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Seemingly divergent sea surface temperature proxy records in the central Mediterranean during the last deglaciation

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Abstract. Sea surface temperatures (SSTs) were reconstructed over the last 25 000 yr using alkenone paleothermometry and planktonic foraminifera assemblages from two cores of the central Mediterranean Sea: the MD04-2797 core (Siculo–Tunisian channel) and the MD90-917 core (South Adriatic Sea). Comparison of the centennial scale structure of the two temperature signals during the last deglaciation period reveals significant differences in timing and amplitude. We suggest that seasonal changes likely account for seemingly proxy record divergences during abrupt transitions from glacial to interglacial climates and for the apparent short duration of the Younger Dryas (YD) depicted by the alkenone time series, a feature that has already been stressed in earlier studies on the Mediterranean deglaciation.

1 Introduction

The Mediterranean region is of particular interest because of its sensitivity to climate and environmental changes and their impacts on ecosystems and human population history. Lying at the boundary between mid-latitude and sub-tropical climates, the Mediterranean basin is subject to complex atmospheric teleconnections that have been variable in time (Lionello et al., 2008; Luterbacher et al., 2006). Today, the Mediterranean climate is strongly influenced by the North Atlantic Oscillation (NAO) in winter (Hurrell, 1995; Trigo et al., 2004), while in summer high-pressure systems develop as the Hadley cell circulation move northward producing the characteristic dry season of this region. El Niño and Asian monsoons would also affect summer precipitation variability, mostly in the Eastern Mediterranean. Changes of these climate regimes such as the mid-latitude storm tracks originating from the North Atlantic, or the position of the subtropical highs thus exerts influence on the Mediterranean temperatures and precipitations. Documentation of past temporal and spatial climate patterns contributes to improve understanding of the Mediterranean climate and predictions.

In this study we discuss seemingly divergent sea surface temperature (SST) reconstructions form the Central Mediterranean Sea over the last 25 kyr obtained using foraminifera assemblages and alkenone paleothermometry, two important information sources to investigate past ocean variability. In the recent years, progress has been made to improve proxy calibrations but few existing comparison between proxy and instrumental time series (20th century) have shown that environmental or dynamical factors (e.g. sea ice) can introduce bias and make it difficult to decipher the climate signal embedded in proxy reconstructions (Conte et al., 2006; Rülhemann and Butzin, 2006; Sicre et al., 2011). Here, we examine the sequence of events that punctuated the last deglaciation period when insolation changes due to orbital forcing was a major climate driver. We present records of planktonic foraminifera and alkenone-derived SSTs as well as the δ^{18}O of *G. bulloides* from the South Adriatic Sea and the central Siculo–Tunisian channel, some of which have been earlier published. We then compare these data to the isotope records of the high latitude Greenland ice (GISP2)

Table 1. Depth-age model for the MD04-2797. Dates were calibrated using CALIB 6.0.

Depth cm	Conventional ^{14}C ages (yr BP)	Error $\pm 1\sigma$	Calibrated year BP range 1σ
0	1105	20	661–674
80	5493	95	5725–5929
160	6700	85	7156–7325
199	7523	81	7917–8017
240	8113	81	8419–8557
330	8888	110	9398–9556
410	10 863	32	12 458–12 528
470	12 728	173	13 786–14 246
510	13 900	141	15 495–16 373
610	15 590	50	18 463–18 986
700	17 660	70	20 287–20 541
940	23 415	163	27 645–28 113

Fig. 1. Map showing the location of the two study cores of the Central Mediterranean Sea: MD90-917 (South Adriatic Sea) and MD04-2797 (Siculo–Tunisian Strait). The red star indicates the location where the La Mine stalagmite has been collecting.

and the nearby stalagmite of La Mine Cave (Tunisia) to understand the expression of centennial scale events of Termination I, i.e. the abrupt cold Younger Dryas (YD) and warm Bølling–Allerød (BA) in Mediterranean proxy records. A thorough regional comparison of marine and terrestrial proxy records is presented by Magny et al. (2013) to produce an integrated view of environmental changes in the central Mediterranean Sea and analyse their causes.

2 Materials and methods

2.1 Site locations

The MD90-917 core was collected during the PROMETE II cruise, performed aboard the French R/V *Marion Dufresne*, in the South Adriatic deep basin (41°17 N, 17°37 E; 1010 m water depth), in a wide circular-shaped depression detached from the Ionian Sea by the sill of the Otranto Strait (780 m) and bordered by the Italian and Albanian shelves (Van Straaten, 1970) (Fig. 1). The second core MD04-2797 (36° 57 N, 11°40 E; 771 m water depth) was retrieved in the central part of the Sicilian–Tunisian channel during the IMAGES cruise in 2004, where Eastern and Western Mediterranean Sea waters exchange (Fig. 1). A description of hydrographic features at the core site can be found in Essalami et al. (2007) and Rouis-Zargouni et al. (2010).

2.2 Age models

The age model of the MD04-2797 core is based on 12 AMS ^{14}C dates (Table 1) performed on planktonic foraminifera in the size fraction $> 150\,\mu$m by the mass accelerator (AMS) ARTEMIS located in Gif-sur-Yvette, France. The ^{14}C ages were converted into calendar age using INTCAL09 (Reimer et al., 2009) and the ^{14}C calibration Sofware CALIB6 (Stuiver and Reimer, 1993; Stuiver et al., 1998). We applied a marine reservoir correction of 400 yr for Holocene, YD and Late Glacial sediments. The correction used for BA is 560 and 800 yr for the Heinrich 1 (H1) and Older Dryas (Siani et al., 2001). Based on the age model, a sedimentation rate of 37 cm kyr^{-1} during the Late Glacial, decreasing to 32 cm kyr^{-1} for the Holocene, and a core-top age of 668 yr cal BP were calculated.

The age model of the MD90-917 core is built on 21 AMS ^{14}C dates (Table 2) performed on monospecific planktonic foraminifera in the size fraction $> 150\,\mu$m (Siani et al., 2010). Ages were corrected for a surface marine ^{14}C reservoir age of 400 yr, except for the early deglaciation where this value is double (Siani et al., 2000, 2001). The presence of 14 ash layers allowed refinement of the chronology (Zanchetta et al., 2008; Siani et al., 2004, 2006). The top core age is estimated to 582 yr. The sedimentation rate is approximately 35 cm kyr^{-1} in the Late Glacial to Holocene portion resulting in a temporal resolution of 40 yr.

2.3 SST reconstructions

SSTs were determined using planktonic foraminifera assemblages (SST$_{\text{foram}}$) for April–May (AM-SST$_{\text{foram}}$) and October–November (ON-SST$_{\text{foram}}$). Each foraminifera sample in the >150 µm size fraction was split into 300–1000 individuals for identification and counting following the taxonomy and ecological inferences of Pujol and

Table 2. Depth-age model for the MD90-917. Dates were calibrated using CALIB 5.0.

Depth cm	Conventional ^{14}C ages (yr BP)	Error $\pm 1\sigma$	Calibrated year BP range 1σ
0–2	1010	60	555–609
140–142	4180	70	4082–4290
167–169	4750	70	4855–4986
175–177	5000	70	5344–5466
190–192	5680	70	5990–6128
230–232	6920	90	7413–7511
240–242	7930	80	8171–8340
250–252	8170	70	8390–8482
275–277	10 390	90	11 304–11 624
295–297	10 800	90	12 116–12 399
305–307	10 830	90	12 225–12 406
315–317	11 140	90	12 721–12 853
335–337	11 520	100	12 939–13 114
395–397	12 660	110	13 827–14 063
403–405	13 000	110	14 595–15 078
423–425	13 270	100	15 035–15 366
434–435	13 880	110	15 232–15 640
490–492	15 050	90	16 757–17 234
530–532	16 320	130	18 978–19 245
540–542	16 800	140	19 447–19 607
580–582	17 850	140	20 400–20 803

Vergnaud Grazzini (1995). Faunal composition of planktonic foraminifera assemblages was used to infer SSTs using the modern analogue technique (MAT) (Hutson, 1979; Prell, 1985) developed in the Mediterranean Sea by Kallel et al. (1997). The reference database is composed of 253 core top sediments, 130 from the Mediterranean Sea and 123 from the Atlantic Ocean (Kallel et al., 1997). Reliability of SST values is estimated from the square chord distance test (dissimilarity coefficient), which represents the mean degree of similarity between the sample and the best 10 modern analogues. For fossil samples with good modern analogues in the reference database, the dissimilarity is generally < 0.25 (Prell, 1985). Above this value, the dissimilarity coefficient indicates no close modern analogues in the database and SST estimates are discarded. The calculated mean standard deviation of SSTs for MD90-917 core is estimated to be 0.7 °C during the Holocene and has been 1.4 °C since the Late Glacial period (Siani et al., 2013). For core MD04-2797, the mean SST standard deviation is estimated to be 1 °C.

SSTs were also derived from the C_{37} alkenone unsaturation index $U_{37}^{K'}$. Alkenones are mainly produced by the ubiquitous marine coccolithophorid *Emiliania huxleyi* inhabiting surface waters that then become incorporated in marine sediments with no significant alteration of $U_{37}^{K'}$ index value (see review by Grimalt et al., 2000; Sicre et al., 1999). Comparison between sediment trap and surface sediments from the NW Mediterranean Sea has shown that SSTs recorded in sediment are close to the annual mean (Ternois et al., 1996). This result essentially reflects the fact that spring and fall are the main seasons of alkenone production. The following equation, established by Conte et al. (2006), was used to translate $U_{37}^{K'}$ into SSTs:

$$T\,(^{\circ}\mathrm{C}) = -0.957 + 54.293\left(U_{37}^{K'}\right) - 52.894\left(U_{37}^{K'}\right)^2 28.321\left(U_{37}^{K'}\right)^3.$$

Internal precision for alkenone-derived estimates is 0.3 °C. A detailed description of the laboratory protocol can be found in Ternois et al. (1997). A lower resolution alkenone SST record of the MD04-2797 core was published earlier by Essallami et al. (2007). Additional data have been generated in this study to increase temporal resolution.

2.4 Oxygen isotopes

Detailed oxygen isotope of the MD04-2797 core was obtained on planktonic foraminifera *Globigerina bulloides* and expressed in ‰ versus VPDB (Vienna Pee Dee Belemnite standard) defined with respect to NBS19 calcite standard (Coplen, 1988). Between 6 and 20 shells were picked in the 250–315 µm size range and analysed on a Finnigan $\Delta +$ and MAT251 mass spectrometers. The mean external reproducibility (1σ) of carbonate standards is ± 0.05 ‰, and measured NBS18 δ^{18}O is -23.2 ± 0.2 ‰ VPDB. It has been shown that the most productive months of *G. bulloides* in the Mediterranean Sea are April–May (Pujol and Vergnaud Grazzini, 1995). A complete description of δ^{18}O measurements can be found in Siani et al. (2013) for core MD90-917 and in Essalami et al. (2007) for core MD04-2797.

3 Results

3.1 South Adriatic Sea MD90-917 core

In the South Adriatic Sea, the δ^{18}O of *G. bulloides* calcite range from mean glacial values of 3.5 to 0.97 ‰ at ~ 8.5 kyr (Fig. 2a, black curve). They then increase towards the present except for a decrease to 0.45 ‰ in the upper most sediments of the warmer Medieval Climatic Anomaly. Note that the centennial-scale events BA and YD are weakly expressed in the δ^{18}O record as compared to Greenland ice. From 11.5 to 9.5 kyr they also show a rather weak decrease, from 2.12 to 1.92 ‰.

AM-SST$_{\mathrm{foram}}$ range from ~ 9 °C during the Last Glacial Maximum (LGM) (21–24 kyr) to ~ 17 °C Holocene values (Fig. 2a, dark blue curve) while ON-SST$_{\mathrm{foram}}$ increase from 10.5 °C to about 20 °C (Fig. 2a, red curve). Core top values of ON-SST$_{\mathrm{foram}}$ (19 °C) and AM-SST$_{\mathrm{foram}}$ (17 °C) are in good agreement with present-day average values for the same two months, 18.5 and 16 °C, respectively (Fichaut et al., 2003). Glacial SST$_{\mathrm{alk}}$ values (Fig. 2a, green curve) are always warmer than ON-SST$_{\mathrm{foram}}$ (13–15 °C) and reach unexpectedly high values of nearly 19 °C at ~ 16.5 kyr, while

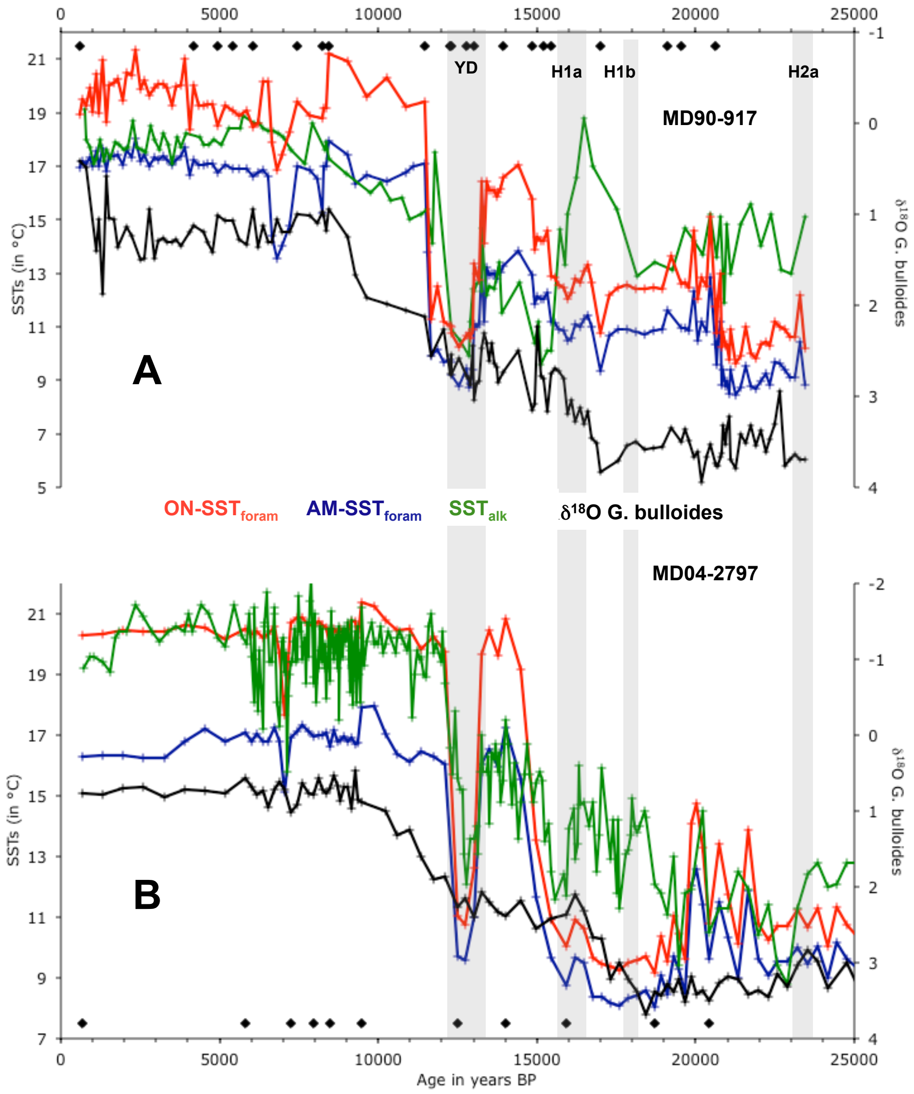

Fig. 2. SSTs derived from planktonic foraminifera assemblages for April–May (AM-SST_{foram}) and October–November ON-SST_{foram} and alkenones (SST_{alk}) and the δ^{18}O determined in *G. bulloides* calcite (in ‰). **(A)** The upper panel shows the South Adriatic Sea core MD90-917 (41° N, 17° E; −1010.0 m) data – δ^{18}O determined in *G. bulloides* calcite (in ‰) (Siani et al., 2004, 2010) – Sea surface temperatures (in °C) derived from planktonic foraminifera assemblages for April–May and October–November (AM-SST_{foram} and ON-SST_{foram}, respectively) (Siani et al., 2004, 2010) – Sea surface temperature derived from SST_{alk} (in °C) (this study). **(B)** The lower panel shows the Siculo–Tunisian Strait core MD04-2797 (36° N, 11° E; −771 m) data. – δ^{18}O determined in *G. bulloides* calcite (in ‰) (Essallami et al., 2007) – sea surface temperatures (in °C) derived from planktonic foraminifera assemblages for April–May and October–November (AM-SST_{foram} and ON-SST_{foram}, respectively) (Essallami et al., 2007) – sea surface temperature derived from alkenones SST_{alk} (in °C) (Essallami et al., 2007 and this study). Shaded areas in grey indicate the Younger Dryas (YD), the Heinrich stadial time intervals H1a (16 kyr), H1b (17.5 kyr) and H2a (23.5 kyr) according to Bard et al. (2000).

during the milder Holocene and BA they were close to AM-SST_{foram}. The SST_{alk} core top value of ∼18 °C is consistent with the annual mean value of 18.2 °C at the core site (Fichaut et al., 2003). The amplitude of the deglacial warming is 6.5 °C for SST_{alk} and 7.5 °C for SST_{foram}, while δ^{18}O of *G. bulloides* decreases only by 0.5 ‰, a difference that underlines significant local salinity changes superimposed to the global ice volume. During the Holocene, SST_{foram} indicate a 2.5 °C cooling at 8.2 kyr, and of 3 °C between 7.3 to 6.3 kyr that are not seen in the SST_{alk} record.

3.2 Siculo–Tunisian Strait MD04-2797 core

In the central Siculo–Tunisian channel, glacial values of δ^{18}O *G. bulloides* (∼3.25 ‰) start to decrease around 18.5 kyr (Fig. 2b, black curve). Between 16.5 and 12.8 kyr, values are relatively stable except for a slight enrichment of

0.5 ‰ between 15 and 16.5 kyr. After a subtle increase during the YD, the δ^{18}O decrease till ∼ 0.45 ‰ at ∼ 9.2 kyr.

$\mathrm{SST_{alk}}$ increase from glacial values of ∼ 8.5 °C at 23 kyr to ∼ 20–21 °C during the Holocene (Fig. 2b, green curve). The core-top value of ∼ 19–19.5 °C is close to mean annual (19.3 °C) (Fichaut et al., 2003). The ON-$\mathrm{SST_{foram}}$ (20.3 °C) and AM-$\mathrm{SST_{foram}}$ (16.3 °C) values of the upper core also reveal a good agreement with present-day values of 20.2 and 16.3 °C, respectively (Fichaut et al., 2003). Except for the LGM, where $\mathrm{SST_{alk}}$ are similar to $\mathrm{SST_{foram}}$ (Fig. 2b, red and blue curves), they show warmer values than ON-$\mathrm{SST_{foram}}$ from 19 kyr till the onset of the H1a, as earlier observed in the South Adriatic Sea. The higher resolution $\mathrm{SST_{alk}}$ signal also reveals imprint of millennial-scale event coolings that seems to coincide with massive iceberg discharges in the North Atlantic (Broecker et al., 1992), namely the H1a (∼ 15.5–16 kyr), H1b (17.6 kyr) and H2a (23.5 kyr) (Bard et al., 2000). Impact of these events on the hydrology of regions well outside the main belt of ice rafted debris (IRDs), such as the Mediterranean Sea, has been reported by Cacho et al. (1999). The presence of IRDs during H1a and H2a off the Iberian margin (Bard et al., 2000), may explain the more pronounced influence of these two Heinrich events on the Mediterranean surface water properties than H1b. Finally, it is noteworthy that $\mathrm{SST_{foram}}$ are similar during the BA and the Holocene, while $\mathrm{SST_{alk}}$ are 3 °C colder during the BA than the Holocene. This is in contrast with the South Adriatic Sea where both proxy records indicate warmer Holocene than BA SSTs by 4–5 °C. Another notable difference between the two proxy records is the onset of the final deglacial warming that occurs earlier in the $\mathrm{SST_{alk}}$ than $\mathrm{SST_{foram}}$ records. Finally, cooling at ∼ 7 kyr in the South Adriatic Sea in $\mathrm{SST_{foram}}$ is also seen in the Siculo–Tunisian Strait but in both proxy records, yet with a different amplitude and duration.

4 Discussion

The SST reconstructions derived from the marine phytoplankton *E. huxleyi* and planktonic foraminifera assemblages show notable differences during the last deglaciation period that might express ecological features. The most remarkable discrepancy between our reconstructions is the anomalous warm $\mathrm{SST_{alk}}$ found in the South Adriatic Sea in the early phase of the deglaciation, centred at ∼ 16.5 kyr. Although we cannot rule out the contribution of advected detrital alkenones (Sicre et al., 2005; Rühlemann and Butzin, 2006), this anomaly most probably reflects a shift in the alkenone production. Today, in the western Mediterranean Sea and Adriatic Sea blooms of *E. huxleyi* occur in spring and fall (Ternois et al., 1996; Sicre et al., 1999; Totti et al., 2000). However, a recent comparison of proxy and instrumental 20th century time series in the North Atlantic has shown that environmental factors can alter alkenone production pattern at interannual to decadal timescale (Sicre et al., 2011). Indeed, during the mid-1960s to early 1970s, large export of ice and freshwater from the Arctic into the subpolar North Atlantic resulted in enhanced stratification of the upper water column that favored warming of a thin surface water layer where small size nanophytoplankton such as coccolithophorid can grow. During these cold and icy years, alkenone SSTs were systematically biased towards warmer months compared to instrumental data suggesting a delayed alkenone production season caused by the presence of sea ice. Anomalously high $\mathrm{SST_{alk}}$ in the South Adriatic Sea could reflect environmental conditions during the early deglaciation period that may have favored water stratification. This time interval of warmer $\mathrm{SST_{alk}}$ coincides with lower diversity of planktonic foraminifera and unusually high abundances of *Globorotalia scitula* in the core (Siani et al., 2010). A sharp increase of *G. scitula* at around 16.3 kyr, contemporary to a decrease of *N. pachyderma*, has also been reported in the Tyrrhenian Sea (Sbaffi et al., 2004). Furthermore, investigations on *G. scitula* in Eastern Mediterranean sediments have shown a link between salinity and the abundances and morphotypes of *G. scitula* (Baumfalk et al., 1987). It is thus likely that during this time span, alkenone production was limited to a few weeks in summer and confined to nutrient depleted surface waters subsequent to enhanced stratification. Ice melting and subsequent continental runoff from surrounding rivers would have created conditions stabilizing the upper water column. In these sedimentary horizons, alkenones were less abundant and sometimes hardly detected. Highest δ^{18}O occur when $\mathrm{SST_{foram}}$ are the lowest, around 17 kyr, suggesting that *G. bulloides* would have developed at the base of a shallow seasonal pycnocline, while a low alkenone production would have been possible in surface layers during the warmest months. Higher $\mathrm{SST_{alk}}$ than ON-$\mathrm{SST_{foram}}$ values between 19 and 16 kyr (and the YD) at both sites of the Central Mediterranean Sea point to preferential summer alkenone production. In contrast, under milder BA and Holocene climates, $\mathrm{SST_{alk}}$ are close to AM-$\mathrm{SST_{foram}}$ except for the Holocene in the Siculo–Tunisian Strait region where they are similar to ON-$\mathrm{SST_{foram}}$ again underlining different seasonal production. Overall, our observations suggest that hydrological changes can introduce bias in the proxy records by modifying the seasonal cycle and/or depth habitat of phyto- and zooplankton therefore complicating the interpretation of climate signals. Multi-proxy records are thus necessary to pinpoint such changes that can be important and misleading in small basins such as the Mediterranean where continental climate exerts a strong influence on surface water properties.

Another substantial difference between proxy records is the onset of the YD, marked by a shift from $\mathrm{SST_{alk}}$ values close to AM-$\mathrm{SST_{foram}}$ during the BA, to values close to ON-$\mathrm{SST_{foram}}$ during the YD. While $\mathrm{SST_{foram}}$ remained low during the YD, $\mathrm{SST_{alk}}$ become warmer than ON-$\mathrm{SST_{foram}}$ pointing out that alkenone production progressively shifted to summer. This change could be responsible for the apparent shorter YD duration, a feature that has been previously documented in $\mathrm{SST_{alk}}$ signals of the Mediterranean Sea. Indeed, earlier warming of $\mathrm{SST_{alk}}$ by about 600 yr and a brief YD (700 yr) compared to Greenland (1200–1300 yr, 12.8–11.5 kyr) has been underlined in the Alboran and Tyrrhenian seas (Cacho et al., 2001, 2002; Sbaffi et al., 2004), but none of these studies were multi-proxy, except for Sbaffi et al. (2001) who reported on MAT and $\mathrm{SST_{alk}}$ data from two Tyrrhenian Sea cores (BS79-38 and BS79-33). Even though the calibration used by these authors to translate U_{37}^{K} into SSTs is different from our study, glacial $\mathrm{SST_{alk}}$ were generally higher than $\mathrm{SST_{foram}}$, while $\mathrm{SST_{foram}}$ during BA were similar to present-day values (17 °C) and $\mathrm{SST_{alk}}$ cooler by 3–4 °C, as we also found in the Siculo–Tunisian Strait. Furthermore, although temporal resolution is lower than in our study, one of the two Tyrrhenian cores (BS79-38) also seems to show earlier $\mathrm{SST_{alk}}$ warming at the end of the YD. Overall, the BS79-38 core, and to a lower degree, the BS79-33 core, share resemblance with the Siculo–Tunisian Strait record. Another notable feature of the late deglaciation period is the brief cold reversal of 260 yr seen in the $\mathrm{SST_{alk}}$ records and in the Greenland isotope record ($\sim$ 11.6 kyr), probably reflecting the Preboreal oscillation. This short episode has been reported by Cacho et al. (2001, 2002) and, within age model uncertainties, would be contemporary to the $\mathrm{SST_{alk}}$ decrease in the Ionian Sea documented by Emeis et al. (2000), when in the Levantine basin salinity and density decrease before S1 deposition. The following slower $\mathrm{SST_{alk}}$ warming in the South Adriatic Sea from 11.5 to 9.5 kyr coincides with the lower rate decrease of δ^{18}O of *G. bulloides*. In summary, while there seems to be some similarity between the South Adriatic and Ionian Sea deglaciation records, the Siculo–Tunisian channel shares a resemblance with the Tyrrhenian Sea (Cacho et al., 2001).

Isotope signal in GISP2 and La Mine stalagmite (Tunisia)

Comparison of $\mathrm{SST_{alk}}$ with the reference GISP2 δ^{18}O curve highlights differences between the North Atlantic and Mediterranean signals over the deglaciation period. During the last glacial, $\mathrm{SST_{alk}}$ indicate warming between 19 and 16 kyr in the Siculo–Tunisian channel and in the Adriatic Sea, while air over Greenland cooled (Fig. 3). After a sharp decline around the onset of the BA, $\mathrm{SST_{alk}}$ increase rapidly in the Siculo–Tunisian channel while in South Adriatic warming towards BA is more gradual. Similarly, $\mathrm{SST_{alk}}$ indicate a cooler early Holocene in the South Adriatic region resulting from a slower warming than the $\mathrm{SST_{foram}}$ since the end of the YD, as also seen in the Greenland ice core. Delayed Holocene Thermal Maximum (HTM) compared to orbitally forced insolation at high- to mid-latitudes has been attributed to the influence of remnant continental ice (Renssen et al., 2012). A late HTM in the South Adriatic Sea would thus be consistent with continental run off from melting ice being more important in the Adriatic Sea than in the Siculo–Tunisian Strait site, which does not show clear evidence for a HTM as was also observed in the MD95-2043 site (Alboran Sea), lying in the Modified Atlantic Waters (Cacho et al., 1999). In contrast, the M40_SL78 core located in the northern Siculo–Tunisian basin indicate cooler early Holocene and a HTM around 8.5 kyr (21 °C) (Emeis and Dawson, 2003), which suggests that the northern and southern Siculo–Tunisian channel were affected differently by continental hydrology. In the Siculo–Tunisian Strait, the Allerød appears as warm as the Bølling and relatively stable.

The $\mathrm{SST_{alk}}$ warming during the YD seems to begin earlier in Siculo–Tunisian by $\sim$ 500 yr than in southern Adriatic Sea, and $\sim$ 1000 yr earlier than in the GISP2. Keeping in mind age model uncertainties, we can speculate that early warming of $\mathrm{SST_{alk}}$ in the Siculo–Tunisian Strait might reflect a more rapid return to interglacial conditions due to more pronounced subtropical influence in this sub-basin. To investigate this hypothesis, we compared our records to the C and O isotope signals of the Northern Tunisia stalagmite La Mine (Min-stm1) that provides a continuous climate record from 25 kyr ago (Fig. 3). The δ^{13}C variations in this stalagmite have been attributed to vegetation changes induced by temperature and soil humidity (Genty et al., 2006). The δ^{13}C rise indicates a decline of the vegetation during the cold/dry YD that is not seen in the δ^{18}O. This cold reversal is followed by a gradual transition to the Preboreal period associated with climate amelioration and vegetation development towards the Holocene. The δ^{18}O stalagmite record is different and shows warming starting around 16.4 kyr progressing until a plateau during the YD. Interestingly, the δ^{18}O of La Mine stalagmite share similarity to some degree with the δ^{18}O of *G. bulloides* from the Siculo–Tunisian Strait suggesting that surface waters could have been major local sources of precipitation. Conversely, δ^{13}C values tend to follow $\mathrm{SST_{alk}}$ trends consistently with temperature being a controlling factor of vegetation and soil activities, but does not the early decrease of the $\mathrm{SST_{alk}}$, and rather parallel the δ^{18}O at GISP2. We can therefore reasonably conclude that if $\mathrm{SST_{alk}}$ warming does occur earlier in the southern than in the northern central Mediterranean Sea, it most likely reflects ecological responses to different local environmental conditions.

5 Conclusions

The Siculo–Tunisian channel and Adriatic Sea surface water temperature signals reveal differences caused by local environmental conditions that likely modified the alkenone production season pattern (timing, amplitude and duration). While alkenone and foraminifera derived SSTs indicate rapid cooling at the onset of the YD *synchronous* to GISP2, final warming to the Holocene occurs seemingly earlier in the $\mathrm{SST_{alk}}$ than $\mathrm{SST_{foram}}$ leading to an apparent shorter duration YD, consistent with previously reports from the Ioanian and Tyrrhenian Sea. We suggest that this bias result

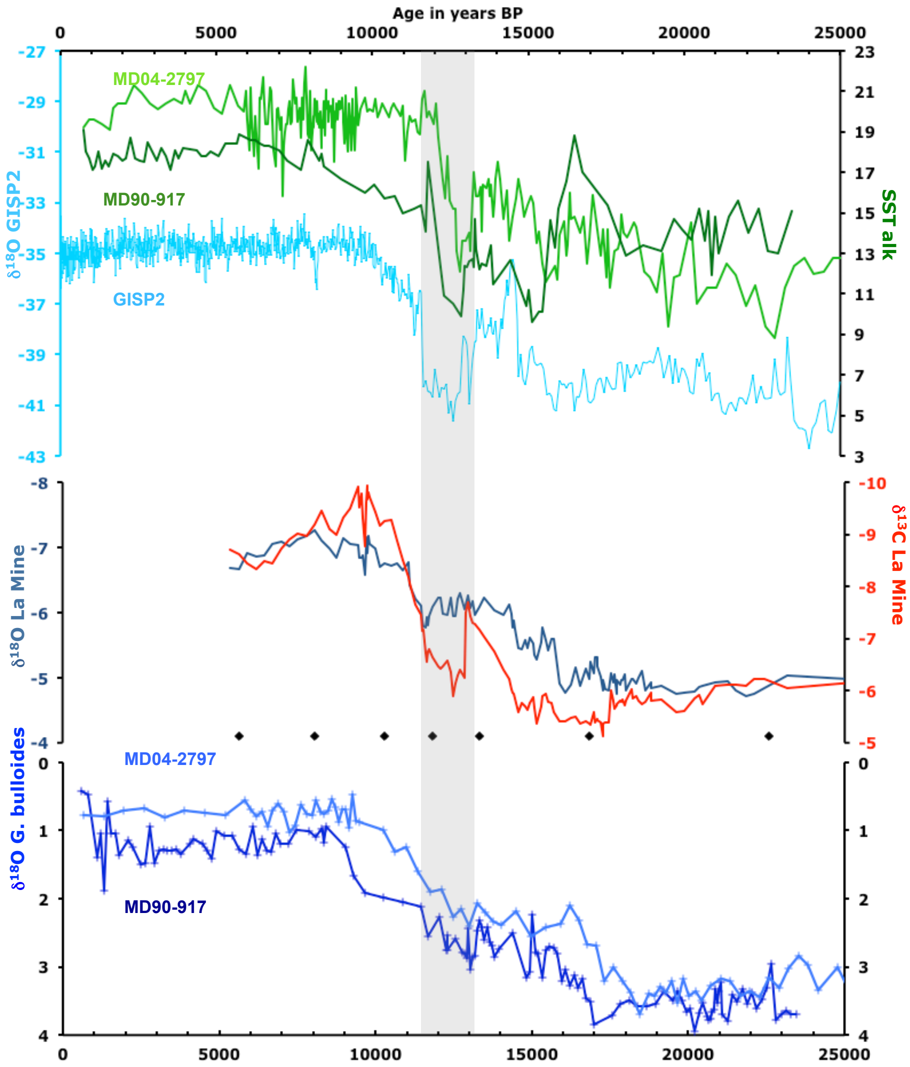

Fig. 3. Comparison between $\mathrm{SST}_{\mathrm{alk}}$ in the South Adriatic Sea (this study) and Siculo–Tunisian Strait (this study and Essallami et al., 2007) cores with the δ^{18}O in the Greenland ice core GISP2, the O and C isotopes in La Mine stalagmite (Tunisia) (this study and Genty et al., 2006) and the δ^{18}O in *G. bulloides* calcite from in the South Adriatic Sea (Siani et al., 2004, 2010) and Siculo–Tunisian Strait (Essallami et al., 2007) cores. Black diamonds indicate U/Th dates performed on La Mine stalagmite.

from alkenone production shifting from spring during the BA, to summer during the YD and back to spring during the Holocene, except for the Siculo–Tunisian Strait region where Holocene $\mathrm{SST}_{\mathrm{alk}}$ are close to $\mathrm{ON\text{-}SST}_{\mathrm{foram}}$. Impact of cold Heinrich stadials on surface water properties are well expressed in the Atlantic Modified Waters flowing along the northern African coast indicating stronger influence of the North Atlantic waters than in the South Adriatic Sea, where these hydrological features are concealed by river runoff resulting from melting of continental ice sheets.

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