

Anomalously weak Labrador Sea convection and Atlantic overturning during the past 150 years

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1 **“Anomalously weak Labrador Sea convection and Atlantic overturning during the past 150**
2 **years”**

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11

12 **The Atlantic meridional overturning circulation (AMOC) plays an essential role in climate**
13 **through its redistribution of heat and its influence on the carbon cycle^{1,2}. A recent decline in the**
14 **AMOC may reflect decadal variability in Labrador Sea convection, but short observational**
15 **datasets preclude a longer-term perspective on the modern state and variability of Labrador Sea**
16 **convection and AMOC^{1,3-5}. Here, we provide several lines of paleoceanographic evidence that**
17 **Labrador Sea deep convection and AMOC have been anomalously weak over the past ~150 years**
18 **(since the end of the Little Ice Age, LIA; ~1850 CE), in comparison to the preceding ~1500 years.**
19 **The reconstructions suggest the transition occurred as an abrupt shift around the end of the LIA,**
20 **or, a more gradual, continued decline over the past 150 years; this ambiguity likely arises from**
21 **additional non-AMOC influences on the proxies or their varying sensitivity to different**
22 **components of the AMOC. We suggest that enhanced freshwater fluxes from the Arctic and**
23 **Nordic Seas, towards the end of the LIA, sourced from melting glaciers and thickened sea-ice**
24 **that had developed earlier in the LIA, weakened Labrador Sea convection and the AMOC. The**
25 **lack of a subsequent recovery may result from hysteresis or twentieth century melting of the**
26 **Greenland ice sheet⁶. Our results highlight that recent decadal variability of Labrador Sea**

27 **convection and the AMOC has occurred during an atypical, weak background state. Future**
28 **work should aim to constrain the role of internal climate variability versus early anthropogenic**
29 **forcing in the AMOC weakening described here.**

30 The AMOC is comprised of northward transport of warm surface and thermocline waters, and
31 their deep southward return flow as dense waters that formed by cooling processes and sinking at high
32 latitudes². The stability of the AMOC in response to ongoing and projected climate change is uncertain.
33 Monitoring of the AMOC by an array at 26°N, spanning the last decade, suggests a weakening of the
34 AMOC, occurring ten times faster than expected from climate model projections¹. However, it remains
35 uncertain if this trend is part of a longer-term decline, natural multi-decadal variability, or a
36 combination of both. Here, we develop past reconstructions of AMOC variability that can be directly
37 compared to instrumental datasets and provide longer-term perspective.

38 The Labrador Sea is an important region for deep-water formation in the North Atlantic⁵.
39 Moreover, modelling studies suggest that deep Labrador Sea density (dLSD) may be a useful predictor
40 of AMOC change^{3,4,7}. This is because density anomalies produced in the Labrador Sea - predominantly
41 caused by varying deep convection - can propagate southwards rapidly (on the order of months) along
42 the western margin via boundary waves, altering the cross-basin zonal density gradient, thus modifying
43 geostrophic transport and therefore AMOC strength^{2-4,7-9}. Building upon these studies, we show that
44 dLSD anomalies are also associated with changes in the velocity of the deep western boundary current
45 (DWBC) and the strength of the AMOC at 45°N in the high-resolution climate model HadGEM3-GC2
46 (see Methods and Fig. 1).

47 In addition to this link between the AMOC and dLSD and the DWBC, changes in AMOC also
48 alter ocean heat transport. Modeling studies suggest that AMOC weakening affects the upper ocean
49 heat content of the eastern subpolar gyre (SPG) with a lag time of ~10 years (ref. ¹⁰), and a distinct
50 AMOC fingerprint on subsurface temperature (Tsub, 400m water depth)¹¹ characterizes weak AMOC
51 phases, with a dipole pattern of warming of the Gulf Stream extension region¹² and cooling of the

52 subpolar Northeast Atlantic. We exploit the model-based covariance of decadal changes in AMOC with
53 dLSD anomalies, SPG upper ocean heat content, and the Tsub fingerprint, to extend constraints on past
54 AMOC variability (see Methods). Over the instrumental era (post ~1950), these indices suggest
55 significant decadal variability in the AMOC, with coherent changes in dLSD, and lagged SPG upper
56 ocean heat content and the Tsub AMOC fingerprint^{3,5,8,10,11}.

57 The model results in Figure 1 imply that we can use flow speed reconstructions of the DWBC
58 to infer past changes in dLSD and AMOC. We analyzed the sortable silt (SS) mean grain size, a proxy
59 for near-bottom current flow speed¹³, in two marine sediment cores (48JPC and 56JPC; see Methods,
60 Extended Data Fig. 1 and 2) located under the influence of southward flowing Labrador Sea Water
61 (LSW) within the DWBC off Cape Hatteras (hereafter DWBC_{LSW}). The high accumulation rates (~0.5-
62 1 cm/yr) and modern core-top enable direct comparison of the record from 56JPC to observational
63 datasets (Fig. 2).

64 In agreement with the model-predicted relationship (i.e. Fig. 1), changes in inferred flow speed
65 of the DWBC_{LSW} show similar, in-phase, variability with observed deep Labrador Sea density⁵.
66 Moreover, there is strong covariability of our DWBC_{LSW} proxy with the lagged (12 year) SPG upper
67 ocean heat content and Tsub index from observational analysis (Fig. 2a). Over the past ~100 years, the
68 spatial correlation of upper ocean heat content anomalies associated with our DWBC_{LSW} proxy closely
69 resembles the Tsub AMOC fingerprint (Fig. 2b,c), supporting the concept that the DWBC_{LSW} proxy
70 and upper ocean temperature changes provide complementary, coherent, information on a common
71 phenomenon, namely AMOC variability. Combined, these datasets imply that decadal variability has
72 been a dominant feature of the past 130 years, with the most recent strengthening of LSW formation
73 during the mid-1990s, and the subsequent decline, being particularly prominent features.

74 To gain insight prior to the instrumental era, we first extend our DWBC_{LSW} flow speed
75 reconstruction (Fig. 3e). The DWBC_{LSW} proxy suggests that AMOC has been weaker during the last
76 ~150 years than at any other time during the last 1600 years. The emergence of this weaker state (i.e.

77 smoothed record exceeds a noise threshold of 2σ pre-Industrial era variability), takes place at ~ 1880
78 CE in both cores. The overall transition occurs from ~ 1750 to ~ 1900 CE, late in the Little Ice Age
79 (LIA, ~ 1350 - 1850 CE) and the early stages of the Industrial era (defined as ~ 1830 onwards¹⁴).
80 Applying the flow speed calibration for sortable silt¹³ suggests a decrease from 17 to 14.5 cm/s at
81 56JPC, and 14 to 12 cm/s at 48JPC, implying a decrease in DWBC_{LSW} strength of $\sim 15\%$ (assuming
82 constant DWBC_{LSW} cross-sectional area). This decrease is equivalent to 3σ and 4σ of the pre-Industrial
83 era variability in 48JPC and 56JPC, respectively.

84 Secondly, we compile quantitative proxy records of subsurface (~ 50 - 200 m) ocean temperatures
85 from key locations to extend the Tsub AMOC proxy (Fig. 3a-c; see Methods and Extended Data Fig. 3
86 & 4). The Tsub proxy reconstruction provides support for the proposed AMOC weakening. Opposing
87 temperature anomalies recorded in the two regions after ~ 1830 CE, with warming of the Gulf Stream
88 extension region and cooling of the subpolar Northeast Atlantic, together suggest a weaker Industrial-
89 era AMOC. Further support for the AMOC weakening is suggested by the spatial pattern of Tsub
90 change in the Northwest Atlantic during the onset of the Industrial era (Extended Data Fig. 5). In
91 contrast to the prominent changes recorded in our proxy reconstructions at the end of the LIA, more
92 subdued variability occurs during the earlier part of our records (400 - 1800 CE). This implies that the
93 forcing and AMOC response was weaker, or it supports mechanisms in which the AMOC does not play
94 a leading role in the (multi-)centennial climate variability of this period^{15,16}.

95 Labrador Sea deep convection is a major contributor to the AMOC, but susceptible to
96 weakening⁵. Combined with its role in decadal variability over the last ~ 100 years (Fig. 2), and model
97 analysis of mechanisms in operation today⁸, it is likely that changes in Labrador Sea convection were
98 involved in the weakening of AMOC at the end of the LIA. Additional correlative (not necessarily
99 causative) support is revealed by paleoceanographic evidence from the Labrador Sea. Strong deep
100 convection in the Labrador Sea is typically associated with cooling and freshening of the subsurface

101 ocean⁵. Therefore, the reconstructed shift to warmer and saltier subsurface conditions in the northeast
102 Labrador Sea¹⁷ over the past ~150 years (Fig. 3d; equivalent to $\sim 2\sigma$ of pre-Industrial era variability) is
103 consistent with a shift to a state characterized by reduced deep convection, with only occasional
104 episodes of sustained deep convection. Reconstructions of the other major deep-water contributors to
105 the AMOC - the two Nordic Seas overflows - suggest that on centennial timescales they have varied in
106 anti-phase and thus likely compensated for one another during the last 3000 years¹⁸. Hence, changes in
107 Labrador Sea deep convection may have been the main cause of AMOC variability over this period.

108 While atmospheric circulation has played a dominant role in recent decadal variability of
109 AMOC (and LSW)^{2,8}, there is no strong evidence that the AMOC decrease at the end of the LIA was
110 similarly caused by a shift in atmospheric circulation¹⁹. Instead, we hypothesize that the AMOC
111 weakening was caused by enhanced freshwater fluxes associated with the melting and export of ice and
112 freshwater from the Arctic and Nordic Seas. During the LIA, circum-Arctic glaciers and multi-year
113 Arctic and Nordic sea ice were at their most advanced state of the last few thousand years, and there
114 were large ice-shelves in the Canadian Arctic and exceptionally thick multi-year sea-ice. Yet, by the
115 early 20th century, many of these features had disappeared or were retreating²⁰⁻²³.

116 Modelling studies suggest enhanced freshwater fluxes of ~ 10 -100 mSv over a few decades can
117 weaken Labrador Sea convection and AMOC²⁴, although models with strong hysteresis of Labrador
118 Sea convection²⁵ suggest this may be as little as 5-10 mSv. Unfortunately, there is little data to
119 constrain the Arctic and Nordic Seas freshwater fluxes associated with the end of the LIA. The earliest
120 observational datasets suggest ~ 10 mSv from sea ice loss in the Arctic and Nordic Seas during 1895-
121 1920^{26,27}, to which we must also add melting of previously expanded circum-Arctic glaciers and ice-
122 shelves, and enhanced melting of the Greenland ice-sheet (GIS). Alternatively, we can estimate that a 1
123 m reduction in average Arctic sea-ice thickness during the termination of the LIA could yield a
124 freshwater flux of 10 mSv for 50 years. While additional work is required to improve this incomplete

125 estimate, there was likely sufficient freshwater stored in the Arctic and Nordic Seas during the LIA to
126 impact Labrador Sea convection and AMOC.

127 The AMOC weakening recorded in our two marine reconstructions is broadly similar to that in
128 a predominantly terrestrial-based AMOC proxy reconstruction⁶ (Fig. 3c). Our Tsub AMOC proxy and
129 the AMOC proxy of ref. 6 (Fig. 3c), both suggest a decline in AMOC through the 20th century, whereas
130 our DWBC_{LSW} AMOC proxy and the observational-based Tsub AMOC index (Fig. 2a and Extended
131 Data Fig. 6) suggest no long-term AMOC decline during the 20th century. These differences may be
132 attributed to several factors. Firstly, our sediment-core based Tsub proxy is subject to artificial
133 smoothing, caused by combining numerous records with substantial (~10-100 year) individual age
134 uncertainties, and compounded by bioturbation. Furthermore, the Tsub proxy sediment cores were
135 retrieved in the late 1990s and early 2000s, therefore they cannot capture the strong Tsub index
136 recovery from ~2000-2010 that reverses the earlier prolonged decline (see Extended Fig. 6).
137 Alternatively, the earlier, more threshold-like change in the DWBC_{LSW} AMOC proxy may be due to
138 local shifts in the position of the DWBC, and/or non-linear dynamics of the DWBC response to AMOC
139 change. However, based on the similarity of the DWBC_{LSW} reconstructions from cores 56JPC and
140 48JPC, located at different water depths, and the strong correlation of DWBC_{LSW} with Labrador Sea
141 density and the Tsub AMOC index over the instrumental period, we suggest these factors are not
142 substantial. Finally, the differences between the AMOC reconstructions may reflect their varying
143 response timescales and sensitivities to the different components of the AMOC and the SPG^{28,29}.

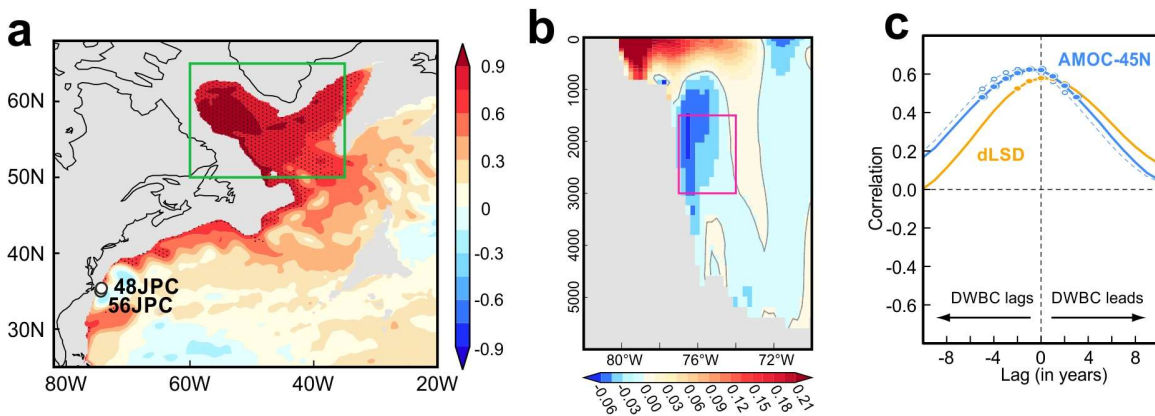
144 Our study raises several issues regarding the modelling of AMOC in historical experiments.
145 The inferred transition to a weakened AMOC occurred near the onset of the Industrial-era, several
146 decades before the strongest global warming trend, and has remained weak up to the present day. This
147 either suggests hysteresis of the AMOC in response to an early climate forcing – natural (solar,
148 volcanic) or anthropogenic (greenhouse gases, aerosols, land-use change) - or alternatively, continued
149 climate forcing, such as the melting of the GIS⁶, has been sufficient to keep AMOC weak. Our

150 reconstructions also differ from most climate model simulations, which show either negligible AMOC
151 change or a later, more gradual reduction³⁰. Many factors may be responsible for this model-data
152 discrepancy: a misrepresentation of AMOC-related processes and possible hysteresis, including
153 underestimation of AMOC sensitivity to climate (freshwater) forcing^{29,31}; the underestimation or
154 absence of important freshwater fluxes during the end of the LIA; and the lack of transient forced
155 behaviour in the “constant forcing” pre-Industrial controls used to initialize historical forcings.
156 Resolving these issues will be important for improving the accuracy of projected changes in AMOC.

157 In conclusion, our study reveals an anomalously weak AMOC over the last ~150 years. Because
158 of its role in heat transport, it is often assumed that AMOC weakening cools the northern hemisphere.
159 However, our study demonstrates that changes in AMOC are not always synchronous with temperature
160 changes. That AMOC weakening occurred during the late LIA and onset of the Industrial era, rather
161 than earlier in the LIA, may point to additional forcing factors at this time, such as an increase in the
162 export of thickened Arctic and Nordic sea ice, or melting of circum-Arctic ice-shelves. The persistence
163 of weak AMOC during the 20th century, when there was pronounced northern hemisphere and global
164 warming, implies that other climate forcings, such as greenhouse gas warming, were dominant during
165 this period. We therefore infer that AMOC has responded to recent centennial-scale climate change,
166 rather than driven it. Regardless, the weak state of AMOC over the last ~150 years may have modified
167 northward ocean heat transport, as well as atmospheric warming through altering ocean-atmosphere
168 heat transfer^{32,33}, underscoring the need for continued investigation of the role of the AMOC in climate
169 change. Determining the future behaviour of AMOC will depend in part on constraining its sensitivity
170 and possible hysteresis to freshwater input, for which improved historical estimates of these fluxes
171 during the AMOC weakening reported here will be especially useful.

172

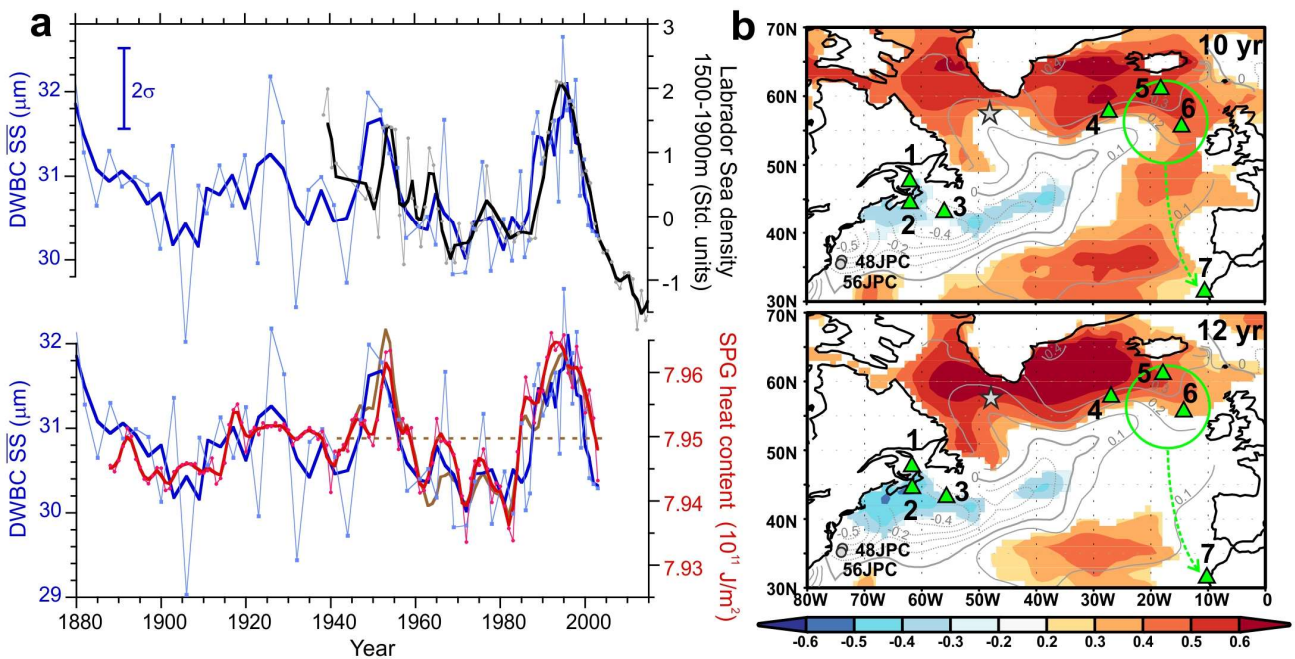
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175 **Fig. 1. Modelled link of DWBC velocity with deep Labrador Sea density and AMOC.** a, Correlation of the
 176 vertically-averaged ocean density (1000-2500m) with dLSD; green box, 1000-2500m average) in HadGEM3-
 177 GC2 control run; cores sites for DWBC flow speed reconstruction shown. b, Climatology of the modelled
 178 meridional ocean velocity (ms^{-1}) 30-35°N (see Methods and Extended Data Fig. 7&8), illustrating the modelled
 179 position of the DWBC. c, Cross-correlations between modelled averaged DWBC flow speed in pink box in b
 180 and indices of dLSD and AMOC at 45°N (dashed line is without the Ekman component).

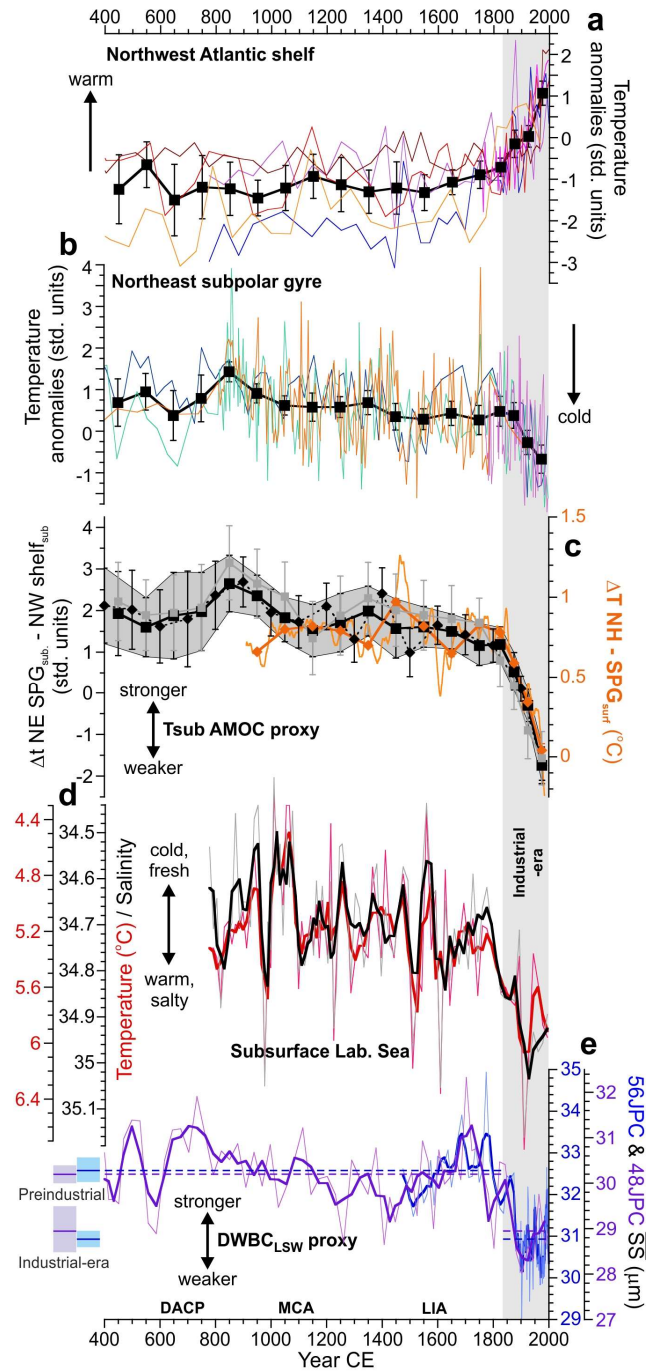
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182

183 **Fig. 2. Proxy validation and recent, multi-decadal variability.** a, SS mean grain size (56JPC, blue) compared
 184 with: central Labrador Sea annual density⁵ (black; $r^2=0.56$, $n=54$), comparable to model-based dLSD (Extended
 185 Data Fig. 9); and with 12-year lagged SPG upper ocean heat content (0-700m, 55-65°N, 15-60°W, EN4 dataset;
 186 red; $r^2=0.58$, $n=116$) and Tsub AMOC fingerprint¹¹ (brown; dashed line zero-line; $r^2=0.76$, $n=55$). Correlations
 187 (and 2σ SS error bar, $n=30$) are for 3-point means (bold). Low resolution 48JPC data not shown. b, 10- and 12-
 188 yr lagged spatial correlation of upper ocean heat content (0-700m) with reconstructed DWBC_{LSW} flow speed
 189 (56JPC), heat content lags. Grey contours, spatial Tsub AMOC proxy¹¹; green triangles, Tsub proxy sites; green
 190 circle, surface region controlling benthic temperatures at site 7. Grey circles, DWBC sites; grey star, core site
 191 ref. 17.

192



195 **Fig. 3. Proxy reconstructions of AMOC changes over the last 1600 years.** a,b, Subsurface Northwest Atlantic
 196 shelf (a) and Northeast Atlantic subpolar gyre (b) temperatures; sites in Fig. 2b; composite stacks, black. c, Tsub
 197 AMOC proxy (black, grey), various binning (see Extended Data Fig 4); orange, Rahmstorf AMOC proxy⁶, $1^{\circ}\text{C} =$
 198 $\sim 2.3\text{Sv}$, 21-yr smooth, thin line; thick line and symbols, binned as for Tsub AMOC proxy. d, *N. pachyderma*
 199 $\text{Mg/Ca-}\delta^{18}\text{O}$ subsurface ($\sim 100\text{-}200\text{m}$) temperature and salinity for northeast Labrador Sea¹⁷. e, SS mean grain
 200 size (56JPC, blue; 48JPC, purple; bold, 3-point means); dashed lines, Industrial/Preindustrial-era averages. Error
 201 bars/shading, $\pm 2SE$. DACP (Dark Ages Cold Period, $\sim 400\text{-}800$ CE), MCA (Medieval Climate Anomaly, $\sim 900\text{-}$
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298

299 **Author contributions**

300 Conceived by DT; NSF project proposal written and managed by DO and DT; cores 56JPC and 48JPC
301 collected by LK; SS analysis and interpretation by DT, with contributions from PS and RD; modelling

302 work by PO and JR; SCP analysis by NR; Monte-Carlo modeling by PS; first draft written by DT; all
303 authors contributed to discussion and final version of the manuscript.

304

305 **Author Information**

306 The authors declare no competing financial interests.

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309

310 **METHODS**

311 **Climate model investigation of AMOC and DWBC changes**

312 The climate model used in this study was the UK Met Office's Third Hadley Centre Global
313 Environmental Model – Global Coupled Configuration two (HadGEM3–GC2). The ocean model for
314 HadGEM3-GC2 is the Global Ocean version 5.0, which is based on the version 3.4 of the Nucleus for
315 European Models of the Ocean model (NEMO)³⁴. The ocean model has 75 vertical levels, and is run at
316 a nominal $\frac{1}{4}^\circ$ resolution using the NEMO tri-polar grid. The atmospheric component is the Global
317 Atmosphere version 6.0 of the UK Met Office Unified Model, and is run at N216 resolution (~60km in
318 mid-latitudes), with 85 vertical levels. More information on the model can be found in Williams et al³⁵.
319 The experiment analyzed here was a 310-year control simulation of HadGEM3-GC2, i.e. it includes no
320 changes in external forcings. This experiment was previously run and analyzed in Ortega et al⁸, where
321 details of the specific model experiment are included. This coupled simulation has a relatively high
322 spatial resolution for a more accurate representation of the boundary currents, and is sufficiently long to
323 resolve a large number of decadal oscillations. All model data has been linearly detrended to remove
324 any potential drift, and smoothed with a 10-year running mean in order to focus on the decadal and
325 multi-decadal variability.

326 We use the model-based relationships to support the interpretation of the proxy-based AMOC
327 reconstructions, which cannot be validated with the limited observations available. The AMOC at 45°N
328 is chosen as this is the latitude with the largest correlations with both the deep Labrador Sea Density
329 (dLSD) and deep western boundary current (DWBC) velocity index in the model. Note that AMOC
330 indices defined at other latitudes (e.g. 35°N, 40°N) produce weaker, but still significant correlations
331 with both dLSD and the DWBC. The simulated DWBC velocity index is the average of 30-35°N as at
332 35°N (the latitude where the sediment cores were taken) the DWBC is found offshore, which we
333 believe is associated with the model's Gulf Stream separating further north than in the observations
334 (Extended Data Fig. 7). It should be noted, however, that changes in the position of the observed Gulf
335 Stream do not appear to directly control the reconstructed flow speed changes in the DWBC_{LSW} (see
336 Extended Data Fig. 10).

337 We have also assessed the robustness of the model-based relationships to the smoothing. For
338 example we reproduced the cross-correlation analysis in Fig. 1c using undetrended and/or unsmoothed
339 data instead. In all cases, the lead-lags relationships are similar, with larger correlations emerging when
340 the decadal smoothing is applied. Furthermore, we also tested the sensitivity of the model-based
341 relationships to the specific model used. In particular, we repeated the analysis of Fig. 1 in the 340 year
342 control experiment using the HiGEM climate model³⁶. HiGEM has a similar horizontal ocean
343 resolution (1/3°), but is based on a different ocean model. Encouragingly, Extended Data Fig. 8 shows
344 that the results are consistent across the two models, in particular the link between dLSD and the
345 DWBC, and between the DWBC and the AMOC at 45°N. However, there are some caveats. For
346 example, both models' Gulfstream separate too far north, which led us to define the DWBC flow
347 indices slightly south of the core sites. HiGEM also has a deeper DWBC than HadGEM3-GC2.
348 Therefore, the DWBC index was computed at different levels in both models in order to represent the
349 link between dLSD and the DWBCs. However, despite these differences, both models support the

350 general interpretation that the DWBC in the vicinity of Cape Hatteras is strongly connected with
351 changes in the dLSD and the AMOC.

352 The interpretation of the model results is consistent with previously published model studies
353 (both low and high resolution) that have revealed a coupling between the AMOC and/or Labrador Sea
354 density, and the DWBC^{3,7,11,37}. These modelled relationships support a causal link for the correlations
355 between the instrumental records of Labrador Sea density and the reconstructed DWBC velocity,
356 presented in Fig 2. Furthermore, recent instrumental data of the DWBC at 39°N spanning 2004-2014
357 reveal that a reduction in the velocity of classical LSW within the DWBC is also accompanied by a
358 decrease in its density³⁸, as hypothesized here. The observed decrease in the velocity and density of
359 classical LSW within the DWBC between 2004 and 2014 is also consistent with the decrease in the
360 density of the deep Labrador Sea over this period (Fig. 2a and Extended Data Fig. 9), although a longer
361 observational DWBC time-series is needed to gain confidence in this relationship.

362

363 **Age models**

364 New and updated age models for the cores are presented in Extended Figures 1 & 2, and are based on
365 ¹⁴C, ²¹⁰Pb and spheroidal carbonaceous particle (SCP) concentration profiles³⁹.

366

367 **Sortable silt data**

368 Two marine sediment cores were used for DWBC flow speed reconstruction: KNR-178-56JPC
369 (~35°28'N, 74°43'W, 1718 m water depth) and KNR-178-48JPC (35°46'N, 74°27'W, 2009 m water
370 depth). Sediments were processed using established methods⁴⁰ taking 1cm wide samples, every 1cm for
371 the top 63cm and then every 4cm down to 200cm in 56JPC, and every 1cm down to 71cm in 48JPC.
372 Samples were analyzed at Cardiff University on a Beckman Coulter Multisizer 4 using the Enhanced
373 Performance Multisizer 4 beaker and stirrer setting 30 to ensure full sediment suspension. Two or three
374 separate aliquots were analyzed for each sample, sizing 70,000 particles per aliquot. Analytical

375 precision was $\sim 1\%$ ($\pm 0.3\mu\text{m}$), whilst full procedural error (based on replicates of $\sim 25\%$ of samples,
376 starting from newly sampled bulk sediment) was $\pm 0.8\mu\text{m}$.

377

378 **Temperature data and constructing the Tsub index**

379 Numerous studies have suggested AMOC variability is associated with a distinct surface or subsurface
380 (400m) temperature fingerprint in the North Atlantic^{6,11,28,41}. However, the lack of long-term
381 observations of AMOC prevents accurate diagnosis of the precise AMOC temperature fingerprint, and
382 models display a range of different AMOC temperature fingerprints^{9,42}. In this study we focus on the
383 Tsub AMOC fingerprint, proposed by Zhang¹¹ on the basis of covariance between modelled AMOC,
384 the spatial pattern of the leading mode of subsurface (400m) temperature variability, and sea-surface
385 height changes. These model-based relationships were supported by similar relationships (spatial and
386 temporal) observed in recent instrumental data of subsurface temperature and sea surface height. The
387 agreement between our DWBC_{LSW} AMOC reconstruction, observed Labrador Sea density changes, and
388 the Tsub AMOC fingerprint, provides support for our approach and suggests the Tsub AMOC
389 fingerprint is capturing an important component of deep AMOC variability. Differences between the
390 various proposed AMOC temperature fingerprints likely reflects their sensitivity to different aspects of
391 AMOC and heat transport in the North Atlantic e.g. AMOC versus SPG circulation²⁸; the temperature
392 response to each of these components may be resolved if more comprehensive spatial networks of past
393 North Atlantic temperature variability are generated⁴³.

394 Records used in the OCEAN 2K synthesis⁴⁴ from the Northwest Atlantic slope and the subpolar
395 Northeast Atlantic were selected and supplemented with additional records that also record past
396 temperature variability in the subsurface ocean of the chosen region. Cores that did not have a modern
397 core top age (1950 CE or younger) or resolution of better than 100 years were not included.
398 Foraminiferal-based temperature proxies were selected because they record subsurface temperatures
399 (typically 50-200m), upon which the Tsub proxy is based. We avoid other temperature proxies (e.g.

400 alkenones, coccolithores, diatoms) that are typically more sensitive to sea surface temperature, rather
401 than Tsub, and which also use the fine fraction that at the drift sites required for the necessary age
402 resolution contains significant allochthonous material, compromising the fidelity of *in situ* temperature
403 reconstruction^{45,46}.

404 All Tsub records were normalized to the interval 1750-2000 CE (the length of the shortest
405 records). The Tsub proxy reconstruction was calculated as the difference between the stacked
406 temperature records of the Northwest and Northeast Atlantic. Our results are insensitive to the precise
407 binning or stacking method, as shown in Extended Data Fig. 4. The sedimentation rates of the cores
408 used, combined with the effects of bioturbation mean we cannot resolve signals on timescales shorter
409 than ~20-50 years. Age model uncertainty is estimated to be up to ~30 years for the last ~150 years
410 where cores have ²¹⁰Pb dating, and ~100 years for 400-1800 CE where ¹⁴C dating is relied upon.
411 Therefore, the optimal bin intervals chosen were 50 years for 1800-2000 CE, and 100 years for 400-
412 1800 CE. Results for only using 50 year and 100 year bins, as well as 30 year bins for the top 200
413 years, are shown in Extended Data Fig. 4.

414

415 **Data Availability**

416 The proxy data that support these findings are provided with the paper as Source Data for Fig. 2, 3,
417 Extended Data Fig 1, 2, 4, 5, 6, 9, and at NGDC Paleoclimatology ([https://www.ncdc.noaa.gov/data-](https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets)
418 [access/paleoclimatology-data/datasets](https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets)). Model data can be made available from Jon Robson
419 (j.i.robson@reading.ac.uk) upon reasonable request.

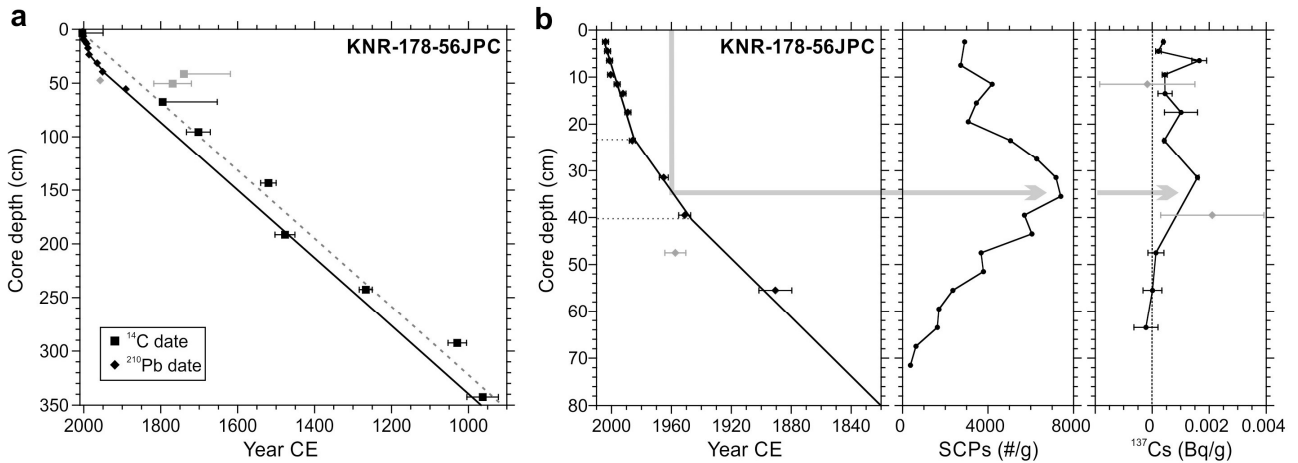
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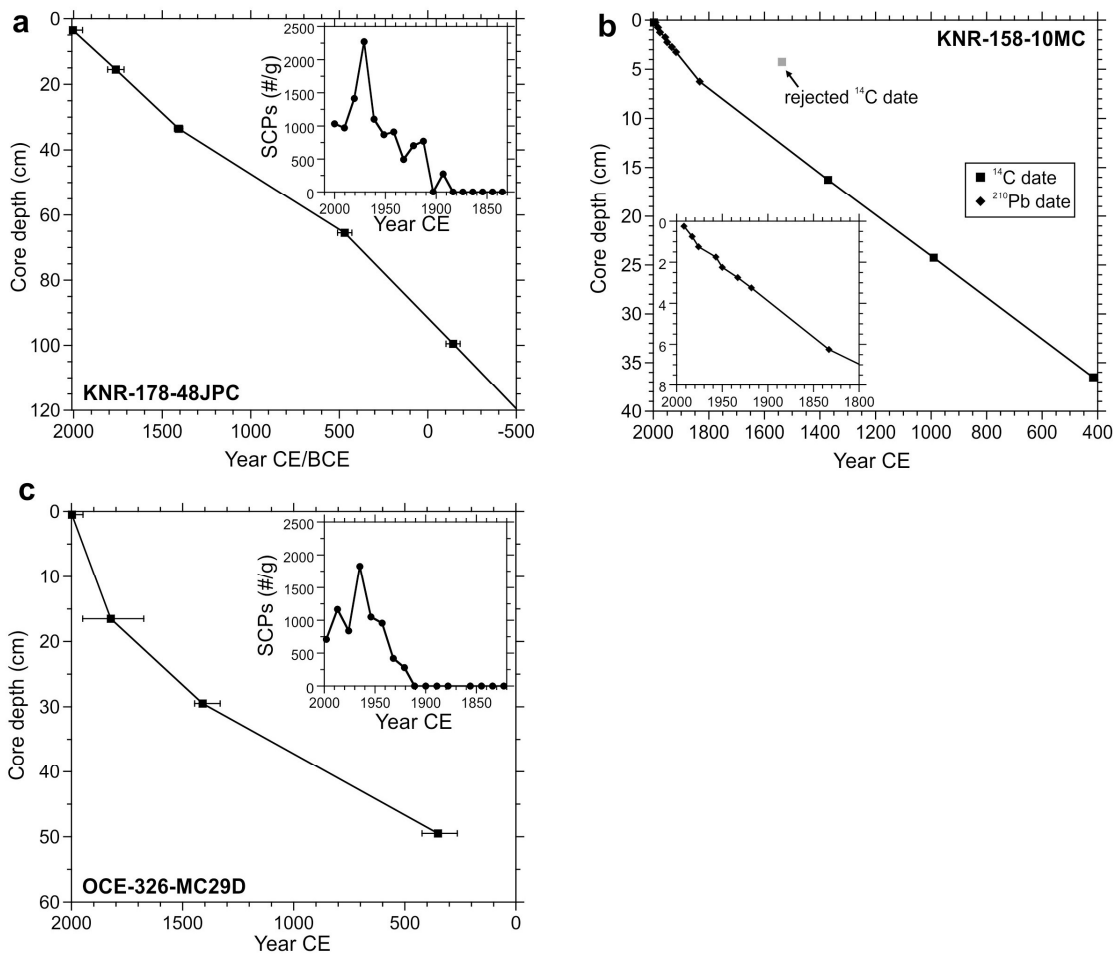
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Extended Data Figure 1. Age model for core KNR-178-56JPC. **a**, ^{14}C and ^{210}Pb dating. ^{14}C ages (with 1σ ranges; grey, rejected dates) on planktonic foraminifera yielded a modern core top age and indicate an average sedimentation rate over the last 1000 years of 320cm/kyr (dashed line). The presence throughout the core of abundant lithogenic grains in the $>150\mu\text{m}$ fraction, alongside the coarse sortable silt mean grain size values, suggest some reworking of foraminifera is likely, resulting in average ^{14}C ages that may be slightly (~ 50 years) older than their final depositional age, consistent with the ^{210}Pb dates not splicing smoothly into the ^{14}C ages (^{14}C ages appear slightly too old). The final age model was therefore based on the ^{210}Pb ages for the last century, and was then simply extrapolated back in time using the linear sedimentation rate of 320cm/kyr. Given that none of our findings are dependent on close age control in the older section of this core (i.e. pre 1880 CE), this uncertainty (converted ^{14}C ages are ~ 50 years older than the extrapolated linear age model) does not affect the conclusions of our study. **b**, The age model for the top 80cm of 56JPC is based on ^{210}Pb dating of bulk sediment assuming the constant initial concentration (CIC) method (rejecting the date at 47cm – likely burrow). A simple two-segment linear fit to the ^{210}Pb dates was adopted (rather than point-to-point interpolation or a spline) because sedimentological evidence - an abrupt increase in the % coarse fraction at 23cm depth, not observed elsewhere in the core, is indicative of a step change in the sedimentation rate. Further support for the age model of 56JPC over the last century is derived from the down-core abundance profile of spheroidal carbonaceous particles (SCPs, derived from high temperature fossil fuel combustion, counted using the methods described in ref. ³⁹) which ramped up from the mid-late 1800s and peaked in the 1950s-70s (40 to 25cm) before declining over recent decades, consistent with the ^{210}Pb based age model. The occurrence of ^{137}Cs in the top $\sim 40\text{cm}$ of the core is also consistent with the ^{210}Pb based age of ~ 1950 at 40cm. Age uncertainty (1σ) for the last 60 years of the core is estimated at $\pm 2\text{-}3$ years. Note, sediment core top is at 3cm depth in core-liner.

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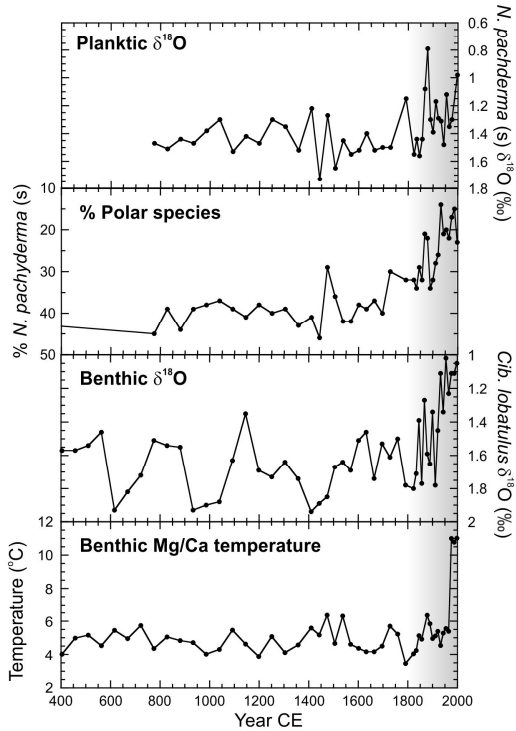
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Extended Data Figure 2. Age models for additional cores. **a**, ^{14}C age model based on linear interpolation of ^{14}C dated planktic foraminifera (with 1σ ranges) in sediment core KNR-178-48JPC (used for the DWBC_{LSW} SS reconstruction); yielding a modern core top age and average sedimentation rate of $\sim 50\text{cm/kyr}$. Note, core top is at 3cm depth in core-liner. Insert shows the SCP profile for 48JPC based on the ^{14}C age model, confirming the modern age of the top sediments, with SCPs showing the expected profile: increasing from the late 1800s onwards, peaking $\sim 1950\text{-}1970$ and then declining afterwards. **b**, Updated age model for KNR-158-10MC (after ref. ⁴⁷; used in Extended Data Fig. 1, examining regional near surface temperature trends in the NW Atlantic during the Industrial era) using new ^{210}Pb dating (CIC method) for the top 7cm and rejecting the anomalously old ^{14}C age at 4cm depth. A single detectable occurrence of ^{137}Cs at 2-2.5cm (equivalent to 1957 on the ^{210}Pb based age model) can be linked to the bomb peak at 1963, supporting the age model. Also note, SCPs were found in the top 5cm of this core, confirming the Industrial era age for the top 5cm, however the low concentrations prevent meaningful interpretation of the down-core trends and are not shown. **c**, Age model for core OCE-326-MC29B (used for Tsub reconstruction of the NW Atlantic shelf). ^{14}C ages of planktic foraminifera (with 1σ ranges) from ref. ⁴⁸. Support for this age model is provided by the SCP concentrations (this study) which show the expected down-core profile³⁹ when plotted using the ^{14}C ages. ^{210}Pb dating⁴⁸ also suggests a sedimentation rate of $\sim 120\text{cm/kyr}$ for uppermost sediments, consistent with the ^{14}C ages and SCP profile.

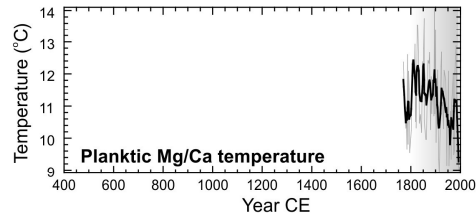
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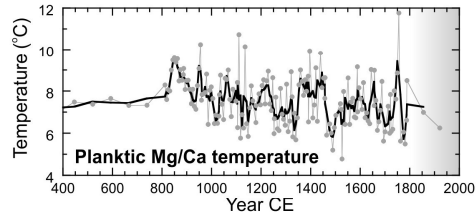
a Emerald Basin (29MC, 250m water depth, site 2)



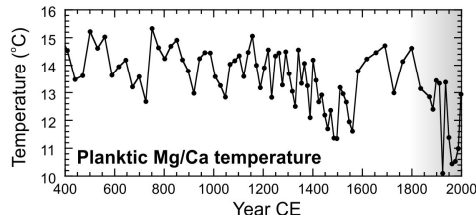
d Gardar drift (site 4)



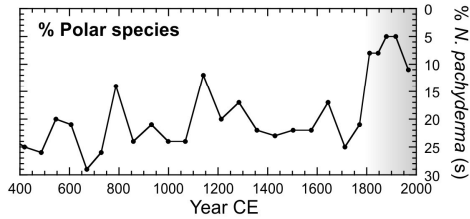
e Bjorn drift (site 5)



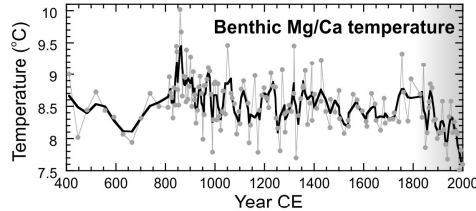
f Feni drift (site 6)



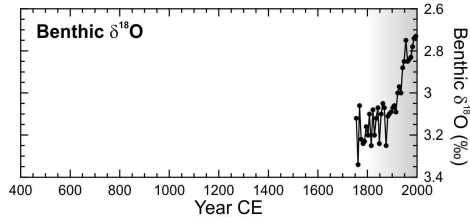
b Laurentian Fan (13MC, site 3)



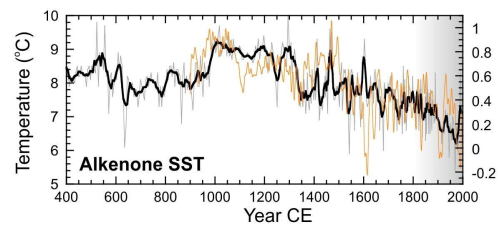
g ENACW, formed in eastern SPG (899m water depth, site 7)



c Gulf of St Lawrence (409m water depth, site 1)



h *North Iceland shelf/Rahmstorf SPG SST



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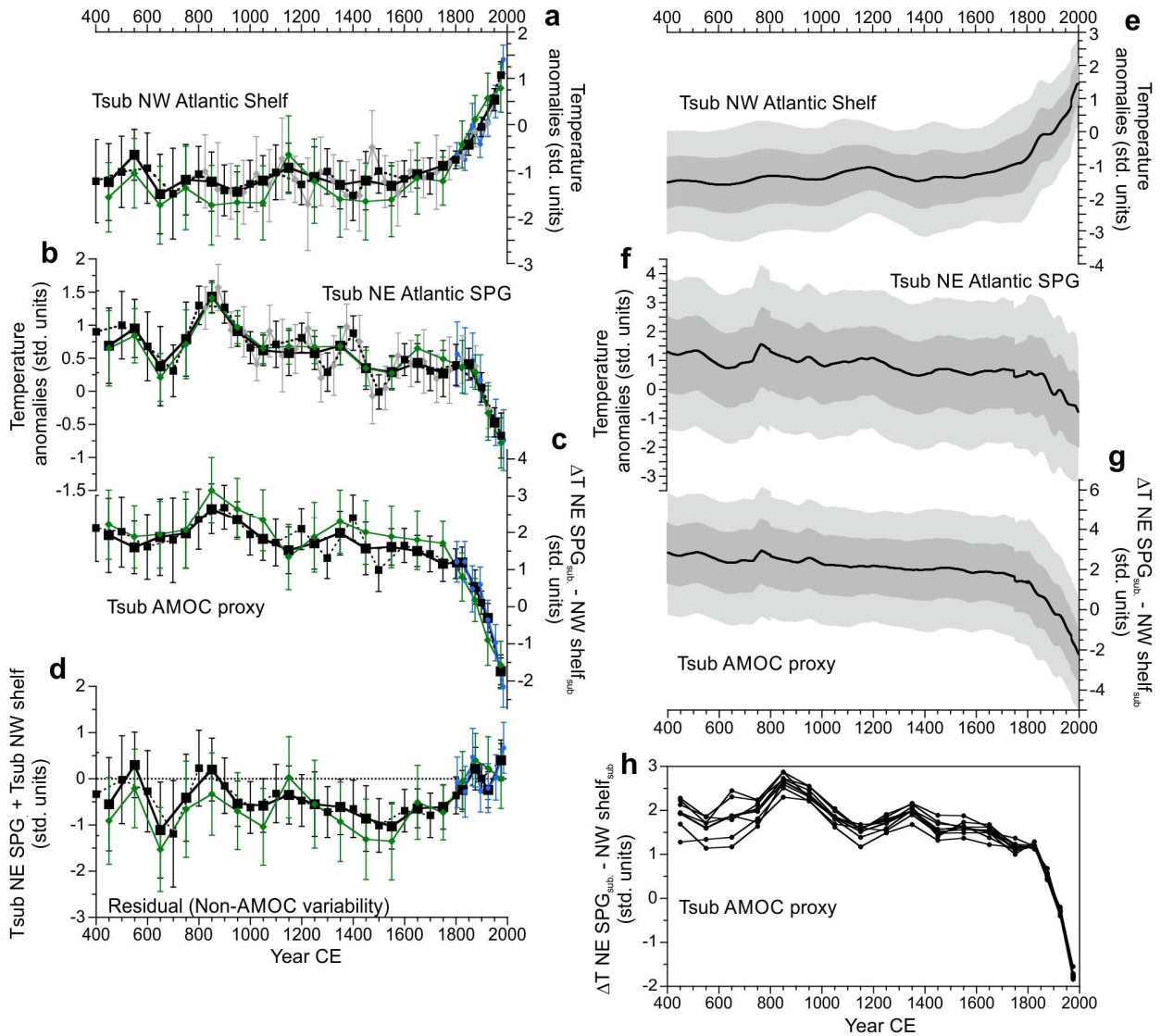
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Extended Data Figure 3. Raw data for construction of Tsub AMOC proxy shown in Fig. 3. Locations are shown in Fig. 2b. **a-c**, Temperature proxy records from refs⁴⁸⁻⁵⁰ used for the Northwest Atlantic stack, where model studies^{11,12} indicate AMOC weakening results in warming of the surface and subsurface waters. **d-g**, records used to reconstruct Northeast Atlantic subpolar gyre subsurface temperatures: **d**, Gardar drift⁵¹, **e**, combined South Iceland data^{52,53}, **f**, Feni drift⁵⁴, **g**, Eastern North Atlantic Central Water (ENACW) largely composed of waters formed in the eastern SPG^{55,56}, **h**, The high resolution alkenone SST record from the North Iceland shelf⁵⁷ was not included because it is not located within the open North Atlantic subpolar gyre, although it does also show the lowest temperature of the last 1600 years occurred during the most recent century, similar to the other Northeast Atlantic records. Also shown for reference is the Rahmstorf central subpolar gyre SST reconstruction (largely based on terrestrial proxies)⁶.



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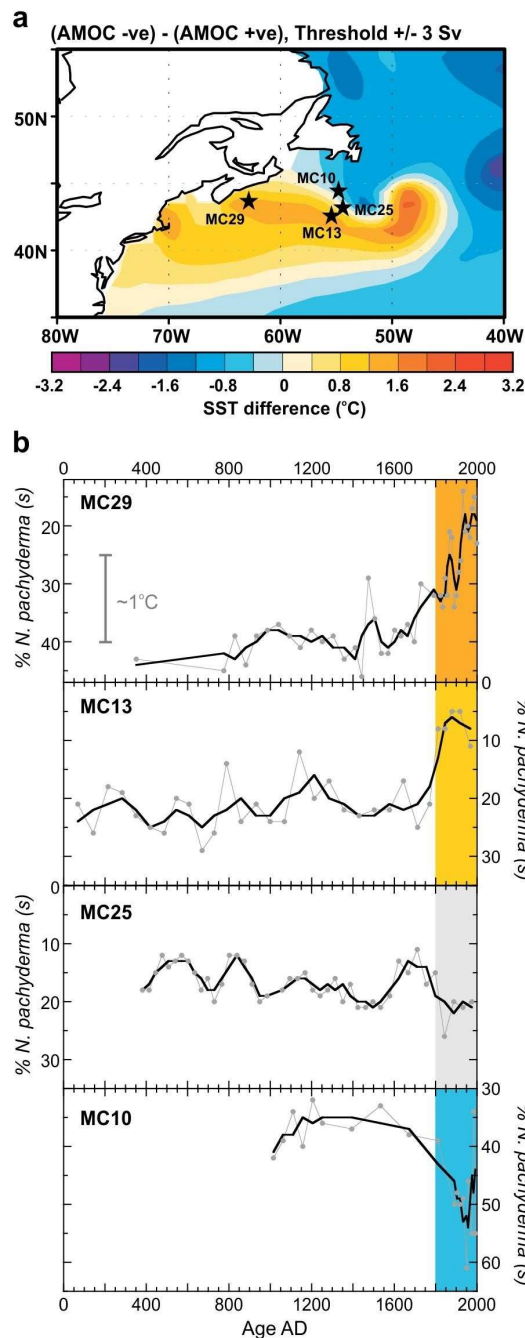
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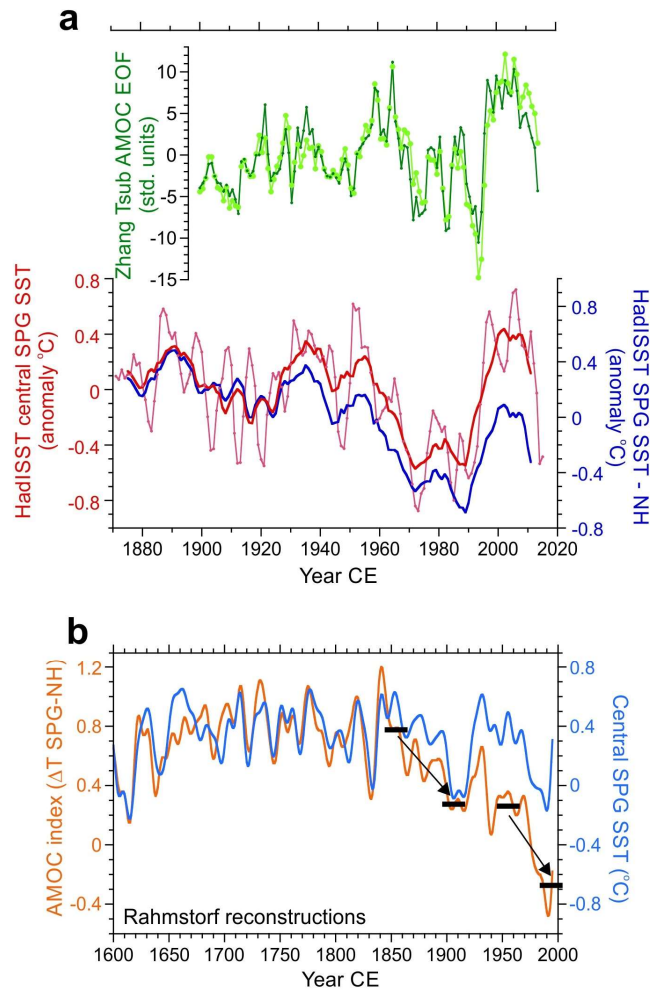
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Extended Data Figure 4. Different binning and averaging approaches and the residual temperature signal.

a & b, Stacked, normalized proxy temperature data from the NW Atlantic shelf/slope (**a**) and NE Atlantic SPG (**b**). **c,** The derived Tsub AMOC proxy calculated as the numerical difference between the stacks shown in **a** and **b**. **d,** The residual temperature variability in stacks **a** and **b** not described by the (anti-phased dipole) Tsub AMOC proxy shown in **c**, i.e. the in-phase temperature variability common to both stacks, calculated as the numerical sum of the two stacks (if divided by two, this would be the numerical mean). This represents the inferred non-AMOC related temperature variability common to both regions, and broadly resembles northern hemisphere temperature reconstructions, most notably colder residual temperatures during the LIA, ~1350-1850. For plots **a-d**: black solid line and squares, preferred binning (50yr for 1800-2000, 100yr for 400-1800); green line and symbols, as for preferred binning but stacks are produced by first binning the proxy data at each site and then averaging these binned site values, as opposed to binning all the proxy data together in one step (the former ensures equal weighting for each site, the latter biases the final result to the higher resolution records); black dashed line and symbols, 100yr bins offset by 50yr from the preferred bins; grey line and symbols, 50yr bins (not shown for **c** and **d**); blue line and symbols; 30yr bins for 1790-2000. Error bars for **a-d** are ± 2 S.E. **e-g,** as for **a-c** except using a Monte Carlo approach, using the published uncertainties for age assignment and temperature reconstructions; light and dark grey shading are $\pm 1\sigma$ and $\pm 2\sigma$. **h,** Jackknife approach version of **c**, with each line representing the Tsub AMOC proxy but leaving out one of the individual proxy records each time.

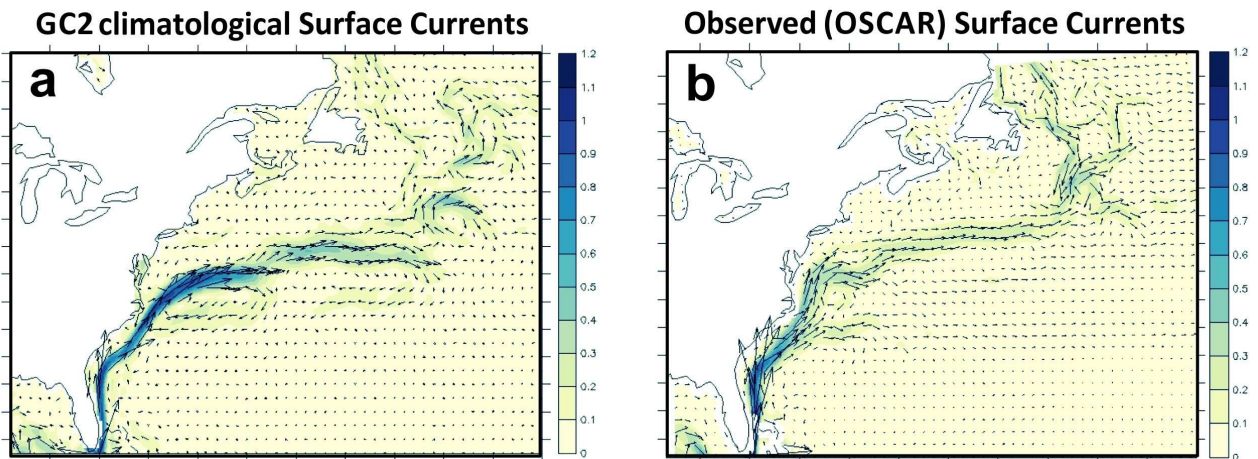


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 578 **Extended Data Figure 5. SST temperature response of the Northwest Atlantic to AMOC weakening. a,**
 579 **Modelled SST difference between weak and strong AMOC⁵⁸. This pattern is model-dependent, with the study**
 580 **cited here chosen because of its good agreement with observations of Gulf Stream variability⁵⁸. Core locations**
 581 **for b are shown by black stars. b, The percentage abundance of the polar species, *N. pachyderma* (sinistral), in**
 582 **marine sediment cores from the Northwest Atlantic, as an indicator of near-surface (~75m) temperatures: a 15%**
 583 **increase indicates ~ 1°C of cooling (note the reversed y-axes). The opposing trends over the last 200 years are**
 584 **consistent with the modelled SST pattern for a weakening of the AMOC, as shown in a. Data and age models for**
 585 **the cores are: OCE326-MC29, ref.⁴⁸, using the original ¹⁴C dating and as shown in Extended Data Fig. 2;**
 586 **OCE326-MC13 and OCE326-MC25, ref.⁴⁹, using the original ¹⁴C age ties at the top and bottom of the core and**
 587 **scaling the intervening sedimentation rate to the %CaCO₃ content^{49,59,60}; KNR158-MC10 from this study and age**
 588 **model presented in Extended Data Fig. 2.**
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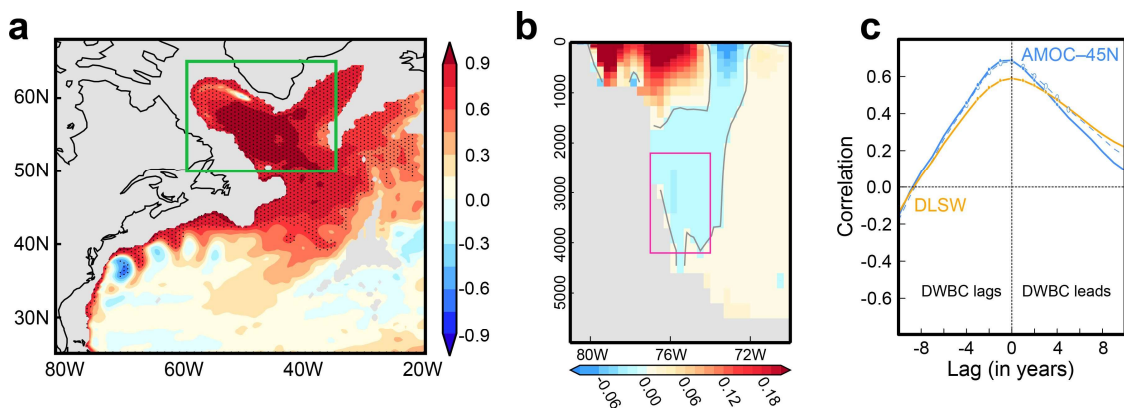


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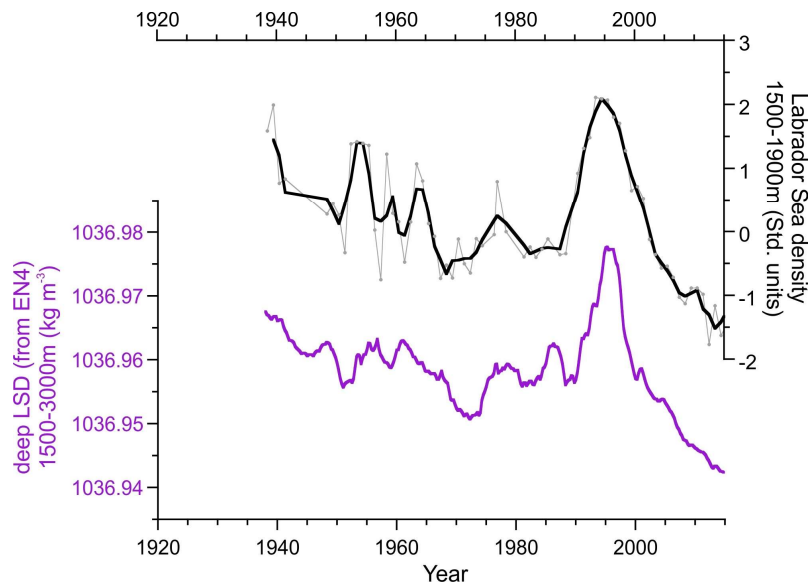
Extended Data Figure 6. Temperature fingerprints of AMOC over the twentieth century. **a**, Top, the Tsub AMOC fingerprint¹¹ using the EN4 dataset (light green is EOF1 of 1993-2003, as defined by Zhang¹¹, applied to the EN4 data; dark green is the 2nd EOF of the North Atlantic) - no 20th century AMOC decline is shown by this observational based reconstruction; bottom, instrumental based reanalysis of the ‘cold blob’ central SPG region (red, 3 yr and 11 yr smooth; 47-57N, 30-45W) used in the Rahmstorf SST AMOC proxy⁶. The reconstructed central SPG SST bears some resemblance to the Tsub AMOC fingerprint record, which is not unexpected since the central SPG forms a significant spatial component of the Tsub fingerprint. No clear decrease is shown by the central SPG SST, and the equivalent Rahmstorf AMOC proxy⁶ (blue; central SPG – northern hemisphere (NH) temperature) declines through the twentieth century only due to the subtraction of the NH warming trend. **b**, Reconstructed (predominantly terrestrial-based proxy network) AMOC proxy (temperature difference between the central SPG and the NH; orange) and the central SPG SST reconstruction⁶ (blue). As for the instrumental data shown in **(a)**, the decline in the Rahmstorf AMOC index throughout the twentieth century is caused by the subtraction of the NH warming trend. There is a two-step decline in the AMOC proxy, at 1850-1900 and 1950-2000, the former mainly being the result of a strong cooling of the SPG (likely weakening northward heat transport, paralleling the weakening shown by our DWBC proxy), whereas the late twentieth century decline was mainly due to the subtraction of the strong NH warming trend, rather than a persistent cooling of the SPG.



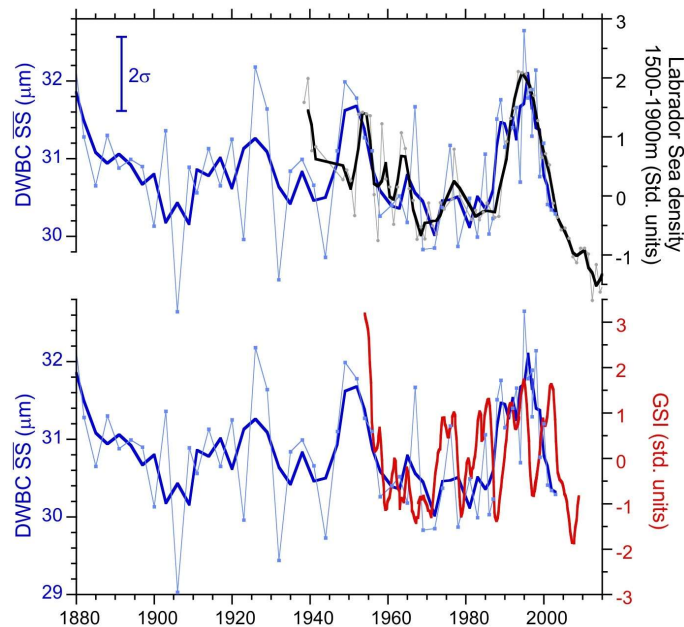
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 611 **Extended Data Figure 7. DWBC changes in model HadGEM3-GC2.** a,b Climatological surface current
 612 direction (in arrows) and speed (shaded, m/s) in the control simulation with HadGEM3-GC2 and the satellite
 613 product OSCAR, respectively.
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 618 **Extended Data Figure 8. The modelled link of DWBC velocity with deep Labrador Sea density and**
 619 **AMOC in the HiGEM model.** a, Correlation of the vertically-averaged ocean density (1000-2500m) with deep
 620 Labrador Sea density index (dLSD as defined by ref. 4; green box, 1000-2500m average) in a 340 year present
 621 day control run of the HiGEM model (see ref 36). b, Climatology of the modelled meridional ocean velocity
 622 (ms^{-1}) averaged between 30-35°N, illustrating the modelled position of the DWBC c, Cross-correlations between
 623 modelled averaged DWBC flow speed in pink box in b and indices of dLSD and AMOC at 45°N (dashed line is
 624 without the Ekman component). Note that the box over which the DWBC flow index in c is averaged has
 625 changed with respect to Fig. 1 in the main paper in order to take into account of the fact that the return flow is
 626 deeper in HiGEM than in HadGEM3-GC2.
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 630 **Extended Data Figure 9. Comparison of Labrador Sea density parameters.** The model-based deep Labrador
 631 Sea density (dLSD) parameter, proposed by ref. 4, using the EN4 reanalysis dataset, incorporates a larger area
 632 and greater depth range than instrumental data-only studies such as ref. 5, which examines past variability in
 633 Labrador Sea convection and focuses on the central Labrador Sea and depths <2000m region, where most
 634 observational data is available. The comparison, here, of dLSD (purple line, 3 yr mean) using the EN4 dataset
 635 with instrumental data of density changes in the central Labrador Sea at 1500-1900m depth (black line, annual
 636 averages and 3 yr mean) illustrates that the two parameters show very similar variability, both being dominated
 637 by the density changes caused by deep convection in the Labrador Sea, which can reach down to ~2000m.
 638 Estimates of uncertainty are discussed in ref. ⁶¹.
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 641 **Extended Data Figure 10. Comparison with Gulf Stream Index (GSI).** The direct influence of the changing
 642 position of the Gulf Stream on the grain size of our core sites can be ruled out through comparison of
 643 instrumental records of the Gulf Stream position (the GSI, from ref. ⁵⁸) with the down-core data in 56JPC. No
 644 clear correlation is observed between the GSI and our SS mean grain size data in core 56JPC, contrasting with
 645 the coupling between our SS data (inferred DWBC_{LSW} flow speed) and density changes in the deep Labrador
 646 Sea. 2σ SS error bar (n=30) is for 3-point mean (bold).