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Centennial-scale Holocene North Atlantic surface temperatures from Mg/Ca ratios in *Globigerina bulloides*

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[1] A high-resolution record of Mg/Ca ratios from the planktonic foraminifer *Globigerina bulloides* has been produced for IMAGES core MD99–2251 from the subpolar North Atlantic. The record extends from the Younger Dryas-Preboreal transition through the Holocene at ~70 year resolution, with a more detailed section at ~20 year resolution through the interval encompassing the major cooling episode 8200 years ago. Mg/Ca derived temperatures show significant variations through the Holocene, with surface temperatures ranging from ~8 to 13°C. The onset of the Holocene is marked by an abrupt warming, with a further increase in early Holocene temperatures occurring prior to 9.5 ka. This is followed by a mid-Holocene period of cooler and more stable conditions before temperatures show a stepped increase at ~3.5 ka. The late Holocene period has the highest temperatures of the entire interglacial but also exhibits coolings of 2–3°C approximately every 500 years. Variations of this magnitude typify the high-frequency component of temperature variability and do not seem to be restricted to the 8.2 ka event or the early Holocene, when stronger freshwater forcing associated with the decay of the ice sheets might be anticipated. However, episodes of enhanced drift ice input to North Atlantic are coincident with many of the Mg/Ca temperature minima over the last 6 ka. The long-term warming trend and stepped increase in temperature at ~3.5 ka are consistent with other planktonic foraminiferal records and appear to reflect regional-scale changes in the atmospheric forcing of the North Atlantic Current during periods of rapid climate change. Alternatively, changes in ecology may contribute to the Holocene Mg/Ca record, either by species changing their depth habitat or by a shift in seasonal production patterns.

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1. Introduction

[2] Recent studies on the climate variability of the present interglacial have highlighted the presence of clear fluctuations, albeit on a lesser scale than those seen during the last glacial [*Stuiver et al.*, 1995; *Bond et al.*, 1997; *Bianchi and McCave*, 1999; *Chapman and Shackleton*, 2000; *Bond et al.*, 2001]. These fluctuations are sometimes considered to be related to freshwater forcings influencing the nature of the North Atlantic meridional

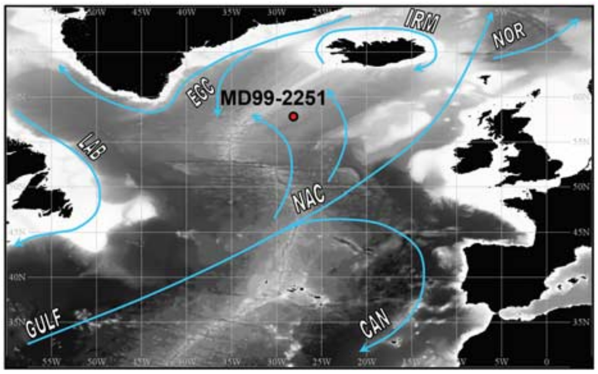

Figure 1. Map showing the location of core MD99–2251 with a simple schematic of surface ocean circulation in the area. GULF, Gulf Stream; NAC, North Atlantic Current; CAN, Canary Current; NOR, Norwegian Current; IRM, Irminger Current; EGL, East Greenland Current; LAB, Labrador Current.

overturning circulation (MOC). It has been suggested that the well documented and widely recorded 8.2 ka event is the result of such forcing, caused by the catastrophic final drainage of the proglacial lakes Agassiz and Ojibway during the collapse of the Laurentide Ice Sheet [*Alley et al.*, 1997; *Barber et al.*, 1999; *Rohling and Palike*, 2005; *Ellison et al.*, 2006; *Kleiven et al.*, 2008]. The resulting pulse of freshwater into the North Atlantic has been recorded across the circum-Atlantic region from a wide range of proxies [*Rohling and Palike*, 2005]. The 8.2 ka event is one feature of what is argued to be a pervasive 1.5 ka cyclicity dominating Holocene climate [*Bond et al.*, 1997; *Bianchi and McCave*, 1999] although the mechanisms and forcings behind this signal are still poorly understood [*Bond et al.*, 2001; *Marchal*, 2005].

[3] Here we present data from IMAGES piston core MD99–2251 derived from Mg/Ca ratios from the surface dwelling planktonic foraminifer *Globigerina bulloides*. The Mg/Ca content of the open ocean is considered to be constant over glacial-interglacial timescales [*Barker et al.*, 2005] and as such, foraminiferal Mg/Ca can be considered as an independent proxy for temperature. Mg/Ca ratios measured using both planktonic and benthic foraminiferal species are now routinely used as a proxy for oceanic temperature, and over recent years, a range of techniques and methodologies have been refined [*Lea and Martin*, 1996; *Nurnberg et al.*, 1996; *Rosenthal et al.*, 1999; *de Villiers et al.*, 2002; *Eggins et al.*, 2003; *Eggins et al.*, 2004]. The Mg/Ca technique is based on the changes in the geochemistry of the foraminiferal test during its formation. As the foraminiferal calcite forms, Mg^{2+} (among other divalent cations) may be substituted into the shell matrix in place of Ca. The substitution is related to the temperature of the surrounding waters, with Mg/Ca ratios increasing exponentially with increasing temperature [*Rosenthal et al.*, 1997; *Lea et al.*, 1999; *Barker et al.*, 2005]. This method of paleotemperature estimation has the advantage that Mg/Ca can be analyzed using the same sample material as δ^{18}O and hence potentially can allow the separation of the foraminiferal δ^{18}O signal into its salinity/seawater δ^{18}O and temperature components [*Elderfield and Ganssen*, 2000; *Dekens et al.*, 2002; *McConnell and Thunell*, 2005; *Came et al.*, 2007] although there has been some recent discussion of palaeosalinity records derived in this way [*Rohling*, 2007].

2. Material and Methods

2.1. Core Location and Chronostratigraphy

[4] Climate change is intrinsically linked to the oceans due to their ability to store and redistribute heat across the globe. The North Atlantic region has been shown to be of critical importance to this system as it is here that the warm southern derived surface waters release their heat back to the atmosphere and convection drives the formation of the deep water components of the MOC [*Dickson and Brown*, 1994; *Broecker*, 1997; *Clark et al.*, 2002; *Rahmstorf*, 2002]. This study of the subpolar North Atlantic is based on analyses of samples from the deep sea sediment core MD99–2251 (57° 26′N, 27° 54′W; 2620 m water depth) recovered from the Gardar Drift during the IMAGES V coring program. The oceanography of the area is dominated by the convection of the warm saline waters of the North Atlantic Current (NAC) at the surface (Figure 1) and the deep water return flow of Iceland Scotland Overflow Water (ISOW) as part of North Atlantic Deep Water (NADW). ISOW is formed as the cold, dense water masses of the Nordic Seas flow at relatively shallow levels over the sills and through channels intersecting the Greenland-Iceland-Scotland Ridge until they finally reach the Iceland Basin and the eastern North Atlantic [*Mauritzen*, 1996; *van Aken and Becker*, 1996; *Saunders*, 2001]. ISOW descends to depth from the overflow sills, successively meeting and mixing with the southern sourced water masses [*van Aken and de Boer*, 1995]: Subpolar Mode Water, the result of the progressive freshening and cooling of water from the NAC [*van Aken and

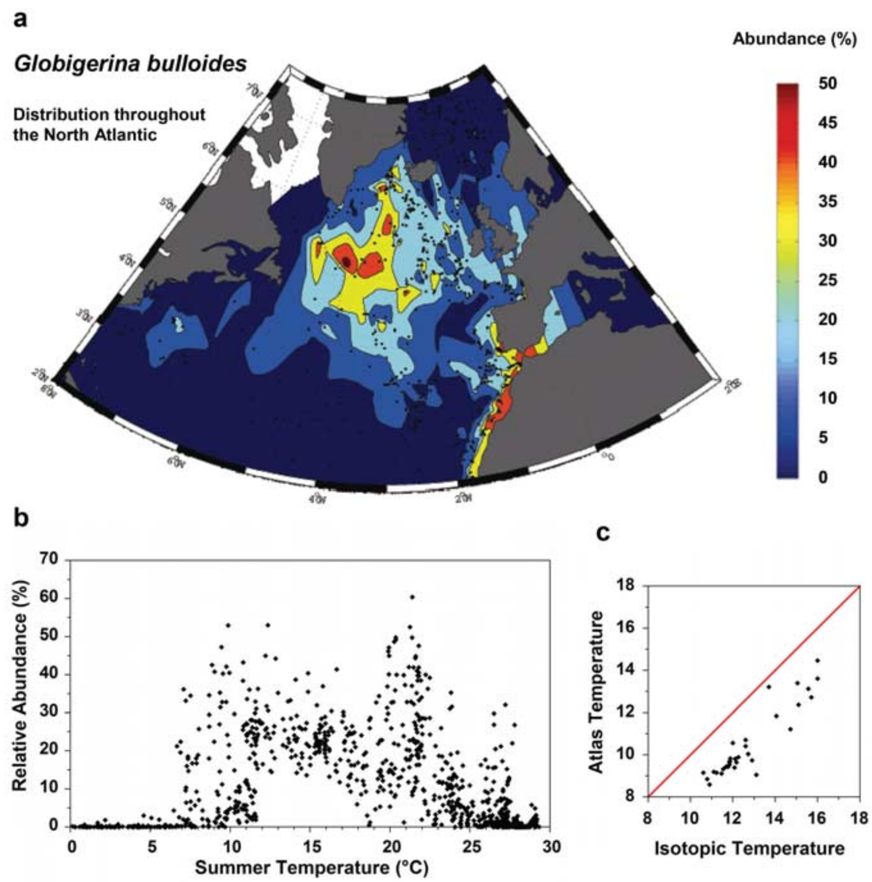

Figure 2. Ecology and distribution of *G. bulloides*. (a) Map showing the distribution and relative abundance of *G. bulloides* throughout the North Atlantic. (b) Relationship between *G. bulloides* abundance and summer surface temperature [*Levitus and Boyer*, 1994]. (c) Relationship between atlas derived summer SST and $\delta^{18}O$ (*G. bulloides*) derived temperatures.

Becker, 1996]; Labrador Sea Water, a final product of the modification of SPMW as it flows through the cyclonic North Atlantic [*Talley and McCartney*, 1982]; and Lower Deep Water, with its high Antarctic Bottom Water component [*Schmitz and McCartney*, 1993; *van Aken and de Boer*, 1995].

[5] The interaction of seabed topography and deep water flow patterns over parts of the Gardar Drift cause sediment focusing [*McCave*, 1994; *Bianchi and McCave*, 2000] and result in exceptionally high sediment accumulation rates. In core MD99–2251 the mean Holocene sediment accumulation rate is of the order of 110 cm ka^{-1} [*Ellison et al.*, 2006]. The core stratigraphy is based on 23 accelerator mass spectrometry (AMS) ^{14}C dates as described by *Ellison et al.* [2006]. All ages are reported in calibrated calendar years before present. Samples were selected to generate a Mg/Ca record with a sampling interval of ~70 years, increasing to ~20 years between 9 ka and 7.5 ka.

2.2. Ecology and Distribution of *Globigerina bulloides*

[6] *G. bulloides* is a wide-ranging species (Figure 2a) that predominantly inhabits the temperate to subpolar regions [*Bé and Tolderlund*, 1971; *Thiede*, 1975] and, to a lesser extent, polar waters [*Kemle-von Mücke and Hemleben*, 1999] and consequently has been commonly used in subpolar regions for temperature reconstructions [*Duplessy et al.*, 1991; *Ganssen and Kroon*, 2000]. However, the species is also associated with zones of upwelling, such as along the NW African margin [*Thiede*, 1975; *Rao et al.*, 1988; *Hemleben et al.*, 1989; *Rao et al.*, 1989; *Schiebel et al.*, 1997; *Chen et al.*, 1998; *Kemle-von Mücke and Hemleben*, 1999], suggesting that nutrient supply, as well as temperature, may be a key factor in controlling the distribution of this species. Analysis of modern core top data from the North Atlantic suggests there is a clear temperature limitation on the distribution of

Table 1. Analytical Reproducibility of Downcore Sample Measurements

Sample Depth (cm)	Number of Replicates	Mg/Ca (mmol/mol) Mean	Mg/Ca (mmol/mol) Standard Deviation	Temperature (°C) Mean	Temperature (°C) Standard Deviation
212	4	2.23	0.02	11.32	0.08
700	3	1.73	0.15	8.47	0.90
750	3	1.89	0.09	9.62	0.49
798	4	2.00	0.16	10.21	0.81
800	4	1.85	0.07	9.44	0.36
814	3	1.96	0.16	9.99	0.80
1606	3	1.83	0.03	9.34	0.15
1614	3	1.64	0.12	8.24	0.72
1644	6	1.87	0.07	9.55	0.36
Mean			0.10		0.52

G. bulloides, with abundances declining rapidly below ~8°C (Figure 2b).

[7] Previous studies of *G. bulloides* also document a well established relationship between $\delta^{18}O$ derived temperature estimates and measured summer sea surface temperature (SST), with the former generally plotting 1–2°C cooler then the latter (Figure 2c). This is consistent with the interpretation that *G. bulloides* largely reflects surface conditions during the late spring to summer, although production may vary as a function of latitude [*Duplessy et al.*, 1992; *Chapman et al.*, 2000; *Elderfield and Ganssen*, 2000]. It is equally important to consider the vertical distribution of *G. bulloides* as well as the biogeographic and seasonal occurrence. Surface dwelling foraminifera may be found throughout the water column above 400 m [*Hemleben et al.*, 1989], but *G. bulloides* is thought to be mainly present in and above the thermocline. In the eastern North Atlantic, *Schiebel et al.* [1997] limited this to the upper 60 m, which is consistent with pump and plankton tow data collected from our study area in July–August 1994 (M. R. Chapman, unpublished data, 1994). *Mekik et al.* [2007] showed that the best relationship between Mg/Ca and temperature is at 30 m water depth, further confirming the near-surface preference of this species.

2.3. Methods

[8] Mg/Ca ratios for the planktonic foraminifera *G. bulloides* were measured using the ICP-AES intensity calibration method of *de Villiers et al.* [2002] and the cleaning routine of *Barker et al.* [2003]. Specimens were picked from the 300–355 μm size range, with an average of 35 specimens per sample. Samples were run on the Vista ICP-AES system at UEA. Analytical reproducibility has been evaluated based on the statistics for the internal consistency standard used several times during each run (based on measurements on the UEA ICP-AES system over a 20 month period) and with replicate samples. The mean standard deviation of the Mg/Ca ratios (mmol/mol) for the internal standard is 0.027, with a mean relative standard deviation (RSD) of 0.49. When calculated with respect to temperature (°C) the mean standard deviation is 0.049, with a mean RSD of 0.25. Analyses of replicate samples also provide valuable information on reproducibility and the nature of intrasample variability. Replicate analyses of between three and six different subsamples were run for nine different depths within the core (Table 1). The mean standard deviation of the Mg/Ca measurements on these replicate samples is 0.10 mmol/mol, which in terms of the temperature calibration employed in this study equates to 0.5°C. Errors relating to the analytical procedure fall well within that of the generally accepted temperature calibration uncertainty of ±1°C [*Lea et al.*, 1999; *McConnell and Thunell*, 2005; *von Langen et al.*, 2005]. Where multiple measurements have been made for a given sample, it is the mean values that are used (a full data listing is provided in Table 2). A 200 year Gaussian smoothing also has been applied to emphasize the trends in Mg/Ca temperatures (Figures 5 and 8).

[9] A range of possible temperature calibrations have been proposed, since vital effects appear to alter the Mg/Ca temperature relationship between species [*Ganssen and Kroon*, 2000; *Dekens et al.*, 2002; *Anand et al.*, 2003; *McConnell and Thunell*, 2005]. Although differences are often minor, it is important to select the most appropriate temperature calibration, depending on both species and location. The North Atlantic based calibration of *Barker and Elderfield* [2002] derived for Mg/Ca ratios of *G. bulloides* encompasses Holocene to full glacial conditions and hence covers the range of

Table 2 (Sample). Downcore Mg/Ca Data From Core MD99–2251 [The full Table 1 is available in the HTML version of this article at http://www.g-cubed.org]

Depth (cm)	Age (ka)	Mg/Ca (mmol/mol)	Mg/Ca Temperature[a] (°C)
4	0.56	2.39	12.02
78	0.63	2.62	12.94
92	0.70	2.22	11.25
92	0.70	2.13	10.87
106	0.77	2.52	12.52
120	0.84	1.78	9.07
134	0.91	2.69	13.18
134	0.91	2.65	13.02
152	0.98	2.53	12.58
174	1.05	2.47	12.33
194	1.12	2.18	11.08
194	1.12	2.27	11.49
208	1.16	2.25	11.40
208	1.16	2.48	12.38
212	1.17	2.23	11.33
212	1.17	2.21	11.21
212	1.17	2.25	11.38
212	1.17	2.25	11.37
216	1.19	2.53	12.57
236	1.26	2.35	11.81
256	1.33	2.04	10.44
274	1.39	2.25	11.38
294	1.47	1.91	9.77
294	1.47	2.00	10.23
314	1.54	2.43	12.16
334	1.61	2.58	12.76
352	1.68	2.34	11.77
362	1.74	2.40	12.05
372	1.82	2.25	11.39
380	1.88	2.21	11.20
390	1.96	2.00	10.23
390	1.96	2.35	11.84
398	2.02	2.24	11.34
398	2.02	2.19	11.14
434	2.17	2.50	12.43
464	2.24	2.62	12.91
488	2.31	2.40	12.02
500	2.38	2.21	11.20
510	2.44	2.12	10.80
510	2.44	1.84	9.40
522	2.52	2.15	10.92
534	2.59	2.32	11.72
544	2.65	2.42	12.10
556	2.73	2.42	12.12
566	2.80	2.36	11.88
574	2.86	2.45	12.25
582	2.93	2.22	11.26
592	3.01	2.41	12.07
600	3.08	2.50	12.45
608	3.14	2.68	13.14
608	3.14	2.49	12.41
618	3.23	2.36	11.87
626	3.29	2.28	11.54
634	3.36	2.29	11.56
642	3.42	2.16	10.97
652	3.50	2.18	11.07
662	3.57	2.14	10.89

[a] Temperatures derived from the *Barker and Elderfield* [2002] Mg/Ca calibration.

temperatures expected to be encountered in this study. Their calibration, Mg/Ca = 0.72 * exp(0.1T), is used in this study and produces temperature estimates that fit within the window of seasonal SSTs derived from faunal assemblage data for the same core [*Ellison et al.*, 2006]. This calibration yields colder temperatures than suggested by a laboratory culture-based calibration for *G. bulloides* [*Lea et al.*, 1999], but the minimum calibration temperatures in the latter study are significantly warmer than the SST conditions likely to be experienced in the subpolar North Atlantic.

[10] One of the potential limitations of Mg/Ca work is the selective dissolution of the foraminiferal test. Where this occurs, Mg-rich calcite is preferentially dissolved, in effect lowering the observed Mg/Ca ratio and thus the estimated temperature. However, surface dwelling species, and *G. bulloides* in particular, have been shown to be far less susceptible to these effects, exhibiting no significant dissolution and leading *Mekik et al.* [2007] to conclude that the Mg/Ca ratios of such species have the potential to provide a pure temperature signal. This evidence gives us further confidence in the reliability of this species for recording changes in temperature at the sea surface.

3. Results

[11] Mg/Ca ratios reveal marked fluctuations throughout the Holocene, with values ranging from 1.6 to 2.6 mmol/mol. The transition into the Holocene is clearly defined by the rapid decline in the abundance of the polar species *Neogloboquadrina pachyderma* sinistral (s.) coiling and the stepped increase in the Mg/Ca ratio from a typical Younger Dryas value of 1.6 mmol/mol to values of 2.1 mmol/mol at the beginning of the Preboreal (Figure 3). Just above this transition at ~15.5 m the *N. pachyderma* (s.) record reaches its minima and plateaus at <2%, where it remains for the rest of the record with the exception of the only significant polar re-advance that is believed to be coincident with the well documented 8.2 ka cooling event [*Ellison et al.*, 2006]. By contrast the Mg/Ca ratios show clear patterns of short-term variability and evidence of a more complex longer-term trend that culminates in the highest Mg/Ca ratios toward the top of the core. The early and middle Holocene intervals are characterized by low to intermediate Mg/Ca ratios and somewhat muted high-frequency variability compared to the late Holocene samples (the top 6 m of the core) which typically have higher Mg/Ca ratios and also are punctuated by

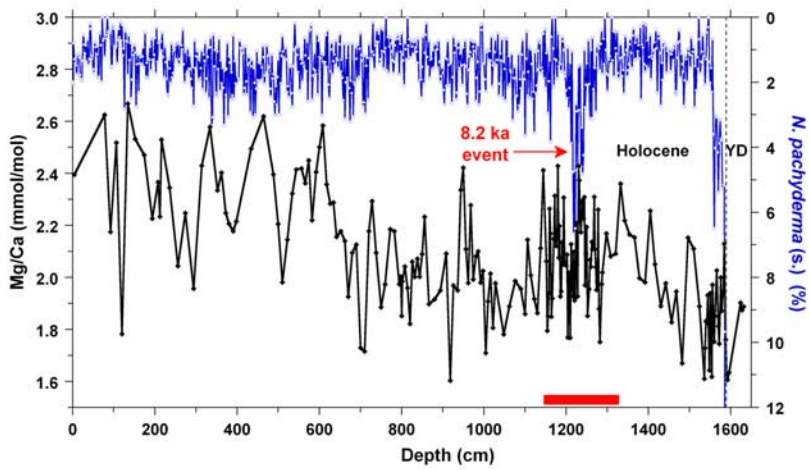

Figure 3. Down core changes in Mg/Ca ratios and the relative abundance of the polar species *N. pachyderma* (s.) in core MD99−2251 plotted against depth. The interval of closer sampling, associated with the detailed study of the 8.2 ka event (arrowed), is indicated by the red bar.

distinct minima. The overall trend in Mg/Ca ratios documented in core MD99−2251 is similar to the Holocene record measured using *G. bulloides* in adjacent core NEAP8K [*Barker and Elderfield*, 2002], even though the NEAP8K data are at a much lower resolution (Figure 4).

4. Discussion

4.1. Younger Dryas-Holocene Transition

[12] Although the Mg/Ca derived temperatures reveal significant variability through the Holocene (Figure 5a), it is notable that the temperatures of 8°C at the base of section during the Younger Dryas do not differ markedly from temperature minima within the Holocene. The deglacial attribution of these sediments is confirmed by the presence of the Vedde Ash, as well as other ice-rafted debris, in the samples. The transition out of the Younger Dryas stadial into the Holocene is marked by a major decrease in the polar *N. pachyderma* (s.) and a synchronous ~3°C increase in Mg/Ca temperatures. There can be little doubt that the oceanographic conditions prevailing at the site of MD99−2251 during the Younger Dryas were quite different from the modern pattern of intraannual surface hydrographic changes summarized in Figure 5b. This is supported by faunal derived estimates of SST obtained from MD99−2251 samples that indicate temperatures of 8°C and 4°C for summer and winter season respectively, in line with other estimates of Younger Dryas temperatures elsewhere in the subpolar North Atlantic [*Kroon*

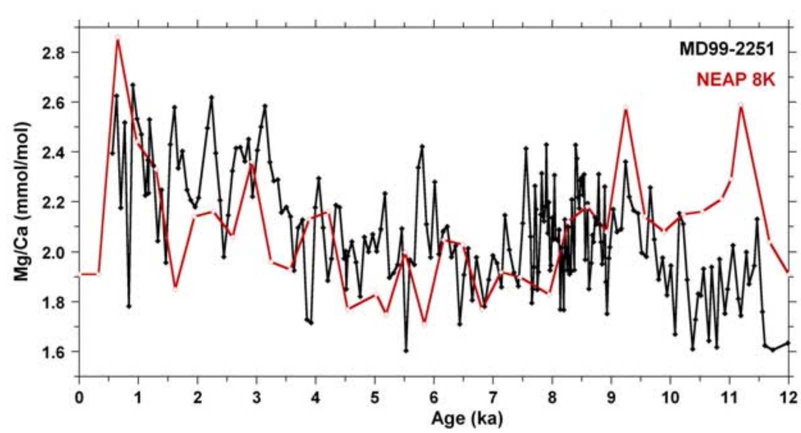

Figure 4. Comparison of Holocene changes in Mg/Ca content of *G. bulloides* in subpolar North Atlantic cores NEAP8K and MD99−2251. NEAP8K data are from *Barker and Elderfield* [2002]. The stratigraphies of the cores are tied at the Vedde Ash horizon and for NEAP8K assume a constant sediment accumulation rate through the Holocene.

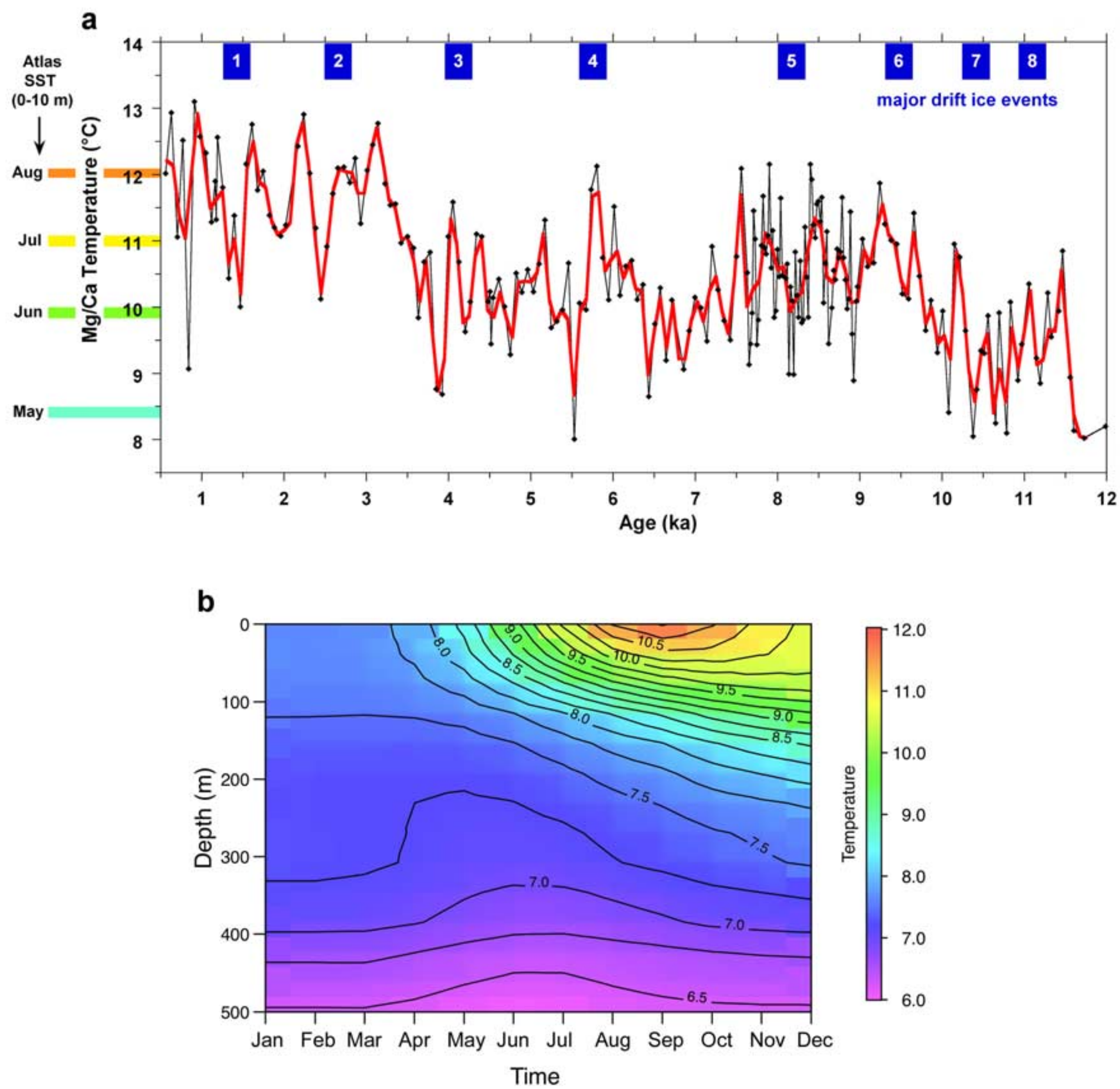

Figure 5. (a) Variations in Mg/Ca derived temperatures through the Holocene. The smoothed record (red) has had a 200 year Gaussian filter applied. Monthly atlas temperature data for the 0–10 m are indicated on the left. Numbered boxes identify periods of increased drift ice production [*Bond et al.*, 1997]. (b) Ocean temperature data from the site of core MD99–2251 showing the seasonal changes of surface and near-surface temperature and increasing stratification throughout the summer. Atlas data are from World Ocean Atlas [*Levitus and Boyer*, 1994].

et al., 1997]. It seems probable that the Mg/Ca temperature of 8°C principally reflects maximum summer conditions at this time and possibly, given the closeness to the temperature limit of this species (Figure 2b), may represent a discontinuous record of production during years/intervals of peak warmth within the Younger Dryas stadial. The apparent lack of difference between Younger Dryas and early Holocene temperatures could to some extent be a result of a switch in seasonal production patterns, from peak summer conditions in the Younger Dryas to late spring in the early Holocene, reducing the contrast across this major climatic transition.

4.2. Holocene Temperature Variability

[13] The initial Holocene peak in Mg/Ca temperatures at ~11.5 ka is followed by an overall decline in temperature over the following 1000 years (Figure 5a). The onset of the initial cooling at ~11.2 ka may be correlative with the Preboreal Oscillation and it is coincident with a brief reversal in the decline of *N. pachyderma* (s.). In the MD99–2251 temperature record there is further cooling with distinct minima reached at 10.7 ka and 10.3 ka, which is quite different from the record of the Preboreal Oscillation as a brief, century-scale cooling event interrupting a long-

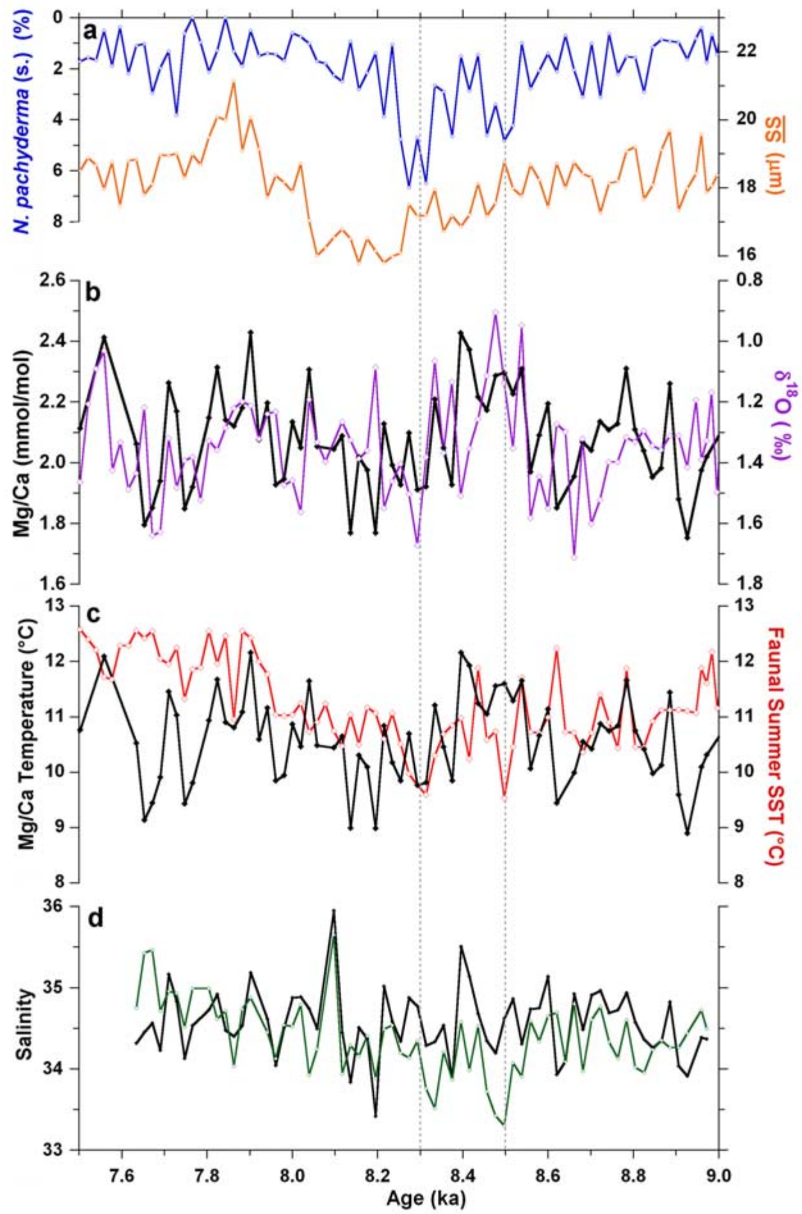

Figure 6. Detail of 8.2 ka event, comparing core MD99–2251 data of *Ellison et al.* [2006] with the Mg/Ca record. (a) Abundance of the polar species *N. pachyderma* (s.) and the mean size of the sortable silt, an indicator of deep flow speed. (b) *G. bulloides* $\delta^{18}O$ and Mg/Ca records. (c) Comparison of Mg/Ca derived temperatures with summer SST estimates calculated from the planktonic foraminiferal assemblage composition. (d) Comparison of paleosalinity records generated using Mg/Ca temperatures (black) and faunal SSTs (green). Mg/Ca based salinity estimates do not indicate any significant surface freshening events coincident with maxima in *N. pachyderma* (s.) abundances.

term warming trend in the Greenland ice cores [*Grootes et al.*, 1993; *Stuiver et al.*, 1995; *Alley et al.*, 1997]. A strong warming trend is evident in the MD99–2251 record over the following part of the early Holocene, with temperatures peaking at ~11.5°C by ~9.5 ka (Figure 5a). The subsequent period from 9.5 to 7.5 ka seems to be one of relatively high temperatures but also significant variability, including four pronounced warm-cold oscillations (discussed in more detail in section 4.3). These cold events appear equally prominent in the Mg/Ca temperature record, even though it is only the event at 8.2 ka that is accompanied by a clear increase in the abundance of *N. pachyderma* (s.) (Figure 6), and partly occur within a longer interval characterized by a wide-scale cooling of climate [*Rohling and Palike*, 2005; *Ellison et al.*, 2006].

[14] The middle Holocene is marked by a generally cooler phase from ~7.5 to 4 ka, with mean temper-

atures of ∼10°C, although this period includes a pronounced warming event at ∼6 ka, with temperatures briefly reaching ∼12°C. The cooling following this warm episode is rapid, with an extreme minima at 5.5 ka indicating temperatures of close to 8°C, a value that is only matched in the late Holocene by the cooling event at 3.9 ka. Although the temperatures attained during these two extreme cooling events are similar, the subsequent patterns of climate evolution differ markedly. Temperatures quickly return to ∼10.5°C after the 5.5 ka event and continue to exhibit small-scale variability until the onset of cooling associated with the 3.9 ka event. By contrast, the magnitude of the warming trend from 3.9 to 3.2 ka is greater than at any other time over the last 12,000 years, with a ∼4°C change resulting in temperatures of ∼12.5°C by 3.2 ka. This elevated maximum temperature is representative of the late Holocene period, which contains the highest temperatures of our Holocene record. The cooling episodes at 5.5 ka and 3.9 ka coincide with two well-documented intervals of widespread glacial expansion [*Denton and Karlen*, 1973], periods of enhanced drift ice input to the North Atlantic [*Bond et al.*, 1997] and, in the case of the 5.5 ka event, a significant strengthening of the polar atmospheric circulation and a decline in solar output [*O'Brien et al.*, 1995; *Mayewski et al.*, 2004].

[15] The relative SST warmth of the last 3.2 ka is punctuated with five distinct cooling episodes: a relatively minor event at 3.0 ka followed by more pronounced and distinct cold events centered at 2.5, 2.0, 1.5, and 0.8 ka. Although the intensity of these events varies, the pattern of change indicates a pacing of ∼500 years for climatic coolings in the late Holocene. In this respect, our finding is similar to results from previous examinations of periodic behavior in Holocene palaeoceanographic records that have identified a 500 year cyclicity [*Chapman and Shackleton*, 2000; *Risebrobakken et al.*, 2003]. The covariation of North Atlantic oceanic circulation patterns and residual $\Delta^{14}C$ data at the ∼500 year frequency has been interpreted as a response to a common forcing, with changes in solar activity seemingly the most plausible mechanism [*Chapman and Shackleton*, 2000]. Although multicentennial variability is persistent throughout the Holocene Mg/Ca temperature record, time series analysis of the entire data set does not reveal consistent peaks in variance at the 500 year period.

[16] The magnitude of high-frequency variability does not appear to be controlled by nor reflect the break up the remaining glacial ice sheets or meltwater release(s) during the final stages of deglaciation in the early Holocene. However, over the last 6000 years, all of the intervals of enhanced drift ice input to the North Atlantic [*Bond et al.*, 1997] are marked by major coolings in our Mg/Ca record (Figure 5), even though these events do not coregister as a significant expansion of *N. pachyderma* (s.) or as an influx of ice-rafted material at the site of core MD99−2251. The degree of correspondence between temperature and records of drift ice input is less convincing for the early Holocene, perhaps in part relating to the different resolution of the proxy records and the greater uncertainties associated with the respective age models. The ice rafting events at 11.3 ka and 10.3 ka could correspond to times of lower temperature but SSTs are generally low during this interval. Any evidence of the 9.3 ka event is masked by a substantial long-term warming trend, while the 8.2 ka event correlates to an unexceptional cooling episode in our record.

4.3. Changes to Surface Hydrography During the 8.2 ka Event

[17] The detailed structure of the Mg/Ca record for the interval surrounding the 8.2 ka event, alongside the published *N. pachyderma* (s.), faunal-derived SST and $\delta^{18}O$ records of *Ellison et al.* [2006] from the same core, are shown in Figure 6. While the overall structure of the temperature records through the period may be similar, there are substantial differences in event timings and magnitudes, with the Mg/Ca data suggesting that temperature variability of 2−3°C was commonplace. *Ellison et al.* [2006] observed that the 8.2 ka event was in fact two separate events, centered at 8.5 and 8.3 ka BP on their timescale, both associated with the cooling and freshening of surface waters and the reduced flow speed of the ISOW. The Mg/Ca temperature record identifies a number of additional cooling events preceding these which are not seen in the faunal SST reconstruction, at 8.9 and 8.6 ka. The 8.5 ka cooling event is absent in the Mg/Ca record. Unlike the faunal SSTs, Mg/Ca temperatures remain relatively high until after 8.4 ka before a rapid decrease of ∼2°C and the establishment of a prolonged interval of cooler temperatures that lasted until 7.9 ka. The initial fall in Mg/Ca temperatures slightly precedes the faunal SST minimum at 8.3 ka but does coincide with an increase in *N. pachyderma* (s.) abundance just prior to the abundance maximum. The 8.3 ka event, although present in the Mg/Ca record, is not particularly pronounced, with the cold extremes of ∼9°C that twice occur between 8.2 and 8.1 ka

post dating the maximum in *N. pachyderma* (s.). The Mg/Ca record then shows a warming interval, which is followed by two pronounced cooler episodes between 7.8 and 7.6 ka. These events, where temperatures fluctuated by >2°C, appear to have some counterpart in the $\delta^{18}O$ record but less so in the faunal SST data.

[18] The robustness of the temperature signal in the Mg/Ca data is supported by the remarkably strong similarity with the *G. bulloides* $\delta^{18}O$ record through this interval. Since the $\delta^{18}O$ of planktonic foraminifera is a function of both temperature and seawater $\delta^{18}O$, it implies that the temperature component of the $\delta^{18}O$ signal is dominant and that relatively little change has occurred in seawater $\delta^{18}O$ (itself a function of ice volume and salinity). We have calculated new estimates of surface ocean salinity for the interval 9 ka to 7.6 ka (Figure 6d), where Mg/Ca ratio, planktonic $\delta^{18}O$ and faunal SST data exist at 2 cm resolution, following the methods of *Chapman et al.* [2000] and *Elderfield and Ganssen* [2000]. The observed differences in salinity values can be attributed directly to differences in the Mg/Ca and faunal temperatures, although the accuracy of the salinity estimates is dependent on other factors such as ice volume corrections. Significantly, just prior to the 8.5 ka event, a 0.6‰ depletion in $\delta^{18}O$ was coincident with a warming of ~1.5°C in the Mg/Ca record (an increase of 0.3 mmol/mol). This means that the pronounced salinity minimum documented by *Ellison et al.* [2006] is not evident in our Mg/Ca based salinity record. The most obvious explanation for these differences is the taxon specific nature of the Mg/Ca data. *G. bulloides* is a near-surface dwelling foraminifer and mainly reflects its preferred niche conditions during its time of production. In contrast faunal SST data are derived from the entire planktonic foraminiferal assemblage providing information through the annual cycle and thus are influenced by the range of species present and their different depth habitats and, as such, are smoothed to some degree over a greater depth of the upper water column. Additional paired Mg/Ca and $\delta^{18}O$ analyses for species with different ecological preferences to *G. bulloides* are required to resolve this issue.

4.4. Holocene Ocean Temperature Trends

[19] There has been debate in recent years over the seemingly contradictory evidence on the long-term changes in Holocene ocean temperatures. Diatom- and alkenone-based records [*Marchal et al.*, 2002; *Moros et al.*, 2004] suggest a long-term cooling following an early Holocene climatic optimum, while an increasing number of foraminiferal based records, to which this new record can be added, indicate an absence of any early thermal optimum and a general long-term warming [*Marchal et al.*, 2002; *Risebrobakken et al.*, 2003; *Came et al.*, 2007]. It has been hypothesized in these studies that the different temperature histories are a result of the varying depth habitats of the proxy sources: foraminifera live in the subsurface, thermocline region that is controlled by winter ventilation, while diatoms and coccoliths live at the sea surface that is dominated by summer insolation. Because summer insolation has decreased over the last 10 ka and over the same interval winter insolation has increased, it is thought that foraminifera may record the subsurface winter insolation increase as a warming signal, whereas diatoms and alkenones reflect the summer insolation decrease at the surface. The difficulty in this argument is that it implies a very discrete partitioning between phytoplankton and zooplankton communities, something that is not borne out by observations of the modern ocean in the case of *G. bulloides*, as this species tends to thrive during or shortly after phytoplankton blooms [*Sautter and Sancetta*, 1992; *Chapman et al.*, 1996].

[20] If we assume that the Mg/Ca record is entirely temperature dependent (the critical requirement for Mg/Ca paleothermometry) then the long-term trend evident in the Mg/Ca derived temperatures must be accounted for by changes to the environment which impact the conditions experienced by the foraminifera. Atlas data indicate that surface temperatures at the core site today are at a maximum in August, with values of ~12°C recorded in the upper 10 m of the ocean [*Levitus and Boyer*, 1994]. Mg/Ca temperatures over the last 3.5 ka are typically in the range of 11–13°C, matching, within the methodological uncertainty (±1°C), both the observational data and core top faunal derived summer SST estimates at the site. Given this evidence, and the ecological preference of this species for near-surface summer-biased conditions, it seems highly improbable that *G. bulloides* could be recording winter changes in insolation.

[21] Mid-Holocene temperatures of ~10°C are typical of June conditions in the modern day and ~2°C cooler than mean SST values over the last 3.5 ka. Assuming our interpretation that at present *G. bulloides* blooms throughout the summer and mainly reflects August surface temperatures is

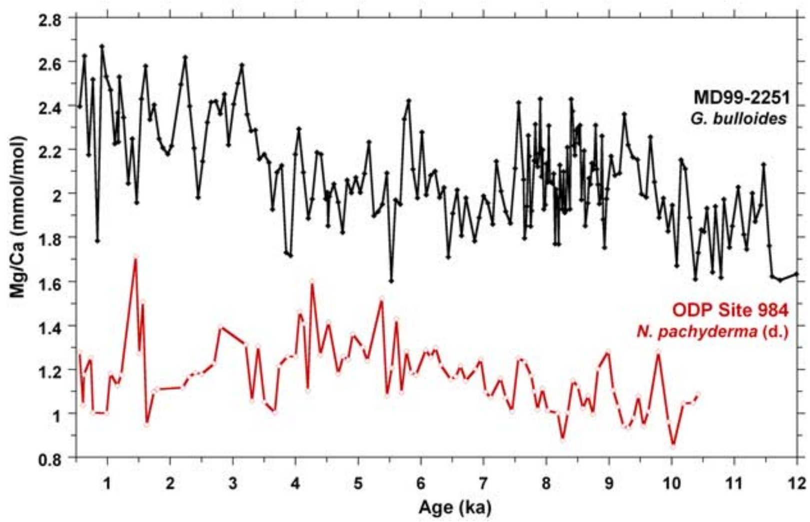

Figure 7. Mg/Ca ratio trends in the subpolar North Atlantic during the Holocene. *G. bulloides* data from core MD99–2251 (57°N, 28°W) are compared to the Ocean Drilling Program Site 984 (61°N, 25°W) *N. pachyderma* (d.) Mg/Ca record of *Came et al.* [2007].

valid, it follows that the conditions that prevailed before 3.5 ka were characterized by either significantly lower maximum summer temperatures, or that the principal periods of *G. bulloides* production were taking place at other times of the year. If the former scenario is correct, a regional scale explanation is required to account for the change in temperature through the Holocene and the step-like increase in SST around 3.5 ka. To some extent this interpretation is supported by the reasonably close correspondence between Mg/Ca temperatures and summer SST estimates between 9 ka and 7.5 ka (Figure 6c). If the alternative scenario is correct, then the observed trend in Mg/Ca temperatures may be a reflection of changing environmental conditions expanding or restricting the potential season of productivity of *G. bulloides*, and hence the Mg/Ca data are not a simple indicator of summer surface temperature change. This raises the question of why it would become more favorable for *G. bulloides* to thrive during peak summer conditions in the late Holocene. The abundance of *G. bulloides* is known to be closely tied to nutrient supply in zones of upwelling [*Sautter and Sancetta*, 1992], which also reflect changes in mixing or stratification of the upper water column, so one potential answer might be a change in the timing and/or the composition of the phytoplankton species that constitute the bloom event.

[22] To resolve these questions it is clearly important to gauge how representative the Holocene Mg/Ca temperature record from MD99–2251 is for the subpolar North Atlantic. One other consistent record exists measured on *G. bulloides* from the Gardar Drift [*Barker and Elderfield*, 2002], but, as stated previously, differences in resolution and dating control make a detailed comparison difficult. Another record is that of *Came et al.* [2007] who used *Neogloboquadrina pachyderma* (dextral) (*N. pachyderma* (d.)) to generate Mg/Ca and δ^{18}O records for the Holocene sediments from Ocean Drilling Program Site 984. This site on the Björn Drift is some 4° to the north of MD99–2251. *N. pachyderma* (d.) calcifies at greater depth than *G. bulloides* and, as expected, shows lower Mg/Ca ratios through the Holocene (Figure 7). A long-term warming trend between 10 ka and 4 ka is even more apparent in the ODP Site 984 record, with no early Holocene thermal optimum. Allowing for differences in data resolution and age models, a number of events through the early and middle Holocene may be common to both Mg/Ca records but establishing robust correlations is problematic. The *N. pachyderma* (d.) Mg/Ca data do not show such a marked temperature increase at 3.5 ka, although there is a significant increase in variability over the last 4 ka which includes the largest temperature oscillations of the Holocene [*Came et al.*, 2007].

[23] Significantly, the patterns of change in our Mg/Ca record over the last ~3.5 ka do appear to be common to a number of high resolution proxy records from the Norwegian Sea (Figure 8). *Risebrobakken et al.* [2003] and *Andersson et al.* [2003], both use a range of foraminiferal based proxies (but not Mg/Ca) on a core in the Nordic

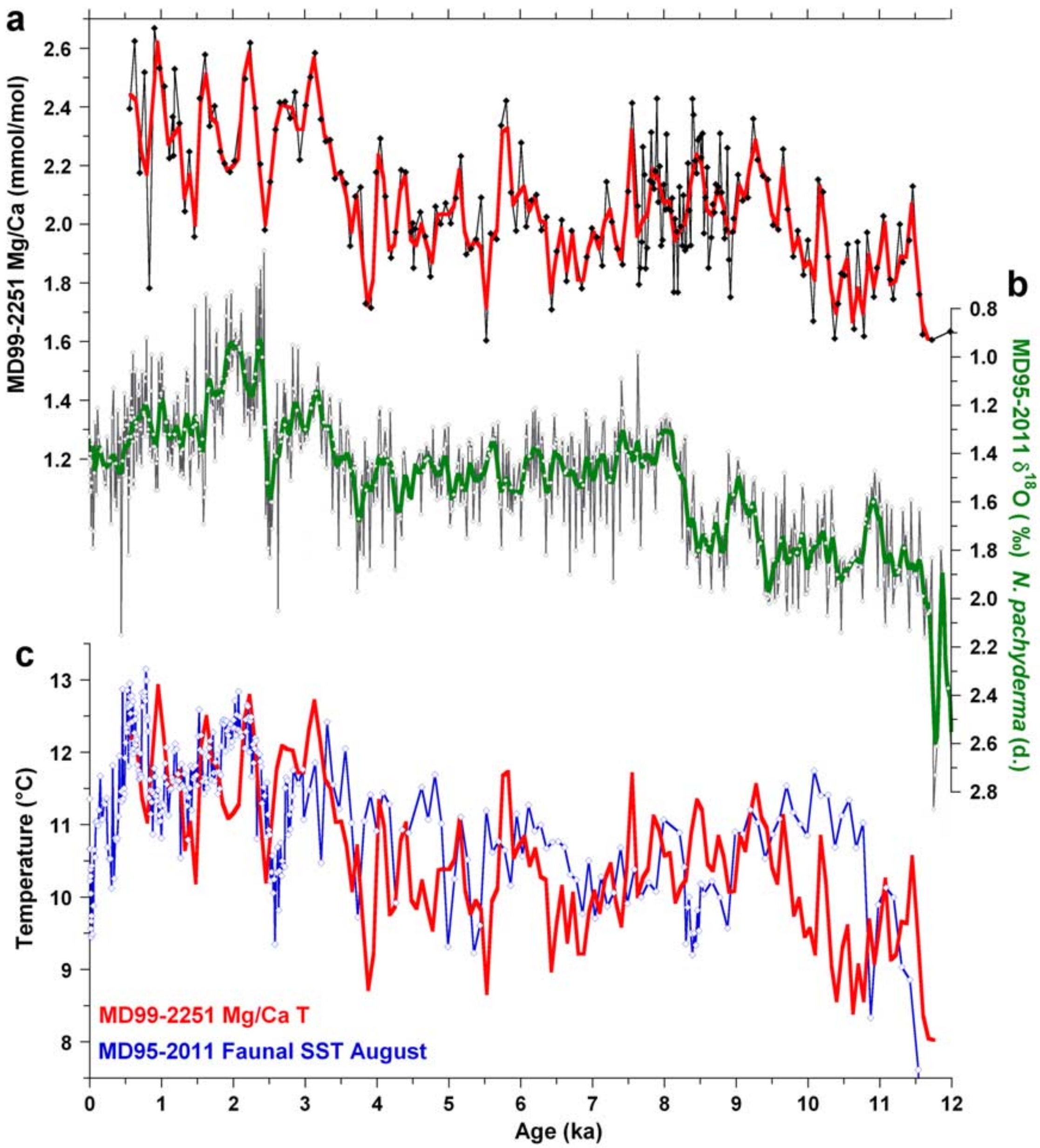

Figure 8. Comparison of North Atlantic Mg/Ca data from MD99–2251 with foraminiferal records from the Nordic Seas [*Andersson et al.*, 2003; *Risebrobakken et al.*, 2003]. (a) Variations in *G. bulloides* Mg/Ca ratio with a 200 year Gaussian smoothing (red). (b) *N. pachyderma* (d.) $\delta^{18}O$ record from core MD95–2011 with a 200 year Gaussian smoothing (green). (c) Summer SSTs (blue) derived from planktonic foraminiferal faunal assemblages in core MD95–2011 compared to the 200 year Gaussian smoothed record of MD99–2251 Mg/Ca temperatures (red). Modern summer surface temperatures for cores MD99–2251 and MD95–2011 are ~12°C and ~11.5°C, respectively.

Seas at 67°N, and *Moros et al.* [2004], use SSTs derived from alkenone data from a core from 59°N and another in the Nordic Seas at 68°N. All see a significant increase in temperatures at this time, often associated with increasing SST variability. Given the uncertainties in the independent age models, which differ by ~300 years for the 8.2 ka cooling event, the temperature records from MD95–2011 and MD99–2251 appear to show a consistent pattern for much of the last 9.5 ka. The surface $\delta^{18}O$ record from MD95–2011 measured on a different warm-indicator species, *N. pachyderma* (d.), likewise resembles the Mg/Ca record, especially over the last 4 ka.

The extent of the similarity between the records, despite the differences in the locations, proxies studied and species used, argues for a common climate linkage and provides clear evidence for a significant change in the climate of the North Atlantic region at this time.

[24] *Risebrobakken et al.* [2003] suggest that changes in solar irradiance could not explain the climatic changes seen in their Nordic Sea core, rather the records primarily reflect the relative importance of warm Atlantic versus cold Arctic waters. Atmospheric forcing (i.e., stronger westerlies) cause the migration of Arctic waters eastward so if this forcing is relaxed, the readjustment of Arctic waters would result in a greater penetration of warmer Atlantic water. They suggest that a weakening of the westerlies occurred around 4–3.5 ka, in good agreement with the major transition observed in the Mg/Ca record. It possible to tie this event in with a number of regional climatic changes, such as reduced monsoon activity in North Africa, changes in vegetation patterns in Scandinavia, and phases of neoglaciation in the arctic [*Risebrobakken et al.*, 2003, and references therein]. In spite of this climate event not being one of most prominent Holocene cooling episodes, the wide distribution of evidence of change at this time does suggest global-scale teleconnections [*Mayewski et al.*, 2004]. A change in atmospheric forcing, affecting subpolar water masses and altering the position and/or advection of heat in the NAC, may account for the marked shift in Mg/Ca values recorded in core MD99–2251. Likewise a similar process occurring relatively rapidly and over shorter timescales could account for some, if not all, of the high-frequency variability in the Mg/Ca temperature record.

5. Conclusions

[25] A high resolution *G. bulloides* Mg/Ca temperature record from the subpolar North Atlantic core MD99–2251 reveals significant variations through the Holocene. A comparison with existing data from MD99–2251 [*Ellison et al.*, 2006] and modern atlas values [*Levitus and Boyer*, 1994], indicates that Mg/Ca ratios from *G. bulloides* provide an oceanic temperature record that is very close to peak summer surface values. The most striking feature of the record is a long-term warming trend that culminates in distinctly warmer conditions over the last 3.5 ka. This late Holocene interval is also characterized by major climatic fluctuations and short-term coolings, typically of the order of 2–3°C, with an apparent periodicity of around 500 years.

[26] The record presented here clearly identifies periods of considerable climatic fluctuation that are, in part, corroborated by existing faunal assemblage SSTs and $\delta^{18}O$ from the same core. However, the 8.2 ka event, while present in the Mg/Ca record, is far less prominent than suggested than by faunal SST estimates and appears to be no different from a number of other temperature fluctuations that are identified in the Mg/Ca record between 9.5 ka and 7.5 ka and of lesser magnitude than later mid Holocene coolings at 5.5 ka and 4 ka.

[27] The long-term warming trend and the stepped increase in temperature at ~3.5 ka are consistent with other planktonic foraminiferal records from the Nordic Sea. These changes most likely signify atmospheric-driven changes in heat transfer by the North Atlantic Current but also could reflect changes in species ecology, either through a change in depth habitat or a shift in seasonal production patterns. Our findings highlight the importance of studying Mg/Ca in the context of other proxies, particularly same-species $\delta^{18}O$ records and faunal-derived SSTs. Indeed, such analysis, as suggested by *Skinner and Elderfield* [2005] may prove to be the great strength of the proxy.

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