Late Pliocene to early Pleistocene changes in the North Atlantic Current and suborbital-scale sea-surface temperature variability

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[1] The strength and latitudinal position of the North Atlantic Current, NAC, determines the position of the Arctic front and heat transport to the high northern latitudes with potentially important consequences for Northern Hemisphere glaciation. A southward shift in the NAC and reduced poleward heat transport is hypothesized to have triggered the last major climate transition in Earth's history—late Pliocene intensification of Northern Hemisphere glaciation (iNHG). In turn, iNHG is hypothesized to have led to the amplification of climate variability on suborbital time scales. To date, however, only a handful of adequately resolved records are available to test these two hypotheses. Here we present a new late Pliocene to earliest Pleistocene record from Integrated Ocean Drilling Program Site U1313 (North Atlantic, 41°N; 2.9 to 2.4 Ma). We use Mg/Ca-derived paleotemperature records in planktic foraminiferal calcite to investigate changes in summer sea-surface temperatures (SST) on orbital and suborbital time scales. Our results call into question the suggestion that significant weakening and/or southward shift of the NAC served as a trigger for Northern Hemisphere cooling and intensified continental ice sheet growth across iNHG. In contrast to the late Pleistocene, during iNHG, we find that the position of the NAC and Arctic Front probably lay well to the north of Site U1313 and that the amplitude of suborbital SST variability did not change on glacial-interglacial time scales. Conservative estimates of Late Pliocene to earliest Pleistocene interglacial summer SSTs in our record are up to 3°C warmer than present, while glacial summer SSTs are only 2°C to 3°C cooler. In fact, our interglacial summer SSTs are remarkably similar to those of the mid-Pliocene. Our findings indicate that iNHG must have involved amplifying feedback mechanisms that are tightly coupled to ice sheet growth but that these processes were insufficiently developed by the late Pliocene/earliest Pleistocene to have triggered large amplitude changes in suborbital climate in the midlatitude North Atlantic.

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1. Introduction

[2] The North Atlantic Current (NAC) constitutes part of the North Atlantic meridional overturning circulation. It represents the northeastern extension of the Gulf Stream and continues into the northeastern North Atlantic as the North Atlantic Drift [e.g., *Dietrich et al.*, 1980; *Krauss*, 1986]. The NAC serves as a transitional zone between the warm, oligotrophic surface waters of the Atlantic subtropical gyre and the cold, more productive polar water masses. The strength and latitudinal position of the NAC, therefore, determines the position of the Arctic front and productivity and sea-surface temperature (SST) across the midlatitude North Atlantic Ocean. Changes in the strength and position of the NAC also affect the amount of heat transport to the northern North Atlantic with important consequences for continental ice sheet growth and climate in the Northern Hemisphere [e.g., *Rossby*, 1996].

[3] The close relationship between primary productivity and SST on the one hand and the strength and position of the NAC on the other has been used in paleoceanographic studies to reconstruct the position of the NAC across the midlatitude North Atlantic Ocean [e.g., *Villanueva et al.*, 2001; *De Schepper et al.*, 2009; *Stein et al.*, 2009; *Naafs et al.*, 2010]. For glacials of the mid-Pleistocene to late Pleistocene,

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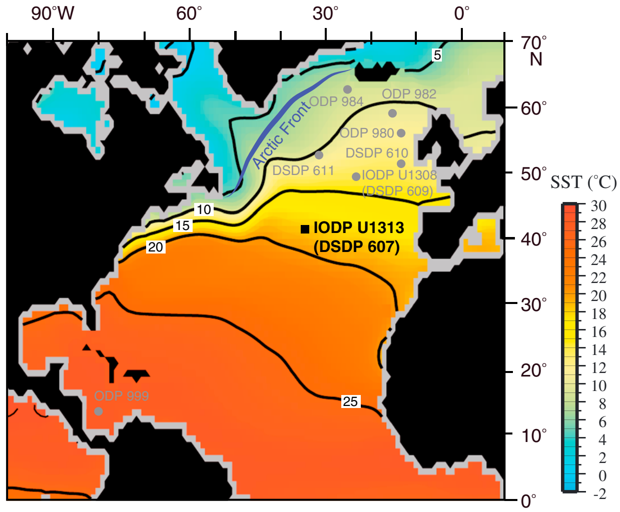

Figure 1. Location map of IODP Site U1313 (black square) and other sites discussed herein (gray dots). Modern summer sea-surface temperatures are shown after World Ocean Atlas [*Locarnini et al.*, 2006]. Position of Arctic Front shown in blue.

faunal and floral changes as well as alkenone-derived SST and alkenone abundance data have been interpreted as showing a southward movement of the high-productivity zone associated with the Arctic Front [e.g., *McIntyre et al.*, 1972; *Calvo et al.*, 2001; *Villanueva et al.*, 2001; *Stein et al.*, 2009]. Census count data of planktic foraminifera suggest a movement of the Arctic Front as far south as 40°N to 45°N during the Last Glacial Maximum [*Pflaumann et al.*, 2003]. These studies have been interpreted to indicate that, on orbital time scales, the NAC shifted southward during the late Pleistocene, reaching an almost pure west-to-east flow direction in the midlatitudes during glacials. The implication is that the NAC did not reach the higher latitudes of the North Atlantic, significantly diminishing heat transport to the north, a process important to the growth of Northern Hemisphere continental ice sheets [*Versteegh et al.*, 1996; *Villanueva et al.*, 2001; *Stein et al.*, 2009; *Hodell et al.*, 2008].

[4] Results from numerical climate modeling experiments suggest that decreased oceanic heat transport into the high northern latitudes played an important role in driving intensification of Northern Hemisphere glaciation (iNHG) [e.g., *Lunt et al.*, 2008; *Brierley and Fedorov*, 2010]. For marine oxygen isotope stage (MIS) M2 (circa 3.3 Ma), dinoflagellate cyst assemblages from the midlatitude North Atlantic (Deep Sea Drilling Project (DSDP) Site 610 and Integrated Ocean Drilling Program (IODP) Site U1308) show a significant decline in warm-water taxa. This floral change has been used to infer a southward shift or slowdown of the NAC and is proposed to have triggered expansion of Greenland ice sheets during MIS M2 compared to preceding and succeeding glacials [*De Schepper et al.*, 2009]. Furthermore, the onset of higher amplitude glacial cooling reflected by decreasing SSTs starting at around 3.1 Ma in high-resolution alkenone biomarker records from IODP Site U1313 and increases in productivity from 2.7 Ma onward are interpreted to reflect a weakening of the NAC and a southward shift of the Arctic front into the midlatitudes [*Naafs et al.*, 2010]. For part of this time interval (2.8 to 2.2 Ma), a shift of the NAC to a position south of DSDP Site 607 (precursor of IODP Site U1313; 41°N; Figure 1) during glacials is proposed based on palynological records [*Versteegh et al.*, 1996].

[5] Diminished heat transport across the iNHG is a potential trigger mechanism for the amplification of suborbital-scale climate variability via its effect on ice sheet growth in the Northern Hemisphere. A threshold behavior in response to ice sheet size/altitude is proposed for the occurrence of high-amplitude climate fluctuations in proxy records from the North Atlantic both for the Pleistocene [e.g., *McManus et al.*, 1999; *Schulz et al.*, 1999] and for ice rafting during the iNHG [*Bailey et al.*, 2010]. A change in the position and/or strength of the NAC therefore should have a significant effect on whether this proposed threshold is reached.

[6] To test the significance of the NAC for northward heat transport and suborbital climate variability, we here present a Mg/Ca record from planktic foraminiferal calcite that records suborbital-scale SST fluctuations in the North Atlantic (Integrated Ocean Drilling Program (IODP) Site U1313, 41°N) over a time interval from 2.9 to 2.4 Ma (MIS 101 to 95; latest Pliocene to late Pleistocene following *Gibbard et al.* [2009]). Our findings suggest only small shifts in the position of the NAC in the region of Site U1313, a pattern at odds with the cooler late Pleistocene climate regime.

2. Material and Methods

2.1. Sample Material

[7] IODP Site U1313 was drilled at a water depth of 3426 m at the base of the upper western flank of the Mid-Atlantic Ridge, approximately 240 nautical miles northwest of the Azores (41°N, 32.5°W; Figure 1). It constitutes a reoccupation of Deep Sea Drilling Project (DSDP) Site 607 (Leg 94; *Ruddiman et al.* [1987]), which has been a benchmark site for studies of subpolar North Atlantic climate evolution [e.g., *Raymo et al.*, 1989, 1992; *Ruddiman et al.*, 1989]. Site U1313 is situated on the southern margin of the North Atlantic ice-rafted debris (IRD) belt [*Ruddiman*, 1977a, 1977b], under the direct influence of North Atlantic Deep Water.

[8] To understand the evolution of NAC positioning and its relation to climate variability, we generated data from a 500 kyr long interval (2.9–2.4 Ma) at orbital resolution (~3–5 kyr) and from a shorter interval (2.6–2.4 Ma) at suborbital resolution (~400 years). For our orbitally resolved record, 10 cc samples were taken at 20 cm spacing along the shipboard primary splice (1313B-12H-2-128 cm to 1313B-13H-6-75 cm and 1313C-12H-3-112 cm to 1313C-14H-3-10 cm) [*Expedition 306 Scientists*, 2006]. For our suborbitally resolved record, samples were taken every 2 cm along the shipboard primary splice (1313B-12H-2-112 cm to 1313B-12H-5-148 cm and 1313C-12H-4-0 cm to 1313C-12H-5-58 cm). Our chronology is that of *Bolton et al.* [2010] and is based on a high-quality benthic-isotope stratigraphy for Site U1313 tuned to the LR04 isotope stack [*Lisiecki and Raymo*, 2005]. Our record spans MIS G11 to 95 and is at least orbitally resolved throughout, reaching suborbital resolution in the interval MIS 101 to 95 (Figures 2 and 3).

2.2. Mg/Ca Analysis and Paleotemperature Reconstruction

[9] For stable isotope [*Bolton et al.*, 2010] and Mg/Ca (this study) analyses, 60 individuals of *Globigerinoides*

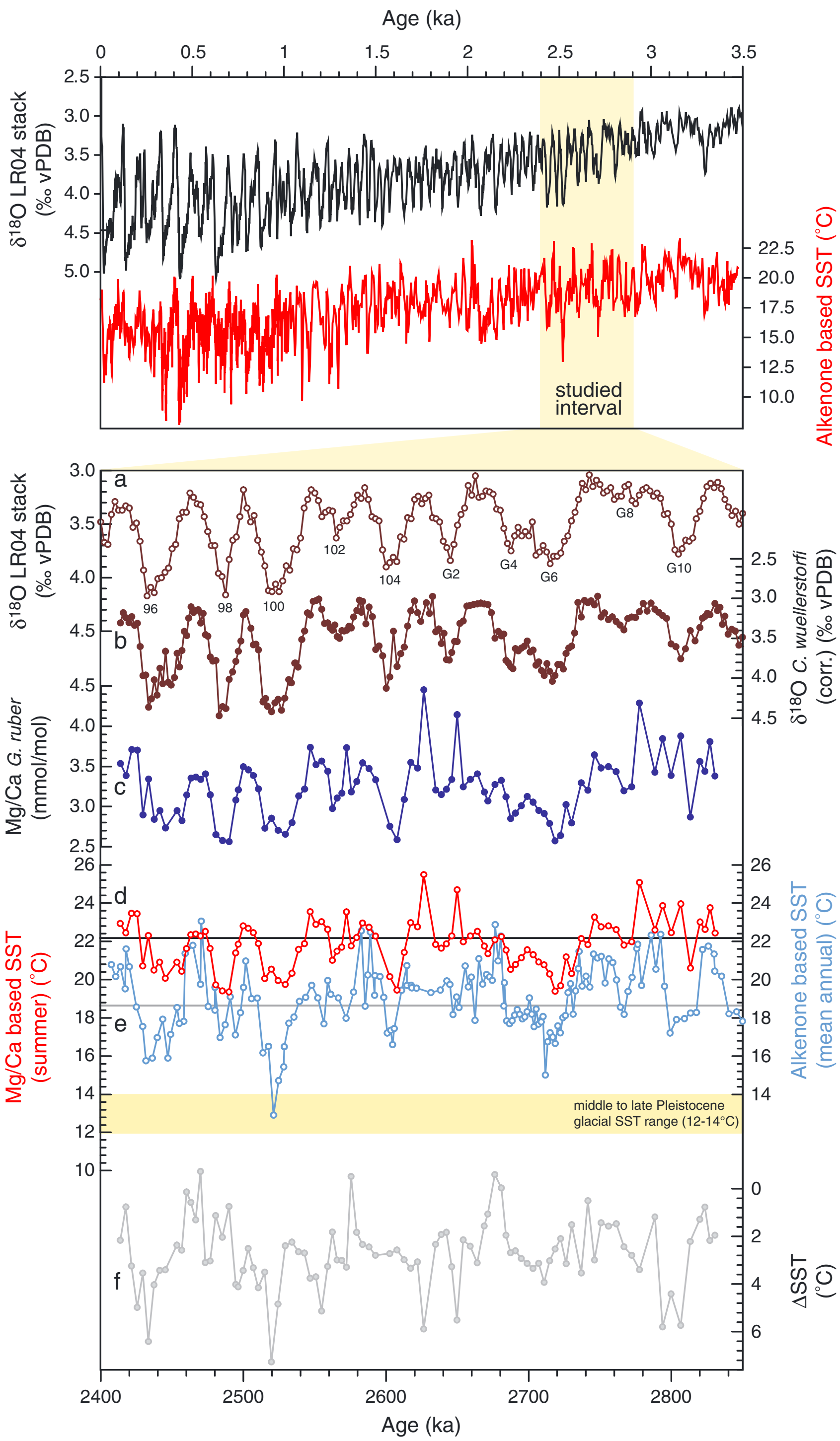

Figure 2. (top) Global benthic foraminiferal $\delta^{18}O$ record (black) [*Lisiecki and Raymo*, 2005] and alkenone-based SST estimates from Site U1313 (red) [*Naafs et al*., 2012a] for the last 3.5 million years. (bottom) Orbitally resolved proxy records from Site U1313 for MIS G11 to 95 (2.9 to 2.4 Ma) tuned to the LR04 stack [*Lisiecki and Raymo*, 2005]. (a) The LR04 stack for MIS G11-95 [*Lisiecki and Raymo*, 2005]. (b) $\delta^{18}O_{benthic}$ from Site U1313 [*Bolton et al*., 2010]. (c) *Globigerinoides ruber* Mg/Ca from Site U1313. (d) *G. ruber* Mg/Ca-based SST estimates from Site U1313. (e) Alkenone-based SST estimates from Site U1313 [*Naafs et al*., 2012a]. (f) Difference between Mg/Ca-based and alkenone-based SST estimates from Site U1313. Black and gray lines in Figures 2d and 2e represent modern mean summer (July, August, September (JAS)) and modern mean annual SST, respectively [*Locarnini et al*., 2006]. Pale yellow bar in Figure 2e represents range of alkenone-based SST estimates for middle to late Pleistocene glacials (without Heinrich event intervals) from Site U1313 for comparison [*Stein et al*., 2009; *Naafs et al*., 2012a].

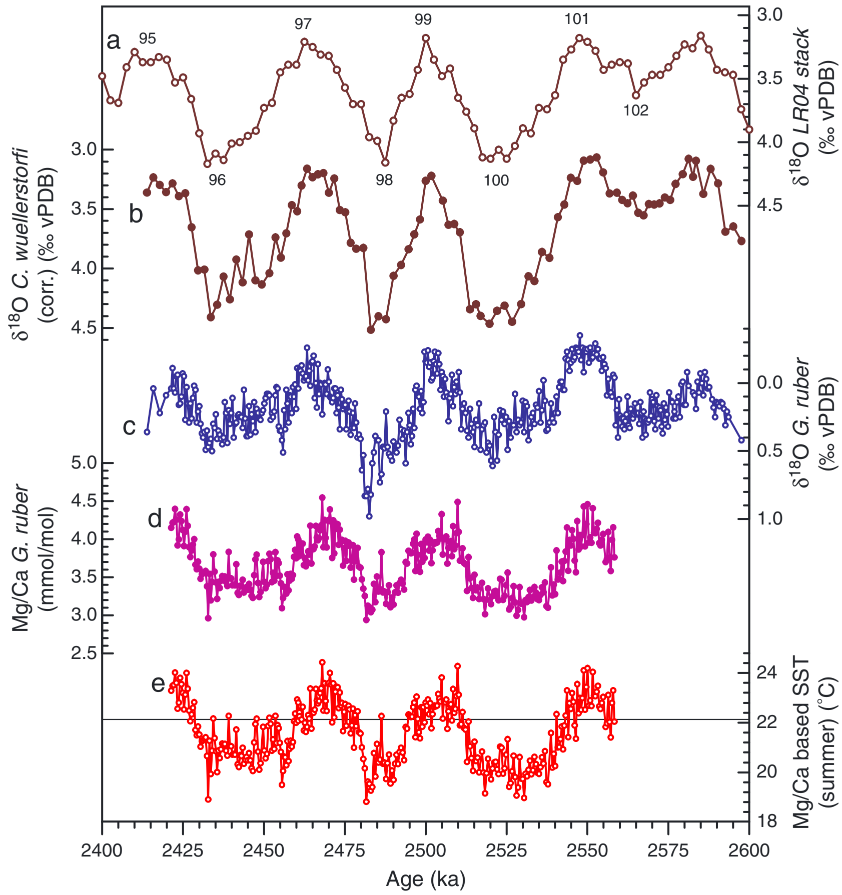

Figure 3. Suborbitally resolved proxy records from Site U1313 for MIS 103 to 95 (2.6 to 2.4 Ma) tuned to the LR04 stack [*Lisiecki and Raymo*, 2005]. (a) The LR04 stack for MIS 103–95 [*Lisiecki and Raymo*, 2005]. (b) $\delta^{18}O_{benthic}$ from Site U1313 [*Bolton et al.*, 2010]. (c) *G. ruber* $\delta^{18}O$ from Site U1313 [*Bolton et al.*, 2010]. (d) *G. ruber* Mg/Ca ratios from Site U1313. (e) *G. ruber* Mg/Ca-based SST estimates from Site U1313. Black line in lower graph represents modern mean summer (JAS) SST [*Locarnini et al.*, 2006].

ruber (white) (*G. ruber* sensu stricto morphotype following *Wang* [2000] and *Aurahs et al.* [2011]) were picked from a narrow size fraction (212–250 µm) to avoid ontogenetic effects [*Friedrich et al.*, 2012]. Preservation of foraminiferal tests is typically good to very good in the studied time interval [*Expedition 306 Scientists*, 2006; own observations]. A planktic foraminiferal dissolution index shows no significant glacial-interglacial fluctuations, and even spines are preserved in some *G. ruber* specimens [*Beer*, 2010]. Tests were gently cracked to reveal individual chambers and then split into two aliquots to allow for paired stable isotope and Mg/Ca measurements on truly representative splits.

[10] For Mg/Ca analyses, cleaning of the tests followed the protocol of *Boyle and Keigwin* [1985] to remove clays and organic matter. The reductive step was omitted because the reducing reagent is corrosive to carbonate, possibly causing partial dissolution of the tests and therefore lower Mg/Ca values (see *Barker et al.* [2003] and *Bian and Martin* [2010] for detailed discussion). To remove any re-adsorbed contaminants, a final weak acid "polish" was performed. Cleaned samples were analyzed using a Perkin Elmer Optima 4300DV Inductively Coupled Plasma-Optical Emission Spectrometer at the National Oceanography Centre, Southampton. Precision for Mg/Ca measurements is better than 0.21% obtained from dilute solutions containing between 1 and 5 ppm Ca^{2+} [*Green et al.*, 2003]. Internal standards run during our study show a mean reproducibility of ±0.01 mmol/mol Mg/Ca.

[11] To convert foraminiferal Mg/Ca ratios into conservative SST estimates, we applied the species-specific equation for *G. ruber* (white) obtained from Atlantic sediment trap samples [$T = (1/0.09) \times \ln(\text{Mg/Ca}/0.449)$; *Anand et al.*, 2003] using the modern sea water Mg/Ca value.

[12] Our calculated Mg/Ca-derived SSTs rest on the assumption that the Mg/Ca ratio of seawater has remained constant over the studied time interval. For time intervals shorter than 1 Ma (as it is the case in our study: ~0.4 Ma), an invariable Mg/Ca ratio of seawater is usually assumed because of residence times for both Mg and Ca that are longer than 1 Ma [e.g., *Fantle and DePaolo*, 2006]. To account for temporal changes in seawater Mg/Ca for the Plio-Pleistocene, the available correction of *Medina-Elizalde et al.* [2008] can be used. Applying this correction to our dataset results in higher Mg/Ca-derived SSTs (by ~2°C higher; see Figure S1 in the supporting information) but does not affect the trend and therefore interpretation of our record. Therefore, we use the somewhat lower SSTs resulting from the *Anand et al.* [2003] calibration without correction for long-term seawater Mg/Ca changes.

3. Results and Discussion

3.1. Species and Seasonality

[13] Our SST estimates based on Mg/Ca in *G. ruber* tests most likely reflect summer temperatures, given the reported present-day preferred temperature range of 13°C to 32°C [*Bijma et al*., 1990; *Schmidt and Mulitza*, 2002] (16°C to 31°C according to *Hemleben et al*. [1989]) and a predominant occurrence of *G. ruber* (white) at the intermediate North Atlantic only in August and September [e.g., *Schiebel and Hemleben*, 2000; *Schiebel et al*., 2001, 2002]. This inference is in agreement with the results of proxy comparison work in the mid-Pliocene suggesting that Mg/Ca-derived SST estimates based on *G. ruber* reflect August SSTs [*Robinson et al*., 2008]. SST did possibly not fall below 13°C during the studied time interval as indicated by the relatively high abundance of *G. ruber* in all samples, with mean relative abundances during glacial intervals only slightly lower than during interglacials [*Bolton et al*., 2010].

[14] The two morphotypes *G. ruber* sensu stricto (s.s.) and *G. ruber* sensu lato (s.l.) have been shown to be formed by two different genotypes [*Aurahs et al*., 2011]. In this study, we used the morphotype *G. ruber* s.s., which records higher Mg/Ca and lower $\delta^{18}O$ values than *G. ruber* s.l. and is inferred to live at shallower water depth in the upper mixed layer than *G. ruber* s.l. [*Wang*, 2000; *Steinke et al*., 2005].

[15] In Figure 2, we compare our Mg/Ca-derived temperature estimates with published alkenone-derived Pliocene to Pleistocene ocean temperature estimates for Site U1313 that are interpreted to track mean annual SST [*Naafs et al*., 2010]. This interpretation is consistent with the view that seasonal fluctuations in alkenone production play only a minor role at midlatitude sites in the modern ocean [e.g., *Müller et al*., 1998; *Conte et al*., 2006], although alkenone data for late Pleistocene interglacials are interpreted to record spring temperatures rather than mean annual temperatures [*Leduc et al*., 2010].

3.2. North Atlantic Glacial-Interglacial SST Variability

[16] The Mg/Ca-derived summer SST record from Site U1313 demonstrates glacial-interglacial cyclicity between 2.9 and 2.4 Ma (Figure 2) following the global benthic foraminiferal $\delta^{18}O$ stack [*Lisiecki and Raymo*, 2005]. During most of the studied interval, summer interglacial SSTs fall between 22°C and 24°C, with even higher temperatures during MIS G1, G3, and G9 (up to 25°C; Figure 2). Summer glacial temperature estimates range between 19°C and 21°C, approximately 3°C to 4°C colder than for interglacials. Comparison of our Plio-Pleistocene data with modern summer (July to September) temperatures of 22.1°C [*Locarnini et al*., 2006] shows that the interglacials between 2.4 and 2.9 Ma were generally warmer by 1°C to 3°C than today (Figure 2). Exceptions are the weakly expressed interglacial G5, where reconstructed summer temperatures are about 1°C below present-day summer SST and MIS 97, characterized by temperatures similar to modern (Figure 2). Glacials were approximately 2°C to 3°C colder than present-day summer SSTs. Our estimates of relatively high summer SSTs are in accordance with the overall picture of a warm North Atlantic during the late Pliocene to early Pleistocene [e.g., *Robinson et al*., 2008; *Lawrence et al*., 2009].

[17] In our data, summer glacial SSTs are consistently lower after 2.6 Ma, whereas before 2.6 Ma (with the exception of the modest glacial MIS 102), only MIS G6 reached temperatures as low as 19°C (Figure 2). In contrast, no significant decreasing trend in interglacial SST is observed over the investigated time interval of iNHG. In fact, the summer interglacial SSTs that we reconstruct for the late Pliocene to early Pleistocene are remarkably similar to *G. ruber* Mg/Ca-derived interglacial summer SSTs reconstructed for the mid-Pliocene warm period derived from the Pliocene Research, Interpretation and Synoptic Mapping (PRISM) project interval [*Robinson et al*., 2008] (note the use of different calibrations that result in slightly lower temperatures in our study; Figure S1). This indicates that the warm interglacial summers that characterized peak Pliocene greenhouse conditions persisted well into the main phase of iNHG in the midlatitude central North Atlantic. In other words, the long-term Plio-Pleistocene signal of deteriorating climate [*Lisiecki and Raymo*, 2005] (Figure 2 upper panel) is clearly seen in our records in glacials (but not in interglacials), lending support to the view that iNHG must involve an amplifying feedback mechanism that is tightly coupled to ice sheet growth (in the Northern Hemisphere) but absent with ice sheet removal during interglacials [see *Shackleton*, 1988; *Bailey et al*., 2010; *Herbert et al*., 2010].

[18] Our SST record elegantly captures the glacial-interglacial pattern of change and in this respect compares favorably with published alkenone-derived SST records for the same location (Sites U1313 and 607) [*Lawrence et al*., 2010; *Naafs et al*., 2010, 2012a]. Our Mg/Ca-derived record, however, is offset to warmer absolute temperatures by between 2 and 3°C (Figure 2). We attribute this offset, for the most part, to the tracking of different seasons. Most likely, close to mean annual SSTs are derived from alkenone data and warm summer SSTs in our *G. ruber*-derived Mg/Ca record (section 3.1). If this interpretation is correct, then our records indicate that the seasonal SST variation in the midlatitude central North Atlantic in the late Pliocene to early Pleistocene was only slightly smaller than the modern seasonal difference of ~3.8°C at the location of Site U1313 [*Locarnini et al*., 2006]. A striking exception to this relatively modest seasonal variability in SST is the large amplitude cooling seen in MIS 100 and, to some extent, MIS 96 and G10 (Figure 2). While summer SSTs during MIS 100 were relatively warm (~19.5°C), mean annual SSTs show a marked decrease to values as low as 12.5°C. This large difference between summer SSTs and mean annual SSTs indicates very cold winters during MIS 100. Increased seasonality dominated by winter cooling during MIS 100 is entirely consistent with the occurrence of IRD at the southern extent of the North Atlantic IRD belt (Site U1313) [*Bolton et al*., 2010] and with a broad body of other work [e.g., *Pross and Klotz*, 2002; *Björck et al*., 2002; *Denton et al*., 2005; *Pross et al*., 2009]

3.3. Changes in the Position of the NAC

[19] Several studies have attempted to assess the position and strength of the Plio-Pleistocene NAC [*Versteegh et al*., 1996; *De Schepper et al*., 2009; *Naafs et al*., 2010, 2012b]. These studies attribute contemporaneous decreases in SST and increasing productivity or changes in dinoflagellate assemblages to a weakening of the NAC and a southward shift

of the Arctic front into the midlatitudes during glacials of the late Pliocene and earliest Pleistocene. The rationale for this suggestion is the same as that used for the late Pleistocene [*McIntyre et al*., 1972; *Stein et al*., 2009]. The SSTs reconstructed for the late Pliocene/earliest Pleistocene glacial North Atlantic [*De Schepper et al*., 2009; *Naafs et al*., 2010, 2012a, 2012b] are, however, several degrees warmer than those documented for the mid-Pleistocene (12–14°C) [e.g., *Stein et al*. 2009] (Figure 2) or latest Pleistocene (8–12°C) [*Naafs et al*. 2011, 2012a]. Our Mg/Ca-based summer SST estimates for the time interval 2.9 to 2.4 Ma show glacial-interglacial variations of 4°C to 5°C, ranging from ~24°C during interglacials to 19 to 20°C during glacials, within a 3°C range of the modern for glacial values [*Locarnini et al*., 2006] (Figures 1–3). This finding is at odds with the proposed shift of the NAC to an eastern flow direction south of Site U1313 and penetration of the Arctic Front into the midlatitude glacial North Atlantic Ocean during the late Pliocene and early Pleistocene, especially during summer. Instead, our data suggest a position of the NAC more comparable to the modern northeastern flow direction or at least north of Site U1313. It is possible that the contrast between our interpretation and those based on published alkenone records (especially *Naafs et al*. [2010]) is partly attributable to different proxies tracking different seasons (section 3.1). The overall warm climate reflected by both summer and mean annual SST records (Figure 2) and a slightly smaller seasonal SST difference than today (section 3.2), however, argue for a smaller seasonal contrast during the early Pleistocene and therefore a less pronounced shift in the position of the Arctic Front on seasonal time scales.

[20] Cooler SSTs during the more intense glacial MIS 100 and perhaps 96 and G10 may indicate a somewhat diminished northward heat transport potentially associated with ice sheet expansion in the Northern Hemisphere over the Pliocene-Pleistocene transition [*Versteegh et al*., 1996; *Lawrence et al*., 2009; *Naafs et al*., 2010]. Over this time interval, however, the NAC and Arctic Front were more likely situated north of Site U1313, based on (1) the large amplitude glacial-interglacial SST changes documented at ODP Site 982 (58°N) [*Lawrence et al*., 2009] and (2) the IRD fluxes documented for MIS 100 at DSDP Site 611 (52°N) [*Bailey et al*., 2012]. Site 611 IRD flux estimates for MIS 100 are akin to ambient last glacial values and are interpreted to reflect a more northerly IRD belt compared to the last glacial IRD belt [*Bailey et al*., 2012]. This hypothesis is supported by the extremely low abundance of IRD recorded for MIS 100 to 98 at Site U1313 [*Bolton et al*., 2010].

[21] Our new temperature records do not support the suggestion that the glacial Arctic front extended into the midlatitude North Atlantic during the iNHG interval, and an alternative mechanism is required to explain the onset of higher amplitude glacial-interglacial change in export productivity indicated by records of alkenone accumulation rates [*Naafs et al*., 2010], dinoflagellate abundances [*Versteegh et al*., 1996], and the relative abundance of long-chained diols [*Naafs et al*., 2012b] at Site U1313. One possibility is a role for glacial delivery of aeolian dust from North America by the midlatitude westerlies [*Naafs et al*., 2012a]. On the other hand, without invoking micronutrient fertilization via dust, an increase in the amplitude of export productivity recorded at Site U1313 is compatible with an equatorward advection of the Southern Ocean nutrient pool. This mechanism is proposed to result in enhanced nutrient delivery to the thermocline waters of the low and midlatitude Atlantic around 3 to 2.5 Ma [*Bolton et al*., 2011]. Since Site U1313 is situated at the northern limit of the oligotrophic subtropical gyre, i.e., the most nutrient depleted waters within the North Atlantic [e.g., *Mix*, 1989], any change in water masses or preformed nutrient content would enhance primary productivity to some degree. The prevalence of a generally low productivity environment throughout the respective time interval is supported by the general dominance of autochthonous oceanic dinoflagellate cysts [*Versteegh et al*., 1996].

3.4. Influence on Suborbital-Scale SST Variability

[22] The occurrence of high-amplitude suborbital-scale climate fluctuations in the North Atlantic has been suggested to show a threshold behavior in response to ice sheet extension [e.g., *McManus et al*., 1999]. Suborbital-scale SST and ice-rafting events of the late Pleistocene are observed whenever benthic oxygen isotope values exceed 4.14‰ [*McManus et al*., 1999], whereas a threshold of 3.7 to 3.9‰ has been suggested for suborbital-scale ice-rafting events during the late Pliocene to early Pleistocene [*Bailey et al*., 2010]. Because the size of Northern Hemisphere ice sheets is most probably a function of northward heat transport, the strength and overall position of the NAC plays an important role in triggering northward heat flow. Our data suggest that the earliest Pleistocene North Atlantic Ocean (2.9 to 2.4 Ma) was characterized by a weaker southward shift of the NAC compared to the late Pleistocene even during the more intense glacials such as MIS 100. Consequently, it is reasonable to infer that oceanic heat transport to the high northern latitudes was not severely diminished during the early Pleistocene, calling into question its influence on the amplification of suborbital-scale climate variations.

[23] Our suborbitally resolved record of Mg/Ca-derived SST for MIS 101 to 95 demonstrates that the amplitude of suborbital-scale SST variability was small (~2°C; Figure 3) compared to that documented in late Pleistocene alkenone and planktic foraminiferal faunal data in the temperate central North Atlantic (up to 10°C) [e.g., *Stein et al*., 2009; *Lawrence et al*., 2010; *Alonso-Garcia et al*., 2011]. Furthermore, our records show no evidence for amplification of SST variability depending on glacial-interglacial state (Figure 3).

[24] For Pleistocene marine sediments, numerous studies suggest a positive relationship between ice sheet volume and amplitude of suborbital-scale climate fluctuations [e.g., *Oppo et al*., 2001; *McManus et al*., 1999; *Weirauch et al*., 2008; *Stein et al*., 2009] with a threshold-like behavior of North Atlantic climate causing higher amplitude variability during glacials [e.g., *McManus et al*., 1999; *Schulz et al*., 1999; *Bailey et al*., 2010; *Alonso-Garcia et al*., 2011]. For the late Pliocene iNHG, data from ODP Site 984 (Reykjanes Ridge, 61°N; Figure 1) are interpreted as showing a progressive increase in the amplitude of suborbital-scale variability [*Bartoli et al*., 2006].

[25] MIS 100, 98, and 96 occur after the onset of increasing amplification in suborbital-scale variability as proposed by *Bartoli et al*. [2006] (MIS G14 to 104, 2.9 to 2.6 Ma) and exceed the benthic oxygen isotope thresholds: (1) 4.14‰,

beyond which suborbital-scale SST and ice-rafting events occur during the late Pleistocene at ODP Site 980 [*McManus et al.*, 1999] and (2) 3.7‰ to 3.9‰, beyond which suborbital-scale ice-rafting events are seen during the late Pliocene/earliest Pleistocene at IODP Site 1308 [*Bailey et al.*, 2010] (all values adjusted to equilibrium; see discussion in *Bailey et al*. [2010]). Yet our SST records from Site U1313 clearly show no evidence of threshold-type amplification of suborbital-scale SST variability, in agreement with a recent study of planktic foraminiferal stable isotope and color reflectance records from the same site [*Bolton et al.*, 2010]. That study excluded a significant influence of meltwater input to explain the low-amplitude suborbital variability in planktic foraminiferal $\delta^{18}O$ and found it unlikely that large-scale change in SST or salinity occurred without being expressed in planktic $\delta^{18}O$, a hypothesis supported by our SST record (SST amplitude of ~2°C; Figure 3). These findings suggest either that suborbital-scale variability in SSTs is independent of ice-volume extent reached during the late Pliocene to earliest Pleistocene (up to ~70–80 m sea level fall equivalent) [e.g., *Bintanja and van de Wal*, 2008; *Sosdian and Rosenthal*, 2009; *Lourens et al.*, 2010] or that a threshold for amplified suborbital-scale SST variability existed but was not crossed until the mid-Pleistocene to late Pleistocene (see discussions in *Bolton et al*. [2010] and *Weirauch et al*. [2008]). It is an unlikely coincidence that we find no change in both the amplitude of midlatitude North Atlantic suborbital surface ocean temperature variability and the position of the NAC and Arctic Front on glacial-interglacial time scales across the iNHG, implying that the two observations are likely linked.

4. Conclusions

[26] Mg/Ca-derived paleotemperature records of the planktic foraminifer *G. ruber* (s.s.) from IODP Site U1313 (midlatitude North Atlantic; 41°N) document orbital- to suborbital-scale variability in summer SST. The major findings revealed by our study are as follows:

[27] 1. Glacial-interglacial SST changes on orbital time scales support a generally warmer climate during the late Pliocene to earliest Pleistocene than today. Compared to modern SSTs, interglacial summer temperatures were 1°C to 2°C warmer, while glacials were characterized by summer SST typically 2°C to 3°C colder than today.

[28] 2. For the time interval 2.9 to 2.4 Ma, high SSTs argue against a significant weakening or southward movement of the Arctic front and NAC; instead they suggest a position of the NAC north of Site U1313 and therefore only modest reduction of heat transport to the high northern latitudes even during glacials.

[29] 3. Reconstructed SSTs show low-amplitude suborbital variability that is independent of glacial-interglacial state. This finding suggests either that suborbital-scale SST variability was independent of the ice-volume extent reached during the late Pliocene to earliest Pleistocene or that a potential threshold for amplified suborbital-scale SST variability was not yet reached. Either way, the persistently warm and relatively constant interglacial SSTs that we report from Site 1313 through our study interval support the suggestion that iNHG must involve amplifying feedback mechanisms that are tightly coupled to ice sheet growth and absent with ice sheet removal.

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References

Alonso-Garcia, M., F. J. Sierro, M. Kucera, J. A. Flores, I. Cacho, and N. Andersen (2011), Ocean circulation, ice sheet growth and interhemispheric coupling of suborbital climate variability during the mid-Pleistocene (ca 800–400 ka), *Quat. Sci. Rev.*, *30*, 3234–3247.

Anand, P., H. Elderfield, and M. H. Conte (2003), Calibration of Mg/Ca thermometry in planktonic foraminifera from a sediment trap time series, *Paleoceanography*, *18*(2), 1050, doi:10.1029/2002PA000846.

Aurahs, R., Y. Treis, K. Darling, and M. Kucera (2011), A revised taxonomic and phylogenetic concept for the planktonic foraminifer species *Globigerinoides ruber* based on molecular and morphometric evidence, *Mar. Micropaleontol.*, *79*, 1–14, doi:10.1029/2002PA000846.

Bailey, I., C. T. Bolton, R. M. DeConto, D. Pollard, R. Schiebel, and P. A. Wilson (2010), A low threshold for North Atlantic ice-rafting from 'low-slung slippery' late Pliocene ice-sheets, *Paleoceanography*, *25*, PA1212, doi:10.1029/2009PA001736.

Bailey, I., G. L. Foster, P. A. Wilson, L. Jovane, C. D. Storey, C. N. Trueman, and J. Becker (2012), Flux and provenance of ice-rafted debris in the earliest Pleistocene sub-polar North Atlantic Ocean comparable to the Last Glacial Maximum, *Earth Planet. Sci. Lett.*, *341–344*, 222–233.

Barker, S., M. Greaves, and H. Elderfield (2003), A study of cleaning procedures used for foraminiferal Mg/Ca palaeothermometry, *Geochem. Geophys. Geosyst.*, *4*(9), 8407, doi:10.1029/2003GC000559.

Bartoli, G., M. Sarnthein, and M. Weinelt (2006), Late Pliocene millenial-scale climate variability in the northern North Atlantic prior to and after the onset of Northern Hemisphere glaciation, *Paleoceanography*, *21*, PA4205, doi:10.1029/2005PA001185.

Beer, C. J. (2010), Planktic foraminifera, ocean sediments and the palaeomarine carbonate system, Doctoral Thesis, 144 p., Sch. of Ocean and Earth Sci., Univ. of Southampton, Southampton, U. K.

Bian, N., and P. A. Martin (2010), Investigating the fidelity of Mg/Ca and other elemental data from reductively cleaned planktonic foraminifera, *Paleoceanography*, *25*, PA2215, doi:10.1029/2009PA001796.

Bijma, J., W. W. Faber, and C. Hemleben (1990), Temperature and salinity limits for growth and survival of some planktonic foraminfers in laboratory cultures, *J. Foram. Res.*, *20*, 95–116.

Bintanja, R., and R. S. W. van de Wal (2008), North American ice-sheet dynamics and the onset of 100,000-year glacial cycles, *Nature*, *454*, 869–872.

Björck, S., O. Bennike, C. Andresen, S. Bohncke, E. Kaas, and D. Conley (2002), Anomalously mild Younger Dryas summer conditions in southern Greenland, *Geology*, *30*, 427–430.

Bolton, C. T., P. A. Wilson, I. Bailey, O. Friedrich, C. J. Beer, J. Becker, S. Baranwal, and R. Schiebel (2010), Suborbital-scale climate variability in the subpolar North Atlantic Ocean during the late Pliocene, *Paleoceanography*, *25*, PA4218, doi:10.1029/2010PA001951.

Bolton, C. T., K. T. Lawrence, S. J. Gibbs, P. A. Wilson, and T. D. Herbert (2011), Biotic and geochemical evidence for a global latitudinal shift in ocean biogeochemistry and export productivity during the late Pliocene, *Earth Planet. Sci. Lett.*, *308*, 200–210.

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

Brierley, C. M., and A. V. Fedorov (2010), The relative importance of meridional and zonal SST gradients for the onset of the ice ages and Pliocene–Pleistocene climate evolution, *Paleoceanography*, *25*, PA2214, doi:10.1029/2009PA001809.

Calvo, E., J. Villanueva, J. O. Grimalt, A. Boelaert, and L. Labeyrie (2001), New insights into the glacial latitudinal temperature gradients in the North

Atlantic: Results from $U^{k'}_{37}$ sea surface temperatures and terrigenous inputs, *Earth Planet. Sci. Lett.*, *188*, 509–519.

Conte, M. H., M.-A. Sicre, C. Rühlemann, J. C. Weber, S. Schulte, D. Schulz-Bull, and T. Blanz (2006), Global temperature calibration of the alkenone unsaturation index (UK'37) in surface waters and comparison with surface sediments, *Geochem. Geophys. Geosyst.*, *7*, Q02005, doi.10.1029/2005GC001054.

De Schepper, S., M. J. Head, and J. Groeneveld (2009), North Atlantic Current variability through marine isotope stage M2 (circa 3.3 Ma) during the mid-Pliocene, *Paleoceanography*, *24*, PA4206, doi:10.1029/2008pa001725.

Denton, G. H., R. B. Alley, G. C. Comer, and W. S. Broecker (2005), The role of seasonality in abrupt climate change, *Quat. Sci. Rev.*, *24*, 1159–1182.

Dietrich, G., K. Kalle, W. Krauss, and G. Siedler (1980), *General Oceanography*, 626 pp., John Wiley, New York.

Expedition 306 Scientists (2006), *Site U1313, in Proceedings of the Integrated Ocean Drilling Program*, edited by J. E. T. Channell, et al., College Station, Texas.

Fantle, M. S., and D. J. DePaolo (2006), Sr isotopes and pore fluid chemistry in carbonate sediment of the Ontong Java Plateau: Calcite recrystallization rates and evidence for a rapid rise in seawater Mg over the last 10 million years, *Geochim. Cosmochim. Acta*, *70*, 3883–3904.

Friedrich, O., R. Schiebel, P. A. Wilson, S. Weldeab, C. J. Beer, M. J. Cooper, and J. Fiebig (2012), Influence of test size, water depth, and species ecology on Mg/Ca, Sr/Ca, $\delta^{18}O$ and $\delta^{13}C$ in nine modern species of planktic foraminifers, *Earth Planet. Sci. Lett.*, *319–320*, 133–145.

Gibbard, P. L., M. J. Head, and M. J. C. Walker (2009), Formal ratification of the Quaternary System/Period and the Pleistocene Series/Epoch with a base at 2.58 Ma, *J. Quat. Sci.*, *25*, 96–102.

Green, D. R. H., M. J. Cooper, C. R. German, and P. A. Wilson (2003), Optimization of an inductively coupled plasma-optical emission spectrometry method for the rapid determination of high-precision Mg/Ca and Sr/Ca in foraminiferal calcite, *Geochem. Geophys. Geosyst.*, *4*(6), 8404, doi:10.1029/2002GC000488.

Hemleben, C., M. Spindler, and O. R. Anderson (1989), *Modern Planktonic Foraminifera*, pp. 1–363, Springer, New York.

Herbert, T. D., L. Cleaveland Peterson, K. T. Lawrence, and Z. Liu (2010), Tropical ocean temperatures over the past 3.5 Myr, *Science*, *328*, 1530–1534.

Hodell, D. A., J. E. T. Channell, J. H. Curtis, O. E. Romero, and U. Röhl (2008), Onset of "Hudson Strait" Heinrich events in the eastern North Atlantic at the end of the middle Pleistocene transition (~640 ka)? *Paleoceanography*, *23*, PA4218, doi:10.1029/2008PA001591.

Kraus, W. (1986), The North Atlantic Current, *J. Geophys. Res.*, *91*, 5061–5074.

Lawrence, K. T., T. D. Herbert, C. M. Brown, M. E. Raymo, and A. M. Haywood (2009), High amplitude variations in North Atlantic sea surface temperature during the early Pliocene warm period, *Paleoceanography*, *24*, PA2218, doi:10.1029/2008pa001669.

Lawrence, K. T., S. Sosdian, H. E. White, and Y. Rosenthal (2010), North Atlantic climate evolution through the Plio-Pleistocene climate transitions, *Earth Planet. Sci. Lett.*, *300*, 329–342, doi:10.1016/j.epsl.2010.10.013.

Leduc, G., R. Schneider, J. H. Kim, and G. Lohmann (2010), Holocene and Eemian Sea surface temperature trends as revealed by alkenone and Mg/Ca paleothermometry, *Quat. Sci. Rev.*, *29*, 989–1004.

Lisiecki, L. E., and M. E. Raymo (2005), A Pliocene-Pleistocene stack of 57 globally distributed benthic delta-18 O records, *Paleoceanography*, *20*, PA1003, doi:10.1029/2004PA001071.

Locarnini, R. A., A. V. Mishonov, J. I. Antonov, T. P. Boyer, and H. E. Garcia (2006), *World Ocean Atlas 2005*, vol. 1, *Temperature*, edited by S. Levitus, 182 p., U.S. Gov. Print. Off., Washington, D.C.

Lourens, L. J., J. Becker, R. Bintanja, F. J. Hilgen, E. Tuenter, R. S. W. van de Wal, and M. Ziegler (2010), Linear and non-linear response of late Neogene glacial cycles to obliquity forcing and implications for the Milankovitch theory, *Quat. Sci. Rev.*, *29*, 352–365.

Lunt, D. J., G. L. Foster, A. M. Haywood, and E. J. Stone (2008), Late Pliocene Greenland glaciation controlled by a decline in atmospheric CO_2 levels, *Nature*, *454*, 1102–1105.

McIntyre, A., W. F. Ruddiman, and R. Jantzen (1972), Southward penetrations of the North Atlantic Polar Front: Faunal and floral evidence of large-scale surface water mass movements over the last 225,000 years, *Deep Sea Res.*, *19*, 61–77.

McManus, J., D. W. Oppo, and J. L. Cullen (1999), A 0.5-million-year record of millenial-scale climate variability in the North Atlantic, *Science*, *283*, 971–975.

Medina-Elizalde, M., D. W. Lea, and M. S. Fantle (2008), Implications of seawater Mg/Ca variability for Plio-Pleistocene tropical climate reconstruction, *Earth Planet. Sci. Lett.*, *269*, 585–595.

Mix, A. C. (1989), Influence of productivity variations on long-term atmospheric CO_2, *Nature*, *337*, 541–544.

Müller, P. J., G. Kirst, G. Ruhland, I. von Storch, and A. Rosell-Melé (1998), Calibration of the alkenone paleotemperature index Uk'37 based on core-tops from the eastern South Atlantic and the global ocean (60°N–60°S), *Geochim. Cosmochim. Acta*, *62*, 1757–1772.

Naafs, B. D. A., R. Stein, J. Hefter, N. Khèlifi, S. De Schepper, and G. H. Haug (2010), Late Pliocene changes in the North Atlantic current, *Earth Planet. Sci. Lett.*, *298*, 434–442, doi:10.1016/j.epsl.2010.08.023.

Naafs, B. D. A., J. Hefter, P. Ferretti, R. Stein, and G. H. Haug (2011), Sea surface temperatures did not control the first occurrence of Hudson Strait Heinrich events during MIS 16, *Paleoceanography*, *26*, PA4201, doi:10.1029/2011PA002135.

Naafs, B. D. A., J. Hefter, G. Acton, G. H. Haug, A. Martinez-Garcia, R. Pancost, and R. Stein (2012a), Strengthening of North Atlantic dust sources during the late Pliocene (2.7 Ma), *Earth Planet. Sci. Lett.*, *317–318*, 8–19.

Naafs, B. D. A., J. Hefter, and R. Stein (2012b), Application of the long chain diol index (LDI) paleothermometer to the early Pleistocene (MIS 96), *Org. Geochem.*, *49*, 83–85.

Oppo, D. W., L. D. Keigwin, J. McManus, and J. L. Cullen (2001), Persistent suborbital climate variability in marine isotope stage 5 and Termination II, *Paleoceanography*, *16*, 280–292.

Pflaumann, U., et al. (2003), Glacial North Atlantic: Sea-surface conditions reconstructed by GLAMAP 2000, *Paleoceanography*, *18*, PA1065, doi:10.1029/2002PA000774.

Pross, J., and S. Klotz (2002), Paleotemperature calculations from the Praetiglian/Tiglian (Plio-Pleistocene) pollen sequence of Lieth, northern Germany: Implications for the climate evolution of northwestern Europe, *Global Planet. Change*, *34*, 253–267.

Pross, J., U. Kotthoff, U. C. Müller, O. Peyron, I. Dormoy, G. Schmiedl, S. Kalaitzidis, and A. M. Smith (2009), Massive perturbation in terrestrial ecosystems of the Eastern Mediterranean region associated with the 8.2 kyr B.P. climatic event, *Geology*, *37*, 887–890.

Raymo, M. E., W. F. Ruddiman, J. Backman, A. C. Clement, and D. G. Martinson (1989), Late Pliocene variation in Northern Hemisphere ice sheets and North Atlantic deepwater circulation, *Paleoceanography*, *4*, 413–446.

Raymo, M. E., D. A. Hodell, and E. Jansen (1992), Response of deep ocean circulation to initiation of Northern Hemisphere glaciation (3–2 Ma), *Paleoceanography*, *7*, 645–672.

Robinson, M. M., H. J. Dowsett, G. S. Dwyer, and K. T. Lawrence (2008), Reevaluation of mid-Pliocene North Atlantic sea surface temperatures, *Paleoceanography*, *23*, PA3213, doi:10.1029/2008PA001608.

Rossby, T. (1996), The North Atlantic Current and surrounding waters: At the crossroads, *Rev. Geophys.*, *34*, 463–481.

Ruddiman, W. F. (1977a), North Atlantic ice-rafting: A major change at 75,000 years before the present, *Science*, *196*, 1208–1211.

Ruddiman, W. F. (1977b), Late Quaternary deposition of ice-rafted sand in the subpolar North Atlantic (lat 40° to 65°N), *Geol. Soc. Am. Bull.*, *88*, 1813–1827.

Ruddiman, W. F., et al. (1987), *Initial Reports of the Deep Sea Drilling Project*, *94*, 1261 p., Govt. Print. Off., Washington, D. C.

Ruddiman, W. F., M. E. Raymo, D. G. Martinson, B. M. Clement, and J. Backman (1989), Pleistocene evolution: Northern Hemisphere ice sheets and North Atlantic Ocean, *Paleoceanography*, *4*, 353–412.

Schiebel, R., and C. Hemleben (2000), Interannual variability of planktic foraminiferal populations and test flux in the eastern North Atlantic Ocean (JGOFS), *Deep Sea Res.*, *47*, 1809–1852.

Schiebel, R., J. Waniek, M. Bork, and C. Hemleben (2001), Planktic foraminiferal production stimulated by chlorophyll redistribution and entrainment of nutrients, *Deep Sea Res.*, *48*, 721–740.

Schiebel, R., B. Schmuker, M. Alves, and C. Hemleben (2002), Tracking the recent and late Pleistocene Azores front by the distribution of planktic foraminifers, *J. Mar. Syst.*, *37*, 213–227.

Schmidt, G. A., and S. Mulitza (2002), Global calibration of ecological models for planktic foraminifera from coretop carbonate oxygen-18, *Mar. Micropaleontol.*, *44*, 125–140.

Schulz, M., W. H. Berger, M. Sarnthein, and P. M. Grootes (1999), Amplitude variation of 1470-year climate oscillations during the last 100,000 years linked to fluctuations of continental ice mass, *Geophys. Res. Lett.*, *26*, 3385–3388.

Shackleton, N. J. (1988), Special section; Quaternary deep-water circulation, *Paleoceanography*, *3*, 317–399.

Sosdian, S., and Y. Rosenthal (2009), Deep-sea temperature and ice volume changes across the Pliocene-Pleisocene climate transitions, *Science*, *325*, 306–310.

Stein, R., J. Hefter, J. Grützner, A. H. L. Voelker, and B. D. A. Naafs (2009), Variability of surface water characteristics and Heinrich-like events in the Pleistocene midlatitude North Atlantic Ocean: Biomarker and XRD records from IODP Site U1313 (MIS 16–9), *Paleoceanography*, *24*, PA2203, doi:10.1029/2008PA001639.

Steinke, S., H.-Y. Chiu, P.-S. Yu, C.-C. Shen, L. Löwemark, H.-S. Mii, and M.-T. Chen (2005), Mg/Ca ratios of two *Globigerinoides ruber* (white) morphotypes: Implications for reconstructing past tropical/subtropical surface water conditions, *Geochem. Geophys. Geosyst.*, *6*, Q11005, doi:10.1029/2005GC000926.

Versteegh, G. J. M., H. Brinkhuis, H. Visscher, and K. A. F. Zonneveld (1996), The relation between productivity and temperature in the Pliocene North Atlantic at the onset of Northern Hemisphere glaciation: A palynological study, *Global Planet. Change*, *11*, 155–165.

Villanueva, J., E. Calvo, C. Pelejero, J. O. Grimalt, A. Boelaert, and L. Labeyrie (2001), A latitudinal productivity band in the Central North Atlantic over the last 270 kyr: An alkenone perspective, *Paleoceanography*, *16*, 617–626, doi:10.1029/2000PA000543.

Wang, L. (2000), Isotopic signals in two morphotypes of *Globigerinoides ruber* (white) from the South China Sea: Implications for monsoon climate change during the last glacial cycle, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *161*, 381–394.

Weirauch, D., K. Billups, and P. Martin (2008), Evolution of suborbital-scale climate variability during the mid-Pleistocene, *Paleoceanography*, *23*, PA3216, doi:10.1029/2007PA001584.