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Climate variability and amplification revealed from indicators in the Gulf of Taranto(*)

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Summary. — A well-dated, high-resolution core (GT90-3), extracted from the Gallipoli Terrace in the Ionian Sea, is used to deduce information about climate variability during the last millennia and in particular before 1000 AD, where few proxy records are available. We present the foraminiferal δ^{18}O record measured in this core and covering the last 2200 years, whose spectral analysis, performed by several advanced methods, reveals highly significant oscillatory components with periods of about 600, 350, 200, 125 and 11 years. These components are discussed also in comparison with those deduced from other archives, concluding that the overall trend and the 200 y component together are very likely temperature-driven. On the contrary, concerning the decadal range the situation is not so clear and salinity and circulation effects probably cannot be completely neglected.

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1. – Introduction

The climate system varies over several time scales, which extend from seasonal patterns to glaciation-deglaciation intervals [1,2]. The key to gaining information on climate analogs and periodicities on decadal to centennial timescales is the measurement of proxy records over the recent millennia with multi-annual resolution and matching accuracy in dating.

Concerning the Holocene climatic variability, the gap between the millennial scale climate changes, revealed in archives as sediment cores from the open ocean, and the decadal

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scale changes, observed in the instrumental data, translates into a lack of information concerning the centennial time scale, which is comparable to the time scale on which anthropogenic warming is thought to be occurring [3]. The instrumental observations cover only a couple of centuries [1, 2, 4-8] and are therefore influenced by human activity [9]. They are anyway too limited in time to detect centennial variability. In order to overcome this problem, several large-scale temperature reconstructions have been proposed, based on both single-proxy (tree rings, corals, varved sediments, cave deposits, ice cores, boreholes, glaciers, ocean and lake sediments) and multi-proxy records [3, 10, 11] measured at different geographical locations: ice cores [3] at high latitudes, tree rings [12,13] at mid-latitudes and corals [11,14] at low latitudes. The multi-proxy approach, however, grounds on the merging of several proxies, reflecting different combinations of temperature and precipitation effects, and generally having different time resolution. Thus, the required interpolation and averaging [3, 10, 11] may lead to spurious variations in the reconstructions [15-17]. Moreover, each study portrays a somewhat different history of the temperature variations and it is affected by measurement uncertainties that increase going backward in time, with the consequence that little confidence can be assigned to large-scale surface temperature profiles prior to about 900 AD. In contrast to the relative scarcity of accurately dated proxy evidences covering the first Millennium of the Christian Era, a general agreement about the last millennium temperature trends is found [2].

Marine cores with very high sedimentation rates allow to investigate climate variations on scales of decades to millennia. In order to avoid possible artefacts produced by the composition of different proxies, we have measured the oxygen isotope composition of planktonic foraminifera (*Globigerinoides ruber* species) in a high-resolution, well-dated Central Mediterranean core. The isotopic composition of the shells deposited on the sea bottom after the death of the organisms reflects the chemical and physical properties of the marine surface water, and therefore can give information about the environmental conditions in which shells grew.

2. – Experimental procedure and data

Since the Nineties, the Torino cosmogeophysics group has been studying shallow-water Ionian Sea sediment cores, drilled from the Gallipoli Terrace in the Gulf of Taranto, a small marginal basin of the Mediterranean Sea. Thanks to its geographical location, this site plays an important role in our researches. In particular, the Gallipoli Terrace, located in the south-eastern part of the Gulf of Taranto, is a particularly favourable site for high-resolution climatic studies based on marine sediments. The whole Gulf of Taranto east coast is in fact a flat area, characterized by weak marine currents and by the lack of direct river discharges. The main advantage of this site, however, comes from the fact that it is placed leeward to the Campanian area, which is the only region of the world for which a detailed documentation of the historical eruptions is available. Historical documents are quite detailed for the last 350 years (a complete catalogue of eruptive events, starting from 1638, is given by [18]), while they are rather sparse before that date. The markers of the eruptions were identified along the cores as peaks of the number density of clinopyroxene crystals, carried by the prevailing westerly winds from the Campanian area towards the Ionian Sea, and deposited there as part of marine sediments. The time-depth relation for the cores retrieved from the Gallipoli Terrace [19-24] was obtained by tephroanalysis, which confirmed, improved and extended to the deeper part of the core the dating performed in the upper 20 cm by the radiometric ^{210}Pb method [25, 19]. Taricco *et al.* [26] recently applied advanced statistical procedures [27, 28], confirming the previous dating,

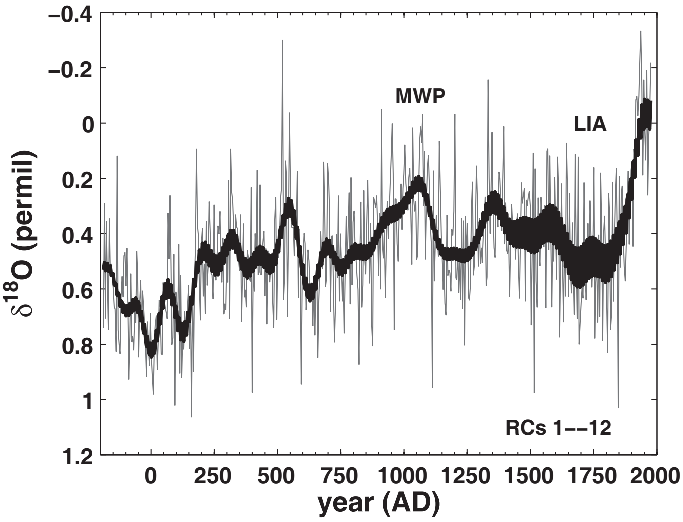

Fig. 1. – Oxygen isotope ratio profile measured in GT90-3 core. Raw data ($x_m = 0.46^0/_{00}$—mean value; $\sigma_x = 0.23^0/_{00}$—standard deviation) are shown in thin black. The singular-spectrum analysis (SSA) reconstruction (RCs 1–12, thick black) is superposed on the original data. The sampling interval is $\Delta t = 3.87$. The data are expressed in VPDB standard.

i.e. that 2.5 mm of sediment are deposited every 3.87 y. The sedimentation rate turned out to be constant at least for the last 2 millennia to a good approximation. Moreover, the measurements performed in different cores retrieved from the same area showed that this rate is also uniform across the whole Gallipoli Terrace [20,21,23]. The high precision of the dating allowed to transform the depth scale into a time scale with an accuracy better than 1%.

In this section we present the δ^{18}O measurements performed in the carbonatic shells of the surface-dwelling foraminifera (*Globigerinoides ruber*) from the 3.57 m long core GT90/3 (39° 45′ 53″ N, 17° 53′ 33″ E). At present, the stable isotope analysis has been performed for the upper 140 cm of the core, thus obtaining a continuous record of 560 points covering the last 2 millennia (200 BC–1979 AD). The high sampling rate (corresponding to $\Delta t = 3.87$ y) makes our paleoclimatic record suitable for the study of both long- and short-term variability components.

Figure 1 shows the δ^{18}O profile. At a first sight we can notice some features, strictly correlated to peculiar climatic periods:

– The low δ^{18}O values around 1000 AD (Medieval Optimum—MO), corresponding to the warm climate from 900 AD to 1200 AD, known as Medieval Warm Period (MWP).

– The high δ^{18}O values during the 18th Century, corresponding to the cool period, usually thought as extending from 1500 AD to 1800 AD, the so-called Little Ice Age (LIA). We can also notice the imprint of the Maunder Minimum of solar activity around 1700 AD.

– The sudden decrease of δ^{18}O values starting from the 19th Century, providing evidence for the modern temperature increase during the Industrial Era (IE).

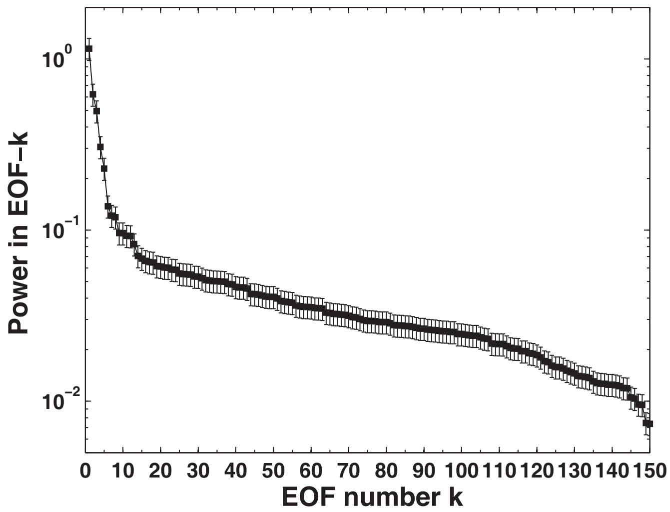

Fig. 2. – Eigenvalue spectrum of δ^{18}O SSA. The units of abscissa are SSA component number (eigenvalue rank), with the variance contributed by each SSA component on the ordinate. The error bars show an *ad hoc* range of the estimation errors.

– The high δ^{18}O values at the beginning of the Christian Era (Roman Classical Period—RCP), suggesting an at least local decrease in temperatures.

However, since δ^{18}O reflects changes both in sea surface temperatures (SSTs) and sea water isotopic composition, it is necessary to extract independent components of variability and identify the temperature-driven ones.

3. – Spectral analysis

With this goal in mind, several classical and advanced spectral methods [29, 30] are applied to the δ^{18}O record, in order to extract its dominant oscillations and trend. Here we focus on the results obtained by Singular Spectrum Analysis (SSA), a methodology which is especially suitable to extract trends and quasi-periodic oscillations from quite noisy and short time series. In spite of the low signal-to-noise ratio, typical of climatic records, SSA also allows assessing the significance of the extracted waves, through Monte Carlo simulations (MC-SSA). A filtering window width $M = 150$ (corresponding to a taper $M\Delta t \approx 600\,$y) is chosen for the analysis. This choice allows detecting periodicities as long as 500–600 y, while maintaining sufficient statistical significance. We obtained very similar results for a fairly wide set of M values, ranging from 120 to 200. The evident robustness of the results to changes in M has been an important test of their reliability.

The corresponding SSA spectrum is shown in fig. 2, where the 150 eigenvalues are plotted in decreasing order of power. At a first qualitative analysis, we can notice the clear break between the initial steep slope (first 12 eigenvalues) and an almost flat floor, representing noise. This visual remark has been further confirmed by assessing statistical significance. A Monte Carlo simulation is chosen to test against a red noise null-hypothesis [31]. Red noise, *i.e.* an autoregressive process of order 1, or AR(1), is chosen to represent the usual background assumption in geophysical applications, where

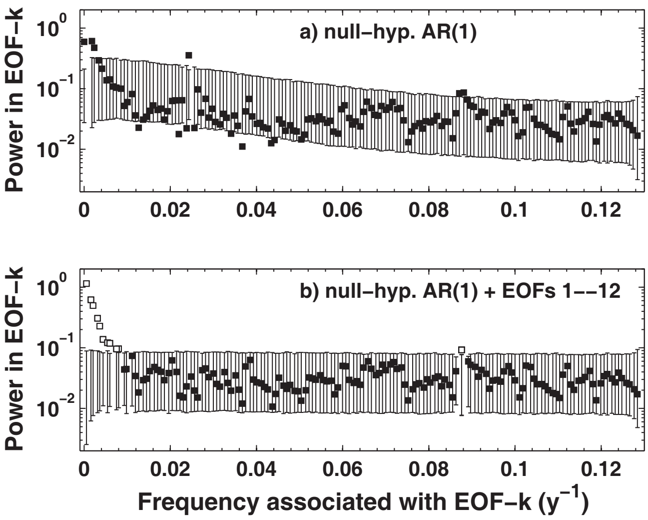

Fig. 3. – Monte Carlo SSA tests. The eigenvalues and the surrogate bars are plotted as a function of the dominant frequency associated with the corresponding EOFs of the composite null-hypothesis basis. The vertical bars indicate the range in which lies the 99% of the eigenvalues determined from the ensemble of Monte Carlo simulations. Panel a: Monte Carlo test against AR(1) null-hypothesis. Panel b: Monte Carlo SSA test using the EOFs 1–12 + AR(1) null-hypothesis [31]. The Monte Carlo ensemble size is 10000. The red points indicate the actual eigenvalues of the δ^{18}O record. No excursions occur outside the 99% limits, indicating that the series is well explained by this model.

the intrinsic inertia of the system leads to greater power at lower frequencies, even in absence of any signal [32]. This allows avoiding overestimation of the system predictability, that might occur if one underestimated the amplitude of the low-frequency stochastic components of the time series. The red-noise process parameters are estimated directly from the data on the basis of maximum likelihood and a large ensemble (10000 in our case) of such red noise surrogate series are generated. The test reveals which components significantly differ from the background noise null-hypothesis at the chosen confidence level, and its graphic representation displays the eigenvalues excursions above the corresponding percentile.

Figure 3 shows two steps of the MC-SSA test. For each step, the plot displays the data projections onto the Empirical Orthogonal Functions (EOFs) computed from the expected covariance matrix of the hybrid basis null-hypothesis process, as described in the following paragraph. Initially, the data have been tested against a pure, data-adaptive red noise process at the 99% confidence level (c.l.) (panel a in fig. 3). In this first step, some SSA components turn out to fall outside their surrogate confidence bar, *i.e.* they show more power than expected under the pure red noise null hypothesis, that is therefore rejected. In the subsequent steps of the test,the EOFs of such components have then been progressively added to the data-adaptive red noise, to form the new null-hypothesis process (hybrid basis). Panel b illustrates the final step of this procedure. As before, the error bars bracket 99% of the eigenvalues obtained by the SSA of 10000 surrogate series, all of them generated by a model that includes EOFs 1–12 and red noise. Since in panel b no excursion occurs outside the 99% limits, we cannot reject the corresponding

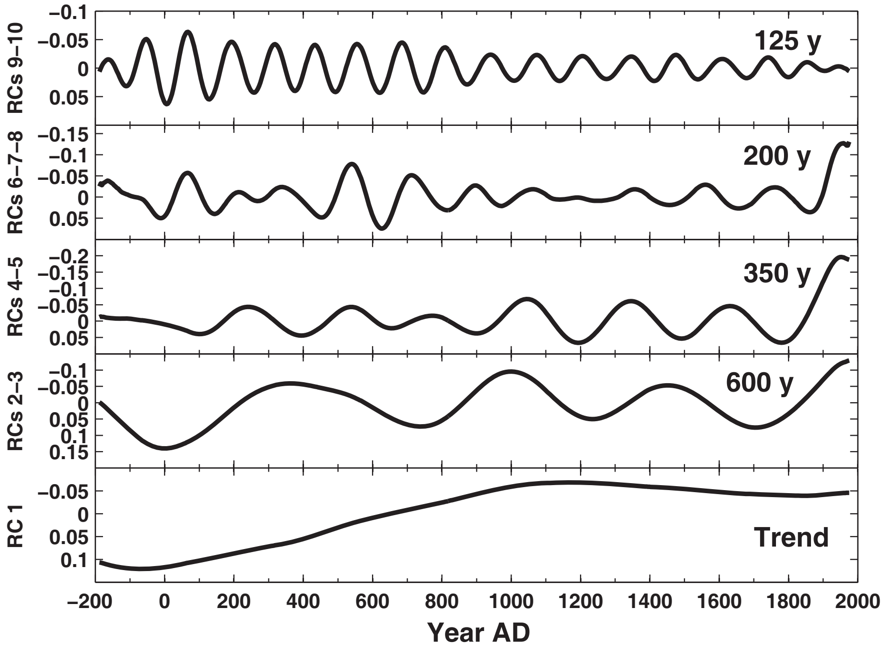

Fig. 4. – Dominant SSA components of δ^{18}O record: RC 1 (trend), RCs 2–3 (600 y), RCs 4–5 (350 y), RCs 6–8 (200 y), RCs 9–12 (125 y), RCs 10–11 (11 y).

null hypothesis. Thus, the Monte Carlo test reveals that *only* the first 12 eigenvalues, explaining roughly 44% of the total variance, are statistically significant at the 99% c.l., *i.e.* the chosen model AR(1)+EOFs 1–12 captures all the significant δ^{18}O variability at the 99% c.l. We drew this conclusion after rejecting, at the same confidence level, a range of null hypotheses, including different combinations of EOFs.

More in detail, SSA reveals at the 99% c.l. a data-adaptive trend (EOF 1) explaining 17.7% of total variance and five dominant oscillatory components of about 600 y (EOFs 2–3), 350 y (EOFs 4–5), 200 y (EOFs 6–8), 125 y (EOFs 9–12) and 11 y (EOFs 10–11), respectively explaining 14.1%, 6.7%, 4.8%, 2.4% and 2.3% of the total variance; the periods associated to each oscillation were computed by the Maximum Entropy Method (MEM) [30].

Figure 4 displays the reconstructions of the trend and of the significant oscillations, separately. The filtered version of the δ^{18}O time series, obtained by summing up Reconstructed Components (RCs) 1–12 (fig. 1, thick black line) well represents the general behaviour of the raw data (fig. 1, thin grey line) and puts into evidence the features, mentioned in sect. **2**, connected to known climatic periods (MWP, LIA, IE δ^{18}O decrease) and the δ^{18}O maximum around 0 AD.

These results were confirmed also by multiresolution analysis using both the continuous wavelet tranform (CWT) and the maximum-overlap discrete wavelet transform (MODWT) (not shown). As we can deduce from fig. 3 of [50], the signal reconstruction by inverse-CWT is in good agreement with SSA long-term reconstruction, thus assuring that results do not depend on the adopted method for perfoming spectral analysis. The analysis turns out to be robust.

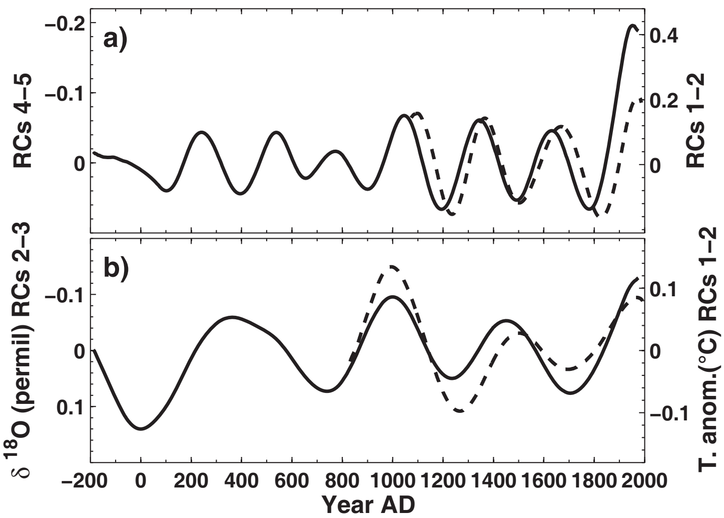

Fig. 5. – Panel a: Reconstruction of the Jasper tree ring profile by Luckman *et al.* [12] (RCs 1–2, dashed line) and 300 y periodicity embedded in the δ^{18}O record (RCs 4–5, continuous line). Such as for the 500-y oscillation, this periodicity has not been revealed in other similar proxy [16]. Panel b: Reconstruction of the 500 y oscillation identified in 1200 year long tree rings reconstruction by Esper *et al.* [13] (RCs 1–2, dashed line) in phase with the 600 y oscillation detected in our δ^{18}O record (RCs 2–3, continuous line). This feature is not present in other proxy [16].

4. – Results and discussion

Most of the Northern Hemisphere temperature reconstructions available in the literature [10, 12, 3, 11, 13] show a trend similar to our record and the typical temperature decrease from the medioeval epoch (MWP) to the XVIII century (LIA). These series also share with our record the presence of a 200 y oscillation at high confidence level. This suggests that the trend and the 200 y wave revealed in our record are temperature driven.

The other multi-centennial oscillations detected by SSA in the δ^{18}O series are also found in some proxy records, but their presence is not ubiquitous.

For example, a 500 y periodicity is the most prominent feature of the atmospheric residual Δ^{14}C series of Stuiver and Braziunas [33], covering the last 12000 y. The authors related it to salinity changes associated with an oscillation of the oceans' thermohaline circulation [34-37]. A similar oscillation is found by applying SSA (with $M\Delta t = 500\,\text{y}$) to the tree-ring based NH temperature reconstruction of Esper *et al.* [13] and its phase is in good agreement with RCs 2–3 of our δ^{18}O record (fig. 5, panel a). However, this feature is not present in other proxy temperature records [16].

The 300 y oscillation is comparable to the dominant component of the Jasper tree ring profile by Luckman *et al.* [12] and is also found in the 1200 y tree-ring based NH temperature reconstruction of Esper *et al.* [13], but it is not present in other proxy records [16]. SSA analysis (with $M\Delta t = 500\,\text{y}$) of the Jasper tree ring profile shows that this oscillation, captured by RCs 1–2, is in good agreement with RCs 4–5 of our series, both in terms of phase and amplitude (fig. 5, panel b).

Concerning the decadal time scale, SSA allows detecting at the 99% c.l. a high-frequency oscillation of about 11 y, notwithstanding its small amplitude and therefore its scarce contribution to the series total variance. Cini *et al.* [22] showed that this cycle in the δ^{18}O measured in our cores is perfectly in phase with the Schwabe solar cycle [38], thus interpreting it as a possible solar imprint on climatic records, possibly through temperature variations. However, the relationship between the Sun and the Earth climate is a very complicated issue, also due to complex feedback processes. At the same time, the presence of a decadal component in NH temperatures is controversial [39].

Recent studies [40] about the Ionian upper-layer circulation, based on the analysis of salinity and density data covering the last decades, detect inversions of the Ionian basin-scale surface circulation, taking place over decadal time scales. For a semi-enclosed and stratified basin, such as the Mediterranean Sea, the contribution of internal oceanic processes to changes of the upper-layer vorticity of the oceans cannot be neglected in favour of the wind effect. As a consequence, these processes seem to be the result of the so-called Adriatic-Ionian Bimodal Oscillating System (BiOS), *i.e.* a feedback mechanism between the redistribution of water masses related to variations of the thermoaline properties of the South Adriatic Sea and to an inversion of the Ionian circulation. In particular, the alternate advection into the Adriatic of saltier water from the Aegean/Levantine basin (Levantine Intermediate Water—LIW) or of fresher water coming from the Atlantic Ocean (Modified Atlantic Water—MAW), associated, respectively, to the Ionian cyclonic and anticyclonic circulation, modifies the thermohaline properties of the Adriatic Sea. Thus a decadal cycle could be related also to sea water salinity and density changes, coherently with changes in the sea level height in the northern Ionian Sea.

In order to better interpret our record in terms of both temperature and salinity we compare it with other neighbouring and local temperature proxies.

We found a good agreement with a well-dated δ^{18}O isotopic record of a stalagmite from the Central Alps (Spannagel cave, Austria), translated by Mangini *et al.* [41] into a high-resolution record of temperature covering the past 2000 y [41]. The record shows a long-term trend similar to our series: maximum temperature values are observed between 800 and 1300 AD, corresponding to the Medieval Warm Period, while lowest values correspond to the LIA event (1400–1850 AD), with a temperature difference between the two periods of about 1.7 °C. The Spannagel record also shows low temperatures around 0 AD ($\approx 1\,^\circ$C lower than MWP). This evidence, coming from a site relatively close to our area, confirms our findings of a cold RCP.

Zooming into the Mediterranean region, we compare the δ^{18}O profile with the alkenone-based ($U_{37}^{k'}$) SSTs proxy record [42], resulting from the combination of measurements performed in our Ionian cores (GT89/3, GT91/1 and GT90/3). The measurements on core GT89/3 cover the interval 1634–1979 AD, those on GT91/1 span 1306–1708 AD, and 16 additional measurements, 1793–1851 AD, were performed on core GT90/3. In the overlapping intervals, the SST values were averaged; the time resolution is the same as for of the δ^{18}O time series, $\Delta t = 3.87$ y. The alkenone record gives a direct information about temperature, since the $U_{37}^{k'}$ only reflects the SSTs at which the alkenone-producing algae lived, thus providing a reliable and robust SST transfer function [43].

At a first sight, we can notice an evident mismatch between the δ^{18}O time series and the alkenones reconstruction, suggesting that the raw δ^{18}O is not simply temperature-driven and that the water δ^{18}O contribution cannot be neglected (fig. 6, panel a). Over the last two centuries, however, the agreement is good. The δ^{18}O increase of about $0.5^0/_{00}$, if entirely due to temperature effects, would approximately correspond—following [44]—to an increase of roughly 2 °C, a value compatible with

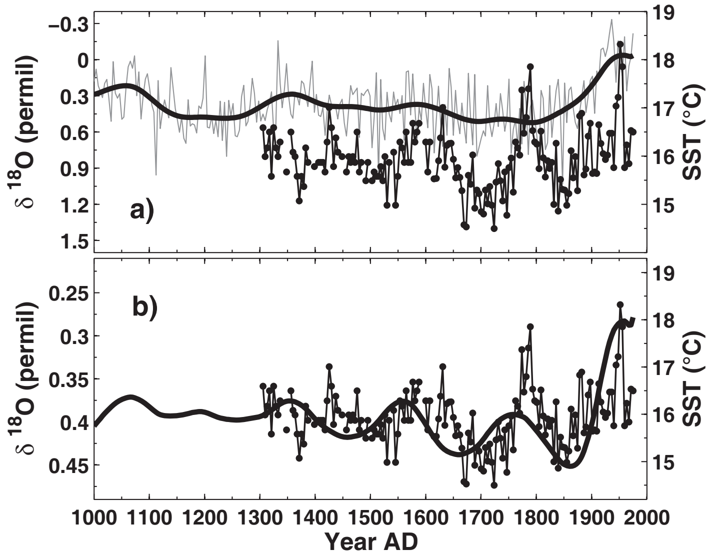

Fig. 6. – Panel a: δ^{18}O series (raw data in light grey; SSA reconstruction by RCs 1–10 in bold solid black) and alkenone-based SST record of sea surface temperatures (SSTs) from [42]. The record combines measurements performed on the GT89/3, GT91/1 and GT90/3 cores (solid black line), and the sampling interval is $\Delta t = 3.87\,$y (same as for the δ^{18}O record). Panel b: Partial reconstruction of δ^{18}O series obtained by summing up RC 1 (trend) and RCs 6–8 (200 y), and alkenone-based SSTs from [42].

the alkenone-derived temperature increase. This suggests that the role of temperature changes is dominant in the modern era, although contributions due to changes in the δ^{18}O and salinity of sea water cannot be completely neglected, even during this period.

The alkenones record, however, is affected by some drawbacks: first of all, this time series results from the composition of the measurements performed on three different cores. Though they were extracted from the same region, and dated with the same accuracy, an unexplained difference of about 1 °C among the separate records is present [42]. Secondly, the composite series has several gaps between 1300 and 1500 AD.

Moreover we compare the alkenones-based SSTs record with a series of annual mean surface air temperatures at Gallipoli from 1861 to 2008 AD (fig. 7) (courtesy of Prof. Maurizio Maugeri, Università degli Studi di Milano). Several authors [45-47] pointed out the meaning of a comparison between SST anomalies and air temperature anomalies. In fig. 7, a low-pass–filtered version is superimposed on the raw air temperature data, with a cutoff at $f = 1/10\,\text{y}^{-1}$; this smoothing was obtained by applying an equiripple Finite Impulse Response (FIR) low-pass filter [48] with order 28. The filtered series well evidences the agreement between the two profiles, both for low and high frequency variations. We can also interpret this agreement between the two records over the last two centuries as a further and independent confirmation of our cores' reliable dating. Both series exhibit a remarkable increase from 1850 to 1979 AD, respectively of roughly 1.5 °C for surface air temperatures and of nearly 2 °C for alkenone-based SSTs. A narrow peak around 1950 AD is particularly evident in the alkenone-derived SSTs, while a peak

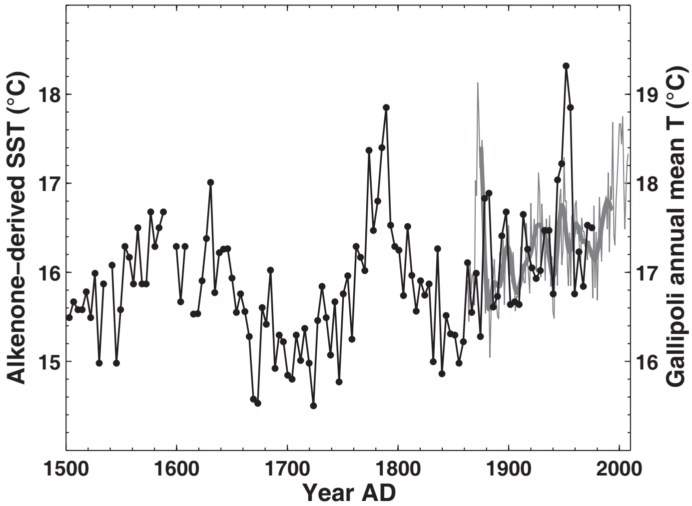

Fig. 7. – Alkenone-based proxy record of sea surface temperatures (SSTs) and mean annual surface air temperatures at Gallipoli, Gulf of Taranto, 1861–2008AD (courtesy of Prof. Maurizio Maugeri, Università degli Studi di Milano). Raw data (thin grey line) and low-pass–filtered version (bold grey line), with a cutoff at $f = 1/10\,\mathrm{y}^{-1}$. Notice that both y-axes span the same temperature interval.

around 1980 AD is shown especially by the air temperature series. The modern increase of about 2 °C indicates a local amplification with respect to the NH temperature increase by a factor of about 3. Metaxas *et al.* (1991) [49] studied instrumental SSTs and surface air temperatures in the Mediterranean region for the last 120 y; they found an amplification of NH temperature variations by a factor of 1.5 for the Mediterranean basin as a whole and by 2 for the Central Mediterranean. For the shallow, semi-enclosed Gulf of Taranto, we might expect an even larger amplification factor, as suggested also by the alkenone data.

Coming back to the features of the alkenones time series, we notice, from visual inspection of fig. 6, panel a), that it is dominated in the range 1300–1800 AD by a 200 y oscillation, superposed on a decreasing trend. This result is confirmed by SSA analysis (not shown). We are thus drawn to compare, in fig. 6, panel b, the alkenone SST signal with the sum of the trend and the 200 y oscillation extracted from the δ^{18}O record. This partial reconstruction of our δ^{18}O record reproduces fairly well the alkenone/derived SST variations, thus suggesting that the 200 y oscillation and trend could be temperature driven.

Concerning fig. 6, panel b, one more remark is needed: the amplitude of the 200 y oscillation in the calcite δ^{18}O before 1850 AD is of about $0.06^0/_{00}$; according to the Shackleton relationship [44], this corresponds to a variation of roughly 0.3 °C, while the SST variation on this time scale is of about 2 °C. This argument suggests a contribution by the isotopic composition of water to this bicentennial component in the calcite record. Actually, if a given decrease of δ^{18}O—similar to that occurring between a maximum and a minimum of the 200 y oscillation—were accompanied by a synchronous increase of the δ^{18}O in the water (due for instance to a decrease in the net difference between precipitation and evaporation) the corresponding temperature change, calculated from the Shackleton equation, would be greater than the one calculated assuming the δ^{18}O of water to be constant. For a more detailed analysis see [50].

In order to overcome our series drawbacks, further information about past temperatures in the Mediterranean area should come from other proxies of SSTs, for instance foraminiferal Mg/Ca [51].

5. – Conclusions

We measured a 2200 year long, high-resolution and homogeneous δ^{18}O record from a Mediterranean (Ionian Sea, Gulf of Taranto) sediment core. A visual inspection of our record reveals the imprint of the most prominent climatic features of the last two millennia. From the time series analysis, carried out by advanced spectral methods, we revealed highly significant oscillatory components in our record, with periods of roughly 600, 350, 200, 125 and 11 y. Comparing our δ^{18}O time series with other temperature proxies, we conclude that the overall trend and the 200 y component are very likely temperature driven. Concerning the other dominant oscillations, especially in the decadal range, the situation is less clear and salinity and circulation effects probably cannot be considered as negligible. In order to better interpret our record in terms of both temperature and salinity, homogeneous series of other SSTs proxies, such as foraminiferal Mg/Ca, are required. These measurements are presently in progress.

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