2024).
https://doi.org:10.1126/sciadv.adk1189

Abstract :
One of the most prominent climate tipping elements is the Atlantic meridional overturning circulation (AMOC), which can potentially collapse because of the input of fresh water in the North Atlantic.

Although AMOC collapses have been induced in complex global climate models by strong freshwater forcing, the processes of an AMOC tipping event have so far not been investigated.

Here, we show results of the first tipping event in the Community Earth System Model, including the large climate impacts of the collapse.

Using these results, we develop a physics-based and observable early warning signal of AMOC tipping: the minimum of the AMOC-induced freshwater transport at the southern boundary of the Atlantic.

Reanalysis products indicate that the present-day AMOC is on route to tipping. The early warning signal is a useful alternative to classical statistical ones, which, when applied to our simulated tipping event, turn out to be sensitive to the analyzed time interval before tipping.

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A) AMOC strength
à 26°N
en Sv
-

$$\mathrm{AMOC}(y = 26°\mathrm{N}) = \int_{-1000}^{0} \int_{x_W}^{x_E} v \; dxdz$$

MHT = Atlantic meridional heat transport

B) sur 50 ans
C) 1701-1750
D) 2151 - 2200

Attention
ce ne sont PAS
les dates actuelles
mais des années
de modélisation !

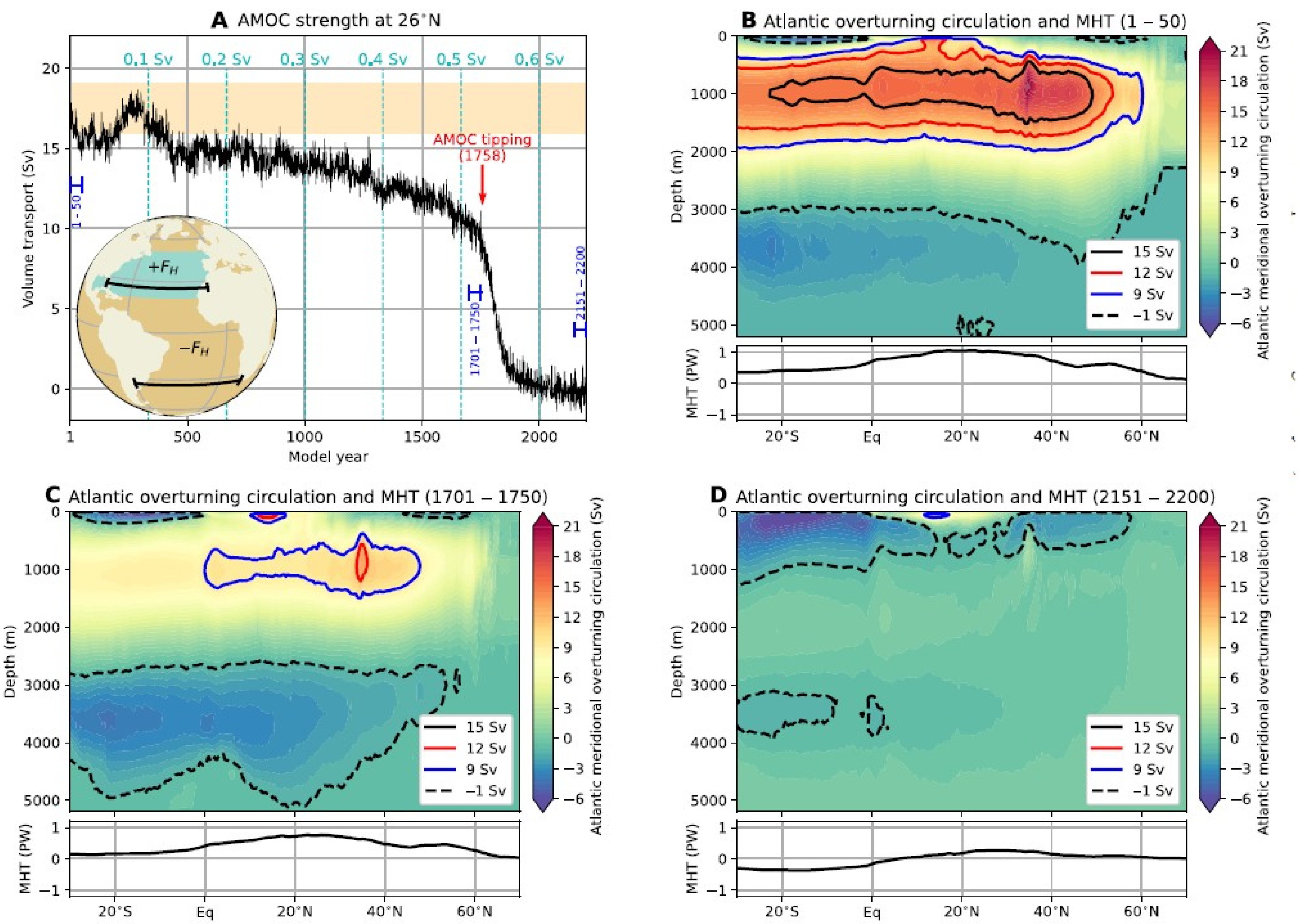

Fig. 1. AMOC collapse. (**A**) The AMOC strength at 1000 m and 26°N, where the yellow shading indicates observed ranges (*60*, *61*). The cyan-colored lines indicate the magnitude of F_H. The red arrow indicates the AMOC tipping point (model year 1758; fig. S1, A and B), and the blue sections indicate the 50-year periods used in (B) to (D). Inset: The hosing experiment where fresh water is added to the ocean surface between 20°N and 50°N in the Atlantic Ocean ($+F_H$) and is compensated over the remaining ocean surface ($-F_H$). The black sections indicate the 26°N and 34°S latitudes over which the AMOC strength and freshwater transport (F_{ovS}) are determined, respectively. (**B** to **D**) AMOC streamfunction (Ψ) and Atlantic meridional heat transport (MHT; see also fig. S2) for model years 1 to 50, 1701 to 1750, and 2151 to 2200. The contours indicate the isolines of Ψ for different values.

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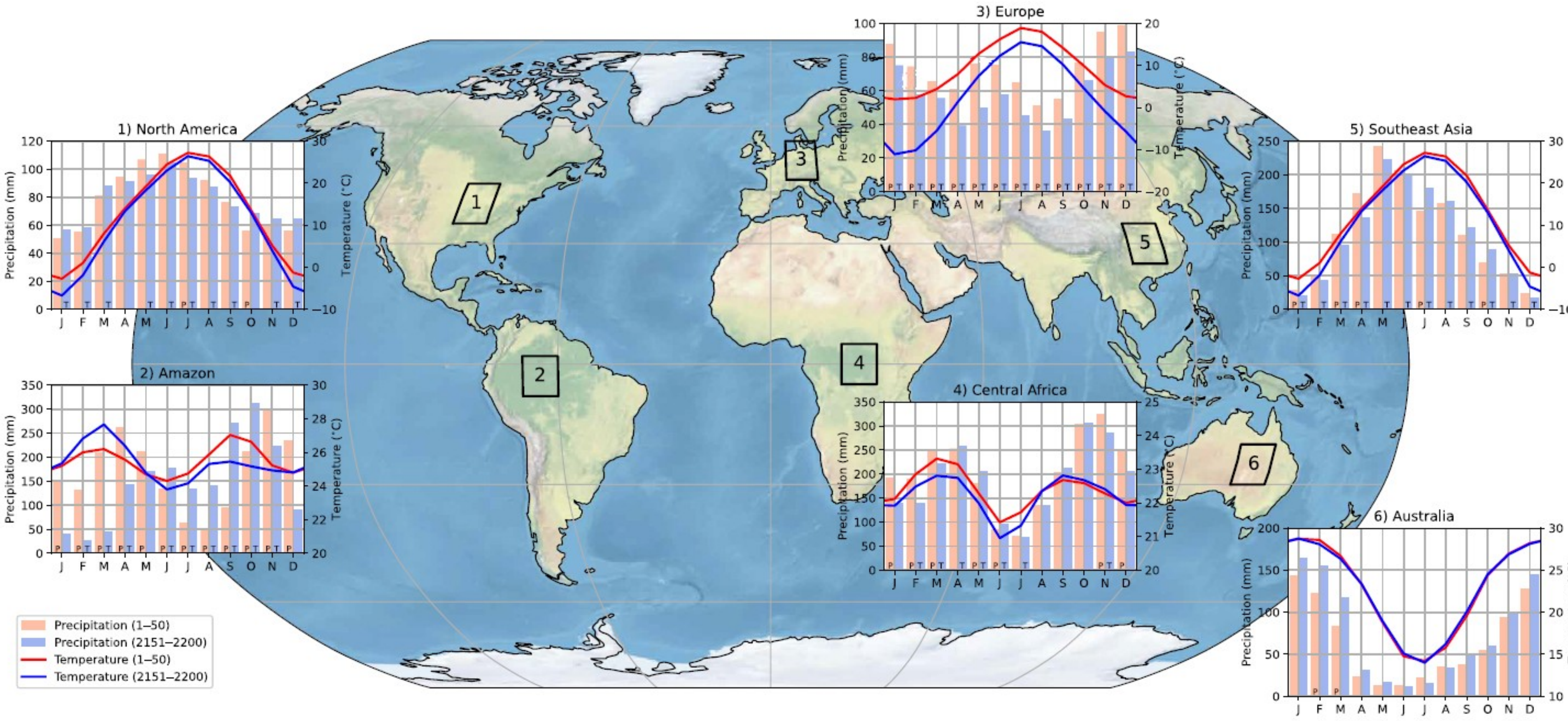

Fig. 2. Climograph for different regions. The climograph for six different regions (spatial average over the 10° × 10° boxes), where the bars indicate the monthly precipitation and the curves indicate the monthly temperatures. The climograph is determined over model years 1 to 50 (red bars and curves) and model years 2151 to 2200 (blue bars and curves). Note the different vertical ranges for each climograph. The letters P and T in the bars indicate significant ($P < 0.05$, two-sided Welch's t test) monthly differences for precipitation and temperature, respectively.

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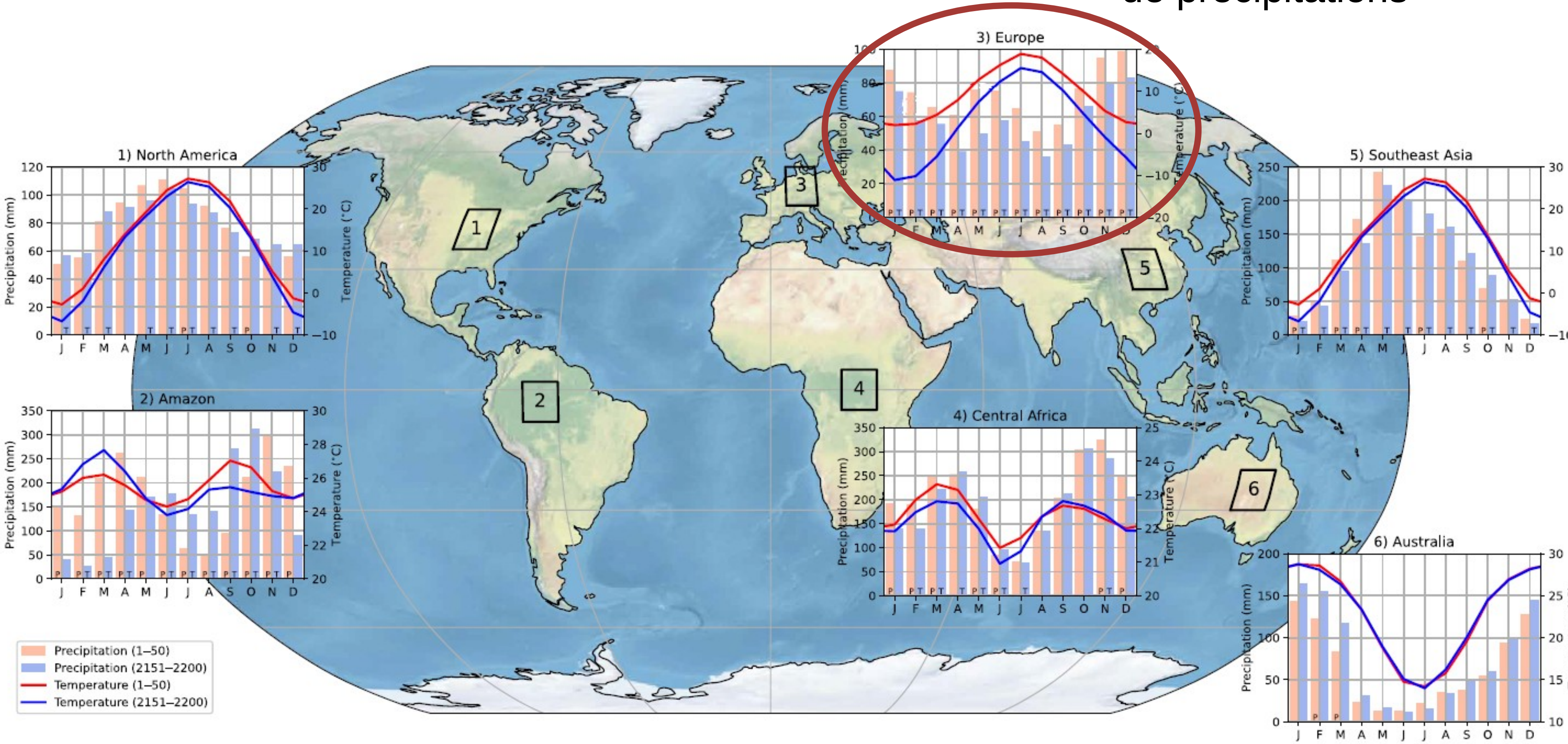
+ grande amplitude de T
(+froid -10°C en hiver)
- de précipitations



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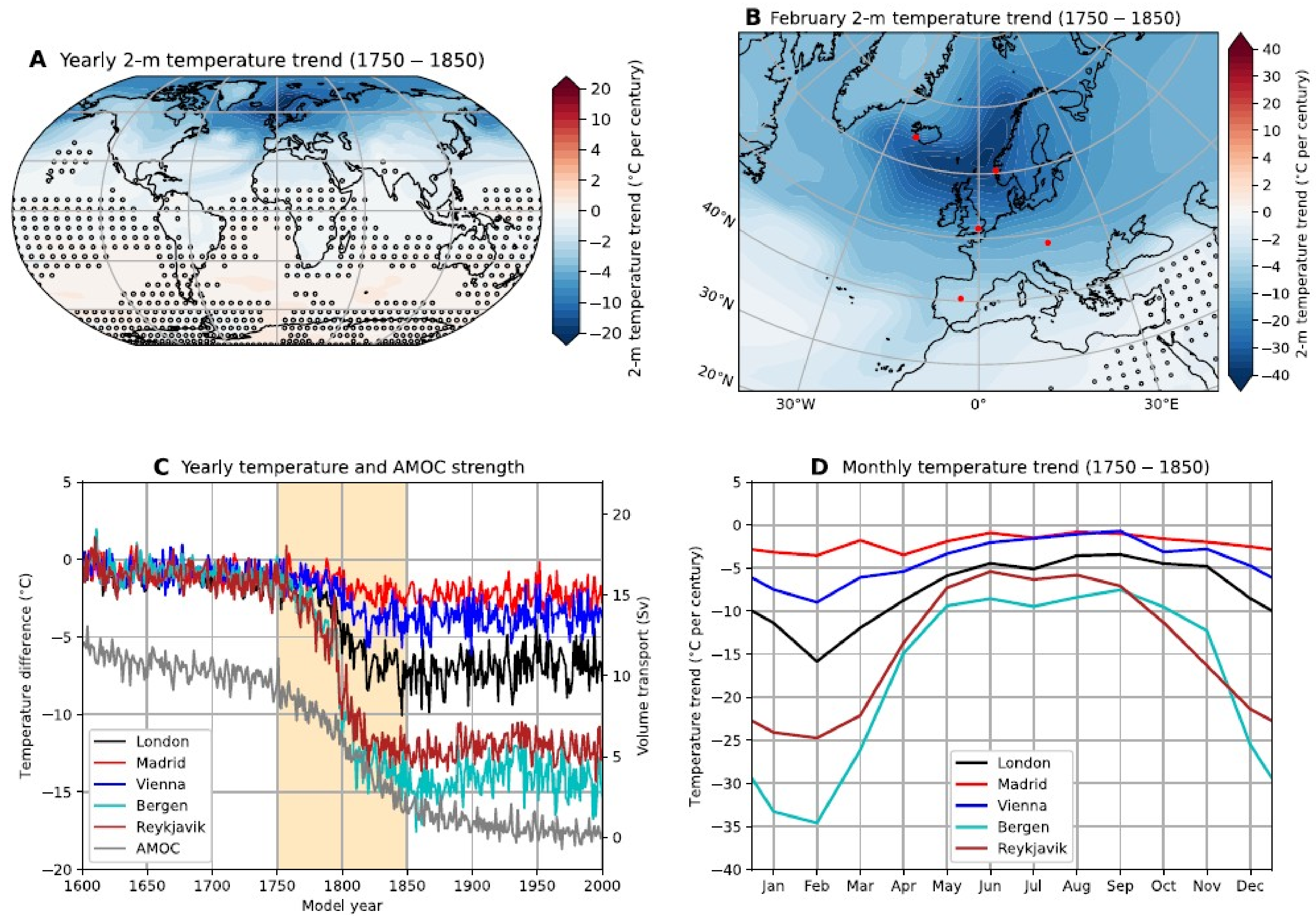

+ grande amplitude de T
(+froid -25°C en hiver
à Bergen, Norvège)

Fig. 3. Surface temperature response during AMOC collapse. (**A**) Yearly averaged 2-m surface temperature trend (model years 1750 to 1850). The markers indicate nonsignificant trends [$P > 0.05$, two-sided *t* test (*23*)]. (**B**) Similar to (A) but now for the February 2-m surface temperature trend. The red dots indicate five different cities used in (C) and (D). Note the different color bar ranges between (A) and (B). (**C**) Temperature difference (with respect to model year 1600) for five different cities, including the AMOC strength. The trends are determined over model years 1750 to 1850 (yellow shading) during which the AMOC strength strongly decreases. (**D**) Monthly temperature trends for the five different cities.

Physics-based early warning signal shows that AMOC is on tipping course.

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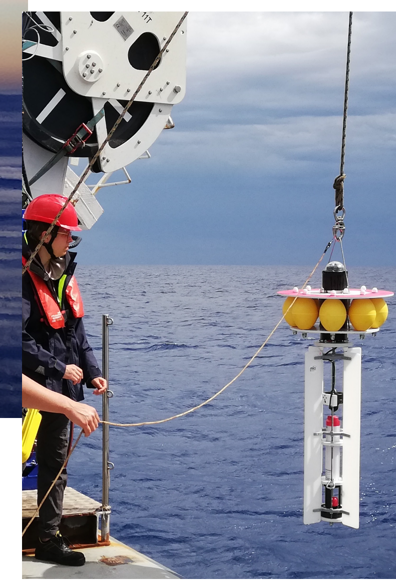
À la fin : « Dans la simulation CESM présentée ici, le basculement de l'AMOC se produit à des valeurs relativement élevées du forçage hydrique. Ceci est dû à des biais dans les précipitations ailleurs dans les modèles, principalement sur l'océan Indien (37).
Par conséquent,
nous avons dû intégrer le CESM à des valeurs relativement élevées du forçage hydrique [~0,6 Sv, soit environ 80 fois plus que le taux de fonte actuel de la calotte glaciaire du Groenland (55)] pour déterminer l'événement de basculement de l'AMOC.

(...)

Une fois les biais corrigés dans le CESM, on s'attend à ce que le basculement de l'AMOC se produise à des valeurs plus faibles du forçage hydrique. Comme l'état actuel du climat et le forçage du changement climatique sont différents de ceux de nos simulations, l'AMOC réel actuel pourrait être beaucoup plus proche de son point de basculement que dans les simulations. »

Thanks for your attention

FF-ADCP
Comby et al., 2022



VVP
Fuda et al., 2023

Mediterranean Institute of Oceanography