New quantitative evidence of extreme warmth in the Pliocene Arctic

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ABSTRACT: The most recent geologic interval characterized by warm temperatures similar to those projected for the end of this century occurred about 3.3 to 3.0 Ma, during the mid-Piacenzian Age of the Pliocene Epoch. Climate reconstructions of this warm period are integral to both understanding past warm climate equilibria and to predicting responses to today's transient climate. The Arctic Ocean is of particular interest because in this region climate proxies are rare, and climate models struggle to predict climate sensitivity and the response of sea ice. In order to provide the first quantitative climate data from this region during this interval, sea surface temperatures (SST) were estimated from Ocean Drilling Program Sites 907 and 909 in the Nordic Seas and from Site 911 in the Arctic Ocean based on Mg/Ca of *Neogloboquadrina pachyderma* (sin) and alkenone unsaturation indices. Evidence of much warmer than modern conditions in the Arctic Ocean during the mid-Piacenzian with temperatures as high as 18°C is presented. In addition, SST anomalies (mid-Piacenzian minus modern) increase with latitude across the North Atlantic and into the Arctic, extending and confirming a reduced mid-Piacenzian pole-to-equator temperature gradient. The agreement between proxies and with previously documented qualitative assessments of intense warming in this region corroborate a poleward transport of heat and an at least seasonally ice-free Arctic, conditions that may serve as a possible analog to future climate if the current rate of Arctic sea-ice reduction continues.

INTRODUCTION

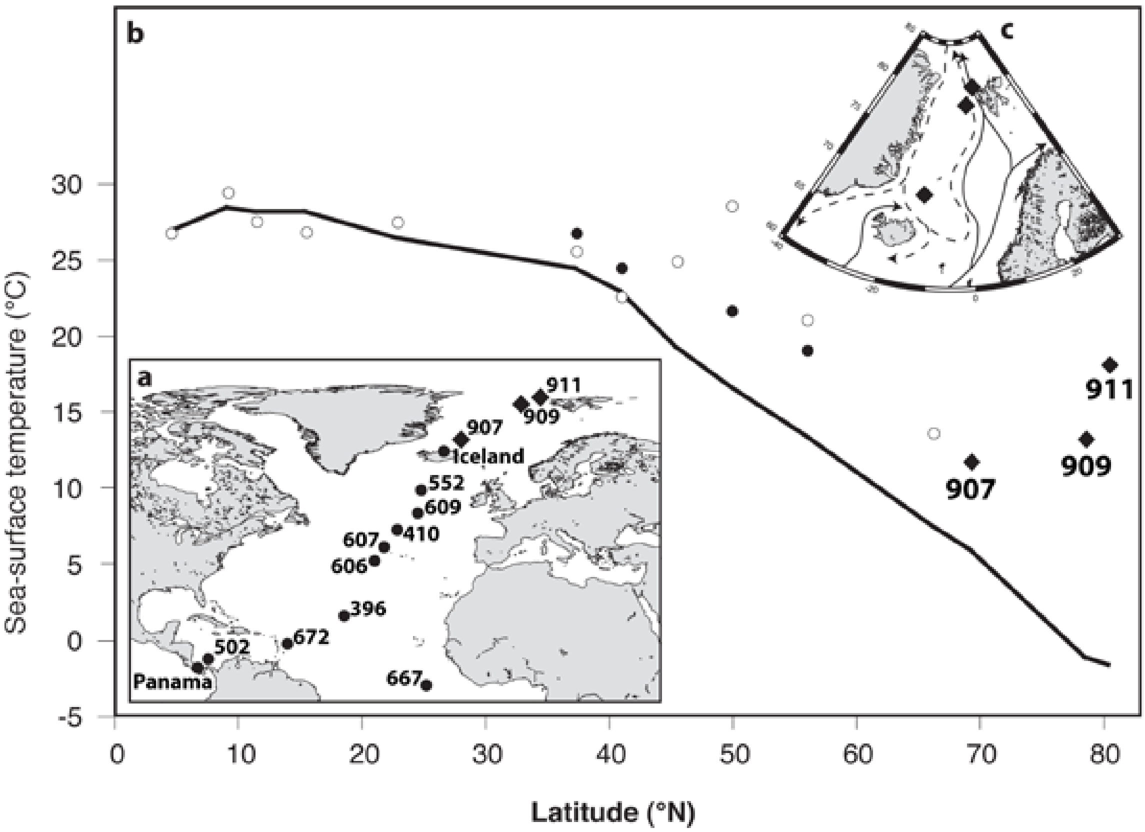
Arctic Ocean surface waters and those of the surrounding seas have been warming since 1965, increasingly since 1995, even more rapidly since 2000, with 2007 and 2008 marking the first two sequential years of extreme summer minimum sea ice coverage (Comiso et al. 2008; Steele et al. 2008; Stroeve et al. 2008). In addition, autumn surface air temperatures during these two years were greater than 5°C higher than the central Arctic average (Wang and Overland 2009). Continuation of this trend could lead to a dramatic change in the Arctic ice-ocean-atmosphere regime (Johannessen et al. 1999). In anticipation of continued warming, climate model scenarios for the near future commonly feature Arctic warmth and sea ice retreat yet struggle to predict climate sensitivity and the response of sea ice in these high latitudes. In fact, model simulations of sea ice retreat compare poorly to observations (Stroeve et al. 2007), some underestimating sea ice minima by at least 30 years (Wang and Overland 2009). Future projections of sea-ice cover vary wildly with some models simulating seasonal ice-free conditions by 2070 while others project virtually no change over the same period of time (Boe et al. 2009).

One way to refine climate models and to improve projections is to attempt to recreate known warm climates of the past from climate proxy data (Robinson et al. 2008a). A model's ability to accurately portray a past climate state, both in terms of magnitude and spatial variability, increases confidence in climate projections based on that model. Due to the high sensitivity displayed by polar regions during the current warming trend, accurate reconstructions of paleo-conditions in high latitude regions during past warm intervals are integral to reliable model results, but data are rare due to the shortage of paleoclimate proxies in high latitudes, and high resolution temporal correlation between regions is complicated.

The most recent geologic interval of global warmth comparable to climate projections for the end of this century was ~3.3 to 3.0 Ma (IPCC 2007), during the mid-Piacenzian Age of the Pliocene Epoch. During this time interval, the positions of the continents and the patterns of oceanic circulation were similar to modern, but mean global temperatures were 2 to 3°C warmer, and sea level was about 25m higher (Dowsett 2007). It was also during the Piacenzian (between 3.6 and 2.4 Ma) that restricted local scale glaciations transitioned to extensive regional scale glaciations on the circum-Arctic continents (e.g. Fronval and Jansen 1996; Mudelsee and Raymo 2005). Paleoclimatologists interested in this warm interval as a possible analog to future warming, as well as other climate researchers intrigued by the transition between this warm period and the subsequent onset of Northern Hemisphere glaciation, recognize the potential of mid-Piacenzian climate reconstructions to reveal uncertainties regarding climate sensitivity. As a result, a wealth of paleoclimate data exists for this warm interval, but most is restricted to lower latitudes where traditional paleoclimate proxy methods (i.e. inferring conditions from faunal assemblage data) work best.

The USGS Pliocene Research, Interpretation and Synoptic Mapping (PRISM) Project is charged with reconstructing global conditions during the ~3.3 to 3.0 Ma time interval (hereafter "the mid-Piacenzian") in an effort to better understand past and possible future climate dynamics. PRISM reconstructions of sea-surface temperature (SST), based largely on planktic foraminifer assemblage data, indicate that temperature differences between the mid-Piacenzian and modern increase with latitude in the North Atlantic (Dowsett et al. 1992). That is, mid-Piacenzian temperatures near the equator were similar to modern temperatures, but temperatures in the higher latitudes were several degrees warmer than at present. This reconstructed equator-to-pole gradient has been indeterminate at and above ~66°N, however, because temperature estimates from polar regions such as the Nordic Seas and Arctic Ocean have remained elusive due to the lack of geologic proxies yielding quantitative results as well as weak age control.

In an effort to expand the data set into the high latitudes, three Ocean Drilling Program (ODP) cores with reliable age control were analyzed for mid-Piacenzian SST estimates: Site 907 (69.25°N, 12.70°W, 1801.2m water depth) in the southwestern part of the Norwegian-Greenland Sea on the Iceland Plateau, Site 909 (78.58°N, 3.07°E, 2518.6m water depth) in the Fram Strait between the Norwegian-Greenland Sea and the Arctic Ocean, and Site 911 (80.47°N, 8.23°E, 901.5m water depth) on



TEXT-FIGURE 1
a) Locations of Sites 907, 909 and 911 as well as other North Atlantic core sites in the PRISM dataset (Dowsett 2007). b) Equator to pole summer SST gradient across the North Atlantic, Nordic Seas and into the Arctic Ocean: Modern SST (Reynolds and Smith 1995) (solid line), PRISM faunal-based SST estimates (Dowsett 2007) (open circles), and mid-Piacenzian multi-proxy SST estimates (solid circles from (Robinson et al. 2008b), diamonds from this study). Sites in 1A are arranged by latitude. c) Modern subpolar North Atlantic and nearby Arctic surface circulation. Solid lines indicate relatively warm currents; dashed lines indicate relatively cool currents. Diamonds represent the locations of Sites 907, 909 and 911.

the shallow southern part of the Yermak Plateau in the Arctic Ocean (text-figure 1A). SSTs were estimated based on Mg/Ca of planktic foraminifer shells and alkenone unsaturation indices, two paleothermometry techniques particularly valuable in high latitudes where traditional methods based on planktic foraminifera assemblages are not suitable due to low abundance, monospecific assemblages or assemblages dominated by extinct species with no extant descendents. The first quantitative SST estimates from the Arctic and subpolar North Atlantic are presented here. These and results from benthic foraminifer sea ice proxies are compared to existing qualitative estimates of paleoclimate conditions in the mid-Piacenzian Arctic Ocean.

HIGH-LATITUDE GEOCHRONOLOGY

Chronostratigraphic certainty in sediment cores generally diminishes with increasing latitude because, in the high latitudes, discontinuous records often render age models based on stable isotopes impossible, and radiometric age control is rare. Therefore, high latitude chronostratigraphy is usually based on paleomagnetic data and supported by age datums provided by calcareous nannofossils and planktic foraminifera and sometimes diatoms and radiolaria, but, unfortunately, geochronologic resolution of calcareous and biosiliceous microfossils decreases sharply in the Arctic where biostratigraphic datums are not well calibrated (Matthiessen et al. 2009). Sampling of Arctic sediments of Pliocene age has historically been restricted to shallow marine sediments on circum-Antarctic continents. Sampled sites contain a wealth of paleoclimatologic information but are usually short sequences that lack age estimates.

Recent advances in ship operations and logistics now allow for more central Arctic coring using ice-breaker ships. The Arctic Coring Expedition (ACEX) in 2004 (IODP Expedition 302) was the first to recover a long-term Cenozoic sediment record from the Arctic Ocean. Previously, Pliocene sediments in the central Arctic Ocean could not be unequivocally identified, and the order of magnitude of average sedimentation rates was hotly debated. Rates of sediment deposition in the deep, central part of the Arctic Ocean are now known, ~1.4 to 1.5 cm/kyr (Backman et al. 2008; Frank et al. 2008), and previous age models based on mm/yr assumptions must be revised and their paleoceanographic interpretations reevaluated. Even with these advances, a sedimentation rate of ~1.4 cm/kyr is low for the Neogene and may miss short-term variability. In addition, a definitive age model extending into the Pliocene sediments in the central Arctic remains elusive due to deterioration of core quality and recovery (O'Regan et al. 2008) as well as the lack of biogenic material and complex downhole paleomagnetic variability (see Backman et al. 2004). As a result, very little information on Pliocene climate was recovered by the ACEX expedition.

Age control and recovery at ODP Sites 907, 909 and 911, though not in the central Arctic, were less problematic with higher temporal

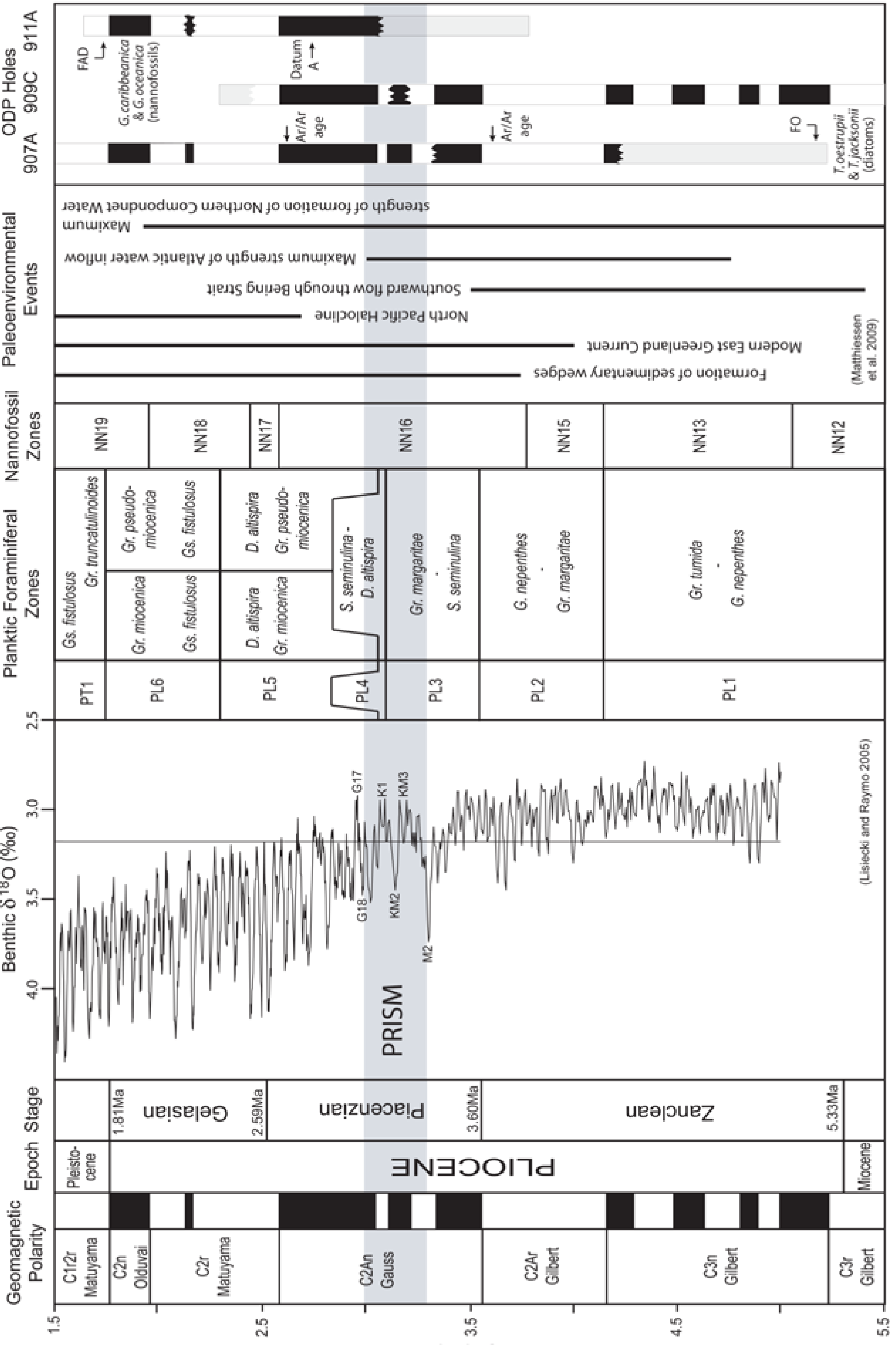
TABLE 1
Sea-surface temperature (SST) estimates for samples used in this study and supporting biomarker and chemical analysis data. $U^{k'}_{37}$ = alkenone unsaturation index; 37tot = total abundance of C_{37} alkenones preserved in sediments. Age models were constructed from paleomagnetics, nannofossil datums and $^{40}Ar/^{39}Ar$ dating (Myhre et al. 1995; Thiede et al. 1996, Lacasse and Van der Bogaard 2002).

Site	Depth (mbsf)	Age (Ma)	$U^{k'}_{37}$	37tot	Mg/Ca (mmol/mol)	Sr/Ca (mmol/mol)	Na/Ca (mmol/mol)	Fe/Ca (mmol/mol)	SST (°C)
907A	59.0	3.0	-	-	1.59	1.25	4.30	0.03	10.7
907A	59.2	3.0	-	-	1.86	1.26	4.21	0.03	12.3
907A	63.4	3.3	-	-	1.81	1.26	4.51	0.00	12.1
								$\bar{x}$	**11.7**
								σ	**0.9**
909C	208.4	3.0	0.46	0.09	-	-	-	-	12.3
909C	218.4	3.1	0.61	0.04	-	-	-	-	16.9
909C	220.4	3.1	0.40	0.06	-	-	-	-	10.5
909C	220.9	3.2	0.43	0.26	-	-	-	-	11.5
909C	221.4	3.2	0.42	0.06	-	-	-	-	11.1
909C	221.9	3.2	0.41	0.16	-	-	-	-	10.9
909C	222.4	3.2	0.42	0.16	-	-	-	-	11.2
909C	224.4	3.2	0.54	0.05	-	-	-	-	14.8
909C	229.9	3.3	0.54	0.09	-	-	-	-	14.7
909C	232.4	3.3	-	-	1.94	1.30	4.47	0.73	12.7
								$\bar{x}$	**12.7**
								σ	**2.0**
911A	447.0	3.3	0.59	0.07	-	-	-	-	16.1
911A	448.0	3.3	0.68	0.35	-	-	-	-	18.9
911A	452.0	3.3	0.69	0.59	-	-	-	-	19.3
911A	453.0	3.3	0.66	0.31	-	-	-	-	18.2
								$\bar{x}$	**18.1**
								σ	**1.4**

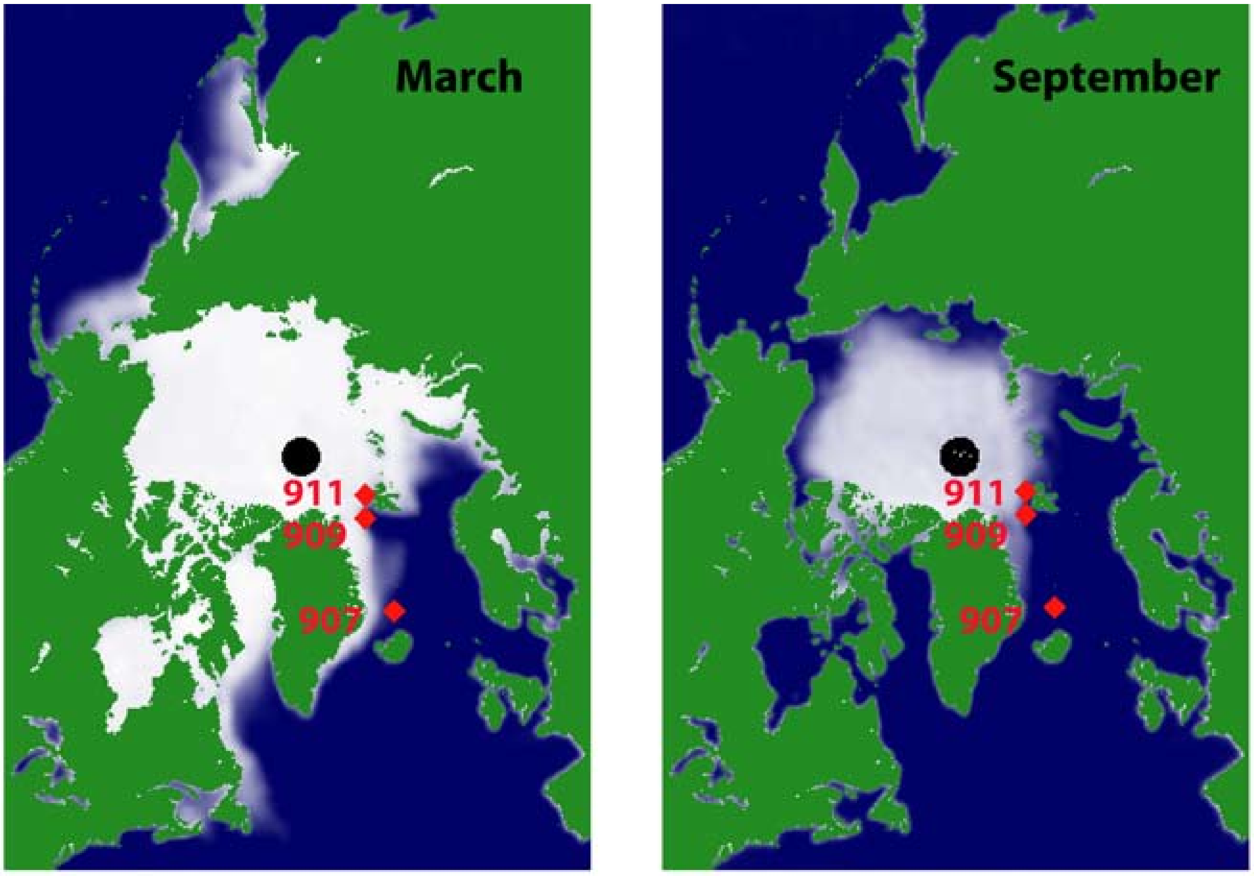
resolution. Text-figure 2 illustrates Pliocene chronostratigraphy and all available geochronologic age control data for ODP Sites 907, 909 and 911 as well as important Arctic paleoceanographic events during this interval. See Matthiessen et al. 2009 for an in depth discussion of Pliocene Arctic paleoceanography. A nearly complete magnetic stratigraphy exists throughout the Gauss geomagnetic polarity chron at Site 907A (Channell et al. 1999), and an age model based on Argon isotope ($^{40}Ar/^{39}Ar$) ages (Lacasse and van den Bogaard 2002) yields a sedimentation rate of 6.1 cm/kyr. At Site 909C an age model based on magnetozone boundaries (Myhre et al. 1995) yields a sedimentation rate of 6.4 to 6.8 cm/kyr. Paleomagnetics of younger sediments (Myhre et al. 1995) and nannofossil datums (Sato and Kameo 1996) were available to construct an age model for Site 911A which yielded a sedimentation rate of 12.5 cm/kyr. This interpolation assumes a constant sedimentation rate through the study interval due to lack of data indicating otherwise. Although relatively few biostratigraphic markers exist for the high-latitude Pliocene, and biostratigraphic determinations based on planktic foraminifers alone are difficult in the high latitudes due to low species diversity, the high percentages of *Neogloboquadrina atlantica* (sin) places these samples in the Pliocene.

ARCTIC SEA ICE

Several decades of observation document the accelerating retreat and thinning of modern Arctic sea ice at rates that are expected to continue (Steele et al. 2008). Average September sea ice in



TEXT-FIGURE 2
Pliocene stratigraphy with shaded band marking the mid-Piacenzian PRISM interval (~3.3 to 3.0 Ma), major paleoenvironmental events of the high northern latitudes, and chronostratigraphy of ODP Holes 907A, 909C and 911A.



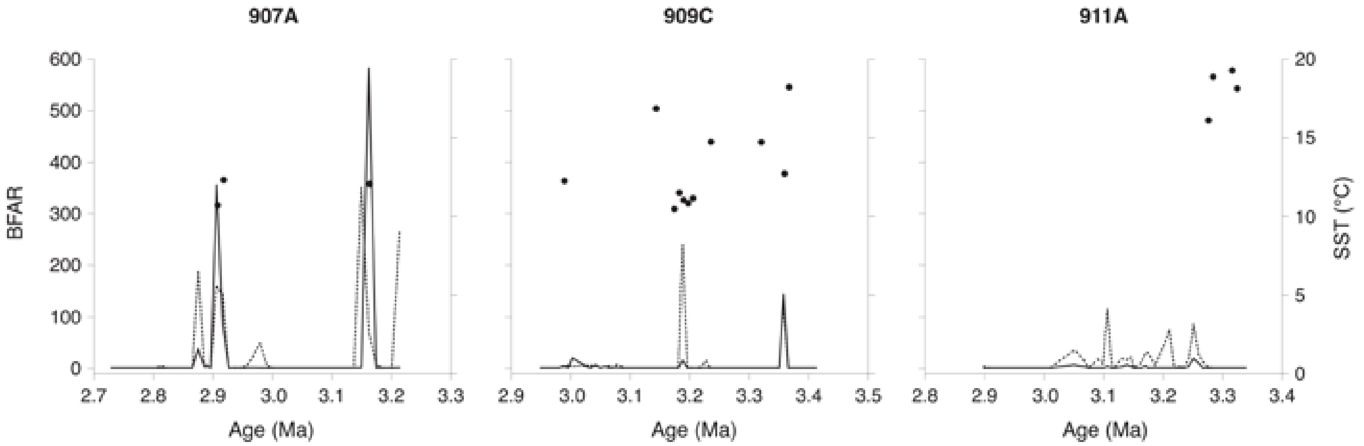
TEXT-FIGURE 3
Arctic maximum (March) and minimum (September) sea ice extent averaged over the years 1978 to 1992 (from Schweitzer 1995). Diamonds indicate locations of ODP Sites 907, 909 and 911.

2007 was the least ever recorded and also 23% lower than the previous September record low in 2005 (Comiso et al. 2008; Stroeve et al. 2008). At the current rate of sea ice retreat and thinning, the Arctic Ocean may be seasonally ice free by 2040 (Holland et al. 2006a; Comiso et al. 2008; Stroeve et al. 2008; Wang and Overland 2009).

Loss of sea ice may have varied and extensive consequences: It may promote Arctic warming through ice-albedo feedback, affect weather systems in the northern high and possibly middle latitudes, affect North Atlantic Ocean circulation and the European and North American climates through changes in freshwater flux out of the Arctic Ocean, accelerate coastal erosion due to increased wave activity, affect large predators (polar bears and seals) that depend on sea ice cover and the indigenous populations that harvest them (Polyak et al. 2009). Reductions in sea ice cover may also result in intensified mid-latitude storm tracks and increased winter precipitation in western and southern Europe (Singarayer et al. 2006) and less rainfall in the American west (Sewall and Sloan 2004). These consequences make it important to know how quickly the ice may melt.

Models as a whole underestimate the sensitivity of sea ice cover to greenhouse gas forcings (Stroeve et al. 2007), and model results based on climate simulations forced by reductions in Arctic sea ice are contradictory. Those focused on the large-scale changes in ocean circulation, including Atlantic meridional overturning circulation (AMOC), project either that the addition of freshwater to the North Atlantic from Arctic sea ice melt will increase the stability of the upper ocean and thus suppress the formation of North Atlantic Deep Water (NADW) and weaken AMOC (e.g., Holland et al. 2001), or that less ice being transported through the Fram Strait into the Greenland, Iceland and Norwegian Seas, and therefore less melting in those Seas, will decrease the stability of the upper ocean, increase NADW production, and strengthen AMOC (Holland et al. 2006b). Less insulating ice cover may contribute to the strength of the AMOC as heat escapes the surface ocean to the atmosphere, leaving a colder surface layer and greater instability, leading to NADW production (Levermann et al. 2007).

Climate models have been shown to underestimate the rate of ice melt and to show conflicting reactions to reductions in sea ice when forced with modern boundary conditions. Understanding the natural variability of Arctic sea ice through reconstructions of warmer climates of the past, especially previous periods of ice reduction, and using actual data to ground-truth model results is essential to both improving model output and interpreting the changes occurring today. At present, the location of Site 907 is south of the maximum extent of sea ice averaged over the period 1978 through 1992, and the locations of Sites 909 and 911 are just within the minimum extent of sea ice averaged over the same time period (using Schweitzer 1995) (text-figure 3).



TEXT-FIGURE 4
Foraminiferal proxies of sea ice at ODP Sites 907, 909 and 911 showing no evidence of continuous perennial sea ice through the mid-Piacenzian. Solid line indicates number of planktic foraminifera/10cc sample; dashed line indicates number of benthic foraminifera/10cc sample (BFAR). Dots represent SST estimates based on Mg/Ca and alkenone unsaturation ratios.

SST ESTIMATION METHODS

Mg/Ca paleothermometry. The ratio of magnesium to calcium in foraminifera tests varies exponentially with temperature (e.g., Nürnberg et al. 1996; Lea et al. 1999) and thus allows for temperature estimation of the water mass at the time and water depth of calcification. *Neogloboquadrina pachyderma* (sin) shells were picked from the >150μ size fraction for Mg/Ca analysis. Mg/Ca cleaning procedures were modified from the standard cleaning method (See Robinson et al. 2008b). Foraminifer shells were crushed to open chambers, then subjected to multiple rinses/sonications with deionized water and methanol, and reductive and oxidative cleaning with intermittent sonication, each followed by deionized water rinses, weak acid rinses/leaches, final deionized water rinses, dissolution, centrifuging, decanting and analysis. Aqueous solutions were analyzed for Mg and Ca simultaneously on a Fisons Instruments Spectraspan 7 Direct Current Plasma (DCP) atomic emission spectrometer at Duke University using matrix-matched calibration standards mixed from ultra-pure plasma-grade standard solutions. Triple-acid-washed, triple-rinsed plastic labware was used throughout the cleaning procedure and analysis. Mg/Ca-derived SST estimates were calculated using an equation developed for high northern latitude studies of *N. pachyderma* (sin) (Nürnberg 1995). This equation is calibrated to surface temperature, not temperature at calcification depth, but *N. pachyderma* is known to occupy a range of water depths in the Arctic Ocean (Bauch et al. 1997). The combined Mg/Ca and alkenone approach helps to distinguish SST from deeper water temperatures.

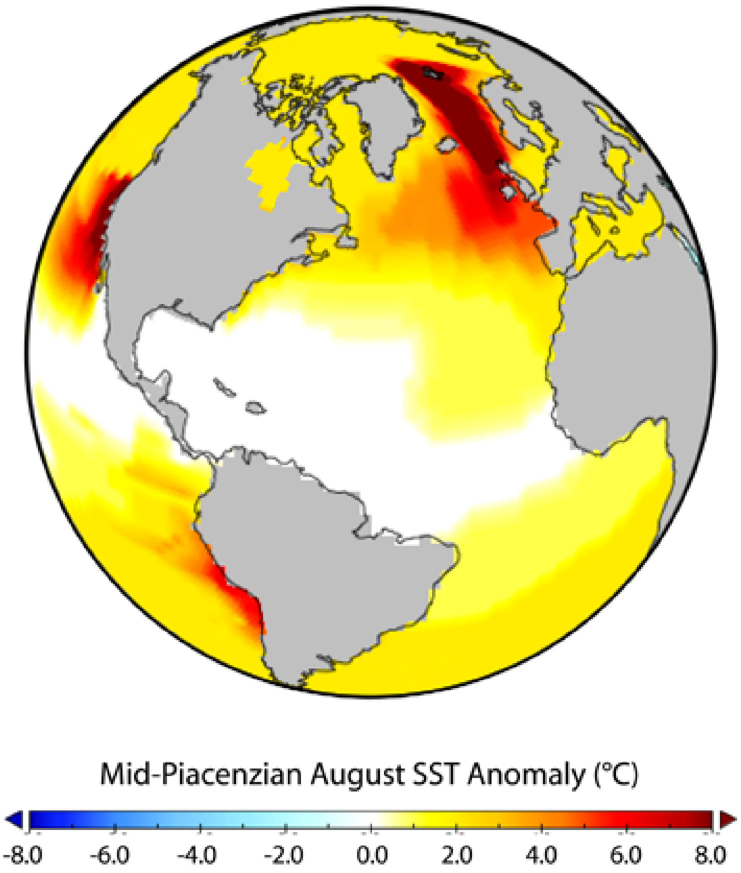
Alkenone unsaturation index paleothermometry. The alkenone unsaturation ($U^{k'}_{37}$) index has been linearly calibrated to ocean near-surface temperature (e.g., Prahl et al. 1988; Conte et al. 2006), allowing for SST estimation. Alkenone analyses were performed at Brown University where sediment samples (~7 g) were freeze-dried and homogenized in preparation for the analysis of alkenones. Lipid extracts were extracted in 100% dichloromethane using a Dionex automated solvent extractor (ASE 200). The ASE 200 exposes each sample to a small volume of solvent (~25 mL) at elevated pressure (1500 psi) and temperature (150ºC). After evaporation under an N_2 stream and dilution with a small volume of toluene (~0.2 mL), the extracts were analyzed using a HP 6890 gas chromatograph equipped with a flame ionization detector and a DB-1 column (60 m x 0.32 m x 0.10 µm file thickness, J&W Scientific). The temperature program used to quantify alkenones starts at 90ºC holding for 2 minutes, then ramps to 250ºC at 40ºC/min, followed by a slow ramp of 1ºC/min to 300ºC, and finishes with an isothermal holding step at 320ºC for 11 minutes. Peak areas of $C_{37:2}$ and $C_{37:3}$ alkenones were determined using Hewlett-Packard Chemstation software and were used to calculate the alkenone unsaturation ($U^{k'}_{37}$) index. All reported $U^{k'}_{37}$ SST estimates in this study were obtained using the standard calibration curve (Prahl et al. 1988).

SEA ICE PROXIES

A variety of foraminiferal proxies can be used to detect the stability of paleo-sea ice cover. Whether sea ice was seasonal or perennial can be estimated through documenting the amount of carbonate found in sediments, the proportion of agglutinated to calcareous benthic foraminifers, and the ratio of planktic to benthic foraminifers.

Wollenberg and Kuhnt (2000), in studies of modern Arctic sediments, found intense carbonate dissolution in seasonally ice-free areas, with intensity increasing with decreasing water depth and with the duration of ice retreat. They found no signs of carbonate dissolution under permanent sea ice cover. A decrease in calcareous species in sediments may indicate higher productivity and the absence of sea ice at least seasonally. Increased organic matter from surface productivity accumulates in the sediment, increases biological degradation of the organic matter, reduces pH levels, and leads to deterioration of carbonate tests. Also, a high planktic to benthic foraminiferal ratio can indicate seasonal sea-ice cover (Scott et al. 2009).

The benthic foraminifer accumulation rate (BFAR), calculated as the number of dead benthic foraminifer specimens in 10cc of sediment, is a convenient way to quantify the conditions described above. In the modern Arctic, the BFAR is lowest under seasonally ice-free areas and highest under permanent ice cover at any given water depth (Wollenberg and Kuhnt 2000).



TEXT-FIGURE 5
August SST anomalies (mid-Piacenzian - modern) produced from incorporating SST estimates from Sites 907, 909 and 911 into the PRISM SST reconstruction (Dowsett 2007). These anomalies show little temperature difference from modern near the equator with mid-Piacenzian warmth increasing toward the pole.

RESULTS

Average mid-Piacenzian SST estimates representing the pooling of proxy data were 11.7°C at Site 907, 12.7°C at Site 909 and 18.1°C at Site 911 (Table 1). Samples from these three cores revealed highly variable numbers of planktic foraminifera, dominated by *N. pachyderma* (sin) and *N. atlantica* (sin). Many samples were barren of microfossils or had alkenone concentrations below the detection limit, suggesting low productivity. The samples yielding results are considered representative of warm intervals when conditions were suitable for both planktic foraminifera and alkenone production. These temperatures are assumed to represent warm peak averages at these sites and not mean conditions over the interval. It is further assumed that both proxies record summer SST, as sediment traps at these high latitudes show maximum fluxes of both alkenones (Prahl et al. 2001) and *N. pachyderma* (Kohfeld et al. 1996) in summer. The estimates presented here are therefore considered directly comparable to existing PRISM summer SST estimates based on warm peak averaging.

In order to indicate the presence of perennial Arctic sea ice using foraminifer proxies, the samples must contain large amounts of carbonate showing little or no dissolution, low planktic to benthic ratios (P/B), and high BFAR. These conditions are not met at Site 907 where samples with high numbers of foraminifera are dominated by planktic species and show SST estimates of ~12°C (text-figure 4).

Very little carbonate accumulated at Site 909. A single spike in the BFAR record, where P/B is very low, coincides with the lowest five SST estimates (~10.5°C) (text-figure 4). The only dropstones (possible ice-rafted debris) found in the study interval are found at 221.41 m, 221.77 m, and 222.94 m core depth (Myhre et al. 1995), surrounding this spike. These data may record a pulse of drifting ice within the warm interval, but no evidence of perennial sea ice exists.

Whereas the foraminifera in samples from Sites 907 and 909 showed very little dissolution, all benthic foraminifera at Site 911 show moderate to severe dissolution. The BFAR is low at Site 911, but the P/B is very low (text-figure 4). These conditions do not indicate sea ice. Furthermore, no dropstones were found in the studied interval of this core (Myhre et al. 1995).

DISCUSSION

Summer temperatures between 10°C and 18°C and very low BFARs imply at least seasonally ice-free conditions in the subpolar North Atlantic and nearby Arctic Ocean during the mid-Piacenzian. Incorporation of these data into the PRISM SST reconstruction provides a possible analog to future climate conditions if the current rate of Arctic sea-ice reduction continues (text-figure 5).

Sea-surface Temperature. The most proximal previously published records of mid-Piacenzian SSTs are from Tjornes, Iceland (text-figure 1A), 3° south of Site 907, and indicate summer temperatures of 13.6°C based on ostracode data (Dowsett 2007). Ostracodes, benthic zoofauna, can be used to estimate SST in regions where shallow bottom water temperatures are very similar to surface temperatures. Other sites in the path of the North Atlantic Current (DSDP Sites 552 and 609) yield summer SST estimates of >20°C based on multiple proxies: planktic foraminiferal assemblages (Dowsett 2007), Mg/Ca of foraminifer shells and alkenone paleothermometry (Robinson et al. 2008b). At least seasonally ice-free conditions in the Arctic Ocean during the mid-Piacenzian have been previously inferred from ostracode migrations as evidence of elevated water temperatures (Cronin et al. 1993). These data and additional ostracode (Cronin and Whatley 1996), pollen (Willard 1996) and dinoflagellate cyst (Knies et al. 2002) data from ODP Sites 910 and 911 indicate much warmer-than-present water being transported through the subpolar North Atlantic and into the Arctic during the mid-Piacenzian.

Pollen from three subarctic sites in the Norwegian Sea, northern Iceland and Labrador Sea indicate that mid-Pliocene January temperatures in Norway, Iceland and southeastern Canada were 4 to 10°C warmer than today (Willard 1994). Many researchers documented Pliocene warmth recorded in the Beaufort Formation of Arctic Canada (Matthews 1987; Fyles 1990; Matthews and Ovenden 1990; Vincent 1990; Fyles et al. 1991; Brigham-Grette and Carter 1992; Fyles et al. 1994). Evidence of both mixed deciduous/coniferous and coniferous forests places mean July temperatures10°C warmer than today (Vincent 1990). In addition, northwestern Alaska air and sea temperatures during peak Pliocene interglacials were considerably warmer than present, by 7 to 8°C, with no permafrost, and absent or severely limited sea ice (Carter et al. 1986; Kaufman and Brigham-Grette 1993).

The mid-Piacenzian - modern SST anomalies presented here increase with latitude as do previously documented SST estimates in the North Atlantic and Arctic. In this study, however, the actual temperature estimates also increase with latitude as the northern-most site records the warmest temperatures (text-figure 1B). Surface currents may help explain the counterintuitive northerly temperature increase if, like today, a strong relatively warm North Atlantic current influenced the western margin of Norway and the Yermak Plateau, while colder polar waters influenced the Fram Strait, the eastern margin of Greenland and the Iceland Sea region (text-figure 1C). Today, cold polar waters overlay warmer Atlantic waters in the central and western Fram Strait. During the mid-Piacenzian, warmer surface water exported from the Arctic may have weakened the halocline that today protects the polar icecap from the underlying heat, thus enforcing the warmth carried north by North Atlantic intermediate water (Cronin et al. 1993).

All SST estimates at Site 911 and most estimates at Site 909 are based on alkenone paleothermometry (Table 1). It is possible that these alkenone-based SST estimates reflect alteration by postdepositional processes such as lateral advection of fine particles from the shelves (Sicre et al. 2002), presumably from time intervals warmer than the Pliocene. In another example of similar results, surprisingly high alkenone-based SST estimates (12.0-16.8°C in summer) were reported for the Nordic Seas during the Last Glacial Maximum (LGM) showing the same northward temperature increase (Rosell-Mele and Comes 1999). These high LGM temperatures are debatable because of the possible inclusion in the alkenone analyses of allochthonous fine material from ice-rafted debris (Rosell-Mele and Comes 1999). Ice-rafted debris, however, was at a minimum in the Nordic Seas during the mid-Piacenzian (Jansen et al. 2000). High summertime temperatures during the LGM are now supported by SST estimates based on dinoflagellate cysts from the northern North Atlantic (10-15°C in August) (de Vernal et al. 2000), other micropaleontologic and sedimentologic evidence of ice-free waters (Norgaard-Pedersen et al. 2003 and references therein) and an increased seasonality relative to present (de Vernal et al. 2000).

In alkenone work specific to modern polar regions, the inclusion of $C_{37:4}$ into the alkenone unsaturation ratio has been shown to increase correlation to SST (Bendle and Rosell-Mele 2004). The $C_{37:4}$ alkenone was not detected in the analyses presented here from Site 909 or 911. Because the $C_{37:4}$ alkenone is produced only in cold regions with SST <10°C (Rosell-Mele et al. 1994), its absence in these samples may support >10°C temperatures.

Sea ice. Results from IODP Leg 302, the Arctic Coring Expedition (ACEX), indicate the onset of perennial sea ice cover in the central Arctic at about 13 Ma based on mineral assemblages in the sediments (Krylov et al. 2008) or 14 Ma based on detrital Fe oxide mineral grains precisely matched to ice rafted debris source areas, combined with the travel time of more than one year required to the ACEX core sites (Darby 2008). Beryllium isotopes suggest essentially continuous sea ice cover over the past 12.3 Ma with short periods of diminished sea ice at 7.8 and 5.5 Ma (Frank et al. 2008). It is possible that any warm excursions were missed in these studies as sampling intervals range from 170 kyr to 360 kyr. No micropaleontological evidence exists that has bearing on the presence of perennial sea ice in the central Arctic Ocean during the mid-Piacenzian.

Despite the state of sea ice in the central Artic during the mid- to late Neogene, the micropaleontologic data and SST estimates presented here suggest that perennial sea ice did not exist continuously in the subpolar North Atlantic or nearby Arctic Oceans during this time interval and that the total extent of summer sea ice was reduced relative to modern. These conclusions echo those of Cronin et al. (1993) based on ostracode analyses from the North American continental margin.

Atlantic Meridional Overturning Circulation. The subpolar North Atlantic and proximal Arctic Ocean is the site of North Atlantic Deep Water formation, a key driver in meridional overturning circulation (MOC). This region is of immense importance to global climate development, and at the same time, seriously underrepresented in paleoclimate reconstructions due to the lack of paleoceanographic records. This paucity of data makes it difficult to test paleoceanographic hypotheses based on conceptual climate models. At present, model-predicted mid-Piacenzian MOC, suggesting a weaker thermohaline circulation, is at odds with interpretations of stronger MOC based on the PRISM surface and deep ocean temperature reconstructions (Chandler et al. 2008). While emphasizing the need for additional data from well-dated, continuous Arctic records, this study provides much needed paleo-data for climate model simulations in the form of the first quantitative Arctic SST data from the mid-Piacenzian.

CONCLUSIONS

In this study, the first quantitative mid-Piacenzian SST estimates for the subpolar North Atlantic and Arctic Oceans show good agreement between proxies, and, when combined with numerous qualitative measures of temperature, refine previous estimates indicating much warmer than modern temperatures and at least seasonally ice-free conditions in the Nordic Seas and nearby Arctic Ocean. Updating the PRISM SST reconstruction with this new data yields a very different pattern of heat distribution than at present with much warmer waters in the high latitudes during the mid-Piacenzian. In addition, these new multi-proxy data extend the reduced SST gradient into the climatically sensitive areas of the subpolar North Atlantic and Arctic Oceans, confirming the previously established gradient based on faunal assemblage data in which temperature anomalies increase with latitude. Finally, these new data imply a major mid-Piacenzian reduction in sea ice similar to what has been observed in recent summers, strengthening the idea that the anomalous sea ice melting we have observed in the Arctic Ocean in recent years may be an early warning for significant global warming.

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