# A precise search for drastic temperature shifts of the past 40,000 years in southeastern Europe

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[1] Climatic models simulate abrupt oscillations that are associated, in the North Atlantic, with Dansgaard-Oeschger and Heinrich events. However, the geographic extension of temperature anomalies is largely uncontrolled due to the scarcity of quantitative records of sufficient time resolution on the European continent. Here, we propose, based on a recently developed temperature proxy ($TEX_{86}$), a reconstruction of millennial-scale temperature variations in a Black Sea sediment archive for the last 40,000 years. Prior to any paleoclimatological interpretations the effects of potential bias, such as seasonality and depth of maximum export production on temperature reconstructions, are considered for the Black Sea. Based on previous work, a tentative method for temperature corrections, taking into account varying terrigenous inputs, is further proposed. Reconstructed temperatures for Black Sea core MD042790 were remarkably stable during the last glacial. However, significant shifts toward lower temperatures of 2°C occurred during Heinrich events 2 and 3. The deglaciation displayed a temperature increase of 10°C consistent with neighboring European reconstructions. A Younger Dryas cooling of approximately 5–6°C was clearly expressed in the reconstruction. In notable contrast to observations from nearby archives, Heinrich events imprinted our glacial temperature record consistent with a strong reorganization of oceanic circulation and a large spreading of the temperature anomaly from the North Atlantic toward the southeast. Furthermore, in contrast to high-latitude records, our Black Sea record lacks the signatures of Dansgaard-Oeschger interstadials, suggesting a decreasing temperature gradient away from the North Atlantic.

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## 1. Introduction

[2] Only a few data sets provide temperature reconstructions on continents at a sufficient time resolution for documenting Heinrich and Dansgaard-Oeschger variability [*Fletcher et al.*, 2010; *Hemming*, 2004; *Voelker et al.*, 2002], in contrast with marine records of temperature changes in the North Atlantic region [*Kucera et al.*, 2005]. Among continental records, the oxygen isotopic composition of speleothems provides a reconstruction of high-resolution variability over the last glacial on the Eurasian continent [*Fleitmann et al.*, 2009; *Genty et al.*, 2006; *Wang et al.*, 2001]. Since the interpretation of such a signal is not straightforward, the isotopic signal is a composite of temperature and precipitation amount and origin [*LeGrande et al.*, 2006]. Pollen sequences within lakes or continental margins allow quantitative reconstructions of temperature through transfer functions or inverse modeling. Differentiation between temperature and precipitation signals, however, is not straightforward either [*Grimm et al.*, 1993, 2006]. Reviews of temperature changes have been performed for key periods such as the Younger Dryas or for the Last Glacial Maximum (among others [*Kageyama et al.*, 2006; *Kuhlemann et al.*, 2008; *Peyron et al.*, 1998; *Wu et al.*, 2007]). However, similar syntheses are not available for abrupt events of the last glacial. Quantitative reconstructions on continents, during this time period, are scarce, especially in central and eastern Europe [*Ampel et al.*, 2010; *Fletcher et al.*, 2010; *Voelker et al.*, 2002].

[3] Sea surface temperatures are often reconstructed, using multiple proxies, for various marine settings [*Kucera et al.*, 2005]. In the Mediterranean Sea, due to extreme salinity contrasts, their use is hampered by a lack of well-established biomarkers [*Essallami et al.*, 2007; *Ferguson et al.*, 2008; *Kucera et al.*, 2005; *Sikes et al.*, 1991; *Ternois et al.*, 1997]. The Black Sea has been deeply influenced by salinity or hydrological changes. Therefore, thus far, a quantitative

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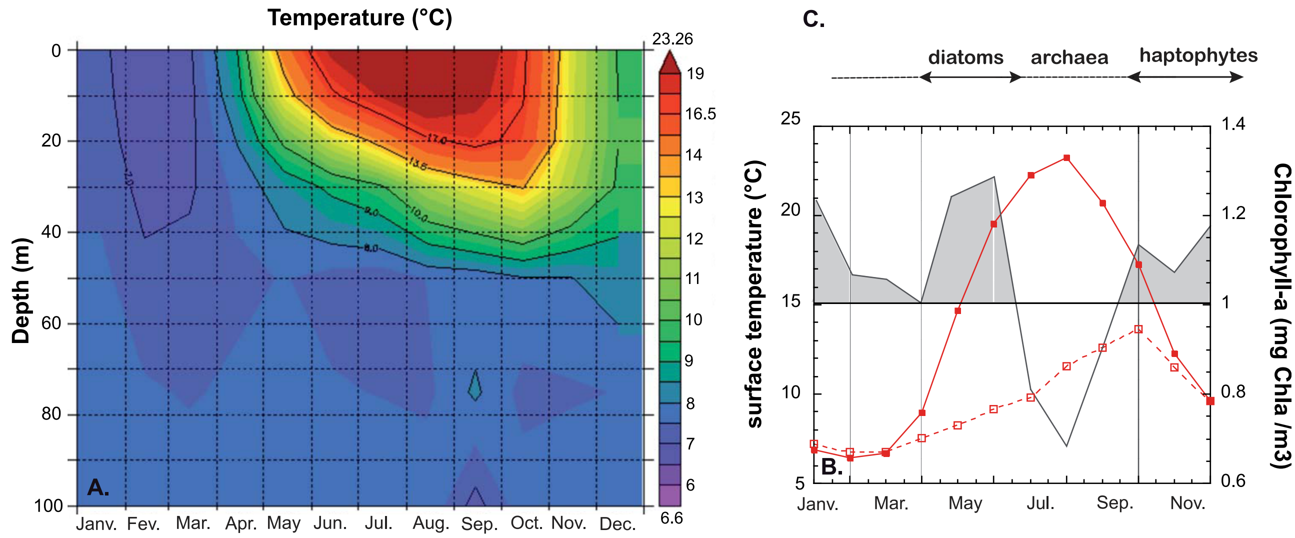


**Figure 1.** Black Sea present-day hydrology. (a) The annual cycle of water temperature variability in the upper 100 m from climatic monthly means in the Black Sea at the core location. (b) Monthly surface temperature variations at the surface (solid red line) and at 30 m (dashed red line), as well as the monthly chlorophyll *a* concentration (solid black line). (c) The succession of the planktonic community within the year (constructed after *Leider et al.* [2010], *Menzel et al.* [2006], and *Sur et al.* [1996]). Climatic data sets were obtained from *Boyer et al.* [2006].

temperature reconstruction for this basin has been unavailable [*Bahr et al.*, 2008]. To avoid the limitations of conventional temperature proxies, a recently developed index that is based on the abundance of water column produced tetraethers, the $TEX_{86}$ index [*Schouten et al.*, 2002], was used for this study. The use of the $TEX_{86}$ index in lacustrine and marine environments is supported by mesocosm experiments that underlie the lack of influence of salinity on this proxy [*Kim et al.*, 2010, 2008; *Powers et al.*, 2004, 2010; *Wuchter et al.*, 2005].

[4] For this work, we took advantage of the unique setting of the Black Sea as an enclosed basin in southeastern Europe in order to document temperatures since the last glacial period using the reconstruction of water column surface temperatures based on a newly developed tetraether paleothermometer. Interpretation of the $TEX_{86}$ record in terms of summer sea surface temperature, based on studies on modern ecology and hydrology of the Black Sea, is discussed. Finally, the clear signatures for Heinrich events 2 and 3 and the lack of imprints for Dansgaard-Oeschger events are put into a perspective of climatological reorganization on the European continent during abrupt events throughout the last glacial.

## 2. Material and Methods

### 2.1. Study Area and Core Location

[5] The Black Sea is the world's largest anoxic basin. It is linked to the Mediterranean Sea through two sills and switches between an endoreic basin and/or a sea connected to the global ocean, depending on sea level. Due to its unique setting, modern hydrology and planktonic abundance and production within the Black Sea have been intensively studied. Water column hydrology within the Black Sea is characterized by strong vertical stratification, with vertical mixing limited by freshwater at the surface, creating strong anoxia beginning at a water depth of 100 m. Chemical stratification accompanies thermal stratification, resulting in a homogeneous deep reservoir with a constant temperature of 8°C (Figure 1a). The annual repartition of surface temperature shows a strong seasonality closely linked to incoming solar radiation (Figure 1).

[6] The northwestern shelf of the Black Sea is heavily influenced by the riverine input of nutrients, mainly from the Danube River but also from the Dnieper and the Dniester Rivers. Inflowing nutrients are redistributed along the western coast by a rim [*Humborg et al.*, 1997; *Morgan et al.*, 2006; *Özsoy and Ünlüata*, 1997]. Therefore, productivity is linked to nutrient loads in the photic zone that are controlled by fluviatile inputs with peak floods during spring and/or by intense mixing by convection in the first 100 m of the water column during cold months [*Sur et al.*, 1996]. In early summer thermal stratification prevents photosynthetic blooms once nutrients are consumed (Figure 1b). The observed seasonal pattern of chlorophyll distribution in the open Black Sea, indicating phytoplanktonic productivity, fits a bimodal curve for the seasonal dynamics typical for temperate waters with high values during spring and winter [*Yunev et al.*, 2002] that are also observed in the Adriatic Sea [*Leider et al.*, 2010] or the eastern Mediterranean Sea [*Menzel et al.*, 2006].

[7] Different photosynthetic populations are associated with productivity maxima. Diatoms are associated with the spring peak, whereas the autumn peak is mainly composed of haptophytes [*Cokacar et al.*, 2001; *Sur et al.*, 1996] (Figure 1c). Between spring and autumn a mixed assemblage develops above the seasonal thermocline and is associated with a deep chlorophyll maximum [*Morgan et al.*, 2006; *Oguz and Merico*, 2006]. In the 1990s, Archaeal plankton has been revealed as being ubiquitous and abundant prokaryotes in the ocean [*Karner et al.*, 2001] in coastal

waters [*DeLong*, 1992] and in freshwater environments [*Keough et al.*, 2003; *Powers et al.*, 2004]. Specifically, in the nearshore waters of the northwestern Black Sea, Crenarchaeota and Euryarchaeota were recently found to constitute an important component of the coastal prokaryotic planktonic community [*Stoica and Herndl*, 2007]. In the Black Sea and elsewhere Archaea are particularly abundant in environments less favorable for phytoplankton both spatially (i.e., in settings characterized by high particule loads or deeper in the water column) and temporally (i.e., after blooms of other species, when nutrients are less abundant) [*Huguet et al.*, 2007; *Karner et al.*, 2001; *Lopes dos Santos et al.*, 2010; *Menzel et al.*, 2006; *Stoica and Herndl*, 2007].

[8] Hydrological and climatological histories of the Black Sea have gained considerable interest when the hypothesis of its catastrophic flooding by Mediterranean waters and its associated abrupt level rise at the early Holocene was proposed [*Ryan et al.*, 1997]. Most studies, however, on the past behavior of the Black Sea have focused on its marine history (i.e., the last 9,000 years) [*Soulet et al.*, 2011a]. Only recently have studies considered hydrological properties on a longer time scale [*Bahr et al.*, 2006; *Kwiecien et al.*, 2009; *Major et al.*, 2002; *Soulet et al.*, 2011b]. Since the catchment of this basin drains a large part of southeastern Europe through the Dnieper and Danube Rivers, its sedimentary archives are expected to integrate a regional climatic signal. In 2004, the ASSEMBLAGE cruise of the R/V *Marion Dufresne* retrieved large cores in the basin providing high-resolution climatic sequences. Core MD042790 (44°13′N, 30°60′E, 358 m water depth) was collected on the direct axis of the Danube River at 130 km of the actual coastline.

[9] Since reservoir ages in the basin vary significantly due to complex hydrology, establishing the chronology of sedimentary sequences in cores obtained from the Black Sea is a major challenge. A separate paper is dedicated to chronology and to establishment of core MD042790 age model by tuning of high-resolution data sets to the Hulu Cave speleothem record [*Soulet et al.*, 2011b].

### 2.2. Extraction and Purification of Organic Compounds

[10] For lipid analysis, 1 to 5 g of sediment was extracted with the accelerated solvent extraction method (ASE 200 system, Dionex, California, USA) at 120°C and 100 bars, using dichloromethane/methanol (90:10 v/v). The total lipid extract was subsequently separated into polar and nonpolar fractions using columns packed with $Al_2O_3$ and hexane/dichloromethane (9:1, v/v) or dichloromethane/methanol (1:1, v/v) as eluents, respectively. Prior to injection, the polar fraction was filtered through a 0.45 $\mu$m, 4 mm diameter PTFE filter.

### 2.3. GDGT Measurements: The $TEX_{86}$ and BIT Indexes

[11] For the quantification of intact GDGTs, samples were analyzed at CEREGE by high-performance liquid chromatography/atmospheric pressure chemical ionization mass spectrometry (HPLC/APCI-MS) using positive ions on a HP LCMS1100 Series (Hewlett Packard, USA). Analytical conditions were similar to those of *Hopmans et al.* [2000]: a Prevail Cyano column (150 mm × 2.1 mm, 3 $\mu$m) was used with 99:1 hexane:propanol (vol:vol) as the eluent. After the first 5 min, over the next 24.5 min at a flow rate of 0.2 ml/mm, the eluent increased by a linear gradient up to 1.4% isopropanol.

[12] Scanning was performed in single ion monitoring (SIM) mode. SIM was set to scan the five $[M + H]^+$ ions of the GDGTs and the three $[M + H]^+$ ions of the branched tetraethers. Similar to the approach proposed by *Huguet et al.* [2006], concentrations of individual GDGT were determined by relating chromatogram peak areas to the concentration of the internal standard C46 GDGT.

[13] The $TEX_{86}$ ratio was calculated according to *Schouten et al.* [2002]. Then, the Branched and Isoprenoid Tetraether (BIT) index, a proxy for soil versus marine organic matter input to sediments, was calculated per *Hopmans et al.* [2004]. Our analytical methodology was tested in the framework of an international laboratory comparison, and our results were found to compare favorably with results from other laboratories (with a standard deviation of 1.8% and 3.3% for BIT values greater and lower than 0.4 and 0.02, respectively; and a standard deviation of 1.9% and 0.3% for $TEX_{86}$ values close to 0.4 and 0.7, respectively [*Schouten et al.*, 2009]). To ensure similar relative ionization efficiencies for the isoprenoid GDGT crenarchaeol and branched GDGTs throughout sample analyses, standard samples with known BIT and TEX indexes were analyzed at regular intervals. All samples (305) were measured at least twice. The mean standard deviation was 0.004 for $TEX_{86}$ and 0.006 BIT units of duplicate runs respectively, which corresponded to 0.2 to 0.3°C, depending on the chosen calibration data set for $TEX_{86}$. The values are consistent with the expected analytical error [*Schouten et al.*, 2009].

## 3. Results and Discussion

### 3.1. The Black Sea Temperature Tetraether-Based Record

[14] The reconstructed temperatures derived from $TEX_{86}$ in core MD042790 vary between 15 and 4°C. The last glacial (i.e., between 15 and 40 kyr) was remarkably stable as compared to the deglaciation with an attenuated variability surrounding a low mean temperature (6.5 ± 1.2°C versus 12.2 ± 3.5°C for the two periods, respectively). Despite this low variability, significant shifts toward lower temperatures of 2°C in amplitude appeared during Heinrich events 2 and 3 (Figure 2). A plateau of high temperatures between 9 to 15 kyr was marked by a shift of 6°C toward lower values during the Younger Dryas (Figure 2b).

### 3.2. Potential Biases for the Tetraether Temperature Record

[15] *The influence of terrestrial input.* Given its location close to the mouth of both the Danube and the Dnieper Rivers, the sedimentary record of core MD042790 is prone to heavy influence by soil organic terrestrial inputs. Down-core fluctuations of organic matter composition were recorded by means of the BIT index, which displayed variations between 0.01 and 0.6, with a decreasing trend from 40 kyr toward the top of the record. Based on the distribution of GDGTs for the equatorial Atlantic Ocean region, *Weijers et al.* [2006] estimated no significant influence of organic matter input on temperature reconstructions within the error bars for BIT between 0.2 and 0.3 and an influence larger than 2°C for BIT values greater than 0.4. Following their approach, we

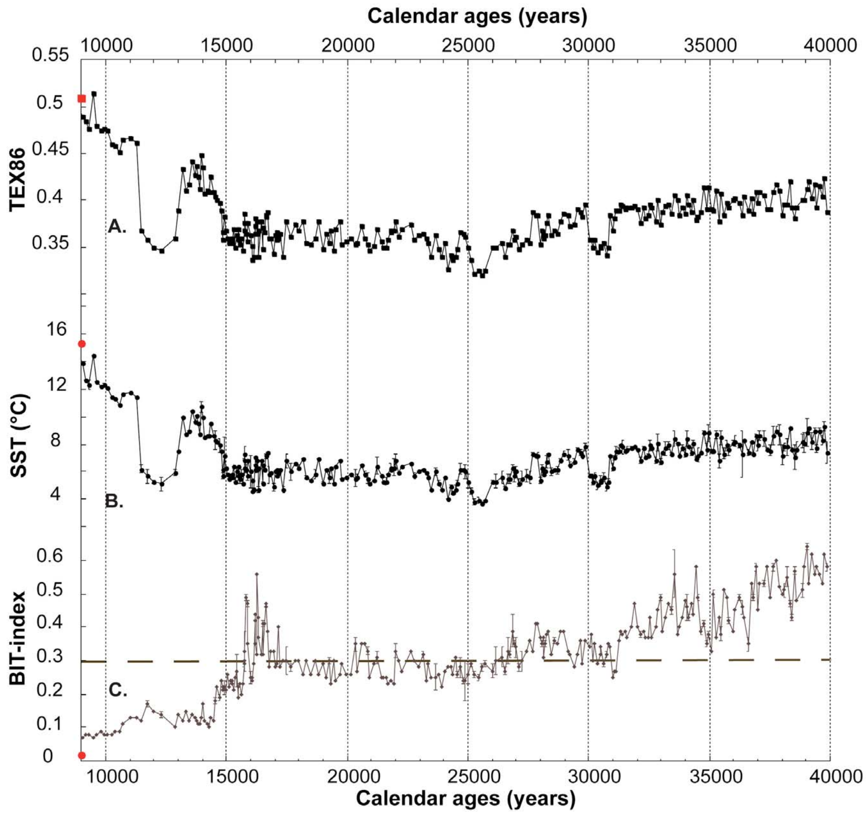


**Figure 2.** GDGT temperatures and terrestrial proxies. (a) $TEX_{86}$ index variations through time. (b) Reconstructed SSTs based on the calibration data set from *Powers et al.* [2010] for the lacustrine portion based on *Schouten et al.* [2002] for marine core top sediments. Error bars on the indexes correspond to two standard deviations for replicated measurements. Errors were propagated on temperature values reconstructed using each equation. (c) BIT index variations versus time.

calculated a temperature deviation associated with the input of terrestrial material in marine sediments using a binary mixing model between two end-members in GDGT distributions: a marine end-member based on core top sediment samples for core MD042790, and a soil end-member corresponding to midlatitude to high-latitude soils selected from the database of *Weijers et al.* [2006] (Figures 3). Going one step further, we propose a correction for the "artificial warming" associated with the BIT record of MD042790, taking into account the equation derived from the previous mixing model. The derived correction is ~−4°C, associated with pulses of the BIT index between 17 and 20 kyr as well as a progressive cooling of ~−2.5°C from 27 to 40 kyr (Figure 4c). As illustrated by the comparison of the light gray and black curves in Figure 4c, the correction does not affect the overall pattern of the reconstructed temperature record.

[16] *Changes in Archaeal composition.* Shifts in the dominant population of Archaea between Euryarchaeota and Crenarchaeota could induce a bias in temperature reconstructions [*DeLong*, 1992; *Turich et al.*, 2007]. However, GDGT-0/Crenarchaeol values are lower than 0.8 along the entire record, and, therefore, typical for Group I Crenarchaeota [*Blaga et al.*, 2009; *Liu et al.*, 2009b; *Schouten et al.*, 2002; *Turich et al.*, 2007]. The GDGT distribution within the lacustrine part of the Black Sea record shows no evidence of changes in Archaeal composition.

[17] *Archaeal production away from the photic zone.* The production of tetraethers deep within the water column [*Karner et al.*, 2001; *Wuchter et al.*, 2005] and/or within the first centimeter of sediment [*Lipp and Hinrichs*, 2009] could be a limitation when using the $TEX_{86}$ index for paleothermometry. A potential impact of Archaeal production away from the photic zone needs to be tested, since the Black Sea is characterized by important bacterial communities in these two habitats [*Morgan et al.*, 2006; *Stoica and Herndl*, 2007]. In different environments sedimentary tetraethers were shown to reflect production in the upper part of the water column and at midlatitudes/low latitudes [*Ho et al.*, 2011; *Richey et al.*, 2011; *Shintani et al.*, 2011] and high latitudes [*Shevenell et al.*, 2011], and more precisely in the Mediterranean area [*Castañeda et al.*, 2010; *Leider et al.*, 2010]. A specific case for use in the Black Sea is validated by studies of the structure of epipelagic communities either through direct counting [*Morgan et al.*, 2006], comprehensive biomarker studies [*Wakeham et al.*, 2003], or DNA/RNA-based studies [*Coolen et al.*, 2007; *Lin et al.*, 2006]. Particular attention has been given to Archaea and their repartition in the water column [*Coolen et al.*, 2007; *Wakeham et al.*, 2004, 2003]. Both direct organism counting and biomarker studies have revealed a

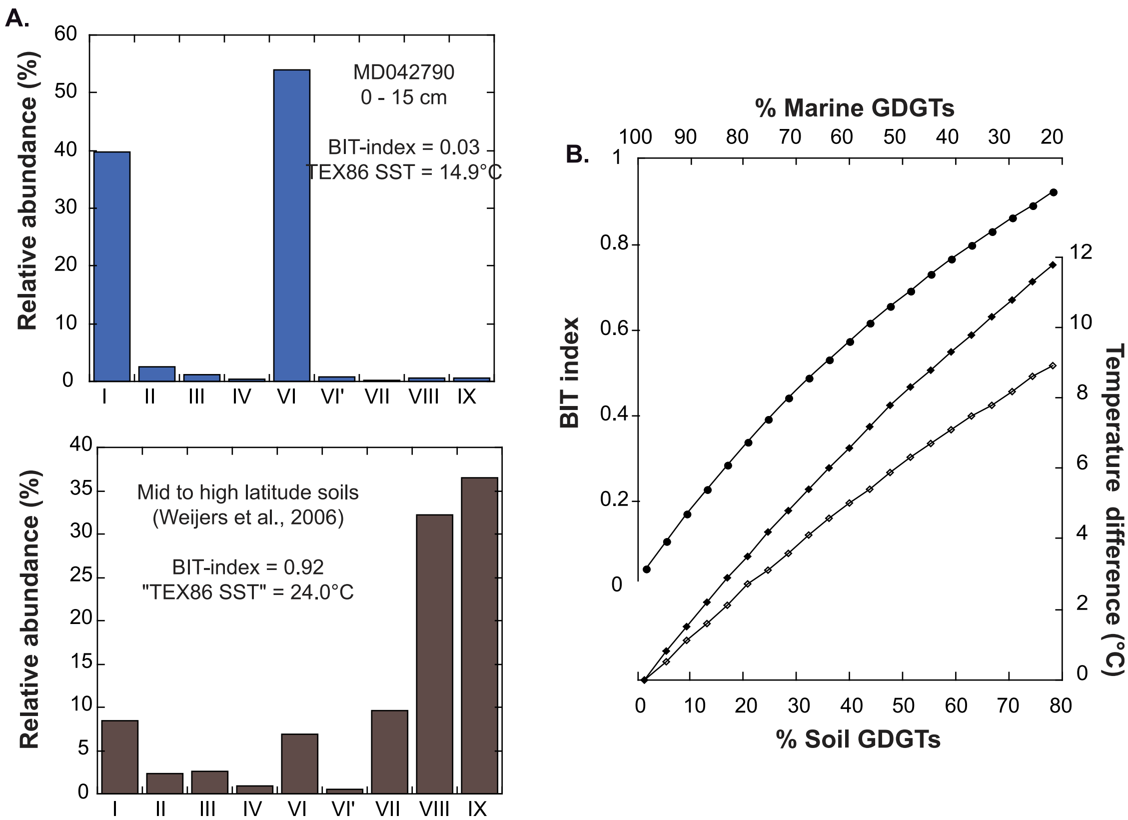


**Figure 3.** The influence of terrigenous material on temperature reconstructions based on a hypothetical binary mixing model (first proposed by *Weijers et al.* [2006]) for the midlatitude northern region composed of (a) an end-member representing the GDGT distribution in a marine sediment sample from the core top of MD042790 and an end-member representing an average GDGT distribution in midlatitudes to high latitudes. (b) The positive temperature difference from the original end-member value according to the $TEX_{86}$ proxy using lacustrine (black diamonds, *Powers et al.* [2010]) and marine (empty diamonds, *Schouten et al.* [2002]) calibrations (with different mixing ratios).

strong concentration of Archaea in the first 100 m of the water column. A second maximum was observed for the methane oxidation zone at greater depths [*Wakeham et al.*, 2003]. An intense comparison of biomarker concentrations in sediment traps and at the surface of sediments indicated that this "deep GDGT signal" was not exported to the sediment. The lack of packaging prevents the exportation of small archaeal cells to the sedimentary surface [*Wakeham et al.*, 2003]. Therefore, the Black Sea sedimentary $TEX_{86}$ record should reflect paleosurface or subsurface water conditions.

[18] *The seasonality of maximum export.* Shifts in the seasonality of production or maximum export could bias the temperature record. Core top temperature reconstruction is consistent with modern surface hydrology and archaeal growth in the first 30 m of the water column during summer in the Black Sea (Figure 1 and the red symbols in Figure 2), supporting results regarding the seasonality of GDGT maximum export production for midlatitude regions which are based on recent regional calibrations for the Adriatic Sea [*Leider et al.*, 2010] and additional work. However, little is known regarding the seasonality of production during the late Glacial. Inferred from differences in alkenones and tetraether-based paleothermometers, spring or autumn production for Archaea has been previously suggested for the eastern Mediterranean [*Castañeda et al.*, 2010]. However, as a lake during the last glacial, the Black Sea is expected to exhibit midlatitude production patterns, with complete mixing of the water column twice a year in spring and winter [*Powers et al.*, 2010]. Therefore, similarly to present day, maximum Archaea export is expected during summer and no evidence supports a shift in the seasonality of maximum production during the last 40,000 years.

### 3.3. Millennial-Scale Temperature Variability During MIS3 on a Regional Scale

[19] *Last Glacial Maximum, Younger Dryas, and Heinrich stadials.* The Black Sea record shows a contrast of ∼10°C between Holocene and glacial temperatures, in agreement with recent temperature reconstructions from the eastern portion of the Mediterranean basin [*Castañeda et al.*, 2010] and from the Marmara Sea [*Ménot and Bard*, 2010]. The amplitude is consistent with the temperature change encountered in the western Mediterranean and the North Atlantic basins (Figure 4) [*Bard et al.*, 2000; *Melki et al.*, 2009; *Pailler and Bard*, 2002; *Rouis-Zargouni et al.*, 2010].

[20] The Younger Dryas is characterized by a distinct minimum in temperature (ΔT ∼6°C, Figure 4), similar to that observed in the western Mediterranean basin and in the Atlantic Ocean [*Bard et al.*, 2000; *Broecker et al.*, 2010]. The first temperature estimation for this interval, determined from

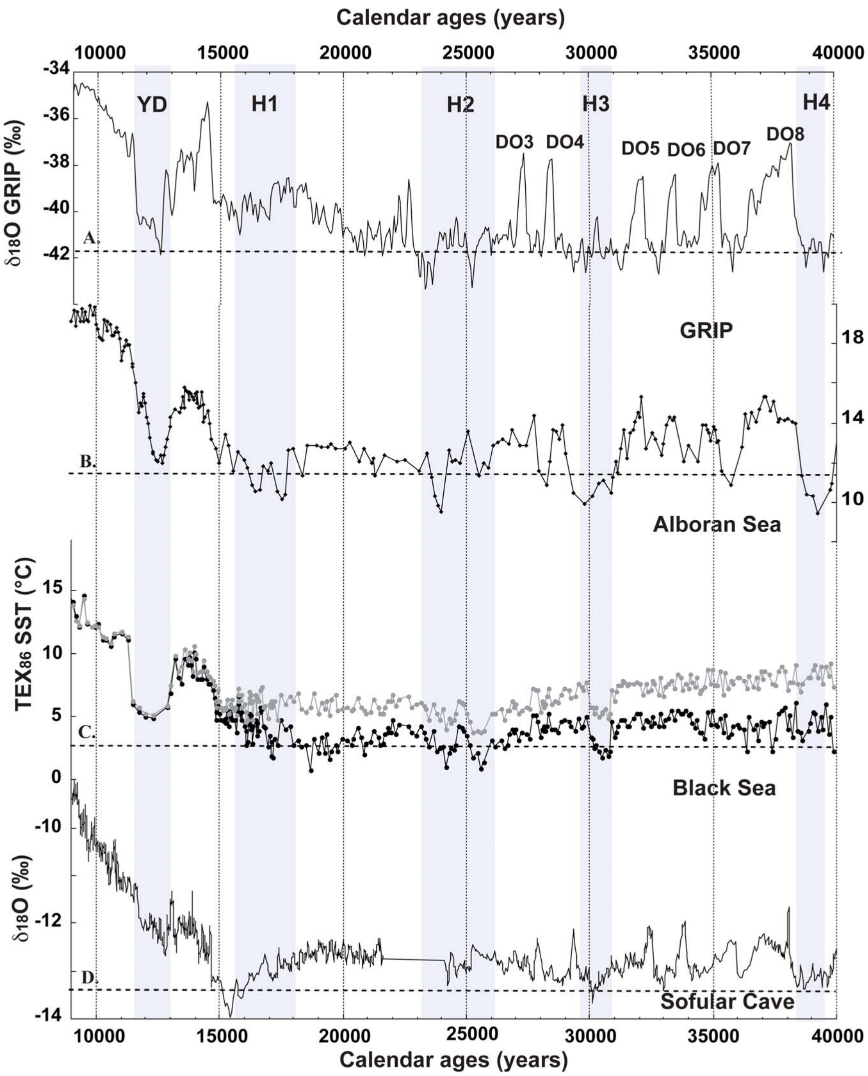


**Figure 4.** Millennial-scale variability during MIS3 on a regional scale. (a) The $\delta^{18}O$ GRIP record reflecting Greenland air temperatures [*Johnsen et al.*, 2001]. (b) Sea surface temperatures based on the alkenone record of core MD952043 in the Alboran Sea [*Cacho et al.*, 1999]. (c) Sea surface temperatures based on the GDGTs record of core MD042790. The BIT-corrected temperatures are shown by the black curve and symbols (this study). (d) The $\delta^{18}O$ record of Sofular cave, Turkey [*Fleitmann et al.*, 2009]. Gray areas indicate Heinrich events 1 to 4 in these records; numbers refer to Greenland interstadials or Dansgaard-Oeschger events (1 to 8).

thermally fractionated gases in polar ice, was recently revisited. Temperatures ~10 ± 4°C lower during the YD than directly before or after were published for GISP2 [*Grachev and Severinghaus*, 2005; *Severinghaus et al.*, 1998]. In the Mediterranean Sea, the transitions to and from the Younger Dryas signature shows also a clear cooling, similar to that observed for the Atlantic Ocean and the western Mediterranean basin [*Cacho et al.*, 2001; *Martrat et al.*, 2004]. Thus far, the Younger Dryas is poorly marked or absent in the Marmara and Aegean Seas [*Gogou et al.*, 2007; *Ménot and Bard*, 2010]. Furthermore, reconstructed temperature Holocene-YD differences are either larger or similar between the western and eastern basins, depending on the selected proxy [*Emeis et al.*, 2000; *Essallami et al.*, 2007].

[21] The comparison of Younger Dryas temperature-sensitive proxies on continents leads to a complicated picture due to uncertainties on the precise nature and sensitivity of the different records (among others [*Lotter et al.*, 2012]). The quantitative reconstructions of summer temperature for the interval have been mainly based on pollen, chironomids, beetle fossils, or glacier fluctuations [*Atkinson et al.*, 1987; *Birks and Ammann*, 2000; *Isarin and Renssen*, 1999; *Lotter et al.*, 2012; *Renssen et al.*, 2000]. Oxygen isotopic records from speleothems or in lacustrine deposits have been compared. However, their interpretation is not straightforward since they are influenced by temperatures, seasonality of precipitation, vapor sources, and ice volume [*LeGrande and Schmidt*, 2009; *McDermott*, 2004]. A clear shift toward more depleted values has been seen in Germany [*von Grafenstein et al.*, 1999] and in France [*Genty et al.*, 2006]. However, only a slight, or no, signal has been seen in Turkey [*Fleitmann et al.*, 2009], Israel [*Bar-Matthews et*

*al.*, 2003], or Lebanon [*Develle et al.*, 2010]. In a similar manner, continental sequences of pollen assemblages or lake levels show a contrasting pattern [*Allen et al.*, 1999; *Harrison et al.*, 1996; *Tarasov et al.*, 2009].

[22] Glacial temperatures reconstructed from the Black Sea are stable but have three significant fluctuations toward low temperatures with values of approximately 3°C, simultaneous with Heinrich events 2 and 3. The structure of these events is surprisingly similar to that of Atlantic Ocean marine records with a paired event for Heinrich 2 and a single temperature depression for Heinrich 3 [*Hemming*, 2004] (Figure 4). The amplitude of the temperature changes is equivalent with that off of the Iberian Margin and in the western Mediterranean Sea [*Martrat et al.*, 2004; *Pailler and Bard*, 2002]. Despite the strong impact that these events have in marine records [*Hemming*, 2004], only a few studies have reported them with a sufficient time resolution for resolving abrupt events in continental archives, especially for Central to Eastern Europe [see *Voelker et al.*, 2002, Figure 1].

[23] *Dansgaard-Oeschger interstadials.* When comparing the glacial Black Sea temperature record to the reference climatic sequence of Greenland ice cores, a surprising feature in our record is the lack of warm events associated with Dansgaard-Oeschger interstadials (Figures 4a and 4d). Warming associated with Dansgaard-Oeschger interstadials in the north GRIP record are on the order of 10 to 15°C for DO 8 to 17 (i.e., beyond the time period covered by our lacustrine record), and no temperature reconstructions have been published, thus far, for the past 30 kyr [*Huber et al.*, 2006; *Landais et al.*, 2004]. In North Atlantic marine archives, warm events could be identified (not as well as cold events), although the amplitude of these events was small—2–4°C [*Martrat et al.*, 2007; *Pailler and Bard*, 2002].

[24] In continental archives, shifts associated with these events are recorded in speleothems [*Fleitmann et al.*, 2009; *Wang et al.*, 2001] and in a few pollen sequences [*Fletcher et al.*, 2010; *Margari et al.*, 2009; *Müller et al.*, 2011; *Wohlfarth et al.*, 2008]. For one of the few quantitative reconstructions for continents, an amplitude of 0.5 to 2°C was reported for the paleolacustrine sequence of Les Echets in western Europe [*Ampel et al.*, 2010]. A general characterization of the vegetation response to millennial-scale variability from pollen records on the European continent revealed, despite the influence of site specific factors related to altitude, topography, and microclimatic effects, a west-east contrast that could partly be attributed to the decreasing severity of the stadial condition away from the North Atlantic, as well as a north-south latitudinal gradient [*Fletcher et al.*, 2010].

### 3.4. The Pattern of Millennial-Scale Temperature Variability in Central Europe

[25] *Simulated millennial-scale temperature variability.* Millennial-scale climatic variability for the last glacial period, particularly the temperature anomalies associated with Dansgaard-Oeschger interstadials and Heinrich cold events are well reproduced using earth system models of intermediate complexity and fully coupled atmosphere-ocean general circulation models [*Stouffer et al.*, 2006]. Water hosing experiments using simplified ocean-atmosphere models show a nonlinear response for the North Atlantic and for Greenland temperatures associated with different states of thermohaline circulation during the glacial period—a "warm" (i.e., interstadial interval), a "cold" (i.e., stadial interval), and an "off" (i.e., Heinrich event) state [*Ganopolski and Rahmstorf*, 2001; *Rahmstorf*, 2002; *Rasmussen and Thomsen*, 2004]. However, models provide generic ocean-atmosphere interactions thereby preventing direct comparison with temperature records. The histogram repartition of simulated temperatures for Greenland and for the North Atlantic illustrates multiple modes, and points out differences in the amplitude of the changes between the models. The differences are larger between Heinrich and glacial states and lower between Dansgaard-Oeschger interstadials and glacial states for North Atlantic sea surface temperatures than for Greenland temperatures (Figures 5a and 5b).

[26] Transitions to states of "cold" and "off" are driven by freshwater perturbations at high latitudes that induce some weakening of thermohaline circulation and a large cooling over the North Atlantic [*Stouffer et al.*, 2006]. Ice sheet dynamics and the release of heat stored in deep-sea reservoirs restore the "warm" oceanic circulation state. Sea ice has been found to play a major dynamic role due to its albedo effect (i.e., the atmosphere energy balance), and due to insulating the ocean from the atmosphere, thereby significantly reducing heat air-sea fluxes [*Kaspi et al.*, 2004]. Therefore, sea ice changes are a strong amplifier of small freshwater inputs and appear sufficient for reproducing warming associated with Dansgaard-Oeschger interstadials in Greenland without major changes to oceanic heat transport [*Li et al.*, 2005]. The hydrologic cycle at high and low latitudes is also enhanced by small temperature anomalies [*Bigg et al.*, 2011].

[27] The climate system is also influenced by stochastic noise, which is controlled by ice cap size that results in significant freshwater forcing in the North Atlantic. Larger ice sheets store more fresh water in ice caps or in subglacial lakes and are prone to rapidly shrink, thereby impacting North Atlantic circulation [*Alley et al.*, 2001]. Such an outcome leads to the temporal pattern seen throughout the last glacial period, which is well captured in paleorecords as the decreasing strength of signals associated with Dansgaard-Oeschger interstadials from the initiation of the last glacial period to its end [*Fletcher et al.*, 2010; *Tzedakis et al.*, 2004].

[28] The driving mechanisms behind DO and Heinrich (abrupt) climatic events under glacial conditions are reasonably well understood (see references above). However, the Younger Dryas and the Bølling-Allerød are different in their initiation since they represent cold and warm events, respectively, that occurred during deglaciation (i.e., forced by changes in insulation, atmospheric greenhouse gas concentrations, continental ice sheets and coastlines [*Liu et al.*, 2009a; *Shakun et al.*, 2012]). Questions remain as to how they compare in terms of amplitude and driving mechanisms with abrupt events during glacial conditions. The spatial distributions of the temperature anomalies associated with abrupt events show, in cases of both cooling and warming, a strong response centered at high latitudes in the North Atlantic and an attenuation while spreading southward and eastward (previous references as well as *Liu et al.* [2009a] and *Stouffer et al.* [2006]).

[29] Transient simulations have captured the succession of Heinrich event 1 and the Bølling-Allerød, and have identified

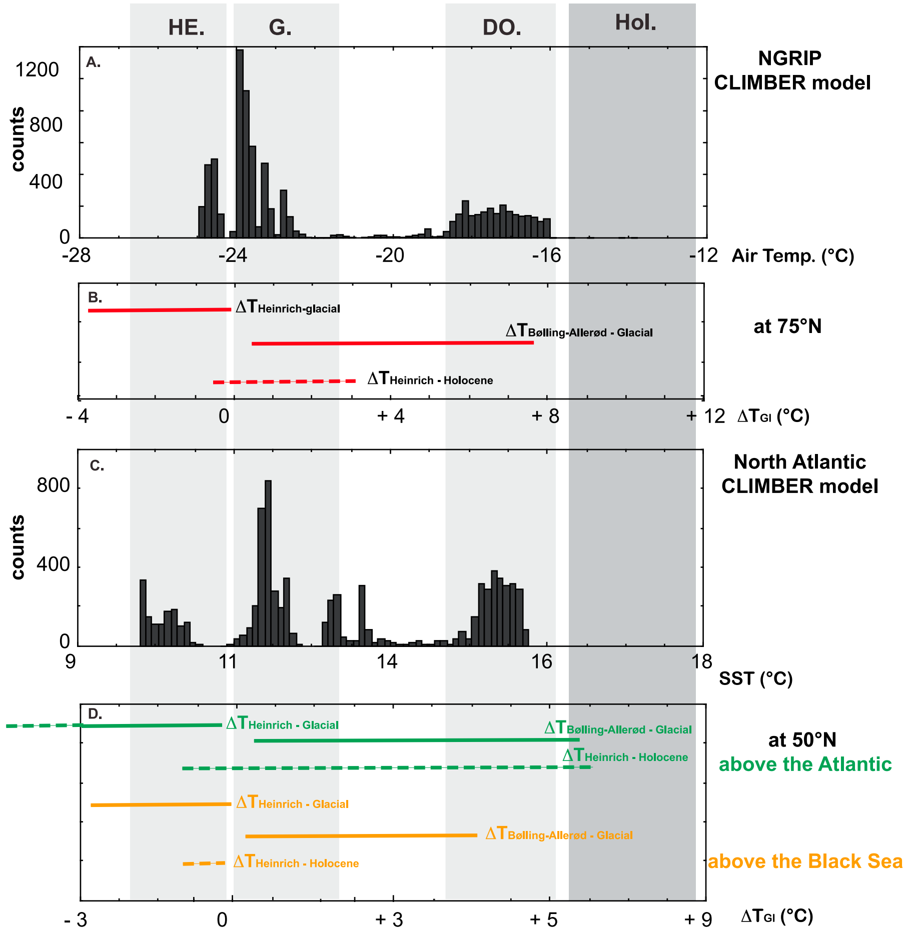


**Figure 5.** A comparison of modeled patterns of millennial-scale variability in Europe during MIS3 and the deglaciation. (a) Histograms of modeled NGRIP air temperature using the CLIMBER model [*Bard*, 2002; *Ganopolski and Rahmstorf*, 2001]. (b) Modeled temperature anomalies during abrupt events of the deglaciation at high latitudes (solid red lines, *Liu et al.* [2009a]; dashed red lines, *Weaver et al.* [2003]). (c) Histograms of modeled North Atlantic temperatures using the CLIMBER model [*Bard*, 2002; *Ganopolski and Rahmstorf*, 2001]. (d) Modeled temperature anomalies during abrupt events of deglaciation at midlatitudes are shown as green lines above the Atlantic Ocean and as orange lines above the Black Sea (solid lines, *Liu et al.* [2009a]; dashed lines, *Weaver et al.* [2003]). Each histogram has a fixed number of bins of 100. The letters H, G, HE, and DO represent the Holocene, the Glacial, a Heinrich event, and Dansgaard-Oeschger interstadial temperatures, respectively.

the mechanism driving the onset of the Bølling-Allerød as fresh water input at high latitudes in the Southern Hemisphere while Atlantic Ocean circulation is in an "off" mode [*Liu et al.*, 2009a; *Weaver et al.*, 2003]. The Younger Dryas temperature event is reproduced in response to an Atlantic Ocean meridional overturning circulation slowdown that is forced by fresh water discharge from the Fennoscandian and Laurentide Ice sheets [*Lunt et al.*, 2006; *Tarasov and Peltier*, 2005].

[30] The amplitude of temperature changes modeled for abrupt events during deglaciation greatly differ depending on models and assumptions regarding the source of fresh water discharge (Figures 5b and 5d) [*Bigg et al.*, 2011; *Liu et al.*, 2009a; *Weaver et al.*, 2003]. At high latitudes, the difference between Bølling-Allerød and Dansgaard-Oeschger temperatures is of the same amplitude as the shifts during the glacial period, while the amplitude of temperature change is larger for the transition to the Bølling-Allerød than for the transitions to the Dansgaard-Oeschger 50°N above the Atlantic Ocean (Figures 5a–5c). However, the amplitude of the Bølling-Allerød transition is strongly attenuated at 50°N above the Black Sea (Figure 5d).

[31] *Reconstructed millennial-scale temperature variability in Europe and in the North Atlantic.* The simulated amplitudes of temperature changes should be compared with those of paleosequences. Due to the scarcity of high-resolution continental temperature sequences, both the amplitude and the extent of temperature anomalies associated with abrupt climatic changes over the last glacial for central Europe are poorly constrained. We selected archives of temperature or temperature-sensitive proxies. In Figure 6, histogram repartitions are compared with the modeled temperature series. The Greenland ice core and the Sofular cave sequences display two modes of oxygen isotopic values, with a larger dispersion for the second (Figures 6a and 6b). Due to the growth hiatus linked with the scarcity of precipitation, there is a few isotopic values associated with Heinrich events in the Sofular cave

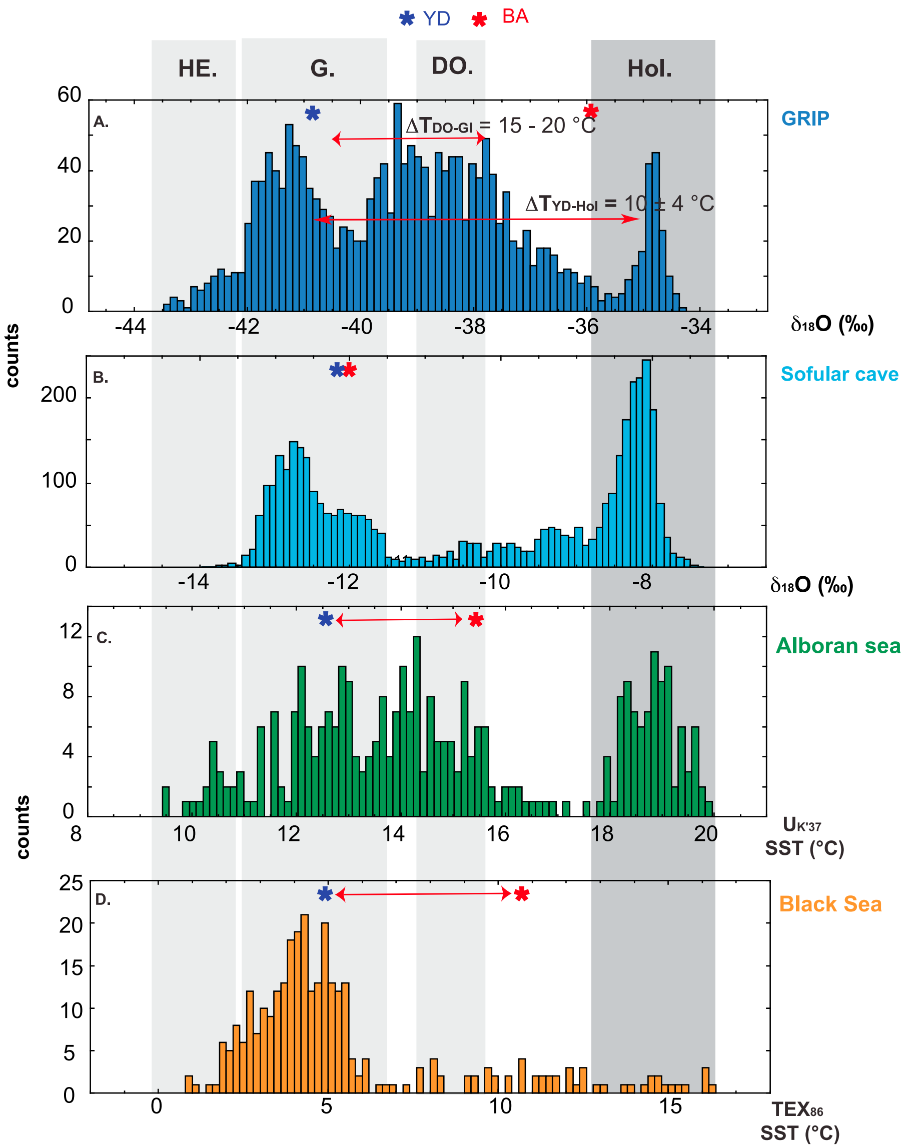


**Figure 6.** A comparison of the measured patterns of millennial-scale variability in Europe during MIS3—histograms of (a) the $\delta^{18}$O GRIP record reflecting Greenland air temperatures [*Johnsen et al.*, 2001]; (b) the $\delta^{18}$O record of Sofular cave, Turkey [*Fleitmann et al.*, 2009]; (c) sea surface temperatures based on the alkenone record of core MD952043 in the Alboran Sea [*Cacho et al.*, 1999]; and (d) sea surface temperatures based on the GDGT record of core MD042790. Each histogram has a fixed number of bins of 100. Note that the number of counts for each mode is dependant on the time resolution of the concerned record, which explains the high mode of Holocene values for the NGRIP ice core and for Sofular cave speleothems. The letters H, G, HE, and DO represent the Holocene, the Glacial, a Heinrich event, and Dansgaard-Oeschger interstadial temperatures, respectively. Red and blue stars represent the respective positions of the Bølling-Allerød and Younger Dryas values.

[*Fleitmann et al.*, 2009]. Furthermore, the contrast in $\delta^{18}$O between Dansgaard-Oeschger and Holocene values is larger in ice cores than in speleothems (Figures 6a and 6b). The Black Sea displays a larger temperature amplitude than the modeled North Atlantic and the reconstructed Alboran Sea temperatures. Part of these differences in amplitude could depend on the proxy temperature calibration equations used for the $TEX_{86}$ and $U^{K'}_{37}$ reconstructions (Figures 6c, 6d, and 5c). However, common features are, first, a distinct Heinrich mode in the temperature sequences, absent or weak in climate-dependant $\delta^{18}$O sequences; and, then, an attenuation of the Dansgaard-Oeschger mode between North Atlantic modeled temperatures and the Black Sea, where it is lacking.

[32] Since it shows distinct Heinrich and glacial modes (Figures 4c and 6d), the Black Sea temperature record for the last glacial is consistent with previously presented driving mechanisms. Heinrich events are characterized by thermohaline circulation changes [*Keigwin and Lehman*, 1994] and the associated temperature anomalies are transmitted through oceanic circulation. Strongly spread over the Atlantic Ocean, they also imprint Mediterranean region temperature records (Figures 6c and 6d). In contrast, the Dansgaard-Oeschger

interstadials that are clearly described in the Greenland record are partly attributed to sea ice forcing and have little impact on thermohaline circulation. The geographic spread of the temperature anomalies is, then, limited to the western border of the European continent [*Ampel et al.*, 2010] (Figures 6c and 6d). Signatures in paleoreconstructions based on speleothems and pollen sequences are likely linked with a reactivation of the hydrologic cycle, with small perturbations in oceanic circulation and temperature [*Vellinga and Wood*, 2002] (Figure 6b).

[33] *Abrupt events during the deglaciation in Europe and in the North Atlantic.* The temperature histogram repartition indicates that Bølling-Allerød values range close to Holocene values in the Black Sea in a similar manner to simulations (Figures 5d and 6d), whereas none of the other considered records exhibited such a large response. In parallel, in all of the records, the Younger Dryas temperature cluster within the glacial mode which is consistent with recent modeling. Therefore, the Bølling-Allerød/Younger Dryas temperature difference is large in the Black Sea record in contrast to other climatic sequences (Figure 6), but of the same order of magnitude in recent modeling experiments designed to reproduce Bølling-Allerød/Younger Dryas succession (Figure 5). The large offset is consistent with a major oceanographic reorganization and the wide geographical extension of the associated temperature anomaly [*Liu et al.*, 2009a].

## 4. Conclusions

[34] We present a continuous quantitative record of Black Sea surface temperatures on the basis of the $TEX_{86}$ proxy for the past 40,000 years.

[35] 1. Prior to deriving any paleoclimatic interpretations of the temperature record, the commonly cited bias, such as changes in the Archaeal composition, the production of GDGTs away from the photic zone, and the seasonality of maximum export were considered and discarded for the Black Sea. Furthermore, following the direction mentioned by *Weijers et al.* [2006], we have proposed a tentative method for temperature correction in order to take into account varying terrigenous inputs. The temperature reconstruction illustrates the reliability of the GDGT based organic biomarker proxy in reconstructing temperature variations of large and low amplitudes (i.e., from 10 to 2°C).

[36] 2. The last glacial period is characterized by low and stable temperatures close to 5°C. In contrast to other climate archives, Heinrich events imprint the glacial temperature background with shifts of 2–3°C toward lower values, synchronous with HE2 and HE3. By comparison, the signature of Dansgaard-Oeschger interstadials is absent in the Black Sea temperature record. Contrasting transmissions of warm and cold anomalies on the European continent are consistent with the various proposed mechanisms. Since Heinrich events are characterized by severe thermohaline circulation changes and, thus, the transmission of temperature anomalies throughout oceanic circulation, they are strongly spread over the Atlantic Ocean and also imprint on Mediterranean region temperature records. In contrast, the Dansgaard-Oeschger interstadials that are clearly described in the Greenland record are partly attributed to sea ice forcing and have little or no impact on thermohaline circulation. The geographic spread of temperature anomalies is then limited to the western border of the European continent, and Dansgaard-Oeschger signatures are expressed in archives based on proxies that are influenced by precipitation and the hydrologic cycle [*Fleitmann et al.*, 2009; *Müller et al.*, 2011].

[37] 3. During deglaciation, the reconstructed temperature profile for the Black Sea displayed an abrupt warming of 10°C synchronous with the Bølling-Allerød and a return to glacial temperatures during the Younger Dryas. The amplitude of the warm/cold transition is large as compared to neighboring locations in continental or marine records, but on the same order of magnitude as temperature differences obtained by recent modeling experiments designed to reproduce the succession of the Bølling-Allerød/Younger Dryas [*Liu et al.*, 2009a]. Our Black Sea record provides a control point in southeastern Europe for testing the geographical extension of the temperature anomaly associated with simulations of coupled atmosphere-ocean general circulation models and it can validate the proposed mechanisms.

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