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Changes in North Atlantic deep-sea temperature during climatic fluctuations of the last 25,000 years based on ostracode Mg/Ca ratios

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[1] **Abstract:** We reconstructed three time series of last glacial-to-present deep-sea temperature from deep and intermediate water sediment cores from the western North Atlantic using Mg/Ca ratios of benthic ostracode shells. Although the Mg/Ca data show considerable variability ("scatter") that is common to single-shell chemical analyses, comparisons between cores, between core top shells and modern bottom water temperatures (BWT), and comparison to other paleo-BWT proxies, among other factors, suggest that multiple-shell average Mg/Ca ratios provide reliable estimates of BWT history at these sites. The BWT records show not only glacial-to-interglacial variations but also indicate BWT changes during the deglacial and within the Holocene interglacial stage. At the deeper sites (4500- and 3400-m water depth), BWT decreased during the last glacial maximum (LGM), the late Holocene, and possibly during the Younger Dryas. Maximum deep-sea warming occurred during the latest deglacial and early Holocene, when BWT exceeded modern values by as much as 2.5°C. This warming was apparently most intense around 3000 m, the depth of the modern-day core of North Atlantic deep water (NADW). The BWT variations at the deeper water sites are consistent with changes in thermohaline circulation: warmer BWT signifies enhanced NADW influence relative to Antarctic bottom water (AABW). Thus maximum NADW production and associated heat flux likely occurred during the early Holocene and decreased abruptly around 6500 years B.P., a finding that is largely consistent with paleonutrient studies in the deep North Atlantic. BWT changes in intermediate waters (1000-m water depth) of the subtropical gyre roughly parallel the deep BWT variations including dramatic mid-Holocene cooling of around 4°C. Joint consideration of the Mg/Ca-based BWT estimates and benthic oxygen isotopes suggests that the cooling was accompanied by a decrease in salinity at this site. Subsequently, intermediate waters warmed to modern values that match those of the early Holocene maximum of ~7°C. Intermediate water BWT changes must also be driven by changes in ocean circulation. These results thus provide independent evidence that supports the hypothesis that deep-ocean circulation is closely linked to climate change over a range of timescales regardless of the mean climate state. More generally, the results further demonstrate the potential of benthic Mg/Ca ratios as a tool for reconstructing past ocean and climate conditions.

Keywords: Ostracode; magnesium/calcium ratio; ocean temperature; deep sea; paleothermometer; shell chemistry.

Index terms: Paleoceanography; Atlantic Ocean; global change.

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1. Introduction

[2] Climatic fluctuations of the last 25,000 years are now reasonably well known from terrestrial, marine, and ice core records; yet their origins, especially those of the Holocene (last ~11,000 years), remain uncertain [*O'Brien et al.*, 1995; *Bond et al.*, 1997; *Keigwin*, 1996]. Of the proposed mechanisms for climate forcing, variability in the circulation of the North Atlantic ocean has received a great deal of support from studies of deep-sea sediment and ice core records [*Boyle and Keigwin*, 1985; *O'Brien et al.*, 1995; *Keigwin*, 1996; *Alley et al.*, 1997; *Bond et al.*, 1997; *Steig et al.*, 1998]. Instrumental records [*Dickson et al.*, 1996; *Curry et al.*, 1998] and modeling studies [*Rahmstorf*, 1994] show that such climate-linked changes in North Atlantic circulation can be rapidly transmitted from the surface to the deep ocean where they are manifested as changes in deep-sea temperatures. Thus North Atlantic deep-sea temperature records may aid our understanding of the linkage between deep ocean circulation and climate change; unfortunately, few records of deep-sea temperature exist for the period covering the last 25,000 years. In this paper we present three records of bottom water temperature (BWT) from deep and intermediate waters of the western North Atlantic based on Mg/Ca ratios in shells of benthic ostracodes. After evaluating the reliability of the Mg/Ca-based BWT records we consider the observed BWT variability in the context of orbital and millennial climate change over the last 25,000 years and the possible factors responsible for BWT variations.

2. Approach

[3] The material used for generating the deep-sea paleotemperature records is sampled from sediment cores collected from three sites that are sensitive to circulation changes in the deep and intermediate waters of the western North Atlantic (Table 1). A schematic diagram (Figure 1) shows the core locations relative to the major water masses and circulation systems of the modern Atlantic Ocean. The deepest record is from a composite core comprising box core HU089-38-BC4 and giant piston core KNR31-GPC5 (33°41′N, 57°37′W) at ~4500-m water depth on the Bermuda Rise (BR). The site has a present-day BWT of 2.2°C [*Bainbridge*, 1981] and is located near the benthic front between warmer (2° to 4°C), southward advected NADW produced by open-ocean convection in the Labrador and Greenland-Iceland-Norwegian Seas, and colder (0° to 2°C), northward advected AABW produced by cooling and sea ice formation around Antarctica [*Bainbridge*, 1981; *Pickard and Emery*, 1982]. To the northeast, at 3427-m water depth, core CHN82-24-4PC (41°43′N, 33°51′W) from the western mid-Atlantic Ridge (WMAR) has a stronger present-day NADW influence and a correspondingly warmer modern BWT of 2.7°C [*Bainbridge*, 1981]. The intermediate

Table 1. Cores Used in This Study and Comparison Between Ostracode Mg/Ca-Based BWT Estimates and Modern (Measured) and Glacial (Benthic Foraminiferal δ^{18}O-Based) BWT[a]

Location/Core	Latitude	Longitude	Water Depth, m	Modern BWT, °C		Glacial[b] BWT, °C	
				Measured	Mg/Ca	δ^{18}O	Mg/Ca
			Little Bahama Banks (LBB)				
OC205-2-103GGC[c]	26°04′N	78°03′W	965	6.8[c]	7.6	4[c]	4.5
			Western Mid-Atlantic Ridge (WMAR)				
CHN82-24-4PC[d]	41°43′N	32°51′W	3427	2.7[e]	2.7	−1	−0.5
			Bermuda Rise Composite (BR)				
HU89-038-BC4[f]	33°42′N	57°37′W	4418	2.2[e]	2.2		
KNR31-GPC-5[g]	33°41′N	57°37′W	4583			1	0.8

[a] Modern Mg/Ca-based BWT is calculated from core top ostracode shells from each of the cores. Glacial δ^{18}O-based BWT is determined from the residual δ^{18}O after subtracting the continental ice volume effect [e.g., *Slowey and Curry*, 1995, and references therein] from the difference between LGM and late Holocene benthic foraminiferal δ^{18}O values. For the deepwater sites we assume a 1.1‰ glacial-late Holocene $\Delta\delta^{18}$O due to ice volume and that the residual $\Delta\delta^{18}$O is due to BWT change and ~0.25‰ for each 1°C change in temperature. This, of course, is an approximation, because of possible issues of contemporary water δ^{18}O variations and phasing of ice volume and temperature signals, among others. These details cannot be properly quantified without direct coupling of δ^{18}O and Mg/Ca analyses on the same sample material.

[b] Note that no true LGM samples were analyzed at the Bermuda Rise site so δ^{18}O and Mg/Ca values from ~18,000 years before present are used for this site. The LGM is also underrepresented in the Mg/Ca record from LBB core OC205-2-103GGC.

[c] *Slowey and Curry* [1995].

[d] *Boyle and Keigwin* [1985].

[e] *Bainbridge* [1981].

[f] *Keigwin* [1996].

[g] *Keigwin et al.* [1991] and *Keigwin and Jones* [1994].

water core, OC205-2-103GGC (26°04′N, 78°03′W, 965-m water depth), is from a site located near the base of the modern thermocline offshore Little Bahama Banks (LBB) in the southwestern sector of the North Atlantic subtropical gyre. Water at this site mostly originates from a northern source area: surface waters are downwelled and recirculated in the subpolar gyre prior to being advected southward along isopycnal (constant density) surfaces [*Pedlosky*, 1990; *Slowey and Curry*, 1995]. Antarctic Intermediate water (AAIW), and Mediterranean outflow (MOW) are subordinate contributors at the site that has a modern BWT of 6.8°C [*Slowey and Curry*, 1995; *Bryden et al.*, 1996].

[4] Benthic foraminiferal stable oxygen isotope (δ^{18}O) records have already been published for all of theses sites [*Slowey and Curry*, 1995; *Boyle and Keigwin*, 1985; *Keigwin et al.*, 1991; *Marchitto et al.*, 1998; *Curry et al.*, 1999]. The δ^{18}O of benthic foraminifers is a function of the oxygen isotopic composition of ambient seawater ($\delta^{18}O_{SW}$), and the BWT at the time of shell secretion and has been used to reconstruct glacial-interglacial changes in deep-sea BWT. However, reliable reconstructions of BWT from benthic δ^{18}O are difficult to achieve because of a number of uncertainties, mostly related to independently constraining the value of $\delta^{18}O_{SW}$ [*Mix*, 1992]. Some of the potential factors controlling $\delta^{18}O_{SW}$ at a given site include changes in continental ice volume, changes in the relative proportion of different water masses impinging on the site, and variations in the preformed values of $\delta^{18}O_{SW}$ of the relevant water masses (independent of ice

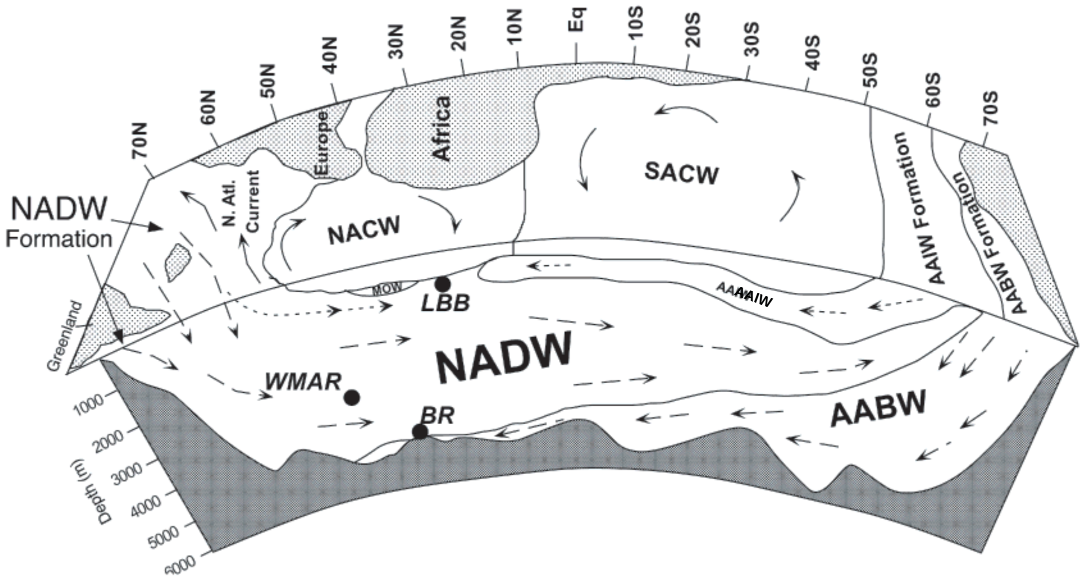


Figure 1. Schematic diagram of Atlantic Ocean showing location of study sites relative to major water masses and Atlantic circulation systems [after *Pickard and Emery*, 1982]. Study sites: LBB, core OC205-2-103GGC (965-m water depth) offshore of Little Bahama Banks; WMAR, core CHN82-24-4PC (3427-m water depth) from the western mid-Atlantic ridge northwest of the Azores; BR, composite core HU089-38-BC4/KNR31-GPC5 (4500-m water depth) from the Bermuda Rise. Water masses: NADW, North Atlantic deep water; MOW, Mediterranean outflow water; AABW, Antarctic bottom water; AAIW, Antarctic intermediate water; NACW, North Atlantic central water; SACW, South Atlantic central water. General current direction of surface (solid), intermediate (short dash) and deep (long dash) waters indicated by arrows.

volume changes). Additionally, changes in some of these factors may have variable temporal phasing with respect to variations in water temperature [*Imbrie et al.*, 1992; *Dwyer et al.*, 1995]. Here we base our estimates of past BWT on Mg/Ca ratios of benthic ostracode shells that have been shown to be primarily controlled by ambient water temperature [*Cadot and Kaesler*, 1977; *Dwyer et al.*, 1995; *Corrège and De Deckker*, 1997]. Time series of ostracode Mg/Ca ratios have previously been used to discern Atlantic and Pacific BWT changes associated with late Pliocene and Quaternary orbital-scale, glacial-to-interglacial climate cycles [*Dwyer et al.*, 1995; *Corrège and De Deckker*, 1997]. Little is known, however, regarding the timing, magnitude, and spatial extent of North Atlantic deep-sea temperature changes since the last glacial maximum.

3. Methods

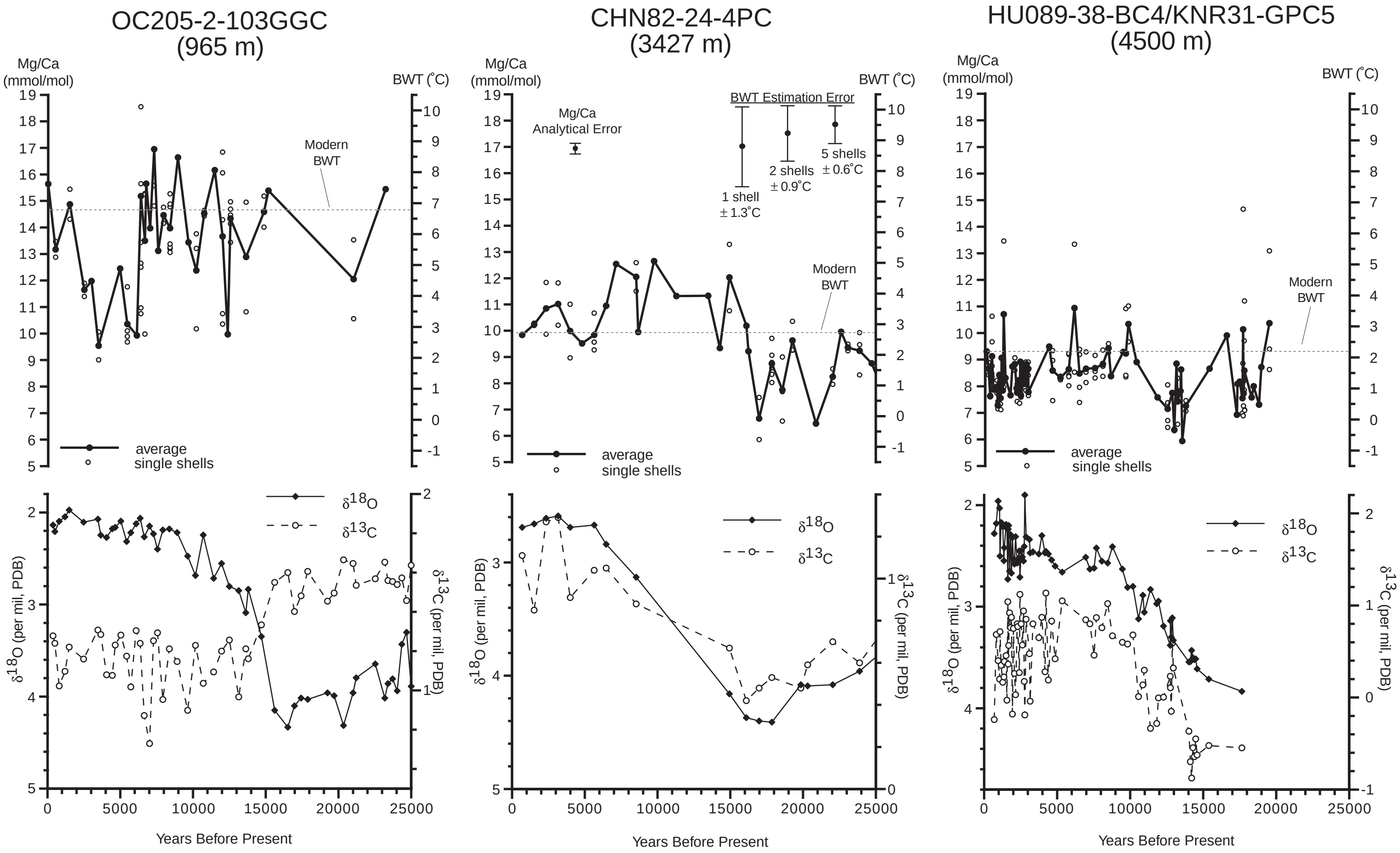
[5] Ostracode Mg/Ca ratios were measured by direct current plasma atomic emission spectrophotometry on individual adult shells of the genus *Krithe* from the three sites following the procedures by *Dwyer et al.* [1995]. Analytical precision on Mg/Ca analyses is better than 3%, based on replicate analyses of a laboratory internal consistency standard. A total of 254 shells were analyzed; 148 from BR composite core HU89038-BC-004/KNR31GPC-5, 50 previously published from WMAR core CHN82-

24-4PC [*Dwyer et al.*, 1995], and 56 from LBB core OC-205-103GGC. Each shell was assigned a dissolution index (visual preservation index, or VPI from *Dwyer et al.* [1995], which has been shown to be related to the extent of shell dissolution [*Dwyer et al.*, 1999; also manuscript in preparation, 2000]) to evaluate possible dissolution effects on shell Mg/Ca ratios. Ostracode Mg/Ca ratios were converted to BWT using the core top calibration equation for adult shells of *Krithe* from *Dwyer et al.* [1995]: BWT (°C) = (0.854 × Mg/Ca) − 5.75, where Mg/Ca is in millimoles per mole. As described by *Dwyer et al.* [1995], this calibration yields a BWT estimation error of ±1.3°C for single-shell analyses. This error can be reduced by a factor of $1/n^{1/2}$ for intrasample averages of multiple shells, where n is the number of shells used in the average [*Dwyer et al.*, 1995]. Thus a two-shell average yields an error of ±0.9°C, and a five-shell average yields an error of ±0.6°C. In this study, the number of shells analyzed per stratigraphic interval varied from 1 to 10. Multiple-shell intervals make up ∼75% of the intervals analyzed. Chronostratigraphies for BR core HU89038-BC4/KNR31GPC-5 [*Keigwin*, 1996; *Keigwin and Jones*, 1994] and LBB core OC-205-103GGC [*Slowey and Curry*, 1995; *Marchitto et al.*, 1998; T. Marchitto, personal communication, 1999] are based on accelerator mass spectrometer (AMS) ^{14}C dates that have been converted to calendar years before present using the calibration of *Stuiver and Reimer* [1993]. Chronstratigraphy for WMAR core CHN82-24-4PC is based on the benthic foraminiferal oxygen isotope record [*Boyle and Keigwin*, 1985]. Sedimentation rates at the BR, WMAR, and LBB sites, respectively, average 10–15 cm/kyr [*Keigwin and Jones*, 1994; *Keigwin*, 1996], 3–4 cm/kyr [*Boyle and Keigwin*, 1985], and 7–20 cm/kyr (2–3 cm/kyr during glacial) [*Slowey and Curry*, 1995; *Marchitto et al.*, 1998], and our sampling rate generally allows for millennial-scale temporal resolution.

4. Results and Discussion

[6] Results are shown in Figure 2 as ostracode Mg/Ca ratios and Mg/Ca-based BWT estimates for the last 25,000 years along with benthic foraminiferal stable oxygen and carbon isotope records [*Slowey and Curry*, 1995; *Boyle and Keigwin*, 1985; *Keigwin et al.*, 1991; *Marchitto et al.*, 1998; *Curry et al.*, 1999]. The Mg/Ca records generally show correspondence with the benthic isotope records, although it's clear that high-frequency variability ("scatter") may be more pronounced in the Mg/Ca records. This is likely due to the fact that the Mg/Ca ratios are from single-shell analyses, which typically leads to higher variability in microfossil chemical data than bulk analyses of multiple specimens or crushed splits from the same samples [*Boyle*, 1995]. As *Boyle* [1995] demonstrated, such scatter is not related to analytical precision or variability in sample preparation. This conclusion is further substantiated by the fact that similar Mg/Ca ratios are obtained on the left and right valves from the same ostracode carapace (genus *Krithe* (G. S. Dwyer et al., manuscript in preparation, 2000)). Instead, the scatter is related to true specimen-to-specimen variability, which in turn can be a function of a number of factors including bioturbational mixing of different age shells and/or variability of temperature. Chemical variability can also be due to contamination of the shells, and it is not uncommon for outliers to be ommitted from microfossil chemical records [e.g., *Marchitto et al.*, 1998]. A few outliers occur in the Mg/Ca records presented here, but there is no obvious reason to exclude any of them, so they have been left in all of the subsequent multiple-shell averages. Ultimately, their effect on the trends in the Mg/Ca records is minimal.

[7] In a number of instances it appears that the short-term Mg/Ca variability is localized around times of known or apparent oceano-

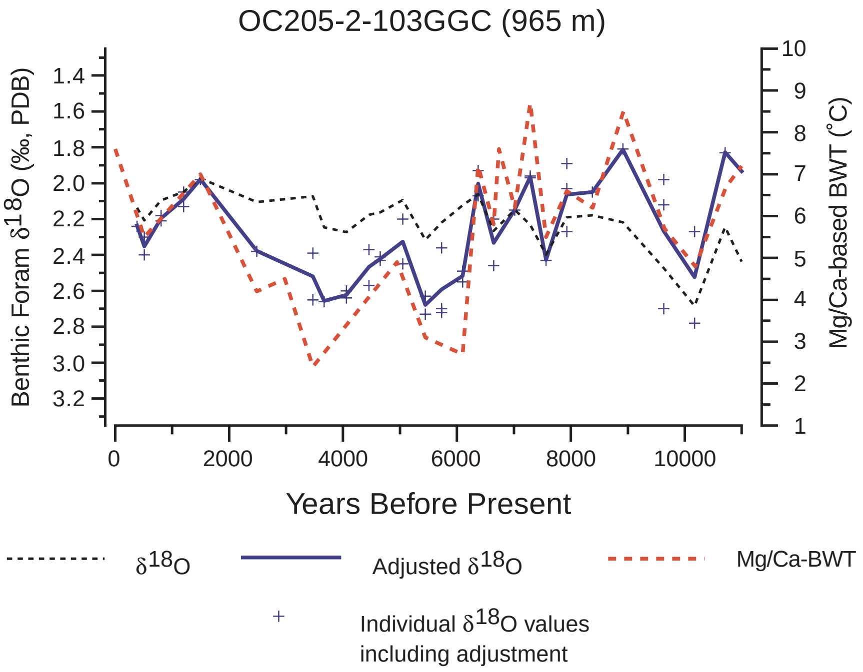

OC205-2-103GGC
(965 m)
CHN82-24-4PC
(3427 m)
HU089-38-BC4/KNR31-GPC5
(4500 m)
Mg/Ca
(mmol/mol)
BWT (˚C)
Modern
BWT
Mg/Ca
Analytical Error
BWT Estimation Error
1 shell
± 1.3˚C
2 shells
± 0.9˚C
5 shells
± 0.6˚C
average
single shells
δ18O
δ13C
δ18O (per mil, PDB)
δ13C (per mil, PDB)
0
5000
10000
15000
20000
25000
Years Before Present

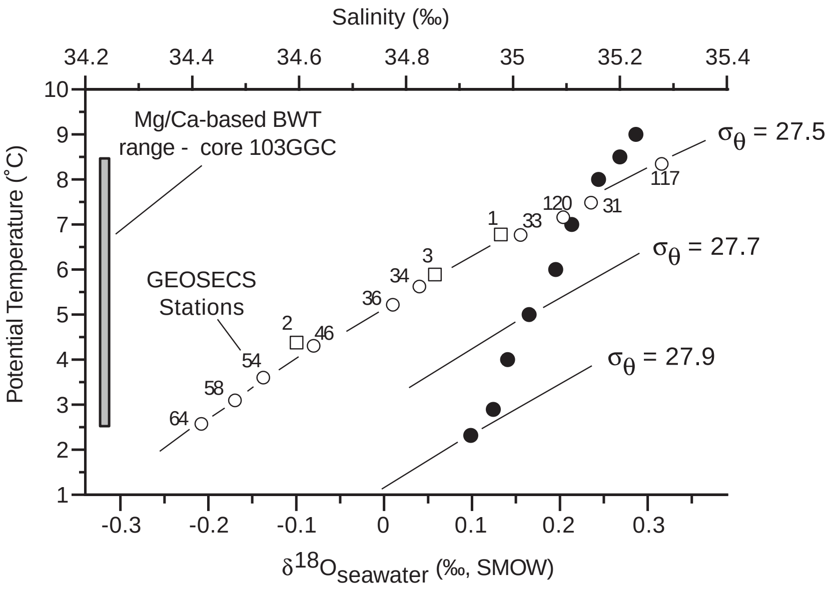
graphic change, supporting the hypothesis that the variability is related to BWT change with some bioturbational mixing. For example, in core 103GGC at 965 m, Mg/Ca ratios are most variable around the time of the Younger Dryas event (~12,500 years ago) when dramatic circulation changes occurred in the North Atlantic [*Boyle and Keigwin*, 1987; *Marchitto et al.*, 1998] and around 7000 years ago (7 ka) when bottom waters at this site apparently cooled dramatically. The 7 ka cooling event appears to be accompanied by an increase in benthic foram $\delta^{13}C$, which would be consistent with reduced influence of relatively warm, $\delta^{13}C$-depleted lower thermocline waters at this site. More generally, it's clear from the isotope records for all three sites (especially $\delta^{13}C$), which in most cases are multiple-shell analyses or averages, that these sites may have experienced significant short-term (century-scale or less) variability in bottom water conditions over the last 25 ka. Thus, although our sampling rate may not be sufficient to characterize the full spectrum of variability at these sites, the Mg/Ca ratios may be providing reliable estimates of BWT changes.

[8] The reliability of the Mg/Ca-based BWT estimates can be further appraised in several other ways. (1) The progressive decrease in the amplitude of the BWT shifts from the shallowest to the deepest site (Figure 2) is realistic in terms of BWT variability measured over the last few decades [e.g., *Bryden et al.*, 1996]. (2) Mg/Ca-based BWT estimates derived from the most recent (core top) shells at each of the sites show good agreement with modern instrumental measurements of bottom water temperature (Table 1, Figure 2). (3) Mg/Ca-based BWT estimates from the last glacial intervals in each of the cores are also comparable to benthic foraminiferal $\delta^{18}O$-based glacial BWT estimates (Table 1). (4) The absolute values and broad pattern of BWT change are also in good agreement with the $\delta^{18}O$ study of *Laberyie et al.* [1987], which although controversial [*Mix and Pisias*, 1988], is perhaps the most detailed previous investigation of late Quaternary deep-sea temperature in the North Atlantic (see also *Dwyer et al.* [1995, and references therein] for discussion of alternative views on late Quaternary glacial-interglacial deep ocean temperature). (5) For the period covering the last ~11 ka in LBB core 103GGC and BR core GPC-5, where a relatively detailed comparison is possible, benthic foraminiferal $\delta^{18}O$ and ostracode Mg/Ca records show good correspondence, after accounting for effects of continental ice volume and possible effects of salinity on $\delta^{18}O_{SW}$ (Figures 3 and 4). Figure 3 shows the comparison between Mg/Ca-BWT and the adjusted benthic foraminiferal $\delta^{18}O$ in core 103GGC at 965 m as well as the modern temperature-salinity (T-S) relationships relevant to this site. For the salinity adjustment (ice volume adjustment described in caption of Figure 3), we use the Mg/Ca-BWT estimates and modern T-S relationship to estimate paleosalinity, which in turn is used to calculate paleo-$\delta^{18}O_{SW}$ based on the S-$\delta^{18}O_{SW}$ relationship of *Craig and Gordon* [1965]. Any changes in paleo-$\delta^{18}O_{SW}$ are then accordingly used to

Figure 2. Single-shell and average ostracode Mg/Ca ratios and Mg/Ca-based BWT estimates for core OC205-2-103GGC (965-m water depth), core CHN82-24-4PC (3427-m water depth), and composite core HU089-38-BC4/KNR31-GPC5 (4500-m water depth) for the last 25,000 years. BWT estimates and estimation error were calculated as discussed in the text. Two single-shell analyses with values of 20 and 27 mmol/mol at 7.3 and 6.4 ka in core 103GGC are not shown, although they are included in intrasample averages. Also shown are benthic foraminiferal stable isotope records (*Cibicidoides*) for each of the cores from previous studies [*Slowey and Curry*, 1995; *Boyle and Keigwin*, 1985; *Keigwin et al.*, 1991; *Marchitto et al.*, 1998; *Curry et al.*, 1999].

adjust the benthic foraminiferal $\delta^{18}O$. Because horizontal mixing of waters along isopycnals likely dominates in this part of the ocean over vertical mixing across isopycnals [e.g., *Knauss*, 1997] or kilometer-scale vertical movement of isopycnals, we elect to use the *T-S* relationship along the modern isopycnal that intersects the 103GGC core site (Figure 3, Table 2). This





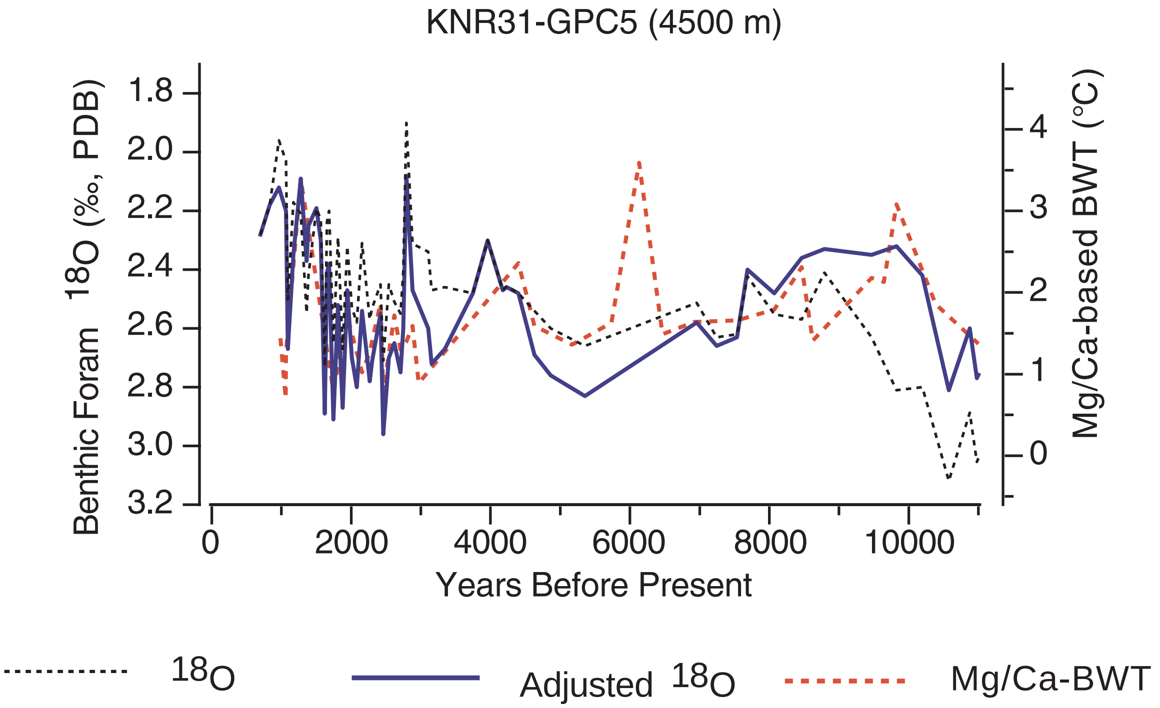


Figure 4. Comparison of average Mg/Ca-based BWT estimates and benthic foraminiferal δ^{18}O values for core KNR31-GPC5 for the last 11,000 years. Similar to top plot in Figure 3, except that the salinity adjustment to the δ^{18}O values was made using the *T-S* and *S*-δ^{18}O$_{\text{seawater}}$ relationships for NADW and AABW from *Craig and Gordon* [1965].

yields a much better amplitude agreement than would be obtained using the local vertical *T-S* relation (Figure 3) due to the larger salinity (and δ^{18}O$_{\text{SW}}$) change per degree change in temperature along this isopycnal. This demonstrates the potential for any BWT change con-

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Figure 3. (top) Comparison of average Mg/Ca-based BWT estimates and benthic foraminiferal δ^{18}O values (*Cibicidoides kullenbergi*) [*Slowey and Curry*, 1995; *Marchitto et al.*, 1998; *Curry et al.*, 1999] for core OC205-2-103GGC for the last 11,000 years. The δ^{18}O axis is scaled so as to be roughly equivalent to the BWT axis. The δ^{18}O values are adjusted for the effects of continental ice volume changes and possible salinity changes. The ice volume adjustment was derived from the sea level record and the assumption of 0.1‰ change in δ^{18}O$_{\text{SW}}$ for each 10-m change in sea level [*Bard*, 1998, and references therein] and decreases exponentially from 0.47‰ $\sim$11 ka to 0.0‰ by $\sim$5 ka. Salinity (*S*) adjustments were made using the Mg/Ca-based BWT estimates, the modern *T-S*, and the modern *S*-δ^{18}O$_{\text{SW}}$ relationship shown in the lower graph. The δ^{18}O$_{\text{SW}}$ was calculated using the North Atlantic *S*-δ^{18}O$_{\text{SW}}$ reported by *Craig and Gordon* [1965], which shows a 0.61‰ shift in δ^{18}O$_{\text{SW}}$ for 1‰ shift in salinity. Two *T-S* relationships are shown; the local vertical *T-S* profile (solid symbols) off Little Bahama Banks ([*Slowey and Curry*, 1995] the two coldest data points are from GEOSECS Station 32 [*Bainbridge*, 1981]), and the *T-S* relationship (open symbols) for Atlantic waters that lie laterally away from the core site along the $\sigma_\theta = 27.5$ isopycnal, the constant density level that intersects the seafloor at the core site. The $\sigma_\theta = 27.5$ *T-S* data are from the Geochemical Ocean Sections Study (GEOSECS) stations listed in Table 2.

Table 2. Locations of the GEOSECS Stations Used in Figure 3[a]

Station	Latitude	Longitude	Water Depth, m
3	51°01′N	43°07′W	407[b]
2	47°58′N	42°32′W	169
1	44°57′N	42°00′W	500
117	30°40′N	38°58′W	952
120	33°16′N	56°33′W	900
31	27°00′N	53°32′W	953
33	21°00′N	54°00′W	893
34	18°01′N	53°59′W	952
36	15°00′N	53°56′W	1009
46	00°59′S	34°02′W	966
54	15°02′S	29°32′W	1001
58	27°00′S	37°01′W	1156
64	39°05′S	48°33′W	1201

[a] *Bainbridge* [1981].
[b] Interpolated, 377–437 m.

tained within the benthic $\delta^{18}O$ record to be strongly masked by counteracting changes in salinity. There remains some slight amplitude mismatches, but these are likely insignificant considering the number of assumptions related to this analysis, the Mg/Ca and foram $\delta^{18}O$ variability (Figure 3), the BWT estimation error, and variations in $\delta^{18}O$ and Mg/Ca sampling rates. The comparison for GPC-5 at 4500 m (Figure 4) shows similar correspondence with perhaps overall better amplitude agreement. The salinity adjustment for GPC-5 relies on the T-S and S-$\delta^{18}O_{SW}$ relationships for modern NADW and AABW [*Pickard and Emery*, 1982; *Craig and Gordon*, 1965]. Isotope data are insufficient for such a comparison in core CHN82-24-4PC. (6) In core CHN82-24-4PC, where detailed benthic faunal studies have been conducted [*Cronin et al.*, 1999], Mg/Ca variations correspond to variations in species abundance and diversity. (7) Partial dissolution of the shells appears to have little if any role in governing Mg/Ca ratios at these sites. As shown in Figure 5, LBB core 103GGC and BR cores BC-4/GPC-5 show no correlation between dissolution (visual preservation index) and Mg/Ca. The weak correlation between dissolution and Mg/Ca in shells from WMAR core CHN82-24-4PC (Figure 5) may be a residual temperature signal resulting from a strong covariance between the level of bottom water calcite saturation and BWT at this site [*Dwyer et al.*, 1995]. Taken together, the factors discussed above suggest that the ostracode Mg/Ca ratios provide reliable estimates of BWT at each of the sites.

[9] Because of the sampling-rate limitations mentioned earlier, we focus primarily on multi-millennial trends in the Mg/Ca-BWT records. To better evaluate these trends, we smoothed the BWT records with a three-point moving average (Figure 6) which further increases the number of shells considered within each average, thereby further reducing the BWT estimation error. The smoothed records are then combined to produce BWT and BWT-anomaly water depth sections for the deep western North Atlantic for the last 25 ka (Figure 7). While the smoothing results in some artifacts where downcore sample spacing is large, most of the primary features are retained in the smoothed records. Another possible shortcoming of this view of the data is that it forces interpolation across a wide depth range of intermediate waters between the records from LBB core

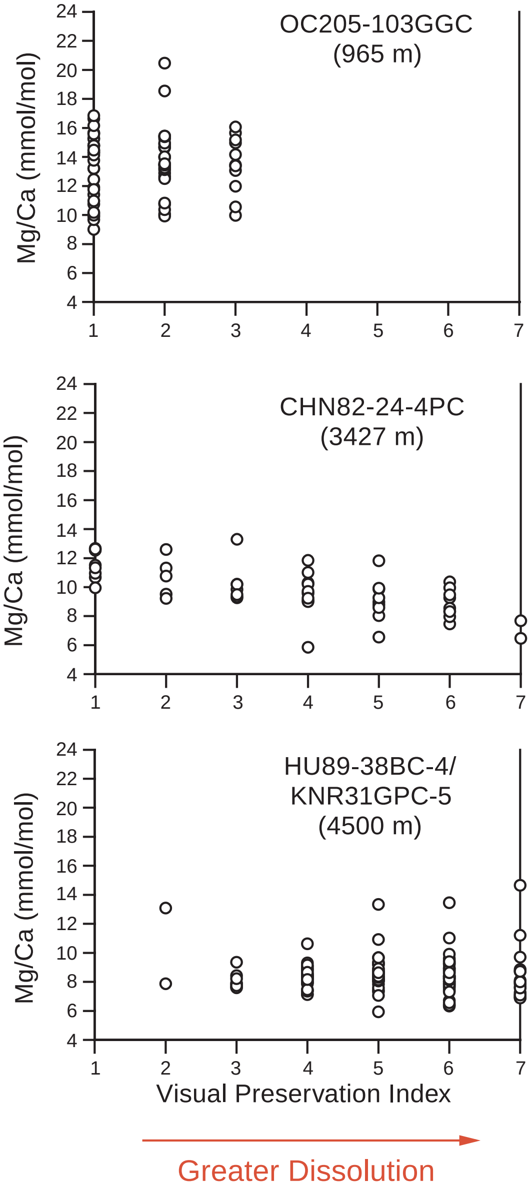

Figure 5. Ostracode Mg/Ca ratios versus visual preservation index. Higher numbers indicate greater dissolution.

OC205-2-103GGC at 965 m and WMAR core CHN82-24-4PC at 3427 m (Figure 7). However, previous studies indicate that the site of OC205-2-103GGC is in a region that should be representative of modern intermediate water [*Schmitz and McCartney*, 1993; *Slowey and Curry*, 1995; *Marchitto et al.*, 1998; *Curry et al.*, 1999]. The BWT sections thus provide a meaningful estimation of the thermal structure of the deep western North Atlantic since the last glacial period.

[10] The BWT sections indicate a pattern of deep-sea temperature change that bears a strong resemblance to climatic changes of the past 25 ka. Extensive BWT cooling occurred during the last glacial maximum (LGM). Note that the LGM is condensed in the LBB core due to low glacial sedimentation rates, [*Marchitto et al.*, 1998] and that any cooling at this site may have been partially mitigated by ~120-m drop in glacial sea level. It should also be noted that the LGM is not represented in the deepest record (BR site), but because this site is located at a water depth 1000 m below the WMAR site, it likely also cooled to BWT at or below that of the WMAR site during the LGM. This is supported by recent Mg/Ca results from the Ceara Rise (Figure 8) in the western equatorial Atlantic which indicate average glacial cooling to temperatures ranging from -1° to 0.5°C below 3100-m water depth (G. S. Dwyer et al., manuscript in preparation, 2000).

[11] Following the LGM, BWT generally increased, with maximum BWT occurring during the early Holocene (the Hypsithermal warm period) in all three records. Figures 6 and 7 suggest that the most intense Holocene warming of the deep North Atlantic was localized in the core of NADW around 3000-m water depth. This seems to be supported by the Ceara Rise results as well (Figure 8). The early Holocene warming was followed by a reduction in BWT near the time of the onset of the late Holocene Neoglacial cool period. BWT increased at the shallow LBB site over the last ~3500 years.

[12] Together the three records provide evidence for large, basin-scale shifts in BWT

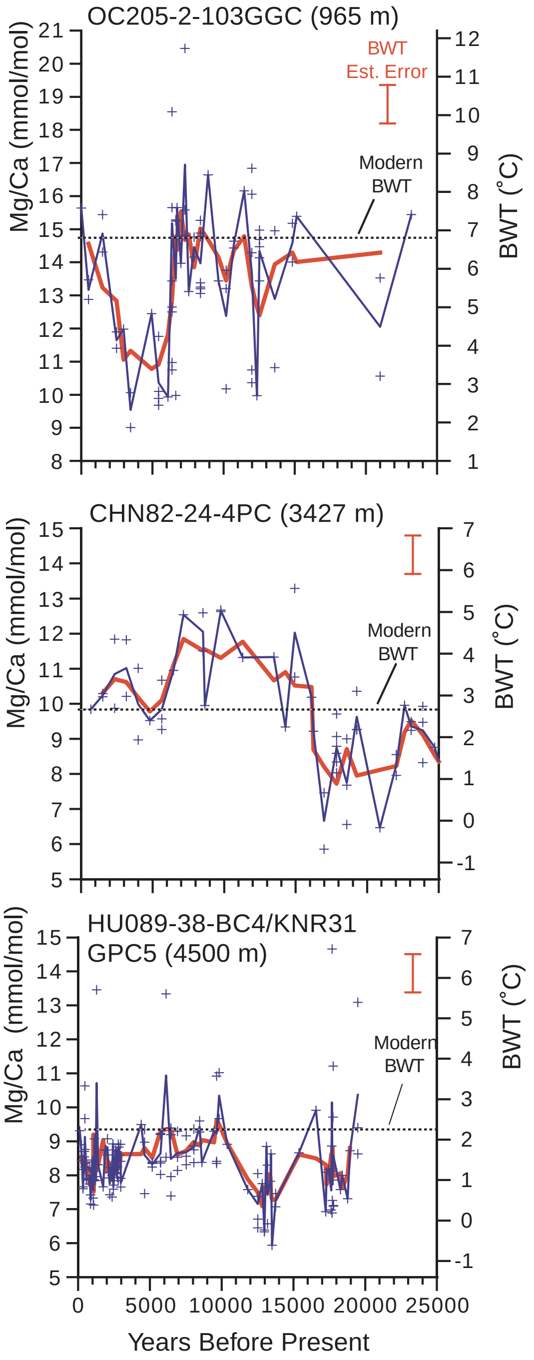

Figure 6. Three-point running means of the average Mg/Ca ratios for the three cores studied. Smoothing increases the number of shells considered in each mean reducing the average BWT estimation error to around ±0.5 for each three-point mean.

and, more generally, previously undocumented variability in BWT over the last 25 ka. Interpreting the physical oceanographic cause(s) of the inferred temperature changes is complex. Three plausible mechanisms [e.g., *Bryden et al.*, 1996] that can change BWT include the following: (1) vertical movement of isopycnal surfaces driven by changes in intensity or position of the North Atlantic subtropical gyre as a result of fluctuations in surface winds, (2) thickness variations of a particular density layer resulting from changes in the formation rate of deep or intermediate waters, and (3) changes in water mass characteristics (temperature and salinity) due to changes in buoyancy loss conditions (cooling and evaporation) at the ocean surface site of water mass formation. Intermediate water temperatures can be affected by all three factors, whereas deep-water temperatures are primarily affected by the latter two.

[13] If the BWT changes at the deeper sites are a function of changes in the formation rate of NADW (or the relative ratio of NADW versus AABW), the records imply that NADW production reached a maximum between ~12 and 6.5 ka during the late stages of deglaciation and the early Holocene. This would likely have resulted in higher air temperatures in middle to high latitudes of the North Atlantic region due to associated increased poleward surface ocean heat flux and high-latitude ocean-atmosphere heat exchange. Such a scenario is similar to the intensified North Atlantic thermohaline circulation associated with the warmer than present ocean climate mode obtained in oceanic modeling studies as a result of insolation-induced variability in the hydrologic cycle [*Weaver and Hughes*, 1994]. The results are also broadly consistent with a paleoceanographic-based conceptual climate model [*Imbrie et al.*, 1992] in which NADW production, in a "two-pump" mode (deep-water convection in both the Greenland-Iceland-Norwegian and Labrador Seas) reaches a maximum during

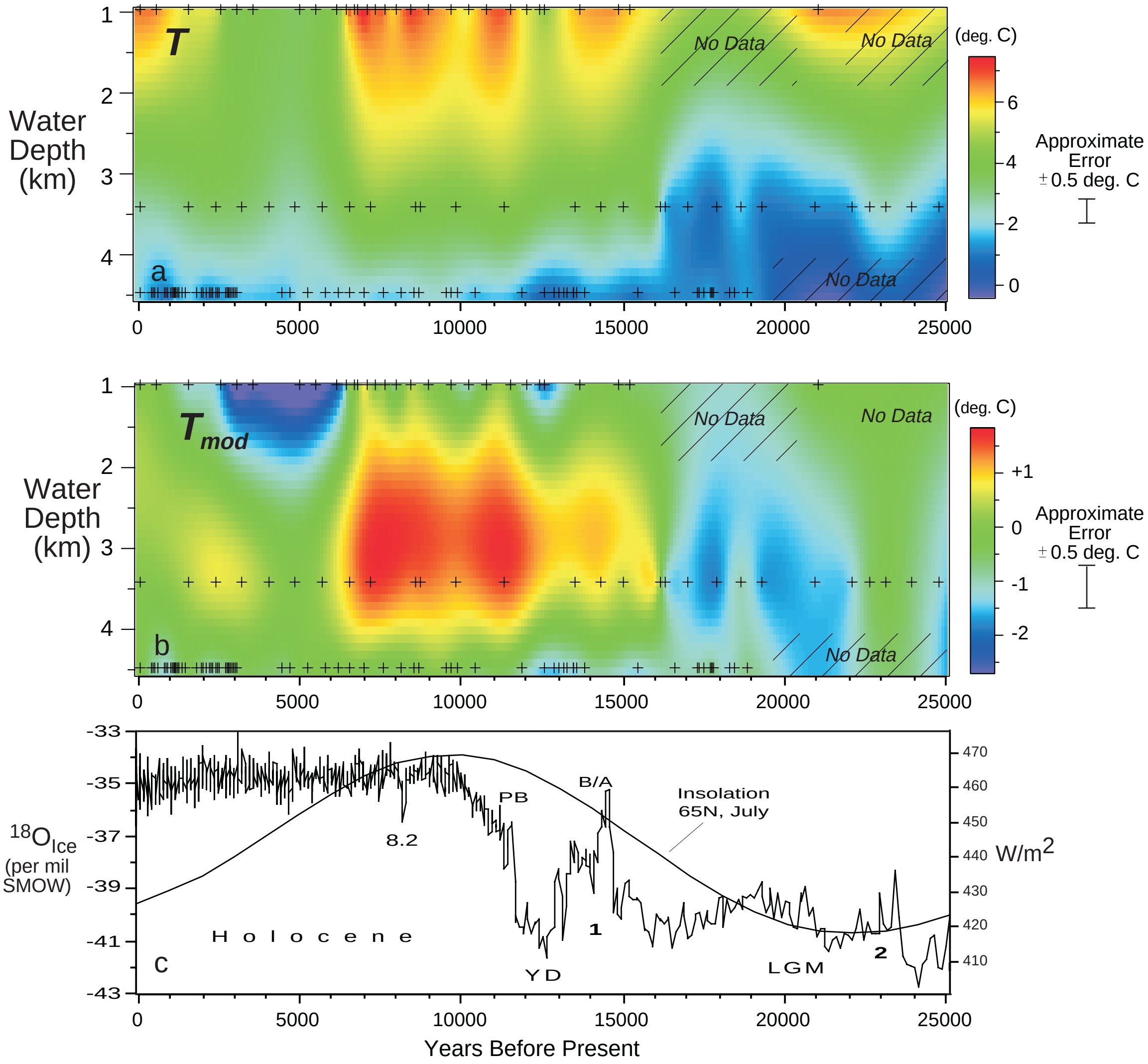

Figure 7. Water depth sections of (a) water temperature and (b) change in water temperature relative to present-day for deep and intermediate waters of the western subtropical North Atlantic for the last 25,000 years. The sections were constructed based on the smoothed versions of the three BWT records presented in Figure 6. The smoothed BWT records were input to the GMT gridding algorithm "surface" [*Smith and Wessel*, 1990] with specified grid-cell dimensions of 100 m in water depth and 100 years in time. ΔT, was derived by subtracting the paleo-BWT from the modern, instrumentally measured [*Bainbridge*, 1981; *Slowey and Curry*, 1995] bottom water temperature at each site. Crosses indicate the stratigraphic position of Mg/Ca analyses used for this reconstruction. The error localized around the data points is about ±0.5°C due to multiple shell averaging. Uncertainty in the T and ΔT reconstructions increases with increasing time gap between data points and is especially large for those the areas marked with diagonal hatching. Also shown (Figure 7c) are the history of insolation for July for 65°N [*Berger and Loutre*, 1991] and the oxygen isotopic composition of ice from central Greenland GISP2 ice core [*Grootes et al.*, 1993] for the period from 0 to 25,000 years B.P.

deglaciation and the early stages of an interglacial, spurred by increasing summer insolation at 65°N. The return to lower BWT values in the late Holocene may mark a shift of NADW production to a dominantly "one-pump" mode (Labrador Sea) when NADW

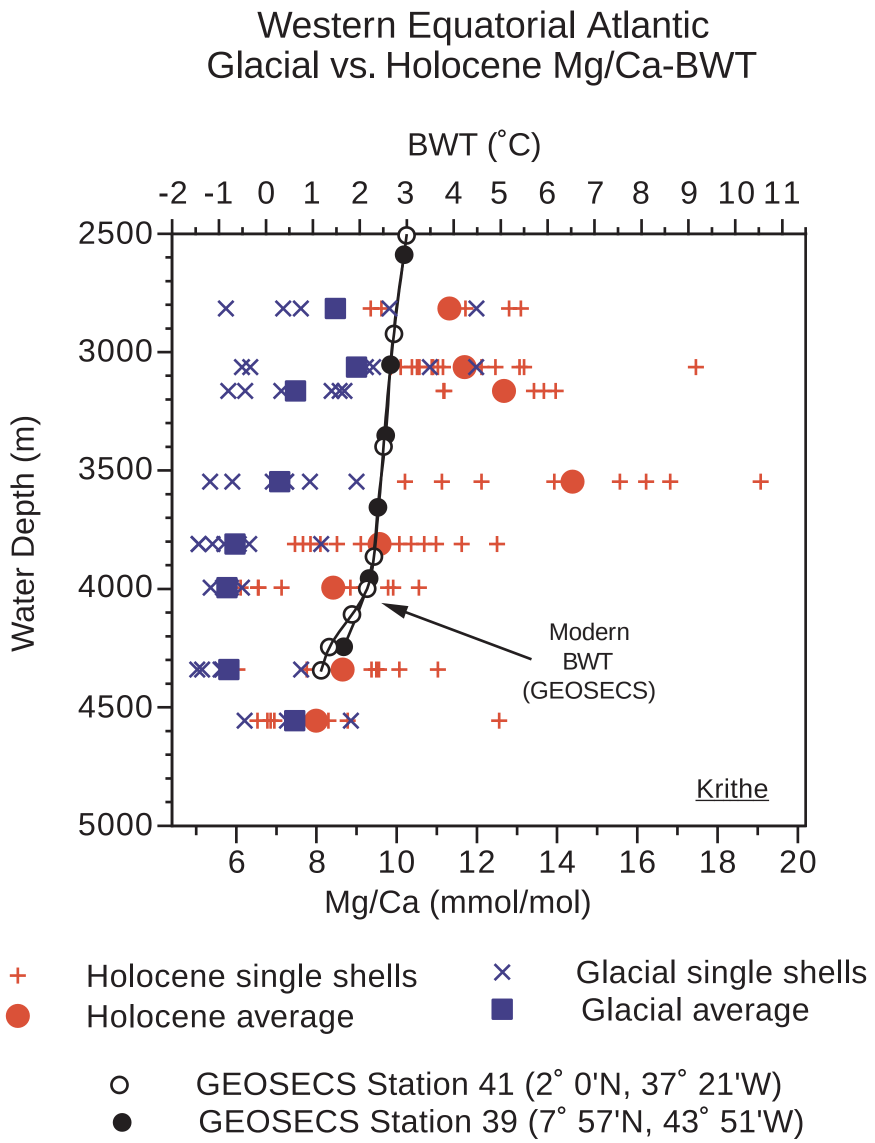

Figure 8. Ostracode Mg/Ca ratios and BWT estimates for western equatorial Atlantic (Ceara Rise) glacial and Holocene deep waters (G. S. Dwyer et al., manuscript in preparation, 2000). The samples are from KNR110 sediment cores 82GGC (2816 m), 75GGC (3063 m), 71GGC (3164 m), 66GGC (3547 m), 91GGC (3810 m), 50GGC (3995), 58GGC (4341 m), and 55GGC (4556 m) located from 4°–5°N, 43°–44°W collected and studied by *Curry and Lohmann* [1990]. GEOSECS station data are from *Bainbridge* [1981].

production and attendant heat fluxes decreased, AABW production increased, or both.

[14] This is a simple view, because the factors that alter the formation rates of deep water typically also affect the buoyancy loss conditions at the formation site [e.g., *Curry et al.*, 1998]. Sorting out the relative influences of these factors requires increased spatial and temporal coverage and direct coupling of

BWT estimates with other paleowater property records (i.e., salinity, nutrients). Nevertheless, the changes in heat flux implied by the BWT data are consistent with reconstructions of sea surface temperature and sea ice distribution in the Nordic seas [*Koç and Jansen*, 1994] and air temperature records derived from thermal diffusion analyses of central Greenland ice core bore holes [*Dahl-Jensen et al.*, 1998], both of which indicate maximum warming in the early Holocene followed by oscillatory cooling during the late Holocene. The Mg/Ca records from the deep sites also show good correspondence with benthic foraminiferal δ^{13}C (Figure 2) and Cd/Ca records, which have been used to track the past strength of NADW [*Boyle and Keigwin*, 1985; *Boyle and Keigwin*, 1987; *Keigwin et al.*, 1991]. Changes in these nutrient-based water mass proxies led to the hypothesis of maximum North Atlantic thermohaline overturning during the early Holocene [*Boyle and Keigwin*, 1987; *Keigwin et al.*, 1991]. The early Holocene deep-sea warming indicated here is consistent with this hypothesis. Early Holocene warming of coastal Antarctica [*Steig et al.*, 1998] may also be consistent with strengthened NADW as it upwells in the Southern Ocean.

[15] The apparently synchronous early Holocene warming of intermediate waters may have been associated with strengthening and northward expansion of the North Atlantic subtropical gyre [*Slowey and Curry*, 1995] at a time when the North Atlantic high-pressure system peaked as a result of maximum summer insolation and seasonality [*Cooperative Holocene Mapping Project (COHMAP) Members*, 1988]. Whatever the mechanism(s), it appears that the system underwent a rapid reorganization at ~6500 years ago signaled by abrupt decreases in intermediate and deep BWT. This dramatic Holocene deep-sea cooling is roughly coincident with the onset of the late Holocene "Neoglacial" cool period. It also corresponds with short-term (millennial) events such as Holocene ice-rafted debris (IRD) event 4 [*Bond et al.*, 1997] and a major shift of ice core glaciochemical species indicative of cooling [*O'Brien et al.*, 1995]. Although the source of this cooling remains unclear, joint consideration and reconciliation of the ostracode Mg/Ca and benthic foraminiferal δ^{18}O records indicates that these waters were not only cooler but also were significantly lower in salinity. This implies a significant shift in the relative proportions of various intermediate waters at this site.

[16] We speculate that shorter-term climate-linked changes in BWT may also be present in the Mg/Ca records such as BWT cooling around the time of relatively large magnitude IRD events Heinrich 1 (H1) and the Younger Dryas (YD) at ~17 and 12.5 years B. P., respectively. There is also a hint of BWT cooling during smaller Holocene IRD events 2, 3, and 5. If confirmed in future studies, this would support the hypothesis that the enigmatic climatic cooling associated with these Holocene events is linked to ocean circulation [*Alley et al.*, 1997; *Bond et al.*, 1997]. Warm climatic events, including the Pre-Boreal (PB), the Bolling/Allerod (BA), and interstadial warmings at ~19 and ~23 ka also appear to be manifested in some of the BWT records, suggesting that deep-sea temperature (and circulation) variability persists regardless of the overall climatic state: glacial, deglacial, interglacial.

5. Conclusions

[17] While further studies are necessary to confirm these correlations and to assess the relative phasing of climate and deep-sea temperature variations, the major result of the present study is to document that significant changes in North Atlantic deep-sea BWT have occurred since the LGM during glacial, deglacial, and interglacial climate regimes. The observed BWT changes

likely are the result of variations in deep and intermediate water production and circulation, thus providing new, independent evidence for climate-related changes in the deep North Atlantic.

[18] Last, combining benthic Mg/Ca ratios and $\delta^{18}O$ records offers the potential to not only reconstruct deep-sea bottom water temperature and continental ice-volume history, but also to reconstruct changes in deep-sea salinity, which in turn should further assist reconstructions of ocean circulation.

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References

Alley, R. B. et al., Holocene climatic instability: A prominent widespread event 8200 yr ago, *Geology*, *25*, 483–486, 1997.

Bainbridge, A. E., *GEOSECS Atlantic Expedition*, vol. 1, *Hydrographic Data*, Natl. Sci. Found., Washington, D. C., 1981.

Bard, E., Geochemical and geophysical implications of the radiocarbon calibration, *Geochim. Cosmochim. Acta*, *62*, 2025–2038, 1998.

Berger, A., and M. F. Loutre, Insolation values for the climate of the last 10 million years, *Quat. Sci. Rev.*, *10*, 297–317, 1991.

Bond, G., et al., A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates, *Science*, *278*, 1257–1266, 1997.

Boyle, E. A., Limits on benthic foraminiferal chemical analyses as precise measures of environmental properties, *J. Foraminiferal Res.*, *25*, 4–13, 1995.

Boyle, E. A., and L. D. Keigwin, Comparison of Atlantic and Pacific paleochemical records for the last 215,000 years: Changes in deep ocean circulation and chemical inventories, *Earth Planet. Sci. Lett.*, *76*, 135–150, 1985.

Boyle, E. A., and L. D. Keigwin, North Atlantic thermohaline circulation during the past 20,000 years linked to high-latitude surface temperature, *Nature*, *330*, 35–40, 1987.

Bryden, H. L., et al., Decadal changes in water mass characteristics at 24°N in the subtropical North Atlantic, *J. Clim.*, *9*, 3162–3186, 1996.

Cadot, H. M., and R. L. Kaesler, Magnesium content of calcite in carapaces of benthic marine ostracoda, *Univ. Kans. Paleontol. Contrib. 87*, pp. 1–23, Univ. of Kans., Lawrence, 1977.

Cooperative Holocene Mapping Project (COHMAP) Members, Climatic changes of the last 18,000 years: Observation and model simulations, *Science*, *241*, 1043–1052, 1988.

Corrège, T., and P. De Deckker, Faunal and geochemical evidence for changes in intermediate water temperature and salinity in the western Coral Sea (northeast Australia) during the late Quaternary, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *313*, 183–205, 1997.

Craig, H., and L. I. Gordon, Deuterium and oxygen-18 variations in the ocean and the marine atmosphere, in *Stable Isotopes in Oceanographic Studies and Paleotemperatures, Spoleto, July 26–27, 1965*, pp. 1–22, Lab. di Geol. Nucl., Cons. Naz.delle Ric., Pisa, Italy, 1965.

Cronin, T. M., D. M. DeMartino, G. S. Dwyer, and J. Rodriguez-Lazaro, Deep-sea species diversity: Response to late Quaternary climate change, *Mar. Micropaleontol.*, *37*, 231–249, 1999.

Curry, R. G., M. S. McCartney, and T. M. Joyce, Oceanic transport of subpolar climate signals to mid-depth subtropical waters, *Nature*, *391*, 575–577, 1998.

Curry, W. B., and G. P. Lohmann, Reconstructing past particle fluxes in the tropical Atlantic Ocean, *Paleoceanography*, *5*, 487–505, 1990.

Curry, W. B., T. M. Marchitto, J. F. McManus, D. W. Oppo, and K. L. Laarkamp, Millennial-scale changes in ventilation of the thermocline, intermediate and deep waters of the glacial North Atlantic, in *Mechanisms of Global Climate Change at Millennial Time Scales, Geophys. Monogr. Ser.*, vol. 112, edited by P. U. Clark, R. S. Webb, and L. D. Keigwin, pp. 59–76, AGU, Washington, D. C., 1999.

Dahl-Jensen, D., et al., Past temperatures directly from the Greenland ice sheet, *Science*, *282*, 268–271, 1998.

Dickson, R., J. Lazier, J. Meincke, P. Rhines, and J. Swift, Long-term coordinated changes in the convective activity of the North Atlantic, *Prog. Oceanogr.*, *38*, 241–295, 1996.

Dwyer, G. S., T. M. Cronin, P. A. Baker, and J. Rodriguez-Lazaro, Mg/Ca ratios in marine ostracodes (abstract), *Eos Trans. AGU*, *80*(17), Spring Meet. Suppl., S172, 1999.

Dwyer, G. S., T. M. Cronin, P. A. Baker, M. E. Raymo, J. S. Buzas, and T. Corrège, North Atlantic Deep Water temperature change during late Pliocene and Quaternary climatic cycles, *Science*, *270*, 1347–1351, 1995.

Grootes, P. M., M. Stuiver, J. W. C. White, S. Johnsen, and J. Jouzel, Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores, *Nature*, *366*, 552–554, 1993.

Imbrie, J., et al., On the structure and origin of major glaciation cycles, 1, Linear responses to Milankovitch forcing, *Paleoceanography*, *7*, 701–738, 1992.

Keigwin, L. D., The Little Ice Age and Medieval Warm Period in the Sargasso Sea, *Science*, *274*, 1504–1508, 1996.

Keigwin, L. D., and G. A. Jones, Western North Atlantic evidence for millennial-scale changes in ocean circulation and climate, *J. Geophys. Res.*, *99*, 12,397–12,410, 1994.

Keigwin, L. D., G. A. Jones, S. J. Lehman, and E. A. Boyle, Deglacial meltwater discharge, North Atlantic deep circulation, and abrupt climate change, *J. Geophys. Res.*, *96*, 16,811–16,826, 1991.

Knauss, J. A., *Introduction to Physical Oceanography*, Prentice-Hall, Englewood Cliffs, N. J., 1997.

Koç, N., and E. Jansen, Response of high-latitude Northern Hemisphere to orbital climate forcing: Evidence from the Nordic Seas, *Geology*, *22*, 523–526, 1994.

Labeyrie, L. D., et al., Variations in the mode of formation and temperature of oceanic deep waters over the past 125,000 years, *Nature*, *327*, 477–482, 1987.

Marchitto, T. M., W. B. Curry, and D. W. Oppo, Millennial-scale changes in North Atlantic circulation since the last glaciation, *Nature*, *393*, 557–561, 1998.

Mix, A., The marine oxygen isotope record: Constraints on timing and extent of ice-growth events (120–65 ka), *Spec. Pap. Geol. Soc. Am.*, *270*, 19–30, 1992.

Mix, A. C., and N. G. Pisias, Oxygen isotope analyses of deep-sea temperature changes: Implications for rates of oceanic mixing, *Nature*, *331*, 249–251, 1988.

O'Brien, S. R., et al., Complexity of Holocene climate as reconstructed from Greenland ice cores, *Science*, *270*, 1962–1964, 1995.

Pedlosky, J., The dynamics of the oceanic subtropical gyres, *Science*, *248*, 316–322, 1990.

Pickard, G. L., and W. J. Emery, *Descriptive Physical Oceanography*, Pergamon, Tarrytown, N. Y., 1982.

Rahmstorf, S., Rapid transitions in a coupled ocean-atmosphere model, *Nature*, *372*, 82–85, 1994.

Schmitz, W. J., and M. S. McCartney, On the North Atlantic circulation, *Rev. Geophys.*, *31*, 29–49, 1993.

Slowey, N. C., and W. B. Curry, Glacial-interglacial differences in circulation and carbon cycling within the upper western North Atlantic, *Paleoceanography*, *10*, 715–732, 1995.

Smith, W. H. F., and P. Wessel, Gridding with continuous curvature splines in tension, *Geophysics*, *55*, 293–305, 1990.

Steig, E. J., et al., Synchronous climate changes in Antarctica and the North Atlantic, *Science*, *282*, 92–95, 1998.

Stuiver, M., and P. J. Reimer, Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program, *Radiocarbon*, *35*, 215–230, 1993.

Weaver, A. J., and T. M. C. Hughes, Rapid interglacial climate fluctuations driven by North Atlantic Ocean circulation, *Nature*, *367*, 447–450, 1994.