Climate variability of the last ~2700 years in the Southern Adriatic Sea: Coccolithophore evidences

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Abstract

New information on paleoenvironmental conditions over the past ~2700 years in the Central Mediterranean Sea have been acquired through the high-resolution study of calcareous nannofossils preserved in the sediment core SW104ND14Q recovered in the Southern Adriatic Sea (SAS) at 1013 m water depth. The surface water properties at this open SAS site are sensitive to atmospheric forcing (acting both at local and regional scale) and the North Ionian Sea driven inflowing waters. Our data show a relationship between reworked coccolith abundances, flood frequency across the Southern Alps and the North Atlantic Oscillation (NAO) confirming their value as indicator of runoff/precipitation. Changes in the abundance of the opportunistic (r-strategist) species *Emiliania huxleyi* and deep dweller taxa *Florisphaera profunda* were used to reconstruct the upper water column stratification and associated changes in coccolithophorid productivity. The negative correlation between reworked coccoliths and the N-Ratio (r=-0.44; p=6^{-7}) suggest that fresh water induced stratification is a controlling factor of the SAS coccolithophorid production. High coccolithophorid productivity levels occurred during dry periods and/or time intervals of inflowing salty and nutrient-rich Levantine Intermediate Waters (LIW) favouring convection while lower levels took place during high freshwater discharge, mainly during the Little Ice Age (LIA) and two centennial scale intervals of weakest NAO around 200 BCE and500 CE.

Keywords

Coccolithophores; reworked coccoliths; coccolithophorid primary productivity; South Adriatic Sea; central Mediterranean; last millennia.

Introduction

Coccolithophores (calcareous nannoplankton) and their fossil remains (calcareous nannofossils) are valuable source of information for paleoclimatic studies (Baumann et al., 2005). Coccolithophores are single cell calcareous algae whose ecology and vital functions are driven by environmental parameters within the ocean euphotic zone (e.g., temperature, salinity, sunlight, and nutrient supply). Therefore, abundances of selected taxa have been used to reconstruct variations of physical and environmental parameters and their relation with climate change and human activity. Their skeletons composed of tiny calcareous platelets (coccoliths) are highly abundant in marine sediments making them ideal fossils to produce high-resolution time series (Baumann et al., 2005). These microorganisms are usually considered to prefer warm, stratified, oligotrophic waters of low and middle latitude regions (e.g., Honjo and Okada, 1974; Ziveri et al., 2004). However, local oceanic features such as coastal currents, gyres, eddies, upwelling, and river runoff are known to regionally affect their productivity (Guerreiro et al., 2013). In addition, reworked coccoliths (i.e., the nannofossils which have been removed from their original sedimentary layer and redeposited in a younger layer) can provide information on sediment transport (Bonomo et al., 2014; Ferreira et al., 2008; Ferreira and Cachão, 2005) and used to reconstruct regional scale runoff and/or precipitation changes (Bonomo et al., 2016a; Incarbona et al., 2010; Sprovieri et al., 2006).

Understanding the trends and variability of the Mediterranean climate at local and regional scales has been subject of intense research. (Bonomo et al., 2016a; Cacho et al., 1999; Frigola et al., 2007; Martrat et al., 2004; Pérez-Folgado et al., 2004; Rodrigo-Gámiz et al., 2011; Rohling et al., 2002, 2015; Sbaffi et al., 2001; Sierro et al., 2005; Sprovieri et al., 2003, 2006; Triantaphyllou et al., 2009, 2016a). Shelf sediments of the Adriatic Sea (AS) provide ideal natural archives for high-resolution paleoclimatic investigations because of expanded Holocene sedimentary sequences and possible use of recurrent tephras for geochronological control (Jalali et al., 2018; Lowe et al., 2007; Marchini et al., 2014; Matthews et al., 2015; Siani et al., 2013). Terrestrial and marine paleoclimate proxy data (e.g., calcareous plankton, lipid biomarkers, palynomorphs, stable isotopes, lake levels, and speleothems) have shown the occurrence of abrupt climate changes during the Holocene (warmer/colder and drier/wetter periods) at decadal, centennial to millennial time scales in the Mediterranean basin (e.g., Bini et al., 2019; Cisneros et al., 2016; Di Bella et al., 2014; Gogou et al., 2016; Goudeau et al., 2015; Grauel et al., 2013; Jalali et al., 2016, 2018; Kouli et al., 2012; Lirer et al., 2013, 2014; Margaritelli et al., 2016, 2018; Piva et al., 2008; Sicre et al., 2016; Skampa et al., 2019; Triantaphyllou et al., 2009, 2010, 2016b).

Many studies have focussed on (late) Holocene climate variability and its impact on the environment and human activity in the SAS (Caroli and Caldara, 2007; Combourieu-Nebout et al., 2013; Di Rita and Magri, 2009; Giunta et al., 2003; Grauel and Bernasconi, 2010; Jalali et al., 2018; Leider et al., 2010; Oldfield et al., 2003; Piva et al., 2008; Sangiorgi et al., 2003; Siani et al., 2013; Sicre et al., 2016). The recent study of Jalali et al. (2018) in the SAS highlighted the links between the centennial scale variability of SSTs and local climatic and oceanographic features, and notably the role of the Bimodal Oscillating System (BiOS) of the Ionian Sea and North Atlantic Oscillation (NAO). Although there has been a substantial number of publications on the investigated area, very few studies have explored calcareous nannofossils as a proxy of past climate and environmental changes (e.g., Giunta et al., 2003; Narciso et al., 2012; Sangiorgi et al., 2003). Narciso et al. (2012) studied a gravity core close to our site between 13000 and 5500 BP, thus focused on the Greenland Stadial 1/Younger Dryas, Pre-Boreal, and Sapropel 1 equivalent periods. Giunta et al. (2003) and Sangiorgi et al. (2003) reported data from 18000 to 2300 yrs BP at a more southern site, documenting the distribution of calcareous nannofossils during the Sapropel S1. As far as living coccolithophores are concerned, the only study carried out in the SAS is that of Balestra et al. (2008) describing assemblages in the water column and surface coastal sediments of the Gulf of Manfredonia (SAS). Other very recent data were restricted to the Mid and North Adriatic Sea (e.g., Cerino et al., 2017; Godrijan et al., 2018; Skejić et al., 2018, and references there in) or are part of phytoplankton biomass and productivity assessments aiming at providing rough estimates of coccolithophore distribution in open SAS (e.g., Fonda Umani, 1996; Ljubimir et al., 2017, and references therein).

The aim of this work is to evaluate the reliability of Coccolithophores/calcareous nannofossils as a proxy of environment and climate variability over the last three millennia in the Central Mediterranean. For this purpose, we carried out a high-resolution study from a deep-sea gravity core recovered in the SAS and from a second shallow coastal gravity core (C5 Composite) from the Tyrrhenian Sea (Gulf of Gaeta) obtained within the framework of the NEXTDATA Project (http://www.nextdataproject.it). Our data evidence major changes in nutricline depth as well as variations of river runoff and precipitation. We explore the cause of the observed changes by comparing our results to alkenone derived Sea Surface Temperatures (SSTs) and terrestrial inputs derived from higher plant biomarkers (Jalali et al., 2018). We also use other indicators of past precipitation changes in the Mediterranean basin: i.e. the flood activity in the Southern Alps (Wirth et al., 2013), the reworked coccolith record from a Southern Tyrrhenian sea core (Bonomo et al., 2016b), the XRF record from lake sediments of the Iberian Peninsula (Moreno et al., 2012) and the reconstruction of the forested fraction of usable land in Central and Western Europe (Kaplan et al., 2009).

Oceanographic setting of the study area

The AS is a semi-enclosed basin located between the Italian Peninsula and the Balkans, connected to the Mediterranean Sea through the Strait of Otranto (Fig.1a). The North Adriatic (NA) is primarily influenced by the southeast Europe climate, while the SAS experiences more arid conditions typical of Mediterranean and Northern Africa climates (Ilijanić et al., 2014). The general surface circulation of the AS is cyclonic (Fig.1b,c) (Sellschopp and

Álvarez, 2003) and consists of a northward current flowing along the eastern Adriatic coast (i.e., the Eastern Adriatic Current, EAC) balanced by southward current flowing along the western coast (i.e., the Western Adriatic Current, WAC). The intermediate layer mainly present in the southern and mid AS is occupied by the Levantine Intermediate Water (LIW) (Artegiani et al., 1997). The deep circulation is characterized by the Adriatic Deep Water (ADW) a dense water mass formed by the mixing of the Northern Adriatic Dense Water (NADW) and Southern Adriatic Dense Water (SADW) (Manca et al., 2002).

The SAS is a sub-basin (South Adriatic Pit, SAP, 1260 m max depth) characterized by a quasi-permanent cyclonic circulation, i.e. the South Adriatic Gyre (SAG; Gačić et al., 1997) (Fig. 1b,c). The physical and chemical properties of SAS surface waters depend on the characteristics of inflowing waters into the basin, the strength of SAG, as well as wind stress and river discharges. Inflowing waters consist mainly of WAC and NADW from the North, the LIW and occasionally Modified Atlantic Water (MAW) from the South. The WAC is strongly influenced by river runoff mostly from the Po River, making it fresher and nutrient rich. The inflow of LIW and MAW depends on the variability of the North Ionian Gyre (NIG) (Fig. 1b,c). According to the BiOS (Bimodal Oscillating System) model, the NIG circulation may either be cyclonic or anticyclonic (Civitarese et al., 2010; Gacic et al., 2010). This mechanism is sustained by internal processes driven by the density of the ADW outflowing the Otranto Strait. When the circulation in the NIG is cyclonic, saltier and warmer LIW enters the SAS promoting deep convection and the formation of a denser ADW. In an anticyclonic NIG mode, fresher and colder MAW enters the SAS leading to the production of lower density ADW. However, some studies invoke the role of more complex driving mechanisms involving the whole Ionian Sea circulation and not just its northern sector (Reale et al., 2016; Simoncelli et al., 2016; Theocharis et al., 2014). The intensity of the SAG depends on local wind intensity and properties of advected waters from the Ionian Sea (Shabrang et al., 2016). Shabrang et al. (2016) reported a significant negative correlation between the NAO index and local wind intensity. However, they did not find unequivocal relationship between the NAO and SAG variability because of additional effects of the advection of the Ionian waters, suggesting that the BiOS mode does not depend on NAO. Nevertheless, Pinardi et al. (2015) reported a sustained BiOS anticyclonic circulation during the period of positive NAO in 1987-1996.

The surface waters of the SAS are more oligotrophic than those of the NA (e.g., Civitarese et al., 1998). The influence of Po River and secondary Apennines rivers flowing into the western AS on the nutrient budget of the SAS seems rather weak and limited to a narrow coastal current flowing over the Italian shelf (Faganeli et al., 1989). The nutrient supply to the SAS occurs mainly via the inflow of LIW lying at about 300 m in the Adriatic Sea (Gačić et al., 2002). Nevertheless, according to Civitarese et al. (2010) larger amounts of nutrients are advected by the MAW during periods of anticyclonic BIOS.

Methods

Core SW104-ND14Q

Core SW104-ND14Q (17°37'3.612''E; 41°17'2.4''N) was recovered at 1013m water depth in the SAS (Fig. 1). The sedimentary sequence was retrieved with a SW104 gravity corer system, which preserves the water-sediment interface and allowed the recovery of 116 cm of undisturbed and uncompressed homogeneous brown-grey hemipelagic sediments. The magnetic susceptibility measured on board with a Bartington Instrument M2 revealed three tephra layers (Fig. 2). The age model used here is from Jalali et al. (2018) and has been constructed combining radionuclides ages (^{210}Pb activity-depth profile and ^{137}Cs activity) for the last ca. 150 years and the additional dates derived from the correlation of three tephra layers with well-dated volcanic events onland [Pompei eruption (79 CE); Pollena eruption (472 CE); 1631 CE] (see Jalali et al. 2018 for details on tefrostratigraphy). Linear interpolation between the tie-points has been used to construct the age-depth profile from the top down to the base core documenting a mean Sed. Rate of 0.04 cm/y (Fig. 2). Based on the age model, core SW104-ND14Q ranges from 700 BCE to 2003 CE and has a mean temporal resolution of ~26 yrs.

Core C5 Composite

To investigate the reliability of the reworked coccoliths as a regional proxy of precipitation, we also used the central Tyrrhenian Sea shallow sequence C5 Composite (C5Comp) (Fig.1). The location of this site in front of Volturno River mouth makes it particularly suitable for reconstructing runoff variability and for comparing coastal and open sea sites (Bonomo et al., 2016). The core C5Comp is a composite marine sequence consisting of two cores: the SW104-C5 and core C5 (710 cmbsf length) both recovered in the Gulf of Gaeta, at 93 m water depth (see Margaritelli et al., 2016 for details). Calcareous nannofossils of the core SW104-C5 (back to 1630 CE) was already published by Bonomo et al. (2016). In this work we extended their reconstruction back to ~ 400 CE. The chronology used is that of Margaritelli et al. (2016) and has been assembled combining radionuclides ages (^{210}Pb activity-depth profile and ^{137}Cs activity) for the last ca. 150 years, planktonic foraminiferal event, tephrostratigraphy and oxygen stable isotope correlation with other marine sites (for details see Margeritelli et al., 2016). The age-depth profile has been constructed by a linear interpolation between the tie-points showing a progressive decrease in sedimentation rate from the top down to the base core.

The analysed time interval of core C5Comp covers the period between ~ 400 and 2013 CE with a mean temporal resolution of ~10 yrs.

Calcareous Nannofossils

116 samples of the SW104-ND14Q core and 108 of the C5Comp were prepared as standard smear slides (Bown, 1998) and analyzed with a transmitted light microscope at x1250 magnification. Some samples of SW104-ND14Q core were analysed with a scanning electron microscope (SEM) in order to solve taxonomic identification for smaller placoliths difficult to achieve by light microscope (e.g., *Emiliania huxleyi*). The relative abundance of *in situ*

species was estimated only in the SW104-ND14Q core based on the count of at least 600 specimens. The abundance of reworked nannofossils was estimated in the SW104-ND14Q and C5Comp as the number of reworked specimens encountered during the count of the *in situ* coccoliths. All abundances are expressed in percentages. SW104-ND14Q coccolith species abundances were also used to calculate the N-ratio as defined by Flores et al. (2000) to assess the nutricline depth fluctuations. The N-ratio is based on the absolute abundances of the main surface r-strategist species (in our record *E. huxleyi* and small placoliths) over that of *F. profunda* (lower photic zone taxon). High values of the N-ratio indicate shallow nutricline/thermocline (relatively high surface coccolithophorid productivity) while low values indicate deep nutricline/thermocline (relatively low surface coccolithophorid productivity). As small placoliths, we counted the placoliths not confidently recognizable as *E. huxleyi* and *Reticulofenestra* spp.

Finally, the reworked coccoliths (RC) group includes taxa from different stratigraphic intervals (Mesozoic, early Cenozoic) and Cenozoic long-range taxa showing poor preservation (etching and/or overgrowth). Raw data are shown in supplementary material.

Ecology of selected taxa

E. huxleyi tolerates a wide range of ecological conditions and is therefore abundant in nearly all oceanic environments (Schwab et al., 2012). This species is considered an opportunistic (r-strategist) taxon capable to quickly respond to nutrient availability in both eutrophic and oligotrophic areas (e.g., Balestra et al., 2008; Broerse et al., 2000; Dimiza et al., 2008, 2015; Haidar and Thierstein, 2001). *E. huxleyi* is generally more abundant in temperate (cold) mixed surface waters (e.g., Hagino et al., 2000; Malinverno et al., 2003), but may also be found in stable regimes in terms of vertical mixing with relatively high nutrient availability (Andruleit et al., 2005). Ausín et al. (2015) further postulated that *E. huxleyi* (size >4 μm) can find optimal conditions for its development in cold water that are also low-salinity.

The lower photic zone species *F. profunda* has a more constrained habitat and has thus been widely used to monitor past changes in nutricline-depth and induced changes in surface productivity (Beaufort, 1997). The abundance of *F. profunda* increases with respect to other coccolithophores when the nutricline is deep and overlaid by a nutrient-depleted upper photic layer (Balestra et al., 2008; Bown et al., 2009; Dimiza et al., 2015; Incarbona et al., 2008, 2010). These conditions generally reveal stable, stratified, oligotrophic surface waters during summer months (Baumann et al., 2005; Malinverno et al., 2009) that can be disrupted under increased wind stress and ⁄ or upwelling and divergence circulation (Bown et al., 2009). Hernández-Almeida et al. (2019), using *F. profunda* relative abundance *vs* MODIS (Moderate Resolution Imaging Spectroradiometer) chlorophyll-α, show a pronounced temperature sensitivity of *F. profunda* and no correlation whit surface net primary production at latitudes higher than 30°N−30°S, such as Mediterranean area. Contrary, Grelaud et al. (2012) showed a strong anticorrelation ($R = -0.76$) between *F. profunda* % and chlorophyll-α in the Aegean Sea (eastern Mediterranean Sea).

Biomarker analyses

Sea surface temperature and TERR-alkane reconstructions along the SW104-ND14Q core have been published by Jalali et al (2018). The method used for biomarker analyses have been described by (Sicre et al., 2002). Fatty alcohol biomarker data were used to calculate the C_{26} fatty alcohol / C_{29} n-alkane + C_{26} fatty alcohol ratio ($C_{26OH}/(C_{26OH}+C_{29})$). This ratio was determined along the core to infer information on water oxygenation as proposed by Cacho et al. (2000). High values of this ratio presumably correspond to low ventilation and *vice versa*.

Results

The coccolithophore assemblages in the SW104-ND14Q core are generally well preserved and abundant. *E. huxleyi* dominates the assemblages with an average abundance of ~80%. *F. profunda* is also well represented with an average abundance of ~10%. Other taxa are largely subordinated with percentages ranging between ~1- 3% (e.g. *Syracosphaera*, *Rhabdosphaera* and *Calciosolenia*) and no significant variations (not shown). Reworked specimens are always present and are found in higher amounts in the upper part of the core. *E. huxleyi*, *F. profunda*, RC, and the N-ratio data shown in Figure 3 are used for the discussion.

E. huxleyi abundance range from 65 to 90 % (Fig. 3a). Its downcore distribution pattern can be divided into two major intervals. A first one that includes the late Iron Age (IA) and the almost entire Roman Period (RP; between ~700 BCE and ~400 CE) with abundance above 80%. This period is followed by a decline to lower values (< 65%) between ~400 and ~800 CE, i.e. from the late RP throughout the Dark Age (DA). *E. huxleyi* returns to moderately higher abundances (65 - 75%) at the late DA and during the Medieval Climate Anomaly (MCA) (800 to 1100 CE). Then, values remain approximately at these levels but with superimposed short-lived oscillations especially during the upper LIA. The distribution of *F. profunda* (Fig. 3b) reveals three main intervals: the first one runs from the bottom of the core till ~400 CE and is characterized by fluctuating values between 7 and 9 %. Over the second interval, from 400 to 1200 CE, the taxon abundances increase almost continuously, except for two time spans of strong decrease centred at 600 and 900 CE. From 1200 CE, *F. profunda* declines till 1550 CE and rises again to Present day values. As shown in Fig. 3d, the N-ratio shows similar trends as *E. huxleyi*, but with more pronounced fluctuations especially in the upper half of the core. During the first 1200 years (700 BCE - 400 CE) the N-ratio value is > 0.9. At ~400 CE a sharp drop sets the beginning of a long-term decreasing trend till Present that suggests a progressive reduction of coccolithophorid productivity.

RC percentages (%RC) along the core range from ~3 to ~25%, and depict a steady increase from the bottom core to ~800 CE. Then, after a period of lower values around 900 CE and 1300 CE, %RC increases up to Present with the highest values (17-25%) during the LIA (~1400 -1800 CE) (Fig. 3c). In the C5Comp core, %RC ranges from ~14 to ~79% with lowest levels found between ~400 and ~1350 CE.

Discussion

Reworked coccoliths and runoff fluctuations

The NAO is one of the dominant atmospheric mode of variability in the North Atlantic sector that has a considerable influence on winter temperature/precipitation in Europe including the Mediterranean region (Hurrell, 1995). In the central Mediterranean, positive NAO conditions result in colder and drier winters than average, while winters are warmer and wetter during negative phases of NAO (Benito et al., 2015; López-Moreno et al., 2011a, 2011b; and references within). Bonomo et al. (2016) were able to evidence a negative correlation between the NAO index of Trouet et al. (2009) and the %RC in the Central Tyrrhenian Sea core SW104-C5 over the last 400 years. Our results show that this relationship could have persisted back to ~700 BCE (Fig. 4). The resemblance between the %RC short and long term trends the flood frequency in Southern Alps (Wirth et al., 2013) and the Southern Tyrrhenian marine record (Gulf of Salerno; Lirer et al. 2013) seems to confirm the link between the %RC and runoff/precipitation in the region on longer time span (Bonomo et al., 2016a; Incarbona et al., 2010; Sprovieri et al., 2006). This finding is supported by the slight negative correlation between the NAO index of Trouet et al. (2009) ($r=-0.4$ $p=5^{-33}$, $n=34$) and Olsen et al. (2012) ($r=-0.2$ $p=0.01$, $n=82$) and the %RC along the SW104 record. Our data agree with the negative correlation between NAO and winter precipitation, for the 1950–2006 period, reconstructed over large areas of Morocco and Tunisia, most of the Iberian Peninsula, southeastern France, Italy, the Balkan Peninsula, and large areas of central and northern Turkey (López-Moreno et al., 2011a). Notwithstanding the age models accuracy of the different cores, the main drier spells recorded in the SAS, in the Central and Southern Tyrrhenian as shown by red dots in Fig. 4 might be considered synchronous as well to the XRF Si fluctuations found in lake sediments of Iberian Peninsula (Moreno et al., 2012). A noteworthy result is the high %RC (RC Acme event) during the late LIA, between ~1600 and

~1850 CE, that coincides with a long standing interval of negative NAO and is consistent with a regional scale humid period already documented in marine and continental sedimentary sequences of the Western and Central Mediterranean (e.g., Barrera-Escoda and Llasat, 2015; Goudeau et al., 2015; Vallefuoco et al., 2012; Moreno et al. 2012) .

Jalali et al. (2018) highlighted similarities between the TERR–alkane record in SW104-ND14Q and the forested fraction of usable land (FF) in Central and Western Europe (Fig.4 f, i) (Kaplan et al., 2009). Considering that FF fluctuations are indicative of anthropogenic deforestation (Kaplan et al., 2009), they concluded that TERR–alkane at SW104-ND14Q reflects primarily human activity rather than climate fluctuations. Since the RC signal does not match with either the TERR–alkanes or FF index but with the flood activity reconstruction and the $C_{26OH}/(C_{26OH}+C_{29})$ ratio (Fig.4), we suggest that RC reflect precipitation changes that are also seen in other Mediterranean RC records overall supporting the hypothesis that %RC is a reliable index of past runoff/precipitation changes in the region.

N-ratio and South Adriatic hydrology

Highest N-ratio values almost all along the RP indicate shallow nutricline (surface productive waters) during this period considered as generally mild (Figs. 3, 5). This is in contrast with the LIA showing deep nutricline (lower surface productivity levels) (Figs. 3, 5), a cold period that one would expect to be favourable to water column mixing and growth of r-strategy taxa *E. huxleyi*. Comparable results has been recorded in the North Aegean Sea during the last 1500 years (Gogou et al., 2016; Skampa et al., 2019). In particularly, in the North Aegean Sea Gogou et al.(2016) and Skampa et al. (2019) recorded periodic occurrence of "*E. huxleyi* dominance" intervals indicating strong water column convection coupled with NAO positive shifts , EMT-like events (Incarbona et al., 2016), cool spells, and enhanced continental inputs as well. In contrast, the occurrence of *F. profunda* dominance intervals may be linked to enhanced stratification of the upper water column and warm surface waters, potentially associated with increased lower salinity Black Sea Water intrusion. During the RP, alkenone-derived SSTs show cold oscillations that do not seem to have any relationship with the N-ratio (Fig. 5 a, d). Local atmospheric and hydrological conditions (i.e. properties of inflowing waters into the basin and strength of SAG) play an important role in the stratification of the upper water column and associated changes in productivity (Civitarese et al., 2010; Ljubimir et al., 2017; Vilibić et al., 2012). Several studies in open sea SAS waters have linked high abundances of coccolithophorids with the inflow of saltier Ionian waters (Fonda Umani, 1996; Totti et al., 2000). In contrast, Ljubimir et al. (2017) reported higher abundances of coccolithophorids in lower salinity SAG waters during years of anticyclonic mode of the BiOS and their absence during cyclonic BiOS years. However, despite the lack of significant correlation between salinity and total coccolithophore abundances, increased abundance of *E. huxleyi* has been often related to the inflow of LIW or eastern Mediterranean surface waters (Malinverno et al., 2003; Skejić et al., 2018). Advection of saltier LIW by promoting deep convection (Gačić et al., 2014) would favour the development of *E. huxleyi* known to rapidly respond to increased nutrient supply to the photic zone (Fig.5 g) (Malinverno et al., 2003). Conversely, reduced inflow of LIW, or enhanced input of less salty waters (mainly the WAC, and occasionally the MAW), and a weak SAG, would lead to higher surface water buoyancy and stratified conditions (Fig.5 f, g). The consequent deepening of the nutricline would thus favour *F. profunda* growth (Fig. 5 f). This conceptual scheme is in agreement with the slight negative correlation (r= -0.44; p=6^{-7}) between the N-ratio and %RC values. For instance, higher values of %RC associated with sustained negative NAO during the LIA are coherent with higher precipitation and runoff (Bonomo et al., 2016a; Incarbona et al., 2010; Sprovieri et al., 2006) and the Po River flood record (Camuffo and Enzi, 1996). Rising $C_{26OH}/(C_{26OH}+C_{29})$ ratio to their highest values suggests an abrupt reduction of water oxygenation that is also compatible with stratified conditions caused by the large freshwater discharge during the LIA and lowest N-ratios. Similar observation can be made for two intervals of weaker NAO, i.e. around 200 BCE and around 500 CE.

Regarding nutrient supply, our results also support the idea of a limited influence of the Po River (and secondary Apennines rivers) on the nutrient budget of the open SAS surface waters and coccolithophore productivity, as the nutrients are usually rapidly consumed during their transport within the WAC. The same have been observed around the eastern Adriatic coasts (Vilibić et al., 2012). Overall, our findings suggest that fresh water input due to increased precipitation and river runoff impact essentially on buoyancy and subsequent stratification in the SAG.

Apart from the LIA and these two major short time intervals that all took place during prolonged negative NAO, other N-ratio fluctuations cannot robustly be attributed to NAO and high river discharge (Fig. 5). Under weaker freshwater forcing, other factors such as the BiOS circulation may have been a more important controlling factor on the SAG dynamics and productivity, but this question will need further investigations to be addressed.

Conclusion

This high-resolution study of calcareous nannofossils from the sediment core SW104-ND14Q was used to provide information on paleoceanographic and climatic conditions in the SAS, over the past ~2700 years. Based on the distribution of *E. huxleyi*, *F. profunda*, the N-ratio, and reworked coccoliths we were able to evidence hydrological variability and related coccolithophore production changes in the SAG.

One outstanding result is the good correspondence we found between the % reworked coccoliths in the SAS and Tyrrhenian Sea cores and flood activity across the Southern Alps, highlighting the value of %RC as a proxy for reconstructing regional scale precipitation and runoff.

We also showed that lowest N-ratio took place during extended weakest NAO phases, i.e. primarily the LIA and two other intervals (200BCE and 500CE), as a result of large fresh water discharge and subsequent stratified surface ocean reducing nutrient supply and production of coccolithophorids in the SAG. Outside these periods of strong negative NAO, whether and to what extent other factors such as the BIOS may have played a role on the hydrology and productivity of the SAG remains an open question.

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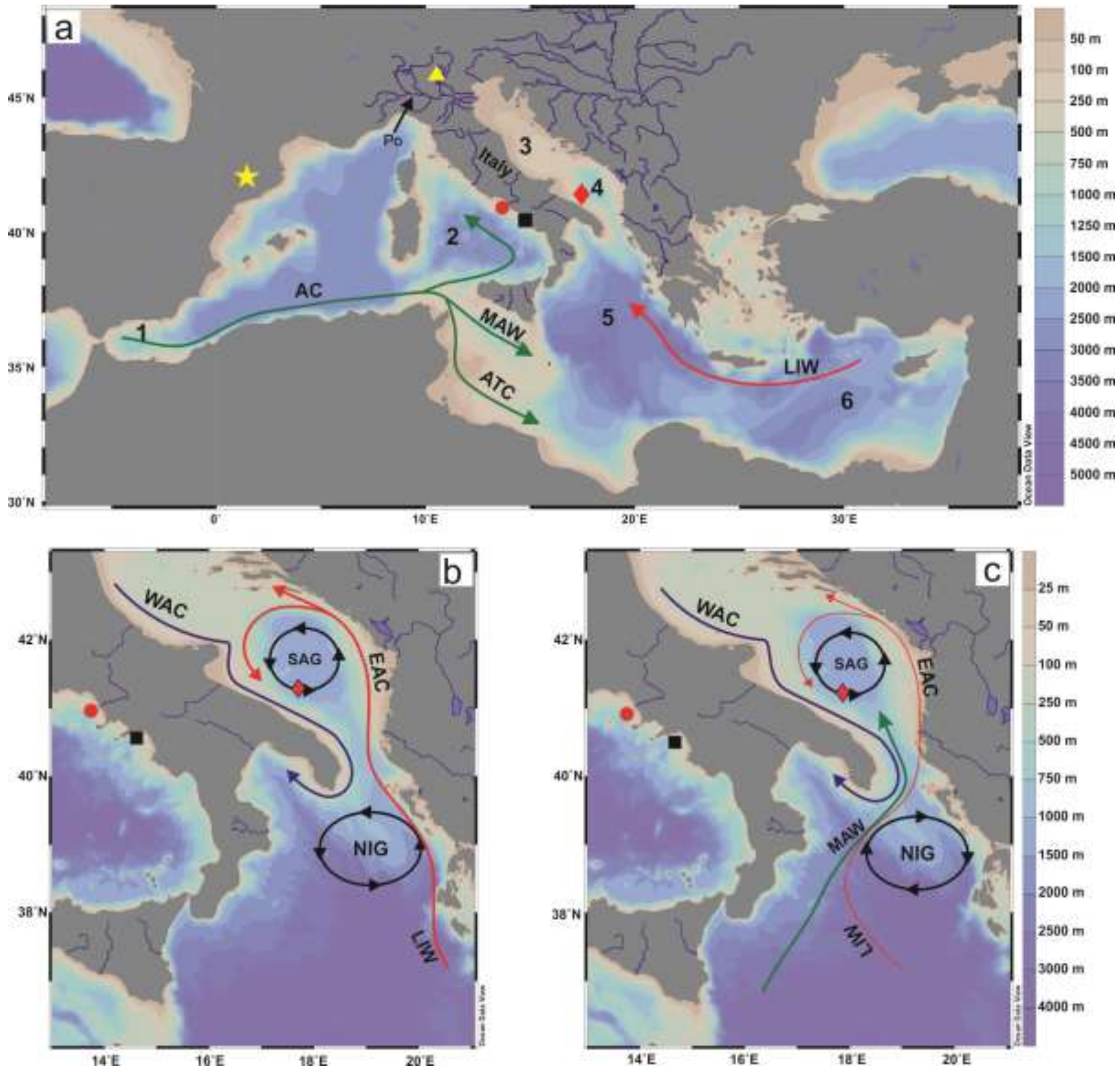


Figure 1. Location of the cores SW104-ND14Q (diamond), C5 Composite (dot), C90 (square, Lirer et al., 2013), Basa de la Mora (star, Moreno et al., 2012), and Ledro (triangle, Wirth et al., 2013). (a): bathymetric map of the Mediterranean Basin and main surface (green arrow) and intermediate circulation pattern (red arrow). AC: Algerian Current; MAW: Modified Atlantic Water ; ATC: Atlantic Tunisian Current; LIW: Levantine Intermediate Water. Numbers 1-6: 1-Alboran Sea; 2-Tyrrhenian Sea; 3-Adriatic Sea; 4-South Adriatic Pit, SAP; 5-Ionian Sea; 6 Levantine Sea. The main catchment basins of river flowing into the Adriatic Sea are reported (blue thick lines). (b) and (c): bathymetric map and main circulation pattern of South Adriatic Sea and North Ionian Sea during cyclonic (b) and anticyclonic (c) mode of the BiOS; WAC: Western Adriatic Current; EAC: Eastern Adriatic Water; LIW: Levantine Intermediate Water; MAW: Modified Atlantic Water; SAG: South Adriatic Gyre; NIG: North Ionian Gyre.

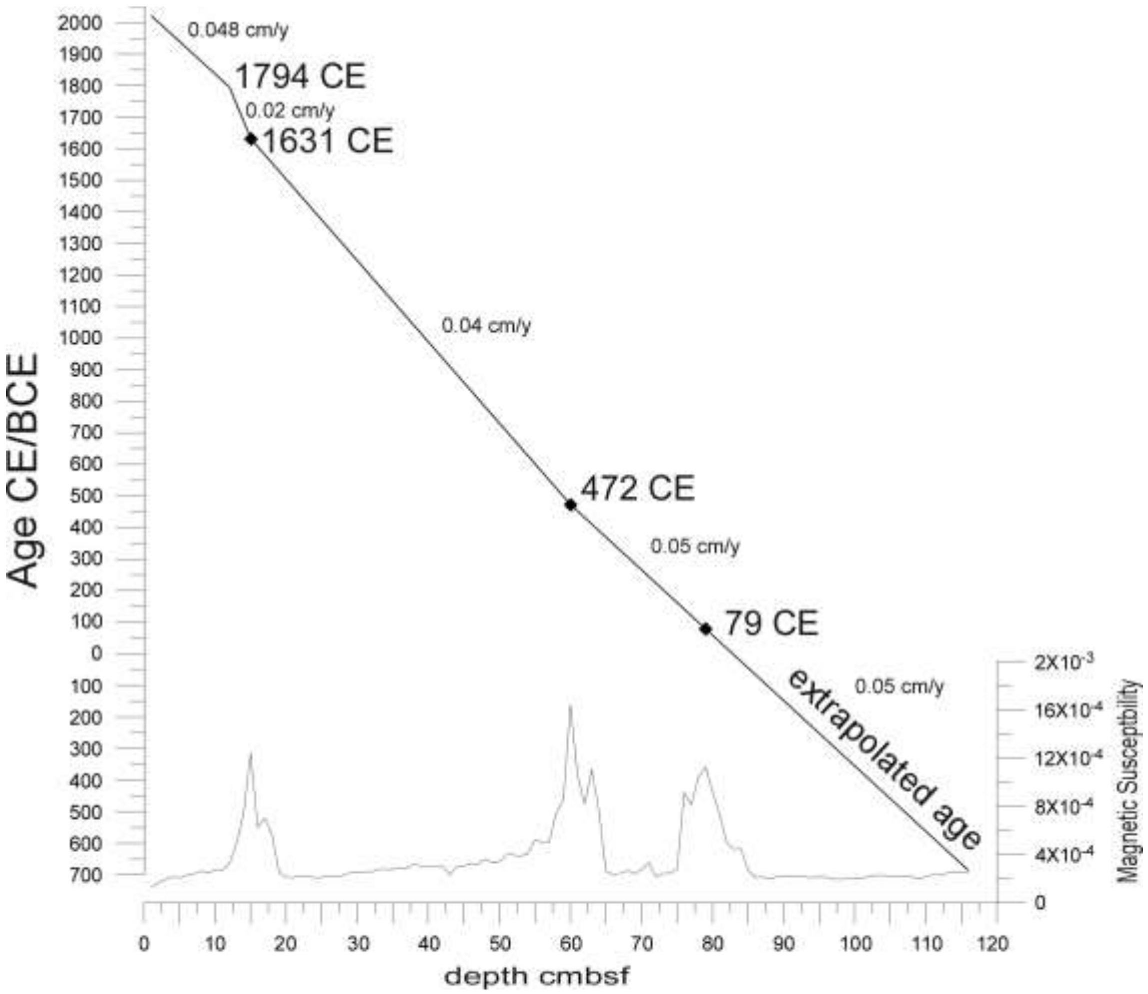


Figure 2. SW104-ND14Q age-depth model and magnetic susceptibility signal. Sedimentation rate and tephra layers (diamond) were reported.

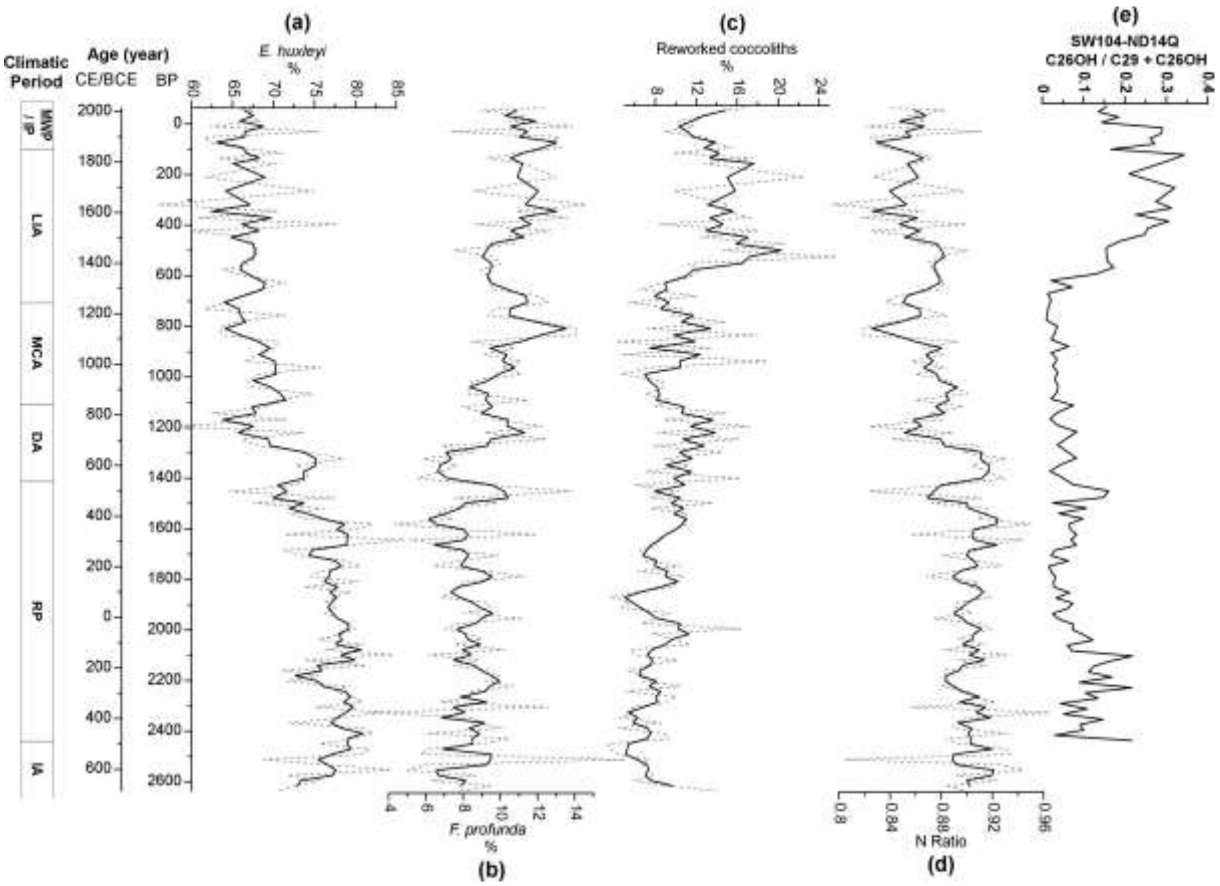


Figure 3. Time domain distribution of (a) *E. huxleyi*, (b) F. *profunda*, (c) RC, (d) N-ratio, and (e) $C_{26OH}/C_{29}+C_{26OH}$ ratio in core SW104-ND14Q. Raw and three points running average data are reported in grey dashed and black full lines, respectively. The age model is from Jalali et al. (2018) and the climate period intervals are those of Margaritelli et al. (2016).

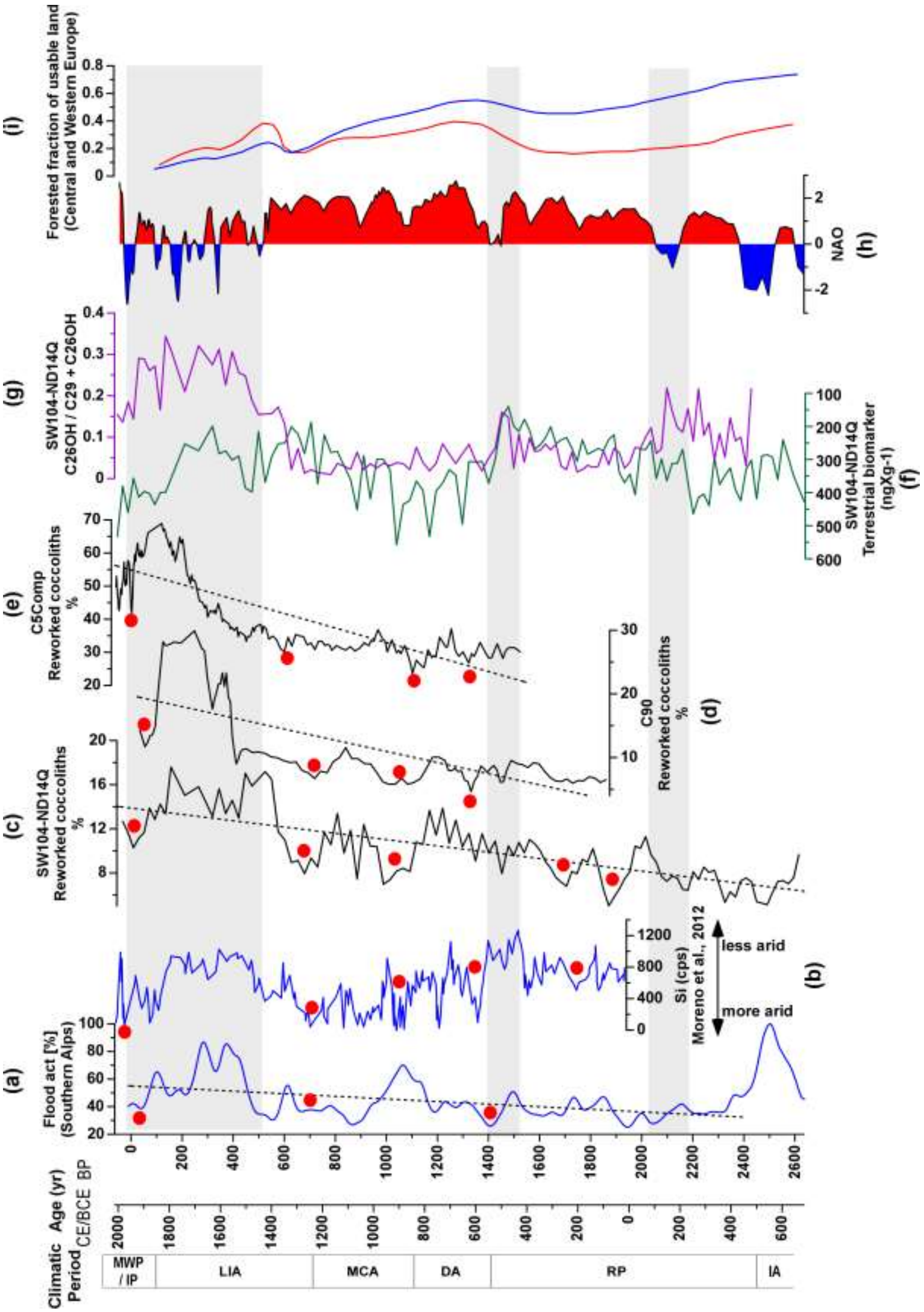
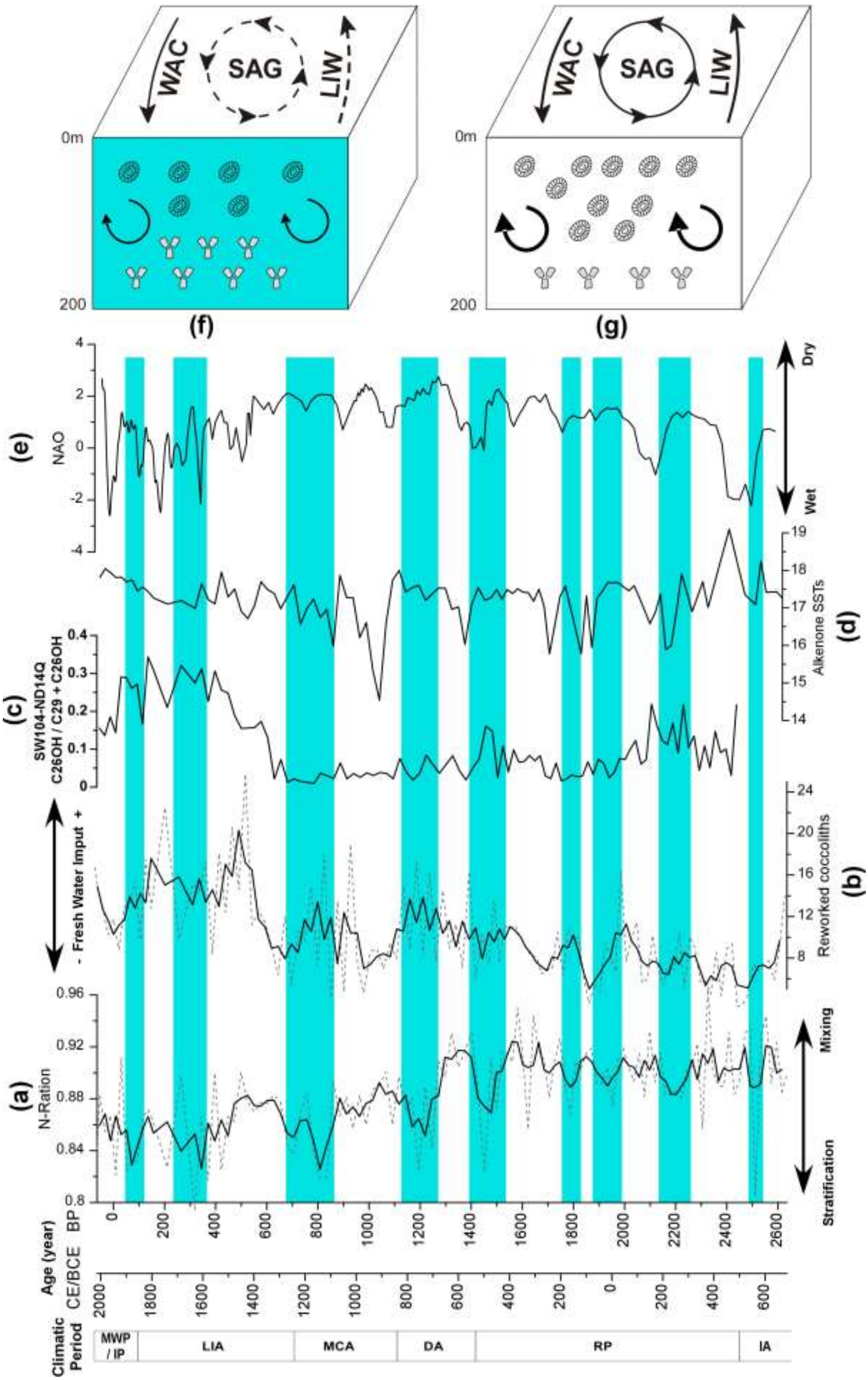


Figure 4. Comparison in time domain between (c) SW104-ND14Q, (d) C90, and (e) C5Comp reworked coccoliths, (g) SW104-ND14Q $C_{26OH}/C_{29}+C_{26OH}$ ratio, (b) Si fluctuations (Moreno et al., 2012), and (a) Flood frequency reconstruction from Southern Alps (Wirth et al., 2013). (f) Terrestrial biomarker concentration (Jalali et al., 2018) and (i) Forest fraction of usable land (Kaplan et al., 2009) are reported. The dots mark the dry spells identified in the records.

The bands highlight the relationship between $C_{26OH}/C_{29}+C_{26OH}$ ratio and negative (h) NAO states. The climate periods are from Margaritelli et al. (2016).



WAC
SAG
LIW
0m
200
(f)
(g)
(e)
NAO
Dry
Wet
(d)
Alkenone SSTs
(c)
SW104-ND14Q
C26OH / C29 + C26OH
(b)
Reworked coccoliths
- Fresh Water Imput +
(a)
N-Ration
Mixing
Stratification
Age (year)
BP
CE/BCE
Climatic Period
MWP / IP
LIA
MCA
DA
RP
IA

Figure 5. Schematic view of inferred relationship between (a) SW104-ND14Q N-Ratio and (f, g) SAS hydrology. (b) %RC fluctuations, (c) $C_{26OH}/C_{29}+C_{26OH}$ ratio, (d) SSTs fluctuations, and (e) winter NAO index (Olsen et al., 2012; Trouet et al., 2009) are reported. The bands highlight the N-Ratio during periods of stratified surface water (diagram f). The climate periods are from Margaritelli et al. (2016).