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CLIMATE VARIABILITY THROUGH MIS 20-MIS 19 IN CORE KC01B, IONIAN BASIN (CENTRAL MEDITERRANEAN SEA)

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ABSTRACT: High resolution quantitative analyses have been carried out on coccolithophore assemblages at the Ionian Sea core KC01B in the time interval crossing the deglaciation between Marine Isotope Stages 20 and 19 (Termination IX, in Lower-Middle Pleistocene). Principal Component Analysis emphasizes the temperature as the first environmental parameter affecting coccolithophore assemblages that reach a higher number of coccoliths per gram of sediment during the interglacial. Patterns of key taxa indicate the occurrence of a terminal stadial phase in the late MIS 20 when the presence of cold, turbid and low salinity surface waters in the Ionian Sea are highlighted by prominent peaks of *Coccolithus pelagicus* ssp. *pelagicus*, *Gephyrocapsa muellerae* >3 μm, and increased abundances of *Syracosphaera* spp., *Helicosphaera carteri*, *Rhabdosphaera* spp. Enhanced reworked coccoliths and lithic elements are recorded in the samples during this phase, and they represent an useful tool to monitoring the amount of detrital input supply during low sea-level and major erosion process on land. Short-term warm and cool events through TIX are evidenced by the fluctuations of all these proxies anticipating the interglacial onset. The latter is marked by distinct surface water conditions suggesting the occurrence of an interval correlated to a sapropelic layer, and specifically to i-cycle 74. The comparison of these short-lived events with the climate pattern recently observed in the nearby Montalbano Jonico succession points to a shared Ionian Sea climatic and oceanographic pattern through TIX and allows to sustain a similar climate evolution recorded during the last deglaciation.

Keywords: coccolithophores; Termination IX; Sapropel i-cycle 74; Lower-Middle Pleistocene.

1. INTRODUCTION

Marine isotope stage (MIS) 19 (Lower-Middle Pleistocene) has been recently studied in high temporal resolution through different proxies since it represents the best analogous of Holocene and the finest past interglacial to forecast future climate trend (e.g. Tzedakis et al., 2012; Ferretti et al., 2015; Giaccio et al., 2015; Sánchez-Goñi et al., 2016; Nomade et al., 2019; Regattieri et al., 2019). Minor attention has been devoted to deglaciation MIS 20-MIS 19 (Termination IX, TIX) except for some studies (Emanuele et al., 2015; Marino et al., 2015; Maiorano et al., 2016a; Nomade et al., 2019). In particular, Maiorano et al. (2016a), based on multiproxy analyses carried out in the Montalbano Jonico section (South Italy), recognized a high frequency climate variability that has been associated to the similar climate pattern during last deglaciation (Termination I, TI). These authors indicated the occurrence of surface water features connected to Heinrich-like (H-like) phase during late MIS 20 followed by warm Bølling-Allerød-like (B/A- like) and cool Younger Dryas-like (Y/D- like) events before the sapropelic layer (red sapropel, i-cycle 74, 784 ka) (Langereis et al., 1997; Lourens, 2004) and the onset of MIS 19. Aim of this study is to provide additional information on MIS 20-19 transition in Ionian basin utilizing as proxy, the phytoplanktonic group of the coccolithophores. Coccolithophores, are calcareous algae (Chromista), dominant marine calcifying phytoplankton and sediment component, able to record changes in the sea surface water properties, such as temperature, turbidity, nutrients, and salinity (e.g. McIntyre & Bè, 1967; Flores et al., 2000; Baumann et al., 2004; Thierstein & Young, 2004; Ziveri et al., 2004; Giraudeau & Beaufort, 2007). The studied sediments are from the core KC01B, recovered in the Ionian Sea and it has been already considered as a reference record for the last 1.1 Ma (Castradori, 1993; Sanvoisin et al., 1993; Langereis et al., 1997; Rossignol-Strick et al., 1998; Lourens, 2004; Konijnendijk et al., 2014). This record has been also used for Mediterranean sapropel stratigraphy and astronomical time scale (Lourens, 2004). In this study, high

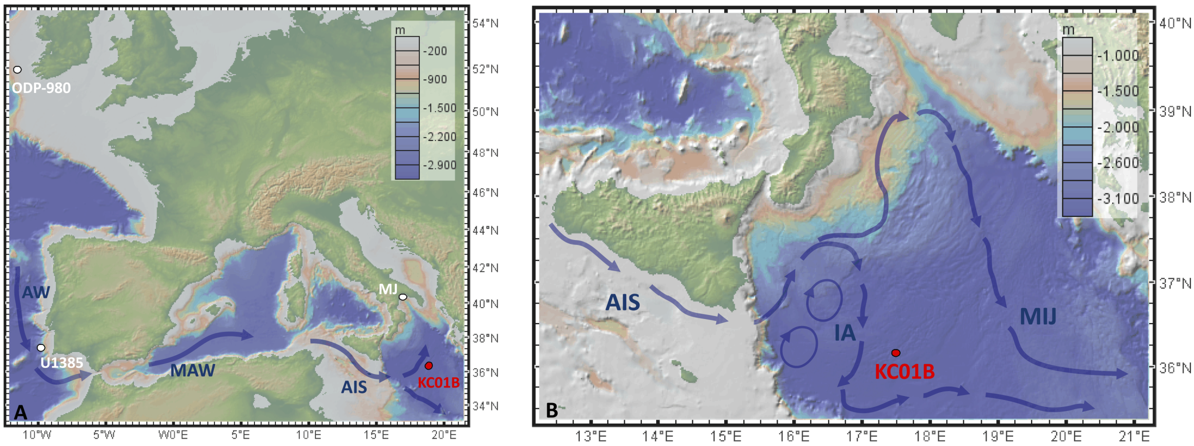


Fig. 1 - A) Location of the studied core KC01B in the Ionian Sea and other sites in Mediterranean area (MJ: Montalbano Jonico) and Atlantic Ocean (ODP 980, IODP U1385) discussed in the text. B) Detail of surface water circulation in the Ionian Sea in agreement with Malanotte-Rizzoli et al. (1997). AW= Atlantic Water; MAW=Modified Atlantic Water; AIS= Atlantic Ionian Stream; IA= Ionian Anticyclone; MIJ= Mid Ionian Jet.

resolution quantitative analyses (0.4-0.7 ka) on coccolithophore assemblages and Principal Component Analysis (PCA) have been performed in order to recognize orbital-suborbital and millennial scale paleoenvironmental variations.

A comparison with climate records from Montalbano Jonico and North Atlantic Ocean has been also performed to give insight on the knowledge of climate pattern in the Ionian basin across TIX and its relationship with North Hemisphere ice-sheet dynamics during Lower-Middle Pleistocene.

2. OCEANOGRAPHIC SETTING

The Mediterranean is a semi-enclosed marginal sea that is characterized by an anti-estuarine circulation system with the Atlantic Ocean through the Strait of Gibraltar (Bormans et al., 1986; Rohling et al., 1998; Rohling & De Rijk, 1999). The Atlantic Water (AW) enters the Mediterranean Sea and travels eastward as Modified Atlantic Water (MAW) which is restricted to a surface layer about 200 m thick (Fig. 1A). As it spreads eastward throughout the basin, it becomes saltier due to continued evaporation (Wüst, 1961; Malanotte-Rizzoli & Hecht, 1988). MAW influences the eastern basin with the Atlantic-Ionian stream jet-like current (AIS) (Malanotte-Rizzoli et al., 1997) and Mid-Ionian Jet (MIJ) through the Ionian Sea and Levantine Basin, respectively (Fig. 1B). The AIS, after having crossed the Strait of Sicily, forms a meander that continues to the north, towards the Ionian, which is influenced by its most superficial part of the MAW; then the AIS branches off and a part goes southward, creating an anticyclonic area (Ionian Anticyclone-IA), the other branch extends to the north and returns to the south, passing through the Ionian Sea (Fig. 1B) (Malanotte-Rizzoli et al., 1997). Recently, the upper-layer circulation in the Ionian Sea has been associated with the deep thermohaline circulation through the Bimodal Oscillating System: the Ionian upper-layer circulation reverses from cyclonic to anticyclonic and vice versa on decadal time scale affecting the biological productivity in the northern Ionian and southern Adriatic Sea (Civitarese et al., 2010; Gačić et al., 2010). Mediterranean Sea is characterized by oligotrophic conditions (Béthoux, 1979; Sarmiento et al., 1988). During winter there are mesotrophic conditions because of vertical mixing or coastal upwelling which bring the nutrients to the photic zone, instead, during the summer, there are oligotrophic conditions due to the thermal stratification and deepening of summer thermocline (Krom et al., 1992, 1993; Crispi et al., 1999; Allen et al., 2002; Siokou-Frangou et al., 2010).

3. MATERIAL AND METHODS

3.1. The studied core

The piston core KC01B has been recovered in the eastern Mediterranean, in the Ionian Sea, on the Calabrian ridge (Pisano plateau, 36°15,25' N, 17°44,34' E) at a depth of 3643 meters below sea level (Fig. 1A and B). Core KC01B was recovered during Cruise MD69 of the French R/N Marion Dufresne (June-July 1991), within the European Union scientific program MAST (Marflux and Palaeoflux), with the aim to reconstruct biogeochemical cycles in the Mediterranean and eastern North Atlantic.

KC01B is one of the longest piston cores ever recovered in the eastern Mediterranean, as it extends for a length of 37.04 meters. The recovery of the sediment is characterized by continuous sedimentation and good preservation, except for the uppermost part of the core (321 cm), which has been damaged due to the coring operations (Sanvoisin et al., 1993). The lithology consists of hemipelagic marls (carbonate content of about 30-50 %), with intercalation of sapropels and the presence of several thin tephra layers and few thin turbidite levels (Castradori, 1993; Sanvoisin et al., 1993; Langereis et al., 1997; Rossignol-Strick et al., 1998; Lourens, 2004). In the studied interval (from 28.86 m to 29.52 m), an oxidized sapropel ("ghost sapropel", Emeis et al., 2000) has been firstly recognized in the hemipelagic marl at the depth of 29 m by Langereis et al.

(1997) based on its rock-magnetic and geochemical properties and referred as i-cycle 74 (785 ka, Langereis et al., 1997). Then, a revised meter depth of the core has indicated the sapropelic level occurrence at 28.87 m (784 ka, Lourens, 2004; 785 ka, Konijnendijk et al., 2014).

In KC01B, sixty-seven samples, with a spacing of 1 cm, were analysed in the hemipelagic marls of section 8, between 13 and 81 cm (from 28.86 m to 29.53 m), crossing the late MIS 20-early MIS 19 interval, in agreement with the isotope stratigraphy of Rossignol-Strick et al. (1998) and Lourens (2004).

3.2. Coccolithophore analysis

Slides for coccolithophore analysis have been prepared according to Flores & Sierro (1997). This technique provides to obtain slides with coccoliths distributed homogeneously and to estimate coccolith abundance per gram of sediment (**N**) according to the formula of Flores & Sierro (1997):

$$\mathbf{N = n * R^2 * V * r^2 * g^{-1} * v^{-1}}$$

where **N** is the number of coccoliths per gram of dry sediment, **n** is the number of coccoliths counted in a random scanned area, **R** the radius of the Petri disk, **V** the volume of water added to the dry sediment in the vials, **r** the radius of the visual field used in the counting, **g** the dry sediment weigh, **v** the volume of mixture withdrawn with the micropipette.

Quantitative analyses have been performed using a polarized light microscope at 1000× magnification and abundances have been determined by counting about 500 coccoliths. This method allows to have 99% probability that a taxon is detected if its real abundance in the assemblage is at least 1% (Crow et al., 1960). During this count, the reworked taxa (Cretaceous to Neogene in age) have been counted separately together with the lithic or mineral elements >10 μm to estimate the amount of inorganic input in each sample. Because most of the assemblage consists of coccoliths of the genus *Gephyrocapsa*, the less abundant taxa, but of important ecological and paleoenvironmental significance, are not detectable in a significant percentage during the first counting. For this reason, an additional count of the less abundant species has been extended on total 30 fields of view. The quantitative abundances of coccolithophores have been expressed both as percentages and number of coccoliths per gram of sediment (N). Coccolithophore taxonomy follows Jordan et al. (2004) and Young et al. (2003) for living coccolithophores, and Maiorano et al. (2013) for the gephyrocapsid group. *Discosphaera tubifera*, *Calciosolenia* sp., *Oolithotus fragilis*, *Oolithotus antillarum*, *Umbilicosphaera sibogae* and *Umbilicosphaera foliosa* have been grouped as warm water taxa (WWT) because they are known as indicative of warm and oligotrophic waters being abundant in tropical-subtropical waters (Winter et al., 1994; Young, 1994; Ziveri et al., 1995; 2004; Andruleit et al., 2003; Baumann et al., 2004; Boeckel & Baumann, 2004; Saavedra-Pellitero et al., 2010). *Helicosphaera pavimentum* and *Calcidiscus* small (<5 μm) have been also included in the WWT. *Helicosphaera pavimentum* is described as a warm taxon found in tropical and sub-tropical areas of the Pacific Ocean and Atlantic Ocean (Okada & McIntyre, 1977; Steinmetz, 1991) and included in the WWT by Marino et al. (2018) in the middle Pleistocene record of Mediterranean Sea. *Calcidiscus* small, although rare in the study site, has been found in equatorial Atlantic waters of the southern Hemisphere, suggesting a preference for warmer waters (Boeckel & Baumann, 2008).

In order to estimate the preservation of the assemblages, the dissolution index (DI) has been calculated accordingly to Dittert et al. (1999) modified by Amore et al. (2012) as: small *Gephyrocapsa*/(small *Gephyrocapsa* + *Calcidiscus leptoporus*).This index, which compares breakable (small *Gephyrocapsa*) versus dissolution resistant placoliths (*Calcidiscus*), includes gephyrocapsids smaller than 3 μm and with open central area, thus excluding the more calcified coccoliths of small *G. caribbeanica*.

Finally, PCA has been performed on the percentage abundance of the assemblages using the software PAST (PAleontology STatistic) (Hammer et al., 2001) with the aim to clarify the relationship between coccolithophore distribution and paleoenvironmental variables. The component with maximum variance (PC1) has been discussed and interpreted in terms of paleoclimate changes through the investigated interval.

4. RESULTS

4.1. Updated chronological frame

The astronomically tuned age model proposed by Langereis et al. (1997) at the core KC01B was slightly revised by Rossignol-Strick et al. (1998) (Fig. 2) who presented the first oxygen isotope record tuned to the ice volume model of Imbrie & Imbrie (1980). Later, Lourens (2004) improved the chronological frame of planktonic oxygen isotope record of Rossignol-Strick et al. (1998) based on sapropel stratigraphy using the high-resolution color reflectance correlation with the Ocean Drilling Project (ODP) Site 964. Recently, a high-resolution benthic isotope stratigraphy (Nomade et al., 2019) has been provided in the interval from late MIS 20 to MIS 18 inception at the Montalbano Jonico on land section (Ionian basin) located not far from the KC01B core (Fig. 1A). The isotope curve of Nomade et al. (2019), together with the low resolution benthic $\delta^{18}O$ (Ciaranfi et al., 2010) and in agreement with the pattern of the LR04 (Lisiecki & Raymo, 2005), highlights a younger age of MIS 20-MIS 19 transition (TIX) with respect to that described by the Lourens's $\delta^{18}O$ chronology at the core KC01B (Fig. 2). We thus propose an updated chronology of the isotope record in the studied interval based on a visual comparison of the $\delta^{18}O$ pattern with the LR04 stacked record. We did not rely on the high resolution $\delta^{18}O$ by Nomade et al. (2019) at the Montalbano Jonico section since the latter covers a shorter time interval. Four tie-points have been selected from the LR04 record (see colored arrows in Fig. 2): the beginning of MIS 20 at 812 ka, the onset of MIS 20-19 deglaciation at 794 ka, the lightest value of $\delta^{18}O$ in MIS 19c at 780 ka, and the MIS 18 inception at 756 ka. These tie-points are critical times in the substage delineation of Railsback et al. (2015, and references therein)

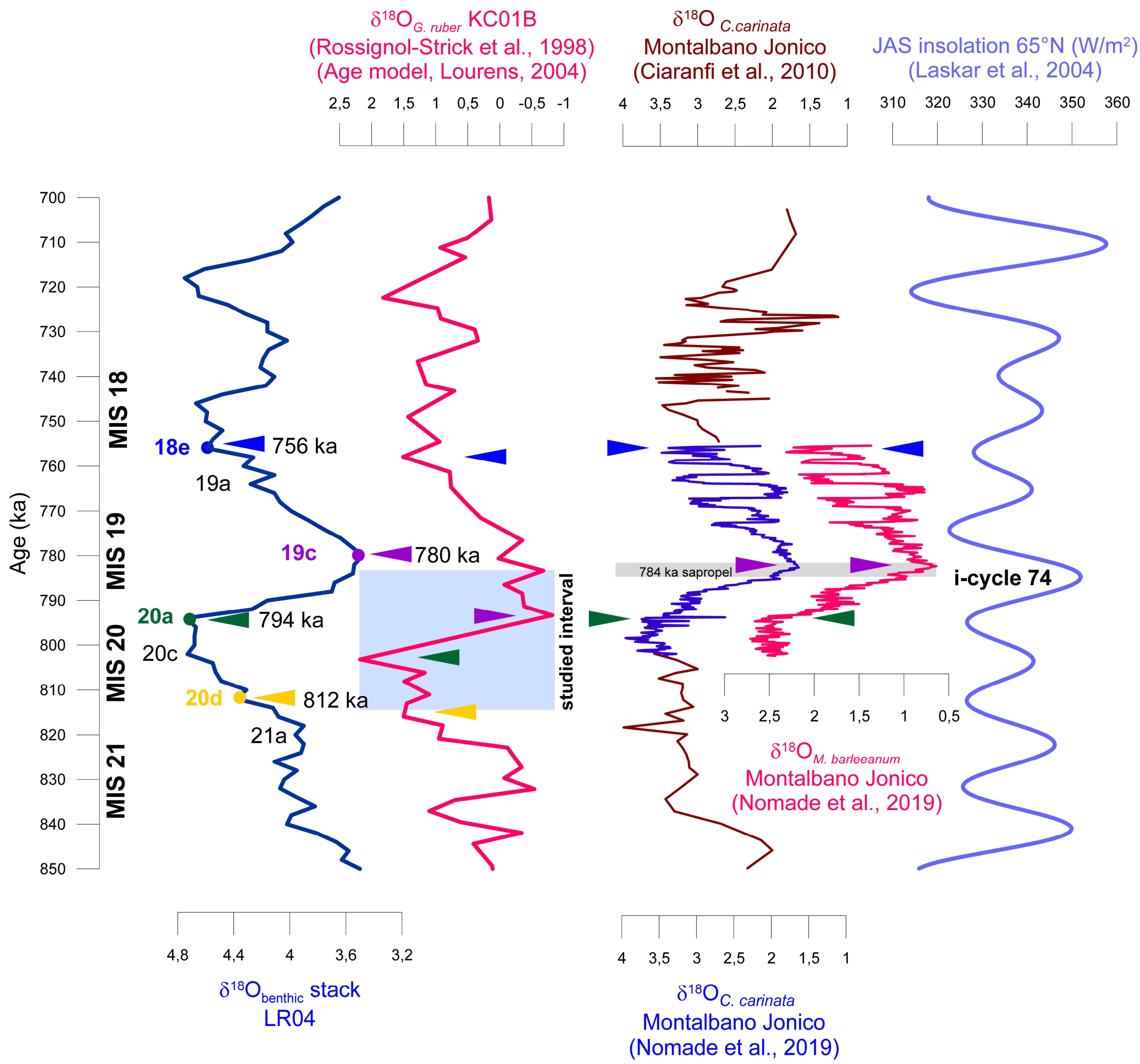


Fig. 2 - Tuning of KC01B δ^{18}O record with the benthic stacked LR04 (Lisiecki & Raymo, 2005). Colored arrows and ages on LR04 are the tie-points used for the new age model at the core KC01B and they are also shown on the high resolution Montalbano Jonico δ^{18}O records of *Cassidulina carinata* and *Melonis barleeanum* (Nomade et al., 2019). The low resolution of benthic δ^{18}O *C. carinata* at Montalbano Jonico section is also drawn (Ciaranfi et al., 2010). On the right the mean summer insolation (JAS, 65°N W/m², Laskar et al., 2004). MIS: Marine isotope stage; 18e-21a: substages according to Railsback et al. (2015); i-cycle: insolation cycle (Lourens, 2004). The shaded area represents the studied interval .

representing respectively MIS 20d, 20a, full 19c, and 18e inception (Fig. 2). These events are also recognizable in the higher resolution δ^{18}O of the Montalbano Jonico section (Fig. 2). The sedimentation rate at the studied core varies from 1.4 cm/ky to 2.4 cm/ky, while the temporal resolution of analysis varies from 0.7 ka to 0.4 ka accordingly to the updated age model.

4.2 Coccolithophore assemblages

The coccolithophore assemblages show good preservation. Thirty-five taxa, at the level of genus, species and subspecies have been recognized and selected taxa are shown in Plate 1. The DI, shown in Fig. 3, records values higher than 0.9 indicating low dissolution. Lower values have been recorded in late MIS 20. The N of the total assemblage ranges from a minimum of 24x10^8 coccoliths per gram of sediment (n°/gr) to a maximum of 410x10^8 n°/gr (Fig. 3). The lowest number of coccoliths has been recorded during glacial stage, while it increases during interglacial phase (Fig. 3). The figure 3 shows the taxonomic composition of the assemblage. The genus *Gephyrocapsa* represents the main component (over than 80%) (Fig. 3). Small *Gephyrocapsa* spp. (from 17% to 58%) includes gephyrocapsids <3 µm with open central area. *Gephyrocapsa* spp. >3 µm with values from 19% to 55%, includes *Gephyrocapsa margereli*

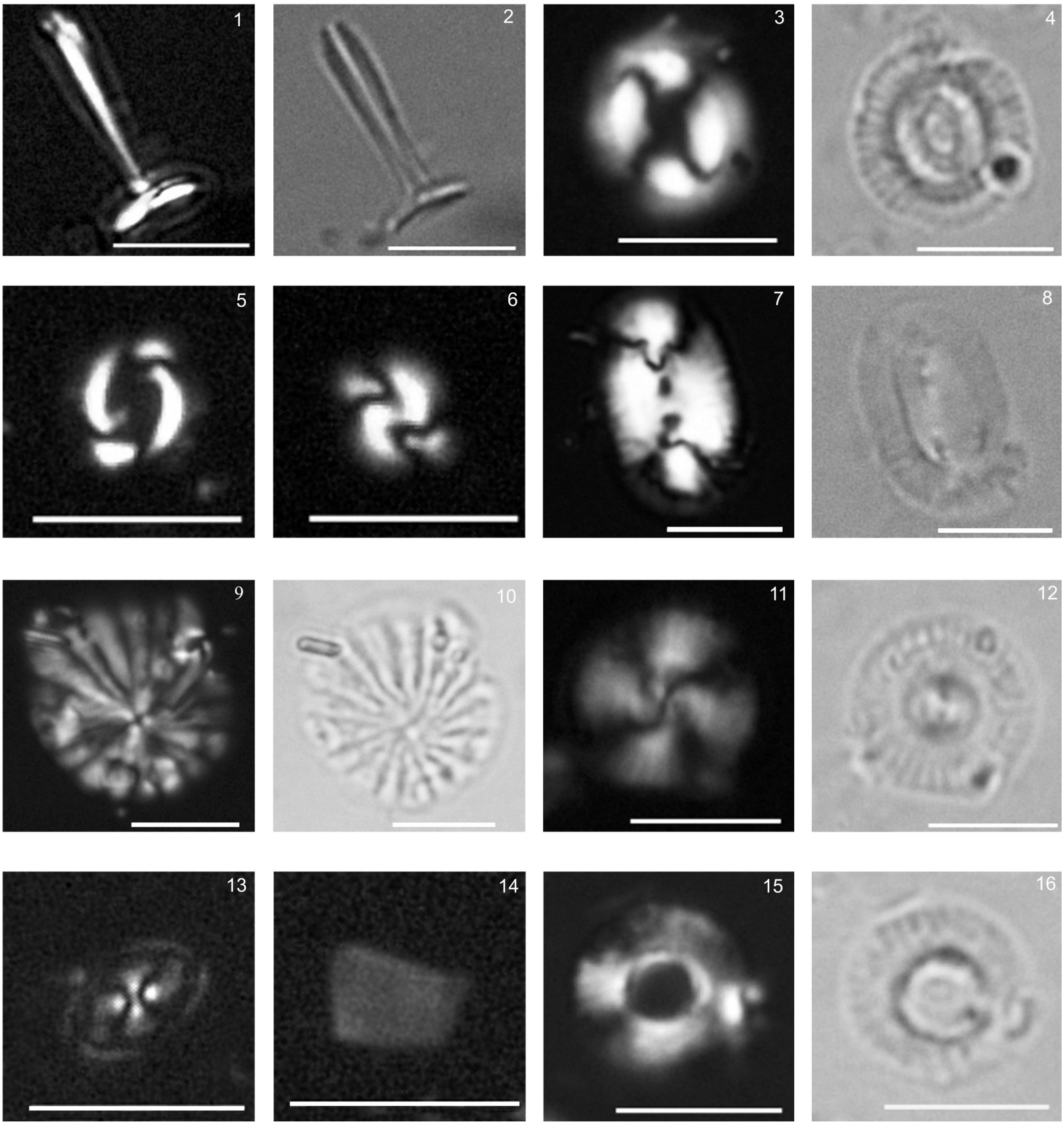


Plate 1 - Selected coccolithophore photographs captured by the polarizing optical microscope. NP: parallel nicol, XN crossed nicol. Scale bar represents 5 μm. 1-2: *Rhabdosphaera clavigera*. KC01B, 28.86 m. 1: XN-2: NP; 3-4: *Coccolithus pelagicus* subsp. *pelagicus.* KC01B, 29.52 m. 3: XN-4: NP; 5: *Gephyrocapsa margereli-G. muellerae*. KC01B, 29.21 m. 5: XN. 6: *Gephyrocapsa caribbeanica*. KC01B, 29.21 m. 6: XN; 7-8: *Helicosphaera carteri.* KC01B, 29.52 m. 7: XN-8: NP; 9-10: *Oolithotus antillarum.* KC01B, 29.51 m. 9: XN-10: NP; 11-12: *Calcidiscus leptoporus* subsp. *leptoporus*. KC01B, 29.52 m. 11: XN-12: NP; 13: *Syracosphaera pulchra.* KC01B, 29.21 m. 13: XN; 14: *Florisphaera profunda.* KC01B, 29.21 m. 14: XN; 15-16: *Umbilicosphaera sibogae*. KC01B, 29.51 m. 15: XN-16: NP.

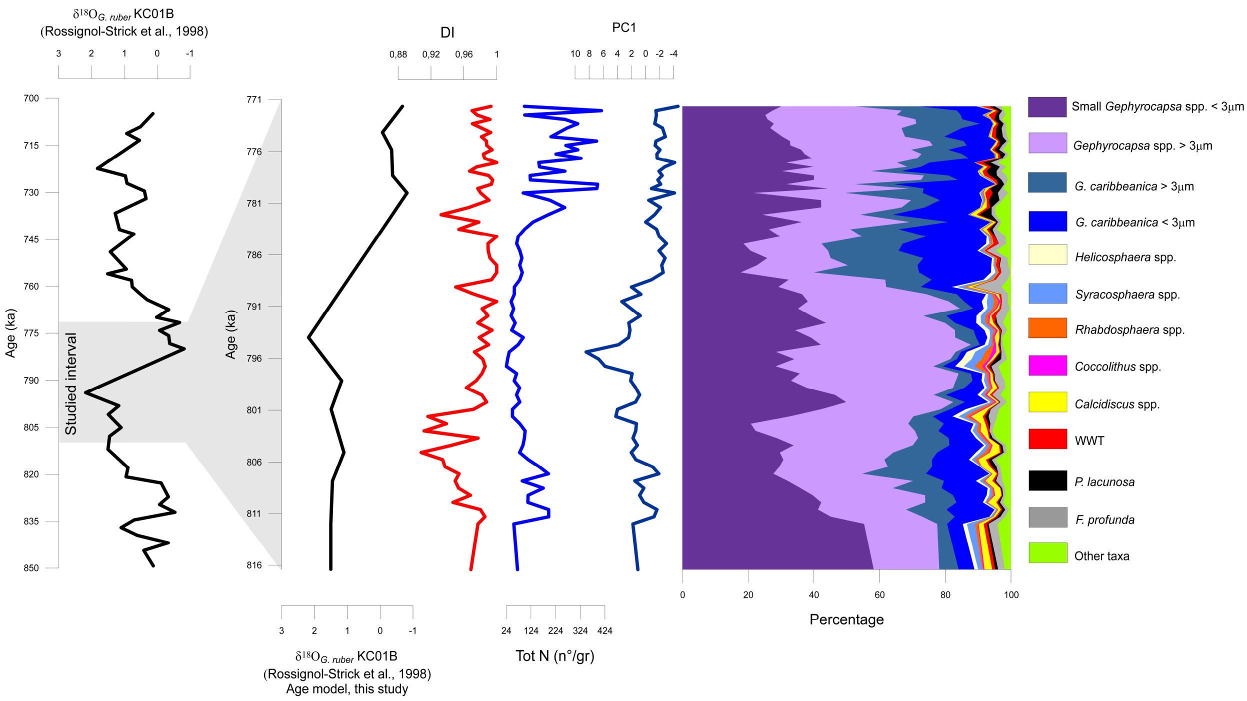


Fig. 3 - From left to right, plotted versus age: $\delta^{18}O$ record at the study core KC01B (Rossignol-Strick et al., 1998); $\delta^{18}O$ record related to the studied interval at the study core KC01B (Rossignol-Strick et al., 1998), with updated age model (this study); coccolithophore dissolution Index (DI); total coccolithophore abundance expressed as number of coccoliths per gram of sediment ($N*10^8$); factor 1 (PC1); cumulative abundance of taxa percentages.

-*G. muellerae*, and very rare and scattered *G. oceanica*, *G. omega* and *G. muellerae*. *G. caribbeanica* >3 µm reaches a percentage of 32% with a minimum of 1.6%, while *G. caribbeanica* <3 µm has values between 1.5% and 30%. Taxa with lower abundances include: *Helicosphaera* spp. (*H. carteri*, *H. hyalina*, *H. wallichii*), with a maximum of 3%; *Syracosphaera* spp. (*S. pulchra*, *S. histrica*) with values up to 3.2%; *Rhabdosphaera* spp. (*R. clavigera* var. *styilifera*, *R. clavigera*) with percentages lower than 2.4%; *Coccolithus* spp. (*C. pelagicus* ssp. *pelagicus, C. pelagicus* ssp. *braarudii*, *C. pelagicus* ssp. *azorinus*) that not reaches percentage higher than 1.3 %; *Florisphaera profunda* that ranges between 0.5 % and 8.5%. *Calcidiscus* spp. (*C. leptoporus* 5-8 µm, *C. quadriperforatus* 8-10 µm) and *Pseudoemiliania lacunosa* have percentage generally lower than 1%, rarely up to 3% (Fig. 3). The WWT group has low abundance with a maximum of 2.6%. "Other taxa", having percentage from 0.2% to 5.6%, include taxa with rare and scattered occurrences: *Ceratolithus* spp., *Reticulofenestra* sp. >3 µm, *Coronosphaera* sp., *Pontosphaera* sp., *Scyphosphaera* sp., *U. hulburtiana,* holococcoliths.

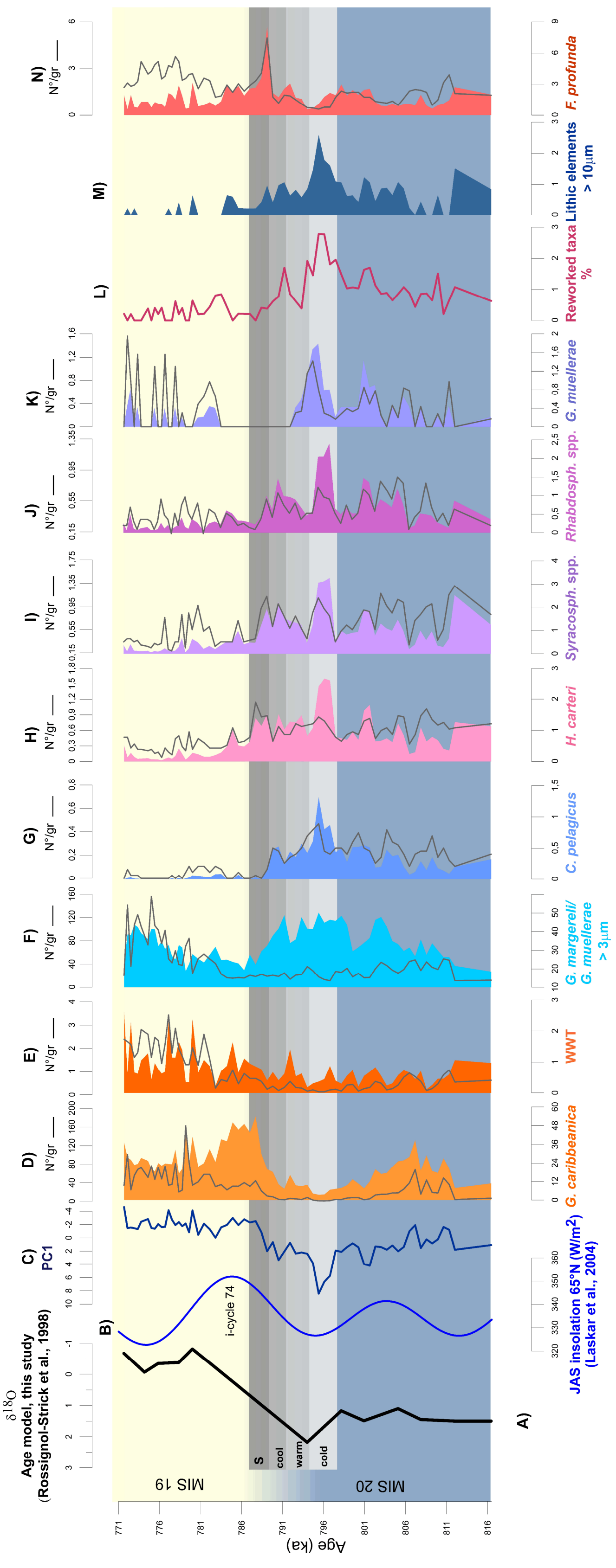
5. DISCUSSION

5.1. Statistical analysis

The PCA indicates that the first and the second components have percentage variance of 33% and 13%, respectively. Only the first component (PC1) was considered since it has a higher value and then a greater control of coccolithophore assemblage. The most

Taxa	PC1
Calcidiscus spp.	0,3652
***G. caribbeanica* > 3µm**	**-0,6744**
G. omega-G. oceanica	0,3905
***G. muellerae* >3 µm**	**0,661**
***G. margereli-muellerae* > 3µm**	**0,585**
G. margereli-muellerae < 3µm	0,2432
***G. caribbeanica* < 3µm**	**-0,691**
U. hulburtiana	0,4311
***Calciosolenia* sp.**	**-0,4653**
C. pelagicus* ssp. *pelagicus	**0,9071**
Discosphaera tubifera	**-0,4104**
F. profunda	0,05158
H. carteri	**0,8235**
H. pavimentum	**-0,5336**
***Syracosphaera* spp.**	**0,8461**
R. clavigera	**0,5364**
R. stylifera	**0,8558**
***Oolithotus* spp.**	**-0,5323**
Umbilicosphaera spp.	-0,3939
Calcidiscus small	-0,2277

Tab. 1 - Loadings of coccolithophore taxa on the first component (PC1) at core KC01B. The most relevant component loadings are indicated in red bold (positive loading) and black bold (negative loading). Percentage of variance is 33%.



relevant negative loadings in coccolithophore assemblage are for the species indicative of warm sea surface waters such as taxa included in WWT group and *G. caribbeanica* (> and <3 µm), a typical taxon of warm and oligotrophic surface waters (Bollmann, 1997) (Tab. 1). PC1 mainly loads with positive score the subarctic species *C. pelagicus* ssp. *pelagicus*, a traditional cold-water indicator (Baumann et al., 2000), *G. margereli-G. muellerae* and *G. muellerae* >3 µm, *Syracosphaera* spp., *R. clavigera*, *R. clavigera* var. *stylifera* and *H. carteri*. *G. margereli-G. muellerae* is considered an indicator of cool/cold surface water condition; in particular, *G. muellerae* has been found in colder surface waters (Weaver & Pujol, 1988; Samtleben & Bickert, 1990; Samtleben et al., 1995; Bollman, 1997; Okada & Wells, 1997; Giraudeau et al., 2010; Amore et al., 2012) and *G. margereli* in transitional assemblages of oceanic area (Bollman, 1997). The positive loadings of *Syracosphaera* spp., *R. clavigera*, *R. clavigera* var. *stylifera* and *H. carteri* may be associated to fresher and turbid surface water condition as recorded in Mediterranean Sea during Pleistocene colder phases (Colmenero-Hidalgo et al., 2004; Maiorano et al. 2013, 2016b; Bazzicalupo et al., 2018; Marino et al., 2018). PCA results make possible to interpret the PC1 as sea surface water temperature with associated condition of oligotrophy during interglacial phase or low salinity and turbidity during colder episodes.

The changes in coccolithophore assemblages observed at the study core, combined with the pattern of the PC1 (Fig. 4), show that environmental modifications occurred at the glacial-interglacial and millennial scale, making it possible to highlight the climate variability starting from late MIS 20 to early MIS 19c.

5.2. MIS 20 and terminal stadial event

During the glacial phase MIS 20, cold sea-surface conditions prevailed in the Ionian Sea, as shown by the increase of cold *C. pelagicus* ssp. *pelagicus* and cool-cold *G. margereli-G. muellerae*, and by the low abundance of WWT (Fig. 4G-F-E), in agreement with their ecological preferences respectively for lower and higher surface water temperatures. The high values of PC1, interpreted as temperature, during this time, may support cold conditions (Fig. 4, Tab. 1). The concomitant abundance of *H. carteri*, *Syracosphaera* spp., *Rhabdosphaera* spp. (Fig. 4H-I-J), although fluctuating, may be an indication of variable condition of low salinity and

Fig. 4 - Comparison of the $\delta^{18}O$ record at the core KC01B in Ionian basin (A), versus time, with the mean summer insolation (JAS, 65°N W/m²) (B), factor 1 (PC1) (C), coccolithophore taxa (D-K; N), reworked calcareous nannofossils (L), lithic elements > 10 µm (M). MIS: Marine isotope stage. Full area in plotted taxa: percentage abundance; grey line: number of coccoliths per gram of sediment ($N*10^8$). The transition between MIS 20 and MIS 19 is represented with soften colours on the left.

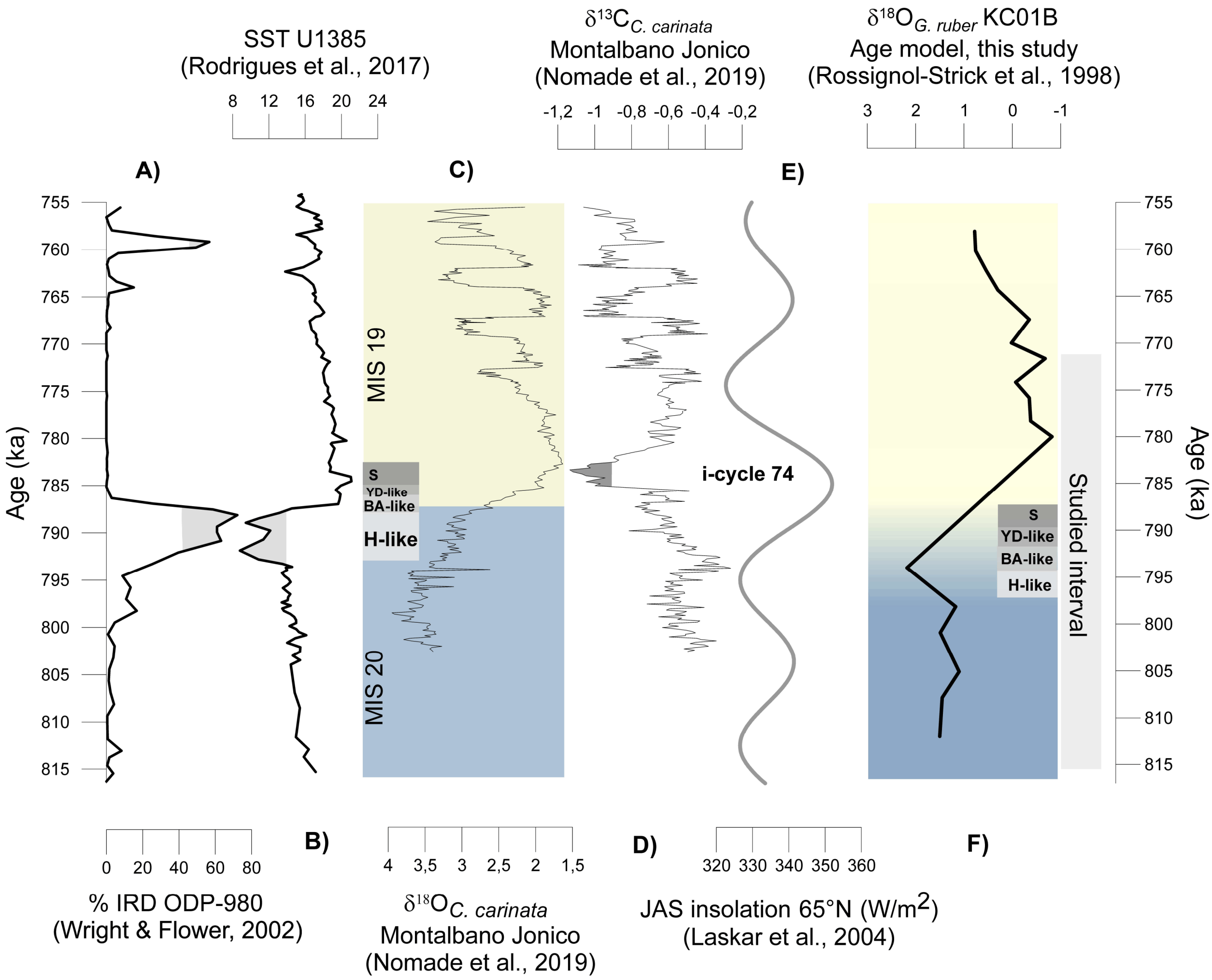


Fig. 5 - Time comparison between climate phases plotted on the δ18O at the core KC01B in Ionian basin (F) and percentage of IRD at ODP -980 site in North Atlantic (A), alkenone derived sea surface temperature (SST) at site U1385 located in North Atlantic (B), oxygen and carbon isotopic curves (C, D, Nomade et al., 2019) and climate phases (colored bands in C, Maiorano et al., 2016a) at Montalbano Jonico section, and mean summer insolation curve (JAS, 65°N W/m², Laskar et al., 2004) (E). MIS: Marine isotope stage. H-like: Heinrich-like event; BA-like: Bølling-Allerød-like event; YD-like: Younger-Dryas-like event; S: sapropel. The transition between MIS 20 and MIS 19 at the studied core KC01B is represented with soften colours.

turbid sea surface waters (Maiorano et al., 2016a, b) in the Ionian basin, possibly as a result of intermittent run off from land. This is supported by the concurrent high abundances of reworked coccoliths and lithic elements >10 µm (Fig. 4L-M) suggesting increased erosion as it may be expected during the glacial low sea level, as already highlighted by Maiorano et al. (2016a, b). During the late MIS 20, between 797.6 ka and 794.1 ka, a colder climate episode may be inferred due to the significant increase of *C. pelagicus* ssp. *pelagicus* and *G. muellerae* >3 µm (Fig. 4G-K), and the maximum value in the PC1 (lower temperature). The prominent increase of the percentage abundances of *H. carteri*, *Syracosphaera* spp., and *Rhabdosphaera* spp. (Fig. 4H-I-J), is a signal of enhanced turbidity and low salinity in stratified surface waters. The major values in the lithic elements >10 µm during this phase (Fig. 4M) point to enhanced low sea level that promoted on land erosional process and higher detrital input toward the basin. Local influence of low salinity waters from surrounding Apennines mountain ice melting through strengthened fluvial payload may have played a significant role, as already conceived by Maiorano et al. (2016a, and references therein).

However, such environmental frame may be associated to a terminal stadial phase of glacial MIS 20 (Hodell et al., 2015) characterized by the arrival of North Atlantic meltwater at the Ionian Sea. Such interpretation finds agreement with the similar oceanographic outline already hypothesized in the Montalbano Jonico section (Fig. 1) during late MIS 20 based on multi-proxy data (Maiorano et al., 2016a) (Fig. 5C), and it can be correlated to the occurrence of Ice Rafted Detritus (IRD) in the North Atlantic ODP sites 980 (Wright & Flower, 2002) (Fig. 5A) and 983 (Kleiven et al., 2011) as a signal of

North Hemisphere ice-sheet collapse. Maiorano et al. (2016a) proposed a "H-like" (Heinrich-like) event for the colder phase of late MIS 20. Cold meltwaters of North Atlantic origin have been also inferred in Mediterranean basin during Pleistocene glacial periods based on different proxies, including peaks of *C. pelagicus* ssp. *pelagicus* and *Neogloboquadrina pachyderma* left coiling (Colmenero-Hidalgo et al., 2004; Sierro et al., 2005; Girone et al., 2013; Capotondi et al., 2016; Marino et al., 2018). Therefore, the peak in abundance of *C. pelagicus* ssp. *pelagicus* at the core KC01B in the late MIS 20 may be an additional evidence that the Ionian Sea recorded the North Atlantic climate via oceanographic connection.

5.3. Short-term climate phases toward MIS 19 onset

Above the terminal stadial of MIS 20, a warm climate episode is recorded from 794.1 ka to 791.3 ka, marked by the reduction in the abundance of *G. margereli-G. muellerae, C. pelagicus* spp. *pelagicus*, as well as by a slight but distinct increase of *G. caribbeanica* and WWT (Fig. 4F-G, D-E). All these taxa record an opposite pattern in the following phase, between 791.3 ka and 789.3 ka, suggesting a restored short-term cool spell, in agreement with the pattern of PC1 (Fig. 4C). *Helicosphaera carteri*, *Syracosphaera* spp., *Rhabdosphaera* spp., reworked taxa and lithic elements >10 μm (Fig. 4I-J-K-L-M) also mimic decrease and increase during these two climate episodes, respectively, highlighting variation in the surface water features, specifically related to turbidity and salinity in addition to temperature. The warm event was therefore characterized by slightly higher temperature and less turbid surface water possibly linked to the first climate amelioration that followed the terminal stadial of MIS 20 toward the interglacial onset. PC1 has in fact lower values (higher temperature) in this phase (Fig. 4C). This warming phase may have favoured melting of local mountain ices promoting detrital input supply to the basin and the following cooling of surface waters that in turn allowed cold species (*C. pelagicus* ssp. *pelagicus, G. margereli-G. muellerae*) to thrive together with taxa able to proliferate in turbid waters (*Syracosphaera* spp., *Rhabdosphaera* spp.). The occurrence of these two short events appears in agreement with the climate pattern known during last deglaciation (TI) which displayed the warm Bølling-Allerød and cold Younger-Dryas events (Mangerud et al., 1974) and correspond to the Greenland Interstadial (GI)-1 and Greenland Stadial (GS)-1 (Björck et al., 1988) just before the Holocene inception. These data support the suggestions of Maiorano et al. (2016a) who referred the short-term warm and cool events following H-like in the Montalbano Jonico section to "B/A-like" and "Y/D-like" (Fig. 5C); moreover, they sustain the high climate variability recognized during glacial terminations in previous Quaternary studies (Martrat et al., 2007; Siddal et al., 2010; Barker et al., 2011).

5.4. Sapropel-like during interglacial MIS 19

The beginning of the interglacial MIS 19c is marked by the decrease of cold taxa and increasing trend of *G. caribbeanica* and WWT (Fig. 4D-E). The PC1 records lower values that remain quite stable for the following studied interval, except for few small fluctuations (Fig. 4C). The establishment of temperate surface waters at the base of MIS 19c (between 789.3 ka and 786.8 ka) is accompanied by surface water stratification. This is supported by the peak in abundance of *F. profunda* (centred at 789.1 ka and at 29.19 m) (Fig. 4N), that is an indicator of deep nutricline and low surface water productivity (Molfino & McIntyre, 1990a, b). Its abundance is accompanied by increase of *Syracosphaera* spp. (Fig. 4I) as a signal of variations in salinity and nutrient content (Flores et al., 1997), quickly followed by the highest N of *H. carteri* (centred at 787.7 ka and 29.17 m) (Fig. 4H), suggesting turbid and less salty waters (Ziveri et al., 1995; Negri et al., 1999; Negri & Giunta, 2001; Colmenero-Hidalgo et al., 2004; Maiorano et al., 2016a). These patterns might be interpreted as linked to oceanographic condition typical of sapropel formation when increased humid condition over the Mediterranean area, linked to strengthened North Africa monsoon, promoted huge fresh water influx that caused surface water stratification and higher amount of suspended detritus. It is interesting to note that the "red interval" indicated at the studied core by Langereis et al. (1997) and tuned to "i-cycle 74" was not identified at 29.17 m, like in this study, but at 29 m where instead we did not find any signal of oceanographic conditions related to sapropel formation based on coccolithophore assemblage.

Accordingly, our interpretation is further supported by good correlations with analogous oceanographic conditions recorded in the near Montalbano Jonico section at the beginning of MIS 19c based on both biological proxies (including peak of *F. profunda* and turbid water tolerant taxa) (Maiorano et al., 2016a) and a prominent minimum in the benthic $\delta^{13}C$ (Nomade et al., 2019) at 783.31 ka (Fig. 5D). All these parameters suggest the occurrence of stratification of the water column and preservation of organic matter in conditions of low oxygenation at the sea bottom, that in turn correspond to the red interval i-cycle 74.

5.5. Correlation of Ionian sites with North Atlantic cores and paleoceanographic implications

The paleoclimatic and paleoceanographic frame reconstructed at the core KC01B through MIS 20-MIS 19 deglaciation seems to be comparable to that described at Montalbano Jonico, in fact, similar climatic events during TIX occur in both sites with the identical progression and rather similar duration (Fig. 5C-F). Therefore, the same terminology proposed in Maiorano et al. (2016a), that is H-like, B/A-like, Y/D-like, has been utilized. The different ages of these events in core KC01B with respect to those recorded in Montalbano Jonico section are in a chronological uncertainty of about 3 ka. The age model at the studied core would thus require a further refinement that cannot be provided without a higher resolution oxygen isotope data-set, which in turn may benefit from the sapropel event as a valuable chronological tie-point at 784 ka (Lourens, 2004), and in agreement with the age assignment of

Nomade et al. (2019). Waiting for a more robust updated chronology, that is not a matter of this study, we would emphasize that the Montalbano Jonico and KC01B results document a shared pattern of climate variability just before MIS 19 inception, that is well comparable to TI climate event occurrence (Asioli et al., 2001; Di Stefano & Incarbona, 2004; Geraga et al., 2010; Siani et al., 2010, 2013; Maiorano et al., 2016a). An oceanographic connection between North Atlantic and Ionian basin during H-like event seems possible based on coccolithophore assemblages (increase of subarctic taxa), even if the atmospheric influence from northern latitudes via variable north westerly winds on the warming/cooling, stratification/mixing of central Mediterranean waters may not be excluded (Poulos et al., 1997; Rohling et al., 1998, 2002; Casford et al., 2001; Melki et al., 2009). Oceanic circulation and atmospheric processes related to ice-sheet dynamics in North Atlantic have been in fact invoked by Nomade et al. (2019) as a possible engine of millennial scale climate variation at Montalbano Jonico section during MIS 19b-a, and by Regattieri et al. (2019) to explain the high frequency climate changes displayed in the Sulmona lacustrine sediments during MIS 19. In this frame, H-like event in the Ionian basin would correspond to an interval of Atlantic Meridional Overturning Circulation (AMOC) slowdown/shutdown (McManus et al., 1999), when iceberg discharge released IRD in North Atlantic (Site 980, Fig. 5A) producing cold-low salinity surface meltwater in the mid latitude of Iberian Margin as well (Site U1385, Fig. 5B). Following, enhanced Atlantic cold-water influx through Gibraltar Strait (Sierro et al., 2005) could have reached the Mediterranean Sea where the arctic-subarctic coccolithophore key taxa (*C. pelagicus* ssp. *pelagicus*, *G. muellerae* >3 μm) did proliferate. This is in agreement with the arrival of Atlantic meltwaters at central Mediterranean already documented by Sprovieri et al. (2012) based on lightening signature in planktonic $\delta^{18}O$ during Heinrich events of the last 70 ka. During this phase, cold and arid atmospheric conditions linked to reduced evaporation and moisture-rich air mass advection towards the Mediterranean region (Tzedakis et al., 2004; Sierro et al., 2005; Margari et al., 2009; Sinopoli et al., 2018), may have enhanced lower surface water temperature and favoured cold taxa. In support of this climate reconstruction, dry condition on land during the Termination IX H-like event has been documented at Montalbano Jonico section (Bertini et al., 2015; Marino et al., 2015; Maiorano et al., 2016a) and correlated to a prominent IRD peak at the ODP 980 and a significant increase of aeolian dust in the eastern Mediterranean (Larrasoaña et al., 2003). Accordingly, semi-desert vegetation establishment has been indicated in the U1385 core, west of Iberian margin (Sánchez-Goñi et al., 2016). Such combined climate signals seem to indicate that oceanic-atmospheric connection may be inferred between central Mediterranean and northern Atlantic climate, linked to oceanographic circulation and ice-sheet dynamics.

6. CONCLUDING REMARKS

The high-resolution analysis on coccolithophore assemblages carried out on the core KC01B has provided the recognition of climate changes at orbital and millennial scale through late MIS 20 and early MIS 19. The PCA has indicated the temperature as the first environmental parameter that influences the distribution of taxa and the abundance of coccolithophores. The pattern of Factor 1 highlights glacial-interglacial phases and millennial scale climate events associated to a Heinrich-like event in late MIS 20, followed by B/A-like, and Y/D-like events before the beginning of major interglacial warming.

The colder surface water conditions during H-like phase have been evidenced by prominent abundance of *C. pelagicus* ssp. *pelagicus* and *G. margereli-G. muellerae* >3 μm. Lower salinity and higher turbidity accompanied this phase due to increase of *Syracosphaera* spp., *H. carteri*, *Rhabdosphaera* spp., reworked coccoliths and lithic elements >10 μm, suggesting enhanced erosion process on surrounding land during prominent low sea level. The quantitative pattern of lithic elements revealed to be a useful tool in monitoring the inorganic input amount toward the location of the studied core. A change has been recorded just above the event, based on the same key coccolithophore taxa and detrital input proxies, pointing to a 2.8 ka warming event characterized by less turbid and normal saline waters, followed by a cool spell event (duration 2 ka) with a re-establishment of turbidity and low salinity conditions.

The H-like phase in both the studied core and the Montalbano Jonico section (Maiorano et al., 2016a) and its correlation with North Atlantic SST at the U1385 and IRD at ODP-980 cores seem to document the arrival of North Atlantic cold meltwaters at the Ionian Sea based on coccolithophore assemblages. However, north westerly winds and atmospheric process related to North Hemisphere ice-sheet dynamics during more arid climate as documented in the Italian peninsula (e.g. Bertini et al., 2015) and at wider scale (Sánchez-Goñi et al., 2016) may have affected surface water features.

In the earlier phase of interglacial MIS 19 an oceanographic surface water condition typical of sapropelic deposition has been inferred based on the abundance peak of *F. profunda* and *H. carteri* that sustain the occurrence of turbid, less salty and stratified surface waters in relation to increased North Africa monsoon, close to insolation maximum i-cycle 74.

The correlation of our data with those provided in the close Montalbano Jonico site underlines a good correspondence of the events recorded from late MIS 20 to MIS 19 onset, in term of progression and duration. The older ages of the climate events and sapropel at the studied site with respect to the chronology of the same events at Montalbano Jonico, highlight the need of a slight updating of the age model at the core KC01B.

The overall data suggest that the Ionian Sea records a strong signature of high frequency climate variability across TIX like that occurred during last deglaciation, that could be relevant in future climate prospecting.

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