Project of Strategic Interest NEXTDATA

Scientific Report for the reference period 1/01/2018-30/06/2018

Deliverable D1.5.C (June 2018)

Relazione tecnico-scientifica, contenente serie temporali e carte paleoclimatiche, sulla risposta del Mediterraneo alle variazioni delle forzanti climatiche negli ultimi millenni, come derivata dall'analisi dei dati di carotaggi marini (D1.5.B) (Task 2)

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The research activities related to Deliverable D1.5B of project is dedicated to the analysis of marine cores recovered in the Adriatic and Tyrrhenian seas to identify the main paleoclimatic oscillations recognized during the last millennia.
The succession of the paleoclimatic events identified through calcareous plankton and pollen signals, stable isotope and SST reconstruction (Mg/Ca ratio and alkenone), have been compared with data collected from marine cores recovered in other areas of the to verify the synchronicity between short and long-term climatic oscillation in the Mediterranean and changes in SST. This research activity has been proposed within a joint research agreement with two international research groups (Isabel Cacho of University of Barcelona and Marie-Alexandrine Sicre of Locean-CNRS Paris).

Correlation between Mediterranean stable isotopic proxy records (data published in Margaritelli et al., 2008_ *Global and Planetary Change* 169, 179–187, updated for this report)

For the first time we provide the correlation among different regions of the Mediterranean Sea during the last 2700 years. This effort permits to verify the synchronicity of climate events

(alternation of cold and warm events) in land and ocean in order to better understand global forcing within the Mediterranean region.
The comparison between the marine records (Fig. 1) of Menorca basin (Margaritelli et al., 2018), north, central and south Tyrrhenian Sea (Lirer et al., 2013, 2014; Margaritelli et al. 2016; Dentici PhD thesis 2018), Taranto Gulf, (Grauel et al., 2013), central and south Adriatic Sea (Piva et al., 2008; Lirer et al., in prep.), west and east Sicily channel (Margaritelli et al., in prep.; Dentici et al., in prep.), Israel (Schilman et al., 2001) and the north European continental ones (Moberg et al., 2005; Hegerl et al., 2006, 2007; Mann et al., 2008; Ljungqvist et al., 2010; Pages 2k Consortium 2013), allows to highlight a similar climate evolution at Mediterranean scale.

Fig. 1. Location Map of the compared marine cores. HERC-MC (Margaritelli et al., 2018), NDT18 (Dentici PhD 2018), C5 (Margaritelli et al., 2016); C90 (Lirer et al., 2013; 2014); ND11 (Margaritelli et al., in prep); ND2 (Dentici et al., in prep); DP30 (Grauel et al., 2013); ND14Q (Lirer et al., in prep); AMC99-1 (Piva et al., 2008); GA-112 (Schilman et al., 2001)

Notwithstanding differences in age model, we underline a general good agreement between the long and short term climate oscillations in sea surface Mediterranean $\delta^{18}O_{G.ruber}$ records (Fig. 2) during the last 2700 years.
The cooling phase at ca. 250 - 300 BCE corresponding to the Greek solar minimum is widely recognised in all the investigated Mediterranean records by $\delta^{18}O_{G.ruber}$ signatures (Fig. 2), excluding the Taranto Gulf as probably due to a regional overprint. The cooling event recorded by $\delta^{18}O_{G.ruber}$ heavy values at ca. - 600 BCE in the study core (Menorca area) has been correlated to the Homeric solar minimum (Fig. 2).
Between 220 and 800 BCE, the cold events Roman II, III and IV are well documented by $\delta^{18}O_{G.ruber}$ signals of the western basins (Fig. 2) and result time equivalent to the solar minima activity as already evidenced by Lirer et al. (2014) and Margaritelli et al. (2016) in the central Mediterranean Sea. In addition, the observed correspondence between the Roman III event with the north hemisphere continental temperature anomaly (Mann et al., 2008; and Ljungqvist et al., 2010) reveal a remarkable connection between continental and marine climatic pattern.
In the upper part of the DA, the prominent cooling event corresponding to the Roman IV solar minimum, marks the beginning of a progressive cooling trend that culminates during the LIA (Fig. 2). Trends to cool temperatures during the DA have been also reconstructed in the north Europe continental records (PAGES 2K Consortium, 2013; McGregor et al., 2015; Büntgen et al., 2016). It results to be almost synchronous with an increase in amplitude change in solar activity (Δ14C, Stuiver et al., 1998) and progressive shift vs negative NAO index according to NAO index reconstruction of Olsen et al., (2012) (Fig. 2).
The MCA was characterized by rather temperate climate conditions as documented by marine (Schilman et al., 2001, Grauel et al., 2013; Lirer et al., 2014; McGregor et al., 2015; Cisneros et al., 2016; Margaritelli et. al., 2016, 2018) and terrestrial paleo - archives (Büntgen et al., 2016).

During this time period, $\delta^{18}O_{G.ruber}$ records and foraminiferal data document mild climate conditions with a short - term cold dry event (MCE) at ca. 1050 CE and also characterized by a arboreal vegetation decrease in the central Tyrrhenian area (Moreno et al., 2012; Margaritelli et al., 2016; Di Rita et al., 2018). The MCA period was coincident with the climax of many Mediterranean cultures. During the twelfth century, the medieval Byzantine Empire goes through an important societal expansion, with substantial agricultural productivity, intensive monetary exchange, demographic growth, and its pre - eminent international political situation (Xoplaki et al., 2015).

The establishment of colder conditions in the climate system from ca. 1200 CE upwards characterized the entire LIA as provided by temperature reconstructions (PAGES 2K Consortium, 2013; Cisneros et al., 2016) and by abrupt oscillation in Mediterranean $\delta^{18}O_{G.ruber}$ records (Fig. 2). In addition, this cooling trend results almost synchronous with a progressive shift vs negative NAO index (Trouet et al., 2009; Olsen et al., 2012). Weak NAO index associated with Atlantic Blocking event during LIA and in particular in the late part of Maunder cold event (Barriopedro et al., 2008), has been considered by Margaritelli et al. (2016, 2018) and Di Rita et al. (2018, 2018a) as internal climate forcing to explain the changes in planktonic foraminiferal assemblage and in pollen data, respectively. In addition, Sicre et al. (2016) suggested persistent blocked regimes under a combined effect of weak NAO index with negative East Atlantic pattern (EA) in the western Mediterranean. Furthermore, Josey et al. (2011) suggest a major effect of the EA respect to the NAO in the eastern and western Mediterranean basin.

During the LIA, three distinct cooling events well documented in prominent heavy values in $\delta^{18}O_{G.ruber}$ signals of western and eastern Mediterranean Sea clearly resembled the Wolf, Sporer and Maunder solar minima recorded in the Δ14C solar oscillation (Stuiver et al., 1998) (Fig. 2). This correlation between the $\delta^{18}O_{G.ruber}$ signals and solar minima supports the influence of solar forcing on the climate variability in the Mediterranean Sea as already introduced in literature (Lirer et al., 2014; Margaritelli et al., 2016; 2018). In addition, as recorded in the previous cold dry event at ca. 1050 CE (MCE), a prominent decline in the forest cover in the central Tyrrhenian area is documented during the Maunder event (Di Rita et al., 2018; 2018a).

These persistent cold climate conditions are also documented in several paintings of winter landscapes showing the severe winter seasons in Europe (i.e., Brueghel 1601; Avercamp 1608) as well in the maximum frequency of freezing of Venice Lagoon occurred between 1700 and 1850 (Camuffo and Enzi, 1995).

Available data for the last two centuries are not enough to have a clear picture for this time interval, but few $\delta^{18}O_{G.ruber}$ data seem to suggest an inversion in climate vs warm conditions (Grauel et al., 2013; Lirer et al., 2014; Margaritelli et al., 2016).

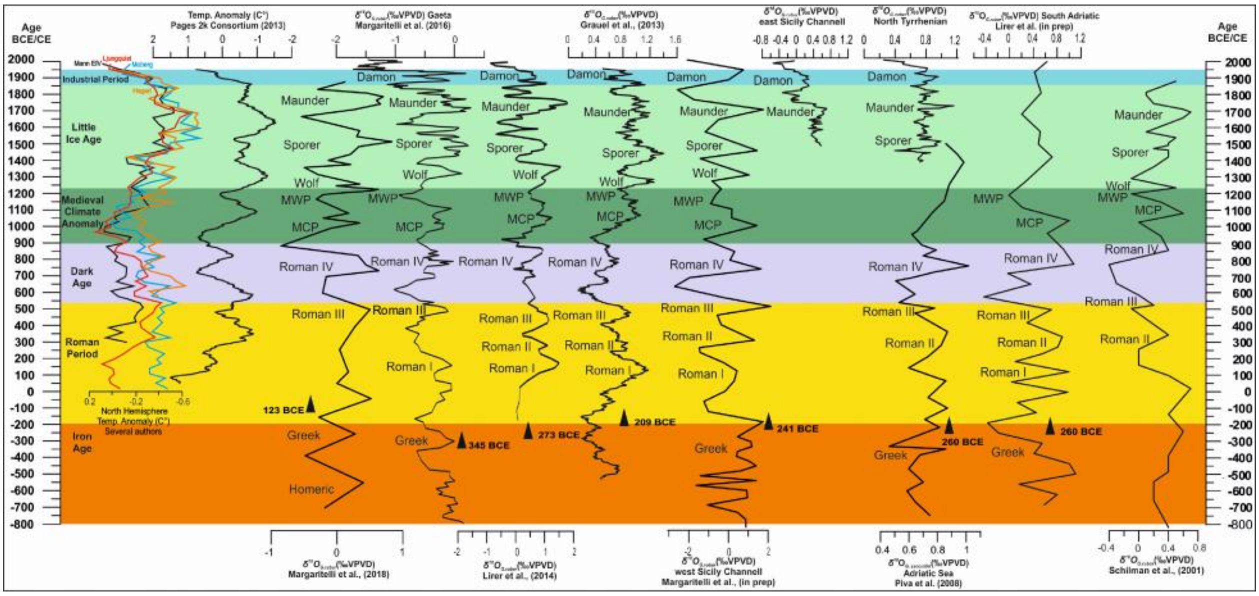

Figure 2 – Comparison in time domain between δ^{18}O G. ruber signals from HERC-MC (Minorca Bsin, Margaritelli et al., 2018), NDT18 (north Tyrrhenian Sea, Dentici PhD 2018), C5 (central Tyrrhenian Sea Margaritelli et al., 2016); C90 (south Tyrrhenian Sea Lirer et al., 2013; 2014); ND11 (west Sicily channel, Margaritelli et al., in prep); ND2 (east Sicily channel, Dentici et al., in prep); DP30 (Tranto Gulf, Grauel et al., 2013); ND14Q (south Adriatic Sea, Lirer et al., in prep); AMC99-1 (central Adriatci Sea, Piva et al., 2008); GA-112 (Schilman et al., 2001). The black arrows with ages represent the ages when this areas becomes part of the Roman Empire.

Sea Surface Temperature (SST) reconstruction in the North Mediterranean Sea and in the South Adriatic Sea over the last millennia using alkenones (data published in Jalali et al., 2018_*Paleoceanography and Paleoclimatology*, DOI: 10.1029/2017PA003298.)

Deltaic and shallow marine sediments represent unique natural archives to study the evolution of surface coastal ocean water properties as compared to environmental changes in adjacent continents.

Sea surface temperatures (SSTs) and higher plant biomarker records were generated from the Rhone and Var River deltaic sediments (NW Mediterranean Sea) (Fig. 3), and three sites in the South Adriatic Sea (Central/Eastern Mediterranean Sea) (Fig. 3), spanning all or part of the past three millennia (Fig. 4). Because of the high sediment accumulation rates at all core sites, we were able to produce time series at decadal time scale.

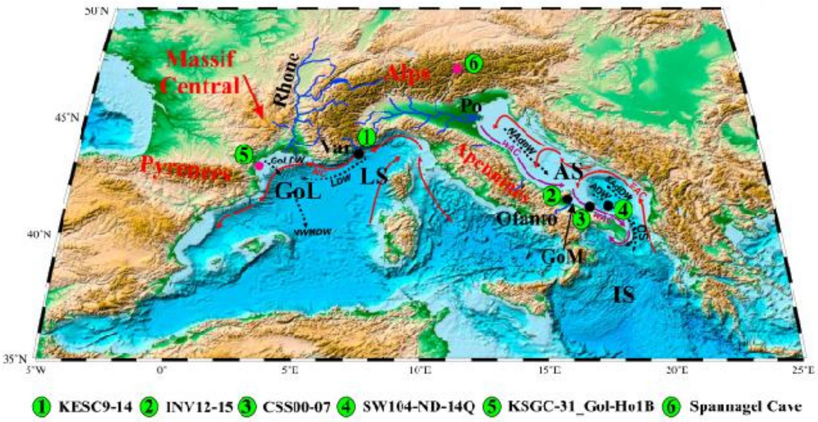

Figure 3 – Map of the western and central/eastern Mediterranean regions showing the location of the investigated cores and main marine currents. Location of the Spannagel Cave is also shown. Rhone, Var, Po, and Ofanto rivers are also shown. GoL: Gulf of Lion; LS: Ligurian Sea; AS: Adriatic Sea; GoM: Gulf of Manfredonia; IS: Ionian Sea; OS: Otranto Strait; NC: Northern Current; LDW: Ligurian dense water; GoLDW: Gulf of Lion dense water; NWMDW: North-Western Mediterranean deep water; WAC: Western Adriatic Current; EAC: Eastern Adriatic Current; NAdDW: Northern Adriatic Dense Waters; SAdDW: southern Adriatic dense water; ADW: Adriatic deep water.

The SST records (Fig. 4) from the Gulf of Lion and Ligurian Sea revealed a long-term cooling culminating during the Dark Ages Cold Period (DACP), which reversed at the onset of the Medieval Climate Anomaly (MCA), superimposed to multidecadal to centennial scale variability reflecting atmospheric forcing from mainly Est Atlantic (EA) and North Atlantic Oscillation (NAO). In addition, SSTs in the Gulf of Lion and the convection area of the South Adriatic Sea indicate similar cold mean values (around 17 °C) and pronounced cold spells, reflecting strong wind-driven surface water heat loss. However, they differ in the rate of post-industrial warming, which is steeper in the Gulf of Lion.

The three Adriatic Sea SST records (Fig. 4) are notably different reflecting different hydrological influence from nearshore to open sea sites. They show contrasting strong centennial time-scale variability, but no clear long-term trend.

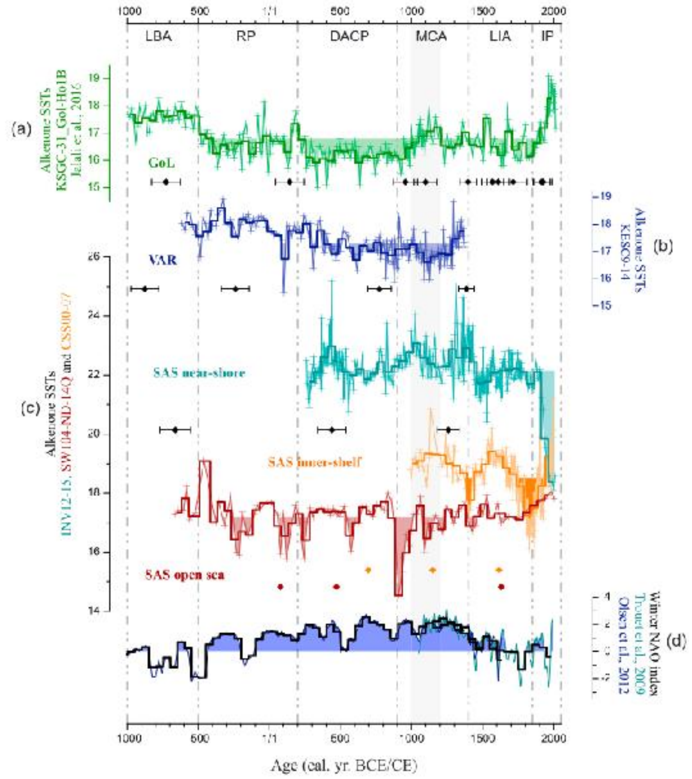

Figure 4 – Regional response of Mediterranean sea surface temperatures (SSTs) to climate variability over the last 3,000 years. (a) Alkenone SSTs at the KSGC-31_GolHo-1B core (GoL, Jalali et al., 2016; Sicre et al., 2016). (b) Alkenone SSTs at the KESC9–14 core (this study). (c) Alkenone SSTs at the INV12–15 (dark cyan curve), CSS00–07 (orange curve), and SW104-ND-14Q (wine curve) cores (SAS, this study). (d) The winter North Atlantic Oscillation index from the paleoreconstruction by Trouet et al. (2009) (dark cyan) and Olsen et al. (2012) (navy). Fifty years of binning is applied to all signals to reduce the effect of proxy reconstruction error (dark lines). The diamonds indicate the control points used for the age models, at 1s uncertainty for the 14C dates. The vertical dashed lines represent boundaries of historical periods. LBA: Late Bronze Age, RP: Roman Period, DACP: Dark Ages Cold Period, MCA: Medieval Climate Anomaly, LIA: Little Ice Age, IP: Industrial Period.

Concentrations and compositional features of n-alkanes (ACL) for all core sites are shown in Figure 5. TERR-alkanes in the GoL depict similar trends as in the Var River, except during the MCA. The ACL values in the Var delta sediments are higher than in the GoL, in agreement with climatic conditions of the catchment of the two rivers (Fig. 5c). Indeed, lower ACL values in the GoL core reflect the generally more humid conditions in the Upper Rhone River drainage basin (Jalali et al., 2017), reaching outside the Mediterranean climate zone, to a more temperate climate regime to the north (Fig. 5c). This is in contrast with the purely Mediterranean drainage basin of the Var River. More zonal and southerly westerlies during negative NAO are today responsible for wetter conditions in the Mediterranean region, whereas a positive NAO is associated with drier conditions. During the MCA, when presumably a positive NAO prevailed, TERR-alkanes consistently increased in the Rhone River sediments but declined in the Var sediments. The 200-year binned Rhone prodelta ACL data show a significant correlation ($r = 0.66$; $n = 12$; at the 95% confidence interval) with summer (April-May-June) precipitation from central Europe over the last 2,400 years (Büntgen et al., 2011). This result outlines the sensitivity of the temperate vegetation in the Upper Rhone watershed to summer precipitation variability in Europe. In contrast, the ACL values of the Var indicate drier conditions, likely reflecting already established Mediterranean climate. In the Adriatic cores, TERR-alkanes have high concentrations during the early RP, decreasing values during the MCA (also seen in the Var River sediments) and a sharp rise over the last 500 years, which is not seen in the GoL sediments (Figg. 5a and 5b). In all Adriatic Sea records, the ACL are rather stable ranging between 30 and 30.2 (Figure 5d) and indicating no major vegetation change in the Italian river watersheds. ACL from the southern Adriatic Sea cores are similar to those from the Var (Figg. 5c and 5d), but the temporal evolution of TERR-alkane concentrations is rather different (Figg. 5a and 5b). The most striking feature of the Adriatic Sea records is the progressive increase over the last 500 years, which is more pronounced at the coastal sites (INV12–15 and CSS00–07 cores; Fig. 5b). Taking into account that the ACL values are stable, this result can be attributed to increased soil erosion, probably due to anthropogenic activities. This finding suggests that the Mediterranean vegetation was already established in this region 2,500 years ago, as also evidenced from palynological data in the southeastern Adriatic borderland (Sadori et al., 2014).

Based on model simulations, Kaplan et al. (2009) were able to estimate the forest fraction of usable land in the Mediterranean region over the past 3,000 years (Fig. 5e). This model is forced by the population history and maps of suitable land for agriculture and pasture. Their reconstruction shows variations of the forest fraction related to human society development and demographic evolution. Human activities such as forest clearing and exploitation of wood for construction are reflected by low forest cover. Comparison with our southern Adriatic records (Figg. 5b and 5d) suggests a notable human influence on soil erosion and subsequent offshore delivery of land-derived material during the past five centuries (Maselli & Trincardi, 2013). This is attested by the very low forested fraction of usable land as a consequence of forest clearance (Fig. 5e) at ~1500 C.E. which appeared to have been more important in Italy than Southern France (see Fig. 6 in Kaplan et al., 2009).

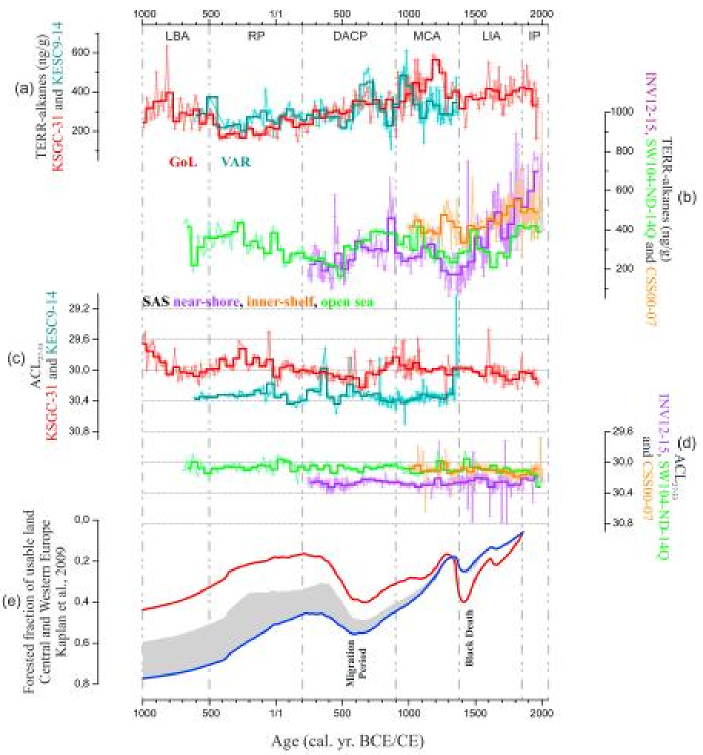

Figure 5 – Rivers discharge and paleoenvironmental changes in the NW and central/eastern Mediterranean during the past 3,000 years. (a) TERR-alkane abundances at the KSGC-31 (Jalali et al., 2016) and KESC9–14 cores (this study). (b) TERR-alkane abundances at the INV12–15, CSS00–07, and SW104-ND-14Q cores (this study). (c) Changes in ACL in the KSGC-31 (Jalali et al., 2017) and KESC9–14 cores (this study). (d) Changes in ACL in the INV12–15, CSS00–07, and SW104-ND14Q cores. Forested fraction of usable land reconstruction from Central and Western Europe (Kaplan et al., 2009). From (a) to (d), 50 years of binning is applied to all signals to reduce the effect of proxy reconstruction error (dark lines). The vertical dashed lines represent boundaries of historical periods.

Mediterranean Sea Surface Temperature (SST) over the last millennia using Mg/Ca ration (data submitted in Margaritelli et al., to *Nature Communication*)

To provide a more complete framework of SST anomaly over the last millennia in the Mediterranean basin, Margaritelli et al. (in prep) produced the first SST Mg/Ca anomaly reconstruction measured on planktonic foraminifer *Globigerinoides ruber* from western part of

Sicily Channel (core SW104-ND11). This record has been compared with the Mg/Ca *Globigerina bulloides* SST anomaly stack of Menorca basin (Cisneros et al., 2016) and with SST U^{k}_{37} anomaly reconstructions from Alboran (Rodrigo-Gamiz et al., 2014) and Aegean seas (Katsouras, 2009; Kontakiotis 2016, and Gogou et al., 2016) (Fig. 6).

Fig. 6. Location Map of the compared marine cores. 434-G (Rodrigo-Gamiz et al., 2014), HERC-MC (Cisneros et al., 2016), ND11 (Margeritelli et al. submitted)), SL-152 (Katsouras, 2009; Kontakiotis 2016), M2 (Gogou et al., 2016).

This comparison allowed us to document for the first time a prominent warm interval characterised by a shift of ca. 2°C (±0.5 °C) *vs* positive anomaly (Fig. 7). This well pronounced warm interval from 100 yr BCE to 500 CE occurs during the Roman Period. This SST evolution during the Roman Period is consistent with the isotopic record of the Gulf of Taranto (Goudeau et al., 2015) and with other records from northern Europe (Bond et al., 2001; Sicre et al., 2008; Esper et al., 2014) and with the continental anomaly reconstruction from North Hemisphere (Ljungquist et al., 2010). However, none of these records highlights the Roman times as the warmest climate period of the last two millennia. Despite the different ecological niche of the planktonic foraminiferal species used to reconstruct the Mg/Ca ratio for the Sicily Channel (*G. ruber proliferates at the end of the summer*) and the Menorca Basin (*G. bulloides distribution is mainly controlled by seasonal spring SST conditions, related to the April–May primary productivity*), this warming phase is recognisable in both marine records.

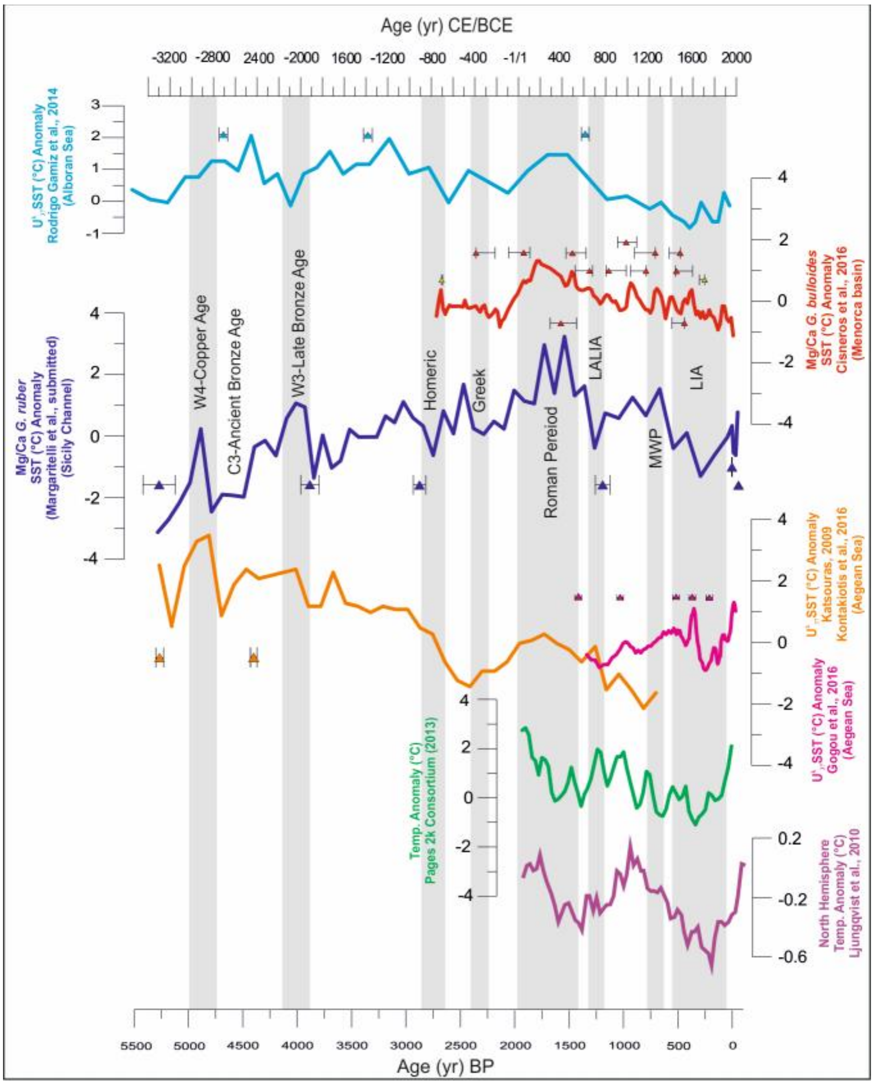

Figure 7 – Comparison in time domain between the Mg/Ca *Globigerina bulloides* temperature anomaly stack of Menorca basin (Cisneros et al., 2016), the Mg/Ca *Globigerinoide ruber* temperature anomaly of Sicily Channel (Margaritelli et al., submitted), the SST U^{k}_{37} anomaly reconstructions from Alboran (Rodrigo Gamiz et al., 2014) and Aegean seas (Katsouras, 2009; Kontakiotis 2016, and Gogou et al., 2016) with the continental temperature anomaly reconstruction from Europe (PAGES 2K consortium, 2013) and with North Hemisphere Temp. Anomaly (Ljungquist et al., 2010). The grey bands shows the main climate events documented in the Mediterranean basin.

In addition, this warm phase during the Roman Period is also recorded in the SST U^{k}_{37} SST anomaly reconstructions (even though the alkenones indicate the mean annual SST) from Alboran (Rodrigo-Gamiz et al., 2014) and Aegean seas (Katsouras, 2009; Kontakiotis, 2016), documenting the occurrence of a Mediterranean global event (Fig. 7).

Chronologically, the warm phase related to the Roman period covers the entire phase of origin, expansion and decline of the Roman Empire even if the expansion of the Roman Empire did not occur synchronously throughout the Mediterranean area because of the political situation, geographical pattern and, probably, also the different climatic conditions in the various areas.

In the Sicily channel, in the Minorca basin and in the Aegean Sea the political events concerning the Roman Empire can be considered almost synchronous (Sicily channel: 241 a.C. – 440 d.C.; Minorca basin 123 a.C. – 455 a.C.; Eastern Mediterranean 27 a.C – 395 d.C) as the trend of temperatures can be easily compared.

Therefore, it is possible to hypothesize that the favourable climatic conditions of this period may have contributed to the expansion of the Roman Empire in the various areas of the Mediterranean Sea.

After this event, all the Mediterranean records shows a generally consistent SST anomaly-decreasing trend vs negative anomaly (Fig. 7). In this period, both the Aegean Sea and Sicily Channel were laid siege by pirates and vandals. In fact, at the end of the IV century, the roman

world was experiencing the beginning of the end that will come just a few centuries later (Gibbon, 1776).
The collapse swept Sicily, which was a major supplier of grain throughout the Empire, and held the greater part of the agrarian economy (Momigliano Arnaldo, 1973). The island, deprived of military defenses, was besieged by a band of pirates Illyrian (438 d.C.) which devastated a large stretch. In the same time, the Eastern part of the Mediterranean Sea was invaded by the Vandals of Genserico (Momigliano Arnaldo, 1973).
Subsequently the end of the Roman Period, the new SST Mg/Ca $_{\textit{G. ruber}}$ anomaly reconstruction from Sicily Channel, documented the sudden short-term cooling phase associated with the Late Antique Little Ice Age (LALIA) event at ca. 650 CE (Dark Age). This event, recorded in several continental fossil archives of North Hemisphere, has been considered as an additional environmental factor contributing to the establishment of the Justinian plague, transformation of the eastern Roman Empire and collapse of the Sasanian Empire, movements out of the Asian steppe and Arabian Peninsula, spread of Slavic-speaking peoples and political upheavals in China (Buntgen et al., 2016).
Upwards, the progressive shift vs positive SST anomaly in Mg/Ca $_{\textit{G. ruber}}$ signal documented an amelioration of climate condition during the Medieval Climate Anomaly interval with a warmest event well-known as Medieval Warm Period (MWP) at ca. 1200 CE (Fig. 7). This latter warm event is also documented in the Alboran (Rodrigo-Gamiz et al., 2014), Balearic (Cisneros et al., 2016) and Aegean (Gogou et al., 2016) areas (Fig. 7).
Between 1320 CE and ca. 1850 CE, the SST anomaly in Mg/Ca $_{\textit{G. ruber}}$ signal of ca. 2°C (±0.5 °C) *vs* negative values, has been associated to the Little Ice Age cold event (Fig. 7). The persistent cold climate conditions during LIA are also documented in several paintings of winter landscapes showing the severe winter seasons in Europe (i.e., Brueghel 1601; Avercamp 1608) as well in the maximum frequency of freezing of Venice Lagoon occurred between 1700 and 1850 (Camu o and Enzi, 1995).
Notwithstanding the resolution over the last two centuries, the study record of Sicily Channel (Mg/Ca $_{\textit{G. ruber}}$ signal) ends with a turnover from ca. 1850 CE to 2014 CE vs a positive anomaly of ca. 1°C (Fig. 7), probably associated to the onset of the Industrial Period/Modern Warm Period. Anyway, as documented by Margaritelli et al. (2018) from the Mediterranean $\delta^{18}O$ data, further studies are needed to have a clear picture for this important time interval.
Another important result obtained from marine archive of Sicily Channel is the good correlation of the SST anomaly in Mg/Ca $_{\textit{G. ruber}}$ signal with the temperature anomaly reconstruction from north Hemisphere (Ljungquist et al., 2010) (Fig. 7). This good visual correlation documented a remarkable connection between continental and marine climatic pattern over the last millennium.

Holocene forest dynamics in central and western Mediterranean: periodicity, spatio-temporal patterns and climate influence (data published in Di Rita et al., 2018_ Scientific Reports, DOI:10.1038/s41598-018-27056-2)

To provide a more complete framework about the forest dynamics in central and western Mediterranean and the connection with climate oscillation over the last five millennia we compared several pollen data from marine and continental fossils archives (Fig. 8).

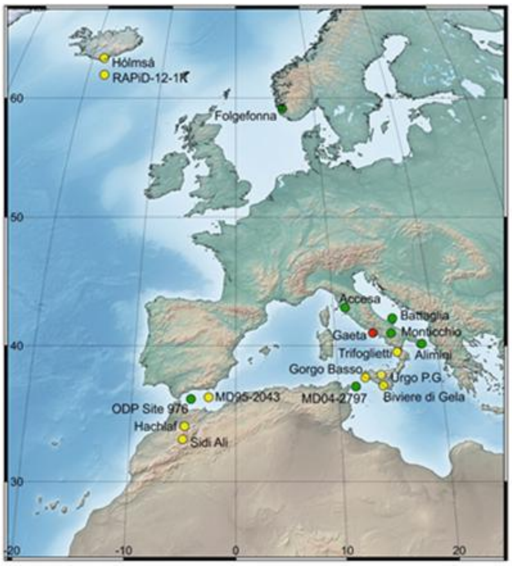

Figure 8 – Location map of the compare sites. Gulf of Gaeta record (red dot), (yellow dots: Sidi Ali; Hachlaf, site MD95-2043, Gorgo Basso, Biviere di Gela, Urgo Pietra Giordano, Trifoglietti, core RAPiD-12-1K, and Hólmsá); and other sites mentioned in the text (green dots: ODP site 976, Folgefonna, site MD04-2797, Lago Alimini Piccolo, Lago Grande di Monticchio, Lago Battaglia and Lago dell'Accesa).

It is well-known that the Holocene exhibits a millennial-scale climate variability. However, its periodicity, spatio-temporal patterns and underlying processes are not fully deciphered yet. The late Holocene vegetation changes recorded in Mediterranean sites are mostly explained by human activity, which is taken for granted since agro-pastoral and silvicultural practices, forest clearance, fires and human settlements are documented up to present time. However, the comparison between several proxy records from several continental and marine sites suggested that near-coeval forest fluctuations, recorded over wide Mediterranean regions, were cadenced by well-known climate fluctuations, identified also by independent climate proxies at a global scale, thus emphasizing the role of climate on the vegetational landscape (Fig. 9).

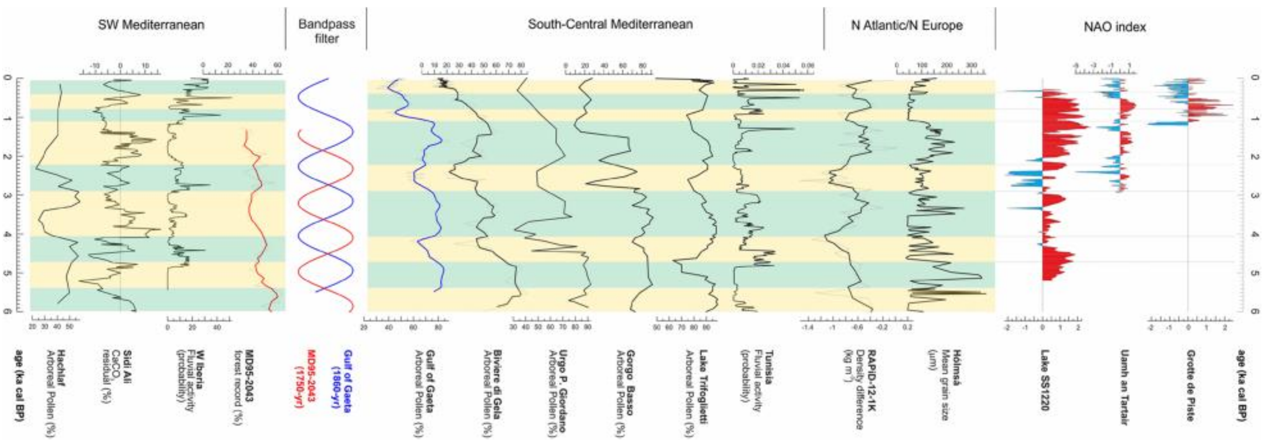

Figure 9 – Palaeoclimate proxy records from the south-western Mediterranean, south-central Mediterranean, North Atlantic/Northern Europe, and NAO index. Hachlaf: Arboreal Pollen record; Sidi Ali: detrended values [3rd order polynomial] of carbonate data; W Iberia: cumulative probability density plots of radiocarbon dates from floods and extreme fluvial event units; MD95-2043: temperate and Mediterranean forest record, with three-point running mean in red; Bandpass filter applied to the MD95-2043 (1750-yr filter) and Gulf of Gaeta (1860-yr filter) pollen records; Gulf of Gaeta (SW104_C5-C5): Arboreal Pollen record, with three-point running mean in blue; Biviere di Gela: Arboreal Pollen record, with three-point running mean in bold; Urgo Pietra Giordano: Arboreal Pollen record; Gorgo Basso: Arboreal Pollen record; Lake Trifoglietti: Arboreal Pollen record; Tunisia: cumulative probability density plots of radiocarbon dates from floods and extreme fluvial event units; core RAPiD-12-1K: upper ocean density stratification proxy, with three-point running mean in bold; Hólmsá (Iceland): loess grain size record; NAO index calculated from Lake SS1220, Greenland; NAO index calculated from Uamh an Tartair, NW Scotland; NAO index calculated from Grotte de Piste, Morocco. Yellow bands correspond to generally arid time intervals; blue bands indicate wet periods.

The keysite recovered for NextData project in the Gulf of Gaeta, analysed in Margeritelli et al. (2016) and Di Rita et al. (2018), revealed a correspondence in the series of events of such different records, suggesting that the explanation of the recurrent palaeoenvironmental changes at Gaeta may have implications well beyond site-specific interests.
The vegetation development at Gaeta (Margaritelli et al., 2016; Di Rita et al., 2018) is consistent with other pollen records from the south-central Mediterranean, a region especially sensitive to climate change, being under the influence of both the North Atlantic circulation and the high-pressure system of North Africa (Fig. 9). In fact, some of the forest declines previously attributed to anthropogenic impact may be linked to this slow-changing component of moisture availability for plant growth. At the same time, the Gaeta record shows a striking antiphase correspondence with the pollen record from core MD95-2043 in the Alboran Sea, in south-western Mediterranean (Fig. 9). This contrasting pattern is confirmed by other climate proxy records from the south-central and south-western Mediterranean, respectively, including carbonate in sediments and fluvial activity, which show alternate wet and dry phases during the last 6000 years. At much higher latitudes, in Iceland and Norway, a succession of environmental changes and periodicity similar to the Gaeta record (Fig. 10, spectral analyses has revealed a recurrent pattern of forest dynamics with a cyclicity of approx. 1860 years) have also been observed.

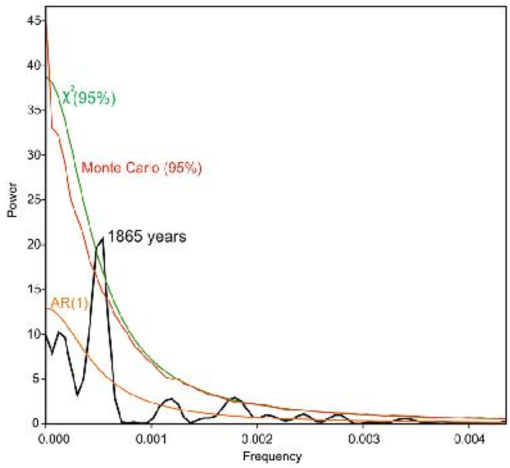

Figure 10 – REDFIT spectral analysis of the Arboreal Pollen (AP) percentages of the Gulf of Gaeta record (black line). The time series is fitted to an AR1 red noise model (orange line). The 95% confidence levels of the χ2 and Monte Carlo tests are reported on the graph with a green line and a red line, respectively.

The main conclusions obtained comparing information from Mediterranean and high latitude proxy records, are as follows:

- Periodicity: the Gaeta record contributes to a growing body of evidence supporting the existence of a ca 1800 yr climate fluctuation during the mid- to late Holocene. Although it is necessary to document in different paleoenvironmental frameworks the nature of this climate periodicity, the convergence of many different sources of evidence towards a 1800-yr cycle strongly suggests that the recurrent vegetation changes in the Gaeta record may have been induced by large-scale changes in climate modes, linked either to changes in solar activity and/or AMOC intensity, influencing the water availability needed for forest expansions.
- Spatio-temporal pattern: the evidence for millennial scale variability in the Gaeta vegetation encompasses the late Holocene, despite a widespread human activity on the territory, which induced a general decline in the forest cover without completely obliterating recurrent vegetation dynamics driven by natural factors at a regional scale.

Although the human impact has exerted an ever-increasing pressure on the natural landscape, the fluctuations in the forest vegetation appear strongly cadenced by climate changes identified also in other proxy records. The same patterns are detected not only in marine pollen records, but also in lacustrine sites, and in other palaeohydrological independent proxy-records from the south-central Mediterranean, latitudinally ranging from Tunisia to southern Italy. These records clearly show dry intervals in correspondence with specific well-known climate events, including the 4.2 ka event, the Medieval Climate Anomaly and the Little Ice Age, but also highlight the relevance of other climate spells, often neglected in the literature including, for example, a deforestation coeval to the so-called "Bond 2" event around 2.8 ka cal BP. The clearly opposed trends observed in several palaeohydrological records from the south-western Mediterranean, indicating generally wet climate conditions during the dry spells found in the Gaeta record, suggest that different expressions of climate modes occurred in the south-western and south-central Mediterranean at the same time. Complex spatial patterns of atmospheric circulation may have acted over the Mediterranean regions.

- Climate processes: a clear temporal correspondence between phases with negative (positive) NAO index and forest declines (increases) in the Gaeta pollen record indicates that the prevailing or predominant phases of NAO-like circulation were prominent factors inducing hydrological variations in the south-central Mediterranean, through changes in zonal winds and different storm track penetration (Fig. 11). However, the observed contrasting hydrologic regimes and vegetation dynamics point also to more complex configuration of the atmospheric circulation, including the EA pattern and its interplay with the NAO, as well as the North African anticyclone dynamics. At a larger geographical scale, considering the tropical engine, displacement of the ITCZ may also have indirectly influenced the recurrent changes observed in the palaeoenvironmental records.

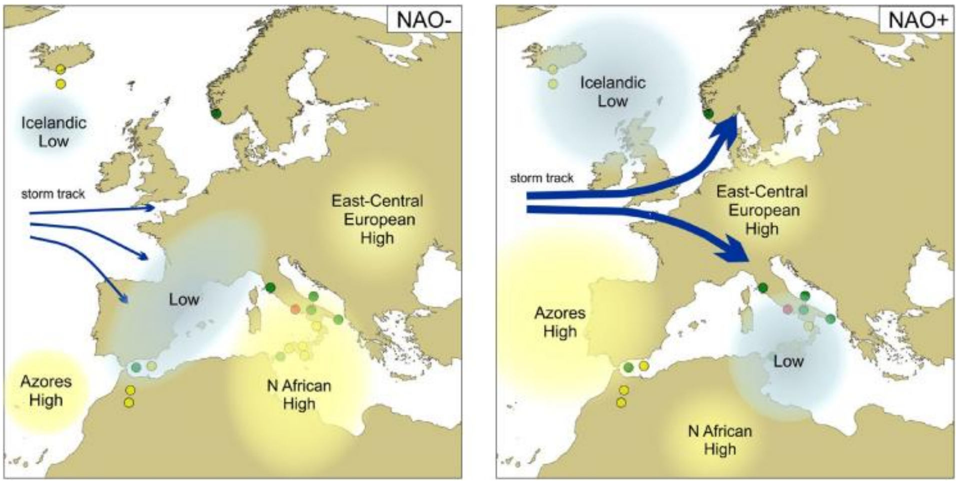

Figure 11 – Tentative reconstruction of atmospheric configurations over Europe and North Africa in correspondence with negative (left) and positive (right) NAO index. Blue arrows indicate the direction and intensity of storm tracks. Possible positions of the Azores High, North African High, Central European High, and Icelandic Low are also indicated, together with low pressure areas with precipitations. The Gaeta record is represented by a red dot, sites shown in Fig. 9 by yellow dots and other sites mentioned in the text by green dots.

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