The deglacial evolution of North Atlantic deep convection

Radiocarbon evidence from the Northeast Atlantic provides new insights into the timing and nature of North Atlantic deep convection changes during the last glacial termination.

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Deep water formation in the North Atlantic by open-ocean convection is an essential component of the overturning circulation of the Atlantic Ocean, which helps regulate global climate. We use water-column radiocarbon reconstructions to examine changes in Northeast Atlantic convection since the last glacial maximum. During cold intervals, we infer a reduction in open-ocean convection and an associated incursion of an extremely ^{14}C-depleted water mass, interpreted to be Antarctic Intermediate Water. Comparing the timing of deep convection changes in the Northeast and Northwest Atlantic, we suggest that, despite a strong control on Greenland temperature by Northeast Atlantic convection, reduced open-ocean convection in both the Northwest and Northeast Atlantic is necessary to account for contemporaneous perturbations in atmospheric circulation.

Vertical density gradients within the global ocean limit the exchange of surface and deep waters. Only in a limited number of locations, characterised by weak stratification of the water column and intense surface buoyancy losses, can surface water be converted into deep water by open-ocean convection (*1*). Through its control on deep water formation, open-ocean convection sets the properties of the deep global ocean and forms an essential component of the global overturning circulation (*1*).

Open-ocean deep convection in the North Atlantic occurs in the Labrador and Greenland Seas (*1*) transforming well-ventilated, nutrient-poor surface waters into North Atlantic Deep Water (NADW), which spreads southwards to occupy much of the deep Atlantic. Paleoceanographic studies suggest that deep convection in the North Atlantic was altered during the last Ice Age as compared with today (e.g. *2,3*). Glacial convection was shallower, forming Glacial North Atlantic Intermediate Water (GNAIW), and possibly weaker, leading to poorer ventilation of the deep Atlantic. Rapid fluctuations between weak and strong modes of deep convection could also be linked with abrupt climate changes across the North Atlantic region because of the associated changes in the poleward flux of warm surface waters. Furthermore, mode switches in deep convection might be triggered by changes in the input of freshwater, with the Younger Dryas (YD) cold reversal being the archetypal example (e.g. *4*). Yet there is growing evidence that the YD may be part of an intrinsic oscillation associated with deglaciation, rather than peculiar to the last termination (e.g. *5,6*). To test these hypotheses we require precise constraints on the timing (and rate) of deep convection changes relative to abrupt climate events and freshwater perturbations.

High-resolution evidence for past North Atlantic mode changes has come primarily from stable isotope and nutrient proxy records (e.g. *2,7* and references therein). However, these proxies are complicated by biological processes and isotopic fractionation during air-sea gas exchange, which may overprint variations caused by water mass changes. Here we reconstruct seawater ^{14}C activities to investigate past changes in deep convection. Our results suggest extremely large variations in water column ventilation and significant differences compared to the mid-latitude Northwest Atlantic (*8*), allowing us to assess the relative role of Northeast (NE) and Northwest (NW) Atlantic convection changes on deglacial climate.

Radiocarbon (^{14}C) is produced in the upper atmosphere by cosmogenic interaction with nitrogen and is taken up by the ocean via air-sea gas exchange. After equilibration with the atmosphere, the radioactive decay of ^{14}C to ^{12}C allows determination of the apparent time elapsed since a water mass was last in equilibrium with the atmosphere ('^{14}C ventilation age'). Because of mixing with 'older' underlying water, the modern average ventilation age, or 'reservoir age', for tropical and North Atlantic surface waters is ~400 yr (*9*). Modern deep convection in the North Atlantic quickly transfers surface waters to depth, forming well-ventilated NADW and resulting in a minimal surface-to-deep gradient in ^{14}C (newly formed NADW has a ventilation age of ~500 yr, just 100 years older than surface waters (*9*)).

To reconstruct past surface and intermediate/deep (I/D) water ^{14}C ventilation ages in the NE Atlantic, we measured planktic and benthic foraminifera $^{14}C/^{12}C$ from four sediment cores located on the South Iceland Rise (spanning a range of water depths from 1237 m to 2303 m), adjacent to the modern open-ocean deep convection site of the Greenland Sea and directly under the overflow path of recently-formed deep water (Iceland-Scotland Overflow Water, ISOW). Independent age models for the cores (*10*) were constructed by correlating Icelandic tephra layers and abrupt changes in the abundance of polar foraminifera, *Neogloboquadrina pachyderma* sinistral (indicative of cooling/warming) with equivalent events in the annually layer counted NGRIP ice core from Greenland (*11*) (Supporting Online Materials, SOM). The original radiocarbon content ($\Delta^{14}C$) of the ambient water masses were determined by correcting for the radioactive decay of ^{14}C since deposition. These values were then compared to the $\Delta^{14}C$ of the contemporaneous atmosphere (*12*) to yield ^{14}C ventilation ages (equivalent to reservoir ages for the surface ocean) (Fig.1).

Deglacial I/D ventilation ages from all cores show similar trends throughout the deglaciation. I/D ^{14}C ventilation ages alternated rapidly (within ~100-200 years) between close-to-modern values (500 years or less) and extremely old ages (3000-5200 years), reflecting abrupt changes in deep convection during this period. In general young I/D ventilation ages are seen during warm intervals (*e.g.* the Bølling-Allerød (B-A), and early Holocene) and reflect the rapid transfer of equilibrated surface waters to depth, similar to today's ocean. However, the occurrence of extremely ^{14}C-depleted waters between 1.2 and 2.3 km during cold intervals (*e.g.* Heinrich stadial 1 (HS1), the Intra-Allerød Cold Period (IACP) and Younger Dryas (YD)) demands not only a shoaling of convection but also the incursion of a very depleted water mass that must already have been in existence.

During the last glacial period, dissolved inorganic carbon (DIC) is thought to have accumulated in the deep Southern Ocean (*13*). Correspondingly, glacial ^{14}C ventilation age estimates (with respect to the atmosphere) of up to ~4000 years have been reported from there (*14*). During deglaciation, intervals of reduced NADW formation (*e.g.* HS1 and the YD, *7*) have been linked to enhanced vertical mixing within the Southern Ocean (*15,16*). Crucially, the formation of Antarctic Intermediate Water (AAIW) along the northern margin of the Southern Ocean, could have allowed the northward migration of these DIC rich and ^{14}C-depleted waters via the surface

Southern Ocean to intermediate waters of the global ocean. So far, such a migration has been invoked for the Pacific and Indian Oceans (*17,18*), although we note that this is a topic under current debate and further work investigating the properties of deglacial AAIW throughout the global ocean is warranted (see SOM). Here we argue that the influence of ^{14}C-depleted AAIW reached as far north as ~60ºN in the North Atlantic.

Today, the influence of AAIW reaches 20-30^{o}N, in the Atlantic Ocean (*9*). A recent study, using Nd isotopes as a water mass tracer, suggested that penetration of AAIW into the Atlantic was enhanced during HS1 and the YD (*19*) while low-resolution $\delta^{13}C$-Cd/Ca data (*20*) hint that AAIW occasionally reached 60ºN during cold intervals. Because of the Coriolis effect, NADW/GNAIW are concentrated into western boundary currents, causing the eastern basins of the North Atlantic to be subject to a greater influence of southern source I/D water than the western basins. Our benthic ^{14}C results reflect the incursion of extremely depleted AAIW to at least 60ºN during cold intervals of the deglacial period. At these times, local deep convection decreased dramatically, allowing the build up of extremely poorly ventilated I/D waters. Modelling studies (e.g. *21*) have demonstrated that, depending upon their respective densities, AAIW may compete with NADW/GNAIW for occupation of the Atlantic between ~1-2.5 km depth. When surface water at AAIW formation sites attains a density greater than that found at the deep convection sites in the North Atlantic (thereby crossing a threshold), NADW formation will decrease, AAIW formation will increase, and vice versa. In this manner, rapid fluctuations in the dominance of AAIW or NADW/GNAIW can occur.

Combining benthic $\delta^{13}C$ with our $\Delta^{14}C$ evidence from the South Iceland Rise also supports our assertion that the most ^{14}C-depleted water influencing our site was

AAIW (Fig. 2). Plotting benthic $\delta^{13}C$ versus $\Delta^{14}C$, our measurements form a separate trend to that formed by measurements from sites influenced by deep Southern Source Water (SSW), with our data likely recording the influence of air-sea exchange processes associated with the formation of AAIW. Moreover, our reconstructed I/D ocean ventilation ages south of Iceland (up to ~5200 years) suggest that current estimates of the ventilation age of the glacial deep Southern Ocean (*14*) provide only a lower limit for the isolated carbon (Fig. 2).

An alternative source for the ^{14}C-depleted water observed south of Iceland during cold intervals may be the deep Nordic Seas and Arctic Ocean, possibly caused by brines flushing out deep waters. However it is difficult to reconcile this hypothesis with our current knowledge of the region. We do not observe a consistent relationship between the timing our ^{14}C-depleted benthic ventilation ages and Nordic Seas overflow, which has a distinctive low $\delta^{18}O$ signal during HS1 (attributed to brine formation processes) (*2*,*10* and references therein). Rather we observe better ventilated I/D water during inferred peak brine formation at 15-16 ka (Fig. 1 and S8, discussed below). Furthermore, if the Nordic Seas were well ventilated during the Bølling, as is widely accepted, it cannot be the source for the 3000-4000 year old water observed south of Iceland during the IACP since there was insufficient time for *in situ* decay of deep water in the Nordic Seas.

We compare our deglacial I/D ocean ventilation age estimates with other high-resolution reconstructions of Atlantic circulation and climate in Figure 3. Increased ventilation ages and inferred incursions of AAIW to the NE Atlantic occurred during Northern Hemisphere cold intervals (HS1, Older Dryas (OD), IACP, YD), which are associated with warming in the Southern Hemisphere via the bipolar seesaw mechanism (Fig. 3, e.g. *21*). There are two notable exceptions to this coupling between NE Atlantic ventilation and Greenland climate.

First, at ~15.9-15.2 ka, improved I/D ocean ventilation south of Iceland is not observed in other Atlantic records (Fig. 3). This ventilation event occurs during a pronounced minimum in seawater $\delta^{18}O$ recorded in *N. pachderma* (s) (Fig. 1), indicating surface freshening and/or sea-ice formation and brine rejection (*22*). Minima in benthic $\delta^{18}O$ records from south of Iceland and the Nordic Seas also occur during this interval, strongly suggesting that local convection occurred via sea-ice formation and brine rejection, which transferred better ventilated surface water (with low seawater $\delta^{18}O$ values) to the I/D ocean. (e.g. *2,10*) (Fig. 1, Fig. S8).

Second, while poorer I/D ocean ventilation in the NE Atlantic occurred both at the onset (~12.8-12.6 ka) and culmination (~12.2-11.7 ka) of the YD, the mid-YD (~12.6-12.2 ka) was characterised by a well-mixed water column on the South Iceland Rise. It is possible that a decrease in freshwater input to the NE Atlantic during the mid-YD (*22*) reduced surface stratification and facilitated overturning of the water column close to Iceland, aided by coastal upwelling and interaction with seafloor topography. During the mid-YD, I/D ocean ventilation ages were reduced but surface ventilation ages were increased, suggesting that overturning of the water column south of Iceland involved upwelling of ^{14}C-depleted AAIW to the (near) surface ocean.

The large amplitude and abrupt changes recorded in benthic ^{14}C south of Iceland allow us to constrain the timing of convection changes in the Northeast Atlantic relative to deglacial climate events. A long-standing view of NH deglaciation has been that the strong resumption of deep convection in the North Atlantic during the B-A was interrupted by a freshwater rerouting or flood event, which reduced convection and triggered the YD cold reversal (*4*). In contrast to this paradigm, our I/D ocean ventilation results show that following the vigorous convection of the early B-A (see SOM), there was a shutdown in open-ocean deep convection in the high-latitude NE Atlantic for a sustained interval beginning ~600 years prior to the onset of the YD, i.e. during the IACP. The occurrence of an earlier shutdown in deep convection in the NE Atlantic prior to the YD suggests that in terms of NE Atlantic convection, the YD was not a unique event during the deglaciation. Instead, the amplified circulation associated with the Bølling warming was probably a transient feature of deglaciation and the stability of deep convection in the NE Atlantic gradually weakened throughout the B-A, with intervals of vigorous deep convection being punctuated by several freshwater events (e.g. *22* and references therein). This interpretation is consistent with the recent recognition of 'YD equivalents' during earlier Terminations of the Late Pleistocene (*5,6*).

The shutdown of deep convection in the NE Atlantic during the IACP contrasts with less pronounced changes in I/D ocean ventilation in the NW Atlantic, which monitors the combined deep waters formed by convection in both the NE and NW Atlantic (Fig. 3 and 4). Therefore continued open-ocean convection in the Irminger and/or Labrador Sea (*2*) was probably sustained throughout the IACP, but weakened significantly during the YD (*8*).

The observed difference in North Atlantic convection between the IACP (weakened NE convection) and the YD (weakened NE and NW convection) allows us to examine the broader climate implications for regional differences in convection in the North Atlantic. Cooling over Greenland is inferred for both the IACP and YD (Fig. 3C), and because model studies (*23*) indicate Greenland ice core δ^{18}O is largely controlled by sea-ice cover in the Nordic Seas (but relatively insensitive to NW

Atlantic ice-cover), it is very likely that these cold events were caused by decreased NE Atlantic convection and an associated increase in sea-ice cover over the Nordic Seas. In contrast, atmospheric circulation proxies (Fig. 3B,C) indicate only a modest change during the IACP, while a much larger shift occurs at the onset of the YD. It therefore seems, that, although NE Atlantic convection was crucial for determining conditions within the NE Atlantic and over Greenland, it was only with further weakening of North Atlantic convection (i.e. by reducing deep convection within the NW Atlantic), that the more significant atmospheric circulation changes of the YD were achieved.

Regional differences in convection and sea-ice coverage may also be implicated in the two-fold division of the 'Mystery Interval' (17.5-14.5 ka), which has been attributed to a shift in atmospheric circulation patterns at ~16 ka (*24*). Reconstructions suggest there was enhanced freshwater discharge from the Laurentide ice-sheet into the NW Atlantic and increased sea-ice cover at ~16-17.5 ka, which was followed by a later input of freshwater into the NE Atlantic from proximal ice-sheets at ~15-16 ka, with an inferred increase in sea-ice and brine formation (*22*). This change in freshwater input and sea-ice cover at ~16 ka may be related to the contemporaneous atmospheric circulation shift.

In this study we have demonstrated that the deglacial NE Atlantic underwent abrupt decreases in deep convection which were associated with the incursion of an extremely ^{14}C-depleted water mass, interpreted to be AAIW. Significant differences in the convective activity of the NE versus the NW Atlantic have been revealed. Of particular note is the strong reduction in NE Atlantic convection for a sustained interval (i.e. during the IACP) beginning ~600 years prior to the onset of the YD. We have suggested that differences in the timing of changes in open-ocean convection and sea-ice coverage between the NE and NW Atlantic may be a significant control on atmospheric circulation and therefore further investigation into the nature of the atmospheric reorganisations associated with this heterogeneity is warranted.

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33. We thank Linda Booth for help picking planktic ^{14}C dates. D.T. thanks Sean Bryan, Ian Hall, Lloyd Keigwin, Gregor Knorr, Tom Marchitto and Luke Skinner for useful discussions. Radiocarbon dates analysed by Natural Environment Research Council (NERC; UK) and National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS; USA) facilities. This work was funded by NERC grants NER/T/S/2002/00436 and NE/F002734/1, and National Science Foundation grant OCE 04-35703.

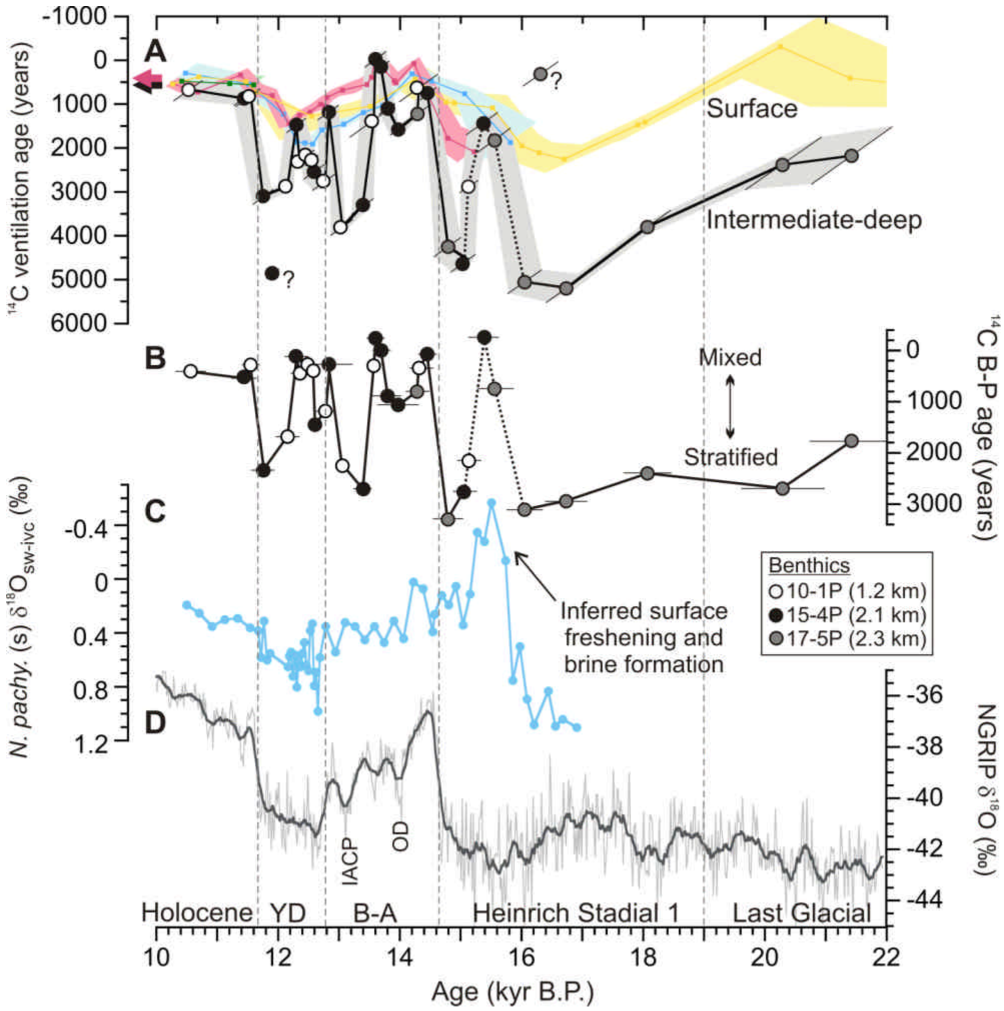

Fig. 1. (**A**) Surface and intermediate/deep ocean ^{14}C ventilation ages, with estimated uncertainty. Surface ocean estimates are from planktic foraminifera picked from the sediments cores: 12-1K, green line; 10-1P, blue line; 15-4P, red line; 17-5P, yellow line. Modern ventilation ages for the surface ocean and NADW are shown by the red and black arrow respectively. Anomalous benthic ^{14}C dates are indicated by question marks. The date at 12 ka may contain reworked material because it is taken from within the Vedde Ash layer, the base of which consists of a basaltic turbidite. The anomalously young benthic ^{14}C date at 16.3 ka suggests contamination by modern carbon; we cannot, however reject this date with certainty, and it is possible that the young age is indicative of a brief interval of local convection, likely brine-induced. (**B**) Benthic-planktic foraminifera ^{14}C difference. Dashed line in (**A**) and (**B**) indicates an interval of inferred local brine-induced convection. (**C**) Reconstructed surface seawater $\delta^{18}O$, corrected for global ice-volume changes, based on *N. pachderma* (s) Mg/Ca-$\delta^{18}O$ in 10-1P (*22*) (**D**) NGRIP $\delta^{18}O$ (*11*).

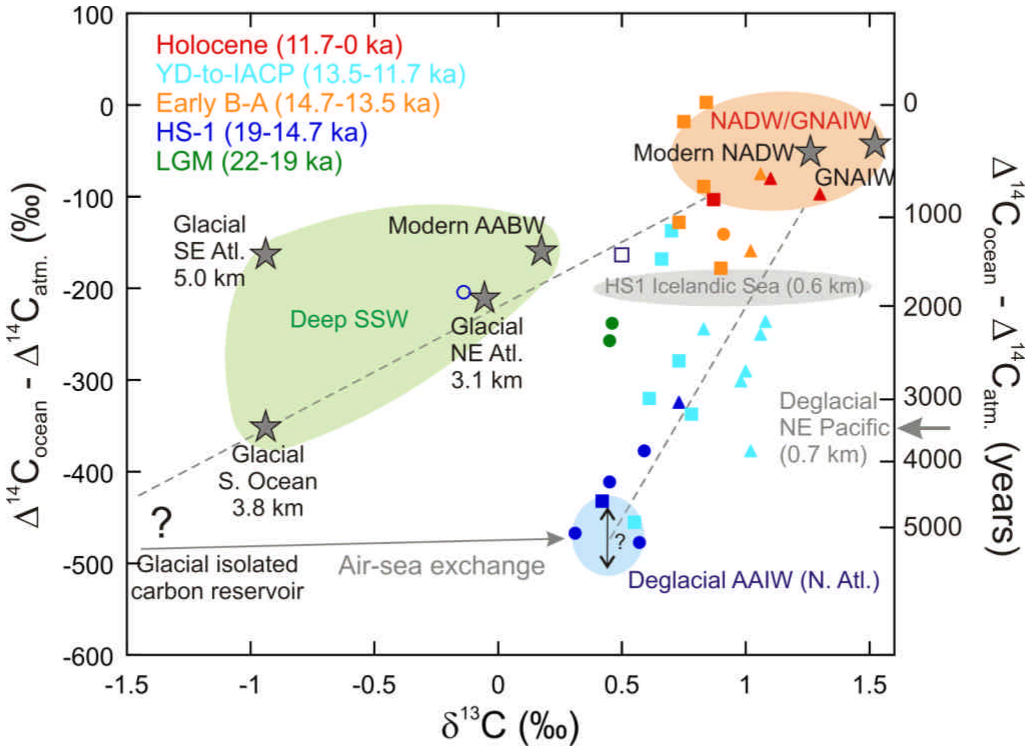

Fig. 2. Comparison of benthic d^{13}C and ventilation age (?^{14}C offset from the contemporaneous atmosphere). Triangles, 10-1P (1237 m); squares, 15-4P (2133 m); circles, 17-5P (2303 m); open symbols indicate local brine-influenced convection during HS-1. Benthic d^{13}C data (*10*); modern end-member values (*9*); GNAIW from the Denmark Strait (*3*,*25*); glacial SE Atlantic (*26*); glacial Southern Ocean (*16*; d^{13}C inferred from*27*); glacial NE Atlantic (*28*); deglacial NE Pacific (*17*); HS1 Icelandic Sea (*3*,*25*). Glacial AAIW had a d^{13}C of 0.3-0.5 ‰ (*27*). Following the work of ref. *29*, during degassing of CO_2 from seawater to the atmosphere, CO_2 (aq.) has an equilibrium isotopic offset from the bulk solution (SCO2) of ~10‰ for d^{13}C and ~20‰ for d^{14}C. For a SCO_2 of ~2500umol/kg, the removal of 500umol/kg (20 %), causes a positive shift of ~2 ‰ in d^{13}C and ~4‰ per mil shift in d^{14}C, the latter being insignificant in comparison to typical ocean values of several tens to hundreds per mille. Additional kinetic fractionation effects may also contribute towards an enrichment of the residual phase (seawater) in ^{13}C and ^{14}C (*29*).

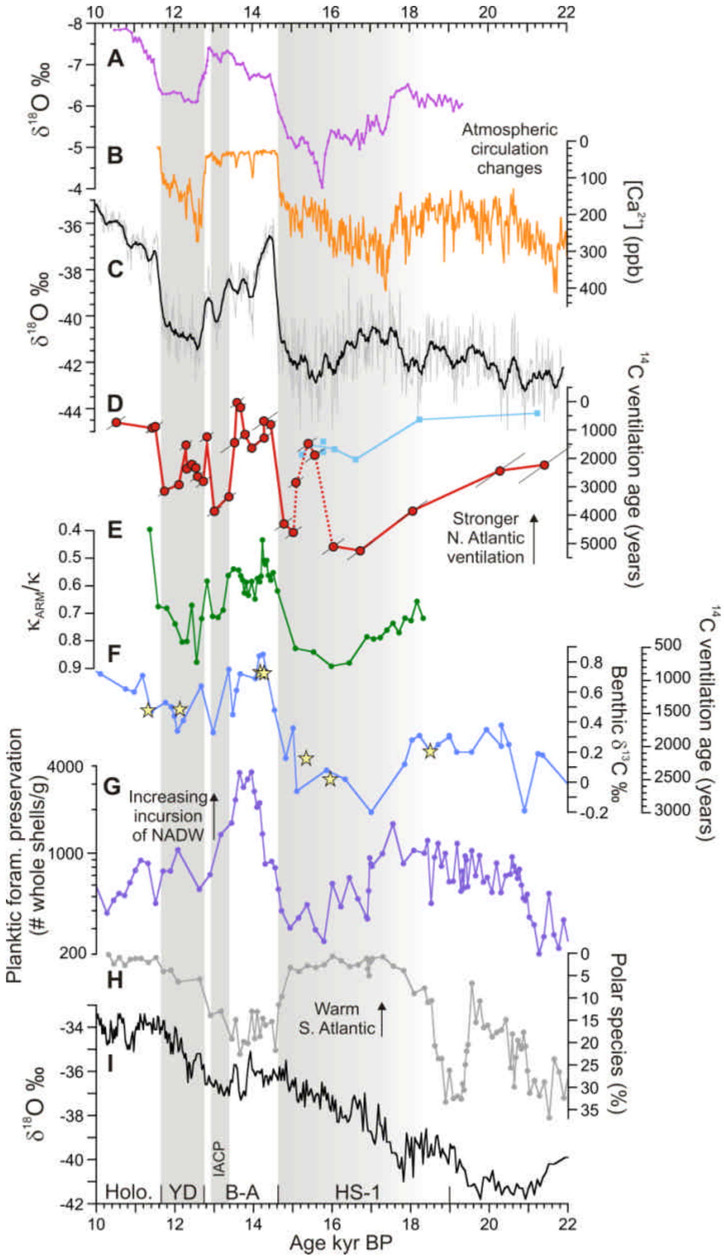

Fig. 3. Comparison of the timing of deep convection changes in the NE Atlantic to other Atlantic Ocean and climate records. (**A**) Hulu Cave (speleothem PD) $\delta^{18}O$ proxy for migration of the inter-tropical convergence zone (*30*); (**B**) NGRIP $[Ca^{2+}]$ proxy for atmosphere circulation changes (*11*);**(C)** NGRIP $\delta^{18}O$ (Greenland) (*11*); **(D)** South Iceland Rise benthic ^{14}C ventilation ages (red) and the Icelandic Seas at 0.6 km depth (*3*); **(E)** Eirik drift (1.9 km, NW Atlantic) flow speed proxy (magnetic mineral grain size) (*31*); **(F)** Iberian margin (3.1 km, NE Atlantic) benthic $\delta^{13}C$ (*28*) and radiocarbon ventilation ages (yellow stars) (*14*,*28*); **(G,H)** Cape basin (5.0 km South Atlantic) foraminifera preservation as a proxy for incursions of high $[CO_3^{2-}]$ NADW (*26*) **(G),** and the abundance of polar planktic foraminifera (*16*) **(H)**; **(I)** Byrd $\delta^{18}O$ (Antarctica) (*32*).

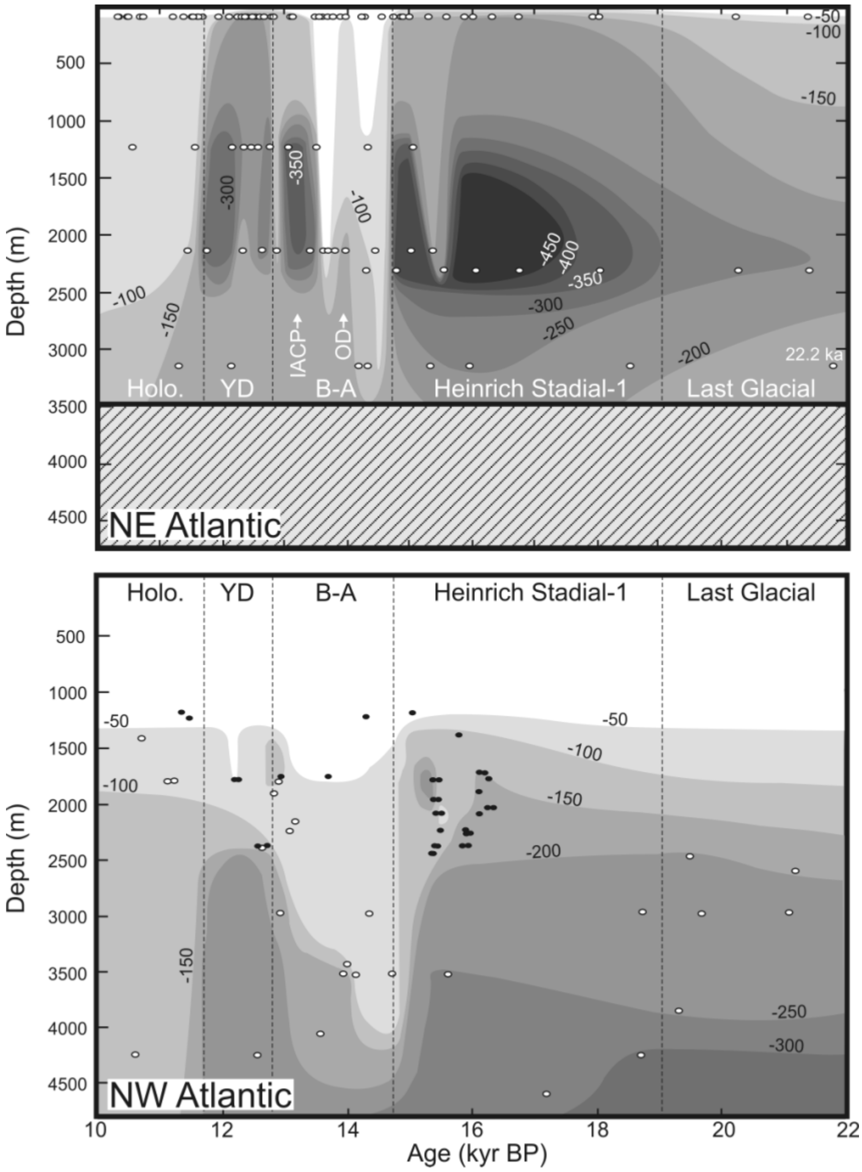

Fig. 4. Cartoon contour plots for the ventilation age (expressed as $\Delta^{14}C$ offset from the atmosphere in ‰) for the NE Atlantic and mid-latitude NW Atlantic (*8*). Data for the NE Atlantic from 3.1 km depth is from the Iberian margin (*14*). Closed circles, coral data; open circles, foraminifera data. Note – foraminifera data from the NW Atlantic assume a constant surface reservoir age of 400 years. Darker shading, poorly ventilated water; lighter shading, better ventilated water.