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Climate variability during MIS 20-18 as recorded by alkenone-SST and calcareous plankton in the Ionian Basin (central Mediterranean)

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	The main processes involved in the climate variability included changes in oceanographic exchanges through the Gibraltar Strait during modulations of Atlantic meridional overturning circulation and/or variations in atmospheric dynamics related to the influence of westerly and polar winds acting in the paleo-Ionian basin. A strong climate teleconnection between the North Atlantic and Mediterranean has been documented, and a prominent role of atmospheric processes in the central Mediterranean has been evidenced by comparing data sets at the IS with Italian and extra-Mediterranean marine and terrestrial records.
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Dear Editor,
I would like to submit for publication the manuscript

Climate variability during MIS 20-18 as recorded by alkenone-SST and calcareous plankton in the Ionian Basin (central Mediterranean),

by the authors Maria Marino (corresponding author), Angela Girone, Salvatore Gallicchio, Timothy Herbert, Marina Addante , Pietro Bazzicalupo, Ornella Quivelli, Franck Bassinot, Adele Bertini, Sebastien Nomade, Neri Ciaranfi, Patrizia Maiorano.

All the co-authors agree with this submission.

Best Regards

Maria Marino
and co-authors

Highlights

The first Mediterranean alkenone-based SST pattern is presented through MIS20-MIS18

The SST data are compared with new high-resolution calcareous plankton variations

The records show orbital-suborbital up to centennial-scale climate changes

Strong similarity occurs in the climate oscillations between Terminations IX and I

Oceanographic and atmospheric mechanisms drive paleoenvironmental changes

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Climate variability during MIS 20-18 as recorded by alkenone-SST and calcareous plankton in the Ionian Basin (central Mediterranean)

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Abstract

This study shows the first Mediterranean high-resolution record of alkenone-derived sea surface temperature (SST) in the marine sediments outcropping at the Ideale section (IS) (southern Italy, central Mediterranean) from late marine isotope stage (MIS) 20 - through early MIS 18 interval. The SST pattern evidences glacial-intergalcial up to centennial-scale temperature variation, with lower values (~13°C) in late MIS 20 and substage 19b, and higher values (up to 21°C) in MIS 19c and MIS 19a interstadials. The SST data are combined with the new calcareous plankton analysis and the available, chronologically well-constrained carbon and oxygen isotope records in the IS. The multi-proxy approach, location of the IS near the Italian coasts, its lower circalittoral-upper bathyal depositional setting, and high sedimentation rate allow to document long-and short-term paleoenvironmental modifications (sea level, rainfall, inorganic/organic/fresh water input to the basin), as a response to regional and global climate changes. The combined proxies reveal the occurrence of a terminal stadial in late MIS 20 (here Med-H_{TIX}), and warm-cold episodes (here Med-BA_{TIX} and Med-YD_{TIX}) during Termination IX (TIX), which recall those that occurred through the last termination (TI). During these periods and the following sapropelic layer (insolation cycle 74, 784 ka) in the early MIS 19, higher frequency internal changes are synchronously recorded by all proxies. The substage MIS 19c is warm but quite unstable, with several episodes of paleoenvironmental changes, associated with fluctuating tropical-subtropical water inflow through the Gibraltar Strait, variations of the cyclonic regime in the Ionian basin, and the southward shift of westerly winds and winter precipitation over southern Europe and Mediterranean basin. Three high-amplitude millennial-scale oscillations in the patterns of SST and calcareous plankton key taxa during MIS 19a are interpreted as linked to gobal changes in temperature as well as in salinity and in periodical column water stratification and mixing. The main processes involved in the climate variability include changes in oceanographic exchanges through the Gibraltar Strait during modulations of Atlantic meridional overturning circulation and/or variations in atmospheric dynamics related to the influence of westerly and polar winds acting in the paleo-Ionian basin. A strong climate teleconnection between the North Atlantic and Mediterranean is discussed, and a prominent role of atmospheric processes in the central Mediterranean is evidenced by comparing data sets at the IS with Italian and extra-Mediterranean marine and terrestrial records

Keywords: Lower-Middle Pleistocene, MIS 19, southern Italy, marine biomarkers, coccolithophores, planktonic foraminifera

1. Introduction

Marine Isotope Stage (MIS) 19 stage is generally considered an excellent analogue for the current interglacial, due to the same astronomical configuration of orbital parameters: low eccentricity and an obliquity maximum almost in phase with the northern Hemisphere precession minimum. For this reason, any high-resolution study of MIS 19 can bring invaluable pieces of information about the natural duration of the current interglacial and the inception of next glacial in absence of human impact. MIS 19 is characterized by an orbital/suborbital climate variability that is evidenced by the partition in substages a, b, and c in the $\delta^{18}O$ oscillations (Railsback et al., 2015), associated to 19.3, 19.2, and 19.1 events (Bassinot et al., 1994). They may have relevant implications in climatostratigraphy (Miller and Wright, 2017), coherently with the wide use of oxygen isotope signature for Quaternary chronostratigraphic subdivision. Specifically, the Lower-Middle Pleistocene chronostratigraphic boundary, close to the Matuyama-Brunhes paleomagnetic reversal, is associated worldwide to the MIS 19c/MIS 19b transition at ~773 ka (Head, 2019, and reference therein). Millennial-scale variations have been also highlighted within MIS 19 as a result of local and North Hemisphere oceanic-atmosphere dynamics. A distinct occurrence of the first climate deterioration marked by MIS 19b after the full interglacial, and climate oscillations in MIS 19a, have been revealed by recent high-resolution proxies in several marine (Kleiven et al., 2011; Tzedakis et al., 2012; Emanuele et al., 2015; Ferretti et al., 2015; Sánchez Goñi et al., 2016; Nomade et al., 2019) and lacustrine sediments (Giaccio et al., 2015; Regattieri et al., 2019), and ice core (e.g. Pol et al., 2010).

These climate episodes, occurring at a wide scale (Nomade et al., 2019), may have not been given coherent chronologies, possibly due to different age-model strategies and the fact that different proxies may have been used to identify them. This makes it difficult to correlate climate stages and events with accuracy and to interpret climate dynamics and temporal relationship (ie. lead/lag) between high and mid latitudes or between marine and terrestrial realms, thus preventing the comprehension of cause-effect connections and the climate propagation of changes at regional and global scale.

The on land marine Ideale section (IS), as part of the Montalbano Jonico section (MJS, southern Italy) crossing MIS 37-MIS 16, offers the opportunity to improve the paleoclimate framework of MIS 19 due to its high sedimentation rate and environmental setting. It was deposited in lower circalittoral-upper bathyal, not far from a peninsular coastline, and thus registered even slight climatically induced modifications such as changes in sea level, precipitation, and inorganic/organic input from land. The water depth of the sediments is also suitable to provide numerous marine proxy data, in the form of planktonic and benthic foraminifera, coccolithophores, and marine biomarkers. The IS has been extensively studied in recent years due to its potential to represent the Lower-Middle Pleistocene chronostratigraphic boundary (e.g. Ciaranfi et al., 2010; Maiorano et al., 2010, 2016a; Bertini et al., 2015; Marino et al., 2015, 2016; Petrosino et al., 2015; Simon et al., 2017; Nomade et al., 2019). Short-term climate episodes in the latest MIS 20 and Termination IX (TIX) have been referred to Heinrich-like (Ht), Bølling-Allerød-like (BAt), and Younger-Dryas like (YDt) based on multi-proxy investigation thus suggesting a climate variability comparable to that documented during the last deglaciation (Maiorano et al., 2016a). The latter authors suggested the need of higher resolution data set to support these evidences in a finer constrained time frame. The more recent, very high-resolution benthic (*Cassidulina carinata*, *Melonis barleeanum*) $\delta^{18}O$ and $\delta^{13}C$ records (Nomade et al., 2019) have improved the chronology of the IS, detailing the pattern of MIS 19 substages and the three interstadial phases in MIS 19a (19a-1, 19a-2, and 19a-3), highlighting the centennial-scale timing of these climate oscillations and their worldwide correlability.

In the present work we present new high-resolution alkenone-SST data acquired at the IS, which are the first recorded in the Mediterranean Sea for the time interval spanning MIS 20-MIS 18 and may improve the understanding of the climate evolution as recorded in marine environment. New quantitative calcareous plankton (coccolithophores and foraminifera) results, obtained on the same samples used for marine biomarkers and for the isotopic study of Nomade et al. (2019), are also presented, providing a paleoecological window into synchronous marine response to major environmental modifications. The combination of this new data set with the detailed benthic isotope records available at the IS provides useful insights into i) the marine surface/subsurface water conditions in the central Mediterranean during an important interglacial of mid-Pleistocene transition considered the best analogue of the current interglacial (Holocene), ii) the terminal stadial event in late MIS 20 and its oceanographic-atmospheric connection with North Atlantic climate,

iii) the high frequency climate variability across TIX, making it possible to better address its apparent similarity with the rapid variability that occurred during TI. The comparison of new data with selected high-resolution climate references from North Atlantic Ocean provides additional highlights on central Mediterranean response to local or global climate via atmospheric-oceanographic processes.

2. Oceanography

Sediments of the MJS were deposited in the paleo Gulf of Taranto (Fig. 1D), in the north Ionian Sea. At this location important detrital sediment supply derives mainly from Apennines rivers (Goudeau et al., 2013). Sediments from the Po River and other Apennines rivers may also arrive in the eastern Gulf of Taranto through the Western Adriatic Current (WAC) (Fig. 1D). This low salinity (37.2 PSU along the southern Italian coast) nutrient-rich current flows southward in a narrow coastal band from the northern Adriatic Sea, and mixes with the more saline Ionian waters (up to 39.5 PSU in the central Ionian Sea) (Poulain, 2001; Bignami et al., 2007; Turchetto et al., 2007; Grauel and Bernasconi, 2010). The WAC has higher influence in winter and spring (Poulain, 2001) than in summer and is characterized by significant inter-annual variability (Milligan and Cattaneo, 2007). In the Gulf of Taranto the highly saline Levantine Intermediate Water (LIW), flowing from the central Ionian Sea, may be recorded at the water depth of 200-600 m (Savini and Corselli, 2010). The Northern Ionian Gyre (NIG) that has decadal scale cyclonic and anticyclonic phases (Civitarese et al., 2010) characterizes the central open ocean area of the Gulf of Taranto. The cyclonic phase is characterized by saltier Levantine/Cretan Intermediate Waters (LIW/CIW) that flow northward into the Adriatic, while anticyclonic phase records advection of less saline Ionian water diluted by Modified Atlantic Waters (MAW) (Civitarese et al., 2010). In the first case poor-nutrient LIW/CIW waters enter the north Ionian Sea and south Adriatic Sea, while the influx of MAW during anticyclonic phase favours upwelling events and nutrients supply at the periphery of the anticyclonic NIG along the souther Italian coasts before reaches the south Adriatic Sea (Civitarese et al., 2010). The alternating anticyclonic and cyclonic states are known as Adriatic-Ionian bimodal oscillation system (Civitarese et al., 2010; Gačić et al., 2010) that may influence nutrient distribution and phytoplankton growth (Civitarese et al., 2010, Batistić et al., 2017).

Modern annual mean SSTs in the Gulf of Taranto are about 19.7 °C (Pujol and Vergnaud-Grazzini, 1995). During summer, they vary from 26°C to 15°C at the surface and at 50 m depth, respectively, and the water column is stratified (Zonneveld et al., 2008; Grauel and Bernasconi, 2010). During winter, SSTs vary between 13°C and 15°C. These seasonal temperature changes can influence the upper 100 m of the water column (Socal et al., 1999; Locarnini et al., 2010).

Today, the high latitude North Atlantic and Arctic climate perturbations rapidly spread to the northern hinterlands of the Mediterranean and are channelized in mountain valleys through intense northerly flows of cold and dry air masses (‘Mistral’, ‘Bora’, ‘Vardar’ winds) over the northwestern Mediterranean, the Adriatic and the Aegean basins (Mariolopoulos, 1961; Leaman and Scott, 1991; Poulos et al., 1997). These polar and continental winter airflows cause intense evaporation and cooling of the sea surface and terrestrial vegetation (e.g., Leaman and Schott, 1991; Saaroni et al., 1996; Poulos et al., 1997; Maheras et al., 1999; Casford et al., 2003; Rohling et al., 2009).

3. Geological setting and stratigraphy

The IS, as part of the Montalbano Jonico succession (MJS), crops out in the south-western margin of the Bradanic Trough, at about 16 km inland from the Ionian Coast (40°17'29.52" N 16°33'10.58"E) (Fig. 1). The Bradanic Trough (e.g. Casnedi, 1988), located between the Apennines Chain to the west and the Apulian foreland eastward (Fig. 1B), is a foredeep basin of the post-Messinian Apennines. Its origin and evolution are associated with the eastward roll-back of the subduction hinge of the Apulia platform and the evolution of the external Apennines thrust front during the Plio-Pleistocene (e.g., Patacca and Scandone, 2007 and references therein). The foredeep was characterized by high rates of subsidence until the Calabrian, after which it underwent a diachronous uplift starting from the Genzano-Banzi area during late Calabrian and proceeding southeastward to the actual Ionian coast by Holocene time. In the late Calabrian, the central sector of the Bradanic Trough emerged while the southern sector, where the study section is located, was still subsiding. The central foredeep sector reached its maximum deepening in the Early-Middle Pleistocene (e.g., Maiorano et al., 2016a). From the Middle Pleistocene, the sedimentation reveals a shoaling-upward trend due to the uplift of the area (uplift rate of 0.1–0.5 mm/years, e.g. Doglioni et al., 1996) that led to the emersion of the area since 0.6/0.7 Ma. Regionally, the gradual emersion of the area is testified by several continental and marine terraces, represented by transitional and continental deposits of ancient alluvial and costal plains developed between 0.7 Ma and the Late Pleistocene (e.g. Vezzani, 1967; Brückner H., 1980 a, b; Pescatore et al., 2009; Sauer et al., 2010, Boenzi et al., 2014).

The MJS (Fig. 1C) belongs to the argille subapennine informal unit (Azzaroli et al., 1968), representing its middle-upper portion, Early to Middle Pleistocene in age (Ciaranfi et al., 2010). It consists of coarsening-upwards deposits ranging from silty clays to silty sands and includes nine tephra layers (V1–V9) (Fig. 1C). The tephra layers (V1-V9) were chemically and mineralogically characterized and correlated to analogous layers from south-central Italy lacustrine and marine successions, within a Lower-Middle Pleistocene Mediterranean tephrostratigraphic frame (Petrosino et al., 2015). The MJS, in its lower part, includes five dark horizons interpreted as sapropel layers (D'Alessandro et al., 2003; Stefanelli, 2004; Stefanelli et al., 2005; Maiorano et al., 2008) and correlated, from oldest to youngest, to insolation cycles i-112, i-104, i-102, i-90, and i-86, based on the Mediterranean sapropel stratigraphy of Lourens (2004) and Lourens et al. (2004). The calcareous nannofossil biostratigraphy indicates that the entire succession belongs to the small *Gephyrocapsa* and *Pseudoemiliania lacunosa* zones, based on the biostratigraphic scheme of Rio et al. (1990) (Fig. 1C). Several deepening-shallowing cycles, from bathyal to circalittoral environments, have been recognized based on micro- and macro-invertebrate benthic assemblages (D’Alessandro et al., 2003; Stefanelli, 2003; Ciaranfi and D’Alessandro, 2005; Girone, 2005). Specifically, benthic paleocommunities from the lower part of succession (Interval A) indicated upper slope environments, with a maximum depth of ca. 500 m, while paleocommunities of upper portion (Interval B) pointed out to outer to inner shelf settings with short-term deepening towards upper slope.

The IS, in Interval B, consists of clays and silty clays bracketed by two tephra layers, V3 and V4. The V3 and V4 layers were radiometrically dated and their $^{40}Ar/^{39}Ar$ ages are 801.2 ± 19.5 ka (Maiorano et al., 2010), 773.9 ± 1.3 ka (Petrosino et al., 2015), respectively. The V3 tephra is located within the MIS 20 interval (at 820 cm) and V4 is at the transition from MIS 19c to MIS 19b (at 3660 cm) (Fig. 1C). Due to its high stratigraphic value in constraining the MIS 19c/19b transition, coincident with the $^{10}Be/^{9}Be$ peak interpreted as the Earth magnetic field collapse during the Matuyama-Brunhes reversal (Simon et al., 2017), V4 has been re-dated at the LSCE laboratory (France). New dating provided a $^{40}Ar/^{39}Ar$ age of 774.1 ± 0.9 ka (Nomade et al., 2019), which is in good agreement with the Ar/Ar age estimate of Petrosino et al. (2015). The dark grey bands (Fig. 1C) correspond to higher kaolinite and smectite content and increased chemical weathering on land (Maiorano et al., 2016a); the clay fraction increases significantly (20–31%, average 24%) from the onset of MIS 19 upwards, although several fluctuations have been observed through the interval encompassing MIS 19a towards MIS 18. In contrast, the light grey bands are related to increases of quartz and dolomite associated with enhanced supplies of the coarser detrital mineral components into the basin (Maiorano et al., 2016a). Dark and light intervals correspond to lower (interglacial, interstadials) and higher (glacial, stadials) benthic $\delta^{18}O$ values, respectively, suggesting the glacio-eustatic/climate control on sedimentary features of the IS. However, the influx of fresh water of on land origin during wetter climate was not excluded during lighter $\delta^{18}O$ and darker sedimentation phases, in contrast to more arid climate during heavier $\delta^{18}O$ intervals (Bertini et al., 2015; Nomade et al., 2019). The shallowing-deepening cycles through MIS 20-18 are also highlighted by marine micro- and macrobenthic assemblages (D'Alessandro et al., 2003; Stefanelli, 2003; Aiello et al., 2015), and pollen distality index (Bertini et al., 2015). In detail, paleodepths range from about 100 m to 180-200 m (Aiello et al., 2015) which implies a water column mainly distributed in the photic zone. A maximum flooding in the mid MIS 19c (MF, Fig. 1C) followed by the maximum depth interval (MD, Fig. 1C) are documented by D'Alessandro et al. (2003) based on the benthic macro-invertebrate communities.

4. Methods

Alkenones and calcareous plankton assemblages were investigated in 170 and 167 samples, respectively, from the same levels analyzed for the high-resolution isotope curves of Nomade et al. (2019). The sample spacing is between 20 and 40 cm and corresponds to a temporal resolution of 200 years in MIS 20, down to about 100 years during selected intervals (mainly Termination IX and MIS 19a), according to the age-model of Nomade et al. (2019).

4.1 *Biomarker analyses*

Lipid biomarker extractions were carried out on 5g freeze-dried, ground samples by accelerated solvent extraction (Dionex ASE-200) at Brown University. The complexity of interfering peaks in the region where C_{37} and C_{38} alkenones elute via gas chromatography (GC), organic extracts were purified by silica gel flash column chromatography prior to GC analysis. Gas chromatography was carried out on an Agilent (60 m, DB-1 column) with the following parameters: GC performance was monitored by running a lab standard extract at the beginning and end of each run, and running replicates (“bookends”) of IS extracts within the run to rule out chromatographic drift. In addition to the $U^{k'}_{37}$ index, we determined comparable C_{38} unsaturation indices for quality control; the signal noise of these determinations was less than for the $U^{k'}_{37}$ index, but they served a redundancy checks that would have indicated the presence of outliers possibly indicating compounds interfering with alkenones in GC analysis. Reproducibility was ~ 0.01 $U^{k'}_{37}$ units and ~5 % relative error for C37total. Estimates of alkenone paleotemperature follow calibration of Müller et al. (1998).

4.2 *Microfossils*

Analyses for planktonic foraminifera were carried out on the residue >150 μm after the sediment was dried and washed on a 63 μm sieve. The residues were split until a representative aliquot, containing about 300 specimens, has been obtained. The species abundances were quantified as percentages on the total number of planktonic foraminifers. Sixteen species or species groups were distinguished: *Globigerinoides ruber* includes morphotype *Globigerinoides ruber* white, and *Globigerinoides elongatus* (sensu Aurahs et al., 2011); *Trilobatus sacculifer* includes *Trilobatus trilobus*, *Trilobatus sacculifer* and *Trilobatus quadrilobatus* (sensu Hemleben et al., 1989; André et al., 2013; Spezzaferri et al., 2015). The SPRUDTS group (sensu Rohling et al., 1993) (*Globigerinella siphonifera*, *Hastigerina pelagica*, *Globoturborotalita rubescens*, *Orbulina universa*, *Beella digitata*, *Globoturborotalita tenella*, and *T. sacculifer*) and *G. ruber* were grouped as warm water indicators (foram-wwt). The criteria adopted for the taxonomy of *Neogloboquadrina* spp. are from Darling et al. (2006): *Neogloboquadrina incompta* corresponds to neogroboquadrinids previously referred to *N. pachyderma* (dextral) and includes intergrades between *N. pachyderma* (dextral) and *N. dutertrei*; *N. pachyderma* includes the left coiling specimens. It is a polar-subpolar taxon in the Northern Hemisphere (Bé and Tolderlund, 1971; Hemleben et al., 1989; Johannessen et al., 1994; Simstich et al., 2003; Darling et al., 2006) and has been found rare (< 5%) in central and eastern Mediterranean Sea during Pleistocene (e.g. Thunell, 1978; Rohling and Gieskes, 1989; Rohling et al., 1993; Hayes et al., 1999, 2005; Sprovieri et al., 2003, 2012; Triantaphyllou et al., 2009; Siani et al., 2010). Increases in the abundance of *N. pachyderma* has been used as a proxy of Atlantic cold (melt) water influx into Mediterranean (Hemleben et al., 1989; Pérez-Folgado et al., 2003; Sierro et al., 2005; Girone et al., 2013; Capotondi et al., 2016; Marino et al., 2018). *N. incompta* is a cold and eutrophic taxon, indicative of deep chlorophyll maximum at the base of the euphotic layer (Hemleben et al., 1989; Reynolds and Thunnel., 1989; Pujol and Vergnaud-Grazzini, 1995; Rohling et al., 1995). *G. bulloides*, due to its opportunistic behavior, has been used as an indicator of high nutrient content, the species preferring eutrophic condition related to upwelling, strong seasonal mixing or river input (Tolderlund and Bé, 1971; Hemleben et al., 1989; Pujol and Vergnaud Grazzini, 1995; Rohling et al., 1997; Bàrcena et al., 2004; Geraga et al., 2005, 2008). *G. inflata* has been used a proxy of cool-temperate waters, deep pycnocline, and ventilated conditions (Hemleben et al., 1989; Pujol and Vergnaud-Grazzini, 1995; Rohling et al., 1995; Barcena et al., 2004).

Slides for coccolithophore analysis were prepared according to Flores and Sierro (1997) to estimate absolute coccolith abundances. Quantitative analyses were performed using a polarized light microscope at 1000× magnification and abundances were determined by counting at least 500 coccoliths of all sizes, in a varying number of fields of view. Species abundances were expressed as percentage and as N (coccolith/gram of sediment). The warm-water taxa *Umbilicosphaera sibogae* s.l., *Calciosolenia* spp., *Discosphaera tubifera*, *Rhabdospaera clavigera*, *Umbellosphaera* spp., *Oolithotus* spp., *Helicosphaera pavimentum* were grouped together (nanno-wwt) according to their ecological preferences and their higher abundances during warmer and oligotrophic conditions (McIntyre and Bé, 1967; Winter et al., 1994; Ziveri et al., 2004; Baumann et al., 2004; Boeckel and Baumann, 2004; Saavedra-Pellitero et al., 2010; Palumbo et al., 2013; Maiorano et al., 2015; Marino et al., 2018). *Coccolithus pelagicus* ssp. *pelagicus*, a subartic taxon (Baumann et al., 2000; Geisen et al., 2002), was used as an indicator of cold meltwater influx in mid-latitude North Atlantic Ocean (Parente et al., 2004; Marino et al., 2011, 2014; Amore et al., 2012; Maiorano et al., 2015), even in Mediterranean basin (Girone et al., 2013; Maiorano et al., 2016a; Marino et al., 2018; Trotta et al., 2019). Increases of *Florisphaera profunda* that thrive in the lower photic zone were considered indicative of deep nutricline (Molfino and McIntyre, 1990). The taxon may also inhabit surface water when turbidity and low light occur due to too high surface detrital input and low light intensity (Ahagon et al., 1993; Colmenero-Hidalgo et al., 2004; Maiorano et al., 2008, 2016a; Girone et al., 2013). Taxonomy of gephyrocapsids follows the criteria of Maiorano et al. (2013). *Helicosphaera carteri* has been used as a proxy of enhanced detrital input, surface water turbidity and low salinity (Colmenero-Hidalgo et al., 2004), conditions associated to higher runoff and enhanced nutrients (Bonomo et al., 2018) or cold glacial phases and low sea level in Mediterranean Sea (Weaver and Pujol, 1988; Colmenero-Hidalgo et al., 2004; Maiorano et al., 2013, 2015, 2016b; Marino et al., 2018).

5. Results

At the IS, SST pattern records values between 12 and ~22°C (Fig. 2D). The lower SSTs characterizes the lower part of the studied section (MIS 20), substage MIS 19b and the stadial episodes in MIS 19a. On the other hand, higher temperatures are recorded in MIS 19c and interstadials 19a-1, 19a-2, and 19a-3 (Fig. 2D). Calcareous plankton key taxa used here for paleoenvironmental reconstruction show relevant fluctuations throught time. Total coccoliths (tot N, Fig. 2F) have abundance mainly lower than 20 coccoliths/g (x 10^7) in MIS 20 and during TIX, and lower than 30 coccoliths/g (x 10^7) from MIS 19b towards the end of the studied section, with slightly increases up to 40 coccoliths/g (x 10^7) during interstadials in MIS 19a. Total N has higher values, up to 100 coccoliths/g (x 10^7), during MIS 19c. Coccolithophore wwt (nanno wwt, Fig. 2G), although low in abundance throughout the section, has fluctuating increases in MIS 19c and interstadial 19a-2, with abundance never higher than 0.5 coccoliths/g (x 10^7). *F. profunda* generally has abundance lower that 1 coccoliths/g (x 10^7) while it shows major fluctuating increase up to 3.2 coccoliths/g (x 10^7) in MIS 19c (Fig. 3D). *Syracosphaera* spp. are a minor component of coccolithophore assemblage (Fig. 3F), however they records a distinct abundance peak of 0.5 coccoliths/g (x 10^7) in the lower MIS 19c. The percentage abundances of planktonic foraminifera wwt (Fig. 2H) vary between 5 and 80% and depict glacial-interglacial and stadial-interstadial episodes with a few short-term minor increases during TIX. In particular, the relative abundances of *T. trilobatus* reach 3.5% in MIS 19c and MIS 19a-2 interstadial (Fig. 2H); *G. ruber* is a significant component reaching relative abundances up to 72% mainly starting from MIS 19c upwards (Fig. 3G). The polar-subpolar *C. pelagicus* ssp. *pelagicus* and *N. pachyderma* are more abundant, with vaules up to 22% and 5%, respectively, in MIS 20, during TIX and in MIS 19b as well as in colder phases of MIS 19a (Fig. 2 K-L). *H. carteri* shows a comparable pattern (Fig. 2M) with fluctuating relative abundances lower than 7.5%. *N. incompta* has discontinuous relative abundance, with peaks up to 17% in MIS 20 and TIX, in lower MIS 19c, and in short-term intervals of MIS 19a, while it is absent in the upper MIS 19c (Fig. 2I). *G. bulloides* is continuously present throughout the IS and shows variable abundances, which seem to increase in the upper portion of IS (Fig. 2J). *G. inflata* records higher abundances, up to 80%, in distinct periods of TIX and in the stadials of MIS 19a, whereas it is absent in MIS 19c and interstadial phases (Fig. 2N). *O. universa* shows abundance variations during the investigated interval, with more proninent peaks, up to 27%, in selected short-term intervals of TIX and in MIS 19a interstadials.

6. Discussion

Results are discussed starting from the lower portion of the studied record upwards focusing on environmental changes occurred in late MIS 20 and TIX (Fig. 2) to MIS 19 onset (Figs 2-3), and towards MIS 19b-19a, and MIS 18 beginning (Fig. 2). Comparisons with climate proxies from other extra-Mediterranean reference sections are presented in fiugre 4.

6.1 Environmental changes through late MIS 20: the terminal stadial event Med-H$_{TIX}$

The lower part of the studied section (800-794 ka) is characterized by fluctuating values of SST between ~ 16 and 20°C (Fig. 2D). Upward, between 794 and 788.5 ka, a terminal stadial (sensu Hodell et al., 2015), hereafter named Med-H_{TIX}, may be recognized, primarily based on the SST decreases and the polar-subpolar *N. pachyderma* and *C. pelagicus* ssp. *pelagicus* increase (Fig. 2 K-L). In more details, SSTs were at least 4-5°C cooler than pre-Med-H_{TIX} (17-21°C) with fluctuating values mainly below 16°C, and minimum at 13°C. These values are compatible with Δ^{47}-derived subsurface temperature of 12.1°C measured on benthic foraminifera at 794 ka (Peral et al., 2020). *C. pelagicus* ssp. *pelagicus* and *N. pachyderma* increase from percentages mainly below 3% and 10%, to values up to 5% and 20%, respectively. The concomitant low abundances of planktonic foraminifera wwt (Fig. 2 G-H) are coherent with colder sea surface water conditions in the basin linked to Med-H_{TIX}, lasting about 5 kyr at the IS. The pollen assemblages at the IS indicated a synchronous large expansion of open landscapes including prevalent (cold) dry steppes on land (Bertini et al., 2015).

6.1.1. Possible oceanographic and atmospheric processes during terminal stadial Med-H_{TIX}

The decreasing trend of temperature in latest MIS 20 is accompanied by a similar pattern of benthic $\delta^{13}C$ (Fig. 2P) suggesting an increasing trend of water column stratification. On the other hand, the terminal stadial is not accompanied by higher $\delta^{18}O$ values, as it may be expected during a very cold phase. The $\delta^{18}O_{M. barleeanum}$ records a lightening of 1‰ (Fig. 2C) that could reflect the influx of lighter fresh water at the site location, possibly lowering salinity down to the sea bottom and then affecting oxygen isotope composition in the *Melonis barleeanum* tests. This process was possible due to the shallow depth (~ 100m, Aiello et al., 2015) of depositional setting of IS at this time, during glacial low sea level (Fig. 2B).

The occurrence of cold and fresher waters at the location of IS may reflect the arrival of melt waters coming from mountain glaciers of the close hinterland (Alpine and Apennines chains), as during the last termination (Maselli et al., 2011). Alternatively, fresher water inflow into the Ionian Sea associated with North Atlantic ice melting may have occurred through the Gibraltar Strait, such a scenario being coherent to what has been observed in the western Mediterranean during recent glacial stadials correlated to Heinrich event in North Atlantic (e.g. Cacho et al., 1999; 2000; Sierro et al., 2005; Frigola et al., 2008; Martrat et al., 2014). In support of our interpretation at the IS are the data from the Balearic Sea (Quivelli, 2020); they indicate cold fresh water inflow from Atlantic or surrounding mountain glacier during the terminal stadial of MIS 20, based on the increases of polar-subpolar *N. pachyderma* and tetra-unsaturared alkenones ($C_{37:4}$), and lower alkenone-derived SST, the last recording values between 8 and 11°C. Analogous evidences of Heinrich-type (Ht) events in the Alboran (Marino et al., 2018), Balearic (Girone et al., 2013; Maiorano et al., 2016b), and Ionian (Maiorano et al., 2013; Capotondi et al., 2016) basins, during the glacial MIS 12 and MIS 10, have been suggested based on calcareous plankton. Similarly, lighter planktonic $\delta^{18}O$ values and calcareous plankton assemblages suggested the arrival of Atlantic water in the central Mediterranean during main terminations of the last 70 ka (Sprovieri et al., 2012; Incarbona et al., 2013).

The arrival of melt waters in the Ionian basin during Med-H_{TIX} has a close temporal relationship with the deposition of ice rafted debris (IRD) in the North Atlantic. Iceberg discharge and North Hemisphere ice sheet instability have been in fact documented by the IRD peaks and low $\delta^{13}C_{benthos}$ values at the sites 980 (Wright and Flower, 2002) and 983 (Kleiven et al., 2011) (see Fig. 4 O-Q), signifying time of water column stratification and shutdown of Atlantic Meridional Overturning Circulation (AMOC) (Ganopolski and Rahmstotf, 2001). We suggest that the Med-H_{TIX} in the late MIS 20 at the IS is coherent with the contemporaneous oceanographic and climate signals at the southwestern Iberian margin and northern Atlantic (Fig. 4). During late MIS 20 or TIX there is no evidence of ice rafted detritus (IRD) at the mid-latitude Iberian margin, a sensitive area that recorded IRD occurrence during colder episodes of the mid-Pleistocene glacials (Stein et al., 2009;

Voelker et al., 2010; Rodrigues et al., 2011). However, clear indications of low salinity and cold melt water inflow have been recently documented in that area, at the Site U1385, during late MIS 20 (Rodrigues et al., 2017). Low alkenone-SST (between 12 and 9°C, Fig. 4N) and higher $C_{37:4}$ (Fig. 4M) occurred at this time (Rodrigues et al., 2017), and a peak of *N. pachyderma* was found, centered at about 790 ka (Martin-Garcia et al., 2018), as a signal of southward migration of Polar Front. This very cold period is nearly synchronous, within the uncertainty of the different age models, with the polar-subpolar *C. pelagicus* ssp. *pelagicus* and *N. pachyderma* increases and alkenone-SST decrease at the IS (Fig. 2D) during the Med-H_{TIX}. At the same time, the minima in $\delta^{13}C_{benthos}$ (Fig. 4L) and in log Ca/Ti patterns at the Iberian margin U1385 core (Fig. 4K) (Hodell et al., 2013, 2015) point to North Atlantic low bottom water ventilation, due to reduced North Atlantic Deep Water formation (Raymo et al., 1990, 1997), and the occurrence of a cold stadial. Such oceanographic conditions have been interpreted as similar to those occurring during the conventional Heinrich events H1 and H2, and older ones (Hodell et al., 2015). These evidences imply a clear Mediterranean response to high latitude North Atlantic climate change through oceanographic connection during mid-Pleistocene stadials.

The slightly warmer temperatures at the IS, compared to those recorded at the same time in the southwestern Iberian margin (Fig. 4N) and Balearic basin (8-11°C; Quivelli, 2020), may be a result of the west-east SST (and salinity) increase of MAW during its eastward route in the Mediterranean (Bélthoux, 1979; Malanotte-Rizzoli et al., 1999, 2014; von Grafenstein et al., 1999; Pinardi and Masetti, 2000). Similar temperature gradient from west (Alboran Sea, ~10-11°C, Cacho et al., 2001; Martrat et al., 2014) to east (Tyrrhenian Sea, 11-14°C, Paterne et al., 1999; eastern Mediterranean, 14-16°C, Castaneda et al., 2010) was also recorded during H1.

The cold climate frame reconstructed for the Med-H_{TIX} based on our marine proxies may have been also controlled by Atlantic-Mediterranean connection via atmospheric processes. Although the past atmosheric dynamic is difficult to be known, relatively more arid climate has been inferred at the IS during H-t in MIS 20 based on pollen assemblages (Bertini et al., 2015; Maiorano et al., 2016a). This is in agreement with the general arid conditions associated to recent Heinrich events (Allen et al., 1999; Combourieu-Nebout et al., 2002; Sánchez Goñi et al., 2002; Naughton et al., 2016). Reduction of evaporation and precipitation has been also proven to occur even in the eastern Mediterranean during the Heinrich events (Bartov et al., 2003; Kwiecien et al., 2009).

Specifically, cold and dry Arctic air masses could have penetrated into the Ionian Sea during the winter season, similarly to what occurred during recent glacial cycles in the central and eastern Mediterranean region, and contributed, through enhanced north-westerly winds, to enhance winter deep water mixing and ventilation. Such winter deep water mixing and ventilation occured in the Mediterranean during North Atlantic Heinrich stadials and shutdown of AMOC (Cacho et al., 1999, 2000; Sierro et al., 2005; Frigola et al., 2008). The cold stadial phase during late MIS 20 in North Atlantic surface waters, as recorded by lower SST on the Iberian Margin (Fig. 4N) (Rodrigues et al., 2017), likely (i) reduced the evaporation and moisture content in air masses advected towards the Mediterranean region, promoting a cold and drier period, and (ii) induced more efficient north winter winds, and lower surface water temperature in the Ionian basin. This may have favored the proliferation of cold calcareous plankton taxa in sea surface water, as discussed above, and the arid conditions on land documented by pollen data at the IS (Bertini et al., 2015; Maiorano et al., 2016a). This seems in line with the higher aridity (Sánchez Goñi et al., 2016) recorded at the U1385 (Fig. 4O). Similar atmospheric mechanisms linked to North Hemisphere ice-sheet dynamics have been suggested by Regattieri et al. (2019) to explain the high frequency climate changes displayed in the Sulmona lacustrine sediments in central Italy during MIS 19. Also, oceanic circulation and atmospheric processes related to ice-sheet dynamics in the North Atlantic have been pointed out by Nomade et al. (2019) as possible drivers of millennial-scale climate variation at the IS section during stadials and interstadials in MIS 19b-a.

Therefore, we believe that the Atlantic colder climate phase in late MIS 20 may have affected the Ionian basin climate by advection of subpolar low-salinity water through the Gibraltar Strait, and polar air outbreaks over the Mediterranean (e.g. Allen et al., 1999; Cacho et al., 1999, 2006; Rohling et al., 2002; Frigola et al., 2008; Rodrigo-Gámiz et al., 2011; Sprovieri et al., 2012).

Centennial-scale variability and environmental instability are recorded by marine proxies within the Med-H_{TIX}, specifically in the oscillating SST values, with differences of temperatures up to 4°C, and in the fluctuations of key calcareous plankton taxa (Fig. 2). In more detail, *N. pachyderma* shows two main abundance peaks (Figs. 2K, 4E) that are surprisingly nearly coeval with two prominent lows in the $\delta^{13}C_{benthos}$ at the Site U1385 (low deep water ventilation, slowdown of AMOC) (Fig. 4L). There, also SST and $C_{37:4}$ (Fig. 4 M-N) show a pattern with two phases of low and high values, respectively (colder and fresher/melting waters). A two-fold pattern is additionally visible in the sea level curve (Fig. 2B) which shows two minima (although in a slightly different timing due to independent age models), that would be coherent with times of higher Atlantic meltwater and polar taxa influx. On the contrary, in the middle of Med-H_{TIX}, *G. inflata* (Fig. 2N) has fluctuating higher abundances, concurrent with fluctuating lower $\delta^{18}O$, indicating time of quite restored MAW inflow and periodic declines in the Atlantic meltwater arrival at the Mediterranean, possibly related to a short phase of less prominent low sea level (Fig. 2B). These data further sustain an Atlantic-Mediterranean hydrological connection even at shorter temporal scale. This variability, within the Med-H_{TIX}, is in line with abrupt changes recorded in Mediterranean Sea during climate phases correlated to Atlantic Heinrich events (Frigola et al., 2008; Martrat et al., 2014; Bazzicalupo et al., 2018). The centennial-scale variability seems to be a regular climate pattern of Heinrich events, when investigated at very high-resolution, as sustained by the moisture spells within the cold and arid H1 event on the northwestern Iberian margin (Naughton et al., 2011, 2016) and Iberian peninsula (Camuera et al., 2019), based on pollen signals. In the IS the multiple, centennial-scale changes may also be associated to discontinuous meltwater influence from mountain glaciers of southern Apennines through rivers or from Alpine chain through WAC. In fact, meltwater pulses from Italian peninsula chains have been documented during last termination and specifically from Alpine glaciers in the Adriatic Sea (Maselli et al., 2011).

6.2 Climate variability throughout Termination IX

Following the Med-H_{TIX}, the sea surface water interglacial warming, starting at about 785 ka, is preceded by an evident climate variability that is visible in the patterns of SST and selected calcareous plankton proxies (Fig. 2).

6.2.1 Med-BA_{TIX} and Med-YD_{TIX} events

The decrease of *C. pelagicus* ssp. *pelagicus* (Fig. 2L) and *N. pachyderma* (Fig. 2 K) and the remarkable peaks of *O. universa* (up to 25%) (Fig. 2O), together with the prominent increase of *Globorotalia inflata* (up to 80%) (Fig. 2N), represent the first signal of the climate amelioration during sea level rise, and may be associated to a Bølling-Allerød-like event (hereafter Med-BA_{TIX}). Decrease of Cupressaceae and increase of dinocysts *S. mirabilis/hyperacanthus*, the latter known to benefit from sea surface temperature between 10 and 15 °C during winter and between 15 and 22 °C during summer, confirm a climate amelioration (Maiorano et al., 2016a). This climate phase is now further supported by the alkenone-SST pattern, which records a distinct temperature increase of ca. 3°C, up to 17.6 °C, from 788.4 to 786.1 ka, resembling the Bølling-Allerød-4°C increase of the last termination in the western Mediterranean (Martrat et al., 2014). The SST profile during Med-BA_{TIX} marks a warming in the first phase followed by a cooling trend, and does not show distinct multiple oscillations like those occurred during the BA of last termination (NGRIP, 2004) that however recorded a similar general temperature decline. Nevertheless, looking in more detail at the planktonic foraminifera key taxa within the Med-BA_{TIX}, the opposite pattern between *O.*

universa and *G. inflata* may be observed, and could suggest that warm and freshening surface water conditions alternated in the region with period of normal salinity. *O. universa* in fact has a broad salinity tolerance and is most abundant in the vertically mixed layer and nutrient-rich areas of the low to mid-latitudes (Be, 1977; Fairbanks et al., 1982; Pujol and Vergnaud Grazzini 1995; Morard et al., 2009). This taxon, during TI, calcified in low salinity waters derived by year-round return of meltwater before and after the main climate deterioration at the H1 and YD events (Spero and Williams, 1990; Vetter et al., 2017). Therefore, we infer that the occurrence of *O. universa* at the IS in the early and late portions of Med-BA$_{TIX}$ may be evidence of short-term climate amelioration that destabilized and melted the local ice caps of the Apennines/Alpes areas leading to increased river runoff, which caused lower sea surface salinity, increase of detrital input and nutrient into the basin, preventing enhanced proliferation of warm and oligotrophic taxa (Fig. 2 G-H). Only the opportunistic species such as *O. universa* could have found suitable environmental conditions to proliferate. On the contrary, *G. inflata*, thriving under normal salinity conditions, has higher abundance in the mid Med-BA$_{TIX}$, since this species undergoes vertical migrations from shallow to intermediate water depths with low vertical salinity gradients (Martinez et al., 2007). Therefore, its occurrence could attest the deepening of pycnocline and a short-term recovery of the Atlantic-Mediterranean exchange during sea level rising (Fig. 2B), in agreement with increased influx of low latitude Atlantic waters during Bølling-Allerød (Sprovieri et al., 2003; Lirer et al., 2013). Because the low-resolution pollen data at the IS do not indicate changes toward wetter condition, it is difficult to understand if the arrival of the freshwater was also supplied by wetter climate on land, but this, although at speculative level, cannot be excluded. In fact, humid climate conditions during the BA at the TI characterized the central and eastern Mediterranean areas (e.g., Combourieu-Nebout et al., 1998; Allen et al., 1999; Frisia et al., 2005; Giraudi et al., 2011; Goudeau et al., 2014) and western basin (Combourieu-Nebout et al., 2009; Bazzicalupo et al., 2018), during rapid sea level rising after the H1 event and before the sapropel S1 formation (Roussakis et al., 2004; Kontiokis, 2016). Similarly, a sapropel occurs in the IS following TIX (see next section).

Upwards, the following and gradual SST decrease of ca 2.5°C centered at 785.8 ka, together with short-term increases of the polar-subpolar *N. pachyderma, C. pelagicus* ssp. *pelagicus,* and of *N. incompta* (Fig. 2), sustain a very short-term cool spell, before interglacial warming inception, that is interpreted as a Younger Dryas-like event (hereafter Med-YD_{TIX}), in agreement with Maiorano et al. (2016a). A slight but distinct increase of benthic $\delta^{13}C$ (Fig. 2P) during the Med-YD_{TIX} marks a short-term restored sea bottom ventilation and deepening of mixed layer before the MIS 19c onset. Such environmental condition may have been driven by more efficient winter winds during an arid period, in agreement with the decreased precipitation/rainfall recorded in the central Italy during the coeval "YD" at TIX (Giaccio et al., 2015). Evidence of cold condition (abundance peak of *C. pelagicus* ssp. *pelagicus*) and enhanced onland erosion (higher reworked coccoliths and lithic elements) have been also recorded, based on coccolithophore assemblages, at the nearby Ionian core KC01B at the same time, following a short term warming referred to a Bølling-Allerød-type episode (Trotta et al., 2019). Similar sequence of warm and cold short term episodes just before the MIS 19c onset has bee recognized in Balearic basin based on calcareous plankton assemblages and alkenone-SST (Quivelli, 2020), thus attesting high-frequency climate changes through TIX at the scale of Mediterranean basin.

The millennial climate variability across the MIS 20-MIS 19 deglaciation, that can be reconstructed in the IS, improves our understanding of climate evolution during terminations. Such high frequency changes seem to be a shared feature of most terminations over the last 800 ka (Barker et al., 2019), especially during times of intermediate glacial ice volume, as it is the case of MIS 20, and transitions between glacial and interglacial state (Ruddiman et al., 2016).

6.2.2 Comparison of TIX between Ionian and Atlantic records

On the whole, the new data set that we obtained through TIX (Med-BA_{TIX} and Med-YD_{TIX}) at the IS reinforces the working hypothesis that there should be a strong similarity between TIX and TI recorded in the Mediterranean Sea (Capotondi et al., 1999; Sbaffi et al., 2001; Asioli et al., 2001; Di Stefano and Incarbona, 2004; Siani et al., 2010, 2013; Geraga et al., 2010; Rouis-Zargouni et al., 2010; Castañeda et al., 2010; Kontakiotis, 2016; Bazzicalupo et al., 2018).

Although analogy with Bølling-Allerød-type and Younger-Dryas-type episodes has not been inferred so far in oceanic waters out of the Mediterranean during TIX, and because we have associated such millennial variability at the IS with North Atlantic climate, we compared our results to selected high-resolution North Atlantic sedimentary records (Fig. 4). They evidence instability in surface and subsurface waters and in climate on land during the MIS 20-19 transition (Fig. 4 H-I, K-L, O, R-S, pink bands). Specifically, oscillations may be observed in the final decreasing trend of semi-desert Mediterranean Taxa at the core U1385 (Sánchez Goñi et al., 2016) (Fig. 4O) just before the very low values occurring during MIS 19c. During this unstable phase, the $\delta^{13}C_{benthos}$ and log Ca/Ti curves indicate short-term climate variations at the Iberian margin in terms of Atlantic Ocean deep-water ventilation/stratification, temperature, and marine productivity, respectively. Vegetation (Fig. 4 H, O) similarly records distinct, although low amplitude fluctuations before the Tajo phase; moreover, a cold spell event occurring during deglaciation is discussed in Sánchez Goñi et al. (2016) (black arrow in Fig. 4H). These oscillations (pink band in Fig. 4) likely sign the equivalent climate variability at the IS through TIX, and therefore a common high frequency variability across TIX between Iberian margin and central Mediterranean records. Similar fluctuations are shown by the $\delta^{18}O_{plankton}$ and $\delta^{13}C_{benthos}$ at the northern Atlantic Site 983 (pink band in Fig. 4 R-S), once more suggesting short-lived changes in temperature, salinity and deep-water ventilation, and in AMOC strength. This unstable phase has been interpreted as a result of no full recovery of ocean circulation (AMOC interglacial mode) and decrease of atmospheric CO_2 (Ruddiman et al., 2016; Barker et al., 2019). Therefore, a link between North Atlantic (AMOC instability) and central Mediterranean climate during deglaciation MIS 20-MIS 19, similarly to MIS 20 terminal stadial phase, may be inferred. However, a full rigorous discussion on the relationships between the different climate proxies or on the timing and propagation of climate signals during TIX among the different areas needs additional investigations. In fact, the climate instability evidenced on the Iberian margin before the Tajo phase and specifically the cold spell in the Mediterranean Forest Pollen (arrow in Fig. 4H) could be correlated to the cold and dry "event 1" in the IS in the earliest MIS 19c as suggested by Asteraceae peak (Bertini et al., 2015; Marino et al., 2015; Maiorano et al., 2016a) and the reduction of Mediterranean Mesothermic Taxa (arrow in Fig. 4F).

6.3 The Ionian Sea "ghost sapropel"-insolation cycle 74

Following the Med-YD_{TIX} event, in the lowermost climate optimum of MIS 19c (Fig. 2), the SST record reveals a quite sharp increase up to 16.5°C at 785 ka together with higher foram-wwt, very close to the mean summer insolation maximum (785.4 ka). While, total N (Fig. 2F) and nanno-wwt (Fig. 2G) do increase just above, suggesting that favorable condition (stable and oligotrophic) for the calcareous phytoplankton did occur not before 784 ka, when temperatures were higher than 18.5 °C (Fig. 2D). The correlation index between total N and alkenone-SST and between nanno-wwt and alkenone-SST are quite positive, respectively +0.57 and + 0.45, and this may suggest that not only temperature but also specific trophic condition may have influenced coccolithophore productivity. The environmental conditions in the early MIS 19 at the IS have been associated (Maiorano et al., 2016a) with the occurrence of the shallow-water analogue of the "red interval" ("ghost sapropel", oxidized sapropel, Emeis et al., 2000a), i-cycle 74 (784 ka, Lourens, 2004; 785 ka, Konijnendijk et al., 2014). The very low values in $\delta^{13}C_{C.carinata}$ also supported such interpretation (Nomade et. al., 2019) (Fig. 3I). Here, some additional elements, specifically the peculiar higher abundance peaks of selected taxa (Fig. 3 D-G), may help in revealing the double environmental signature of the ghost sapropel. During the low $\delta^{13}C_{C.carinata}$ values, a general high *G. ruber* abundance is recorded (Fig. 3G), indicative of warm oligotrophic and stratified surface waters (Bé and Hamlin, 1967; Bé, 1971; Bé and Tolderlund, 1971; Hemleben et al., 1989; Pujol and Vergnaud-Grazzini, 1995). However, the taxon shows a distinct decrease at 783.5 ka signifying a short-lived environmental change. At the same time, on the contrary, *F. profunda* and *Syracosphaera* spp. (Fig. 3D, F) show a prominent peak, perfectly concurrent with the $\delta^{13}C_{C.carinata}$ minimum (Fig. 4I). *Syracosphaera* spp. is capable to tolerate less saline and turbid surface water (Weaver and Pujol, 1988; Colmenero-Hidalgo et al., 2004; Maiorano et al., 2013, 2016a, 2016b), while *F. profunda* may thrive in low light surface waters when high turbidity and nutrient availability drive the taxon upwards (Ahagon et al., 1993; Colmenero-Hidalgo et al., 2004; Maiorano et al., 2008, 2016a; Girone et al., 2013). These combined patterns at 783.5 ka suggest enhanced runoff/organic matter input from surrounding hinterland, close to insolation maximum and North Africa monsoon strengthening, promoting enhanced low oxygen conditions and organic matter preservation at the sea floor. *G. bulloides* (Fig. 2 J), that records a contemporary prominent abundance peak at 783.5 ka and an opposite pattern with respect to $\delta^{13}C_{C.carinata}$ during sapropel deposition, may have been favored in such condition as it is an opportunistic species that proliferates in eutrophic condition. Accordingly, low total coccolitophore abundance (Fig. 2F) is likely related to turbidity increase by river terrigenous input in the Montalbano Jonico basin also supported by coarser sediment at this time (Maiorano et al., 2016a), during insolation maximum. The enhanced detrital input is a common signature observed during sapropel layers in the MJS as indicated by the increase of Al and decrease of CaO in the older sapropels i-cycles 112, 102, and i-c 86 in the lower portion of the section (Fig. 1C) (Girone et al., 2013; Maiorano et al., 2008). Starting from the $\delta^{13}C_{C.carinata}$ minimum and the decreasing trend of *G. bulloides,* stable and oligotrophic surface water conditions restored. The sharp increase of total coccolithophore assemblages and nanno-wwt (Fig. 2F) indicates warmer and more stable surface water conditions with respect to the first phase of sapropel. A very short-term peak of *Braarudosphaera bigelowii* (Fig. 3E), although with low abundances, marks a low salinity spell at the end of sapropel, concurrent with increasing trend of $\delta^{13}C$ (Fig. 3I), in agreement with data of Narciso et al. (2010) for the end of sapropel S5 during MIS 5.5 in the Adriatic Sea.

It is worth to note that recently an organic rich layer (ORL) has been recognized, for the first time, in the Balearic Sea at the TIX (Quivelli et al., 2020), supporting the basin scale event occurrence and the not in phase ORL and sapropel deposition in the western and eastern Mediterranean (Rogerson et al., 2008).

6.4 Was MIS 19c a stable full interglacial?

During MIS 19c, higher SST and calcareous plankton warm water taxa, and enhanced values of total coccolith production (> 60 and up to 100 coccoliths/g x 10^7) (Fig. 2D, F-H), starting from the post sapropelic layer, are evidence of climate amelioration and warmer oligotrophic sea surface waters. SST values, mainly between 18 and 21.9°C (Fig. 2D), are very similar to modern ones, and are similar to Holocene values in the region (Alkenone-SST, Emeis et al., 2000b) and in the western Mediterranean (Alkenone-SST, Cacho et al., 2001; Martrat et al., 2014). However, they are lower than in the easternmost Mediterranean (TEX86-SST, Castañeda et al., 2010) and Red Sea (Alkenone-SST, Arz et al., 2003) where Holocene SSTs are higher, as expected, ranging from about 24 °C to 27-28 °C. A higher temperature value (25 °C) has been provided by Peral et al. (2020) at the IS based on *G. ruber*-Mg/Ca estimate in one sample from MIS 19, at the level just above the end of sapropel (~781.5 ka). Nevertheless, the authors discuss possible biases of the Mg/Ca method in the Mediterranean Sea.

Two subtle phases may be distinguished at the IS during MIS 19c based on planktonic foraminifera. The first phase, starting about 2 ka after the end of sapropel up to 780 ka, was characterized by seasonal contrast with slightly lower winter temperatures, which were able to induce mixing and advection of nutrients to the surface waters, and the development of seasonal

DCM over warm, well stratified and oligotrophic waters in summer. This inference is based on the occurrence of *N. incompta* (Fig. 2I), and, although with very low abundances, of *G. inflata* (Fig. 2N). Similar condition immediately after the end of S1 has been documented in all records from eastern Mediterranean, Adriatic and Ionian basins during the Holocene (Rohling et al., 1997; Capotondi et al., 1999; de Rijk et al., 1999; Geraga et al., 2000; 2008). The second phase of MIS 19c at the IS, from about 780 ka to the end of full interglacial, is characterized by the absence of *N. incompta* and *G. inflata* in relation to higher abundances of *G. ruber* (Fig. 3G), suggesting that during the late MIS 19c the prevailing environmental conditions in the Ionian basin were closer to those of the modern Levantine basin than to the modern western Mediterranean Sea. Such a frame may be associated to a more permanent cyclonic regime in the Ionian Sea (Fig. 1D) leading the northern internal border of the basin under the direct influence of poor-nutrient LIW (Civitarrese et al., 2010). This is consistent with the modern regional distribution of *G. inflata* that it is absent in the northern Ionian Sea (Mallo et al., 2017; Di Donato et al., 2019) but occurs in the southern basin following the path of Atlantic waters that, under cyclonic regime, does not arrive in the northern sector of the basin. The distribution of *G. inflata*, during MIS 19c seems similar to its pattern during Holocene in the northern Ionian Sea. There, during the last 6 kyr, starting from about 2 ka after the end of S1 deposition (like at the IS after sapropel i-cycle 74), *G. inflata* is absent, with the exception of short incursions during period of reversed circulation (Di Donato et al., 2019), which depends upon variations in the atmospheric forcing on cyclonic-anticyclonic oceanographic regime (Poulin et al., 2012).

Higher frequency variable environmental conditions may be distinguished in the uppermost surface waters looking in more details at the patterns of the main climate proxies during MIS 19c. Specifically, six oscillations in about 11 kyr may be observed in total N and SST curves (Fig. 2D, F). These in-phase fluctuations, if smoothed-out by a 5-points running average, appear as three main warmer phases (violet arrows in Fig. 2D, F-G). The curve of Mediterranean Mesothermic taxa at the IS (Fig. 2 E), although at low resolution, seems to record a similar pattern as well, almost in phase with the three higher alkenone-SST in MIS 19c, pointing to an in-phase high climate variability in both marine and continental settings, and then implying both oceanographic and atmospheric processes. The main increases of Mediterranean Mesothermic taxa at the IS (Fig. 2E) may be linked to southward westerly shift and higher winter precipitation in south Europe and Mediterranean basin (Wagner et al., 2019), perhaps in analogy to processes operating like the modern or recent North Atlantic Oscillation mode (Xoplaki et al., 2003; Moreno et al., 2002, 2004, 2005; Hurrel et al., 2004; Roberts et al., 2008; Fletcher et al., 2009; Ulbrich et al., 2012). The main increases of nanno-wwt in sea surface water (Fig. 2G) would be the result of increased inflow of warm tropical-subtropical waters through the Gibraltar Strait toward central Mediterranean.

Additional seasonal climate insights derive from the distribution pattern of foraminifer *Trilobatus sacculifer* (Fig. 2 H), a tropical-subtropical taxon (Bé, 1977; Vincent and Berger, 1981) that has a peculiar occurrence in MIS 19c, showing multiple oscillations and an opposite distribution with respect to *G. ruber* (Fig. 2S). This pattern could be related to low seasonality and milder winters (Bé and Hutson, 1977; Fraile et al., 2008; Hemleben et al., 1989; Vincent and Berger, 1981), or to short term periods of relative less humid conditions; this in accordance with findings during the mid Pleistocene interglacial MIS 11 (Maiorano et al., 2016b; Marino et al., 2018) and Holocene in the Mediterranean and Red Sea basins (Piva et al., 2008; Edelman-Furstenberg et al., 2009). The inferred periods of less humid conditions during the two major peaks of *T. sacculifer* are supported by the correlative phases of reduction of Mediterranean Mesothermic taxa, especially in the upper MIS 19c (Fig. 2).

The unstable climate character of MIS 19c climate has been recorded in the high-resolution records from central Italy Sulmona sediments and at the U1385, and related to North Atlantic oceanic-atmospheric-climate processes (Sánchez Goñi et al., 2016; Regattieri et al., 2019). In particular, three main increases of the Mediterranean Forest Pollen during Tajo phase were detected on the Iberian margin similarly to what occurs in the MIS 19c at the IS, whereas a decoupled response between terrestrial (pollen, Fig. 4 H, O) and marine ($C_{37:4}$, alkenone-SST, Fig. 4 M-N) signals (the latter recording a certain stability throughout the entire full interglacial) was evidenced at Site U1385. This was explained as a direct and synchronous response of Iberian vegetation to northern Atlantic climate via atmospheric process (like at the IS), whereas sea surface temperatures remained almost stable at the location of core U1385 due to the effect of warm retaining of subtropical gyre (Repschläger et al., 2015), even during reduced Mediterranean Forest Pollen (Fig. 4H) (Sánchez Goñi et al., 2016). It is possible that during MIS 19c the common feature of vegetation patterns, as recorded in IS and Iberian margin, was a shared response to atmospheric processes that in concert also influenced the marine proxies (SST, total N and coccolithophore wwt) in the Ionian Sea, contrary to what happened in the Atlantic waters west of Iberia.

6.5 The stadial-interstadial phases in MIS 19b-a

The first signal of climate deterioration at the end of full interglacial MIS 19c occurs at ~773-774 ka when alkenone-SST displays a prominent drop of about 8-9°C with a minimum of 12.1°C at 772.8 ka; this temperature drop is even stronger than in Med-H_{TIX}. Warm water taxa decrease at the same time (Fig. 2 D, G-H), thus marking the first significant cooling and the substage MIS 19b, synchronous with the first enrichment of $\delta^{18}O$ values (Figs. 2, 4). MIS 19b is very distinctive in the IS, being very close to the Ar/Ar dated V4 and $^{10}Be/^{9}Be$ peak (interpreted as the Earth magnetic field collapse during the Matuyama-Brunhes reversal, Simon et al., 2017), and associated to the beginning of polar ice-sheet increase and instability (Maiorano et al., 2016a), synchronously with the first IRD occurrence after full interglacial MIS 19 in northern Atlantic (Kleiven et al., 2011). At this time, the Mediterranean Mesothermic taxa (Fig. 2E) decrease while the steppic and halophyte vegetation advance at the IS, highlighting cold and arid condition over the central Mediterranean hinterland (Bertini et al., 2015). A quite concurrent slight increase of semi-desert vegetation centered at ~772.6 ka (Fig. 4O) and decrease of Mediterranean Forest Pollen (Fig. 4H) occur at the core U1385, suggestive of a cooling/arid episode on the southwestern Iberian. On the other hand, no coeval noticeable variation occurs in the alkenone records at the Site U1385 (Fig. 4M-N). Our data set at the IS seems to underline that at the time of MIS 19b the response of calcareous plankton (Fig. 2F-G, L) and alkenone-SST (Fig. 2 D) is clearly in phase with the vegetation response (Fig. 2 E), and both are in phase with the pollen data at the Iberian margin (Fig. 4M, O). While at Site U1385 the subtropical gyre was responsible for the still presence of warm waters, a southward influx of cold and dry arctic air masses towards the IS location promoted efficient cooling of both marine and terrestrial environments, maybe more efficiently than during Med-H_{TIX}. It is possible that continental cold and dry air flux by enhanced Siberia High (SH) pressure had a role in the central Mediterranean at this time. An equivalent pattern is seen in the Holocene record in the eastern Mediterranean, where intensified SH has been suggested for the cold and dry spell at 8.2 ka (Pross et al., 2009). Accordingly, rapid transmission of high latitude Arctic/North Atlantic perturbations to the northwestern and eastern Mediterranean has been documented in several studies for recent and past severe cold events (Leaman and Scott, 1991; Mariolopoulos, 1961; Poulos et al., 1997; Rohling et al., 1998, 2002, 2009; Casford et al., 2001; Melki et al., 2009) and they would support our environmental reconstruction for MIS 19b.

Above MIS 19b, the most prominent feature of climate evolution in the IS is the occurrence of multiple oscillations in all climate proxies (Figs 2, 4) that are related to the reestablishment of millennial-scale variability and, presumably, of the bipolar seesaw (Tzedakis et al., 2012). This climate trend toward the glacial stage 18 onset is very well recorded at the IS, as widely discussed in Nomade et al. (2019, to whom we refer) based on oxygen and carbon isotopes, and is now finely improved by our new data set (Fig. 2). The three distinct interstadial oscillations during MIS 19a (19a-1, 19a-2, and 19a-3) at the IS are evidenced by the impressive parallel fluctuating increase/decrease of alkenone-SST pattern as well as of warm and cold water taxa indicators (Figs.

2-4). In addition, total coccolith production increased during warmer and oligotrophic interstadial phases; these were characterized by lower deepwater ventilation (lower $\delta^{13}C$, Fig. 2T), even if not as pronounced as during sapropel deposition in MIS 19c (Fig. 2). The inceptions of these interstadials were characterized not only by sudden warming but also by abrupt changes in the surface hydrological regime in the basin. This paleoenvironmental reconstruction is based on the sharp increases of *O. universa* at the beginning of the interstadials 19a-1 and 19a-2, when the SST did not reach maximum values, the $\delta^{13}C$ was lower than in the second half of interstadials, and the stadial-interstadial $\delta^{18}O$ lightening shifts are very sharp. We believe that abrupt climate amelioration at the onset of interstadials would have destabilized local mountain glaciers resulting in the return of local meltwater input into the basin. This frame reflects superimposed local process on global climate signals and definitively sustains the local freshwater discharge hypothesized by Nomade et al. (2019) to explain the very rapid (<200 years) and high amplitude stadial-interstadials oscillations described by the $\delta^{18}O$ record during MIS 19a. Wetter climate conditions on land, as suggested by pollen assemblages at the IS (Fig. 2E), contributed to increase the freshening conditions of sea surface waters leading to the reduction of bottom water ventilation (low benthic $\delta^{13}C$), in agreement with the higher precipitation over the Italian peninsula documented by both the Pianico-Sellere and Sulmona paleolake records (Moscariello et al., 2000; Rossi, 2003; Giaccio et al., 2015; Nomade et al., 2019). Such a pattern points to a marked corrispondence between terrestrial and marine records and then between atmospheric and oceanographic processes during MIS 19a in the central Mediterranean.

Among the interstadials, 19a-2 appears as the warmest, in agreement with higher SST and the occurrence of tropical *T. sacculifer* (Fig. 2 H), suggesting the establishment of surface water condition similar to the MIS 19c climate optimum. Low eccentricity combined with weak insolation maximum and obliquity minimum (Fig. 2A) could have favored the establishment of the year-round condition of low seasonal contrast. In the final part of MIS 19a, the shallowing trend of the Montalbano basin has been reconstructed (Ciaranfi et al., 2010, and references therein), simultaneous with a global sea level lowering trend (Fig. 2B). The lower depths during stadials of MIS 19a were characterized by increased turbidity in surface water, as evidenced by higher *H. carteri* abundances (Fig. 2M) that, like during glacial MIS 20, increase in relation to times of lower sea level, which enhances erosion on land and inorganic input influx into the basin. Associated to these events may be the supply of nutrients to the sea. The general increasing trend of the opportunistic *G. bulloides* in the upper section (Fig. 2J) is in fact evidence of enhanced nutrient availability likely of on land origin. A cooling trend toward the top of the study section up to the MIS 18 glacial onset at 757 ka (Nomade et al., 2019) co-occurs, and is sustained by the heavier values of $\delta^{18}O$ together with the increased occurrence of cold water taxa *C. pelagicus* ssp. *pelagicus* and *N. pachyderma* and decreasing trend of wwt and total N (Fig. 2).

7. Conclusions

The high-resolution data set obtained at the Ideale section based on alkenone-SST and calcareous plankton analyses, combined with the available high-resolution $\delta^{18}O$ and $\delta^{13}C$ records, evidence orbital-suborbital climate oscillations which delineate a detailed climatostratigraphic frame through late MIS 20 to early MIS 18. This is a crucial time interval of the mid-Pleistocene transition that includes the Lower-Middle Pleistocene chronostratgraphic boundary close to the Matuyama-Brunhes paleomagnetic reversal associated to MIS 19c/MIS 19b.

The alkenone-SST, that is the first record in the Mediterranean Sea in this time interval, distinctly records the climate pattern across MIS 20-18 and makes it possible to identify substages and shorter-term climate variations. The oscillations of SST and calcareous plankton key taxa confirm that there exists a strong analogy between TIX and last deglaciation, and sustain the identification of Heinrich-type, BA-type and YD-type events during TIX, here named Med-H_{TIX}, Med-BA_{TIX}, and Med-YD_{TIX}, respectively. The recognition of these episodes improves our knowledge on the climate evolution during terminations of last 800 kyr. Multiple very short-term SST fluctuations characterized the Med-H_{TIX} event confirming the regular climate pattern of Heinrich events when studied at very high-resolution. The Med-BA_{TIX} is marked by higher SST at the beginning followed by a long cooling trend towards the Med-YD_{TIX} episode. The paleoenvironmental conditions during the sapropelic layer occurring at the beginning of interglacial 19, during insolation maximum (i-c 74), are characterized by centennial-scale internal variability, synchronously displayed by the multiple proxies.

Unstable conditions in MIS 19c have been discovered, with three main phases of increased SST, calcareous plankton warm water taxa. Higher frequency variability has been revealed by the uppermost surface water proxies and corresponds to multiple pulses of tropical-subtropical water inflow into the basin and variable hydrological cyclonic regime in the Ionian Sea. The distinct climate fluctuations in MIS 19b-a interval are the result of global climate changes being correlatable worldwide, but they are emphasized by the location of the IS close to Italian hinterland, suited to record local changes in freshwater/detrital/nutrient inputs, influencing the calcareous plankton taxa, making them powerful proxies for detailed environmental reconstruction.

Comparison of our results with selected mid- and high-latitude North Atlantic marine and terrestrial climate proxies, pinpoints to the occurrence of similar climate oscillations, in spite of the different age models among sites and the influence of different control factors in diverse oceanographic settings. Data suggest that the North Atlantic and polar climate dynamics strongly affected the climate evolution at the IS location and that atmospheric processes, other than oceanographic, may have had a prominent role on marine and terrestrial environments in central Mediterranean. The clarification of timing and areal propagation of climate signals through oceanographic and/or atmospheric connection requires additional high-resolution multi-proxy studies from different regions in well-constrained chronological frameworks.

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Supplementary data

Supplementary data to this article can be found online at ...

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Figure captions

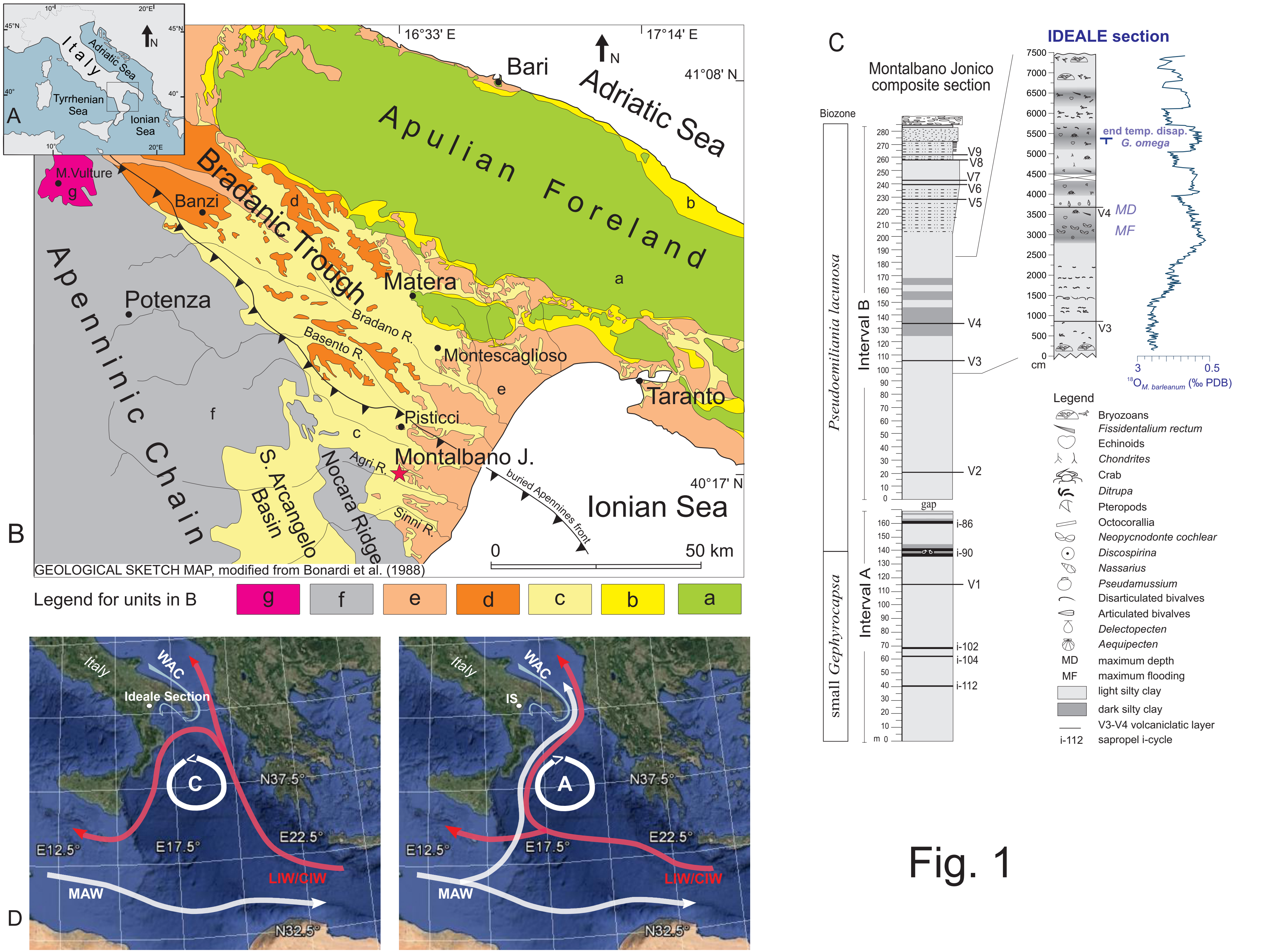
Fig. 1. **A**: location of the study area. **B:** Simplified regional geological setting of southern Italy. The location of the Montalbano Jonico section is indicated by the red star. Legend of the geological map in figure B: a) Cretaceous units of the Apulian Foreland; b) Calcareous units of the Plio-Pleistocene Apennines Foreland; c) Siliciclastic units of the Plio-Pleistocene Apennines Foreland; d) Lower Pleistocene regressive conglomerates of the Bradanic Trough; e) Middle-Upper Pleistocene marine terraced deposits of the Bradanic Trough; f) Triassic-Neogene units of the Apennines Chain; g) Quaternary volcanic units. **C**: lithological features of Montalbano Jonico composite section (Intervals A and B), with details on paleontological and oxygen isotope data at the Ideale section (Ciaranfi et al., 2010; Maiorano et al., 2010; Nomade et al., 2019). MD: maximum depth; MF: maximum flooding. The end of temporary disappearance of *Gephyrocapsa omega* is also shown on the Ideale section. **D**: main sea surface and subsurface water currents in the Ionian Sea, according to Gacic et al. (2010), redrawn (see text for details). MAW: modified Atlantic water; LIW/CIW: Levantine/Cretan intermediate waters; WAC: western Adriatic water.

Fig. 2. Quantitative abundance patterns of selected calcareous plankton taxa (F-O) and alkenone-SST (D), and benthic oxygen (C) and carbon (P) isotope records at the Ideale section. Modern annual SST (19.6°C) is shown on alkenone-SST record according to Pujol and Vergnaud-Grazzini (1995). A: mean summer insolation, obliquity and eccentricity (65° N) from Laskar et al. (2004). B: sea level curve; 19a1-19a3 are interstadial phases (yellow bars) during 19a according to Nomade et al. (2018). Stage boundaries and climate optimum are marked according to Nomade et al. (2019). Light blue bands on proxy records are stadial phases.Violet arrows indicate the main phases of ameliorated climate condition.

Fig. 3. Quantitative abundance patterns of selected calcareous plankton taxa (D-G) and alkenone-SST (C), and benthic oxygen (B) and carbon (I) isotope records at the Ideale section. Star symbol in the sapropel interval is the acme occurrence of dinocyst *Polysphaeridium zoharyi* (Bertini et al., 2015; Maiorano et al., 2016a), that has been associated to Mediterranean sapropel formation (Giunta et al., 2006; Sangiorgi et al., 2006); diamond symbol in the sapropel interval is the increase episode of benthic foraminifera infauna/epifauna ratio (Stefanelli, 2003) as signal of stressed condition at the sea bottom (Marino et al., 2015). A: sea level curve. H: mean summer insolation (65° N) from Laskar et al. (2004).

Fig. 4. Quantitative abundance patterns of selected taxa (E, G), pollen (F), benthic oxygen (B), alkenone-SST (C) and carbon (D) isotope records at the Ideale section. A: mean summer insolation (65° N) from Laskar et al. (2004); climate proxies from Iberian margin core U1385 (H-O), North Atlantic cores 980 (P-Q), 983 (R-S) are represented each in its original age model. Pink bands indicate intervals of climatic instability (see text). Light blue bands on proxy records are stadial phases. Stage boundaries and climate optimum/Tajo phase are marked according to Nomade et al. (2019) at the Ideale section, and according to Hodell et al. (2015) and Sánchez Goñi et al. (2016) at the Iberian margin.

Figure 1



A
Italy
Adriatic Sea
Tyrrhenian Sea
Ionian Sea
B
Bari
Adriatic Sea
Apulian Foreland
Bradanic Trough
Apenninic Chain
M.Vulture
Banzi
Potenza
Matera
Bradano R.
Basento R.
Montescaglioso
Pisticci
Montalbano J.
Agri R.
Sinni R.
S. Arcangelo Basin
Nocara Ridge
Taranto
Ionian Sea
buried Apennines front
16°33' E
17°14' E
41°08' N
40°17' N
0
50 km
GEOLOGICAL SKETCH MAP, modified from Bonardi et al. (1988)
Legend for units in B
g
f
e
d
c
b
a
C
Montalbano Jonico composite section
Biozone
Pseudoemiliania lacunosa
small Gephyrocapsa
Interval B
Interval A
V9
V8
V7
V6
V5
V4
V3
V2
V1
gap
i-86
i-90
i-102
i-104
i-112
IDEALE section
end temp. disap. G. omega
MD
MF
V4
V3
cm
3
0.5
$^{18}O_{M. barleanum}$ (‰ PDB)
Legend
Bryozoans
Fissidentalium rectum
Echinoids
Chondrites
Crab
Ditrupa
Pteropods
Octocorallia
Neopycnodonte cochlear
Discospirina
Nassarius
Pseudamussium
Disarticulated bivalves
Articulated bivalves
Delectopecten
Aequipecten
MD maximum depth
MF maximum flooding
light silty clay
dark silty clay
V3-V4 volcaniclastic layer
i-112 sapropel i-cycle
D
Italy
WAC
Ideale Section
C
N37.5°
E12.5°
E17.5°
E22.5°
LIW/CIW
MAW
N32.5°
Italy
WAC
IS
A
N37.5°
E12.5°
E17.5°
E22.5°
LIW/CIW
MAW
N32.5°
Fig. 1

Figure 2

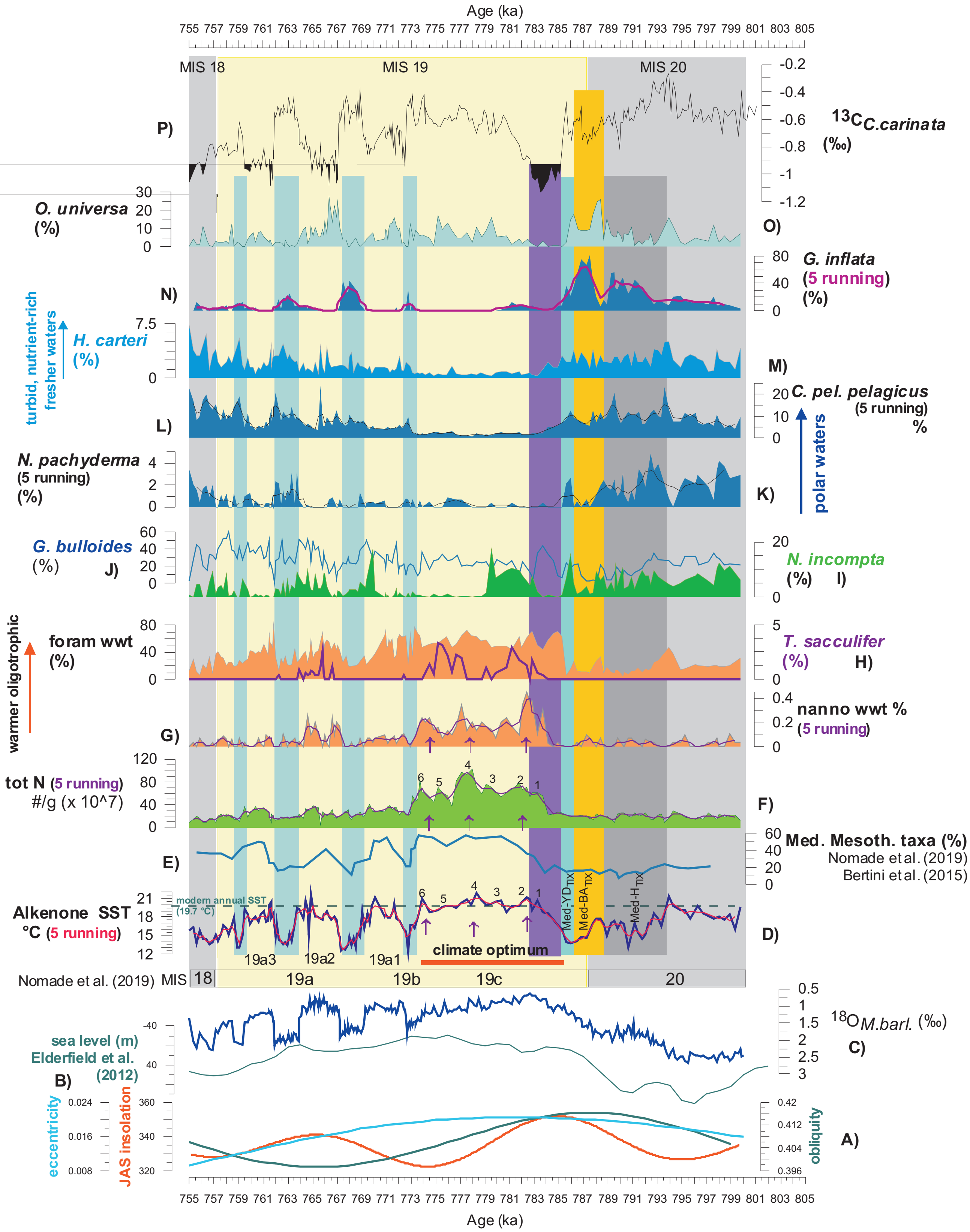


Fig. 2

Figure 3

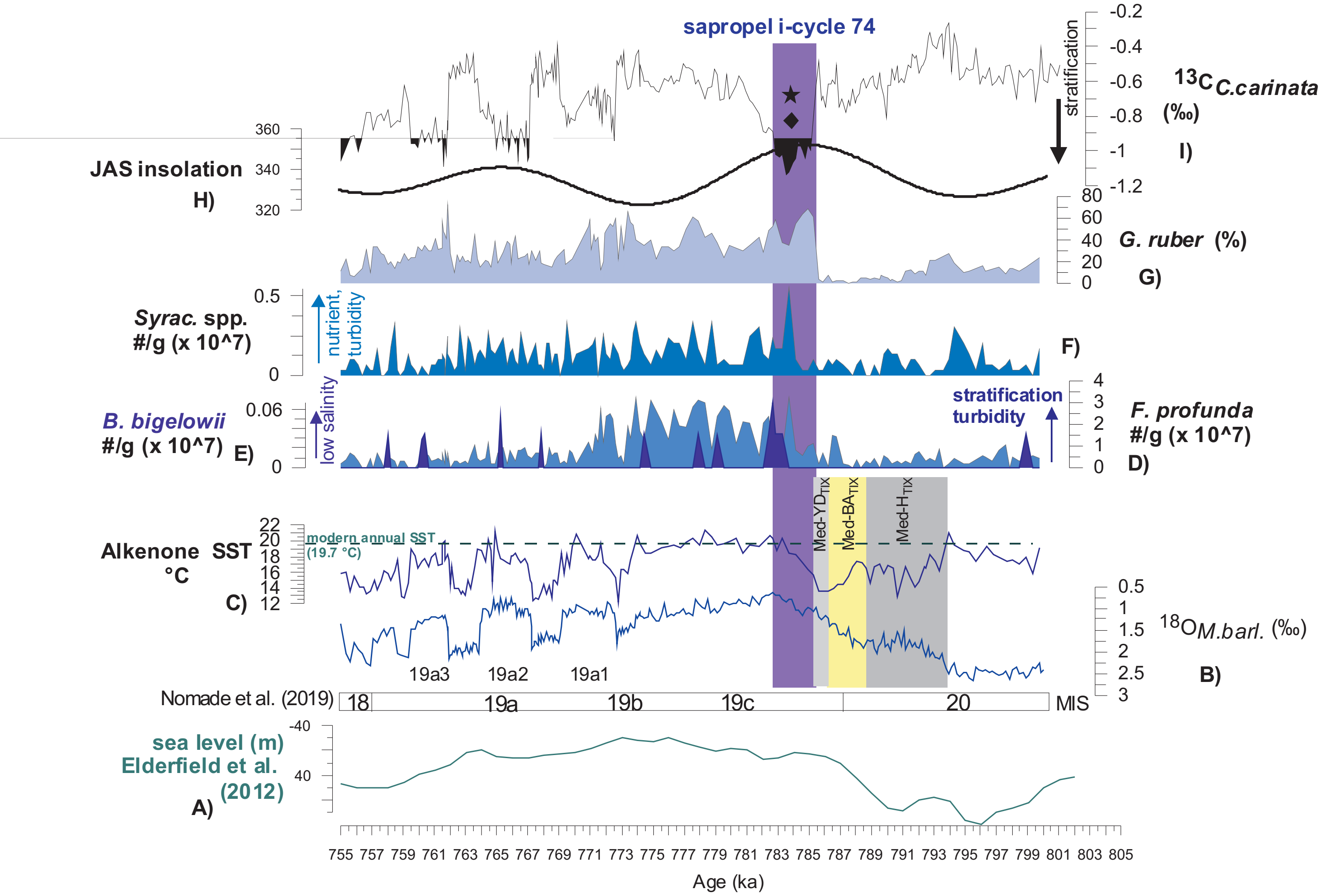


Fig. 3

Figure 4

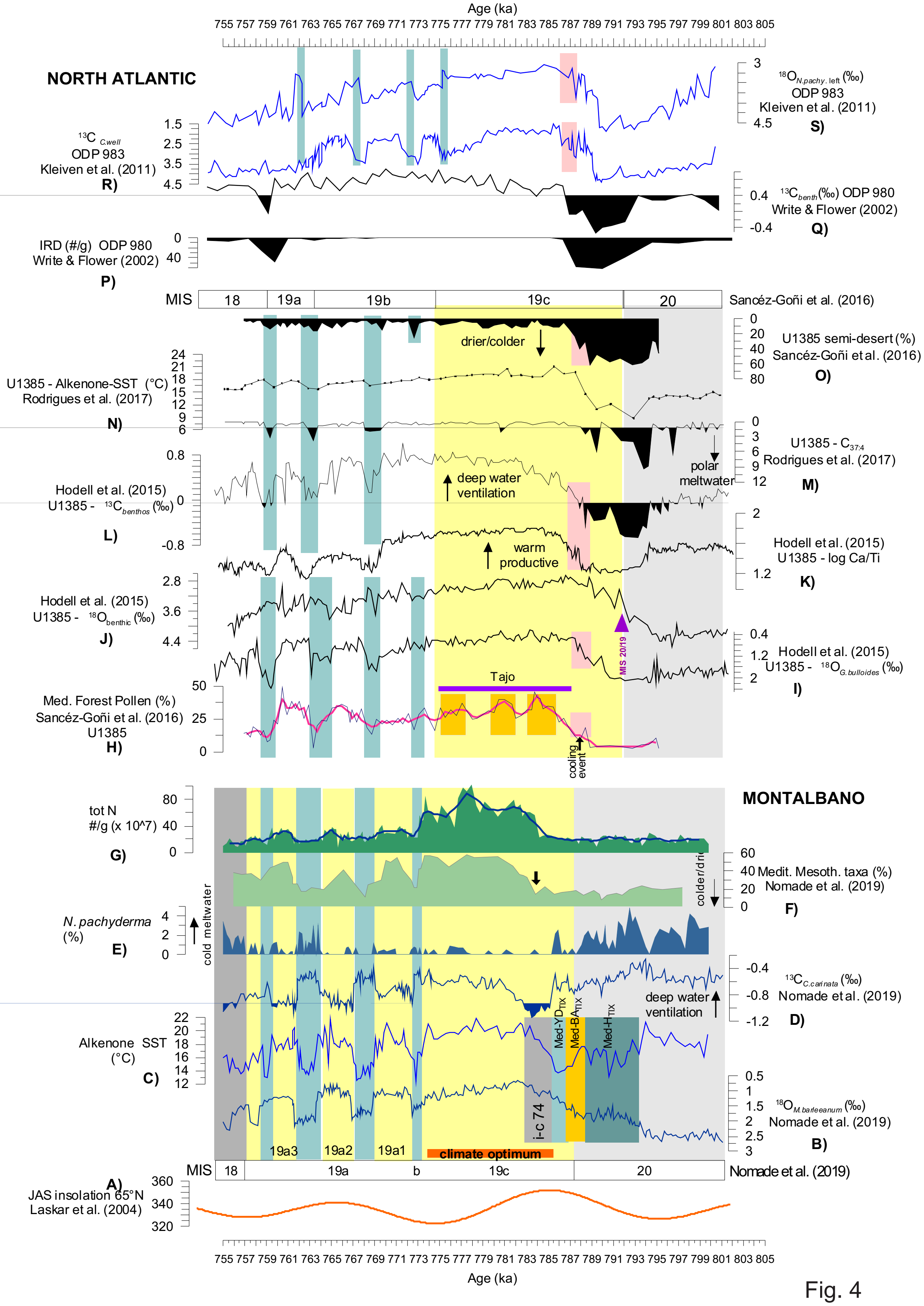


Fig. 4

Declaration of interests

☐X The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Best Regards

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