

Holocene seasonal sea-surface temperature variations in the southern Adriatic Sea inferred from a multiproxy approach

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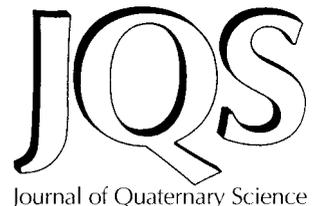
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Sangiorgi, F., Capotondi, L., Nebout, N. C., Vigliotti, L., Brinkhuis, H., Giunta, S., Lotter, A. F., Morigi, C., Negri, A. and Reichart G.-J. 2003. Holocene seasonal sea-surface temperature variations in the southern Adriatic Sea inferred from a multiproxy approach. *J. Quaternary Sci.*, Vol. 18 pp. 723–732. ISSN 0267-8179.

Received 15 November 2002; Revised 6 June 2003; Accepted 1 July 2003

ABSTRACT: Holocene cooling events have been reconstructed for the southern Adriatic Sea (central Mediterranean) by means of analyses of organic walled dinoflagellate cysts, planktonic foraminifera, oxygen isotopes, calcareous nanoplankton, alkenones and pollen from a sediment core. Two cooling events have been detected, during which sea-surface temperatures (SSTs) were ca. 2°C lower. Unravelling the SST signal into dominant seasonal components suggests maximum winter cooling of 2°C at around 6.0 ka, whereas the cooling at ca. 3.0 ka might be the result of a spring temperature cooling of 2–3°C. The events, lasting several hundred years, are apparently synchronous with those in the Aegean Sea, where they have been related to known cooling events from the Greenland ice-core record. A distinct interruption in Adriatic Sea sapropel S1 is not clearly accompanied by a local drop in winter temperatures, but seems to be forced by ventilation, which probably occurred earlier in the Aegean Sea and was subsequently transmitted to the Adriatic Sea. Copyright © 2003 John Wiley & Sons, Ltd.



KEYWORDS: Adriatic Sea; Holocene; multiproxy approach; SST; seasonality.

Introduction

Mediterranean Sea climate and hydrodynamics are closely linked to both the subtropical climate system (Rossignol-Strick, 1985) and the North Atlantic (e.g. Asioli *et al.*, 1999, 2001; Cacho *et al.*, 1999, 2001; Paterne *et al.*, 1999; Siani *et al.*, 2001; Sangiorgi *et al.*, 2002). Large and long-term changes in hydrography are intimately tied to the monsoonal circulation in the southern catchment and are expressed as organic-rich sediment layers (sapropels) that denote anoxic conditions in bottom waters (e.g. Olausson, 1961; Cita *et al.*, 1991; Rohling, 1994). Their periodicity is typically on orbital time-scales (e.g. Rossignol-Strick, 1983; Hilgen, 1991; Lourens *et al.*, 1996). Influences of North Atlantic climate are more subtle,

and may be transmitted and amplified by strong continental winds (Rohling *et al.*, 1998; Cacho *et al.*, 2001). Rohling *et al.* (2002) recently demonstrated that several Holocene cooling events affected the Aegean Sea (northeast Mediterranean), showing an atmospheric link between Aegean surface water temperatures and high-latitude climate.

Presently, the climate in the Adriatic Sea region during winter is regularly perturbed by mid-latitude wind systems. Two major wind systems affect the Adriatic basin. During winter, the dominating wind is the Bora, a dry and cold northeastern wind. The other is the Scirocco, a characteristic wind of the southern Adriatic, which brings rather humid and relatively warm air from the southeast into the region. The Bora, which produces appreciable buoyancy loss through evaporative and heat loss, induces both wind-driven and thermohaline circulation, and is thus important for deep-water formation in the Mediterranean Sea. (e.g. Zore Armada, 1963; Artegiani *et al.*, 1989; Bignami *et al.*, 1990; Orlic *et al.*, 1992).

The research presented in this paper aims to evaluate potential Holocene Mediterranean seasonal cooling events using a multiproxy temperature reconstruction. We have analysed a

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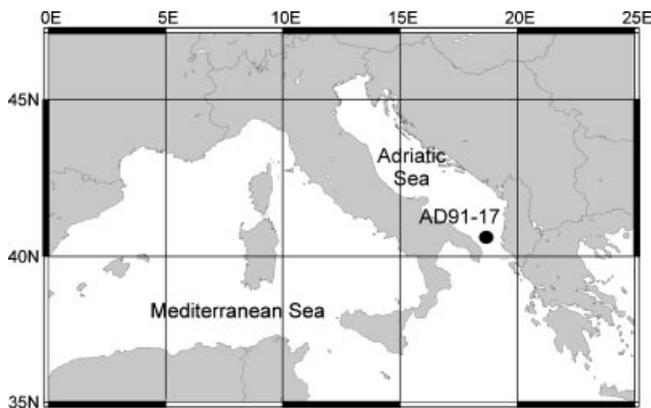


Figure 1 Location of core AD91-17

sediment core from the southern Adriatic Sea, as this area is key for unravelling interferences between the subtropical climate prevailing during summer and the mid-latitude climate predominant in winter. The fossil record represents the complex interplay of seasonal changes in the environment that were recorded by living organisms. As changes throughout the year are integrated in the recorded signal, it is not possible to explain unequivocally the temperature records. Difficulties encountered when comparing different organism-based sea-surface temperature (SST) reconstructions and the frequent mismatching between proxies are considered and discussed.

Materials

Sediment samples were taken from the upper 2 m of core AD91-17 (40°52.17'N, 18°38.15'E, 845 m) recovered in the Otranto Strait, southern Adriatic Sea (Fig. 1). The sediment consists of hemipelagic mud with intercalated tephra layers at 1 cm, 39 cm, 73 cm, 170 cm and 195 cm depth. Between 125 and 190 cm a well developed sapropel (S1) layer is present, containing a distinct interruption between 154 and 162 cm. Magnetic susceptibility was measured on the whole core. Discrete samples were analysed for foraminiferal stable oxygen isotopes, organic-walled dinocysts, alkenones, calcareous nanoplankton, planktonic foraminifera and pollen.

Methods

For dinocyst and pollen analysis, volumetric sediment samples were dried at 60°C, weighed and treated with 10% HCl and 38% HF in five alternate and subsequent steps; decantation was carried out after each step. *Lycopodium* was added to check the reliability of quantitative data. Samples were then sieved over a 10 µm sieve and the residue was centrifuged and concentrated to 1 ml. Subsamples of a known volume of homogenised residue were placed on a microscope slide, embedded in glycerine jelly and sealed with paraffin wax. Dinocysts and pollen grains were counted on the same slides; the average number of dinocyst specimens counted is 400 and the minimum number of pollen grains counted is 100, *Pinus* grains excluded. Dinocyst taxonomy follows Williams *et al.* (1998) and Rochon *et al.* (1999).

The samples for planktonic foraminiferal analyses were dried at 50°C, weighed, washed and sieved through a 63 µm screen.

For each sample, splits containing at least 300 planktonic foraminiferal specimens were identified and counted in each sample, as a basis for estimating assemblage composition in percentages. Stable oxygen isotope ratios of *Globigerina bulloides* were performed at the LODYC Laboratory (Catherine Pierre, Paris VI University, France) using 30–40 adult specimens picked from the residual fraction >63 µm. The tests were washed ultrasonically in order to eliminate fine-fraction contamination. The CO₂ was extracted from the carbonate of the foraminifers with 103% phosphoric acid on the automatic device, coupled with a triple collector Optima Isogas mass spectrometer. The results are reported as per mille deviation with respect to the international PDB standard. The reproducibility of the measurements is ± 0.1‰.

Calcareous nannofossil samples were taken with a toothpick. Smear slides were mounted with Norland Optical Adhesive. In order to retain the original composition of the nannofossil assemblage, samples were not centrifuged. Analyses were undertaken with a light microscope at magnification 1250× by counting at least 300 specimens per sample and the counts were converted into specimens per mm². Baumann *et al.* (1998) showed that data obtained with this method represents all major abundance features, although there might be minor differences in absolute magnitude of individual peaks.

Sample preparation and analyses of alkenone unsaturation ratios ($U_{37}^{K'}$) in lipid extracts are described in Giunta *et al.* (2001) and Giunta *et al.* (2003). Alkenones were quantified by gas chromatography through comparing retention times and detector responses with those of synthetic and in-house standards. Peak areas were used to calculate the unsaturation index ($U_{37}^{K'}$), and subsequently sea-surface temperature: $SST = (U_{37}^{K'} - 0.044)/0.033$ according to the calibration given by Müller *et al.* (1998).

Age assessment

Chronology for core AD91-17 is based on five accelerator mass spectrometry (AMS) ¹⁴C ages using planktonic foraminiferal tests picked from the fraction >63 µm. Three of the tephra layers (at 1, 170 and 195 cm core depth) were used as additional chronostratigraphical constraints. Based on their stratigraphical position and by comparison with other cores, these layers were attributed to known eruptions from the Campanian area. Considering the dispersal axis of the tephra and the ¹⁴C dating available for the core, we correlate the tephra at 195 cm with the 'Agnano' tephra (ca. 9500 ¹⁴C yr BP), that at 170 cm with 'Mercato-Ottaviano' (ca. 8000 ¹⁴C yr BP) and that at 1 cm with the historical Vesuvius eruption at AD 472 (Narcisi, 1996; Narcisi and Vezzoli, 1999). The ¹⁴C dating at 30.5 cm (3.08 ± 0.06 kyr BP) and at 80.5 cm (4.48 ± 0.05 kyr BP) suggests that the two magnetic susceptibility peaks at 39 and 73 cm correspond to the tephra of 'Avellino' (3550 ± 130 ¹⁴C yr BP, Rolandi *et al.*, 1998; 3510 ± 50 ¹⁴C yr BP, Delibrias *et al.*, 1986) and 'Agnano Monte Spina' (4100 ¹⁴C yr BP, Di Vito *et al.*, 1999), respectively. However, both these peaks are too scattered (Fig. 2) to allow a precise correlation and they were not used as chronological tie points. Furthermore, geochemical data carried out on core MD917 (Siani *et al.*, 2001), collected in the same area, did not identify the Avellino tephra, suggesting that it could be missing in this part of the basin. On the other hand, the onset of sapropel S1 (recorded at 190 cm), which in the Adriatic Sea occurs at ca. 8600 ± 100 ¹⁴C yr BP (Combourieu Nebout *et al.*, 1998; Asioli *et al.*, 1999; Rossignol-Strick, 1999, and references therein; Mercone *et al.*, 2000), was incorporated into the age model.

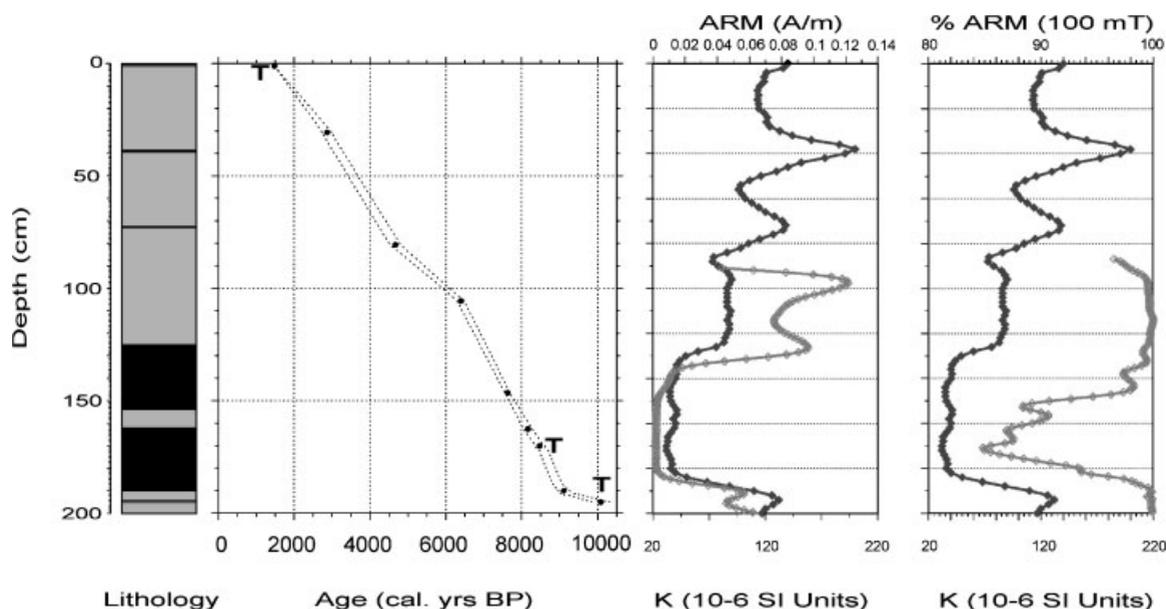


Figure 2 Age control points used in the age model applied to the record of AD91-17 together with the lithological log (grey colour indicates hemipelagic mud, black indicates sapropel S1 layer, T indicates tephra layers). Calibrated years have been calculated using Calib 4.3 (Stuiver *et al.*, 1998) with 2σ error interval (dashed lines). Down-core variations in magnetic susceptibility (black line) in combination with the anhysteretic remanence (ARM; grey line) and the percentage of ARM remaining after an AF of 100 mT

Table 1 Chronostratigraphical data for core AD91-17 used in the age model, indicating the measured ^{14}C years (performed at the Lawrence Livermore National Laboratory, USA), the average calibrated ages obtained with the Calib. 4.3 Program (Stuiver *et al.*, 1998) and the sedimentation rates

Depth (cm)	Age (^{14}C yr BP)	Laboratory code	Age source	Average age (cal. yr BP)	Sedimentation rate (cm kyr $^{-1}$)
1	AD 472 ^a		TL	1478	
30.5	3080 ± 60	65048	^{14}C AMS	2860	21.3
80.5	4480 ± 50	65049	^{14}C AMS	4665	27.7
105.5	5990 ± 40	70040	^{14}C AMS	6391	14.5
146.5	7170 ± 40	70041	^{14}C AMS	7630	33.1
162.5	7710 ± 40	70042	^{14}C AMS	8161	30.1
170	8000 ^a		TL	8465	24.7
190	8600 ± 100 ^a		Onset sapropel S1	9150	29.2
195	9500 ^a		TL	10080	5.4

^a See text and Narcisi and Vezzoli (1999).

In this case, the base of the sapropel can be used as tie point because, in such rapidly accumulating sapropels, oxidation and bioturbation processes can be excluded (Mercone *et al.*, 2000). All ^{14}C ages have been calibrated using Calib 4.3 (Stuiver *et al.*, 1998) which incorporates a reservoir correction of about 400 yr (Table 1). Sedimentation rates between calibrated points have been calculated by linear interpolation. The age model is plotted in Fig. 2, together with the magnetic susceptibility curves. Hereafter ages will be discussed as cal. kyr BP.

Temperature reconstructions based on the marine and terrestrial biota

The proxies selected and discussed in this paper, which we use for a Holocene seasonal temperature reconstruction, have been described in detail in Giunta *et al.* (2003).

Following published dinocyst ecological information, distribution patterns of some dinocyst species are mainly related to SST (e.g. Wall *et al.*, 1977; Turon, 1984; Edwards and Andrieu,

1992; Dale, 1996; Rochon *et al.*, 1999). These temperature-sensitive species have been used to construct a warm/cold (W/C) dinocyst ratio (Versteegh, 1994; Targarona, 1997; Combourieu Nebout *et al.*, 1999; Sangiorgi *et al.*, 2002). However, overall surface waters have been warm during the Holocene, therefore the W/C ratio lacks sensitivity because warm-water species are dominant. Alternatively, in the absence of a dinocyst-based SST transfer function for the Mediterranean Sea, decreases in the relative abundance of the warm-water species in the assemblages may be used as an indicator for surface water cooling. According to the literature available for the Adriatic Sea, the species *Impagidinium aculeatum*, *I. paradoxum*, *I. patulum*, *I. striatum*, *Spiniferites mirabilis* and *S. hyperacanthus* are considered to be the most thermophilic (Zonneveld, 1995; Targarona, 1997; Combourieu Nebout *et al.*, 1998; Sangiorgi *et al.*, 2002). The relative abundance of warm water dinocysts was calculated from a total including oxygen resistant dinocyst species only (according to Versteegh and Zonneveld, 2002). This calculation avoids a possible overprint of productivity and/or preservation changes on the SST reconstructions. For instance, in sedimentary records where a sapropel layer is present, the *Protoperidinium* spp. group

always displays very high relative abundances (Zonneveld, 1995; Targarona, 1997; Combourieu Nebout *et al.*, 1998; Sangiorgi *et al.*, 2002). *Protoperidinium* spp. are heterotrophic species, which increase in abundance mainly with enhanced sea-surface primary productivity, but are also very sensitive to aerobic degradation (Zonneveld *et al.*, 2001; Versteegh and Zonneveld, 2002) and therefore dominates the sapropel layer, where anoxia or hypoxia facilitate its preservation. To distinguish between productivity and preservation the accumulation rates (in cysts per $\text{cm}^2 \text{yr}^{-1}$) of *Impagidinium aculeatum*, an oxygen resistant species, which accumulates at higher rates during times when nutrient concentrations in waters increase (Zonneveld and Brummer, 2000; Marret and Zonneveld, 2003), is considered. Among the calcareous nannoplankton, *Syracosphaera pulchra* is indicative of a subtropical environment (Roth, 1994) and a decrease in its concentration is here used as a proxy for decreased SSTs.

The record of relative SST changes based on planktonic foraminifera is obtained by calculating the decrease in the relative abundance of 'warm' species, considering their modern habitat in the Mediterranean Sea (Thunell, 1978; Hemleben *et al.*, 1989; Rohling *et al.*, 1993; Pujol and Vergnaud-Grazzini, 1995). The 'warm' assemblage consists of species widely used to reconstruct first-order SST variation in the Mediterranean Sea (see Rohling *et al.*, 2002, for an overview). At present, the 'warm' group dominates warm oligotrophic summer mixed layers in tropical–subtropical regions (e.g. Pujol and Vergnaud-Grazzini, 1995) and includes *Globigerinella calida*, *G. digitata*, *G. siphonifera*, *Globigerina rubescens*, *Globigerinoides ruber* (pink and white, counted together), *G. sacculifer*, and *Orbulina universa*.

The oxygen isotope values measured on calcite foraminiferal tests are, during the Holocene, mostly related to changes in sea-water temperature and salinity, the latter mainly influencing isotopic composition during sapropel times. In order to estimate changes in SST from shifts in $\delta^{18}\text{O}$ we used the species-specific equation of Spero *et al.* (2000), also reported in Bemis *et al.* (2002).

Pollen found in the southern Adriatic Sea sediments represent an integration of the major vegetation zones in the mountainous European borderlands (e.g. Rossignol-Strick *et al.*, 1992; Willis, 1994; Combourieu Nebout *et al.*, 1998; Rossignol-Strick, 1999). Among pollen taxa, the variations in deciduous *Quercus* and in semi-desert (*Artemisia*, Chenopodiaceae and *Ephedra*) are assumed to be indicative of climatic change, with the latter mainly reflecting aridity. The occurrence of *Pistacia* in the Mediterranean forest is used to indicate mild winters (e.g. Willis, 1994; Combourieu Nebout *et al.*, 1998).

Magnetic parameters

Whole-core magnetic susceptibility measurements were carried out using a Bartington MS2 sensor. A palaeomagnetic study including the natural remnant magnetisation (NRM) and the anhysteretic remanence (ARM) has been carried out on a U-channel obtained from section II of the core by using a 2G cryogenic magnetometer at the INGV Palaeomagnetic Laboratory (Rome, Italy). The procedure used for the magnetic measurements implies measurements of the low-field mass-specific magnetic susceptibility and acquisition of anhysteretic remnant magnetisation (ARM). It is made by subjecting the samples to an AF field of 100 mT biased by a 0.1 mT direct field and by progressive AF demagnetisation in six steps (10, 20, 30, 40, 60 and 100 mT). Rock-magnetic parameters such as K and

ARM reflect diagenetic processes and climate-related variations in the concentration, mineralogy and grain size of the magnetic minerals contained within the sediments. Several studies show that under suboxic–anoxic conditions the bacterial degradation of organic matter induces a diagenetic process in the sediments. Magnetic content and grain size discriminate between oxic and anoxic layers, with the latter characterised by a lower magnetic content and a larger grain size (Karlin and Levi, 1985; Leslie *et al.*, 1990; Vigliotti, 1997).

Results

The temperature curve obtained using the alkenone unsaturation index U_{37}^K (Fig. 3) infers a surface water temperature of 10.7°C during the late Younger Dryas (11.4 kyr BP), followed by an increase of 4°C to 9.1 kyr BP. The Holocene SST inferred from U_{37}^K ranges from a minimum of 13.8°C to a maximum of 16.8°C in our record. Between 6.9 and 5.6 kyr BP SSTs from U_{37}^K are remarkably stable and display the highest values (16.4–16.8°C). Later, alkenone-derived SST estimates show a generally decreasing trend. Only between 2.5 and 2.1 kyr BP do SSTs reach values of about 16°C again, but they then drop once more between 1.8 and 1.6 kyr BP.

In the early Holocene, before sapropel S1 deposition, detailed reconstructions are hampered by a very condensed sediment interval. All our proxies, however, show a warming trend corresponding to the transition from the Younger Dryas to the Holocene. At the same time the relative decrease in semi-desert pollen taxa and an increase in *Quercus* indicate an increase in humidity.

Magnetic parameters identify an interval of reductive diagenesis between 9.1 and 7.0 kyr BP, corresponding to sapropel S1. Concentration related parameters K and ARM exhibit minimum values (Fig. 2) related to diagenetic dissolution of magnetic minerals as a consequence of suboxic/anoxic conditions occurring in this interval. Magnetic susceptibility shows an interruption of these conditions between 8.1 and 7.9 kyr BP, whereas ARM data are more constant (Fig. 2), implying that only multidomain (MD) magnetite survives during the interruption. The magnetic coercivity expressed by the percentage of ARM after 100 mT of demagnetisation shows maximum values in the first part of the sapropel (Fig. 2), suggesting that strongest anoxic conditions occur between 8.8 and 8.5 kyr BP.

During sapropel deposition, both warm-water dinocysts and warm-water foraminifera show generally low values, although they display a rather high variability. Oxygen isotopes, on the other hand, are relatively stable at somewhat depleted values (Fig. 3). Pollen data confirm that the sapropel was deposited during times when high humidity was also being experienced in the borderlands (e.g. Rossignol-Strick *et al.*, 1992; Combourieu Nebout *et al.*, 1998). Similarly, the calcareous nannoplankton species *Syracosphaera pulchra* indicates a stable environment during sapropel deposition, except for one sample that shows a deviation from this trend.

Samples collected within the lithological interruption of the sapropel layer (dated in this core to 8.1–7.9 kyr BP), yield relatively high values of warm-water dinocysts, and also the alkenones indicate a modest warming at this time. Later, between 8.0 and 7.8 kyr BP, the alkenone record suggests a temperature decrease of about 2°C and warm water dinocysts decrease. The relative abundance of the semi-desert pollen taxa remains unchanged during the sapropel interruption. Moreover, high-altitude trees such as *Abies* and *Picea* slightly increase (Giunta

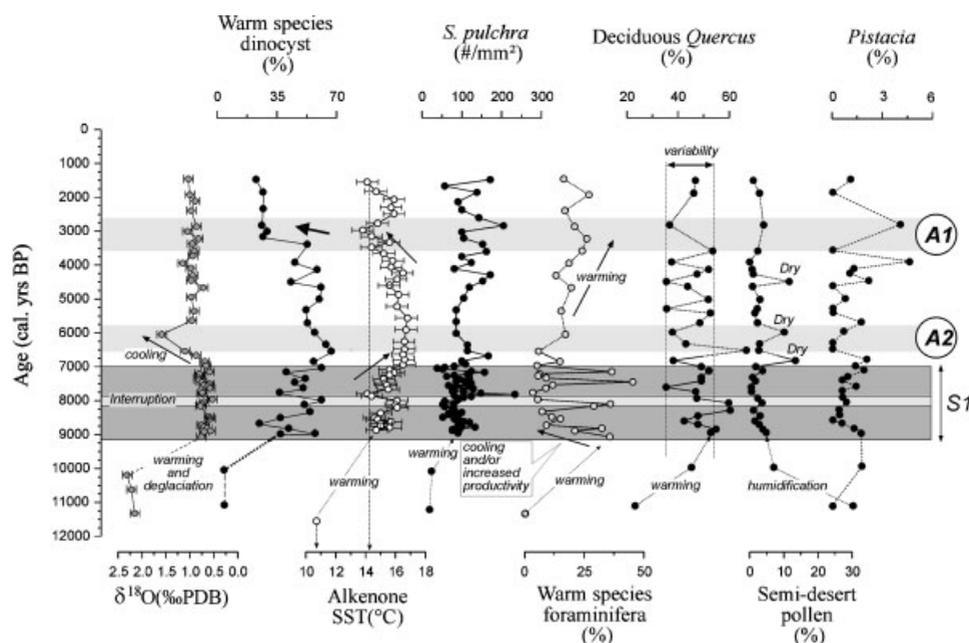


Figure 3 Down-core records of different SST proxies in core AD91-17. From left to right: oxygen isotopes measured on *G. bulloides*; relative abundance of warm-water dinocyst species calculated on the oxygen resistant dinocyst sum; alkenone-based SST; number of *Syracosphaera pulchra* per mm²; relative abundance of warm-water Foraminifera; relative abundance of deciduous *Quercus*, semi-desert pollen and *Pistacia*. Error bars for oxygen isotopes and for the alkenone-based temperatures are based on the analytical standard deviation. No error bars could be given for dinocysts, *S. pulchra*, Foraminifera and pollen data. Darker grey horizontal band indicates sapropel S1, the lighter band within, its interruption. The two upper lighter grey bands (A1 and A2) indicate different Adriatic cooling events

et al., 2003) and the Mediterranean taxa *Pistacia* is present (Fig. 3).

A progressive cooling and/or increased salinity trend in the oxygen isotopes profile marks the end of the sapropel, with increased semi-desert pollen taxa (>10% shift), indicating relatively high aridity. The dinocyst species and *S. pulchra* show a slight decrease in species normally associated with higher SSTs. In contrast, the alkenone unsaturation index indicates a warming at the end of the sapropel. There is no apparent change in planktonic foraminiferal fauna associated with the transition from sapropel conditions to normal sedimentation. The cooling and/or increased salinity trend, which begins at the end of the sapropel as indicated by the $\delta^{18}\text{O}$, culminates in a maximum cooling of ca. 2°C according to the temperature equation (Shackleton, 1974), or increased salinity up to 4 PSU according to the local salinity calibration ($\delta^{18}\text{O} = 0.25 \times S - 8.2$; Pierre, 1999), at 6.0 kyr BP. Although a sudden cooling event was reconstructed previously for this time interval in the Adriatic Sea (Siani *et al.*, 2001), associated with a peak in *N. pachyderma* (Capotondi *et al.*, 1999), which would leave little isotopic change for salinity, somewhat drier conditions can be inferred from an increase in semi-desert vegetation, which shows another sudden increase of ca. 12%.

The next cooling event is indicated by both a gradual U_{37}^K shift and a more abrupt decrease in warm-water dinocyst abundance. The cooling inferred from the warm-water dinocyst assemblage seems to occur somewhat later (3.2 kyr BP), compared with the U_{37}^K temperatures, which decrease from 4.1 kyr BP onward, reaching a SST of about 13.8°C at 3.0 kyr BP. At the time of these last two cooling events, it has been noted that high-altitude trees increase slightly in conjunction with *Fagus*. During the first event, *Pistacia*, when present, has low percentage values (1–2%), whereas during the second cooling it displays higher values (up to 4.5%, Fig. 3; for a complete description of pollen assemblages see Giunta *et al.*, 2003).

Finally the U_{37}^K record suggests a gradual decrease from 2.0 ka BP onwards, resulting in a SST of 14.1°C for the uppermost sample. The other proxy records show only minor changes synchronous with this last cooling.

Discussion

Comparing six different temperature proxies from the southern Adriatic Sea clearly shows that these proxies are related to temperature in different ways, and not unambiguously to the mean annual temperature. The occurrence of a single organism or group of organisms is not only connected to a single parameter of the water column (e.g. SST), but rather to a wide and complex set of features characterising the surrounding environment. Recent multiproxy studies have underlined the frequent discrepancy between U_{37}^K and flora- or fauna-based temperature reconstructions (Sbaffi *et al.*, 2001; Marchall *et al.*, 2002). Such offsets have been attributed to differences in timing and duration of growth season and to differences in depth habitats in the water column. For example, variations of U_{37}^K in dinocyst and calcareous nannoplankton assemblages may trace primarily SST changes in the uppermost part of the water column (ca. 25 m), whereas planktonic foraminiferal assemblages and oxygen isotope ratios of test calcite of most species generally integrate temperatures over larger water depth intervals. However, in our study oxygen isotopes were measured on *G. bulloides*, which thrives in the upper approximately 100 m of the water column, but calcifies in the upper 50 m (Hemleben and Spindler, 1983; Hemleben *et al.*, 1989).

Our interpretation of SSTs includes a seasonal component. As seasonality provides an extra boundary condition, different parts of the SST records are interpreted in a different way. In our opinion this makes our SST reconstruction more consistent,

although different proxies may have a different importance at different time intervals.

The only clear temperature change apparent in all proxies used is the warming from the Younger Dryas to the Holocene. Pollen data show at the same time an increase in humidity. This humidity increase is probably directly linked with sapropel formation, which follows almost immediately the early Holocene warming. Although the sapropel in the eastern Mediterranean has been deposited during the so-called 'Holocene climatic optimum' (e.g. Rossignol-Strick, 1999), alkenone-based SST reconstruction in core AD91-17 remains somewhat low during sapropel formation, as was previously observed for the Ionian and Levantine Seas (Emeis *et al.*, 2000). Low SST values also can be caused by a relative shift in the blooming season of the alkenone-producing algae (mainly *Emiliana huxleyi*) (Knappertsbusch, 1993; Winter and Siesser, 1994), to earlier in the year. Presently, in the Mediterranean Sea the predominant production seasons of coccolithophorids are winter and spring (Knappertsbusch, 1993), whereas in the mid-Adriatic Sea, *Emiliana huxleyi* typically increases in April (Totti *et al.*, 2000) and may bloom even later, indicating a preference for stratified water column conditions (Brand, 1994), which develop during spring, following winter mixing and associated nutrient injection to the surface waters. If surface waters remain relatively stratified during the year, or they restratify earlier, this could cause a shift of the *E. huxleyi* growing season towards periods with lower SSTs. Such an offset of recorded temperature owing to a shift in timing of maximum coccolithophorid production from summer during glacial conditions to the present late spring to early summer bloom has been suggested previously for the open ocean (Chapman *et al.*, 1996).

We observed an interruption in sapropel deposition (between 8.1 and 7.9 kyr BP), time equivalent with the well documented interruption throughout the eastern Mediterranean and in the Adriatic Sea. This interruption is generally associated with a cold spell (e.g. Rohling *et al.*, 1997; De Rijk *et al.*, 1999; Ariztegui *et al.*, 2000; Myers and Rohling, 2000). However, in our record, $U_{37}^{K'}$ suggests increased temperatures before and during the sapropel interruption followed by a sharp SST drop above the interruption. This might indicate that during the interruption *E. huxleyi* bloomed later in the year, and therefore $U_{37}^{K'}$ recorded summer–autumn rather than spring temperatures. The apparent warming in SSTs as determined by $U_{37}^{K'}$ could also reflect a decreased river outflow and evaporation, a deepening of the halocline and more mixing. This would lead to a deeper thermocline and a higher mean temperature over the area of alkenone production by coccolithophorids, as suggested by Oldfield *et al.* (2003). In combination with the cooling inferred from other records (e.g. Rohling *et al.*, 1997; Ariztegui *et al.*, 2000) this suggests that intensified winter mixing postponed stratification of the water column. Still, oxygen isotopes derived from *G. bulloides* indicate that such a cooling is not reflected by a local drop in winter temperatures. According to Pujol and Vergnaud Grazzini (1995) the main growing season of *G. bulloides* is winter to early spring. If we calculate the temperature recorded from $\delta^{18}\text{O}$ measured on *G. bulloides* for the present-day physical characteristics of southern Adriatic sea-water, and we apply the species-specific calibration of Spero *et al.* (2000), we derive a SST of $T = 13.6^\circ\text{C}$, which indeed correlates with the average winter SST for this area ($T = 13.73^\circ\text{C}$, Zavatarelli *et al.*, 1998).

During the sapropel interruption, the increase in high-altitude trees (*Abies* and *Picea*, Giunta *et al.*, 2003) may be related to a slight temperature decrease in the continental climate, perhaps induced by an increase in intensity of the northeastern and eastern winds. Nevertheless, the presence of the Mediterranean taxa *Pistacia*, which requires mild winters, indicates

that winter temperatures did not drastically decrease (Fig. 3). This implies that if convective turnover was responsible for the sapropel interruption, stronger sea-surface coolings were restricted to the easternmost parts of the basin (e.g. Aegean Sea). This would leave local surface waters in the Adriatic relatively unaffected by lowered temperatures, and would point to an origin of the winter winds being responsible for the sapropel interruption and associated mixing and re-oxygenation, different from the Bora. Rohling *et al.* (2002) proposed an increased Siberian winter high causing more frequent outbreaks of cold air over the eastern Mediterranean. Cold climatic conditions over the Aegean Sea can lead to the formation of Aegean Deep Waters, which could replace Adriatic Deep Waters as the main deep water source for the eastern Mediterranean Sea (Casford *et al.*, 2002, and references therein).

During sapropel interruption primary productivity was high in the Adriatic Sea and preservation was poor, as indicated by high accumulation rates of the oxygen resistant *Impagidinium aculeatum* and low relative abundances of the oxygen sensitive *Protoperidinium* spp. (Fig. 4). Rohling *et al.* (1997) have suggested that the process of sapropel formation in the Adriatic Sea is not a very stable mode, and that it may be easily interrupted in response to subtle rearrangements in the balance between productivity and deep-water ventilation.

Dinocysts associated with warm SSTs do not show a clear trend within the sapropel, but are in high abundance during the sapropel interruption. This value, however, is the result of a high percentage of *Impagidinium aculeatum* (Giunta *et al.*, 2003). An interpretation only in terms of surface-water temperature is, however, problematic because at the same time the rapid and strong switch in sea-surface productivity could interfere with temperature reconstruction. The warm water dinocyst *Impagidinium aculeatum* not only inhabits warm waters but is also tolerant of a broad range of nutrients and salinities; although it often dominates assemblages in oligotrophic conditions, it forms a prominent part of the cyst association in eutrophic environments (e.g. Zonneveld and Brummer, 2000; Marret and Zonneveld, 2003, and references therein).

Warm-water foraminiferal species and the nannoplanktonic species *Syracosphaera pulchra* also tend to be related to oligotrophic conditions (e.g. McIntyre *et al.*, 1970; Pujol and Vergnaud Grazzini, 1995), meaning that temperature interpretation is not straightforward.

The end of sapropel S1 deposition is characterised by a progressive cooling, indicated by the oxygen isotope record, starting at about 6.8 kyr BP and culminating at about 6.0 kyr BP, coeval with a marked cooling trend previously described in the Adriatic Sea (Siani *et al.*, 2001; Oldfield *et al.*, 2003). At the same time we find a shift towards drier conditions on land indicated by a sudden increase (ca. 12%) of semi-desert pollen, although evidence for marked changes in salinity has not been reported for the area (e.g. Emeis *et al.*, 2000; Oldfield *et al.*, 2003). This trend is in contrast with the SST reconstruction based on $U_{37}^{K'}$ and the relative abundance of warm-water dinocysts.

Again, high temperatures recorded by $U_{37}^{K'}$ also can be associated with an increased mixing of the water column. This opposite trend can be reconciled by cooling of winter to early spring temperatures on one hand, resulting in a shift of the blooming season to later in the year because of reduced winter temperatures, and fairly stable summer temperatures on the other hand. The increase in pollen of high-altitude trees, associated with *Fagus* (Giunta *et al.*, 2003), may indicate intensification of northeastern and eastern winds and cooling of the continental climate in the Adriatic borderlands. In this case, the absence or low percentage of *Pistacia*, which requires mild winters, confirms a decrease in winter temperatures (Fig. 3).

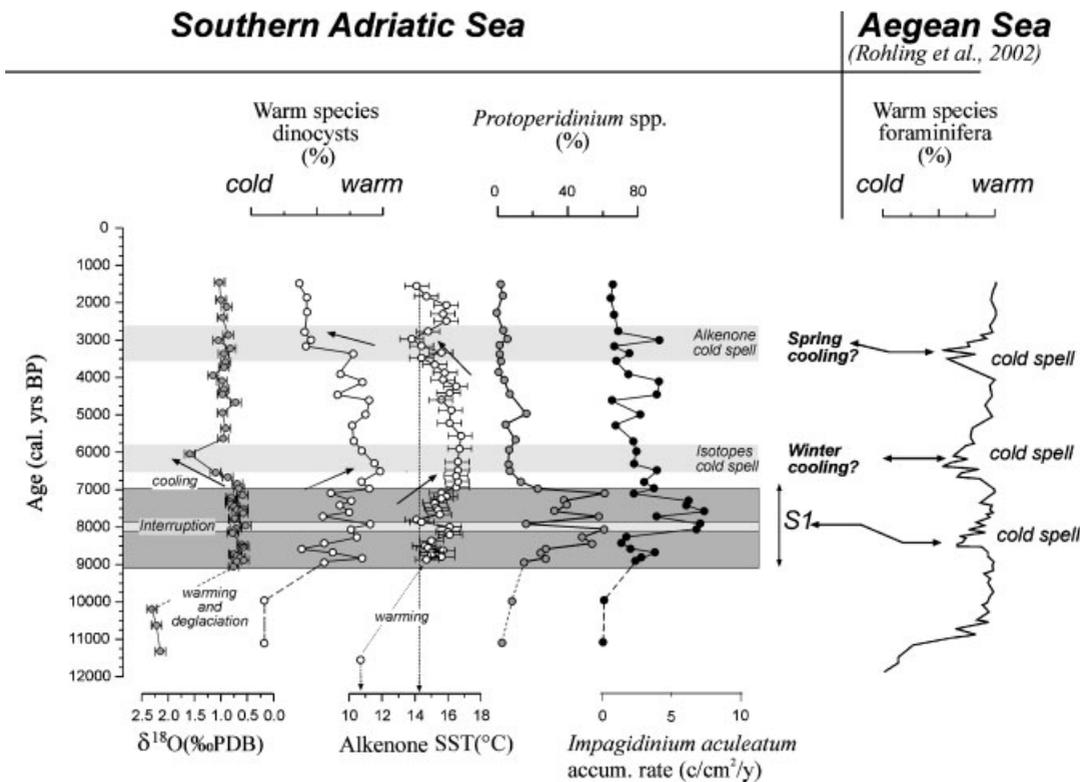


Figure 4 Schematic overview of the down-core changes as reconstructed using all available proxy information. The relative abundance of *Proto-peridinium* spp. cysts and the accumulation rate of *Impagidinium aculeatum* (in cysts per $\text{cm}^2 \text{yr}^{-1}$) are added as local preservation and productivity indicators. Shading is similar to Fig. 3. For the dinocyst-based temperature reconstruction we used the sum including oxygen resistant species only. The Aegean Sea temperature reconstruction is based on planktonic foraminiferal census data (Rohling *et al.*, 2002)

Therefore, lower winter temperatures may be caused by strengthened Bora winds.

Indirectly, changes in productivity might affect temperature reconstructions through changes in preservation of both organic and carbonate-based proxies. For example, the sapropel layer is dominated by heterotrophic organic-walled dinocysts grouped as *Proto-peridinium* spp. (Fig. 4), which usually is interpreted as a proxy for high primary productivity (e.g. Zonneveld, 1995; Combourieu Nebout *et al.*, 1998; Sangiorgi *et al.*, 2002; Giunta *et al.*, 2003; Reichart and Brinkhuis, in press). However, as these cysts are oxygen sensitive (Zonneveld *et al.*, 2001) their presence in the sapropel layer could be enhanced further by increased preservation owing to hypoxia/anoxia. To avoid a dominant productivity and preservation overprint we calculated the percentage of warm-water dinocysts including only oxygen resistant species in the dinocysts total (Figs 3 and 4). The high covariation between dinocyst reconstruction and the U_{37}^K temperatures furthermore confirms this.

When interpreting the dinocyst assemblage in terms of SSTs changes it should be noted that at present in the Adriatic Sea dinoflagellates typically reach their maximum abundance during late spring to summer, favoured by stratification of the water column (Totti *et al.*, 2000). Similar to the alkenone-based SST reconstruction, a shift in growing season could explain the observed change. However, because the cause leading to dinocyst formation is still poorly understood (e.g. Dale, 2001, for an overview), it is more difficult to directly correlate SST and timing of cyst formation.

The next cooling trend starts at about 4.1 kyr BP in the alkenone record and it is also observed in the dinocyst record around 3.2 kyr BP, whereas oxygen isotopes remain fairly constant. Such contrasting trends again could be reconciled by a shift in *E. huxleyi* bloom timing, similar to the one inferred

for the sapropel. However, the dinocyst assemblage also indicates a cooling with clear evidence for major changes in productivity (Figs 3 and 4). Although the high degree of upper water column stratification as inferred for times of sapropel formation is unknown for the remainder of the Holocene, increased water column stratification could lead to lower U_{37}^K values and higher dinocyst productivity. Pollen data infer a slight deterioration of climate on land (with increased high-altitude trees and *Fagus*), but an increase up to fairly high percentages (up to 4.7%) of *Pistacia* tends to suggest that winters were still mild (Fig. 3).

The reconstructed SSTs derived from U_{37}^K are low (reaching a value of 13.8°C), even compared with modern spring temperatures in the southern Adriatic Sea (ca. 16°C, Zavatarelli *et al.*, 1998). As the oxygen isotope and pollen data (with the presence of *Pistacia*) rule out a significant winter cooling, this implies that spring, and possibly also summer, temperatures were reduced. As, apparently, no changes in winter temperature have been observed, we imply a reduced seasonal contrast occurring in this period, as also inferred from speleothem records from the Alps between 5.2 and 2.4 kyr BP (Frisia *et al.*, 2000). Although records from the easternmost part of the Mediterranean do indicate cooler winter SSTs (e.g., Rohling *et al.*, 2002) this also might be related to spring, rather than reduced winter, temperatures.

Conclusions

Multiproxy reconstruction of Holocene climatic variability in the southern Adriatic Sea suggests several changes in seasonality and temperature. The well-known cooling responsible for

the sapropel interruption was not clearly recorded in the southern Adriatic Sea core studied. This implies that locally the sapropel interruption was not caused by a local reduction in winter SSTs. Water mixing and bottom water re-oxygenation were forced rather by ventilation in the Aegean Sea, subsequently transmitted to the Adriatic Sea. We infer that the cooling event around 6.0 kyr BP was limited to the winter season, whereas the apparent cooling at 3.0 kyr BP seems primarily to be related to lower temperatures during spring, possibly extending to the summer season.

Acknowledgements We thank Professors A. M. Borsetti and G. Gabbianelli for providing samples of core AD91-17. Dinocyst analyses were possible thanks to a Ministero dell'Università Ricerca Scientifica & Tecnologica funded PhD (F. Sangiorgi). We thank J. P. Cazet for his efficient technical support for palynological process. The manuscript benefitted in an earlier stage from comments by Elco Rohling and Kay Emeis. This work was supported by the French-Italian Galilee Project. We greatly acknowledge the two referees, Karin Zonneveld and Daniel Ariztegui for their valuable suggestions. We thank Catherine Stickley who helped to improve the English. This is Istituto per la Geologia Marina, Consiglio Nazionale delle Ricerche contribution number 1326 and Laboratoire des Sciences du Climat et de l'Environnement contribution number 0954.

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