Inferring past ocean circulation and AMOC from proxies/fingerprints

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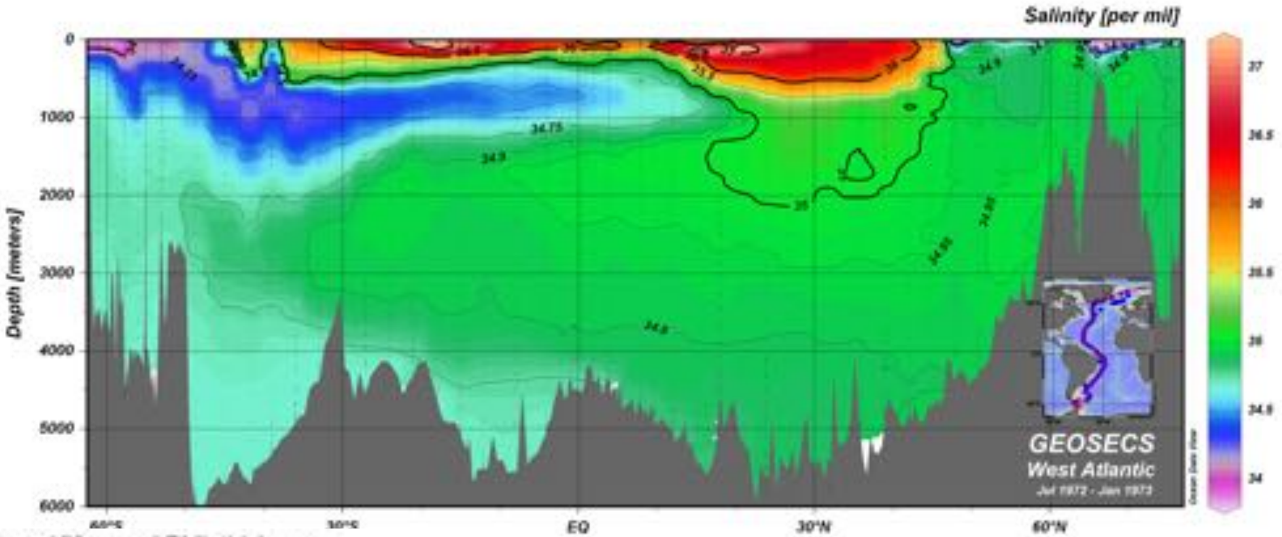
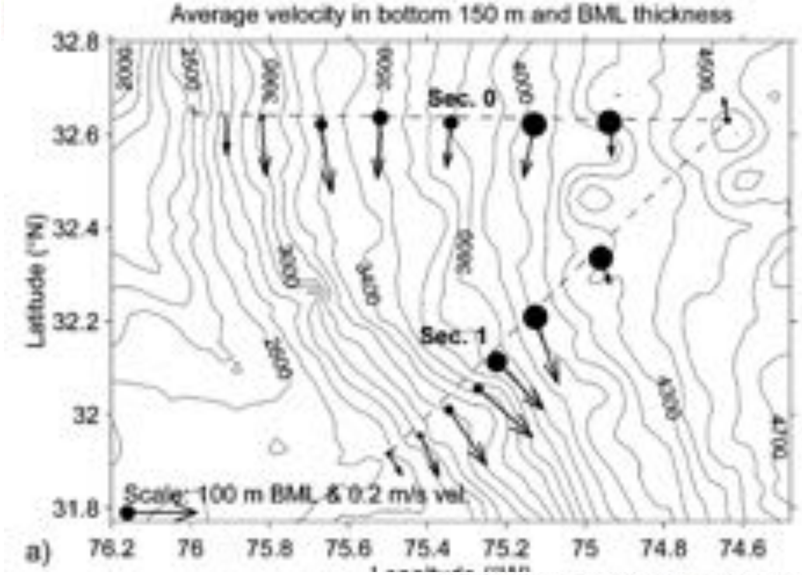
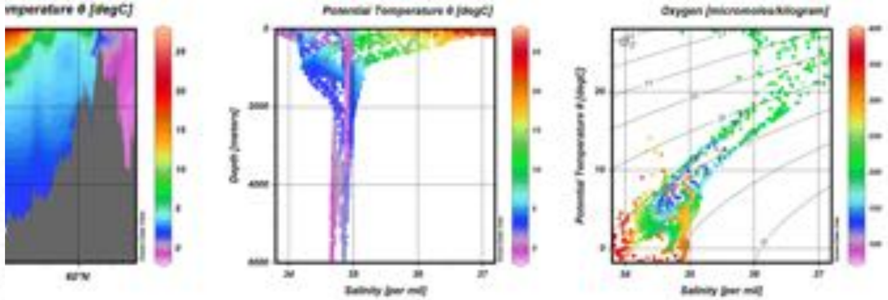
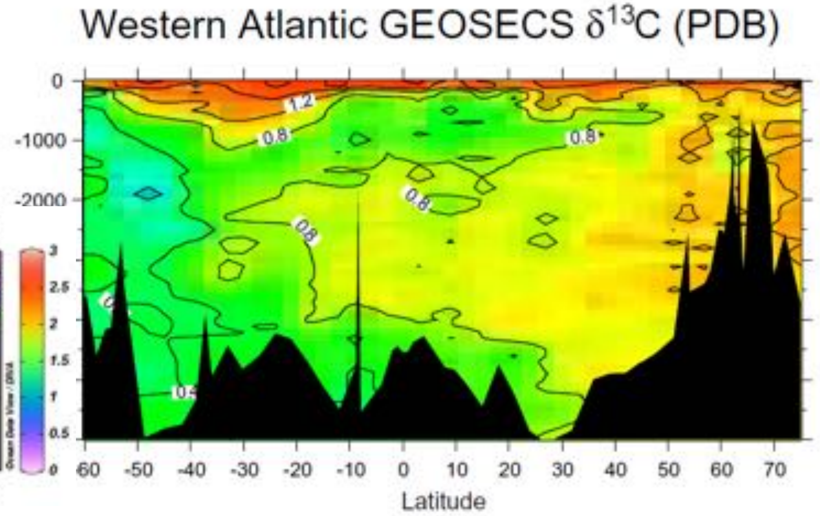
Paleoceanography: relevant for understanding modern AMOC?

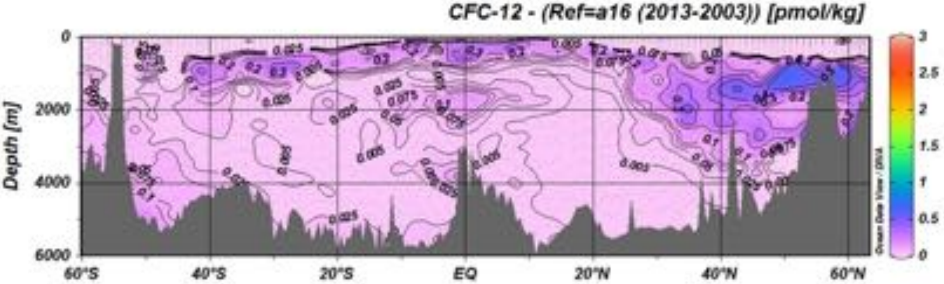
- Requires that paleodata can:
  - (i) in theory, be quantitatively related to circulation, and
  - (ii) is good enough to do this.
- Longer timescale physical processes have relevance today:
  - (i) Legacy (& ongoing) effect of recent changes, such as the Little Ice Age (LIA)
  - (ii) Useful lessons can be learnt from past climates whose boundary conditions differed from today.
- What do we want paleo to do?:
  - (i) Quantify natural AMOC/ocean variability on timescales longer than observational data?
  - (ii) Exploratory science, revealing new behaviour not seen in modern observations?
  - (iii) Constrain forcing and response (hysteresis; sensitivity – will expected fw fluxes → collapse)?
  - (iv) Examine the likely impact of AMOC changes on other components of the Earth system (climate/atmospheric CO_2/ecosystems)?











Measuring the ocean

Paleoceanography uses the same types of tools:

Surface (& thermocline) and bottom (but not in-between!)

Kinematic vs water-mass/volumetric

Conservative vs Non-conservative properties

Looking at different states: Glacial abrupt events

Abrupt climate events coupled to changes in ocean properties (esp. Nordic Seas and surface Atlantic); but timing and extent of integrated AMOC weakening remains uncertain

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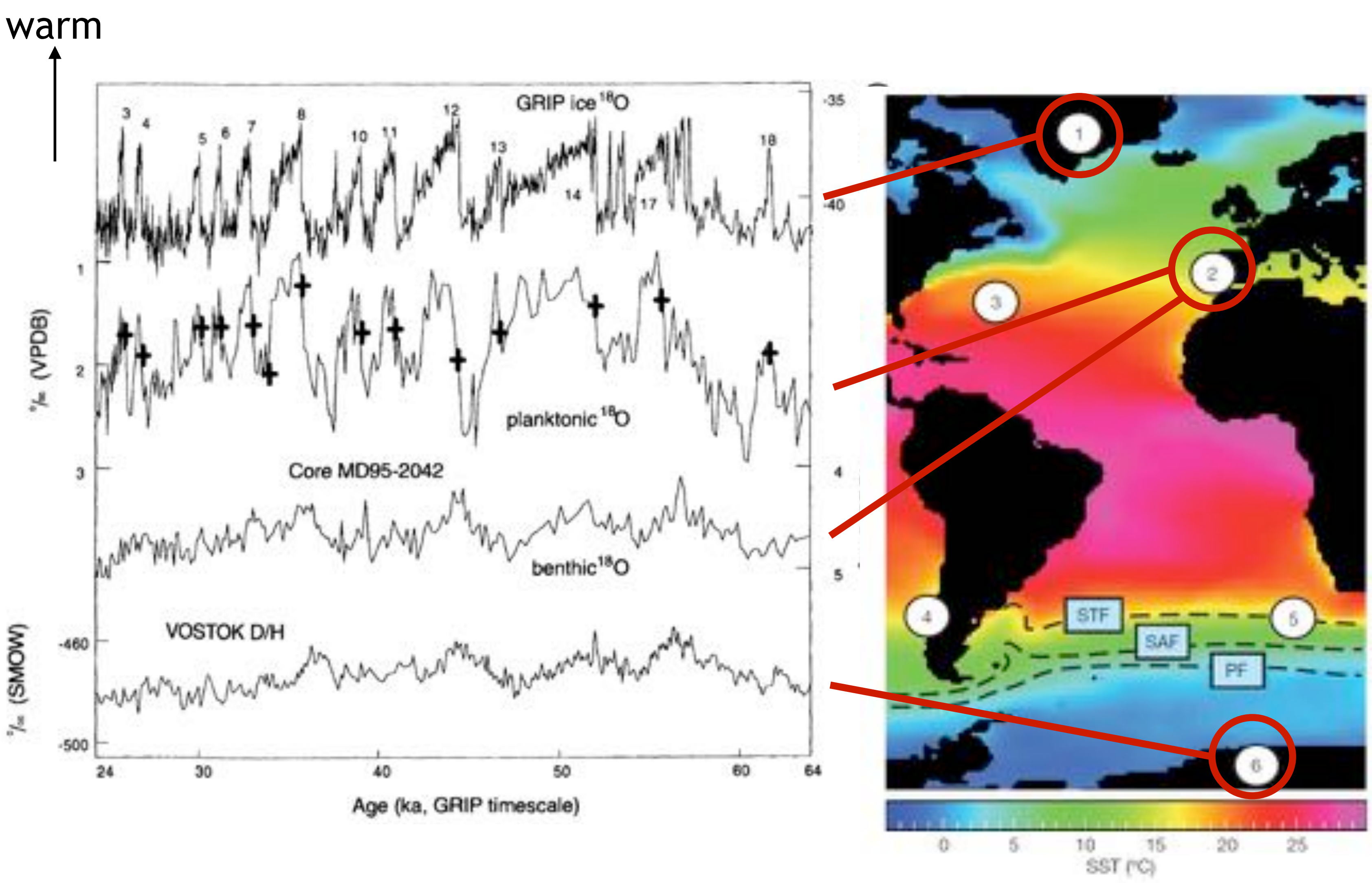


Shackleton et al., 2000

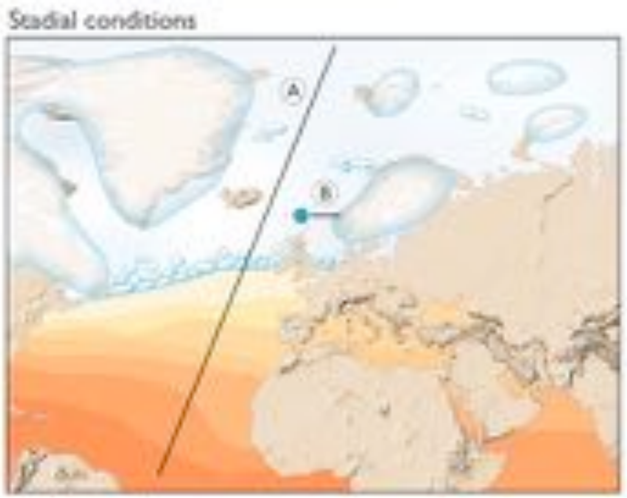
The bipolar seesaw

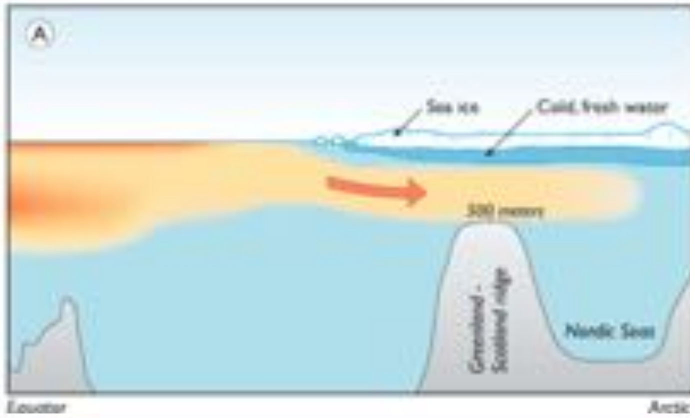
Ice cores and marine sediments reveal abrupt glacial climate events.

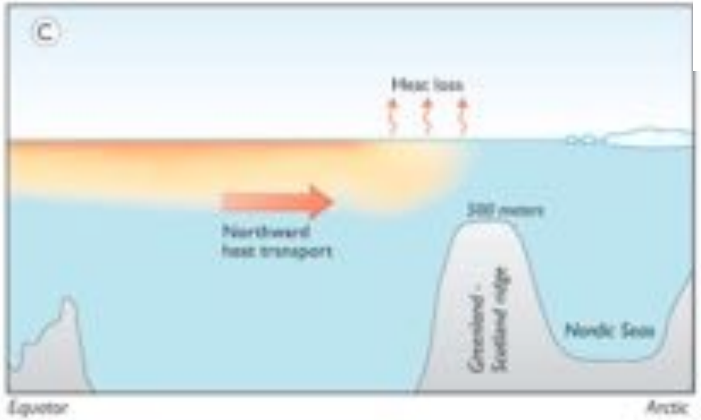
Synchronisation of ice-cores via CH_4 revealed asynchrony.

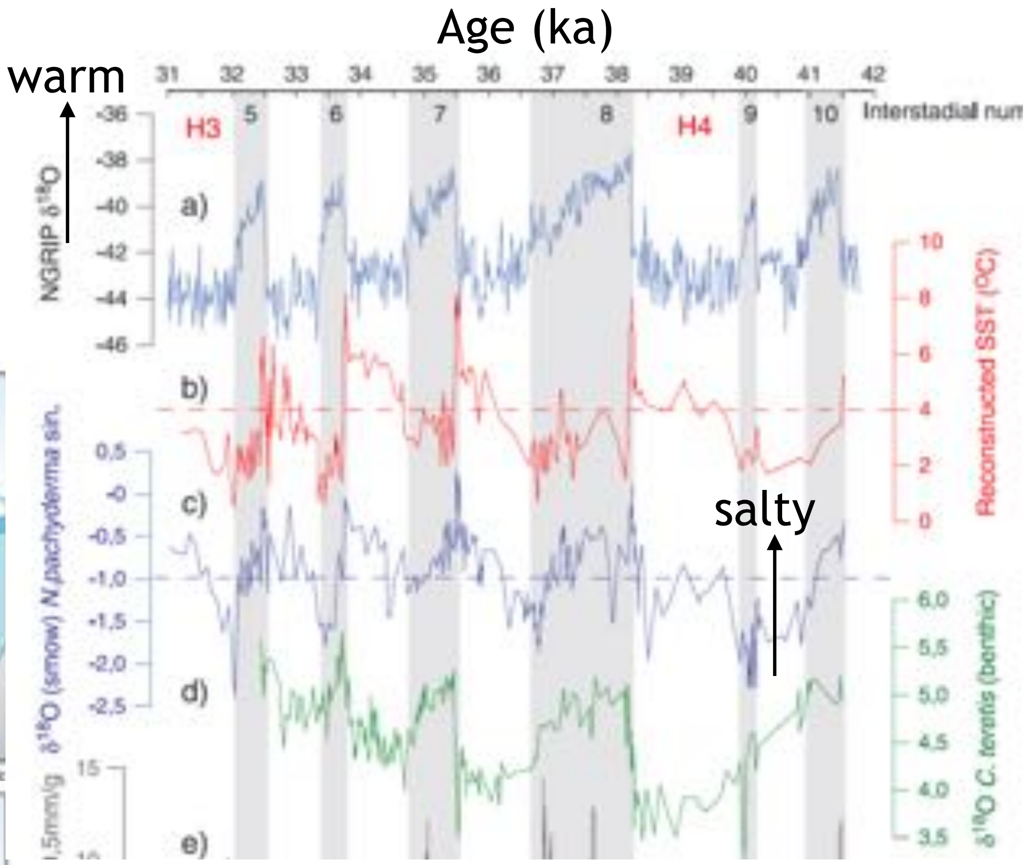
Also shown using single marine core!: surface ocean temperature signal resembles Northern Hemisphere (Greenland); deep ocean temperature signal resembles Southern Hemisphere (Antarctica)

Highly reproducible





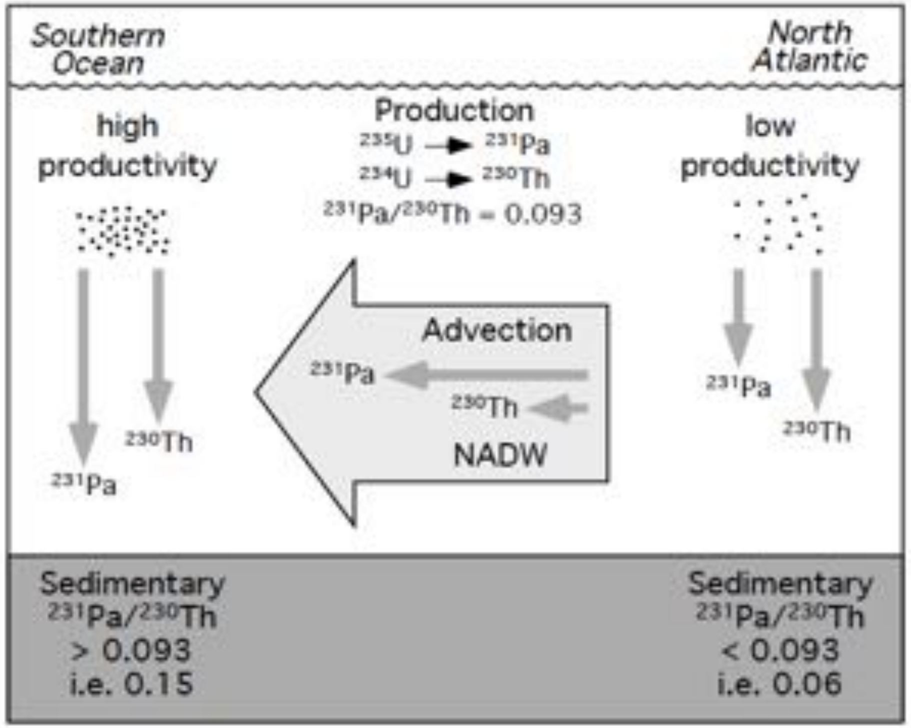


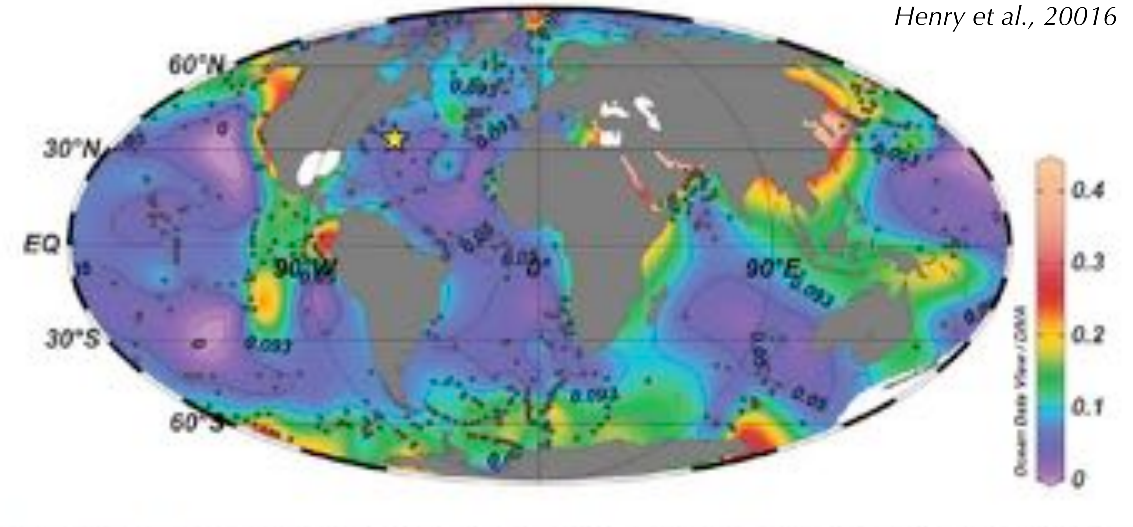


Dokken et al., 2013

Shifts in the Nordic Seas

- High resolution marine cores in Nordic Seas
- Reveal abrupt changes in surface and deep ocean properties
- Suggested weaker open ocean convection
- Subsurface warming under expanded sea-ice
- Mechanisms of abrupt shifts in circulation





Henry et al., 20016

Fig. 1. Study core location and coretop distribution of Pa/Th. Location sediment core CDH19

What about overall AMOC? Use the Pa/Th proxy?

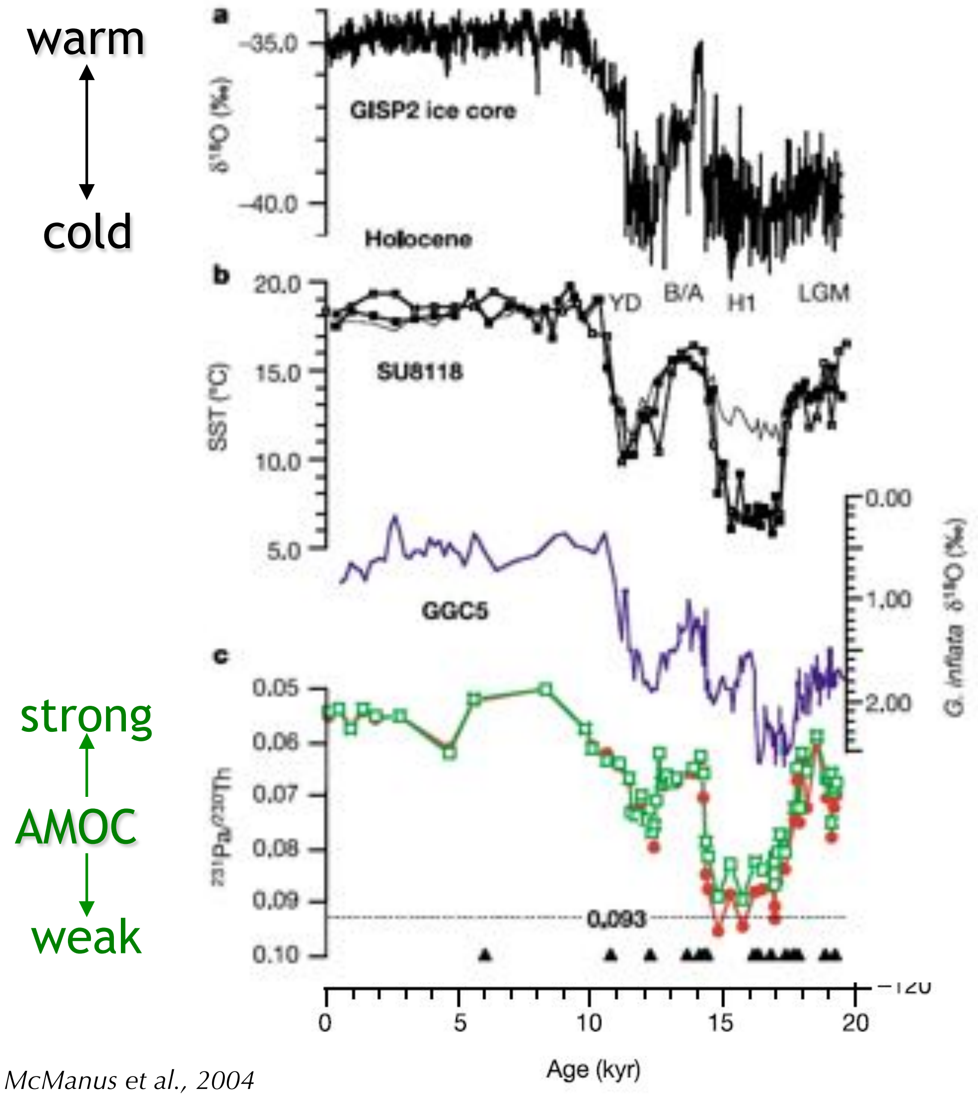
Geostrophic method using $\delta^{18}O$ useful in Florida Straits, but difficult to apply elsewhere (lack of suitable cores and uncertain $\delta^{18}O$-density)

Pa/Th very promising in theory

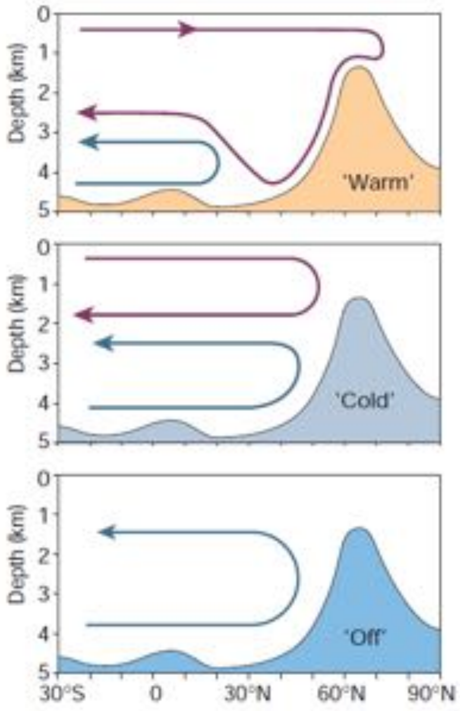
^{231}Pa and ^{230}Th produced in seawater

Differential scavenging rates → ratio can reflect rate of advection of water out of basin

AMOC shutdown during H1



McManus et al., 2004



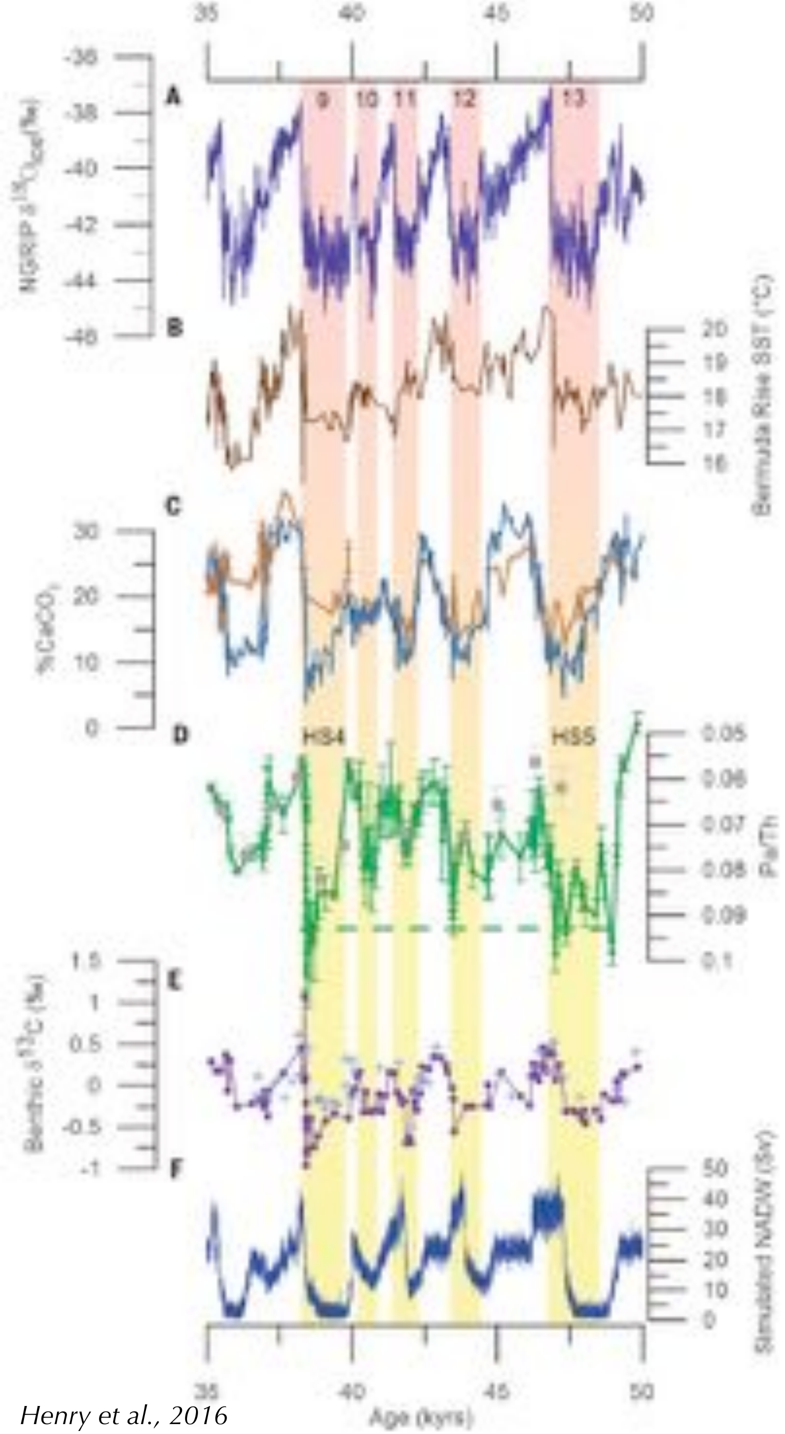
Rahmstorf, 2002

'Iconic' record from Bermuda Rise

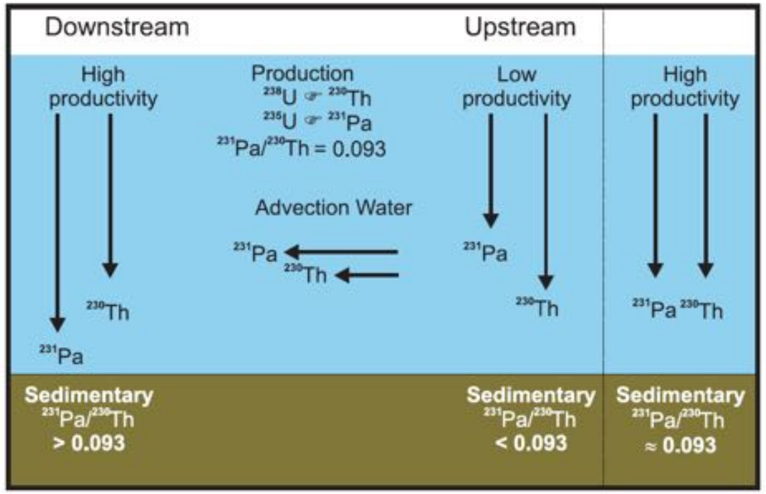
Suggests coupling of AMOC with abrupt climate change

Prolonged shutdown of AMOC during H1

…robust?



Henry et al., 2016



AMOC shutdown or productivity?

Export of water out of N Atlantic not only control on Pa/Th; particle type and flux are key controls.

Correlation of opal and Pa/Th at Bermuda Rise (note - opal is not always preserved).

Productivity can affect $\%CaCO_3$ and $\delta^{13}C$ as well as Pa/Th

Two hypotheses: proxies directly record AMOC changes; or change in (regional) circulation altered productivity

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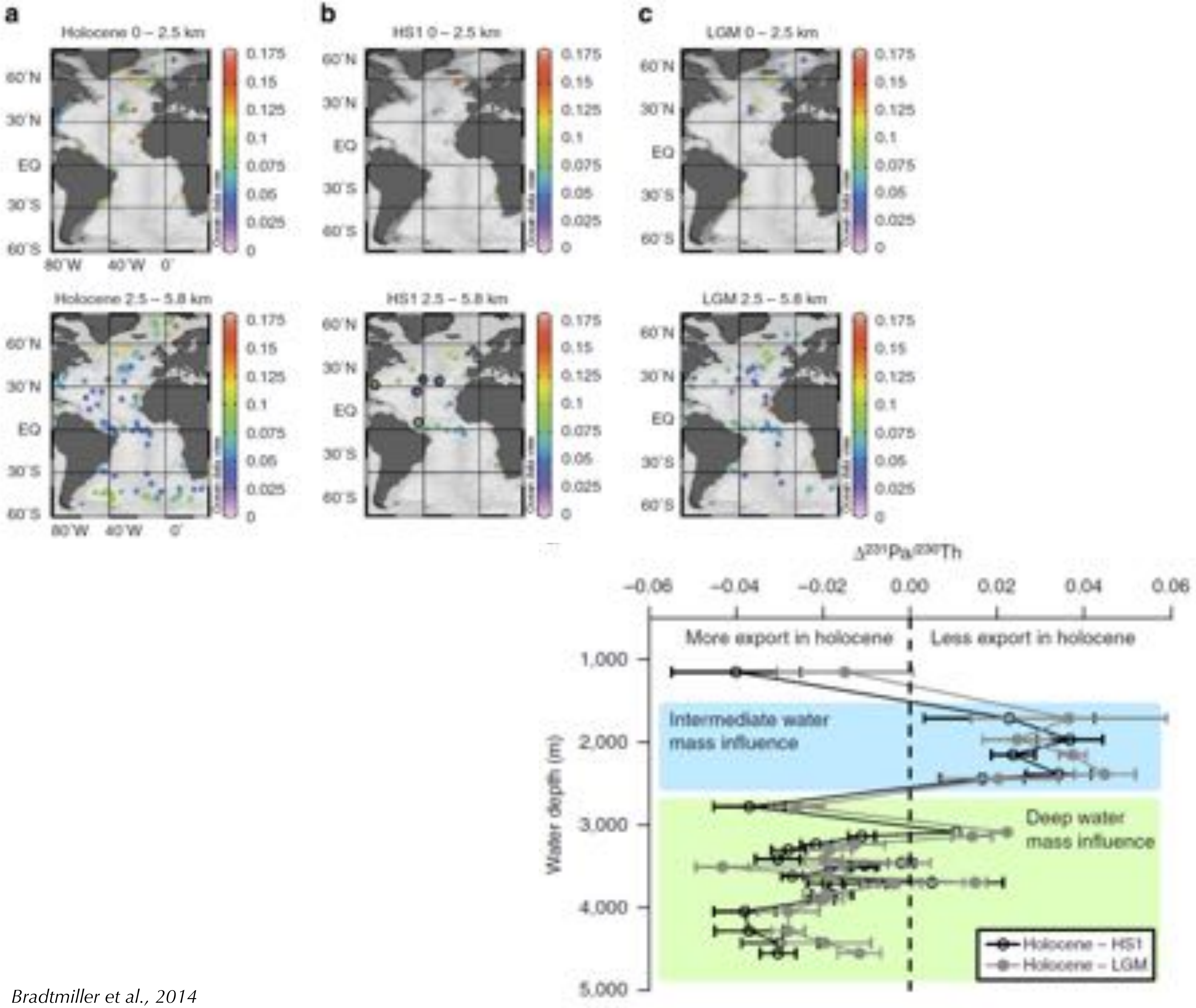

Bradtmiller et al., 2014

The way forward: spatial coverage

Rather than one core, use a spatial network (as done for ‘older’ proxies like d13C, Cd/Ca).

Can compare trends at sites with different variations in opal, or likely nepheloid layers

AMOC weakened but not shutdown.

But now lack resolution (just time slices) – a lot of work to have many high res, well-dated Pa/Th records

Looking at different states: Glacial abrupt events

- Paleo revealed abrupt climate changes and associated shifts in ocean circulation
- Lots of evidence supporting, for example, changes in Nordic Seas and surface Atlantic; less certain evidence for integrated AMOC change
- Quantification and details on timing and mechanisms still ongoing – a young science
  - H1 shutdown of AMOC is a good example of 'Wunsch' case of story being told to explain data, being widely accepted and other records interpreted in this framework, until overwhelming evidence requires revision or new story – community slow to move on from Bermuda Rise Pa/Th as AMOC
- Why care about timing:
  - Bermuda Rise Pa/Th used as 'definitive' AMOC proxy eg target in transient modelling (Liu et al 2009); consequences for investigating what is relationship between forcing and AMOC response (hysteresis, sensitivity, recovery timescale)
  - Deglacial useful analogue for determining role of AMOC on atm CO_2 and mechanisms (eg abrupt jumps during H1; Marcott et al 2014).

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AMOC: extending instrumental data

Convergence of findings from observations, modelling, paleoceanography. Use spatial network of sites. Outstanding issues of timing, cause and fingerprints of AMOC change.

AMOC: extending instrumental data

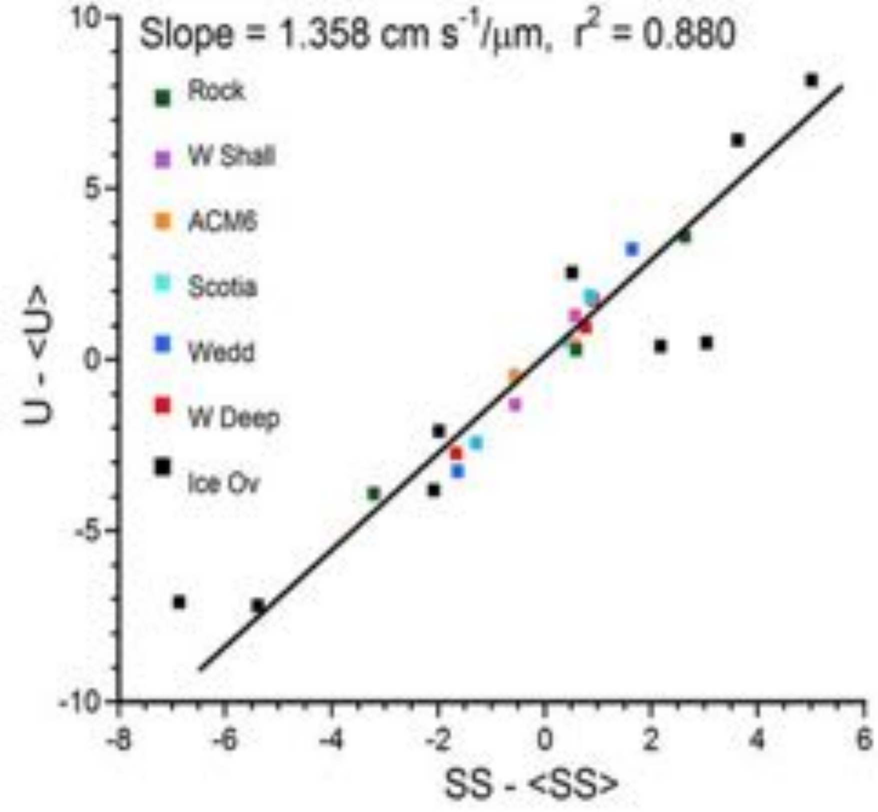
- Is there a recent AMOC trend? Is it exceptional? Is it anthropogenic? Multidecadal or longer?
- What causes AMOC changes, now and during Holocene?: Overflows; Lab Sea; deep water formation; DWBC transport?
- Random juxtaposition of different variability in components determines overall AMOC? Or a common driver, or one component dominates?
- Did AMV increase (why?), and was it linked to AMOC? Tipping points, thresholds and predictability.
- Impacts – correlate past AMOC changes to other Earth System components (inc. ecosystems) and use models to explore possible mechanisms.

Investigating components: deep-sea currents

Depth transects of cores using grain size analysis to reconstruct boundary currents

Calibrated sortable silt mean grain size

Obtained depth transects of high res sediment cores in suitable location



McCave, Thornalley & Hall, 2018

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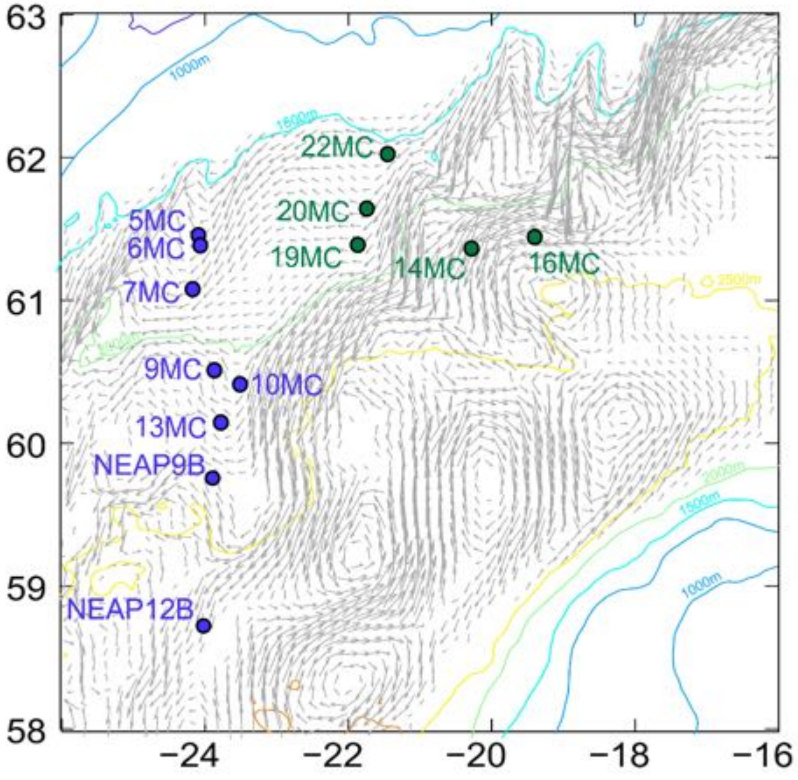


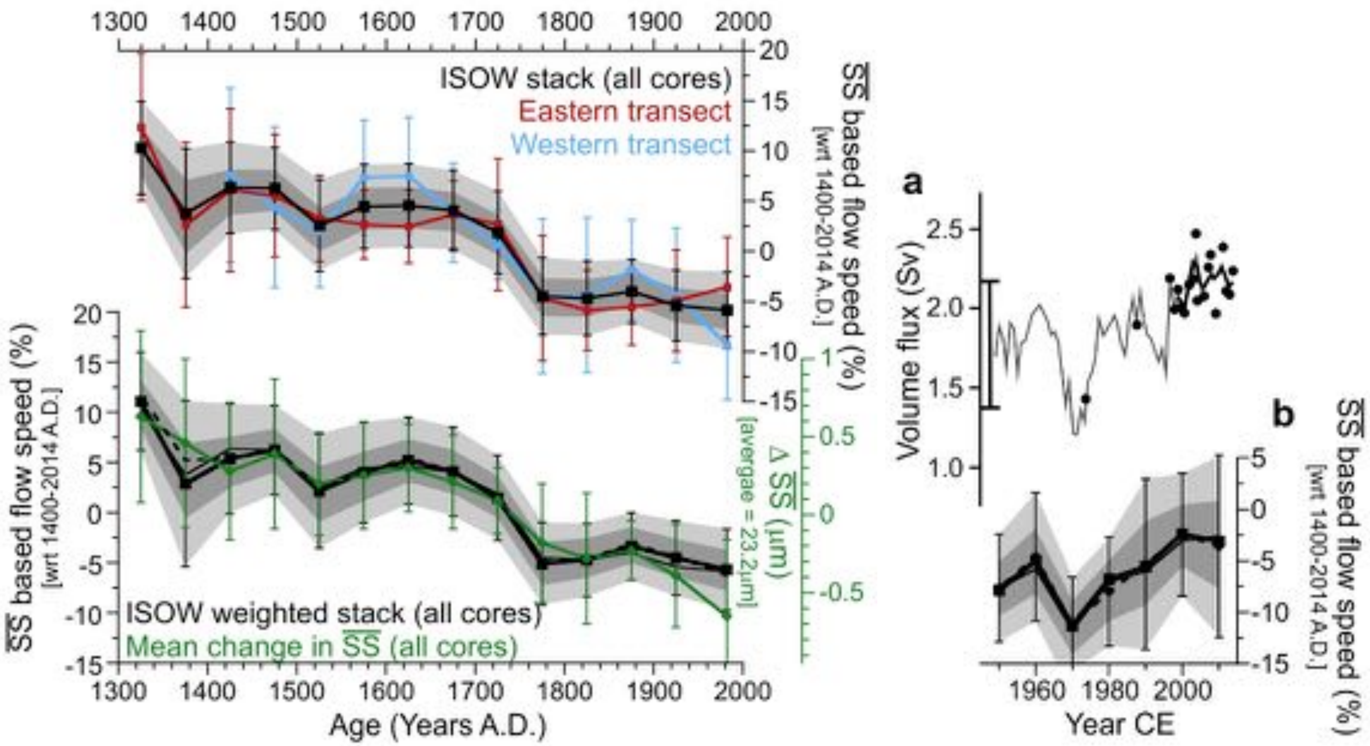
Investigating components: deep-sea currents

Long-term decline of ISOW, yet little C20th change (agree with obs.)

Explore mechanisms of control on ISOW (similar to regional climate → convection in Nordic Seas

Differs to DSOW (not shown), where strong EGC (and sea-ice export) associated with vigorous DSOW

~10-15% decline in flow speed



No clear change in 20th century

Thornalley et al., in prep.

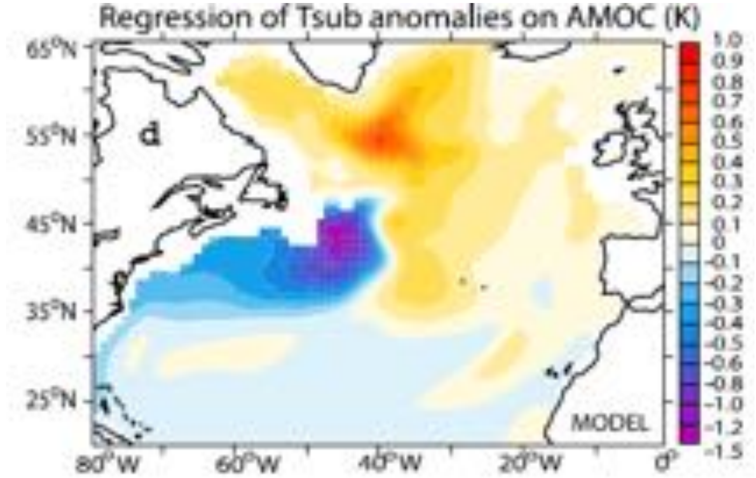
What about integrated AMOC proxies: beyond the Rapid array

Temperature fingerprints

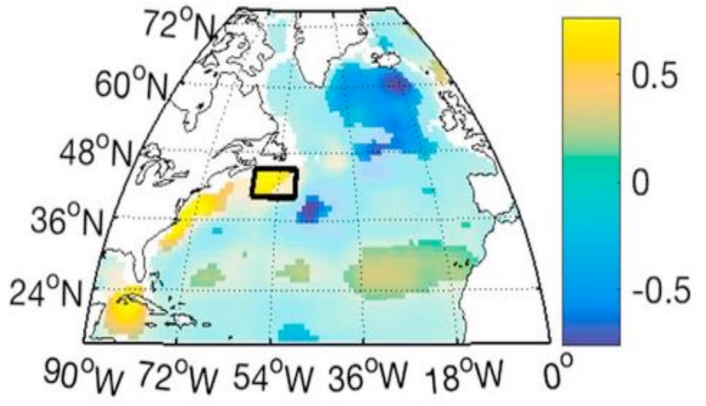
Subsurface vs surface

EOF/dipole vs anomaly wrt global av.

Warming hole varies in models; not explained by local mixing; generally upstream of deep water formation sites; DWF MLD leads to weaker AMOC and then warming hole

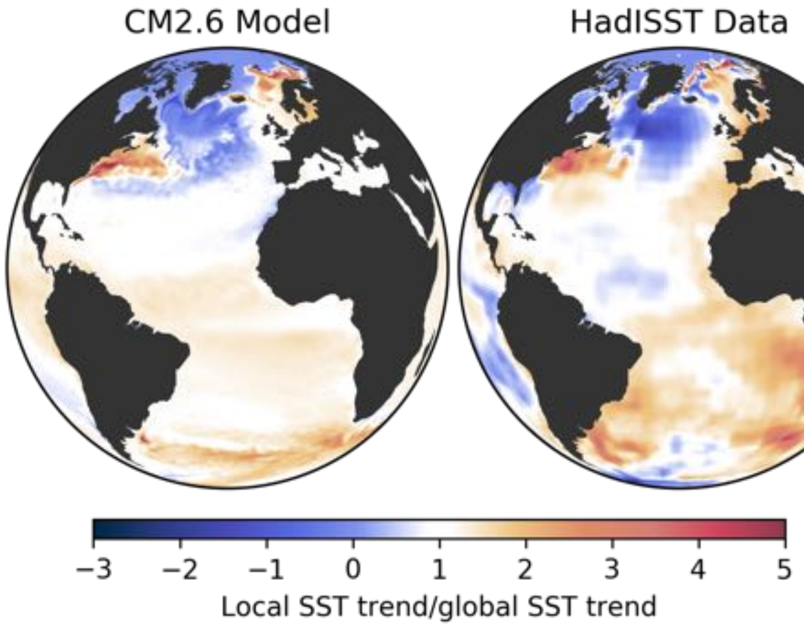


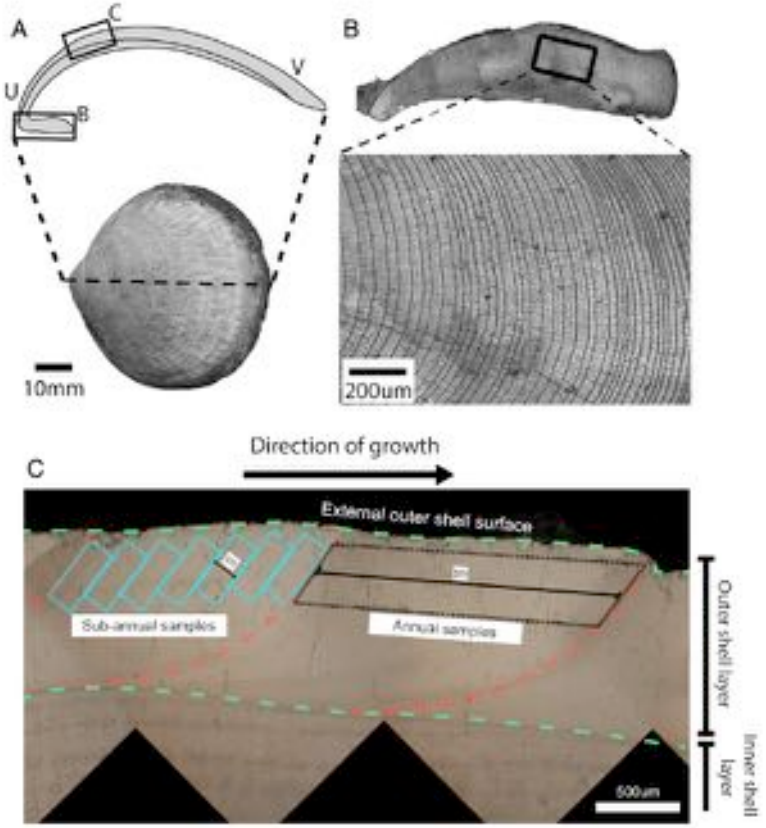
Zhang 2008, model Tsub (400m)
(also similar to observed leading EOF)

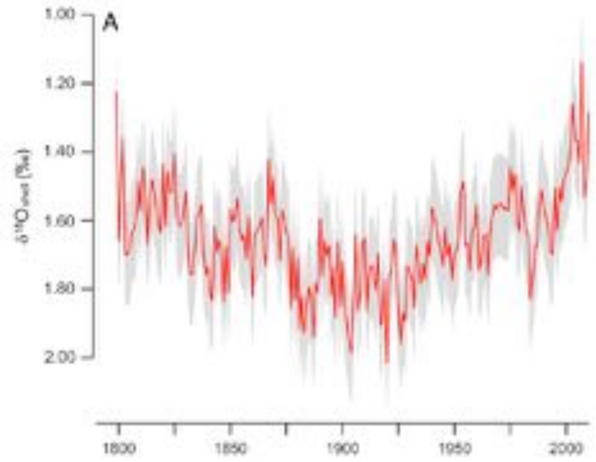


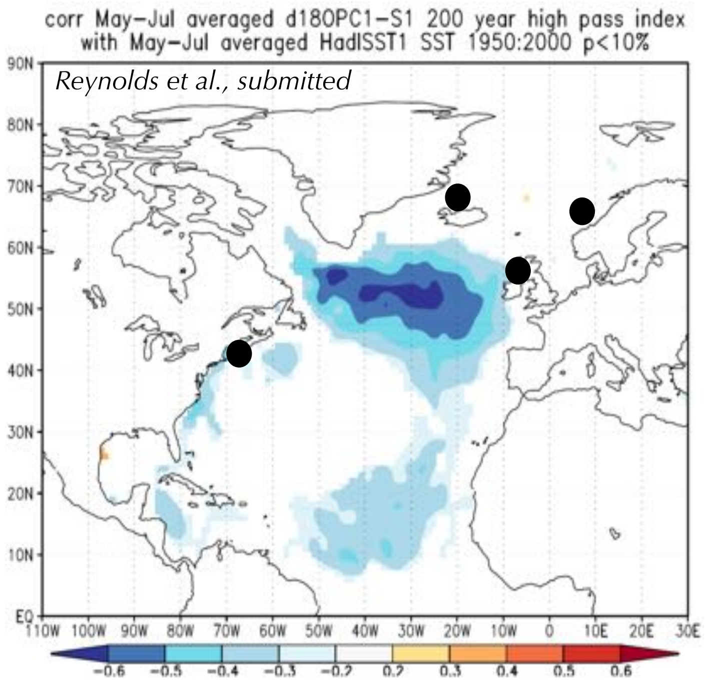
Smeed et al 2018 Tsub (top 1km) obs
weak-strong AMOC (Rapid 26N)

Rahmstorf et al 2015; Caesar et al 2018, SPG SST – NH/global SST







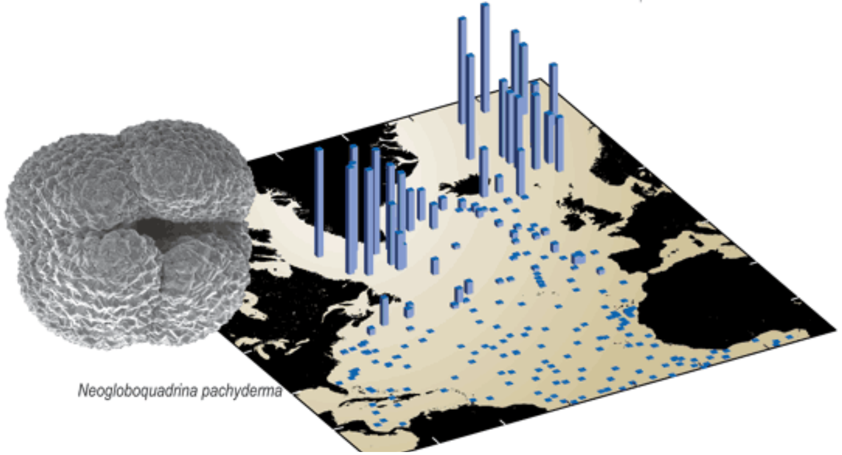


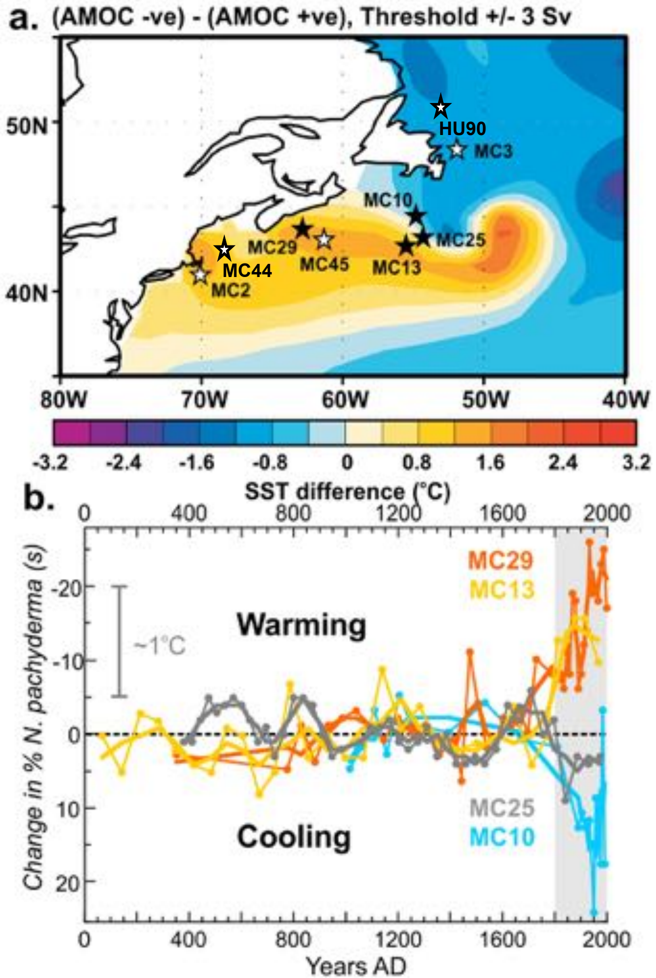
Spatial networks of sites

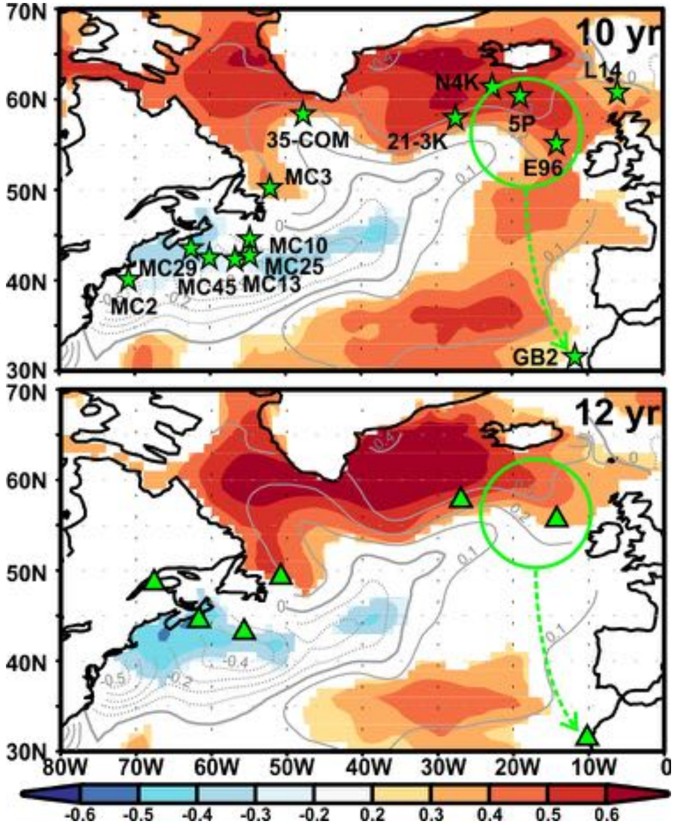
Temperature fingerprints of AMOC require spatial network of sites

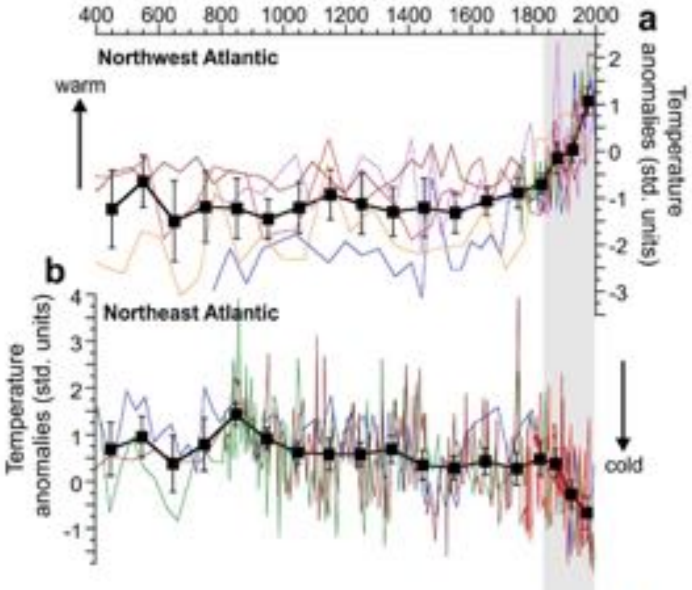
Long-lived molluscs (eg *A. islandica*), **annually** banded

But restricted to coastal sites and only $\delta^{18}O$ (varies with both T and S; poor density proxy at low temperatures)









Spatial networks of sites

Temperature fingerprints of AMOC require spatial network of sites

Sediment cores – foram temperature proxies – simple and established

Slightly broader site distribution but more uncertain dating

We have used existing data to reconstruct spatial patterns; many other (higher) res cores exist to improve network

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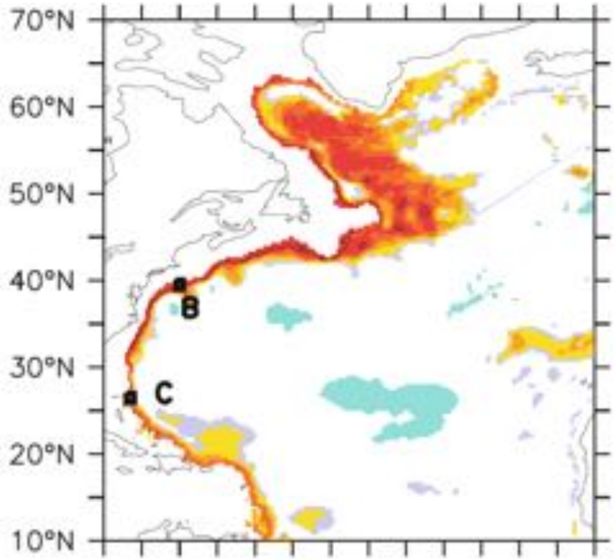
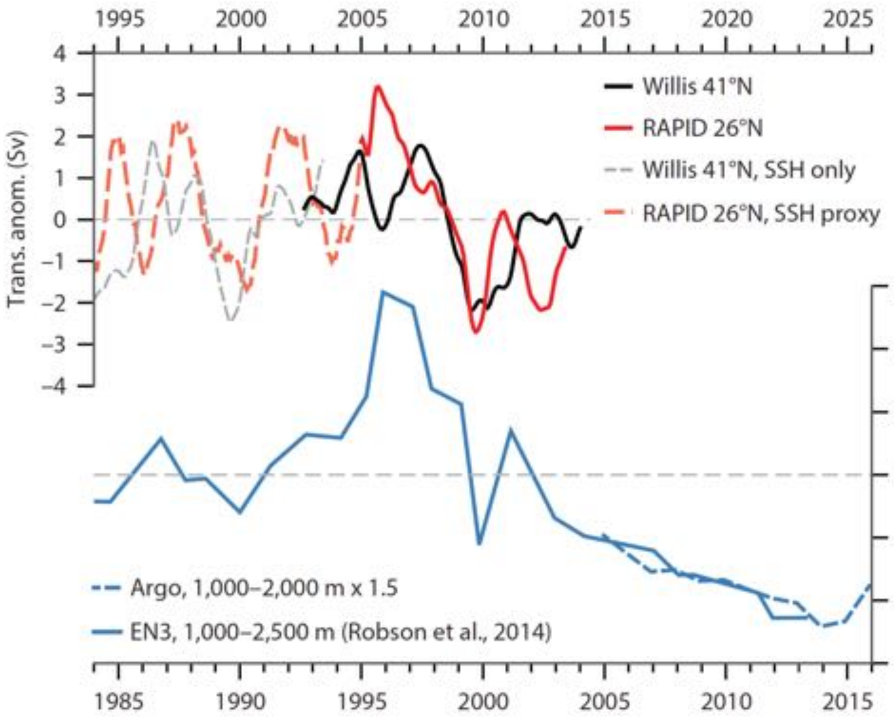
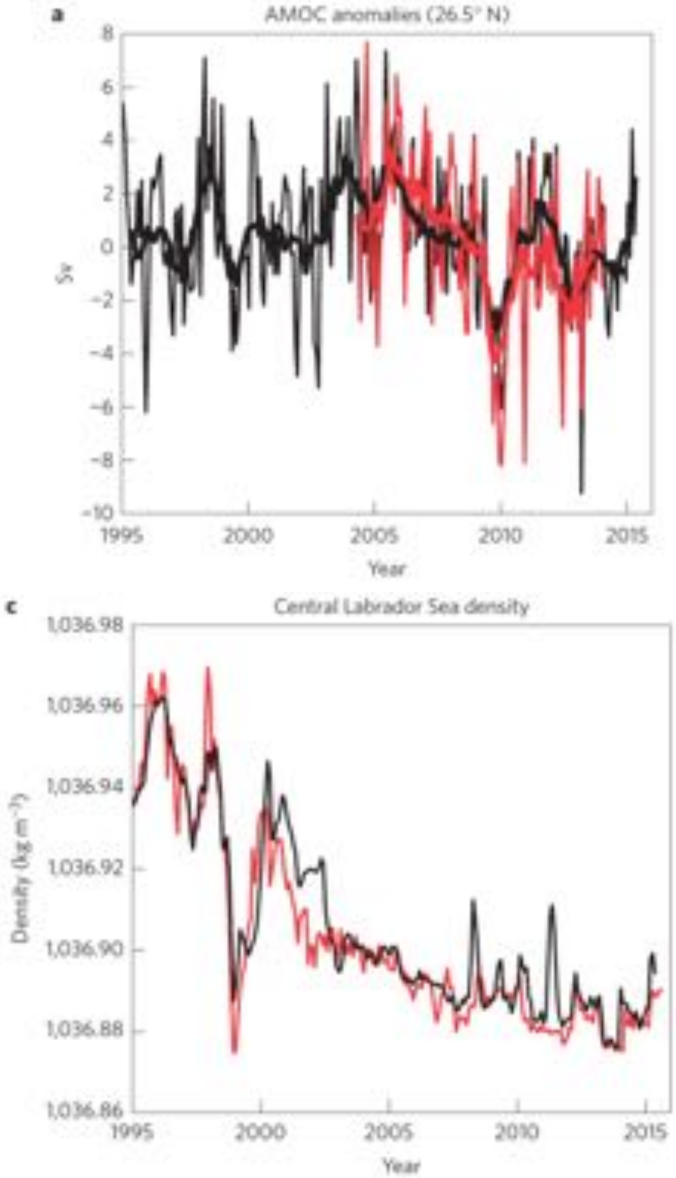


Hodson & Sutton, 2012



Frajka-Williams et al., 2016



Jackson et al., 2016

AMOC and deep Lab Sea density

Models suggest coupling of deep Labrador Sea density and AMOC (with 10yr lag)

Longer observations of density used to constrain AMOC further back

Propagation of density anomalies along western boundary,

Also alters DWBC velocity, which can be reconstructed using grain size analysis in cores

dLSD and Tsub proxies for Industrial era

dLSD, DWBC flow speed, SPG UOHC and Zhang Tsub suggest persistent multidecadal variability throughout C20th.

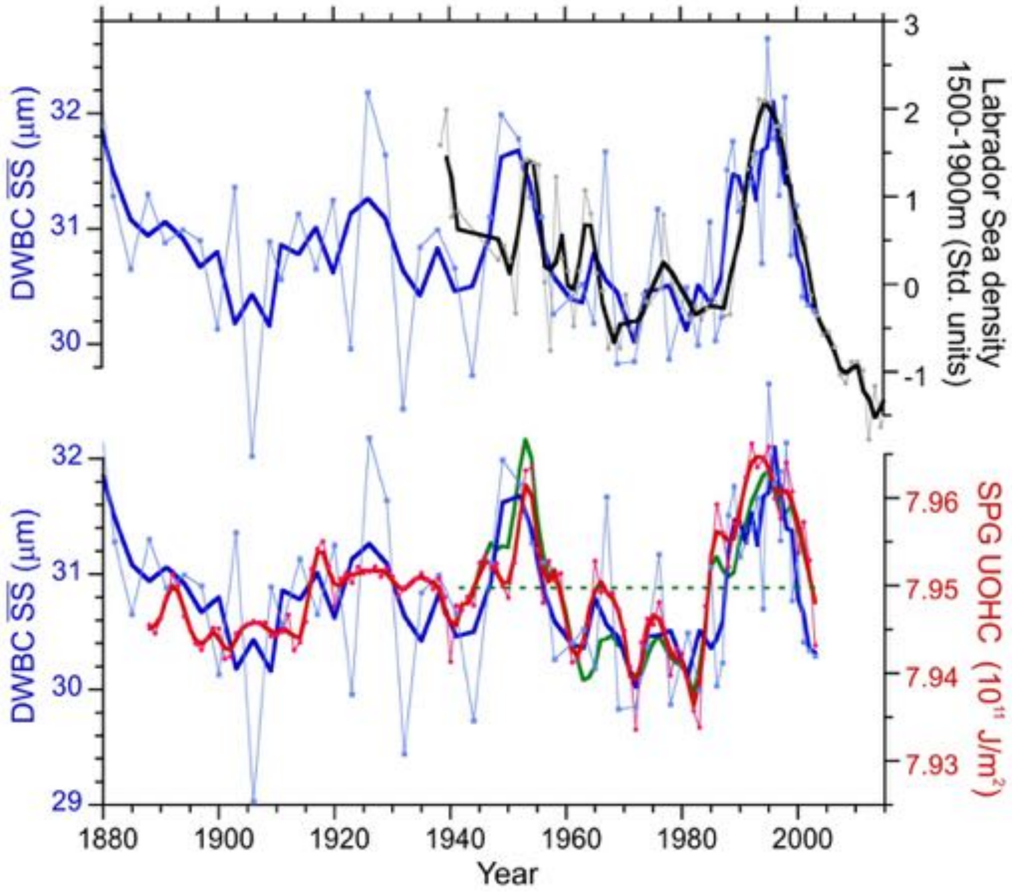
Thornalley et al 2018:

-Proxy reconstructed flow speed of DWBC [1.7km Cape Hatteras]

-Deep Labrador Sea density [from Yashayaev]

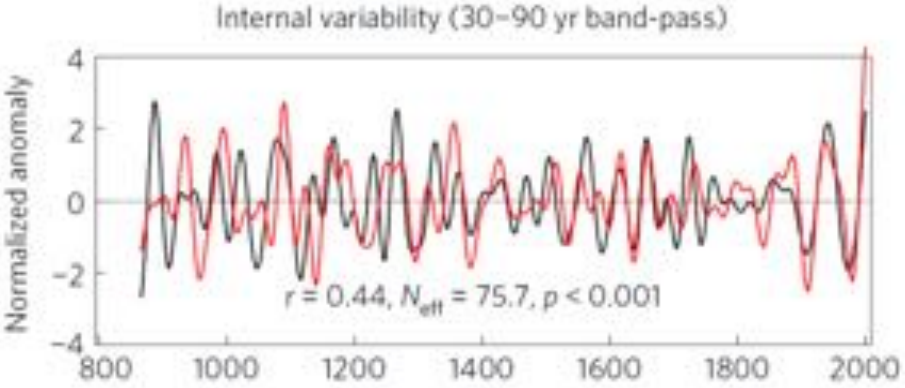
-Subpolar gyre upper ocean heat content (12 yr lag) [EN4 data]

-Tsub AMOC fingerprint (12 yr lag) [from Joyce and Zhang 2010; WOD09 data]



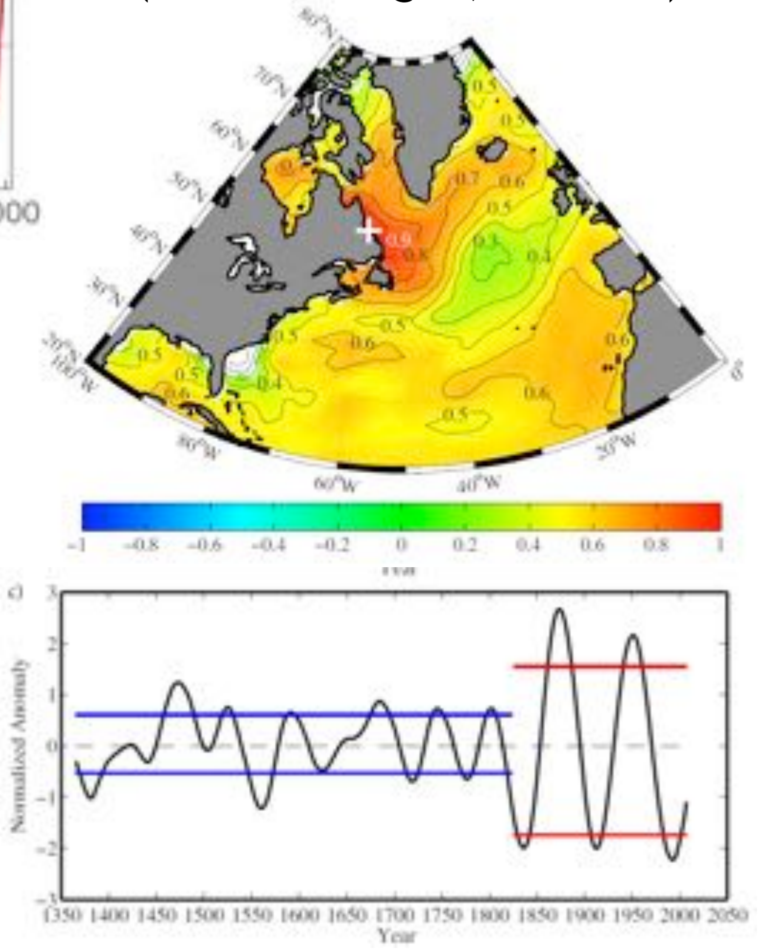
AMV and AMOC

AMV reconstruction (terrestrial based)



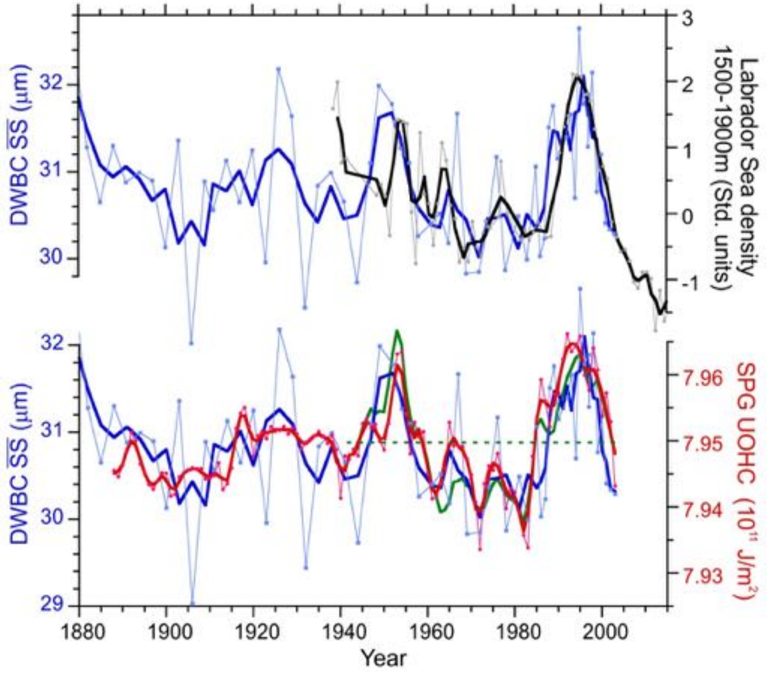
Wang et al., 2017

AMV reconstruction (coralline algae, Lab Sea)



Moore et al., 2017

Atlantic circulation proxies



Thornalley et al., 2018

AMV linked to AMOC?

Shift in AMV in the Industrial era?

Extend high res DWBC and Tsub proxy records to explore (multi)decadal variability in AMOC

Are any shifts in AMOC associated with indicators of approaching tipping point?

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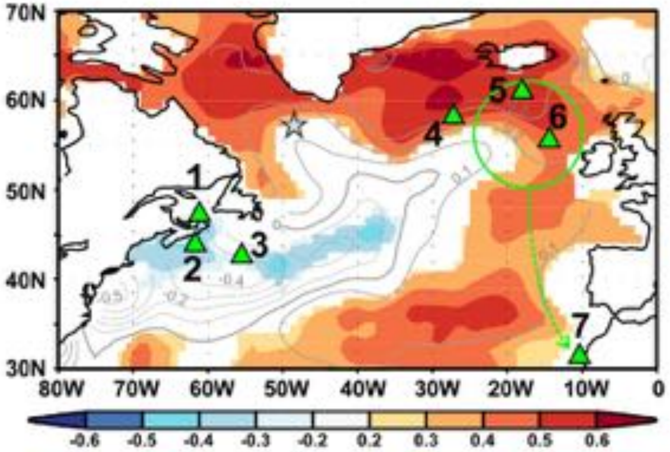
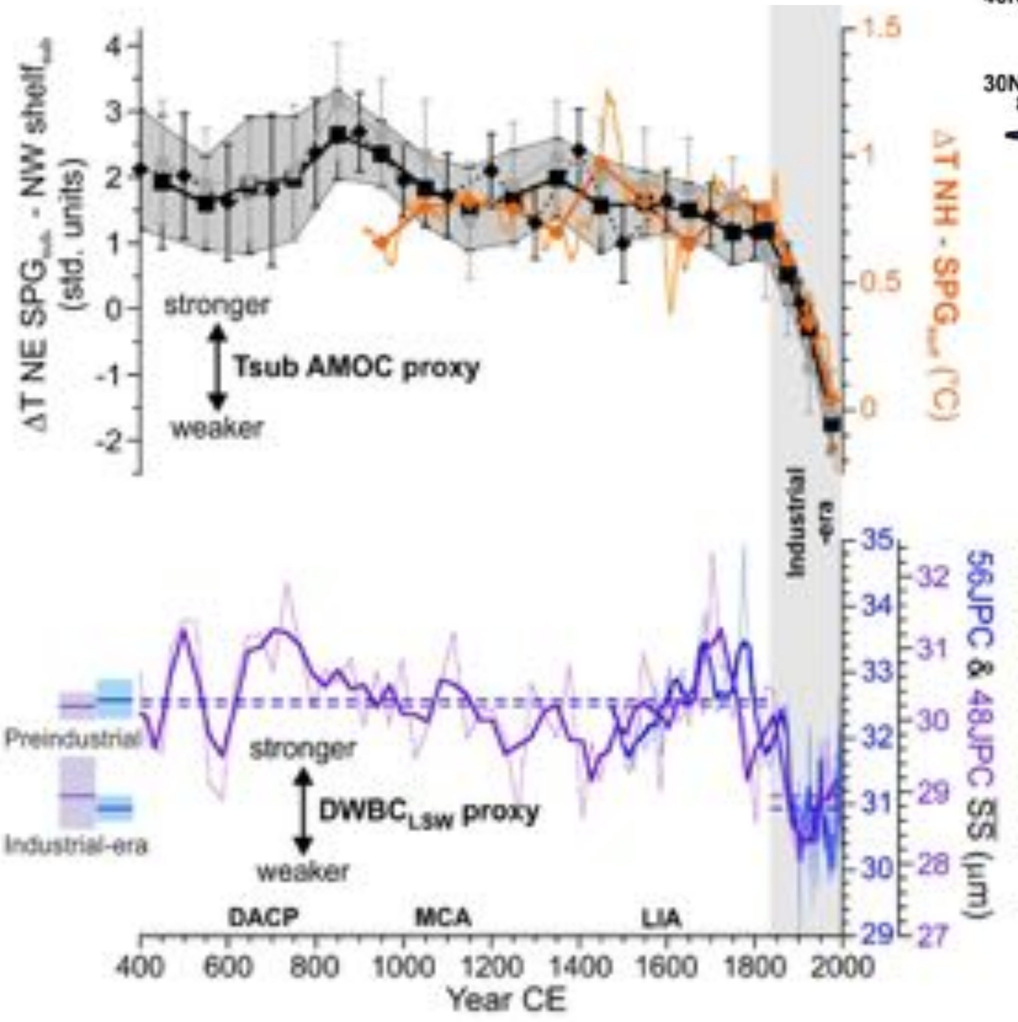




Thornalley et al., 2018

Context of recent change

Proxies suggest recent variability sits on a larger shift from stronger AMOC prior to ~1850 AD to modern weaker state.

Tsub (and Rahmstorf) suggest continued, gradual decline

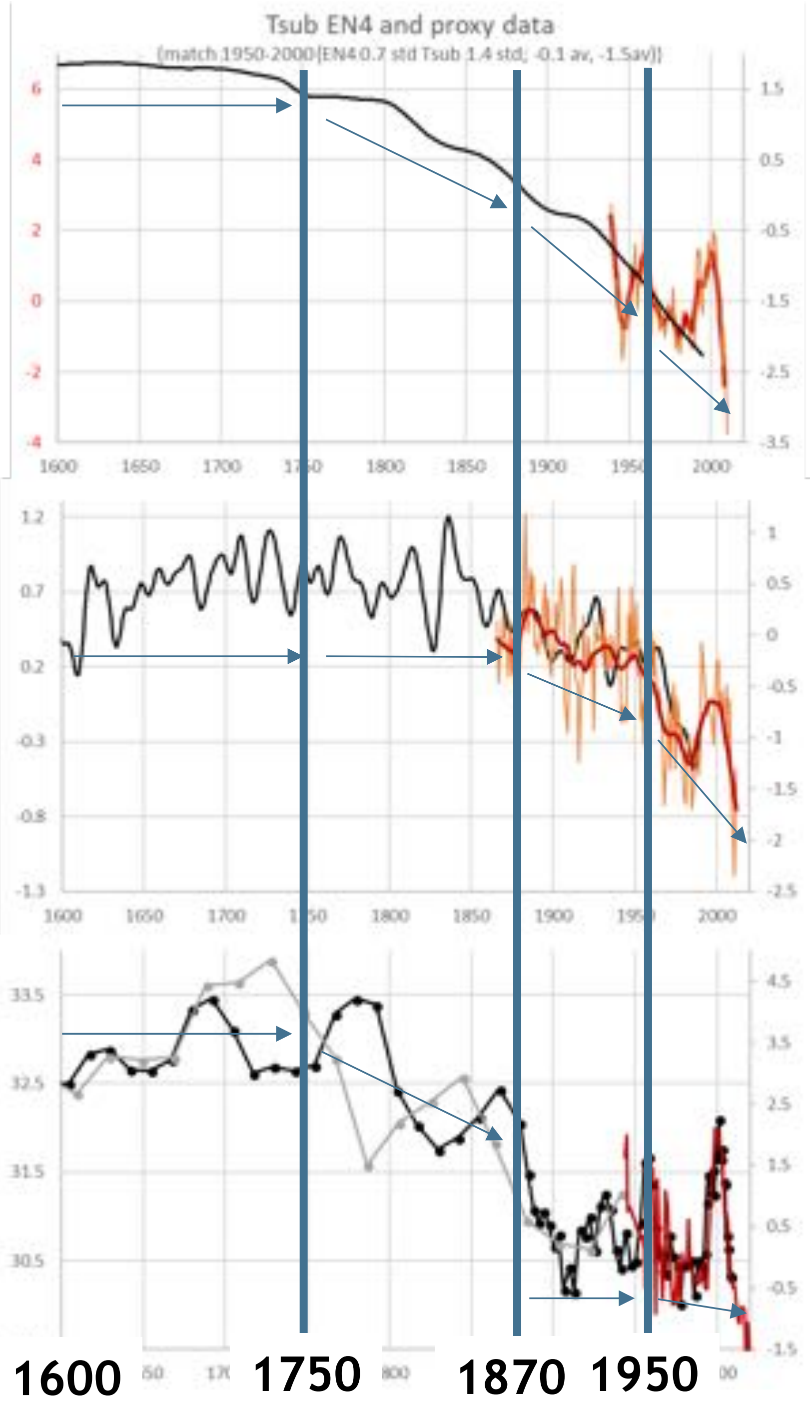
DWBC (and observational based Zhang Tsub) suggest little C20th decline

Instrumental/proxy data

Zhang Tsub EOF/dipole (NWATL-NEATL)

Rahmstorf SST index (SPG-global/NH)

DWBC flow speed (dLSD)



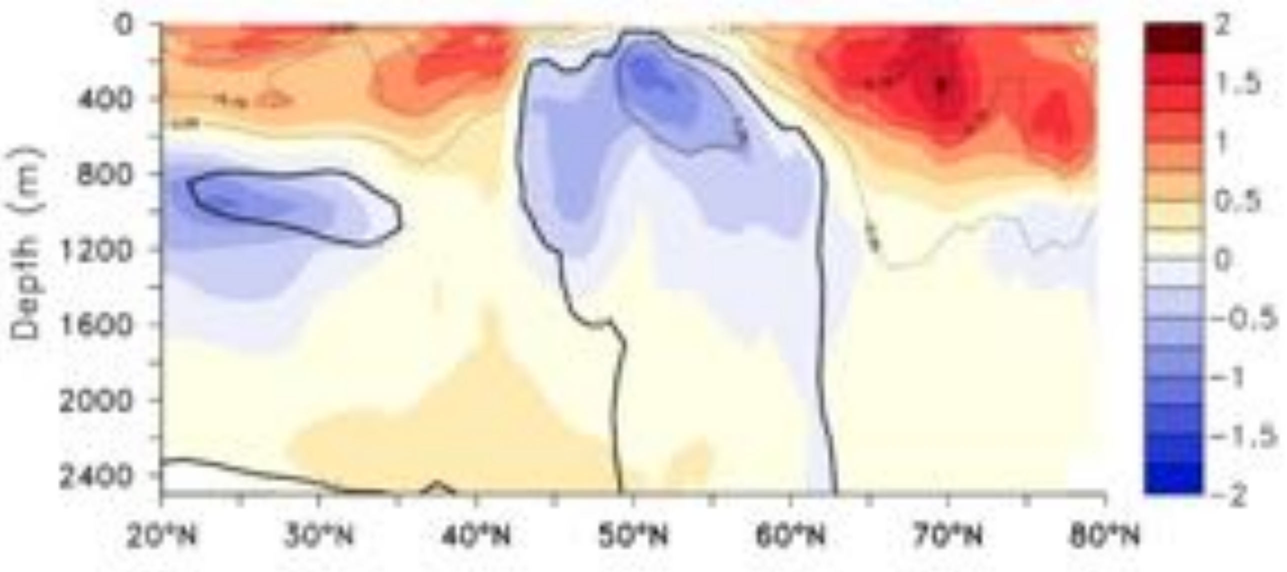
The timing of recent AMOC weakening

Tsub vs SST (EOF vs anomaly...validity of removing NH/global)

DWBC sensitive to LSW, non-linear

Warming hole caused by OHT, also affected by SPG. AMOC, or SPG, or both alter, not necessarily in phase.

Last millennium MPI-ESM simulation
C20th linear trend in ocean temperature



Jungclaus et al., 2014

The timing of recent AMOC weakening

LIA – weak SPG, strong AMOC (heat convergence)

C20th – strong SPG, weak AMOC (heat divergence – warming hole.

But timing of SPG and AMOC change? Requires:

(i) spatial network of cores to constrain patterns. Compare subpolar SST with Tsub and reconstructions of various AMOC components.

(ii) Modelling and observation of patterns associated with AMOC and SPG and "a more dynamical understanding of how the subpolar warming hole arises in association with an AMOC decline".

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Lessons & Suggestions (1)

- AMOC is hard to reconstruct; AMOC components easier...and just as useful?
  a. AMOC at what latitude?
  b. Presumably AMOC can vary in different ways
- We can measure quantities in archives very well, but difficulty is sometimes the link to the ocean parameter → use simple proxies, well (replicated, high res, well-dated, spatial network). Convergence of different approaches to provide weight of evidence.
- Paleoceanography has not (always) focussed on questions that this community has been addressing. Moving forwards:
  a. Use predictions based on obs/model findings (eg AMOC fingerprint)
  b. Collect a spatial network of data to test the hypothesis (eg of AMOC weakening)
  c. Use stats and inverse methods to test robustness of results (reject null hypothesis)
- Targeted approach: what locations and ocean properties would help us constrain which models are behaving more like the real world

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Lessons & Suggestions (2)

- Recognise common question between paleo/obs/models:
  a. What is the link between deep water formation, the DWBC and AMOC?
  b. What is ‘natural’ AMOC variability?
  c. What are the fingerprints of AMOC (& its individual components; & SPG) in SST, Tsub, SL?
  d. What are the Earth system impacts of AMOC and its components? (eg LIA not AMOC)
- Paleo has (inherent) weaknesses, but it is also essential: observational records are short (being extended at 1yr/yr), therefore how else can we test model behaviour on decadal and longer timescales?
- Paleo work on AMOC is not a separate discipline, but just one tool we can use alongside observational and modelling work to answer the subset of questions that we are all interested in.