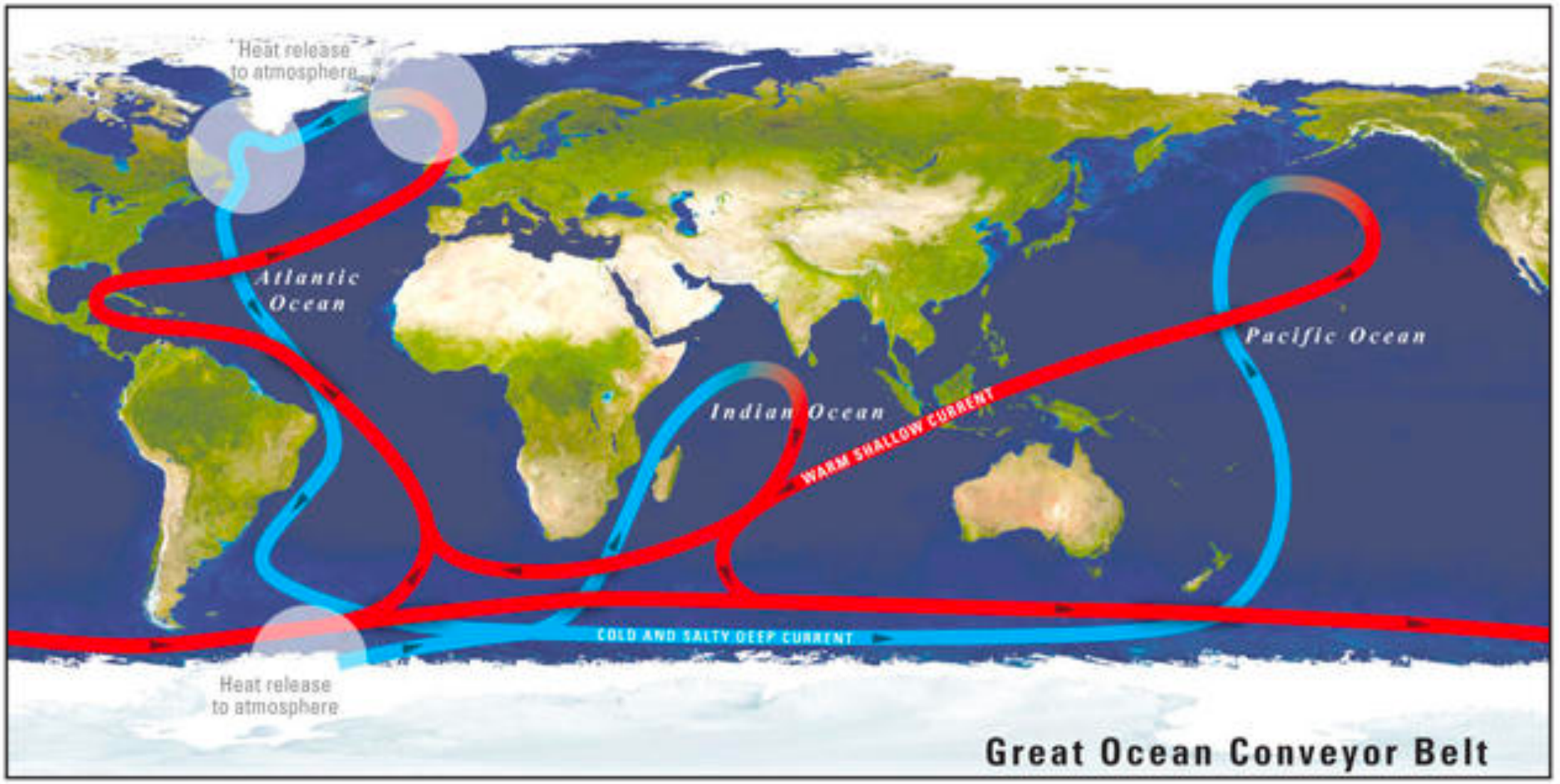
Ocean circulation collapse

Global Warming Science, EPS101

Eli Tziperman

https://courses.seas.harvard.edu/climate/eli/Courses/EPS101/

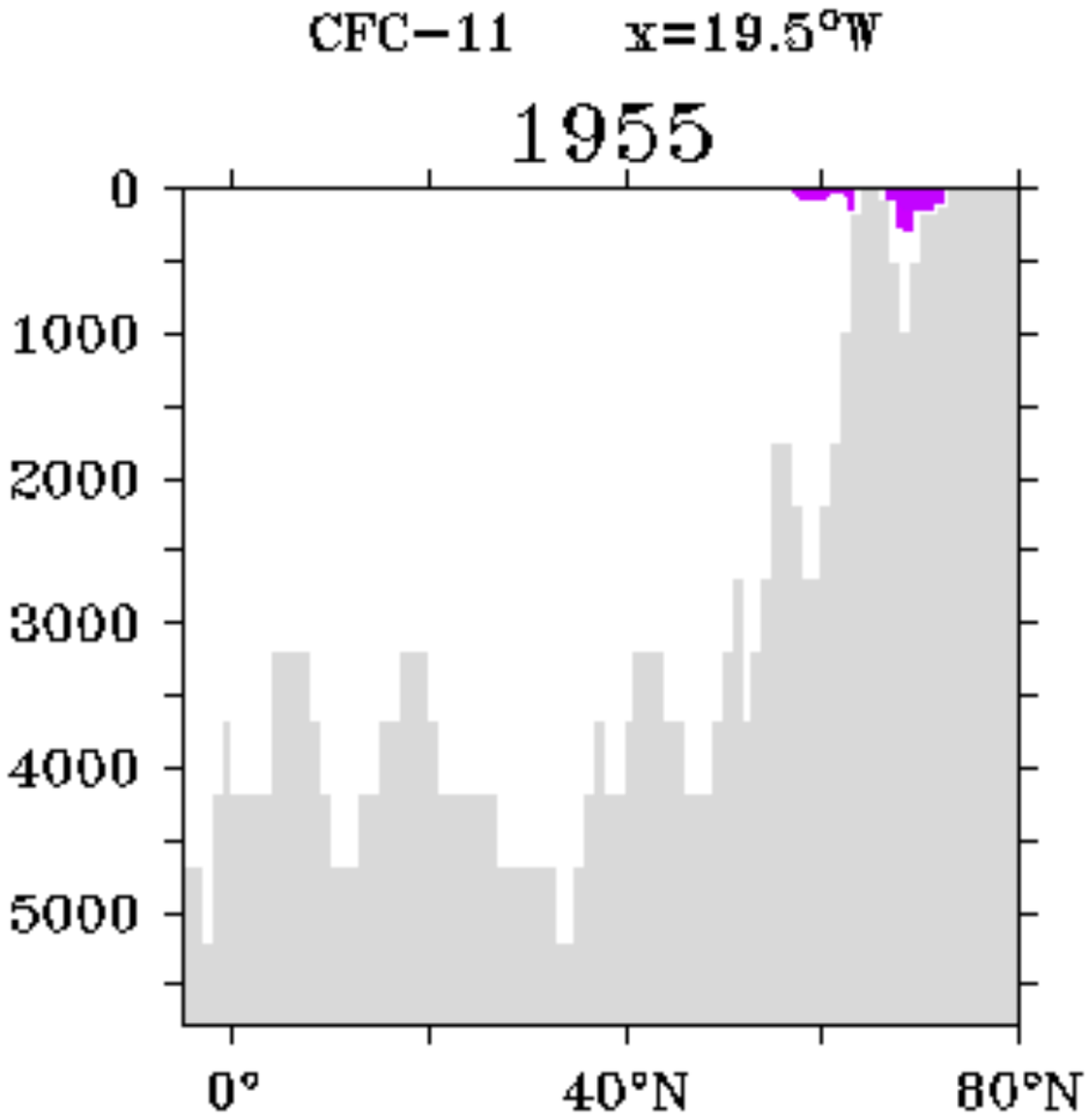
The Atlantic Meridional Overturning Circulation (AMOC)



https://www.cbsnews.com/news/climate-change-atlantic-ocean-gulf-stream-system-amoc-weakest-1600-years/

AMOC schematics: the sinking occurs over very small high-latitude areas in the ocean. The upwelling back to the surface is very broad, in the Southern Ocean and over entire ocean basins, not as depicted.

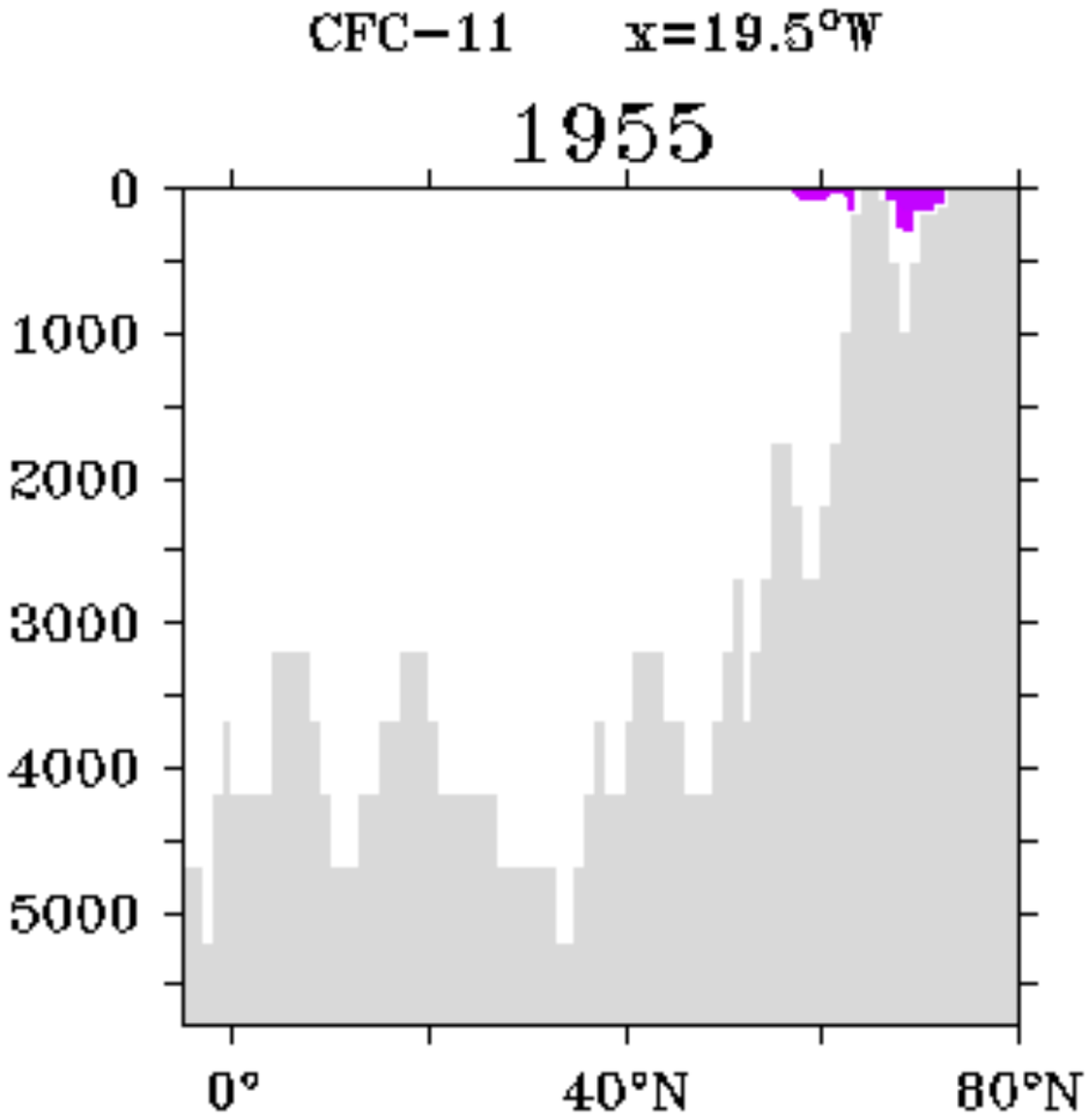
The Atlantic Meridional Overturning Circulation (AMOC)



Observations of CFC spreading in the North Atlantic Ocean, showing the sinking of deep water there.

http://puddle.mit.edu/~mick/cfcsec.html
(link does not work anymore?)

The Atlantic Meridional Overturning Circulation (AMOC)



Observations of CFC spreading in the North Atlantic Ocean, showing the sinking of deep water there.

http://puddle.mit.edu/~mick/cfcsec.html
(link does not work anymore?)

The Atlantic Meridional Overturning Circulation in the news

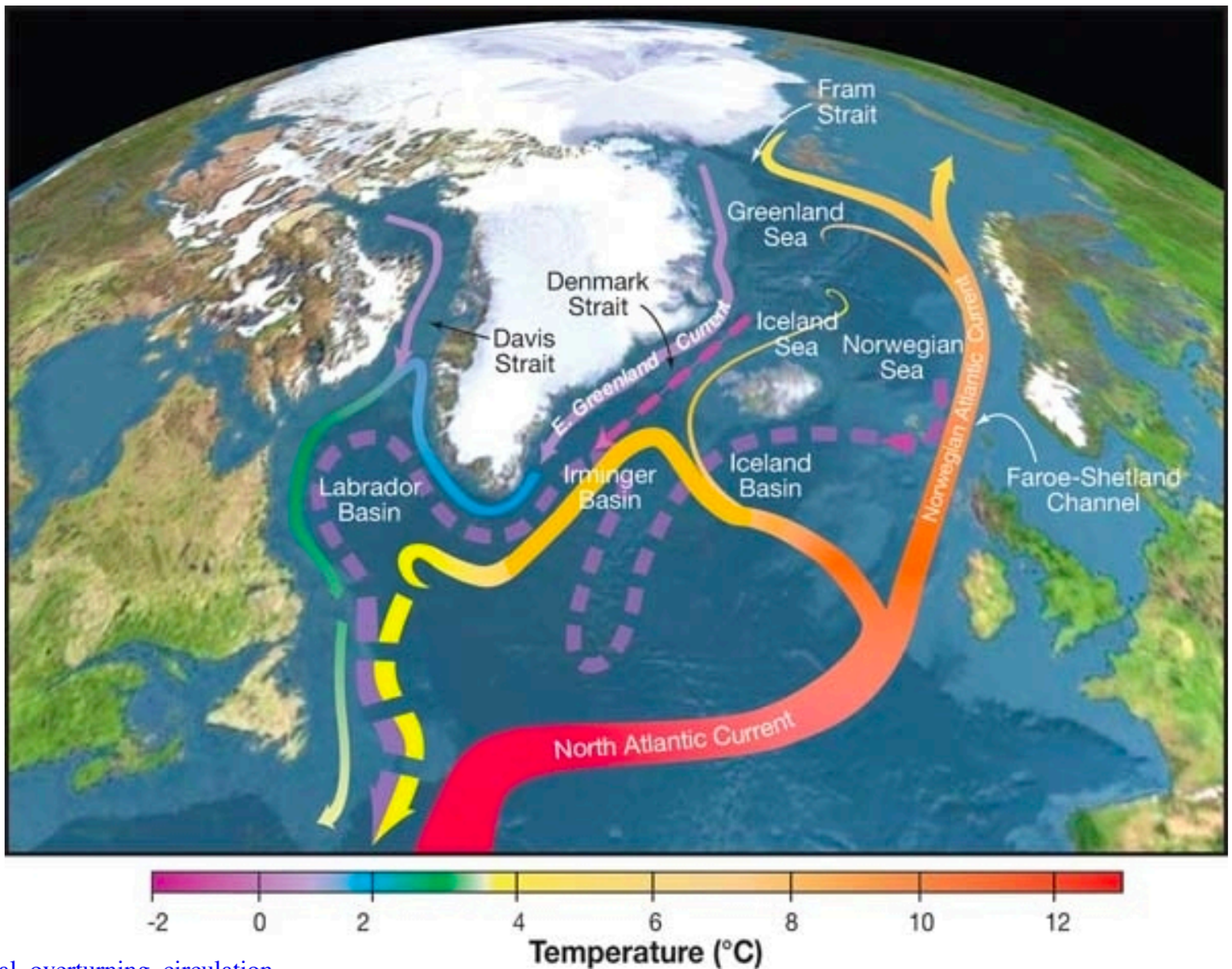
The New York Times

Altantic Ocean current shows weakening signs

By Andrew C. Revkin

Nov. 30, 2005

NEW YORK — Atlantic Ocean currents that make Northern Europe warmer than it would otherwise be have weakened by about a third over the last 50 years, British oceanographers are reporting.



https://en.wikipedia.org/wiki/Atlantic_meridional_overturning_circulation

The day after tomorrow

https://www.youtube.com/watch?v=Ku_IseK3xTc

The day after tomorrow

https://www.youtube.com/watch?v=Ku_IseK3xTc

A news update about AMOC

The New York Times

Altantic Ocean current shows weakening signs

By Andrew C. Revkin

Nov. 30, 2005

NEW YORK — Atlantic Ocean currents that make Northern Europe warmer than it would otherwise be have weakened by about a third over the last 50 years, British oceanographers are reporting.

A news update about AMOC

The New York Times

Altantic Ocean current shows weakening signs

By Andrew C. Revkin

Nov. 30, 2005

NEW YORK — Atlantic Ocean currents that make Northern Europe warmer than it would otherwise be have weakened by about a third over the last 50 years, British oceanographers are reporting.

The New York Times

Scientists Back Off Theory of a Colder Europe in a Warming World

May 15, 2007

Gradual melting of the Greenland ice sheet, above left, might weaken the North Atlantic Current, which bathes parts of Europe with equatorial water. But any cooling effect in Europe would be overwhelmed by a general warming of the atmosphere.

Trying to estimate the warming effect of the Atlantic Meridional Overturning Circulation (AMOC)

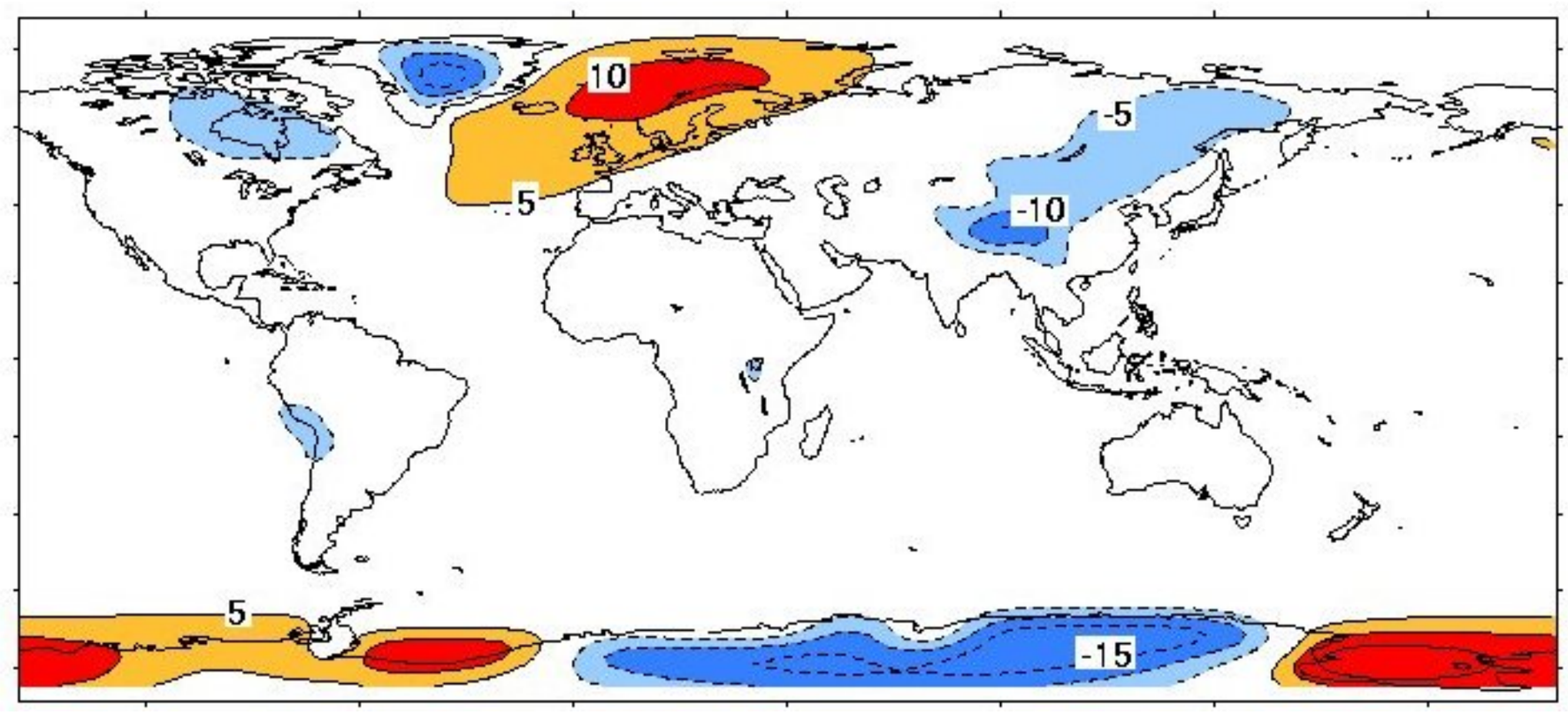


Figure 1. Deviation of the annual-mean surface air temperature from its zonal average, computed from the NCAR air temperature climatology. Anomalously cold areas are found over some continental regions, anomalously warm areas over ocean deep water formation regions.

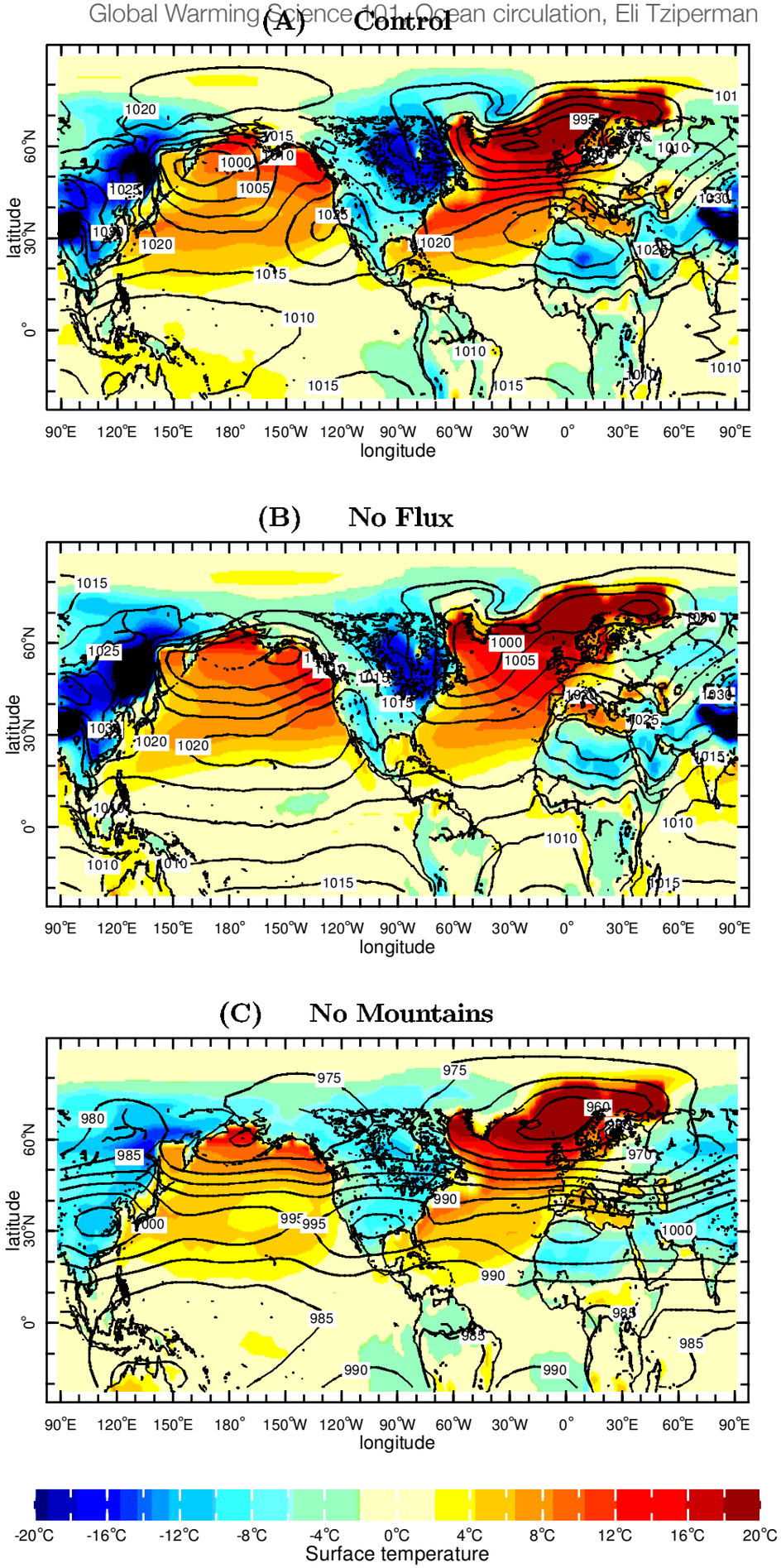
[Whether this pattern should be attributed to the AMOC is debatable, see next slide.]

Rahmstorf, S. and A. Ganopolski, Long-term global warming scenarios computed with an efficient coupled climate model. ClimaUc Change, 1999. 43: p. 353-367.

Is the Gulf Stream responsible for Europe's mild winters?

SEAGER, BATTISTI, YIN, GORDON, NAIK, CLEMENT & CANE, 2002

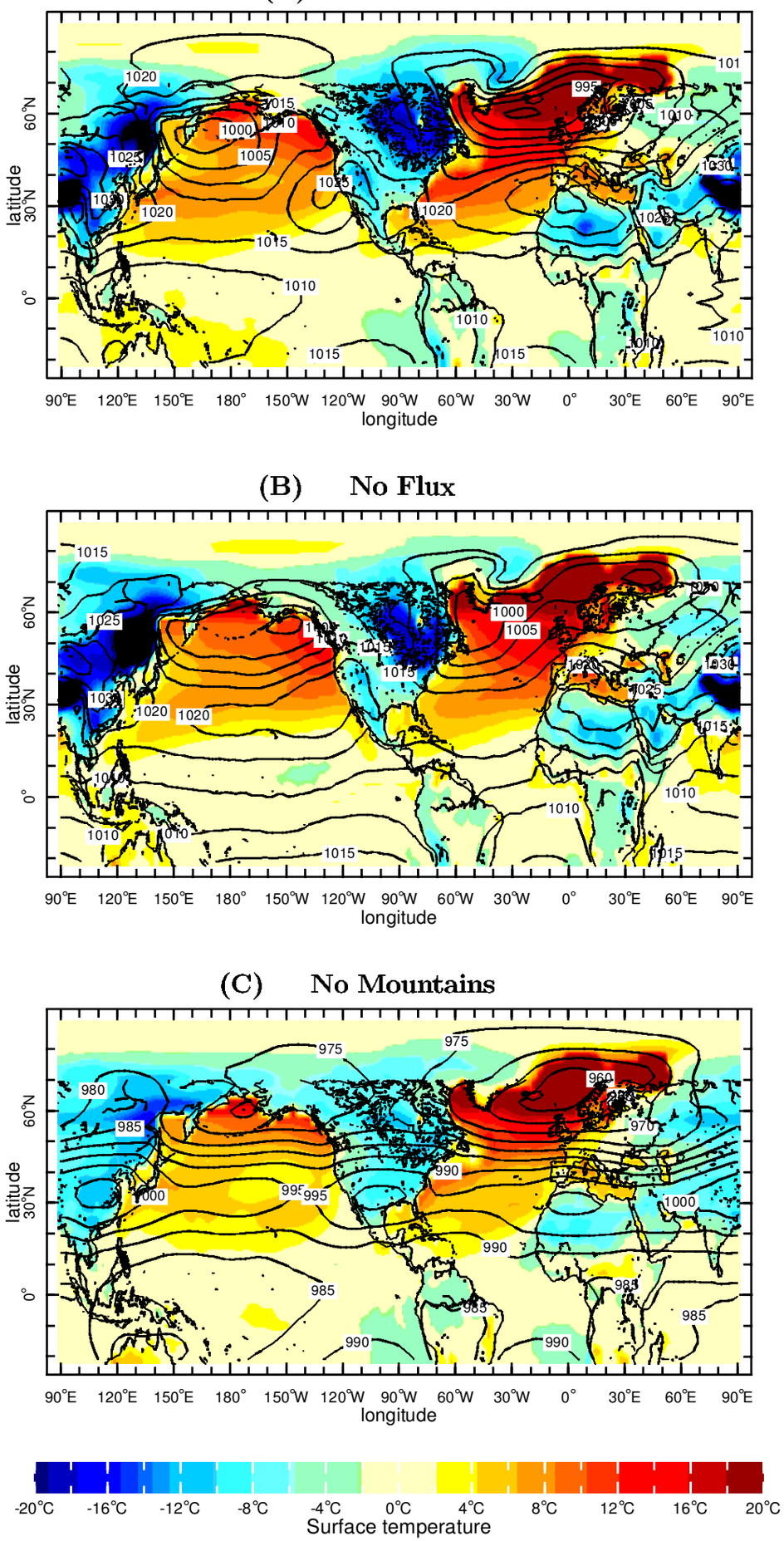
Figure 14. Sea-level pressure (mb) and zonal eddy surface temperature in degC (colours) for January for (a) the case with mountains and q-flux, (b) the case with mountains and the q-flux set to zero, and (c) the case without mountains but with the q-flux.

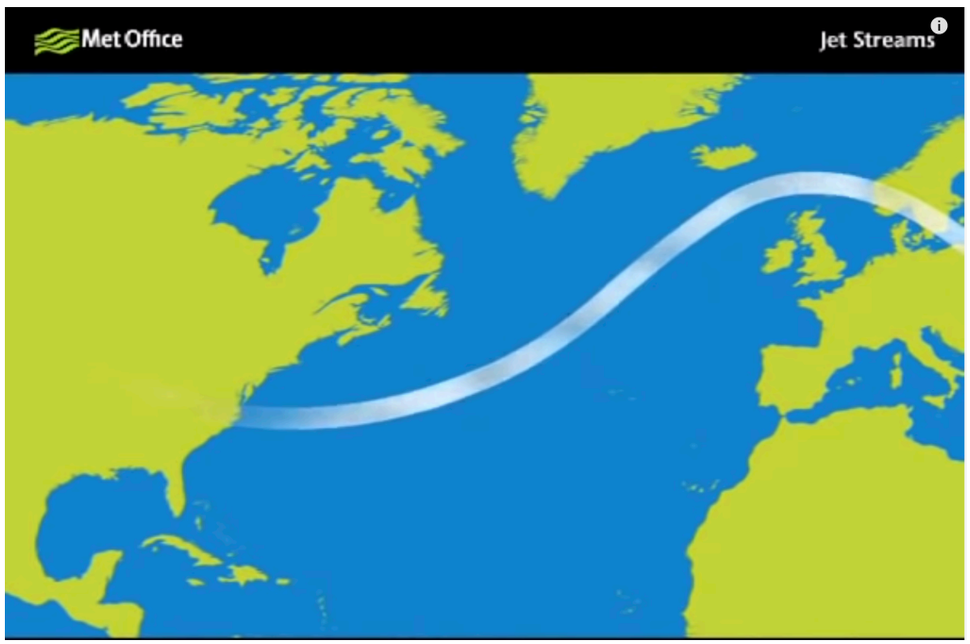


Is the Gulf Stream responsible for Europe's mild winters?

SEAGER, BATTISTI, YIN, GORDON, NAIK, CLEMENT & CANE, 2002

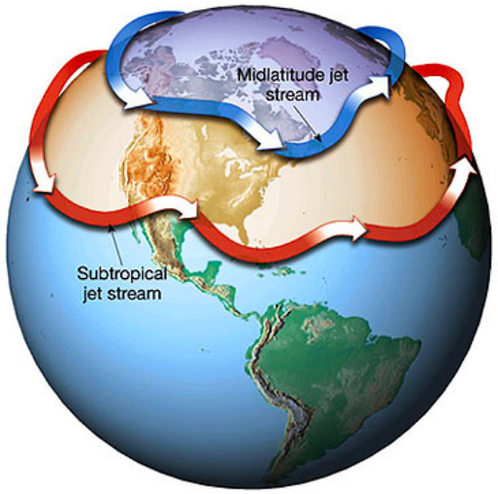
Figure 14. Sea-level pressure (mb) and zonal eddy surface temperature in degC (colours) for January for (a) the case with mountains and q-flux, (b) the case with mountains and the q-flux set to zero, and (c) the case without mountains but with the q-flux.





https://www.youtube.com/watch?v=huweohIh_Bw

https://www.constantinealexander.net/2013/02/ozone-depletion-trumps-greenhouse-gas-increase-in-jet-stream-shift.html



➨ (some of) Europe's warmth relative to same latitude in North America is attributed to the position of the atmospheric jet stream, which is, in turn, affected by the Rocky mountains.

Observing the Atlantic Meridional Overturning Circulation

RAPID: monitoring the Atlantic Meridional Overturning Circulation at 26.5°N

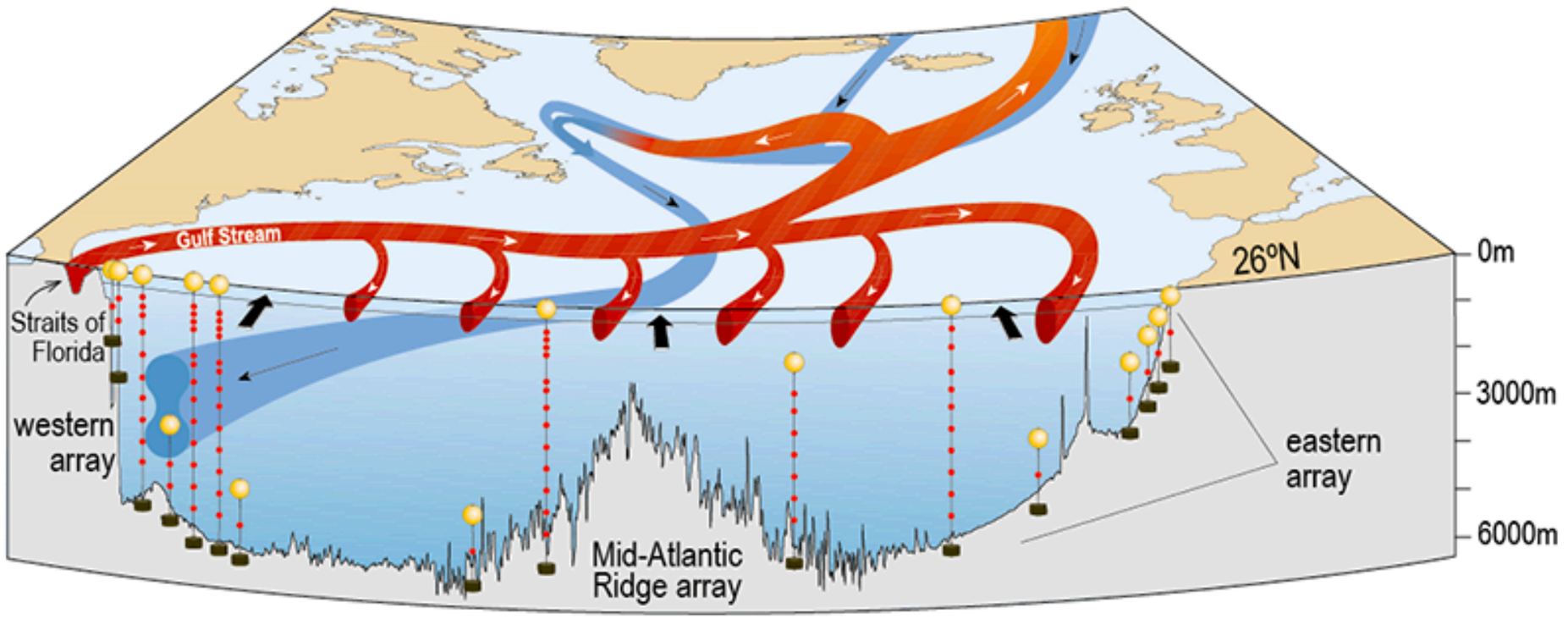
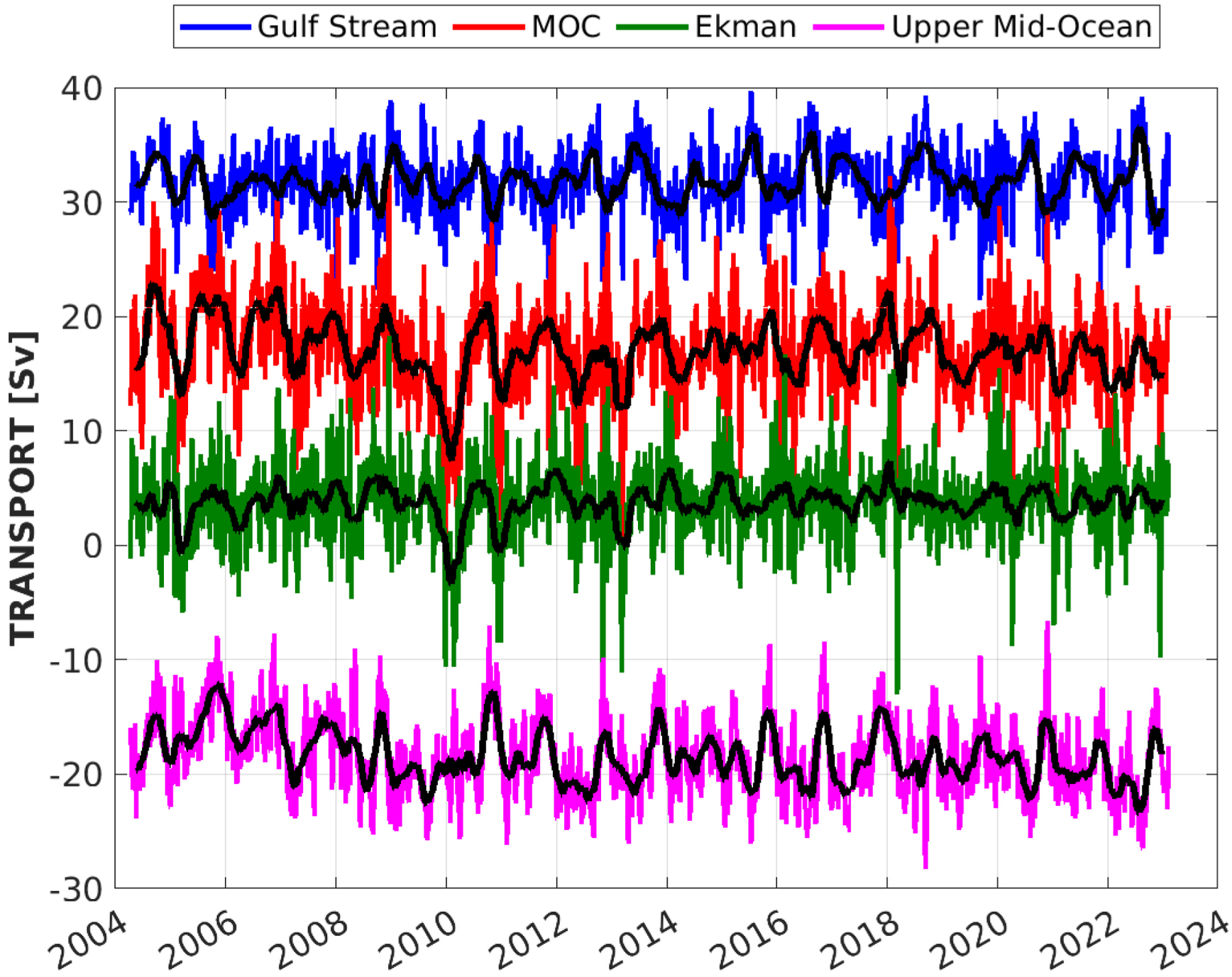


Figure 5. The North Atlantic overturning circulation with the location of the RAPID array moorings along 26°N. Modified from Church, 2007.

A view of the back deck of the RRS James Cook during the RAPID cruise in April 2014.

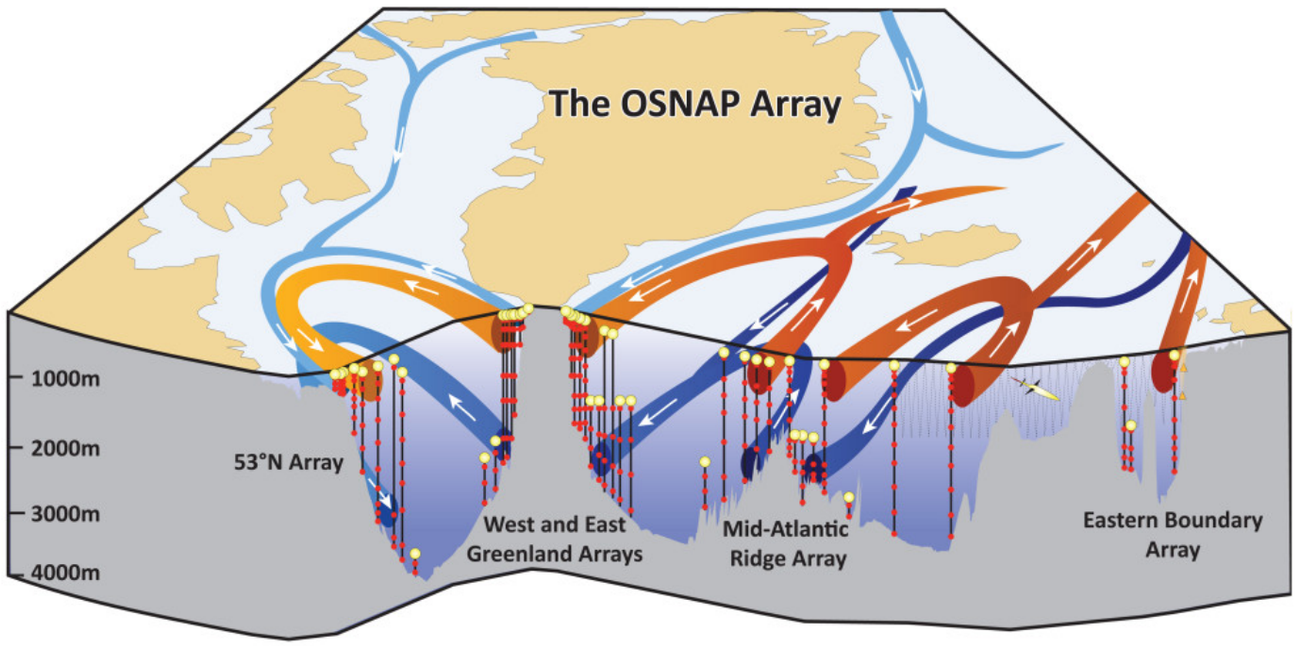
https://www.rapid.ac.uk/background.php

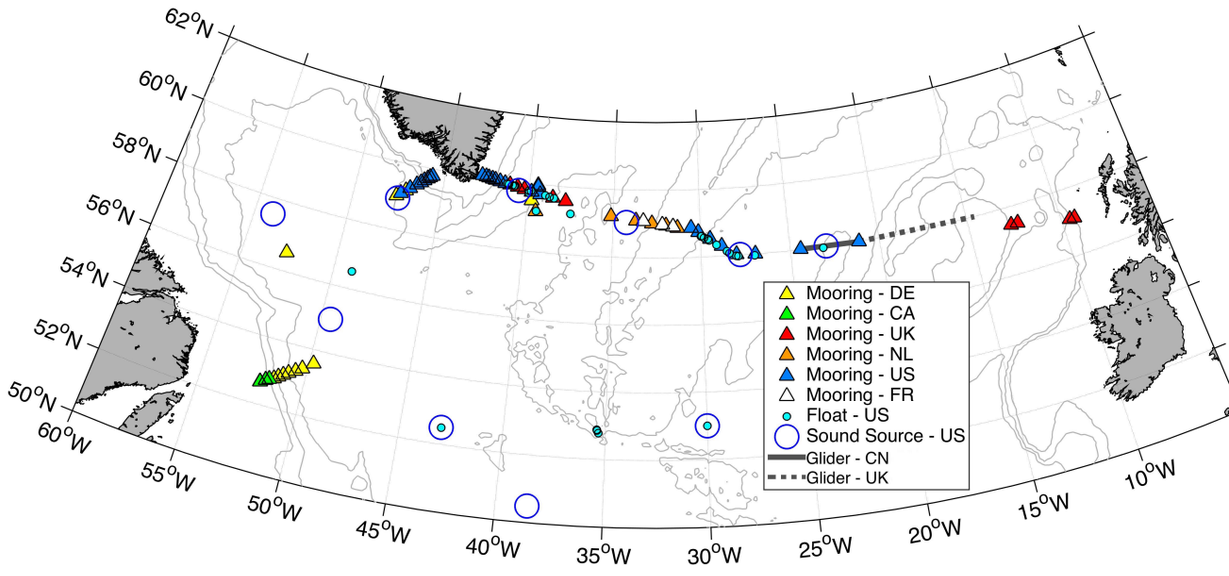
RAPID: monitoring the Atlantic Meridional Overturning Circulation at 26.5°N



https://rapid.ac.uk/data

OSNAP: monitoring AMOC at ~55–60°N
“Overturning in the Subpolar North Atlantic Program”



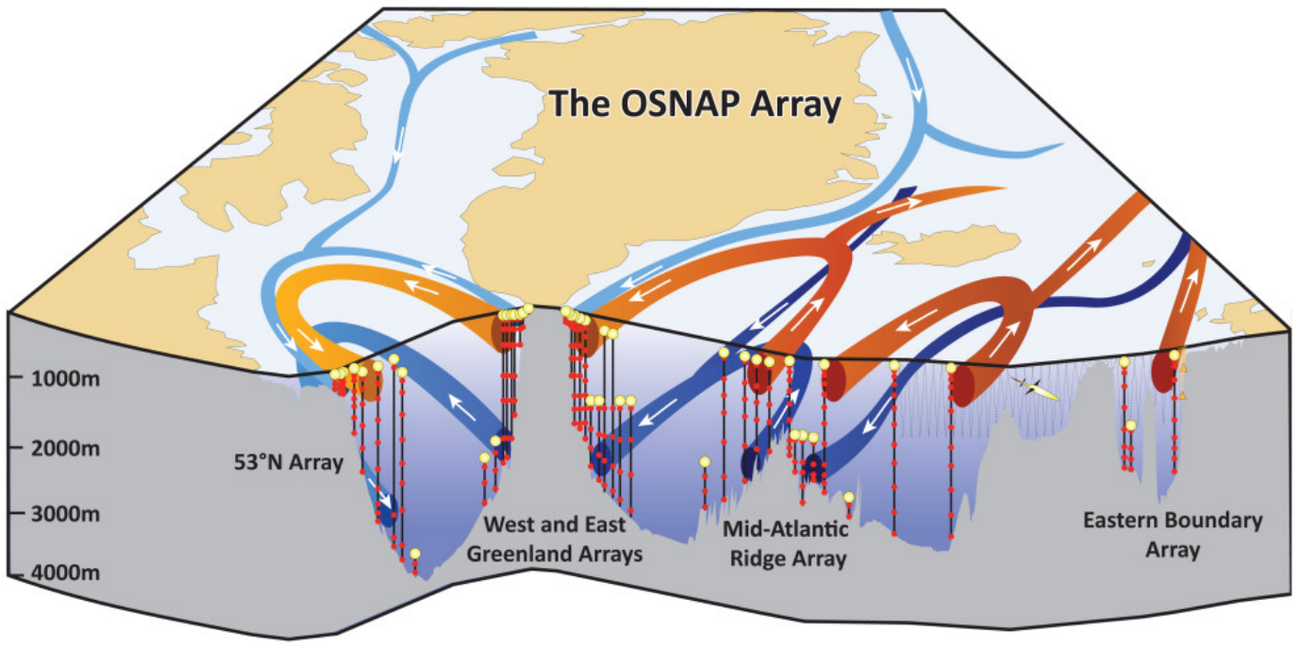


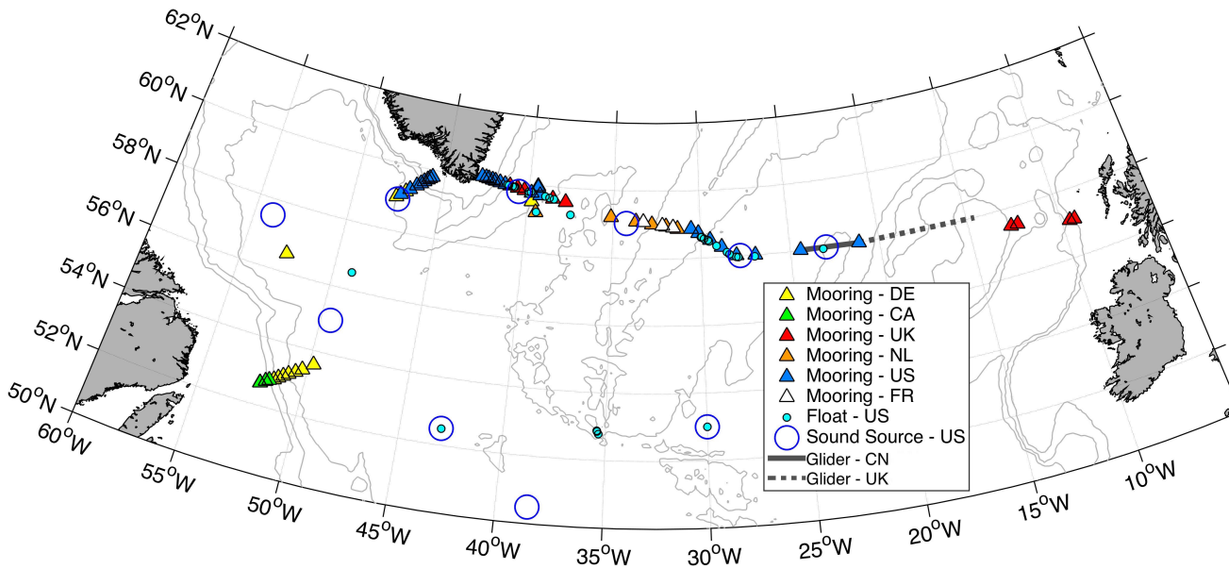
A view of the OSNAP array and mooring locations

https://www.o-snap.org/

OSNAP: monitoring AMOC at ~55–60°N

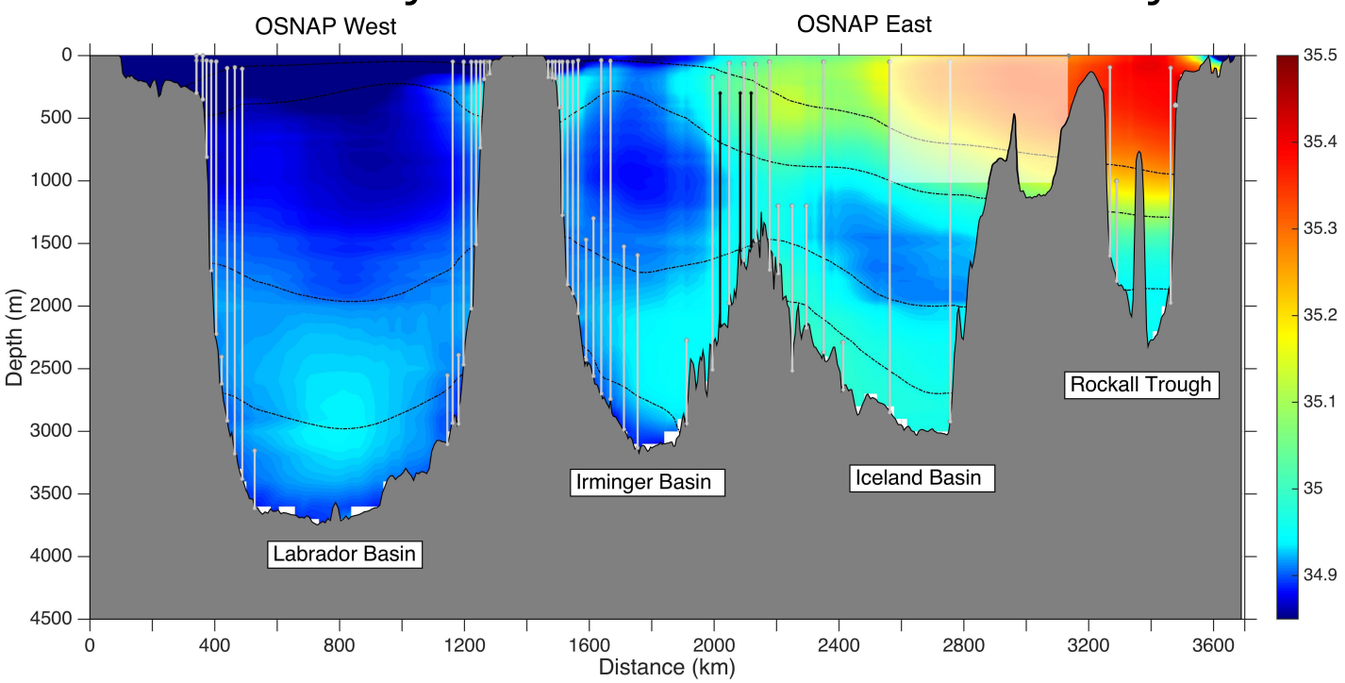
"Overturning in the Subpolar North Atlantic Program"

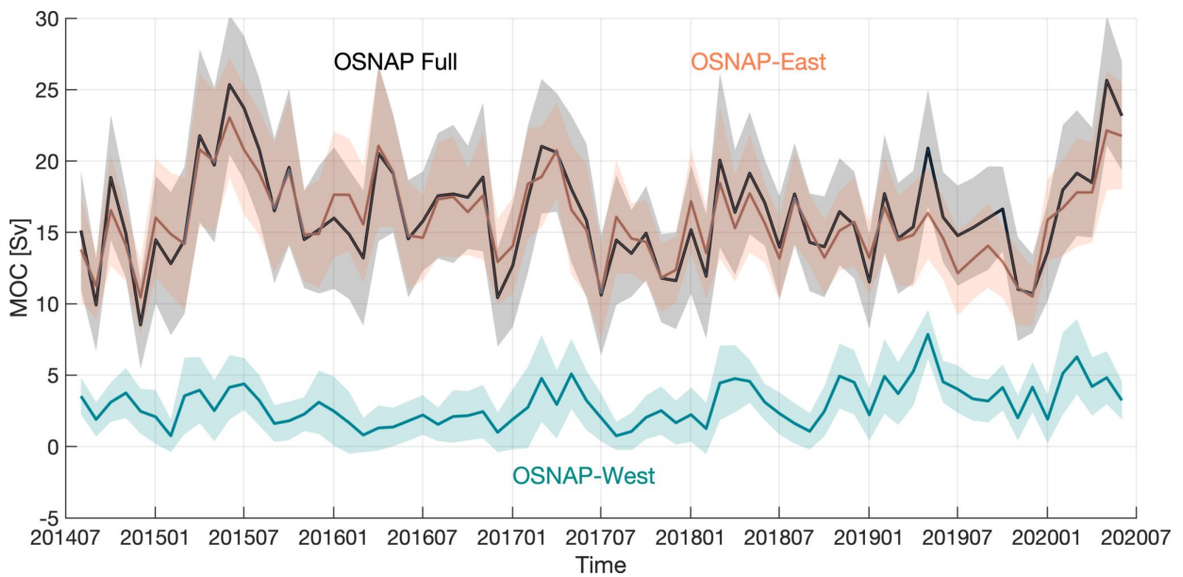




A view of the OSNAP array and mooring locations

A salinity section across the array



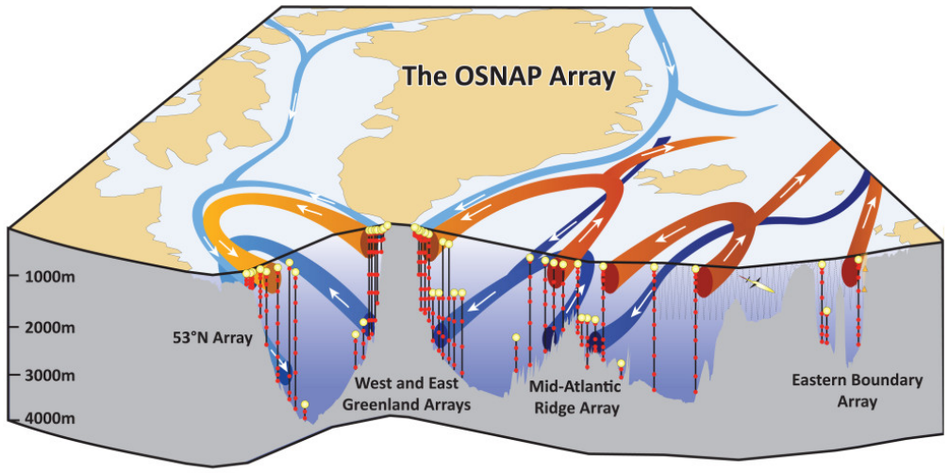


Time series of transport across the array

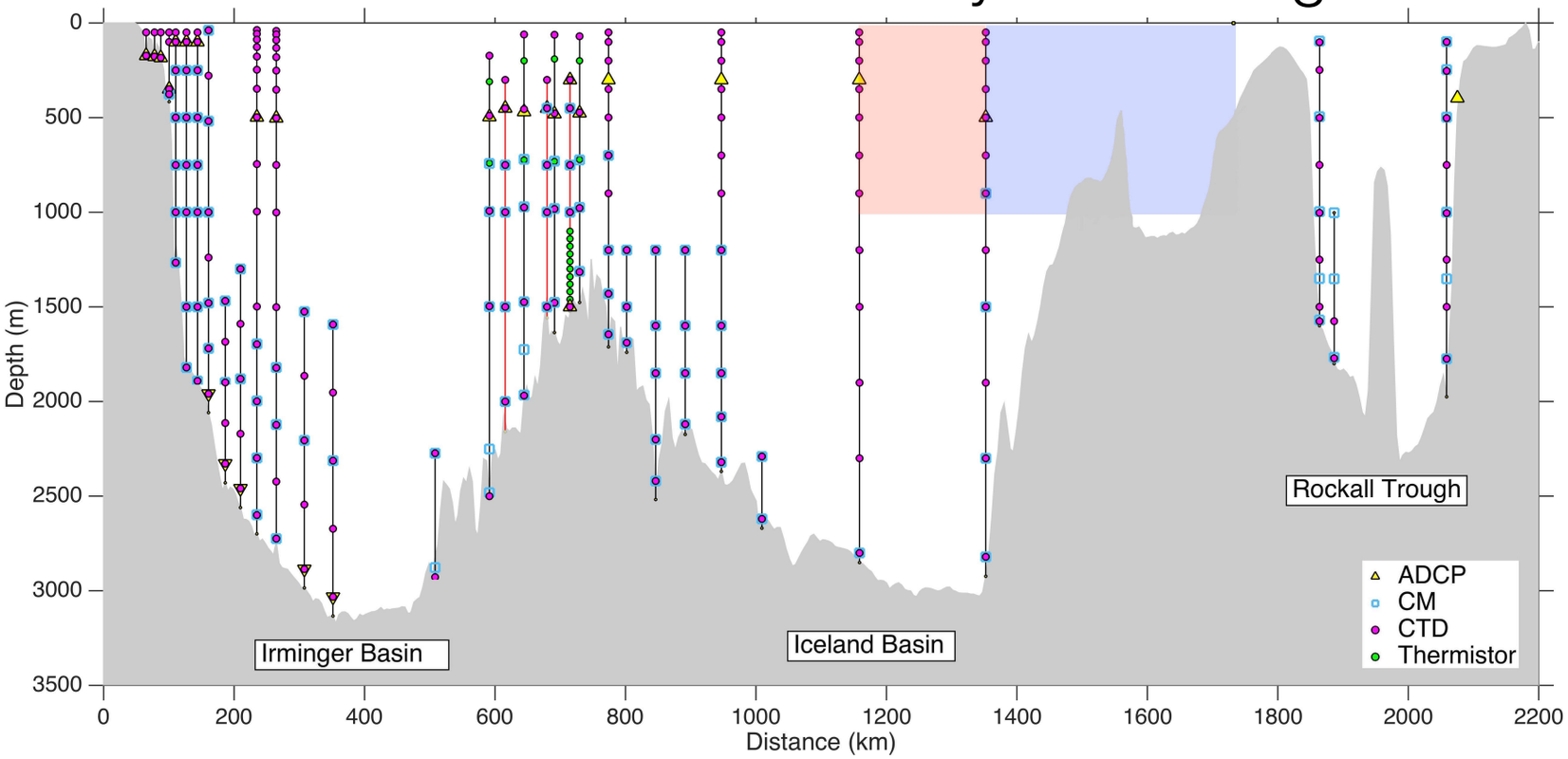
https://www.o-snap.org/

OSNAP: monitoring AMOC at ~55–60°N

"Overturning in the Subpolar North Atlantic Program"

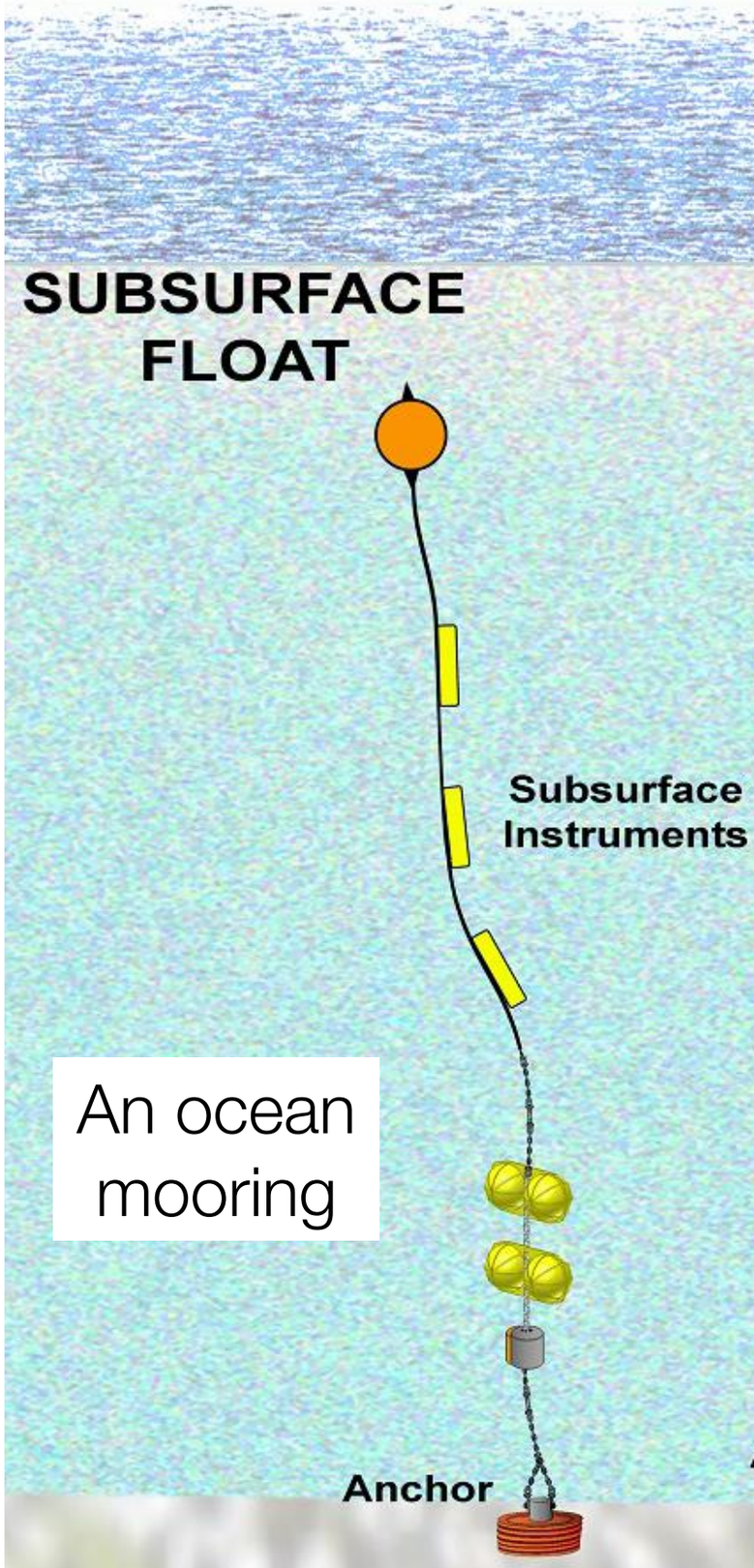


OSNAP East array of moorings



https://www.o-snap.org/

https://www.frontiersin.org/articles/10.3389/fmars.2019.00180/full



Is the Atlantic Meridional Overturning Circulation collapsing already due to global warming?? **Part 1, 2005**

Table 1 | Meridional transport in depth classes across 25° N

	1957	1981	1992	1998	2004
Shallower than 1,000 m depth					
Gulf Stream and Ekman	+35.6	+35.6	+35.6	+37.6	+37.6
Mid-ocean geostrophic	−12.7	−16.9	−16.2	−21.5	−22.8
Total shallower than 1,000 m	+22.9	+18.7	+19.4	+16.1	+14.8
1,000–3,000 m	−10.5	−9.0	−10.2	−12.2	−10.4
3,000–5,000 m	−14.8	−11.8	−10.4	−6.1	−6.9
Deeper than 5,000 m	+2.4	+2.1	+1.2	+2.2	+2.5

Values of meridional transport are given in Sverdrups. Positive transports are northward.

(Bryden et al 2005)

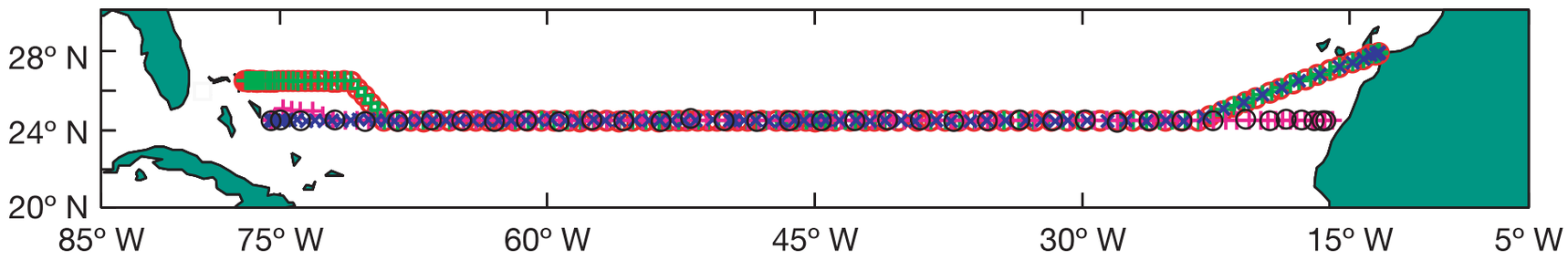
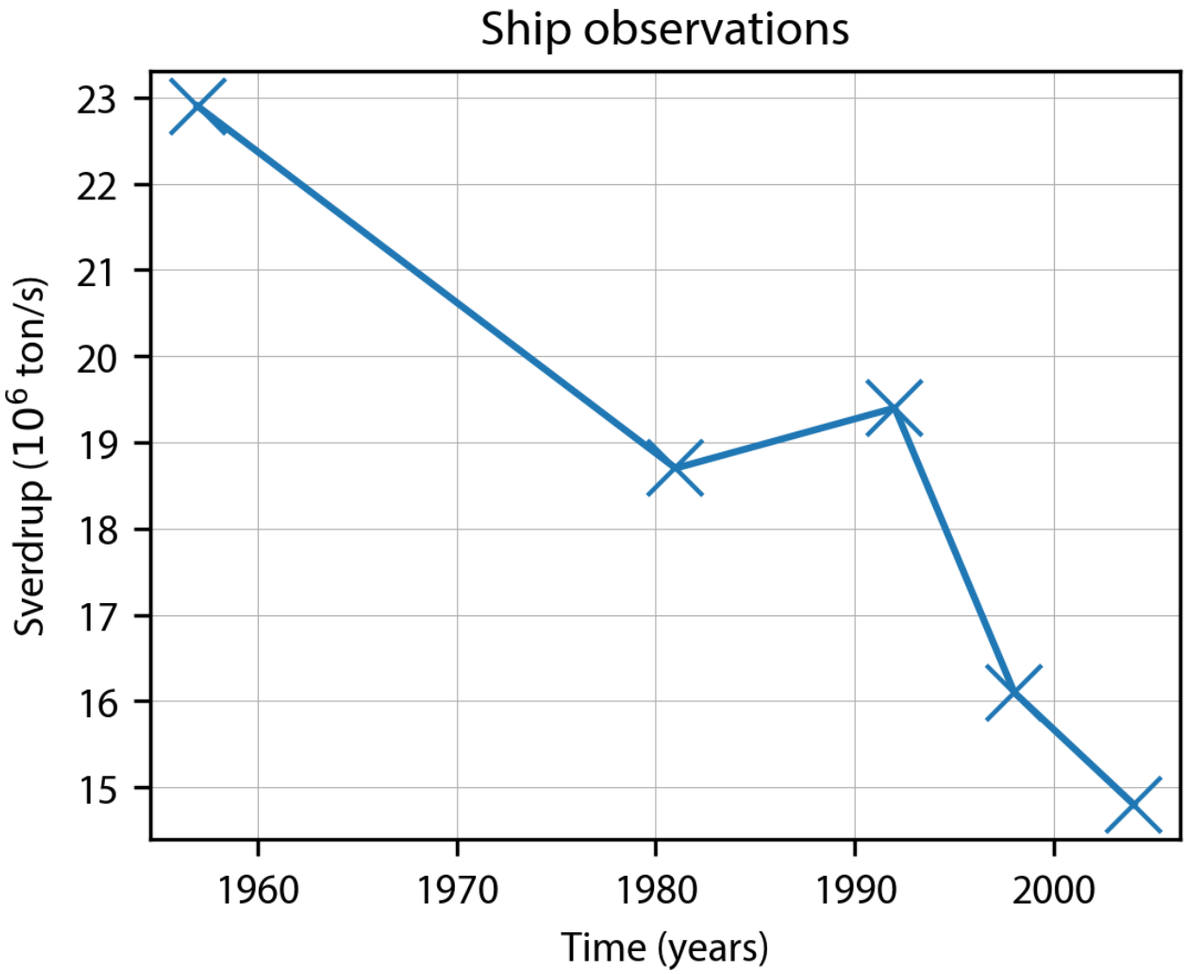
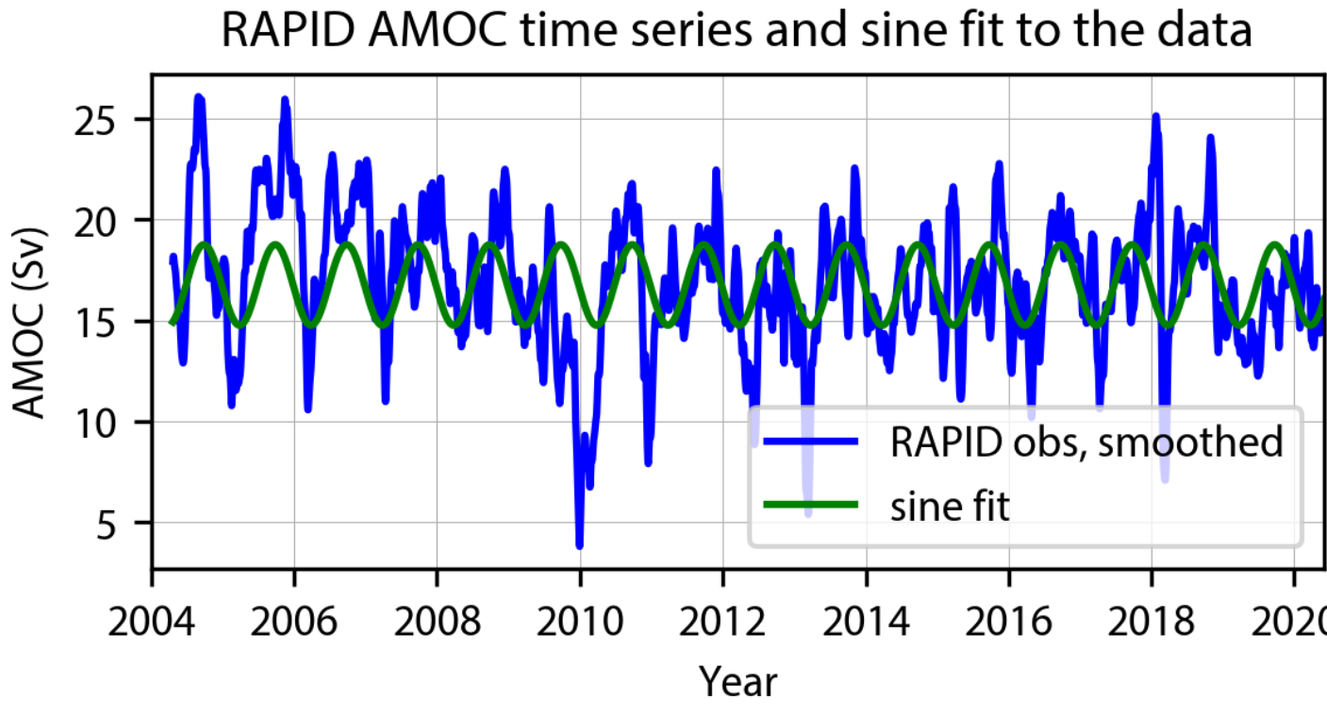


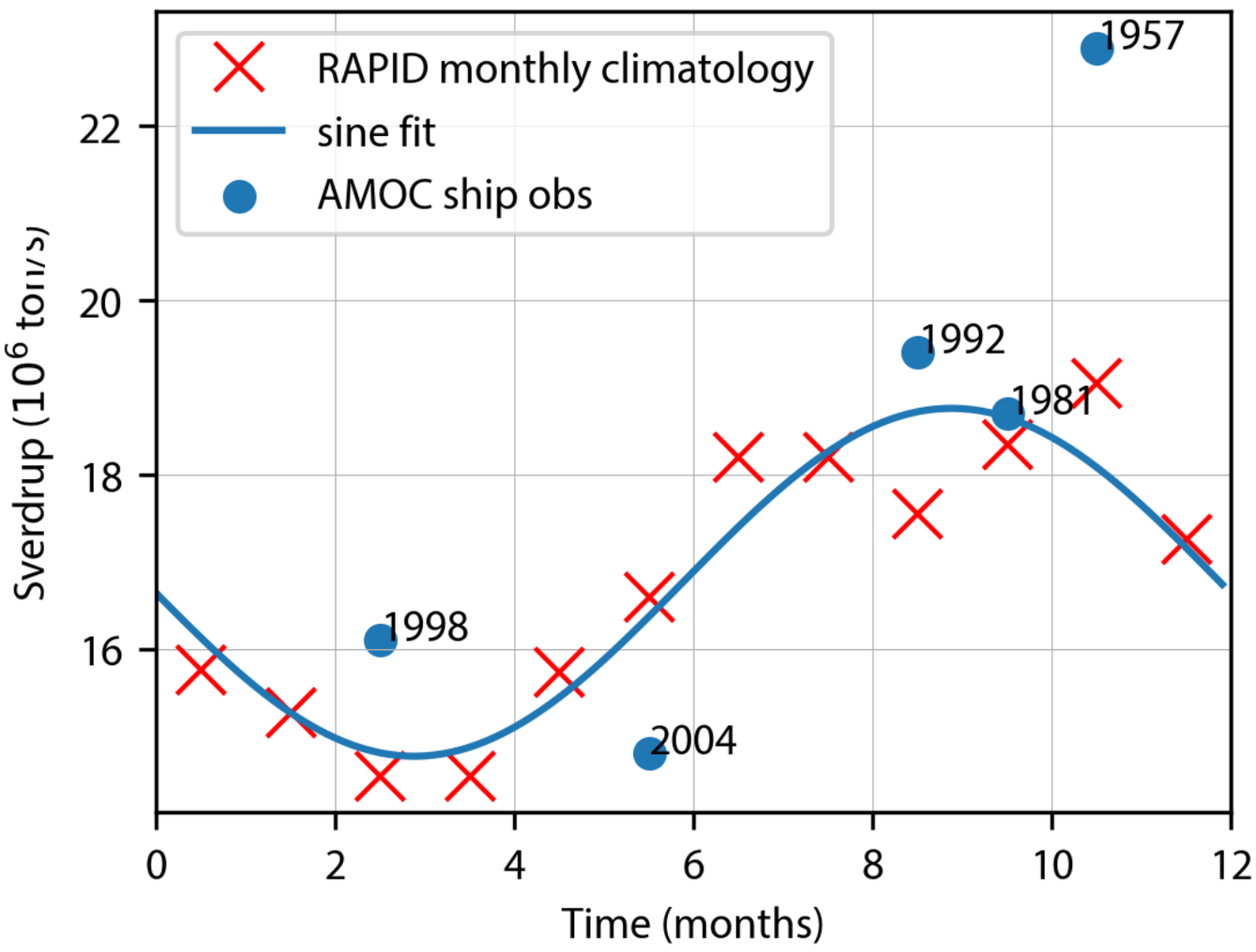
Figure 1 | Station positions for transatlantic hydrographic sections taken in 1957, 1981, 1992, 1998 and 2004. The 1957 and 1992 sections each went zonally along 24.58 N from the African coast to the Bahama Islands. Because of diplomatic clearance issues, the 1981, 1998 and 2004 sections angled southwestward from the African coast at about 288 N to join the 24.58 N section at about 238 W. The 1998 and 2004 sections angled northwestward at about 738 W to finish the section along 26.58 N.

Workshop 1:
AMOC observations

Workshop 1: AMOC observations



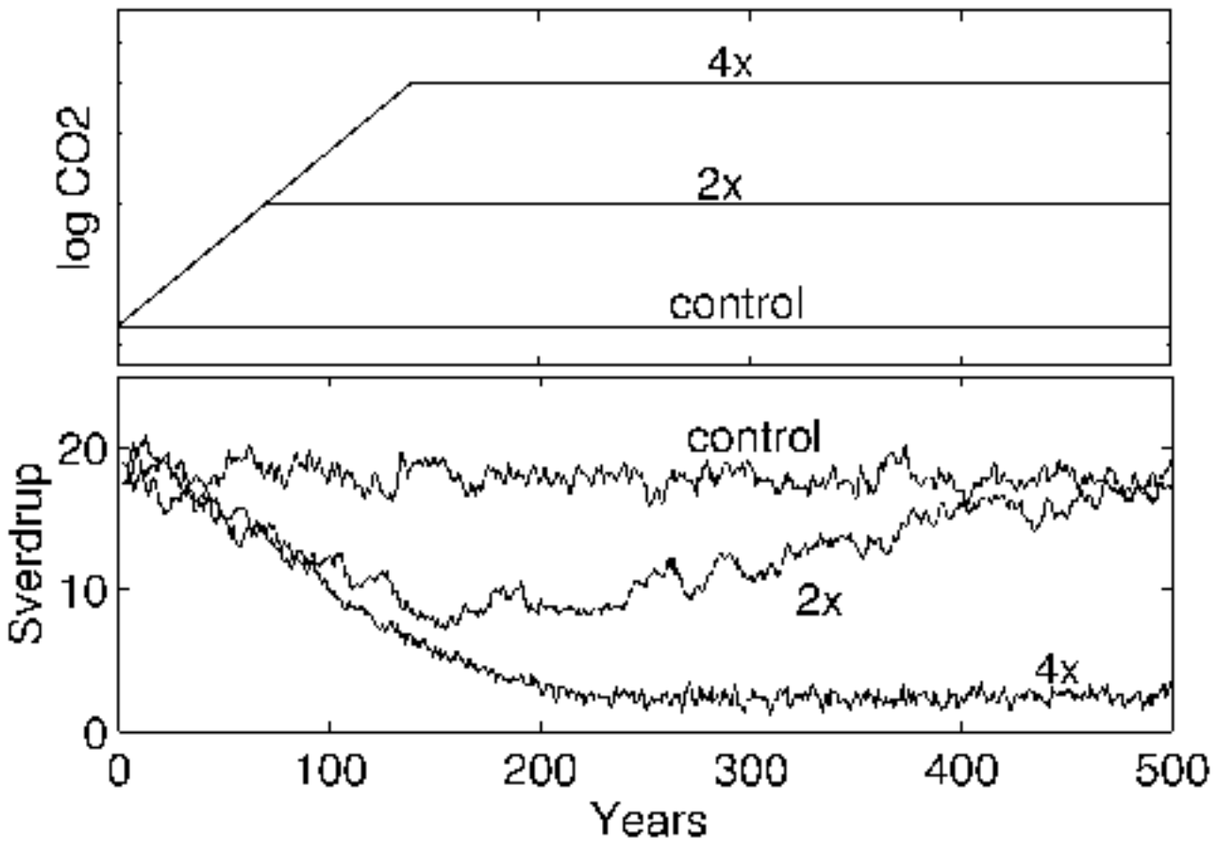




Projections:
The Atlantic Meridional Overturning Circulation Under a future climate change

Collapse of the Atlantic Meridional Overturning Circulation (AMOC) in a global warming scenario

Manabe and Stouffer 1993



VELLINGA and WOOD 2002

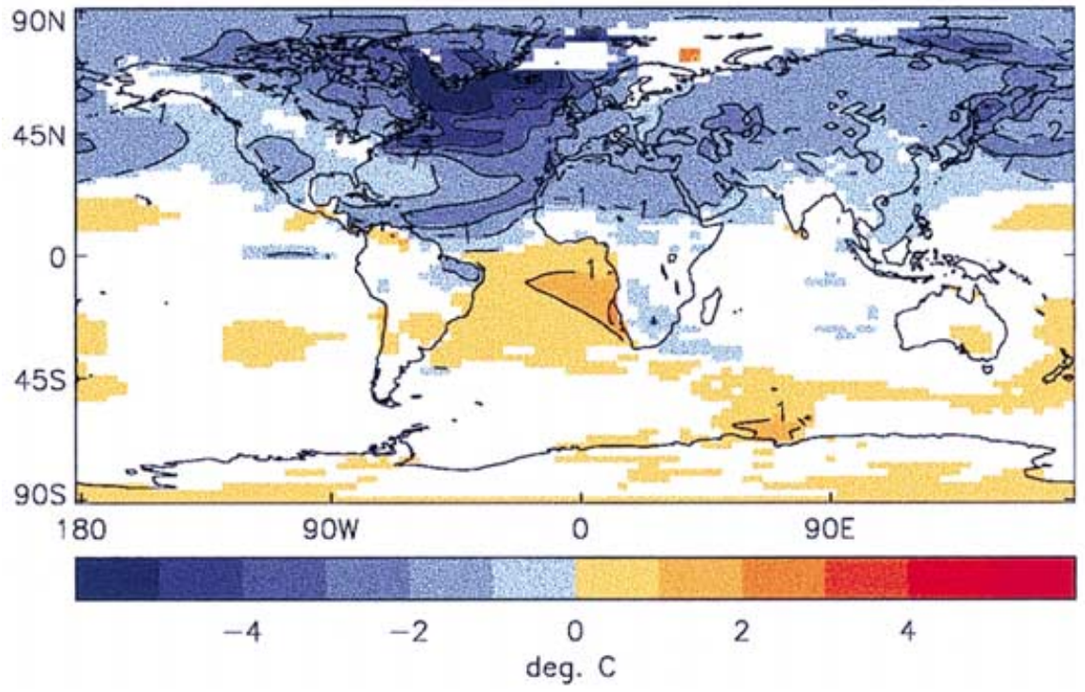
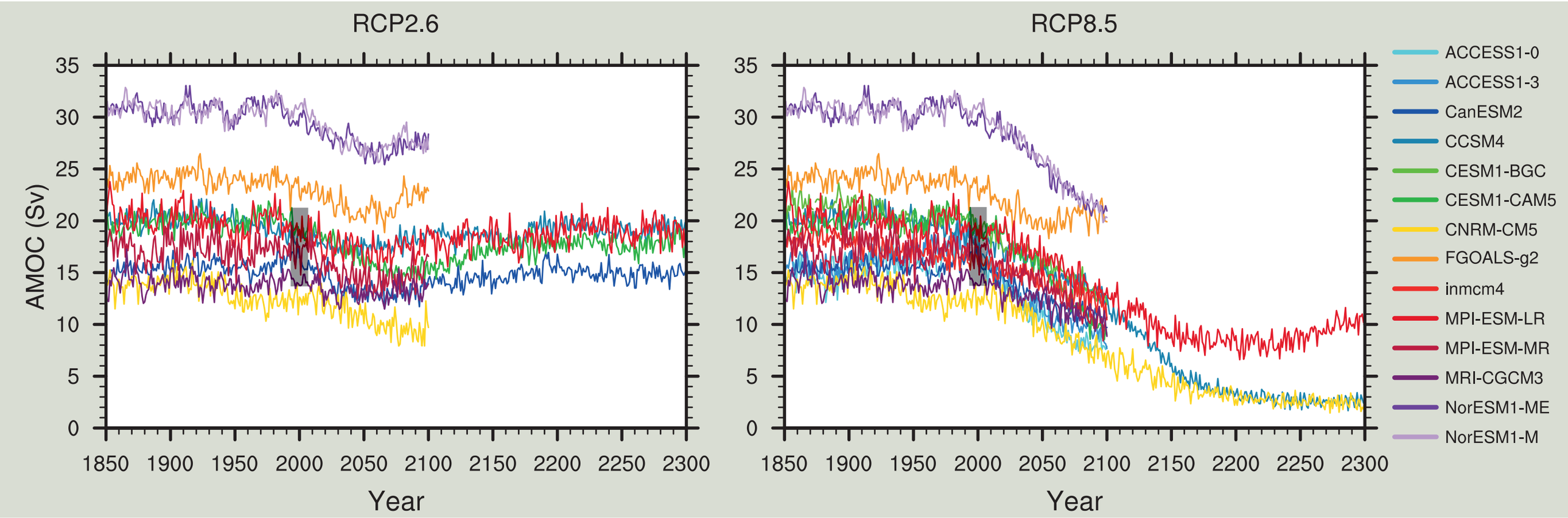


Figure 3. Change in surface air temperature during years 20–30 after the collapse of the THC. Areas where the anomaly is not significant have been masked.

Collapse of the Atlantic Meridional Overturning Circulation (AMOC) in a global warming scenario

IPCC AR5, 2013



TFE.5, Figure 1 | Atlantic Meridional Overturning Circulation (AMOC) strength at 30°N (Sv) as a function of year, from 1850 to 2300 as simulated by different Atmosphere–Ocean General Circulation Models in response to scenario RCP2.6 (left) and RCP8.5 (right). The vertical black bar shows the range of AMOC strength measured at 26°N, from 2004 to 2011 {Figures 3.11, 12.35}

The Atlantic Meridional Overturning Circulation (AMOC) in the IPCC report

- "There is no observational evidence of a trend in the Atlantic Meridional Overturning Circulation (AMOC), based on the decade-long record of the complete AMOC and longer records of individual AMOC components. {3.6}"

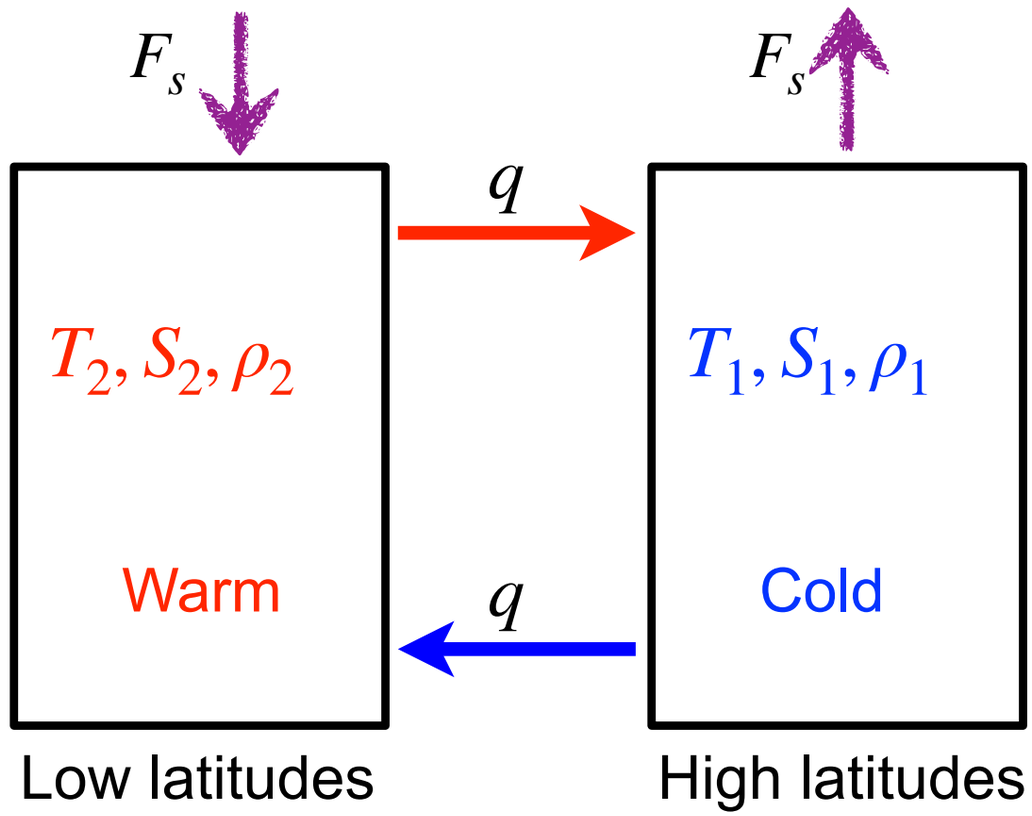
The Atlantic Meridional Overturning Circulation (AMOC) in the IPCC report

- "There is no observational evidence of a trend in the Atlantic Meridional Overturning Circulation (AMOC), based on the decade-long record of the complete AMOC and longer records of individual AMOC components. {3.6}"

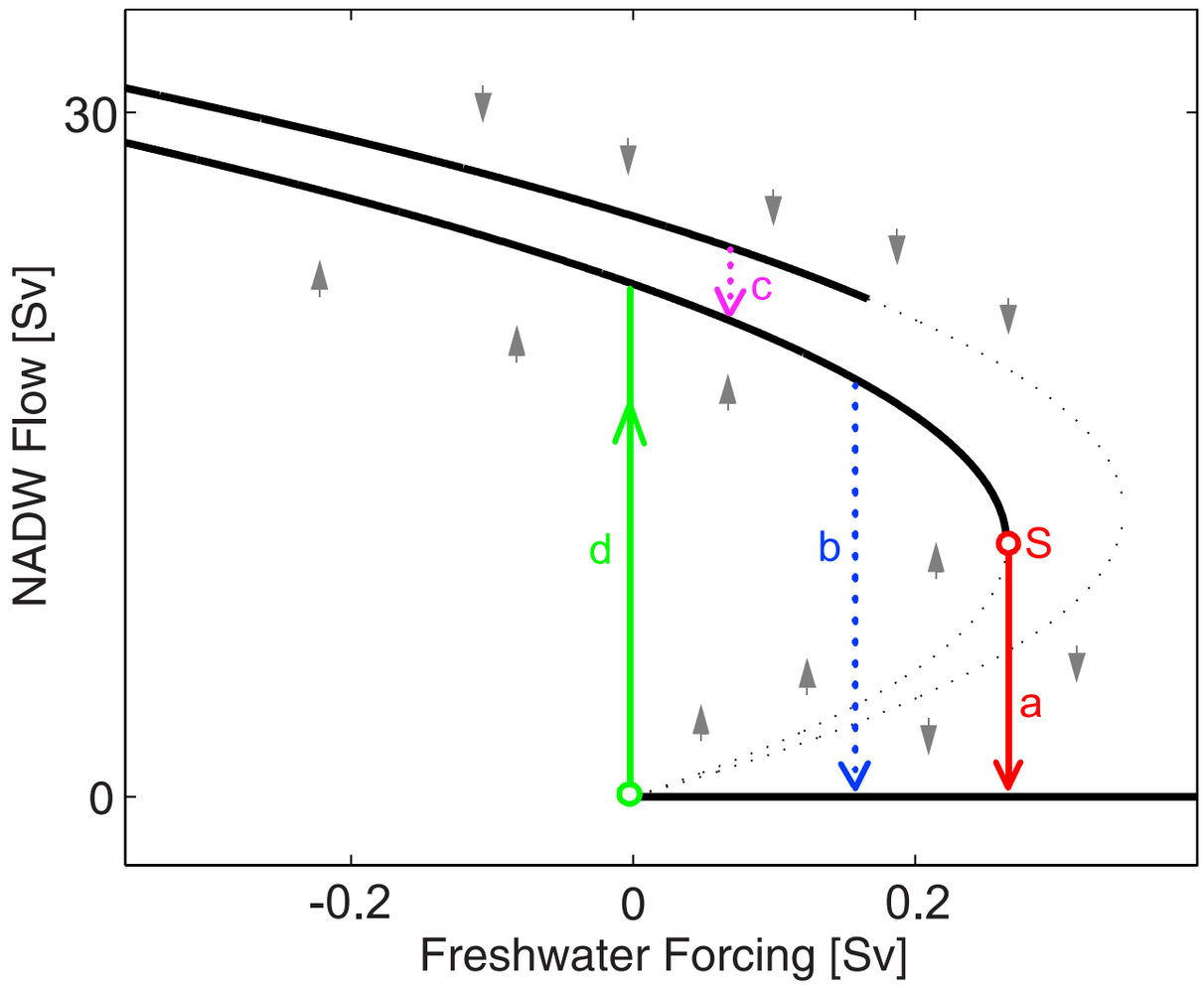
- "It is very likely that the Atlantic Meridional Overturning Circulation (AMOC) will weaken over the 21st century. Best estimates and ranges for the reduction are 11% (1 to 24%) in RCP2.6 and 34% (12 to 54%) in RCP8.5. It is likely that there will be some decline in the AMOC by about 2050, but there may be some decades when the AMOC increases due to large natural internal variability. {11.3, 12.4}"

Workshop 2:
Future projections

notes section 6.2:
The Stommel model, understanding AMOC tipping points
(use next slides)



Multiple equilibria and hysteresis of the Atlantic Meridional Overturning Circulation (AMOC)



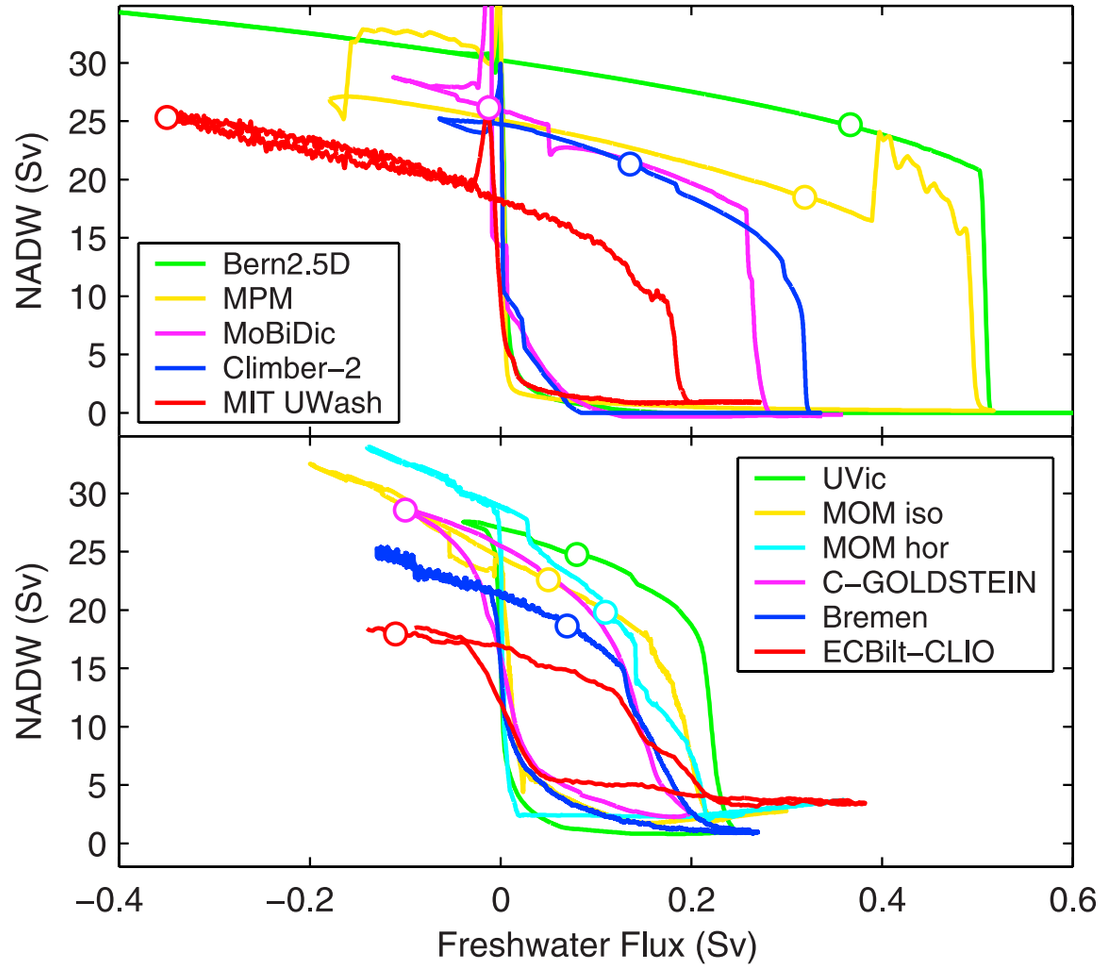


Figure 2. Hysteresis curves found in the model inter- comparison. The bottom panel shows coupled models with 3-D global ocean models, the top panel those with simplified ocean models (zonally averaged or, in case of the MIT_UWash model, rectangular basins). Curves were slightly smoothed to remove the effect of short-term variability. Circles show the present-day climate state of each model.

Rahmstorf et al 2005

Multiple equilibria and hysteresis of the Atlantic Meridional Overturning Circulation (AMOC)

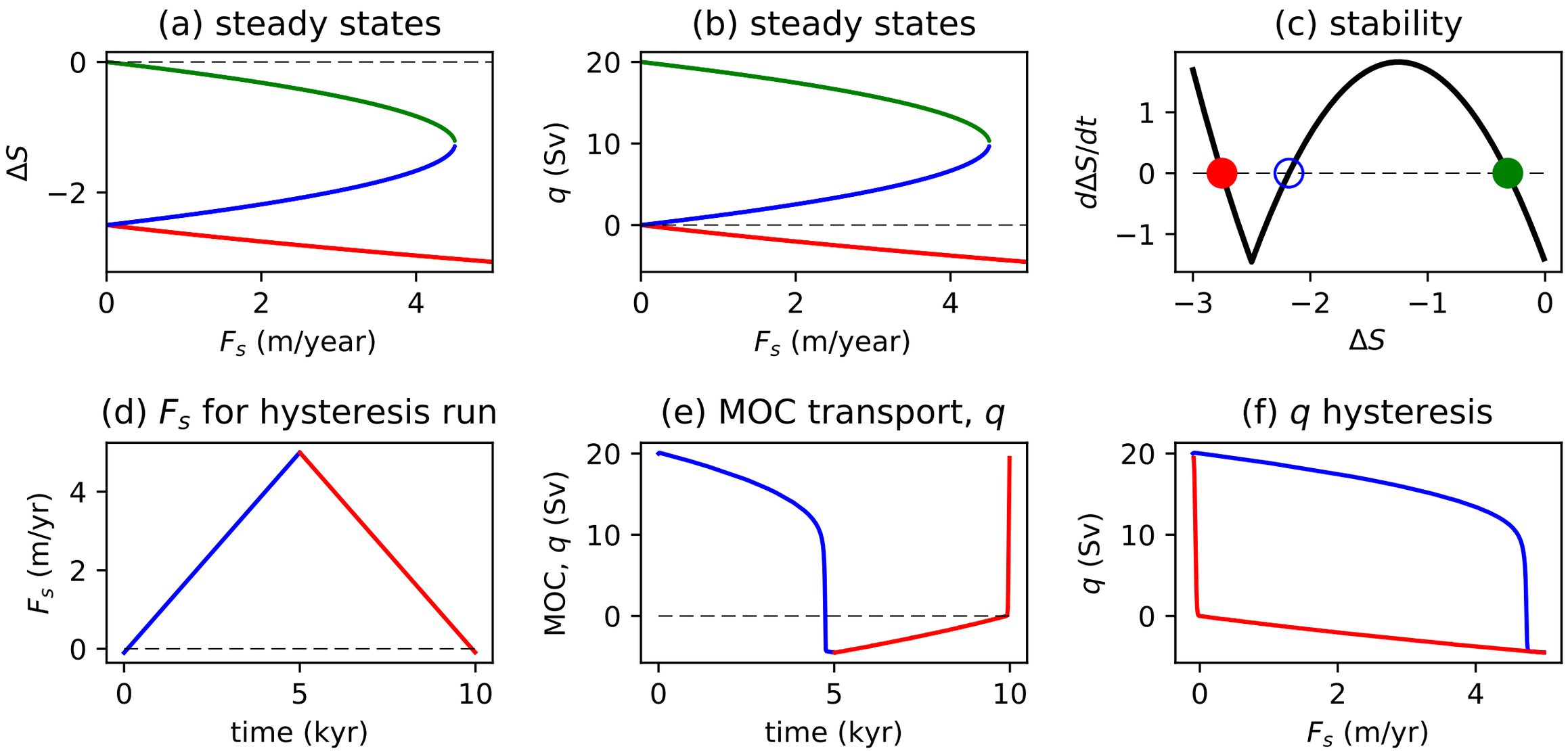
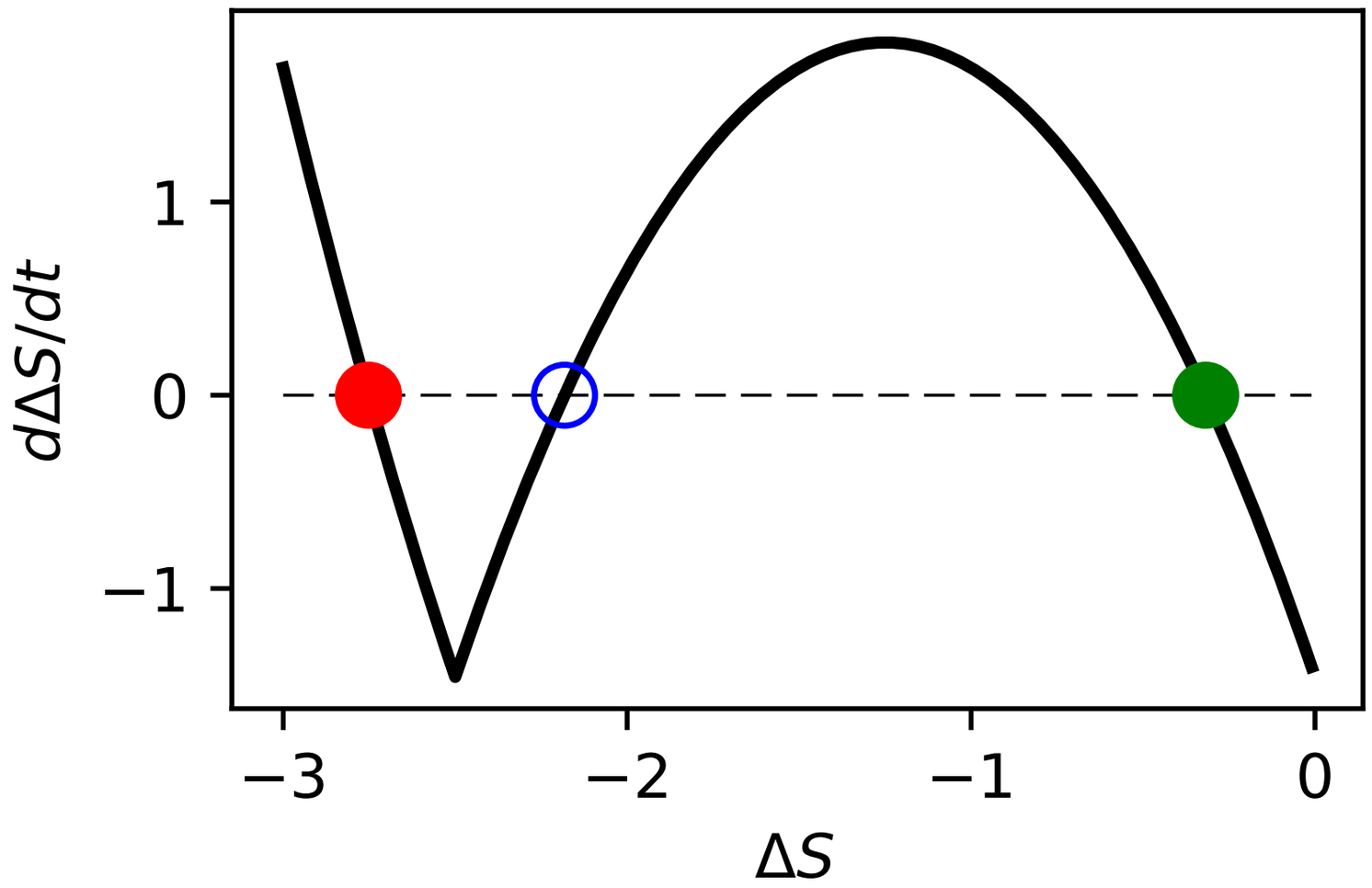


Figure 6.5: Solution of the 2-box model: (a, b) Steady states of salinity difference and MOC as function of fresh water forcing. (c) Stability analysis. (d) Fresh water forcing for hysteresis run. (e, f) Hysteresis results.

Multiple equilibria and hysteresis of the Atlantic Meridional Overturning Circulation (AMOC)



Analyzing stability of a nonlinear dynamical system: Stommel-Taylor box model example

Consequences of collapse of Atlantic Meridional Overturning Circulation (AMOC)

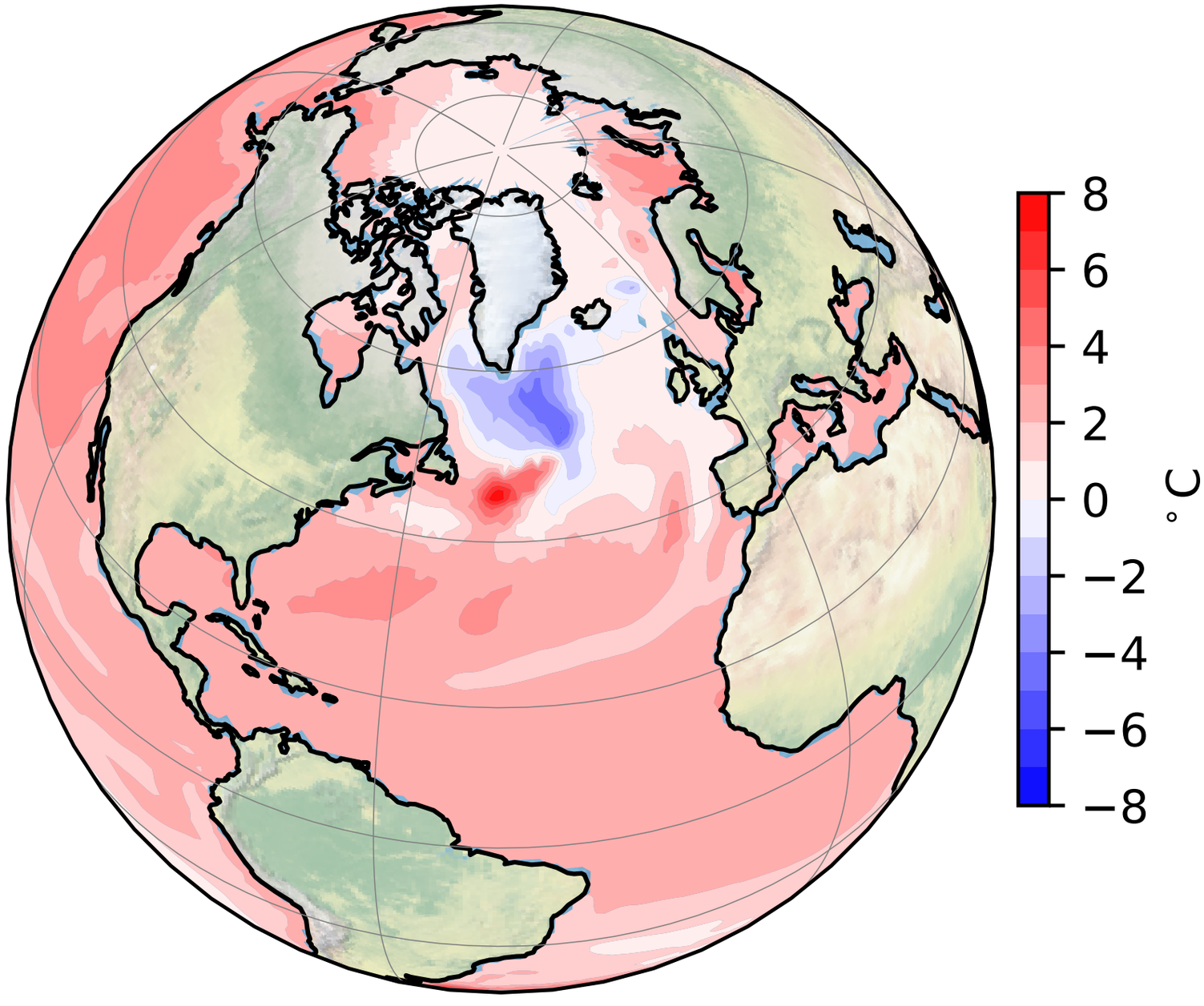


Figure 6.6: SST at 2100 minus that at 2006 in an RCP8.5 scenario.

Positive feedback behind the AMOC collapse mechanism

Start with a perturbation corresponding to an enhanced salinity at the higher latitudes (e.g., box 1 of the Stommel model)

➡ Higher density there

➡ Stronger transport due to large meridional density gradient

➡ Enhanced advection/transport of salt from lower latitudes (box 2)

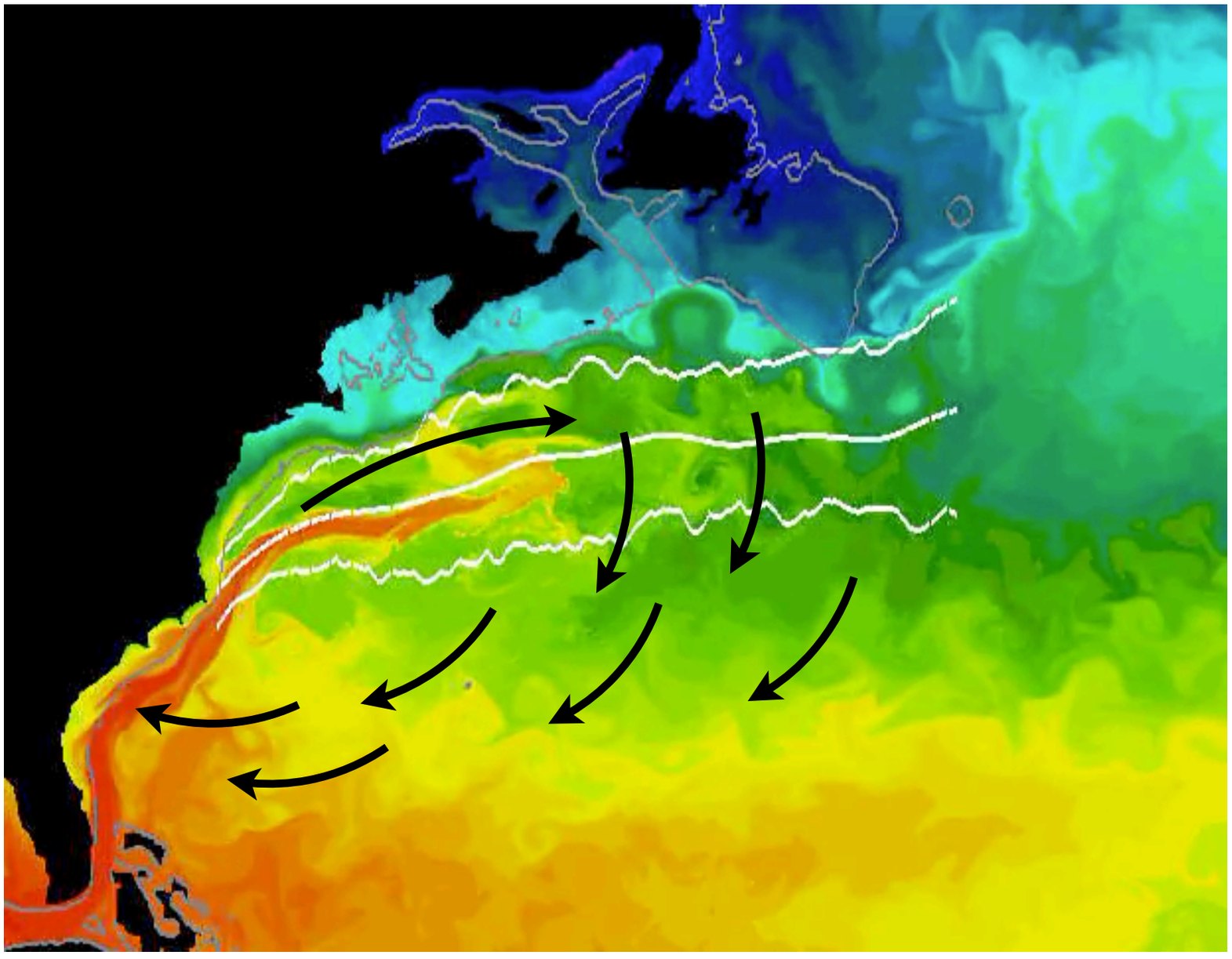
➡ Warmer temperature of advected water rapidly dissipated by cooling to the high-latitude atmosphere

➡ Left with a net additional salt perturbation to higher latitudes

➡ positive “advective feedback” mechanism leading to a collapse

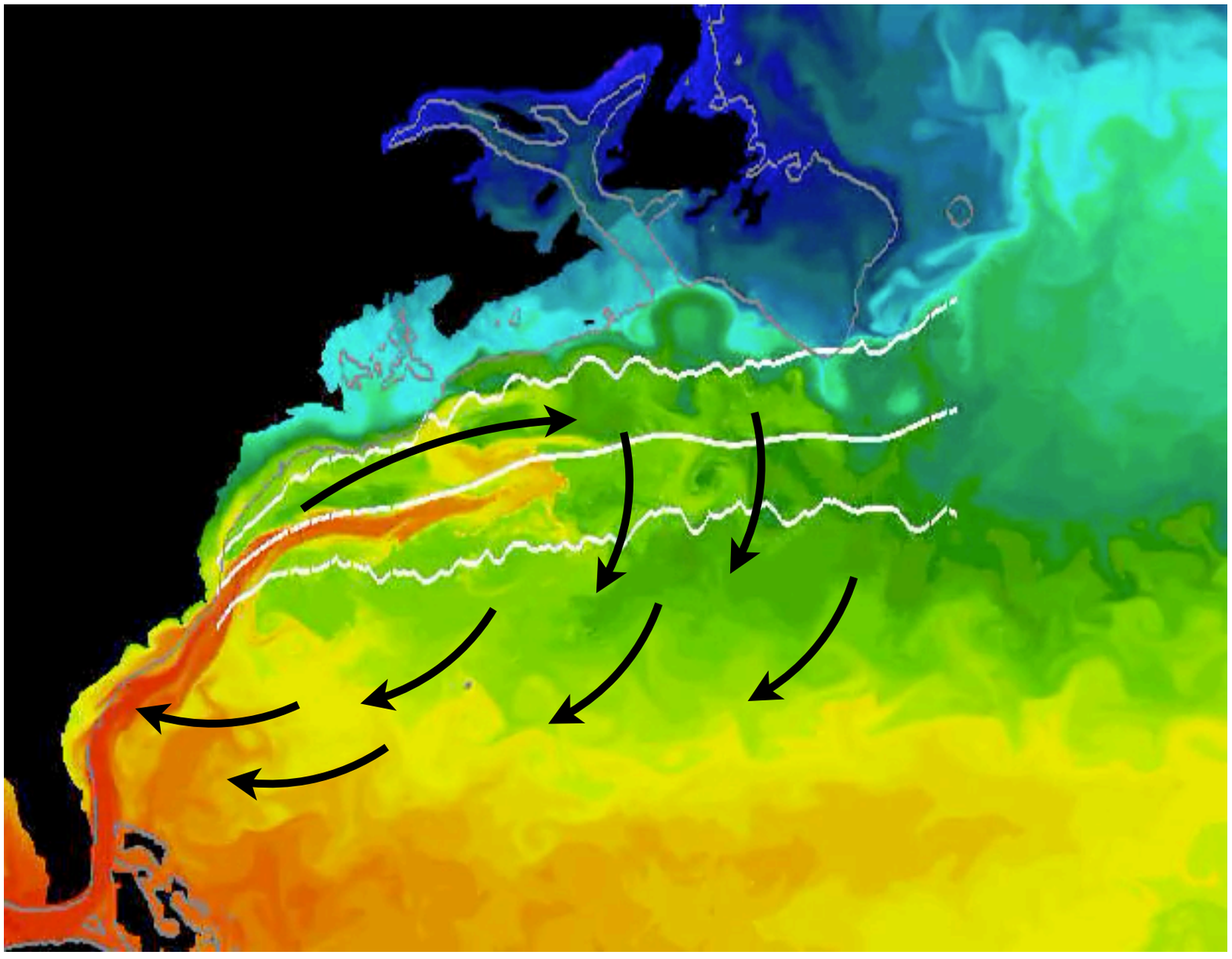
A true tipping point must have a positive feedback destabilizing mechanism.

AMOC vs the Gulf Stream



The Gulf Stream is driven by winds, and is balanced by a horizontal south-westward return flow. It is not expected to weaken significantly. A small fraction of the Gulf Stream transport sinks in the northern North Atlantic and returns as a deeper current as part of AMOC.

AMOC vs the Gulf Stream



The Gulf Stream is driven by winds, and is balanced by a horizontal south-westward return flow. It is not expected to weaken significantly. A small fraction of the Gulf Stream transport sinks in the northern North Atlantic and returns as a deeper current as part of AMOC.

Is the AMOC reaching a tipping point soon?? **Part 2, 2023**

Warming Could Push the Atlantic Past a 'Tipping Point' This Century

The system of ocean currents that regulates the climate for a swath of the planet could collapse sooner than expected, a new analysis found.

NYTimes, July 2023; https://www.nytimes.com/2023/07/25/climate/atlantic-ocean-tipping-point.html

Is the AMOC reaching a tipping point soon?? **Part 2, 2023**

Warming Could Push the Atlantic Past a 'Tipping Point' This Century

The system of ocean currents that regulates the climate for a swath of the planet could collapse sooner than expected, a new analysis found.

NYTimes, July 2023; https://www.nytimes.com/2023/07/25/climate/atlantic-ocean-tipping-point.html

nature communications

Article https://doi.org/10.1038/s41467-023-39810-w

Warning of a forthcoming collapse of the Atlantic meridional overturning circulation

Published: 25 July 2023

Peter Ditlevsen [1,3] & Susanne Ditlevsen [2,3]

AMOC is a major climate tipping element & a future collapse would have severe impacts… **A recent weakening in circulation has been reported…** Tipping to an undesired state is a growing concern. Predictions based on observations rely on early-warning signals: increase in variance (loss of resilience) & increased autocorrelation (critical slowing down), recently reported for AMOC. **We provide statistical significance & data-driven estimators for the time of tipping: around mid-century…**

Is the AMOC reaching a tipping point soon?? **Part 2, 2023**

Warming Could Push the Atlantic Past a 'Tipping Point' This Century

The system of ocean currents that regulates the climate for a swath of the planet could collapse sooner than expected, a new analysis found.

NYTimes, July 2023; https://www.nytimes.com/2023/07/25/climate/atlantic-ocean-tipping-point.html

nature communications

Article

https://doi.org/10.1038/s41467-023-39810-w

Warning of a forthcoming collapse of the Atlantic meridional overturning circulation

Published: 25 July 2023

Peter Ditlevsen [1,3] & Susanne Ditlevsen [2,3]

AMOC is a major climate tipping element & a future collapse would have severe impacts… **A recent weakening in circulation has been reported…** Tipping to an undesired state is a growing concern. Predictions based on observations rely on early-warning signals: increase in variance (loss of resilience) & increased autocorrelation (critical slowing down), recently reported for AMOC. **We provide statistical significance & data-driven estimators for the time of tipping: around mid-century…**

The Guardian US

Total collapse of vital Atlantic currents unlikely this century, study finds

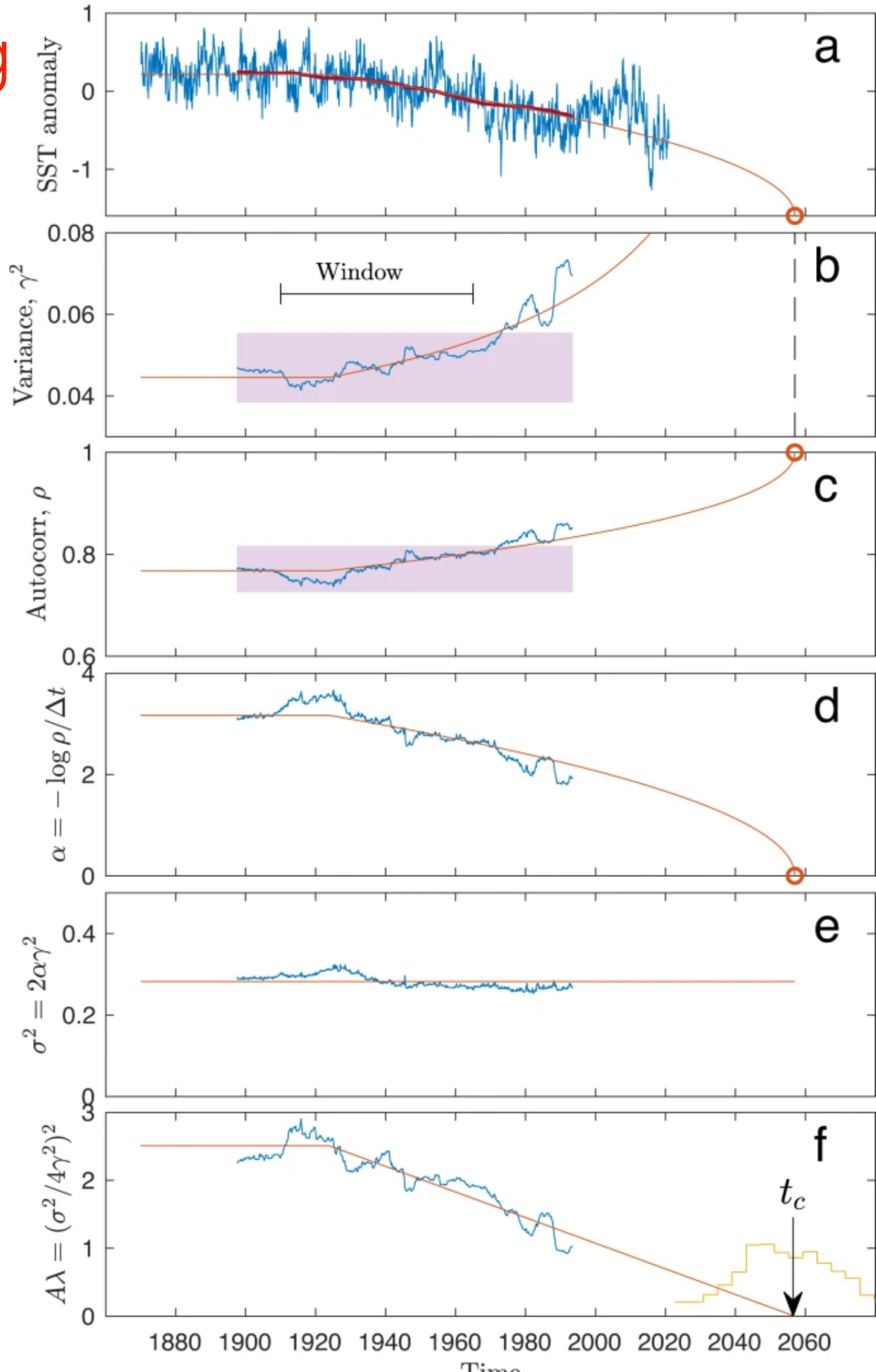
Climate scientists caution, however, that even weakened currents would cause profound harm to humanity

Damian Carrington, Environment editor, 26 Feb 2025

The study does not rule out an AMOC collapse after 2100, and other modeling research suggests collapses will occur after that time.

Is the AMOC reaching a tipping point soon?? **Part 2, 2023**

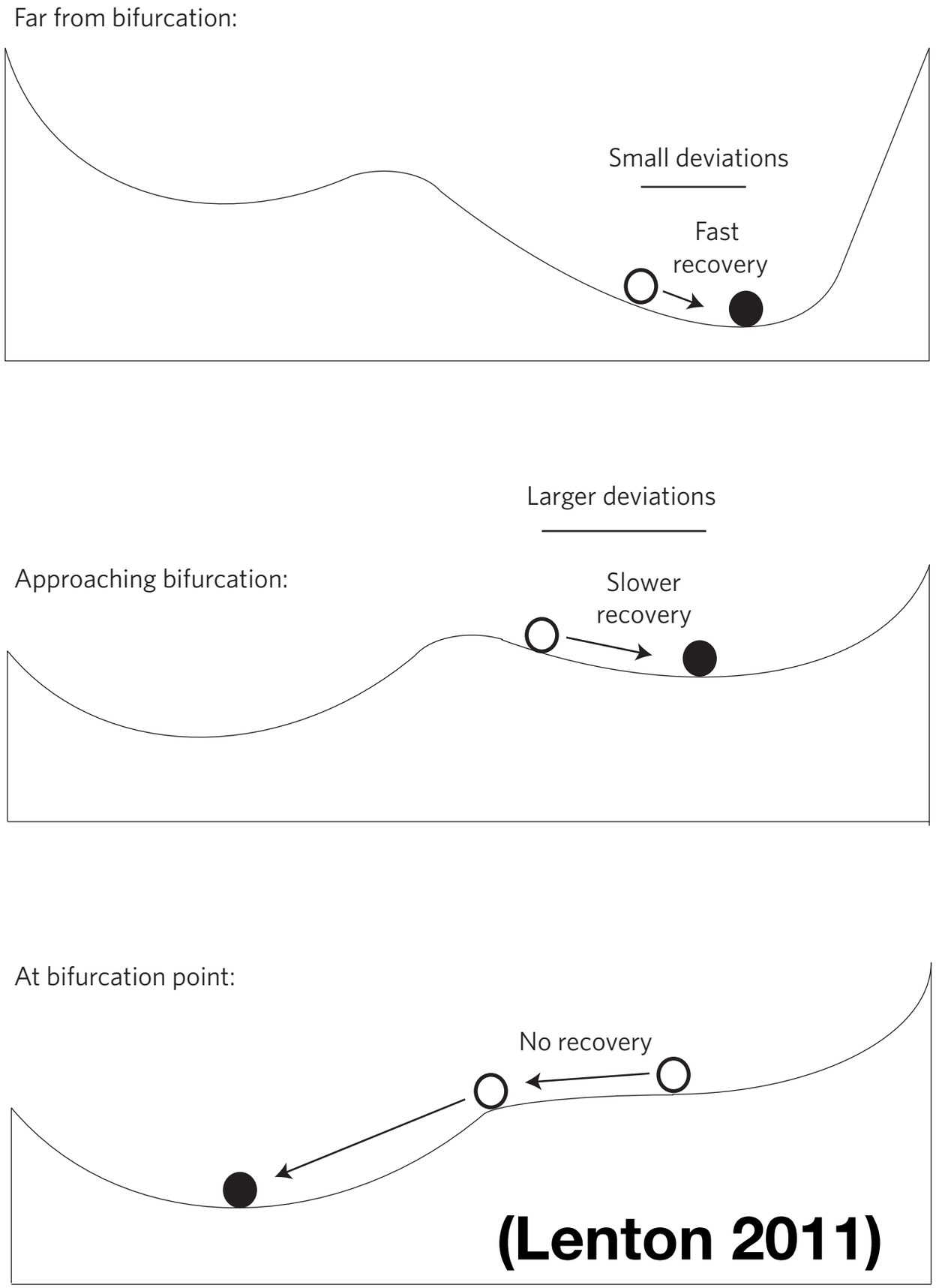
a Sea surface temperature anomaly together with the best estimate model of the steady state approaching a critical transition. **b, c** Variance and autocorrelation calculated within running 50-year windows. The two-standard error level (purple band) is obtained using the model to estimate the time-varying 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.



https://www.nature.com/articles/s41467-023-39810-w 2023

Early warning signs for an approaching tipping point

Heuristic basis for early warning of an approaching bifurcation point. The valleys/ potential wells represent stable attractors, and the ball represents the state of the system. Under gradual forcing, the right potential well becomes shallower and finally vanishes (bifurcation), causing the ball to roll abruptly to the left. Picture the system being nudged around by a short-term stochastic process (noise). The radius of the potential well is directly related to the system's response time to such small perturbations, which tends towards infinity as bifurcation is approached, that is, the system becomes more sluggish in response to perturbations ('critical slowing down'). Larger fluctuations are also expected as bifurcation is approached.



Other potential climate tipping points

- Arctic sea ice

Other potential climate tipping points

- Arctic sea ice
- AMOC

Other potential climate tipping points

- Arctic sea ice
- AMOC
- Antarctica's "doomsday" Thwaites Glacier

Other potential climate tipping points

- Arctic sea ice
- AMOC
- Antarctica's "doomsday" Thwaites Glacier
- Greenland's ice sheet

Other potential climate tipping points

- Arctic sea ice
- AMOC
- Antarctica's "doomsday" Thwaites Glacier
- Greenland's ice sheet
- The West Antarctic ice sheet

Other potential climate tipping points

- Arctic sea ice
- AMOC
- Antarctica's "doomsday" Thwaites Glacier
- Greenland's ice sheet
- The West Antarctic ice sheet
- Sahara's vegetation

Other potential climate tipping points

- Arctic sea ice
- AMOC
- Antarctica's "doomsday" Thwaites Glacier
- Greenland's ice sheet
- The West Antarctic ice sheet
- Sahara's vegetation
- Amazon Forest

Other potential climate tipping points

- Arctic sea ice
- AMOC
- Antarctica's "doomsday" Thwaites Glacier
- Greenland's ice sheet
- The West Antarctic ice sheet
- Sahara's vegetation
- Amazon Forest
- Corals

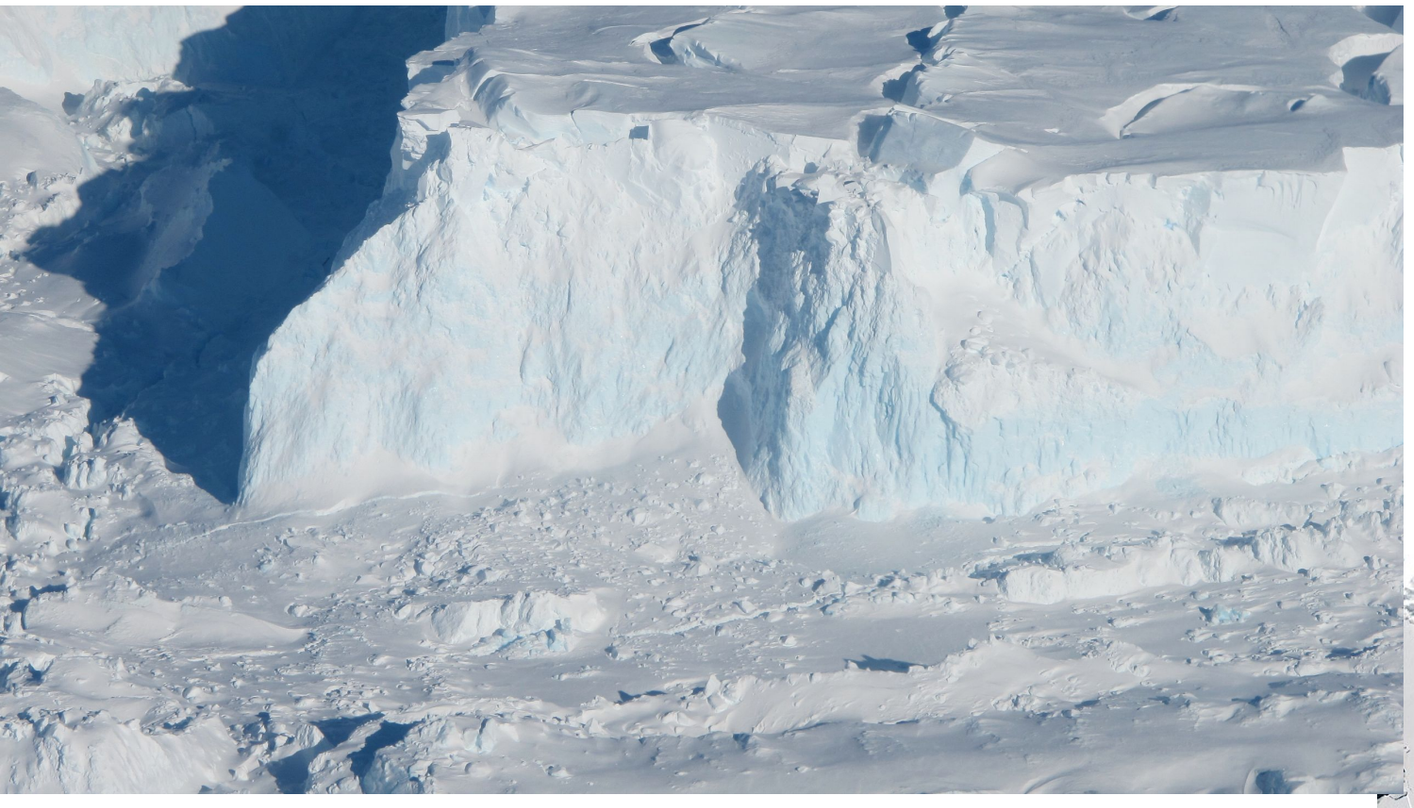
Other potential climate tipping points

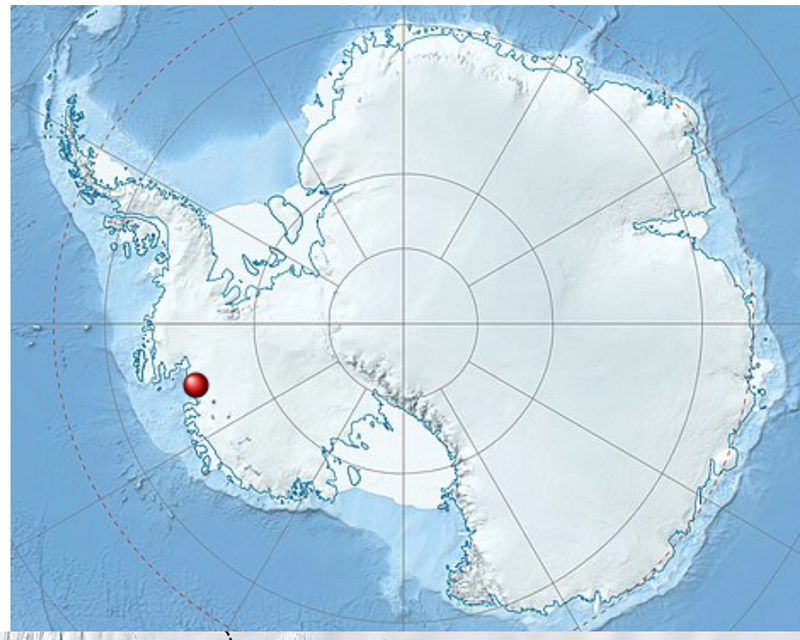
- Arctic sea ice
- AMOC
- Antarctica's "doomsday" Thwaites Glacier
- Greenland's ice sheet
- The West Antarctic ice sheet
- Sahara's vegetation
- Amazon Forest
- Corals
- Permafrost

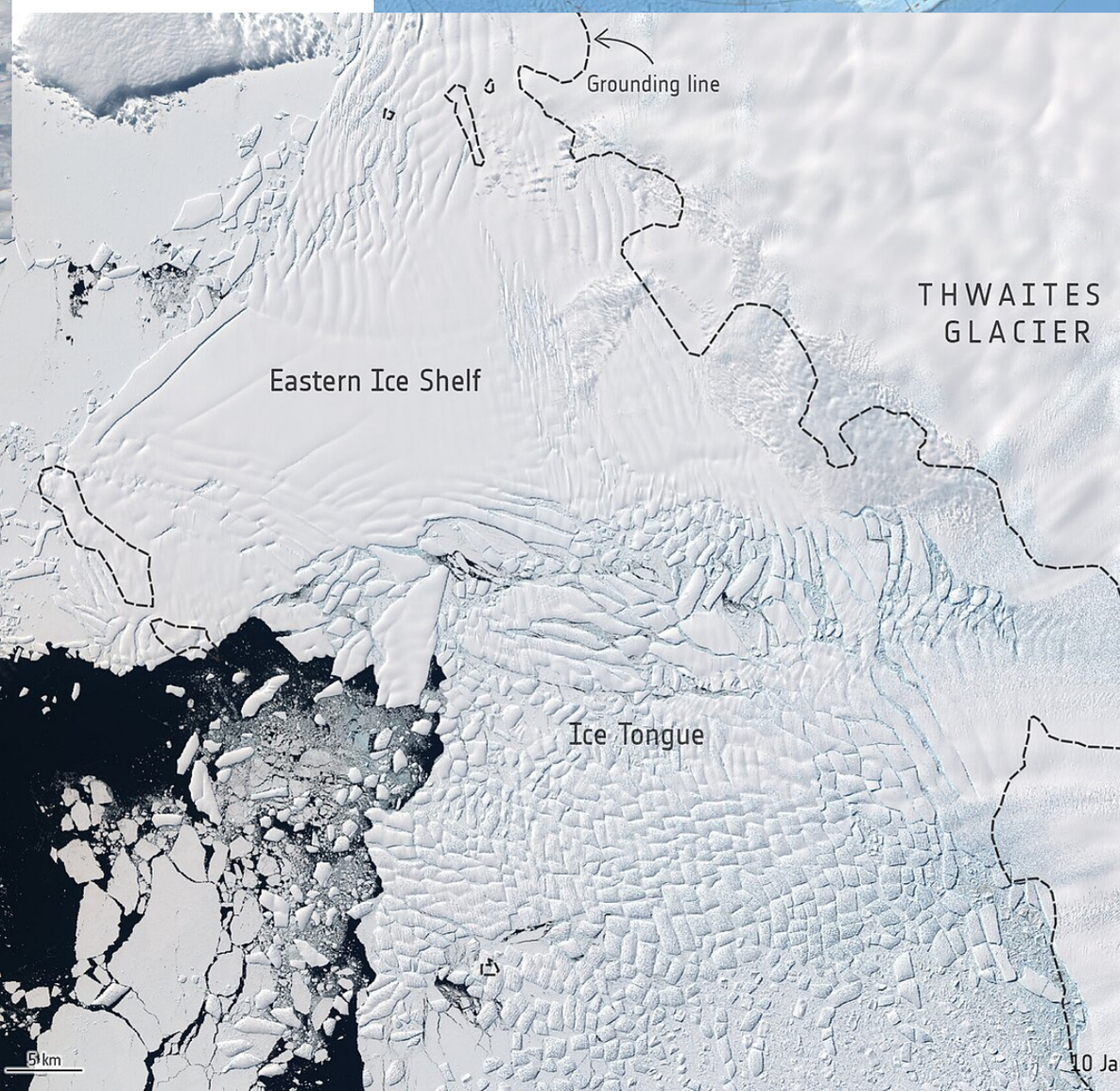
Other potential climate tipping points

- Arctic sea ice
- AMOC
- Antarctica's "doomsday" Thwaites Glacier
- Greenland's ice sheet
- The West Antarctic ice sheet
- Sahara's vegetation
- Amazon Forest
- Corals
- Permafrost
- Methane clathrate gun hypothesis

Antarctica's "doomsday" Thwaites Glacier







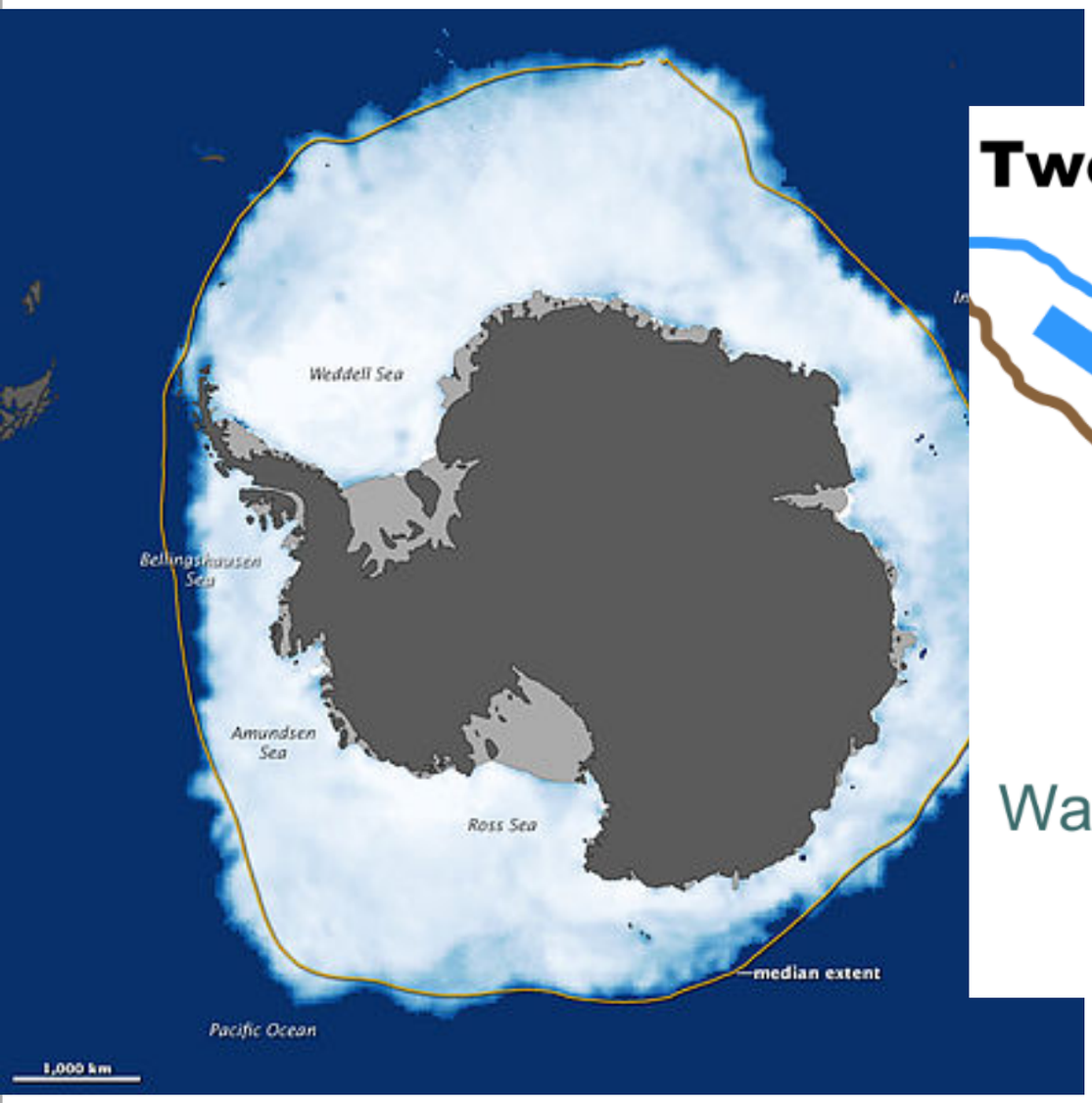
The ice shelf (floating ice, flowing from land, 500–1000 m thick)

wikipedia.org/wiki/Thwaites_Glacier

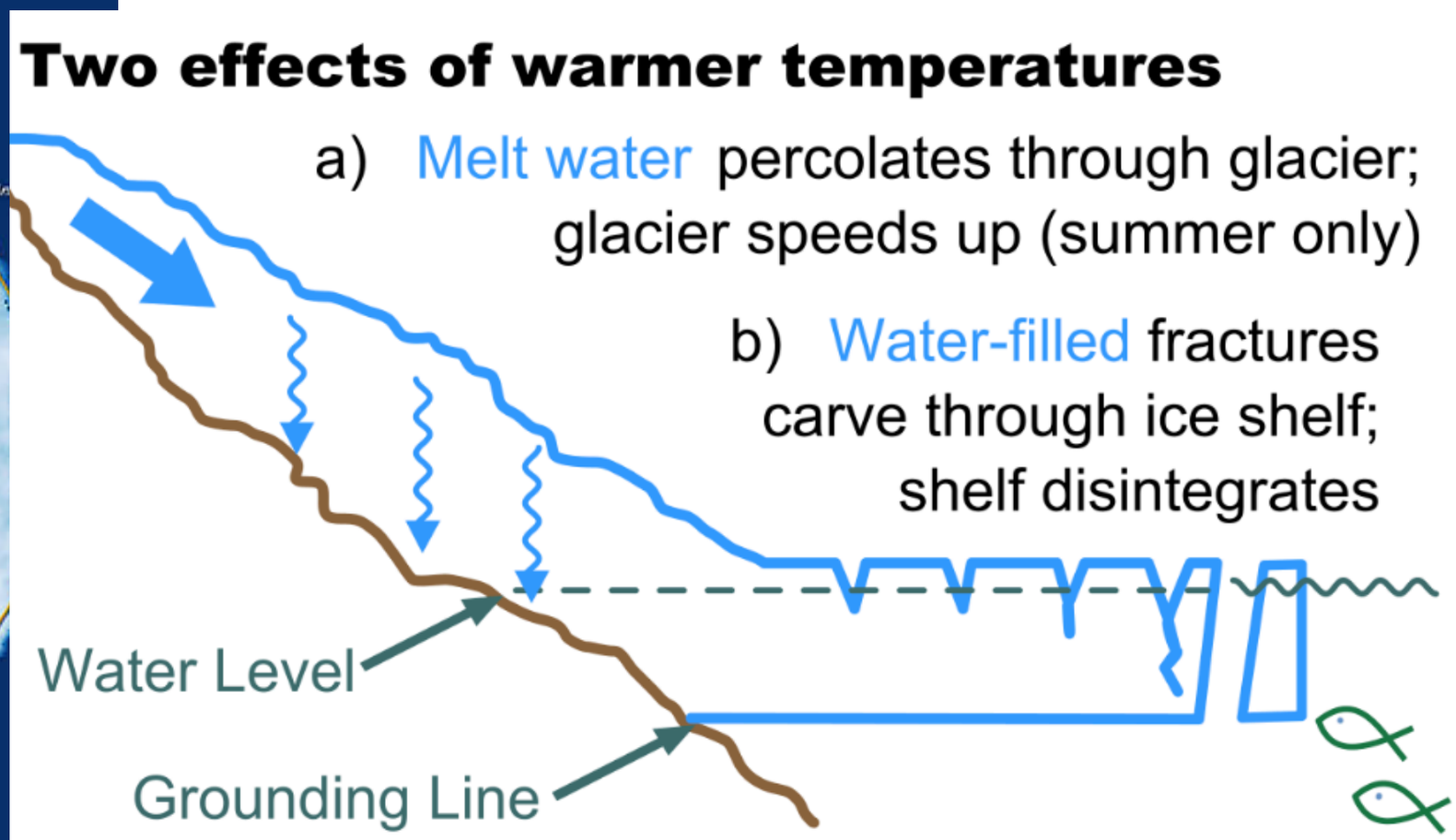
Thwaites glacier = 65 cm sea level rise

Remains of ice tongue reduced to a "mélange" of icebergs, much less effective at supporting the glacier and preventing calving events.

Antarctica's "doomsday" Thwaites Glacier



ice shelves (gray) and sea ice

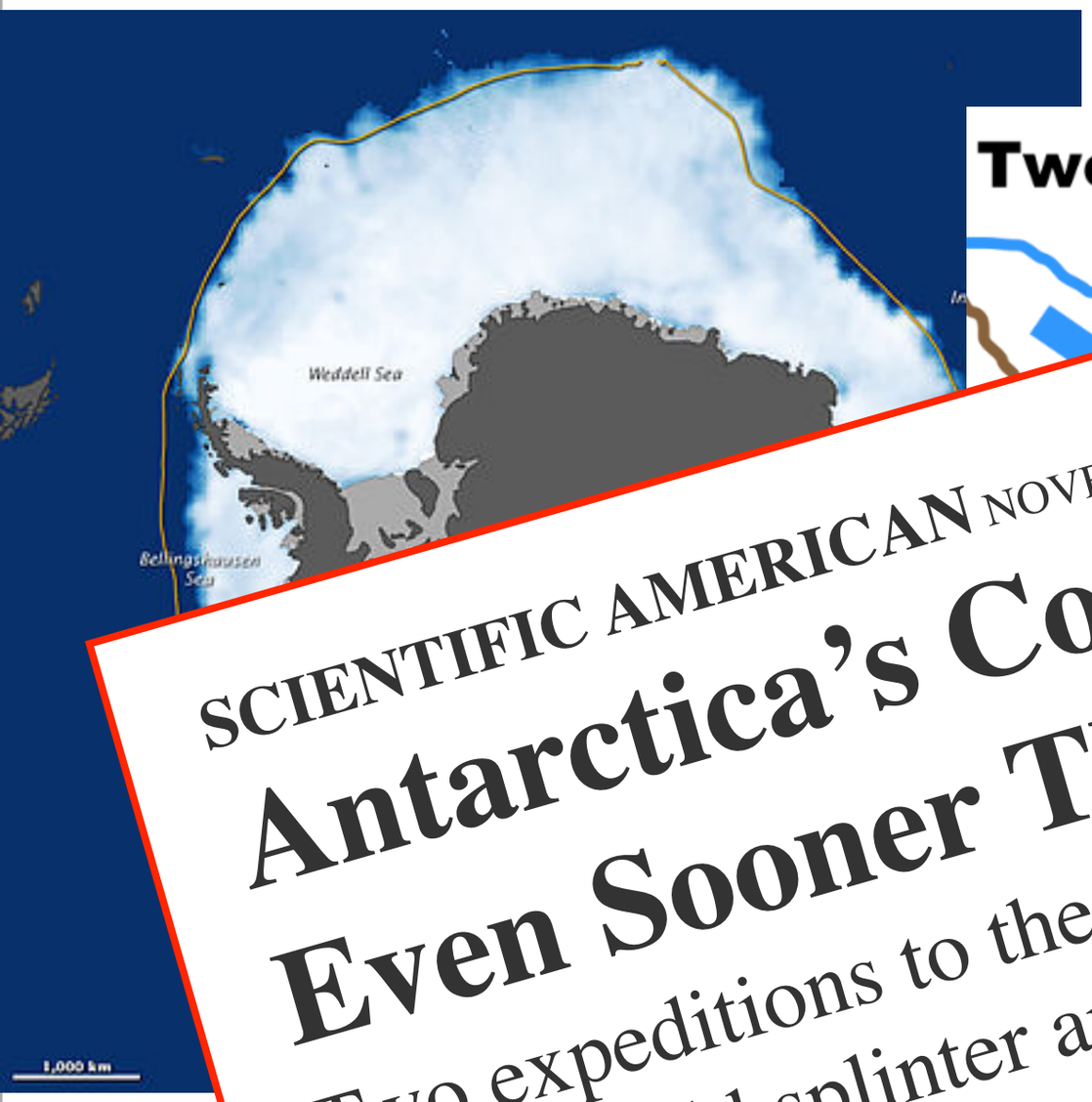


wikipedia.org/wiki/Ice_shelf

Thwaites glacier = 65 cm sea level rise

Remains of ice tongue reduced to a "mélange" of icebergs, much less effective at supporting the glacier and preventing calving events.

Antarctica's "doomsday" Thwaites Glacier



Two effects of warmer

a) M

glacier;
r only)
ures
elf;
es

ice she

.org/wiki/Ice_shelf

SCIENTIFIC AMERICAN NOVEMBER 1, 2022

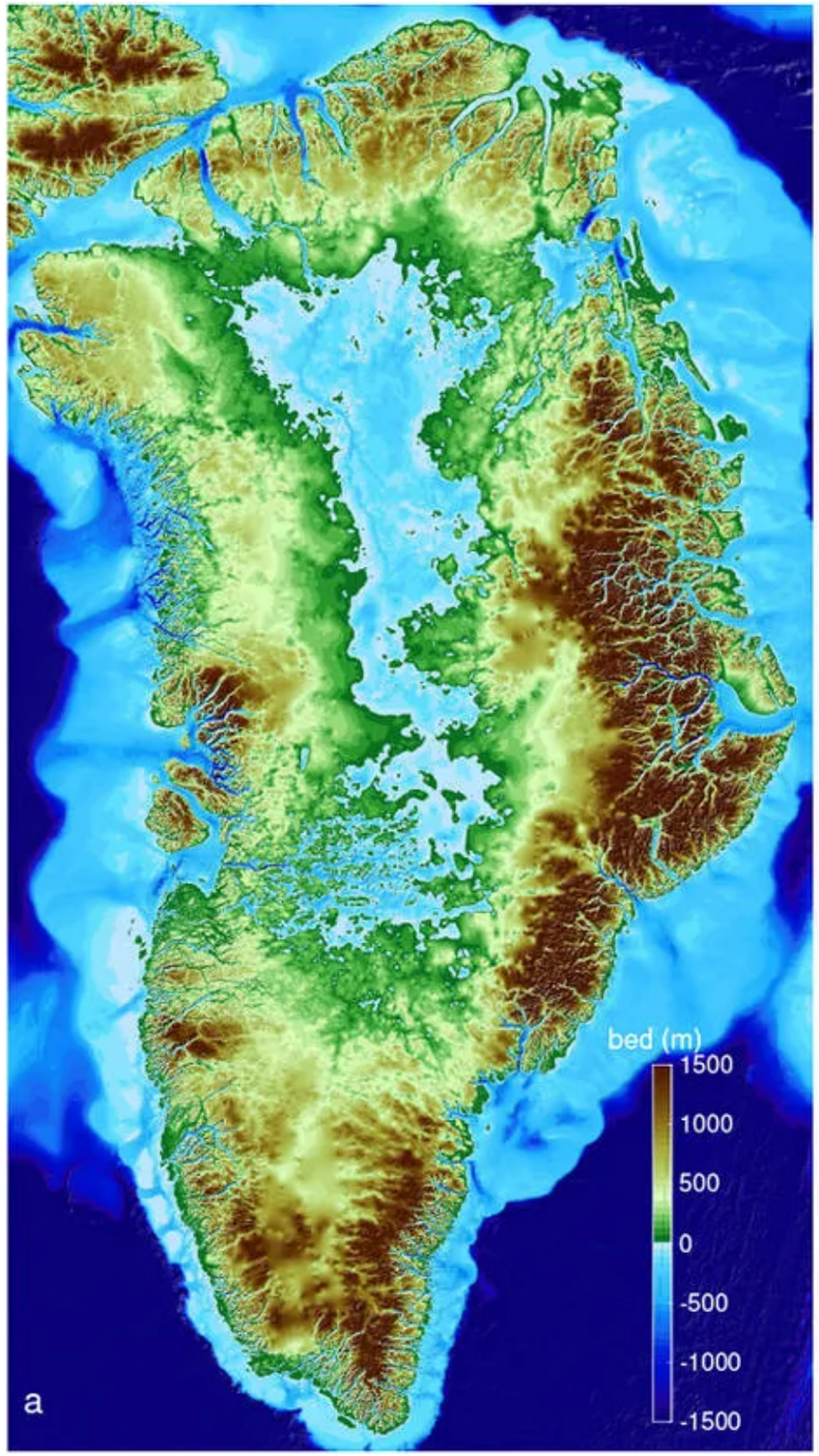
Antarctica's Collapse Could Begin Even Sooner Than Anticipated

Two expeditions to the Thwaites Ice Shelf have revealed that it could splinter apart in less than a decade, hastening sea-level rise worldwide

Thwaites 65 cm sea level rise

Remains of ice tongue reduced to a "mélange" of icebergs, much less effective at supporting the glacier and preventing calving events.

The Greenland ice sheet



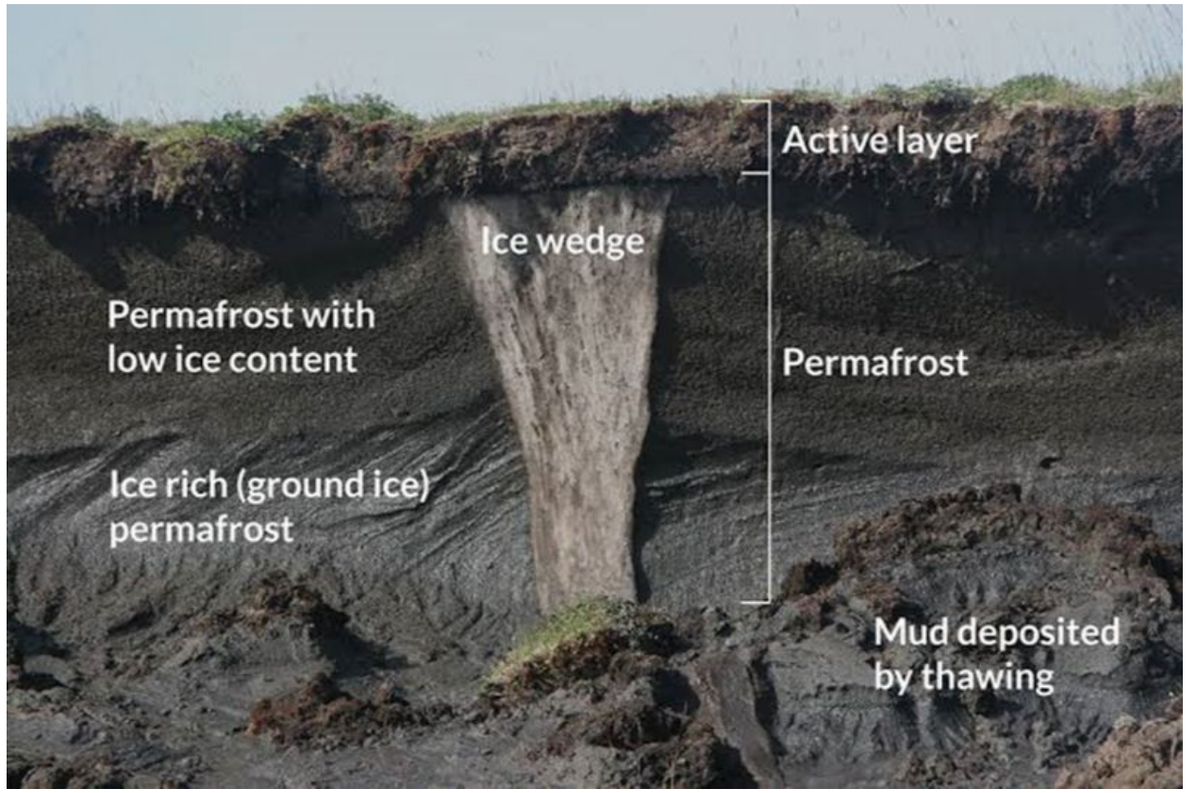
ttps://www.smithsonianmag.com/smart-news/aked-map-greenland-helps-understanding-ice-loss-180967562/

https://en.wikipedia.org/wiki/Greenland_ice_sheet

7 m of sea level rise

Thawing of Arctic permafrost

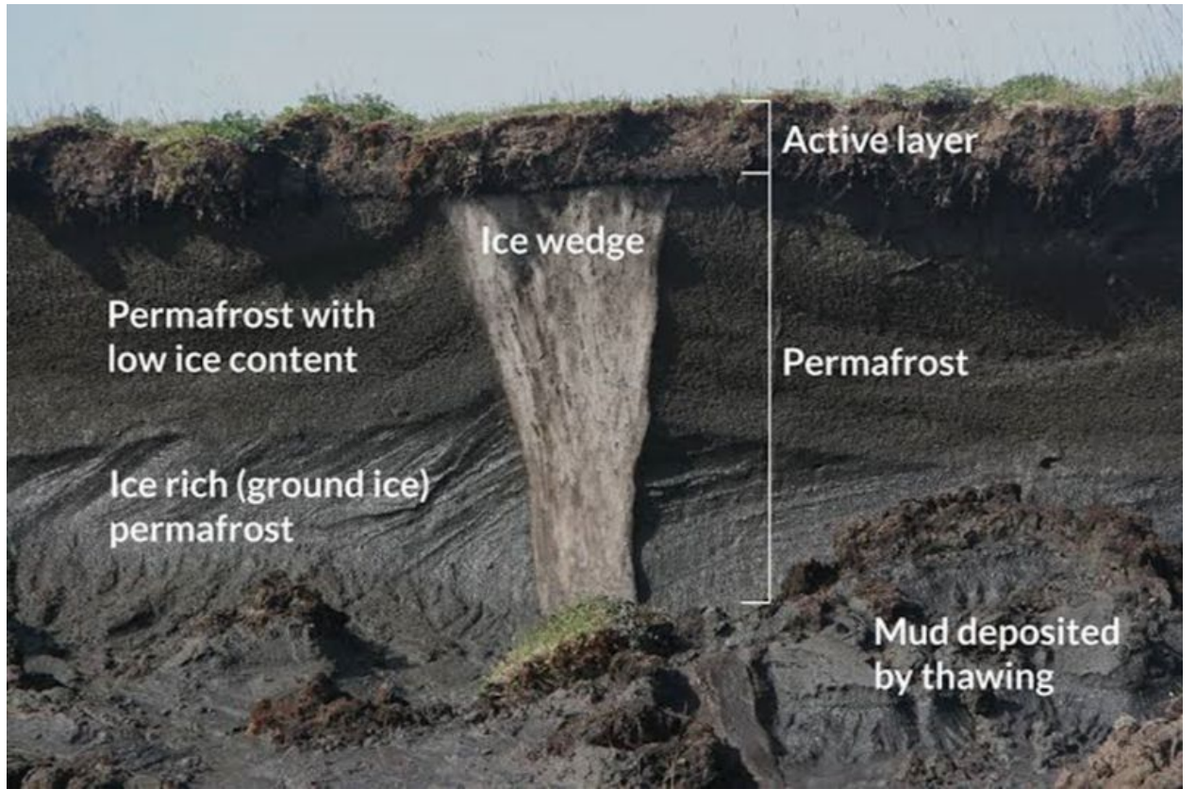
https://earth.org/data_visualization/what-is-permafrost/



Mass of carbon in Arctic permafrost: ~1,500 GtC; ~150x our annual carbon emissions

Thawing of Arctic permafrost

https://earth.org/data_visualization/what-is-permafrost/

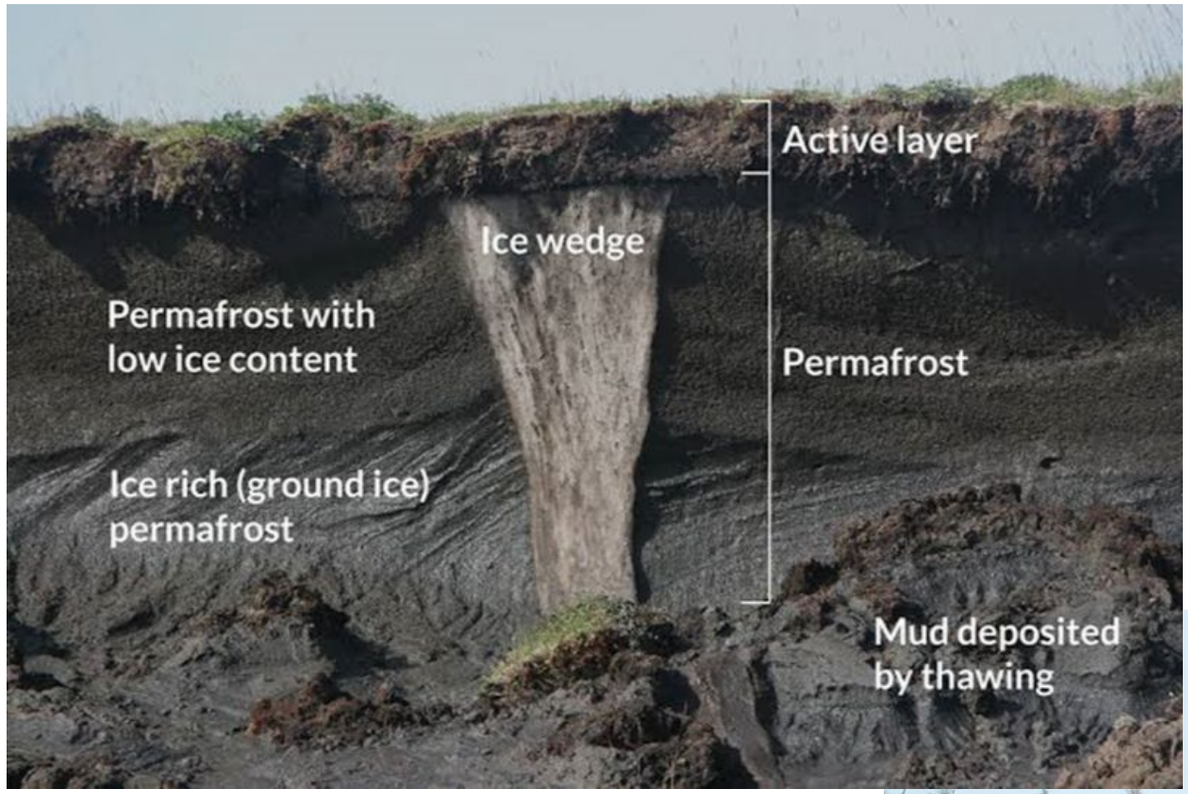


Mass of carbon in Arctic permafrost: ~1,500 GtC; ~150x our annual carbon emissions

https://www.jpl.nasa.gov/news/thawing-permafrost-could-leach-microbes-chemicals-into-environment/

Thawing of Arctic permafrost

https://earth.org/data_visualization/what-is-permafrost/



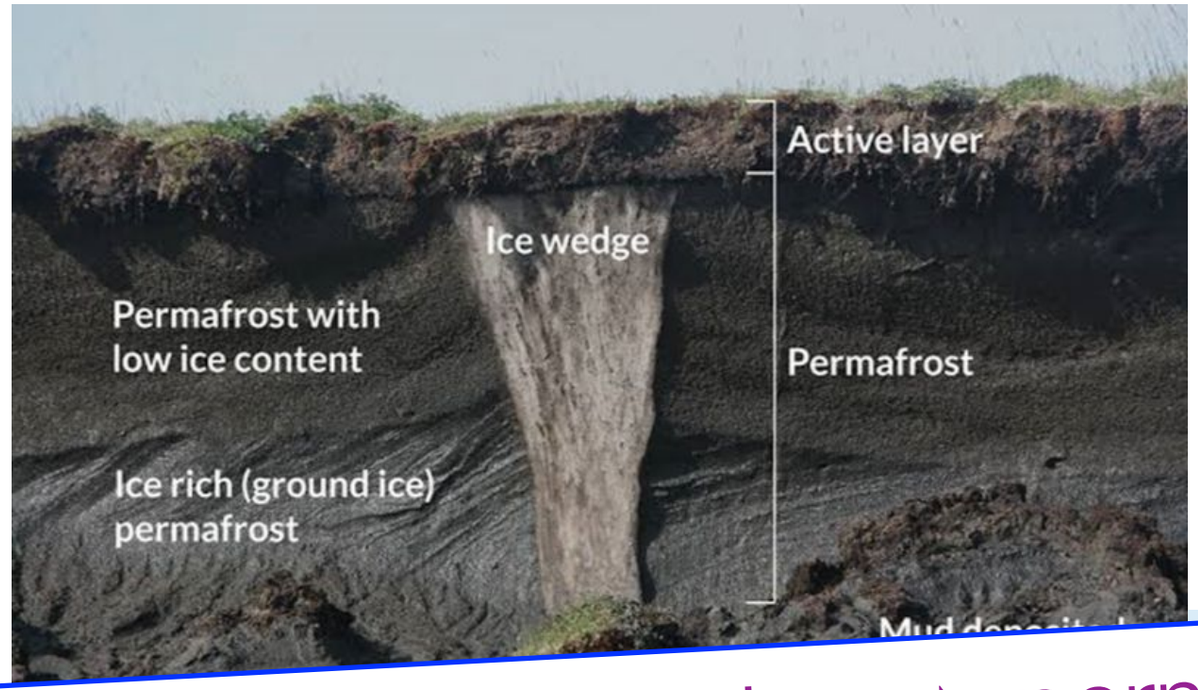
Mass of carbon in Arctic permafrost: ~1,500 GtC; ~150x our annual carbon emissions

https://www.jpl.nasa.gov/news/thawing-permafrost-could-leach-microbes-chemicals-into-environment/

https://e360.yale.edu/digest/melting-permafrost-could-damage-infrastructure-for-3-6-million-people

Thawing of Arctic permafrost

https://earth.org/data_visualization/what-is-permafrost/



Mass of carbon in Arctic permafrost: ~1,500 GtC; ~150x our annual carbon emissions

The danger: warming ➡ permafrost melt ➡ CO_2 release ➡ more warming…

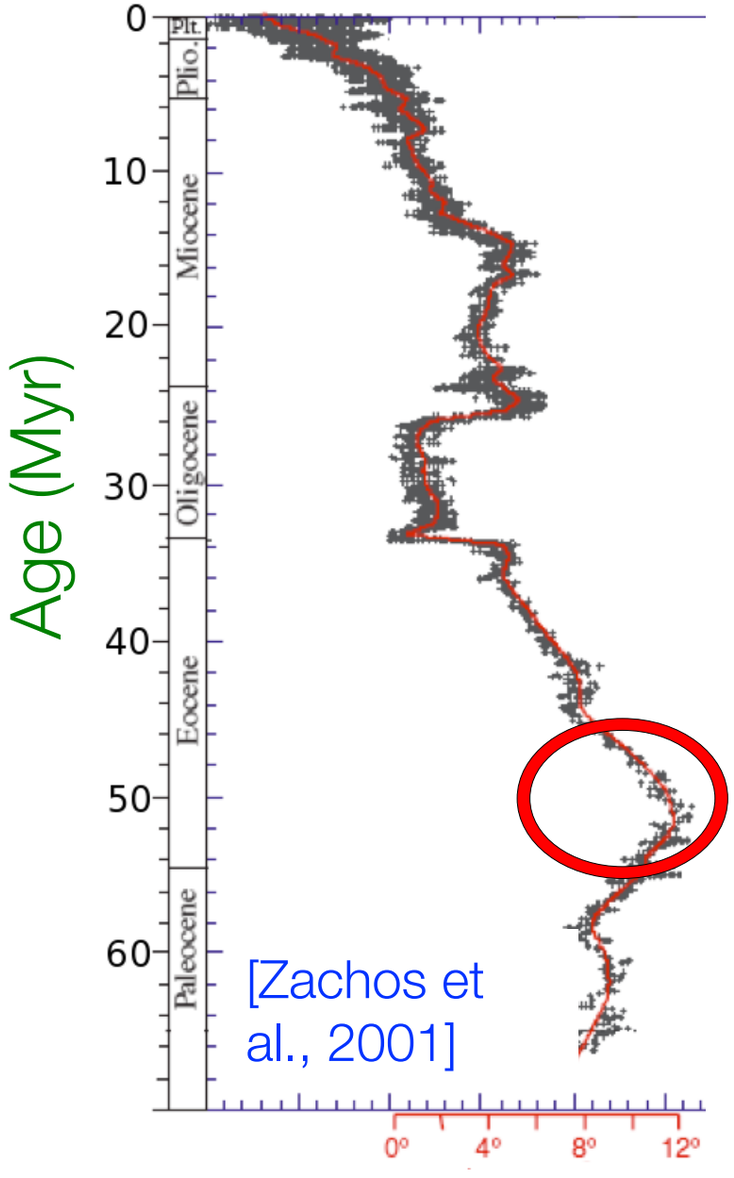
https://www.jpl.nasa.gov/news/thawing-permafrost-could-leach-microbes-chemicals-into-environment/

https://e360.yale.edu/digest/melting-permafrost-could-damage-infrastructure-for-3-6-million-people

Useful lessons on climate tipping points from past climates

- Earth has seen naturally occurring warm climates before.
- The Pliocene, 2–5 Myr ago, had CO_2~400 ppm, similar to present. The Eocene, ~146–34 Myr ago, was so warm that there was no ice anywhere.
- We can use this to learn what could and what might not happen in a warm climate.
- Was there ice over Greenland/Antarctica melt (no…!) Permafrost? (no…!) Corals extinct? Polar bears? Amazon dieback?

Gradual cooling over past 55 Myr



Deep ocean Temperature

workshop 3:
The Stommel model, AMOC tipping points

Summary

- A climate tipping point is an abrupt & possibly large change in response to a gradual CO_2 increase.

Summary

- A climate tipping point is an abrupt & possibly large change in response to a gradual CO_2 increase.
- This may occur when a climate system (sea ice, AMOC, Sahara, Thwaites) has two equilibria for a given CO_2.

Summary

- A climate tipping point is an abrupt & possibly large change in response to a gradual CO_2 increase.
- This may occur when a climate system (sea ice, AMOC, Sahara, Thwaites) has two equilibria for a given CO_2.
- As CO_2 rises, if one of the equilibria cannot be sustained anymore, the system must jump to the other.

Summary

- A climate tipping point is an abrupt & possibly large change in response to a gradual CO_2 increase.
- This may occur when a climate system (sea ice, AMOC, Sahara, Thwaites) has two equilibria for a given CO_2.
- As CO_2 rises, if one of the equilibria cannot be sustained anymore, the system must jump to the other.
- Irreversibility & hysteresis are expected consequences.

Summary

- A climate tipping point is an abrupt & possibly large change in response to a gradual CO_2 increase.
- This may occur when a climate system (sea ice, AMOC, Sahara, Thwaites) has two equilibria for a given CO_2.
- As CO_2 rises, if one of the equilibria cannot be sustained anymore, the system must jump to the other.
- Irreversibility & hysteresis are expected consequences.
- An AMOC weakening will cool the local SST in the North Atlantic and shut off the ventilation of the deep ocean.

Summary

- A climate tipping point is an abrupt & possibly large change in response to a gradual CO_2 increase.
- This may occur when a climate system (sea ice, AMOC, Sahara, Thwaites) has two equilibria for a given CO_2.
- As CO_2 rises, if one of the equilibria cannot be sustained anymore, the system must jump to the other.
- Irreversibility & hysteresis are expected consequences.
- An AMOC weakening will cool the local SST in the North Atlantic and shut off the ventilation of the deep ocean.
- So far AMOC has not shown signs of weakening.

Summary

- A climate tipping point is an abrupt & possibly large change in response to a gradual CO_2 increase.
- This may occur when a climate system (sea ice, AMOC, Sahara, Thwaites) has two equilibria for a given CO_2.
- As CO_2 rises, if one of the equilibria cannot be sustained anymore, the system must jump to the other.
- Irreversibility & hysteresis are expected consequences.
- An AMOC weakening will cool the local SST in the North Atlantic and shut off the ventilation of the deep ocean.
- So far AMOC has not shown signs of weakening.
- Regardless of whether an AMOC tipping point exists, it is robustly expected to weaken in a warmer climate.

The End