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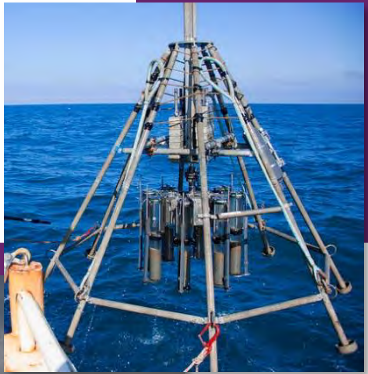
Paleo-AMOC Review



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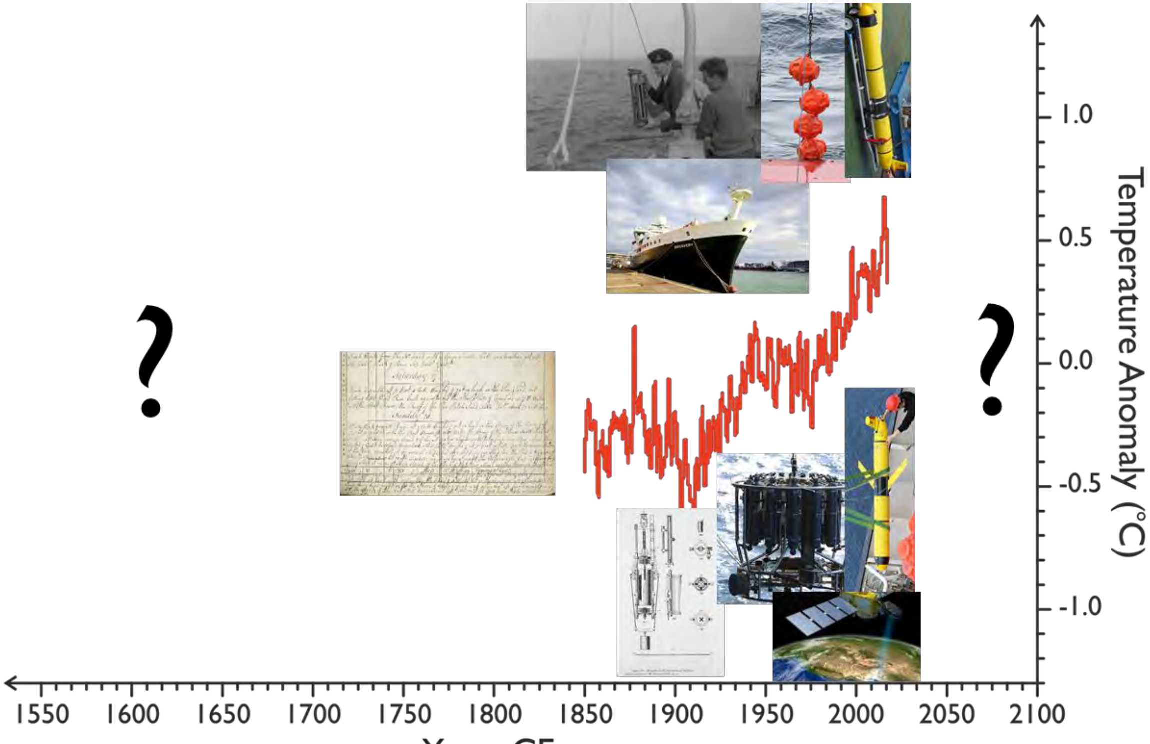
Thanks to all co-authors, collaborators and the AMOC community

Outline

- Paleoceanography and progress studying past AMOC
- The role of AMOC on past climate changes
- AMOC during the last millennia – What have we learnt?

Motivation to study the past ocean

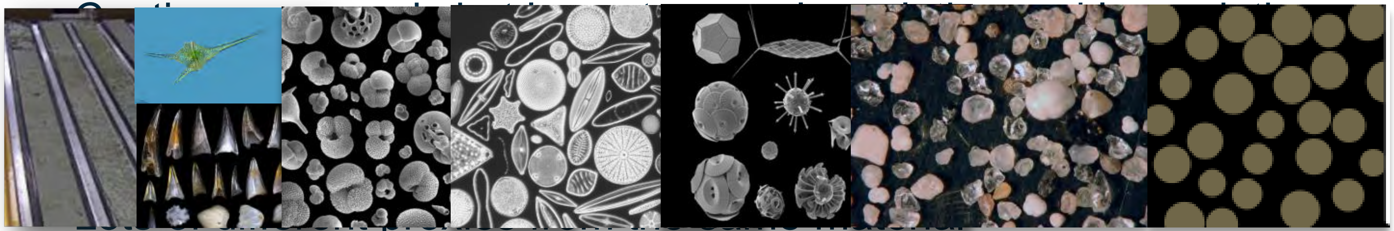


Global SST_Kennedy et al., 2011_JGR

'The lack of long-term measurements of the global ocean and changes in the observing system over time makes documenting and understanding change in the oceans a difficult challenge' IPCC13 report

Progress made in reconstructing the past ocean

Sedimentary Archives



Banded Archives

Mg/Ca

Sr/Ca

Cd/Ca

El/Ca

$\delta^{18}O$

$\delta^{13}C$

εNd

$^{231}Pa/^{230}Th$

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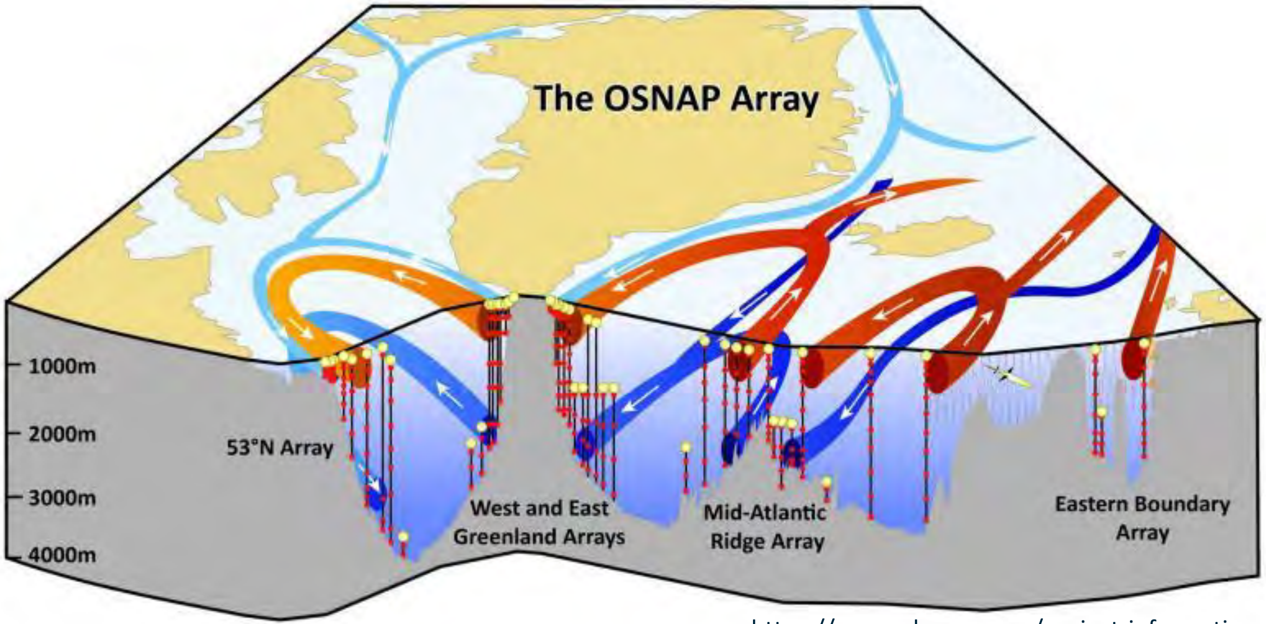
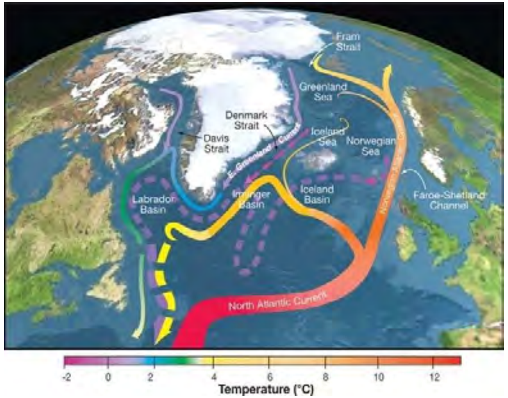
What can we learn from these about past AMOC?



https://www.ukosnap.org/project-information

What can we learn from these about past AMOC?

Curry and Mauritzen 2005

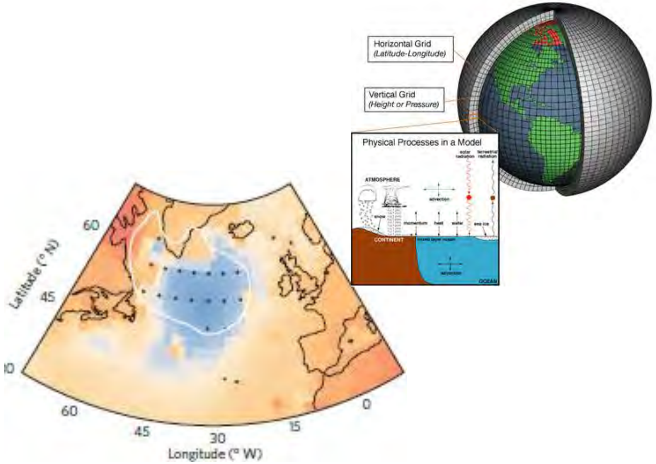


1. Past changes in ocean properties of certain AMOC branches

(e.g. temperature, salinity, nutrients, sea-ice, drift ice, primary productivity, frontal shifts)

2. Climate Model Analysis

- Data-Model comparisons to study ocean processes
- AMOC surface fingerprints *(e.g.Thornalley et al., 2018)*



Rahstorf et al, 2015, Nat.Clim.Change

3. Proxies representing dynamic ocean processes:

- Whole basin overturning proxies *($^{231}Pa/^{230}Th$; e.g. Lippold et al., 2019)*
- Near Bottom Deep Flow Vigour *(e.g. SS, k; e.g. Thornalley et al., 2018, Kissel et al., 2013)*
- Water mass geometries *(e.g. NADW, SPMW using $\delta^{13}C$;εNd;Cd/Ca; e.g. Oppo et al., 2000, Gebbie et al., 2014)*
- Ocean ventilation *(e.g. ^{14}C, Robinson et al., 2005)*
- Combining ocean properties to calculate ocean dynamics *(e.g. Gulf Stream transport; Lynch-Stieglitz et 1999, Lund et al., 2006)*

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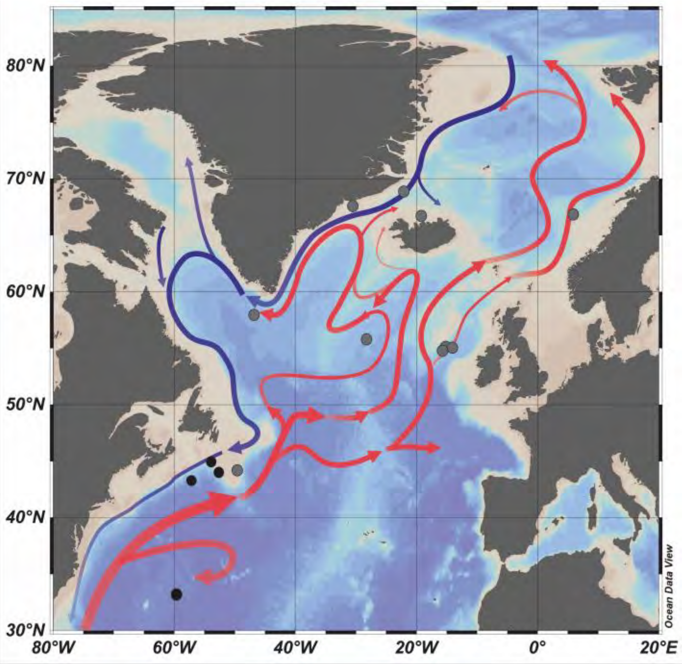
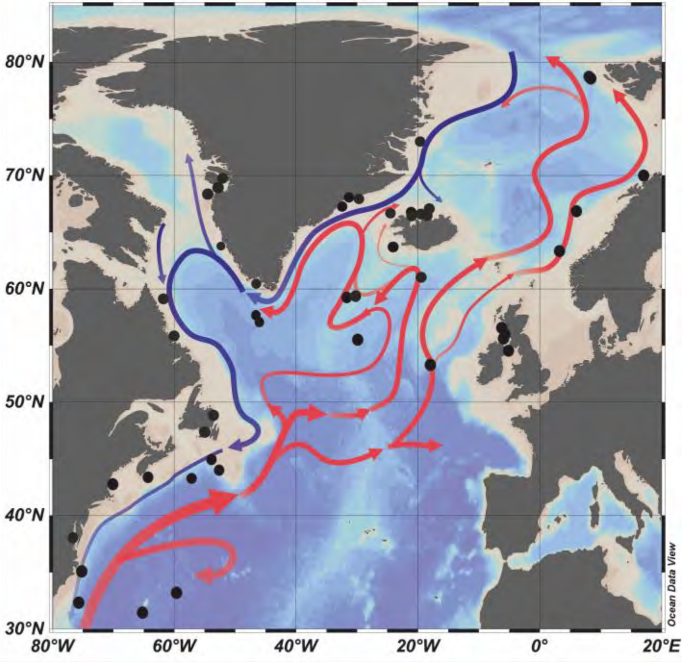
Progress in the last 20 years

Grey indicate marine records with no complete last 500 years/ >100 years/sample/limited age constraints

Available records ~20 years ago



Marine records to date



- Uneven distribution of records
- Large concentrations in coastal/shelf regions
- Disparities in resolution
- Insufficient overlap with ocean observations

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Records synthesized in Moffa-Sanchez et al., 2019 P&P

Progress in last few decades

- Increase the number of high-quality archives (temporal resolution)
- Increase in new proxies (more data)
- Better proxy calibrations →quantitative ocean reconstructions
- Better spatial coverage (regional versus localized picture)
- Computation advances have allowed physic-based interpretation of paleo-data

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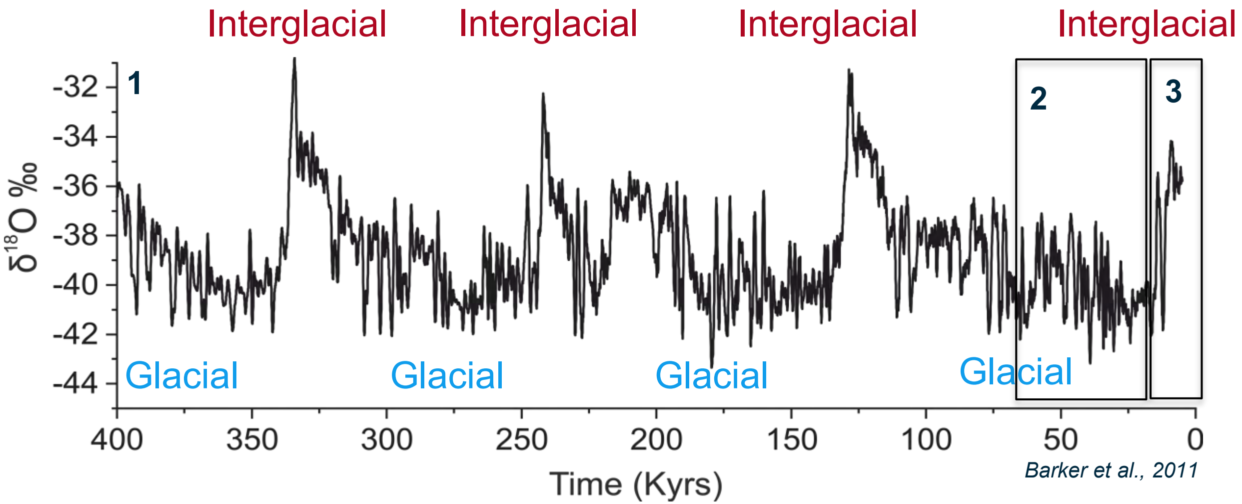
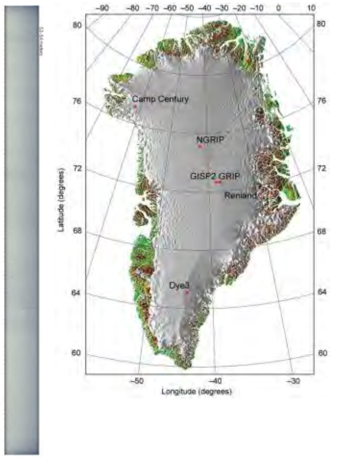
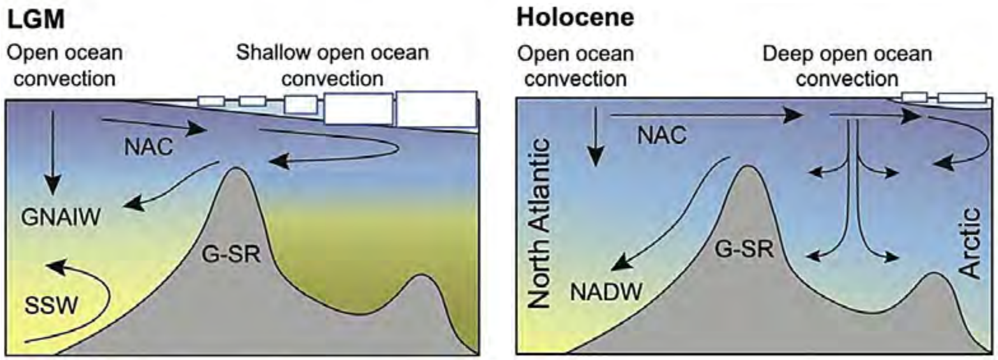
Role of the AMOC in Glacial-Interglacials



Barker et al., 2011





Mackensen and Schmiedl 2019, Earth Sci. Rev

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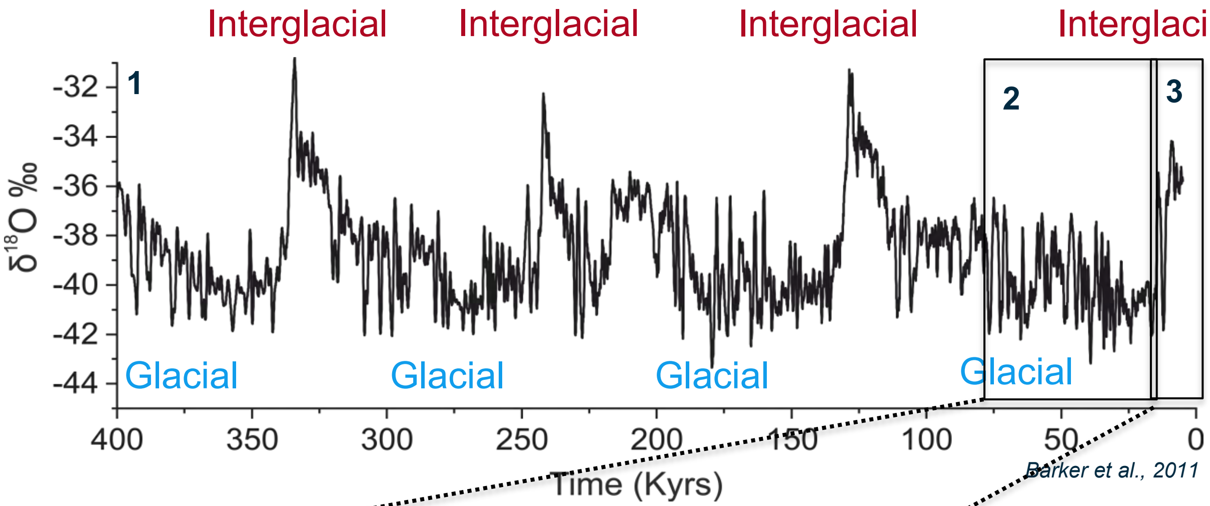
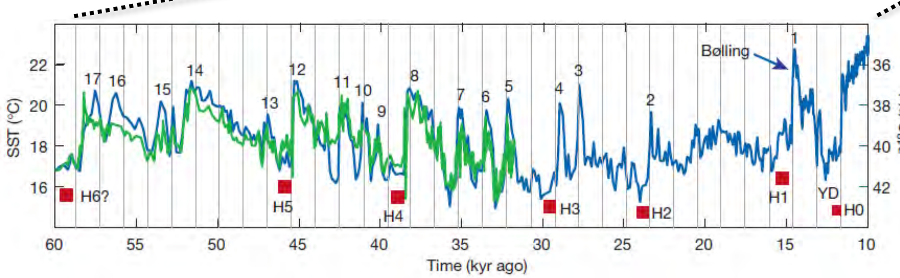
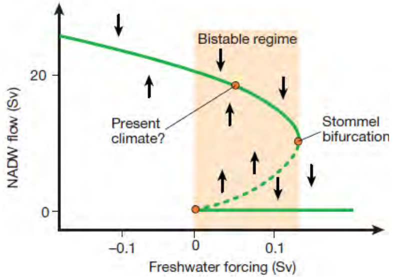
Role of the AMOC in Abrupt Climate Changes

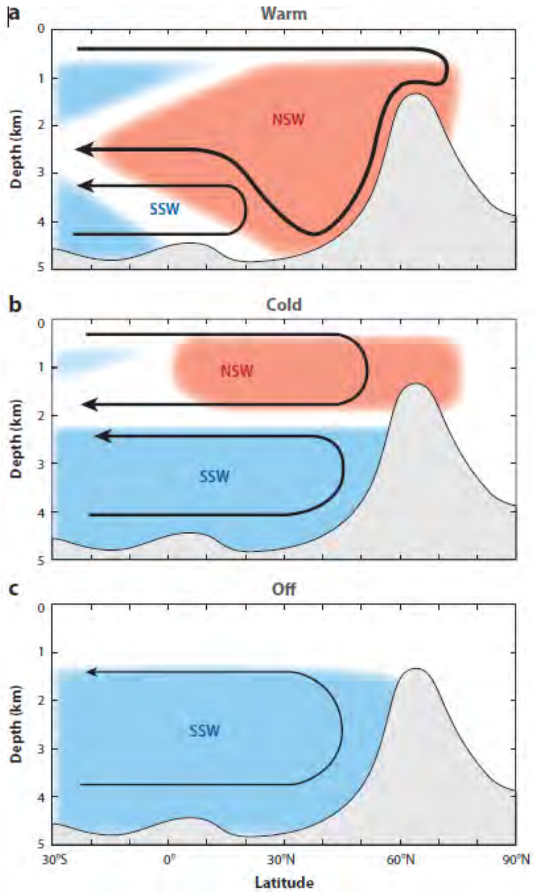


Barker et al., 2011



Rahmstorf et al., 2002





Lynch-Stieglitz 2016, Ann Reviews

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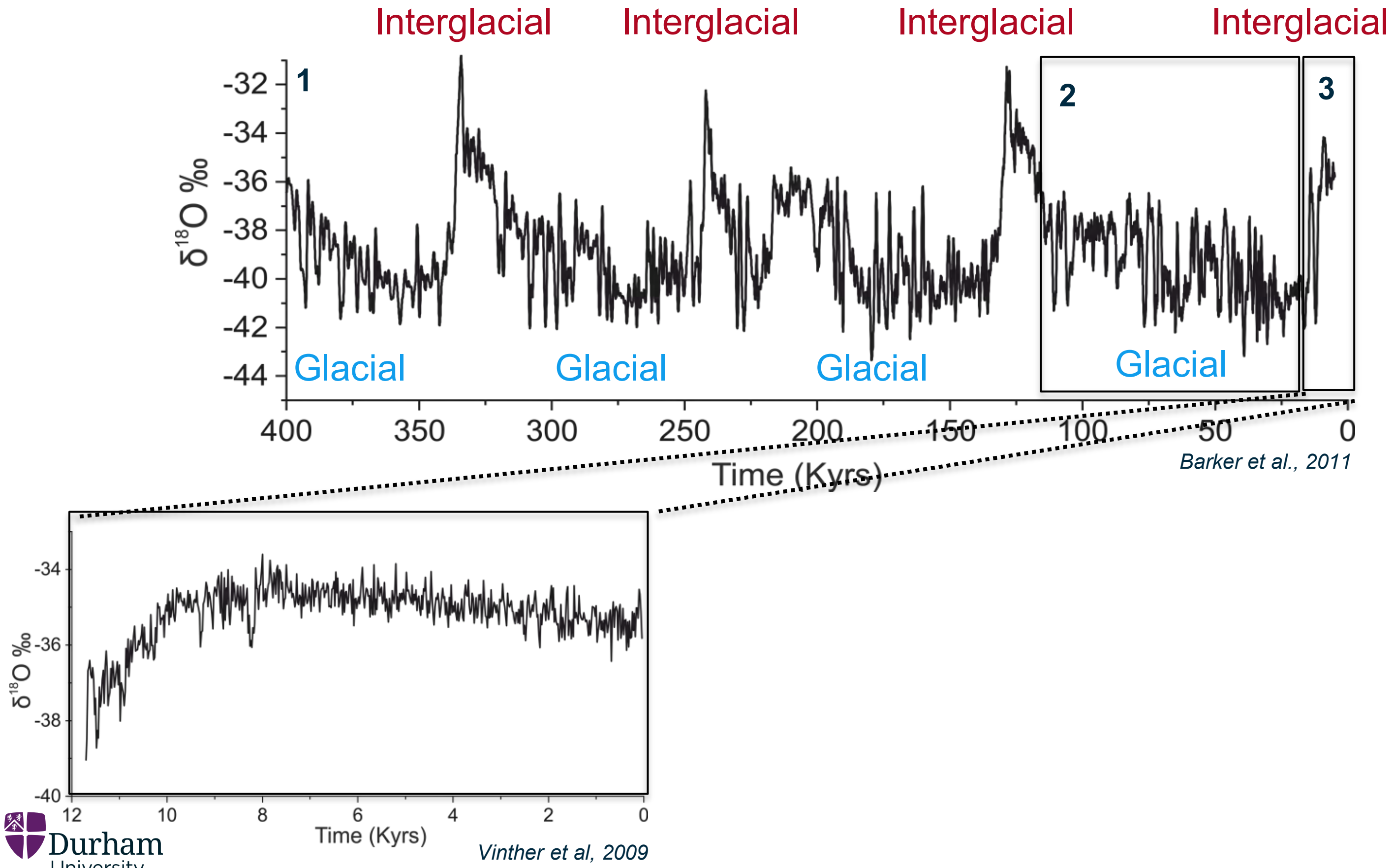
Role of the AMOC in the Holocene



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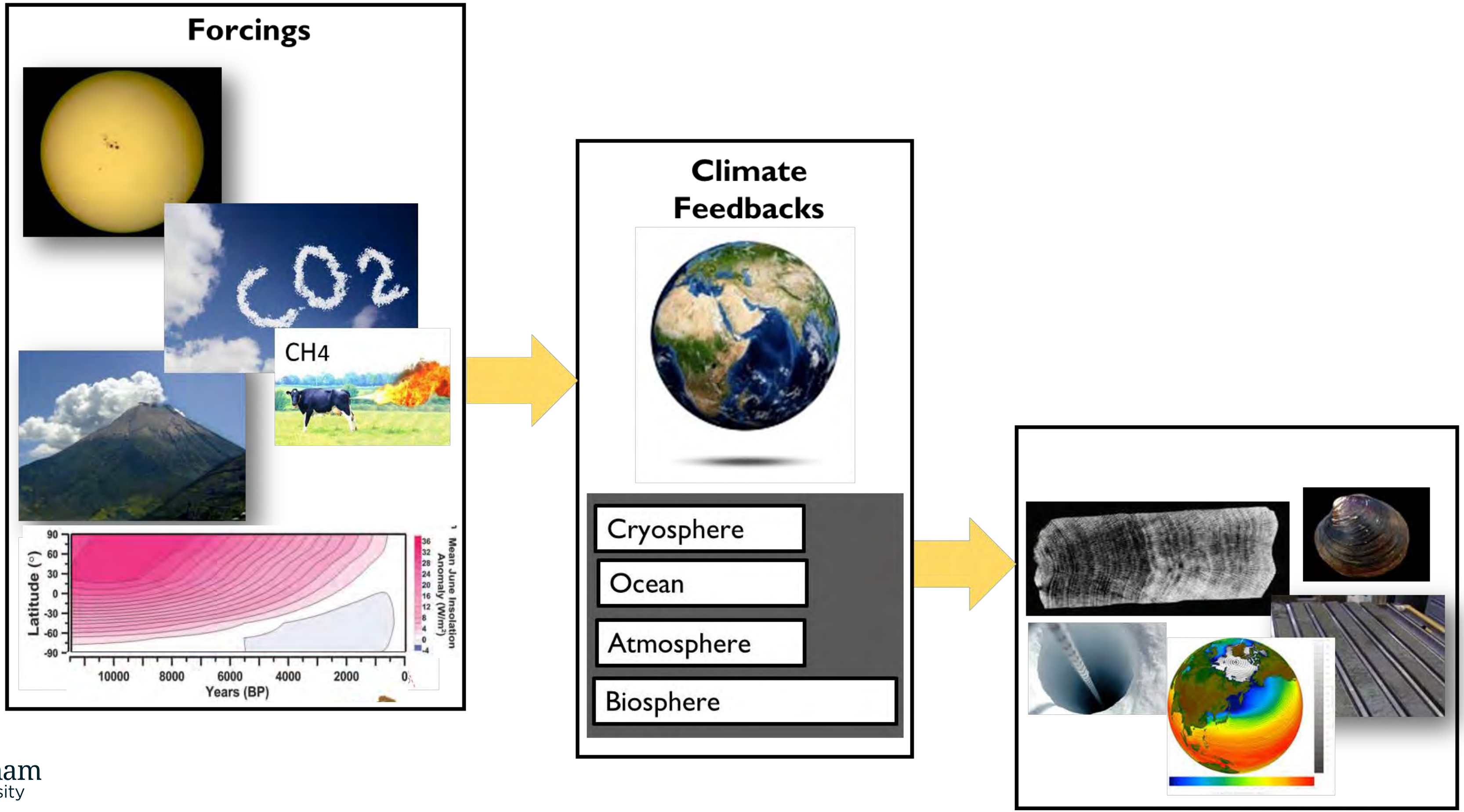
Potential explanations for Holocene climate variability



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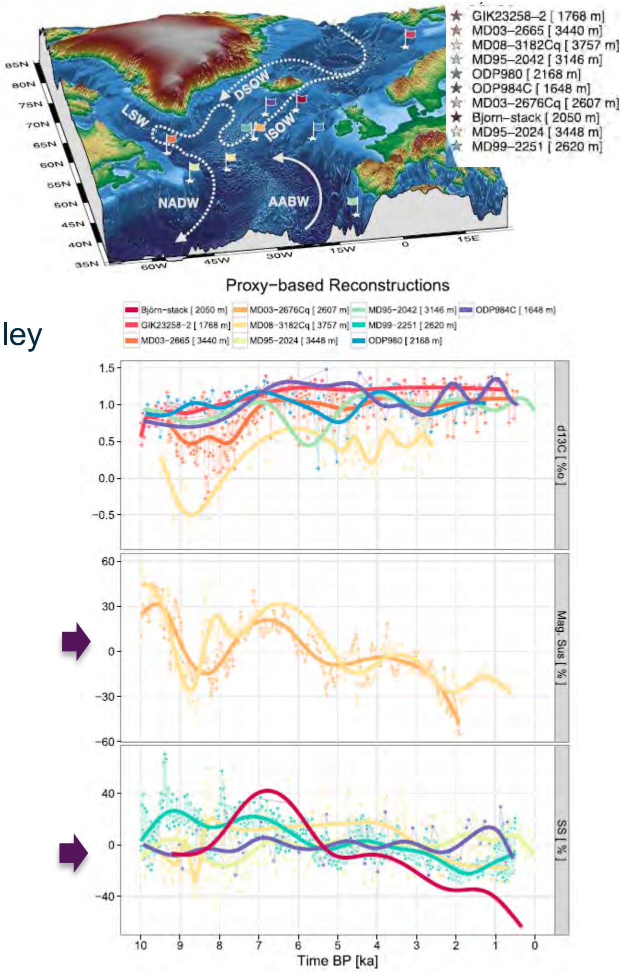
Holocene AMOC long-term evolution

Data: Contrasting proxy results

- Diverging trends in specific deep AMOC branches (Nordic Overflows, DWBC)
- Consistent I-S Overflow weakening over the Holocene (Thornalley et al., 2013, Kissel et al., 2013, Mjell et al., 2016)
- Data compilation uses models to calculate an AMOC index which is in agreement with ISOW changes (Ayache et al 2018)



Blasheck et al., 2015, Paleoceanography

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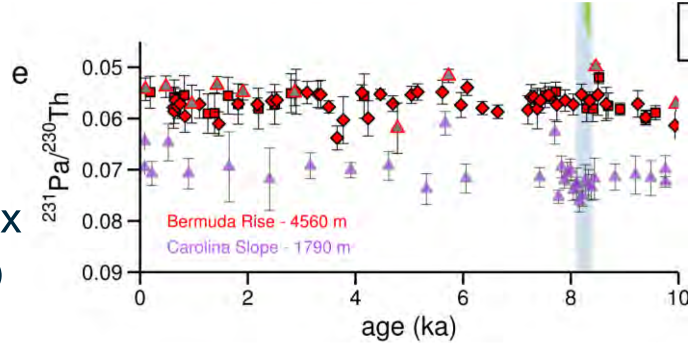
- Data compilation uses models to calculate an AMOC index which is in agreement with ISOW changes (Ayache et al 2018)
- Overturning from $^{231}Pa/^{230}Th$ indicates AMOC stability over the Holocene (Lippold et al., 2019, Hoffman et al., 2018)



Lippold et al., 2019, Hoffman et al., 2018

Models: Discrepancies of AMOC's long-term evolution and between 6K and Pre-Industrial. Although HR models show weakening but still differences across CMIP5 models (Shi and Lohman et al., 2016, GRL)

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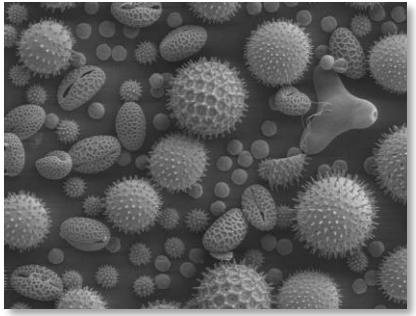
Climate of the last millennia around the North Atlantic

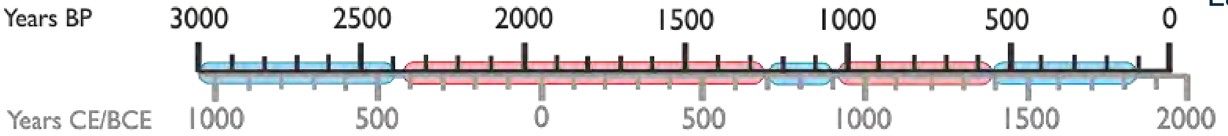
Circum-North Atlantic glacier advances (e.g. Denton and Karlen 1973, Solomina et al. 2016)

Tree ring
(e.g. Büntgen et al. 2011, 2016)

Ice-cores
(e.g. Kobashi et al. 2008, 2017)



Pollen (e.g. Seppa et al. 2009)
Other proxies from laminated lake sediments (e.g. LaPointe et al., 2020)



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For reviews of centennial climate variability see Mayewski et al., 2004 and Warner et al., 2011

Centennial variability of the AMOC during the last millennia

Palaeo-oceanography

Deepwater variability in the Holocene epoch

Delia W. Oppo*, Jerry F. McManus*, James L. Cullen†

Was a change in thermohaline circulation responsible for the Little Ice Age?

Wallace S. Broecker†

Gulf Stream density structure and transport during the past millennium

David C. Lund[1]†, Jean Lynch-Stieglitz[2] & William B. Curry[3]

Detecting Holocene changes in thermohaline circulation

L. D. Keigwin* and E. A. Boyle

Holocene periodicity in North Atlantic climate and deep-ocean flow south of Iceland

Giancarlo G. Bianchi & I. Nicholas McCave

A Pervasive Millennial-Scale Cycle in North Atlantic Holocene and Glacial Climates

Gerard Bond,* William Showers, Maziet Cheseby, Rusty Lotti, Peter Almasi, Peter deMenocal, Paul Priore, Heidi Cullen, Irka Hajdas, Georges Bonani

Wobbly ocean conveyor circulation during the Holocene?

George H. Denton[a,1], Wallace S. Broecker[b,*]

Persistent Solar Influence on North Atlantic Climate During the Holocene

Gerard Bond,[1*] Bernd Kromer,[2] Juerg Beer,[3] Raimund Muscheler,[3] Michael N. Evans,[4] William Showers,[5] Sharon Hoffmann,[1] Rusty Lotti-Bond,[1] Irka Hajdas,[6] Georges Bonani[6]

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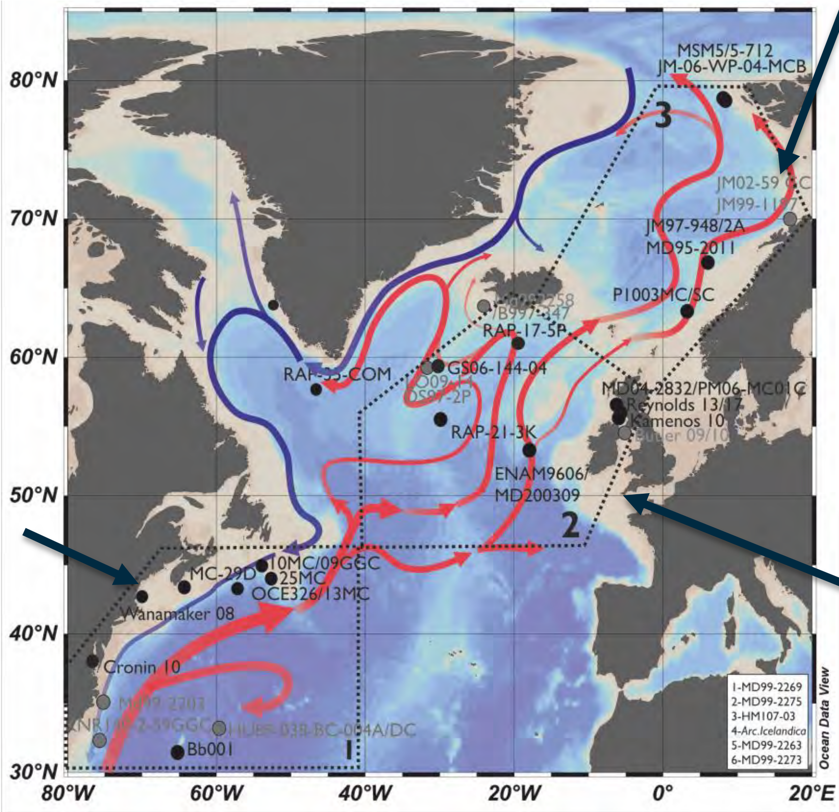
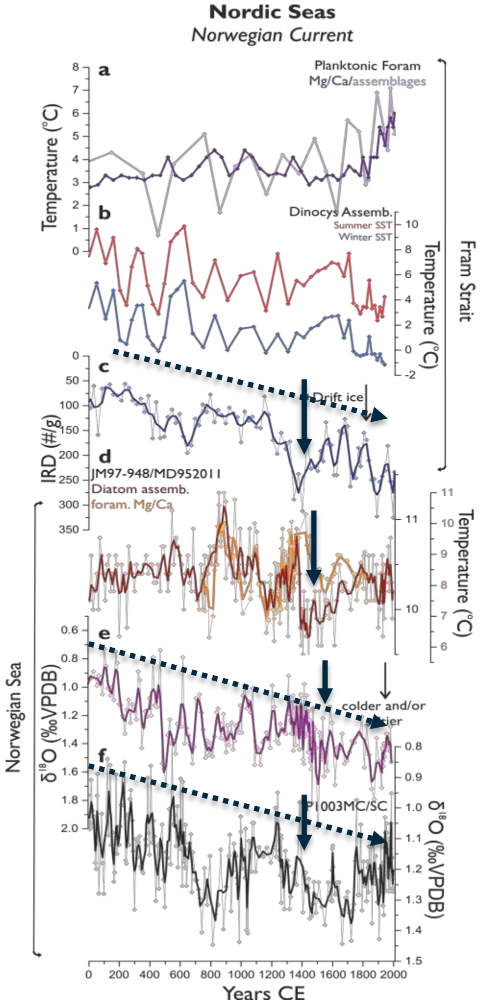
What have we learnt? Warm Atlantic Waters

Region 1 (Fig.2)
Large regional variability:
(1) Enclosed bays
(2) Scotian Shelf: Interaction between Slope Waters, Ext Labrador Current and Gulf Stream Waters



Region 3 (Fig.4)
Consistent millennial scale cooling with cooling at 1200-1500 years AD.

Region 2 (Fig.3)
Open Ocean: Proxy diff. → seasonal biases proxy carriers
Scottish Shelf: Recent warming of coastal waters



Records synthesized in Moffa-Sanchez et al., 2019 P&P

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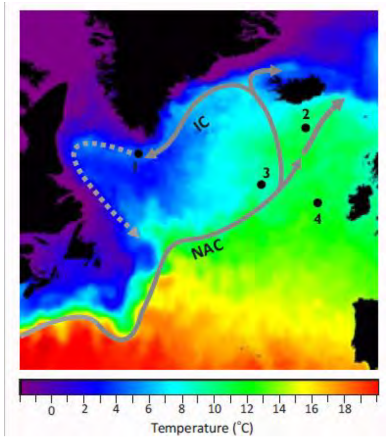
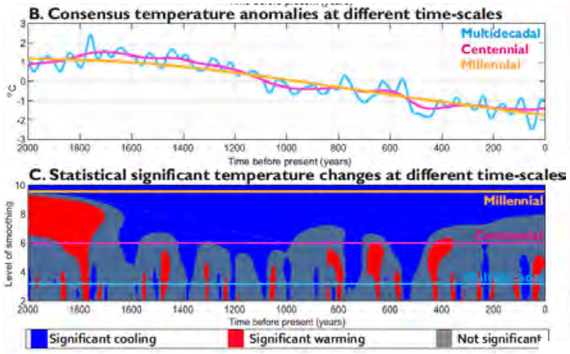
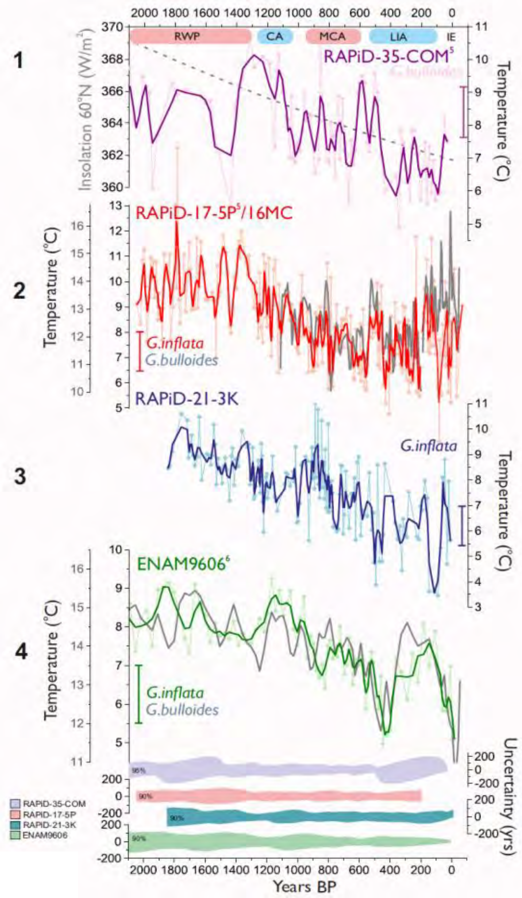
What have we learnt? Warm Atlantic Waters



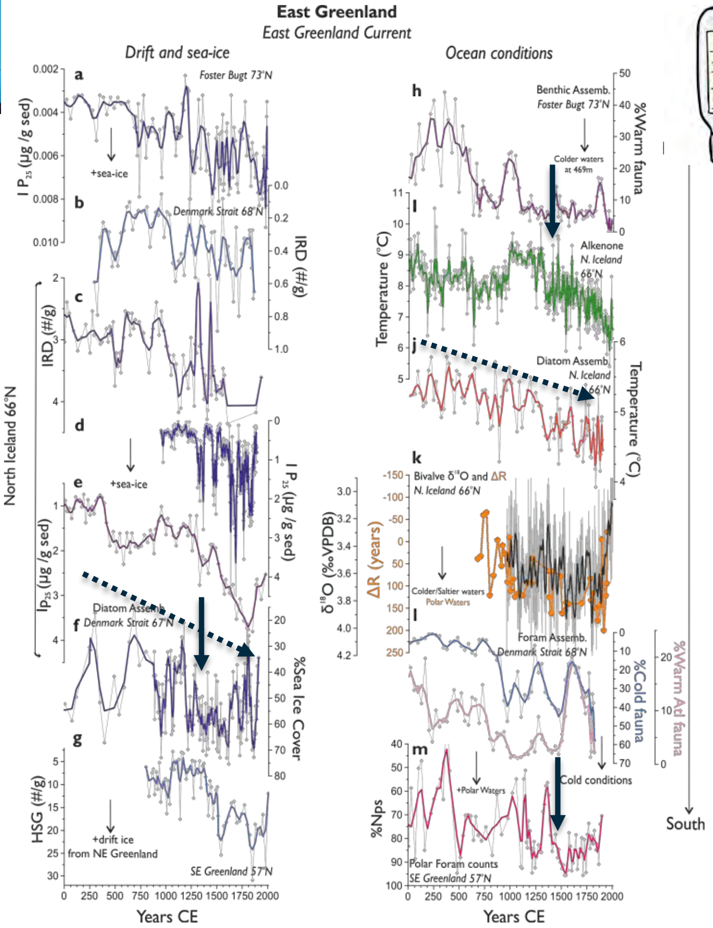


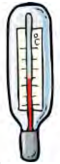


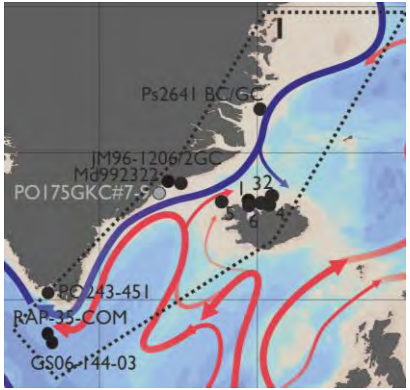
- Records of subsurface temperatures
- Consistent proxies across sites
- Accounting proxy and age uncertainty consensus analysis of the four records found in Warm Atlantic Waters or in the pathway of the NAC and its branches.
- Results reveal coherent patterns.

Moffa-Sanchez et al., in prep.

What have we learnt? East Greenland Current







(a) [*Kolling et al.*, 2017] (b) [*Perner et al.*, 2016,(d) [*Massé et al.*, 2008] (e) [*Cabedo-Sanz et al.*, 2016], (f) [*Miettinen et al.*, 2015] (g)[*Alonso-Garcia et al.*, 2017] (h)[*Perner et al.*, 2015], (i) [*Sicre et al.*, 2008], (j) [*Jiang et al.*, 2005], (k) [*Reynolds et al.*, 2016] [*Wanamaker et al.*, 2012] ,(l) [*Perner et al.*, 2016] (m) [*Moffa-Sánchez and Hall*, 2017]. Other work in agreement with this Miles et al., 2020.

- Millennial cooling with an increase in ice presence around East&South Greenland
- Records close to the polar front suggest southward shifts
- Most records present coldest and more ice-laden conditions during the Little Ice Age with a step-like transition ~1100-1500 years CE

Records synthesized in Moffa-Sanchez et al., 2019 P&P

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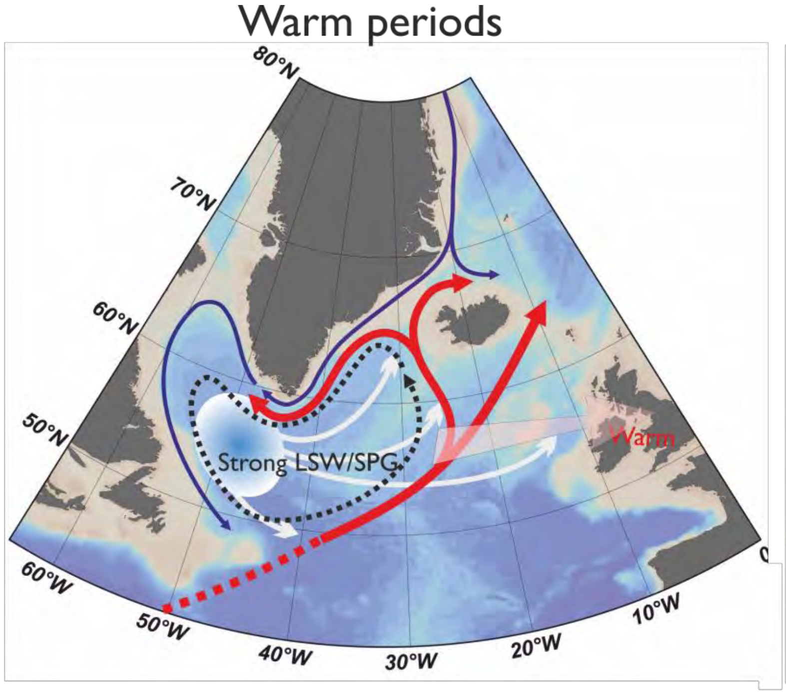
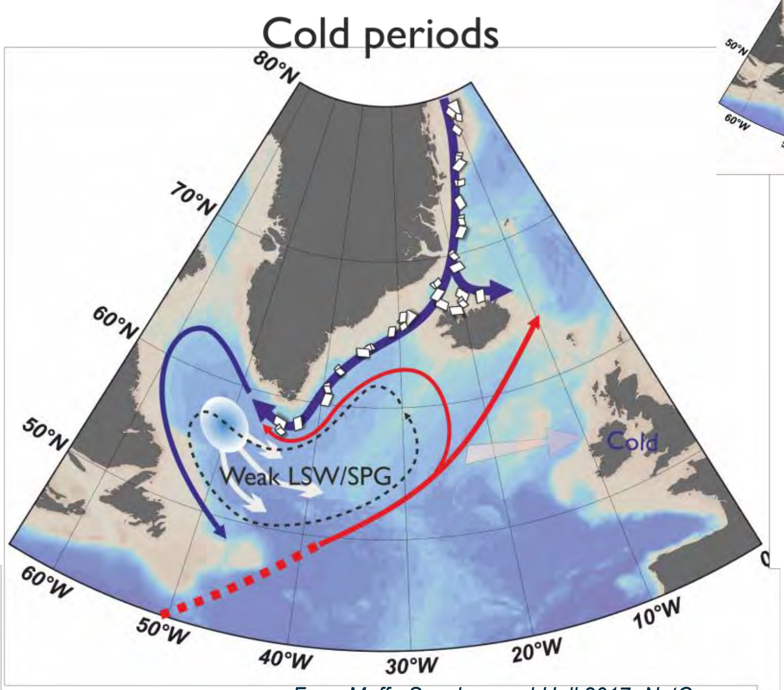
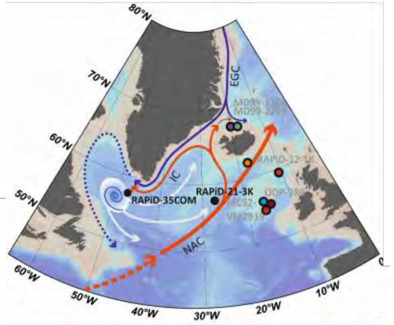
What have we learnt? Surface Circulation





From Moffa-Sanchez and Hall 2017, NatComms



Data: Moffa-Sanchez and Hall 2017; Moffa-Sanchez et al., 2014, NatGeo; Moffa-Sanchez et al., 2014b, Perner et al., 2015, Bond et al., 2001.

Models: Moreno-Chamarro et al. 2017, Moreno-Chamarro et al., 2015, 17a, 17b; Moffa-Sanchez et al., 2014a; Lehner et al., 2012; Jogma et al., 2007; Schulz et al., 2007

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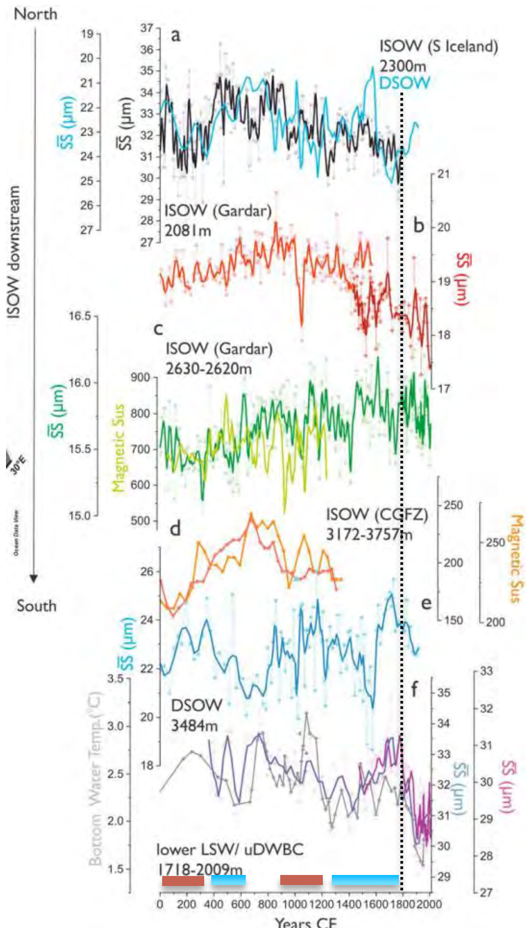
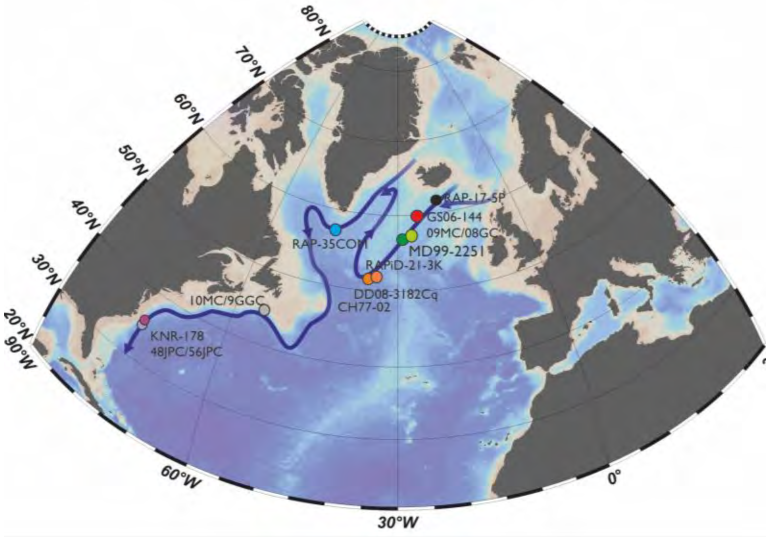
Outstanding Questions: (1) What was the trigger? External forcing (Solar/volcanism), internal dynamics, role of atmospheric changes (NAO/EAP)? (2) Was the AMOC affected during these cold periods?

What have we learnt? Deep AMOC branches





- Slowdown of ISOW close to the ridge last 1500 years. Evidence of multidecadal variability (Mjell et al., 2015, Moffa-Sanchez et al., 2015).
- DSOW antiphased with ISOW vigour
- uDWBC show centennial scale variability with some similarities to DSOW

Records synthesized in Moffa-Sanchez et al., 2019 P&P

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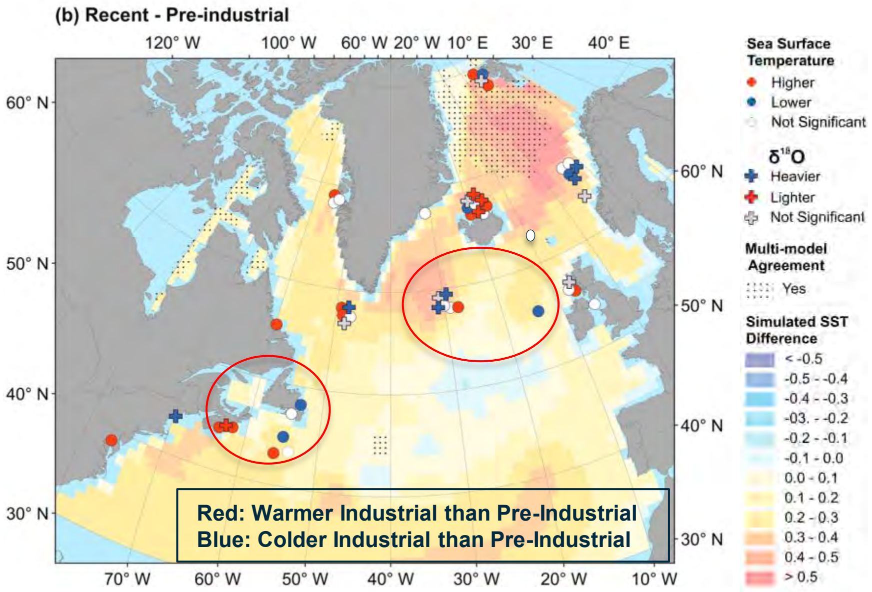
No clear paleo-evidence (yet) for recent AMOC



Moffa-Sanchez et al., 2019,P&P

- Discrepancies across datasets
- No obvious AMOC fingerprint in SST in SPG (Rahmstorf et al., 2015, Caesar et al., 2018) or Tsub (not 400m) (Zhang et al., 2008) for an AMOC slow down
- Caveats (it is there but we cannot see it):

- Not enough data points in the last 200 years
- SST records (noise&strong seasonal bias)

→ We need more high-resolution paleodata from the recent centuries

Conclusions and some thoughts…

- Important progress in understanding past North Atlantic circulation thanks to an increase in high-quality archives and proxies
- Coupling data and model results have allowed to understand ocean dynamics at centennial time-scales.
- Consistent picture emerging for North Atlantic surface circulation changes to explain centennial-scale climate variability over the last millennium. Although still some disparities across records and some data-model comparison challenges.
- Moving forward we should aim to:
  - Understand disparities across records (proxy biases)
  - Exploit and design statistical methods to assemble data accounting for spatio-temporal and proxy uncertainties
  - Seek original avenues to combine proxy records to gain insights into ocean dynamic processes.

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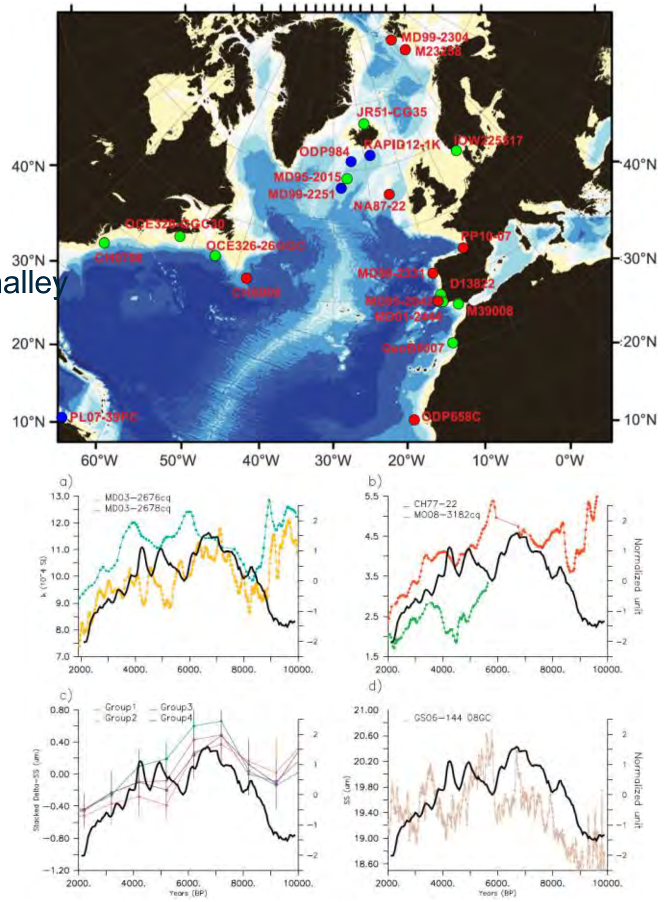
- Proxy data compilations use models to calculate an AMOC index which is in agreement with ISOW changes (Ayache et al 2018)



Ayache et al., 2018

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