Atlantic Meridional Overturning Circulation

Why its collapse would be dangerous to the climate of Europe and why I do not believe it will happen in our lifetime.

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Institute of Oceanology PAN, Sopot, Poland

IGF UW Seminar, Warsaw (remotely), May 29th, 2026

CLIMATE • 4 MIN READ

A critical system of Atlantic Ocean currents could collapse as early as the 2030s, new research suggests

UPDATED AUG 3, 2024

By Angela Dewan, Angela Fritz

Physics > Atmospheric and Oceanic Physics

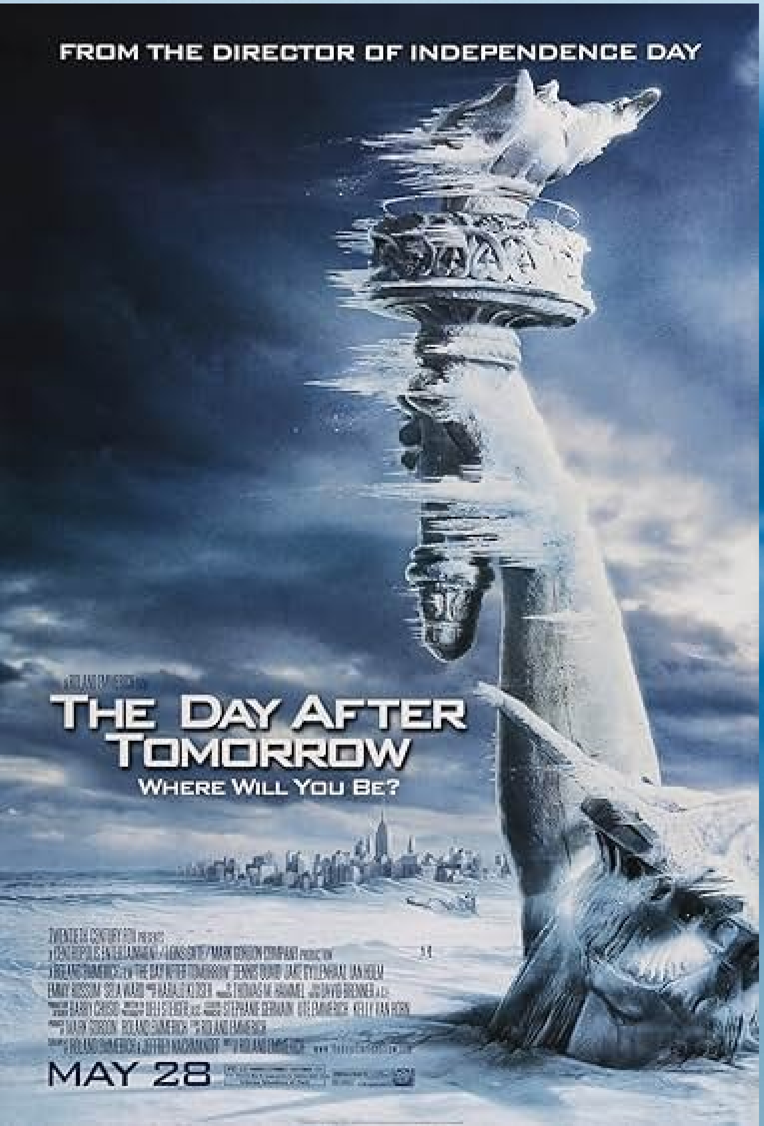
[Submitted on 17 Jun 2024]

Probability Estimates of a 21st Century AMOC Collapse

Emma J.V. Smolders, René M. van Westen, Henk A. Dijkstra

There is increasing concern that the Atlantic Meridional Overturning Circulation (AMOC) may collapse this century with a disrupting societal impact on large parts of the world. Preliminary estimates of the probability of such an AMOC collapse have so far been based on conceptual models and statistical analyses of proxy data. Here, we provide observationally based estimates of such probabilities from reanalysis data. We first identify optimal observation regions of an AMOC collapse from a recent global climate model simulation. Salinity data near the southern boundary of the Atlantic turn out to be optimal to provide estimates of the time of the AMOC collapse in this model. Based on the reanalysis products, we next determine probability density functions of the AMOC collapse time. The collapse time is estimated between 2037-2064 (10-90% CI) with a mean of 2050 and the probability of an AMOC collapse before the year 2050 is estimated to be 59 +/- 17%.

The Day After Tomorrow

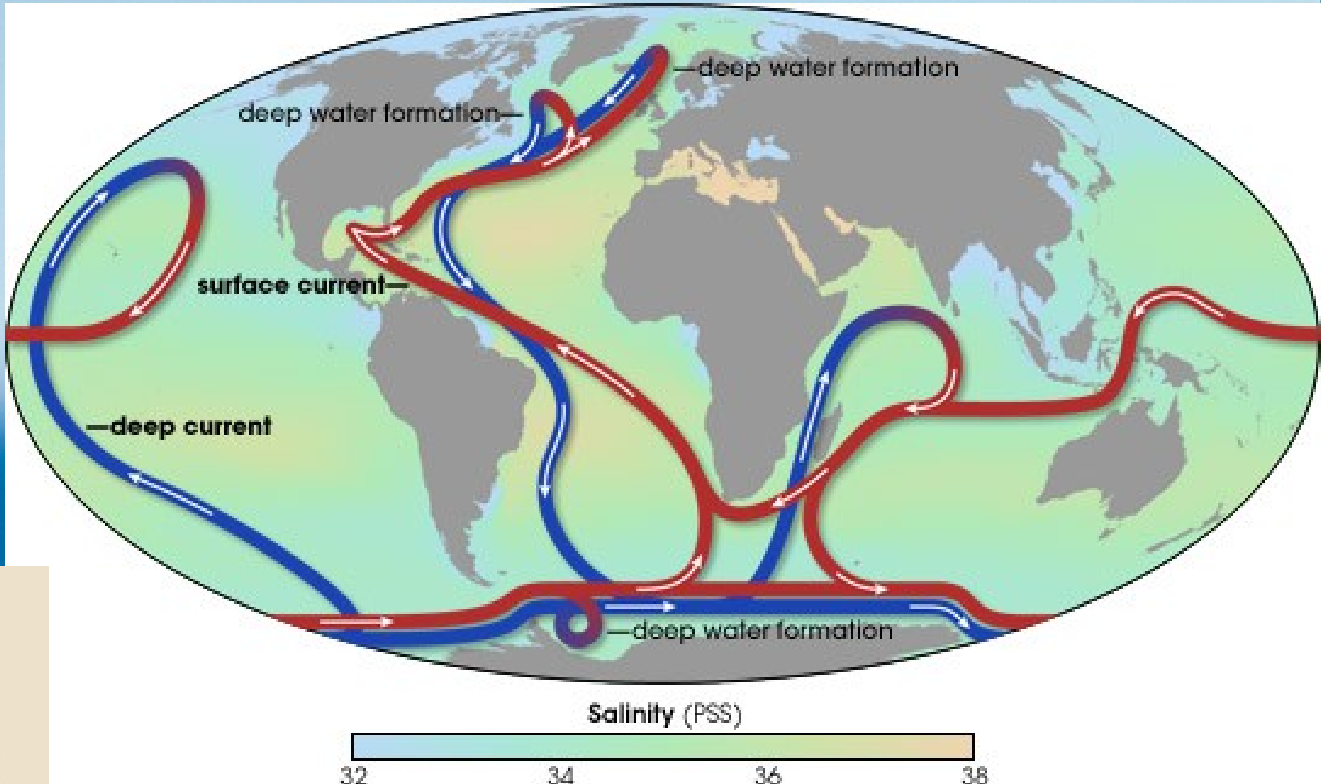


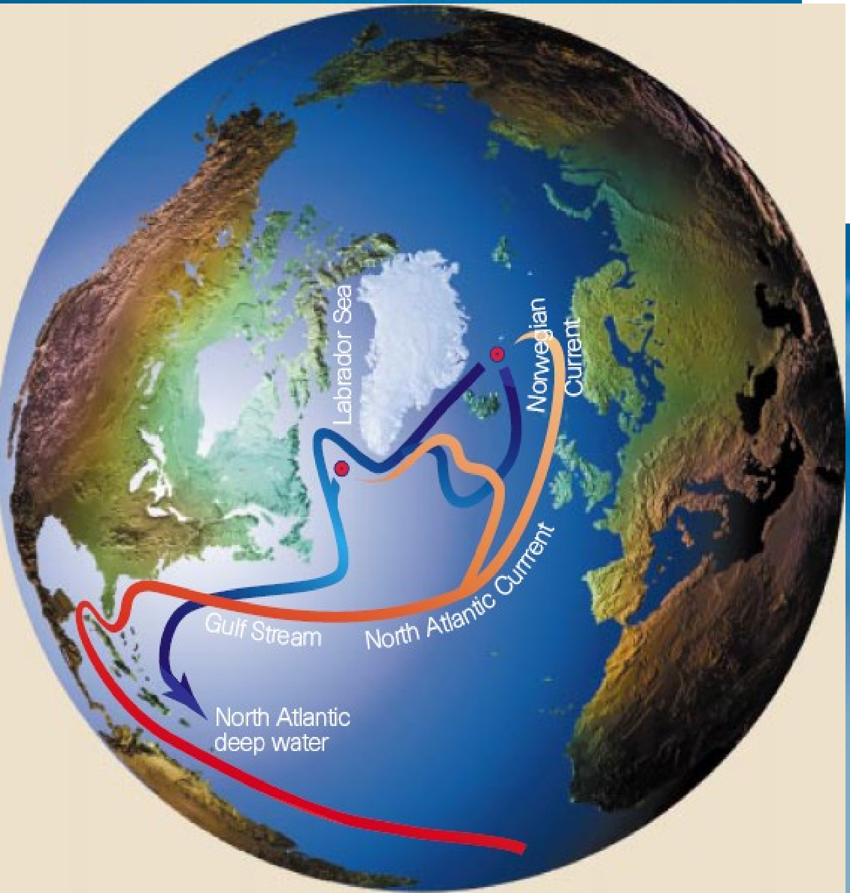
There was even a Hollywood movie about the AMOC collapse, the 2004 “The Day After Tomorrow”, with a horrendously exagerrated rate and magnitude of the climate effects of such an event.

Thermohaline circulation

The thermohaline circulation is that part of the ocean circulation which is driven by fluxes of heat and freshwater across the sea surface and subsequent interior mixing of heat and salt.

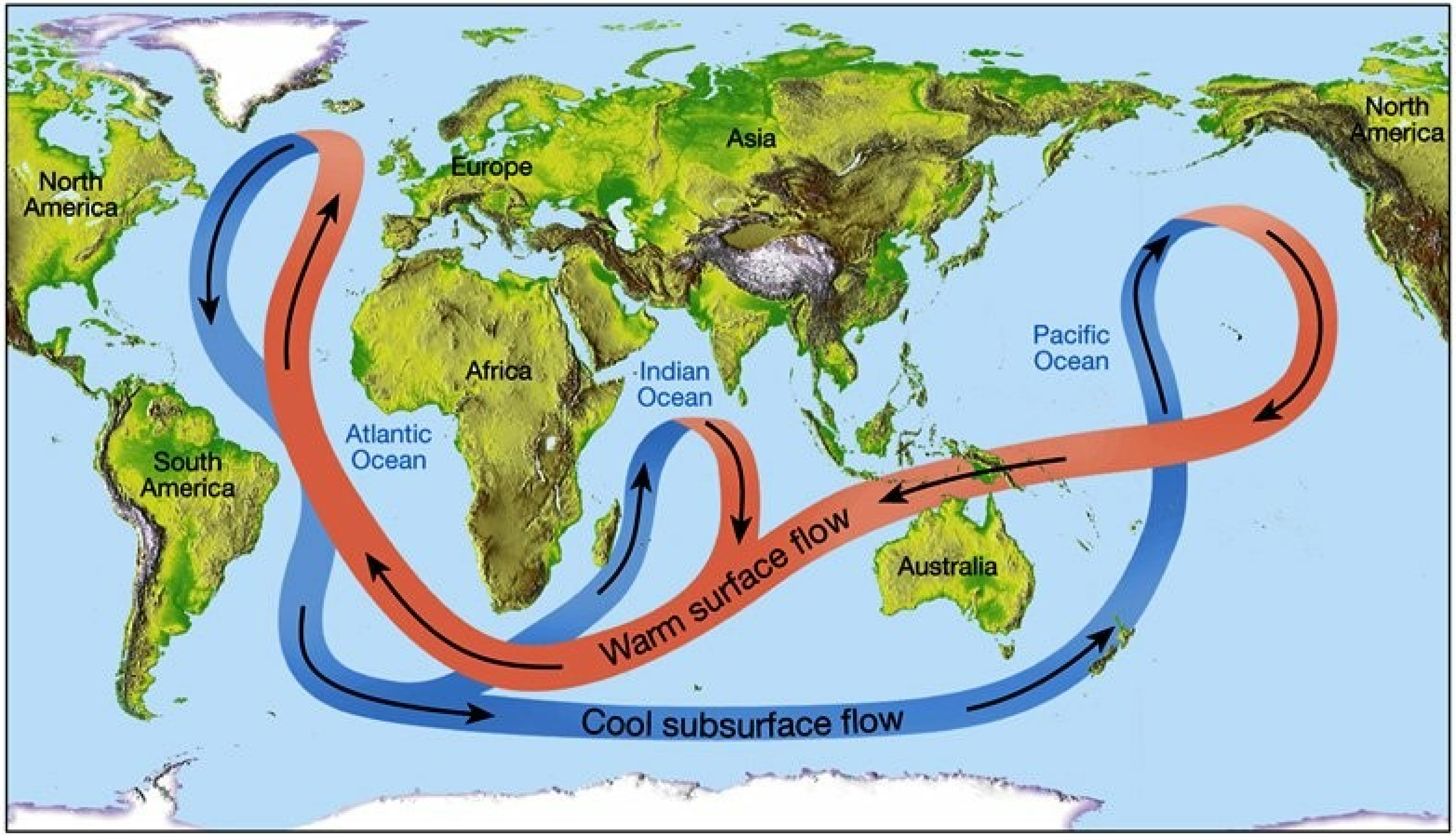
Stefan Rahmstorf, 2006





The thermohaline circulation (THC) is an effective mechanism for transporting heat from the tropics to the North Atlantic.
It is also a source of deep sea waters that ventilate the World Ocean. THC is the main mechanism of gas exchange (including CO_2) between surface and deep-sea waters.

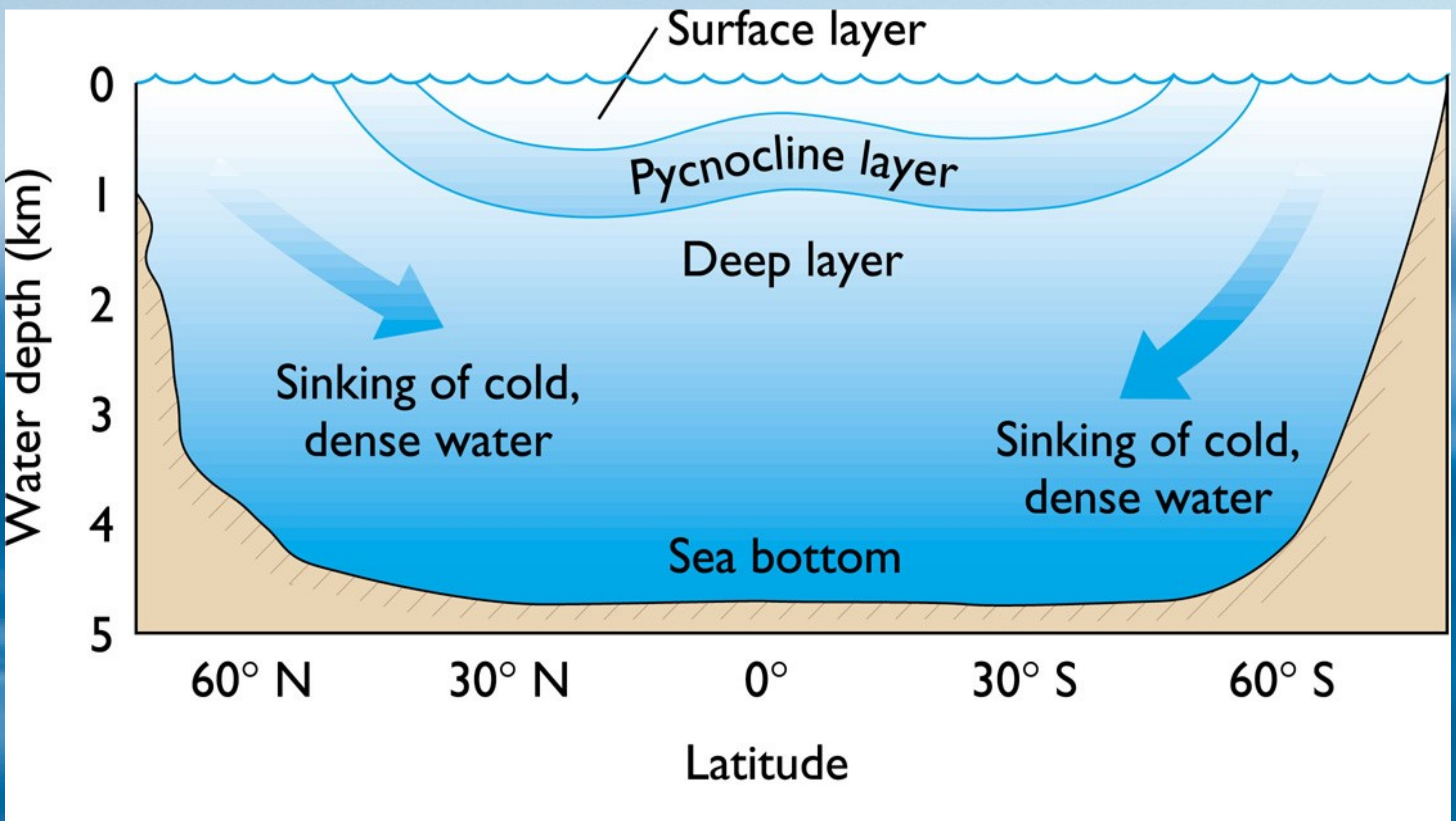
A popular picture of THC



Source: Science (alas!)

What's wrong? The Gulf Stream (Golfstrom) flows along Africa here; currents flow on top through New Guinea and New Zealand; we probably have an ice age here (deep water forms south of Iceland), but it does not form near Antarctica (as it should); no circumantarctic current; there is only one transmission belt (too much of a simplification).

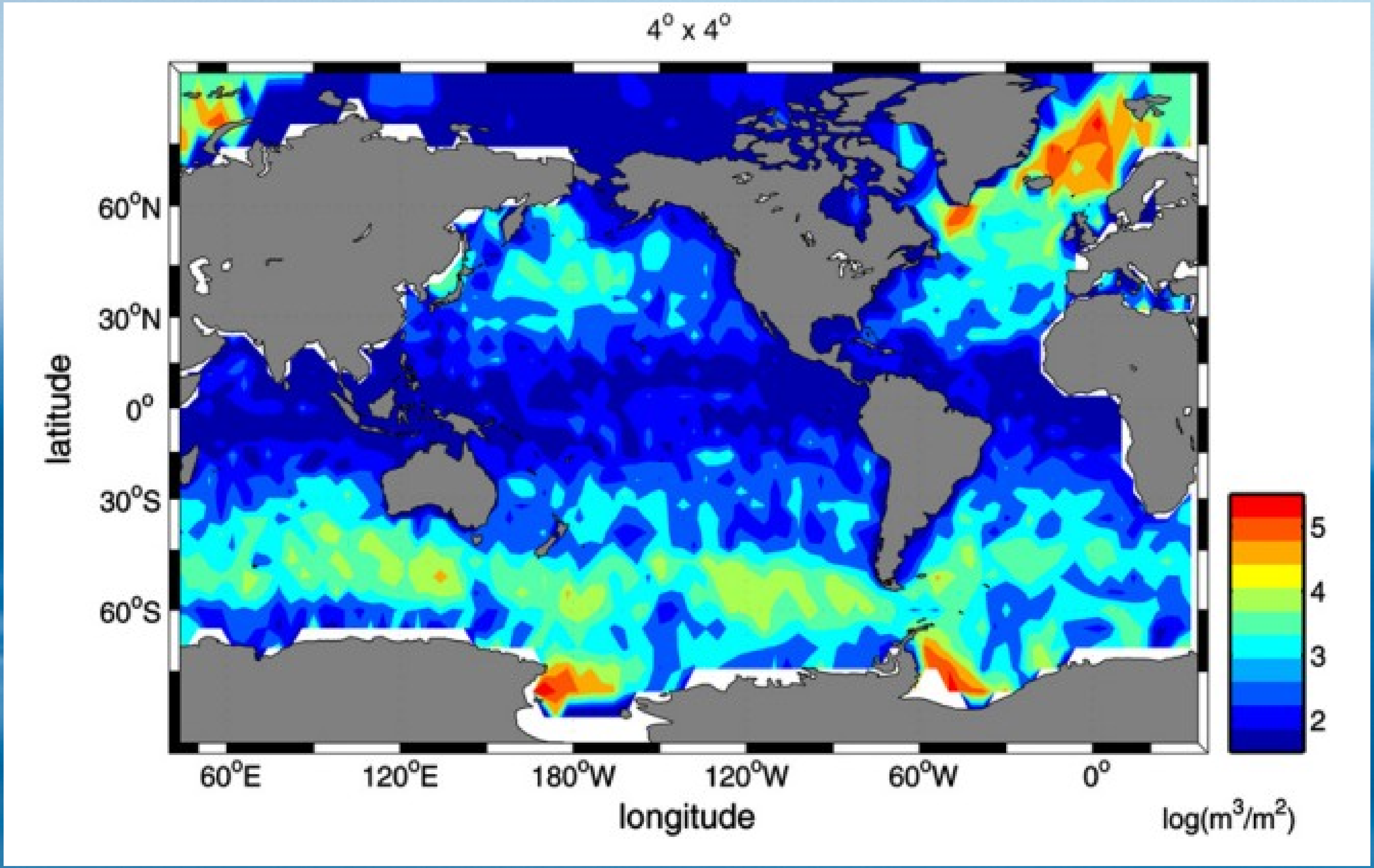
Where are the deep waters getting formed?



(c) DENSITY STRUCTURE OF THE OCEANS

Deep waters are formed in places with the highest density of surface waters: low temperature and high salinity. The only candidates are salty subpolar seas in winter (but not the parts covered with sea ice!)

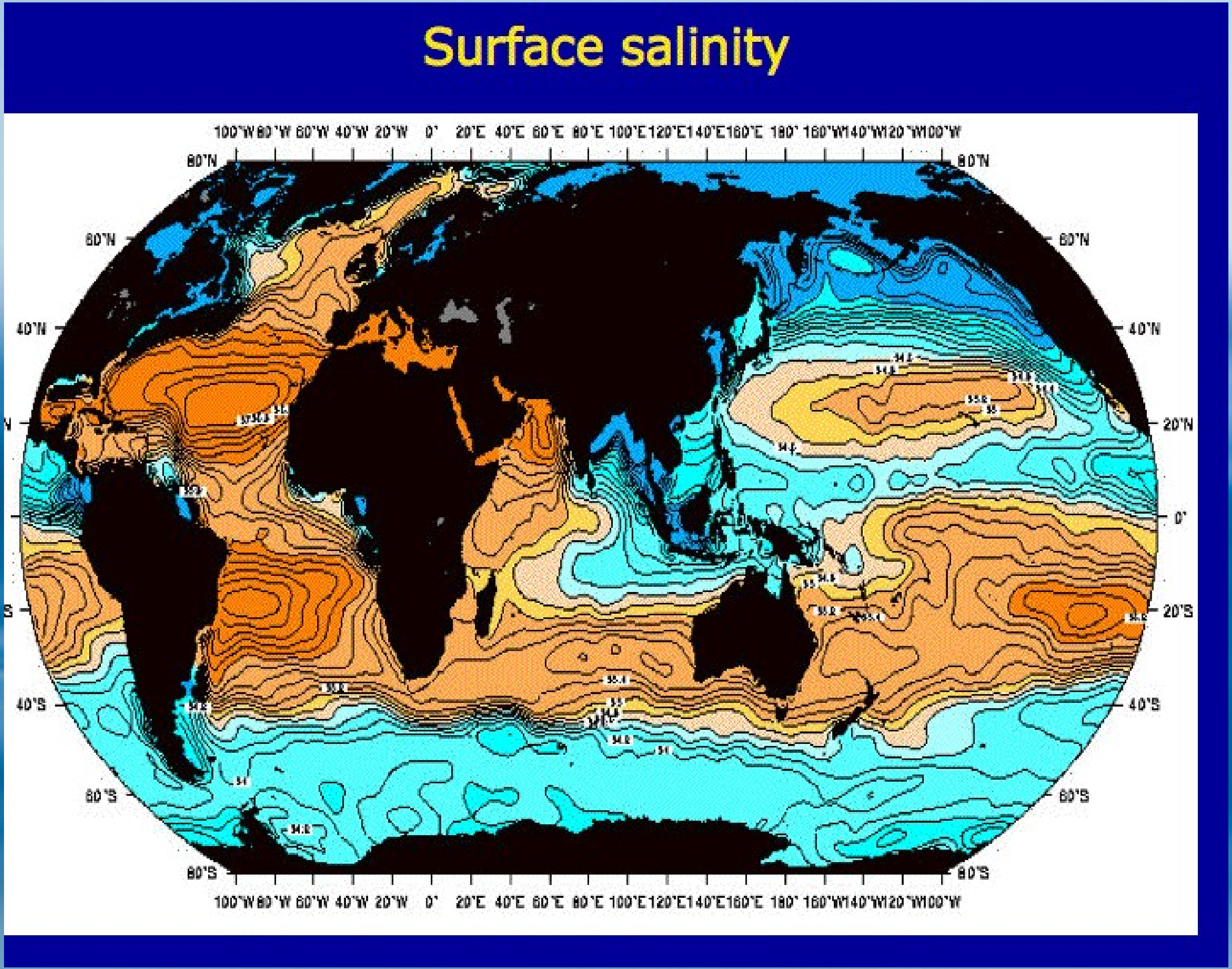
Where do deep sea waters actually form?



Areas in which deep water is formed (result of "reverse" modeling) in km^3 of deep water per km^2 of surface. *Note: the scale is a decimal logarithm, so each number is one order of magnitude!*

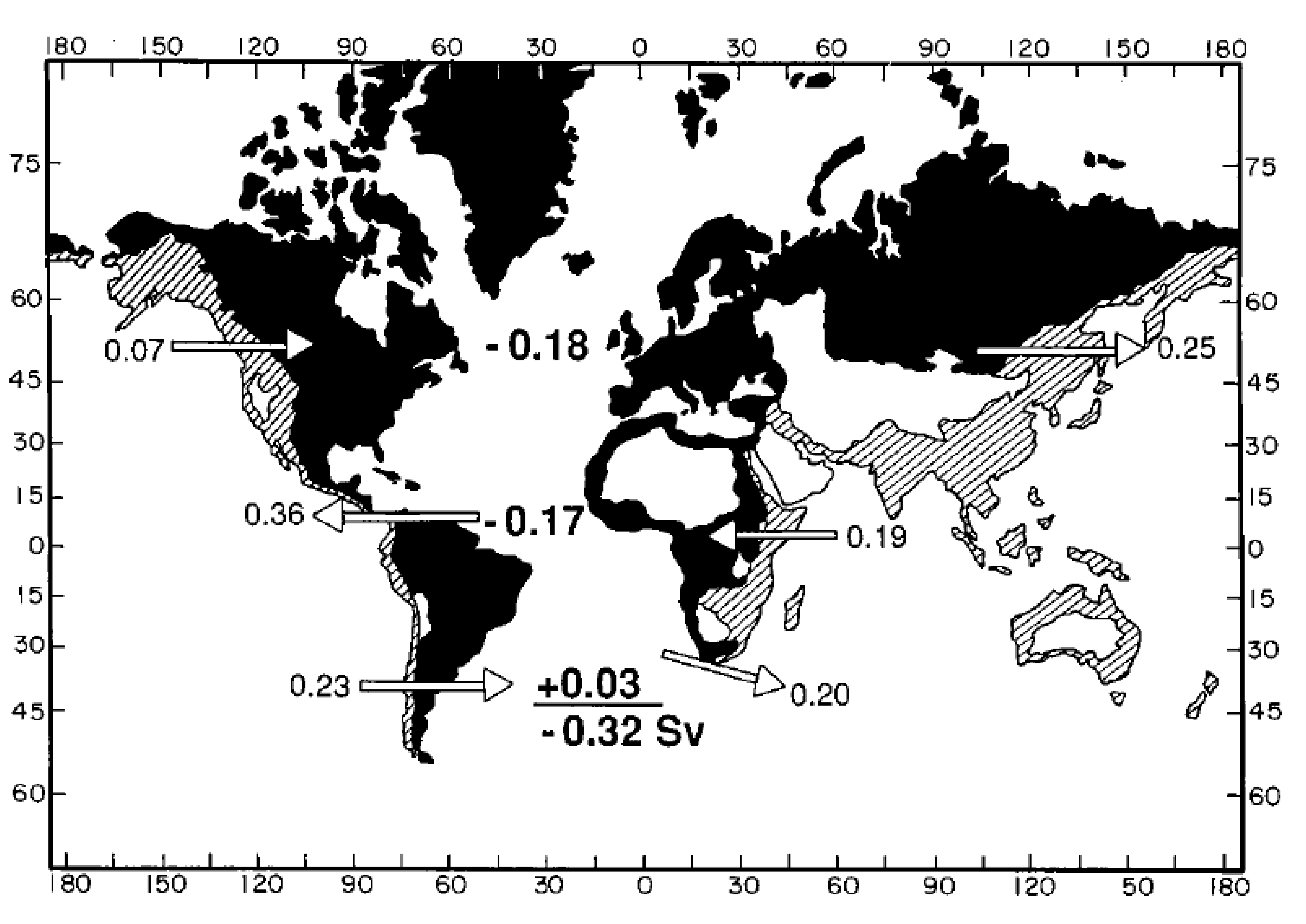
Wunsch 2010 (Quaternary Science Reviews), fig. from Gebbie & Huybers

Why deep waters are not formed in the Pacific?



The Pacific, where it is cold enough, is at the same time too "fresht" for deep convection (vertical mixing). The Antarctic seas are moderately salty, but deep sea water is formed during the formation of (mostly freshwater) sea ice.

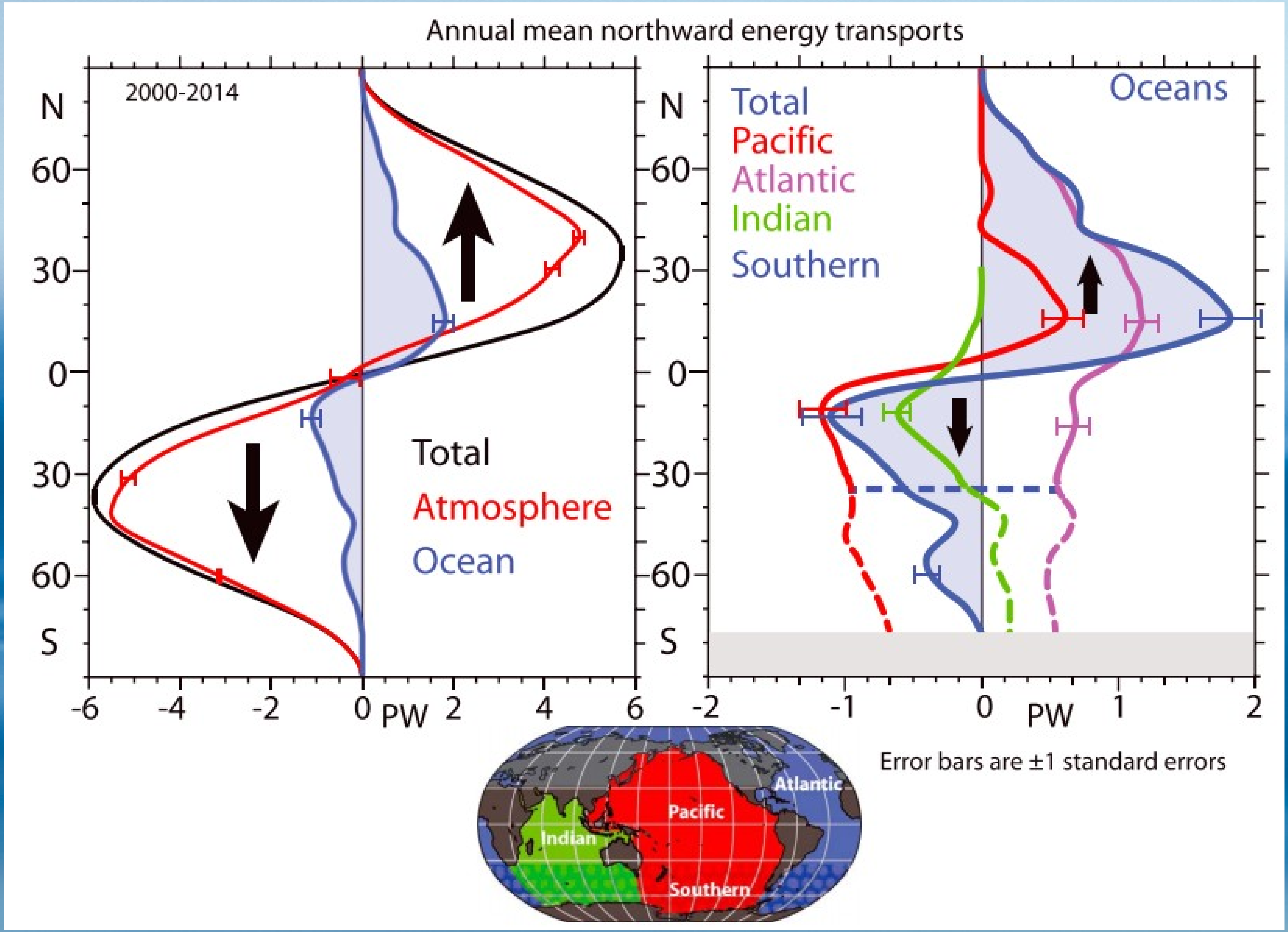
Why is Atlantic so salty?



The Atlantic watershed has a negative freshwater balance everywhere except in the southern part of the ocean: clouds and atmospheric humidity carry away more water than they bring from the other watersheds.

Broecker 1997 (Science)

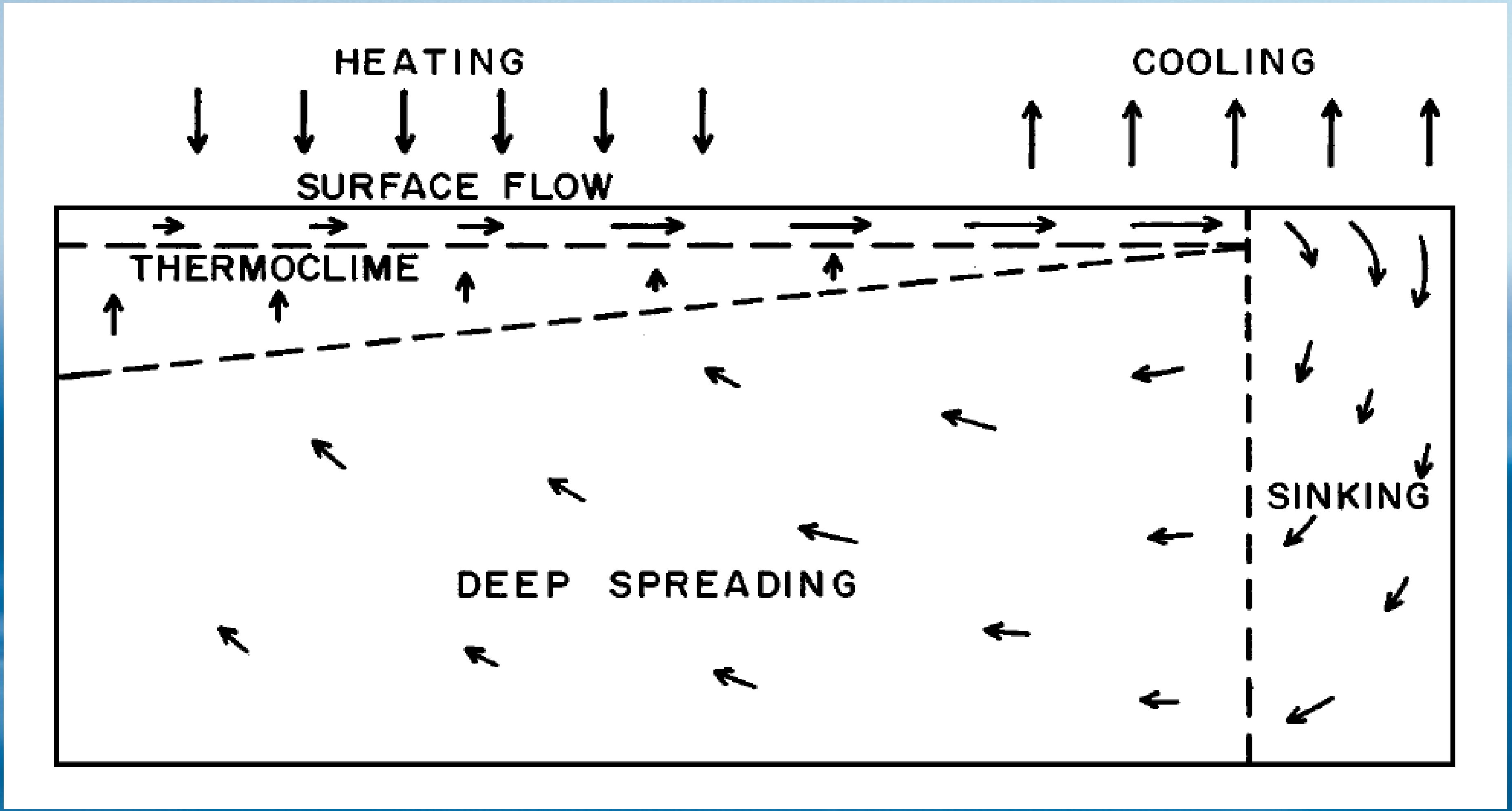
Meridional transport of heat: the Atlantic exception



Meridional transport in the atmosphere and in the ocean.

Trenberth & Fasullo, 2018 (GRL)

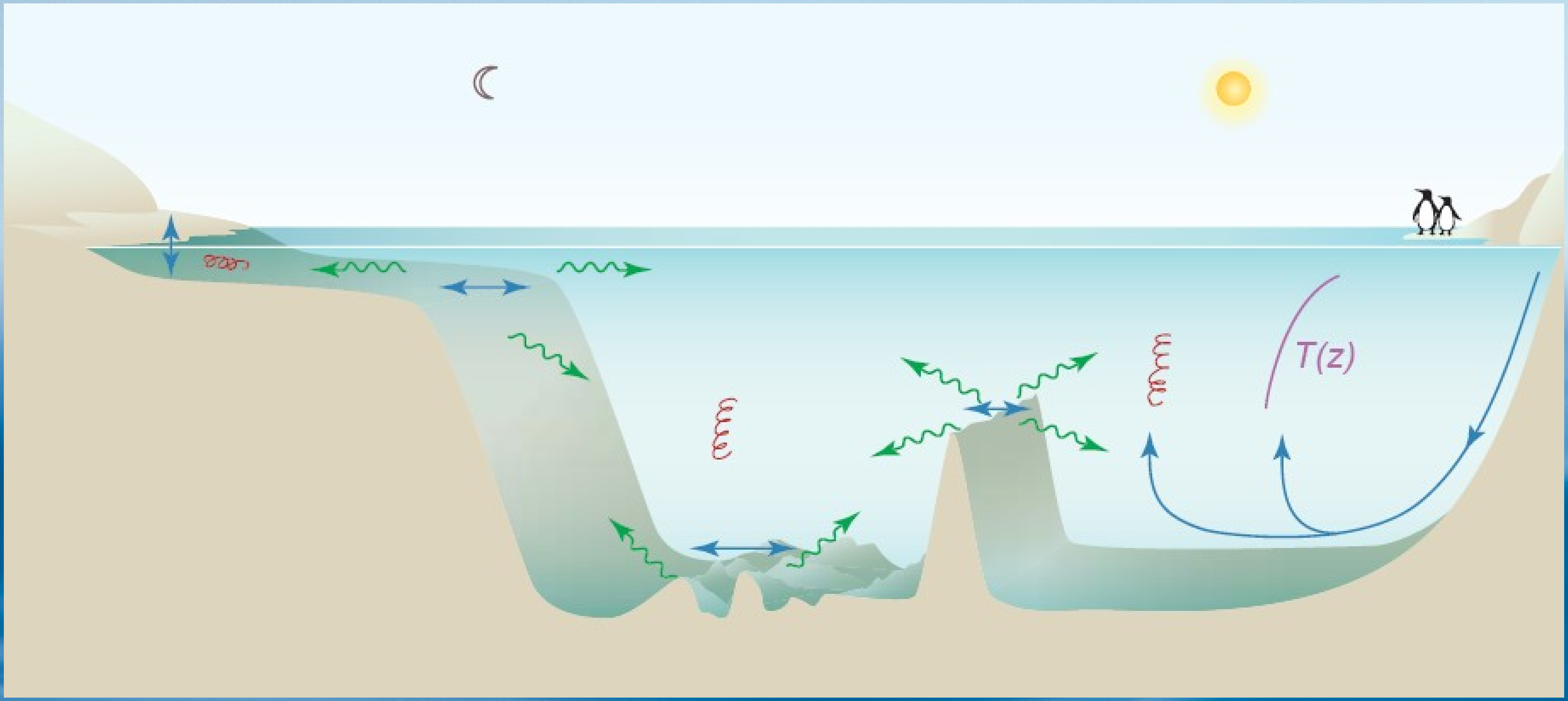
A classic picture of the THC



In the classic THC model (Stommel & Arons 1960), circulation is caused solely by differences in temperature and salinity.
However, there is a problem: already in 1908, Sandström showed that circulation in a liquid is impossible if the heat source and the cooling are located at the same depth (e.g. on the sea surface).

Weaver et al. 1999 after Wyrtki 1961

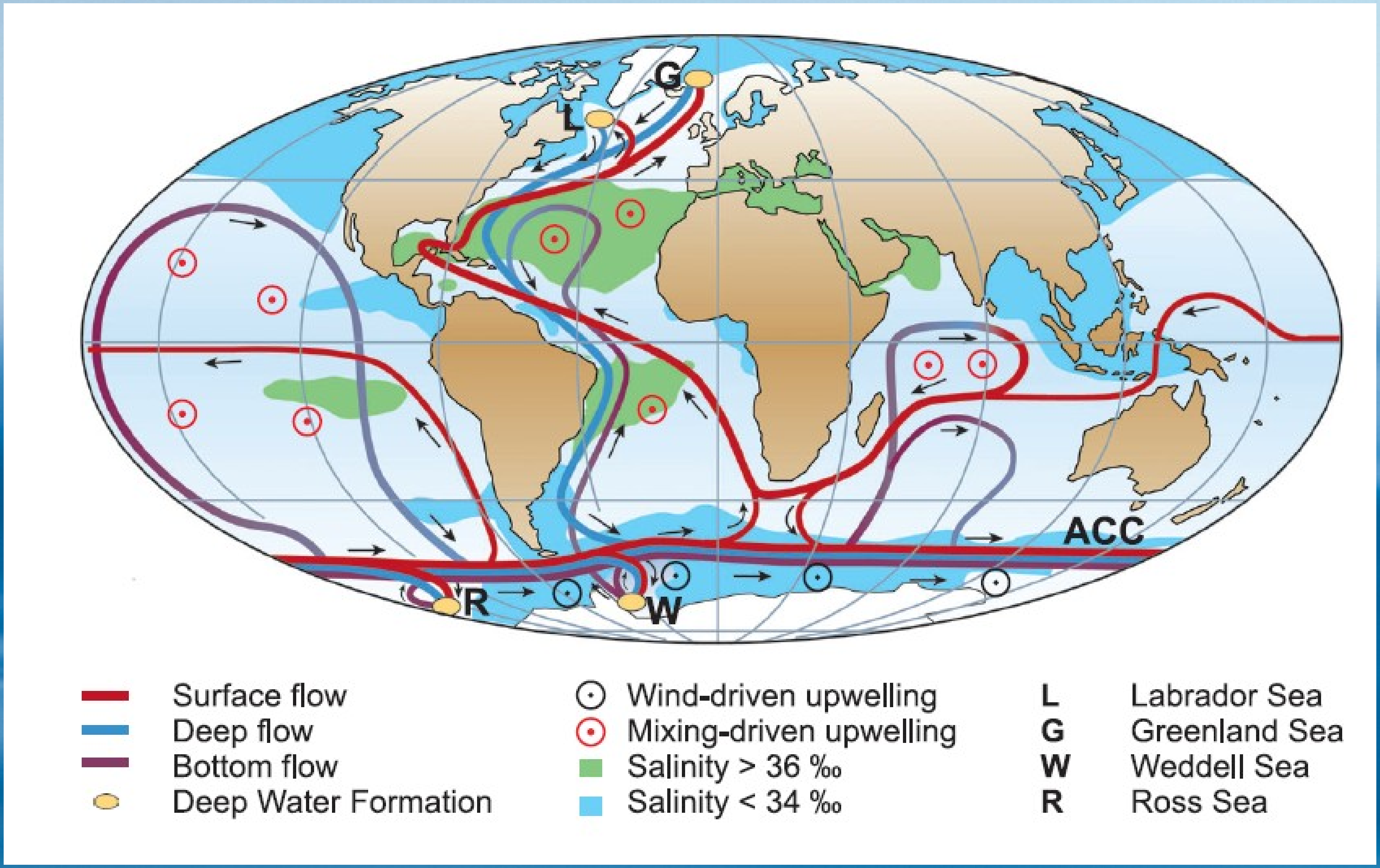
Why does dense water surface at all?



Dense (salt and cold) water can only rise to the surface when mixed with lighter water. One mechanism (in addition to wind-related mixing) is the generation of internal waves (green) on bottom irregularities (continental ridges and slopes) by tidal movements. Internal waves lead to turbulent mixing (red).

Garrett 2003 (Science)

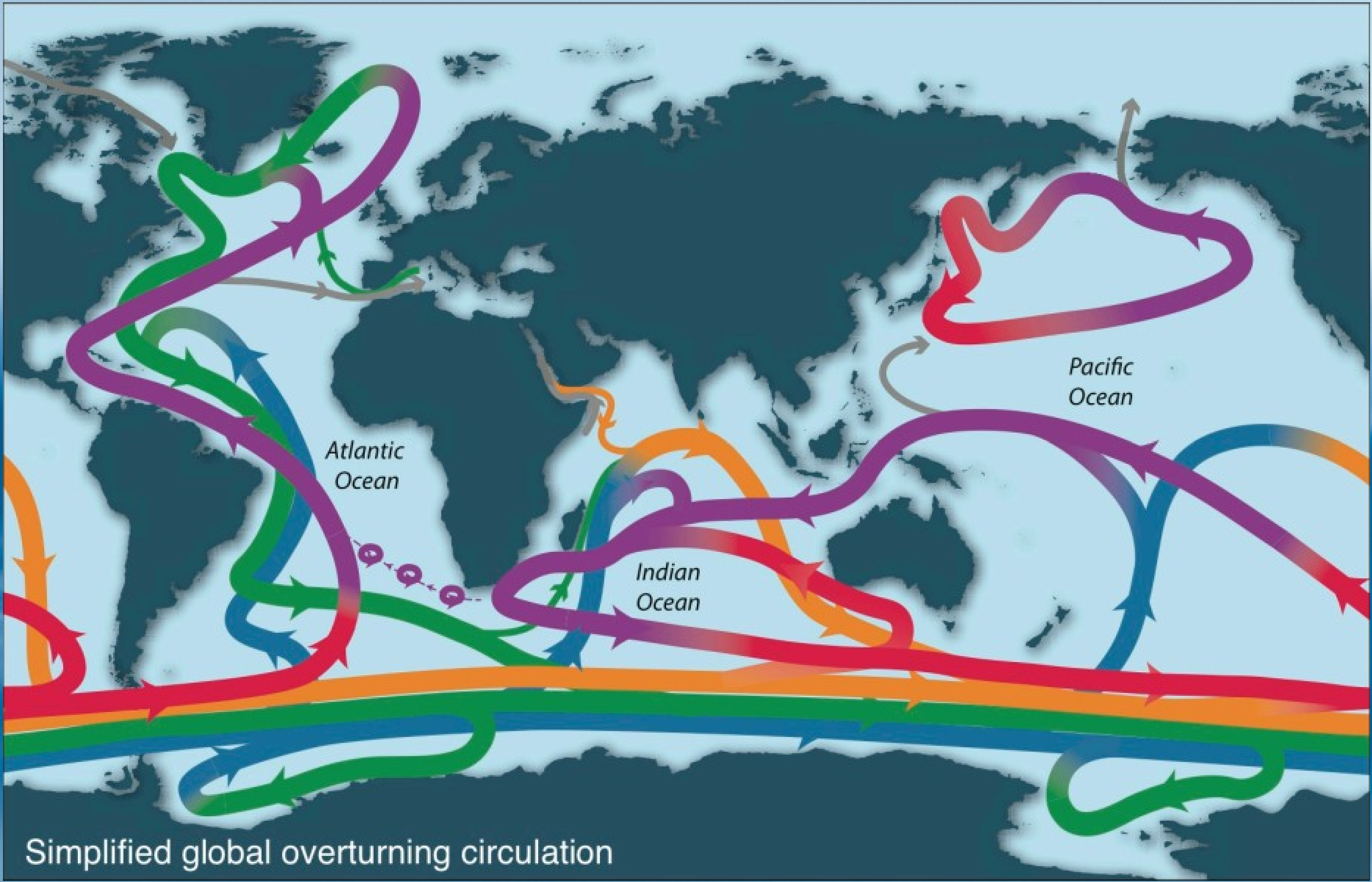
Moderm picture of the overturning circulation



Deep sea waters return to the surface due to turbulent mixing (particularly at submarine ridges) and upwelling (flux towards the surface) associated with Ekman transport around Antarctica. *Why does Ekman transport work "to the left"? Because it's the southern hemisphere!*

Kühlbrodt et al 2007 (Reviews of Geophysic), modified from Rahmstorf 2002

The newest picture of overturning circulation



We know more and more about MOC. That's why the above diagram is... "*simplified*".

Talley 2013 (Oceanography)

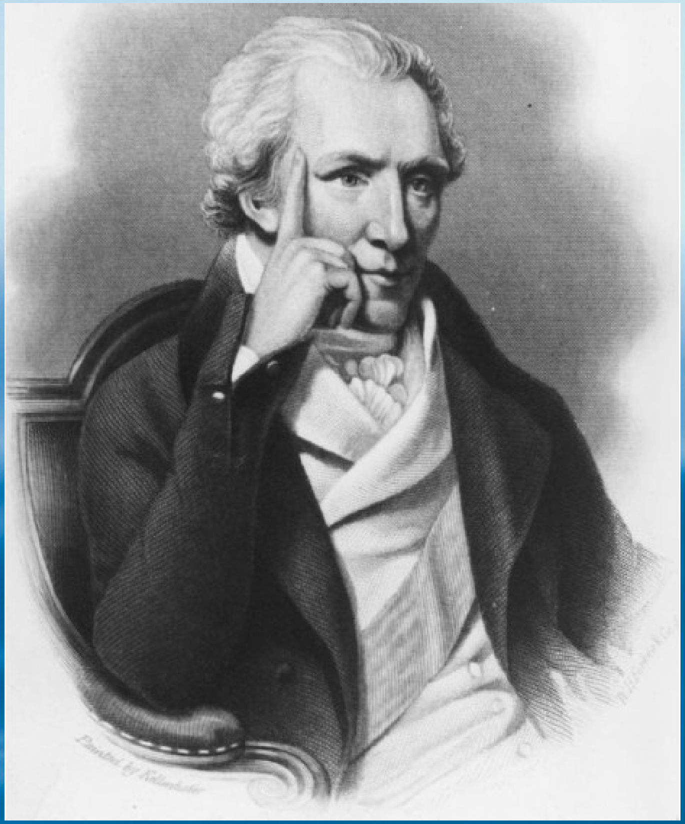
Some boring stuff

Termohaline circulation (THC) is not forced only by differences in temperature and salinity. It is difficult to separate from wind driven circulation. Part of its energy comes from internal ocean mixing caused by wind and tides (but not zooplankton).

Wunsch (2002) proposed that THC should be used only for the mechanism, budgets of fresh water and heat and the part of ocean circulation related to „production" of deep water masses to be named Meridional Overturning Circulation (MOC). This name dominates the modern literature of the subject (in Polish it has no counterpart, yet).

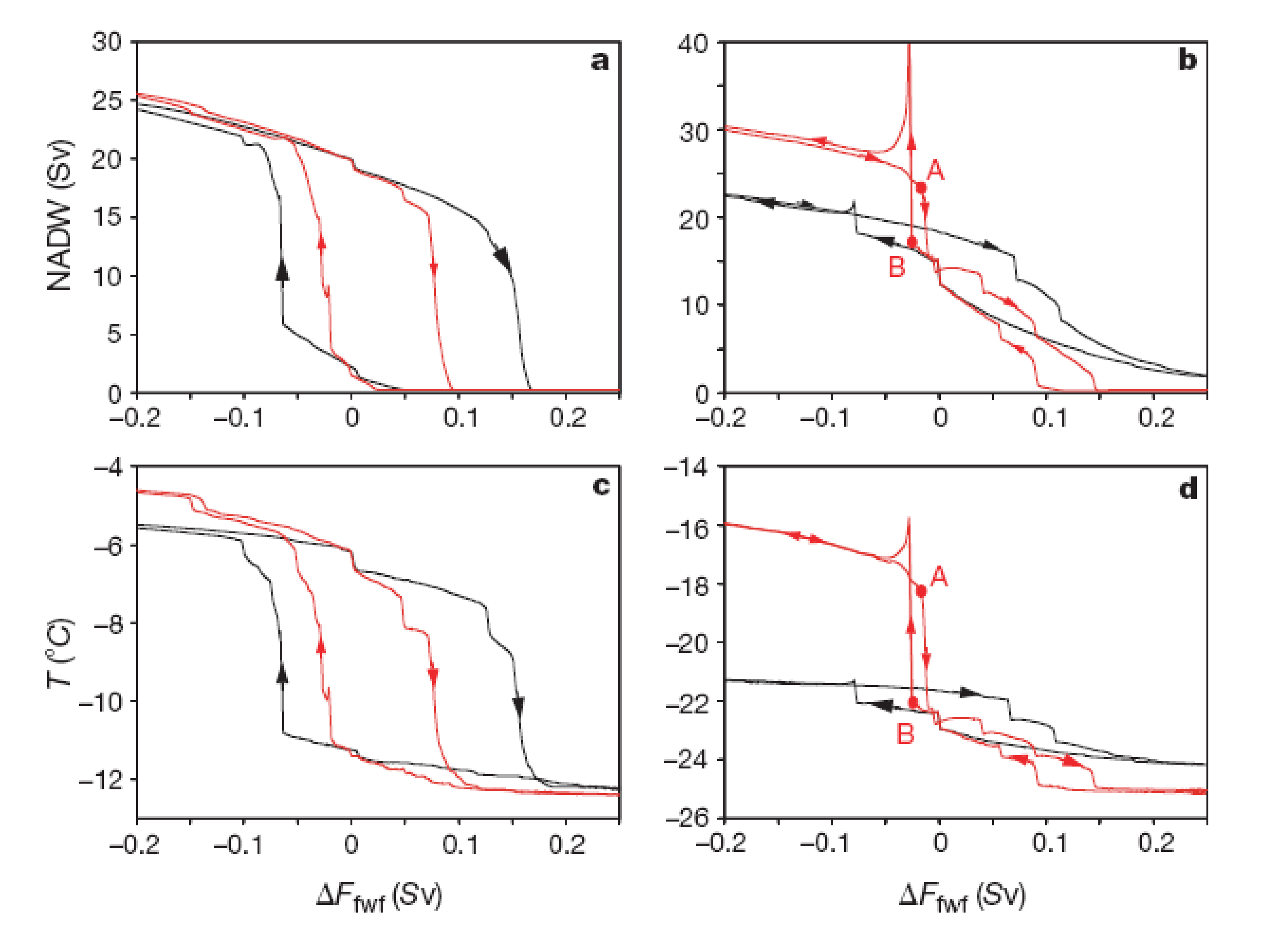
Rahmstorf (2006) defined THC as „that part of the ocean circulation which is driven by fluxes of heat and freshwater across the sea surface and subsequent interior mixing of heat and salt.".

If we speak about its Atlantic part, we call it AMOC.



Sir Benjamin Thompson, who discovered in 1798 that surface waters transport heat towards the Poles while cold water returns towards the equator in the deep ocean.

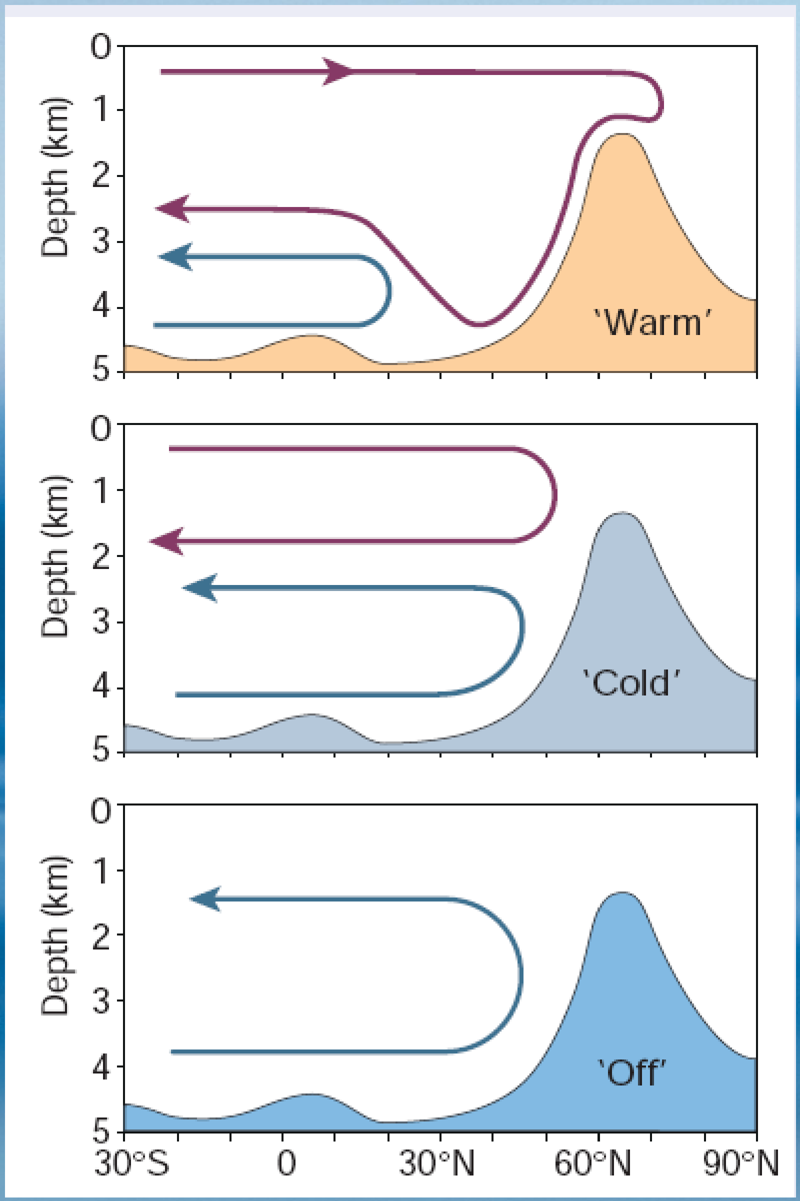
Freshwater forcing and the THC



Variability of North Atlantic deep water (NADW) production and air temperature (60-70º N) as a function of freshwater inflow today (left) and during the last ice age maximum (right) at latitudes 20-50º N (black) and 50- 70 º N (red).

Ganopolski i Rahmstorf, 2002

THC in the ice age

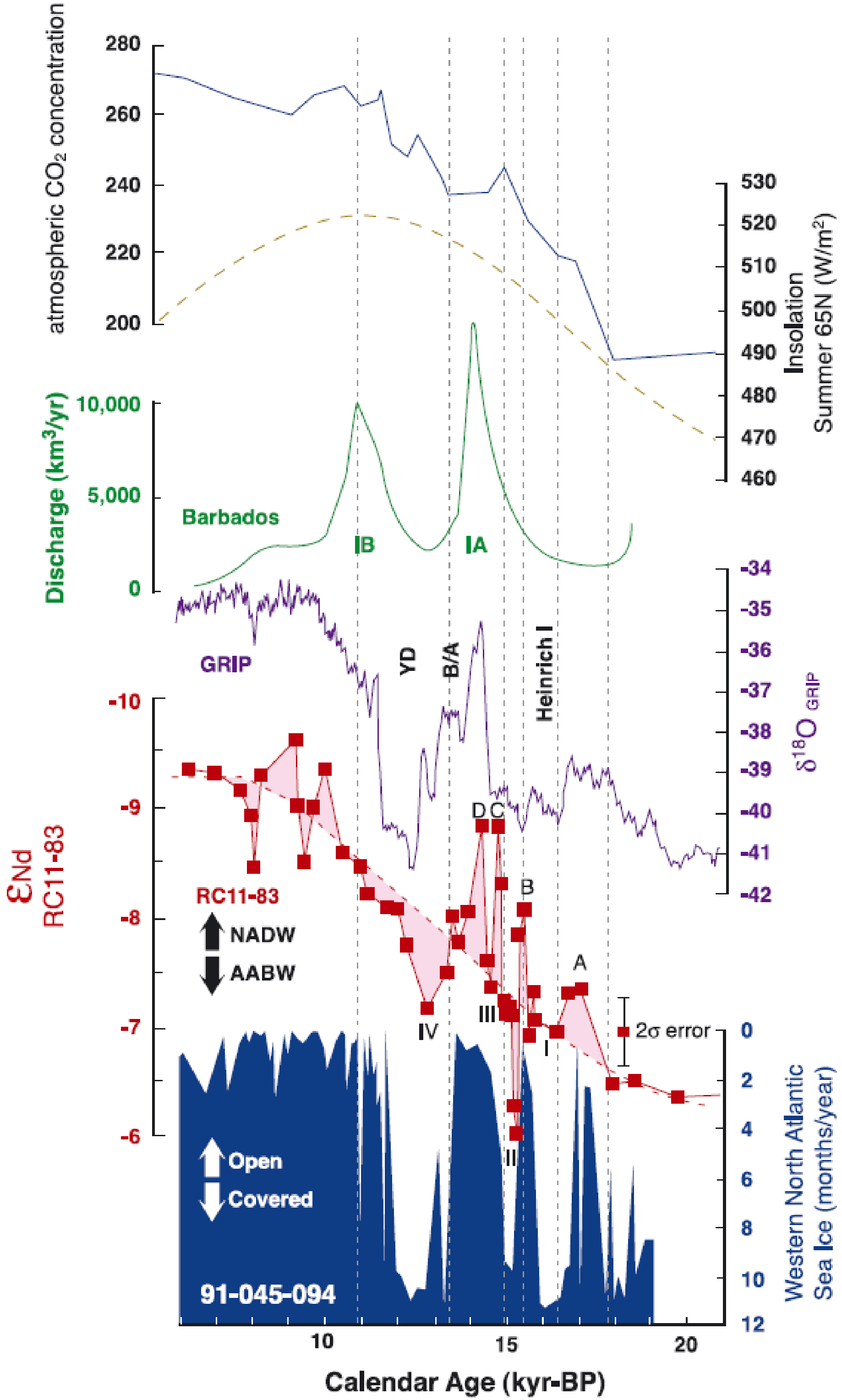


Three phases of THC

- D/O warm phase: THC similar to current, NADW forming in Nordic Seas, Antarctic Deep Waters pushed far south.
- Cold Phase D/O: Atlantic Intermediate Waters form south of Iceland; Antarctic Deep Seas fill the depths of the Atlantic.
- Heinrich event: thermohaline circulation stops completely..

Rahmstorf 2002 (Nature)

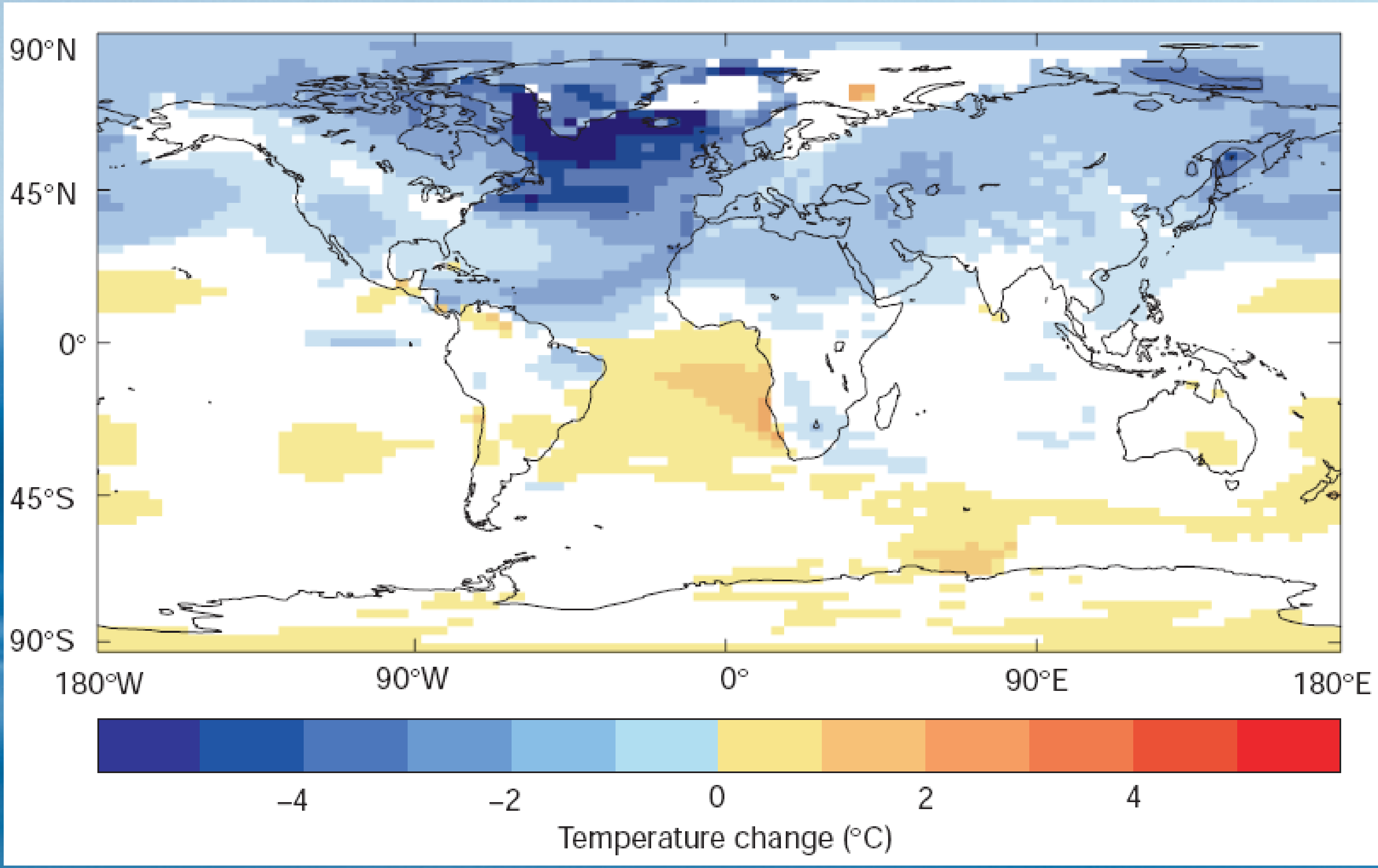
THC during the deglaciation



The content of neodymium isotopes in seawater indicates its origin (the lowest in the Labrador Sea, the highest in the Pacific). This parameter (red line), from cores from the South Atlantic, indicates a systematic increase in the influence of North Atlantic Deep Water at the expense of Antarctic Deep Water, i.e. a systematic strengthening of THC. Younger Dryas is a local minimum on the chart.

Piotrowski et al. 2004
(Earth and Planetary Science Letters)

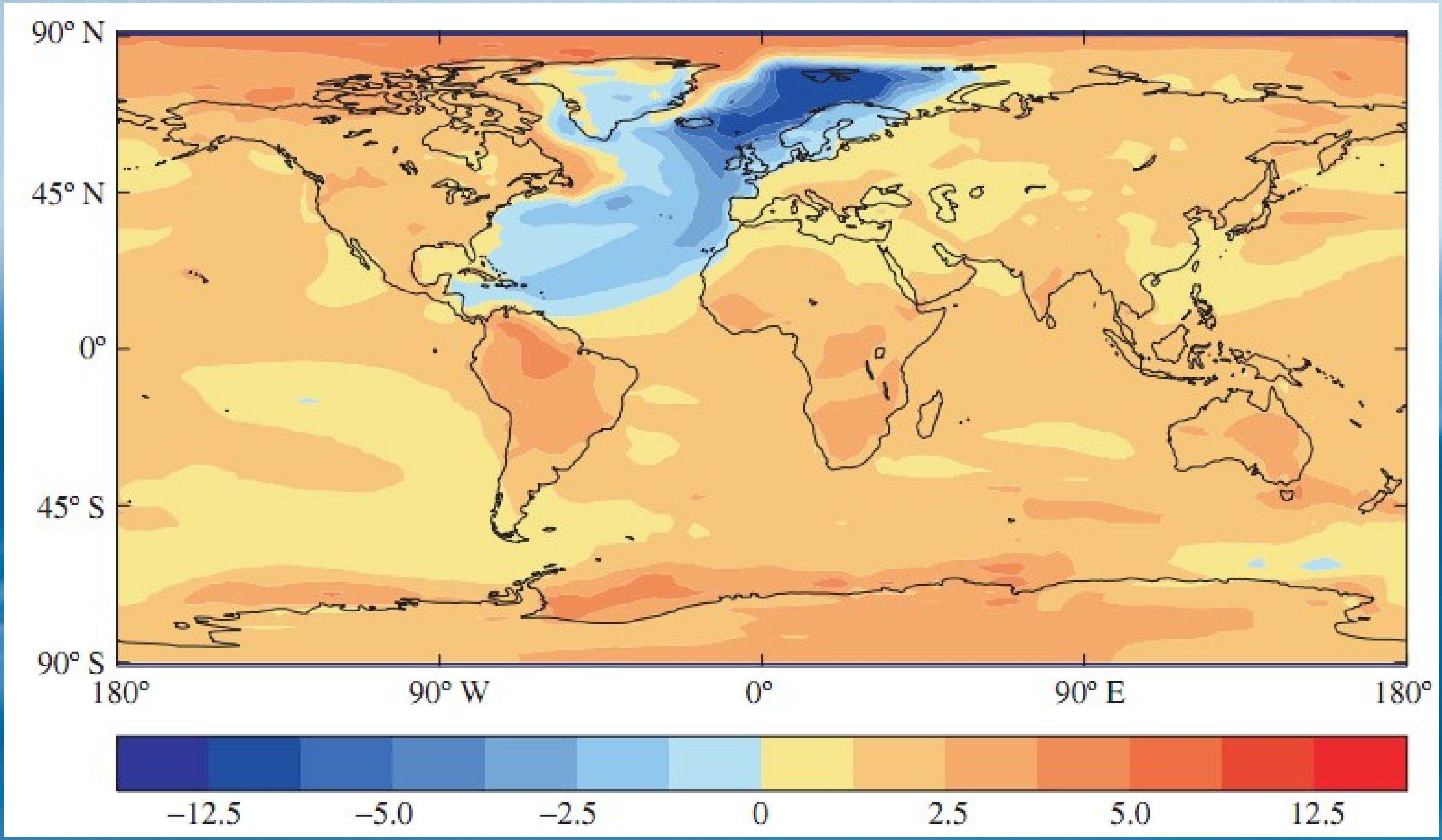
The impact of thermohaline circulation on



Modeling results (HadCM3 model) show that the possible halting of THC would cause significant cooling of the Northern Hemisphere, especially the North Atlantic region, while warming the Southern Hemisphere.

Rahmstorf 2002

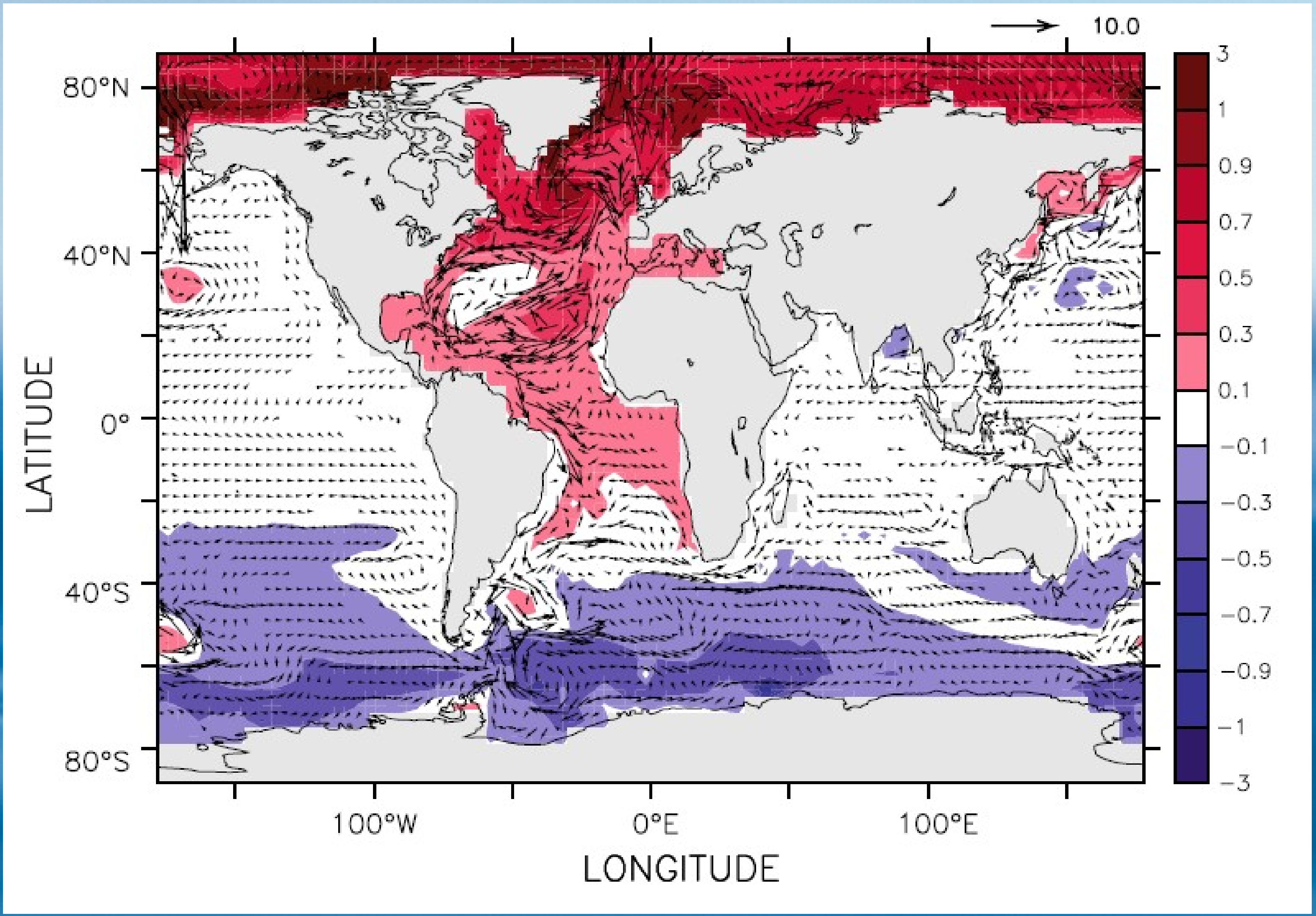
What if we stopped THC in 2049?



Modeling results (HadCM3 model) show that a possible stoppage of THC in the middle of the century would only cause local cooling in the North Atlantic region.

Wood Velling Thorpe 2003 (Phil. Trans. R. Soc. Lond. A)

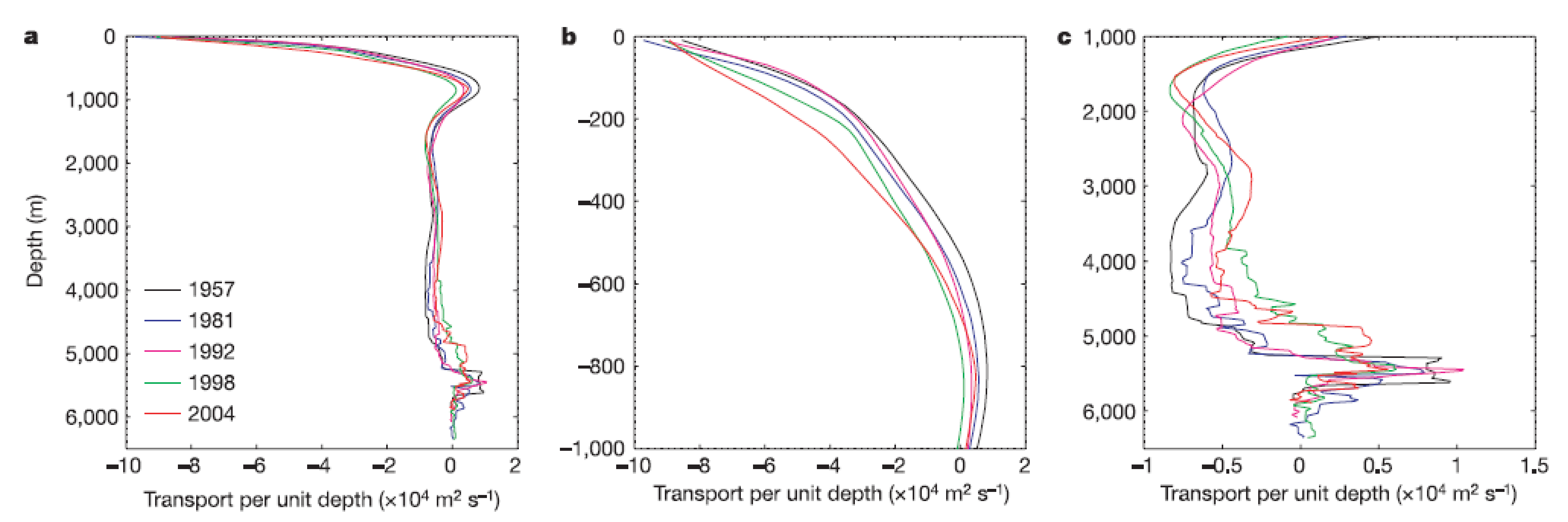
Effect of THC stopping on sea level change



The effect of stopping the thermohaline circulation on sea level (*note the non-linear scale!*) and changes in currents (arrows). The sea level of the North Atlantic and adjacent seas would be up to 1 m higher than today. This result should be added to future changes related to climate change.

Levermann et al. 2005 (Climate Dynamics)

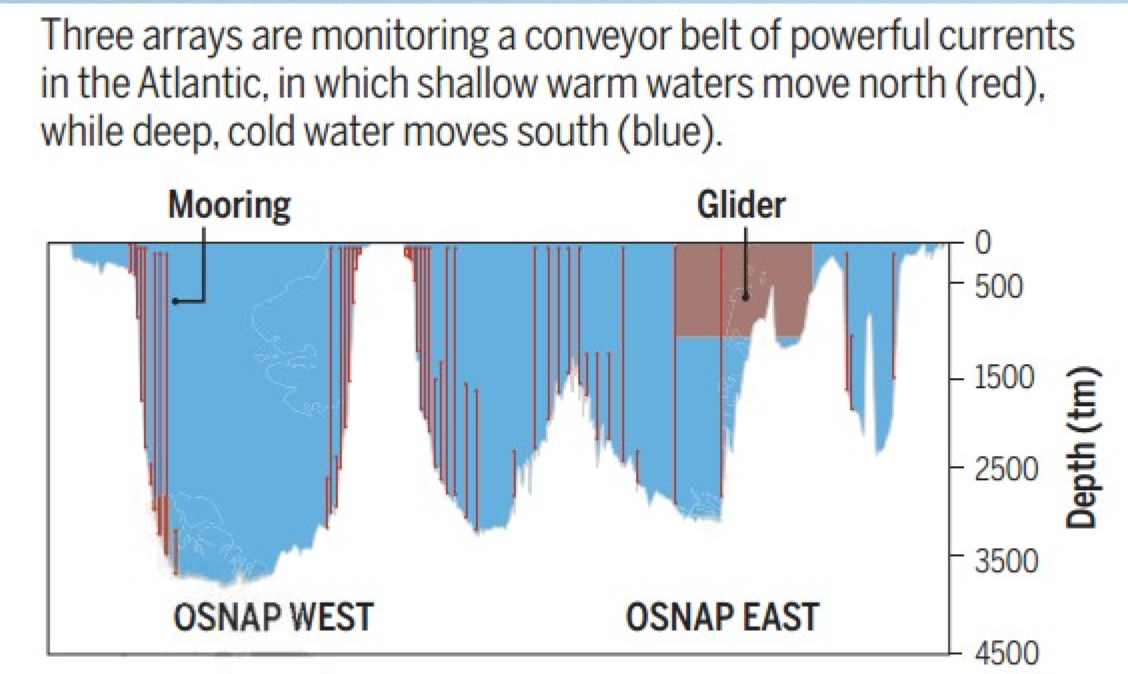
THC weakening? A false alarm

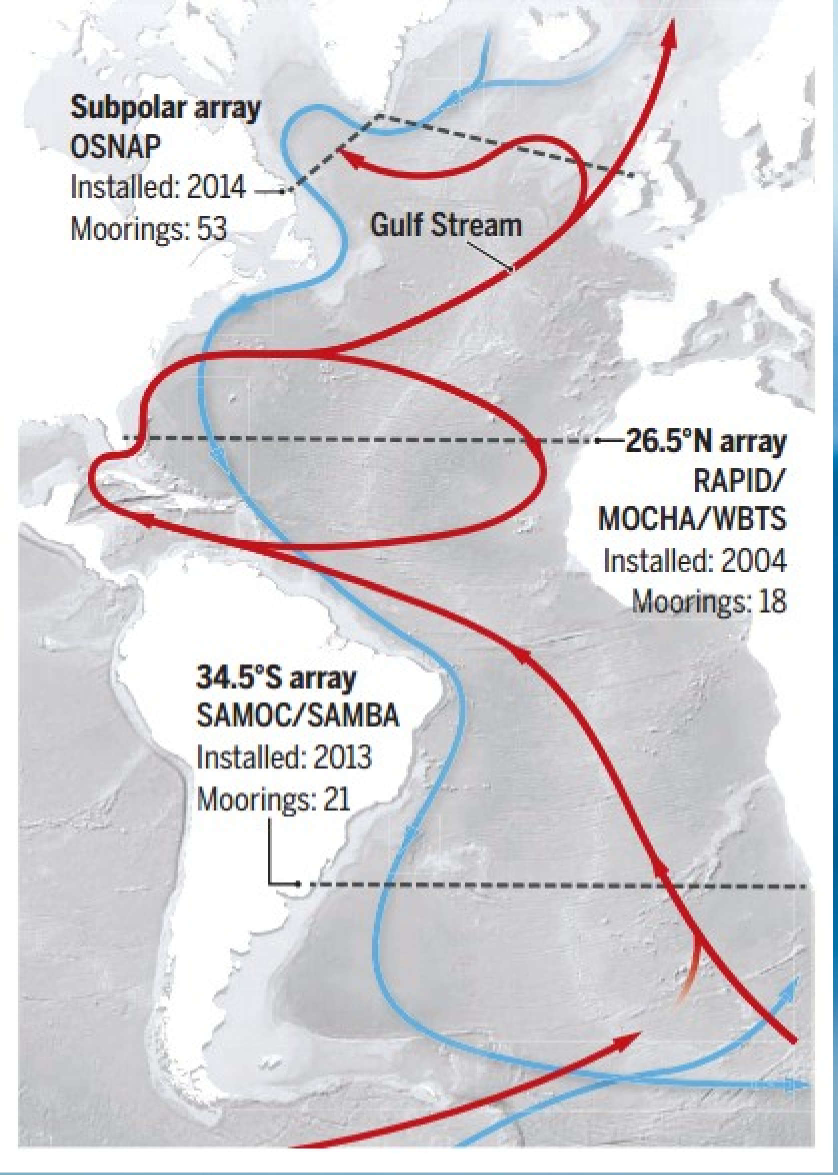


The measurement of Atlantic currents at the 25º N profile in 2004 seemed to indicate that the flow across this parallel had weakened by 30%. However, measurements from 19 RAPID moorings (26.5º N) seem to deny the existence of such a trend - although they do confirm high interannual variability (Nature, November 17, 2006). Also, continuous measurements of the intensity of the Gulf Stream at 27 º N since 1982 (Baringen & Larsen 2001) using the electric potential difference on submarine telephone cables do not show a decreasing trend in its flow..

Bryden, Longworth & Cunningham 2005 (Nature)

How do we measure THC / AMOC?

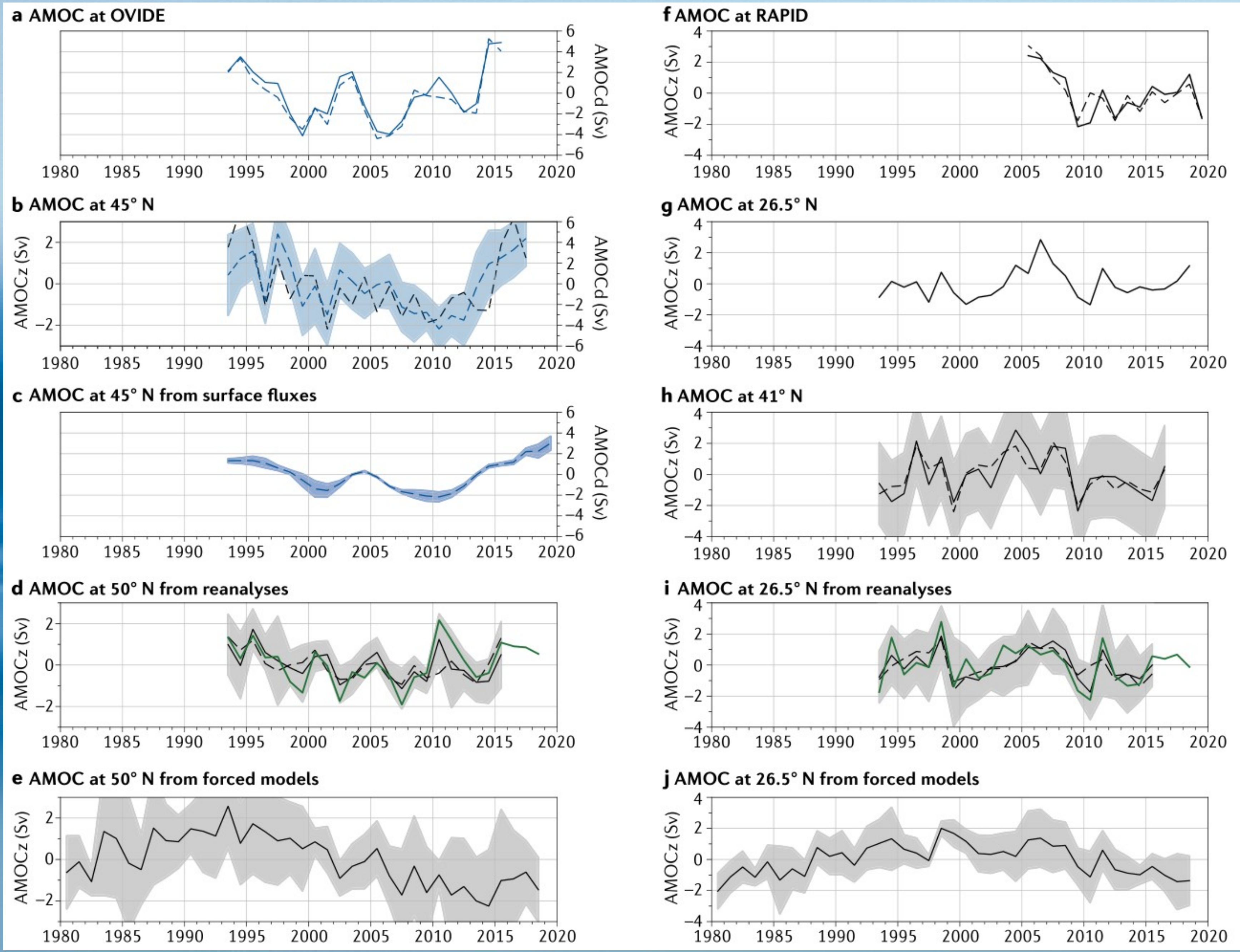




Currently, in addition to the RAPID/RAPID program buoy (26.5º N), we have two other measurement lines: the subpolar OSNAP and the first in the southern hemisphere, SAMOC/SAMBA (34.5º S). However, it will take several years to determine any possible trends.

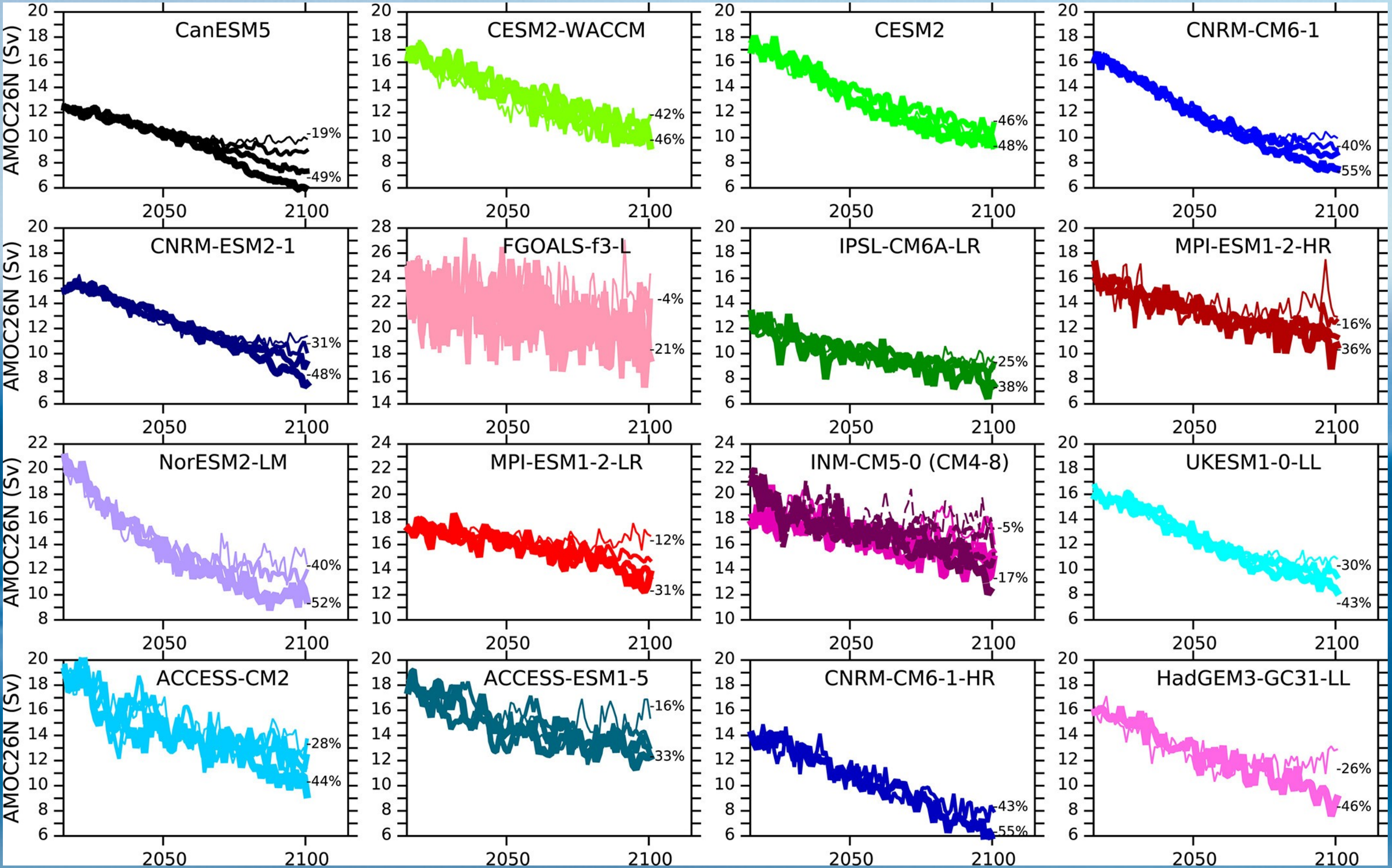
Hand 2016 (Science)

AMOC weakened? So far (2022) not



Jackson et al 2022 (Nature Reviews: Earth & Environment)

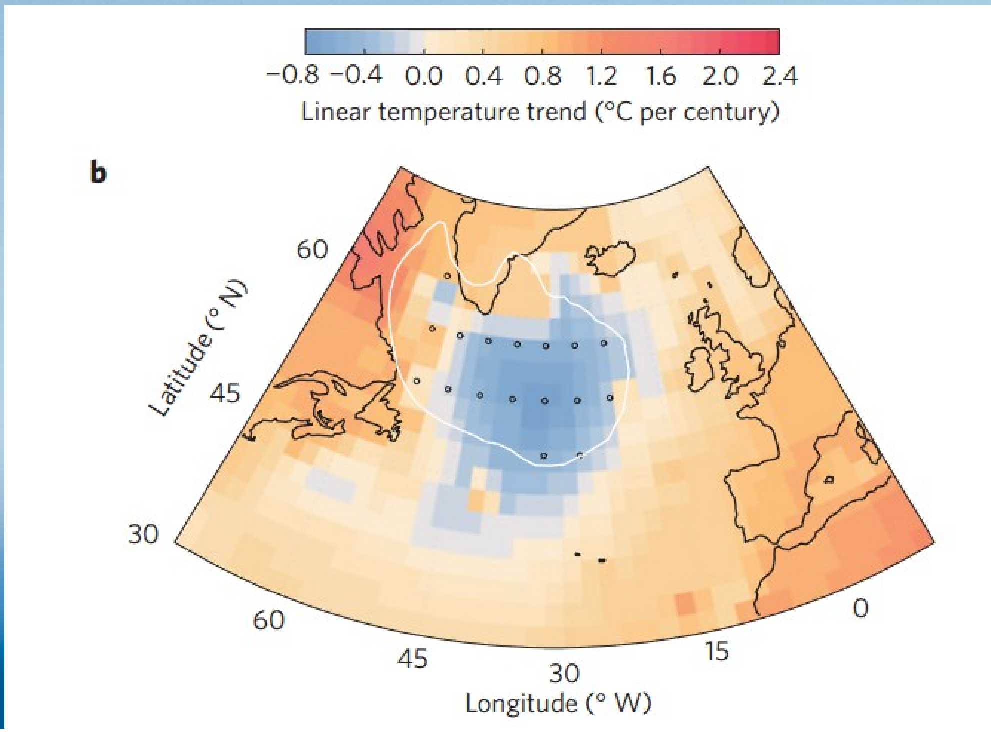
AMOC in the 21st century in CMIP6 models

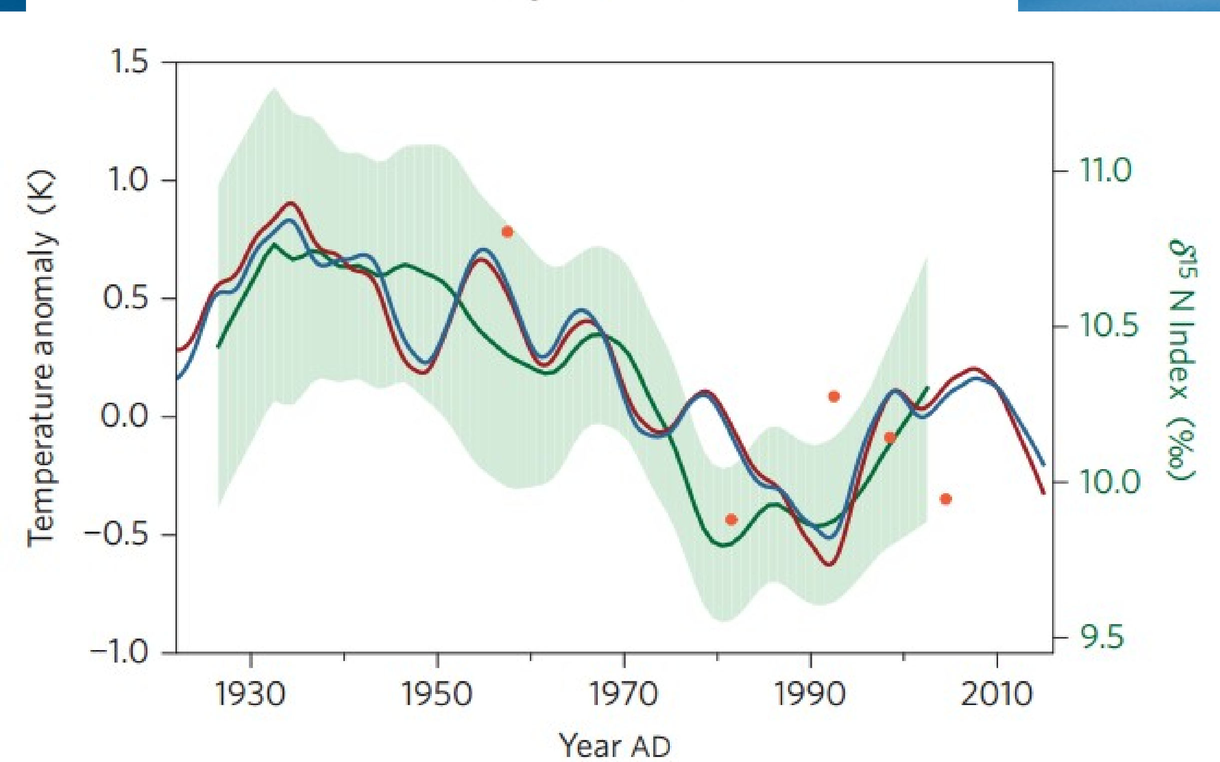


Time series of AMOC at 26°N in 17 CMIP6 models. The modelling results project a significant AMOC decrease but not yet a collapse. Progressively thicker lines are emission parhways from SSP2.6 to SSP8.5.

Weijer et al. 2020 (GRL)

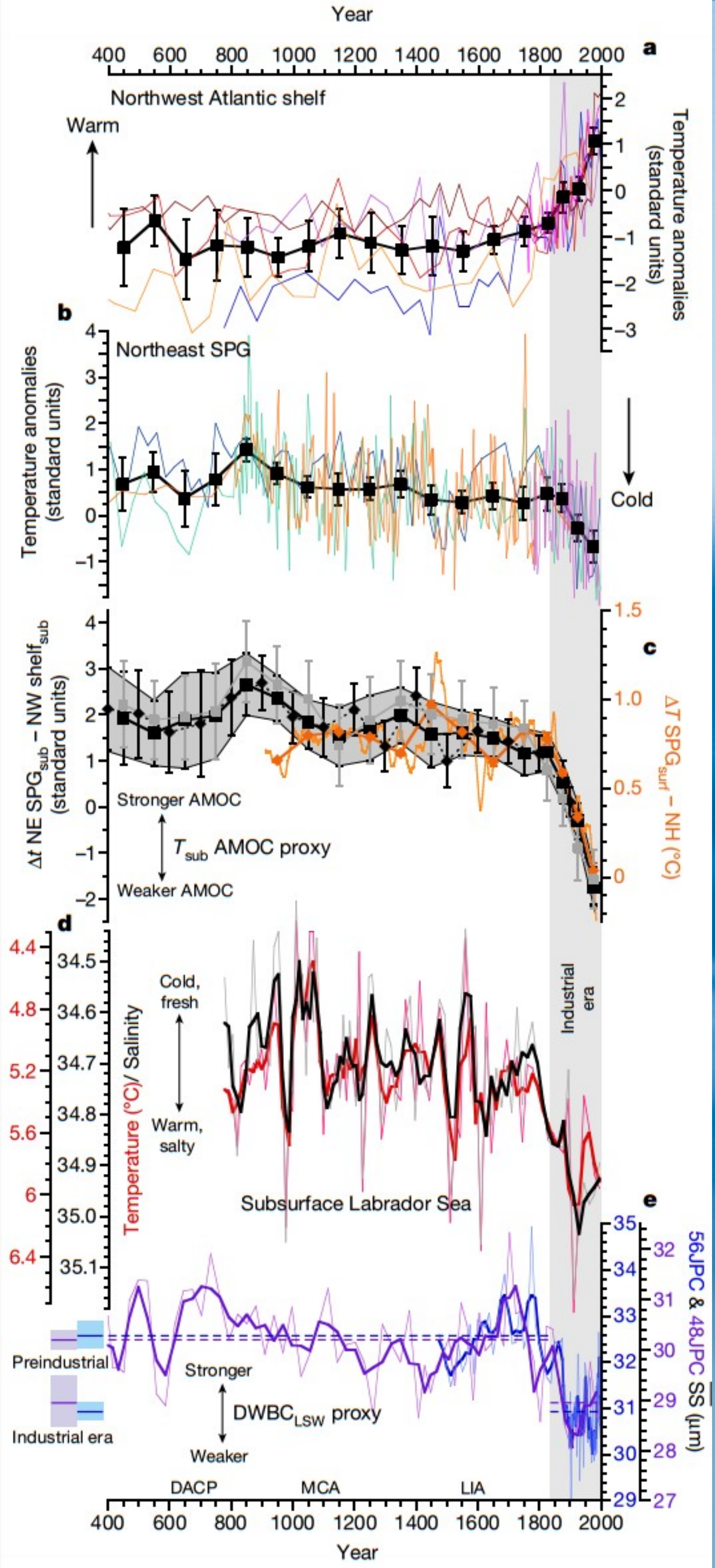
Was AMOC slowing down most of the 20th century?





Rahmstorf et al 2015 used an index of AMOC based on the difference of temperature between the Subarctic Gyre and North Hemisphere. They claim to observe a weakening of AMOC between 1930 and 1990 using climate proxies (blue), GISTEMP (red) and a coral based proxy (green with uncertainty band). They also compare it to 29 N AMOC measurements (red dots).

Rahmstorf et al 2015 (Nature Climate Change)

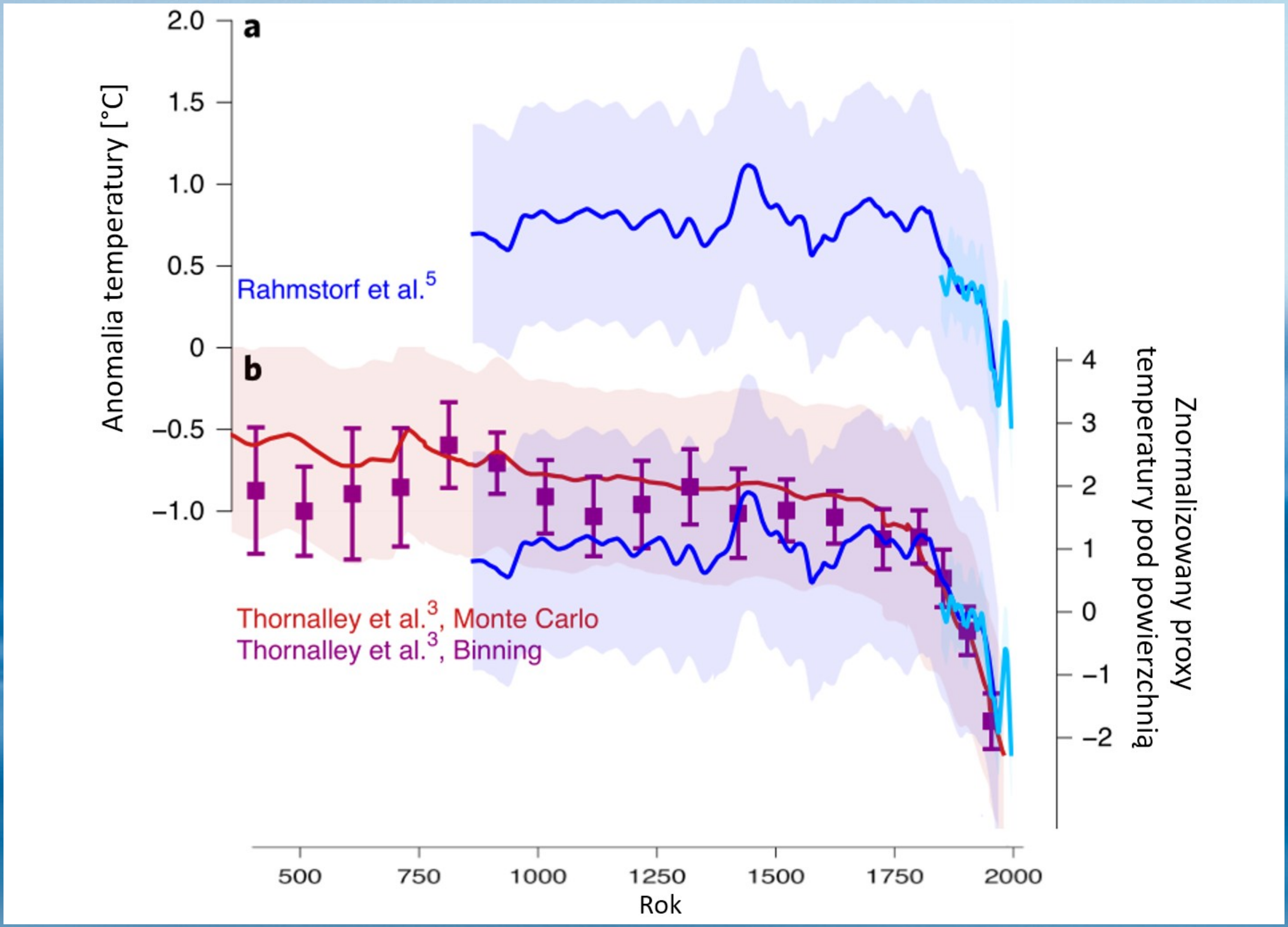


And maybe AMOC was weakening already since the 19th century?

Proxy reconstructions of AMOC changes over the past 1,600 years. **a**, **b**, Subsurface Northwest Atlantic shelf (a) and Northeast Atlantic SPG (b) temperatures, taken at sites shown in Fig. 2b. Composite stacks are in black. **c**, Black and grey, our Tsub AMOC proxy with different types of binning. Orange: AMOC proxy from Rahmstorf et al; 1º C = 2.3 Sv; thin line, 21-year smoothing; thick line and symbols, binned as for our Tsub AMOC proxy. NE SPG, Northeast Atlantic subpolar gyre; NW shelf, Northwest Atlantic shelf; NH, Northern Hemisphere; sub, subsurface; surf, surface. **d**, Subsurface (around 100–200 m) temperature and salinity of the northeast Labrador Sea, based on Mg/Ca-δ18O analysis of the planktic foraminifera *Neogloboquadrina pachyderma*. **e**, Sortable silt (SS) mean grain size. Blue, core 56JPC; purple, 48JPC; bold, three-point means; dashed lines, industrial/pre-industrial era averages; error bars/shading, ±2 s.e. DACP, Dark Ages Cold Period (around ad 400–800); MCA, Mediaeval Climate Anomaly (around ad 900–1250).

Thornalley et al 2018 (Nature)

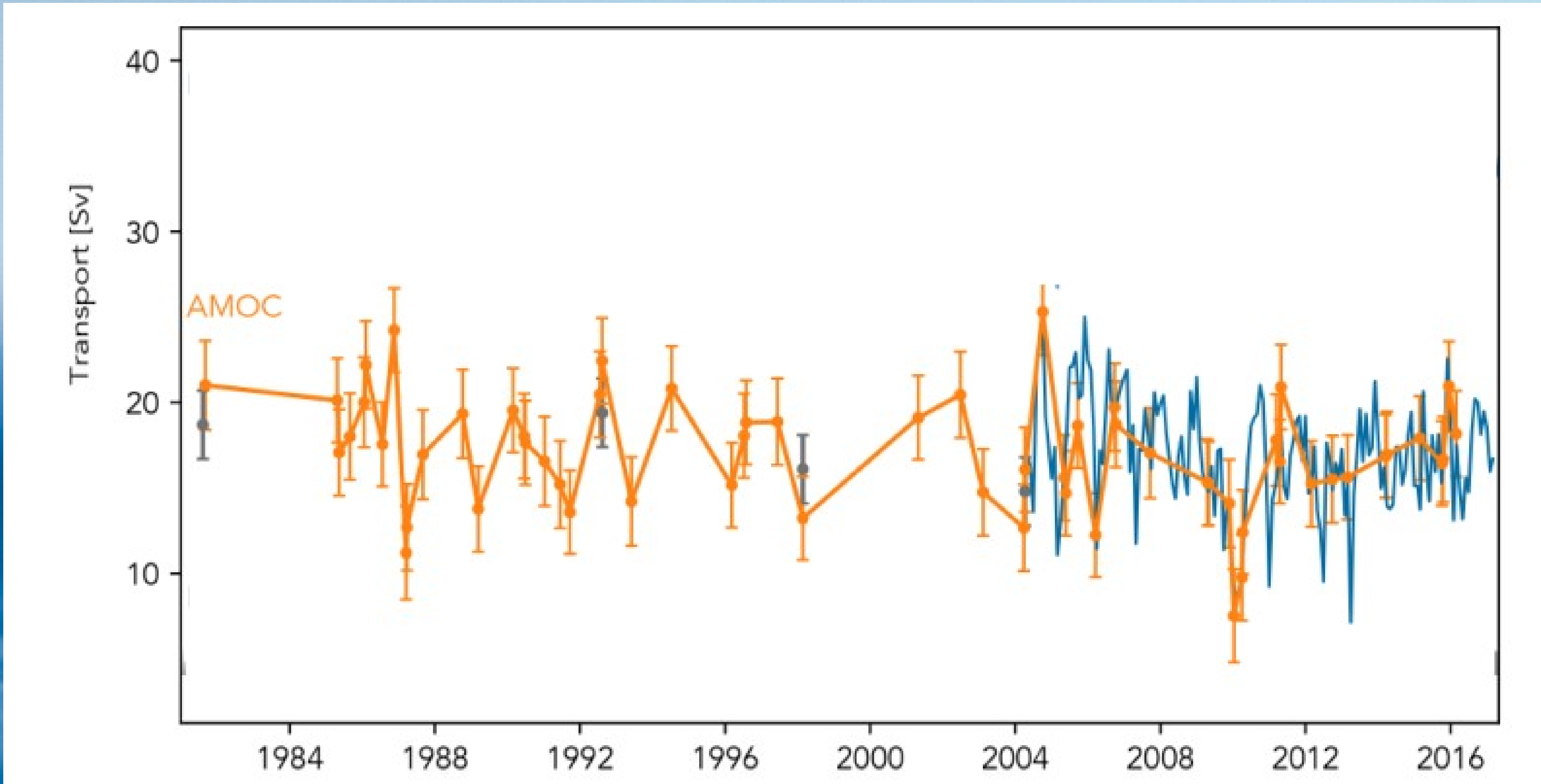
The story goes on. Another “decreasing AMOC” paper



This study uses several proxies, mostly Labrador Sea related to show that AMOC has been decreasing since 1850 (the Polish text comes from using this in a popular text on *Nauka o klimacie*).

Caesar et al. 2021 (Nature Geoscience)

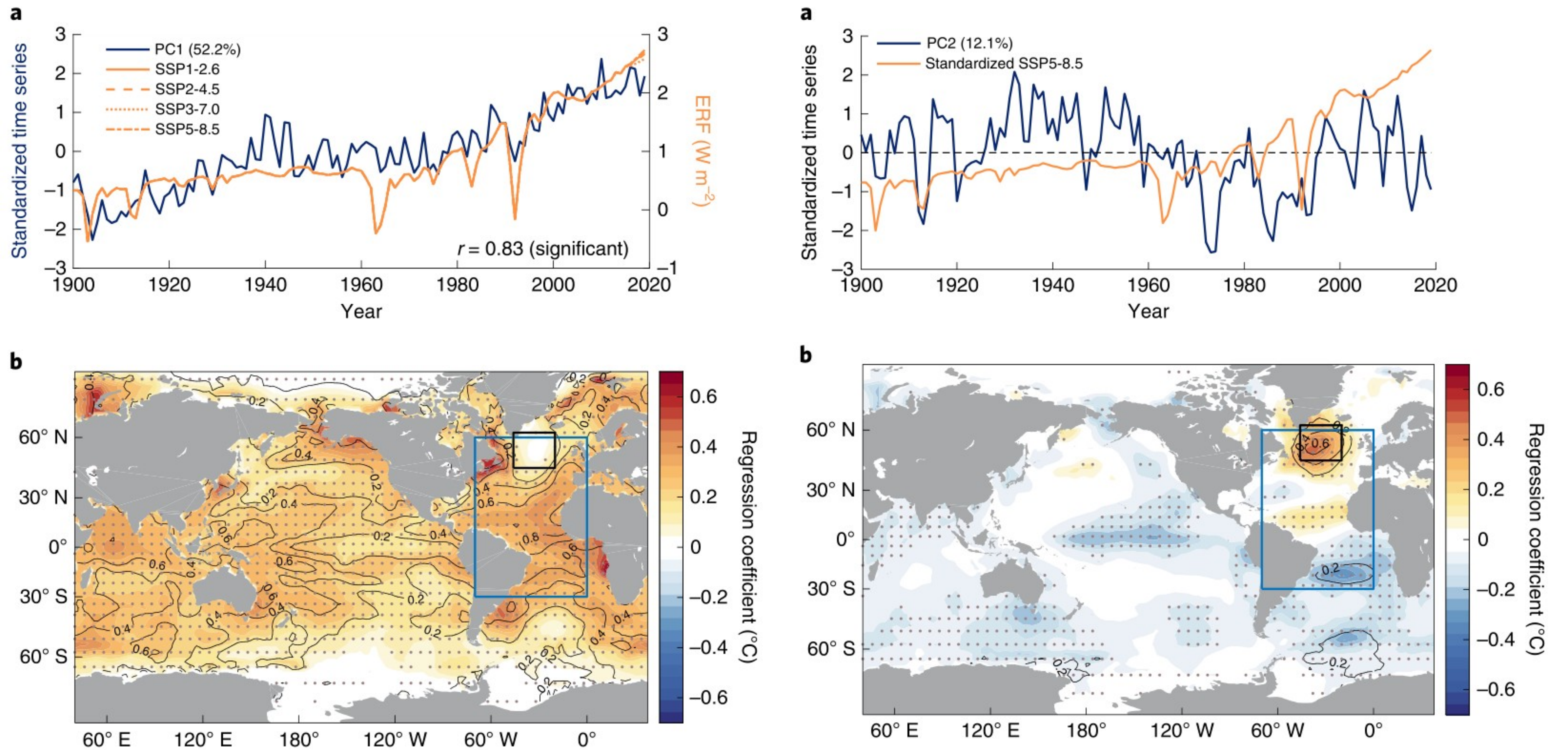
A whiff of observation data



This study correlates measured AMOC values with densities at four depth layers and creates an AMOC index from measurements of salinity and temperature profiles (CTD) going back 30 years. No significant decrease of AMOC have been detected.

Worthington et al. 2021 (Ocean Science)

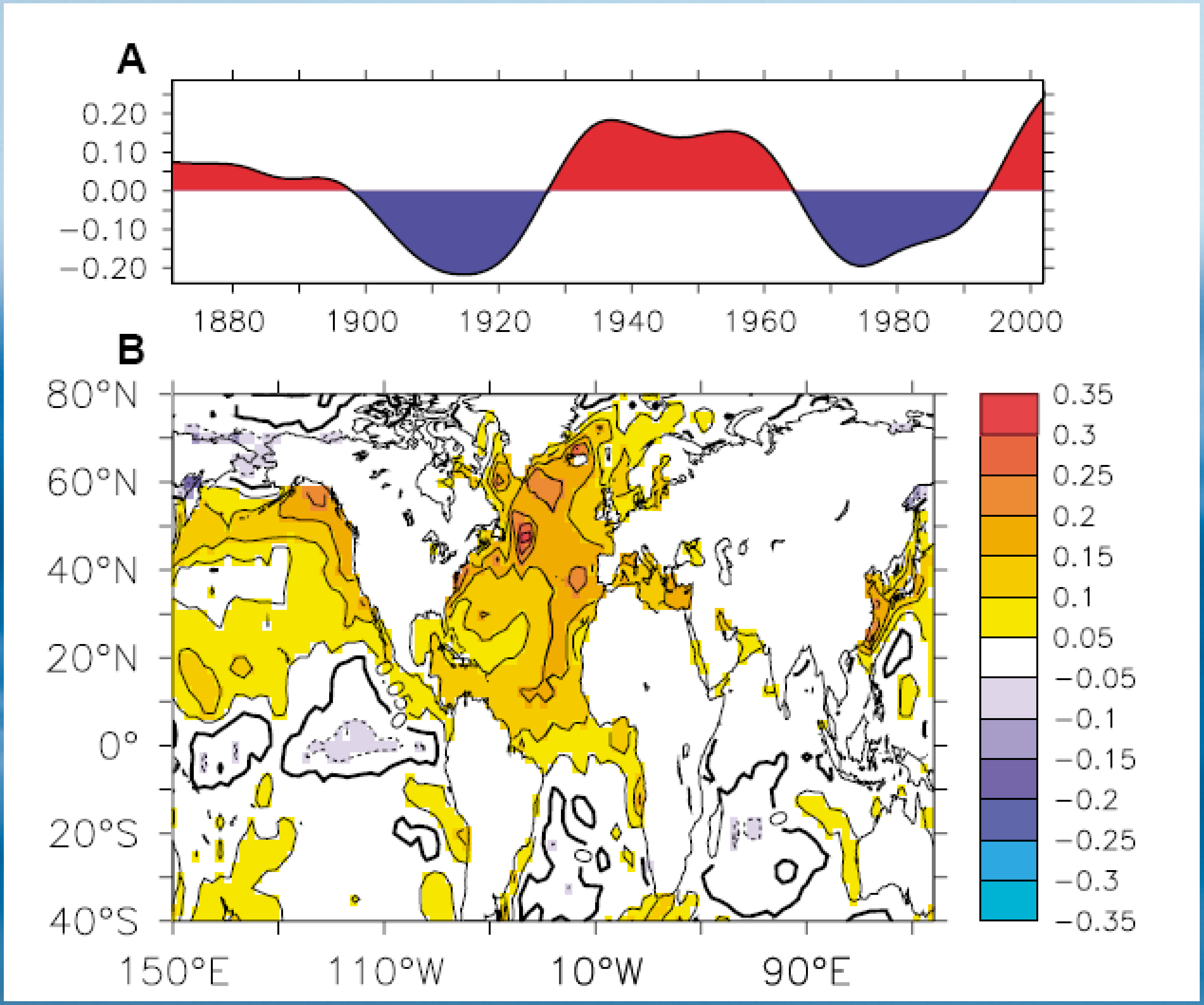
“Natural variability has dominated AMOC since 1900”



This study found two EOFs in global SST variability, the first one (left) related to greenhouse gas forcing and the second (right, independent of it. The conclusion of the authors is that the “Warming Hole” is the result of natural variability.

Latif et al. 2022 (Nature Climate Change)

Atlantic Multidecadal Oscillation

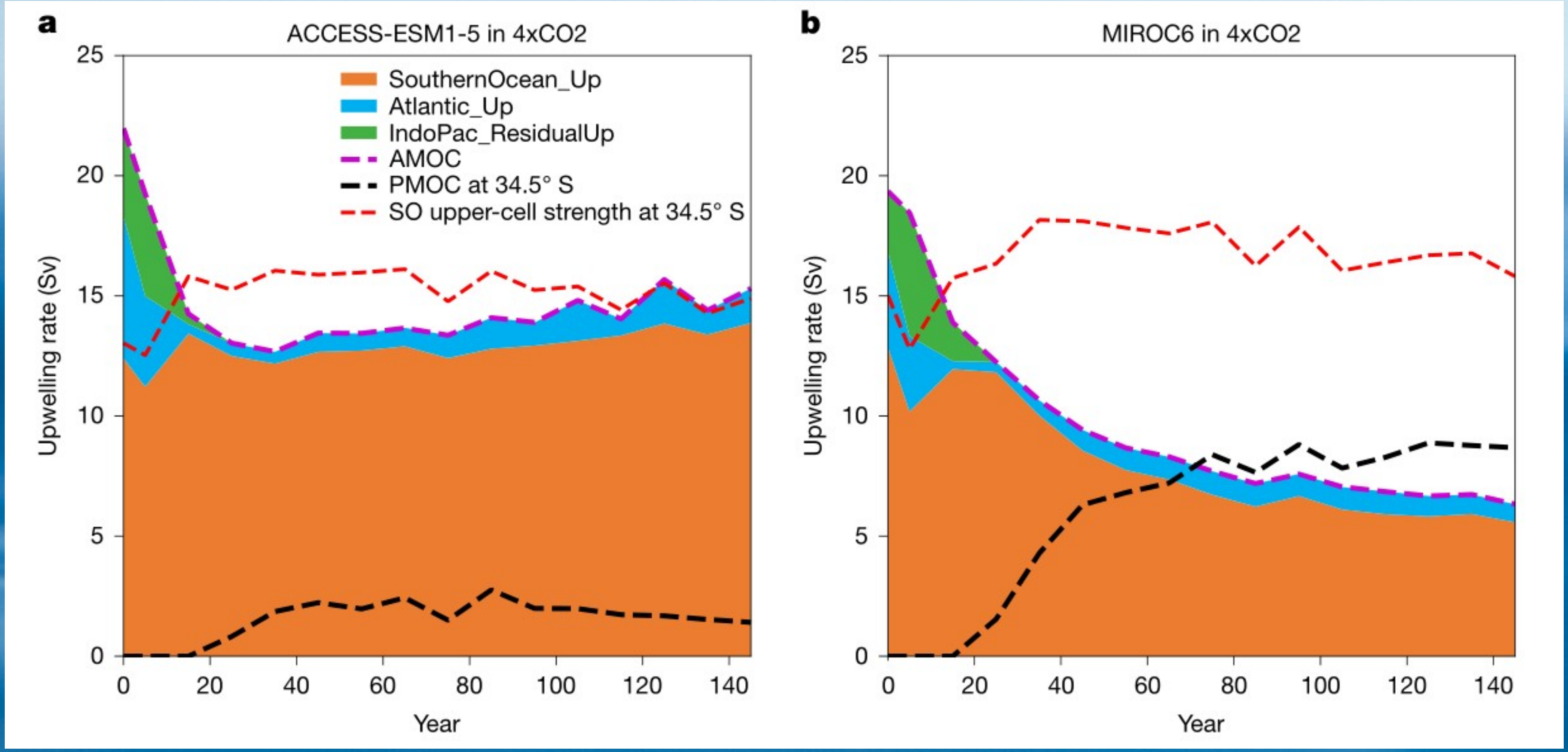


Atlantic Multidecadal oscillation is a periodical (60-70 years) warming and cooling of North Atlantic. The temperature anomaly of North Atlantic (top) is used as the AMO index.

Sutton, Hodson 2005 (Science)

Article

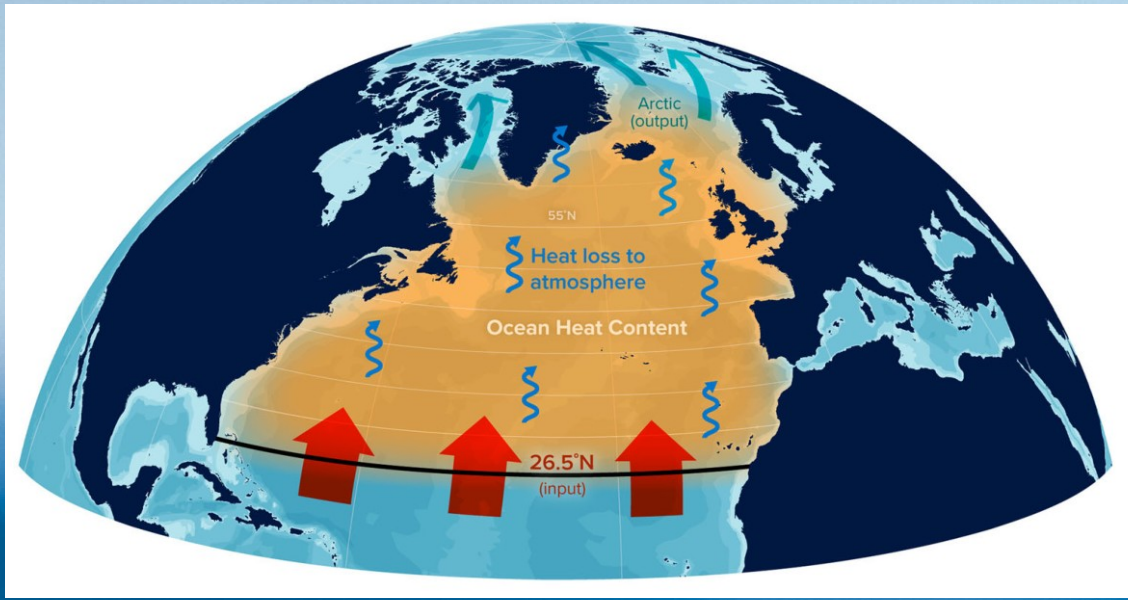
Continued Atlantic overturning circulation even under climate extremes

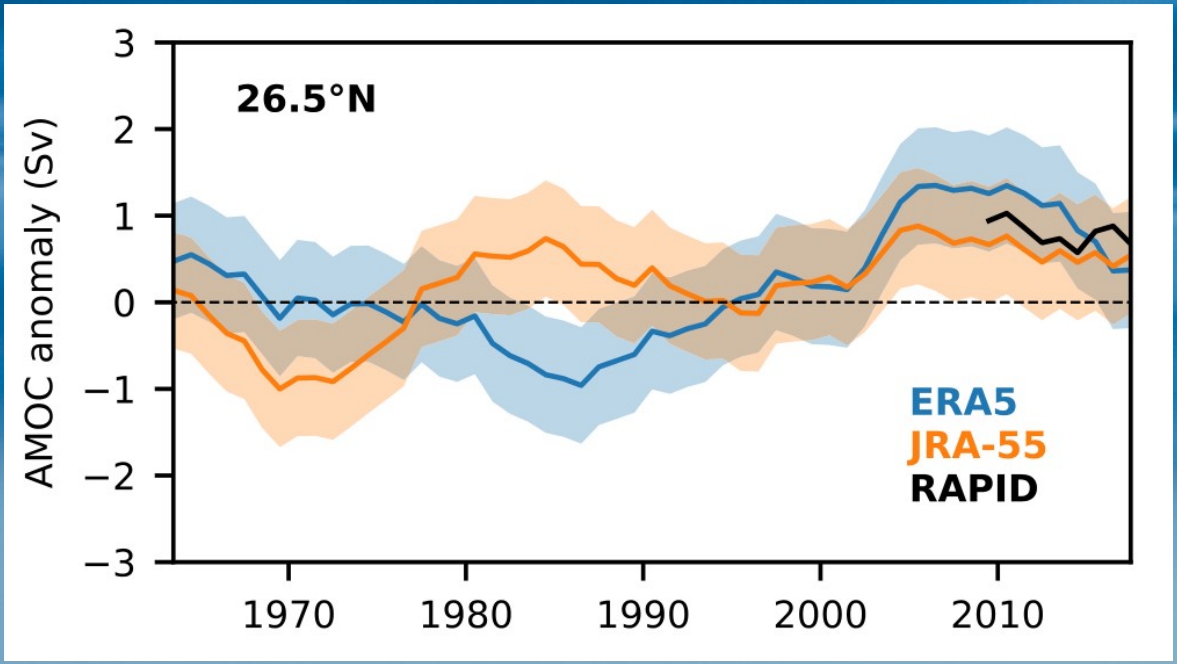


The authors used CMIP6 model ensemble result to show that not only AMOC is unlikely to collapse in experiments where CO2 is quadrupled in 140 years but also that only the models where PMOC develops show significant weakening of AMOC. The factor Saving AMOC is the strength of Southern Ocean upwelling sustained by strenthening winds around Antarctica.

Baker et al 2025 (Nature)

Again, no AMOC decrease





A study using the relationship between northward heat transport and air-sea heat exchange anomaly north of the latitude (here 26.5 ºN) and historical series of SST temperatures, shows no decreasing trend in the studied period (1960-2017). RAPID is the measurement series at that latituude. ERA5 and JRA-55 are two reanalyses.

Terhaar, Vogt & Foukal 2025 (Nature Communications)

Jens Terhaar receiving a medal for young scientists at the EGU 2025 in Vienna conference for the very paper.

nature climate change

ARTICLES

https://doi.org/10.1038/s41558-020-0819-8

Check for updates

Multiple drivers of the North Atlantic warming hole

Paul Keil[1], Thorsten Mauritsen[1,2], Johann Jungclaus[1], Christopher Hedemann[1], Dirk Olonscheck[1] and Rohit Ghosh[1,3]

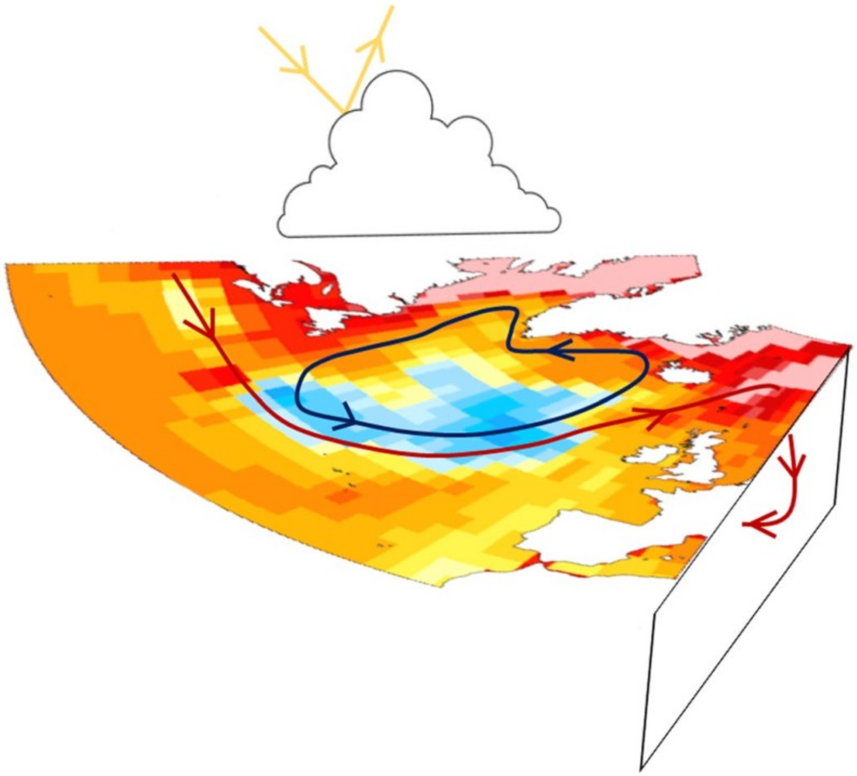
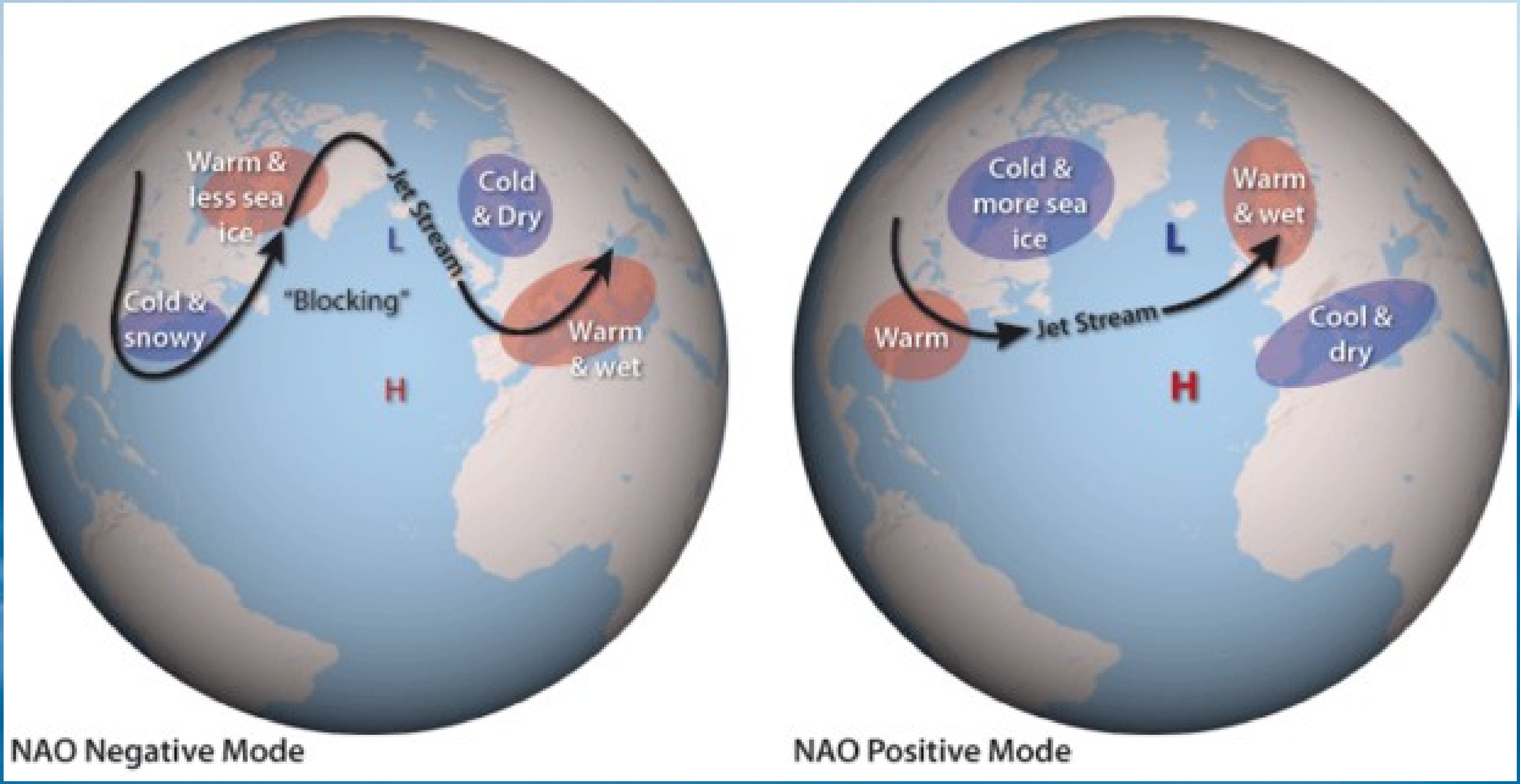


Fig. 5 | Schematic illustration of the drivers of the WH. The AMOC is indicated by red arrows, the gyre circulation by blue arrows and cloud feedback in the form of reflected shortwave radiation by yellow arrows. Shading represents the surface temperature trend of the 1pctCO_2 increase per year ensemble.

"Consequently, the long-term evolution of the WH [Warming Hole] in a forced scenario, in contrast to internal variability, is driven by a multitude of factors: OHT [Ocean Heat Transport] changes at low and high latitudes associated with both the overturning and gyre circulation along with atmospheric processes (Fig. 5)

Keil et al 2020 (Nature Climate Change)

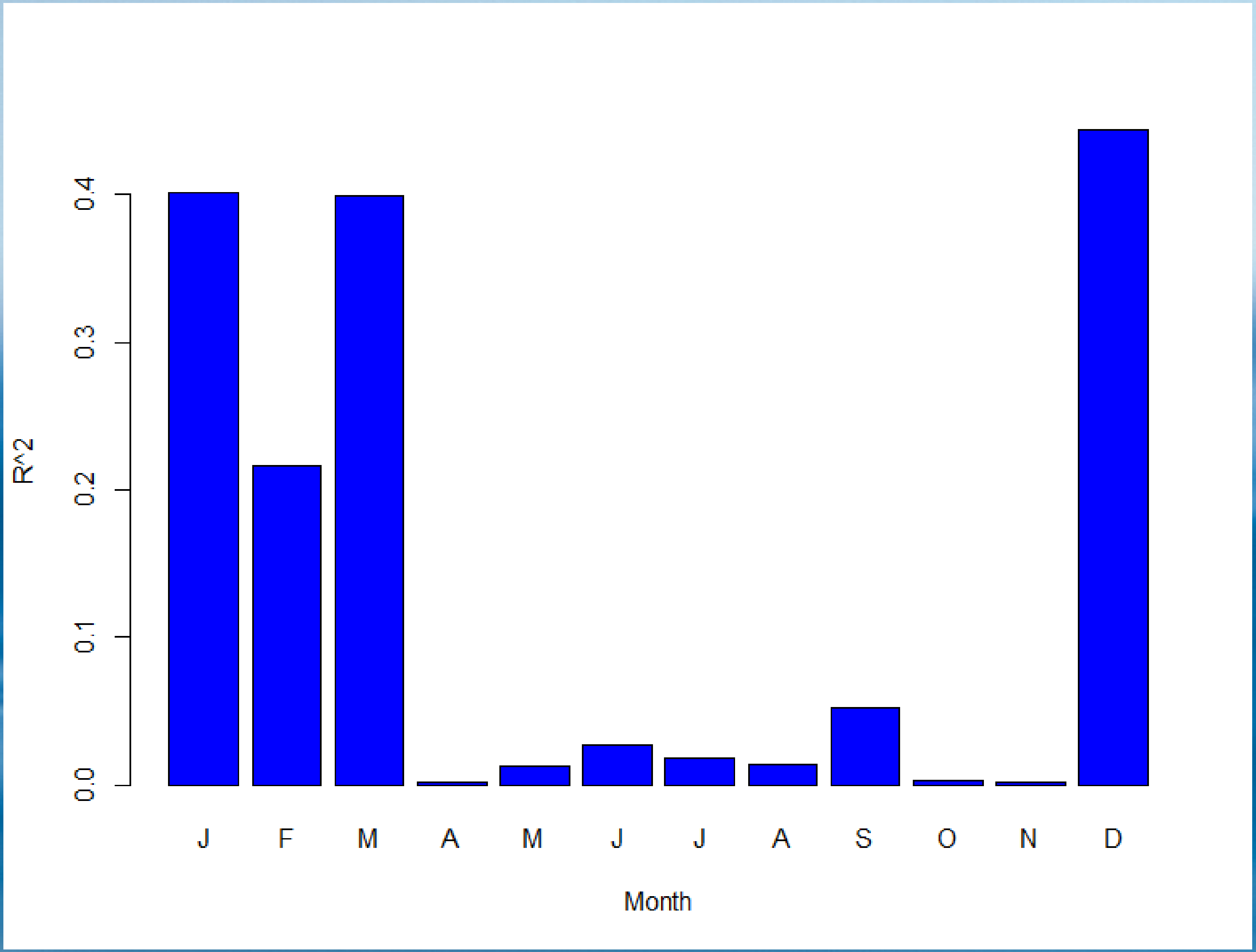
North Atlantic Oscillation (NAO)



The NAO index, identified by Walker (1924), historically defined as the pressure difference between Lisbon and Reykjavik (positive NAO situation in the figure). This index explains 31% of the variation in winter temperatures north of 20º N.

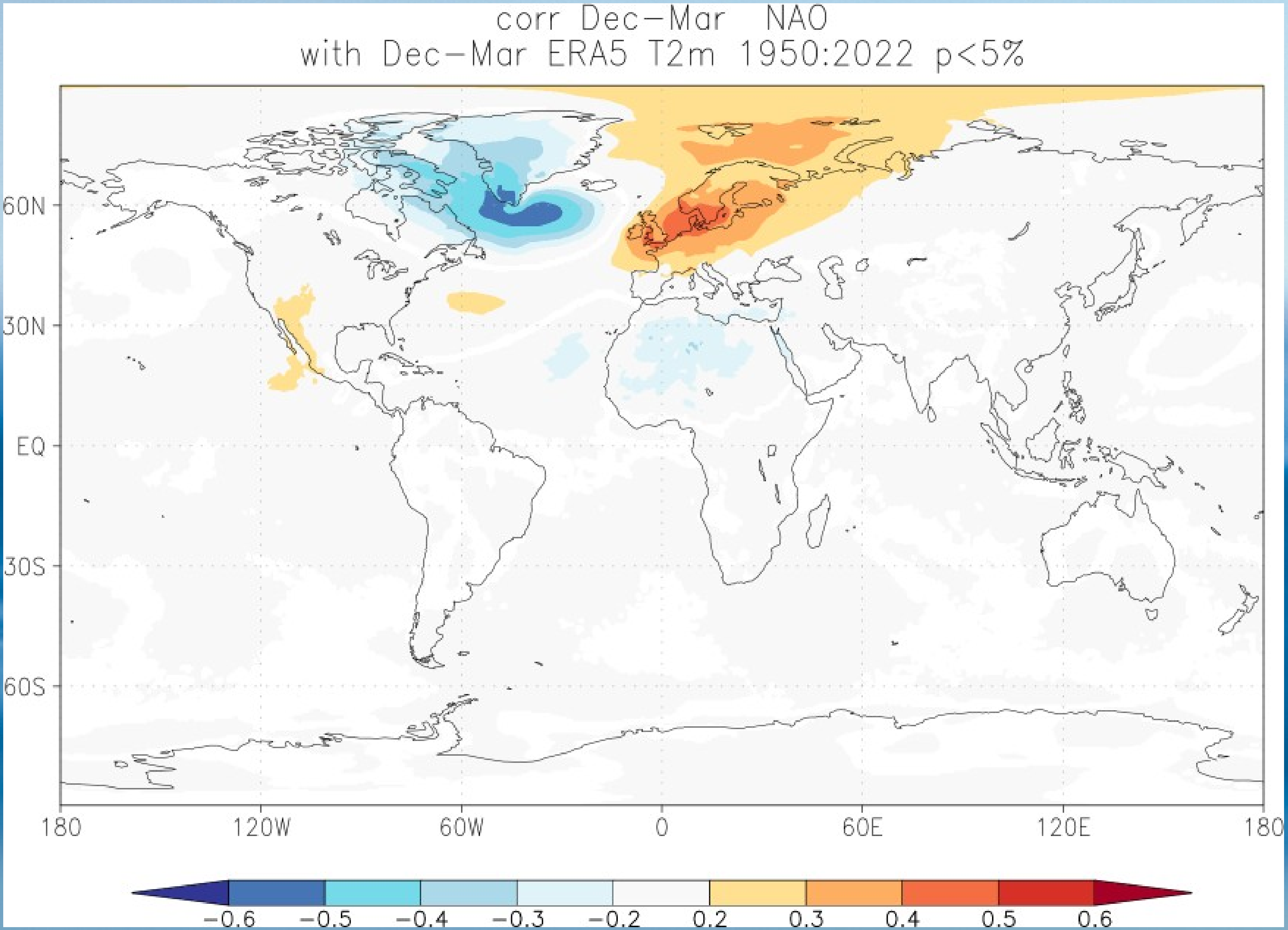
NOAA

Why winter NAO?



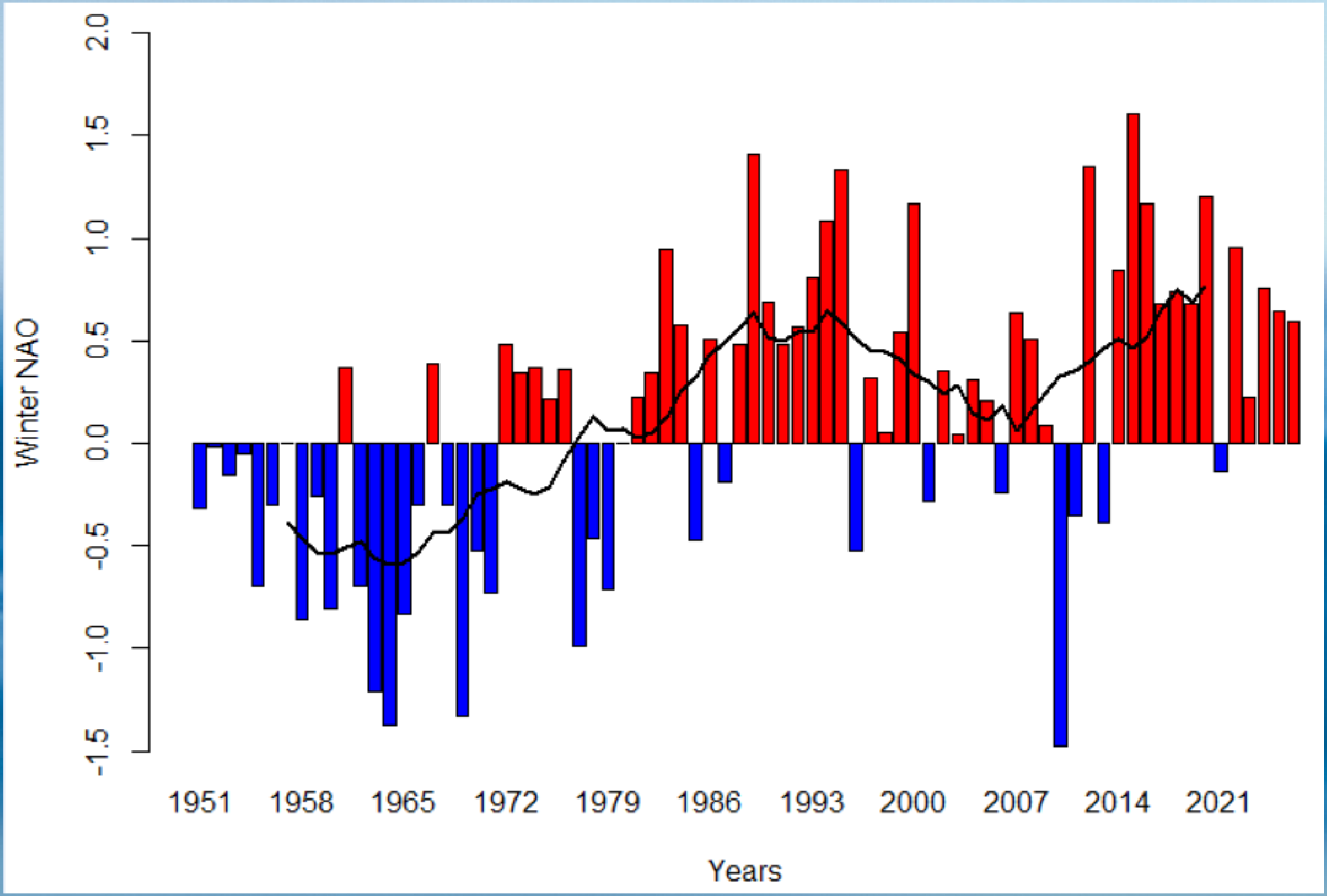
Coefficient of determination (squared correlation) of temperatures in Poland and the NAO since 1950 for individual months.

Opracowanie własne na podstawie danych NOAA i serii Poltemp (https://meteomodel.pl/klimat/poltemp/)



The correlation map of winter DJFM NAO and local temperatures, 1950-2022 showing where positive NAO takes heat from to warm Europe.

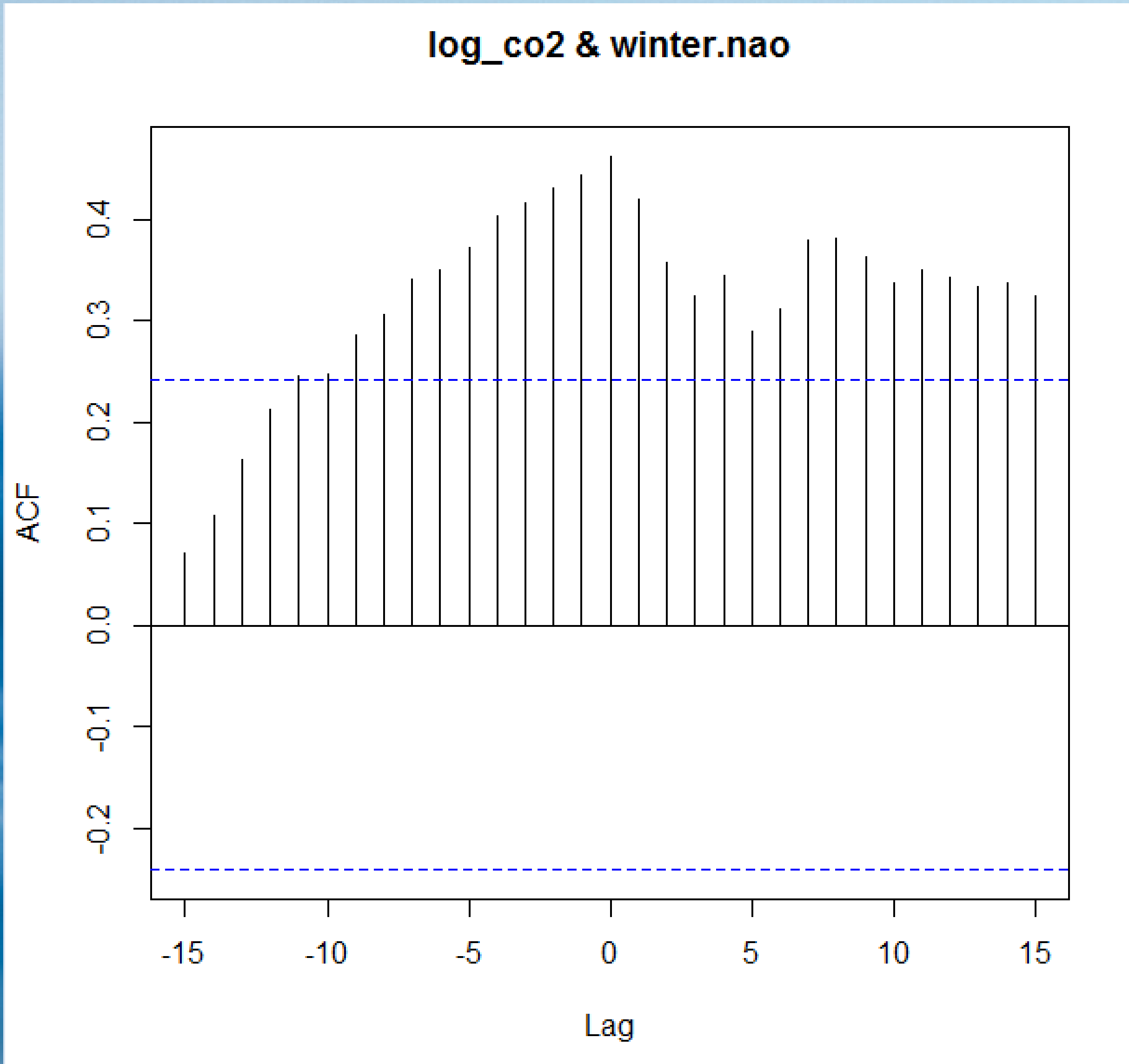
Winter (DJFM) NAO since 1950



Noteworthy is the period of low values in the 1960s and high values in the 1990s, as well as the decreasing value until 2010 and the strong increase in recent years.

Opracowanie własne na podstawie danych NOAA

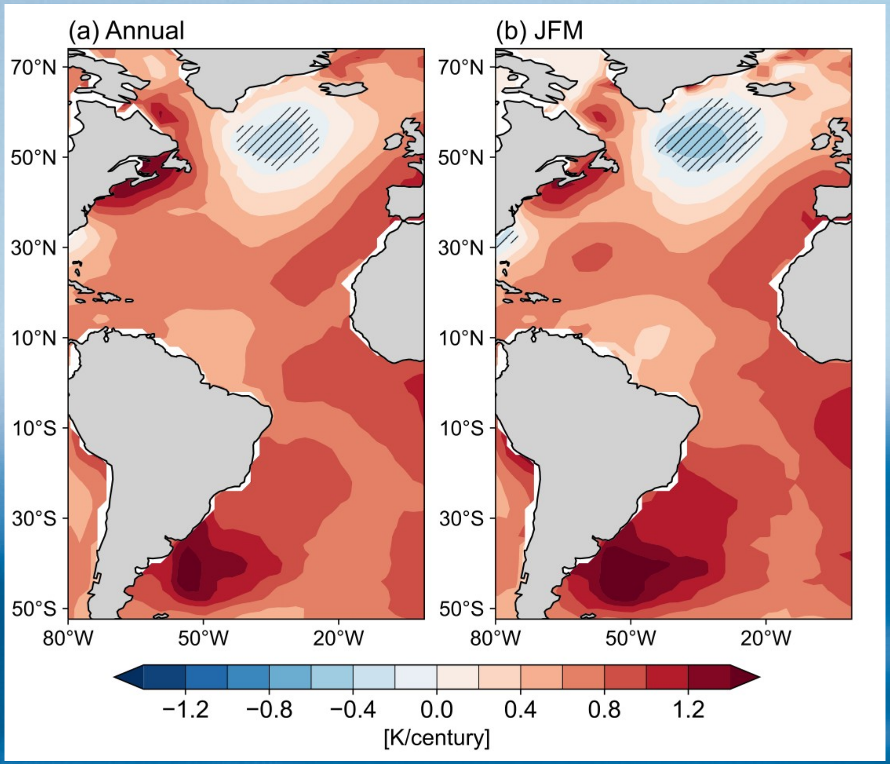
Atmospheric CO_2 cross-correlated with NAO

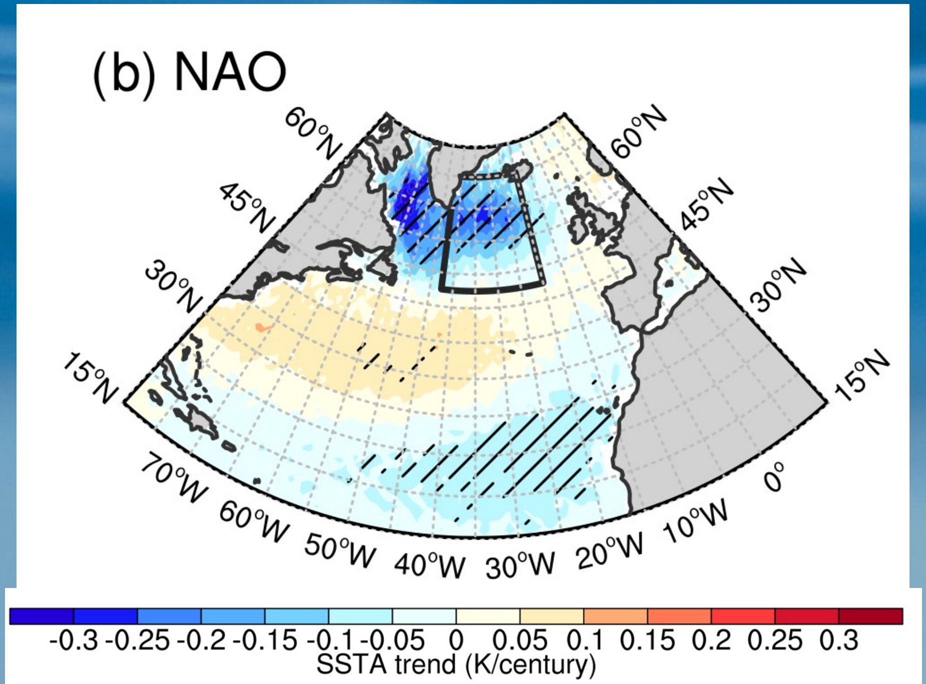


Winter NAO is significantly correlated with logarithm of atmospheric CO2 (roughly CO2 radiative forcing) for data starting in 1950, with a broad range of lags. There is a maximum at 0 lat and all the other highest correlations for short lads of NOA versus CO2.

Piskozub 2018

The cold blob is mostly caused by more positive NAO

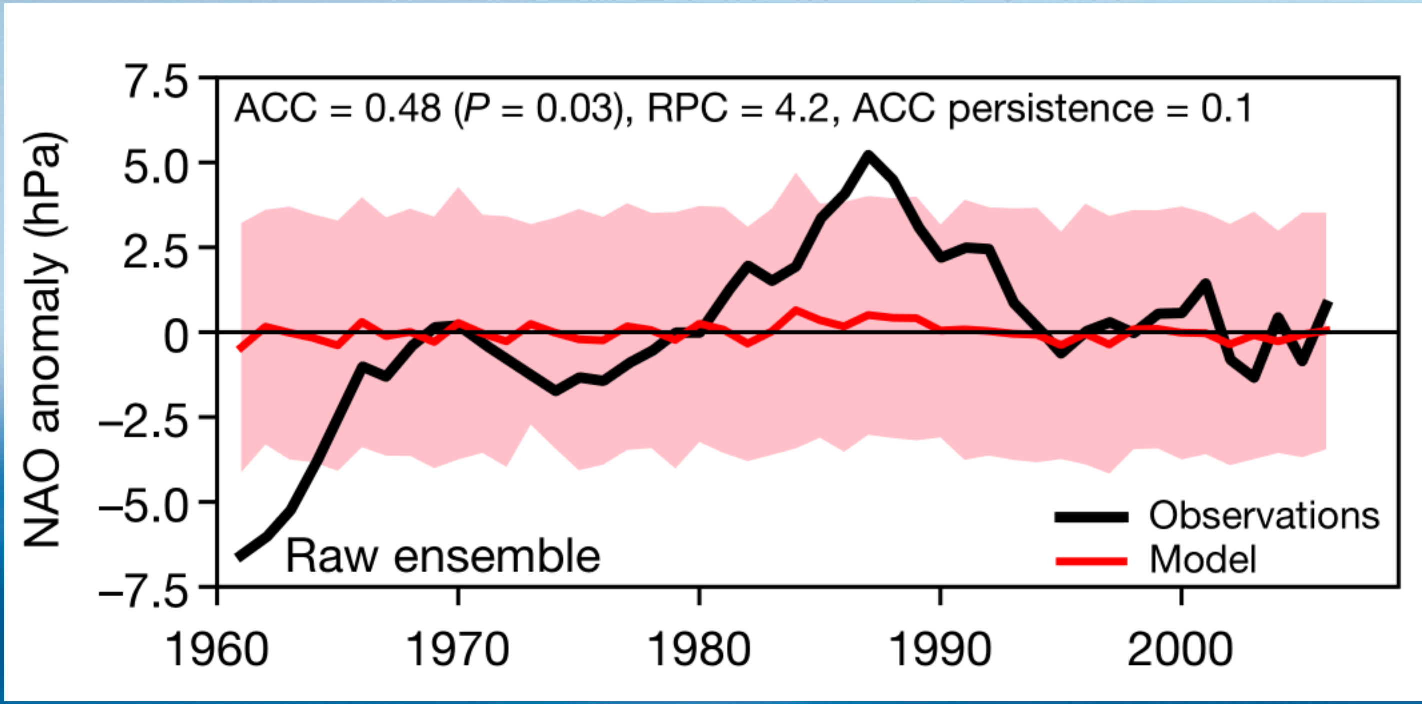




The analysis in this study shows that the observer cold trend in Subpolar Gyre (top, both annual and JFM) is caused in 67% by increase in NAO. The bottom graph shows SST trends caused by NAO variability (from their regression).

Fan et al 2023 (Climate Dynamics)

The models are unable to repoduce NAO variability



Observed (black) and model-forecast (years 2–9; red) 8-yr running means for the boreal winter (December to March) NAO index. The red curve shows the ensemble mean of the 169 members; the red shading shows the 5%–95% confidence interval diagnosed from the individual members.

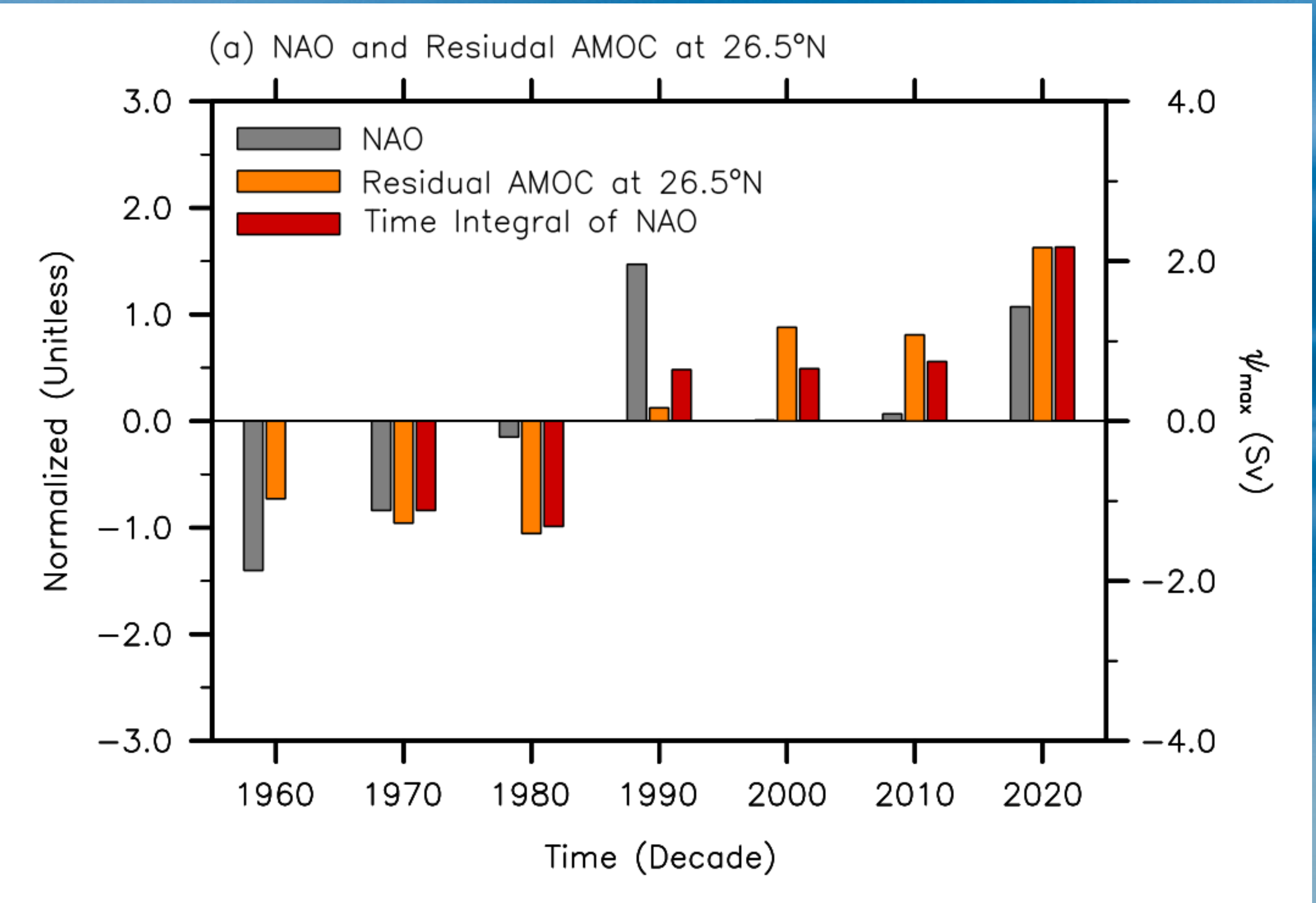
From the paper abstract:
"current models underestimate the predictable signal (the predictable fraction of the total variability) of the North Atlantic Oscillation (the leading mode of variability in North Atlantic atmospheric circulation) by an order of magnitude".

Smith et al 2020 (Nature)

nature communications

Article https://doi.org/10.1038/s41467-024-54903-w

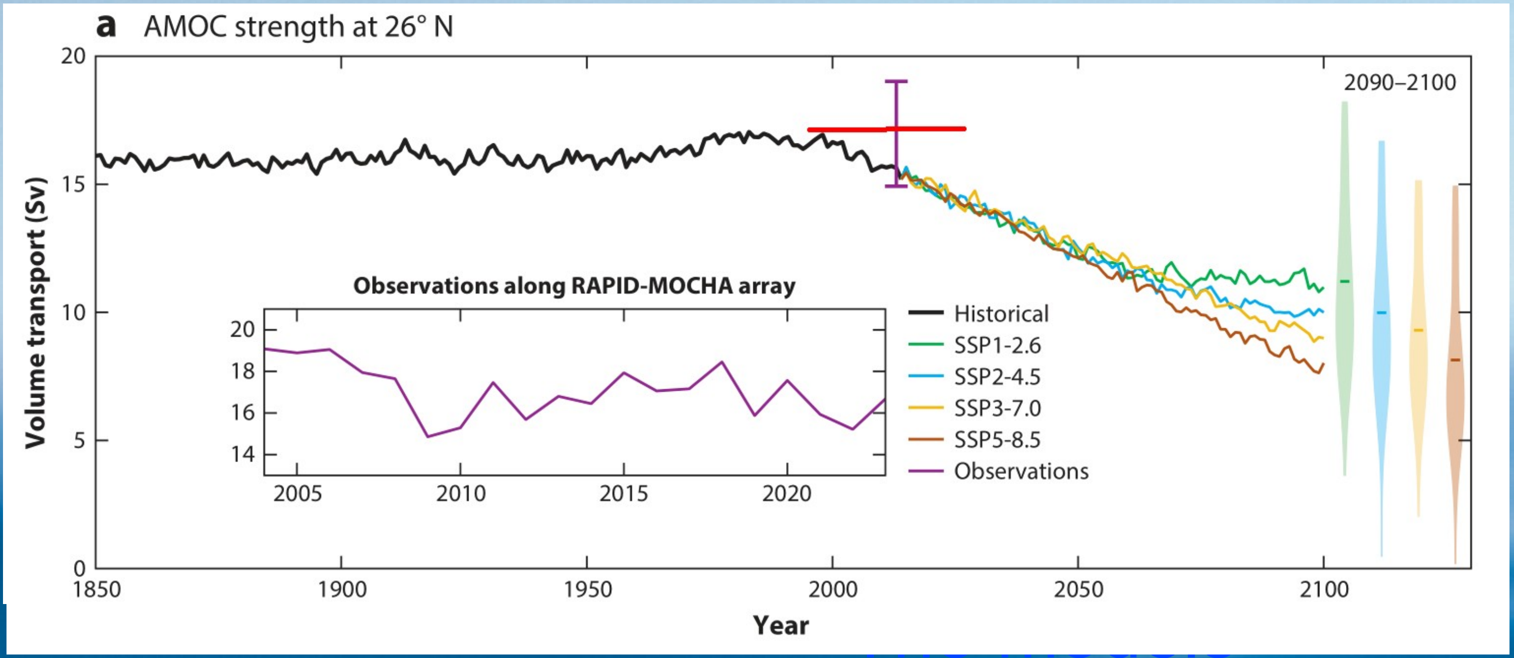
A pause in the weakening of the Atlantic meridional overturning circulation since the early 2010s

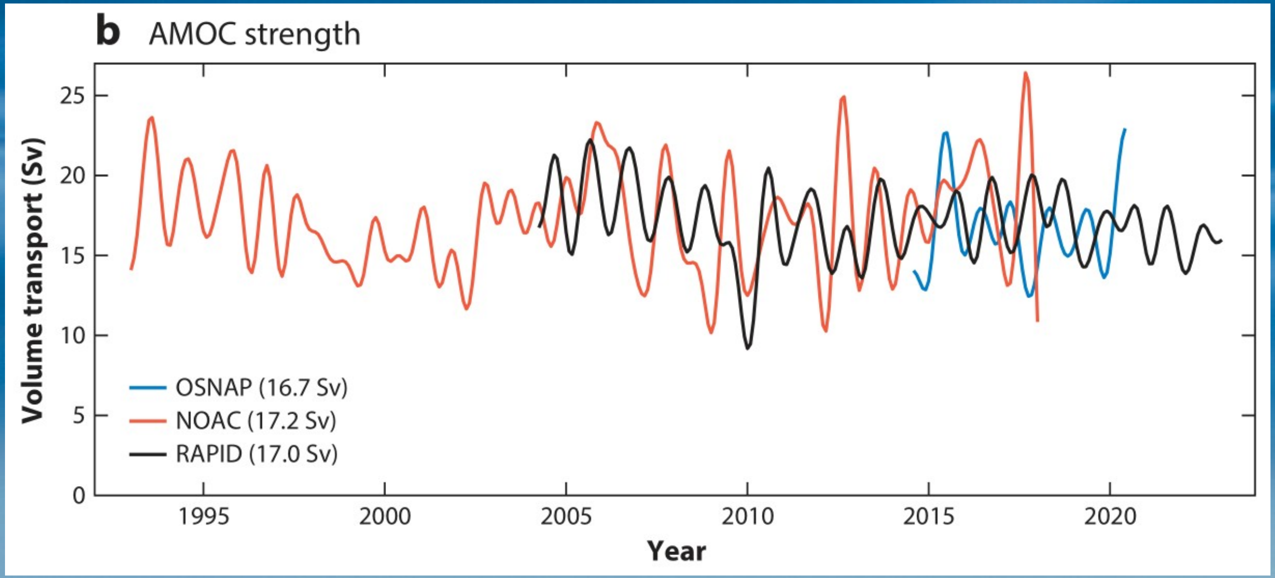


This paper compares changes in AMOC in observations and models and calls the difference a "residual". It shows that the residuals can be explained by time integrated NAO. This means that NAO is the factor that saves AMOC from decrease.

Sang-Ki Lee et al 2024 (Nature Communications)

Reality check: models vs. measurements





CMIP6 model projections show on average about 30% AMOC drop to the wend of the century. However, observation do not see so far the decline which should have started before year 2000. The red horizontal line is the observational period.

Dijkstra & van Westen 2026 (Annual Reviews)

Conclusions

- AMOC transports 1-2 PW heat from the Southern Hemisphere northwards along the Atlantic. This is the main reason why Europe is warmer than other land masses of similar latitude.
- The release of this heat into the atmosphere requires warm and salty waters to reach Nordic Seas still on the sea surface. This may be hindered by fresh meltwater from the Greenland ice sheet.
- Models project a decrease of about 30% (but not a collapse) of AMOC in this century.
- However observations do not confirm a decline of AMOC beyond the historical range of natural variability.
- A possible reason of the cold spot used for reconstructing past AMOC values is strengthening of western circulation (NAO), also possibly a result of anthropogenic greenhouse gas emissions (a process not visible in modern circulation models).

Awardees of these prices always appear to be great, but...

u^b 01:42

UNIVERSITÄT BERN

OESCHGER CENTRE CLIMATE CHANGE RESEARCH

- When defending my PhD, I had not published a single paper
- During my PhD, I was not working for months because of mental health problems
- Other more senior scientist have accused me of a lack of critical thinking
- Balancing a family (3 children) and academia has been really tough at times and takes opportunities away from you – it can make you feel guilty at work and at home
- During my relatively few years of academia in my different functions, I have witnessed forms of sexual harassment, plagiarism, and discrimination with positive and negative responses by the different institutions