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Fabrizio LIRER [1*], Giulia MARGARITELLI [2], Ines ALBERICO [1], Sergio BONOMO [3], Lucilla CAPOTONDI [4], Antonio CASCELLA [5], Federico DI RITA [6], Luciana FERRARO [1], Donatella Domenica INSINGA [1], Donatella MAGRI [6], Nicola PELOSI [1], Paola PETROSINO [7] & Mattia VALLEFUOCO [1]

CLIMATIC VARIABILITY OVER THE LAST TWO MILLENNIA IN THE MEDITERRANEAN AREA: A REVIEW FROM MARINE PALEOARCHIVES

Abstract: Lirer F., Margaritelli G., Alberico I., Bonomo S., Capotondi L., Cascella A., Di Rita F., Ferraro L., Insinga D.D., Magri D., Pelosi N., Petrosino P. & Vallefuoco M., *Climatic variability over the last two millennia in the Mediterranean area: a review from marine paleoarchives.* (IT ISSN 0391-9838, 2019).

A review of the climatic variability over the last two millennia based on oxygen stable isotopic ($\delta^{18}O_{G. ruber}$) signals from different areas of the Mediterranean Basin (Minorca Basin, central and south Tyrrhenian Sea, Taranto Gulf, south Adriatic Sea and Israel) has been proposed. The correlation of data testifies an almost synchronicity of the identified climate events, suggesting an homogeneous response of the marine system to climate oscillations. This overall picture documents that the collapse of the Western Roman Empire results chronologically related to cold event Roman III solar minimum and that the Roman IV solar minimum (Dark Age), marks the transition *vs* a long term cooling trend, spanning ca. 1100 years, that culminates during the Maunder solar minimum (LIA). In addition, during the Maunder cold event, the strong increase in abundance of planktonic foraminifer *Globlorotalia truncatulinoides*, suggest the establishment of vertical mixing during the winter season induced by strong winds linked to an atmospheric blocking event.

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Key words: Last two millennia, Mediterranean Basin, Oxygen stable isotope, Marine records, Climate changes.

Riassunto: Lirer F., Margaritelli G., Alberico I., Bonomo S., Capotondi L., Cascella A., Di Rita F., Ferraro L., Insinga D.D., Magri D., Pelosi N., Petrosino P. & Vallefuoco M., *La variabilità climatica durante gli ultimi due millenni nell'area del Mediterraneo: una revisione da archivi fossili marini.* (IT ISSN 0391-9838, 2019).

Una ricostruzione dettagliata delle oscillazioni climatiche riconosciute negli ultimi 2000 anni viene proposta tramite confronto di dati sugli isotopi stabili dell'ossigeno misurati sul foraminifero planctonico *Globigerinoides ruber* in diverse aree del Bacino del Mediterraneo (Bacino di Minorca, Mar Tirreno centrale e meridionale, Golfo di Taranto, Mar Adriatico Meridionale e Israele). Questa correlazione mostra che gli eventi climatici riconosciuti sono abbastanza sincroni e ben documentati nei vari settori del Bacino del Mediterraneo, indicando una risposta omogenea del sistema marino alle oscillazioni climatiche. Questo quadro di sintesi mostra che la caduta dell'Impero Romano d'Occidente coincide con l'evento freddo associato al minimo dell'attività solare Roman III e che il successivo minimo dell'attività solare Roman IV (Alto Medioevo) marca l'inizio di un lungo periodo di raffreddamento che dura circa 1100 anni e che termina durante il minimo solare del Maunder (Piccola Età Glaciale). Inoltre, durante la fase fredda del Maunder, il forte aumento in abbondanza del foraminifero planctonico *Globorotalia truncatulinoides*, suggerisce lo stabilizzarsi di un *mixing* verticale della colonna d'acqua durante il periodo invernale. Il perdurare di queste condizioni oceanografiche durante il Maunder è stato messo in relazione a eventi di "blocking" atmosferico che hanno innescato venti forti verso il Mediterraneo che possono aver attivato il *mixing* invernale delle acque.

Termini chiave: Ultimi due millenni, Bacino del Mediterraneo, Isotopi stabili dell'ossigeno, Record marini, Cambiamenti climatici.

INTRODUCTION

The climatic changes of last millennia have been played an important role in the organization of civilization on all sides of the Mediterranean (Holmgren & *alii*, 2016; Sadori & *alii*, 2016; Büntgen & *alii*, 2016), as human societies have been living adapting to a variable climate and environment (Holmgren & *alii*, 2016). Therefore, climate reconstructions at sub-decadal resolution are important to determine natural climate variability and contribute to the understanding of the human influence on climate (Jones & *alii*, 2009; Berkelhammer & *alii*, 2010; Macias Fauria & *alii*, 2010).

For a better prediction and understanding of possible future climate evolution, it is essential to know mechanisms, causes, and amplitude of natural climate variability. Paleoclimate investigations facilitates understanding of Earth system feedbacks on time scales longer than a few centuries, which cannot be evaluated from short instrumental records [Intergovernmental Panel on Climate Change (IPCC) 2013]. In particular, the analysis of climate data of the past is an essential tool for studying the dynamics of the Earth's climatic system in conditions different from present ones, and irreplaceable for testing the validity of medium- and long-term forecasting models.

As previously reported in the IPCC report 2007 and recently stated by McGregor & *alii* (2015), the last two millennia represent an important time interval for testing the past climate oscillations and for the determination of the reliability of medium and long term prediction models.

The study of the last two millennia allows comparison of data from historical documents, instrumental and paleodata records with multi-decadal-to-centennial variability arising from external forcing and internal climate variability (IPCC, 2013 and 2014). Previous studies have documented the occurrence of significant climate oscillations with different amplitude and duration that played an important role in social reorganization in Europe (Abrantes & *alii*, 2005; Holzhauser & *alii*, 2005; Lebreiro & *alii*, 2006; Griggs & *alii*, 2007; Martín-Puertas & *alii*, 2008; Kaufman & *alii*, 2009; Büntgen & *alii*, 2011, 2016; Kobashi & *alii*, 2011; Nieto-Moreno & *alii*, 2011, 2013b; Morellón & *alii*, 2012; Moreno & *alii*, 2012; Wassenburg & *alii*, 2013; Esper & *alii*, 2014; McGregor & *alii*, 2015; Gogou & *alii*, 2016; Margaritelli & *alii*, 2018).

In this framework, the Mediterranean area is considered one of the climatically highly sensitive regions (hotspots) to global change (Giorgi, 2006) due to its paleo-latitudinal and land locked configuration. Additionally, it is an ideal archive to investigate paleoclimate changes at secular scale thanks to the high-sedimentation rate of their marine deposit (i.e., Oldfield & *alii*, 2003; Martrat & *alii*, 2004; Taricco & *alii*, 2009, 2015; Nieto-Moreno & *alii*, 2011; Moreno & *alii*, 2012; Cisneros & *alii*, 2016; Sicre & *alii*, 2016; Jalali & *alii*, 2018; Margaritelli & *alii*, 2016, 2018).

In the Mediterranean area, the effects of the climate change, likely enhanced by human activities (Rohling & Bryden, 1992), are rapidly (within decades) transferred to the deep sea via an effective thermohaline circulation (Béthoux & *alii*, 1990, 1998; Roether & *alii*, 1996; Skliris & *alii*, 2007), pointing to the exceptional sensitivity of the coupled ocean and atmosphere dynamics to combined anthropogenic and natural climate forcing in the region.

This paper is focused on a review of data about the climatic variability over the last two millennia in the Mediterranean area through the oxygen stable isotopic records ($\delta^{18}O$) of different areas. The $\delta^{18}O$ of foraminiferal calcite, controlled by temperature-dependent isotopic fractionation between water and calcite and by the isotopic composition of seawater, represents a valid tool to reconstruct oscillation in Mediterranean past climate regime (i.e., Capotondi & *alii*, 1999; Margaritelli & *alii*, 2016, 2018)

The goal is to verify the synchronicity of the climate phases and to provide an overall picture of the climate changes in the Mediterranean region. We present updated oxygen stable isotope ($\delta^{18}O_{G.\ ruber}$ records) based correlations involving different Mediterranean sites which record the last ca. 2000 years of CE (Common Era), previously proposed by Margaritelli & *alii* (2018).

In addition, we focus on the the Little Ice Age time interval using the planktonic foraminifer *Globorotalia truncatulinoides* an dwelling planktonic foraminifera used to track the upper ocean thermal structure in the past (Reynolds & *alii*, 2018).

STUDY AREA

The Mediterranean Sea

The Mediterranean represents an excellent "natural laboratory" where the effect of the climate changes can be studied in conveniently-reduced spatial scales and with a better signal to noise ratio than may be expected in the open ocean (Rohling, 2001). Due to its geographic location, the Mediterranean Basin is influenced by both the mid-latitude westerly winds and the subtropical high-pressure belt over northern Africa. Its complex orography exert a strong control on ocean and atmospheric circulation resulting in high spatial variability and mesoscale features.

It is a semi-enclosed sea divided by the Sicily Channel in two main geographical basins: i.e the Eastern and Western Mediterranean. In more detail, several satellite basins may be distinguished such as the Alboran, Balearic, Ligurian, Tyrrhenian, Adriatic, Ionian and Aegean seas. The only connection with the open North Atlantic Ocean is represented by the relatively narrow Straits of Gibraltar.

The Mediterranean circulation is driven by water exchange through the various straits, wind stress, and thermohaline fluxes, with the latter depending on the basin's freshwater and heat budgets (Robinson & *alii*, 2001). The vertical distribution of the Mediterranean water masses includes the surface waters (0-200 m), the intermediate waters (200-600 m), and the deep waters (>600 m) (Tsimplis & *alii*, 2005; Pinardi & *alii*, 2015).

The sites examined in this work are located in five different areas (Menorca basin, central and southern Tyrrhenian Sea, Taranto Gulf, south Adriatic Sea and Israel) to provide an overall picture of the climate changes in the Mediterranean region (fig. 1).

MATERIAL AND METHODS

Oxygen stable isotopes

In this review we have used published stable isotope records measured on the planktonic foraminifer *Globigerinoides ruber* white variety and they are as follows: i) Menor-

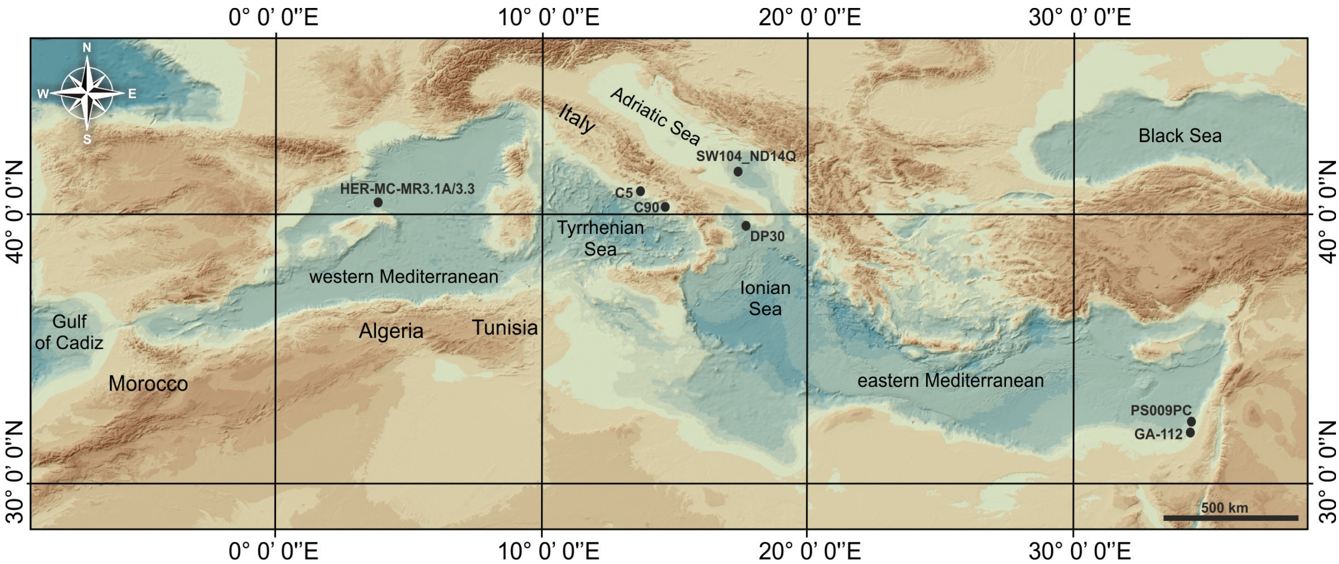

FIG. 1 - Maps of the Mediterranean Sea with the location of the sites. HER-MC-MR3.1A/3.3 (Margaritelli & *alii*, 2018), C5 (Margaritelli & *alii*, 2016), C90 (Lirer & *alii*, 2013, 2014), DP30 (Grauel & *alii*, 2013), SW104_ND14Q (this study), PS009PC (Hennenkam & *alii*, 2014) and GA-112 (Schilman & *alii*, 2001).

ca basin (core HER-MC-MR3.1A/3.3, Margaritelli & *alii*, 2018); ii) central (core C5, Margaritelli & *alii*, 2016) and south Tyrrhenian Sea (core C90, Lirer & *alii*, 2013, 2014), Taranto Gulf (core DP30, Grauel & *alii*, 2013), south Adriatic Sea (core SW104_ND14Q, this work) and Israel (core GA-112, Schilman & *alii*, 2001; core PS009PC, Hennekam & *alii*, 2014) (fig. 1).

The oxygen isotope analyses on the sediment core SW104_ND14Q (south Adriatic Sea; fig. 1) are proposed for the first time herein. Ten specimens of *G. ruber* white variety from size fraction >125 micron were picked and the analyses were performed with an automated continuous flow carbonate preparation Gas BenchII device (Spötl & Vennemann, 2003) and a ThermoElectron Delta Plus XP mass spectrometer, at the ISMAR-CNR (Naples, Italy). Acidification of samples was performed at 50 °C and calibration to Vienna Pee Dee Belemnite (VPDB) was carried out following NBS-19 international standard (Coplen, 1996). Standard deviations of carbon and oxygen isotope measures were estimated at +0.1 ‰.

RESULTS AND DISCUSSION

Climate variability over the last millennia in the Mediterranean area

Over the last two millennia, the Mediterranean Sea has been characterized by an alternation of humid/dry and cold/warm periods often globally recognizable (i.e., Moreno & *alii*, 2012; Nieto Moreno & *alii*, 2013; Lirer & *alii*, 2013, 2014; Cisneros & *alii*, 2016; Margaritelli & *alii*, 2016, 2018; Di Rita & *alii*, 2018, 2018a; Gogou & *alii*, 2016; Jalali & *alii*, 2016, 2017, 2018; Sicre & *alii*, 2016; Incarbona & *alii*, 2019).

The most significant changes observed in the fossils archives, chronologically well correlate to the historical climatic phases reported in literature, corresponding to the major cultural and social reorganization of the Mediterranean region. This correspondence suggests a consequent possible anthropogenic impact on marine ecosystems (i.e., Nieto-Moreno & *alii*, 2011, 2013a, 2013b; Moreno & *alii*, 2012; Lirer & *alii*, 2013, 2014; Margaritelli & *alii*, 2016, 2018). However, it is worth noting the discrepancy, over the last two millennia, concerning the chronology of the climate phases (see Margaritelli & *alii*, 2016).

In fact, local overprint, related to the continental river input, the not homogeneous response and sensitivity of the biotic and abiotic proxies amongst the various basins, could have affect the chronology of the identified climatic phases. In particular, the identified climate phases over the last two millennia and the related ages (CE/BCE) are reported in tab. 1 as follows: pre Roman Period, Roman Period, Dark Age, Medieval Climate Anomaly (MCA), Little Ice Age (LIA), Industrial Period and Modern Warm Period.

Notwithstanding differences in resolution and age models, the sea surface Mediterranean $\delta^{18}O$ signals, over the last two millennia, documented an almost synchronicity (fig. 2). It is interesting to note that the comparison of the marine signals with north European continental ones (Ljungqvist, 2010), shows a similar climate evolution (fig. 2).

Roman Period

The Roman Period, chronologically associated with the Roman Empire, covers the time interval from ca. 1 CE to ca. 500 CE (fig. 2). The extended warming phase of this period, probably favorable for the prosperity and expansion of the civilizations (McCormick & *alii*, 2012), is well documented in the Sea Surface Temperature (SST) reconstruction in the Alboran Sea (SST-alkenones, Rodrigo-Gamiz & *alii*, 2014), in the Minorca basin (SST- Mg/Ca *G. bulloides*, Cisneros & *alii*, 2016) and in the eastern Mediterraanean (SST-alkenones, Kontakiotis, 2016).

TAB 1. Table with ages and nomenclature of the climatic events documented in marine Mediterranean records for the last two millennia compared with the archaeological periods reported by Roberts & *alii* (2011). The acronym LBA corresponds to Late Bronze Age.

Nieto Moreno & *alii* (2011)		Nieto Moreno & *alii* (2012)		Margaritelli & *alii* (2018)		Jalali & *alii* (2018)		Margaritelli & *alii* (2016)		Lirer & *alii* (2014)	
west Algerian-Balearic basin		western Alborean Sea		Micorca basin		Gulf of Lion		central Tyrrhenian Sea		south Tyrrhenian Sea	
Climatic phase	*Ages*	*Climatic phase*	*Ages*	*Climatic phase*	*Ages*	*Climatic phase*	*Ages*	*Climatic phase*	*Ages*	*Climatic phase*	*Ages*
								Modern Warm Period	upwards - 1950 CE	Modern Warm Period	1940 CE - upwards
		Industrial Period	1800 CE - upwards	Industrial Period	top core - 1850 CE	Industrial Period	upwards - 1850 CE	Industrial Period	1950 CE - 1850 CE	Industrial Period	1940 CE - 1850 CE
Little Ice Age	1800 CE - 1300 CE	Little Ice Age	1800 CE - 1300 CE	Little Ice Age	1850 CE - 1200 CE	Little Ice Age	1850 CE - 1400 CE	Little Ice Age	1850 CE - 1250 CE	Little Ice Age	1850 CE - 1240 CE
Medieval Classic Anomaly	1300 CE - 800 CE	Medieval Classic Anomaly	1300 CE - 800 CE	Medieval Climate Anomaly	1200 CE - 850 CE	Medieval Climate Anomaly	1400 CE - 900 CE	Medieval Climate Anomaly	1250 CE - 860 CE	Medieval Classic Anomaly	1240 CE - 840 CE
Dark Age	800 CE - 350 CE	Dark Age	800 CE - 300 CE	Dark Age	850 CE - 500 CE	Dark Age Cold Period	850 CE - 200 CE	Dark Age	860 CE - 550 CE	Dark Age	840 CE - 530 CE
Roman Humid Period	350 CE- 650 BCE	Roman Humid Period	300 CE - 650 BCE	Roman Period	500 CE - 50 BCE	Roman period	200 CE - 500 BCE	Roman period	550 CE - 500 BCE	Roman period	top - 530 CE
LBA/ Iron Age	650 BCE - 1650 BCE			Balearic Bronze Age	50 BCE - base core	Late Bronze Age	500 BCE-				

Grauel & *alii* (2013)		Goudeau & *alii* (2015)		Piva & *alii* (2008)		Gogou & *alii* (2016)		Roberts & *alii* (2011)	
Ionian Sea		Ionian Sea		Adriatic Sea		Aegean Sea		Italy	
Climatic phase	*Ages*	*Climatic phase*	*Ages*	*Climatic phase*	*Ages*	*Climatic phase*	*Ages*	*Archaeological Period*	*Ages*
		Present	1904 CE - 1958 CE						
Little Ice Age	1850 CE - 1400 CE	Little Ice Age	1850 CE - 1400 CE	Little Ice Age	1840 CE - 1400 CE	Little Ice Age	1850 CE- 1300 CE		
Medieval Warm Period	1200 CE - 800 CE	Medieval Classic Anomaly	1200 CE - 800 CE	Medieval Warm Period	1200 CE - 600 CE	Medieval Warm Period	1300 CE - 900 CE		
Dark Age	750 CE - 500 CE			Dark Age	600 CE - 350 CE	Dark Age	900 CE - 500 CE		
Roman Warm Period	200 CE - 1 CE	Roman Humid Period	0 CE - 450 BC	Roman Warm Period	350 CE - 100 BCE	Roman Warm Period	500 CE - 0 CE	Roman Period	top - ca. 500 BCE
		Bronze Age	500 BCE - 1500 BCE	Iron Age	ca. 100 BCE - 1500 BCE			Greek - Etrurian	ca. 500 BCE - 750 BCE

The oxygen isotopic variability of *G. ruber* (white) shows that the Roman Period is puctuated by three short term cooling events (fig. 2) which chronologycally correspond to solar minima activity (Lirer & *alii*, 2014; Margaritelli & *alii*, 2016, 2018). In particular, the Roman III cold event approximates the 476 CE when the fall of Western Roman Empire is hystorically documented. This cold event was characterized by dry conditions, as likely documented by the reduction of arboreal pollen, and chronologically spanned the well-known Migration Period (fig. 2). In addition, this cold and dry event fits with a northern hemisphere continental temperature negative anomaly (Ljungqvist, 2010) revealing a possible connection between continental and marine climatic signature (fig. 2).

The fall of the Roman Empire was associated to the collapse of the agricultural-food production due to the unfavourable climtic conditions and the barbarian invasions, which led the population to leave the country towards new areas of subsistence (Behringer, 2009).

Dark Age

After the fall of the Roman Empire, heavy values in $\delta^{18}O_{G.\ ruber}$ records document ameliorate regional climate conditions at the base of the Dark Age (ca. 550 to 700 CE). This climate phase, corresponding to the wetter phase documented by Sadori & *alii* (2016) in lake sediment of Sicily, results almost coeval with the Justinian Plague (541-749 CE). Afterwards, according to Margaritelli & *alii* (2018), a prominent cooling event in the upper part of Dark Age is also documented in the continental records from north Europe (Ljungqvist, 2010). It corresponds to the Roman IV

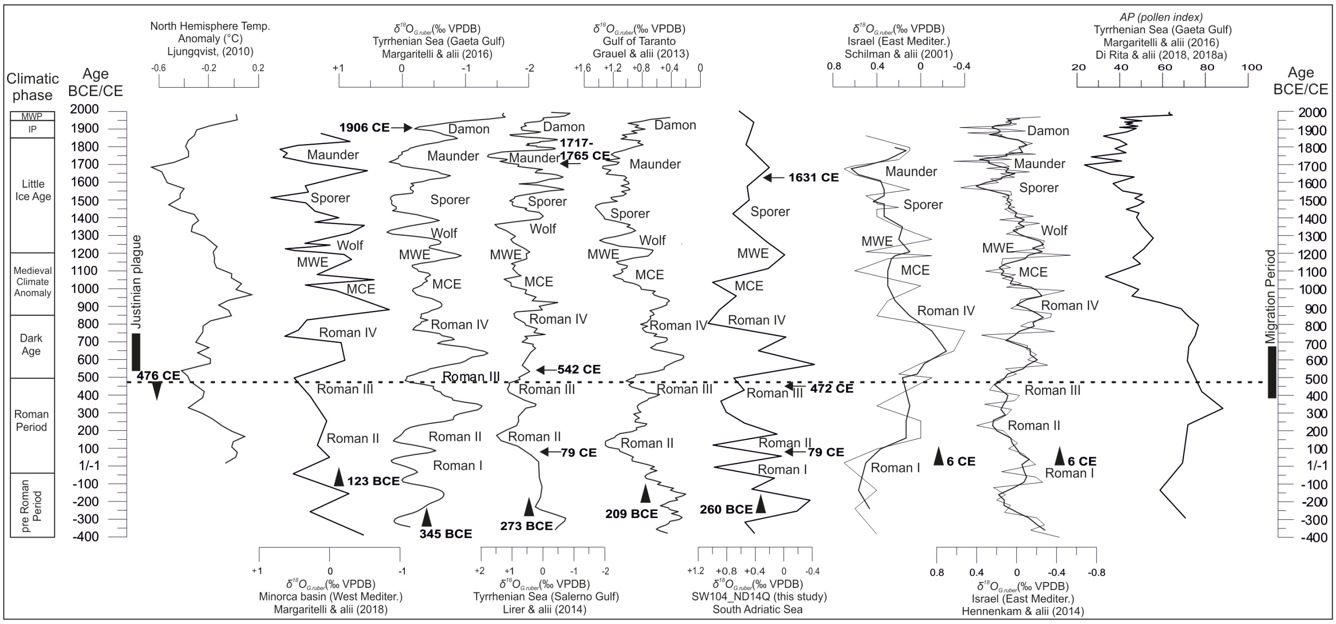

FIG. 2 - Comparison in time domain between North Hemisphere mean temperatures reconstruction from Ljungqvist (2010), $\delta^{18}O_{G. ruber}$ (‰VPDB) of Minorca Basin (Margaritelli & *alii*, 2018), $\delta^{18}O_{G. ruber}$ (‰VPDB) of Gaeta Gulf (central Tyrrhenian Sea, Margaritelli & *alii*, 2016), $\delta^{18}O_{G. ruber}$ (‰VPDB) of Salerno Gulf (south Tyrrhenian Sea, Lirer & *alii*, 2013, 2014); $\delta^{18}O_{G. ruber}$ (‰ VPDB) of Taranto Gulf (Grauel & *alii*, 2013), $\delta^{18}O_{G. ruber}$ (‰ VPDB) of south Adriatic Sea (core SW104_ND14Q, this study), $\delta^{18}O_{G. ruber}$ (‰ VPDB) of Israel (Schilman & *alii*, 2001; Hennenkam & *alii*, 2014), AP (alborean pollen index, Margaritelli & *alii*, 2016; Di Rita & *alii*, 2018, 2018a). The acronym MWE corresponds to Medieval Warm Event, and MCE to Medieval Cold Event. The black vertical arrows with ages represent the ages when this areas becomes part of the Roman Empire. The horizontal arrows represent the position of tephra layers with relative ages (yr CE). The dotted line represents the end of Roman Empire. The black vertical bars represent the Justinian Plague and the Migration Period.

solar minimum and marks the beginning of a long term cooling trend (spanning ca. the following 1100 yrs) that culminates during the Little Ice Age (fig. 2). This pattern is also visible in the progressive arboreal pollen decrease (fig. 2).

Medieval Climate Anomaly

Medieval Climate Anomaly (MCA) is a time interval of natural pre-industrial climate change connected with marked temperature and hydroclimatic variability (i.e, see for details Lüning & *alii*, 2019). The MCA represents the most recent natural warm phase that was characterized by rather temperate (Schilman & *alii*, 2001; Grauel & *alii*, 2013; Lirer & *alii*, 2014; McGregor & *alii*, 2015; Büntgen & *alii*, 2016; Cisneros & *alii*, 2016; Margaritelli & *alii*, 2016, 2018) and probably arid (i.e., Moreno & *alii*, 2012; Morellon & *alii*, 2012) climate conditions. The strong decrease in arboreal pollen (fig. 2), documented in the central Mediterranean as well as in the whole central-southern Mediterranean area, confirms the arid condition at the beginning of the MCA (Di Rita & *alii*, 2018a).

Heavy values in $\delta^{18}O_{G. ruber}$ Mediterranean records, detected in the lower part of the MCA, result almost in phase with the northern Hemisphere positive temperature anomalies (fig. 2), confirming the amelioration of the regional scale climate condition. Between ca. 1050-1100 CE, Margaritelli & *alii* (2016, 2018) documented a short-term cold dry event (MCE - Medieval Cold Event) in the $\delta^{18}O_{G. ruber}$ Mediterranean records, also characterised by a decrease in arboreal vegetation (Moreno & *alii*, 2012; Margaritelli & *alii*, 2016; Di Rita & *alii*, 2018, 2018a) and suggesting more arid climate conditions. The MCA ends with a short-term warm event (MWE - Medieval Warm Event) between ca. 1150 and 1200 CE (fig. 2).

In terms of social and cultural reorganization, the MCA period corresponded to a climate optimum of many Mediterranean cultures. During the twelfth century, the medieval Byzantine Empire had an important social expansion, with significant agricultural productivity, severe monetary exchange, demographic growth, and its preminent international political dominance (Xoplaki & *alii*, 2015).

Little Ice Age

The transition between MCA and LIA (Little Ice Age), ca. 1200-1250 CE, chronologically corresponds to the last global scale Rapid Climate Change (RCC) of Mayewski & *alii* (2004), when the last onset of alpine glacier advance is documented (Holzhauser & *alii*, 2005).

The establishment of cooling conditions in the regional climate system from ca. 1200 CE upwards, characterized the entire LIA time interval as documented in northern Hemisphere temperature anomalies (PAGES 2K Consortium, 2013), in Mediterranean SST temperature reconstructions (Grauel & *alii*, 2013; Rodrigo-Gamiz & *alii*, 2014; Cisneros & *alii*, 2016) and in abrupt oscillation in Mediterranean $\delta^{18}O_{G. ruber}$ records (figs 2, 3). In particular, four climatic oscillations chronologically related to minima in solar activity (Wolf, Spörer, Maunder, and Dalton

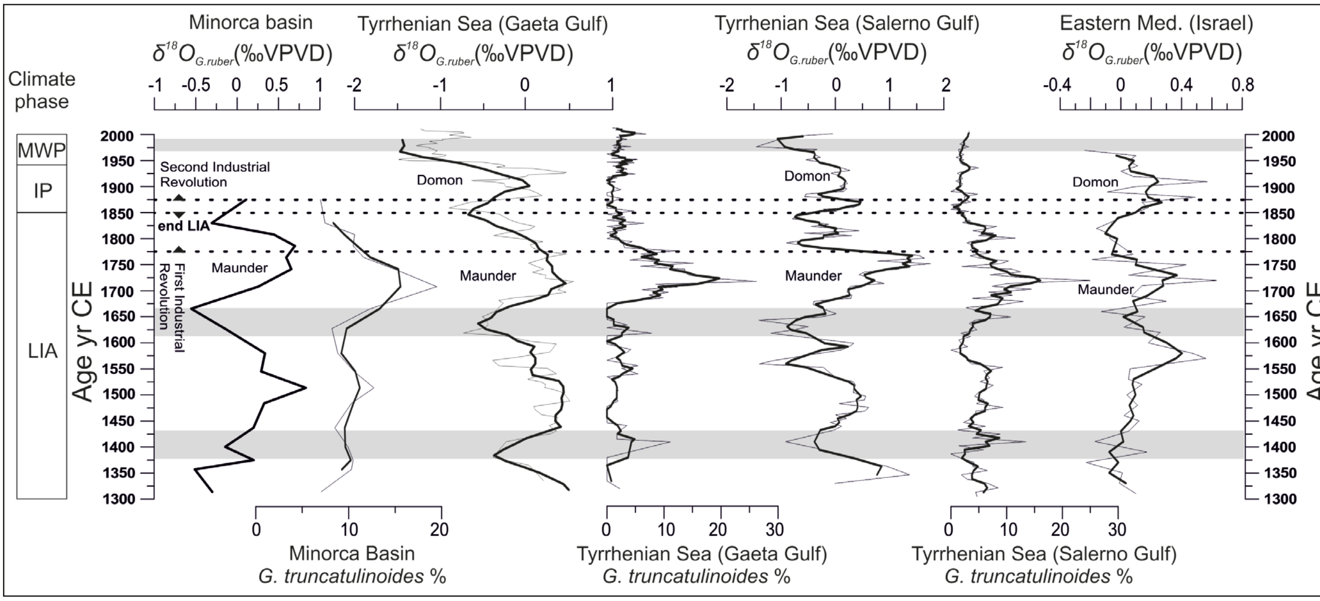

FIG. 3 - Comparison over the last 1300 yr CE between $\delta^{18}O_{G.\ ruber}$ (‰ VPDB) and *G. truncatulinoides* left coiled (%) of Minorca Basin (Margaritelli & *alii*, 2018), Gaeta Gulf (central Tyrrhenian Sea, Margaritelli & *alii*, 2016) and Salerno Gulf (south Tyrrhenian Sea, Lirer & *alii*, 2014). For comparison, we also plot the $\delta^{18}O_{G.\ ruber}$ (‰ VPDB) record from Israel (Hennenkam & *alii*, 2014). Thick black curves are 3-point moving average. Grey bands are prominent warm oscillation is documented in $\delta^{18}O_{G.\ ruber}$ Mediterranean signals.

cold events) have been indentified in the prominent heavy values of Mediterranean $\delta^{18}O_{G.\ ruber}$ records (Lirer & *alii*, 2014; Margaritelli & *alii*, 2016, 2018) (figs 2, 3). 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 the literature (Lirer & *alii*, 2014; Taricco & *alii*, 2015; Margaritelli & *alii*, 2016, 2018). In addition, according to Di Rita & *alii* (2018, 2018a), the prominent decline in the forest cover during the Maunder event confirms a cold and dry climate condition at a regional scale, as aslo documented in the eastern Mediterranean basin by Kaniewski and Van Campo (2014).

The cooling climate phases are bounded by short-term warm oscillations. The most prominent warm oscillation is documented in $\delta^{18}O_{G.\ ruber}$ Mediterranean signals, just before the onset of the Maunder event, which occurred between 1614 and 1660 CE (fig. 3) and is well documented in the European summer temperatures reconstructed (Luterbacher & *alii*, 2016). Recently, Cascella & *alii* (2020) documented through the LIA interval, in the Thyrrenian and South Adriatic seas, a strong increase of reworked coccolith abundances, which are considered a reliable proxy index of past runoff/precipitation changes in the region (Bonomo & *alii*, 2016).

During the Maunder event, the planktonic foraminiferal assemblages from western Mediterranean [Minorca basin, (Margaritelli & *alii*, 2018), central (Margaritelli & *alii*, 2016) and southern Tyrrhenian Sea (Lirer & *alii*, 2014), and in the Sicily Channel (not reported in the figure and see for details Incarbona & *alii*, 2019)] document a strong abundance increase of the planktonic foraminifer *Globlorotalia truncatulinoides* (fig. 3), while this species is absent in the south Adriatic Sea (Oldfield & *alii*, 2003), Gulf of Taranto (Di Donato & *alii*, 2019) and in the eastern Mediterranean (Mojtahid & *alii*, 2015). This geographical distribution suggests that this species prolifers during the Maunder only in the central and western Mediterranean basin. *G. truncatulinoides* migrates from deep water masses to the pycnocline for reproduction during the beginning of the spring and then, the new generation descends to deep waters where it spends most of its life span (Hemleben & *alii*, 1985; Schiebel & Hemleben, 2005; Schiebel & *alii*, 2002). This explain the elevated fluxes of *G. truncatulinoides* during the winter-spring transition in the Gulf of Lion (Rigual-Hernández & *alii*, 2012). These ecological features suggest that the high abundance percentage of this species is linked to deep water turbulent mixing and vertical mixing during the winter season. Margaritelli & *alii* (2016) explained the strong increase in abundance of *G. truncatulinoides* during the Maunder with the presence of a deep water mixing induced by strong winds linked to an atmospheric blocking event. Strong continental northeasterly winds over the western Europe and Mediterranean region are also inferred by Sicre & *alii* (2016) from Gulf of Lion, suggesting the connection of cold sea surface temperature of the LIA with prevailing negative East Atlantic pattern (EA) states and associated anticyclone blocking over the North Atlantic. Furthermore, Josey & *alii* (2011) suggest a major effect of the EA respect to the North Atlantic Oscillation (NAO) in the eastern and western Mediterranean Basin.

Similarly, the changes observed in planktonic foraminiferal assemblage (Margaritelli & *alii*, 2016) as well as in the pollen composition (Di Rita & *alii*, 2018; 2018a) were related to the weak NAO index associated with Atlantic Blocking event during the late part of Maunder cold event (Barriopedro & *alii*, 2008).

FIG. 4 - Paintings of winter landscapes in Europe
1) Pieter Bruegel the Elder, Winter Landscape with a Bird-trap, ca. 1601. Image via Wikimedia Commons (https://commons.wikimedia.org/wiki/File:Circle_of_Pieter_Bruegel_the_Elder_-_Winter_Landscape_with_a_Bird_Trap.jpg);
2) Avercamp 1608 (https://en.wikipedia.org/wiki/Hendrick_Avercamp#/media/File:Hendrick_Avercamp_-_Winterlandschap_met_ijsvermaak.jpg)
3) Two Etchings by V. Coronelli of the Lagoon frozen over, Coronelli, 1708 [More Veneto, i.e. 1709 A.D.]. View towards Murano (above); View towards Mestre (below). Libray of the Correr Museum, Venice. Images from Camuffo & *alii* (2017).

Later 1800 CE, *G. truncatulinoides* occurs with very low abundances, suggesting the end of particular oceanographic features.

The particular climatic conditions of the Maunder minimum had several feedbacks. For example Burkle & Grissino-Mayer (2003) suggest that during Stradivari's latter decades, he used spruce wood that had grown mostly during the Maunder Minimum. In fact, the true explanation for their superior sound likely lies in the type of wood these instruments are made of. Burkle & Grissino-Mayer (2003) hypothesize that the longer winters and cooler summers produced slow, even tree growth, with desirable properties for producing higher-quality sounding boards.

In addition, numerous paintings of winter landscapes in Europe (i.e., Brueghel, 1601; Avercamp, 1608) and of freezing of Venice Lagoon occurred between 1700 and 1850 (Camuffo & Enzi, 1995) show these persistent cold climate condition during LIA (fig. 4).

Industrial Period and Modern Warm Period

Following the LIA, at 1850 CE, $\delta^{18}O_{G.\ ruber}$ data show a further cooling event, between 1870 and 1930 CE, chronologically associated to Damon solar minimum (figs 2, 3). The onset of this cooling event fits with the second Industrial revolution period.

Later 1945 CE, a progressive trend *vs* $\delta^{18}O_{G.\ ruber}$ light values suggests an inversion in regional scale climate *vs* warm condition (Grauel & *alii*, 2013; Lirer & *alii*, 2014; Hennenkam & *alii*, 2014; Margaritelli & *alii*, 2016). This warming trend (fig. 3) is also confirmed in Sea Surface Temperature reconstruction from Alboran Sea (Nieto-Moreno & *alii*, 2013), Minorca Basin (Cisneros & *alii*, 2016), Gulf of Lion (Sicre & *alii*, 2016), Taranto Gulf (Versteegh & *alii*, 2007; Grauel & *alii*, 2013) and Aegean Sea (Gogou & *alii*, 2016).

CONCLUSIONS

Based on *G. ruber* (white) oxygen stable isotope record from different basins of the Mediterranean Sea, we provide a reconstruction of the climatic variability over the last two millennia. Although some discrepancies related to local chronologies, the almost synchronicity of the identified short term events, suggest an homogeneous response of the marine system to climate oscillations.

The collapse of the Western Roman Empire results associated with the cold and dry phase, related to Roman III solar minimum and it is almost coincident with the Justinian Plague. The Dark Age, and in particular the Roman IV solar minimum, represents the transition *vs* a long term cooling trend, spanning ca. 1100 yrs, that culminates during the Maunder solar minimum. During the Maunder cold event, the planktic foraminiferal assemblages occurring in the western Mediterranean Sea is characterised by the strong increase in abundance of the planktonic foraminifer *Globlorotalia truncatulinoides*, suggesting the establishment of vertical mixing during the winter season. These oceanographic features may be induced by an Atmospheric blocking event. From 1945 to 1995 CE, $\delta^{18}O_{G.\ ruber}$ data document the onset of a warm phase.

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