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Muted change in Atlantic overturning circulation over some glacial-aged Heinrich events

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Heinrich events—surges of icebergs into the North Atlantic Ocean—punctuated the last glacial period. The events are associated with millennial-scale cooling in the Northern Hemisphere. Fresh water from the melting icebergs is thought to have interrupted the Atlantic meridional overturning circulation, thus minimizing heat transport into the northern North Atlantic. The northward flow of warm water passes through the Florida Straits and is reflected in the distribution of seawater properties in this region. Here we investigate the northward flow through this region over the past 40,000 years using oxygen isotope measurements of benthic foraminifera from two cores on either side of the Florida Straits. These measurements allow us to estimate water density, which is related to flow through the thermal wind balance. We infer a substantial reduction of flow during Heinrich Event 1 and the Younger Dryas cooling, but little change during Heinrich Events 2 and 3, which occurred during an especially cold phase of the last glacial period. We speculate that because glacial circulation was already weakened before the onset of Heinrich Events 2 and 3, freshwater forcing had little additional effect. However, low-latitude climate perturbations were observed during all events. We therefore suggest that these perturbations may not have been directly caused by changes in heat transport associated with Atlantic overturning circulation as commonly assumed.

Layers of ice-rafted debris, Heinrich layers, appear periodically in the sediments of the North Atlantic that were laid down during the last glacial period. These layers are thought to represent surges of the large continental ice sheet that covered North America, discharging fresh water in the form of debris-laden ice into the North Atlantic. The input of fresh water into the North Atlantic is postulated to have disrupted deep and bottom water formation, leading to a weaker Atlantic meridional overturning circulation (AMOC).

The times surrounding the Heinrich events (Heinrich stadials) are clearly marked by extreme conditions in many records of oceanic and climatic change far from the North Atlantic. These stadials are associated with drier than normal conditions in China[1] and the Sahel[2], and reduced ventilation of intermediate waters in the Arabian Sea[3]. Some Heinrich stadials are marked by warming of both the ocean and climate in the Southern Hemisphere[4]. It is thought that many of these far-field effects of the ice discharges are transmitted by changes in the AMOC-driven heat transport from the Southern to the Northern Hemisphere, and the associated changes in atmospheric and oceanic circulation. If this were the case, we would expect to see evidence for changes in AMOC for each of the Heinrich stadials.

Deep ocean changes over Heinrich stadials

Reconstructions of the water mass properties in the Atlantic during glacial times have yielded a picture of a nutrient-poor water mass (glacial North Atlantic intermediate water), overlying a nutrient-rich water mass, presumably sourced from the south[5]. Reconstructions of the density gradient in the upper ocean and model–data comparisons with deep water carbon isotope data suggest that if this configuration was associated with a shallower AMOC, this circulation was quite a bit weaker than the present day[6–8]. However, a recent model–data comparison suggests that sedimentary Pa and Th data are consistent with a strong, shallow AMOC (ref. 9).

It has been suggested that during Heinrich stadials, this shallower AMOC was disrupted by freshwater input to the North Atlantic, leading to a virtual shutdown in the AMOC (ref. 10). This idea was based on both ocean general circulation models that showed such a response to a large freshwater input, and data that suggested high nutrient values[11] in deep waters around the time the most recent Heinrich layer (H1) was deposited. The idea of a weakened or non-existent overturning associated with H1 was bolstered by the discovery that the ratio of the particle reactive decay products of U, ^{231}Pa and ^{230}Th, are buried in the same ratio at which they are produced in the overlying water column in the open North Atlantic[12].

Evidence for circulation changes associated with the Heinrich events other than H1 has remained equivocal. The Pa and Th in deep Atlantic sediments do show a higher ratio during the stadials associated with H2 and H3, but these higher ratios are accompanied by evidence for an increase in opal flux to the sea floor, so may not necessarily indicate a circulation change[13]. Despite extensive efforts to reconstruct changes in water mass properties in the North Atlantic using carbon isotopic and trace metal measurements in the calcite tests of foraminifera, these records also do not show a clear

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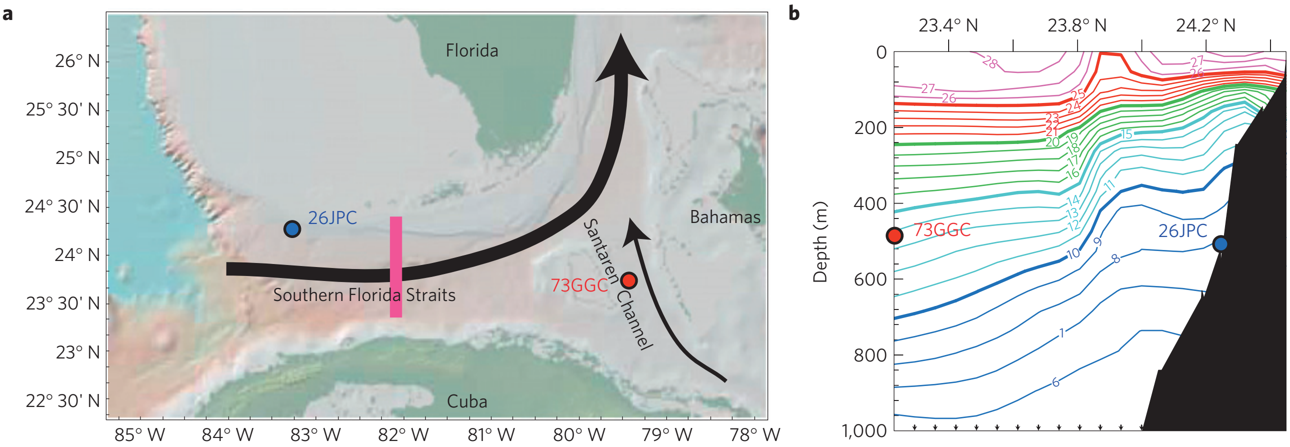

Figure 1 | Core locations and context. a, Location of sediment cores for the data shown in Fig. 2. The location of the temperature section shown in **b** is indicated with the pink line, and the approximate path of the Florida Current with the large black arrow. **b**, A north–south section of climatological temperature (°C) across the Florida Straits at 82° W, with the depth of the two sediment cores used to monitor the cross-strait density gradient indicated with circles[38].

picture of water mass changes for earlier Heinrich events. This work is often hampered by poor time resolution and noisy data, perhaps due to productivity overprints[14]. Some records suggest the presence of nutrient-rich waters at intermediate (<2 km) depths during some of the Heinrich stadials but not others[15–20]. However, the response is inconsistent among different locations in these upper water masses, suggesting that regional changes in productivity or circulation may have been responsible for these excursions towards more nutrient-rich values. Deep water (>2 km) records show clear excursions towards a more nutrient-rich water mass during the stadials associated with H4 and H5 but not all records show changes around the time of H2 or H3 when deep water nutrient concentrations are already high (Supplementary Figs 1 and 2). However, the link between the extent of the high- and low-nutrient water masses and circulation is indirect. It is possible that despite changes in circulation, a core site is bathed by the same water mass and this circulation change is not reflected in the nutrient status at this core site. Similarly, if the change in circulation persists for only a short period of time, the chemical properties of the deep water might not fully reflect the changes for several hundred years.

Here we present time series of the oxygen isotopic composition of benthic foraminifera from the Florida Straits that we believe to be sensitive to changes in the upper branch of the AMOC, and the carbon isotopic composition of benthic foraminifera from the same region, which can be used to reconstruct the nutrient concentration of intermediate waters. We use these records, together with existing reconstructions from other sites, to argue that if any reductions in the AMOC accompanied the two Heinrich events that occurred during full glacial conditions (H2 and H3), they were of a much smaller magnitude and/or shorter duration than the reductions occurring during H1 and the Younger Dryas.

Heinrich Stadials in the Florida Straits

As it flows through the Florida Straits, the strength of the Florida Current reflects both the western limb of the wind-driven subtropical gyre and the warm surface waters that cross the Equator and travel to the North Atlantic as part of the upper branch of the large-scale overturning circulation associated with deep water formation. Any change in either this large-scale overturning or wind-driven gyre circulation can change the strength of this current. To first order, this current is in geostrophic balance so the vertical shear in the flow is proportional to the horizontal density gradient across the strait (the thermal wind balance). The density gradient at times in the past can be inferred from the oxygen isotopic composition of the calcite tests of benthic foraminifera from sediment cores on both sides of the current. The oxygen isotope ratio reflects both the temperature and oxygen isotopic composition (related to salinity) of the sea water in which it forms, and is therefore related to seawater density. Using this approach we have shown that the cross-strait gradient was reduced during both the Last Glacial Maximum[7] (LGM) and the Younger Dryas[21]. The reduced gradient can be explained by a reduction in the strength of the AMOC during the LGM and Younger Dryas relative to the modern state, consistent with inferences based on other palaeoceanographic studies using different methods.

Although it is not possible to exclude the possibility that a reduced cross-strait gradient reflected a reduced wind-driven flow or a more barotropic Florida Current, we do show that the link among AMOC strength, Florida Current strength and cross-strait density gradient holds in a previously published model experiment (Supplementary Fig. 5). In this model experiment, an AMOC reduction of ~11 Sv was induced in the Community Climate System Model (CCSM) by freshwater input into the subpolar North Atlantic under LGM conditions[22]. This AMOC reduction was accompanied by a reduction in Florida Straits transport of ~10 Sv, and a reduction in the cross-strait density gradient at all depths below 300 m. Details on the model experiment can be found in the Methods.

Here, we show isotopic data from two cores on either side of the Florida Straits (KNR166-2-26JPC, 24° 19.61′ N, 83° 15.14′ W, 546 m, KNR166-2-73GGC, 23° 44.73′ N, 79° 25.78′ S, 542 m, Fig. 1). Details on the methods including age model development and isotopic measurements can be found in the Methods. The core on the Florida margin extends through 36 ka (thousand years ago), has high sedimentation rates (15–35 cm kyr^{-1}) during Marine Isotope Stages 2 and 3, and should be able to resolve changes associated with Heinrich events during this interval. This core shows prominent excursions towards lower $\delta^{18}O$ values (warmer or less saline, less dense waters) during the Younger Dryas and around the time of the most recent Heinrich event (Heinrich Stadial 1, HS1; Fig. 2a). The Younger Dryas excursion is associated with a reduction in the cross-strait $\delta^{18}O$ gradient as inferred from three sediment cores on each side of the strait[21]. Owing to the low sedimentation rates between 13 and 20 ka on the Bahamas side of the strait, we have no direct evidence that the HS1 excursion was similarly associated with a reduction in the cross-strait density gradient. However, by analogy to the Younger Dryas excursion, such a reduction certainly seems plausible.

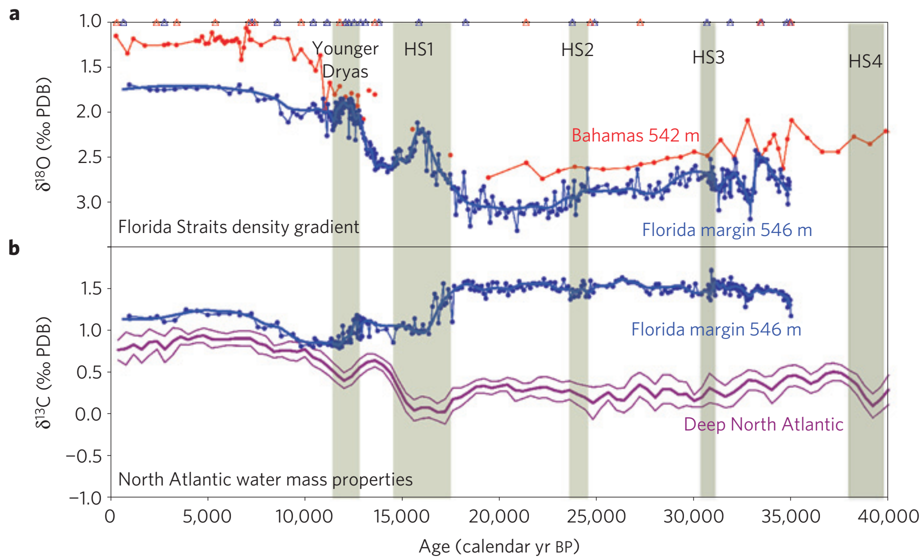

Figure 2 | Glacial and deglacial records. a, Oxygen isotope ratio in benthic foraminifera from two cores on either side of the Florida Current (blue, KNR166-2-26JPC; red, KNR166-2-73GC, locations shown on Fig. 1). Depths of radiocarbon dates in these cores are indicated by triangles on the top axis. PDB, PeeDee Belemnite. **b**, Carbon isotope ratios from the benthic foraminifera *P. ariminensis* from the same core on the Florida side of the strait (blue, KNR166-2-26JPC; location A on Fig. 5), and average (800-year window) and ±2 standard error (purple) of eight high-resolution *Cibicidoides wuellerstorfi* $\delta^{13}C$ records from the deep Atlantic[17,39–45] (core locations shown in Fig. 5). Shaded vertical bars extending through all of the plots indicate the timing of the Younger Dryas and Heinrich stadials from ref. 1.

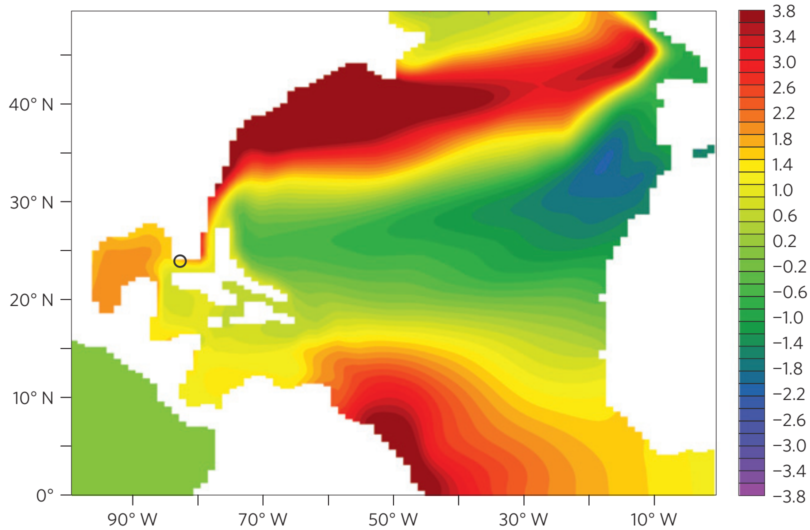

Figure 3 | Modelled temperature anomaly. Temperature anomaly (K) at 579 m for water hosing experiment (0.25 Sv) with LGM boundary conditions in CCSM3 (11 Sv AMOC reduction)[22]. The location of KNR166-2-26JPC is indicated with a black circle.

More generally, many general circulation models show mid-depth warming in the subtropical North Atlantic when the AMOC is weakened in water hosing experiments in which extra freshwater forcing is distributed over the northern North Atlantic[23]. The warming is often particularly apparent along the western margin of the subtropical North Atlantic[22,24]. As an example, we show the mid-depth temperature anomaly from the model experiment with the 11 Sv freshwater-induced AMOC reduction described above (Fig. 3). There is a positive mid-depth temperature anomaly associated with the AMOC weakening along the entire western margin of the basin. The mechanisms for this western margin warming are probably multiple and linked, involving the dynamic adjustment of the density structure in association with the circulation change, decreased heat transport out of the subtropics into the mid-latitude North Atlantic, and a decreased contribution of the relatively cooler and fresher intermediate waters from the South Atlantic[22,25]. In light of the results from these models, the negative excursion in benthic foraminiferal $\delta^{18}O$ along the Florida margin, even in the absence of information about the cross-strait density gradient, supports the scenario of an AMOC reduction during HS1. In the model study shown in Fig. 3, an AMOC reduction of 11 Sv was associated with an increase in temperature at 550 m water depth along the South Florida margin of 1.8 °C, which all else being equal would correspond to a $\delta^{18}O$ change in benthic foraminifera at this site of about −0.5‰, the same magnitude that is observed for HS1. There was only a small (<0.1 psu) salinity anomaly at this location associated with the weakened AMOC. Regardless of the dominant process, an interpretation of the excursion towards lower $\delta^{18}O$ at the Florida margin as reflecting a reduced AMOC is

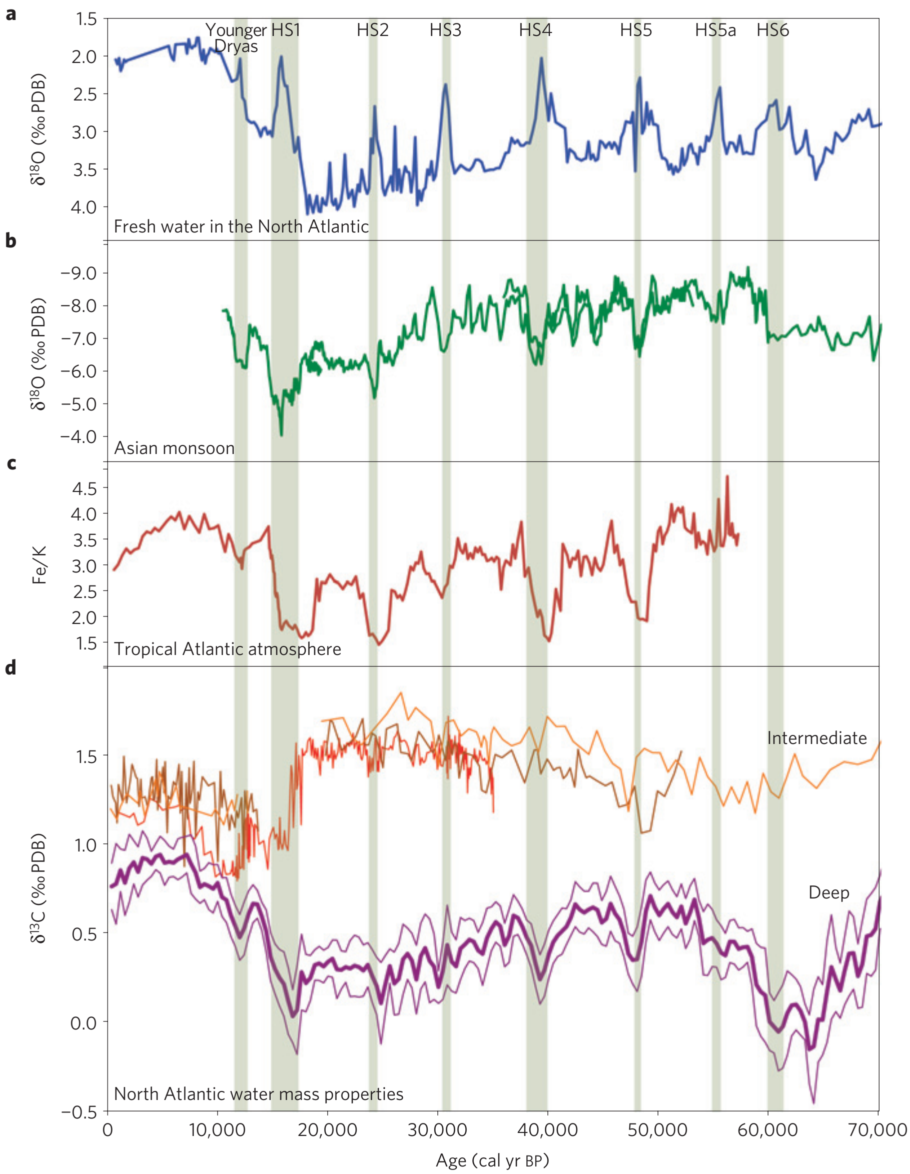

Figure 4 | Stage 3 records. a, Oxygen isotope ratio in the planktonic foraminifera *Neogloboquadrina pachyderma* (*l*) from the western North Atlantic[36] (location E in Fig. 5). Low values reflect the presence of glacial melt water. **b**, Oxygen isotope ratio in cave deposits in China, reflecting changes in monsoon precipitation[1]. Green vertical bars extending through all of the plots indicate the timing of the Younger Dryas and Heinrich stadials from this record. **c**, The Fe/K ratio, an indicator of aridity in the West African Sahel[2] (location D in Fig. 5). **d**, Carbon isotope ratios in benthic foraminifera from intermediate waters (red, 546 m location A in Fig. 5; orange, 542 m location B in Fig. 5; this study) and (brown, 965 m location C in Fig. 5)[20]. Average (800-year window) and ±2 standard error (purple) of seven high-resolution *C. wuellerstorfi* $\delta^{13}C$ records from the deep Atlantic[17,39–45] (locations in Fig. 5; individual records in Supplementary Fig. 2).

consistent with the multiple lines of evidence for such a reduction during HS1 (refs 11,12).

In contrast, there is no indication of a significant change in cross-strait $\delta^{18}O$ for the stadials associated with Heinrich Events 2 and 3 (HS2 and HS3). However, the resolution of the Bahamas core may be insufficient to capture a short-lived reduction in the cross-strait gradient. Nevertheless, we do not see excursions towards lower benthic $\delta^{18}O$ values similar in magnitude to those observed for the Younger Dryas and HS1 in the much higher resolution Florida core for HS2 or HS3. It is possible that competing processes (for example, water mass property changes of the opposite sign that exactly matched in magnitude the changes associated with the flattening of isopycnals across the Florida Current, or a strengthening of the wind-driven flow compensating a weakening of the AMOC) led to a very muted or non-existent change in $\delta^{18}O$ at this site, despite significant changes in the AMOC. However, it seems more reasonable to conclude, especially in light of the lack of compelling evidence for changes in the properties or extent of the deep Atlantic water masses during these Heinrich stadials, that any changes in the AMOC in response to these two Heinrich events were not comparable in size to the changes observed for the Younger Dryas or HS1. Whereas the Younger Dryas and HS1 are almost always associated with excursions in deep Atlantic $\delta^{13}C$ (a proxy for nutrient content and water mass ventilation), similarly coherent excursions are not observed for HS2 and HS3 (Fig. 2b and Supplementary Fig. 2). Although it is possible that the nutrient tracers would not fully respond to a very short duration change in ocean circulation, the upper ocean density structure, and thus the $\delta^{18}O$ of foraminifera on the Florida margin, would adjust very quickly to reflect a different flow state.

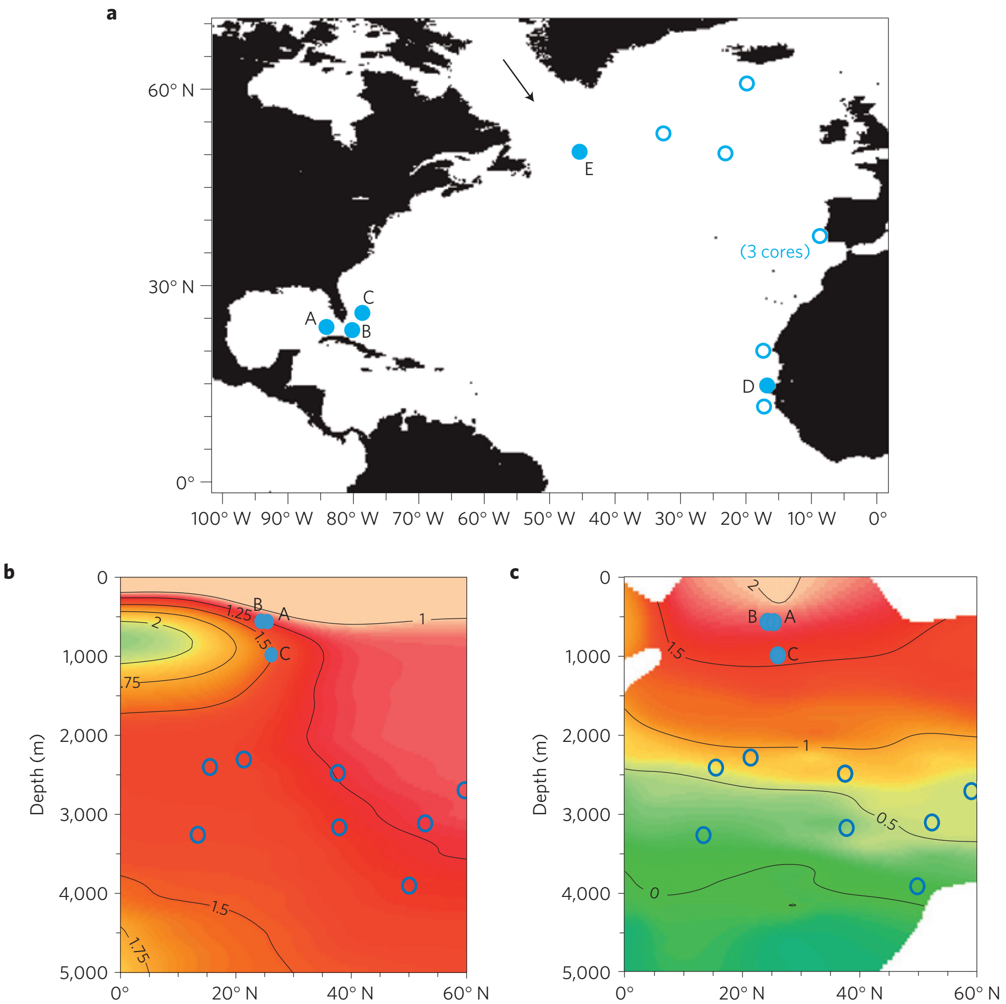

Figure 5 | Location of other records. a, Location of sediment cores for the data shown in Figs 2 and 3 (filled circles) and that contributed towards the deep North Atlantic $\delta^{13}C$ averages (open circles). The source of the Heinrich ice surges from the Hudson Straits is marked with an arrow. **b**, Modern PO_4 ($\mu mol\ kg^{-1}$) distribution in the North Atlantic[46] with the location of the sediment cores for the carbon isotope records shown in Fig. 4 indicated with filled circles and those contributing towards the deep North Atlantic $\delta^{13}C$ averages with open circles. **c**, Glacial $\delta^{13}C$ (‰ PDB) distribution in the North Atlantic[47].

It is perhaps unsurprising that H3 may not be associated with pronounced circulation changes. The sediments in this Heinrich layer are geochemically distinct from the others, it often shows up as a smaller peak in the concentration of ice-rafted debris in sediment cores, and it is limited to a smaller area in the North Atlantic than the other events[26]. It is certainly plausible that a smaller volume of melt water, or the discharge of melt water into a different region within the North Atlantic, could explain the lack of interruption of the AMOC. However, H2 seems robust and geochemically similar to the events that do seem to be associated with circulation changes (H1, H4 and H5). The lack of a large circulation change associated with H2 would therefore require a different explanation.

Ocean circulation and climate response to Heinrich events

The earlier Heinrich Events (H4 and H5) appear at a time (~33–60 ka, early Marine Isotope Stage 3) when the contrast between deep and intermediate $\delta^{13}C$ values was not as extreme as during the full glacial state (Fig. 4d). The excursions in deep water $\delta^{13}C$ at the time of these earlier Heinrich events seem to reflect transitions from more weak stratification in the geochemical water mass properties (modern type, associated with strong AMOC today), to the more strongly stratified LGM water mass configuration that is associated with a weaker AMOC (Fig. 5). The Younger Dryas AMOC weakening is also thought to be meltwater induced, and like HS4 and HS5 seems to reflect a transition from a modern water mass configuration to one more similar to the glacial state[27].

We postulate that as the circulation was already in this more geochemically stratified, weakened glacial state for the interval encompassing H2 and H3, the freshwater discharge associated with these events was not able to weaken the AMOC further. This result apparently contradicts ocean general circulation model studies suggesting that a given freshwater input has a stronger impact on AMOC strength in the glacial climate state than the modern state[28–30]. Heinrich Event 1 also occurs during full glacial time, but the circulation event that is associated with it seems particularly long and intense, lasting several thousand years, starting around the time of the ice-rafting event (16.8 ka, ref. 26) and persisting well into the deglaciation until about 14.7 ka (Fig. 2)[12]. It is possible that the additional melt water entering the North Atlantic as the Northern Hemisphere ice sheets began to decay helped to develop and sustain the circulation change beyond the time of the Heinrich event.

If the ice sheet surges significantly impact the AMOC for only some of the Heinrich events, this has implications for the mechanisms responsible for the global expression of the Heinrich events. There are some well-resolved palaeoclimate records in the

Northern Hemisphere that suggest strong changes in atmospheric circulation for all of the Heinrich stadials, including HS2 and HS3 (Fig. 4). These include records of the Asian Monsoon from China[1] and the intertropical convergence zone (ITCZ)/monsoon areas of the tropical Atlantic[2,31] and ventilation in the Arabian Sea[3]. Although changes in the heat transport associated with the AMOC can change the position of the Atlantic ITCZ (ref. 24), if there were no, or only very subtle, changes in the AMOC over HS2 and HS3, a mechanism involving atmospheric transmission is needed to explain the large signals for both the 'circulation Heinrich events' (H1, H4, H5 and H6) and the Heinrich events that occur during peak glacial times (H2 and H3). More generally, cooling and increased land or sea ice cover in North Atlantic has also been shown to cause shifts in the ITCZ (refs 32,33), providing a potential mechanism for ITCZ changes not directly linked to the AMOC. Shifts in the Northern Hemisphere planetary wave patterns in response to either North Atlantic sea ice extent or changes in ice sheet height[34] might also provide a link between the Heinrich events in the North Atlantic and these lower-latitude indicators of atmospheric change.

Methods

Core KNR166-2-26JPC was taken from a water depth of 546 m on the Florida margin and KNR166-2-73GGC was from a water depth of 542 m in the Santaren Channel (Bahamas). The age models for both cores were developed by linear interpolation between radiocarbon dates converted to calendar years using Calib 6.0 and the MARINE09 calibration data set[35]. In addition to the radiocarbon dates, the ages of Marine Isotope Stage 3–4 and 4–5 boundaries were used to refine the age model for KNR166-2-73GGC (Supplementary Table 1). For KNR162-2-26JPC, the out-of-sequence dates between 344 and 408 cm were not used in the age model as was discussed in a previous publication on the deglacial portion of this core[21]. In addition we do not use the date at 1032.25 cm depth owing to the large error in the radiocarbon measurement or the out-of-sequence date at 1,088.25 cm.

For core KNR166-2-26JPC, both small single-species groups (up to four individuals) and individuals of *Planulina ariminensis, Cibicidoides pachyderma* and *Cibicidoides mollis* from the size fraction >250 μm were analysed for oxygen and carbon isotopes. Isotope measurements were made on a GV Instruments Optima with Multiprep at the Lamont-Doherty Earth Observatory and a Finnigan MAT253 with a Kiel carbonate preparation device at the Georgia Institute of Technology. Values were calibrated using NBS-19 and NBS-18, and in all laboratories internal precision met or exceeded 0.08‰ (1 σ s.d. of replicate analyses of NBS-19 or in-house standards). We then averaged the $\delta^{18}O$ values for all species at each depth interval, with an average of five individuals contributing to the average value at each depth. A small number of measurements show very low $\delta^{18}O$ values, and presumably represent individuals that were transported down slope from shallower water depths. The values that were greater than 2 s.d. away from a robust loess smoothed version of the record were flagged (4% of the data) and not included in the average $\delta^{18}O$ calculated for each depth (Supplementary Fig. 4). The average value for each depth (outliers removed as described above) and the robust loess smooth are shown in Fig. 2a. For the carbon isotope data shown in Figs 2b and 4d, only the data from *P. ariminensis* are averaged at each depth, as the $\delta^{13}C$ values of the other species are consistently lower suggesting a phytodetritus effect at this location (Supplementary Fig. 4). Most data from the portion of the core younger than 15,000 ka were previously published[21].

For core KNR166-2-73JPC, individuals of *P. ariminensis* and *C. pachyderma* from the size fraction >250 μm were analysed for oxygen and carbon isotopes. Isotope measurements were made on a Finnigan MAT253 with a Kiel carbonate preparation device at Georgia Institute of Technology. We averaged the $\delta^{18}O$ values for all species at each depth interval, with between 1 and 3 individuals contributing to the average value at each depth. For the $\delta^{13}C$ record shown in Fig. 3d, only values from *C. pachyderma* are averaged, because analyses for this species were available for the entire length of the record. Where both species are analysed in the Holocene portion of the record, the $\delta^{13}C$ of *C. pachyderma* is about 0.2‰ lower than that for *P. ariminensis*.

The age model for the *N. pachyderma* $\delta^{18}O$ record for MD95-2024P (ref. 36; Fig. 4a) was constructed by correlating the detrital layers in this core to the dates of the Heinrich stadials in the Hulu Cave oxygen isotope record[1]. The original age model for this core was determined in a similar manner by correlating the detrital layers to the cold stadials in the Greenland ice core record[37]. All other data sets plotted in Fig. 4 are shown on their original published age models.

The water hosing experiment shown in Fig. 3b was performed using the CCSM, version 3.0, a fully coupled ocean–atmosphere global circulation model developed at the National Center for Atmospheric Research. The model experiment was initialized at year 400 of a control run under LGM climate boundary conditions. Extra freshwater forcing of 0.25 Sv was uniformly distributed over the subpolar North Atlantic (50°–70° N) for the 100 yr duration of the experiment. The maximum overturning weakens from 17 Sv in the LGM control run to 6 Sv in the last 30 years of the experiment. The Florida Straits transport is well simulated in this model and weakens from 33 Sv in the control run to 23 Sv in the experiment. This weakening is accompanied by a decrease in the density gradient across the Florida Straits as all depths below 300 m (Supplementary Fig. 5). Further details on the model and experiment can be found in the original publication[22].

Data. All radiocarbon dates and isotope data reported in this study are archived at World Data Center-A for Paleoclimatology located at the US National Oceanic and Atmospheric Administration National Climatic Data Center Paleoclimatology Program, Boulder, Colorado.

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J.L-S., W.B.C., M.W.S. and L.G.H. collected and analysed the sedimentary materials from KNR166-2, L.C.S. and S.M. contributed to the benthic carbon isotope compilation and P.C. and R.Z. contributed model output. All authors contributed to the interpretation of the data and model results and participated in the preparation of the manuscript.

Additional information

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Competing financial interests

The authors declare no competing financial interests.