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High-amplitude variations in North Atlantic sea surface temperature during the early Pliocene warm period

Kira T. Lawrence,[1] Timothy D. Herbert,[2] Catherine M. Brown,[2] Maureen E. Raymo,[3] and Alan M. Haywood[4]

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[1] We provide the first continuous, orbital-resolution sea surface temperature (SST) record from the high-latitude North Atlantic, a region critical to understanding the origin of the Plio-Pleistocene ice ages and proximal to regions that became frequently glaciated after ~2.7 Ma. We analyzed sediments from Ocean Drilling Program Site 982 over the last 4 Ma for their alkenone unsaturation index and compared this surface water signal to a benthic $\delta^{18}O$ record obtained from the same section. We find that while ocean surface temperatures were significantly warmer (~6°C) than modern temperatures during the early Pliocene, they were also as variable as those during the late Pleistocene, a surprising result in light of the subdued variance of oxygen isotopic time series during the interval of 3–5 Ma. We propose two possible explanations for the high orbital-scale SST variability observed: either that a strong, high-latitude feedback mechanism not involving large continental ice sheets alternately cooled and warmed a broad region of the northern high latitudes or that by virtue of its location near the northern margin of the North Atlantic Drift, the site was unusually sensitive to obliquity-driven climate shifts. On supraorbital time scales, a strong, sustained cooling of North Atlantic SSTs (~4.5°C) occurred from 3.5 to 2.5 Ma and was followed by an interval of more modest cooling (an additional 1.5°C) from 2.5 Ma to the present. Evolutionary orbital-scale phase relationships between North Atlantic SST and benthic $\delta^{18}O$ show that SST began to lead $\delta^{18}O$ significantly coincident with the onset of strong cooling at Site 982 (~3.5 Ma). We speculate that these changes were related to the growth and subsequent persistence of a Greenland ice sheet of approximately modern size through interglacial states.

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1. Introduction

[2] The last major climate transition in Earth's history occurred between the Pliocene and Pleistocene epochs. This transition was marked by the glaciation of the high latitudes of the Northern Hemisphere and major changes in both regional and global climate [e.g., *Ravelo et al.*, 2004, 2007; *Raymo*, 1994; *Zachos et al.*, 2001]. Benthic oxygen isotope records suggest that from the early Pliocene to the Pleistocene the climate transitioned from warmer, more ice-free, more stable (i.e., low-amplitude variations) conditions to colder, more variable, glaciated conditions [*Lisiecki and Raymo*, 2005; *Mudelsee and Raymo*, 2005; *Zachos et al.*, 2001]. The ultimate cause of global cooling and increased climatic variability during the Plio-Pleistocene remains enigmatic. A decrease in atmospheric CO_2 and a change in oceanic or atmospheric heat transport are the most commonly invoked mechanisms for this transition [*Crowley*, 1996; *Driscoll and Haug*, 1998; *Haug and Tiedemann*, 1998; *Haywood and Valdes*, 2004; *Raymo and Horowitz*, 1996; *Raymo et al.*, 1996]. However, what occurred within the Earth system to initiate these changes is still widely debated [*Cane and Molnar*, 2001; *Driscoll and Haug*, 1998; *Haug and Tiedemann*, 1998; *Ravelo et al.*, 2007; *Philander and Fedorov*, 2003].

[3] A number of processes that occur in the North Atlantic strongly influence both regional and global climate: the formation of sea ice, the transfer of sensible and latent heat to the atmosphere, and the formation and ventilation of deep water [*Shipboard Scientific Party*, 1996a]. Because the North Atlantic was the region most directly affected by Northern Hemisphere glaciation (NHG) and it continues to play an important role in the modern climate system, the Neogene history of the region has been intensively studied [e.g., *Baumann and Huber*, 1999; *Cronin and Dowsett*, 1990; *Dowsett and Loubere*, 1992; *Dowsett et al.*, 1992; *McIntyre et al.*, 1999; *Nikolaev et al.*, 1998; *Raymo*, 1994; *Raymo et al.*, 1992, 1989, 2004; *Ruddiman et al.*, 1989]. Previous studies using geochemical, sedimentological, and faunal data document the progressive development of glacial conditions in the North Atlantic from the middle Miocene to the late Pleistocene. Toward the present, they indicate a decrease in deep water ventilation [*Ravelo and Andreasen*, 2000; *Raymo et al.*,

[1]Department of Geology and Environmental Geosciences, Lafayette College, Easton, Pennsylvania, USA.
[2]Department of Geological Sciences, Brown University, Providence, Rhode Island, USA.
[3]Department of Earth Sciences, Boston University, Boston, Massachusetts, USA.
[4]School of Earth and Environment, University of Leeds, Leeds, UK.

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1990b, 1989], a major decrease in carbonate preservation [*Baumann and Huber*, 1999; *Fronval and Jansen*, 1996; *Wolf-Welling et al.*, 1996], a shift in microfauna toward more polar species [*Baumann and Huber*, 1999; *Raymo et al.*, 1986; *Thunell and Belyea*, 1982], and the appearance and increasing abundance of ice-rafted debris (IRD) in sediment cores [*Jansen et al.*, 2000; *Larsen et al.*, 1994; *Raymo et al.*, 1986, 1989; *Ruddiman et al.*, 1987; *Shackleton et al.*, 1984; *St. John and Krissek*, 2002; *Wolf-Welling et al.*, 1996].

[4] Modeling studies contrasting the warmer and more ice-free conditions that preceded widespread glaciation of the Northern Hemisphere with modern North Atlantic climate conditions suggest that significant differences in atmospheric pressure systems and the transport of heat to high latitudes may have accompanied the shift in climate state [e.g., *Haywood et al.*, 2000b; *Raymo et al.*, 1990a]. Changes in high-latitude atmospheric pressure systems and atmospheric and oceanic heat transport should have a profound effect on surface ocean conditions, in particular, ocean surface temperatures. Yet because existing sea surface temperature (SST) records characterize temperature variations only during restricted time windows (*Bartoli et al.* [2005], 3 to 2.5 Ma; *Dowsett and Poore* [1991], *Dowsett et al.* [1996], and *Dowsett et al.* [1992], 3 to 3.3 Ma; *Haug et al.* [2005], 3 to 2.4 Ma), we have a very limited sense of how the high-latitude surface ocean evolved through the Plio-Pleistocene transition.

[5] Using the alkenone organic proxy, we reconstructed changes in ocean surface conditions in the North Atlantic Ocean over the past 4 Ma, presenting the first continuous, high-resolution, high-latitude record of Plio-Pleistocene SSTs. The orbital-scale resolution of our record in the interval from 4 to 3 Ma offers the first high-resolution glimpse of high-latitude SST variability prior to widespread glaciation of the Northern Hemisphere and a detailed picture of the relationship between North Atlantic sea surface temperature and the rapid growth of Northern Hemisphere ice in the late Pliocene. We complement this continuous record with an approximately 500 k long window of alkenone paleotemperature data from Deep Sea Drilling Project (DSDP) Site 607 to the south of Site 982 in order to provide a regional perspective on SST variance before the intensification of NHG. The general picture of a warm, low-variability early Pliocene painted by existing time series of benthic and planktonic δ^{18}O and low-latitude sea surface temperature [e.g., *Billups et al.*, 1998; *Cannariato and Ravelo*, 1997; *Lawrence et al.*, 2006; *Lisiecki and Raymo*, 2005] would predict that in the absence of the strong feedbacks imposed by large Northern Hemisphere ice sheets, a time series of high-latitude North Atlantic SST should show subdued variation in the early Pliocene. Instead, our Site 982 data indicate that high-latitude North Atlantic sea surface conditions were as variable during the early Pliocene (3–4 Ma) as they were during the late Pleistocene (0–0.8 Ma) and that major changes in the mean state of North Atlantic climate occurred well before the intensification of NHG at ~2.7 Ma.

2. Methods

[6] We analyzed ocean sediments for the interval from 4 Ma to the present from Ocean Drilling Project (ODP) Site 982 (58°N, 16°W, 1134 m water depth, mean annual surface temperature 11°C), located on top of the Rockall Plateau in the North Atlantic Ocean, and in the time window from 4 to 3.5 Ma at DSDP Site 607 (41°N, 33°W, 3427 m water depth, mean annual surface temperature 18.5°C), located to the south of Site 982 in the midlatitudes of the North Atlantic Ocean on the western flank of the Mid-Atlantic Ridge (Figure 1). The sites' locations, sedimentation rates (2–4.5 cm/k), and seismic data all suggest that sediments at ODP Site 982 and DSDP Site 607 were deposited via settling through the overlying water column and were not transported to these localities by deep underwater currents (i.e., they are not "drift sites") [*Shipboard Scientific Party*, 1987; 1996b], which can, in some cases, compromise the interpretation of organic geochemical proxies [*Ohkouchi et al.*, 2002].

[7] Sediment samples were analyzed for alkenones, a suite of organic compounds uniquely synthesized by a few species of marine surface-dwelling haptophyte algae. The degree of unsaturation (i.e., the number of double carbon bonds) of alkenones depends on growth temperature [*Brassell et al.*, 1986; *Prahl and Wakeham*, 1987; *Prahl et al.*, 1988]. The now widely used alkenone unsaturation index ($U_{37}^{K'}$) produces rapid, reliable estimates of past near-surface ocean temperature [*Conte et al.*, 2006; *Müller et al.*, 1998].

[8] We extracted alkenones from freeze-dried sediment samples (average dry weight ~5 g) with 100% dicholoromethane using a Dionex accelerated solvent extractor (ASE) 200. Extracts were evaporated under a nitrogen stream and then reconstituted using 200 μL of toluene spiked with *n*-hexatriacontane (C_{36}) and *n*-heptatriacontane (C_{37}) standards. We quantified the C_{37} alkenones present in each sample using an Agilent Technologies 6890 gas chromatograph–flame ionization detector (GC-FID) by injecting 5 μL of each sample solution onto an Agilent Technologies DB-1 column (60 m × 0.32 mm × 0.10 μm film thickness). Starting from an initial temperature of 90°C, we increased the temperature at a rate of 40°C/min to 255°C and then slowly increased the temperature by 1°C/min to 300°C, concluding with a temperature increase of 10°C/min to 320°C and holding there for 10 min. We used the *Prahl et al.* [1988] calibration equation to translate alkenone unsaturation ratios to estimates of past sea surface temperatures. Replicate sample analysis indicates a reproducibility of ± 0.007 $U_{37}^{K'}$ units, equivalent to a temperature uncertainty of ±0.2°C. The concentration of alkenones in sediment samples ranged from 11 ng/g to 775 ng/g with average values during the interval before 2.5 Ma of 180 ng/g and average values after 2.5 Ma of 47 ng/g. While concentrations of alkenones in these samples are low, in particular, for the interval after 2.5 Ma, internal laboratory dilution experiments conducted at Brown University indicate that the amount of alkenones injected with each sample is above the threshold required to avoid the adverse effects of preferential adsorption of alkenones on the chromatographic column, which has been documented in previous studies [e.g., *Villanueva and Grimalt*, 1997].

[9] A previous North Atlantic–specific core top calibration study indicates that the alkenone unsaturation index is

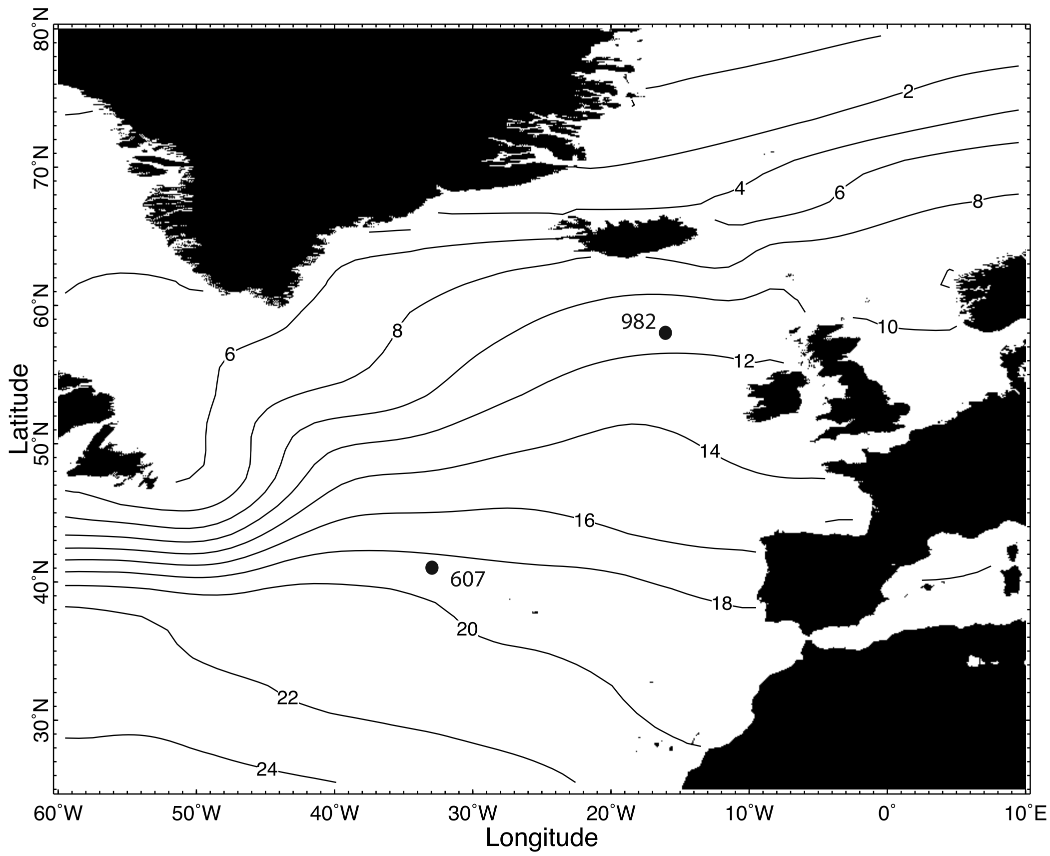

Figure 1. Locations of ODP Site 982 (58°N, 16°W) and DSDP Site 607 (41°N, 33°W). The site locations are superimposed on a map of North Atlantic mean annual SST [*Levitus and Boyer*, 1994]. Contours are in 2°C increments.

highly correlated with mean annual SST as well as SST for each of the four seasons ($R \geq 0.978$ in all cases) [*Rosell-Melé et al.*, 1995]. Here, we elect to use the most widely applied calibration equation, that of *Prahl et al.* [1988], which has been validated by several global core top calibration studies [*Conte et al.*, 2006; *Müller et al.*, 1998]. However, there is a distinct possibility that at the latitude of Site 982, alkenone temperature estimates reflect summer sea surface conditions rather than mean annual temperature. Water column and satellite data indicate that most coccolithophorid productivity in subpolar ocean regions, including the North Atlantic, occurs from summer to early autumn [*Brown and Yoder*, 1994; *Holligan et al.*, 1983; *Holligan et al.*, 1993; *Milliman*, 1980; *Samtleben and Bickert*, 1990]. A comparison of modern SSTs at Site 982, which have an annual range from 9 to 13°C [*Levitus and Boyer*, 1994], with the core top alkenone SST estimate, which is 13°C, also suggests a bias toward a summer season for alkenone production at Site 982. The existence of a summer alkenone production bias at high latitudes in the North Atlantic is also hinted at by an evaluation of the $U^{K'}_{37}$ data presented by *Rosell-Melé* [1995], which consistently fall above the expected global mean annual relationship in the northernmost samples of that study but converge to the global pattern at temperatures >15°C. However, we acknowledge that we have not precisely determined the age of our Site 982 core top sample beyond late Holocene age (as constrained by benthic δ^{18}O values) and that its $U^{K'}_{37}$ value could represent an integrated average of conditions hundreds to thousands of years before present.

[10] We also recognize the possibility that seasonal biases in the alkenone production may have shifted over the long time span of our study. In particular, in light of evidence presented below and other indications of high-latitude Pliocene warmth, it seems likely that alkenone production might have been much less seasonal in the warm early Pliocene. If alkenone paleotemperatures more closely approximated mean annual conditions early in the Site 982 record and summer temperatures (e.g., warmer than mean annual SST) in the late Pleistocene, then our long-term estimates would actually underestimate the total cooling that has occurred over the past 4 Ma at Site 982.

[11] The alkenone SST time series from ODP Site 982 is sampled at orbital resolution (an average of ~3 k) over the last 4 Ma, with the exception of the intervals between 2.5 and 1.75 Ma and 1.25 and 0.4 Ma, which are sampled at

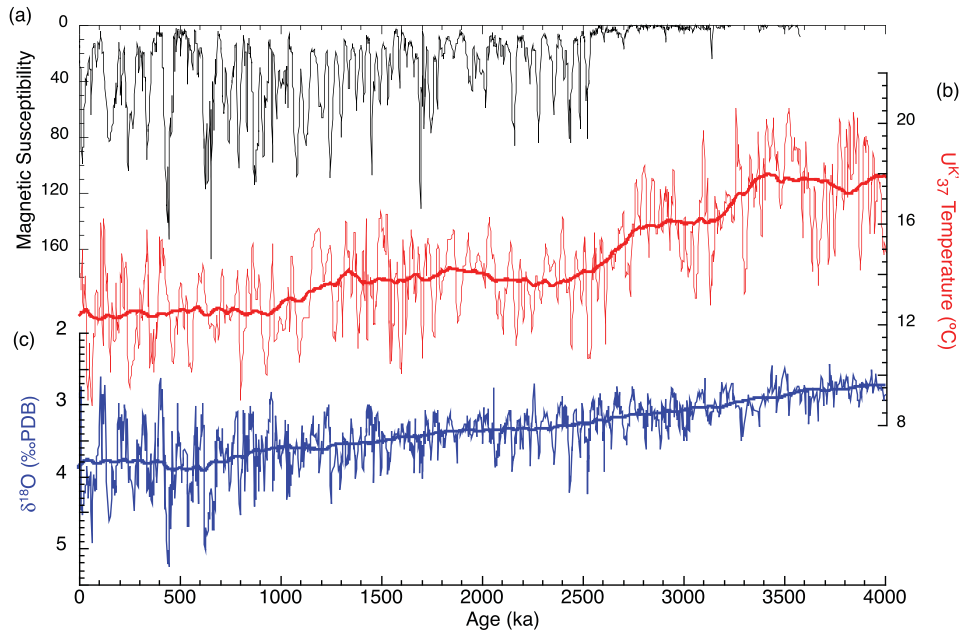

Figure 2. Paleoclimate data from ODP Site 982. (a) Magnetic susceptibility variations, which are interpreted as variations in ice-rafted debris (IRD) [*Shipboard Scientific Party*, 1996a] (black line) (note the inverted axis), (b) $U^{K'}_{37}$ temperature (°C) (red line), and (c) benthic δ^{18}O (blue line) [*Lisiecki and Raymo*, 2005; *Venz and Hodell*, 2002; *Venz et al.*, 1999]. The thick lines in Figures 2b and 2c are smoothed running means using a 400 k window.

∼10 k resolution. We compare our alkenone-derived record to high-resolution (∼3 k) stable oxygen isotope [*Lisiecki and Raymo*, 2005; *Venz and Hodell*, 2002; *Venz et al.*, 1999] and magnetic susceptibility (a proxy for past variations in ice-rafted debris (IRD)) [*Shipboard Scientific Party*, 1996b] records from the same site (Figure 2). Data from DSDP Site 607 are sampled at ∼4.5 k resolution for the interval from 3.5 to 4 Ma. Age models for both sites were developed by *Lisiecki and Raymo* [2005] on the basis of the correlation of the benthic oxygen isotope record from each site to the LR04 Stack [*Lisiecki and Raymo*, 2005] using the Match 2.0 program [*Lisiecki and Lisiecki*, 2002] and were obtained directly from L. Lisiecki (2006).

[12] We used the Arand software package [*Howell*, 2001] to conduct our spectral and cross-spectral analyses. Given the strong evidence [e.g., *Lawrence et al.*, 2006; *Lisiecki and Raymo*, 2005; *Raymo et al.*, 1989; *Ruddiman et al.*, 1989; *Zachos et al.*, 2001] for the importance of changes in obliquity in driving climatic variations in the Pliocene and early Pleistocene, we are particularly interested in characterizing the 41 ka band spectral evolution. We present the evolutionary spectra of our data both with and without prewhitening (Figures 3 and 4). While prewhitening helps reduce the red spectral background arising from the nonlinear long-term evolution of the time series, allowing for better resolution of SST variability in the frequency range of obliquity and precessional variations, it also attenuates some of the spectral power concentrated in the 100 k band (Figures 3a and 3b). Because of the variable resolution of our SST record, in which some intervals are sampled at ∼3 k resolution and others are sampled at ∼10 k resolution, we present obliquity band evolutionary phase relationships between our $U^{K'}_{37}$-derived SST record and the Site 982 benthic δ^{18}O record only in the time windows for which we have orbital (∼3 k) resolution (Figure 5).

3. Results

[13] $U^{K'}_{37}$ SST estimates indicate a significant cooling at Site 982 over the past 4 Ma. The mean value during the interval between 4 and 3.5 Ma was ∼17.5°C, whereas after 2.5 Ma the mean value was ∼13°C (Figure 2). Most surface ocean cooling occurred during the interval between ∼3.5 and ∼2.5 Ma (4.5°C/Ma) (Figure 2). After ∼2.5 Ma, mean SST changed much more slowly (0.7°C/Ma), with most of the remaining cooling (1.5°C) occurring between ∼1.4 and 0.9 Ma across the mid-Pleistocene transition (Figure 2). These features give the Site 982 temperature record a stepped profile. Importantly, after ∼2.5 Ma the warmest interglacial temperatures remain essentially constant (∼16°C), whereas the extreme glacial temperatures exhibit progressively colder values toward the present (Figure 2).

[14] Comparisons between the Site 982 SST record and other previously published long-term (>1 Ma long) SST time series from the North Atlantic Ocean [*Ruddiman and McIntyre*, 1984; *Ruddiman et al.*, 1986, 1989] show a marked similarity in trend and structure but a difference in the absolute value of the temperature estimates. A 1.1 Ma faunal-based composite record from piston core K708-7 (54°N, 24°W) and DSDP Site 552 (56°N, 23°W) located

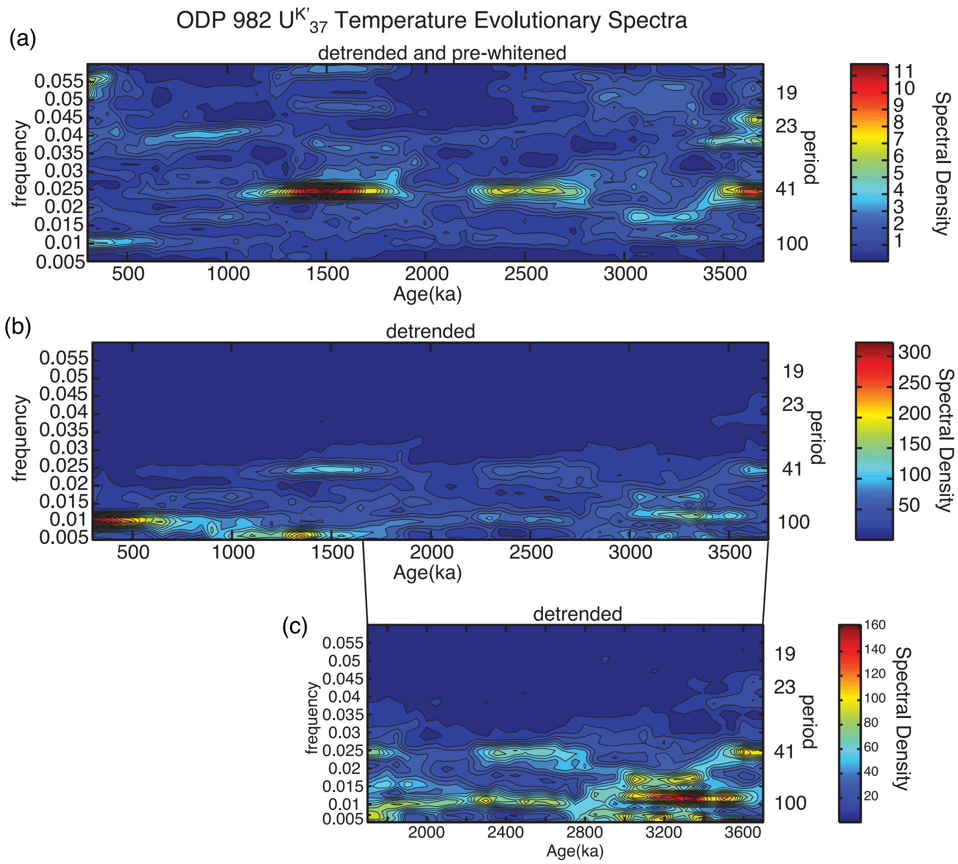

Figure 3. Evolutive spectra of ODP Site 982 $U^{K'}_{37}$ temperature. (a) Detrended and prewhitened time series, (b) detrended time series, and (c) Pliocene subset of the detrended time series. Spectra were computed using the Arand software [*Howell*, 2001] spectral program's iterative mode. All responses were interpolated to even intervals of 2 k resolution prior to analysis. We applied the autocovariance function, a full linear detrend, a 600 k window, a 50% lag, and an increment of 50 k to each of the time series. Each plot is scaled to its own maximum spectral density. The time series for Figure 3a was prewhitened by setting prewhitening equal to 1. Comparing Figure 3a to Figure 3b illustrates the attenuation of the lower-frequency part of the spectrum achieved through prewhitening. Figure 3c highlights the important low frequencies present in the Pliocene portion of the temperature record where the absolute spectral density is lower than that in the latest Pleistocene.

just to the south and west of Site 982 yields a mean summertime SST estimate of ~10°C (3°C colder than the mean for this interval (0–1.1 Ma) at Site 982) and a mean wintertime SST estimate of ~5°C (8°C colder than the mean for this interval (0–1.1 Ma) at Site 982) [*Ruddiman and McIntyre*, 1984]. Another faunal-based North Atlantic SST record from DSDP Site 607 (41°N, 33°W) [*Ruddiman et al.*, 1986] located 17°S and 17°W of Site 982 provides a mean summertime SST estimate of ~19°C (6°C warmer than the mean for this interval (0–1.1 Ma) at Site 982) and a mean wintertime SST estimate of ~13°C (comparable to the mean for this interval (0–1.1 Ma) at Site 982). Because these previously developed SST time series are derived from a different (faunal-based) paleotemperature estimation technique as well as from different localities, it is unclear to what extent the difference in absolute values of the temperature estimates reflect real differences in SST at these different sites or stem from the use of different paleotemperature proxies and their associated calibration uncertainties.

[15] The interval of pronounced sea surface cooling at ODP 982 terminates at about 2.5 Ma, the same time that high-amplitude fluctuations in magnetic susceptibility characteristic of strong glacial-interglacial variations in IRD begin (Figure 2). The cooling therefore apparently culminated by crossing a threshold sufficient to generate IRD south of Iceland for nearly all glacial periods after 2.5 Ma (Figure 2). A comparison of the $U^{K'}_{37}$ SST and benthic $\delta^{18}O$ records indicates that pronounced coolings at 3.66 Ma (marine oxygen isotope stage (MIS) Gi4), 3.63 Ma (MIS Gi2), 3.30 Ma (MIS M2), 2.61 Ma (MIS 104), 2.52 Ma (MIS 100), 2.42 Ma (MIS 96), and 1.70 Ma (MIS 60) in the SST record are also evident in the $\delta^{18}O$ record (i.e., coolings

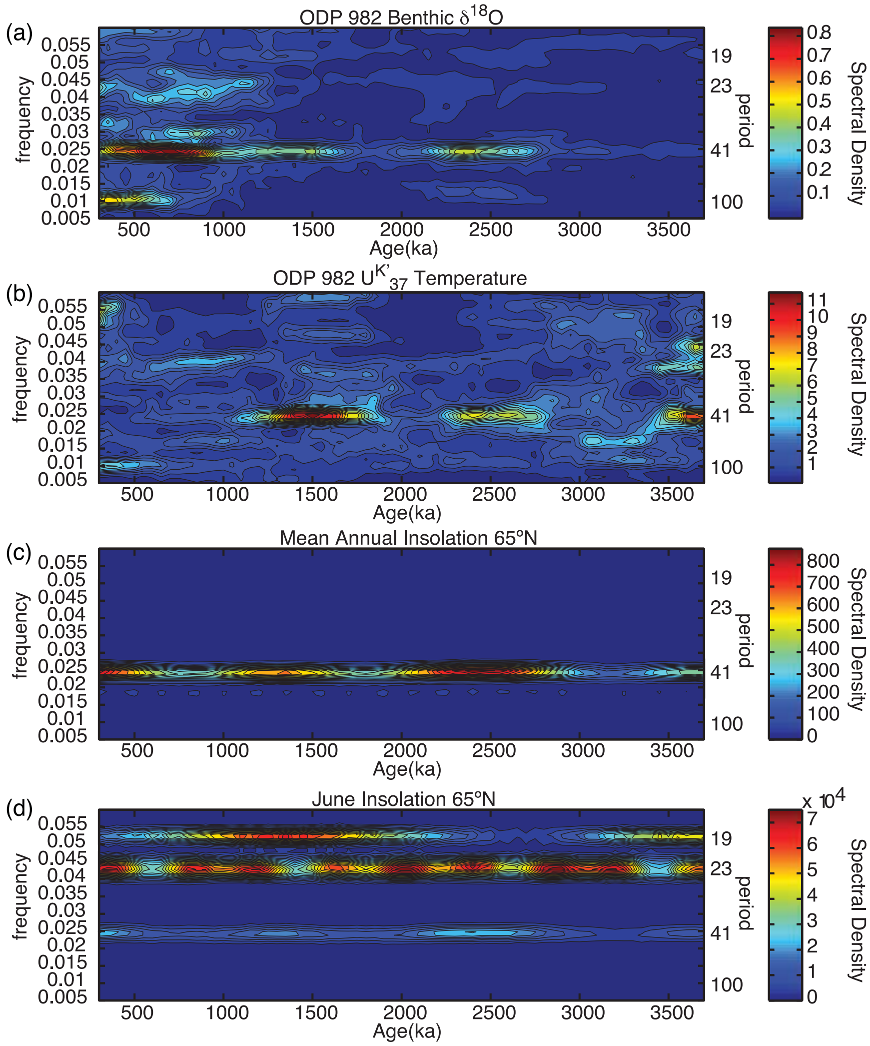

Figure 4. Evolutive spectra of ODP Site 982 paleoclimate proxies and 65°N insolation. (a) Benthic δ^{18}O, (b) $U^{K'}_{37}$ temperature, (c) 65°N mean annual insolation, and (d) 65°N June insolation. Insolation time series are based on the La90 orbital solutions [*Laskar*, 1990]. Spectra were computed using the Arand software [*Howell*, 2001] spectral program's iterative mode. All responses were interpolated to even intervals of 2 k resolution prior to analysis. We applied the autocovariance function, a full linear detrend, a 600 k window, a 50% lag, and an increment of 50 k to each of the time series. The $U^{K'}_{37}$ temperature and benthic δ^{18}O time series were prewhitened by setting prewhitening equal to 1. Each plot is scaled to its own maximum spectral density. Note that during the time intervals 2.5 to 1.75 Ma and 1.25 to 0.4 Ma the temperature record was sampled at 10 k resolution, which may result in an underrepresentation of the spectral density in the precession and obliquity bands during these time periods.

are greater than 2σ from both running means) (Figure 2). Like Plio-Pleistocene records of δ^{18}O [e.g., *Lisiecki and Raymo*, 2005], the Site 982 $U^{K'}_{37}$ SST record consistently bears the imprint of obliquity variations during most of the Plio-Pleistocene transition (Figures 4a and 4b). However, in contrast to Plio-Pleistocene oxygen isotope records, the Site 982 SST record indicates that high-amplitude, obliquity-driven variations existed in the interval before 2.7 Ma (Figure 4b). SST variance during the interval between 3.7 and 2.7 Ma (σ^2 = 3°C) was 50% greater than during the interval between 2.7 and 1.7 Ma (σ^2 = 2°C). Before ~3 Ma, the $U^{K'}_{37}$ SST record was characterized by high-amplitude cycles, with SST variations as large as 8°C on orbital time scales (Figure 2). The SST variations appear to be strongly paced by high-latitude, obliquity-driven insolation variations (Figures 4b–4d), although quasi 100 k cycles accompany the interval with the greatest-amplitude SST variations (~3.5–3 Ma) (Figure 2). Spectral analysis reveals that these

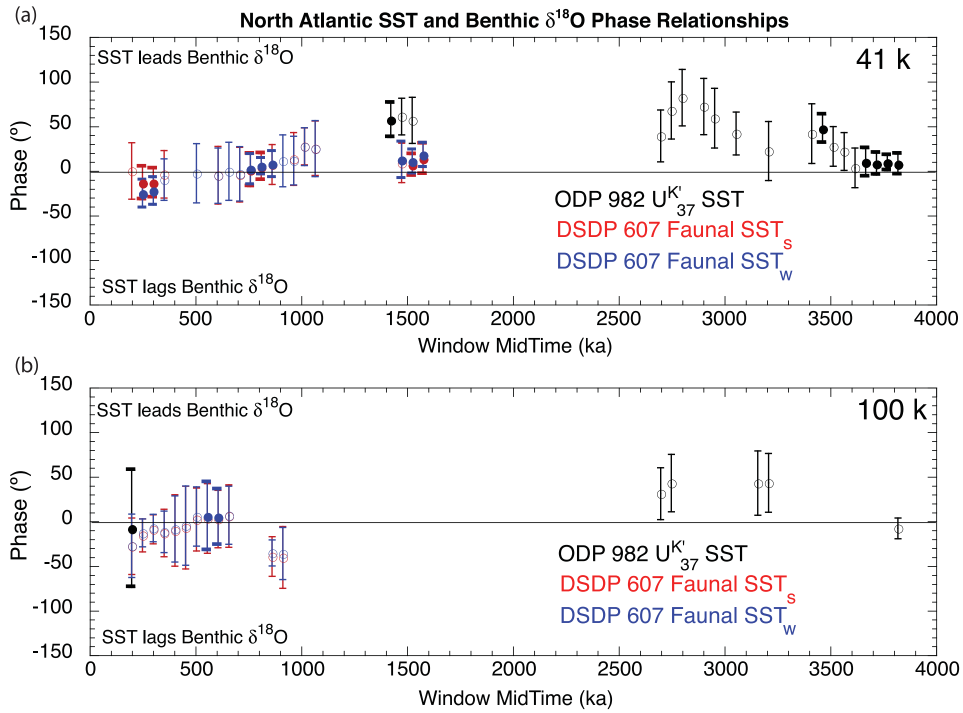

Figure 5. ODP Site 982 and DSDP Site 607 phase and coherency between sea surface temperature and benthic records ($-\delta^{18}$O) for (a) 41 k band and (b) 100 k band. Black circles indicate 982 $U^{K'}_{37}$ SST (this study), red circles indicate DSDP faunal summertime SST [*Ruddiman et al.*, 1989], and blue circles indicate DSDP Site 607 faunal wintertime SST [*Ruddiman et al.*, 1989] phases relative to the benthic $-\delta^{18}$O from each site. Intervals that are coherent at the 80% confidence level are shown as empty circles, while those that are coherent at the 95% confidence level are shown with solid circles. We used the inverse of benthic δ^{18}O in our coherency and phase analyses to be consistent with paleoclimatic convention and the axes in Figure 2. Prior to coherency and phase analysis all records were interpolated to even intervals of 3 k resolution. For our 982 SST time series we show phases only in intervals that are resolved at ~3 k resolution (i.e., 4 Ma to 2.5 Ma, 1.75 Ma to 1.25 Ma, and 0.4 Ma to present). Phases were computed using the Arand software [*Howell*, 2001] Crospec program's iterative mode with a 400 k window, 200 lags, and a 50 k increment.

quasi 100 k cycles have periods that are multiples of obliquity beats (1.5, 2, and 3 times the fundamental period, e.g., approximately 60, 80, and 120 k) (Figure 3c). As in most other climate time series that span the Pleistocene, the most prominent Milankovitch beat in our North Atlantic SST record shifts from 41 k to 100 k between ~1 and ~0.5 Ma during the mid-Pleistocene transition (Figures 3a and 3b). Some precessional power is evident in the $U^{K'}_{37}$ SST record, particularly in the interval between 4 and 3.5 Ma (Figure 4b). Note that during the low sampling rate time intervals (2.5–1.75 Ma and 1.25–0.4 Ma), our spectral analysis may be missing some of the variance in the precessional and obliquity bands.

[16] In the obliquity band, where much of the Milankovitch variability in this record is concentrated, $U^{K'}_{37}$ SST and benthic δ^{18}O are coherent in most of our orbitally resolved windows during the Pliocene and early Pleistocene (Figure 5). SST and benthic δ^{18}O are nearly in phase, with SST leading benthic δ^{18}O by ~2 k in the early Pliocene (before 3.5 Ma) (Figure 5). Commencing at ~3.5 Ma, well before the canonical date associated with the intensification of NHG (~2.7 Ma), the phase lead of SST over benthic δ^{18}O in the obliquity band begins to grow, reaching a maximum of 9 k between 2.8 and 2.7 Ma (Figure 5). By the end of our high-resolution interval in the Pliocene (2.5 Ma) as well as during our high-resolution window in the early Pleistocene (1.75–1.25 Ma) the phase lead of SST relative to benthic δ^{18}O is between 4.5 and 6.5 k (Figure 5). During our high-resolution window in the late Pleistocene (0–0.4 Ma), spectral density of the 41 k component of SST is low (Figure 4b), and SST and benthic δ^{18}O are not coherent in the 41 ka band (Figure 5). In contrast, in the 100 ka band, Site 982 SST and benthic δ^{18}O are not coherent in our high-resolution early Pleistocene window (1.75–1.25 Ma) but are coherent and nearly in phase (2 k SST lag) during our late Pleistocene high-resolution window (0–0.4 Ma) (Figure 5).

[17] *Ruddiman and McIntyre* [1984] and *Ruddiman et al.* [1989] produced the only other existing North Atlantic SST record long enough to examine the evolving orbital phase

relationships between SST and other climate variables. They used planktonic foraminiferal assemblages recovered from DSDP Site 607 to infer the relationship of SST to benthic δ^{18}O over the past 1.6 Ma. *Ruddiman and McIntyre* [1984] and *Ruddiman et al.* [1989] concluded that SST was in phase with or slightly lagged benthic δ^{18}O in both the 41 ka and 100 ka bands in the late Pleistocene North Atlantic (Figure 5). Comparing Site 982 phase responses to those from Site 607, we find that during our high-resolution window in the latest Pleistocene (0–0.4 Ma), both Site 982 and Site 607 SST records are nearly in phase with benthic δ^{18}O in the 100 ka band (Figure 5). In contrast, during our early Pleistocene high-resolution window (1.75–1.25 Ma) the phase lead of SST over benthic δ^{18}O in the 41 ka band is larger at ODP 982 ($\sim$6.5 k) than at DSDP Site 607 (1.5 k) (Figure 5). Absent time series of the same proxy, it is unclear whether the existing differences in SST-δ^{18}O phase evolution between Sites 982 and 607 are indicative of real differences in the response to obliquity forcing at these sites or are artifacts of mixing proxies.

4. Discussion

[18] Several notable observations emerge from our $U_{37}^{K'}$ temperature record. Surface ocean conditions at ODP Site 982 in the North Atlantic during the early Pliocene were both warm and highly variable. Furthermore, our $U_{37}^{K'}$ temperature record shows that pronounced cooling of the North Atlantic surface ocean (4.5°C/Ma at Site 982) started well before the date typically invoked as the start of the intensification of Northern Hemisphere glaciation ($\sim$2.7 Ma) [e.g., *Bartoli et al.*, 2005; *Haug et al.*, 1999; *Maslin et al.*, 1996; *Raymo*, 1994; *Sigman et al.*, 2004] and was followed by a late Pliocene to Pleistocene interval with a modest long-term temperature decrease ($\sim$1.5°C) (Figure 2).

[19] As with all surface temperature records, the Site 982 paleotemperature changes reflect processes operating at multiple spatial and temporal scales. SSTs at the site were dictated by a combination of regional and global processes and resulted from climatic sensitivities that could range in time scale from rapid (e.g., direct forcing by insolation cycles, changes in the surface wind fields, growth and decay of sea ice) to slow (e.g., growth of continental ice sheets). Of particular interest to this study is the question of the extent to which Site 982 SSTs reflect circum–North Atlantic processes directly tied to the intensification of Northern Hemisphere glaciation. This is not a forgone conclusion; studies of Pliocene climatic variations find significant regional deviations of paleotemperature and other variables from the pattern set by the global δ^{18}O curve [*Ravelo et al.*, 2004]. To a surprising extent, the Site 982 SST patterns do in fact mirror the Northern Hemisphere glaciation template. The major steps in Plio-Pleistocene cooling observed precisely correlate with major developments in the Plio-Pleistocene ice ages: the majority of cooling took place between approximately 3.5 and 2.5 Ma, matching the major "step" in the marine δ^{18}O record [*Mudelsee and Raymo*, 2005], and the remaining cooling occurred over the mid-Pleistocene transition, when glacial cycles switched their timing from 41 to 100 k cycles (Figures 2 and 4). The end of the Pliocene cooling step coincides with the establishment of regular ice rafting, as seen by the magnetic susceptibility proxy for IRD (Figure 2). And individual ice ages as captured by the benthic δ^{18}O values at Site 982 (including precursor glaciations such as MIS Gi4 (3.66 Ma), Gi2 (3.63 Ma), and M2 (3.3 Ma)) coincide in every case with low SST as inferred by alkenone unsaturation.

[20] The evolution of SST at Site 982 may shed light on the substantial ambiguities in interpreting the benthic δ^{18}O record over the Plio-Pleistocene and help to better understand the dramatic shift of Earth's climate from the warm early Pliocene into the icehouse state of the Pleistocene. In sections 4.1 and 4.2, we place the most significant patterns that emerge from Site 982 into the context of previous Pliocene surface temperature reconstructions and current understanding of the development of the Plio-Pleistocene ice ages. We focus particular attention on two unexpected results: the high variability in SST recorded before the generally accepted date for sustained Northern Hemisphere glaciation and the phase separation of SST from benthic δ^{18}O that begins at $\sim$3.5 Ma.

4.1. A Warm and Variable Early Pliocene in the High-Latitude North Atlantic

[21] Virtually all climate records spanning the Plio-Pleistocene transition support the notion that Earth's climate before the development of large ice sheets in the Northern Hemisphere was both warmer and more stable than the late Pleistocene [*An et al.*, 2001; *Draut et al.*, 2003; *Lawrence et al.*, 2006; *Lisiecki and Raymo*, 2005; *Thiede et al.*, 1998]. Our $U_{37}^{K'}$ temperature record suggests that average SSTs at 58°N during the early Pliocene were 17°C ($\sim$6°C warmer than the modern mean annual temperature at this site), with individual interglacials as warm as 21°C ($\sim$10°C warmer than the modern mean annual temperature at this site). Our inference that warm conditions prevailed at high northern latitudes during the early Pliocene is consistent with results from a diverse array of previous work. Foraminiferal faunal assemblages from a set of sites at high latitudes in the North Atlantic indicate that SSTs were approximately 3–8°C warmer than modern values at latitudes between 45° and 66°N during the interval from approximately 3.3 to 3 Ma [*Dowsett and Poore*, 1991; *Dowsett et al.*, 1996, 1992]. Terrestrial climate records from the early Pliocene warm period suggest that air temperatures were 10–15°C warmer than modern values in northern Alaska and the Arctic [e.g., *Ballantyne et al.*, 2006; *Brigham-Grette and Carter*, 1992; *Elias and Matthews*, 2002; *Matthews and Ovenden*, 1990; *Tedford and Harington*, 2003]. Additional qualitative evidence for high northern latitude warmth during the early Pliocene comes from ostracode assemblages and palynological and paleobotanical data from marine sediments recovered from the Yermak Plateau and northern Iceland [*Cronin and Whatley*, 1996; *Cronin et al.*, 1993; *Willard*, 1996].

[22] In contrast, Mg/Ca-derived estimates of surface temperatures suggest SSTs were, on average, 10°C during the interval from 3 to 2 Ma at Site 984 (61°N, 24°W) to the north of 982 and 14°C at Site 609 (50°N, 24°W) to the south of 982 during the interval from 3.5 to 2.5 Ma [*Bartoli et al.*,

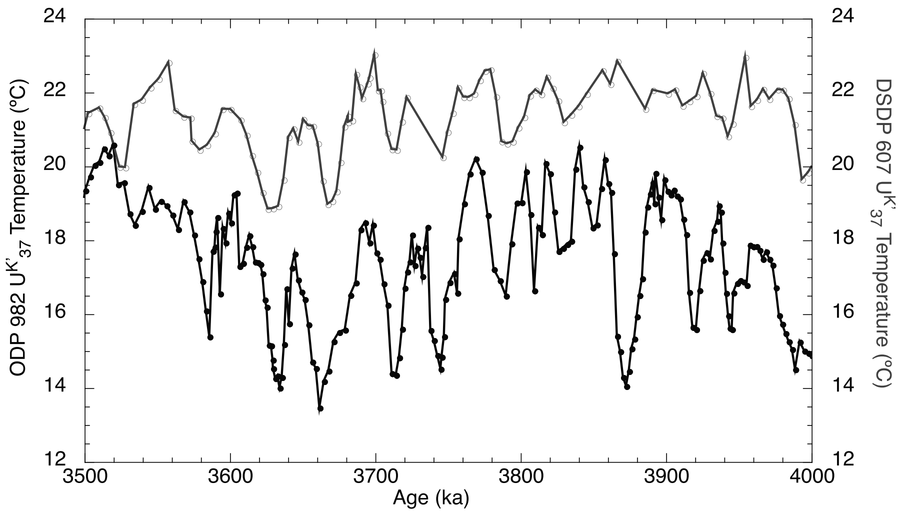

Figure 6. $U_{37}^{K'}$ temperature (°C) for the interval from 3.5 to 4 Ma from North Atlantic Sites ODP 982 (black line with filled black circles) and DSDP Site 607 (gray line with empty circles).

2005]. These Mg/Ca-derived estimates are similar to modern values and are considerably colder than those derived from other proxies at other sites in the region. Mg/Ca paleotemperature estimates are strongly calibration dependent [*Anand et al.*, 2003; *Dekens et al.*, 2002; *Elderfield and Ganssen*, 2000; *Mashiotta et al.*, 1999]. Thus, we suggest calibration uncertainties may account for the mismatch between Mg/Ca-derived SST estimates and all other North Atlantic proxy data during this time period.

[23] The warm and highly variable SSTs observed at Site 982 during the early Pliocene are in keeping with results from the faunal assemblage data produced by Pliocene Research, Interpretation and Synoptic Mapping 2 (PRISM2) North Atlantic SST reconstructions for the short time window (approximately 3–3.3 Ma) [*Dowsett et al.*, 2005]. However, the high amplitude of orbital-scale SST change at Site 982 in the 3–4 Ma time window, which is comparable to late Pleistocene glacial-interglacial variability at the site, greatly exceeds the variability found in other existing climate time series for this time period. Benthic δ^{18}O records, which monitor changes in high-latitude ice volume and deep ocean temperature, show very low amplitude (0.2–0.3‰ at the 41 k frequency, equivalent to 20–30 m of sea level change or 1–1.5°C of bottom water temperature change) variations throughout the early Pliocene [*Lisiecki and Raymo*, 2005]. Variability in benthic δ^{18}O records, including Site 982, increases dramatically at ~2.7 Ma with the intensification of NHG (Figures 2c and 4a). Similarly, high-resolution, alkenone-based reconstructions of SST from the low latitudes [e.g., *Lawrence et al.*, 2006], high-resolution records of eolian dust flux and grain-size variations from the Chinese Loess Plateau [*An et al.*, 2001], as well as biogenic opal and terrigenous flux records from the equatorial Atlantic [*Ruddiman and Janecek*, 1989] show the same pattern as the benthic δ^{18}O record, with muted orbital-scale variations through the mid-Pliocene followed by marked increases in variability coincident with the intensification of NHG (~2.7 Ma). Finally, modest (2–3°C) amplitude variations in early Pliocene $U_{37}^{K'}$ temperature at DSDP Site 607 (41°N, 32°W), located less than 20° of latitude south of Site 982 in the midlatitudes of the North Atlantic Ocean (Figure 1), also suggest a stable early Pliocene climate (Figure 6). In this context, the $U_{37}^{K'}$ temperature record ODP Site 982 is anomalous because it indicates that North Atlantic Ocean surface temperatures were highly variable well before the intensification of NHG at ~2.7 Ma.

[24] What gave rise to the high variability of Site 982 SSTs during the early Pliocene? One possibility is that our early Pliocene SST estimates reflect strong regional high-latitude feedbacks to obliquity-induced insolation changes that existed even prior to the development of substantial Northern Hemisphere ice volume. In order to be consistent with the early Pliocene benthic δ^{18}O record, the amplifying effects would need to operate without producing large isotopic effects in the deep ocean. For example, ice albedo feedbacks related to the development of sea ice in regions to the north of Site 982 or the presence of large but thin ice sheets at high northern latitudes could have resulted in substantial high-latitude variability before NHG was felt by the deep-sea isotopic record (~2.7 Ma). Recent studies illustrate the plausibility of these scenarios. Cosmogenic radionuclide dating of glacial deposits in the central United States (~39°N) suggests the Laurentide ice sheet may have covered that region during the Pliocene [*Balco et al.*, 2005]. Results from the Arctic Coring Expedition (ACEX) indicate that extensive sea ice may have existed in the Arctic long before the intensification of Northern Hemisphere glaciation [*Darby*, 2008; *Moran et al.*, 2006]. Several ACEX-derived studies argue that ice rafting in the Northern Hemisphere stretches back to the middle Eocene (~46 Ma) [*Moran et al.*, 2006] and that perennial Arctic ice cover has persisted

since ∼14 Ma [*Darby*, 2008]. Furthermore, a modeling sensitivity study examining the climatic effects of reduced Arctic sea ice indicates that regional temperatures are highly sensitive to changes in the extent of Northern Hemisphere sea ice [*Raymo et al.*, 1990a].

[25] Corroboration of the high variability and strong obliquity beat observed at ODP Site 982 at other sites to the north of Site 982 would indicate that a strong high-latitude obliquity response did not first appear with the intensification of NHG. Instead, such data would suggest that a growing high-latitude climate instability finally culminated in a persistent Northern Hemisphere ice volume response at ∼2.7 Ma. If our ODP Site 982 results are representative of the high-latitude North Atlantic or high-latitude climate as a whole, then they are a significant challenge to our prior notions about the stability of early Pliocene climate.

[26] Alternatively, the high variability as well as the warmth observed at ODP Site 982 during the early Pliocene warm period may instead be explained by changes in the strength and position of the North Atlantic Drift, which would imply that large Pliocene SST oscillations were of limited regional extent, did not necessarily penetrate to the highest latitudes of the North Atlantic, and did not necessarily correspond to episodes of sea ice or continental ice growth and decay. Today, Site 982 underlies the sluggish North Atlantic Drift (1–3 cm/s) and is located just south of the boundary between the polar easterlies and the midlatitude westerlies, placing it in a region that is highly sensitive to the position of atmospheric pressure systems and thus ocean currents. *Dowsett et al.* [2005] invoked the strength and position of ocean currents to explain their early Pliocene North Atlantic faunal assemblage data. They too observe significant warmth and high SST variability during the early Pliocene relative to today at sites spanning a band of latitudes from 40° to 66°N. They attribute the overall warmth of North Atlantic SSTs to increased early Pliocene oceanic heat transport via the Gulf Stream and North Atlantic Drift [*Dowsett et al.*, 1992] and the high SST variability to variations in the position of these poleward flowing currents [*Dowsett et al.*, 2005].

[27] Several modeling studies that investigated “Pliocene-like” conditions in the North Atlantic also suggest that ODP Site 982 may lie in a position of unusual sensitivity. These studies found significant changes in pressure systems over the North Atlantic Ocean relative to today [*Haywood et al.*, 2000a, 2000b, 2002a; *Raymo et al.*, 1990a]. Using an atmospheric climate model and imposing middle Pliocene (approximately 3.3–3 Ma) boundary conditions from the PRISM2 data set [*Dowsett et al.*, 1999], including warmer SSTs and reduced Northern Hemisphere ice cover, *Haywood et al.* [2002b] reported a significant deepening of the Icelandic low and an increase in the Azores high-pressure system (Figures 7a and 7b). These changes in pressure systems increased the surface pressure gradient and thus augmented wind stress over the North Atlantic Ocean (Figures 7c and 7d), which may have enhanced surface gyre circulation and the flow of warm surface currents from the tropics to the North Atlantic. Sensitivity experiments from the same Pliocene modeling study suggest that significant changes in the strength of North Atlantic pressure systems and the latitudinal position of the strongest westerly winds occur in response to orbitally driven changes in solar insolation [*Haywood et al.*, 2002a].

[28] In another modeling study using an atmospheric general circulation model, *Raymo et al.* [1990a] examined the sensitivity of Northern Hemisphere climate to a reduction of Arctic sea ice extent relative to the modern day. In response to more ice-free conditions in the Arctic, a weaker Arctic polar high and a more northerly and localized Icelandic low resulted in enhanced cyclonic activity over the Nordic seas, allowing for increased heat transport from the south into the Nordic seas and Arctic Ocean [*Raymo et al.*, 1990a]. On the basis of these modeling study results, we propose that the very warm SSTs at ODP Site 982 during the early Pliocene may have been due to greater atmospheric and oceanic heat transport to the North Atlantic caused by changes in regional atmospheric pressure gradients under more ice-free conditions in the Northern Hemisphere. In addition, we suggest that the high-amplitude, short-term variations in SST at ODP Site 982 during the early Pliocene may have been related to orbitally induced variations in the position of the North Atlantic Drift. In this interpretation, the large temperature swings at the site derive more from orbital-scale coupling of the North Atlantic gyre to high-latitude insolation than to regional high-latitude (sea ice?) feedbacks.

[29] Variability in the Site 982 SST record during the Pliocene and early Pleistocene is primarily concentrated in the 41 k band and the spectral bands of its multiples (i.e., ∼60 k, ∼80 k, and ∼120 k) (Figure 3c). Perhaps the “bundling” of 41 k SST cycles into longer-term multiples reflects nonlinear responses of the North Atlantic Drift to obliquity forcing. Milankovitch-induced fluctuations in insolation should lead to changes in atmospheric pressure systems and thus also the location of the northern margin of the westerly wind belt. Because of Site 982’s location at the boundary of the westerlies and polar easterlies, modest changes in the position of these wind belts could have caused a replacement of warm North Atlantic Drift waters from the south by cooler waters from the north, resulting in very high amplitude changes in SST on orbital time scales. Depending on the exact location of the North Atlantic Drift and the amplitude of any given orbital obliquity cycle, the North Atlantic Drift may or may not move entirely off of Site 982. A shift in the North Atlantic Drift off the site would give rise to high-amplitude variations in SST. In contrast, the continuous presence of the North Atlantic Drift over the site would result in lower-amplitude 41 k cycles. If the large fluctuations in Site 982 SST during the early Pliocene are due to its location near the northern margin of the North Atlantic Drift, variability of SST at sites both north and south of Site 982 should be much lower than at Site 982. Low-amplitude early Pliocene SST variations at DSDP Site 607, located in the northern part of the North Atlantic gyre and south of Site 982, are consistent with the suggestion that Site 982 is in a particularly sensitive location (Figure 6). However, additional data to the west and north of Site 982 (i.e., away from the North Atlantic Drift) are required to test this hypothesis.

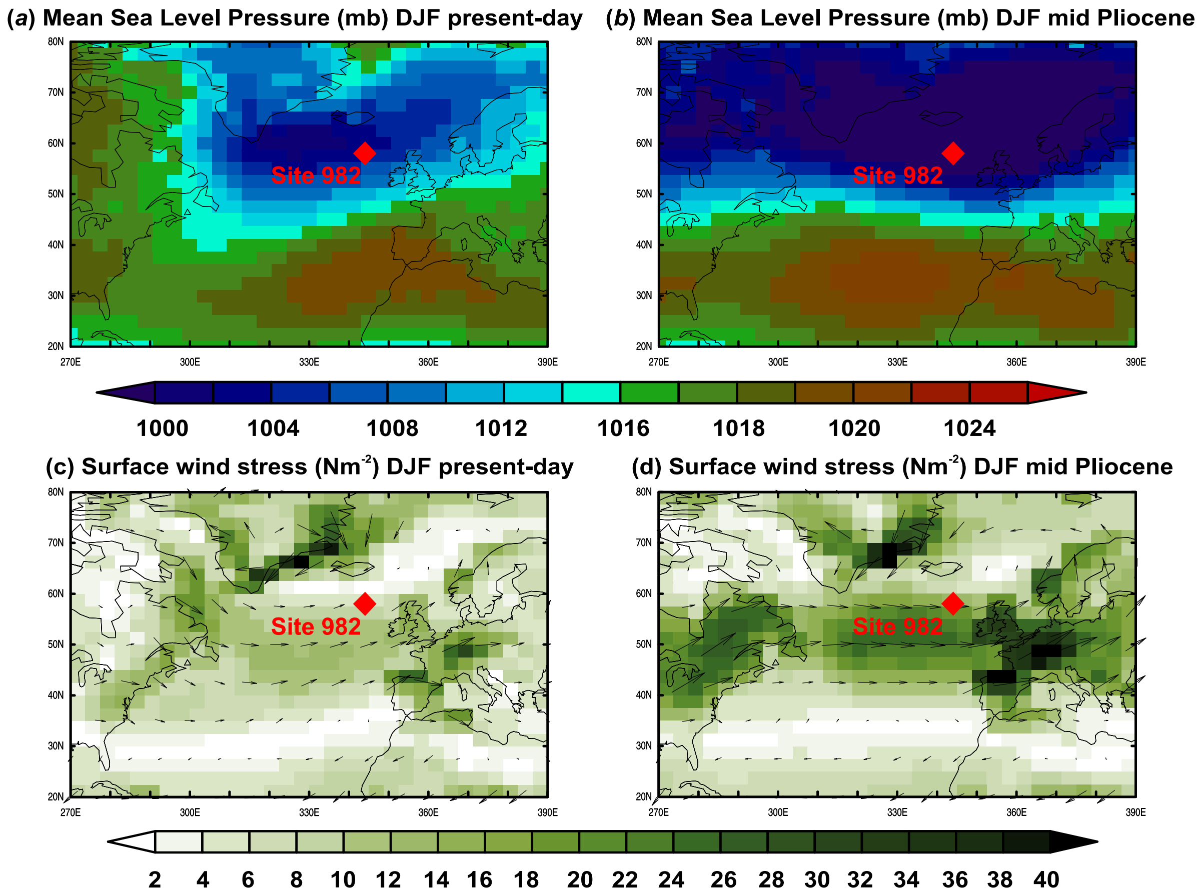

Figure 7. North Atlantic climate parameters from general circulation climate model simulations of the present-day and mid-Pliocene using the UK Met Office Unified Model (Hadley Centre Model) [*Haywood et al.*, 2000b]. (a) Mean December, January, February (DJF) sea level pressure (mbar) for the present day. (b) Mean DJF sea level pressure for a control mid-Pliocene simulation. (c) Mean DJF surface wind stress (Nm^{-2}) and vectors for the present day. (d) Mean DJF surface wind stress and vectors for a control mid-Pliocene simulation. Note the large differences between mid-Pliocene and present-day mean sea level pressure and surface wind stress.

4.2. Gradual Cooling and the Intensification of Northern Hemisphere Glaciation

[30] The idea that Northern Hemisphere glaciation began abruptly at ~2.7 Ma is both correct and potentially misleading. Ice rafting increased dramatically at this time in both the North Atlantic and North Pacific [*Maslin et al.*, 1996; *Shackleton et al.*, 1984]. This increase in ice rafting coincides with a major enrichment in benthic $\delta^{18}O$ that almost certainly signals the first of the large glacial-interglacial cycles of climate that continue to the present day. However, one can also make a compelling case that in many ways Northern Hemisphere glaciation developed gradually. Our new SST data fit this more gradual model.

[31] As documented by a new synthesis of the marine $\delta^{18}O$ record, the time period between 3.6 and 2.4 Ma marks a sustained time of ice sheet growth and/or deep-sea cooling [*Mudelsee and Raymo*, 2005]. In this context, the ~2.7 Ma date for the intensification of Northern Hemisphere glaciation is the outcome of a long-term shift toward an icehouse state and the first of many large orbital-scale glacial to interglacial cycles in climate. Furthermore, *Lisiecki and Raymo* [2005] demonstrated that the variance of the entire 5 Ma benthic $\delta^{18}O$ record can be modeled to first order as an exponential trend increasing toward the present. The pronounced cooling that we observe from 3.5 to 2.5 Ma at Site 982 also supports the notion that Northern Hemisphere glaciation set in as a gradual [e.g., *Mudelsee and Raymo*, 2005] rather than abrupt [e.g., *Bartoli et al.*, 2005] evolution in climate.

[32] Marine oxygen isotope time series harbor considerable ambiguities that may eventually be resolved with proxies that isolate the ocean's temperature history over time. By themselves, the isotopic data cannot constrain factors that were certainly critical over Plio-Pleistocene time, such as when the Greenland ice sheet formed, where ice grew during glacial expansions, how sea ice evolved

over this interval, and whether the tempo of ocean cooling was gradual or abrupt. On the basis of the Site 982 SST record, we propose the following sequence of events: northern sea ice was already a substantial amplifying factor on orbital time scales prior to 3.5 Ma, the time period between 3.5 and 2.5 Ma saw a broad cooling of the high-latitude North Atlantic that allowed a sizable Greenland ice cap to persist for the first time through interglacial stages of climate, and the ice volume component of the 3.6–2.4 Ma "step" [*Mudelsee and Raymo*, 2005] lagged significantly the deep-sea temperature component of the signal; that is, most of the initial trend came from deep-sea cooling, but ice volume came to dominate the later phase of the step.

[33] Site 982 is well situated to record the regional effects of a growing Greenland ice sheet. We hypothesize that the sustained temperature decrease recorded between 3.5 and 2.5 Ma records the gradual cooling of the high North Atlantic necessary to sustain a Greenland ice cap of approximately modern extent through interglacial states. The cooling may in turn reflect the positive feedbacks that a growing Greenland ice sheet produced in regional albedo and wind systems. An examination of IRD studies from the North Atlantic region suggests that Greenland was the locus for the first substantial ice sheet in the Northern Hemisphere. Glaciers large enough to calve into the ocean existed in southeast Greenland starting in the late Miocene (~7 Ma), and several marked expansions of Greenland ice growth occurred in the interval from 3.5 to 2.5 Ma [*Elverhøi et al.*, 1998; *Flesche Kleiven et al.*, 2002; *Jansen et al.*, 2000; *Larsen et al.*, 1994; *Raymo et al.*, 1989; *St. John and Krissek*, 2002]. Furthermore, the persistence of this Northern Hemisphere ice sheet alone in recent interglacials [*de Vernal and Hillaire-Marcel*, 2008] reinforces the idea that Greenland has provided the interglacial refuge for Northern Hemisphere ice for some time. The cooling at Site 982 terminates at about 2.5 Ma, when ice rafting becomes a common phenomenon in the North Atlantic (Figure 2). We therefore see the high-latitude cooling and growth of a persistent near modern sized Greenland ice cap as setting the baseline for the succeeding 2.5 Ma of glacial cycles, which have seen relatively little long-term cooling in the North Atlantic region.

[34] We note that the isotopic contribution of an interglacial-sized Greenland ice sheet (7 m of sea level, or ~0.07‰ in δ^{18}O) is small enough that it is dwarfed by the ~0.4‰ enrichment trend in the Pliocene portion of the isotopic record. *Mudelsee and Raymo* [2005] attribute the lion's share of the trend to an increase in glacial ice volume rather than deep ocean cooling; as the Greenland contribution is small, they necessarily locate the ice growth on Antarctica. We suggest that high-latitude ocean cooling perhaps played a bigger role in this largest step into glaciation than that study acknowledged. We base this contention on the exceptional resemblance of the major steps in the Site 982 SST record to the oxygen isotope record (nearly all the long-term temperature changes happen at two times of profound transition in the isotope record at 3.6–2.4 Ma and 1.4–0.7 Ma) and from a more subtle observation: the phase evolution of Site 982 SST relative to the benthic δ^{18}O record captured in the same sediments.

[35] The obliquity band phase relationship between these variables helps shed new light on the growth of Plio-Pleistocene ice sheets. SST should respond rapidly to insolation forcing and any fast responding feedback mechanisms in the climate system (e.g., atmospheric CO_2 or regional sea ice changes). In contrast, the phase of the deep ocean isotopic response (benthic δ^{18}O) presumably integrates both a faster temperature component and a slower ice volume component. The net phase of the δ^{18}O signal with respect to obliquity forcing represents the relative contributions of temperature (little to no phase lag) and ice volume (substantial phase lag). Here, we take Site 982 SST as an index of the "fast" temperature response of the North Atlantic to obliquity forcing and compare it to the benthic δ^{18}O in order to parse out the temperature and ice volume components of that signal over the Plio-Pleistocene ice ages. Because we do not estimate bottom water temperatures themselves, we do not precisely constrain the temperature and ice volume components but rather provide a picture suggestive of what a more accurate temperature deconvolution might look like.

[36] The phase difference between Site 982 SST and benthic δ^{18}O evolves in a manner clearly related to the intensification of Northern Hemisphere glaciation. Before 3.5 Ma, there is essentially no difference in the phase of either proxy in the obliquity band. This implies that both proxies largely reflect the fast temperature component of orbital forcing at high latitudes. After 3.5 Ma, the growing phase lead of SST over ice volume in the 41 k band (Figure 5) indicates a growing δ^{18}O response time which was most likely caused by the expansion of continental ice in the Northern Hemisphere and a growing contribution of ice volume to the benthic δ^{18}O signal [e.g., *Clemens et al.*, 1996]. It is important to note that the timing of the phase separation mirrors that of the δ^{18}O "step" and the strong increase in the variance of δ^{18}O at that time [*Lisiecki and Raymo*, 2005; *Mudelsee and Raymo*, 2005]. By about 2.7 Ma, the phase relationship of SST relative to benthic δ^{18}O appears to stabilize as a substantial lead ($\geq\sim$5 k) (Figure 5). The gradual phase separation of the variables can be interpreted as the increase in the relative importance of ice volume to the benthic signal over time, which would impose a progressively longer lag relative to the obliquity forcing and to SST. It is probably not coincidental that the first widespread signs of ice rafting appear in the North Atlantic near the end of what we interpret to be the first significant interval of sustained ice sheet growth (approximately 3.5 to 2.7 Ma).

[37] We note that there is some indication that this phase story changes once more, during the mid-Pleistocene transition. *Ruddiman and McIntyre* [1984] and *Ruddiman et al.* [1989] use faunal-derived SST estimates from DSDP Site 607 to deduce that SST changed from a fast to a slower response (relative to δ^{18}O) in both the 41 ka and 100 ka bands (Figure 5). They suggest these results indicate the dominance of ice sheet feedbacks on regional ocean temperatures with the transition to the "100 k world" [*Ruddiman et al.*, 1989]. The phase evolution of SST relative to benthic δ^{18}O supports these results (Figure 5), although we would

feel more confident in this assertion if our record were sampled at 3 k resolution throughout.

5. Conclusions

[38] The high variability of sea surface conditions observed at ODP Site 982 during the early Pliocene warm period is surprising when compared to other high-resolution records of early Pliocene climate conditions which show only low-amplitude variations throughout the warm period. Orbitally derived high-amplitude variations may be unusually large at ODP Site 982 because of its location in a region highly sensitive to changes in the strength and position of North Atlantic atmospheric pressure systems and the position of the North Atlantic Drift. Alternatively, the large circa 41 k swings in SST observed at Site 982 may turn out to be the first example of widespread high-latitude, feedback-driven instability in the early Pliocene that has simply not been observed at sites to the south and is muted or invisible in ocean oxygen isotopic records.

[39] The strong but gradual cooling of SSTs at ODP Site 982 which occurs synchronously with the most rapid interval of change in δ^{18}O records and the southward progression of IRD across high latitudes of the Northern Hemisphere suggests that intensification of NHG at ~2.7 Ma was the result of a gradual long-term change in global climate. Regional cooling may have permitted the establishment of a permanent Greenland ice cap by ~2.5 Ma. Since that time, the primary climatic pattern in the North Atlantic has been an intensification of glacial extrema, rather than major additional long-term cooling.

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A. M. Haywood, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK.

T. D. Herbert and C. M. Brown, Department of Geological Sciences, Brown University, Box 1846, Providence, RI 02912, USA.

K. T. Lawrence, Department of Geology and Environmental Geosciences, Lafayette College, 102 Van Wickle Hall, Easton, PA 18042, USA. (lawrenck@lafayette.edu)

M. E. Raymo, Department of Earth Sciences, Boston University, 685 Commonwealth Avenue, Boston, MA 02215, USA.