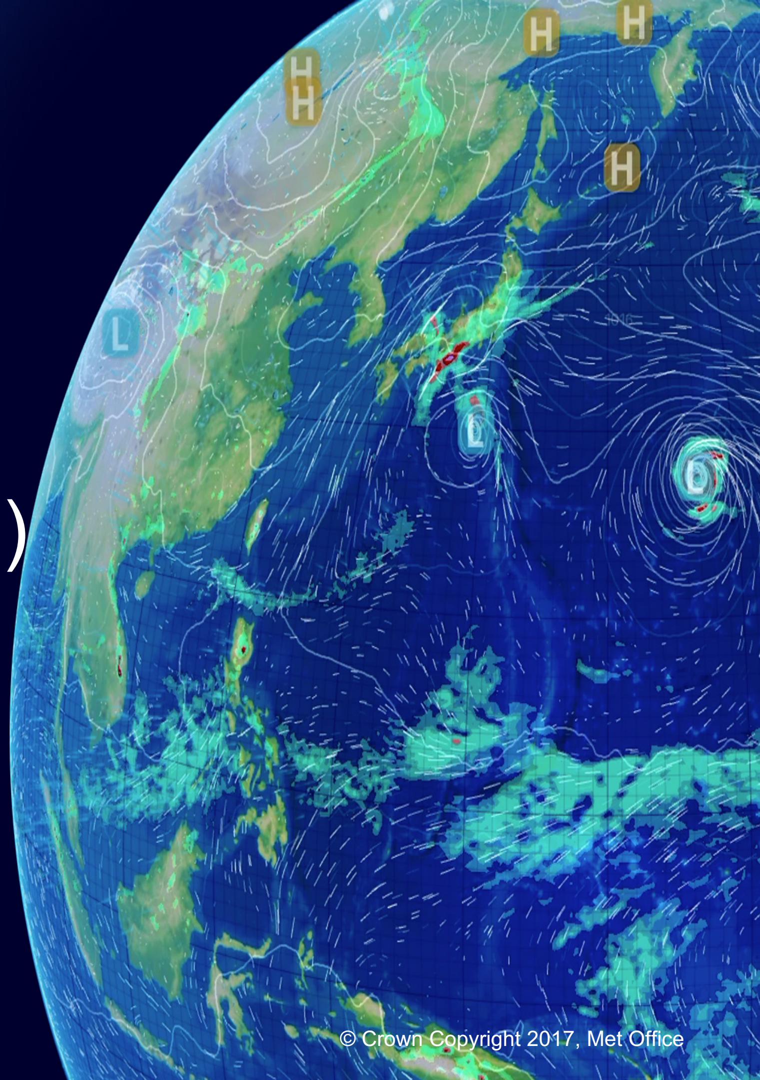
The Atlantic Meridional Overturning Circulation (AMOC)

October 2020

L Jackson



Met Office Hadley Centre

Contents

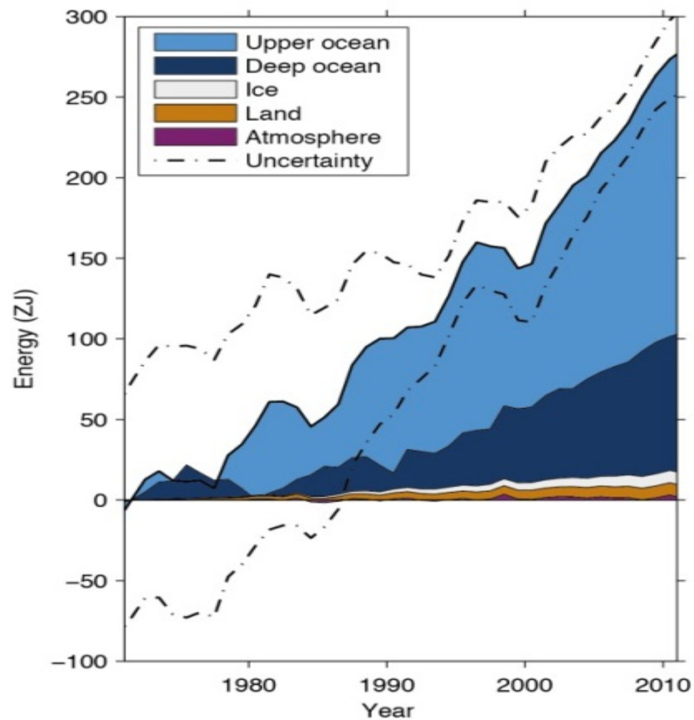
Why is the ocean important for climate change?

Water has high heat capacity, so the ocean takes up most heat

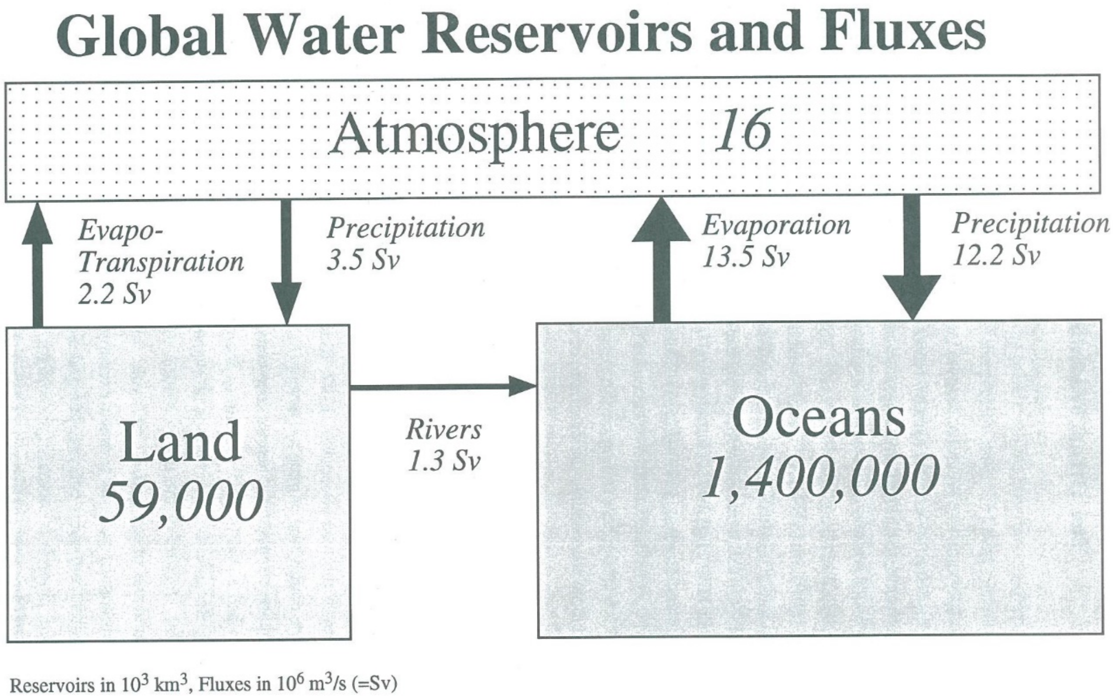
Heat change =

heat capacity x temperature change

IPCC 2013

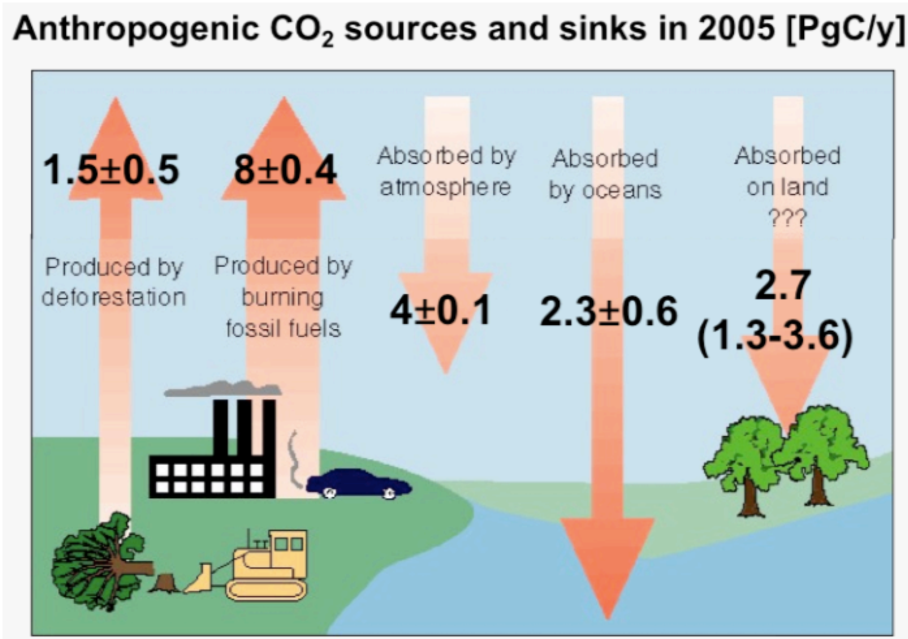


Oceans are the store of most fresh water on the planet



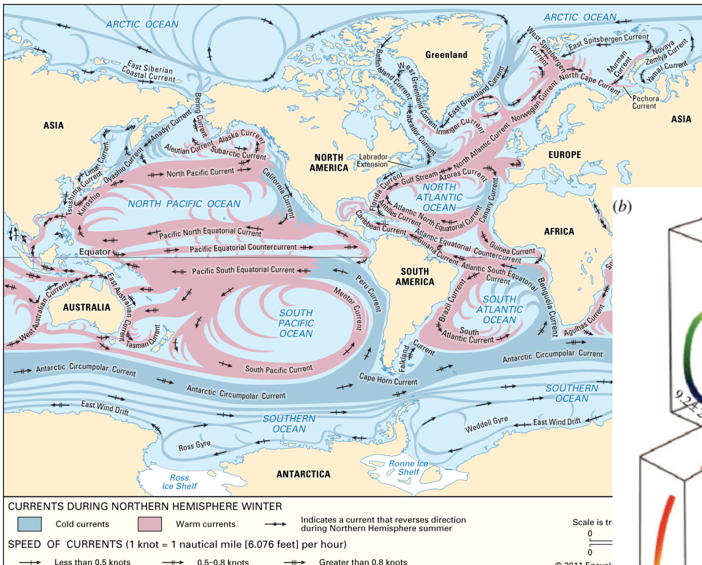
Estimates of the global water storage in oceanic, terrestrial and atmospheric reservoirs and the fluxes among them, using data of *Baumgartner and Reichel (1975)*

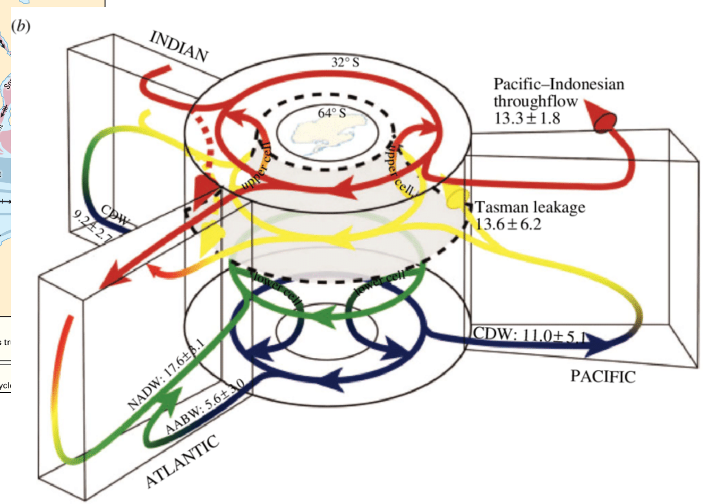
Oceans take up CO_2 and store it in the surface and deep ocean.



CO2 dissolves in the ocean making it more acidic.
Also taken up by plankton, eaten by fish etc and eventually falls to ocean floor

Oceans move properties around: at the surface and through upwelling/downwelling





What is the (Atlantic) Meridional Overturning Circulation?

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What is the Thermohaline Circulation (THC)?

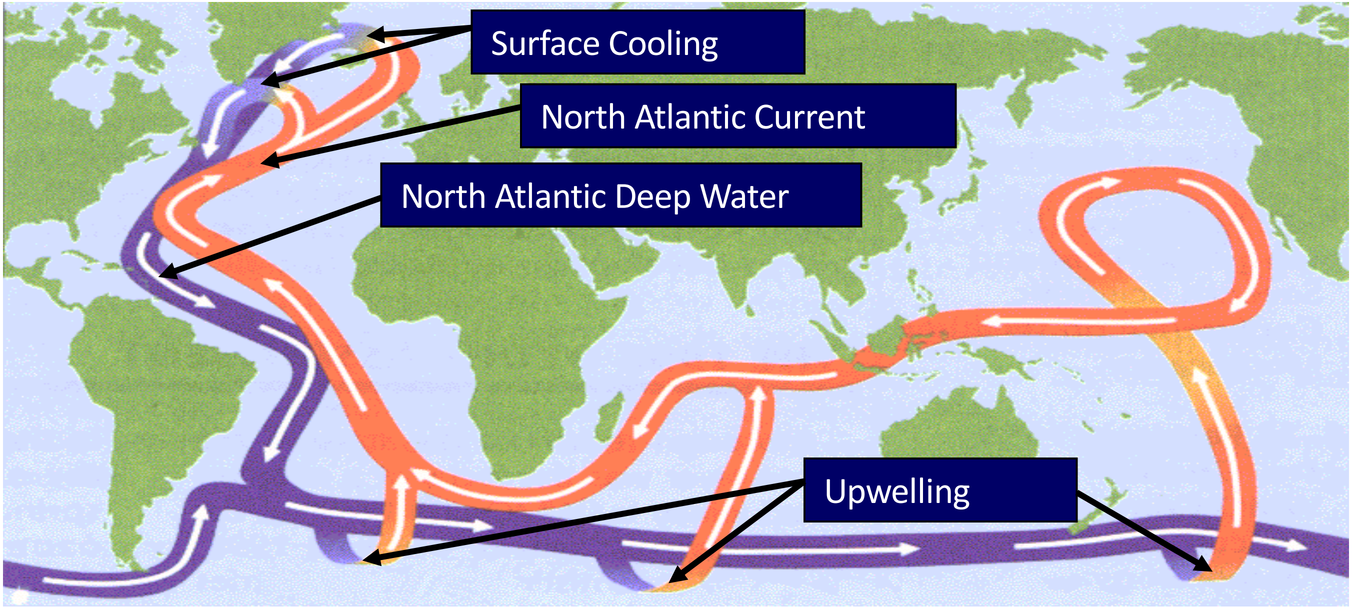
It is the circulation which is driven by **density differences** (as opposed to wind and tides). Because the ocean density is a function of **temperature** (thermo) and **salinity** (haline), this circulation is referred to as the themohaline.

These density differences are primarily caused by surface fluxes of heat and freshwater and subsequent interior mixing. The oceanic density distribution is itself affected by the currents and associated mixing. Thermohaline and wind driven currents interact with each other, and therefore can’t be completely separated.

THC is not observable!

The ‘global conveyor belt’

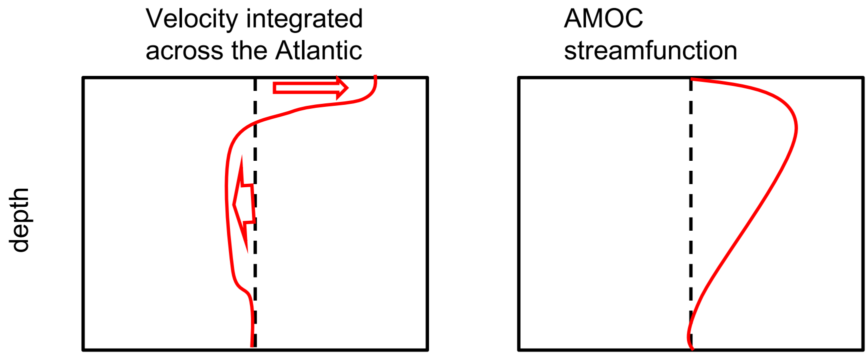
or ‘Thermohaline Circulation’ THC or ‘Meridional Overturning Circulation’ MOC



See https://www.youtube.com/watch?v=eu7ZDi2wHqY

What is the Meridional Overturning Circulation (MOC)?

It is related to the THC but is measurable. MOC is the projection of the circulation into the depth and latitude plane.



The AMOC strength is the integral of the meridional velocity in the upper ocean (which is balanced by the deep return flow).

More generally the AMOC streamfunction is defined as:

$$Q(y,z,t) = \int_{z}^{0}\int_{west}^{east} v(x,y,z',t)\,dx\,dz'$$

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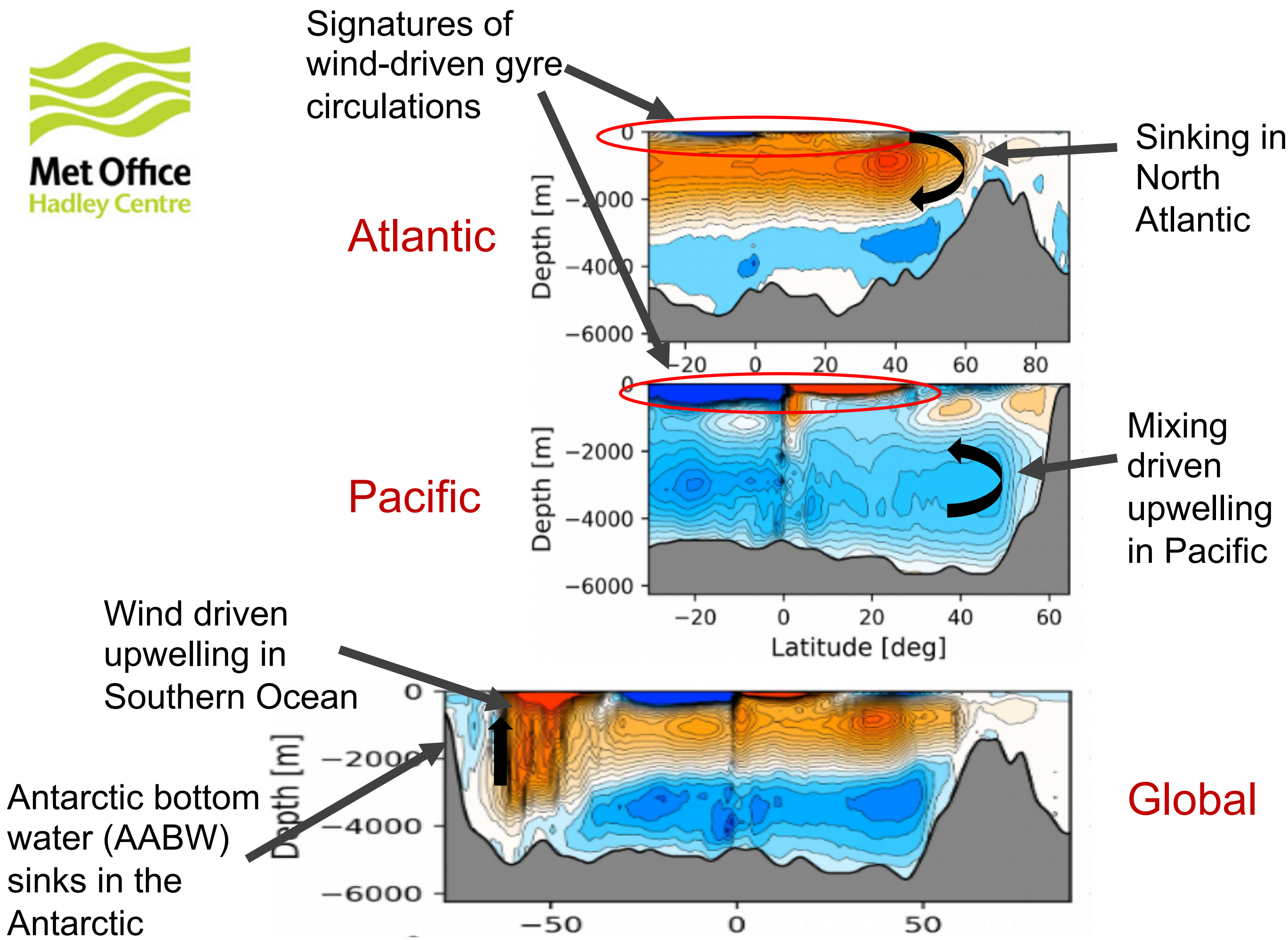
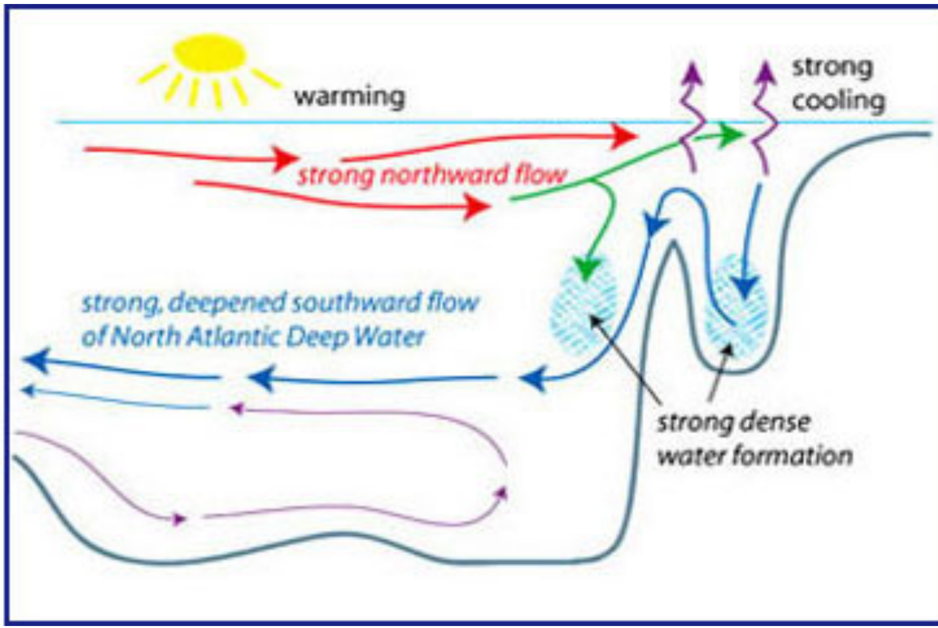


Controlling mechanisms:

1. Density changes at high latitudes

As warm water in the North Atlantic flows north it cools and becomes denser.

This dense water eventually sinks and returns as North Atlantic Deep Water – the lower limb of the MOC.

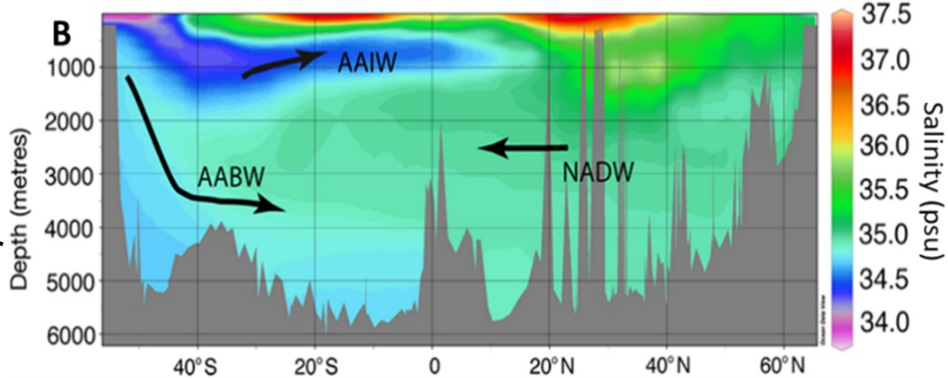


Controlling mechanisms:

2. Mixing

One process that balances the downwards transport is mixing.

NADW mixes with other water masses including some which are lighter, reducing the density of NADW. This upwelling occurs in all basins and gradually returns water to the upper limb.

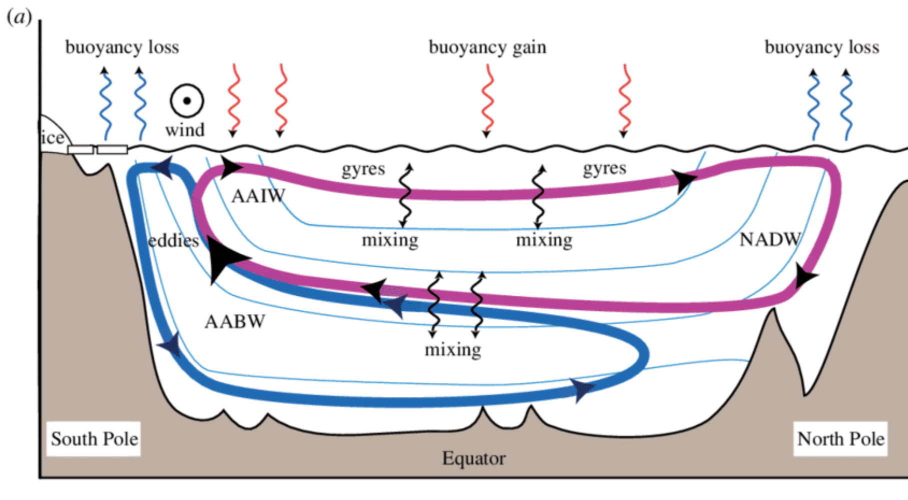


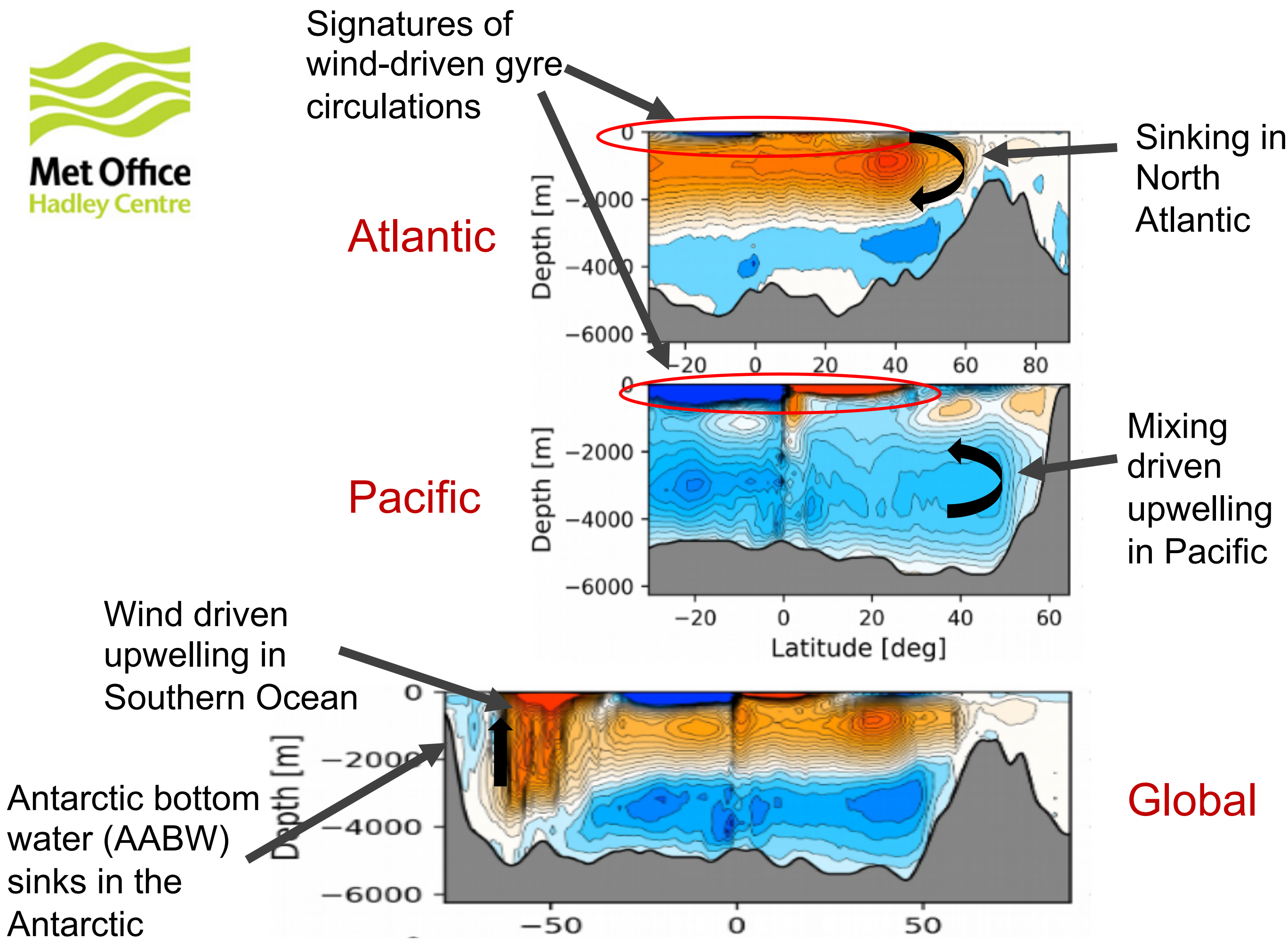
Controlling mechanisms:

3. Wind-driven upwelling

South ocean winds drive upwelling, drawing deep waters to the surface.

These deep waters then warm and become part of the upper limb of the MOC once more.




Signatures of wind-driven gyre circulations
Sinking in North Atlantic
Atlantic
Depth [m]
0
−2000
−4000
−6000
−20
0
20
40
60
80
Pacific
Mixing driven upwelling in Pacific
Latitude [deg]
Wind driven upwelling in Southern Ocean
Antarctic bottom water (AABW) sinks in the Antarctic
Global
−50
50

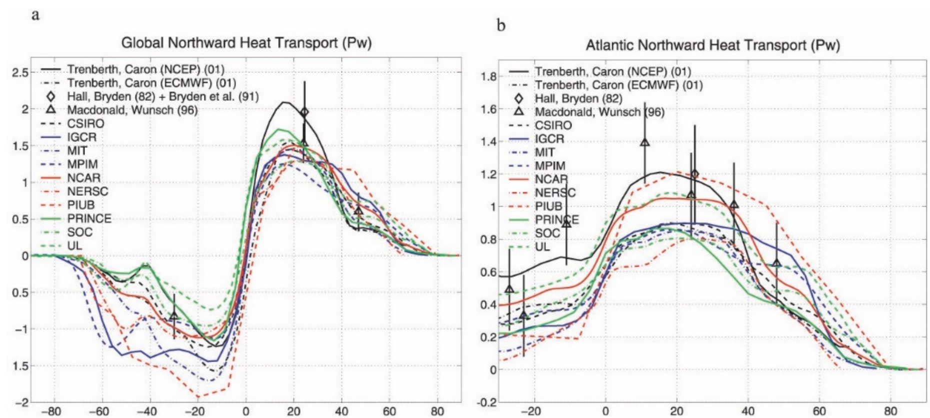
Evidence from observations and ocean/climate models shows that the Atlantic MOC (AMOC) can change on many timescales.

- Seasonal/interannual variability generally related to local wind patterns and not related to THC
- Decadal/multidecadal/centennial variability related to changes in sinking in the North Atlantic
- Decadal-centennial weakening of the AMOC can be forced by increases in greenhouse gases.

Mixing and wind-driven upwelling become more important on longer timescales.

Why is the AMOC important for climate?

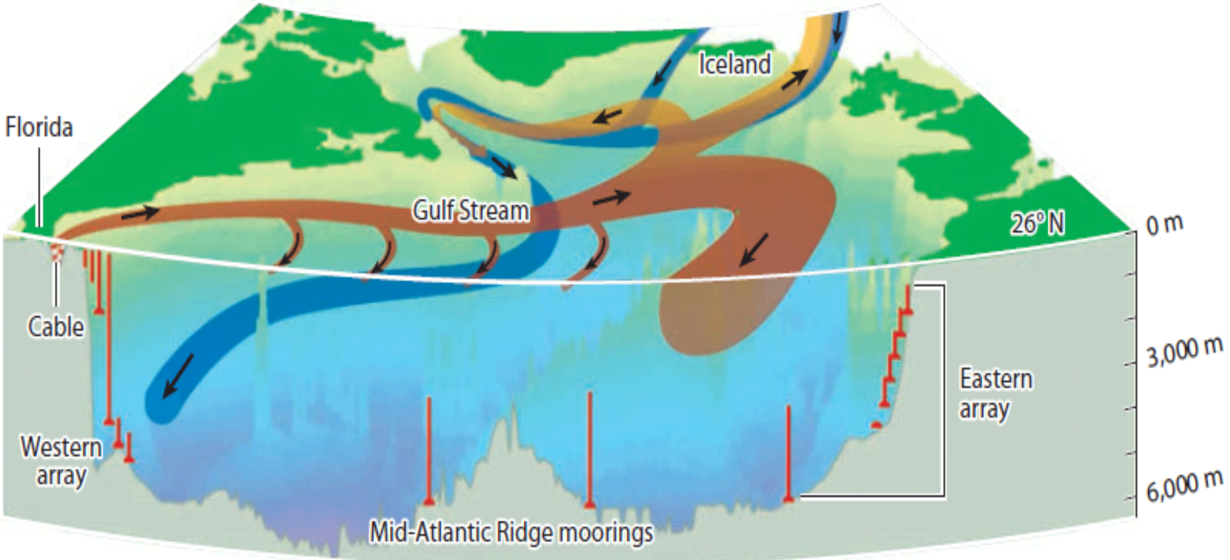
The AMOC transports heat northwards in the Atlantic, resulting in the North Atlantic/Europe being warmer than otherwise.



Weakening of the AMOC weakens the northwards heat transport and cools the North Atlantic. Changes in surface temperatures also then impact on precipitation, weather patterns, winter storms etc.

What do we know from observations?

Monitoring of the AMOC by the RAPID array

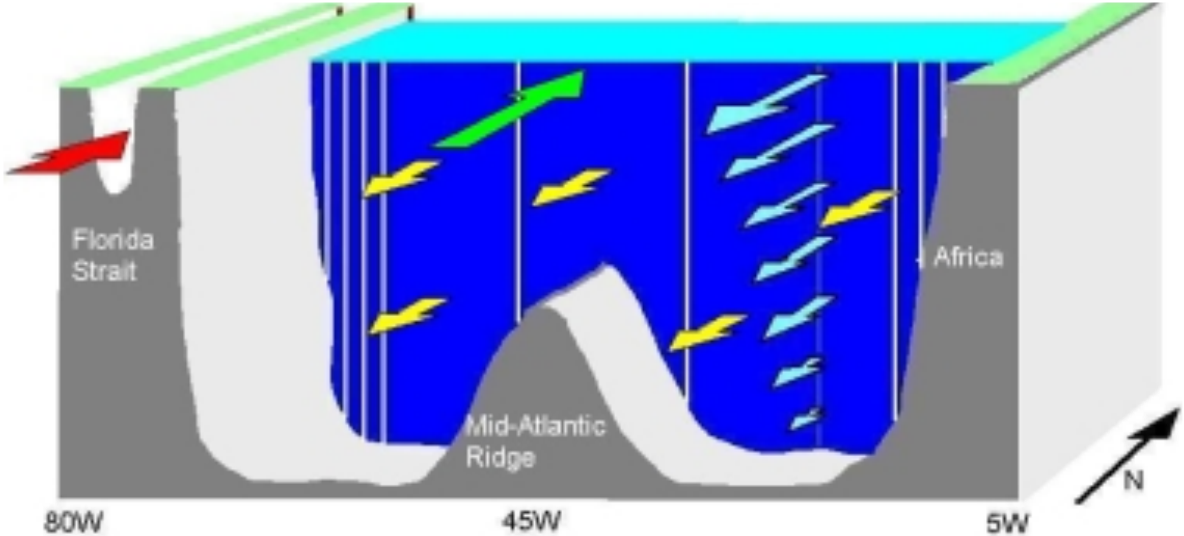


See www.rapid.ac.uk

Meridional velocity field

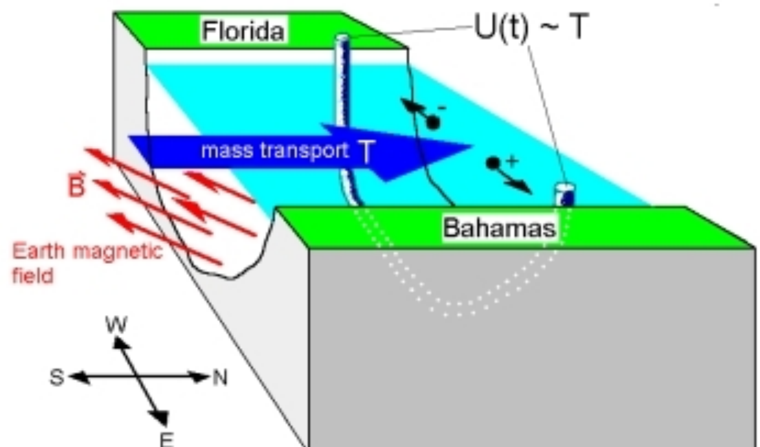
Total meridional transport

= Gulf Stream + Ekman + Interior



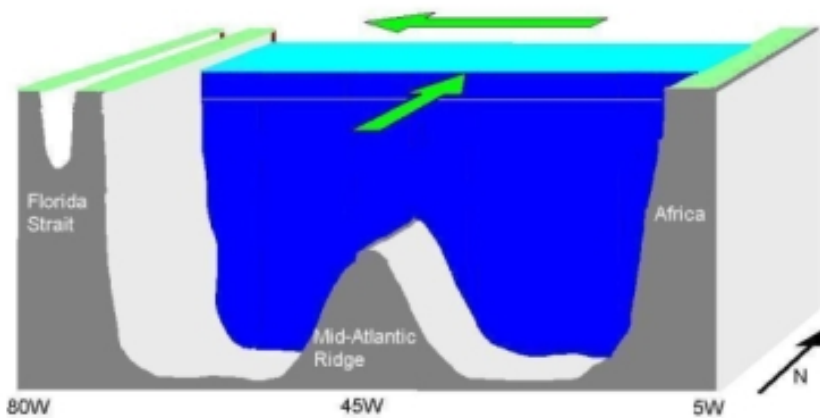
Gulf Stream transport

- Transport through the Florida Straits measured using electromagnetic cables
- Continuous monitoring since 1982
- Mean transport ~ 31Sv



Ekman transport

Zonal wind stress acting at the surface generates a meridional (Ekman) transport $-\tau_x / f$



Estimate heat transport in Ekman layer from wind stress observations and temperature

Upper mid ocean transports

In the interior (away from surface and boundary currents), the thermal wind balance applies:

$$f\frac{\partial v}{\partial z} = -\frac{g}{\rho_0}\frac{\partial \rho}{\partial x}$$

- If density (ρ) is known, *v* can be calculated by integrating vertically from a reference level with zero (or known) velocity.

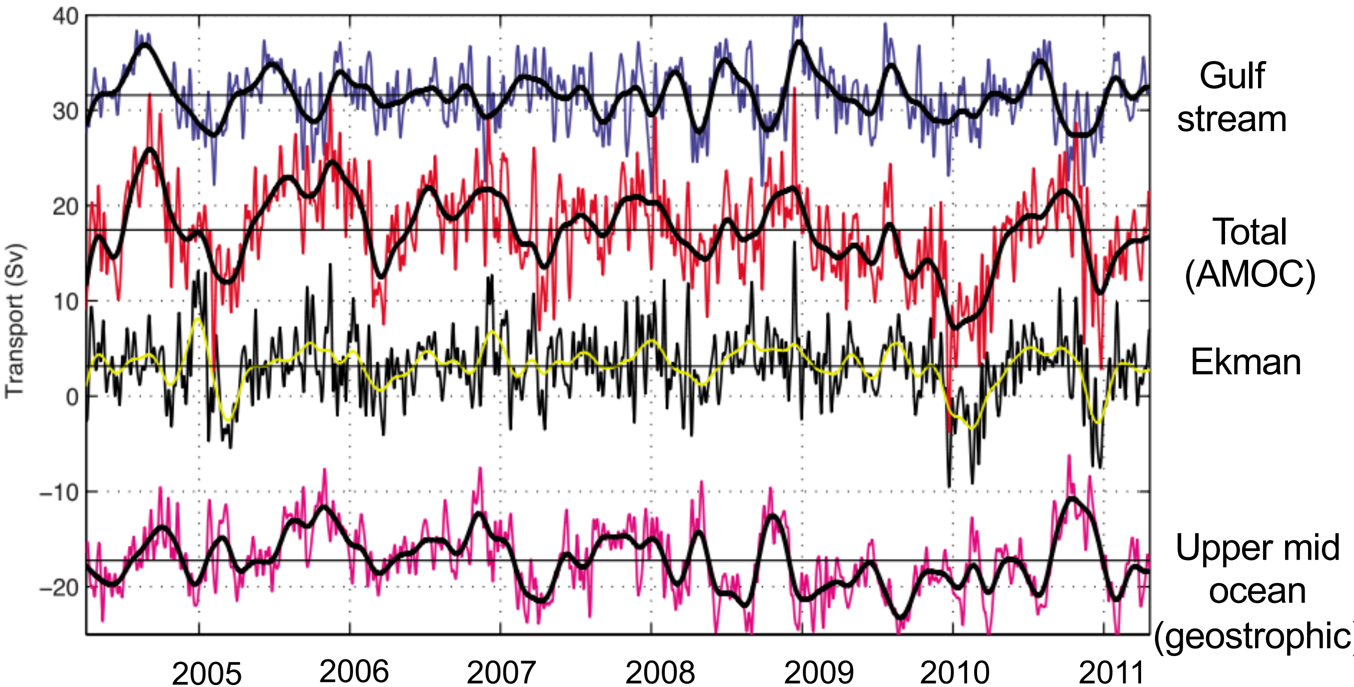
$$v(z) = v(z_0) - \frac{g}{f\rho_0}\int_{z0}^{z}\frac{\partial \rho}{\partial x}dz$$

ref level

- The total velocity can be calculated from pressures at end points

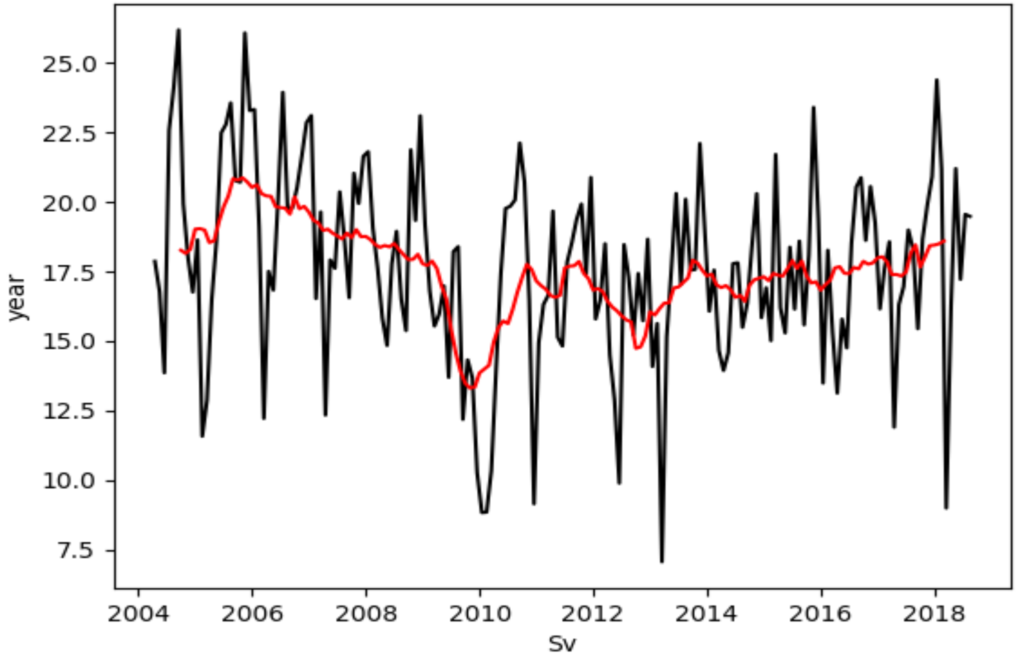
$$\int_z^0 \int_{west}^{east} v dx\, dz = \frac{1}{f\rho_0}\int_z^0 (p_{west} - p_{east})dz$$

Observed timeseries

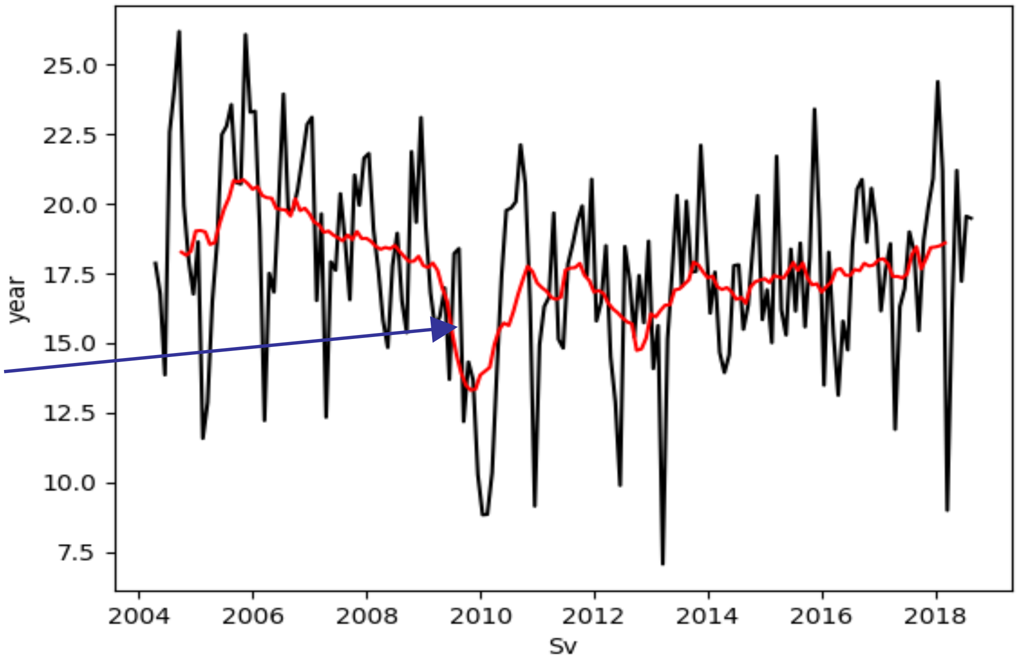


McCarthy et al 2012

RAPID timeseries

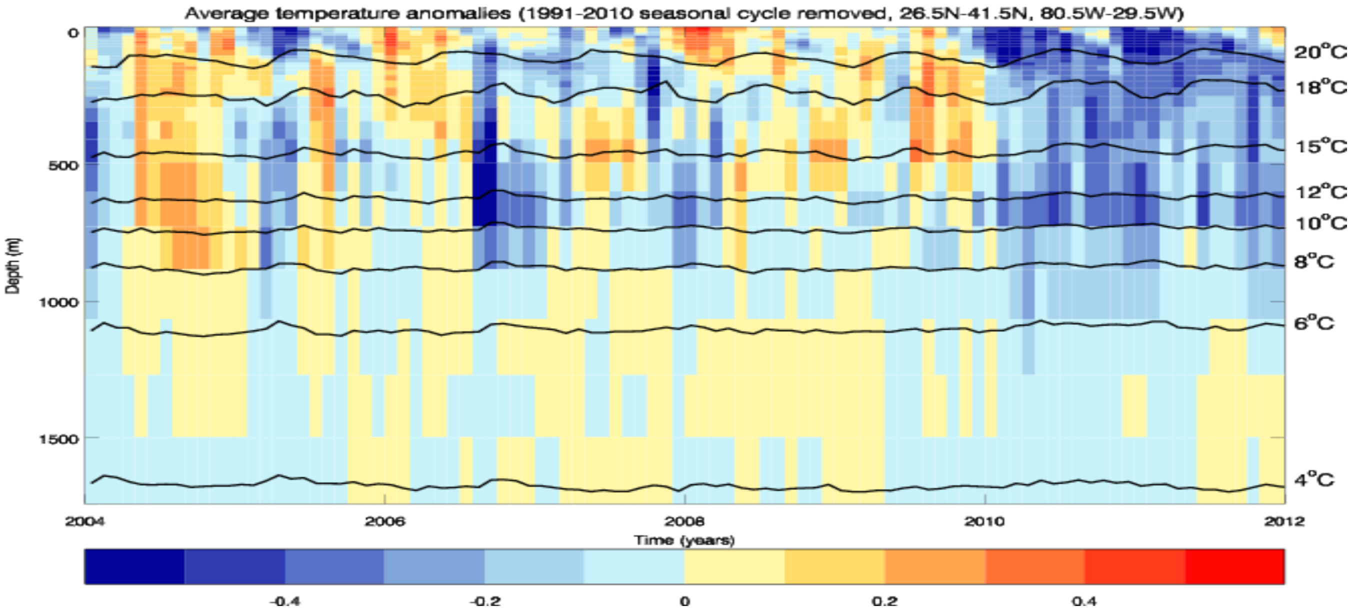


RAPID timeseries



Temporary weakening from extreme negative mode of North Atlantic Oscillation

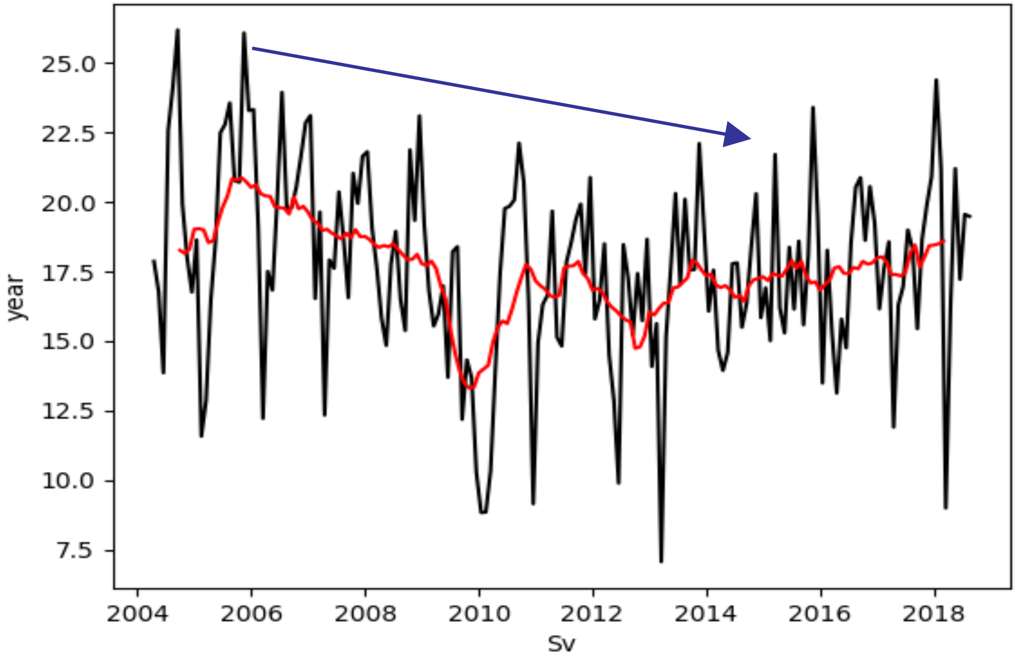
This resulted in cooling in the Atlantic in 2010 in the subtropics which later recovered



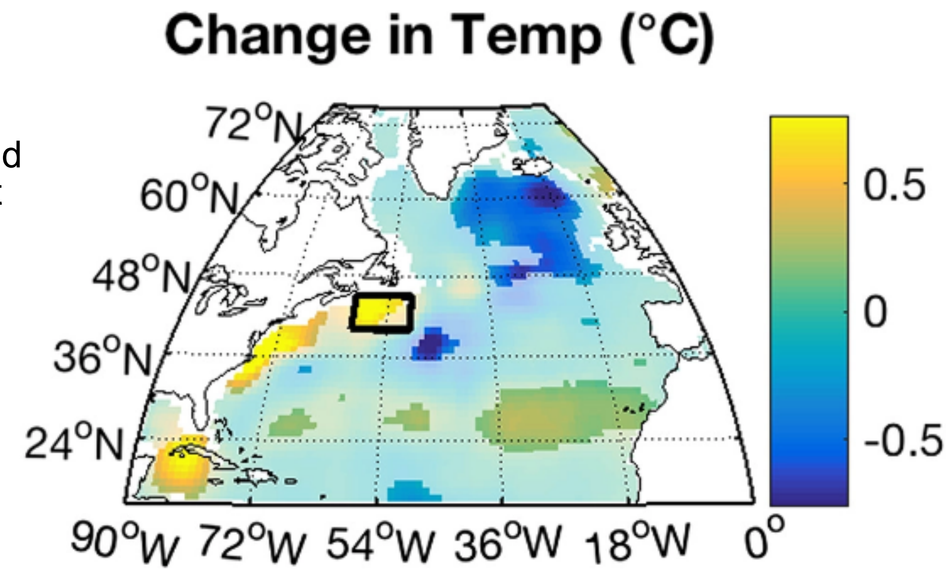
Cunningham et al, 2013

RAPID timeseries

Decadal weakening, thought to be variability



Impacts of the AMOC weakening on temperature and sea surface height

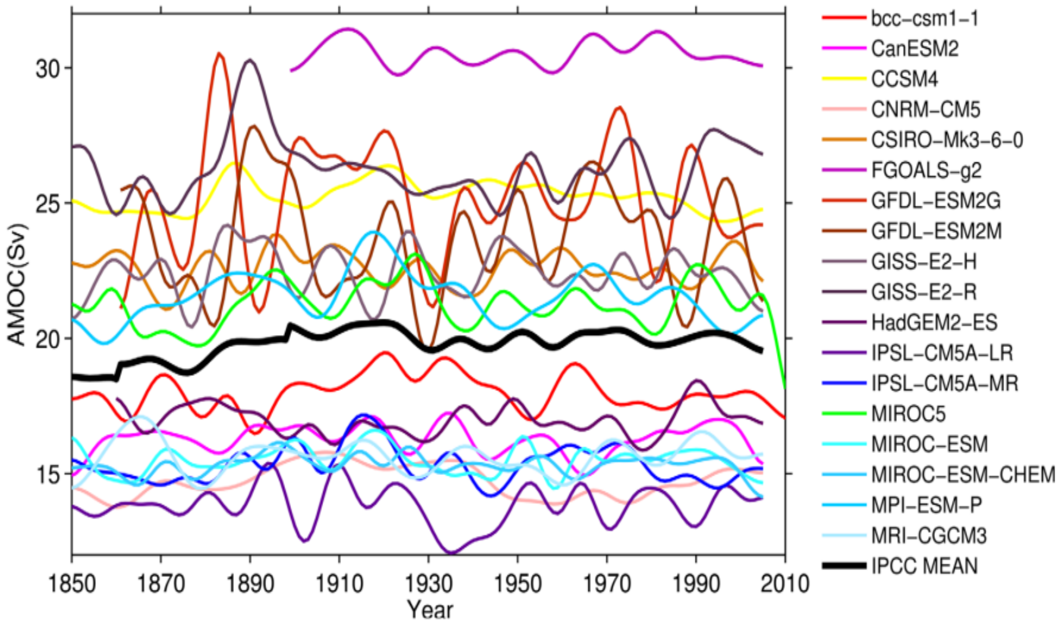


Smeed et al 2018

AMOC variability

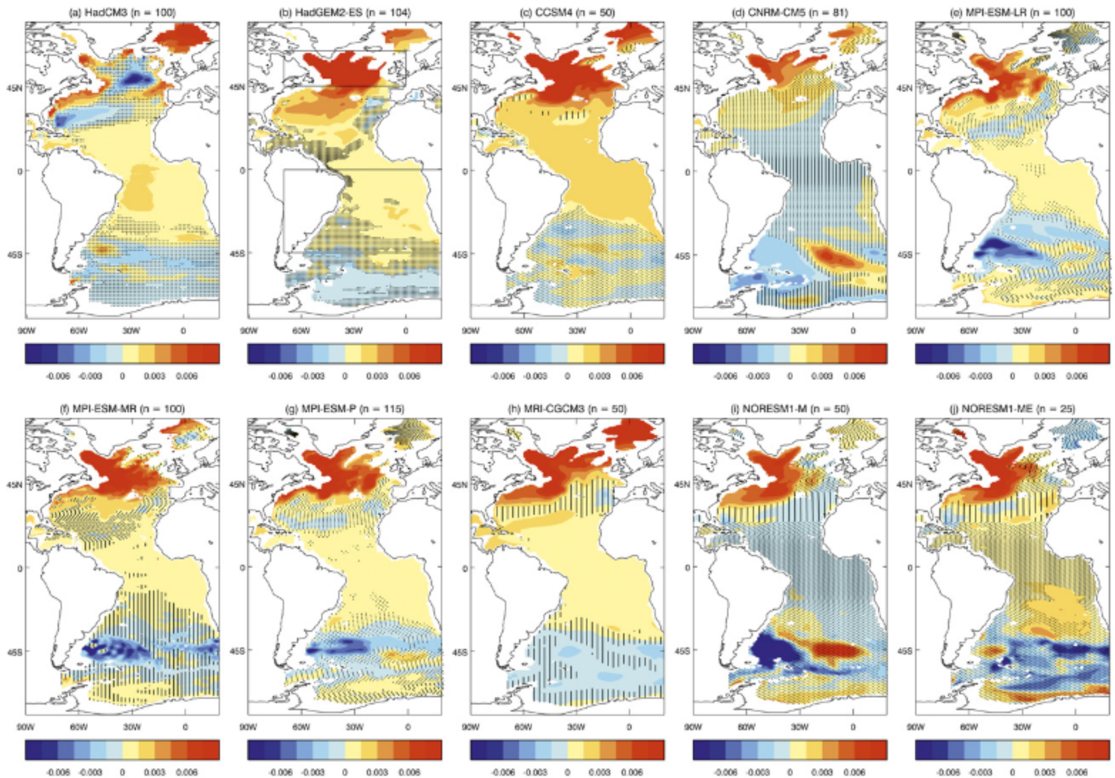
Models show AMOC variability but disagree about the magnitude and timescales.

ZHANG AND WANG: AMO AND AMOC SIMULATIONS IN CMIP5

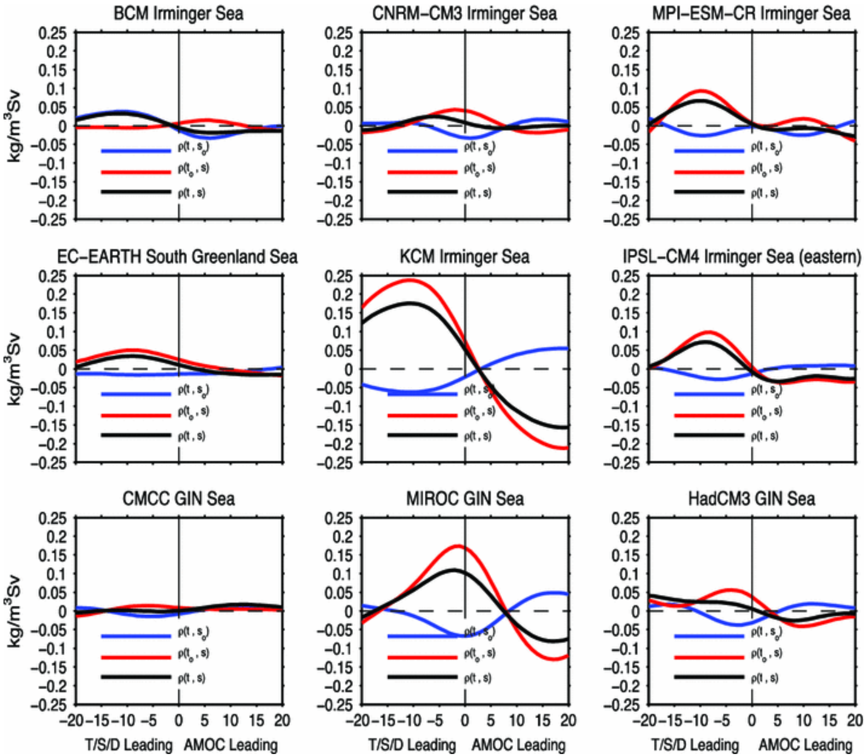


Zhang and Wang, JGR, 2013

Models show relationships between AMOC and densities in the subpolar gyre.



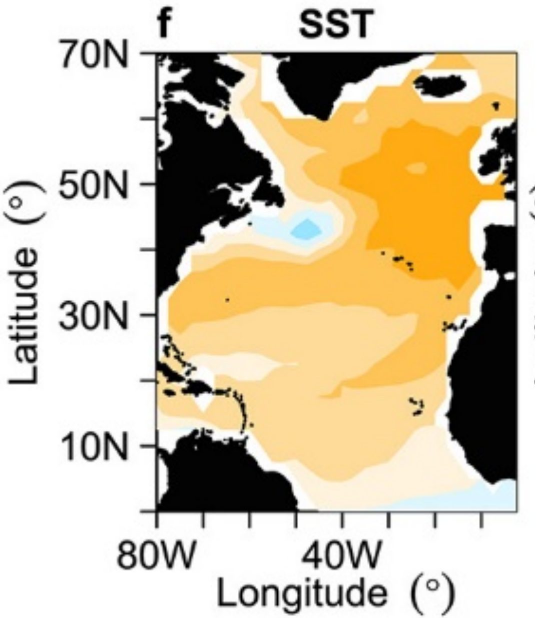
Roberts et al, J Clim. 2013



Ba et al (2014) looked at variability in a number of CMIP5 models and found:

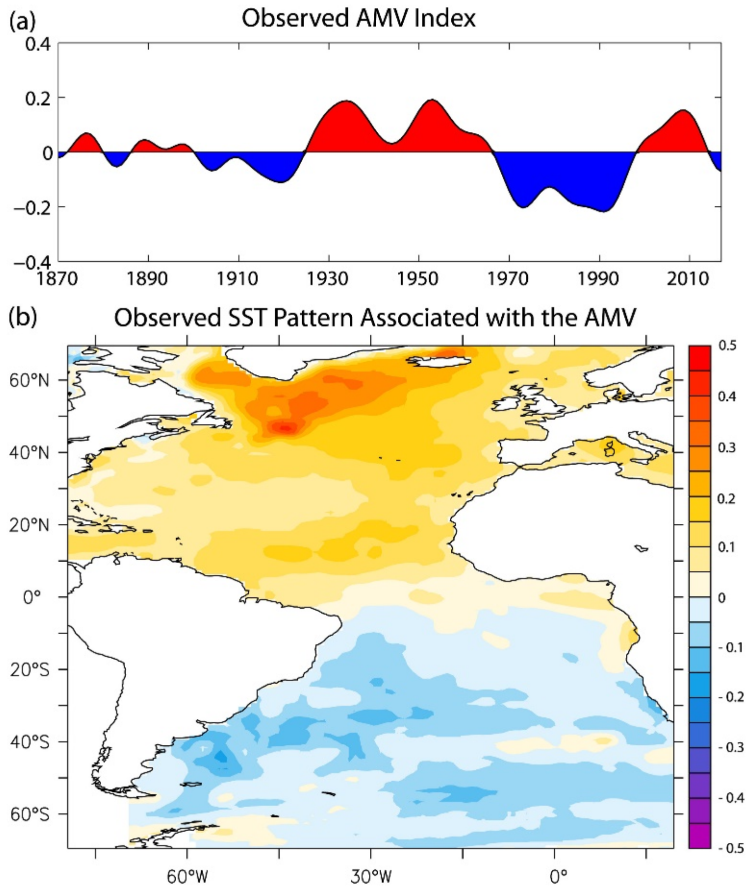
- Relationship of AMOC with high lat convection and density, but in different regions in different models

AMOC variability is associated with SST variability (see regression pattern). Hence Atlantic Multidecadal variability (AMV) is believed to be driven by the AMOC.



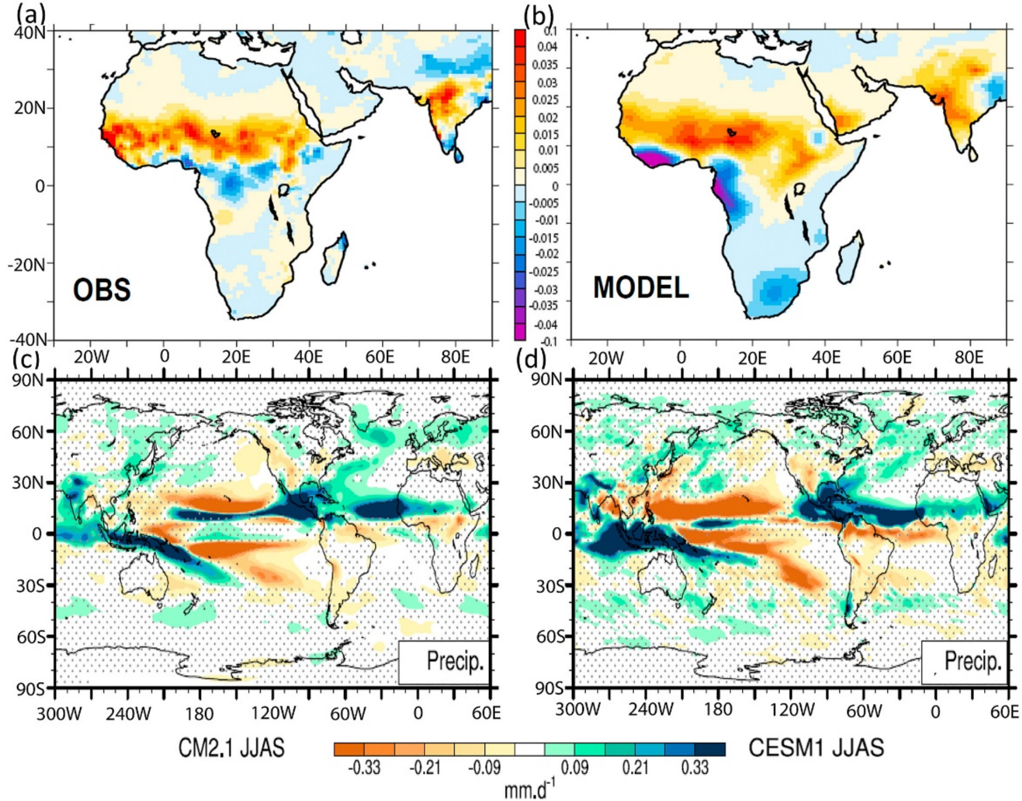
Yan et al (2018)

Observations show multidecadal variability of sea surface temperatures



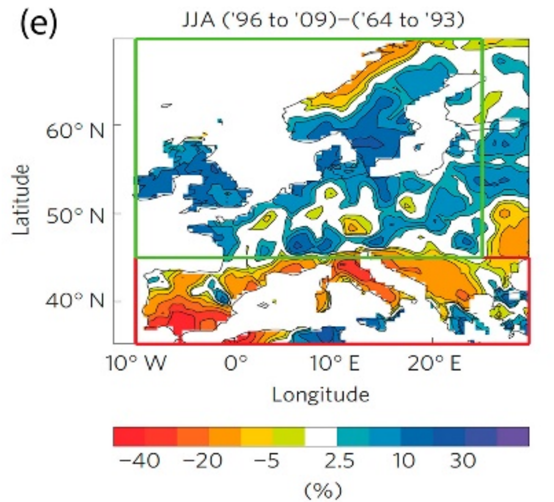
Zhang et al, Reviews of Geophys (2019)

AMV is also associated with driving other impacts. Sea temperature gradients in the tropical Atlantic drive changes in tropical precipitation and monsoons.



Ruprich-Robert et al (2017)

AMV is also associated with summer precipitation over Europe (see right) and also winter storms and strength of hurricane seasons



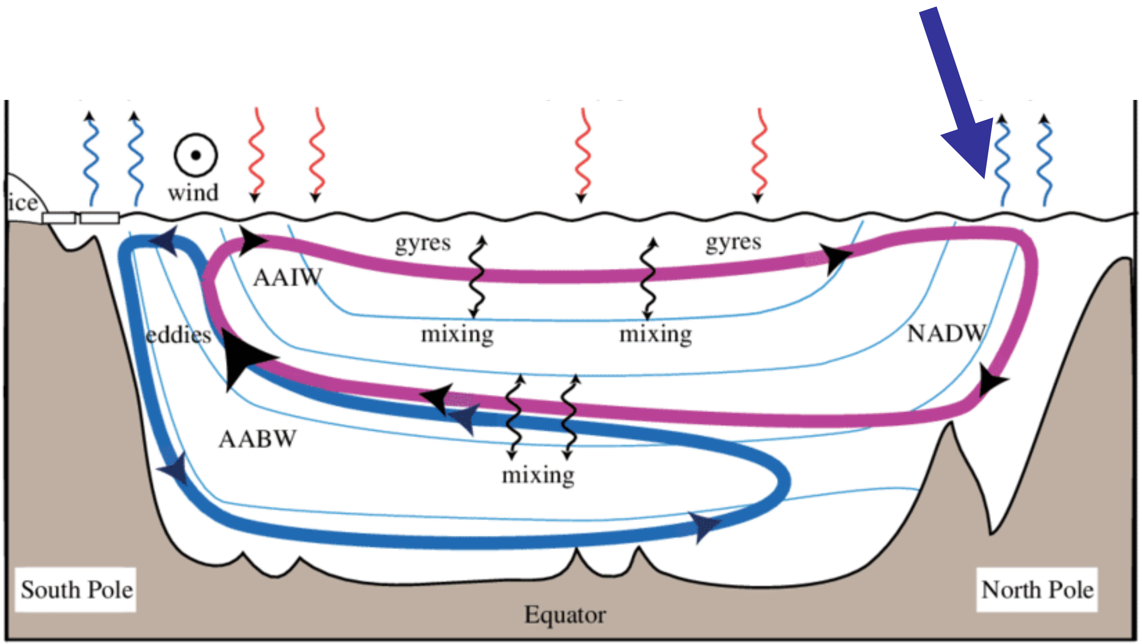
Sutton and Dong (2012)

Future AMOC changes

Future AMOC change

Less cooling → warmer,
more precipitation and more ice melting → fresher

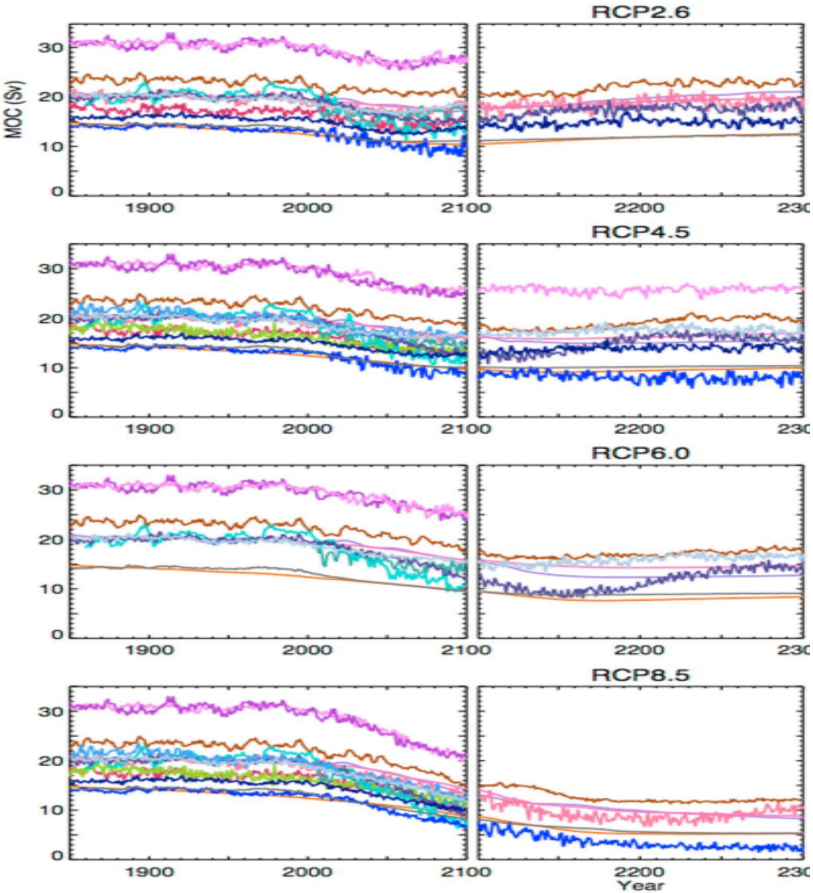
So less dense water sinking weakens the AMOC



Projections of MOC decrease

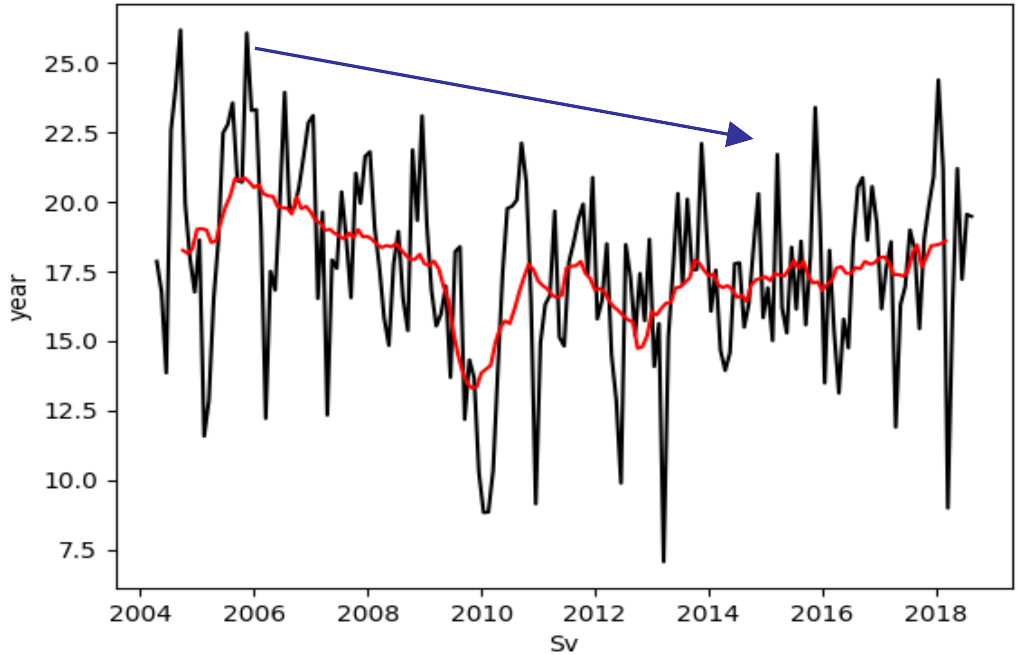
IPCC AR5: AMOC is very likely to weaken over the next century. However rate of weakening is uncertain: depends on model and scenario

Weaver et al (2012)

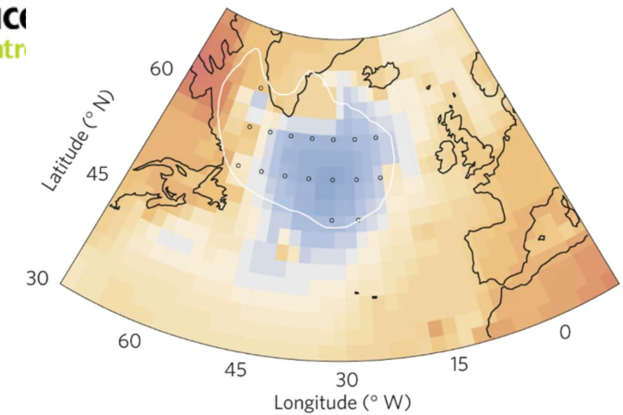


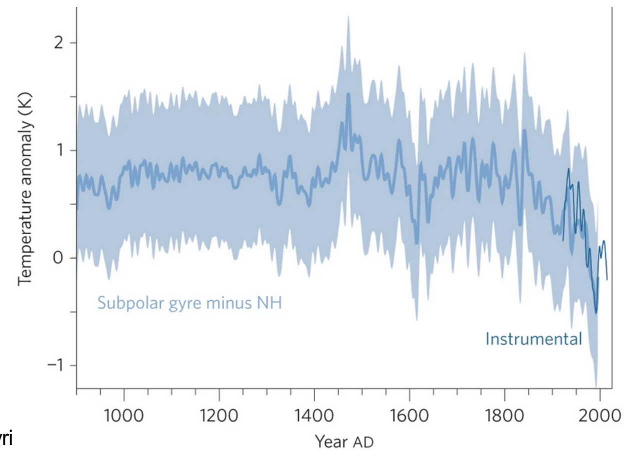
RAPID timeseries

Decadal weakening, thought to be variability



Is the AMOC weakening?





Can try to extend AMOC timeseries back by using ‘fingerprints’ – observable quantities that are related.

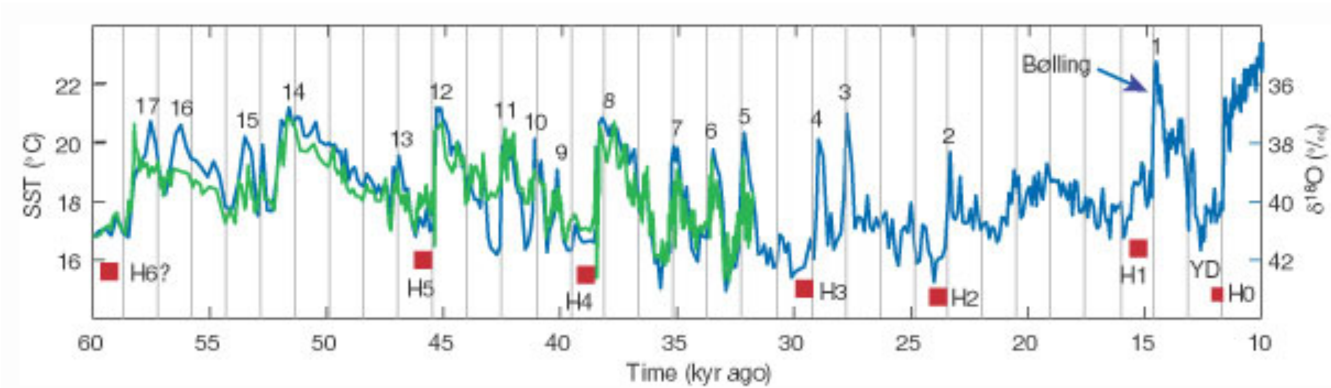
Models show relationships between AMOC and temperatures in the subpolar North Atlantic. Using this as a proxy shows AMOC weakening.

However there are uncertainties about the method and paleo data.

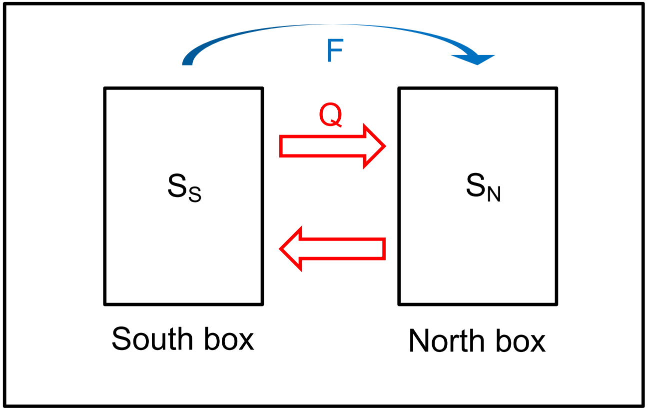
Rahmstorf et al (2015), Caesar et al (2018)

Tipping points, hysteresis and abrupt changes of the AMOC

Evidence for more abrupt changes in climate?



Simple box model of the AMOC by Stommel (1961)



AMOC strength (Q) is proportional to density difference (which depends on salinity difference S_N-S_S).

$$Q \quad = Q_0 + \lambda(S_N - S_S)$$

Salt flux into north box balances salt flux out and fresh water surface flux in (F)

$$|Q|S_S = |Q|S_N + F$$

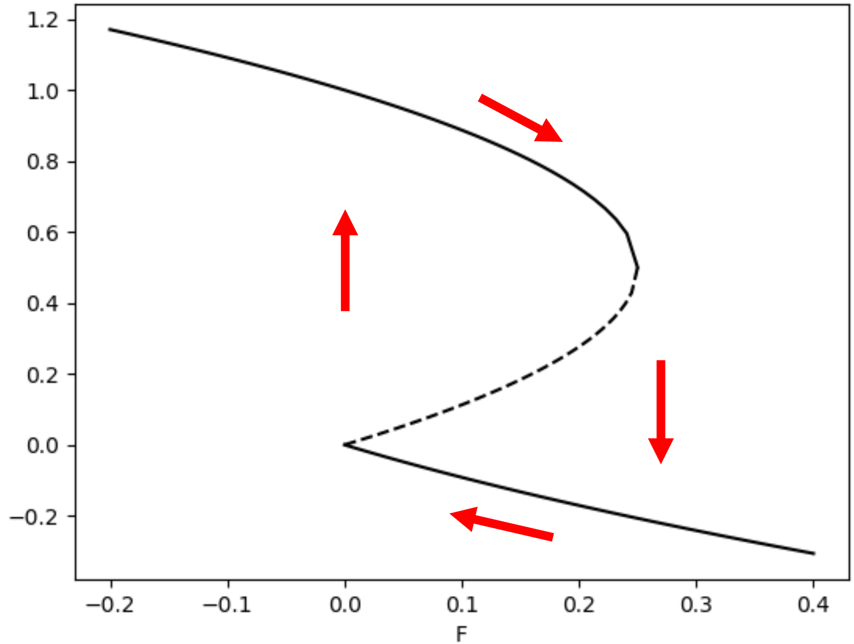
Putting these together gives:

$$|Q|\,(Q - Q_0) = -\lambda F$$

Which has 3 solutions, 2 stable and 1 unstable:

$$Q = \frac{1}{2}\left(Q_0 \pm \sqrt{Q_0^2 - 4\lambda F}\right) \qquad Q > 0$$

$$Q = \frac{1}{2}\left(Q_0 - \sqrt{Q_0^2 + 4\lambda F}\right) \qquad Q < 0$$



Increasing the freshwater input into the North Atlantic (F), weakens the AMOC until the stable 'on' branch is no longer viable. Then the AMOC collapses to the 'off' branch.

For some values of F there are 2 stable states and the system displays hysteresis (reversal of fresh water forcing leads to different response)

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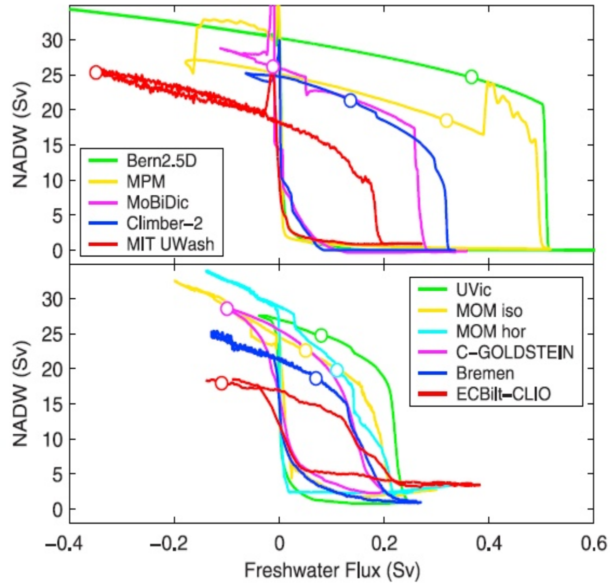
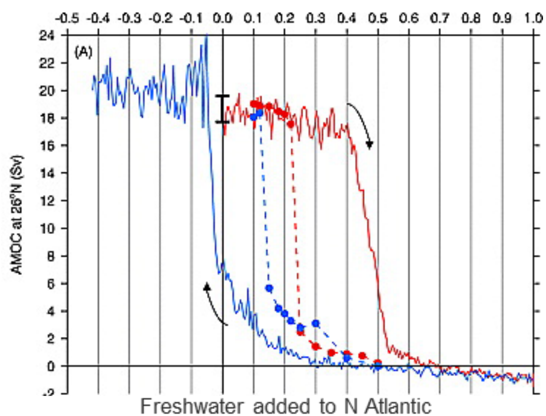
Hysteresis has been seen in the AMOC in simple/intermediate complexity models of the ocean and even in one low resolution climate model.



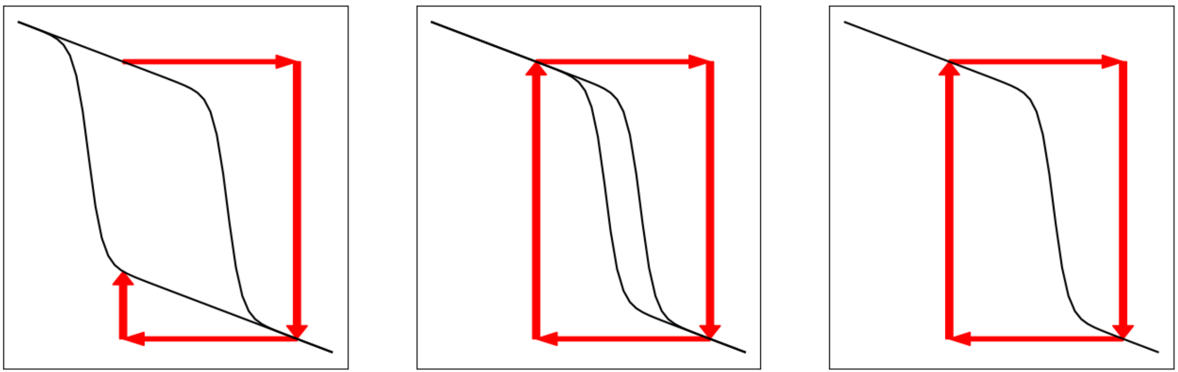
Rahmstorf et al. 2005



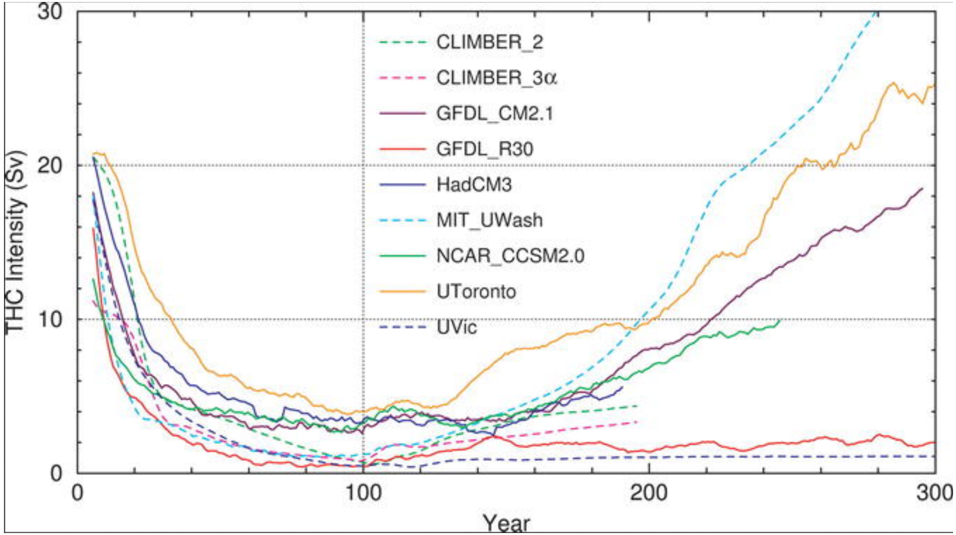
Hawkins et al. 2011

These experiments require slowing varying F so that climate has time to adjust. This is too expensive to do with complex coupled climate models.

Instead change F instantaneously and wait till reach equilibrium.



However if you don't find both on and off states it doesn't mean they don't exist.



Stouffer et al, 2006

Most models in the past have shown AMOC recovery after hosing, particularly coupled climate models. Some less complex models (dashed lines above and solid red line) show AMOC stays in weak state.

Is this because those more complex models have more processes?

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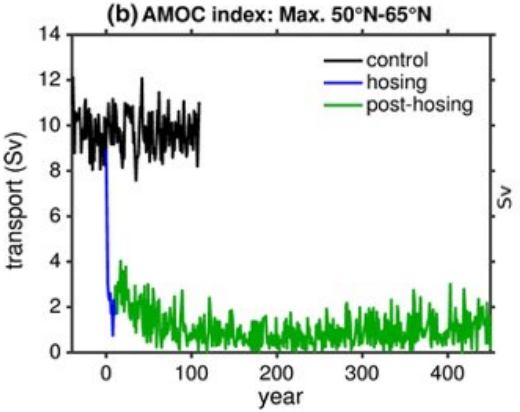
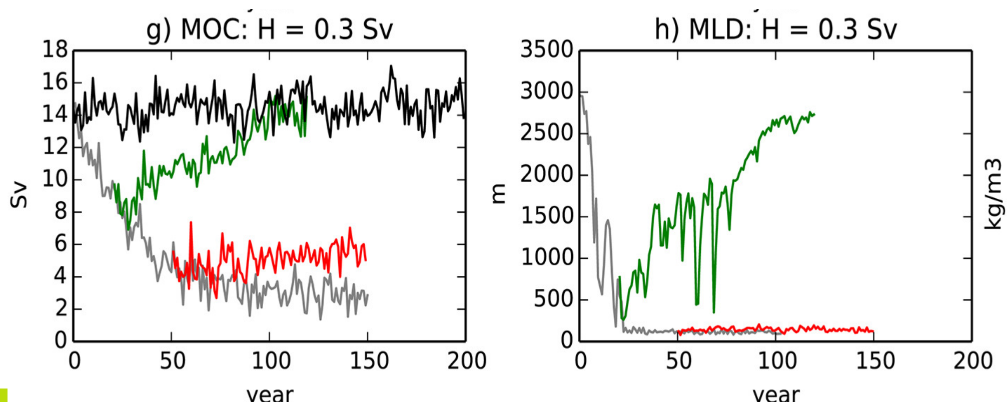


Left: *Mecking et al (2016)* showed that the AMOC in a post CMIP5 climate model (HadGEM3 GC2) can stay in a weak off state.

Bottom: *Jackson and Wood (2018)* used the same model and showed if AMOC weakens enough from adding fresh water, it does not recover, although the limit is probably model dependent. We are now investigating this problem in a small ensemble of CMIP6 models.



Stommel advective feedback

We can adjust our equation for the salt flux to include a time-varying part (where V is a volume factor)

$$V\frac{dS_N}{dt} = |Q|(S_s - S_N) - F$$
$$Q = Q_0 + \lambda(S_N - S_S)$$

If we consider anomalies from the equilibrium, with Q>0

$$Q = \bar{Q} + q, \quad S_S - S_N = \Delta\bar{S} + \Delta\sigma$$

Then linearising gives

$$V\frac{dS_N}{dt} = \bar{Q}\Delta\sigma + q\Delta\bar{S}$$

The second term is found to be an important feedback, known as Stommel's feedback.

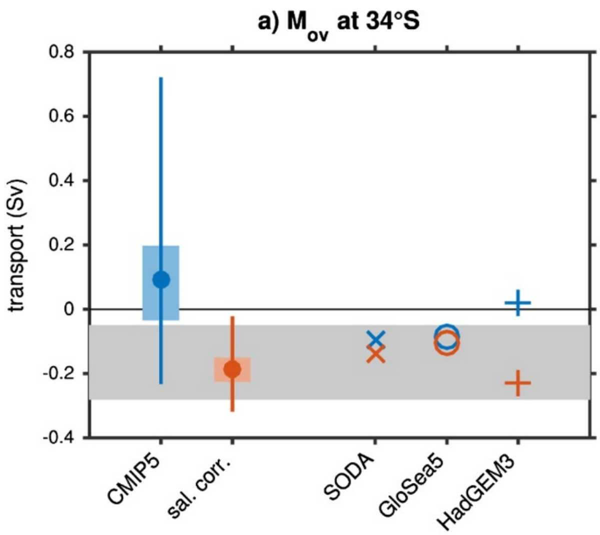
Feedbacks

We can use the advection of fresh water by the overturning as an indicator of this feedback $M_{ov} = -\bar{Q}\Delta\bar{S}$ so $q\Delta\bar{S} = -\frac{q}{\bar{Q}}M_{ov}$

If Mov < 0 then a weakening of the AMOC (q<0) causes a freshening of the North Atlantic and hence a further weakening of the AMOC. This is a positive feedback.

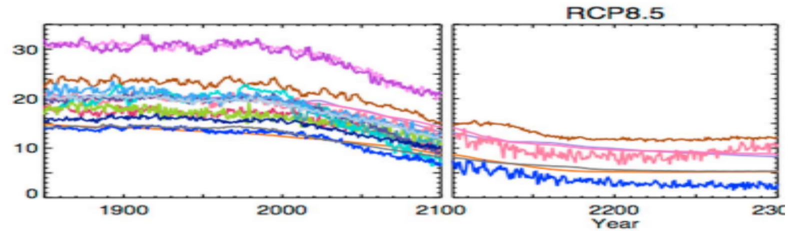
If Mov > 0 then a weakening of the AMOC (q<0) causes a salinification of the North Atlantic and hence a recovery of the AMOC. This is a negative feedback.

Many climate models have Mov>0, while observations show Mov<0, suggesting that many climate models are biased too stable (Figure from *Mecking et al, 2017*)



More recent climate models are improving this bias. However in a complex climate model there are other feedbacks (some **negative**, counteracting the AMOC weakening), which are not well understood. Which feedbacks are the most important? See also *Weijer et al (2019)* for a review of AMOC stability.

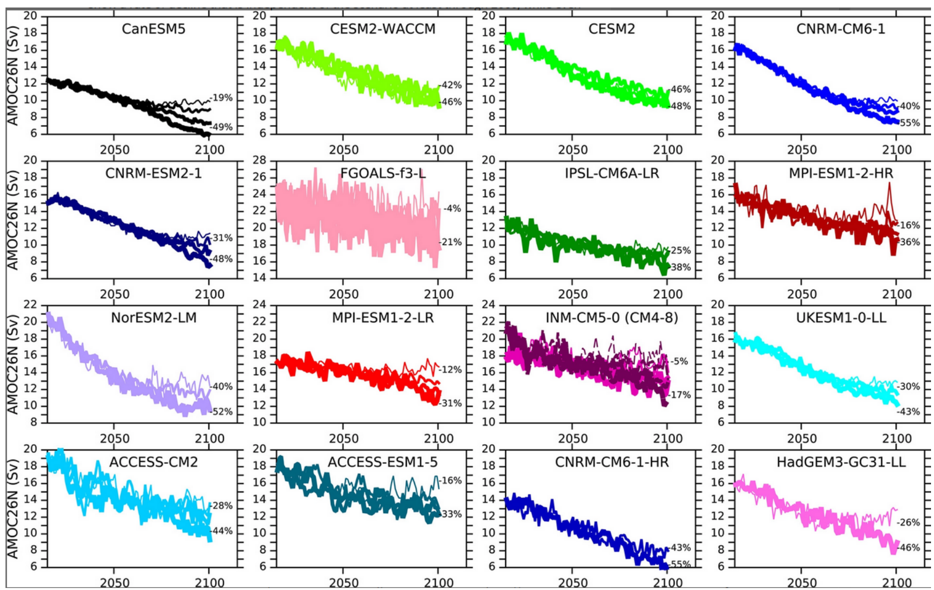
CMIP5 RCP8.5



However, there is no evidence of an abrupt collapse in projections in CMIP models (including HadGEM3-GC2), though some show large weakening, particularly past year 2100.

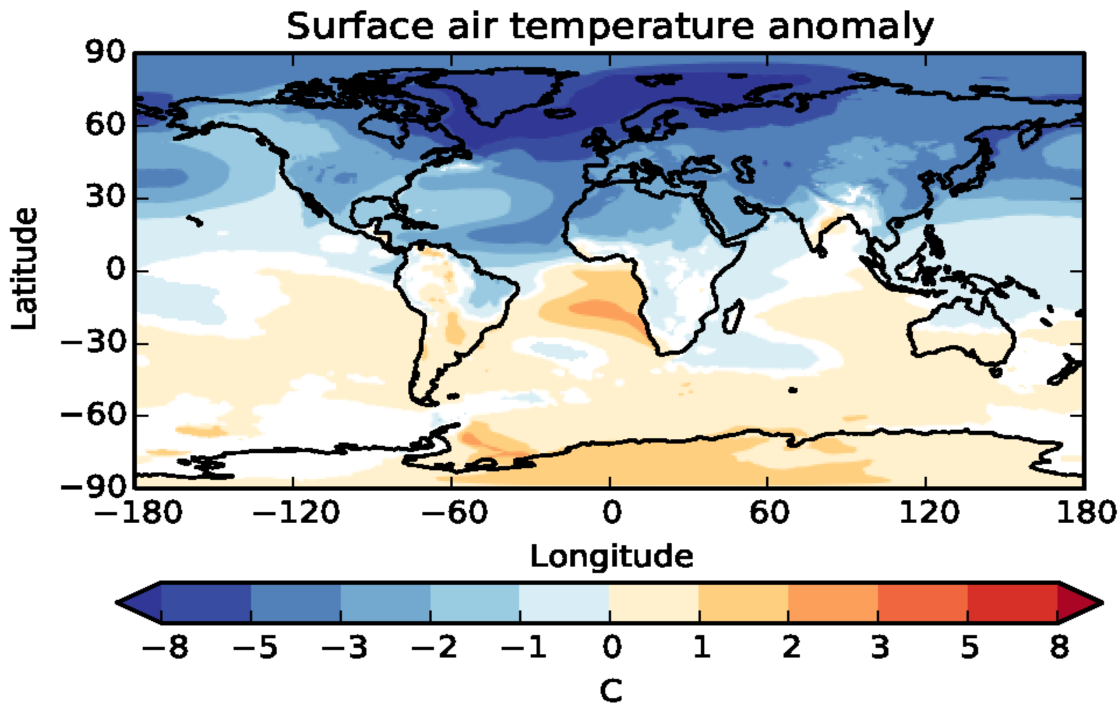
IPCC conclude that a collapse before year 2100 would be unlikely.

CMIP6 various scenarios



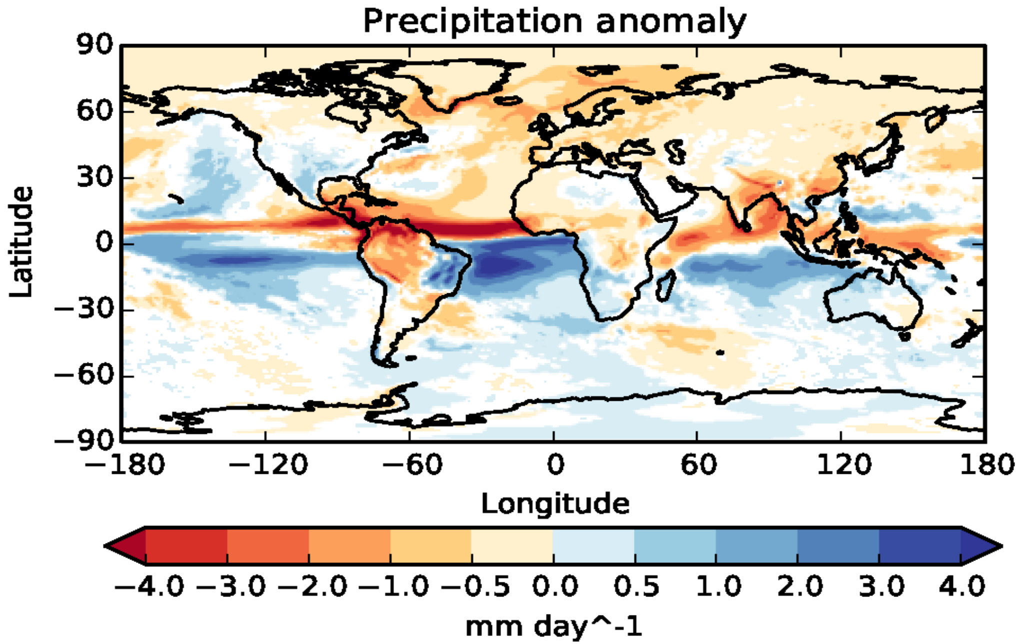
Impacts of an AMOC collapse

Widespread cooling over North Atlantic and northern hemisphere



Jackson et al, 2015

Less precipitation over North Atlantic. Shift southwards of Intertropical Convergence Zone.



Jackson et al, 2015

Met Office
Hadley Centre

Increase in sea surface height over North Atlantic

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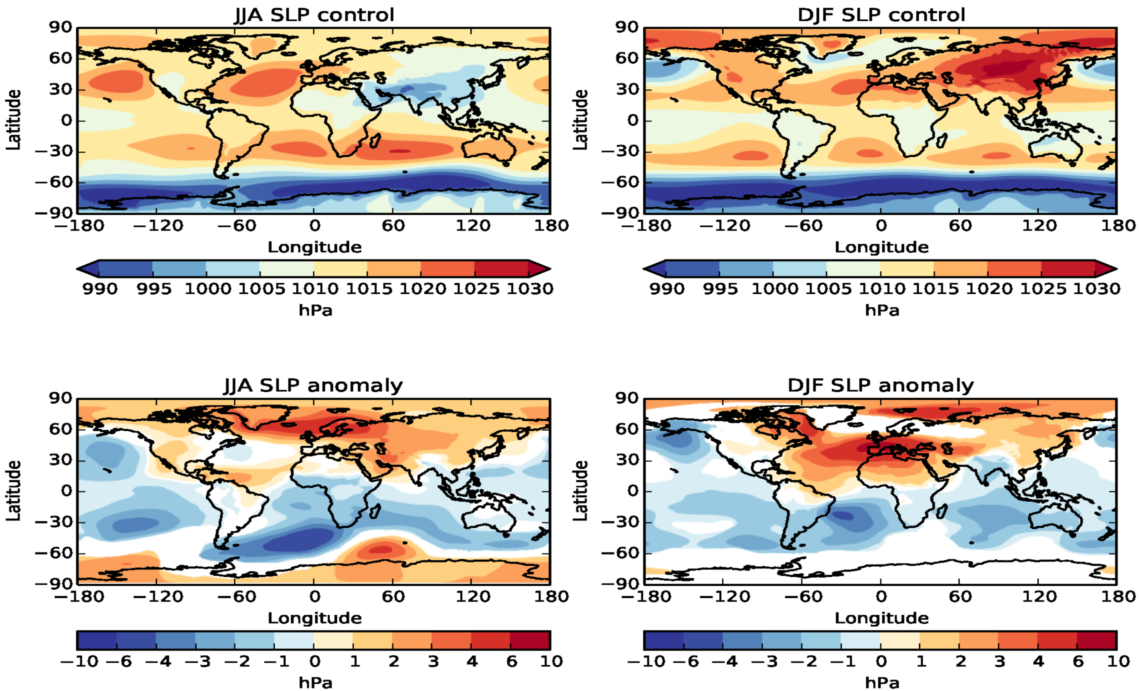
Leverman et al, 2005

Met Office
Hadley Centre

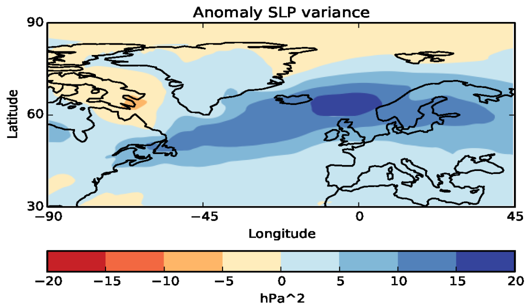


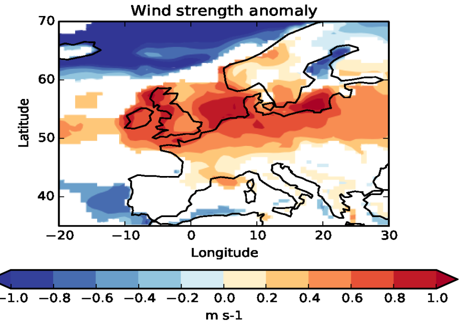
More positive winter NAO

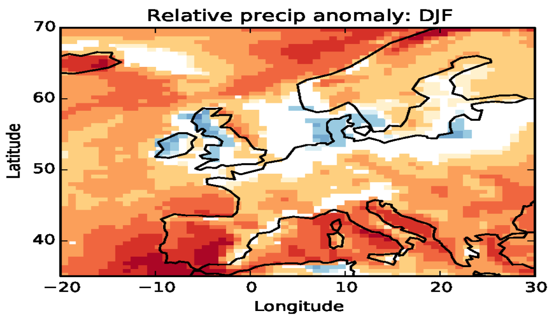
More negative summer NAO

Jackson et al, 2015

European precip - winter







More positive winter NAO →

- More winter storms
- Stronger winds over N Europe
- More precipitation from storms on western coasts of N Europe

Jackson et al, 2015

Summary

- The AMOC plays an important role in climate through transporting heat northwards in the Atlantic
- The AMOC experiences variability at many timescales
  - Seasonal-interannual variability is mostly driven by local winds
  - Decadal-multidecadal variability is mostly driven by density changes in the subpolar North Atlantic and Arctic
  - Mixing and wind-driven upwelling are important at long timescales
- We have been monitoring the AMOC for about 15 years but variability makes a long term trend difficult to detect.
- AMOC is very likely to weaken over the next century, but unlikely to collapse (IPCC).
- Impacts from a collapse (especially an abrupt collapse) would be serious