ATLAS Deliverable D1.3

Recent AMOC and N Atlantic gyre properties and dynamics

Recent decadal-centennial changes in AMOC components and SPG circulation

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Author:	David Thornalley, UCL
Contributors	Peter Spooner, UCL

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1. Introduction

One of the goals of ATLAS is to examine how changing circulation in the North Atlantic has affected deep-sea marine ecosystems. Strong motivation for this comes from recent instrumental-based data showing a weakening of the large-scale overturning circulation of the Atlantic from 2004 onwards (Srokosz & Bryden, 2015). As part of WP1 Objective 1, ATLAS has undertaken analysis of high resolution proxy archives of circulation over multi-decadal to centennial timescales, providing longer term context for currently observed variability. There are two dominant large-scale features of ocean circulation in the North Atlantic that potentially influence the case study sites of ATLAS:

(1) The Atlantic Meridional overturning Circulation (AMOC)
(2) The Subpolar Gyre (SPG) circulation.

The AMOC is comprised of northward transport of warm surface and thermocline waters, and their deep southward return flow as dense waters that formed by cooling processes and sinking at high latitudes (Fig. 1). As well as the vertically overturning of the North Atlantic, there is also horizontal circulation linked to surface ocean currents. An anti-clockwise circulation of surface currents in the northern North Atlantic forms the SPG. ATLAS work led by UCL has helped constrain the recent behaviour of these two large-scale circulation systems (Thornalley et al., 2018 & in prep.; Spooner et al., in prep).

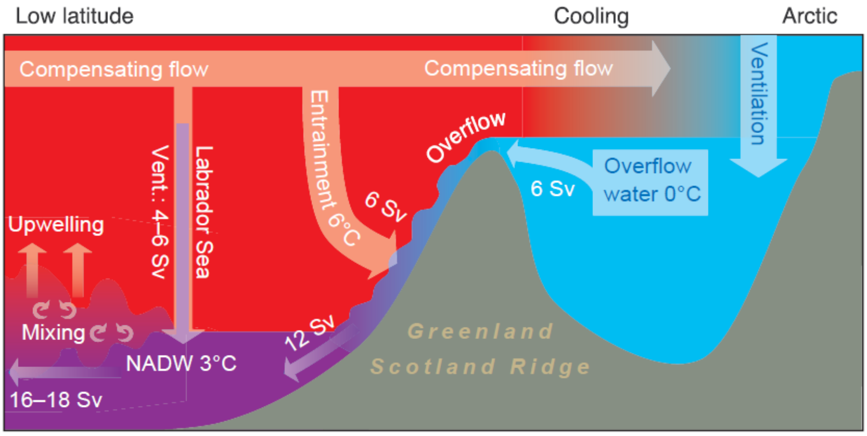

Fig. 1. The main processes in the AMOC. Warm, salty surface water flows northward to the Nordic Seas and Labrador Sea. Here, cooling causes the density of the water to increase, thereby sinking and ventilating the deep ocean. Dense water formed in the Nordic Seas overflows the Greenland Scotland Ridge as Iceland Scotland Overflow Water and Denmark Straits Overflow water, combining with Labrador Sea Water and entrained water to form North Atlantic Deep Water (NADW). NADW flows south as the main deep return limb of the AMOC. Ultimately NADW upwells and mixes back up to the surface ocean. From Hansen et al., 2004.

2. Recent decadal-centennial changes in AMOC

2.1. The importance of AMOC

The AMOC is a key component of Earth's climate system, involving the northward transport of warm surface waters to the high latitude North Atlantic, where they cool (thereby releasing heat to the atmosphere), sink and flow back southwards at depth (reviews by Srokosz & Bryden, 2015; Buckley & Marshall, 2016). The associated inflow of warm Atlantic water to the Nordic Seas causes substantial regional warming, affecting ice-sheet balance, sea-ice extent, and the climate of Northwest Europe. The transport of oceanic heat by the AMOC also alters the inter-hemispheric heat budget, impacting the location of the Intertropical Convergence Zone (ITCZ) which affects large-scale precipitation patterns across the tropics, as well as East Asian monsoon systems. AMOC variability can change sea-level around the North Atlantic by tens of cm, can alter the distribution and properties of water masses, and have an impact on socio-economically important surface and deep marine ecosystems. Furthermore, the formation of North Atlantic Deep Water (NADW) is a major oceanic sink of atmospheric CO_2 and at present is the main conduit by which anthropogenic CO_2 enters the deep ocean. Thus, AMOC variability is of major importance to human societies and global climate.

2.2. Uncertainty regarding the stability and variability of AMOC – the need for paleo-proxies

There are concerns regarding the strength and stability of AMOC in the future because predicted increases in surface ocean temperature and freshwater fluxes are expected to weaken the formation of dense water that helps drive the AMOC on decadal to centennial timescales (Buckley & Marshall, 2016). Theoretical, modelling and paleoclimate studies have suggested that the AMOC may have different stable states, raising the possibility that the AMOC could rapidly switch to a weak - or even an 'off' - state under global warming scenarios, with a severe impact on global climate. IPCC models do not predict an abrupt weakening of the AMOC under typical 21st century scenarios; yet there are suggestions that current climate models may have an excessively stable AMOC (Rahmstorf et al., 2015; Srokosz & Bryden, 2015). Since observations began in 2004, AMOC has weakened at a rate of ~0.5 Sv/year, ten times faster than predicted by most models (Srokosz & Bryden, 2015). Yet the limited time span of the RAPID array records means it is not possible to gain an understanding of the nature of AMOC variability on timescales longer than interannual-to-decadal from direct instrumental data, therefore paleo-reconstructions of AMOC strength must be used to reconstruct changes beyond the instrumental record. ATLAS work has used two approaches to constrain AMOC over recent centuries, described in sections 2.3 and 2.4, and published in Thornalley et al. (2018).

2.3. The subsurface temperature (Tsub) AMOC fingerprint

Changes in the strength of the AMOC are expected to be related to temperature changes in the North Atlantic because of its role in ocean heat transport. Similarities between the leading mode of variability in North Atlantic subsurface (400 m) temperatures (Tsub) and modelled AMOC and Tsub relationships (Zhang, 2008) identify a distinct subsurface AMOC fingerprint (Fig. 2): a weaker AMOC is associated with cooling around the subpolar North Atlantic and warming of the Gulf Stream extension region (Zhang, 2008; Robson et al., 2016). This weak AMOC signature is due to the reduced northward heat transport to the subpolar region, and the northward displacement of the Gulf Stream due to weakening of the Northern Recirculation Gyre induced by a slower deep western boundary current (DWBC; Caesar et al., 2018). Observational AMOC data provides further support, with upper ocean temperature differences between the period of strong (2004-2008) and weak (2009-2016) AMOC recorded by the Rapid 26N array also showing the same general pattern of warming in the Gulf Stream Extension region and cooling of the subpolar North Atlantic (Smeed et al., 2018). Paleo-temperature reconstruction can be used to constrain the Tsub AMOC fingerprint and thus provide a means to examine past AMOC variability.

2.4. Deep Labrador Sea density (dLSD)

Climate models and reanalyses show that decreases in the density of the deep Labrador Sea (dLSD) are associated with AMOC weakening (Robson et al., 2016). Density anomalies from the Labrador Sea rapidly propagate southwards along the western margin (Jackson et al., 2016) and project onto the cross-basin zonal density gradient, causing changes in the geostrophic transport of the southward flowing DWBC, thus altering AMOC strength (Buckley & Marshall, 2016).

It is not possible to accurately reconstruct mid-column density anomalies in the Labrador Sea for the Holocene. However, because of their strong dynamical link with dLSD anomalies (Jackson et al., 2016), DWBC flow speed changes are closely correlated with deep Labrador seawater density changes and are therefore a useful AMOC proxy. Past flow speed changes in the DWBC can be reconstructed by using the sortable silt (SS) mean grain size in sediment cores - an established proxy for near-bottom current flow speed (McCave et al., 2017). Because both are associated with AMOC changes, dLSD anomalies are predicted to correlate with the Tsub AMOC fingerprint (with a ~10 yr lag), as shown for recent decades (Robson et al., 2016) and the last ~120 years using DWBC flow speed reconstruction data (Fig. 2; Thornalley et al., 2018).

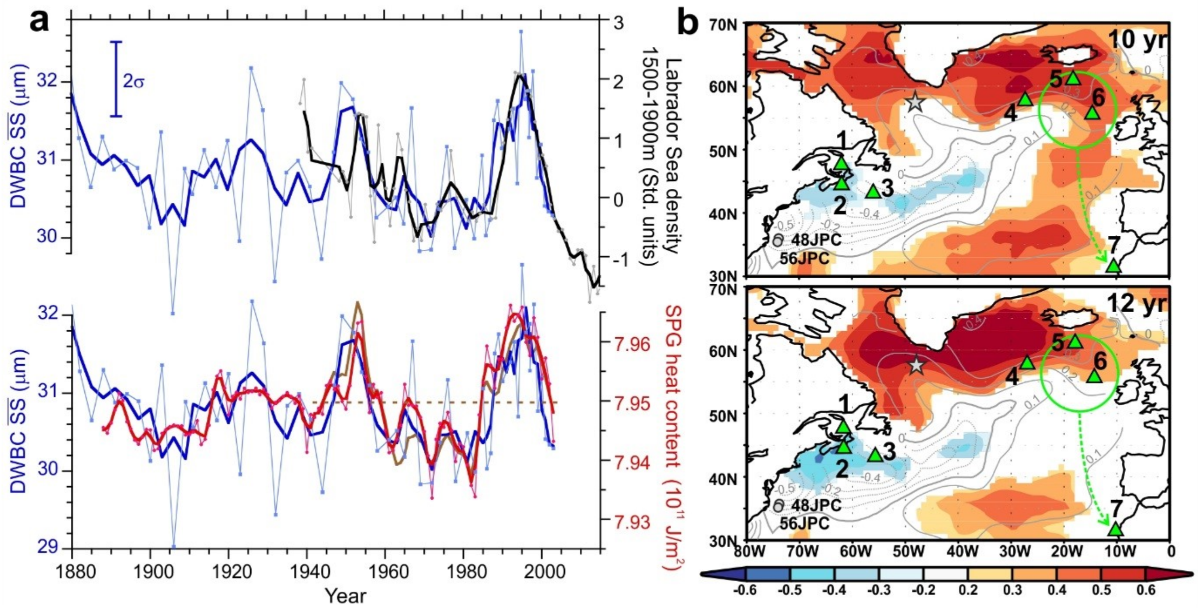

Fig. 2. AMOC proxy validation and recent, multi-decadal variability. a, Deep western boundary current (DWBC) flow speed reconstruction using SS mean grain size (core 56JPC, blue) compared with: instrumental central Labrador Sea annual density (black); and with 12-year lagged SPG upper ocean heat content (0-700 m, 55-65°N, 15-60°W, EN4 dataset; red) and the Tsub AMOC fingerprint (brown; dashed line zero-line). **b**, 10- and 12-yr lagged spatial correlation of upper ocean heat content (0-700 m) with reconstructed DWBC flow speed (56JPC), heat content lags. Grey contours show the spatial pattern of the Tsub AMOC proxy; green triangles, Tsub proxy sites; green circle, surface region controlling benthic temperatures at site 7. Grey circles, DWBC sites. From Thornalley et al. (2018).

2.5. Reconstructed AMOC variability over the last 1600 years

Both the DWBC and Tsub fingerprint AMOC proxies were applied over the past ~1.6 ka to constrain past AMOC variability (Fig. 3; Thornalley et al., 2018).

- The DWBC proxy suggests that AMOC has been weaker during the last ~150 years than at any other time during the last 1600 years. The emergence of this weaker state takes place at ~1880 CE in both cores. The overall transition occurs from ~1750 to ~1900 CE, late in the Little Ice Age (LIA, ~1350-1850 CE) and the early stages of the Industrial era (defined as ~1830 onwards). Applying the flow speed calibration for sortable silt suggests a decrease from 17 to 14.5 cm/s at 56JPC, and 14 to 12 cm/s at 48JPC, implying a decrease in DWBC strength of ~15% (assuming constant DWBC cross-sectional area).
- The Tsub proxy reconstruction provides support for the proposed AMOC weakening. Opposing temperature anomalies recorded in the two regions after ~1830 CE, with warming of the Gulf Stream extension region and cooling of the subpolar Northeast Atlantic, together suggest a weaker Industrial-era AMOC. In contrast to the prominent changes recorded in our proxy reconstructions at the end of the LIA, more subdued variability occurs during the earlier part of our records (400-1800 CE). This implies that the forcing and AMOC response was

weaker, or it supports mechanisms in which the AMOC does not play a leading role in the (multi-)centennial climate variability of this period, such as changes in the strength of the SPG and/or sea-ice feedbacks.

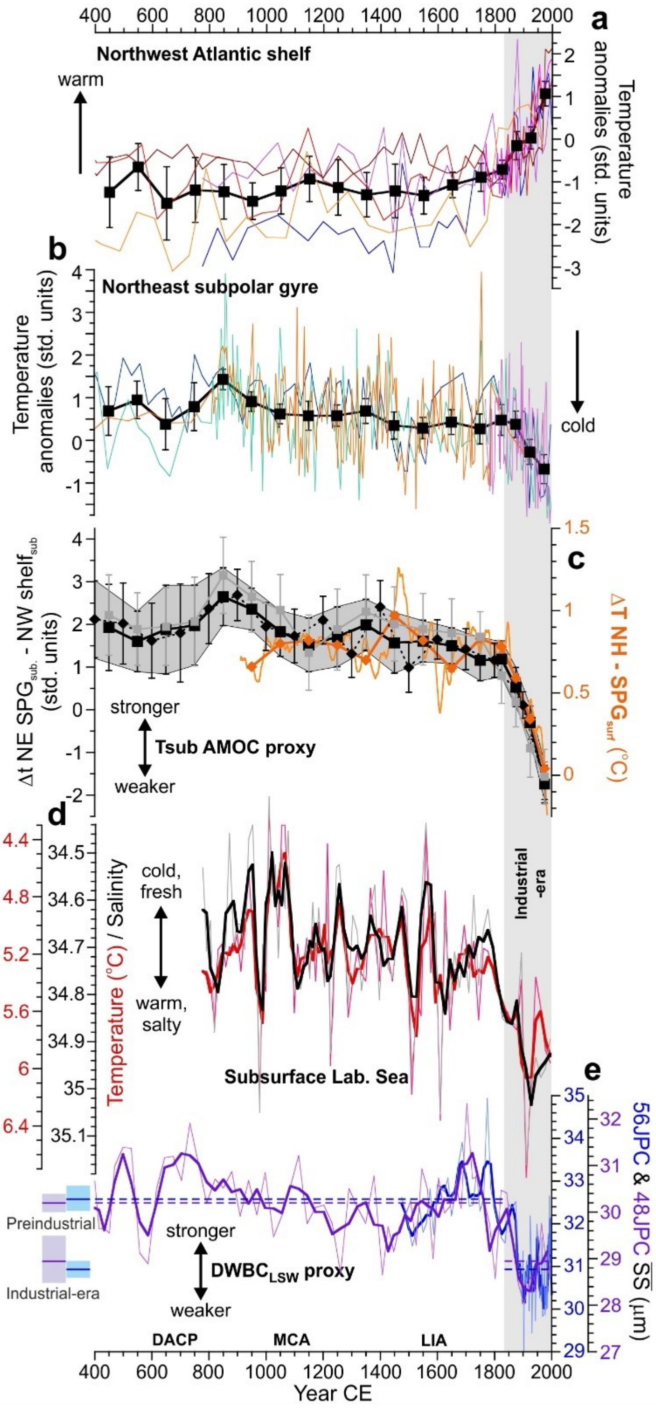

Fig. 3. Proxy reconstructions of AMOC changes over the last 1600 years. a,**b**, Subsurface Northwest Atlantic shelf (**a**) and Northeast Atlantic subpolar gyre (**b**) temperatures; sites in Fig. 2b; composite stacks, black. **c**, Tsub AMOC proxy (black, grey), various binning (see Extended Data Fig 4); orange, Rahmstorf AMOC proxy, 1°C = ~2.3Sv, 21-yr smooth, thin line; thick line and symbols, binned as for Tsub AMOC proxy. **d**, *N. pachyderma* Mg/Ca-d^{18}O subsurface (~100-200 m) temperature and salinity for northeast Labrador Sea. **e**, SS mean grain size (56JPC, blue; 48JPC, purple; bold, 3-point means); dashed lines, Industrial/Preindustrial-era averages. Error

bars/shading, ±2SE. DACP (Dark Ages Cold Period, ~400-800 CE), MCA (Medieval Climate Anomaly, ~900-1250 CE). From Thornalley et al. (2018).

2.6 Causes of Industrial-era AMOC weakening

Labrador Sea deep convection is a major contributor to the AMOC, but susceptible to weakening. Combined with its role in decadal variability over the last ~100 years (Fig. 2), and model analysis of mechanisms in operation today (Robson et al., 2016), it is likely that changes in Labrador Sea convection were involved in the weakening of AMOC at the end of the LIA. Strong deep convection in the Labrador Sea is typically associated with cooling and freshening of the subsurface ocean. Therefore, the reconstructed shift to warmer and saltier subsurface conditions in the northeast Labrador Sea over the past ~150 years (Fig. 3) is consistent with a shift to a state characterized by reduced deep convection, with only occasional episodes of sustained deep convection. Hence, changes in Labrador Sea deep convection may have been a significant contributor to AMOC variability over this period.

To constrain the potential role of the Nordic Seas Overflows to the recent AMOC weakening, sortable silt mean grain size measurements were also conducted in a suite of cores from south of Iceland to reconstruct changes in the strength of the Iceland Scotland Overflow (Fig. 4), which were combined with published data constraining the Denmark Strait Overflow (Fig. 5).

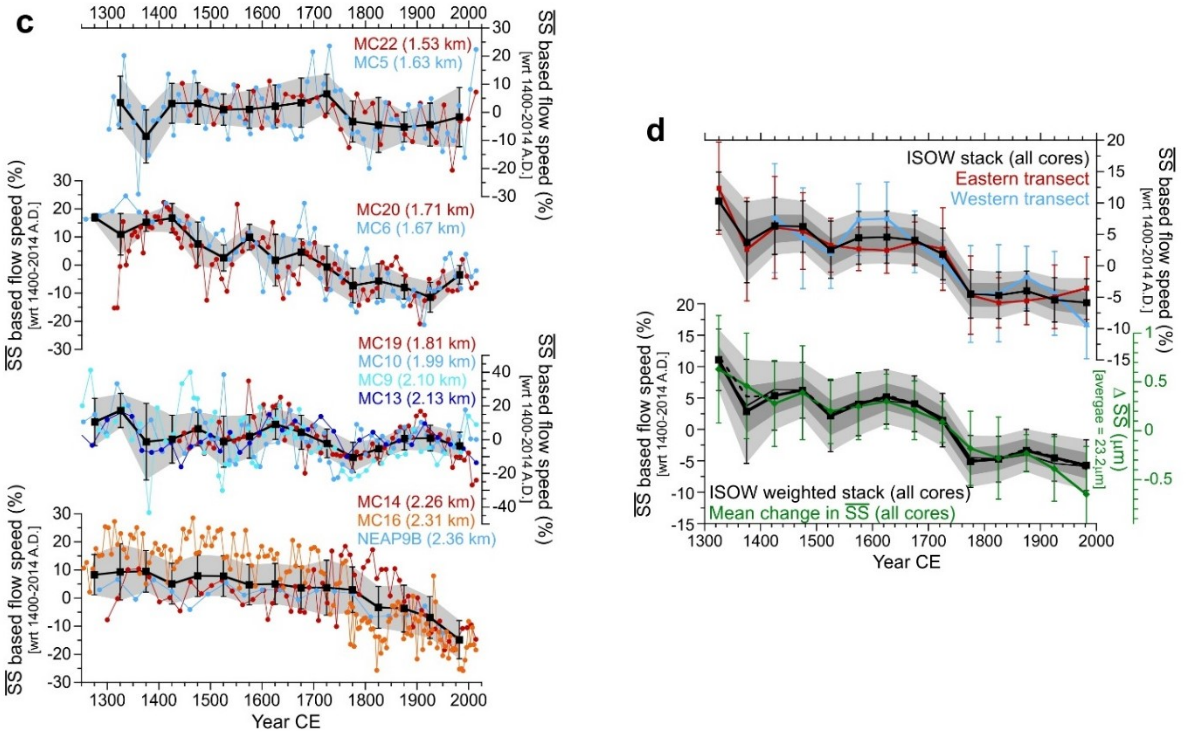

Fig. 4. Reconstructed flow speed of Iceland Scotland Overflow Water (ISOW) using mean sortable silt grain size analysis in 11 sediment cores (left). The cores form two depth transects south of Iceland; both indicate that ISOW has been weak since ~1750 CE. Thornalley et al. in prep.

Previous work has shown that there has been a long-term decline in ISOW over the last 7000 years by ~15%, likely caused by an orbital-induced increase in Arctic sea-ice and freshwater export from the Arctic (Thornalley et al., 2013). The new grain size results (Fig 4) show that this weakening of ISOW has continued over the last millennium, with a further ~15% decline occurring in the last 700 years.

Previous studies have suggested that there was compensation of ISOW and DSOW on multi-centennial timescales (Moffa-Sanchez et al., 2015), however it appears that the most recent pronounced weakening of ISOW was not (fully) compensated for by a strengthening DSOW (Fig 5). Therefore the recent AMOC weakening may likely be due to a combination of a reduction in both LSW and ISOW.

It is hypothesized that the AMOC weakening was caused by enhanced freshwater fluxes associated with the melting and export of ice and freshwater from the Arctic and Nordic Seas associated with end of the Little Ice Age (Thornalley et al., 2018).

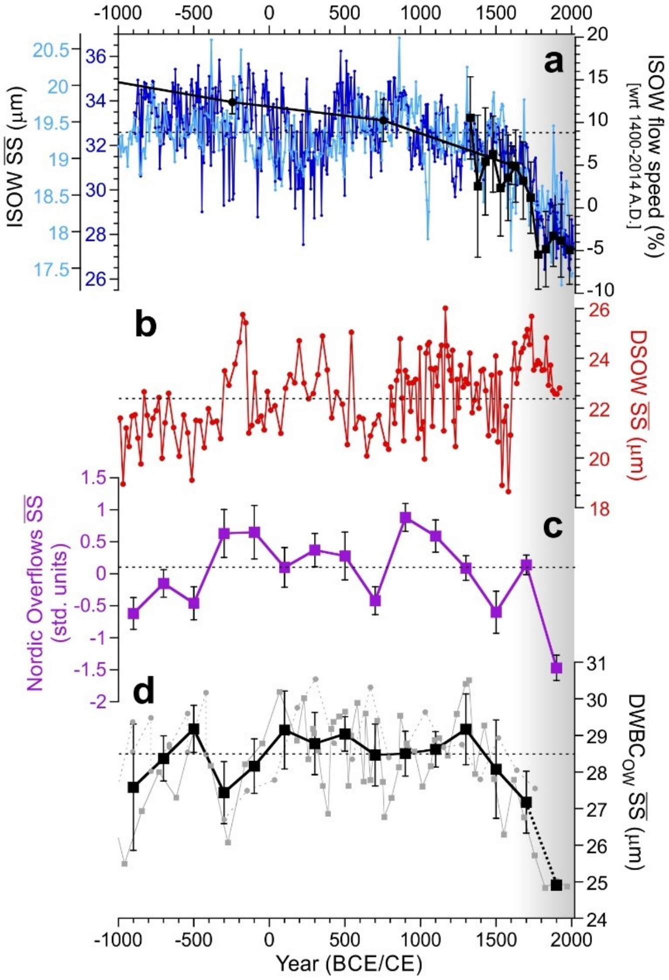

Fig. 5. Sortable silt grain size analysis reconstructions of the Nordic Seas Overflows. (a) Iceland Scotland Overflow Water (ISOW) and (b) Denmark Straits Overflow Water (DSOW) reconstruction. (c) The combined Nordic Seas Overflows (from panel a and b) as well as flow speed reconstructions from the DWBC off Cape Hatteras (3.0 km and 3.5 km water depth) also monitoring the Nordic Seas Overflow Waters. Thornalley et al., in prep.

2.7 Implications of reconstructed AMOC changes

The new finding of a recent AMOC decline raises several issues (Thornalley et al., 2018):

- Regarding the modelling of AMOC in historical experiments, the inferred transition to a weakened AMOC occurred near the onset of the Industrial-era, several decades before the strongest global warming trend, and has remained weak up to the present day. This either suggests hysteresis of the AMOC in response to an early climate forcing – natural (solar, volcanic) or anthropogenic (greenhouse gases, aerosols, land-use change) – or alternatively, continued climate forcing, such as the melting of the Greenland Ice Sheet, has been sufficient to keep AMOC weak or cause further weakening.

- The AMOC reconstructions differ from most climate model simulations, which show either negligible AMOC change or a later, more gradual reduction. Many factors may be responsible for this model-data discrepancy: a misrepresentation of AMOC-related processes and possible hysteresis, including underestimation of AMOC sensitivity to climate (freshwater) forcing; the underestimation or absence of important freshwater fluxes during the end of the LIA; and the lack of transient forced behaviour in the “constant forcing” pre-Industrial controls used to initialize historical forcings. Resolving these issues will be important for improving the accuracy of projected changes in AMOC.

- Furthermore, because of its role in heat transport, it is often assumed that AMOC weakening cools the northern hemisphere, however, the new work demonstrates that changes in AMOC are not always synchronous with temperature changes. The persistence of weak AMOC during the 20th century, when there was pronounced northern hemisphere and global warming, implies that other climate forcings, such as greenhouse gas warming, were dominant during this period. It is therefore inferred that AMOC has responded to recent centennial-scale climate change, rather than driven it.

- The weak state of AMOC over the last ~150 years may have modified northward ocean heat transport, as well as atmospheric warming through altering ocean-atmosphere heat transfer, underscoring the need for continued investigation of the role of the AMOC in climate change. Determining the future behaviour of AMOC will depend in part on constraining its sensitivity and possible hysteresis to freshwater input, for which improved historical estimates of these fluxes during the AMOC weakening reported in this work will be especially useful.

- The recent AMOC decadal variability appears relatively minor in comparison to the centennial-scale event that occurred at the end of the LIA. This raises concerns that future AMOC variability may not simply be dominated by decadal variability but longer-term trends may already be occurring and contributing to an ongoing weakening of AMOC.

3. Recent decadal-centennial changes in SPG circulation – a perspective from the Iceland Basin

3.1 The Subpolar Gyre and recent context

The North Atlantic is a critical region in the global climate system due to its role in deep water formation, poleward heat transport and Atlantic-Arctic exchange. It is also home to a rich diversity of marine life, including many important fisheries species. From 1997-2005 the North Atlantic underwent a transition to a state with a ‘weak’ subpolar gyre (SPG), with warming, salinification and nutrient decline in the Iceland Basin (Robson et al 2016). This decade-long event was associated with warmer water entering the Nordic Seas and a range of socially important ecosystem regime shifts and species migrations (Hátún et al., 2009).

Of crucial importance to understanding future ocean dynamics and its effects on Atlantic and Arctic climate is whether these recent events can be characterized as decadal/multidecadal variability about a steady baseline (as suggested by short-term records of sea-surface-temperature, SPG index) or whether longer-term climatic/oceanographic trends are present. Traditional paleoceanographic techniques have been applied to a suite of very rapidly accumulating sediment cores retrieved from the north Iceland Basin. They are located in a sensitive location at the modern eastern boundary of the SPG under the northern flank of the North Atlantic Current (NAC), a group of fronts and currents that separates the subpolar and subtropical gyres (Figs. 6 and 7). The resolution of these sediment cores is sufficient to capture the most recent decadal variability, and place recent events in a longer term context.

3.2 Abrupt 20th century changes in the subpolar gyre

Results derive from planktic foraminifera faunal assemblage data which, because of the habitat preferences of different species of foraminifera, is a well-established proxy for determining changes in past ocean conditions, particularly switches between different water masses (e.g. Ottens et al., 1991). We also report the total abundances of both planktic and benthic foraminifera which reflect surface productivity, and bulk sediment nitrogen isotope ($\delta^{15}N$) values which record the extent of nutrient utilisation in surface waters.

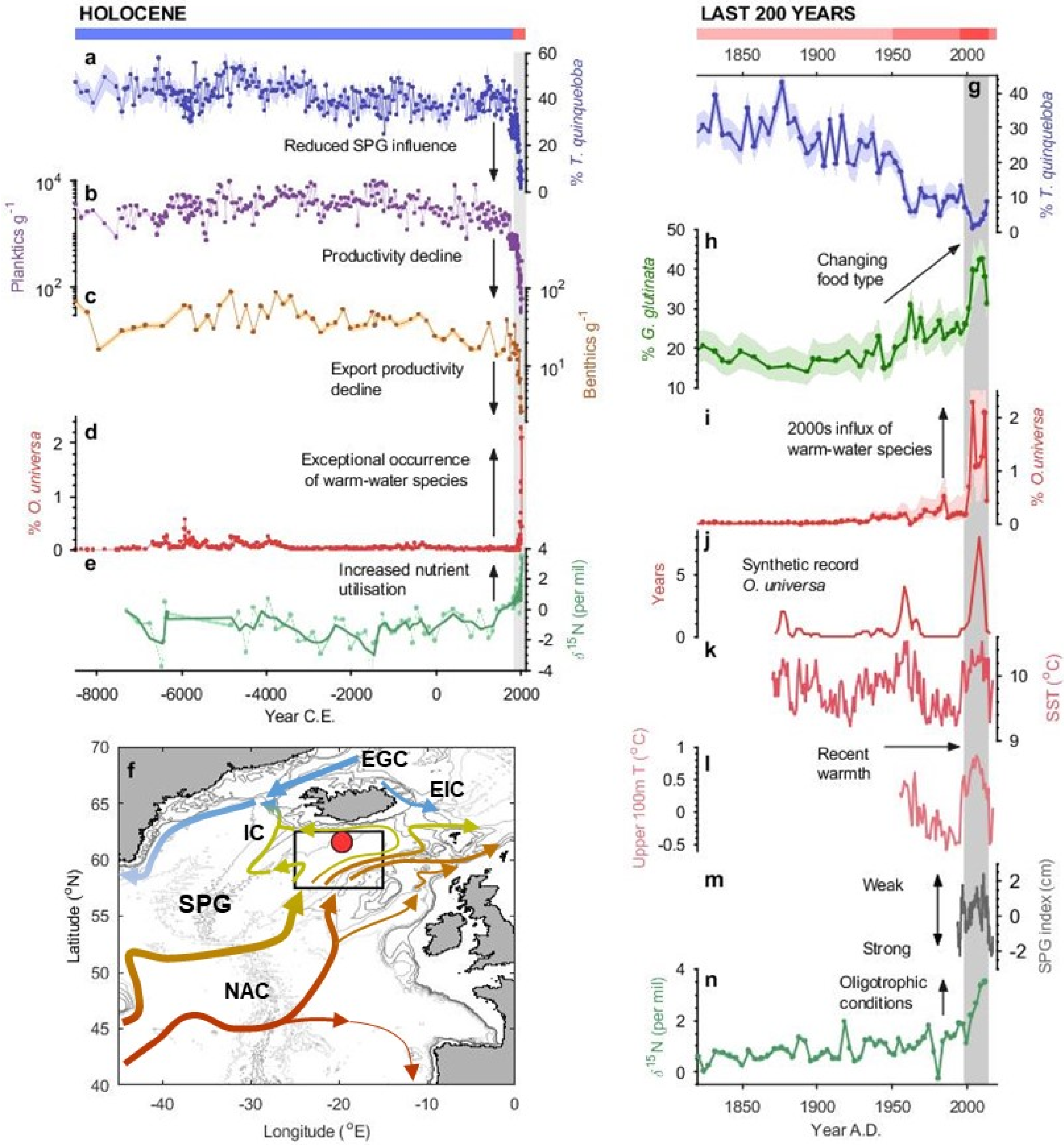

Fig. 6: Sedimentary records of SPG changes in the Iceland Basin from the cores EN539-MC16-A and RAPID-17-5P. a) Holocene *T. quinqueloba* relative abundance; b) Holocene abundance of planktic foraminifera; c) Holocene abundance of benthic foraminifera; d) Holocene *O. universa* relative abundance; e) Nitrogen isotope ratios of bulk sediment; f) Map showing core site and major ocean currents in the northeast Atlantic; g) last 200 years of *T. quinqueloba* relative abundance; h) last 200 years of *G. glutinata* relative abundance; i) last 200 years of *O. universa* relative abundance; j) 5 year smooth of the number of consecutive years where the annual sea surface temperature (SST) of the box in f exceeded 10.5 °C; k) SST data from HADISST used to create the record in j; l) Average temperature anomaly of the top 100 m using the same box as in i and j and data from INODC; m) SPG index (Hátún and Chafik, 2018); n) last 200 years of nitrogen isotope ratios of bulk sediment.

T. quinqueloba was more abundant at all core sites before the 20th century, but most notably it constituted 30-40 % of the assemblage in RAPID-17-5P/EN539-MC16-A (hereafter 5P/MC16A) for ~10,000 years prior to 1750 CE, indicating particularly favourable habitat conditions for *T. quinqueloba* at this site, similar to conditions within the southern and eastern SPG today (Figs. 6 and 7). Such high abundances, along with an enhanced lateral gradient in *T. quinqueloba* abundances across the core sites prior to the mid-20th century (Fig. 7), suggests the presence of a frontal feature close to 5P/MC16A for much of the Holocene.

There was a significant increase in the abundance of the warm-water foraminifera *Orbulina universa* during the 20th century, with an abrupt peak of up to 2.5 % and high absolute abundance during the 2000s present in each of the easternmost core sites (Figs. 6 and 7), responding to exceptional warmth/subtropical penetration via the NAC during the 1990s-2000s, i.e. the period with the greatest number of consecutive warm years of any in the observational record (Fig. 6). Some specimens of the tropical planktic foraminifera *Globigerinoides ruber* (both white and pink) were also observed in the most modern samples, anecdotally supporting the *O. universa* data.

There were substantial recent changes in surface productivity and nutrient utilization (Fig. 6). The total accumulation rates of planktic and benthic foraminifera show similar patterns to the relative abundance of *T. quinqueloba*, with high values prior to 1750 CE and then falling to values not recorded during the previous 10,000 years (Fig. 1). These changes were more marked in 5P/MC16A compared to the other core sites, again suggesting the collapse of a highly-productive subpolar frontal zone. Finally, bulk sediment δ^{15}N underwent a 3 ‰ increase during the 20th and 21st centuries (Fig. 6), indicating more complete nutrient utilization (from ~80 % to ~100 %,), typical of oligotrophic waters sourced from the subtropics.

In summary, the changes suggested by each of these records show that the penetration of subtropical water into the Iceland Basin has increased since ~1750 CE, with the major change occurring during the 20th and 21st centuries, from a previously stable dominance of subpolar water. The data therefore suggest that the recent decadal retreat of subpolar waters from the Iceland Basin was part of a much longer-term retreat since ~1750 (Fig. 7), unprecedented in the last 10,000 years.

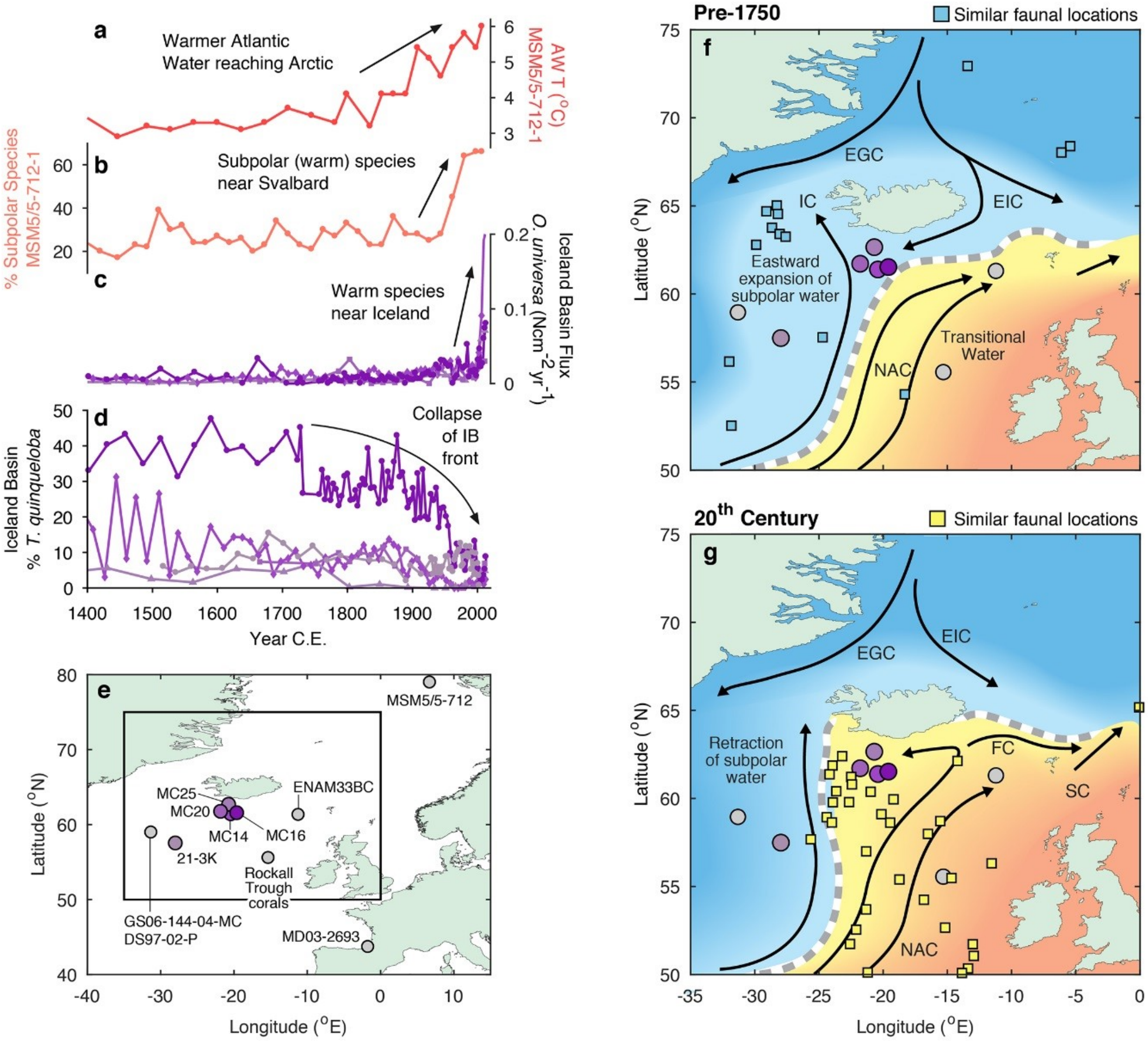

Fig. 7: Comparison of multi-core data and schematic maps of past and present water mass locations. a) Temperature of the Atlantic Water (AW) reaching west Svalbard derived from planktic foraminiferal faunal assemblages (Spielhagen et al., 2011); b) relative abundance of subpolar species (relatively warm) reaching west Svalbard (Spielhagen et al., 2011); c) comparison of multi-core *O. universa* relative abundance from EN539-MC16-A, MC14-A, MC20-B, MC25-A and RAPID-21-3K; d) comparison of multi-core *T. quinqueloba* relative abundance from the cores listed in c; e) map of the core sites; f) schematic of the Iceland Basin pre-1750 CE. Core sites with a high degree of faunal similarity to RAPID-17-5P are shown in blue, and are located within subpolar waters, suggesting subpolar influence at the 5P core site during this time. The location of the suggested frontal system is indicated by the dashed line; g) as f but for the modern day. The fauna in EN539-MC16-A in the last decade was most similar to core sites located in the transitional water of the NAC pathway.

3.3. Likely causes for the SPG changes

The timing and exceptional nature of the reported changes in the Iceland Basin are similar to recent reconstructions of past AMOC behaviour, suggesting linkages between the phenomena. Paleoceanographic data suggest that a decline in the DWBC component of the AMOC began around 1750 CE, possibly as a result of late Little Ice Age freshwater input into the North Atlantic, and weakening of the integrated AMOC - based on temperature fingerprint proxies - is suggested to have continued through the 20th century, likely due to anthropogenic warming (Thornalley et al., 2018, Caesar et al., 2018). Such freshening and reduced dense water formation, as well as weakening AMOC, could also have led to a weakening of the SPG via decreased deep isopycnal doming. The weaker gyre may then have contracted, allowing warm subtropical water to penetrate into the Iceland Basin.

3.4. Implications for the SPG changes

The evidence for a recent exceptional weakening of the SPG raises concerns about a reduction in subpolar convection. The SPG is linked to upper ocean density in the Iceland and Irminger Sea (Hátún and Chafik, 2018), which will decrease due to warming and freshwater input. The finding of an exceptional contraction of the SPG may therefore be an indicator of an ongoing decrease in upper ocean density which has been highlighted as a concern in future global warming scenarios (Sgubin et al., 2017).

These results also suggest that warming of the Iceland Basin and contraction of SPG influence may have contributed to a warmer Atlantic Inflow to the Nordic Seas and the Arctic over the 20th century. The result of the changing SPG circulation and Iceland Basin warming would have been to increase the heat content of waters entering the Nordic Seas via the Iceland Basin inflow region, with the heat retained far to the north due to insulation from the atmosphere by fresh surface water. This increase in Atlantic Water heat content could have contributed to the exceptional decline in Nordic Seas and Barents Sea sea-ice extent since 1900 CE (Fauria et al., 2010), the appearance of relatively warm water planktonic species near Svalbard since ~1800 CE (Fig. 7), and the enhanced melting of Greenland's outlet glaciers (Straneo and Heimbach, 2013).

Similar to the findings from the AMOC reconstruction, the SPG results also imply that aspects of modern North Atlantic circulation are not typical of the Holocene, or even the last millennium. Rather, regions of the North Atlantic appear to have already undergone substantial long-term (multi-decadal to multi-centennial) changes due to both natural (post-Little Ice Age) and anthropogenic drivers. Rather than relying on 'business as usual', marine management and industry organisations will likely have to adapt to increasingly unusual circulation and ocean properties as climate change progresses. Therefore, there is an urgent need for further high-resolution studies combined with model work to inform adaptation planning and the future management of marine resources.

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Appendix: Document Information

EU Project N°	678760	**Acronym**	ATLAS
Full Title	A trans-Atlantic assessment and deep-water ecosystem-based spatial management plan for Europe		
Project website	www.eu-atlas.org		

Deliverable	**N°**	1.3	**Title**	Recent AMOC and N Atlantic gyre properties and dynamics.
Work Package	**N°**	1	**Title**	Ocean Dynamics Driving Ecosystem Response

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Authors (Partner)	**UCL**			
Responsible Authors	**Name**	David Thornalley	**Email**	d.thornalley@ucl.ac.uk
		Peter Spooner	**Email**	p.spooner@ucl.ac.uk

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