

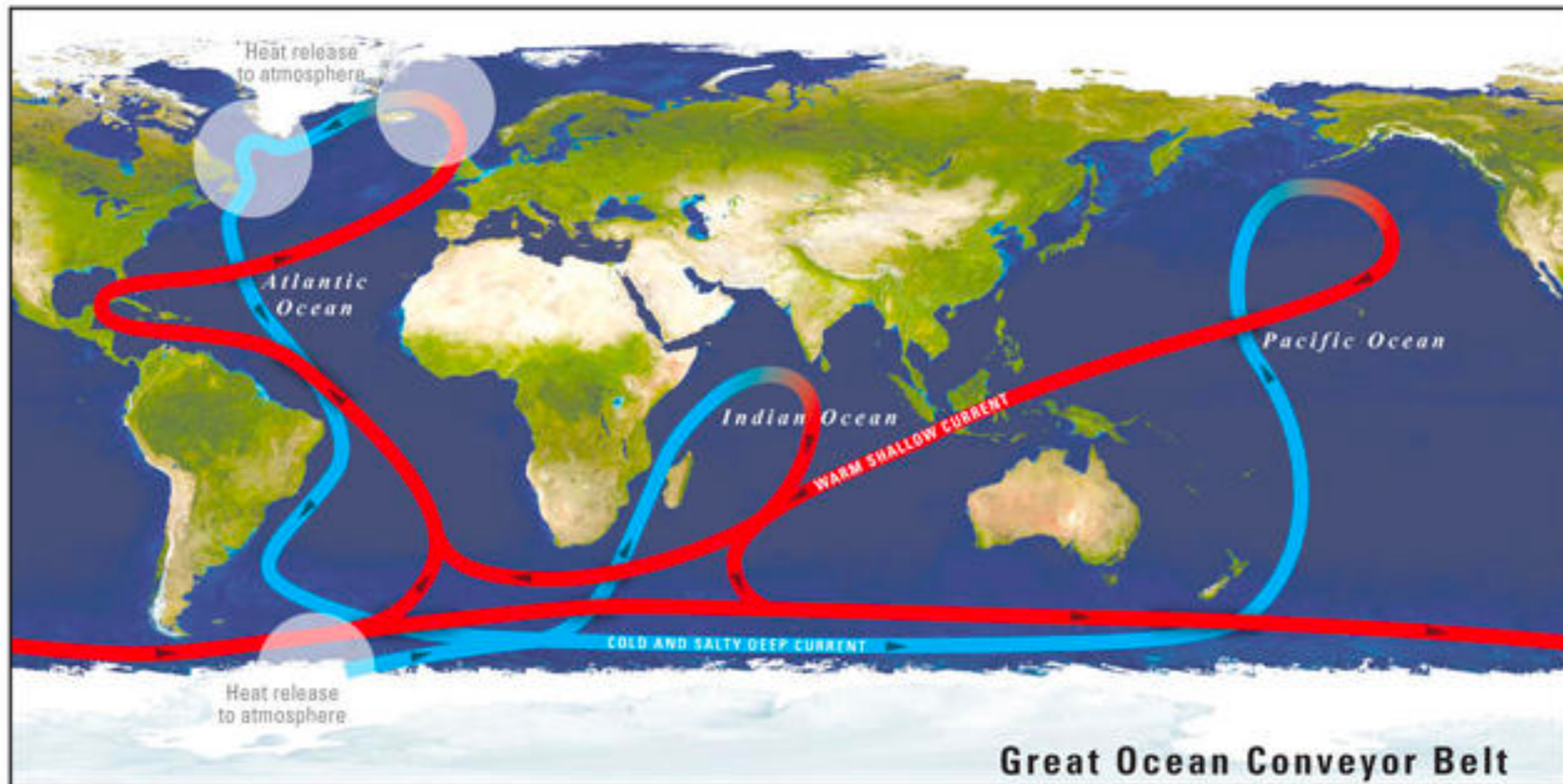
# Ocean circulation collapse

Global Warming Science, EPS101

**Eli Tziperman**

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

# The Atlantic Meridional Overturning Circulation (AMOC)

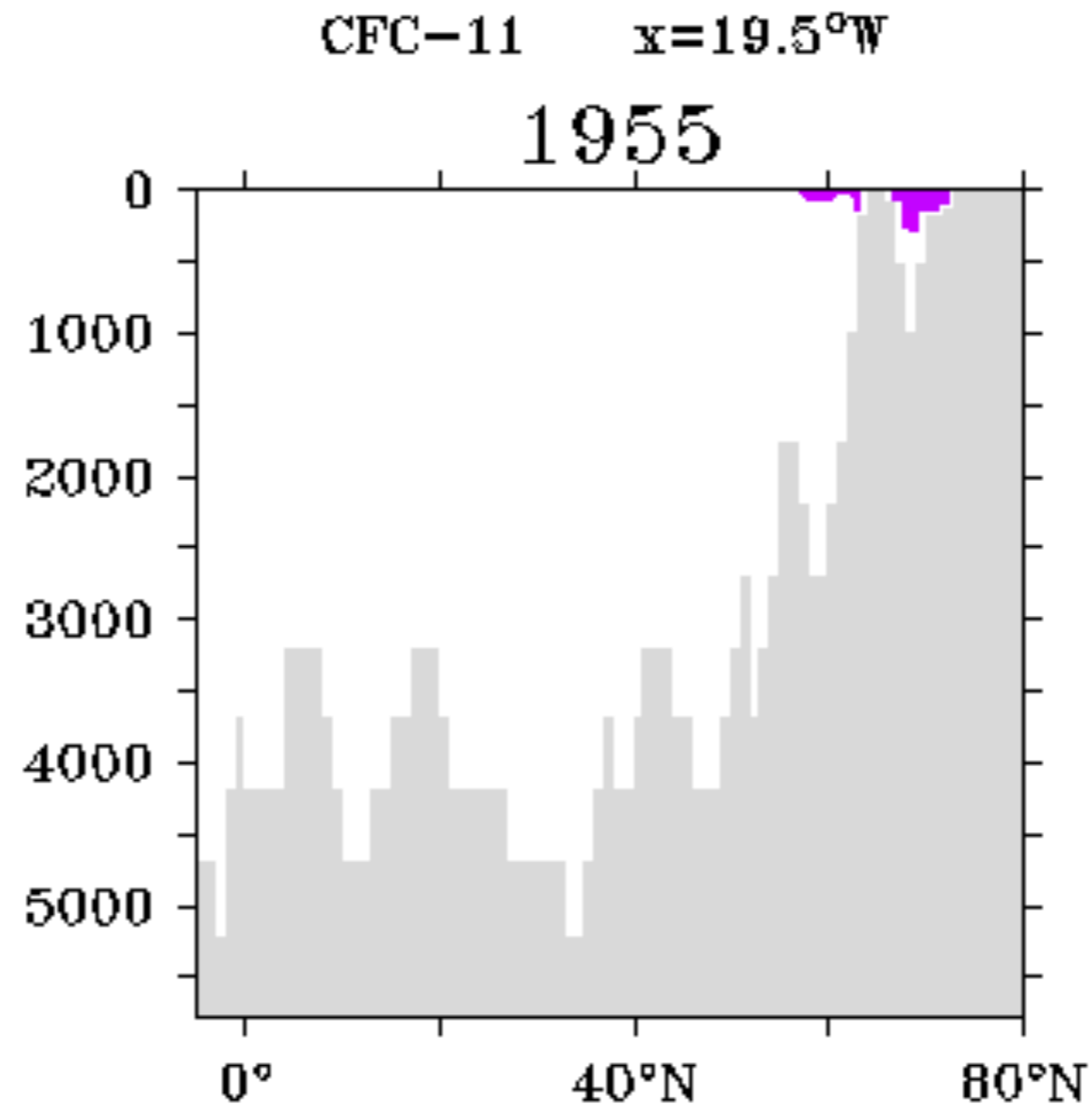


<https://www.cbsnews.com/news/climate-change-atlantic-ocean-gulf-stream-system-amoc-weakest-1600-years/>

**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.



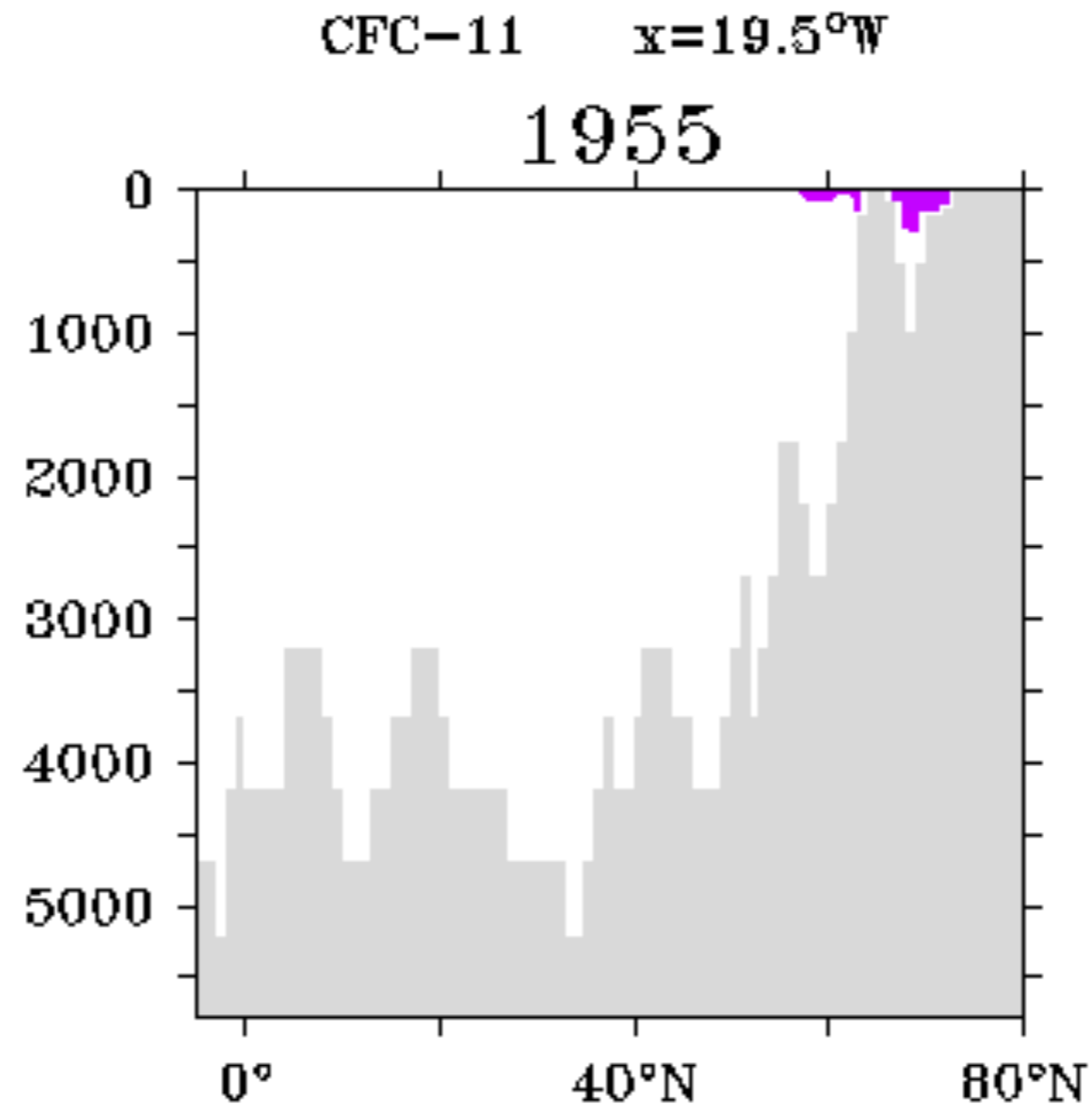
# The Atlantic Meridional Overturning Circulation (AMOC)



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)



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# The Atlantic Meridional Overturning Circulation in the news

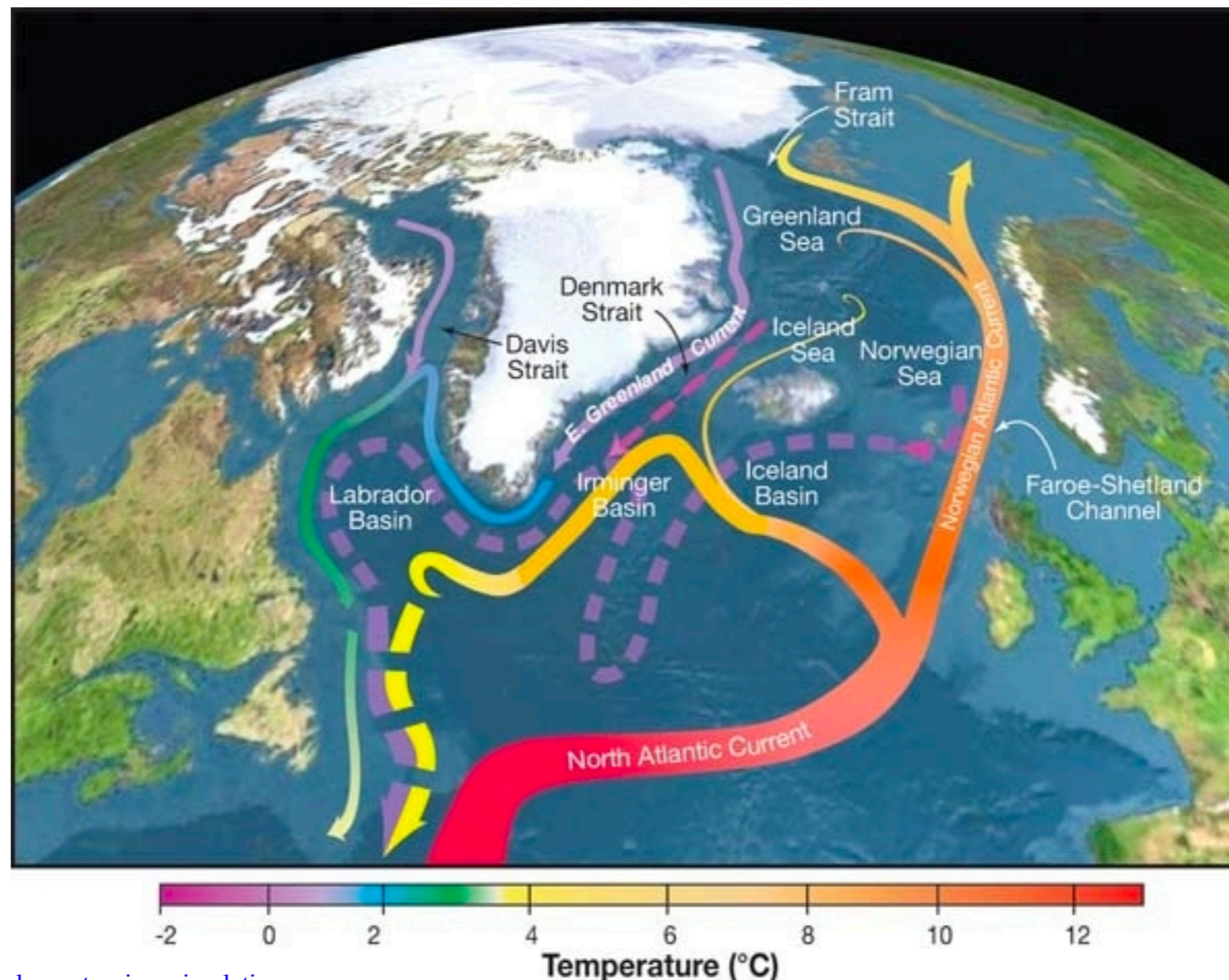
The New York Times

## Atlantic 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 day after tomorrow

[https://www.youtube.com/watch?v=Ku\\_lseK3xTc](https://www.youtube.com/watch?v=Ku_lseK3xTc)

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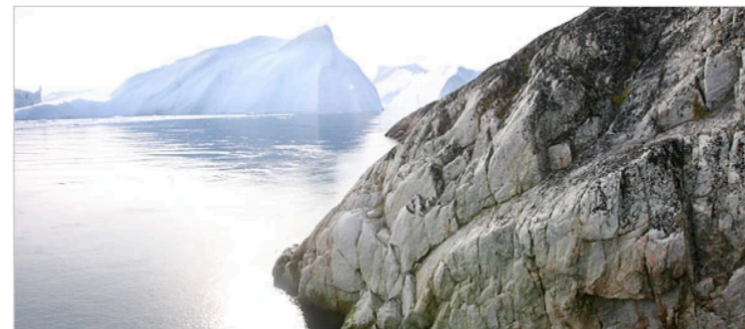


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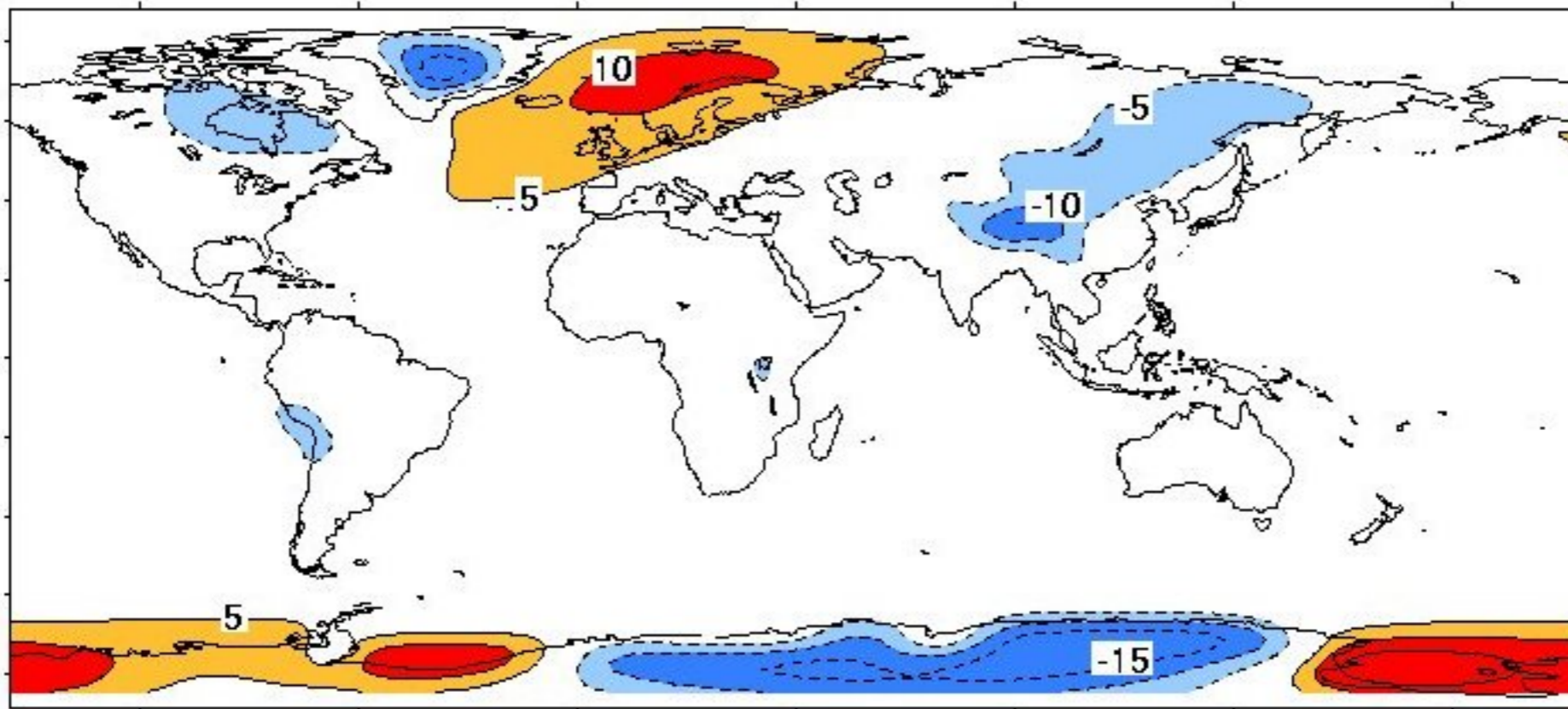
## *Scientists Back Off Theory of a Colder Europe in a Warming World*

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)



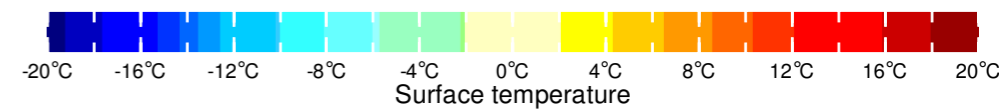
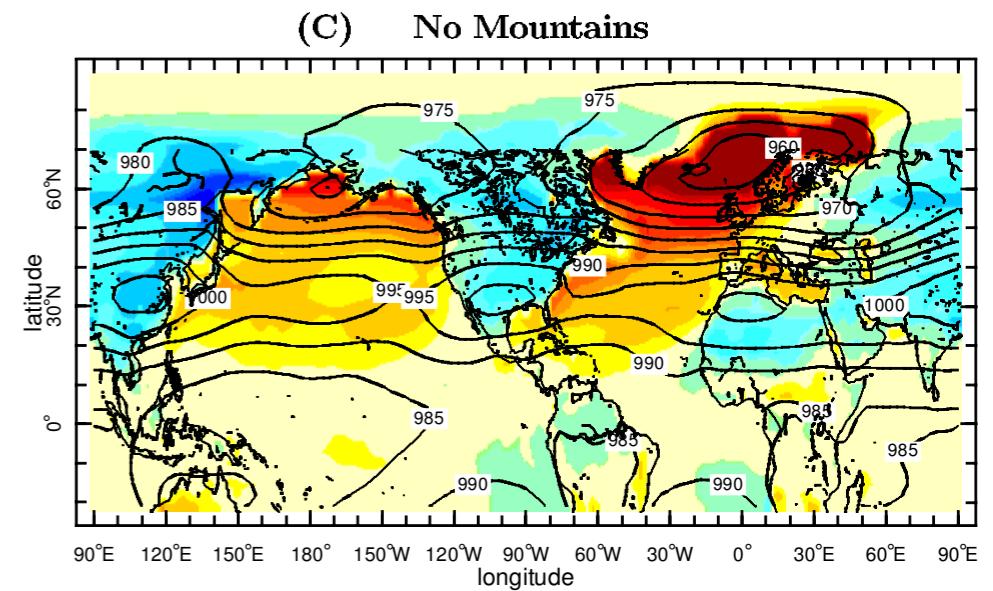
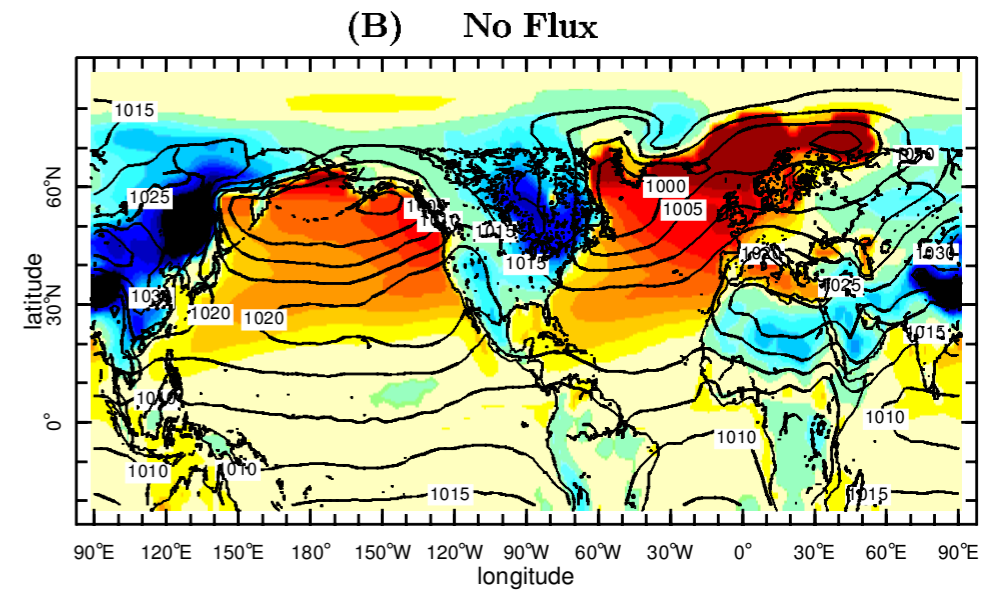
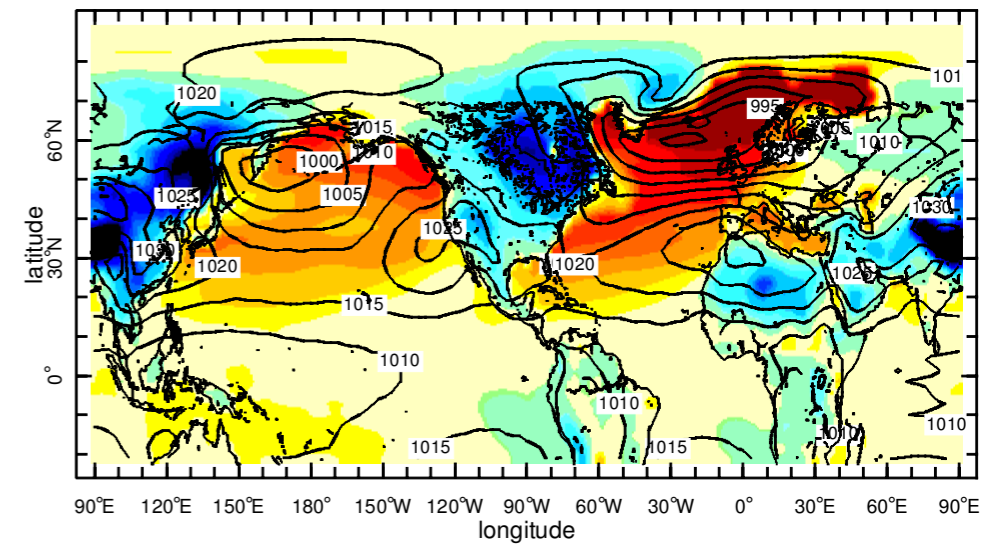
**Figure 1.** Deviation of the annual-mean surface air temperature from its zonal average, computed from the NCAR air temperature climatology. Anomalously cold areas are found over some continental regions, anomalously warm areas over ocean deep water formation regions.

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

# 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.

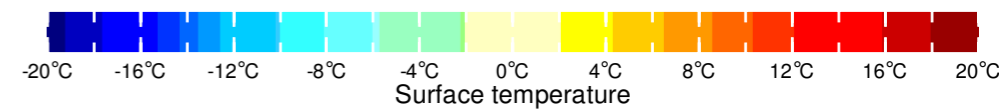
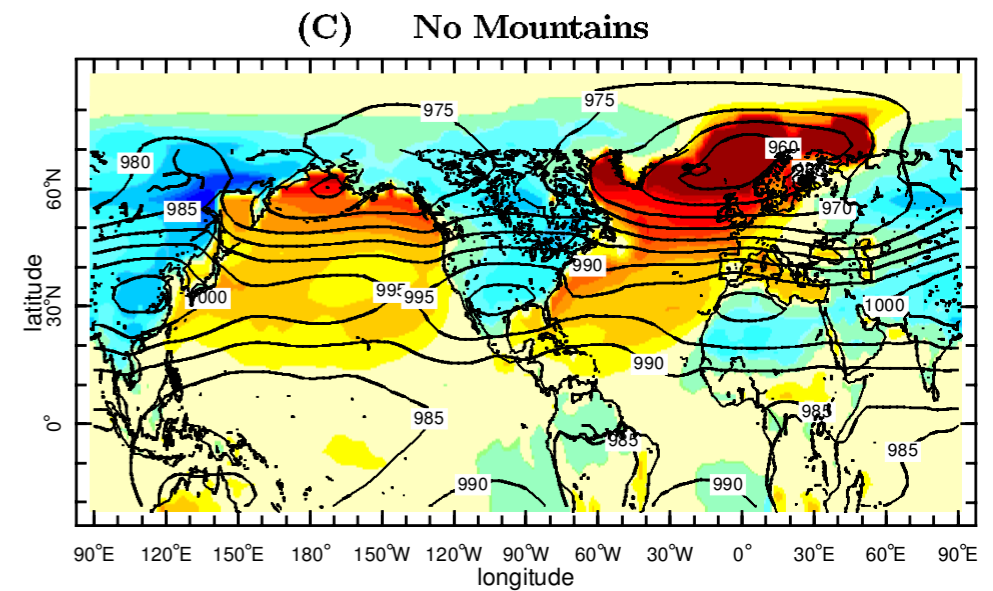
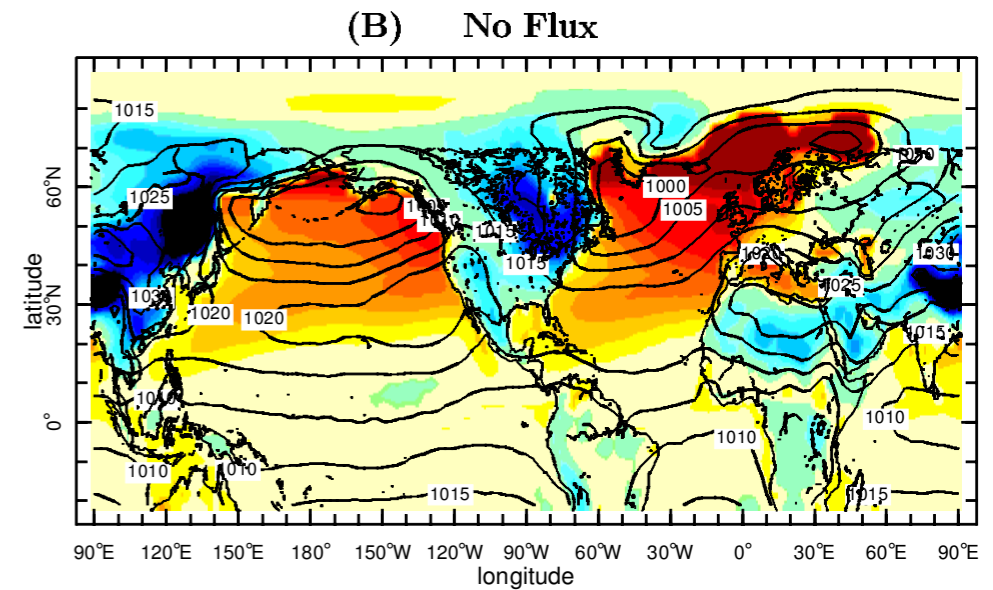
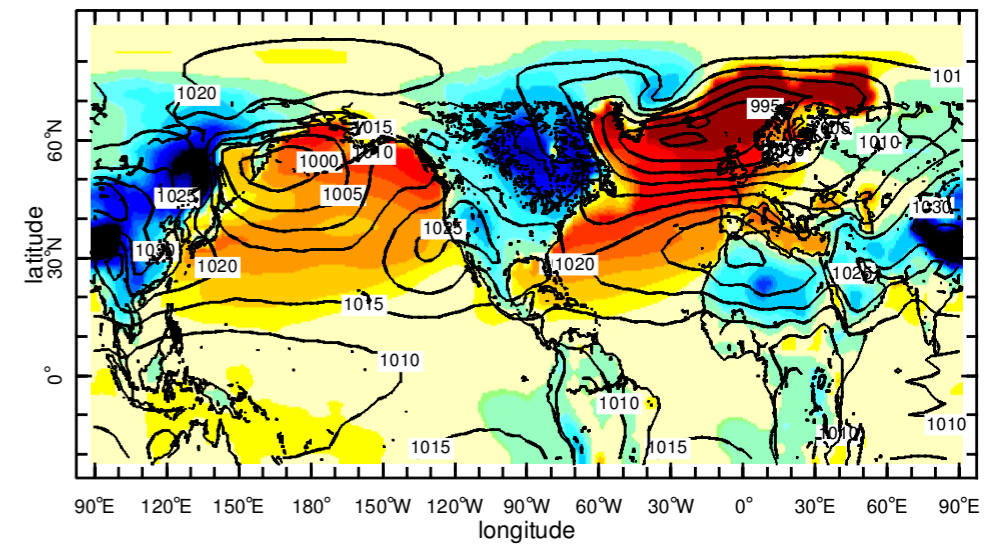




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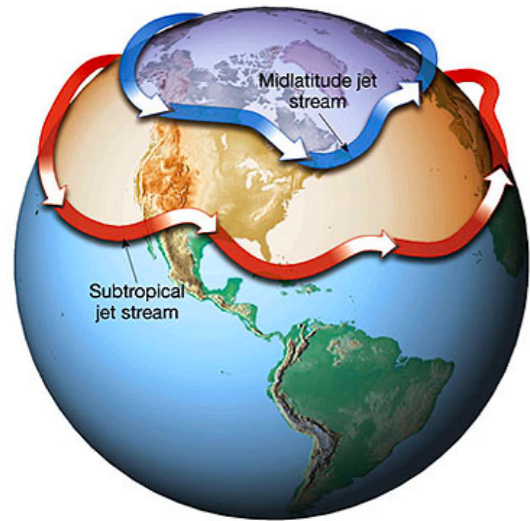
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[https://www.youtube.com/watch?v=huweohIh\\_Bw](https://www.youtube.com/watch?v=huweohIh_Bw)

<https://www.constantinalexander.net/2013/02/ozone-depletion-runs-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

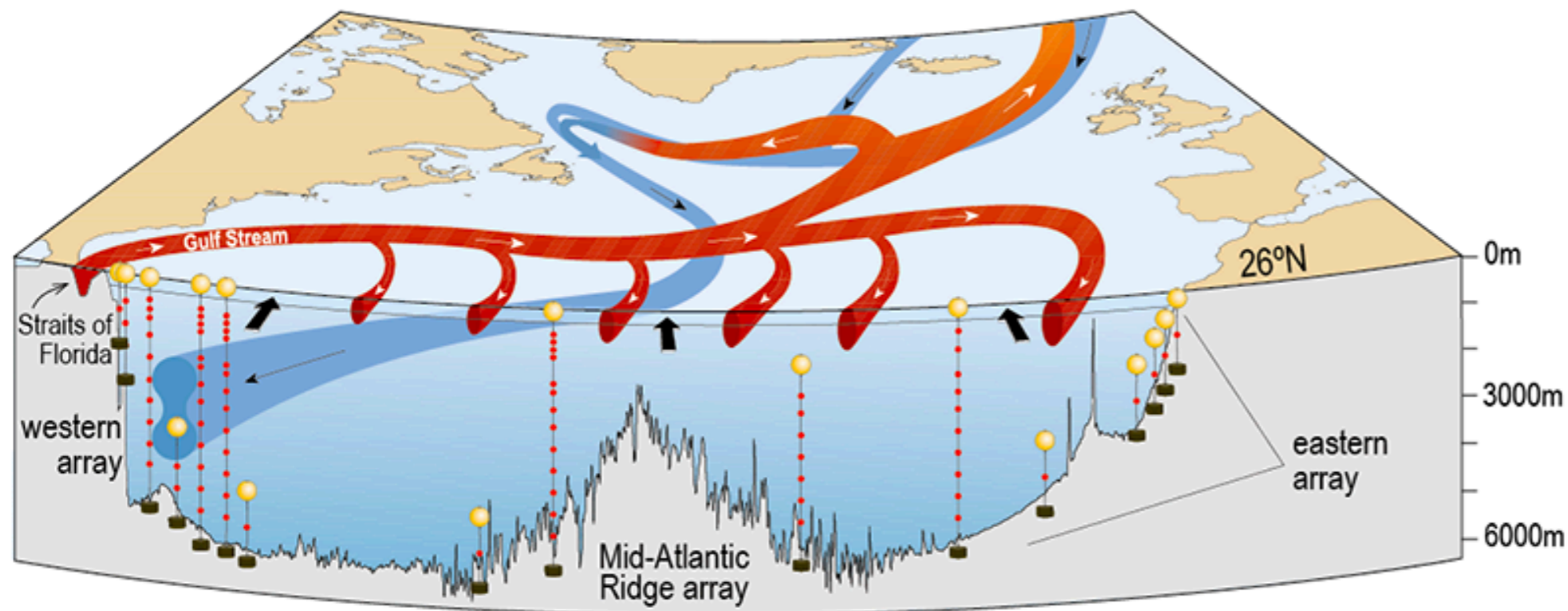


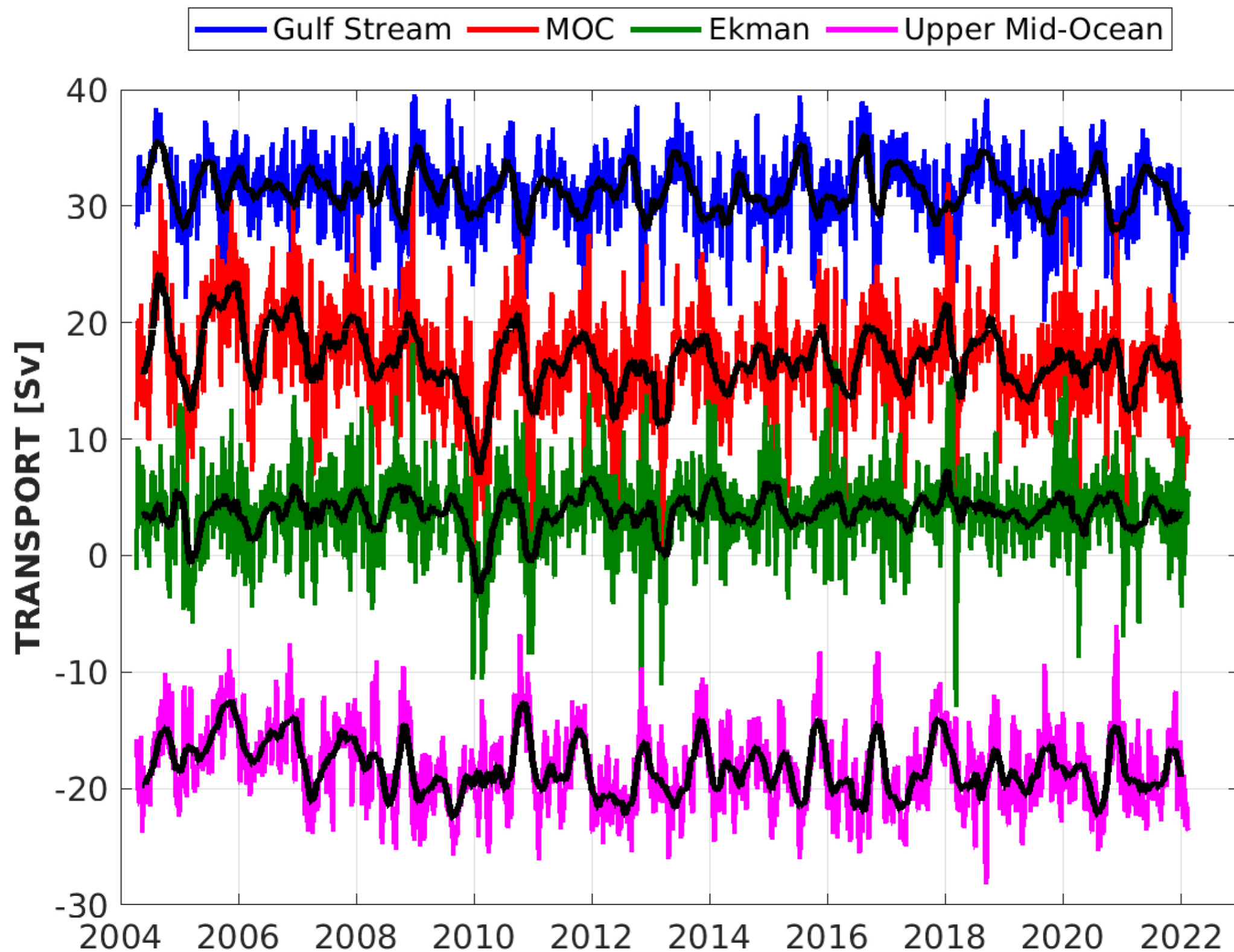
Figure 5. The North Atlantic overturning circulation with the location of the RAPID array moorings along 26°N. Modified from Church, 2007.

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



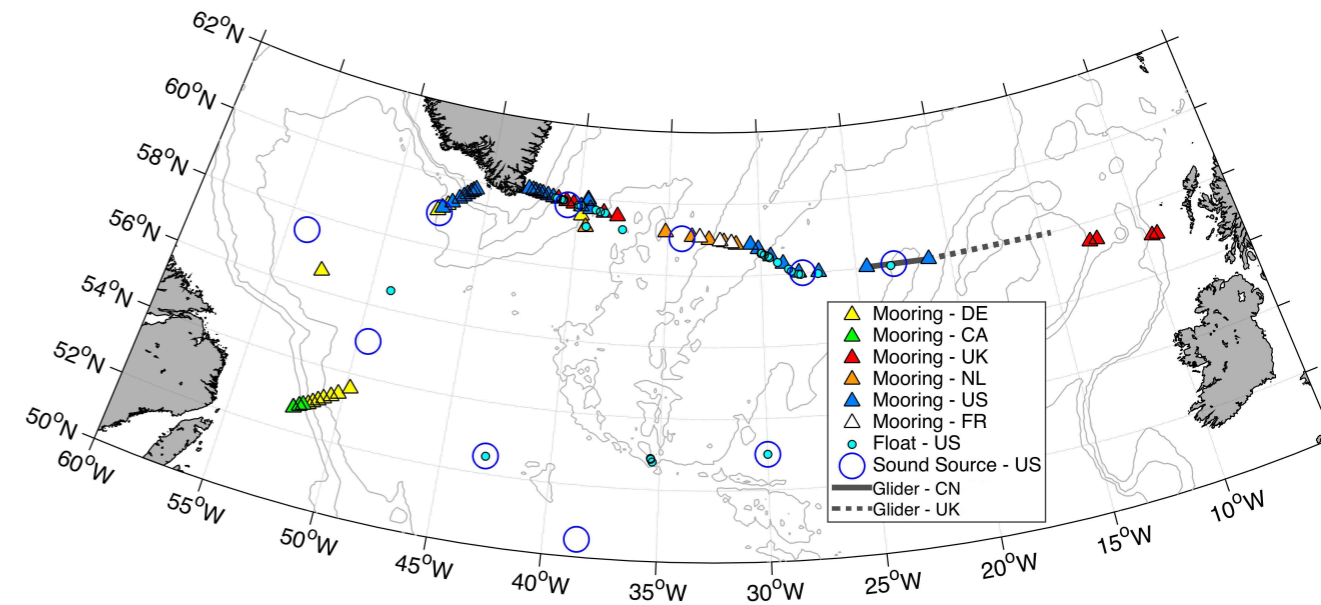
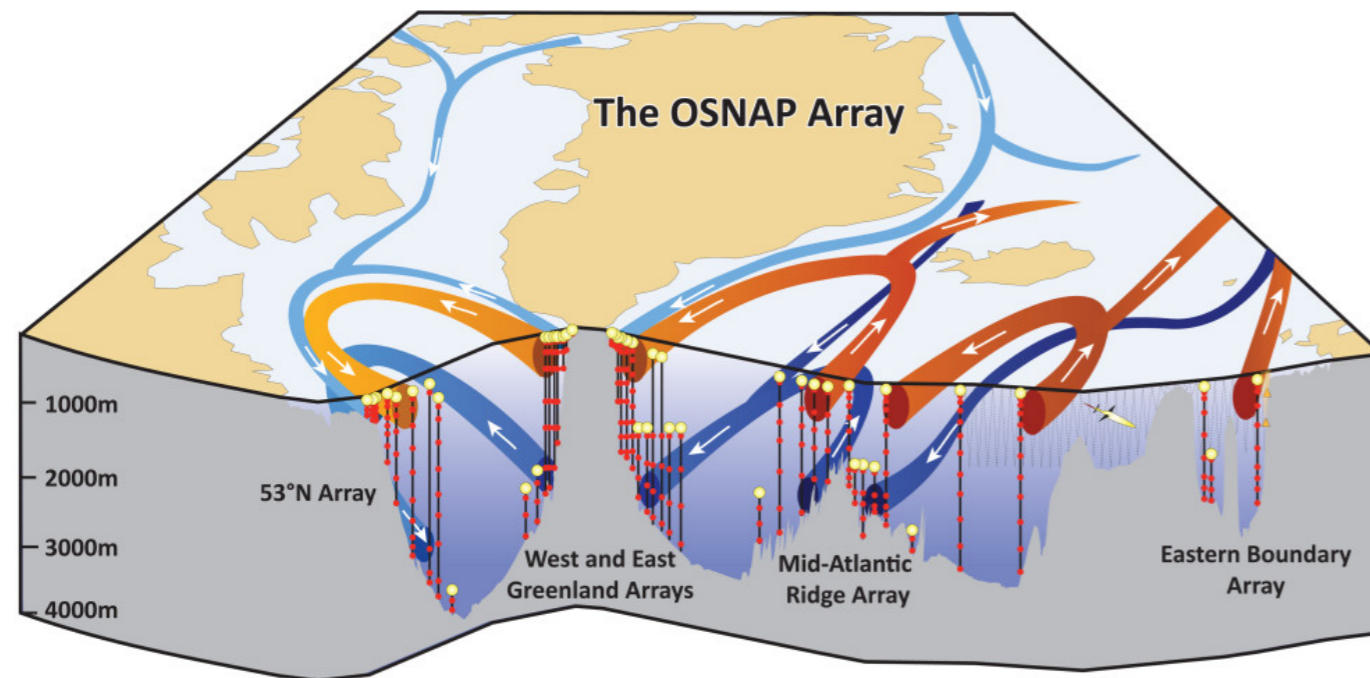


# RAPID: monitoring the Atlantic Meridional Overturning Circulation at 26.5°N



# OSNAP: monitoring AMOC at $\sim 55\text{--}60^\circ\text{N}$

## “Overturning in the Subpolar North Atlantic Program”

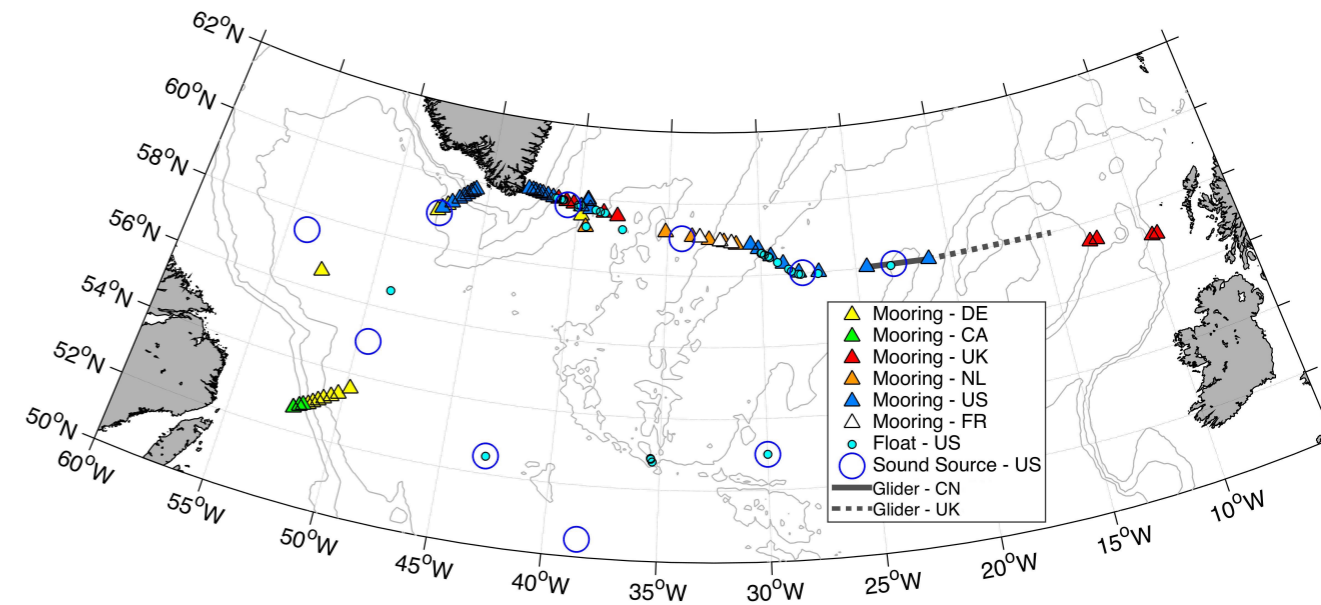
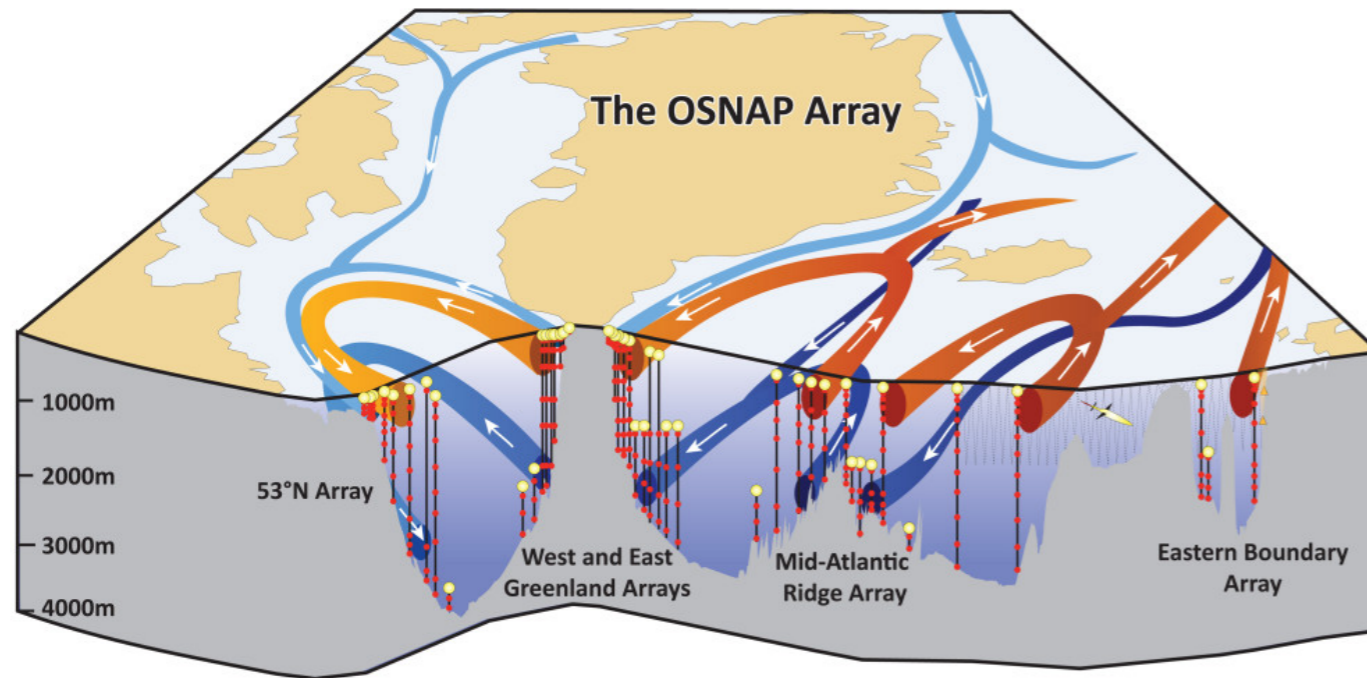


A view of the OSNAP array and mooring locations



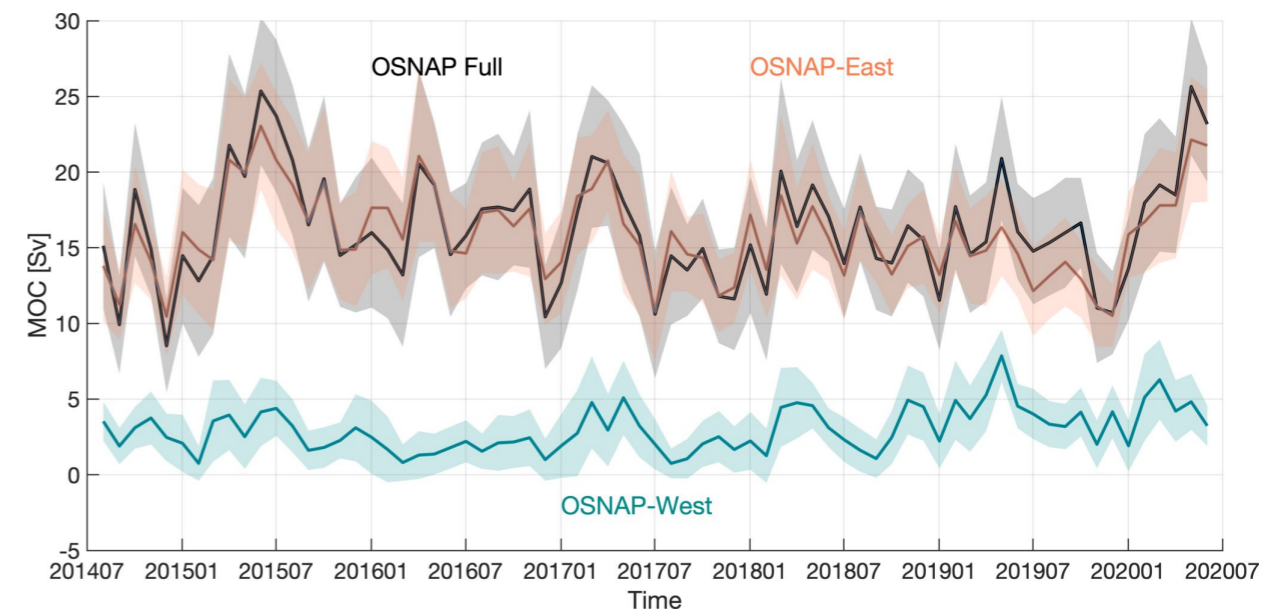
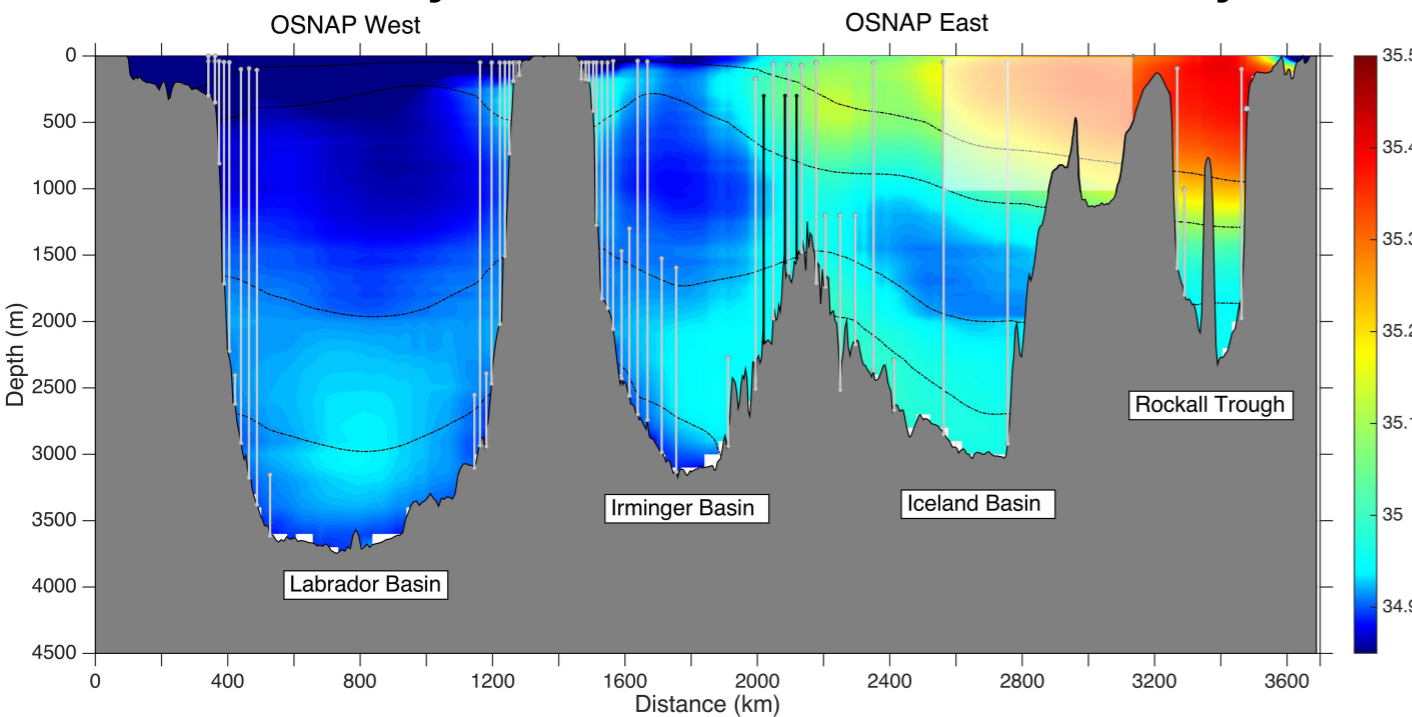
# OSNAP: monitoring AMOC at ~55–60°N

## “Overturning in the Subpolar North Atlantic Program”



A view of the OSNAP array and mooring locations

### A salinity section across the array

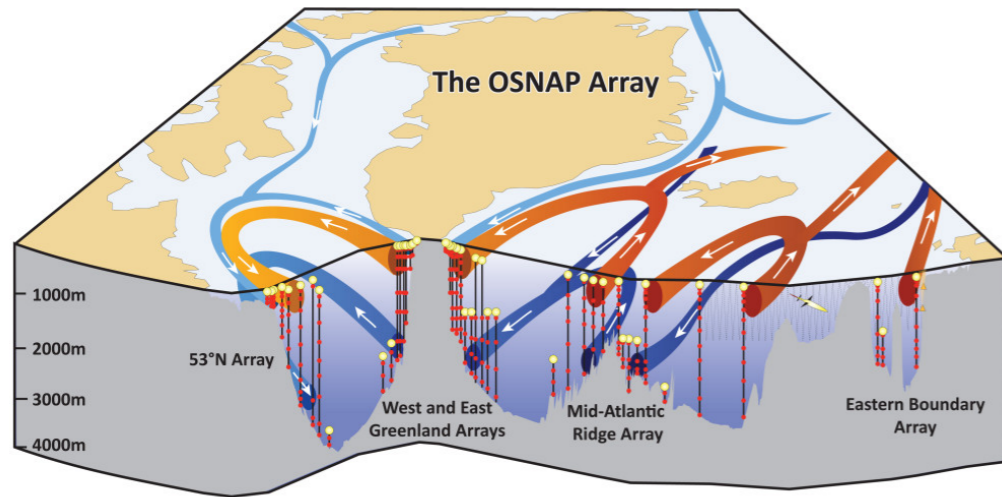


Time series of transport across the array

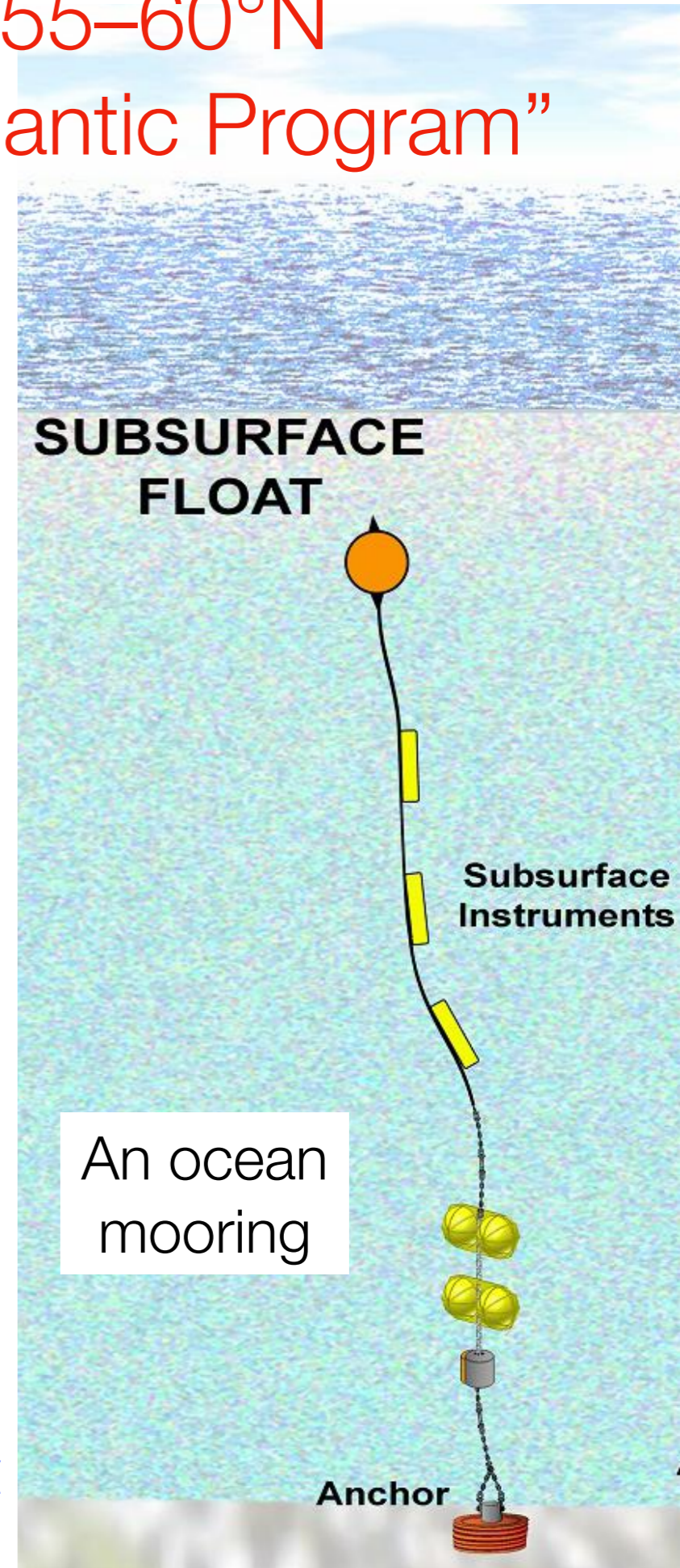
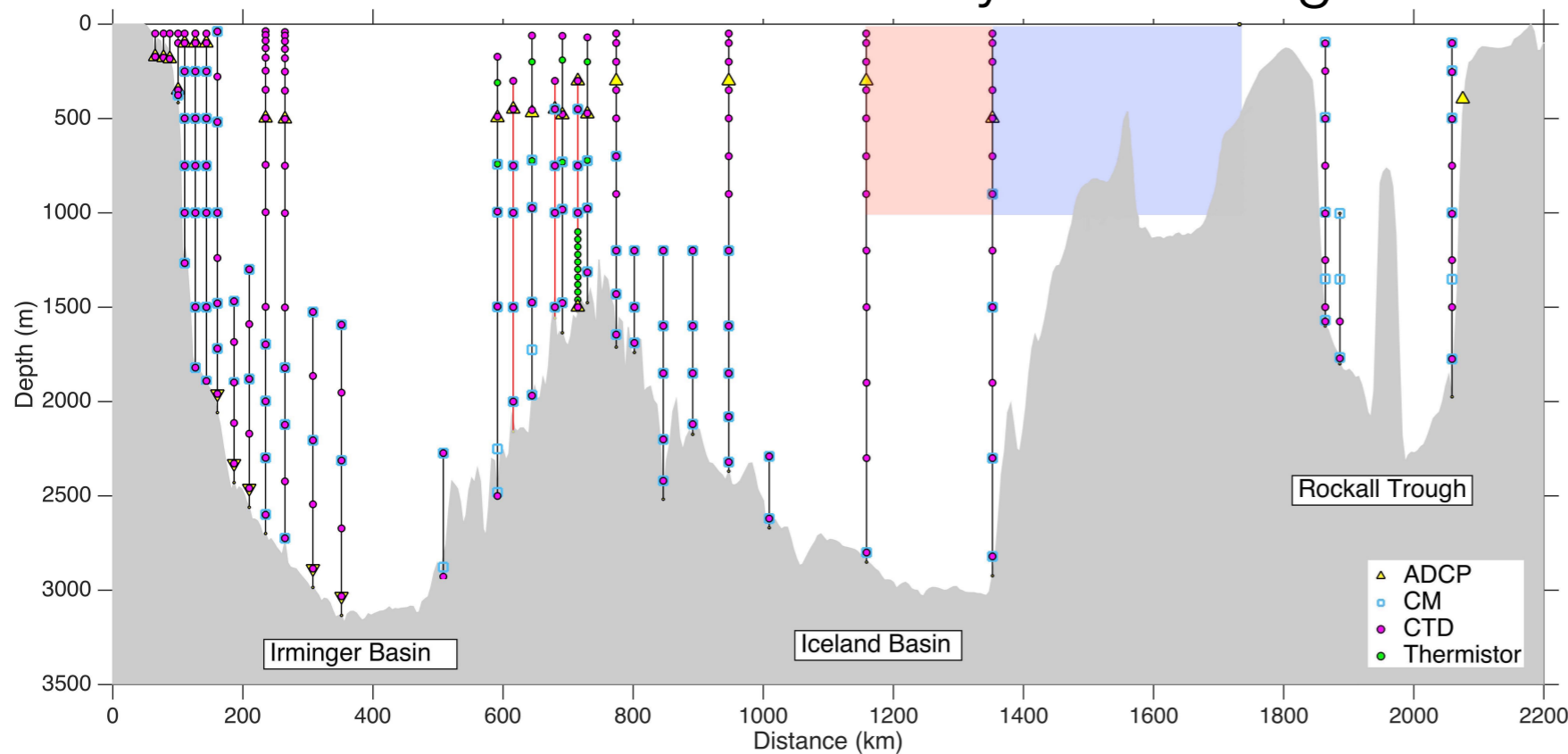


# OSNAP: monitoring AMOC at ~55–60°N

## “Overturning in the Subpolar North Atlantic Program”



### OSNAP East array of moorings



# 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
<b>Total shallower than 1,000 m</b>	<b>+22.9</b>	<b>+18.7</b>	<b>+19.4</b>	<b>+16.1</b>	<b>+14.8</b>
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)

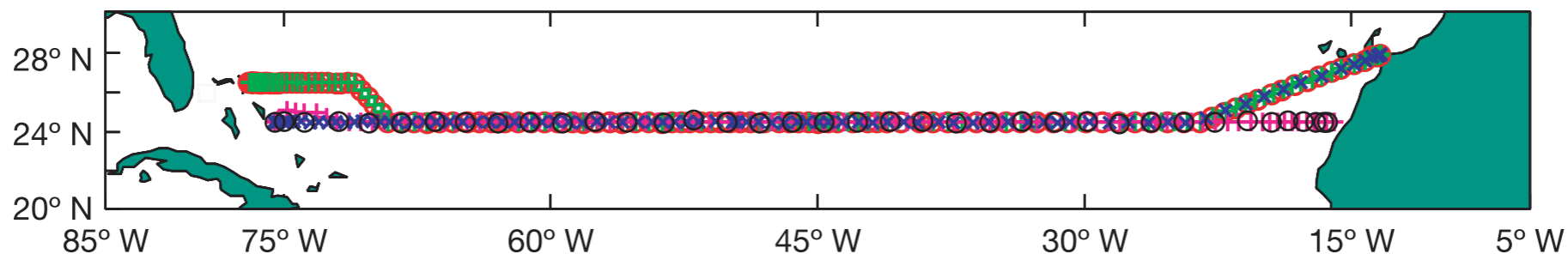


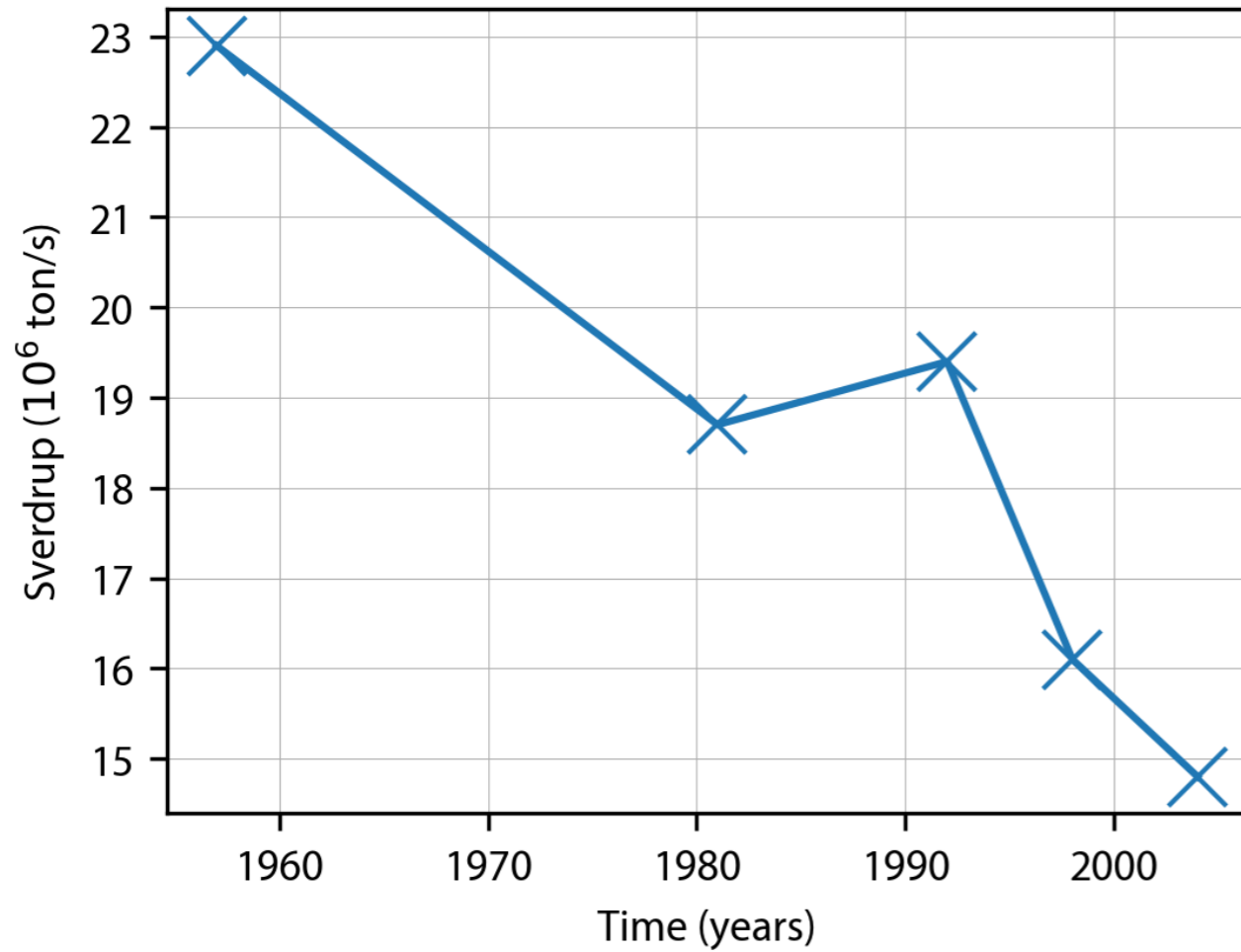
Figure 1 | Station positions for transatlantic hydrographic sections taken in 1957, 1981, 1992, 1998 and 2004. The 1957 and 1992 sections each went zonally along 24.58 N from the African coast to the Bahama Islands. Because of diplomatic clearance issues, the 1981, 1998 and 2004 sections angled southwestward from the African coast at about 28° N to join the 24.58 N section at about 73° W. The 1998 and 2004 sections angled northwestward at about 73° W to finish the section along 26.58 N.



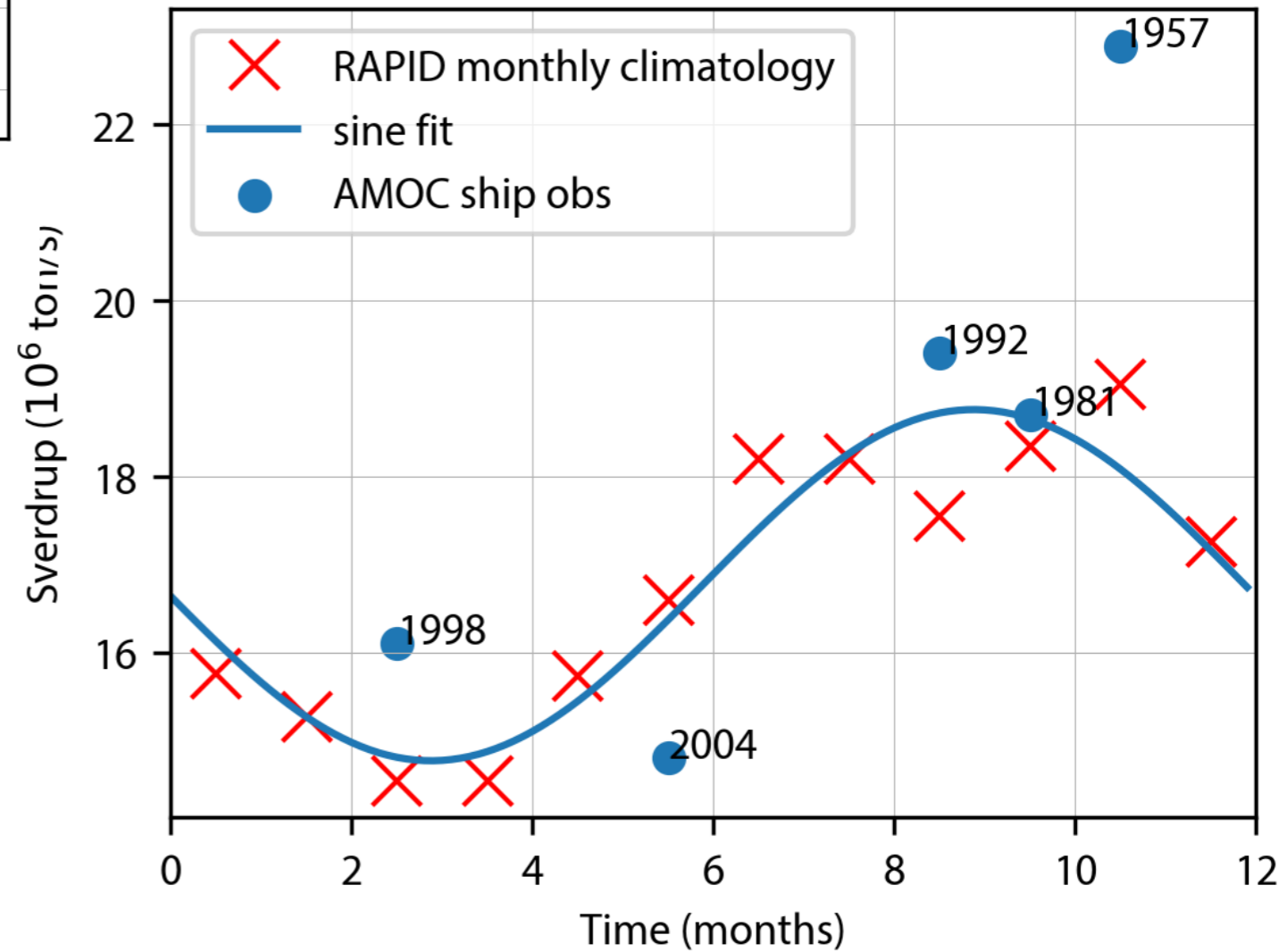
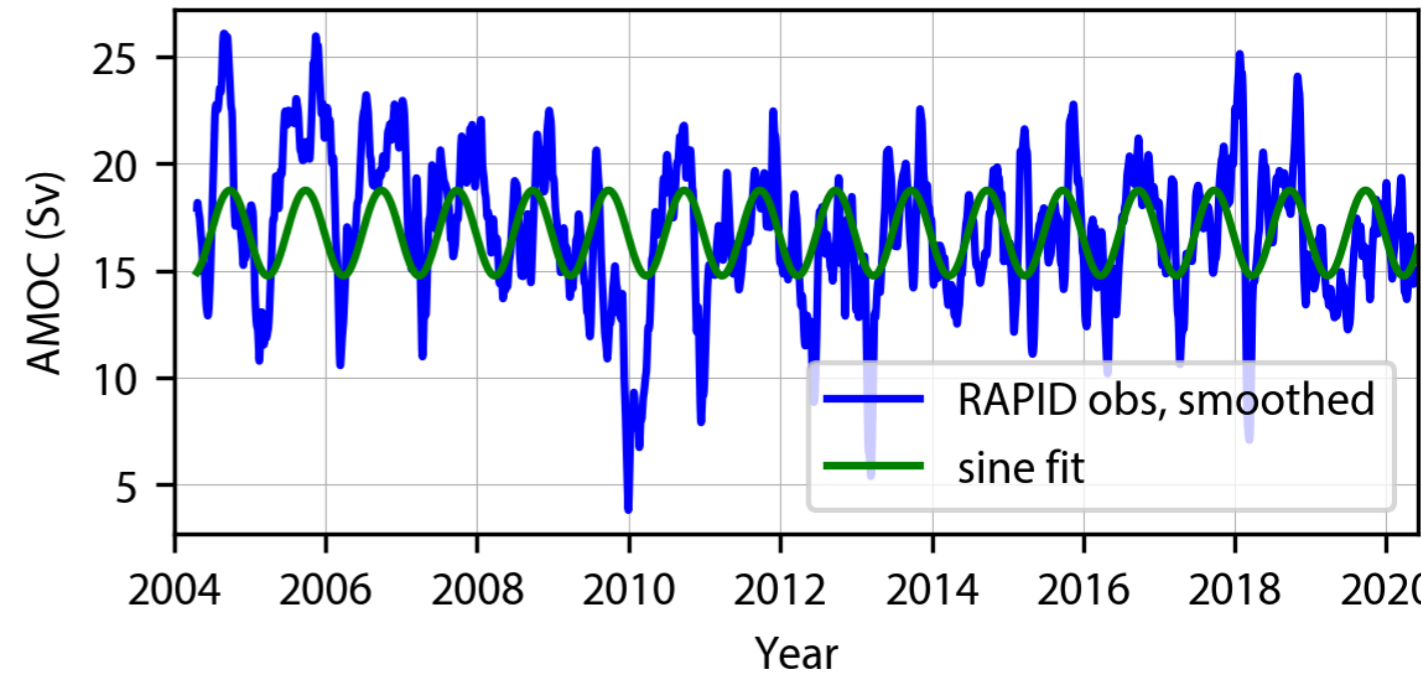
# Workshop 1: AMOC observations

# Workshop 1: AMOC observations

## Ship observations



## RAPID AMOC time series and sine fit to the data

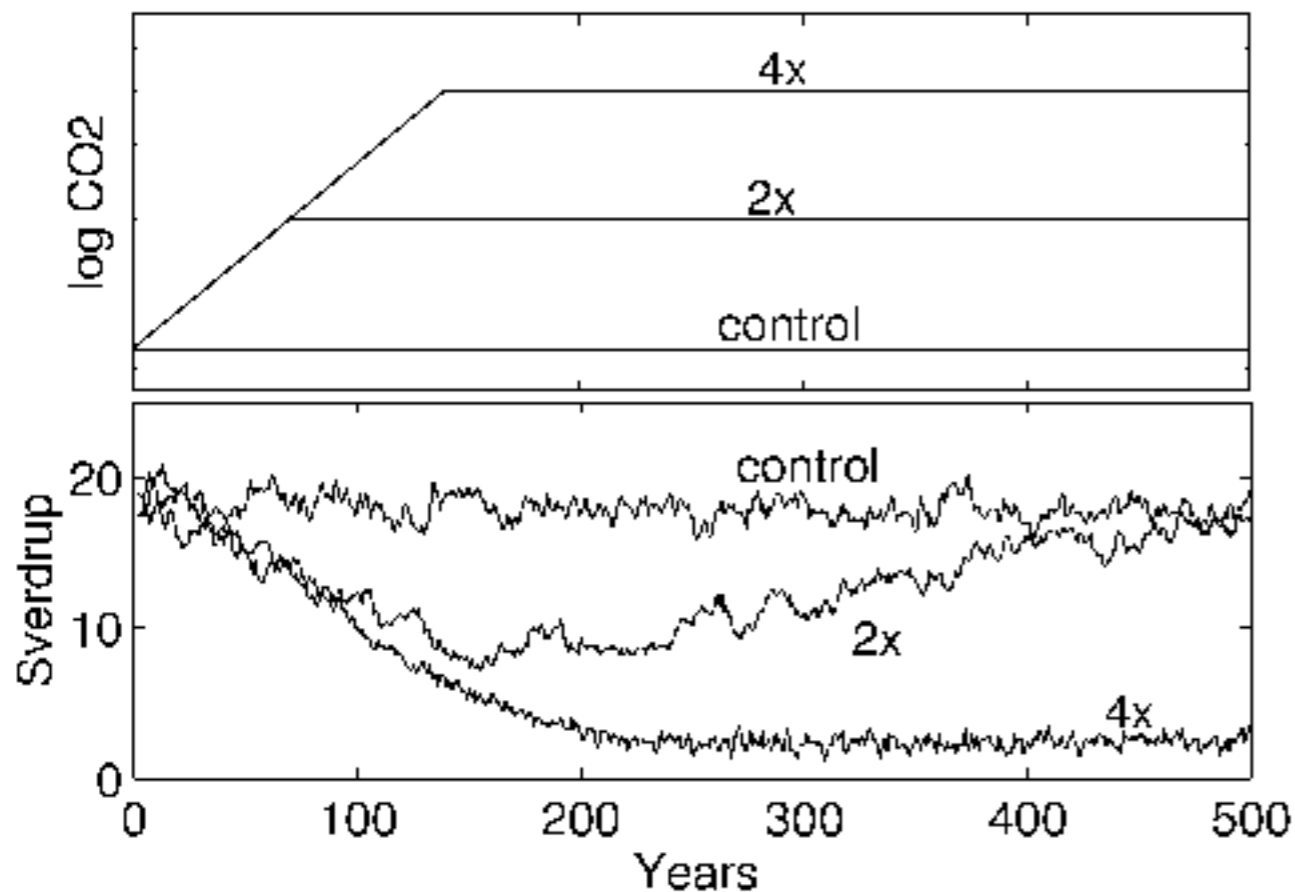


Projections:

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

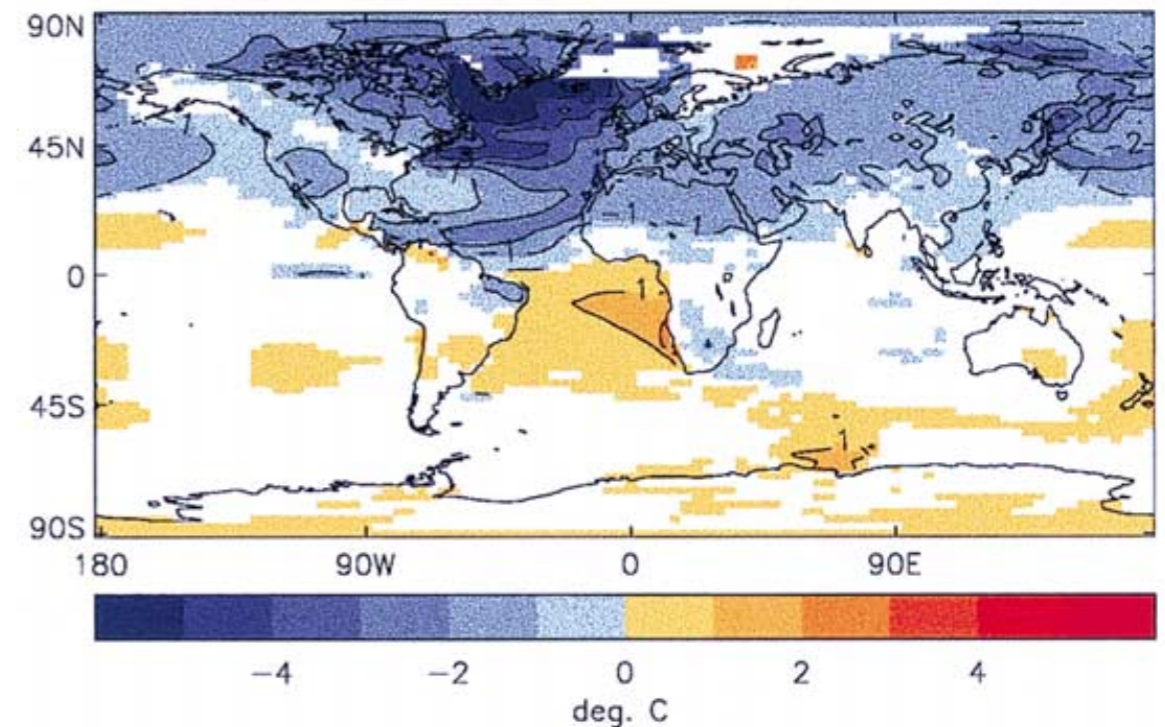
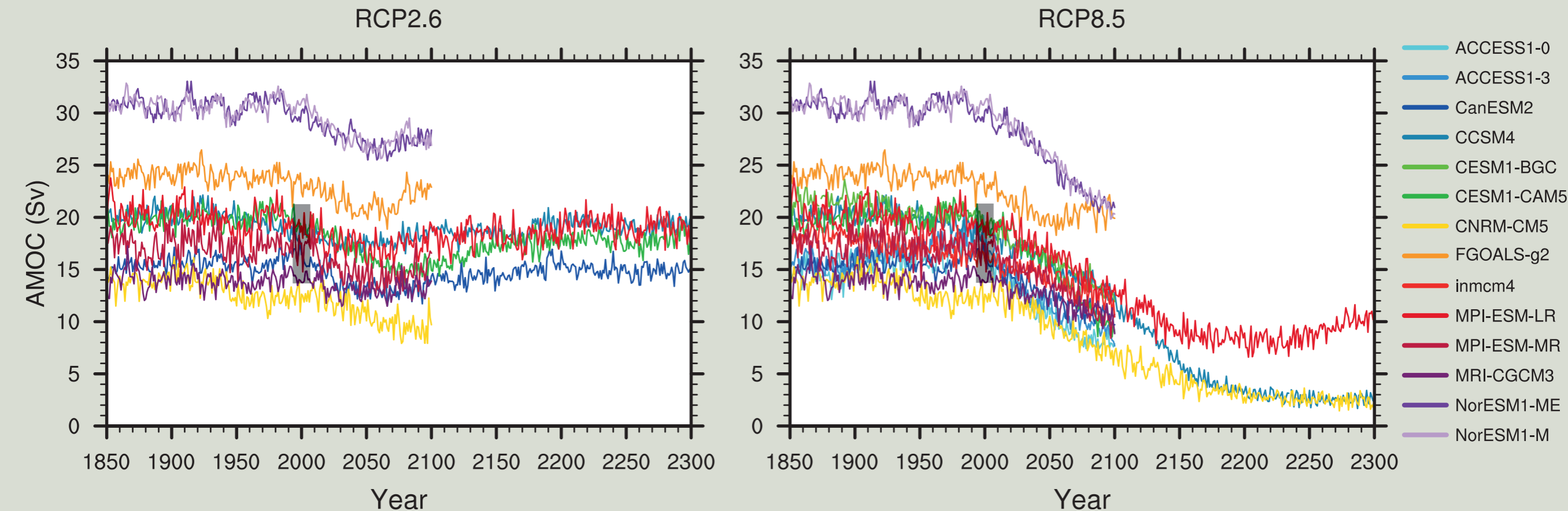


Figure 3. Change in surface air temperature during years 20–30 after the collapse of the THC. Areas where the anomaly is not significant have been masked.



# 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

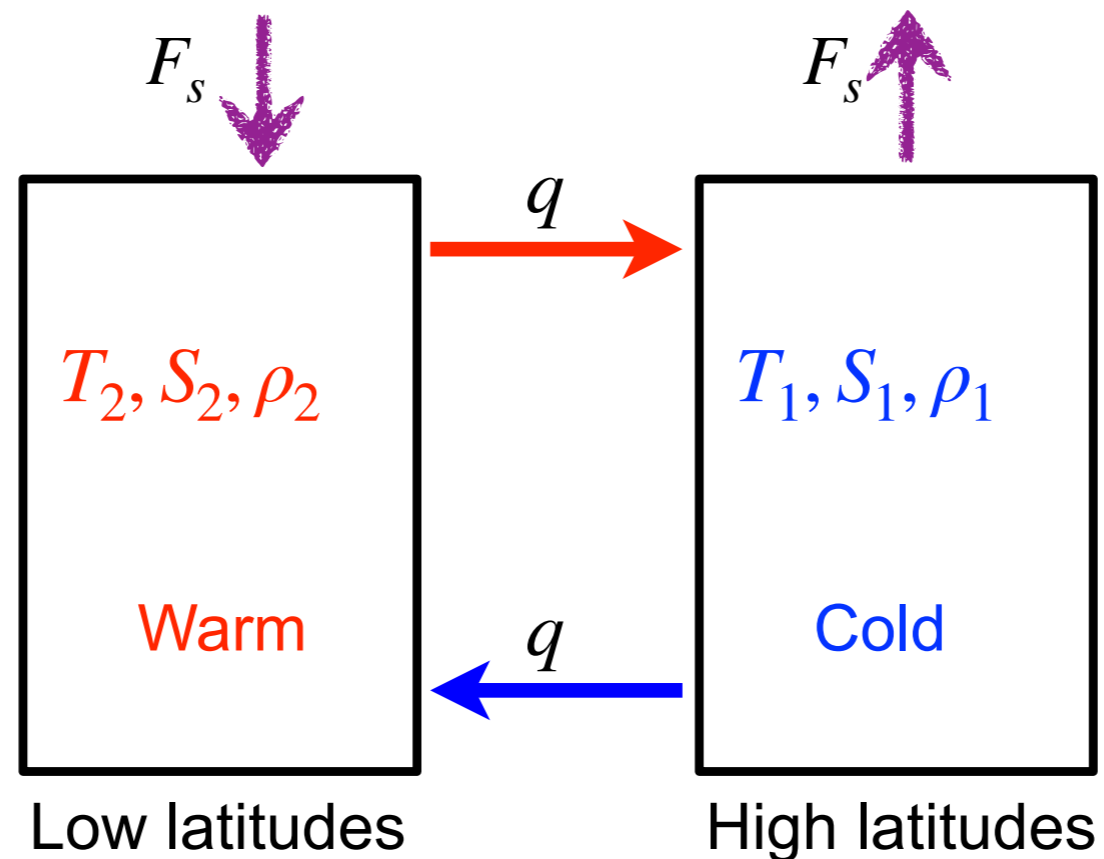
- “There is no observational evidence of a trend in the Atlantic Meridional Overturning Circulation (AMOC), based on the decade-long record of the complete AMOC and longer records of individual AMOC components. {3.6}”
- “It is very likely that the Atlantic Meridional Overturning Circulation (AMOC) will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

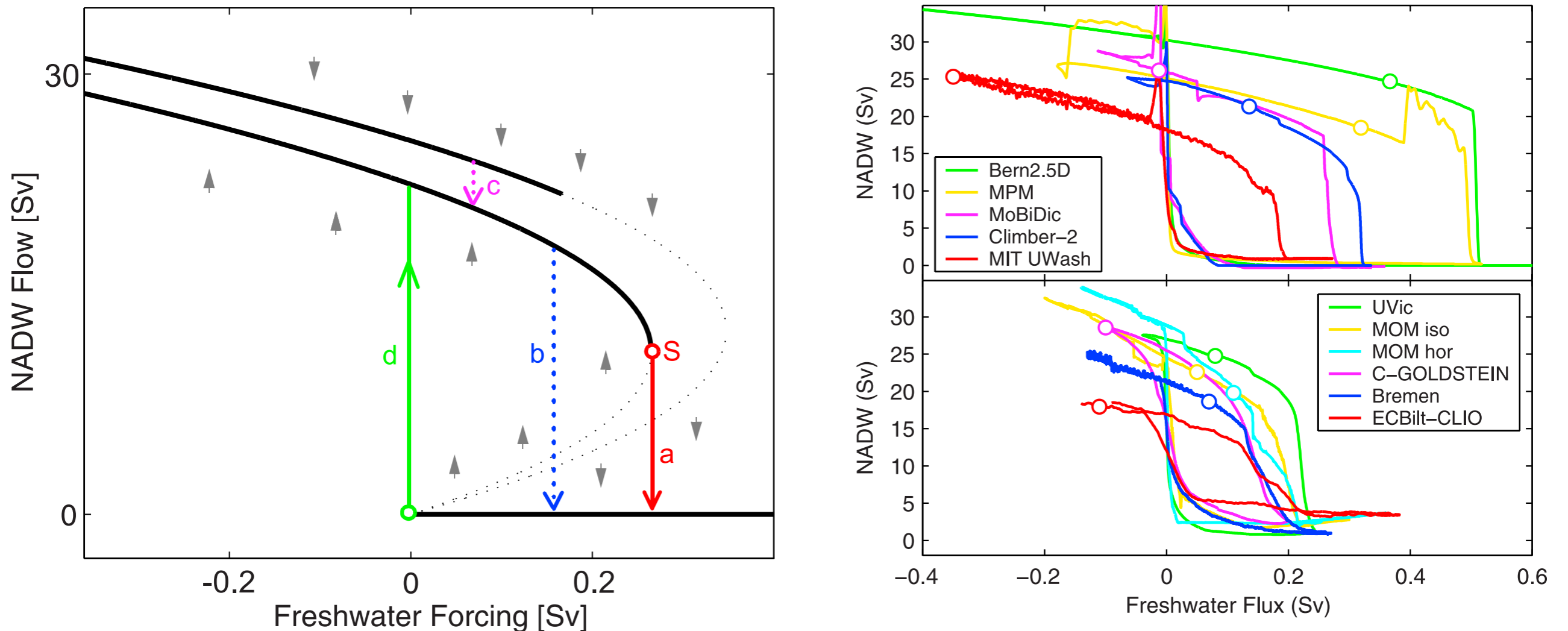


Figure 2. Hysteresis curves found in the model inter-comparison. The bottom panel shows coupled models with 3-D global ocean models, the top panel those with simplified ocean models (zonally averaged or, in case of the MIT\_UWash model, rectangular basins). Curves were slightly smoothed to remove the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

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

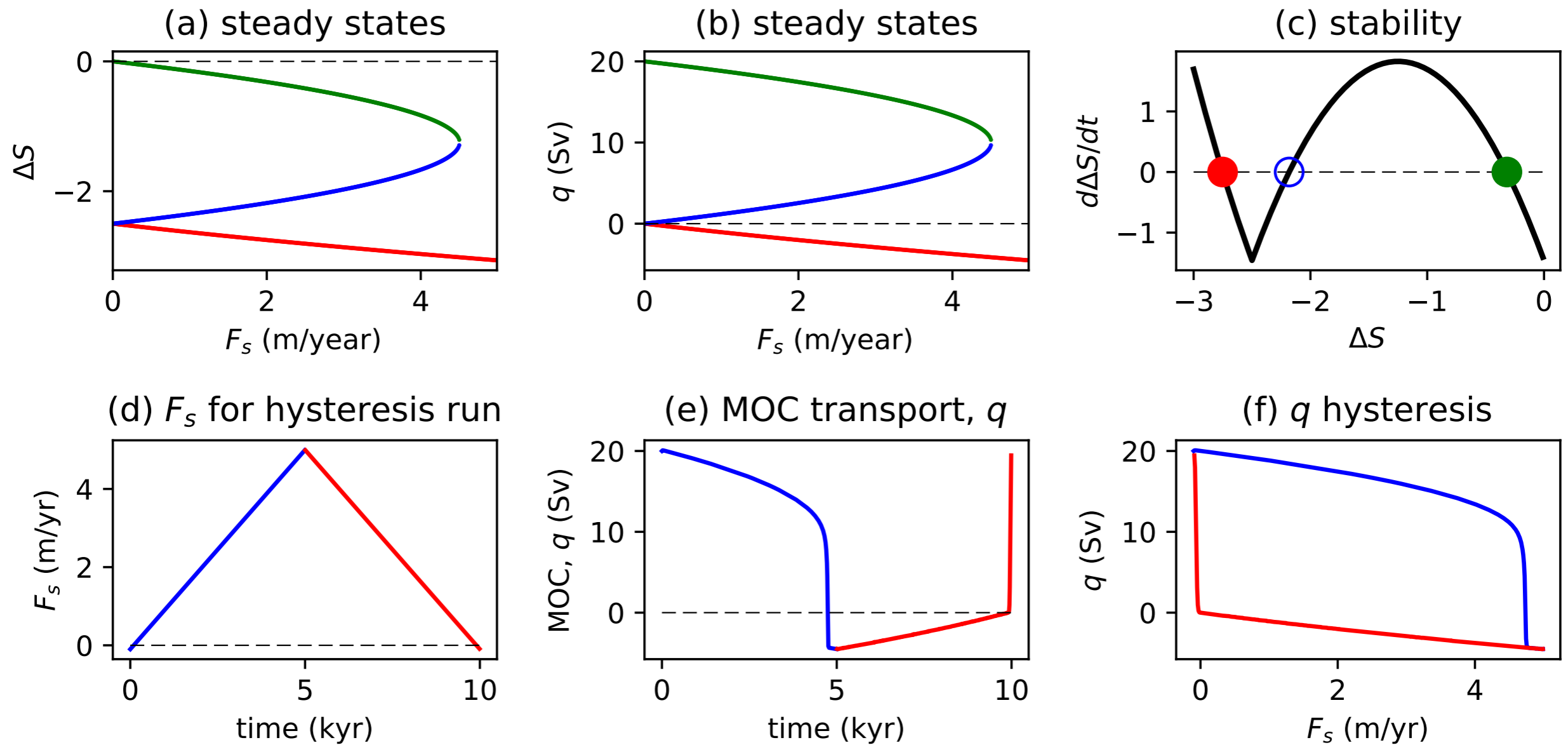
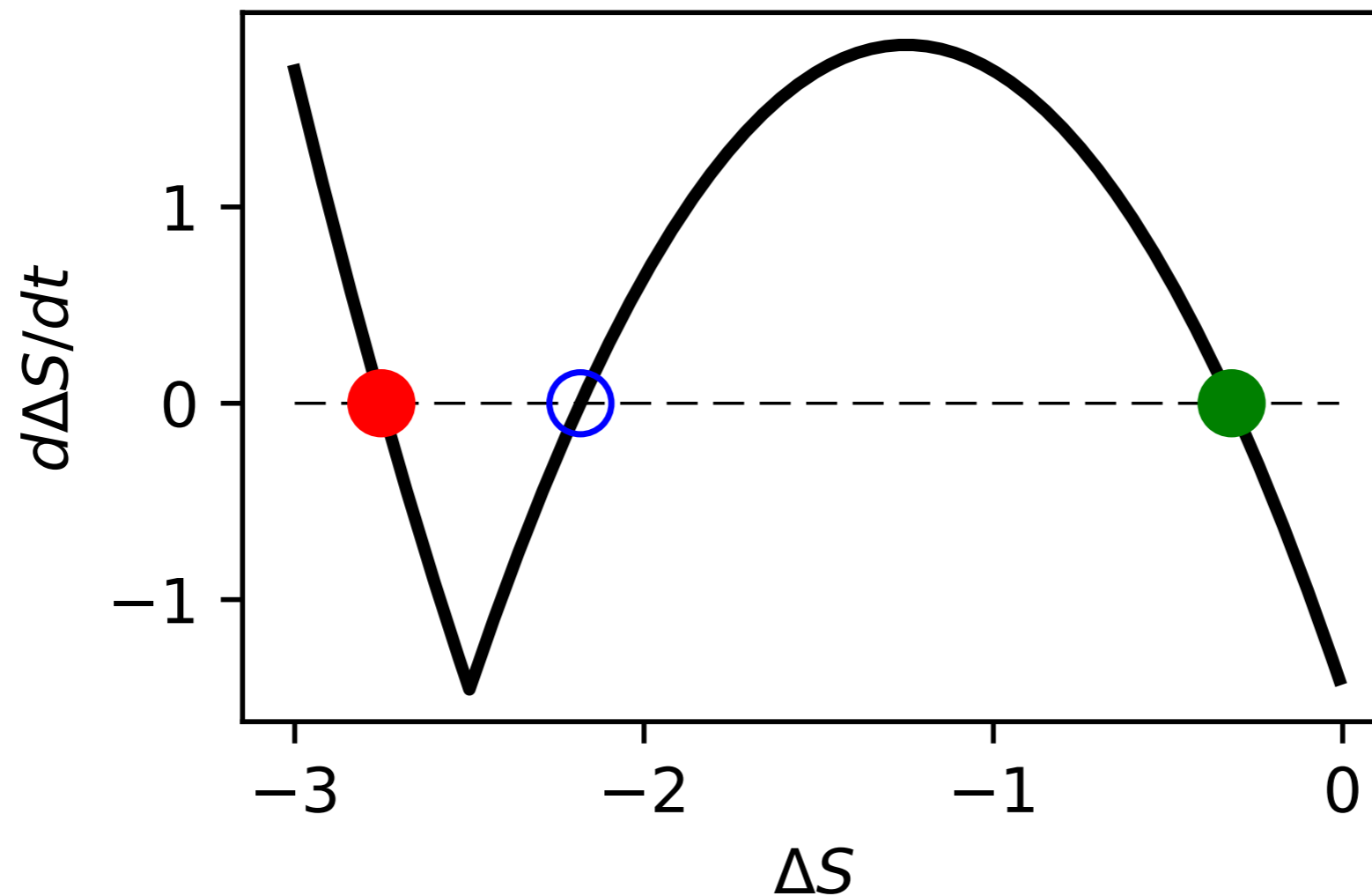


Figure 6.5: Solution of the 2-box model: (a, b) Steady states of salinity difference and MOC as function of fresh water forcing. (c) Stability analysis. (d) Fresh water forcing for hysteresis run. (e, f) Hysteresis results.

# 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)

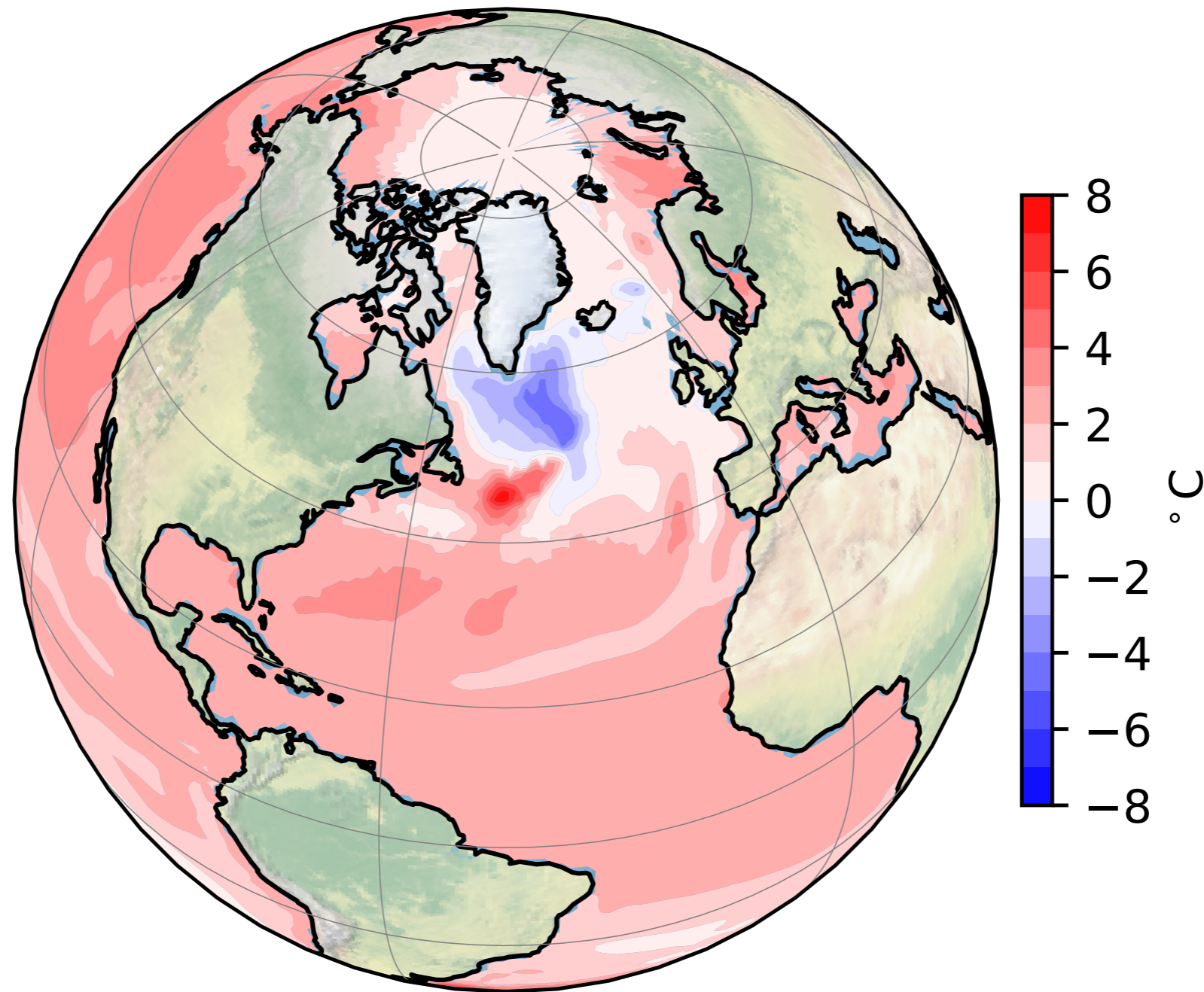


Figure 6.6: SST at 2100 minus that at 2006 in an RCP8.5 scenario.

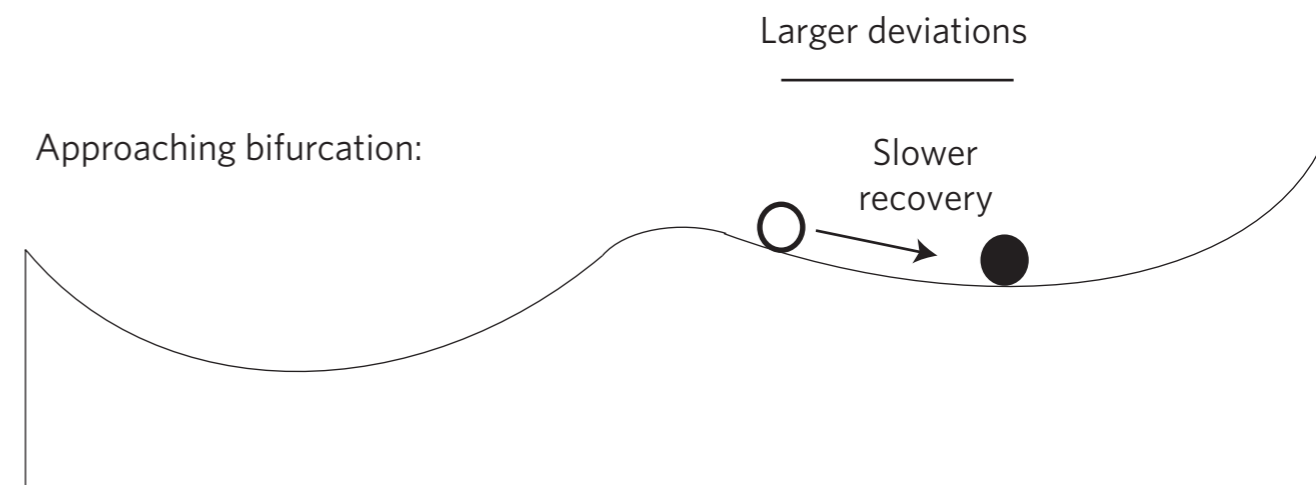
# Early warning signs for an approaching tipping point

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.

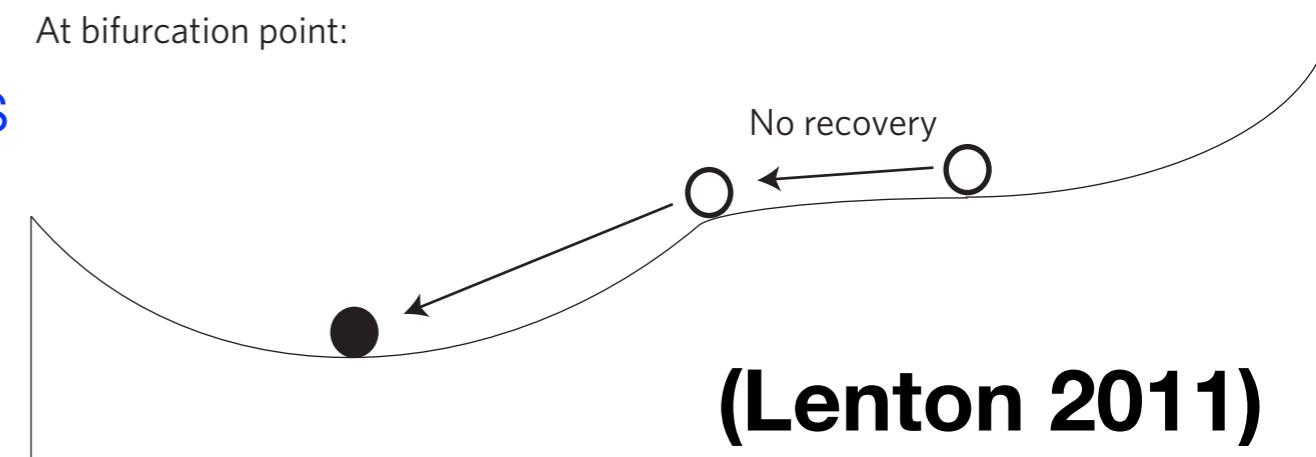
Far from bifurcation:



Approaching bifurcation:



At bifurcation point:



# 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

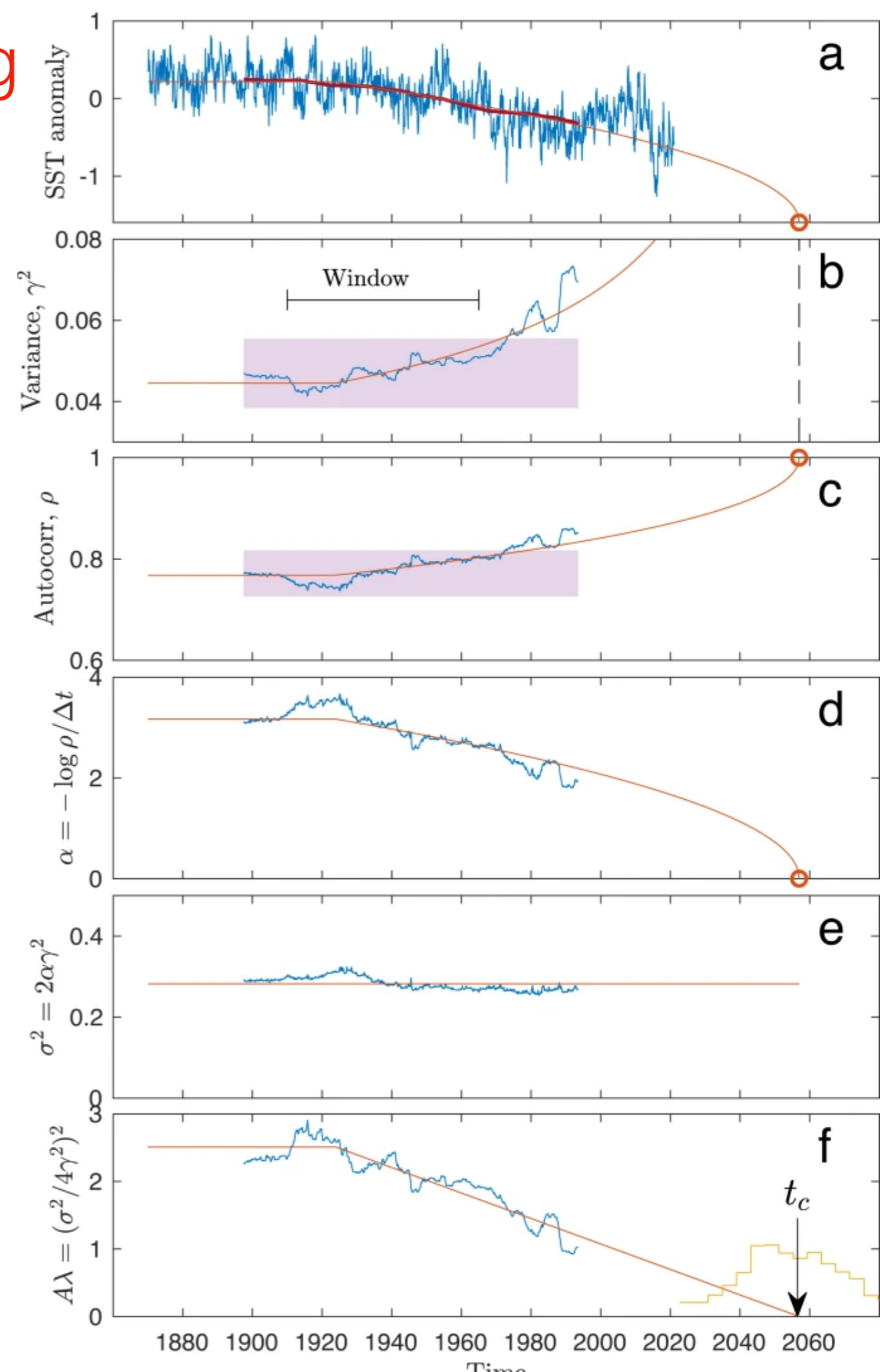
<https://www.nytimes.com/2023/07/25/climate/atlantic-ocean-tipping-point.html>

## **Warning of a forthcoming collapse of the Atlantic meridional overturning circulation**

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

# 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  $\alpha$  (**d**) and  $\sigma^2$  (**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.





# Other potential climate tipping points

- Arctic sea ice

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- Arctic sea ice
- AMOC

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- Arctic sea ice
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- Sahara's vegetation

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# Other potential climate tipping points

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- AMOC
- Sahara's vegetation
- **Antarctica's "doomsday" Thwaites Glacier**
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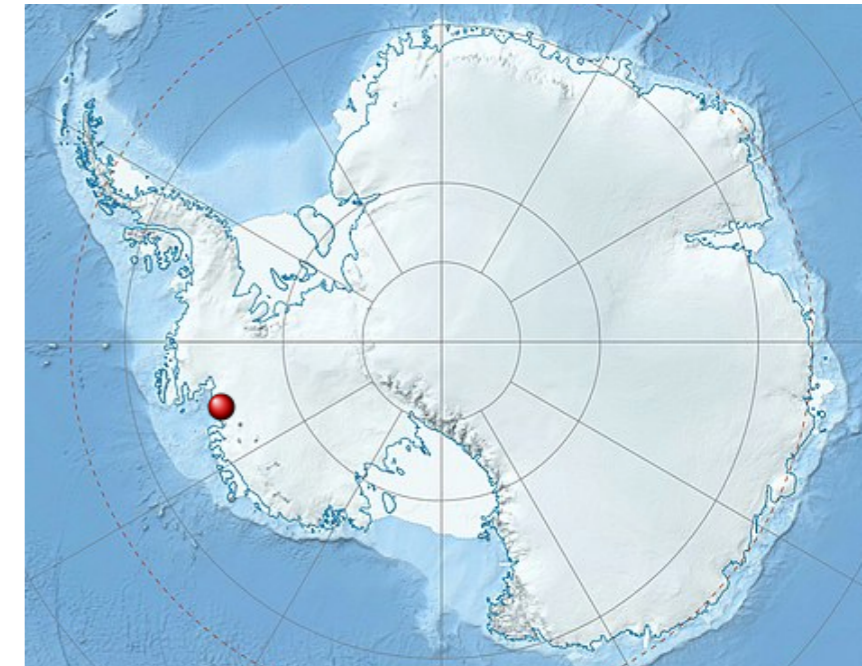
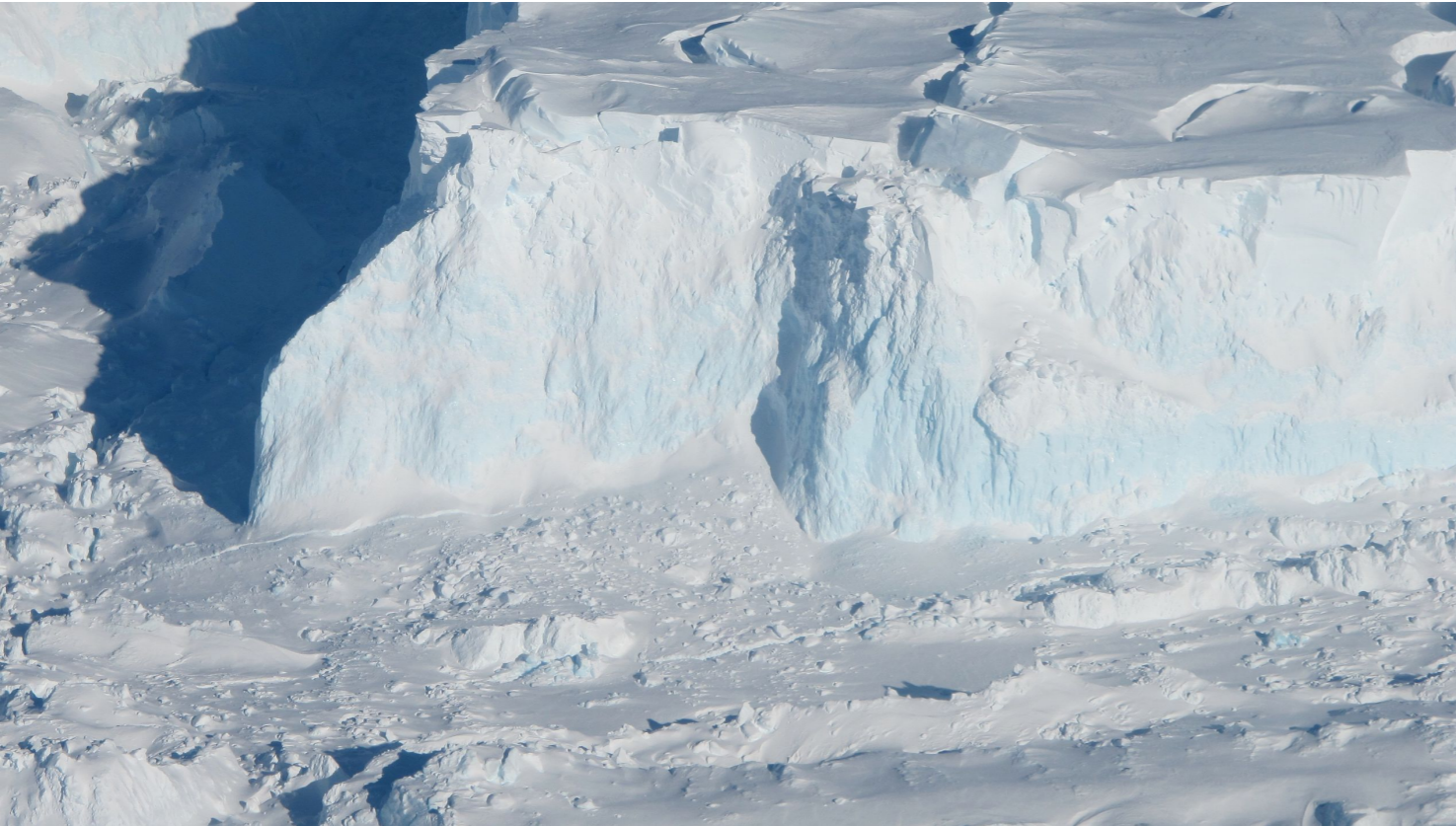
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# Other potential climate tipping points

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- Amazon Forest



# Antarctica's "doomsday" Thwaites Glacier

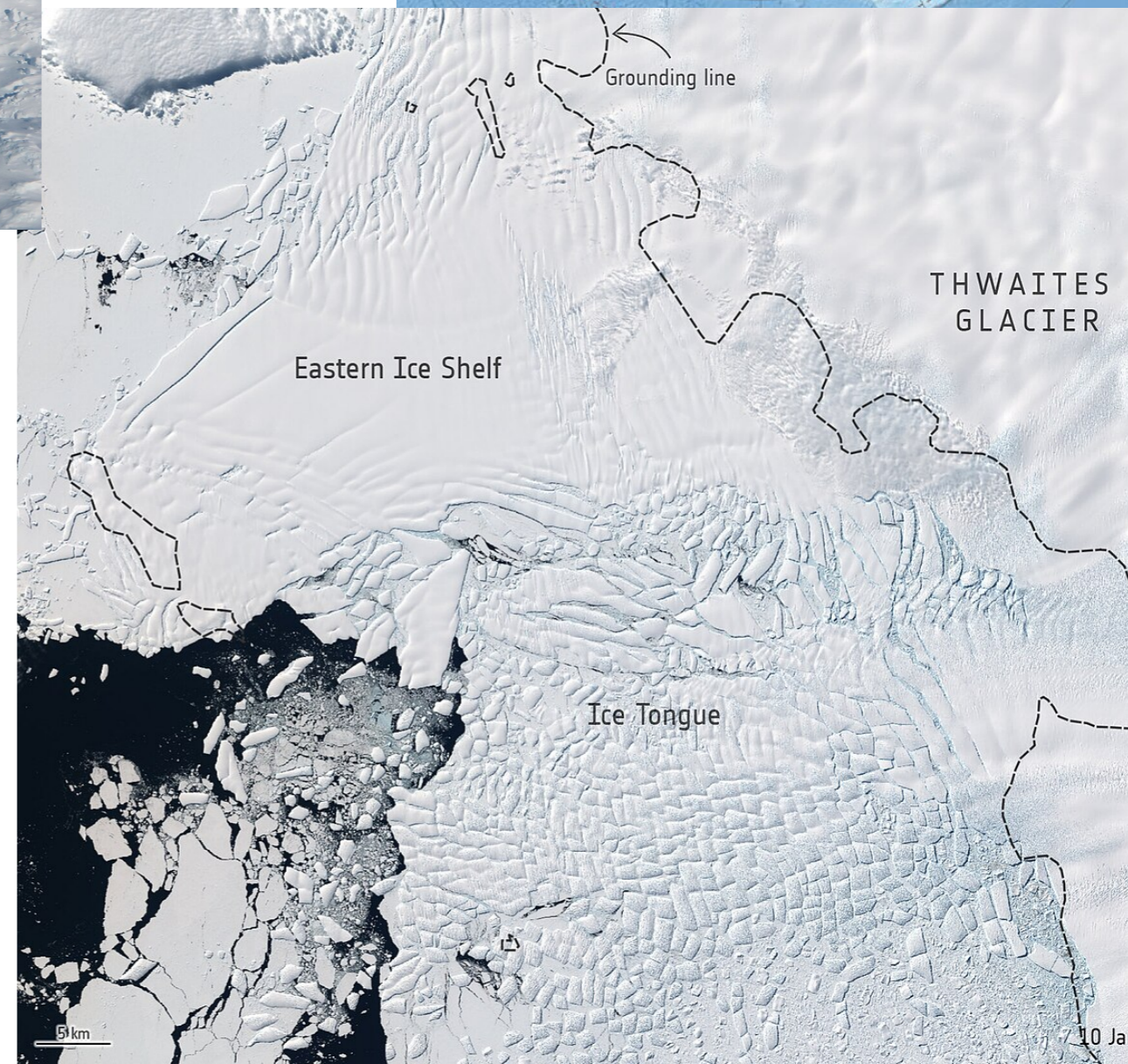


The ice shelf (floating ice, flowing from land, 500–1000 m thick)

[wikipedia.org/wiki/Thwaites\\_Glacier](https://wikipedia.org/wiki/Thwaites_Glacier)

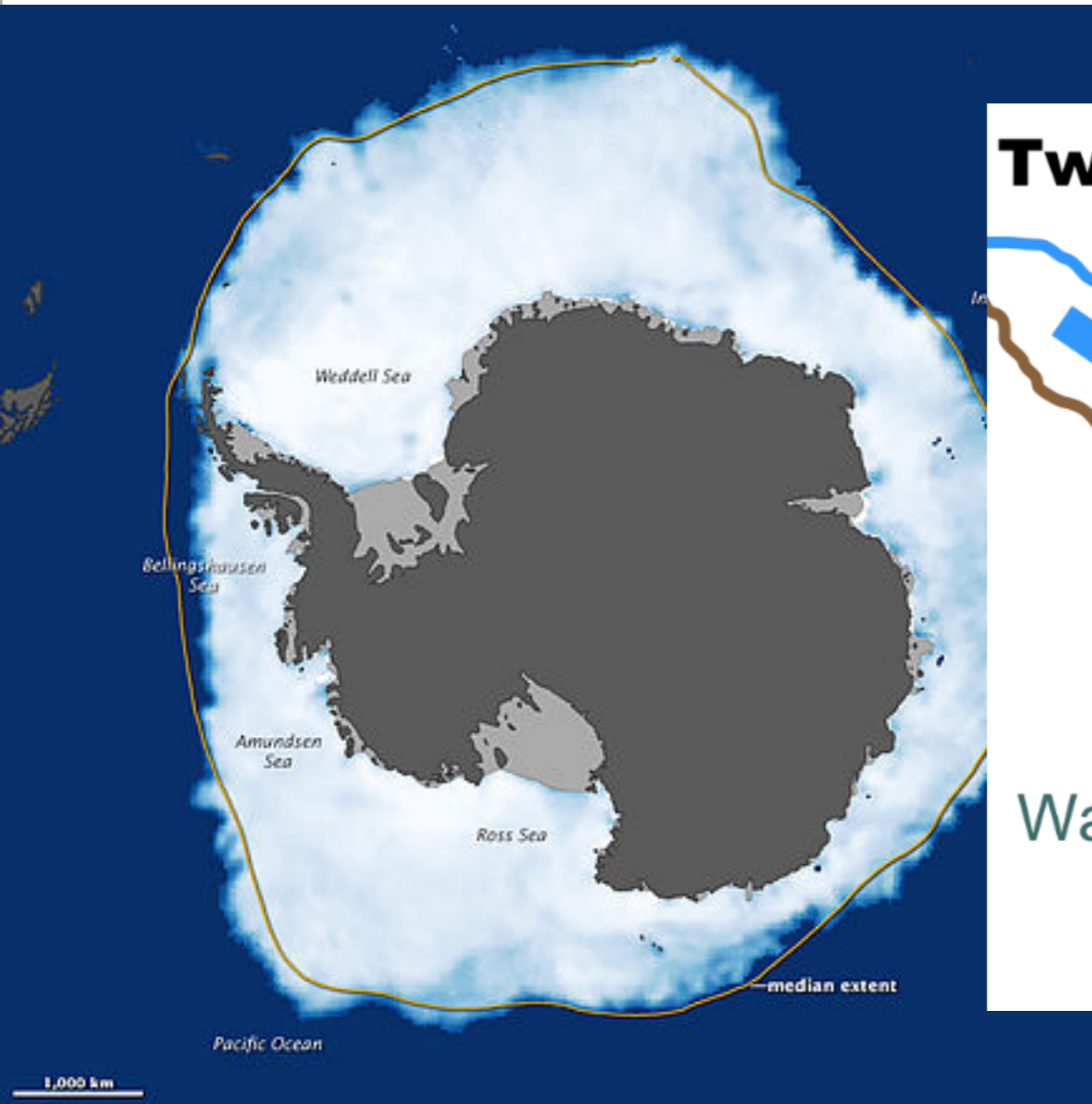
Thwaites glacier = 65 cm sea level rise

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



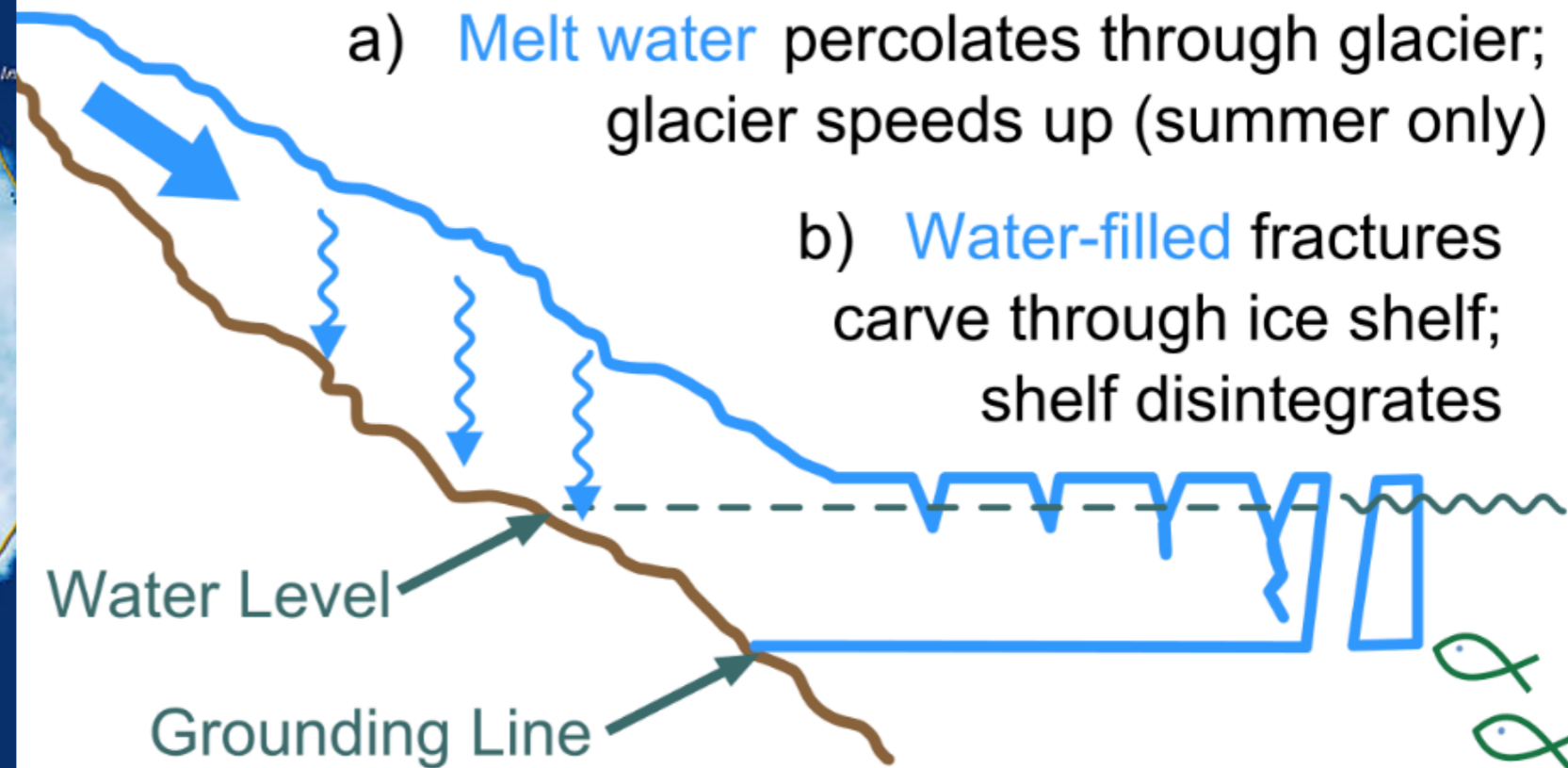


# Antarctica's "doomsday" Thwaites Glacier



ice shelves (gray) and sea ice

## Two effects of warmer temperatures



[wikipedia.org/wiki/Ice\\_shelf](https://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...



glacier;  
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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

[https://www.earth.org/wiki/Ice\\_shelf](https://www.earth.org/wiki/Ice_shelf)

ice she

Thwaites ... 50 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.



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<sub>2</sub> increase.

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# Summary

- A climate tipping point is an abrupt & possibly large change in response to a gradual CO<sub>2</sub> increase.
- This may occur when a climate system (sea ice, AMOC, Sahara, Thwaites) has two equilibria for a given CO<sub>2</sub>.
- As CO<sub>2</sub> rises, if one of the equilibria cannot be sustained anymore, the system must jump to the other.



# Summary

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- 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