

Millennial scale coccolithophore paleoproductivity and surface water changes between 445 and 360 ka (Marine Isotope Stages 12/11) in the Northeast Atlantic

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ABSTRACT

A high resolution coccolithophore study was carried out in order to improve the understanding of the paleoceanographic evolution and changes in paleoproductivity occurring off the Iberian Margin (IM) between 445 and 360 ka, i.e. during late Marine Isotope Stage 12 to 11. Coccolithophore assemblages allowed reconstructing surface water changes characterized by millennial-scale oscillations (~1.5 kyr cycles) involving Portugal or Iberian Poleward Currents (PC and IPC) prevalence. Changes in paleoproductivity, possibly related to the upwelling of Eastern North Atlantic Central Waters (ENACW) – of sub-tropical (ENACWst) or sub-polar origin (ENACWsp) – were also recognized. This study also permitted detecting abrupt events (stadial/interstadial-type oscillations) and revealed that changes in paleoproductivity are related to opposite dynamics during glacial and interglacial stages, with the reversed setting being established during the deglaciation. Furthermore, a possible control of half and fourth precessional cycle components, on the occurrence of abrupt changes within the assemblages' structure, during the deglaciation, is proposed on the basis of wavelet analysis results applied to selected taxa.

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1. Introduction

Marine Isotope Stage (MIS) 11 is a key period in the understanding of global climate evolution. Eccentricity minima occurred only five times over the last 2 Myr: one was during MIS 11 (425–360 ka), another one is at present because Earth is entering, nowadays, into a new eccentricity minimum stage (Loutre and Berger, 2003). Due to Earth's similar orbital configuration, several authors (Hodell et al., 2000; Berger and Loutre, 2002; Loutre and Berger, 2003; Barker et al., 2006; among others) considered MIS 11 as an analog of the Holocene. In addition, an important transition, the Mid-Brunhes Event (Jansen et al., 1986), occurred between MIS 13 and MIS 11 separating two climatic modes (Candy et al., 2010) and centered at around 400 ka. Early Middle Pleistocene interglacial periods (780–450 ka) were characterized by only moderate warmth while Middle and Late Pleistocene interglacials (occurring after 450 ka) were characterized by greater warmth consistent with, or warmer than, the Holocene (EPICA members, 2004; Candy et al., 2010).

The Iberian Margin (IM) is a strategic area for studying paleoceanographic and paleoclimatic variability, because high sedimentation rates allow reconstructions at millennial-to-centennial time scale (e.g., Shackleton et al., 2000). Moreover, the western and southern sections of the Iberian Peninsula's Atlantic coast belong to an active seasonal upwelling system (Wooster et al., 1976; Fiuza, 1982, 1983) and the changes of this system over time have been studied using different proxies (Soares and Dias, 2006 and references therein; Salgueiro et al., 2010).

Coccolithophore records have been widely used as valid proxy for surface ocean paleo-reconstructions at glacial-interglacial time scale (McIntyre and Bè, 1967; McIntyre et al., 1972; Flores et al., 1997; Kinkel et al., 2000; Amore et al., 2003, 2004, 2012; Rogalla and Andruleit, 2005; Lopez-Otalvaro et al., 2008; Marino et al., 2008; Triantaphyllou et al., 2009 among others) as well as short-term variability (Colmenero-Hidalgo et al., 2004; Alvarez et al., 2005; Giraudeau et al., 2010) in several basins. Previous studies demonstrated the power of coccolithophore assemblages in studying oceanographic changes off the IM in the present day (Moita, 1993; Abrantes and Moita, 1997; Silva et al., 2008) as well as in Holocene (Cachão and Moita, 2000; Colmenero-Hidalgo et al., 2002; Parente et al., 2004; Abrantes et al., 2005; Alvarez et al., 2005; Narciso et al., 2006; Flores et al., 2010; Incarbona et al., 2010) and Pleistocene sediments (Incarbona et al., 2008; Amore et al., 2012).

Climatic variability off the IM has been widely described for the last four climate cycles (e.g., de Abreu et al., 2003; Tzedakis et al.,

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2003; Martrat et al., 2004; Roucoux et al., 2006; Desprat et al., 2007; Martrat et al., 2007; Salgueiro et al., 2010). More recently, several authors contributed to define the paleoceanographic evolution off Portugal, providing high-resolution data for the period of MIS 15–9 (Voelker et al., 2010; Rodrigues et al., 2011; Amore et al., 2012). A possible role of orbital parameters and insolation on main glacial–interglacial paleoceanographic changes was proposed by Voelker et al. (2010) and Rodrigues et al. (2011). They reconstructed, on the basis of ice-rafted debris (IRD), stable isotope and alkenone records, millennial-scale variability and identified the occurrence of stadial/interstadial cycles and Heinrich-type events (Ht). Successively, Amore et al. (2012) discussed changes in coccolithophore abundances related to glacial–interglacial cycles. Superimposed on these, they also observed variability in the coccolithophore assemblages linked to precession harmonics. However, because a signal interruption occurred during the eccentricity minimum interval of MIS 11, when precession variability was low, Amore et al. (2012) suggested a higher resolution study to better understand paleoproductivity change in this period and the possible influence of higher frequency cycles on coccolithophore assemblages.

Here, for the first time, is presented a millennial-scale analysis of coccolithophore assemblages, between 445 and 360 ka, off the IM. The study, integrated with available data of previous studies on the same core (Voelker et al., 2010; Rodrigues et al., 2011; Amore et al., 2012), is devoted to:

- better understand coccolithophore production changes during the period of low precession variability of MIS 11;
- investigate the main changes occurring during the deglaciation;
- recognize changes in coccolithophore assemblages related to millennial-scale variability and to abrupt events.

2. Methods

2.1. Modern hydrographic and atmospheric conditions of the study area

Deep-sea core MD03-2699 (Fig. 1) was recovered at the western IM (39°02.20'N, 10°39.63'W; Estremadura spur) about 100 km offshore

and from 1895 m water depth. The IM (eastern North Atlantic) is characterized by seasonal upwelling (May to October; Wooster et al., 1976; Fraga, 1981; Fiuza, 1983, 1984) associated with high primary productivity that leaves an imprint in the sediment beneath these areas, as reported by Monteiro et al. (1983), Abrantes and Sancetta (1985) and Abrantes (1988).

The mechanism behind the seasonality of the surface ocean flow along Western Iberia is the seasonal migration of the semi-permanent subtropical high-pressure system (Azores High, AH; Coelho et al., 2002): during spring/summer the center of the AH migrates southward (Fig. 1a), between 27°N (March) and 33°N (August), leading to stronger north/north-westerly winds in summertime, which are favorable to upwelling (Coelho et al., 2002).

The predominately equatorward winds start to prevail in late spring/early summer and drive an offshore Ekman Transport with the upwelled waters being transport southward with the Portugal Current (PC; Fig. 1a) causing the upwelling of colder, less salty and nutrient-rich subsurface waters along the coast (Smyth et al., 2001; Soares and Dias, 2006; Relvas et al., 2007). During the winter, the northerly component of the winds weakens, or even reverses, leading to a reversal of the surface flow that can be identified in satellite images as the warm Iberian Poleward Current (IPC; Fig. 1b; Coelho et al., 2002). The poleward flow is characterized by a transport of warm, poorer in nutrients and salty waters, the Eastern North Atlantic Central Waters (ENACW) sub-tropical origin (ENACWst, Fig. 1b), and by a coastal downwelling on the western coast of the Iberian Peninsula during the fall/winter seasons until the spring transition in April–May, when the northerly winds begin to dominate (Relvas et al., 2007).

The upwelled waters are replenished by ENACWst or its subpolar counterpart (ENACWsp; Fig. 1a, b), forming a permanent thermocline at water depths below 100 m. The ENACWst and, depending on the wind strength, either type can be upwelled. The ENACWsp is formed in the eastern North Atlantic near 46°N (Fiuza, 1984; Rios et al., 1992; Fiuza et al., 1998). It was hypothesized (Rios et al., 1992; Peliz et al., 2005) that the poleward flow off western Iberia could also be connected to a northward recirculation of the Azores Current (AzC; Fig. 1b); this would explain

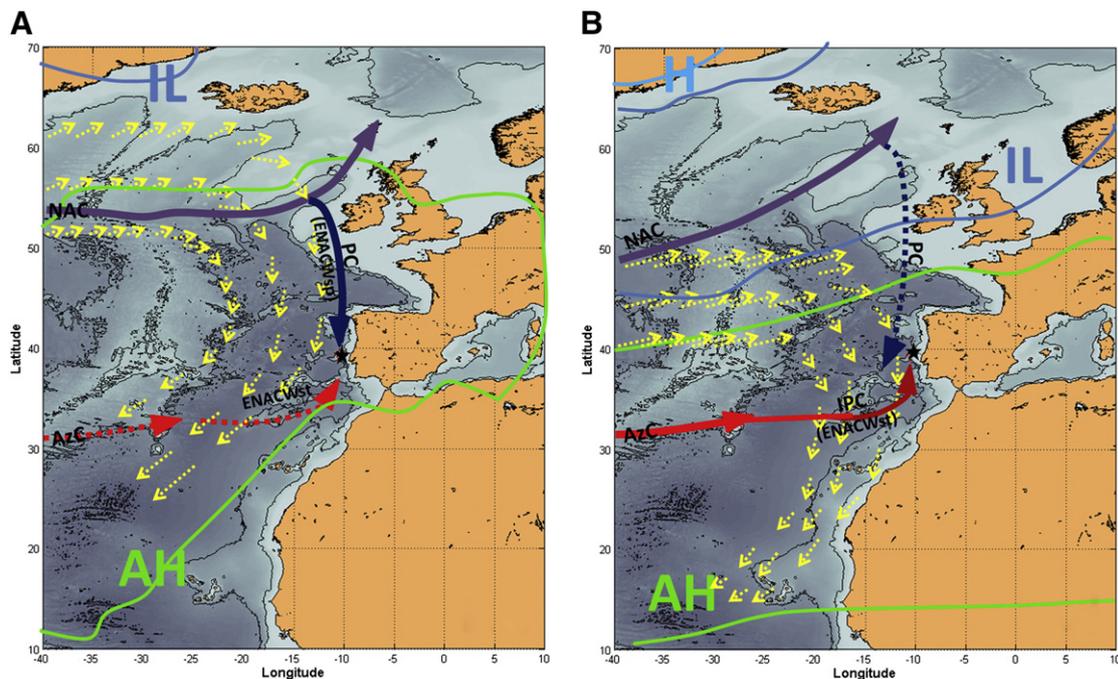


Fig. 1. Core location (black star) and modern oceanography of the study area in spring/summer [A] and autumn/winter [B], modified from Voelker et al. (2010) and Amore et al. (2012). AH = Azores High pressure center. IL = Icelandic Low pressure center. H = Polar High pressure center. AzC = Azores Current. ENACWst = Eastern North Atlantic Central Water of sub-tropical origin. ENACWsp = Eastern North Atlantic Central Water of sub-polar origin. IPC = Iberian poleward Current. PC = Portugal Current. NAC = North Atlantic Current. Yellow, dotted line arrows = direction of winds; arrow length reflects wind intensity.

the different characteristics (higher salinities) of ENACW in the northwestern part of the IM.

The AH experienced not only seasonal displacements but also intra-seasonal oscillations. In fact, the present-day climate of the Iberian Peninsula is mainly influenced by the winter interannual variability mode that defines the North Atlantic Oscillation (NAO; Trigo et al., 2004). Prevailing negative NAO index conditions are defined by a weak AH and/or Icelandic Low (IL; Hurrell, 1995), which give rise to reduced westerlies over the eastern North Atlantic and to increased winter precipitation and river flow in western Iberia (Trigo et al., 2004). In contrast, prevailing positive NAO index conditions occur when a strong pressure gradient exists between the AH and IL (Hurrell, 1995). This gradient generates the strengthening and northward displacement of the westerlies over Europe (Trigo et al., 2004). In addition, general warm and cold conditions occur respectively during negative and positive NAO phases over Iberia (Hurrell, 1995) and anomalies in winds regime also influence changes on ocean surface circulation characteristics as a consequence of the interplay between the SST-wind coupling system (Sánchez et al., 2007). A significant relation between NAO index and strengthening of upwelling-favorable northerlies (downwelling-favorable southerlies) and associated temperature drop (increase) close to the coast has been observed during its positive (negative) phases by Sánchez et al. (2007). As shown by Hurrell et al. (2001), the NAO forcing is most active between November and April, when the ocean mixed layer is deep and much of the ocean's uptake of gases occurs. A NAO signature in the summer season can be identified, but it is weaker, less persistent and explains only a small fraction of the total variance (Visbeck et al., 2001). Off Iberia, however, the NAO index showed positive correlation with the number of upwelling filaments in summer and negative correlation with the intensity of the IPC as a consequence of, respectively, northerly winds persistence and south-westerly wind anomalies (Sánchez et al., 2007). During positive NAO, when the Azores anti-cyclone intensifies and stronger westerlies across the northern North Atlantic prevail, enhanced upwelling occurs along the IM (Fiuza, 1982; Bartels-Jónsdóttir et al., 2006).

2.2. Age model

The age model of core MD03-2699 is based on benthic oxygen isotope record correlation supported by biostratigraphic events (Fig. 2A; Voelker et al., 2010; Amore et al., 2012).

The benthic oxygen isotope record of core MD03-2699 (Voelker et al., 2010) was correlated with the one of ODP Site 980 (McManus et al., 1999; Flower et al., 2000), providing several control points (Fig. 2A). In addition the age model is supported by coccolithophore biostratigraphic events recognized by Amore et al. (2012) regarding the Last Occurrence (LO) of *Pseudoemiliania lacunosa*, the First Common Occurrence (FCO) of *Gephyrocapsa caribbeanica* and the First Occurrence (FO) of *Helicosphaera inversa* (Fig. 2A).

The sub-stages MIS 11c and MIS 11b were identified by Voelker et al. (2010) on the basis of benthic $\delta^{18}\text{O}$ records and fixed, respectively, between 425 and 398 ka and 398–386 ka (Fig. 2B). Stadial/Interstadial (S/I) cycles, both during late MIS 12 and MIS 11, were identified by Rodrigues et al. (2011) based on alkenones-derived SST (U_{37}^k index) and the period from 386–360 ka was, in particular, named as timing of S/I cycles (Fig. 2B). However, because the terms Greenland stadial and interstadial often refer to Late Pleistocene Dansgaard/Oeschger (D/O) oscillations (Vallelonga et al., 2012), in this study stadials/interstadials recognized by Rodrigues et al. (2011) are reported as stadial/interstadial-type (St/It) intervals, preserving the same numbering. Finally, the occurrence of Ht events were identified by Voelker et al. (2010) on IRD records and successively on percentages of tetra-unsaturated alkenone ($C_{37:4\%}$) by Rodrigues et al. (2011; Fig. 2B). A total of 8 Ht events were recognized between 580 and 300 ka, of which four Ht events occurred between 445 and 360 ka

(Ht5 440.27–436.36 ka; Ht4 429.47–426.23 ka; Ht3 391.04–388.18 ka; Ht2 383.88–381.60 ka; Fig. 2B). Because late Pleistocene millennial-scale D/O oscillations and Heinrich events (Hs) are usually considered as abrupt climate changes (NRC, 2002), here analogous variability represented by St/It oscillations and Ht events is also referred to as abrupt changes.

In this study, the age of each sample was calculated by linear interpolation between two following control points. The age of the studied interval ranges from 445.15 to 360 ka. A total of 219 samples, spaced every 2 cm, were analyzed. The sedimentation rate (Fig. 2A) is in the order of ~6 cm/ky, with a time resolution of about 0.386 ky.

2.3. Coccolithophore assemblages

Samples for coccoliths analyses were prepared following the methodology of Flores and Sierro (1997). Quantitative analyses were performed using a light microscope at 1000x magnification and counting 300 specimens from each sample in a random number of visual fields. This allows a 95% level of confidence to be reached for all species present in at least 1% abundance (Patterson and Fishbein, 1989). In addition, to remove noise due to particularly abundant species (small placoliths <3 μm long), an additional counting of at least 300 specimens > 3 μm long was carried out, reaching a total of more than 700–800 counted specimens. This additional counting makes the abundance of species that previously did not reach the value of 1% significant at the 95% level of confidence with an estimated error of 0.44% (Patterson and Fishbein, 1989). The Nannofossil Accumulation Rate (NAR; Fig. 3) was calculated according to Flores and Sierro (1997) using the formula:

$$\text{NAR} = \text{Nc} * \text{Dd} * \text{LSR}$$

where: NAR is nannofossil accumulation rate (number of coccoliths $\text{cm}^{-2} \text{ kyr}^{-1}$), Nc is number of coccoliths/g of sediment, Dd is the dry bulk density (g cm^{-3}), and LSR is the linear sedimentation rate (cm kyr^{-1}). In this study, accumulation rates were estimated also for the small *Gephyrocapsa* group (Fig. 3).

The quantitative estimation of dissolution was evaluated using the Dissolution Index (DI; Fig. 3) proposed by Amore et al. (2012) and is based on the following ratio:

$$\text{DI} = \text{small Gephyrocapsa} / (\text{small Gephyrocapsa} + \text{C. leptoporus}).$$

Values close to 1 indicate low or absent dissolution, while high dissolution is testified by values close to 0.

Reworked species (Fig. 3) were counted separately and were mainly represented by Neogene taxa.

2.4. Coccolithophore paleoproductivity indicators

Absolute abundances and the NAR are good indicators for paleoproductivity of coccolithophores and particle flux out of the mixed layer (e.g., Steinmetz, 1994; Baumann et al., 2004; Lopez-Otalvaro et al., 2009; Saavedra-Pellitero et al., 2011; Amore et al., 2012). Particularly, higher NAR values, in the absence of dissolution, indicate higher nutrient availability and coccolithophore productivity (Saavedra-Pellitero et al., 2011). The assemblages at site MD03-2699 are dominated by *G. caribbeanica*, as testified both by its absolute and percentage data (Fig. 3); so the NAR mainly reflects paleo-production of this species. Alkenones are produced by coccolithophorids and our data on *G. caribbeanica* relative and absolute abundance agrees well with the total C_{37} alkenone concentration (Fig. 3), obtained by Rodrigues et al. (2011). During the period of *G. caribbeanica* dominance, the total amount of alkenone production could be affected by the enhanced production of coccoliths belonging to this species. The potential cause of dominance, during MISs 15 to 8, might be related

to a rapid phylogenetic evolution; hence this is a global and synchronous event (Bollmann et al., 1998; Flores et al., 1999, 2003; Baumann and Freitag, 2004; Baumann et al., 2004). However, also changes of environmental conditions are suggested as possible cause of the significant increase of *G. caribbeanica*, but the species' ecology is quite controversial and little information about it is available (Bollmann, 1997; Amore et al., 2012). For these reasons we avoid using total NAR, which mainly reflects the paleo-production of *G. caribbeanica*, as a productivity proxy.

In our data the second most abundant group is represented by small *Gephyrocapsa* (Fig. 3), whose ecology is widely discussed and related to high nutrients content. In upwelling areas, small *Gephyrocapsa* indicate medium to high productivity (Beaufort et al., 1997; Okada and Wells, 1997; Wells and Okada, 1997; Colmenero-Hidalgo et al., 2004) of the upper photic zone (Gartner et al., 1987; Gartner, 1988; Okada and Wells, 1997). At the study site, percentages of this group were used as indicators of PC prevalence during the Middle Pleistocene (Amore et al., 2012). The ratio between Noerhabdaceae (including *Emiliania huxleyi*, small and medium *Gephyrocapsa*) and *Florisphaera profunda*, a typical lower photic zone inhabitant in medium and low latitudes (Okada and Honjo, 1973), has been defined as *N* ratio and is used as indicator of primary productivity of the upper photic zone (Flores et al., 2000). However, in this study, *F. profunda* shows low amplitude fluctuations and the *N* ratio provides few and hardly relevant information about paleoproductivity. For the reasons above, we used as upwelling proxy only the NAR of small *Gephyrocapsa* (Fig. 3), reflecting changes in the prevalence of PC over time.

2.5. Coccolithophores as sea surface temperature indicators

In accordance with their documented ecology (McIntyre et al., 1972; Honjo and Okada, 1974; Roth and Berger, 1975; Okada and McIntyre, 1977; Roth and Coulbourn, 1982; Giraudeau, 1992a,b; Kleijne, 1993; Winter et al., 1994; Flores et al., 1999; Takahashi and Okada, 2000a,b; Triantaphyllou et al., 2004; Dimiza et al., 2008 among others), the sum of warm species *Rhabdosphaera* spp., *Syracosphaera* spp., *Umbilicosphaera sibogae*, *Pontosphaera* spp., *Umbellosphaera* spp., *Discosphaera tubifera*, and *Calciosolenia murrayi* is here used as proxy for warm and nutrient-poor surface waters (Fig. 4) and thus as proxy of IPC prevalence, following Amore et al. (2012). *C. pelagicus* subsp. *azorinus* (Fig. 4) is discussed separately from the group of warm species since this taxon is regarded as indicator of a northward recirculation of AzC waters and sub-tropical gyre, in agreement with Parente et al. (2004).

Finally, *C. pelagicus* subsp. *pelagicus* and *G. margereli* (Fig. 4) were used as indicators of cold surface waters (McIntyre and Bè, 1967; Bréhéret, 1978; Roth, 1994; Winter et al., 1994; Amore et al., 2012). In particular, *C. pelagicus* subsp. *pelagicus*, a subspecies living bordering on the subarctic biogeographic province (McIntyre and Bè, 1967; Roth, 1994; Winter et al., 1994), was used as proxy for subpolar waters in accordance with Parente et al. (2004) and Amore et al. (2012).

Coccolithophore data were compared with the abundance of IRD and with available SST proxies, such as the U'_{37} index and the percentage tetra-unsaturated alkenone ($C_{37:4}$) to total alkenones, indicating cold surface waters and reduction in surface water salinity, respectively (Fig. 4; Voelker et al., 2010; Rodrigues et al., 2011).

2.6. Time series analysis

Sample cross correlation was applied to selected proxies (Fig. 5) in order to determine the possible relationship between two time series using the “crosscorr” Matlab function. The output arguments provided by the function are the LAG, correlation coefficients and the bounds. The LAG, multiplied with the sample period, indicates the time offset between the two cross-correlated time series. Correlation coefficients represent the amplitude of the correlation: positive (negative) coefficients indicate that the time series are in phase (opposition of phase). The horizontal bounds are two-element vectors indicating the approximate upper and lower confidence bounds fixed at 95% significance.

In order to estimate the long-term oscillations of selected time series (Fig. 4), curves fitting was obtained using “polyfit” and “polyval” Matlab functions. Polyfit function computed the coefficients of a polynomial of tenth degree that fitted the data set in a least-squared sense. The linear regression provided x-values of the new data set, polyval function was used to calculate the correspondent y-values. The code uses a 95% confidence interval.

In order to better understand periodic signals recorded by the coccolithophore assemblages, related to main climatic forcings, spectral analysis is applied to the coccoliths data. Because spectra of paleoclimatic time series frequently show a continuous decrease of spectral amplitude with increasing frequency (“red noise”), usually a first-order autoregressive (AR1) process is sufficient to explain this climatic signature (Schulz and Mudelsee, 2002). The REDFIT software was used for estimating the red-noise spectra (AR(1)) directly from the unevenly spaced paleoclimatic time series (Fig. 6). In addition to a fixed set of false-alarm levels (90% and 95%), the program also reports a “critical” false-alarm level (χ^2 90% and χ^2 95% in Fig. 6) that depends on the segment length (Thomson, 1990). Peaks showing spectral power higher than critical levels are considered to be significant.

Time variability of the major periodicities was estimated using Matlab wavelet analysis software (Figs. 7, 8) provided by Torrence and Compo (1998). For this analysis, we avoid using the signals within the Cone Of Influence (COI) because it represents the region of the spectrum where errors could occur because of the padding of zero (Torrence and Compo, 1998). With the aim to better visualize cycles of about 6 and 11 kyr, only a part of the studied samples was analyzed with wavelet analysis, spaced every about 10 cm corresponding to a mean sample period of 1.9 ka (Fig. 7). All the counted samples, spaced every 2 cm, were additionally analyzed with wavelet analysis in order to investigate higher frequency cycles (Fig. 8).

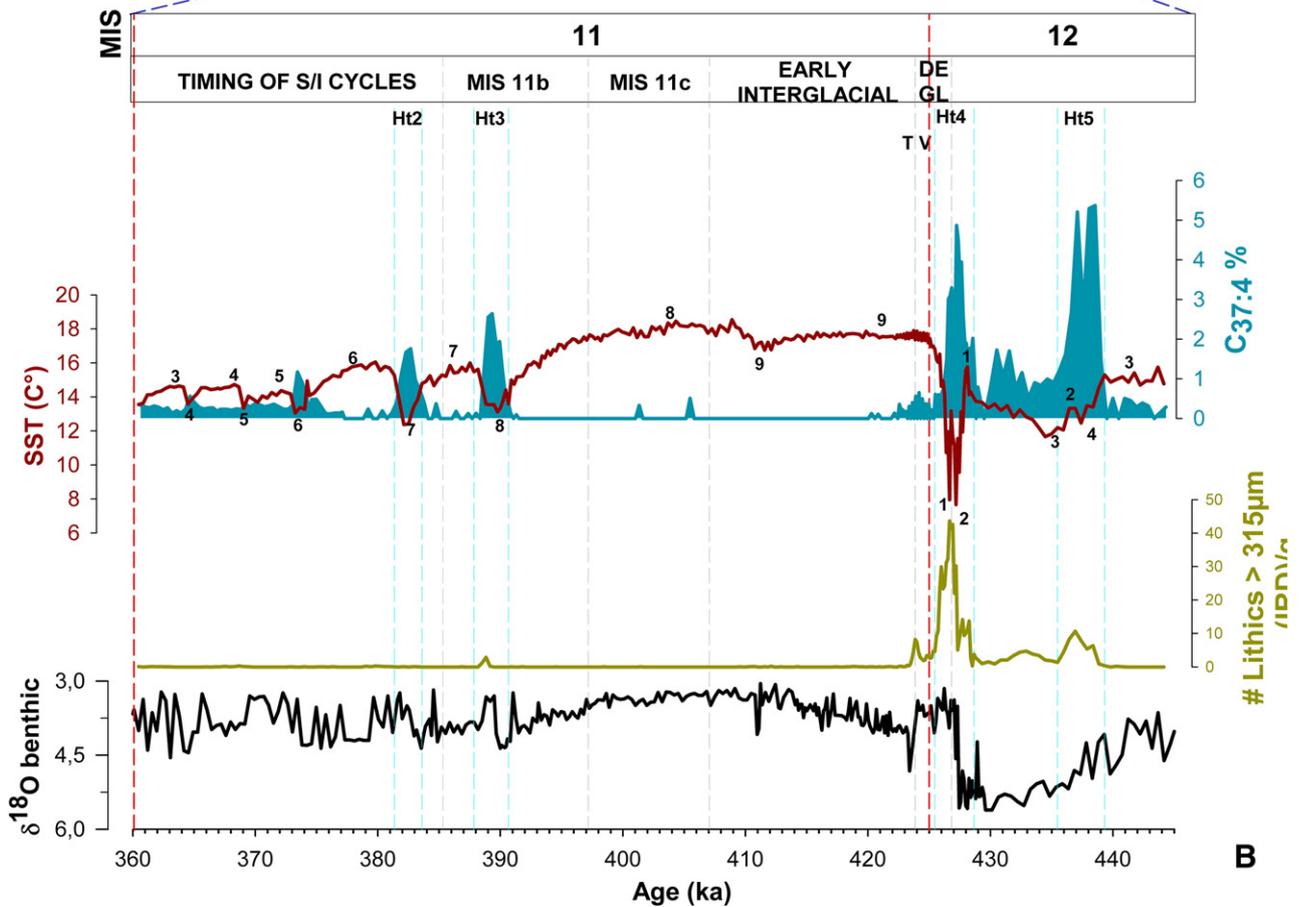
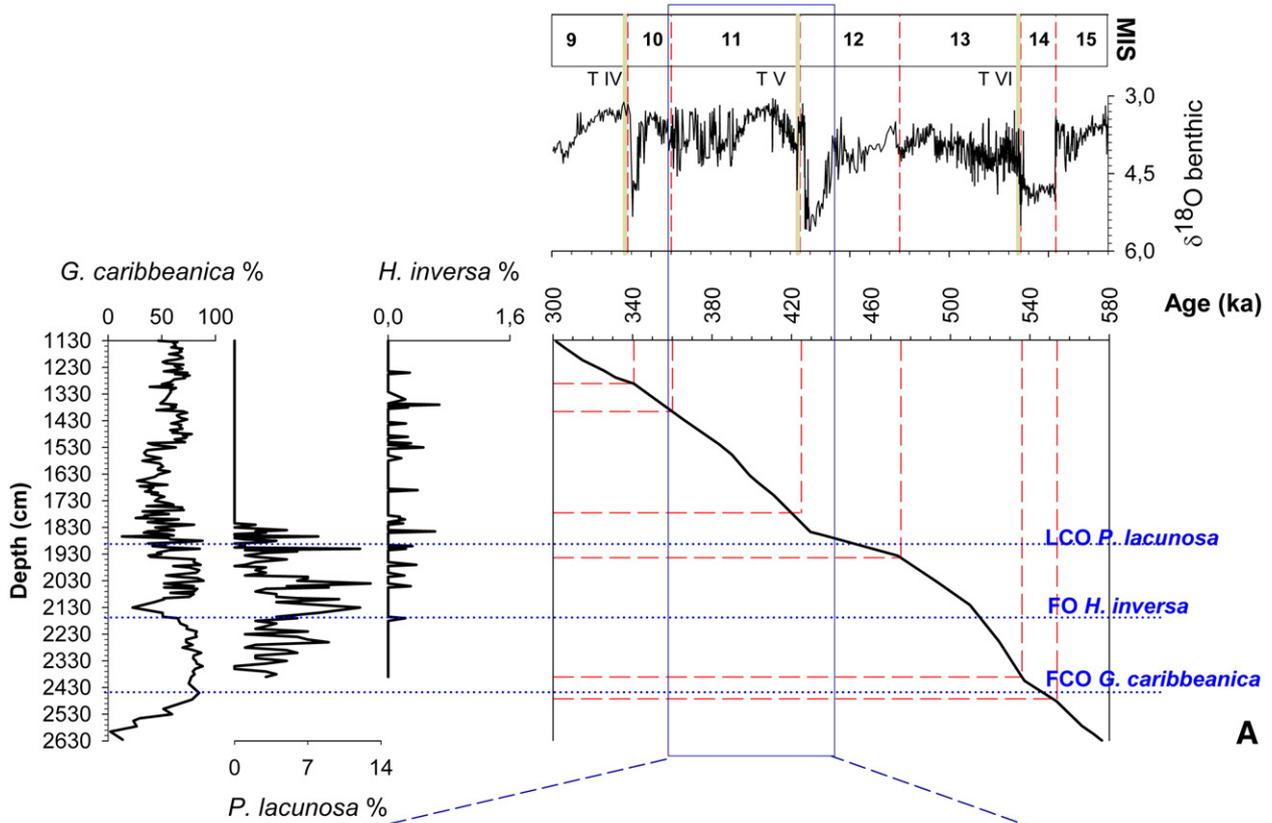
Data can be accessed through the following link: <http://doi.pangaea.de/10.1594/PANGAEA.742794>.

3. Results

3.1. Coccolithophore assemblages

The studied interval corresponds to the upper part of MIS 12 to MIS 11. Coccolithophore assemblages are abundant and generally well preserved. Quantitative abundances of the most significant species are shown in Figs. 3, 4; the most abundant taxa are *G. caribbeanica* and the small *Gephyrocapsa* group (mainly *Gephyrocapsa aperta*; Fig. 3).

Fig. 2. (A) Isotopic record (Voelker et al., 2010) and biostratigraphic events (Amore et al., 2012) used for the age model. Percentages of *G. caribbeanica*, *H. inversa* and *P. lacunosa* from Amore et al. (2012); LCO = Last Common Occurrence; FO = First Occurrence; FCO = First Common Occurrence. $\delta^{18}O$ benthic and sedimentation rate from Voelker et al. (2010). Dotted red lines indicate Marine Isotope Stages (MIS) boundary; numbers are referred to MIS; TIV, TV and TVI indicate, respectively, Termination IV, V and VI. (B) Zooming on investigated time subdivision. $\delta^{18}O$ benthic from Voelker et al. (2010). Substage subdivision (Deglaciation, Early Interglacial, MIS11c and MIS11c) from Voelker et al. (2010). SST (°C), percentages of tetra unsaturated alkenones ($C_{37:4}$) and lithics > 315 μm (no./g) from Rodrigues et al. (2011). Numbers above and below the SST curve indicate interstadials and stadials, respectively (Rodrigues et al., 2011). Timing of stadial/interstadial cycles according to Rodrigues et al. (2011). Cyan dotted lines indicate Heinrich-type events (Ht) following Voelker et al. (2010) and Rodrigues et al. (2011). DEGL = Deglaciation.



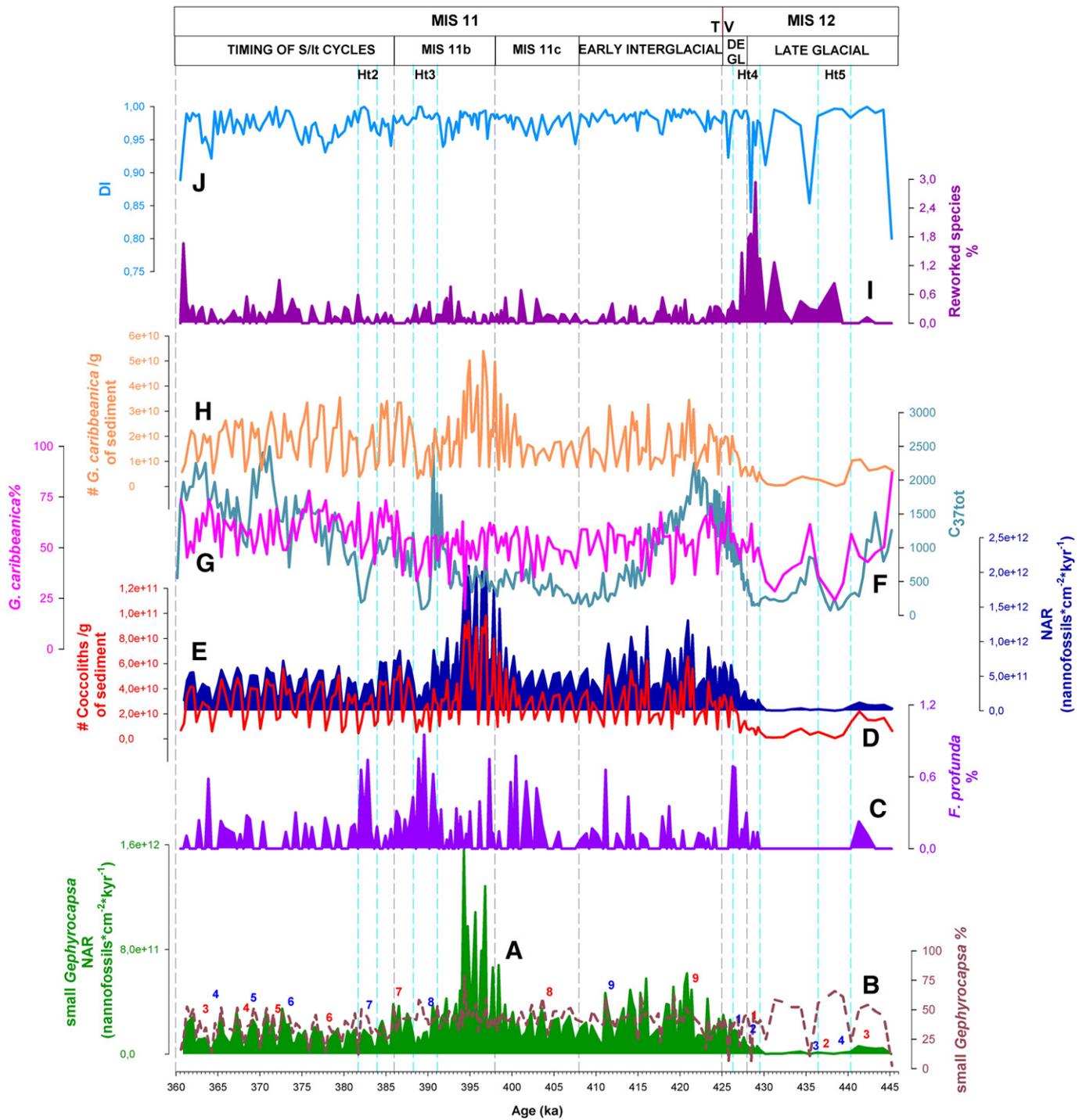


Fig. 3. [A] Small *Gephyrocapsa* NAR (nanofossil* cm^{-2} * kyr^{-1}) and [B] percentages; [C] *F. profunda* percentages; [D] #coccoliths/g of sediment and [E] NAR (nanofossil* cm^{-2} * kyr^{-1}); [F] [Total alkenones concentration ($C_{37\text{tot}}$) from Rodrigues et al. (2011); [G] *G. caribbeanica* percentages and [H] #*G. caribbeanica*/g of sediment; [I] Reworked species percentages; [J] DI. Cyan dotted lines indicate Heinrich-type events (Ht) from Rodrigues et al. (2011); Marine isotope Stages (MIS) and substages (DEGL, Early Interglacial, MIS11c and MIS11b) subdivision from Voelker et al. (2010); red and blue numbers on small *Gephyrocapsa* NAR curve refer to, interstadial-type and stadial-type intervals, respectively, as numbered by Rodrigues et al. (2011).

The warm species percentages show a peak of abundance, reaching values $> 1\%$, at around 445 ka. After this episode, a strong decline of these species occurred showing values always below 1% up to 430 ka (Fig. 4). Between 440 and 430 ka, a decrease of small *Gephyrocapsa* NAR (Fig. 3) is also recorded with values passing from $\sim 6.0 \times 10^{10}$ liths $\text{cm}^{-2} \text{kyr}^{-1}$ at 441 ka to 1.5×10^9 liths $\text{cm}^{-2} \text{kyr}^{-1}$ at 435 ka and maintaining similar levels up to 430 ka. In the same interval, centered at around 438 ka, the highest percentages of *C. pelagicus* subsp. *pelagicus*

are observed together with high percentages of tetra-unsaturated alkenones $C_{37:4}$ and low SSTs (Fig. 4; Rodrigues et al., 2011).

A slight increase of small *Gephyrocapsa* NAR marked MIS 12 interstadial-type period 3 while the stadial-type intervals 3 and 4 were characterized by decreases (Fig. 3).

Between 429 and 425 ka, small *Gephyrocapsa* NAR (Fig. 3) shows low values, while warm and cold species show inverse trends pointing towards higher and lower percentages, respectively. Peaks

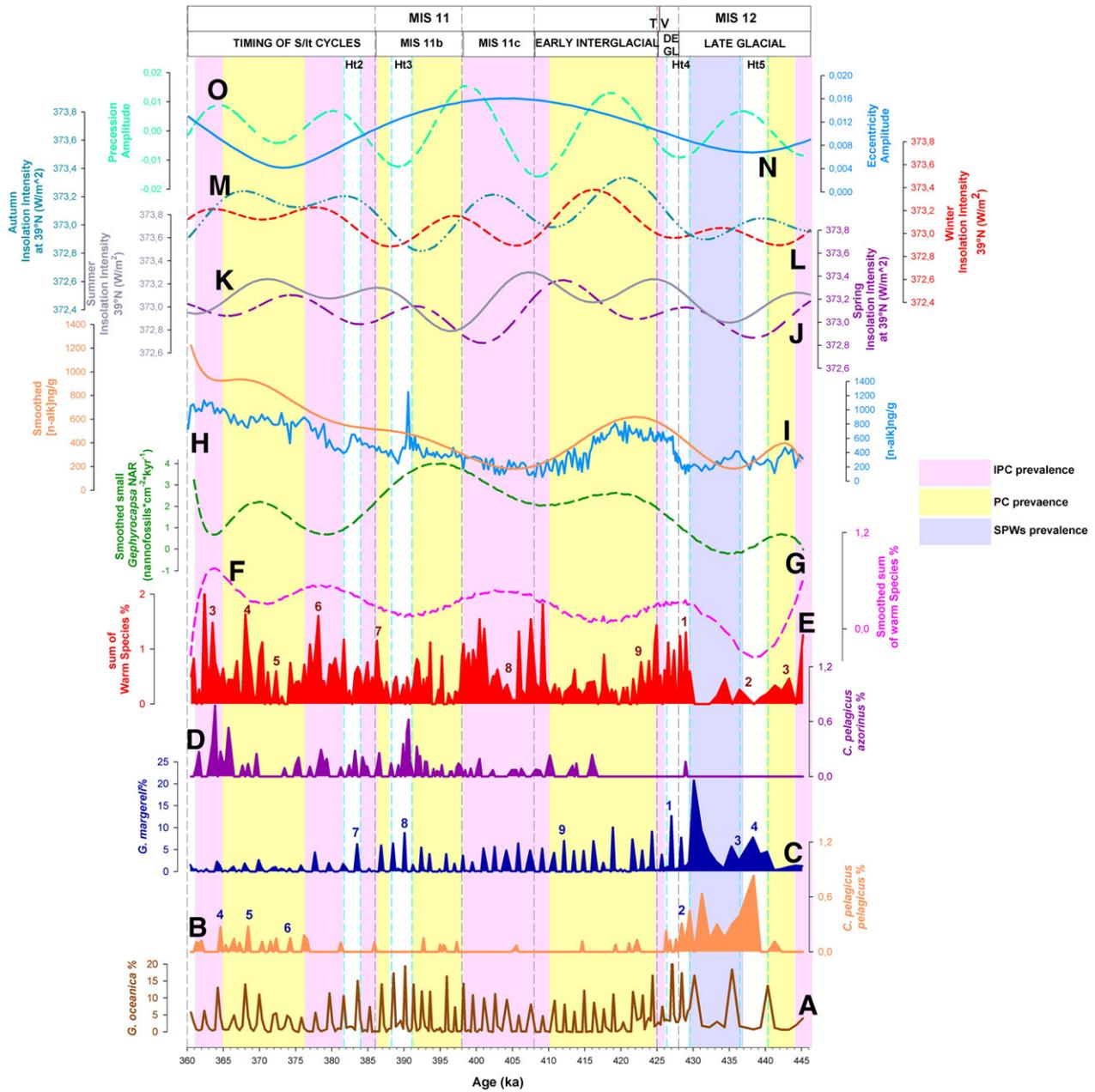


Fig. 4. Percentages of: [A] *G. oceanica*, [B] *C. pelagicus* subsp. *pelagicus*, [C] *G. margereli*, [D] *C. pelagicus* subsp. *azorinus*; [E] sum of warm species percentages and [F] smoothed curve; [G] small *Gephyrocapsa* NAR smoothed curve (nannofossil*cm⁻²*kyr⁻¹). [H] Concentration of total n-alkanes (ng/g; [n-alk]ng/g) from Rodrigues et al. (2011) and [I] smoothed curve. Insolation Intensity (W/m²) estimated for astronomical seasons: [J] Spring, [K] Summer, [L] Winter and [M] Autumn. [N] Eccentricity and [O] Precession amplitudes from Berger and Loutre (1991). Red numbers on warm species percentages curve indicate interstadial-type intervals, following Rodrigues et al. (2011); blue numbers on *G. margereli* and *C. pelagicus* subsp. *pelagicus* curves stadial-type periods. Abbreviations, climate periods and events as in Fig. 3.

of *F. profunda* are also recognized during this period (Fig. 3). A gradual increase of warm water species percentages occurred around 430 ka and lasted until 425 ka (Fig. 4), but showing minima at 428.3 and 427 ka, during deglacial stadial-type oscillations, together with peaks of *G. margereli* (with values ranging from 7 to 12%) and the presence of *C. pelagicus* subsp. *pelagicus* (Fig. 4). After the glacial maximum, during MIS 12 interstadial-type event 1, the presence of *C. pelagicus* subsp. *azorinus* is observed at 428.9 ka (Fig. 4).

Almost the entire period between 425 and 410 ka was marked by the increase of small *Gephyrocapsa* NAR (Fig. 3). From 410 to 398 ka, the higher percentages of warm species, with values reaching ~2%, and the warmest SST values occurred (Fig. 4).

The interval between 398 and 386 ka was characterized by the highest values of small *Gephyrocapsa* NAR with the maximum centered between 397 and 393 ka, reaching values around 1.2×10^{12} liths cm⁻² kyr⁻¹ (Fig. 3).

Finally, from 386 to 360 ka, the assemblages show peculiar structures. Weak increases of small *Gephyrocapsa* NAR are coeval with the presence of *G. margereli* (Fig. 4) at 373.42, 369.15 and ~365 ka. Low small *Gephyrocapsa* NAR are recorded together with peaks of tetra unsaturated alkenones between ~383–382 and ~390–388 ka. High percentages of warm species, reaching values around 2%, occurred in correspondence to decreases of small *Gephyrocapsa* NAR and to SST increases (Figs. 3, 4) at 386.20, ~378, 372.26, 367.99, and 363.44 ka,

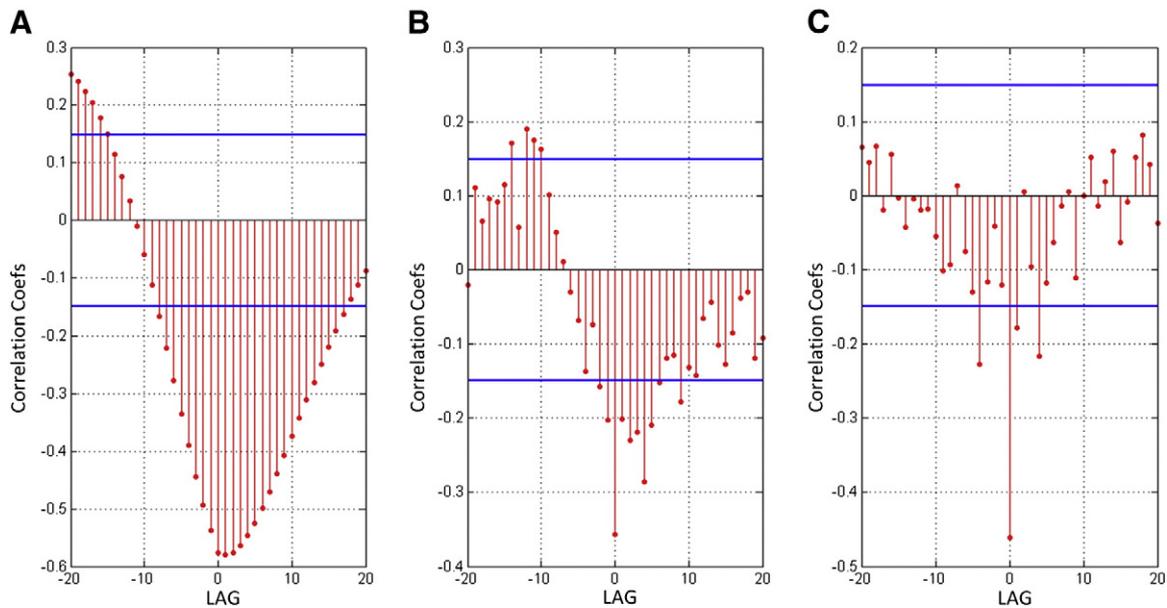


Fig. 5. Cross correlation plots for the interval 360–430 ka between: [A] small *Gephyrocapsa* NAR and sum of warm species percentages smoothed curves; [B] small *Gephyrocapsa* NAR and sum of warm species percentages; [C] small *Gephyrocapsa* NAR and *G. oceanica* percentages. Blue lines indicate upper and lower 95% significance levels; x-axis indicates LAG, which, multiplied for sample period, indicates the offset between two time-series; y-axis indicates values of correlation coefficients.

respectively. In addition, during this period (386–360 ka), the frequent presence of *C. pelagicus* subsp. *azorinus* and of *C. pelagicus* subsp. *pelagicus* (Fig. 4) was observed.

3.2. Time series analysis

For the time window from 430 to 360 ka, cross correlation analysis was performed using different coccolithophore proxies. The smoothed curves of small *Gephyrocapsa* NAR and sum of warm species percentages show a negative correlation at a Lag of Zero indicating that the two time series are always in phase opposition without offset (Fig. 5). A similar result is observed by the cross correlation analysis performed between the two proxies using their original (not smoothed) trend, indicating a similar statistical relationship also for higher amplitude signals (Fig. 5). A negative correlation with a Lag of Zero is also shown by the cross correlation analysis performed between the small *Gephyrocapsa* NAR and the *G. oceanica* percentage records (not smoothed) (Fig. 5).

The periodograms of warm species percentages and of small *Gephyrocapsa* NAR show a significant signal for the 19–23 kyr cycles (Fig. 6). Using a time resolution of 1.9 kyr, the wavelet power spectra of *F. profunda*, *G. margereli* and *C. pelagicus* subsp. *pelagicus* percentages show significant power at the periods of ~11 and ~6 kyr between 435 and 420 ka (Fig. 7). Considering a higher time resolution of 386 yrs, the periodograms of all proxies, except small *Gephyrocapsa* NAR, show significant peaks (>95% of significance) at frequencies higher than 0.4 ka^{-1} (Fig. 6). Also the wavelet power spectra of all these proxies, using a 386 yrs sample period, indicate a significant (>95% of significance within global wavelet power spectra) time variability of cycles between 0.8–1 and 1.5 (1.8–1.6) kyr (Fig. 8).

4. Discussion

4.1. Paleoproductivity changes at suborbital timescale as marked by small *Gephyrocapsa*

A slight increase in paleoproductivity between 444 and 440 ka most likely suggests the influence of the PC (Fig. 3). Starting with the SST drop, recognized at 440 ka (Rodrigues et al., 2011), paleoproductivity

decreased until 429 ka (Fig. 3) and changes in the coccolith assemblages structure occurred as consequence of the surface ocean's cooling. This is due to the arrival of subpolar waters as testified by the highest percentages of *C. pelagicus* subsp. *pelagicus* (Fig. 4) and by the alkenones records (Rodrigues et al., 2011).

During almost the entire early interglacial period (425–410 ka), the increase of paleoproductivity, due to enhanced nutrients availability as suggested by an increase of the small *Gephyrocapsa* group (Fig. 3), indicates a persistent PC presence. Furthermore, during this interval, the combination of high small *Gephyrocapsa* NAR, higher SSTs (Rodrigues et al., 2011) and low planktonic $\delta^{13}\text{C}$ values (Voelker et al., 2010) suggest that the upwelled waters were more likely replenished by ENACWst and the upwelling was activated by relative intense prevalent westerly winds. Substage MIS 11b (398–386 ka) was characterized by the highest increase of coccolith paleoproductivity, as testified by the highest values of smoothed small *Gephyrocapsa* NAR with the maximum centered between 397 and 393 ka (Fig. 4), suggesting a PC influence at this site and enhanced nutrients availability (Fig. 4). Increases of small *Gephyrocapsa* NAR are also observed between 376 and 365 ka, indicating again PC prevalence. During this interval, the frequent presence of *C. pelagicus* subsp. *pelagicus* (Fig. 4) suggests that the upwelled waters were more likely replenished by ENACWsp as a consequence of more intense westerly winds.

The reconstructed productivity and wind regimes during the early interglacial period and substage MIS 11b are in agreement with the terrestrial biomarkers evidence (Rodrigues et al., 2011). The contemporary oscillations seen in the smoothed curves of the terrestrial biomarkers and small *Gephyrocapsa* NAR are coherent with the suggested wind strength reconstruction and indicate a continuous gradual intensification of the westerly winds towards the end of the interglacial substage MIS 11c.

As also observed in Amore et al. (2012), the periods of PC prevalence alternate with periods of IPC prevalence, here observed occurring together with a decrease in terrestrial biomarkers and thus weak/failing westerly winds (Fig. 4). Furthermore, a northward recirculation of the AzC, affecting the site, as testified by presence in the assemblages of *C. pelagicus* subsp. *azorinus*, is observed between 365 and 360 ka (Fig. 4).

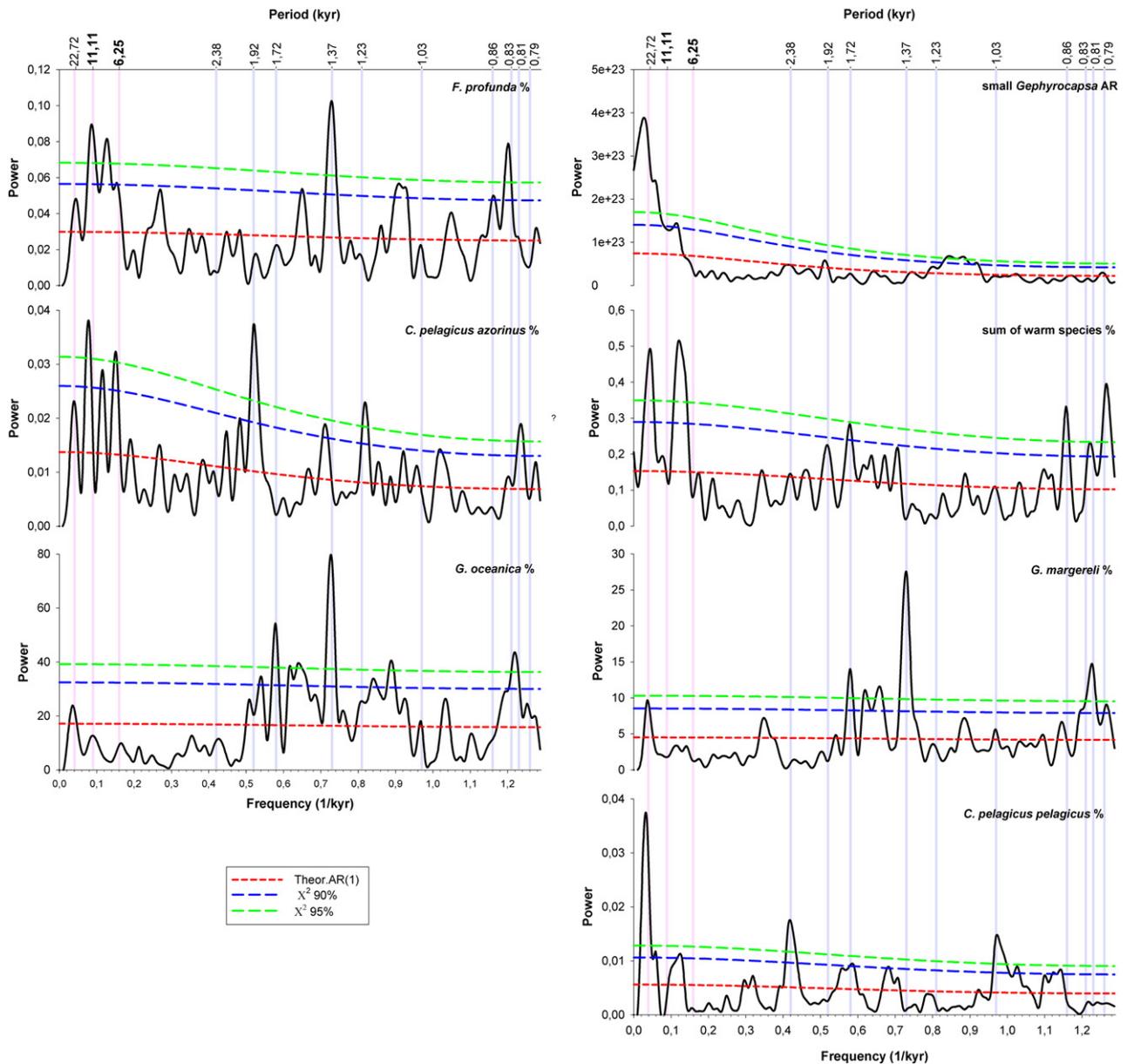


Fig. 6. Periodograms of investigated taxa obtained using REDFIT. In the periodograms, dotted red lines indicate red noise (Theor AR(1)), blue and green dotted lines represent 90% and 95% significance levels, respectively. Bottom x-axis refers to frequency scale, top x-axis to periodicity scale. Light pink vertical bars highlight precession periodicities; half and fourth precession cycles (~11 and ~6 kyr) are evidenced by bold numbers in each periodicity scale. Light gray vertical bars highlight cycles discussed in this paper.

Small *Gephyrocapsa* NAR and warm species percentages variability show, during the investigated interval, different relationships to Insolation Intensities estimated during the four astronomical seasons. During the interglacial period, the smoothed curves of these proxies are always in phase opposition (Figs. 4, 5) and the precession-related mechanism driving paleoproductivity changes can explain PC and IPC variability at orbital time scale (Amore et al., 2012). Between 445–430 and 386–360 ka, paleoproductivity changes follow Spring–Summer Insolation Intensities. Between 430 and 386 ka (corresponding to the eccentricity minimum) paleoproductivity fits quite well with Autumn–Winter Insolation Intensities (Fig. 4). The higher resolution presented in this study overcame the main question raised in Amore et al. (2012). During periods of low eccentricity, the configuration of Earth's orbit is quasi-circular, insolation variability due to precession is reduced and lower seasonality occurs (Herbert and Fischer, 1986; Premoli Silva et al., 1989; Herbert and D'Hondt, 1990; Erba, 1992; Galeotti et al., 2003;

Lanci et al., 2010). Our data allows hypothesizing that between 430 and 386 ka the NH was more irradiated during autumn–winter than during spring–summer, causing a strengthening of predominant westerly winds during the periods when the coccolithophore assemblages indicate PC prevalence (Fig. 4).

4.2. Deglaciation

During the deglaciation, the reversal in the trends of warm and cold species indicate the transition towards the warming and testify a general IPC prevalence occurring around 430 ka and lasting until 425 ka (Fig. 4). The combination of the increase of warm species and the peaks of *F. profunda* (Fig. 3) indicate that the deglaciation was marked by stratified and less productive conditions and that the influence of subpolar waters was weaker as consequence of the strengthening of IPC/AzC prevalence. The prevalence is interrupted

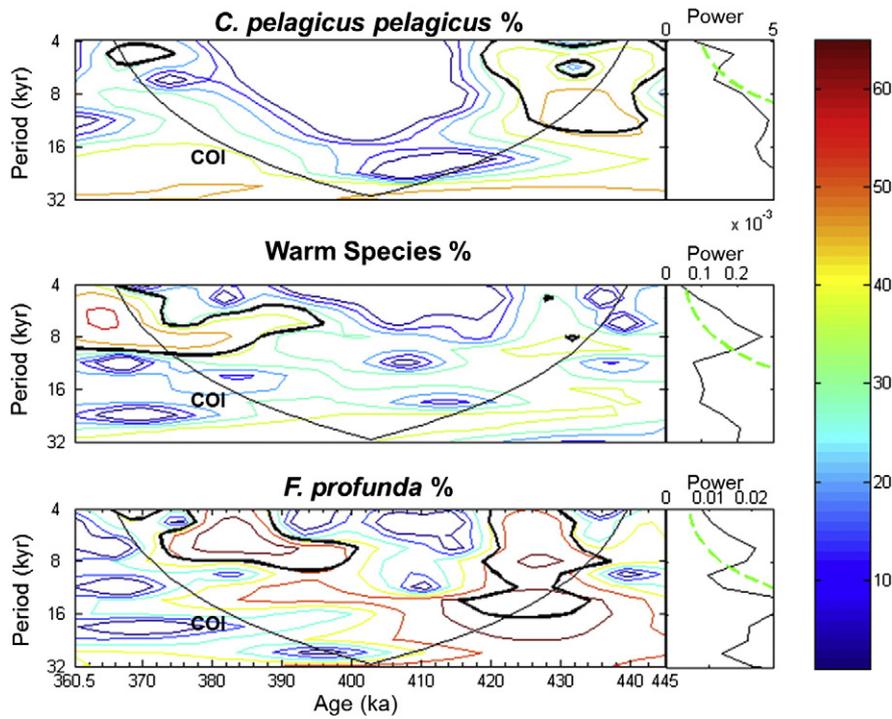


Fig. 7. Wavelet powerspectra and global wavelet powerspectra of selected taxa using Torrence and Compo (1998) algorithm at 1.9 ka sample period. COI = Cone Of Influence; black lines in wavelet powerspectra indicate 95% significance levels and COI; green dotted lines in global wavelet powerspectra indicate 95% significance levels. Color bar marks the magnitude of wavelet coefficients.

by the Ht 4 ice-rafting event (Rodrigues et al., 2011) when, with the arrival of cold and less salty waters, the number of warm species decreased and peaks of *C. pelagicus* subsp. *pelagicus* and *F. profunda* occurred (Fig. 4). Cycles of ~11 and ~6 kyr are recorded in the *G. margineli*, *C. pelagicus* subsp. *pelagicus* and *F. profunda* wavelet power spectra (Fig. 7), indicating that the occurrence of an abrupt change affected

mainly these species. In fact, during the deglaciation, cold species and *F. profunda* show an abrupt decrease and increase, respectively, testifying the occurrence of substantial changes within the water column (Figs. 3, 4) passing from quasi-prevalent cold waters persistence to more stratified conditions with higher temperatures in the Lower Photic Zone (LPZ), which established during Ht 4. Cycles of about 11

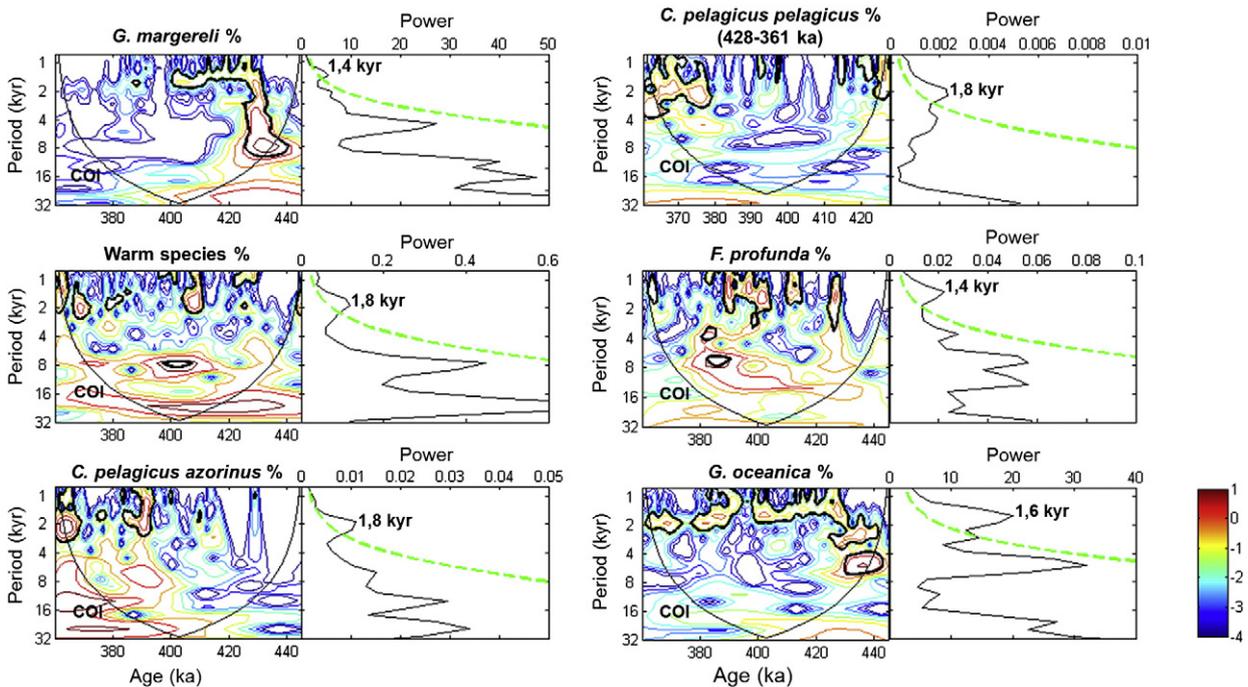


Fig. 8. Wavelet powerspectra and global wavelet powerspectra of selected taxa using Torrence and Compo (1998) algorithm at ~386 years sample period. COI = Cone Of Influence; black lines in wavelet powerspectra indicate 95% significance levels and COI; green dotted lines in global wavelet powerspectra indicate 95% significance levels. Color bar marks the magnitude of wavelet coefficients.

and 6 kyr have been recognized in Equator Insolation record by Berger et al. (2006) and are associated in North Atlantic mid-latitude paleoclimate records (Weirauch et al., 2008; Ferretti et al., 2010; Amore et al., 2012) to half and fourth precession components, respectively. Some authors, recently, found evidences of a possible control of Southern Hemisphere (SH) summer insolation changes on the terminations (Knorr and Lohmann, 2003; Weaver et al., 2003; Peeters et al., 2004). The onsets of the last five Terminations were characterized by a contemporaneous increase of the NH and SH summer insolation and probably triggered by the interplay of precession and obliquity (Schulz and Zeebe, 2006). An exception is represented by Termination V, because it was the most prominent one after the Mid Pleistocene Revolution (Schulz and Zeebe, 2006). Even if the influence of cycles related to the half and fourth precessional components (6 and 11 kyr cycles) on insolation is still unclear, our results indicate a control of these forcings on Termination V. Thus it can be proposed that the deglaciation was most likely controlled by higher frequency precession cycles, concurring with abrupt changes of the insolation received by Earth.

4.3. IPC/PC variability at millennial time-scales

Throughout the interglacial, small *Gephyrocapsa* NAR and percentages of warm species, *F. profunda* and *G. oceanica* show peculiar relations. The negative correlation between small *Gephyrocapsa* NAR and warm species percentages (Fig. 5) indicates that the surface waters suffered high frequency oscillations passing from warm water conditions, characterized by poorer nutrient content, to cooler waters with more productive conditions. The interpretation, as suggest by the frequent correspondence of *F. profunda* percentage peaks (Fig. 3) with warm species percentage peaks (Fig. 4) and decreasing values of small *Gephyrocapsa* NAR (Fig. 3), is that less productive conditions occurred frequently in correspondence to thermo-nutricline deepening (Figs. 3, 4). The IPC is a surface current warmer and poorer in nutrients than the PC, thus the transitional phase between both currents' prevalence could be associated with more productive and less warm waters. The comparison between *G. oceanica* percentages, small *Gephyrocapsa* NAR and warm species percentages (Fig. 6) suggests a clear preference of *G. oceanica* towards cooler and nutrient richer waters than the warm water species; so its peaks can be read as an intermediate step from IPC to PC prevalence.

If the long-term alternation of small *Gephyrocapsa* NAR and warm species percentages could be used as indicator of long-term variations in the prevalence of the PC and IPC, the same criterion could be used at shorter time scales. Considering this approach, the high frequency fluctuations of PC and IPC prevalence suggest the occurrence of constant millennial scale variations in interglacial seasonality, independent of the general variations triggered by insolation at orbital time-scale. The transitional phases were, instead, characterized by less productive, but not stratified, and less salty surface waters. During the glacial period, because of the general cooling, seasonality is less pronounced and less salty waters affected the site due to the arrival of subpolar waters (Voelker et al., 2010; Rodrigues et al., 2011). In fact, between 440 and 430 ka, *G. oceanica* peaks are coeval with *C. pelagicus* subsp. *pelagicus* increases, allowing hypothesizing that SST is not a relevant factor controlling *G. oceanica* abundances (Fig. 4) in respect to the lower salinity amount that is also typical of subpolar waters. During this period the most important advection of less salty waters at the site occurred. A second period occurred during the glacial inception, i.e. during MIS 11 b. In addition, because our data was constantly sampled and the sedimentation rate is quite constant (the only weak change is observed at around 400 ka), the most rapid fluctuations are recorded during the early interglacial and MIS 11 b (Figs. 3, 4).

High frequency cycles are present within periodograms of *F. profunda*, *G. margereli*, *C. pelagicus* subsp. *pelagicus*, *C. pelagicus* subsp. *azorinus*, *G. oceanica*, and warm species percentages (Fig. 7). The occurrence of cycles between 0.8–1 kyr and 1.8–1.6 kyr is recorded in the wavelet power

spectra of these taxa (Fig. 8). In last glacial and Holocene records, cycles of ~1.5 kyr were related to ocean–atmosphere system oscillations (Schulz et al., 2002; Timmermann et al., 2003), to the Greenland ice-sheet and to solar variability (van Geel et al., 1999; van Kreveld et al., 2000; Bond et al., 1997, 2001). Cycles of ~0.9 kyr were also recognized by Lamy et al. (2001) in the Southeast Pacific and related to Hadley cell intensity oscillations induced by changes in solar activity. If we consider the likelihood that these cycles could have also occurred during the Middle Pleistocene, one of these mechanisms or a combination of them could be responsible for the continuous interglacial seasonality recorded off Portugal.

Even if *F. profunda* shows a good correspondence with peaks of warm species, the occurrence of a short increase can be recognized during substage MIS 11c (between 405 and 401 ka) characterized by paleoproductivity and warm species decreases (Figs. 3, 4). However, neither changes in SST (Rodrigues et al., 2011) nor an increase in cold species occurred even if very small and sporadic peaks of tetra alkenones percentages (Rodrigues et al., 2011) and *C. pelagicus* subsp. *pelagicus* occurred (Figs. 3, 4). Thus a hypothesis of increase in stratification due to cold waters arrival is not supported. These episodes occurred generally during periods of high SST (Fig. 4; Rodrigues et al., 2011) and IPC prevalence, thus this could explain why small *gephyrocapsids* did not increase. Moreover, if we take into account the hypothesis of increase in surface water column turbidity, the reduced penetration of sunlight could explain the general decrease also of warm species and the increase of *F. profunda*. In fact this species is supposed to be able to grow at much lower light intensities than most phytoplankton (Brand, 1994). Minor peaks of reworked species also occur in correspondence of *G. oceanica* maxima with a short offset just prior to *F. profunda* peaks (Figs. 3, 4). These short episodes occurred with a decrease of higher-plant biomarkers related to less dry conditions (Rodrigues et al., 2011), occurring synchronously with the onset of the humid period in NW Africa (Helmke et al., 2008). These rapid episodes could be related to the arrival of freshwaters coming from Portuguese rivers. The combination of *G. oceanica*-reworked species peaks during similar episodes was discussed also by Amore et al. (2012) as related to the continental freshwater input through the Tagus River, which is controlled by precipitation over the Iberian Peninsula. Core MD03-2699 is localized between the Iberian and Tagus Abyssal Plains where possibly river flood-generated turbidity currents can reach through the Nazaré and Setúbal Canyons, respectively (Arzola et al., 2008). During winter months, with southerly winds leading to downwelling and onshore transport of warm surface waters, turbidity layers could originate by sharp density contrast due to the development of internal waves (Arzola et al., 2008). Other factors that may have an influence are floods (increased export of suspended sediment) and storms (increased wave velocity and turbulence), suggesting that re-suspension would be most prominent during the winter months (Arzola et al., 2008). Because the IPC is nowadays prevalent during winter months, we suggest, as a hypothesis, that the occurrence of sub-stage MIS 11c exceptional episode could be explained by a likely increase of turbidity within the surface water column. However, further studies based on additional proxies are needed for better understand this episode.

4.4. Oceanographic changes during abrupt climatic oscillations

The occurrence of abrupt paleoceanographic changes marked the end of MIS 12, the deglaciation and late MIS 11 (Voelker et al., 2010; Rodrigues et al., 2011; Amore et al., 2012), as stadial-/interstadial-type oscillations and Ht events. Our data suggests that different paleoceanographic settings established during these episodes mainly involved changes in paleoproductivity and SST as summarized in Table 1.

Moreover, coccolithophore assemblages show that the prevalence of ice-melting waters during Ht 5 was strong enough to mitigate the

Table 1

Main abrupt paleoceanographic changes and currents influence related to paleoproductivity and coccolithophore assemblages changes.

Interval	Abrupt paleoceanographic changes	arrival of surface		arrival of AzC	IPC influence		PC influence		paleoproductivity		coccolithophore assemblages evidences
		cold waters	warm waters		more	less	more	less	decrease	increase	
MIS 12	Ht 5										maxima % of the sub-polar <i>C. pelagicus</i> pelagius; low small <i>Gephyrocapsa</i> NAR
	stadial-type periods 4 and 5										
	interstadial-type 3										
DEGLACIATION	interstadial-type period 1										<i>C. pelagicus azorinus</i> % peak
	stadial-type period 2										<i>G. margereli</i> % peak
sub-stage MIS 11b	Ht events 4 and 3										
386–390 ka	stadial-type periods 8, 7, 6, 5 and 4										<i>G. margereli</i> % peak
	Ht events 2 and 3										
	interstadial-type periods 7, 6, 5, 4 and 3										higher warm species %

warming recorded by the alkenones SST that allowed identifying MIS 12 interstadial-type oscillation 2 by [Rodrigues et al. \(2011\)](#).

Our data also indicates different surface paleoceanographic dynamics occurring during glacial and interglacial periods. Only Ht events are always characterized by the same surface water structure, even if the influence of subpolar waters is testified only by *C. pelagicus* subsp. *pelagicus* for the glacial. The inversion of conditions seems to occur during the deglaciation. The main difference between glacial stadial-type and MIS 11 stadial-type intervals consists in the fact that during glacial stadial-type periods reduced paleoproductivity was observed; on the contrary, weak paleoproductivity increases were recorded during MIS 11 stadial-type intervals.

MIS 12 interstadial-type period 3 is characterized by a weak increase in paleoproductivity and no evidence for an increase in warm species. The interstadial-type intervals occurring during the deglaciation and MIS 11, instead, are characterized by a decline of paleoproductivity and increase of warm species. Hence, the strengthening of the prevalent westerly winds controls the availability of nutrients off the IM inducing the persistence of PC and upwelling. During MIS 12 interstadial-type period 3 these winds were more intense than during MIS 11 stadial-type intervals and the combination of increased SST and paleoproductivity could suggest that the upwelled waters were more likely provided by ENACWst. During MIS 11, on the other hand, the westerly winds were more intense during stadials-type periods and the upwelled waters were more likely replenished by ENACWsp. However, the different origin of ENACW could suggest that the intensification of upwelling was stronger during MIS 11 stadial-type periods than MIS 12 interstadial-type interval 1.

Studies on the Late Pleistocene and MIS 3 D/O cycles and Hs suggest a possible shifting northward (southward) of the Atlantic jet and prevalence of easterly (westerly) winds during stadials (interstadials) causing a decrease (increase) of paleoproductivity in the IM

and western Mediterranean Sea. The scenarios were related to the millennial-scale prevalence of different NAO phases, negative during Greenland interstadials and positive during Greenland stadials ([Moreno et al., 2005](#); [Bout-Roumazeilles et al., 2007](#); [Penaud et al., 2011](#)) and Hs ([Naughton et al., 2007](#)). If this reconstruction is applied also to our data, glacial stadial/interstadial-type variability could be explained by these mechanisms, while interglacial ones seem to be controlled by different processes. However, if we consider that a different setting of atmospheric pressure centers established during glacial and interglacial periods ([Amore et al., 2012](#)), the apparent differences could be explained taking into account the quasi-permanent position that the AH and IL reached during MIS 12 and MIS 11. Thus a weakening or strengthening of the two pressure centers could implicate different consequences, depending on their mean quasi-fixed positions and different gradients, on the intensity of westerly winds and displacement of the Atlantic jet. In addition, considering that nowadays, negative modes of NAO are associated to a strengthening of the IPC ([Sánchez et al., 2007](#)), this process could more likely explain interglacial interstadial-type conditions. Moreover, the increase of upwelling during the positive mode of NAO ([Fiuza, 1982](#); [Bartels-Jónsdóttir et al., 2006](#)) could explain interglacial stadial-type conditions. This interpretation seems to be coherent with modern NAO variability and glacial/interglacial stadial-type (interstadial-type) periods could be related to millennial-scale persistence of a positive (negative) NAO mode.

5. Conclusions

High-resolution coccolithophore records allowed reconstructing millennial-scale changes in surface water paleoceanography off the IM between 445 and 360 ka. Subpolar and less salty waters affected the site during the last part of glacial MIS 12 as consequence of low

summer insolation intensity received at medium latitudes, testified by the occurrence of subarctic species. The deglaciation was characterized by the general prevalence of subtropical waters interrupted by the occurrence of Ht 4. Cold species (*C. pelagicus* subsp. *pelagicus* and *G. margereli*) and *F. profunda* percentages show within their wavelet power spectra, the presence of (half and fourth) precession cycles between 430 and 420 ka suggesting a possible control of this parameter on deglaciation. During the transition from glacial to interglacial stage, substantial changes within the assemblages were indicated by the abrupt transition from cold to stratified surface paleoceanographic conditions.

The high-resolution study allowed better understanding the role of precession and insolation on the possible replenishing of ENACWst or ENACWsp during enhanced upwelling periods related to PC prevalence. In addition, high frequency opposite fluctuations of paleoproductivity and warm species suggested the occurrence of a continuous seasonality with PC/IPC prevalence over the area. Decrease of paleoproductivity always occurred associated to increase of surface stratification. A transitional phase characterized by moderate productive waters, between IPC and PC prevalence, was recognized thanks to peaks of *G. oceanica* percentages. As a consequence, passing from high to low salinity typical of the IPC and PC, respectively, this species also suggests a transitional phase with the presence of moderate salty surface waters. These fluctuations were likely modulated by 1.5 kyr cycles. The structure of coccolithophore assemblages during the abrupt events indicate a possible change of upwelling intensity due to a different displacement and strengthening of westerly winds from glacial to interglacial periods.

An exceptional episode characterized by increase of *F. profunda* and reworked species was recognized during MIS 11c associated to an increase of surface turbidity.

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