Millennial-scale changes in North Atlantic circulation since the last glaciation

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Ocean circulation is closely linked to climate change on glacial–interglacial and shorter timescales. Extensive reorganizations in the circulation of deep and intermediate-depth waters in the Atlantic Ocean have been hypothesized for both the last glaciation[1–6] and the subsequent Younger Dryas cold interval[3,6–10], but there has been little palaeoceanographic study of the subtropical gyres[11–13]. These gyres are the dominant oceanic features of wind-driven circulation, and as such they reflect changes in climate and are a significant control on nutrient cycling and, possibly, atmospheric CO_2 concentrations. Here we present Cd/Ca ratios in the shells of benthic foraminifera from the Bahama banks that confirm previous suggestions[11,12] that nutrient concentrations in the North Atlantic subtropical gyre were much lower during the Last Glacial Maximum than they are today (up to 50% lower according to our data). These contrasting nutrient burdens imply much shorter residence times for waters within the thermocline of the Last Glacial Maximum. Below the glacial thermocline, nutrient concentrations were reduced owing to the presence of Glacial North Atlantic Intermediate Water. A high-resolution Cd/Ca record from an intermediate depth indicates decreased nutrient concentrations during the Younger Dryas interval as well, mirroring opposite changes at a nearby deep site[3,9]. Together, these observations suggest that the formation of deep and intermediate waters—North Atlantic Deep Water and Glacial North

Atlantic Intermediate Water, respectively—wax and wane alternately on both orbital and millennial timescales.

The flanks of Little and Great Bahama banks border the Northwest Providence Channel (~26° N, 78° W), which connects the North Atlantic basin (Sargasso Sea) to the Florida Straits. The waters within this channel are derived from the Sargasso Sea, and can be roughly divided into two water masses: the main thermocline of the North Atlantic subtropical gyre (<1,000 m depth) and the upper (Labrador Sea) component of North Atlantic Deep Water (NADW) (~1,000–2,000 m depth) (ref. 12). The gyre's upper thermocline waters outcrop (intersect with the base of the mixed layer) at latitudes to the north, where Ekman pumping and buoyancy flux subduct waters along deepening isopycnals to lower latitudes, following the anticyclonic circulation of the subtropical gyre. Along this route, productivity in overlying surface waters adds decaying organic matter and nutrients. Waters near the base of the thermocline outcrop farther north (above ~50° N) in a region of positive wind stress curl, Ekman upwelling, and poor ventilation. These waters circulate in the subpolar gyre before entering the subtropical gyre[14] and are therefore higher in nutrients and depleted in O_2, creating a phosphate (PO_4^{3-}) maximum and O_2 minimum near 800 m depth at Bahama banks[11]. Deeper waters are largely derived from deep convection in the Labrador Sea[15].

Dissolved cadmium has an oceanic distribution that is very similar to that of phosphorus (ref. 16). Typically, both elements are absent in surface waters, increase rapidly to shallow maxima (~800–1,000 m depth), then decrease slightly in deeper waters. Because the Cd content of overlying water is recorded by the Cd/Ca ratio of benthic foraminifera shells[17], the nutrient content of water masses can be estimated during the past, both in terms of Cd concentration and inferred P concentration (via the modern Cd:P relationship)[16,18]. This method was first put to use in showing that the strength of NADW (which is relatively low in Cd and P) was substantially decreased during severe glaciations[1]. Here we use glacial and Holocene Cd/Ca data from the Bahama banks to investigate the nutrient contents and circulation histories of the North Atlantic subtropical gyre and upper deep waters. Previous $\delta^{13}C$ work implied that Bahamian Last Glacial Maximum (LGM) waters had ~30–60% less PO_4^{3-} than today[11,2]. These results were disputed, however, because in addition to reflecting reduced nutrient levels, high $\delta^{13}C$ values can result from colder temperatures of air–sea CO_2 exchange[19]. Cd/Ca ratios have the advantage of being unaffected by such thermodynamic artefacts.

A suite of 15 sediment cores and grab samples span the depth range 334–1,468 m on the Bahama banks. Previous $\delta^{18}O$ measurements on individual benthic foraminifera shells identified the late Holocene and LGM sections of each core[12]. We picked samples of the aragonitic benthic foraminifer *Hoeglundina elegans* from these two time periods. This species faithfully records bottom-water Cd concentrations with an apparent partition coefficient $D_p = [(Cd/Ca)_{foram}/(Cd/Ca)_{water}] \approx 1.0$ (ref. 18). This D_p shows little or no dependence on water depth, in contrast to calcitic species which vary between 1.3 and 2.9 (ref. 20). Shells of *H. elegans* are also less prone to contamination than calcitic species, mainly because they appear to be immune to $MnCO_3$ overgrowths which add sedimentary Cd that is not effectively removed by cleaning[18].

A total of 54 late Holocene Cd/Ca measurements were made on *H. elegans* from the 15 core-tops. The resulting water-column profile of the inferred seawater Cd concentration, Cd_W, follows the predicted profile (based on seawater $[PO_4^{3-}]$ measurements) quite closely (Fig. 1). Mean Cd_W values range from 0.04 nmol kg^{-1} at 334 m depth to a maximum of 0.42 nmol kg^{-1} at 865 m, with concentrations ~0.35 nmol kg^{-1} below 1,000 m depth. A total of 22 Cd/Ca measurements were made on *H. elegans* from the LGM sections of six cores, from 303 to 1,200 m palaeodepth (120 m was subtracted from the present core depths to account for the glacial sea level drop)[21]. Below 600 m, LGM Cd_W averaged 0.18 nmol kg^{-1}, or ~0.1–0.2 nmol kg^{-1} lower than today, a reduction of 40–60% (Fig. 1). Application of the modern global Cd:P relationship[16,18] to our data gives PO_4^{3-} concentrations (below 600 m) of 1.5–1.6 μmol kg^{-1} during the late Holocene and 0.8–0.9 μmol kg^{-1} during the LGM, for changes of 0.6–0.8 μmol kg^{-1}. These results are in good agreement with the marked LGM $\delta^{13}C$ increase and implied 0.4–0.9 μmol kg^{-1} PO_4^{3-} decrease seen previously[11,12]. Although these PO_4^{3-} estimates are subject to some error, arising in part from regional scatter in the global Cd:P relationship[22], the magnitude of the inferred LGM–Holocene shift is a reasonable approximation. The concordance between Cd and $\delta^{13}C$ suggests that there was little or no difference in the air–sea component of Bahamian $\delta^{13}C$ ($\delta^{13}C_{as}$) between the LGM and today, although air–sea exchange effects may influence the $\delta^{13}C$ record on shorter timescales.

Three main processes could have reduced nutrients in the Bahama banks glacial thermocline: (1) the disappearance of high-nutrient Antarctic Intermediate Water (AAIW), (2) decreased productivity in gyre surface waters, and (3) decreased transit times from where isopycnals outcropped. AAIW contributes <5% of Bahamian lower thermocline waters today[23], so its complete removal would account for <10% of the glacial nutrient decrease. If modern circulation rates were maintained and if glacial North Atlantic preformed PO_4^{3-} values were no lower than today, an unrealistically large (~80%) glacial reduction in productivity would be required to explain the low Bahamian PO_4^{3-} levels. We therefore conclude that LGM subtropical gyre waters had much shorter transit times from where isopycnals outcropped[11,12], primarily due to stronger winds, a southward shift of thermocline outcrop areas[24], and a decreased contribution from the poorly

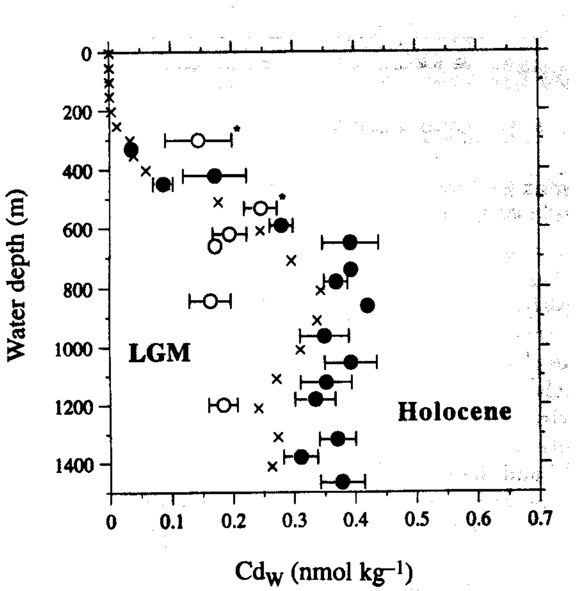

Figure 1 Vertical profiles of inferred seawater cadmium concentration, Cd_W. Values of Cd_W (=$[(Cd/Ca)_{foram}/D_p][Ca]_{water}$, where $[Ca]_{water}$ = 0.01 mol kg^{-1})[20] are based on *H. elegans* from Late Holocene (filled circles) and LGM (open circles) sediments from the Bahama banks. Each symbol is a mean of several measurements, and error bars are standard errors ($1\sigma/n^{1/2}$). LGM depths are shifted upward by 120 m (relative to modern core depths) to account for the glacial sea level lowering[21]. Also shown are predicted modern Cd_W values (crosses) based on water-column PO_4^{3-} measurements and the global Cd:P relationship[16,18]. Two of the 54 Holocene Cd measurements and one of the 22 LGM measurements were considered to be significantly contaminated (Cd_W much higher than expected) and were not included in the means. The two LGM data marked with asterisks are biased toward high (Holocene) concentrations because core 106GGC (534 m palaeodepth) is heavily bioturbated, and core 149JPC (303 m palaeodepth) barely penetrated glacial sediments[12].

ventilated subpolar gyre. The existence of a faster, nutrient-depleted gyre is consistent with the 'nutrient deepening' mechanism for lowering atmospheric CO_2 levels[25].

As waters below the modern Bahamian nutrient maximum are not strongly influenced by wind-driven circulation, their glacial nutrient reduction is best explained by changes in deep-water formation. During the LGM, formation of NADW was substantially reduced[1,2], being replaced by the shallower (<2,500 m) low-nutrient Glacial North Atlantic Intermediate Water (GNAIW)[3–5]. At 1,800 m in the Caribbean, GNAIW had a Cd_W of 0.21 nmol kg^{-1} (ref. 20), about the same as the glacial Cd_W estimate at 1,200 m in the Bahamas (0.19 ± 0.02 nmol kg^{-1}). Although it is difficult to make any clear distinction between the lower gyre and upper deep water, it is likely that the core from 965 m (OC205-2-103GGC) was at least partially influenced by the deep water. A high-resolution record of *H. elegans* Cd_W from this radiocarbon-dated core chronicles the transition from marine isotope stage 3, through the LGM, to the present (Fig. 2; see Supplementary Information for dates). Concentrations of Cd_W were relatively low during stages 3 and 2, averaging 0.17 nmol kg^{-1}. The deglaciation is characterized by a general increase between ~19,500 and 8,500 calendar years before present (cal. yr BP), with Holocene concentrations averaging 0.35 nmol kg^{-1}. Within this rise is a period of decreased Cd_W coincident with the Younger Dryas interval. Comparison to a high-resolution Cd record from the deep North Atlantic (4,450 m, Bermuda rise)[3,9] reveals a striking inverse correlation (Fig. 3). This suggests that at times of weak NADW formation (high Cd_W at 4,450 m), GNAIW formation was strong (low Cd_W at 965 m). Another potential source of nutrient-depleted intermediate waters, Mediterranean Outflow Water, does not appear to have strengthened during either the Younger Dryas[6] or the LGM[26]. We

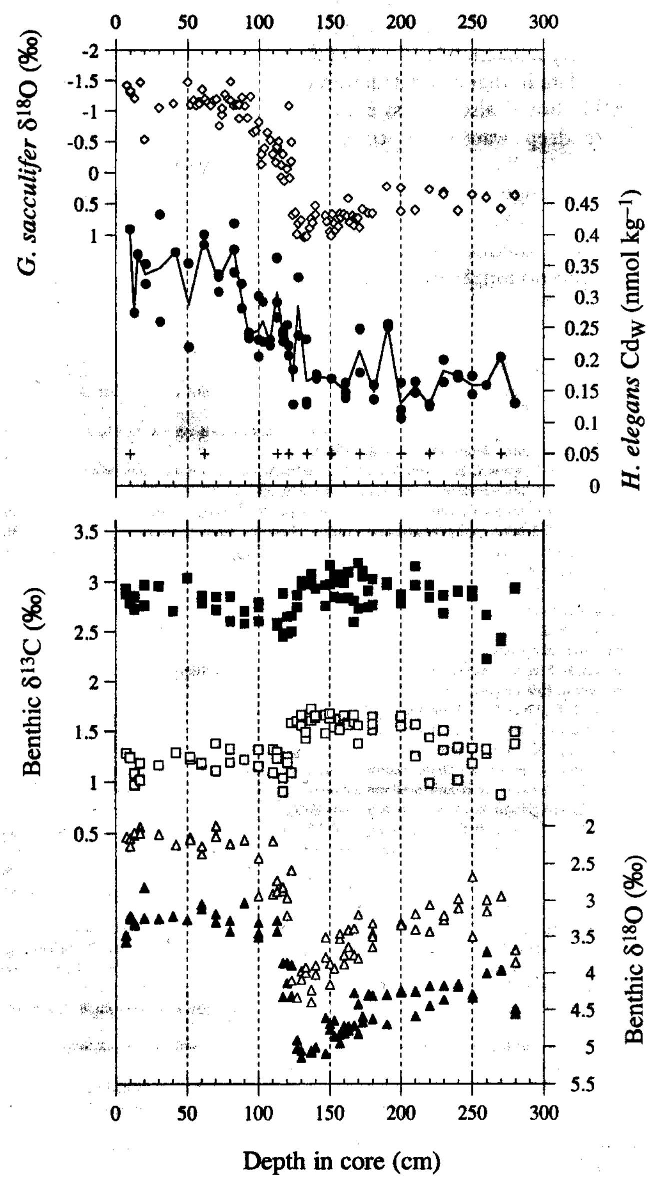

Figure 2 Data from core OC205-2-103GGC (26° 04′ N, 78° 03′ W; 965 m). Shown are records of planktonic $\delta^{18}O$ (*Globigerinoides sacculifer*, open diamonds), benthic Cd_W (*H. elegans*, filled circles), benthic $\delta^{13}C$ (*H. elegans*, filled squares; *Cibicidoides kullenbergi*, open squares), and benthic $\delta^{18}O$ (*H. elegans*, filled triangles; *C. kullenbergi*, open triangles). Crosses indicate the depths of accelerator mass spectrometer (AMS) radiocarbon dates (see Supplementary Information). Most of the *C. kullenbergi* isotopic data have been presented previously[12]. The large isotopic offsets between *H. elegans* and *C. kullenbergi* are due to their different mineralogies. Benthic isotopes were measured on single shells, whereas planktonic $\delta^{18}O$ and benthic Cd_W used multiple (~3–15) shells per analysis. Of the 79 Cd measurements, three were considered to be significantly contaminated (Cd_W much higher than expected) and were omitted.

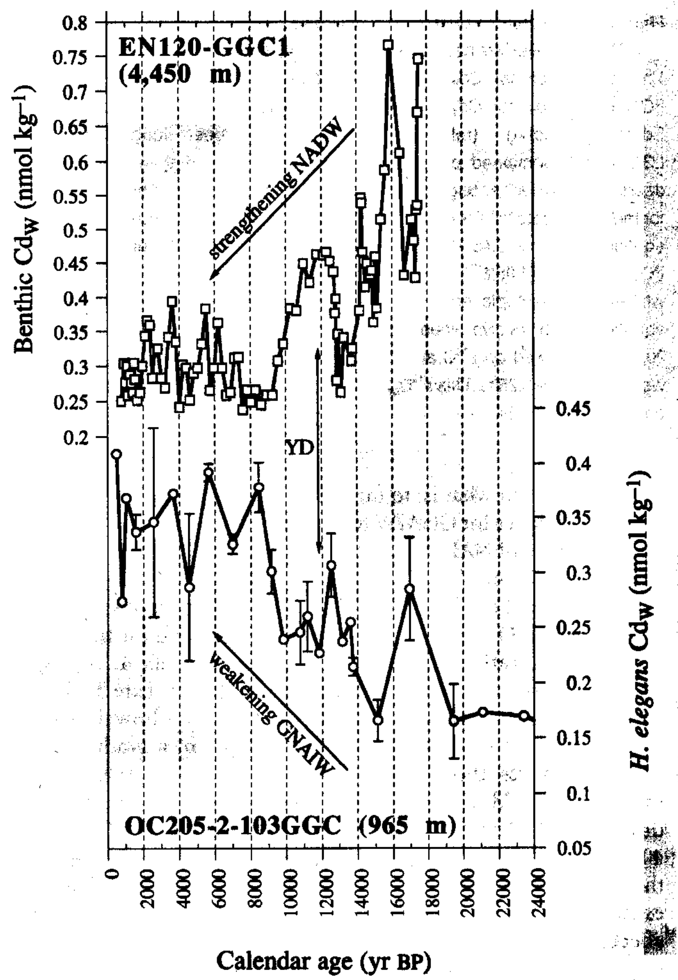

Figure 3 Records of Cd_W from the deep and intermediate-depth western North Atlantic. The EN120-GGC1 record (33° 40′ N, 57° 37′ W; 4,450 m; squares)[3,9] is based on measurements of the benthic foraminifera *C. wuellerstorfi*, *Nutallides umbonifera*, and *Uvigerina* spp., using a D_p of 2.9. The OC205-2-103GGC record (26° 04′ N, 78° 03′ W; 965 m; circles) shows *H. elegans* means with standard errors. Dates for GGC1 are based on a multi-property correlation[9] to nearby core KNR31-GPC5 (33° 41′ N, 57° 37′ W; 4,583 m), which has 13 AMS radiocarbon dates. Ten AMS dates were obtained for 103GGC. All radiocarbon dates were converted to calendar age BP using dendrochronological and coral-derived models (see Supplementary Information). 'YD' denotes the Younger Dryas.

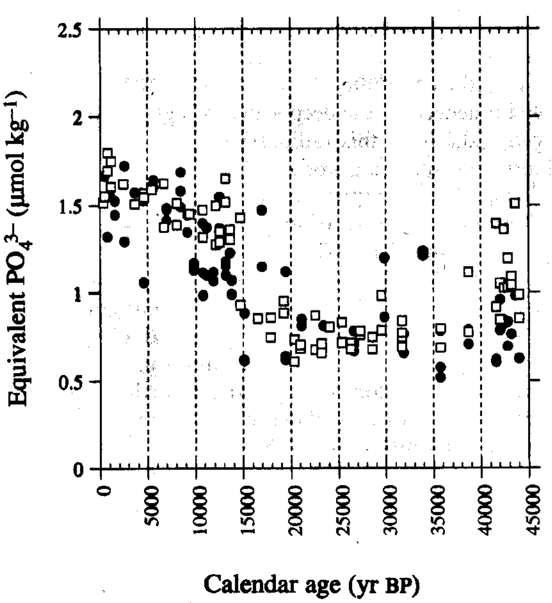

Figure 4 Estimated seawater PO_4^{3-} concentrations recorded in core OC205-2-103GGC. Estimates are based on *H. elegans* Cd_W (filled circles) and *C. kullenbergi* $\delta^{13}C$ (open squares). Cd_W was converted using the global Cd:P relationship: $PO_4^{3-} = 4.81\,Cd_W$ for $Cd_W < 0.28\,nmol\,kg^{-1}$, and $PO_4^{3-} = 0.638 + 2.51\,Cd_W$ for $Cd_W > 0.28\,nmol\,kg^{-1}$ (refs 16, 18). Although it has been suggested that the LGM ocean contained perhaps 13% less dissolved Cd than today, such a decrease is not well enough constrained to warrant the use of different equations for the glacial data[20,27]. For data ≤5,000 yr BP, $\delta^{13}C$ was converted using the modern equation, $PO_4^{3-} = 2.45 - [0.91(\delta^{13}C - \delta^{13}C_{as})]$ (ref. 27). The glacial equation $PO_4^{3-} = 2.16 - [1.05(\delta^{13}C - \delta^{13}C_{as})]$ (ref. 27), which accounts for the glacial whole-ocean isotopic shift[4,5], was used for data ≥20,000 yr BP. Intermediate equations that evolve linearly with time were used between 5,000 and 20,000 yr BP. Based on $\delta^{13}C$ and Cd_W from the cores presented in Fig. 1, $\delta^{13}C_{as}$ was taken to be 0.25‰. This $\delta^{13}C_{as}$ may also contain some foraminiferal disequilibrium ('vital') effects.

therefore present what is, to our knowledge, the first direct palaeonutrient evidence for GNAIW formation during the Younger Dryas, at the expense of NADW.

The raw benthic $\delta^{13}C$ record from 103GGC looks significantly different from the Cd record (Fig. 2). Converting all $\delta^{13}C$ and Cd_W to equivalent PO_4^{3-} (refs 16, 18, 27), and accounting for the whole-ocean glacial carbon isotopic shift of 0.3‰ (refs 4, 5), again produces reasonably good agreement during the Late Holocene and LGM (Fig. 4). Although it is difficult to estimate how the whole-ocean $\delta^{13}C$ shift evolved across the deglaciation, a gradual linear change removes the $\delta^{13}C$ minimum seen at ~13,000 cal. yr BP, improving the Cd–$\delta^{13}C$ agreement. Discrepancies remain, however, during the Younger Dryas and during stage 3 (before 40,000 cal. yr BP). These may be attributed to the obscuring effects of the whole-ocean isotopic shift and to the influences of air–sea exchange on $\delta^{13}C$ (ref. 19). For example, the opposing air–sea isotopic effects of cooling (raising $\delta^{13}C$) and decreased air–sea contact time (lowering $\delta^{13}C$) may have been roughly balanced during the LGM, but decreased air–sea contact may have dominated over the less extreme coolings of the Younger Dryas and stage 3. Given such complications to the $\delta^{13}C$ record, we believe that Cd is a more reliable indicator of short-term nutrient changes, especially within the main climate transitions.

Our results demonstrate that periods of enhanced intermediate-water production alternate with periods of enhanced deep-water formation on both orbital and millennial timescales. Analogous dynamics operate in the modern North Atlantic on much shorter (decadal) timescales, with deep convection alternating between regions of upper (Labrador Sea) and lower (Greenland Sea) NADW formation[28]. However, these brief reconfigurations have smaller effects on oceanic temperature and nutrient structure than the larger-scale events occurring during the last deglaciation.

The cooling of the North Atlantic during the Younger Dryas has long been linked to a reduction or cessation of NADW formation, which today releases a great deal of heat to the high-latitude atmosphere[3,7–9]. Recent modelling suggests that a peak in atmospheric radiocarbon activity during the Younger Dryas is best explained by a cessation of NADW and a subsequent increase in GNAIW formation[29]. Our Cd data from 965 m indeed indicate that GNAIW partially replaced NADW during this cold period, though to a lesser extent than during the LGM. A Younger Dryas $\delta^{13}C$ section through the eastern Atlantic[6] supports this view of a moderately weakened NADW, but there are too few well-positioned shallow data in that reconstruction to discern a clear GNAIW mass; GNAIW should also be less evident in the eastern North Atlantic because deep waters are concentrated into western boundary currents. The Younger Dryas cooling may have thus been accomplished through the formation of intermediate waters that were less efficient at heating the North Atlantic than NADW[30]. It is clear that North Atlantic climate change at the end of the last glacial period can no longer by explained by a simple convection 'on/off' switch. □

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Supplementary Information is available on *Nature*'s World-Wide Web site (http://www.nature.com) or as paper copy from the London editorial office of *Nature*.

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