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Antonio Cascella, Sergio Bonomo, Bassem Jalali, Marie-Alexandrine Sicre, Nicola Pelosi, Sabine Schmidt, Fabrizio Lirer

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

### Coccolithophore evidences

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17

18 **Abstract**

19 New information on paleoenvironmental conditions over the past ~2700 years in the Central  
20 Mediterranean Sea have been acquired through the high-resolution study of calcareous  
21 nanofossils preserved in the sediment core SW104ND14Q recovered in the Southern  
22 Adriatic Sea (SAS) at 1013 m water depth. The surface water properties at this open SAS site  
23 are sensitive to atmospheric forcing (acting both at local and regional scale) and the North  
24 Ionian Sea driven inflowing waters. Our data show a relationship between reworked coccolith  
25 abundances, flood frequency across the Southern Alps and the North Atlantic Oscillation  
26 (NAO) confirming their value as indicator of runoff/precipitation. Changes in the abundance  
27 of the opportunistic (r-strategist) species *Emiliania huxleyi* and deep dweller taxa  
28 *Florisphaera profunda* were used to reconstruct the upper water column stratification and  
29 associated changes in coccolithophorid productivity. The negative correlation between  
30 reworked coccoliths and the N-Ratio ( $r=-0.44$ ;  $p=6^{-7}$ ) suggest that fresh water induced  
31 stratification is a controlling factor of the SAS coccolithophorid production. High  
32 coccolithophorid productivity levels occurred during dry periods and/or time intervals of  
33 inflowing salty and nutrient-rich Levantine Intermediate Waters (LIW) favouring convection  
34 while lower levels took place during high freshwater discharge, mainly during the Little Ice  
35 Age (LIA) and two centennial scale intervals of weakest NAO around 200 BCE and 500 CE.

36

37 **Keywords**

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

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41

42 **Introduction**

43 Coccolithophores (calcareous nanoplankton) and their fossil remains (calcareous  
44 nannofossils) are valuable source of information for paleoclimatic studies (Baumann et al.,  
45 2005). Coccolithophores are single cell calcareous algae whose ecology and vital functions  
46 are driven by environmental parameters within the ocean euphotic zone (e.g., temperature,  
47 salinity, sunlight, and nutrient supply). Therefore, abundances of selected taxa have been used  
48 to reconstruct variations of physical and environmental parameters and their relation with  
49 climate change and human activity. Their skeletons composed of tiny calcareous platelets  
50 (coccoliths) are highly abundant in marine sediments making them ideal fossils to produce  
51 high-resolution time series (Baumann et al., 2005). These microorganisms are usually  
52 considered to prefer warm, stratified, oligotrophic waters of low and middle latitude regions  
53 (e.g., Honjo and Okada, 1974; Ziveri et al., 2004). However, local oceanic features such as  
54 coastal currents, gyres, eddies, upwelling, and river runoff are known to regionally affect their  
55 productivity (Guerreiro et al., 2013). In addition, reworked coccoliths (i.e., the nannofossils  
56 which have been removed from their original sedimentary layer and redeposited in a younger  
57 layer) can provide information on sediment transport (Bonomo et al., 2014; Ferreira et al.,  
58 2008; Ferreira and Cachão, 2005) and used to reconstruct regional scale runoff and/or  
59 precipitation changes (Bonomo et al., 2016a; Incarbona et al., 2010; Sprovieri et al., 2006).

60 Understanding the trends and variability of the Mediterranean climate at local and regional  
61 scales has been subject of intense research. (Bonomo et al., 2016a; Cacho et al., 1999; Frigola  
62 et al., 2007; Martrat et al., 2004; Pérez-Folgado et al., 2004; Rodrigo-Gámiz et al., 2011;  
63 Rohling et al., 2002, 2015; Sbaffi et al., 2001; Sierro et al., 2005; Sprovieri et al., 2003, 2006;  
64 Triantaphyllou et al., 2009, 2016a). Shelf sediments of the Adriatic Sea (AS) provide ideal  
65 natural archives for high-resolution paleoclimatic investigations because of expanded  
66 Holocene sedimentary sequences and possible use of recurrent tephras for geochronological

67 control (Jalali et al., 2018; Lowe et al., 2007; Marchini et al., 2014; Matthews et al., 2015;  
68 Siani et al., 2013). Terrestrial and marine paleoclimate proxy data (e.g., calcareous plankton,  
69 lipid biomarkers, palynomorphs, stable isotopes, lake levels, and speleothems) have shown  
70 the occurrence of abrupt climate changes during the Holocene (warmer/colder and  
71 drier/wetter periods) at decadal, centennial to millennial time scales in the Mediterranean  
72 basin (e.g., Bini et al., 2019; Cisneros et al., 2016; Di Bella et al., 2014; Gogou et al., 2016;  
73 Goudeau et al., 2015; Grauel et al., 2013; Jalali et al., 2016, 2018; Kouli et al., 2012; Lirer et  
74 al., 2013, 2014; Margaritelli et al., 2016, 2018; Piva et al., 2008; Sicre et al., 2016; Skampa et  
75 al., 2019; Triantaphyllou et al., 2009, 2010, 2016b).

76 Many studies have focussed on (late) Holocene climate variability and its impact on the  
77 environment and human activity in the SAS (Caroli and Caldara, 2007; Combourieu-Nebout  
78 et al., 2013; Di Rita and Magri, 2009; Giunta et al., 2003; Grauel and Bernasconi, 2010; Jalali  
79 et al., 2018; Leider et al., 2010; Oldfield et al., 2003; Piva et al., 2008; Sangiorgi et al., 2003;  
80 Siani et al., 2013; Sicre et al., 2016). The recent study of Jalali et al. (2018) in the SAS  
81 highlighted the links between the centennial scale variability of SSTs and local climatic and  
82 oceanographic features, and notably the role of the Bimodal Oscillating System (BiOS) of the  
83 Ionian Sea and North Atlantic Oscillation (NAO). Although there has been a substantial  
84 number of publications on the investigated area, very few studies have explored calcareous  
85 nannofossils as a proxy of past climate and environmental changes (e.g., Giunta et al., 2003;  
86 Narciso et al., 2012; Sangiorgi et al., 2003). Narciso et al. (2012) studied a gravity core close  
87 to our site between 13000 and 5500 BP, thus focused on the Greenland Stadial 1/Younger  
88 Dryas, Pre-Boreal, and Sapropel 1 equivalent periods. Giunta et al. (2003) and Sangiorgi et al.  
89 (2003) reported data from 18000 to 2300 yrs BP at a more southern site, documenting the  
90 distribution of calcareous nannofossils during the Sapropel S1. As far as living  
91 coccolithophores are concerned, the only study carried out in the SAS is that of Balestra et al.  
92 (2008) describing assemblages in the water column and surface coastal sediments of the Gulf

93 of Manfredonia (SAS). Other very recent data were restricted to the Mid and North Adriatic  
94 Sea (e.g., Cerino et al., 2017; Godrijan et al., 2018; Skeji et al., 2018, and references there  
95 in) or are part of phytoplankton biomass and productivity assessments aiming at providing  
96 rough estimates of coccolithophore distribution in open SAS (e.g., Fonda Umani, 1996;  
97 Ljubimir et al., 2017, and references therein).

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

112

### 113 **Oceanographic setting of the study area**

114 The AS is a semi-enclosed basin located between the Italian Peninsula and the Balkans,  
115 connected to the Mediterranean Sea through the Strait of Otranto (Fig.1a). The North Adriatic  
116 (NA) is primarily influenced by the southeast Europe climate, while the SAS experiences  
117 more arid conditions typical of Mediterranean and Northern Africa climates (Ilijani et al.,  
118 2014). The general surface circulation of the AS is cyclonic (Fig.1b,c) (Sellschopp and

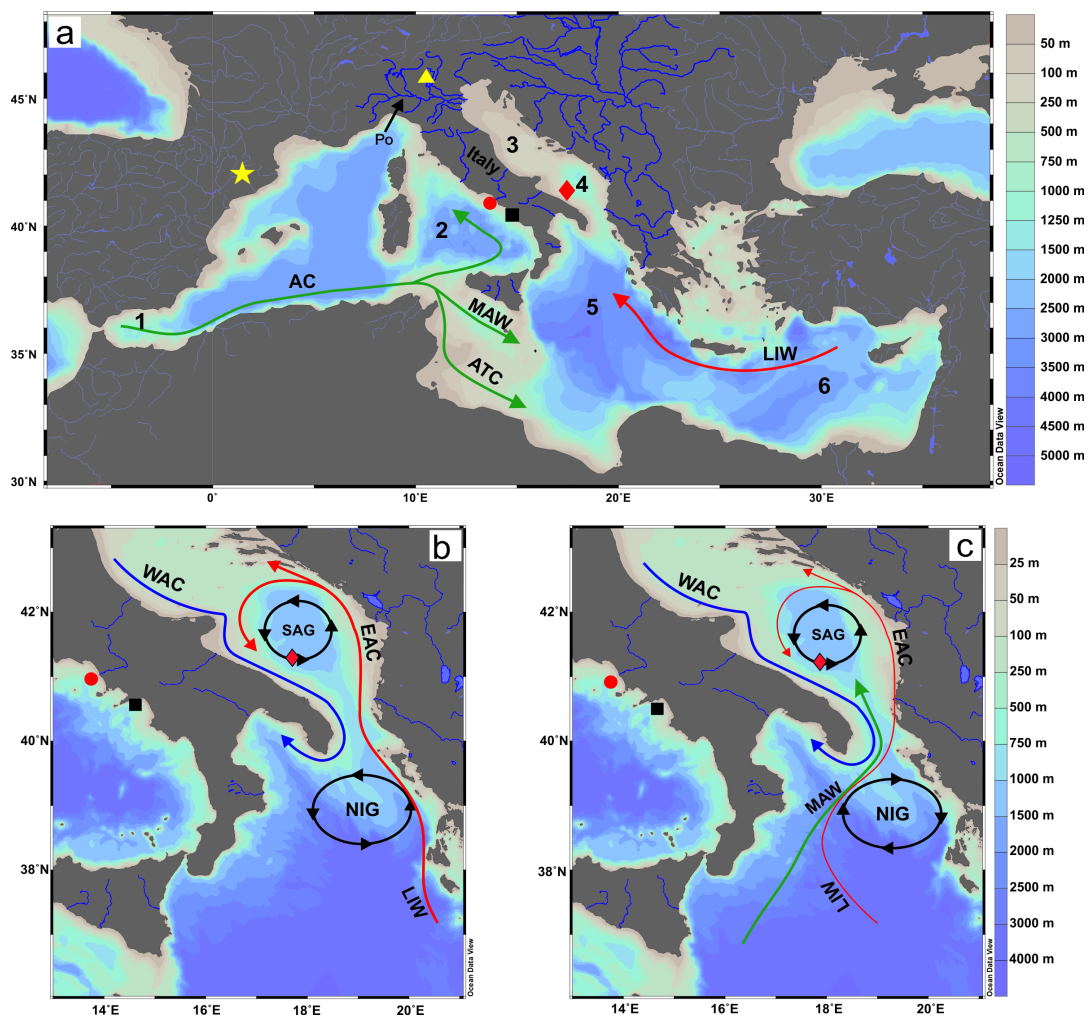
119 Álvarez, 2003) and consists of a northward current flowing along the eastern Adriatic coast  
120 (i.e., the Eastern Adriatic Current, EAC) balanced by southward current flowing along the  
121 western coast (i.e., the Western Adriatic Current, WAC). The intermediate layer mainly  
122 present in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

126 The SAS is a sub-basin (South Adriatic Pit, SAP, 1260 m max depth) characterized by a  
127 quasi-permanent cyclonic circulation, i.e. the South Adriatic Gyre (SAG; Ga i et al., 1997)  
128 (Fig. 1b,c). The physical and chemical properties of SAS surface waters depend on the  
129 characteristics of inflowing waters into the basin, the strength of SAG, as well as wind stress  
130 and river discharges. Inflowing waters consist mainly of WAC and NADW from the North,  
131 the LIW and occasionally Modified Atlantic Water (MAW) from the South. The WAC is  
132 strongly influenced by river runoff mostly from the Po River, making it fresher and nutrient  
133 rich. The inflow of LIW and MAW depends on the variability of the North Ionian Gyre (NIG)  
134 (Fig. 1b,c). According to the BiOS (Bimodal Oscillating System) model, the NIG circulation  
135 may either be cyclonic or anticyclonic (Civitarese et al., 2010; Gacic et al., 2010). This  
136 mechanism is sustained by internal processes driven by the density of the ADW outflowing  
137 the Otranto Strait. When the circulation in the NIG is cyclonic, saltier and warmer LIW enters  
138 the SAS promoting deep convection and the formation of a denser ADW. In an anticyclonic  
139 NIG mode, fresher and colder MAW enters the SAS leading to the production of lower  
140 density ADW. However, some studies invoke the role of more complex driving mechanisms  
141 involving the whole Ionian Sea circulation and not just its northern sector (Reale et al., 2016;  
142 Simoncelli et al., 2016; Theocharis et al., 2014). The intensity of the SAG depends on local  
143 wind intensity and properties of advected waters from the Ionian Sea (Shabrang et al., 2016).  
144 Shabrang et al. (2016) reported a significant negative correlation between the NAO index and



145 local wind intensity. However, they did not find unequivocal relationship between the NAO  
 146 and SAG variability because of additional effects of the advection of the Ionian waters,  
 147 suggesting that the BiOS mode does not depend on NAO. Nevertheless, Pinardi et al. (2015)  
 148 reported a sustained BiOS anticyclonic circulation during the period of positive NAO in  
 149 1987-1996.

150 The surface waters of the SAS are more oligotrophic than those of the NA (e.g., Civitarese et  
 151 al., 1998). The influence of Po River and secondary Apennines rivers flowing into the western  
 152 AS on the nutrient budget of the SAS seems rather weak and limited to a narrow coastal  
 153 current flowing over the Italian shelf (Faganeli et al., 1989). The nutrient supply to the SAS  
 154 occurs mainly via the inflow of LIW lying at about 300 m in the Adriatic Sea (Gai et al.,  
 155 2002). Nevertheless, according to Civitarese et al. (2010) larger amounts of nutrients are  
 156 advected by the MAW during periods of anticyclonic BIOS.



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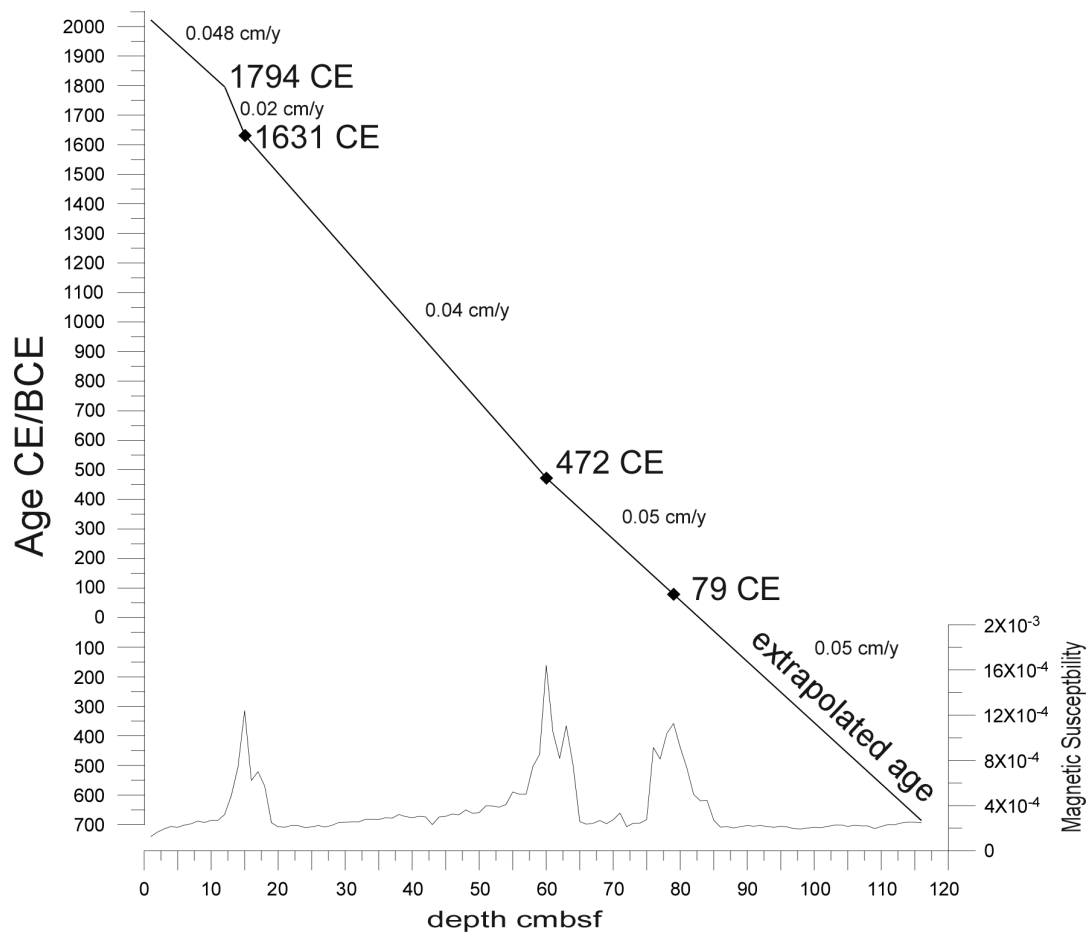
158 **Figure 1.** Location of the cores SW104-ND14Q (diamond), C5 Composite (dot), C90 (square,  
159 Lirer et al., 2013), Basa de la Mora (star, Moreno et al., 2012), and Ledro (triangle, Wirth et  
160 al., 2013). (a): bathymetric map of the Mediterranean Basin and main surface (green arrow)  
161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

170

## 171 **Methods**

### 172 *Core SW104-ND14Q*

173 Core SW104-ND14Q (17°37'3.612''E; 41°17'2.4''N) was recovered at 1013m water depth in  
174 the SAS (Fig. 1). The sedimentary sequence was retrieved with a SW104 gravity corer  
175 system, which preserves the water-sediment interface and allowed the recovery of 116 cm of  
176 undisturbed and uncompressed homogeneous brown-grey hemipelagic sediments. The  
177 magnetic susceptibility measured on board with a Bartington Instrument M2 revealed three  
178 tephra layers (Fig. 2). The age model used here is from Jalali et al. (2018) and has been  
179 constructed combining radionuclides ages ( $^{210}\text{Pb}$  activity-depth profile and  $^{137}\text{Cs}$  activity) for  
180 the last ca. 150 years and the additional dates derived from the correlation of three tephra  
181 layers with well-dated volcanic events onland [Pompeii eruption (79 CE); Pollena eruption  
182 (472 CE); 1631 CE] (see Jalali et al. 2018 for details on tephrostratigraphy). Linear  
183 interpolation between the tie-points has been used to construct the age-depth profile from the  
184 top down to the base core documenting a mean Sed. Rate of 0.04 cm/y (Fig. 2). Based on the  
185 age model, core SW104-ND14Q ranges from 700 BCE to 2003 CE and has a mean temporal  
186 resolution of ~26 yrs.



187

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

190

191 *Core C5 Composite*

192 To investigate the reliability of the reworked coccoliths as a regional proxy of precipitation,

193 we also used the central Tyrrhenian Sea shallow sequence C5 Composite (C5Comp) (Fig.1).

194 The location of this site in front of Volturno River mouth makes it particularly suitable for

195 reconstructing runoff variability and for comparing coastal and open sea sites (Bonomo et al.,

196 2016). The core C5Comp is a composite marine sequence consisting of two cores: the

197 SW104-C5 and core C5 (710 cmbsf length) both recovered in the Gulf of Gaeta, at 93 m

198 water depth (see Margaritelli et al., 2016 for details). Calcareous nannofossils of the core

199 SW104-C5 (back to 1630 CE) was already published by Bonomo et al. (2016). In this work

200 we extended their reconstruction back to ~ 400 CE. The chronology used is that of

201 Margaritelli et al. (2016) and has been assembled combining radionuclides ages ( $^{210}\text{Pb}$

202 activity-depth profile and  $^{137}\text{Cs}$  activity) for the last ca. 150 years, planktonic foraminiferal

203 event, tephrostratigraphy and oxygen stable isotope correlation with other marine sites (for  
204 details see Margeritelli et al., 2016). The age-depth profile has been constructed by a linear  
205 interpolation between the tie-points showing a progressive decrease in sedimentation rate  
206 from the top down to the base core.

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

### 209 *Calcareous Nannofossils*

210 116 samples of the SW104-ND14Q core and 108 of the C5Comp were prepared as standard  
211 smear slides (Bown, 1998) and analyzed with a transmitted light microscope at x1250  
212 magnification. Some samples of SW104-ND14Q core were analysed with a scanning electron  
213 microscope (SEM) in order to solve taxonomic identification for smaller placoliths difficult to  
214 achieve by light microscope (e.g., *Emiliania huxleyi*). The relative abundance of *in situ*  
215 species was estimated only in the SW104-ND14Q core based on the count of at least 600  
216 specimens. The abundance of reworked nannofossils was estimated in the SW104-ND14Q  
217 and C5Comp as the number of reworked specimens encountered during the count of the *in*  
218 *situ* coccoliths. All abundances are expressed in percentages. SW104-ND14Q coccolith  
219 species abundances were also used to calculate the N-ratio as defined by Flores et al. (2000)  
220 to assess the nutricline depth fluctuations. The N-ratio is based on the absolute abundances of  
221 the main surface r-strategist species (in our record *E. huxleyi* and small placoliths) over that of  
222 *F. profunda* (lower photic zone taxon). High values of the N-ratio indicate shallow  
223 nutricline/thermocline (relatively high surface coccolithophorid productivity) while low  
224 values indicate deep nutricline/thermocline (relatively low surface coccolithophorid  
225 productivity). As small placoliths, we counted the placoliths not confidently recognizable as  
226 *E. huxleyi* and *Reticulofenestra* spp.

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

230

### 231 *Ecology of selected taxa*

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

241 The lower photic zone species *F. profunda* has a more constrained habitat and has thus been  
242 widely used to monitor past changes in nutricline-depth and induced changes in surface  
243 productivity (Beaufort, 1997). The abundance of *F. profunda* increases with respect to other  
244 coccolithophores when the nutricline is deep and overlaid by a nutrient-depleted upper photic  
245 layer (Balestra et al., 2008; Bown et al., 2009; Dimiza et al., 2015; Incarbona et al., 2008,  
246 2010). These conditions generally reveal stable, stratified, oligotrophic surface waters during  
247 summer months (Baumann et al., 2005; Malinverno et al., 2009) that can be disrupted under  
248 increased wind stress and / or upwelling and divergence circulation (Bown et al., 2009).  
249 Hernández-Almeida et al. (2019), using *F. profunda* relative abundance vs MODIS (Moderate  
250 Resolution Imaging Spectroradiometer) chlorophyll- $\alpha$ , show a pronounced temperature  
251 sensitivity of *F. profunda* and no correlation with surface net primary production at latitudes  
252 higher than 30°N–30°S, such as Mediterranean area. Contrary, Grelaud et al. (2012) showed a

253 strong anticorrelation ( $R = -0.76$ ) between *F. profunda* % and chlorophyll- $\alpha$  in the Aegean  
254 Sea (eastern Mediterranean Sea).

### 255 *Biomarker analyses*

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

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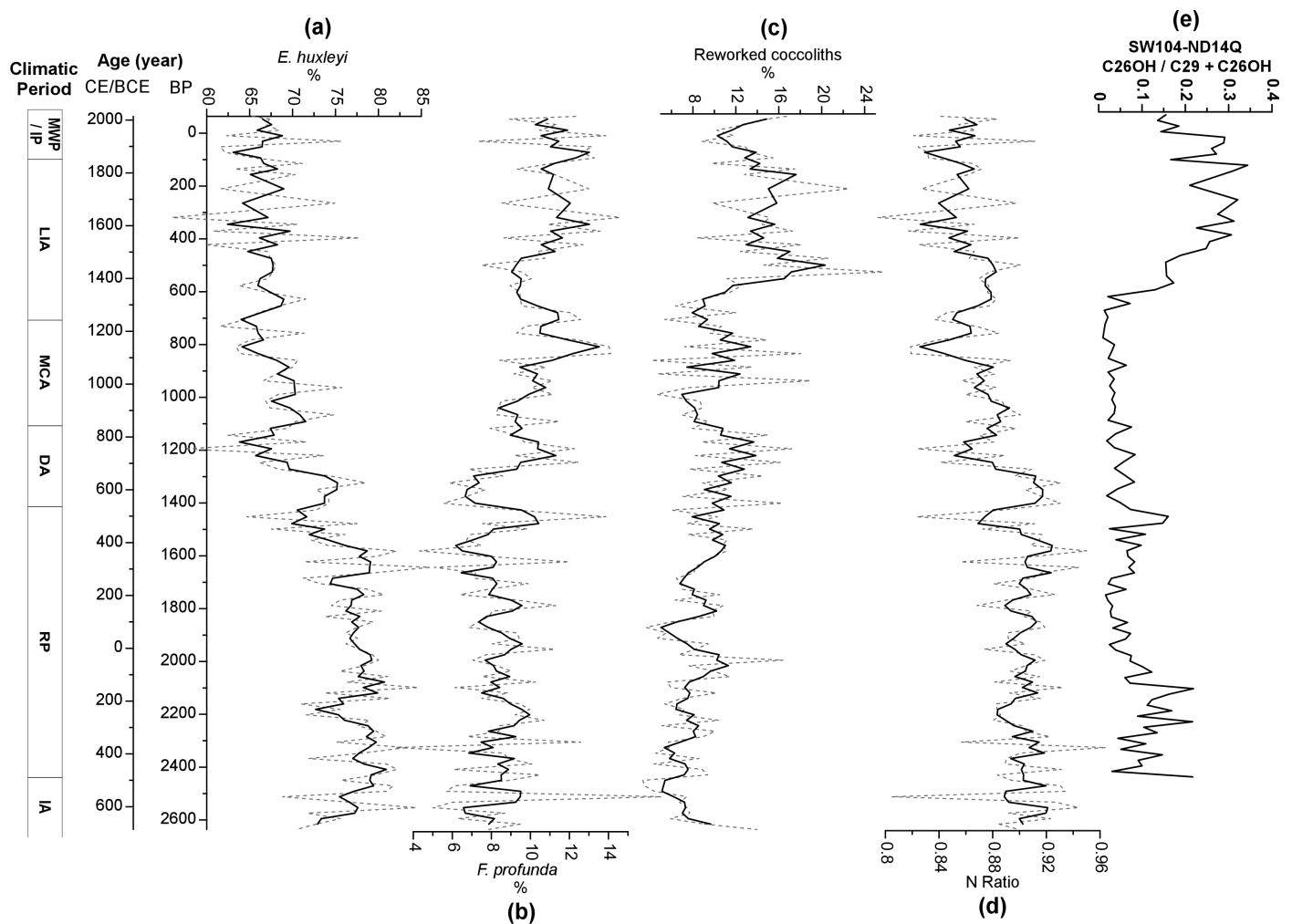
### 263 **Results**

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

271 *E. huxleyi* abundance range from 65 to 90 % (Fig. 3a). Its downcore distribution pattern can  
272 be divided into two major intervals. A first one that includes the late Iron Age (IA) and the  
273 almost entire Roman Period (RP; between ~700 BCE and ~400 CE) with abundance above  
274 80%. This period is followed by a decline to lower values (< 65%) between ~400 and ~800  
275 CE, i.e. from the late RP throughout the Dark Age (DA). *E. huxleyi* returns to moderately  
276 higher abundances (65 - 75%) at the late DA and during the Medieval Climate Anomaly  
277 (MCA) (800 to 1100 CE). Then, values remain approximately at these levels but with  
278 superimposed short-lived oscillations especially during the upper LIA. The distribution of *F.*

279 *profunda* (Fig. 3b) reveals three main intervals: the first one runs from the bottom of the core  
280 till ~400 CE and is characterized by fluctuating values between 7 and 9 %. Over the second  
281 interval, from 400 to 1200 CE, the taxon abundances increase almost continuously, except for  
282 two time spans of strong decrease centred at 600 and 900 CE. From 1200 CE, *F. profunda*  
283 declines till 1550 CE and rises again to Present day values. As shown in Fig. 3d, the N-ratio  
284 shows similar trends as *E. huxleyi*, but with more pronounced fluctuations especially in the  
285 upper half of the core. During the first 1200 years (700 BCE - 400 CE) the N-ratio value is >  
286 0.9. At ~400 CE a sharp drop sets the beginning of a long-term decreasing trend till Present  
287 that suggests a progressive reduction of coccolithophorid productivity.

288 RC percentages (%RC) along the core range from ~3 to ~25%, and depict a steady increase  
289 from the bottom core to ~800 CE. Then, after a period of lower values around 900 CE and  
290 1300 CE, %RC increases up to Present with the highest values (17-25%) during the LIA  
291 (~1400 -1800 CE) (Fig. 3c). In the C5Comp core, %RC ranges from ~14 to ~79% with lowest  
292 levels found between ~400 and ~1350 CE.



294 **Figure 3.** Time domain distribution of (a) *E. huxleyi*, (b) *F. profunda*, (c) RC, (d) N-ratio, and  
 295 (e)  $C_{26OH}/C_{29}+C_{26OH}$  ratio in core SW104-ND14Q. Raw and three points running average data  
 296 are reported in grey dashed and black full lines, respectively. The age model is from Jalali et  
 297 al. (2018) and the climate period intervals are those of Margaritelli et al. (2016).  
 298

## 299 Discussion

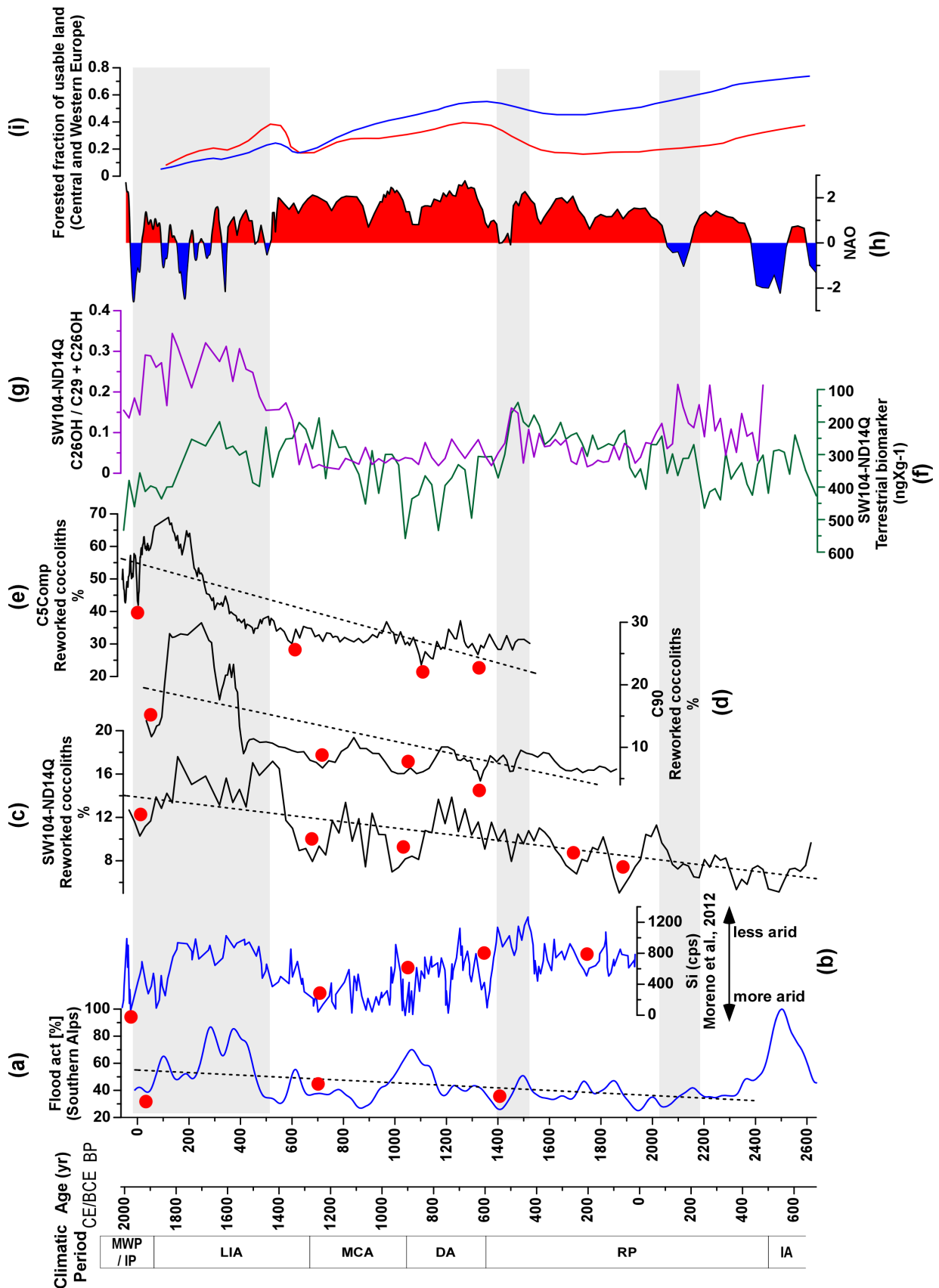
### 300 *Reworked coccoliths and runoff fluctuations*

301 The NAO is one of the dominant atmospheric mode of variability in the North Atlantic sector  
 302 that has a considerable influence on winter temperature/precipitation in Europe including the  
 303 Mediterranean region (Hurrell, 1995). In the central Mediterranean, positive NAO conditions  
 304 result in colder and drier winters than average, while winters are warmer and wetter during  
 305 negative phases of NAO (Benito et al., 2015; López-Moreno et al., 2011a, 2011b; and  
 306 references within). Bonomo et al. (2016) were able to evidence a negative correlation between  
 307 the NAO index of Trouet et al. (2009) and the %RC in the Central Tyrrhenian Sea core



308 SW104-C5 over the last 400 years. Our results show that this relationship could have  
309 persisted back to ~700 BCE (Fig. 4). The resemblance between the %RC short and long term  
310 trends the flood frequency in Southern Alps (Wirth et al., 2013) and the Southern Tyrrhenian  
311 marine record (Gulf of Salerno; Lirer et al. 2013) seems to confirm the link between the %RC  
312 and runoff/precipitation in the region on longer time span (Bonomo et al., 2016a; Incarbona et  
313 al., 2010; Sprovieri et al., 2006). This finding is supported by the slight negative correlation  
314 between the NAO index of Trouet et al. (2009) ( $r=-0.4$   $p=5^{-33}$ ,  $n=34$ ) and Olsen et al. (2012)  
315 ( $r=-0.2$   $p=0.01$ ,  $n=82$ ) and the %RC along the SW104 record. Our data agree with the  
316 negative correlation between NAO and winter precipitation, for the 1950–2006 period,  
317 reconstructed over large areas of Morocco and Tunisia, most of the Iberian Peninsula,  
318 southeastern France, Italy, the Balkan Peninsula, and large areas of central and northern  
319 Turkey (López-Moreno et al., 2011a). Notwithstanding the age models accuracy of the  
320 different cores, the main drier spells recorded in the SAS, in the Central and Southern  
321 Tyrrhenian as shown by red dots in Fig. 4 might be considered synchronous as well to the  
322 XRF Si fluctuations found in lake sediments of Iberian Peninsula (Moreno et al., 2012). A  
323 noteworthy result is the high %RC (RC Acme event) during the late LIA, between ~1600 and  
324 ~1850 CE, that coincides with a long standing interval of negative NAO and is consistent  
325 with a regional scale humid period already documented in marine and continental sedimentary  
326 sequences of the Western and Central Mediterranean (e.g., Barrera-Escoda and Llasat, 2015;  
327 Goudeau et al., 2015; Vallefucio et al., 2012; Moreno et al. 2012) .  
328 Jalali et al. (2018) highlighted similarities between the TERR–alkane record in SW104-  
329 ND14Q and the forested fraction of usable land (FF) in Central and Western Europe (Fig.4 f,  
330 i) (Kaplan et al., 2009). Considering that FF fluctuations are indicative of anthropogenic  
331 deforestation (Kaplan et al., 2009), they concluded that TERR–alkane at SW104-ND14Q  
332 reflects primarily human activity rather than climate fluctuations. Since the RC signal does  
333 not match with either the TERR–alkanes or FF index but with the flood activity

334 reconstruction and the  $C_{26OH}/(C_{26OH}+C_{29})$  ratio (Fig.4), we suggest that RC reflect  
 335 precipitation changes that are also seen in other Mediterranean RC records overall supporting  
 336 the hypothesis that %RC is a reliable index of past runoff/precipitation changes in the region.



337

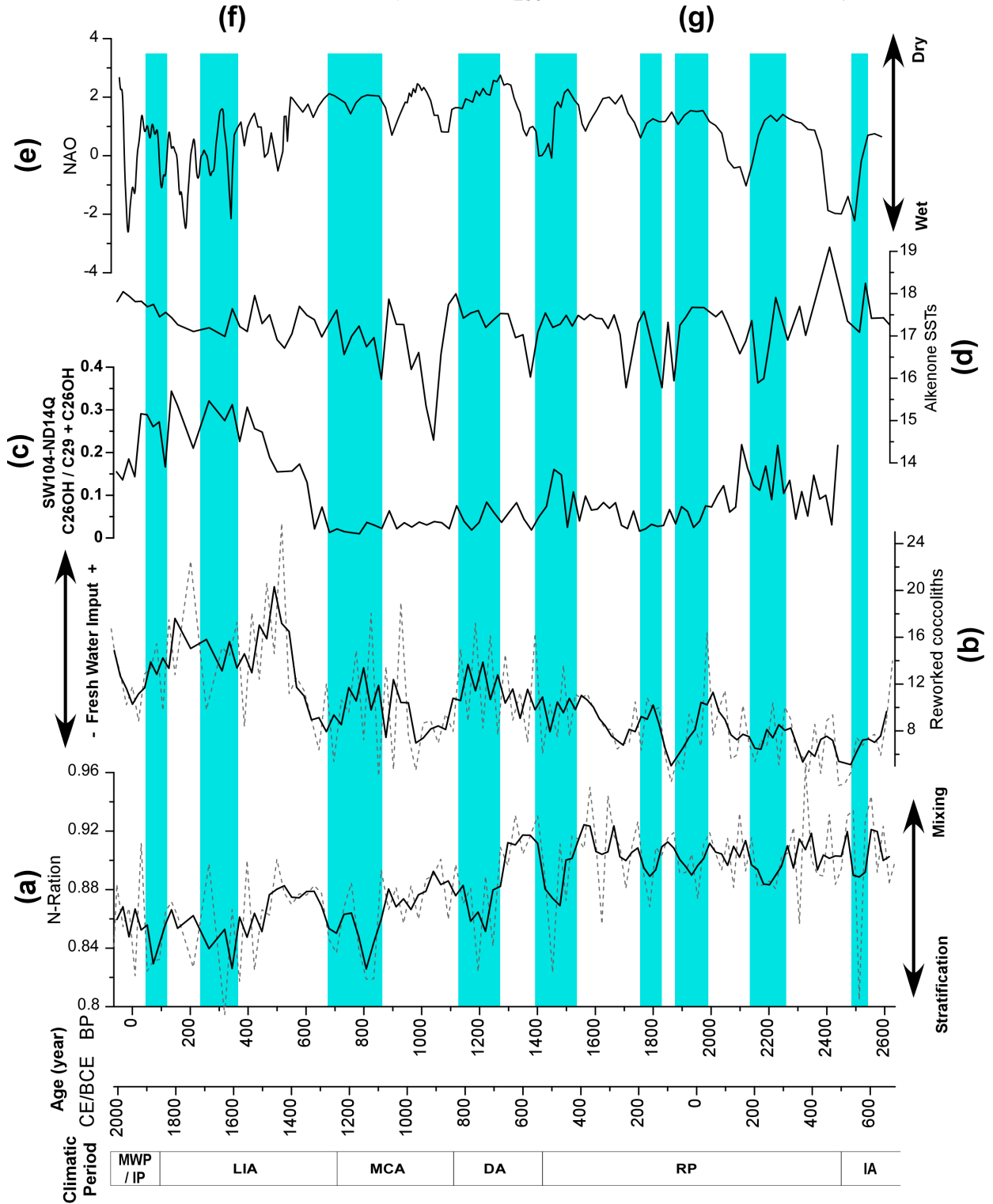
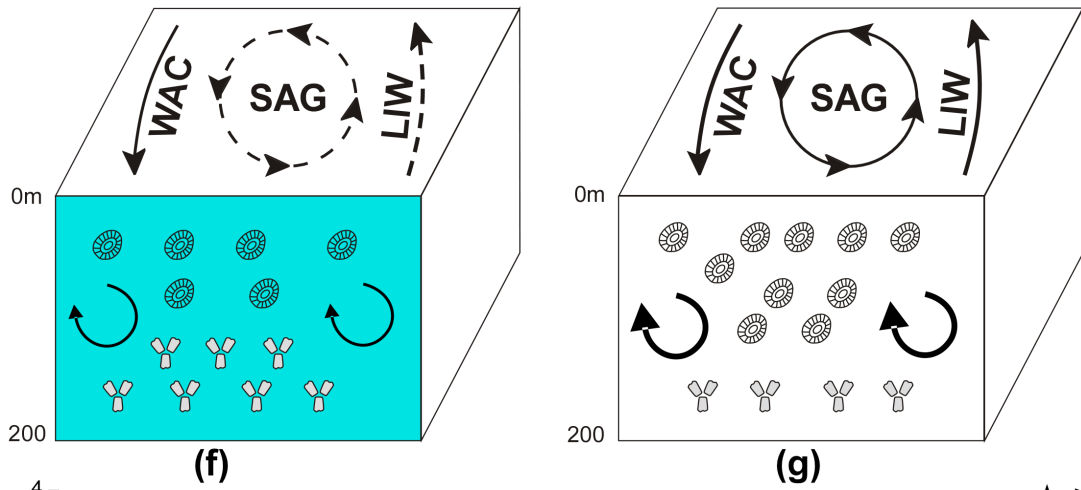
338 **Figure 4.** Comparison in time domain between (c) SW104-ND14Q, (d) C90, and (e) C5Comp  
339 reworked coccoliths, (g) SW104-ND14Q  $C_{26OH}/C_{29}+C_{26OH}$  ratio, (b) Si fluctuations (Moreno  
340 et al., 2012), and (a) Flood frequency reconstruction from Southern Alps (Wirth et al., 2013).  
341 (f) Terrestrial biomarker concentration (Jalali et al., 2018) and (i) Forest fraction of usable  
342 land (Kaplan et al., 2009) are reported. The dots mark the dry spells identified in the records.  
343 The bands highlight the relationship between  $C_{26OH}/C_{29}+C_{26OH}$  ratio and negative (h) NAO  
344 states. The climate periods are from Margaritelli et al. (2016).  
345

#### 346 *N-ratio and South Adriatic hydrology*

347 Highest N-ratio values almost all along the RP indicate shallow nutricline (surface productive  
348 waters) during this period considered as generally mild (Figs. 3, 5). This is in contrast with  
349 the LIA showing deep nutricline (lower surface productivity levels) (Figs. 3, 5), a cold period  
350 that one would expect to be favourable to water column mixing and growth of r-strategy taxa  
351 *E. huxleyi*. Comparable results has been recorded in the North Aegean Sea during the last  
352 1500 years (Gogou et al., 2016; Skampa et al., 2019). In particularly, in the North Aegean Sea  
353 Gogou et al.( 2016) and Skampa et al. (2019) recorded periodic occurrence of “*E. huxleyi*  
354 dominance” intervals indicating strong water column convection coupled with NAO positive  
355 shifts , EMT-like events (Incarbona et al., 2016), cool spells, and enhanced continental inputs  
356 as well. In contrast, the occurrence of *F. profunda* dominance intervals may be linked to  
357 enhanced stratification of the upper water column and warm surface waters, potentially  
358 associated with increased lower salinity Black Sea Water intrusion. During the RP, alkenone-  
359 derived SSTs show cold oscillations that do not seem to have any relationship with the N-  
360 ratio (Fig. 5 a, d). Local atmospheric and hydrological conditions (i.e. properties of inflowing  
361 waters into the basin and strength of SAG) play an important role in the stratification of the  
362 upper water column and associated changes in productivity (Civitarese et al., 2010; Ljubimir  
363 et al., 2017; Vilibi et al., 2012). Several studies in open sea SAS waters have linked high  
364 abundances of coccolithophorids with the inflow of saltier Ionian waters (Fonda Umani,  
365 1996; Totti et al., 2000). In contrast, Ljubimir et al. (2017) reported higher abundances of  
366 coccolithophorids in lower salinity SAG waters during years of anticyclonic mode of the

367 BIOS and their absence during cyclonic BIOS years. However, despite the lack of significant  
368 correlation between salinity and total coccolithophore abundances, increased abundance of *E.*  
369 *huxleyi* has been often related to the inflow of LIW or eastern Mediterranean surface waters  
370 (Malinverno et al., 2003; Skeji et al., 2018). Advection of saltier LIW by promoting deep  
371 convection (Gai et al., 2014) would favour the development of *E. huxleyi* known to rapidly  
372 respond to increased nutrient supply to the photic zone (Fig.5 g) (Malinverno et al., 2003).  
373 Conversely, reduced inflow of LIW, or enhanced input of less salty waters (mainly the WAC,  
374 and occasionally the MAW), and a weak SAG, would lead to higher surface water buoyancy  
375 and stratified conditions (Fig.5 f, g). The consequent deepening of the nutricline would thus  
376 favour *F. profunda* growth (Fig. 5 f). This conceptual scheme is in agreement with the slight  
377 negative correlation ( $r = -0.44$ ;  $p = 6^{-7}$ ) between the N-ratio and %RC values. For instance,  
378 higher values of %RC associated with sustained negative NAO during the LIA are coherent  
379 with higher precipitation and runoff (Bonomo et al., 2016a; Incarbona et al., 2010; Sprovieri  
380 et al., 2006) and the Po River flood record (Camuffo and Enzi, 1996). Rising  
381  $C_{26OH}/(C_{26OH}+C_{29})$  ratio to their highest values suggests an abrupt reduction of water  
382 oxygenation that is also compatible with stratified conditions caused by the large freshwater  
383 discharge during the LIA and lowest N-ratios. Similar observation can be made for two  
384 intervals of weaker NAO, i.e. around 200 BCE and around 500 CE.  
385 Regarding nutrient supply, our results also support the idea of a limited influence of the Po  
386 River (and secondary Apennines rivers) on the nutrient budget of the open SAS surface  
387 waters and coccolithophore productivity, as the nutrients are usually rapidly consumed during  
388 their transport within the WAC. The same have been observed around the eastern Adriatic  
389 coasts (Vilibi et al., 2012). Overall, our findings suggest that fresh water input due to  
390 increased precipitation and river runoff impact essentially on buoyancy and subsequent  
391 stratification in the SAG.

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



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

403

#### 404 **Conclusion**

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

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

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

420

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429

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