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Relation of subtropical Atlantic temperature, high-latitude ice rafting, deep water formation, and European climate 130,000–60,000 years ago

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Abstract

A new, high-resolution record of sea surface temperature from the subtropical western North Atlantic documents a series of abrupt coolings within marine isotope stage 5 which can be objectively correlated with marine-core evidence for increased ice-sheet discharge at subpolar latitudes and reduced North Atlantic deep water formation. These results indicate that ice-sheet forcing of deep ocean circulation influenced surface temperatures over much of the North Atlantic. A proposed correlation to the pollen record of Grande Pile, France, indicates that each cold event seen in the pollen sequence has a unique counterpart in the record of subtropical ocean temperature. If this correlation is correct, it suggests that the warmest part of the European Eemian ended suddenly in response to oceanographic changes, and that the subsequent post-temperate phase of the Eemian extended well into the interval of ice sheet growth corresponding to marine isotope substage 5d.

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1. Introduction

Despite longstanding interest in the climate of the last interglaciation, there are as yet few well-resolved, quantitative records of sea surface temperature (SST) spanning the interval in the open North Atlantic. Furthermore, prior studies have generally been restricted to subpolar latitudes where sites of rapid sediment accumulation are well known, and proxies of surface water conditions, ice sheet discharge, and deep circulation can be obtained from the same samples. But the presence of any associated temperature variations in the subtropics would be most significant—such a widespread change in the ocean surface boundary condition would be expected to influence terrestrial climate over a broad region, especially Europe.

Here, we present a new SST record based on measurements of the alkenone unsaturation ratio (Brassell et al., 1986; Prahl and Wakeham, 1987) in sediments of the Bermuda Rise, a sediment drift in the subtropical western North Atlantic. The new record comprises 1100 SST determinations spanning the period 130,000–60,000 yr BP, and is an extension of the earlier paleo-temperature reconstruction of Sachs and Lehman (1999) for marine isotope stage (MIS) 3.

2. Materials and methods

Core MD95-2036 (33°41.444′N lat., 57°34.548′W long.) was collected from 4462 m water depth on the Bermuda Rise. In the present study, we analyzed an approximately 12 m section of the 53 m long core corresponding to MIS 4 and 5 (from 4400 to 3200 cm). SSTs were determined in (mostly) adjacent 1 cm thick samples via the alkenone paleo-temperature technique using methods described in Sachs and Lehman (1999) and the linear $\mathrm{U}^{k'}_{37}$-temperature regression relation for cultures of *Emiliania huxleyi* of Prahl et al. (1988). This relation (for which the temperature of synthesis is precisely known) is indistinguishable within

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uncertainties from the relation of Müller et al. (1998) based on comparison of a global compilation of core-top measurements and annual average climatological SSTs. Analytical error of the $U_{37}^{k'}$ measurement was between 0.0077 and 0.0053 $U_{37}^{k'}$ units at 1 sigma (or, expressed as SST estimates, 0.23°C and 0.16°C) based on 67 replicate measurements of 2 in-house Bermuda Rise sediment standards run concurrently with authentic samples.

For this study, we develop an age model based on new and previously published benthic δ^{18}O measurements in order to permit objective correlation of our SST results with other marine records. New measurements were performed on *Cibicidoides wuellerstorfi* approximately every 10 cm between ~4200 and 3600 cm core depth (Fig. 1). Between 4400 and 4200 cm we use benthic δ^{18}O values determined approximately every 1 cm from Adkins et al. (1997). For the interval corresponding to MIS 5d–4 the age model was established by linear interpolation between ages determined by correlation to the orbitally tuned SPECMAP isotope stack of Martinson et al. (1987), using control points listed in Table 1. For the interval around MIS 5e (~4400 and 4200 cm), the age model is the same as that of Adkins et al. (1997). The latter accounts for changes in the sediment focusing factor, and thus sedimentation rate, based on the amount of unsupported (excess) ^{230}Th in the sediment.

3. Results

As discussed in previous studies, rates of sedimentation at Bermuda Rise (inset to Fig. 1) are exceptionally

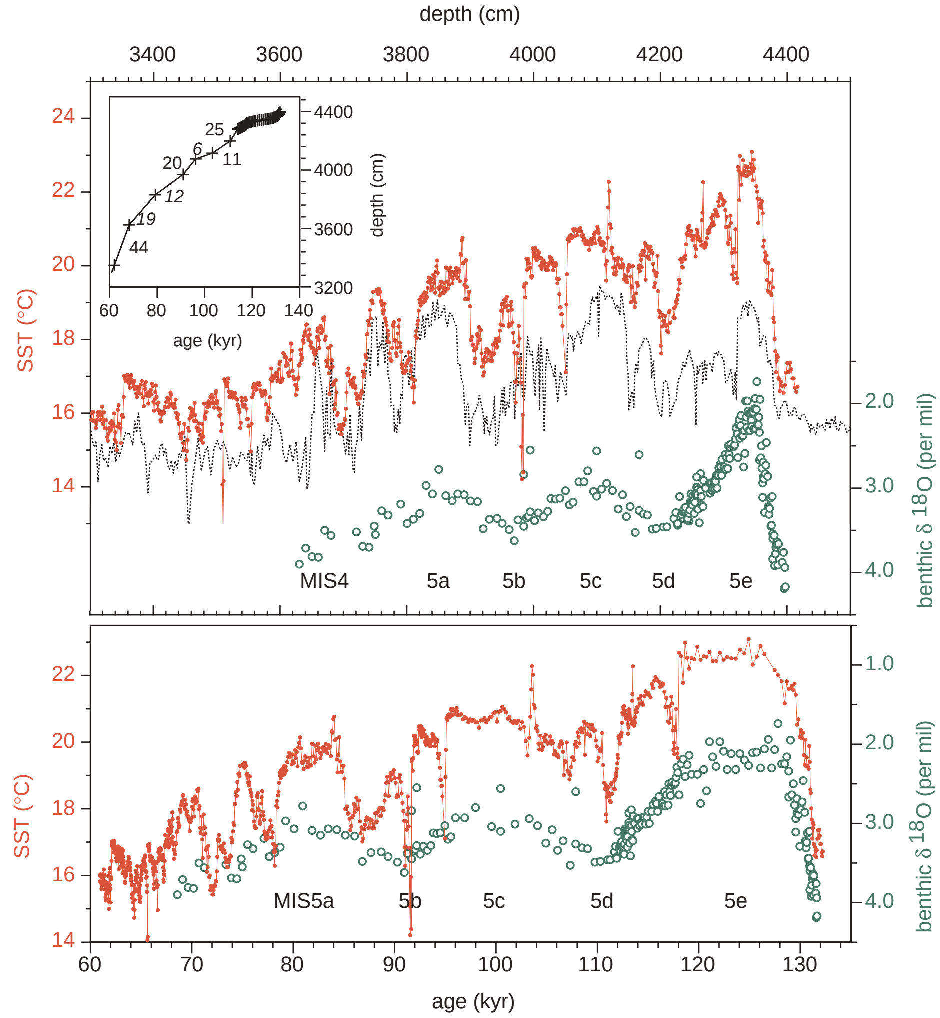

Fig. 1. Alkenone-derived SST results (red symbols and scale) to depth (upper panel) and age (lower panel) for Bermuda Rise core MD95-2036, along with results of benthic δ^{18}O measurements (green symbols and scale) from this study and Adkins et al. (1997). Shipboard sediment "Lightness" results (dotted line, upper panel), a proxy for wt% carbonate content of sediments at Bermuda Rise, have a range of approximately 45–55 units (Boyle, 1997). The age-depth model is shown in the inset, along with inferred sedimentation rates in cm/kyr for each linear segment. As discussed in the text, for the interval between ~4400 and 4200 cm, the age model is that of Adkins et al. (1997). Warm anomalies at ~4270 and 4120 cm are associated with unusually high-alkenone concentrations and may reflect anomalous warm season productivity associated with recently documented volcanic events (Wästegard and Rasmussen, 2001).

Table 1
MD95-2036 age–depth model

Depth (cm)	Age (kyr)	Event
3624.5	68.25	4.23
3830.5	79.25	5.1
3969.5	90.95	5.2
4075.5	96.21	5.31
4115.5	103.29	5.33
4199	110.79	5.4
4280	114	
4380	131	

Numbered events are those of Martinson et al. (1987). Below 4280 cm, the age model is that of Adkins et al. (1997).

high for an open-ocean location, and appear to vary as a function of climate, with elevated (lower) rates of sedimentation associated with periods of harsh (mild) climate (Keigwin and Jones 1989, 1994). Thus, temporal resolution of the warmest parts of the SST series is generally less than during colder intervals. According to the timescale of Adkins et al. (1997), the resolution drops to 400 yr/sample during the warmest part of the MIS 5e, but increases to 30–40 yr/sample during bounding transitions centered at ~4370 and 4330 cm. The latter is comparable to the resolution of the remainder of the series.

Recently, direct ^{14}C dating of alkenones in Bermuda Rise box cores has suggested that "Little Ice Age" sediments at the site may contain pre-aged C36–C39 alkenones (Eglinton et al., 2001). If these alkenones were reworked from higher latitude, higher productivity locations, they may have biased alkenone-derived SST estimates to low values at times, and transport events may have produced "cold events" that did not occur in local surface waters. We note, however, that measures of potential allochthonous fine-grained sedimentation (wt% carbonate and sediment lightness) and alkenone SST and concentration are often decoupled in our records (i.e. Fig. 1; and Fig. 1 of Sachs and Lehman, 1999). Furthermore, wherever planktonic isotope results are available, they corroborate the timing and approximate magnitude of SST changes inferred from alkenone measurements (Keigwin and Jones, 1994; Keigwin and Boyle, 1999). As there is no evidence for reworking of sand-sized materials at Bermuda Rise (Keigwin and Jones, 1994), the planktonic δ^{18}O results can be taken as confirmation of the alkenone record. For example, the cold event at ~4320 cm (to be referred to as "C26", as explained later) occupies a position stratigraphically analogous to the Little Ice Age in MIS 1, with very similar lithologic and geochemical characteristics (i.e. Adkins et al., 1995, 1997; Lehman, 1997). Nonetheless, both isotope and alkenone results document the same timing and approximate magnitude of cooling for event C26 (Fig. 2). Furthermore, alkenone concentrations remain low during the event (and reach local maxima during bounding warmings), in contrast to what would be expected if cooling were an artifact arising from the addition of high-latitude alkenone. This process would also be expected to contribute excess C37:4 alkenone to the sediments (Prahl and Wakeham 1987; Prahl et al., 1988), which is not present in our samples. We, therefore, conclude that data presented here afford a reliable SST reconstruction for the region.

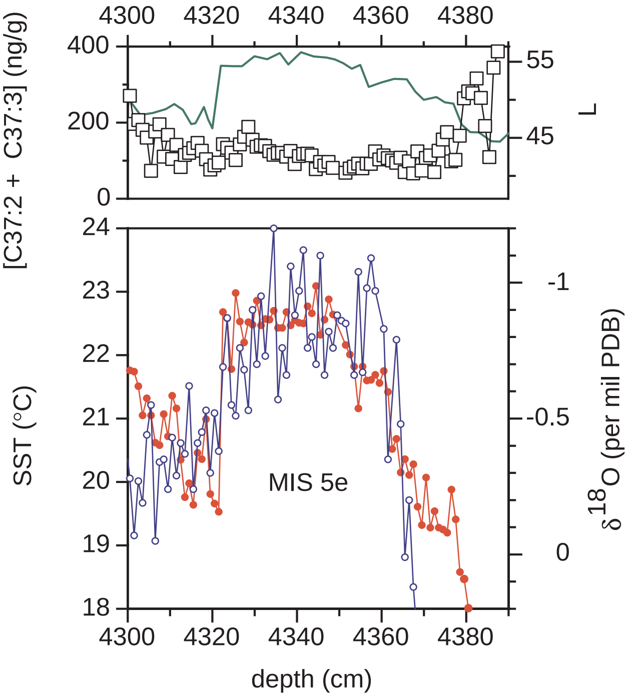

Fig. 2. Alkenone-derived SST results (red symbols) and δ^{18}O results for *Globigerinoides ruber* from Adkins et al. (1997) (blue symbols) scaled 0.24 per mil to 1°C to reflect the temperature dependence of oxygen isotope fractionation between sea water and calcite (Shackleton, 1973). Also shown are total sedimentary concentrations of C37:2 and C37:3 alkenone used for SST reconstruction (squares), and shipboard "Lightness" results (green line) as in Fig. 1. The continued increase in planktonic δ^{18}O following the sudden cooling at ~4320 cm is attributable to increasing ice volume (i.e., associated benthic δ^{18}O data in Fig. 1).

3.1. Subtropical SST

SSTs (Fig. 1) average 22.6°C during the warmest part of MIS 5e, with a range at 1 sigma of only 0.25°C ($n = 28$). The average value is similar to the mean annual SST at the site today (22.8°C at 0 m; Antonov et al., 1998) and approximately 1°C above the late Holocene average SST determined in nearby box cores (Sachs and Lehman, 1999). During the coldest portion of MIS 4, SSTs drop to an average of 16°C. During the warm portions of interstadial substages 5c and 5a, SSTs are 21°C and 20°C, respectively. The interstadial substages are punctuated by brief cooling episodes of

2–5°C and of several hundred years duration. As expected, low SSTs are also observed during stadial substages 5d and 5b. These generally coincide with attainment of maximum benthic $\delta^{18}O$ values, and are much shorter than the $\sim$20 kyr-long precession cycles that pace the isotopic substages and inferred changes in ice volume.

A novel feature of the record is the sudden cooling at the end of the interval of minimum benthic $\delta^{18}O$ within MIS 5e. This is followed by a significant re-warming of the ocean surface that is sustained well into the ice growth stage culminating in the MIS 5d benthic $\delta^{18}O$ maximum. The general picture of ocean warmth extending into the ice growth stage is broadly consistent with the findings of Ruddiman and McIntyre (1979), who argued that a transient combination of ocean warmth and a cooling land mass may have promoted northern hemisphere ice sheet growth. Earlier studies have (apparently) failed to identify the intervening cold event, most likely due to its brevity and/or lack of proxy sensitivity (but see for instance Chapman and Shackleton, 1999).

4. Discussion

4.1. Subtropical SST and subpolar ice rafting and cold events

McManus et al. (1994) provided the first detailed view of suborbital scale ice-rafting and cold events within MIS 5 in the North Atlantic. Using simple faunal and lithologic measures, they showed that the subpolar sea surface remained relatively warm during much of MIS 5, cooling only intermittently in association with evidence for increased ice sheet discharge. Because, coolings were sudden, brief and easily identified as departures from a dominantly warm climate regime, they were labeled as cold anomalies (i.e. events C19–C24). These results are shown in Fig. 3a on the original age scale (developed largely by correlation to the Greenland ice core record of paleo-temperature). Unfortunately, the accompanying benthic $\delta^{18}O$ record for this core (V29-191) does not permit an objective correlation with isotope results from MD95-2036. We therefore also show counts of ice rafted debris (IRD) from another subpolar Atlantic core, NEAP18 K, which has an excellent benthic $\delta^{18}O$ record (Fig. 3b) (Chapman and Shackleton, 1999).

The NEAP18K series appears to capture each of the previously documented cold/IRD events in V29-191 (Chapman and Shackleton, 1999). In addition, the NEAP18K data confirm the presence of a small event during the MIS 5e–d transition which Chapman and Shackleton (1999) label C25. In order to compare IRD results from NEAP18K (and, by correlation, from V29-191) objectively to SST results from MD95-2036, we made a simple adjustment (Fig. 3 caption) to the original age model of Chapman and Shackleton (1999) to maximize correlation of benthic $\delta^{18}O$ results for the two cores (Fig. 3b, lower panel). MD95-2036 is used as the target record because of additional chronologic control afforded by the ^{230}Th-based timescale adjustment of Adkins et al. (1997) between 100 and 130 kyr BP.

Comparison of the IRD and SST series indicates that each of the cold events in the MD95-2036 record is associated with evidence of a transient increase in ice-sheet discharge to the subpolar Atlantic. The only exception is the pronounced cooling marking the end the warmest part of MIS 5e. We tentatively designate this event "C26" to correspond with planktonic $\delta^{18}O$ evidence for a brief cooling near the transition from minimum to increasing benthic $\delta^{18}O$ within MIS 5e documented in NEAP18K and discussed previously by Chapman and Shackleton (1999). The event is not associated with a discernible IRD peak, presumably because little or no tidewater ice remained in the Atlantic basin by the end of the warm part of the Last Interglacial (e.g. Letreguilly et al., 1991; Cuffey and Marshall, 2000).

Covariation of the SST and IRD series indicates an oceanic response to ice sheet forcing that extended from subpolar to subtropical latitudes. The alternative possibility, that lowered SSTs promoted ice sheet discharge, is unlikely given the relatively long time constant of ice sheet response to climatological forcing (Weertman, 1964; Oerlemans, 1993). As discussed extensively by others, one likely mechanism for amplification of the direct cooling effects of ice sheet discharge and iceberg melting is local suppression of deep-water formation.

4.2. Subtropical SST and deep water formation

SST results are compared in Fig. 4 to proxies of the relative proportion of NADW in the deep western North Atlantic. The top panel shows benthic Cd/Ca results spanning MIS 5e in MD95-2036 from Adkins et al. (1997). Also shown are benthic $\delta^{13}C$ results for all of MIS5 in core KNR31-GPC9, from 4758 mwd on the west flank of the Bahama Outer Ridge (Keigwin et al., 1994). In order to compare the latter to results from MD95-2036, we adjusted the original age model of Keigwin et al. (1994) to maximize correlation of benthic $\delta^{18}O$ results for the two cores (Fig. 4, lower panel). Although the isotope data may not constrain the correlation to better than several kyr, there nevertheless emerges a clear correspondence of high-frequency features in the associated SST and $\delta^{13}C$ series. In particular, SST events C26, C24, C23, C22, C20 and C19 appear to have unique, low $\delta^{13}C$ counterparts in the

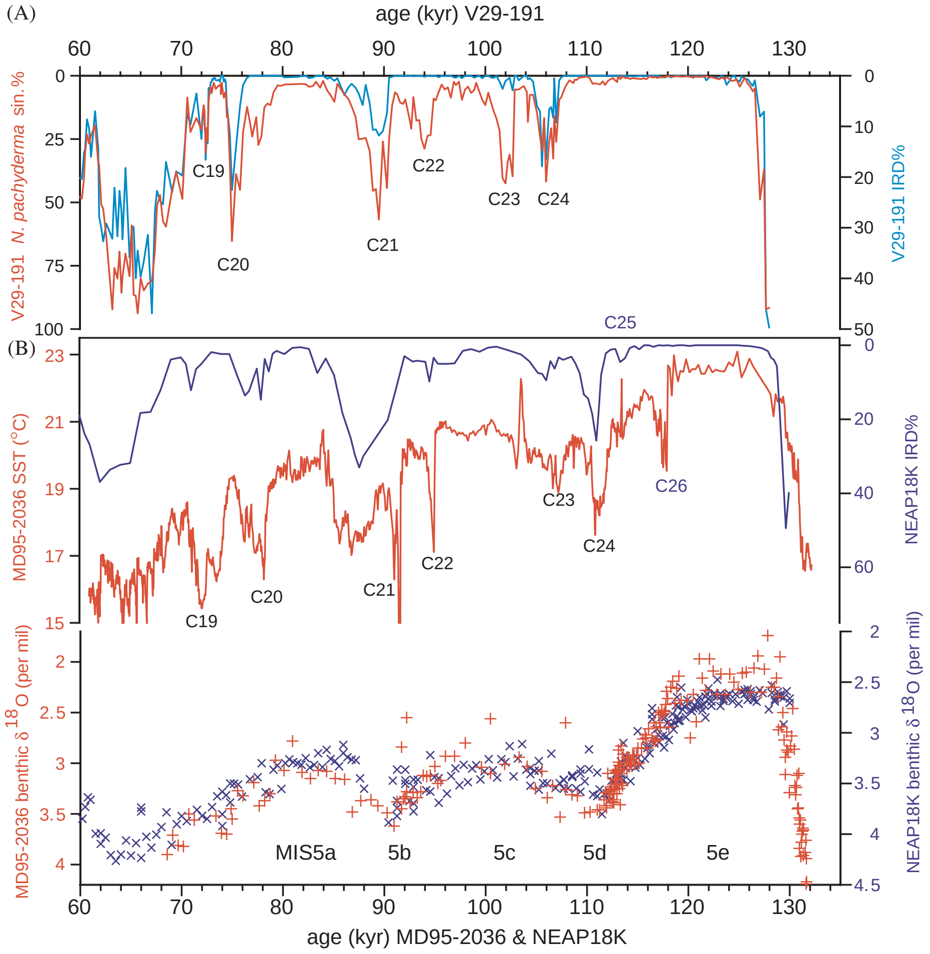

Fig. 3. Faunal and IRD records from the subpolar Atlantic compared to the MD95-2036 SST record for MIS 5: (A) Shows faunal (red line and scale) and IRD counts (blue line and scale) from V29-191 on its previously published age model (McManus et al., 1994); (B) Shows MD95-2036 SST results (red line and scale) and IRD results from NEAP18K (blue line and scale) from Chapman and Shackleton, 1999) on a common timescale based on correlation of benthic δ^{18}O results for the two cores. The original NEAP18K age model was adjusted by +2 kyr after the MIS 5b δ^{18}O maximum (at 430 cm) and +4 kyr before in order to improve correlation of the isotope records, as discussed in the text. The amplitude of δ^{18}O change is slightly larger at Bermuda Rise due most likely to proximity to an abyssal watermass boundary (e.g. Broecker et al., 1976). Cold events C19–C24 (labeled in black) were originally designated by McManus et al. (1994) and correlative events were later identified at NEAP18K by Chapman and Shackleton (1999). C25 and C26 (in blue) were suggested by Chapman and Shackleton (1999). All eight events appear to have counterparts in the subtropical SST record.

benthic data. The interval around MIS 5b is data poor in GPC9, but there is still broad correspondence between low SSTs and δ^{13}C evidence for reduced NADW at approximately the time of C21. A limited number of previously unpublished benthic Cd/Ca results from MIS5e in GPC9 (upper panel, Fig. 4) confirm that both the Bermuda Rise and Bahama Outer Ridge sites recorded the same deep circulation change at the glacial termination and support the use of benthic δ^{13}C as a faithful proxy of deep ocean chemistry and circulation in the remainder of the record.

Taken together, relationships in Figs. 3 and 4 indicate that SSTs in the subpolar and subtropical Atlantic responded rapidly and strongly to the discharge of icebergs to the subpolar Atlantic and the associated interruption or weakening of NADW formation. The exception is the subtropical SST event marking the end of the warmest part of MIS 5e (C26). The event is associated clearly with δ^{13}C evidence for a brief but very pronounced reduction in NADW in KNR31-GPC9. A reduction in NADW at this time is also indicated by benthic Cd/Ca results from MD95-2036, although the Cd/Ca increase (noted by arrow in Fig. 4) is not as large as expected from the correlative δ^{13}C change. In addition, variations in the mean size of current-sortable silt in MD95-2036 and NEAP18K (located upstream in the Charlie-Gibbs fracture zone) indicate a contemporaneous weakening of the deep western boundary current and its feed waters (Hall et al., 1998)—an expected consequence of reduced NADW formation. However, the lack of an associated IRD signal leaves the cause of the circulation event in question.

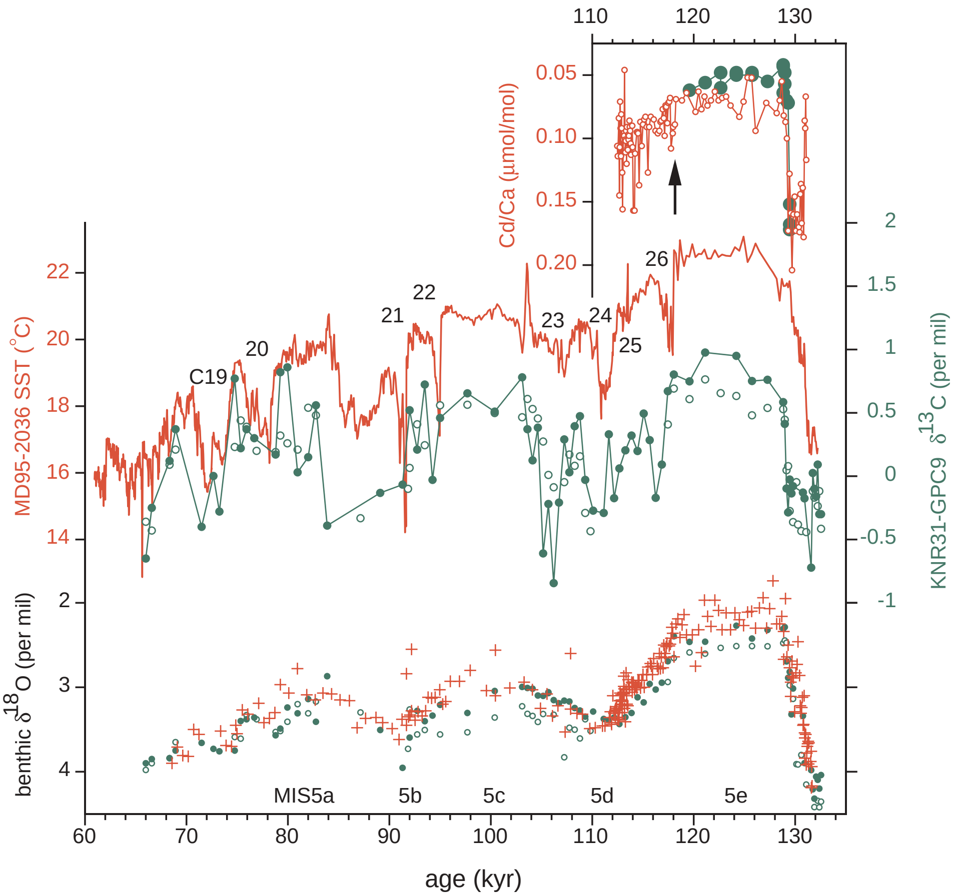

Fig. 4. Comparison of subtropical SST results (red line and scale, middle panel) with benthic Cd/Ca results from MD95-2036 of Adkins et al. (1997) (red symbols, top panel) and benthic δ^{13}C results from Bahama Outer Ridge core KNR31-GPC9 (28°14.7′N lat., 74°26.4′W long.) of Keigwin et al. (1994) (green symbols, middle panel). The data are shown on a common timescale, based on correlation of benthic δ^{18}O results for the two cores, as dicussed in the text. Filled green symbols are results for *Cibicidoides* spp., and open symbols are results for *Nutallides umbonifera* (Keigwin et al., 1994). A limited number of previously unpublished Cd/Ca results for *N. umbonifera* from GPC9 are also shown (filled green symbols, upper panel).

4.3. Implications for climate change in Europe

Although the general relationship between the oceanographic record of the North Atlantic and the pollen record of Europe has been agreed upon for some time, the details remain the subject of some interest and controversy. For example, based on correlation of events in core V29-191 and the pollen record from Grande Pile, located in the alpine foreland of France (Woillard, 1978, 1979). Kukla et al. (1997) have argued that the European Eemian may have extended well into the ice growth phase of MIS 5d. This is in contrast to the long held view that the Eemian equates with MIS 5e alone (Shackleton, 1969; Mangerud et al., 1979). Here we use the detailed subtropical SST series from MD95-2036 to evaluate the relationship between the European pollen sequence and the marine record of ice volume and temperature. Given the similarity between the events in the subpolar and subtropical ocean (Fig. 3), it is not surprising that the new subtropical SST results support many of the correlations already proposed by Kukla et al. (1997) (and earlier by Keigwin et al., 1994). However, the SST data resolve an additional event at the end of the Last Interglacial high sea stand (global ice volume minimum period) that may also signal the abrupt end of the warmest part of the Eemian in Europe.

Fig. 5 shows the proposed relationship between cold events in the subtropical SST record and tree pollen minima at Grande Pile. Dotted lines join cold events C19–24 identified in the SST record with correlative events in the pollen record as proposed by Kukla et al. (1997). Data from MD95-2036 confirm that cold events on land (marked by lower tree pollen %) have unique equivalents in the record of ocean temperature. Furthermore, a comparison to the marine isotope timescale confirms the implied brevity of cold intervals on land. The latter appears to be a general feature of the European climate sequence (e.g. Allen and Huntley, 2000).

Prior to C24 (Melisey I at Grande Pile), the relative abundance of tree pollen reaches a maximum and varies

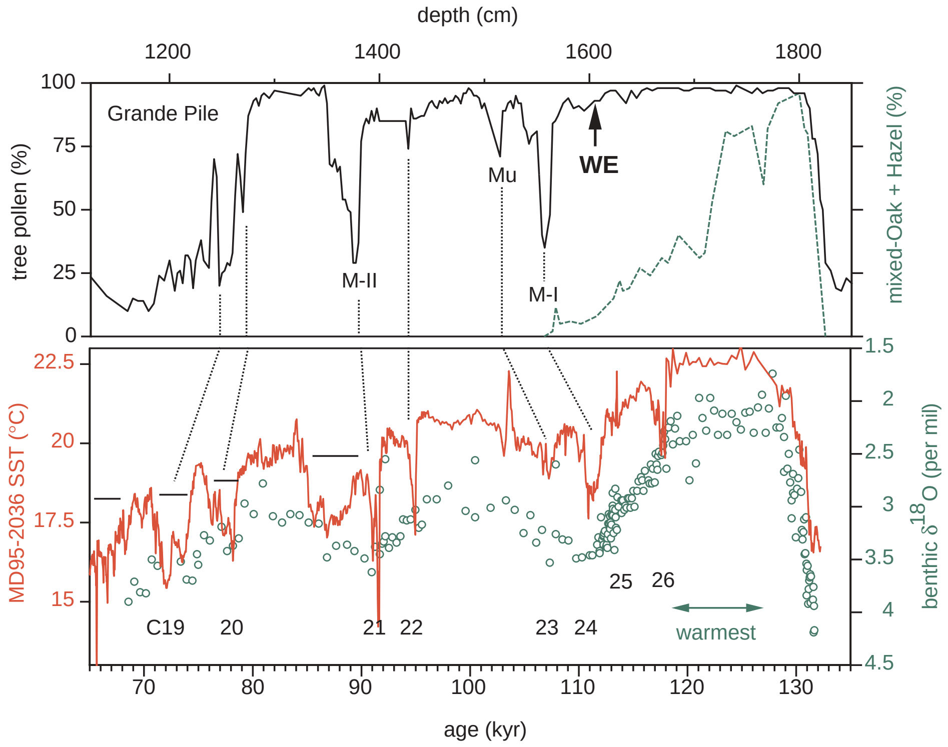

Fig. 5. Comparison of subtropical SST and benthic δ^{18}O results from MD95-2036 (lower panel) with pollen results from Grande Pile, France (Woillard, 1978, 1979) (upper panel). The % sum of total tree pollen (black line and scale) and of mixed-Oak species plus Hazel (dashed green line) are from Woillard (1979). Dashed lines connecting cold events C19–24 to tree pollen minima at Grande Pile are the same as correlations proposed by Kukla et al. (1997). Cold events at Grande Pile are labeled M-I and M-II (Melisey I and II) and Mu (Montaigu), after Woillard (1978). Woillard event (WE) refers to the sudden replacement of broad-leafed species by pine (Woillard, 1979). Horizontal lines indicate possible intervals of accelerated sedimentation at the Bermuda Rise that may not be accounted for by correlation to the SPECMAP timescale.

little. Within this part of the sequence, however, evidence of at least two coolings has been suggested. The first is at the end of the interval dominated by "mixed Oak" species (Woillard, 1978, 1979), taken by Cheddadi et al. (1998) to record the end of the Eemian climatic optimum and the sudden transition to cooler, more variable conditions. The second is the abrupt transition to pine forest (Woillard, 1979), known as the Woillard Event, correlated previously to C25 by Kukla et al. (1997). If the latter is correct, then the decline in mixed-Oak species and inferred "irreversible cooling" of Cheddadi et al. (1998) may correspond to C26 in the SST record.

Our data indicate that there were no significant variations in subtropical SST during the marine (and, probably, terrestrial) climatic optimum and associated ice volume minimum period of the last interglaciation, at least none of more than several hundred years duration (the limit of our resolution for the warm part of MIS 5e). However, near the end of the period of minimum ice volume (minimum benthic δ^{18}O), the subtropical ocean cooled abruptly (~2.5°C in 100–200 yr) in response to altered thermohaline circulation. Apparently, this irreversibly altered the climate and vegetation of Europe. Such a progression of events underscores the need to understand how the current interglacial may develop, particularly in view of possible human impacts on the thermohaline circulation (Manabe and Stouffer,1994; Stocker and Schmittner, 1997).

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