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Monsoonal dynamics and evolution of the primary productivity in the eastern Arabian Sea over the past 30 ka

E. Cabarcos [a,*], J.A. Flores [a], A.D. Singh [b], F.J. Sierro [a]

[a] Department of Geology, University of Salamanca, Plz. de la Merced s/n, Salamanca, 37008, Spain
[b] Department of Geology, Banaras Hindu University, Varanasi, 221 005, India

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ABSTRACT

This study presents a high-resolution primary productivity record for the last 30 ka in the eastern Arabian Sea (EAS) based on the coccolithophore assemblage at SK 17 core in the continental slope off Goa (India). Coccolithophores were proposed as indicators of primary productivity and nutricline position, and the results were used to reconstruct the monsoonal dynamics, which is a main factor controlling productivity changes in the EAS. Both seasons in the Indian monsoon (winter and summer monsoon) exert a strong control over the primary productivity in the Arabian Sea. An increased productivity was recorded during the late glacial period in the EAS, contrasting with records obtained in the western and northern Arabian Sea. This enhanced productivity was related to strengthened winter monsoon winds. Planktonic foraminifera data suggested a weakened winter mixing during the last deglaciation, which would reduce productivity in the area. However, our coccolithophore data reveal a high primary productivity during the deglaciation, provably maintained by the nutrient supply from the continental runoff due to the presence of enhanced summer monsoon. Regarding the Holocene, surface waters were highly stratified since 10.5 ka. Our data were compared with ice cores isotopic records from high latitudes of both hemispheres, allowing us to observe a good correlation between the stratification of the EAS and the climate variability over high latitude regions in the northern hemisphere. However, there has been some inconsistency between our coccolithophore data and planktonic foraminiferal records particularly during the short time intervals corresponding to the Heinrich cold events described in the north Atlantic region.

1. Introduction

The Arabian Sea is one of the most productive areas in the world (e.g. Bauer et al., 1991), and its productivity is strongly controlled by the monsoon system. It is expressed in two distinct phases with very different oceanographic implications: the Southwest Monsoon (SW) during summer, and the Northeast Monsoon (NE), in winter. Plankton productivity is directly dependent on the changing wind system during both seasons. The summer monsoon produces little productivity in the eastern Arabian Sea (EAS) (Naidu and Malmgren, 1999), but winter monsoon promotes a moderate upwelling in the west coast of India (e.g. Colborn, 1975; Schott and McCreary, 2001).

The evolution of the primary productivity in the Arabian Sea may be different depending on the geographic location. Previous studies showed diminished productivity in the western and northern Arabian Sea during the Last Glacial Maximum (LGM) (Spaulding and Oba, 1992; Anderson and Prell, 1993; Emeis et al., 1995), related to weakened summer monsoon winds (Anderson and Prell, 1993). In contrast, the EAS showed an increased productivity during the LGM (Rostek et al., 1997; Cayre and Bard, 1999; Schulte et al., 1999; Singh et al., 2011), related to intensified winter monsoon winds (Rostek et al., 1997).

Coccolithophores are one of the major primary producers in the ocean, and due to their ability to get fossilized they represent one of the major components of the oceanic sediment. The distribution of coccolithophores in the ocean is controlled by environmental parameters, such us nutrients availability, light, temperature, etc (Winter et al., 1994). Consequently, the analysis of coccolithophores assemblages preserved in the sediment record is a useful tool to reconstruct paleoenvironmental conditions. Earlier have shown the utility of the coccolithophores in reconstructing paleoproductivity (Kleijne et al., 1989; Molfino and McIntyre, 1990; Giraudeau, 1992; Young, 1994; Beaufort et al., 1997; Okada and Wells, 1997; Bollmann et al., 1998; Flores et al., 1999, 2000; Beaufort et al., 2001; Flores et al., 2003; Baumann and Freitag, 2004; López-Otálvaro et al., 2009; Amore et al., 2012).

The present study aims to obtain a continuous record of the coccolithophore assemblage and primary productivity in the EAS during the last 30 ka. As productivity in the area is mainly controlled by the seasonal monsoonal wind circulation, the focus of the present study is to

* Corresponding author at: Departamento de Geología, Universidad de Salamanca, Plz. de la Merced s/n, Salamanca, 37008, Spain. Tel.: +34 923 294 497.
E-mail address: eloycabarcos@usal.es (E. Cabarcos).

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better understand the seasonal monsoonal dynamics in the EAS during the late glacial, deglaciation, and the Holocene periods. Additionally, we also explored the existence of some teleconnection effects such as, how is the relation between high latitudes and tropical regions, e.g. the Arabian Sea.

2. Seasonal monsoon circulation

The Arabian Sea is characterized by a highly seasonal dynamics controlled by the monsoonal system, which shows two seasons along the year: the Northeast Monsoon or winter monsoon, and the Southwest Monsoon or summer monsoon, separated by two inter-monsoonal periods (spring and fall). During the summer monsoon, increased isolation promotes the development of strong low-pressure centres above the Asian continent. This generates the southeast winds from high-pressure areas in the southern Indian Ocean, blowing along the Somali and Arabian coasts (Fig. 1). These winds induce the formation of coastal upwelling cells, resulting in the presence of cold and rich-nutrients waters off the coast of Somalia and Arabian Peninsula (Currie et al., 1973; Nair et al., 1989; Anderson et al., 1991; Anderson and Prell, 1992; Emeis et al., 1995). Owing to the Ekman Transport the upwelling area extends along the east and north of the Arabian Sea (Wyrtki, 1973; Colborn, 1975), resulting in a significant increase of the primary productivity (Fig. 1). The summer monsoon also produces an increased fluvial runoff over the eastern Arabian Sea which brings nutrients into the upper layers of the water column and can induce a local increase of the productivity. During the boreal winter, high pressure develops over Tibetan Plateau and Central Asia, leading to the occurrence of dry and cold northeastly winds blowing over the Arabian Sea (Fig. 1). These winds generally prevent the upwelling in northern and western Arabian Sea, which reduce the primary productivity in the area, but induce a moderate upwelling along the central coast of India (e.g. Colborn, 1975; Schott and McCreary, 2001).

3. Material and methods

3.1. Material

Gravity core SK 17 was collected in 1999 by the ORV *Sagar Kanya* from the upper continental slope off Goa (15°15'N; 72°58'E), at around 150 km from the coast and a water depth of 840 m. For this work, samples were taken with a spacing of 2 to 4 cm. The sediments in the core were composed intermittently of dark coloured laminated, with abundant foraminifera, and light coloured homogenous facies, with abundant pteropod shells (Singh et al., 2006). The core site is situated under the low-salinity plume developed by runoff from the Western Ghats during the summer monsoon (Sarkar et al., 2000). This low-salinity runoff brings nutrients from the land into the upper layers of the water column. The area of the core is also influenced by the moderate upwelling which occurrs in the west coast of India during the winter monsoon, which substantially increases productivity in this area. Therefore, the core location is suitable for the reconstruction of the paleoproductivity in the west coast of India, related to the monsoonal system.

The independent age model was constructed based on AMS^{14}C dates, measured on monospecific samples of *Globigerinoides ruber*, white variety (Singh et al., 2011) (Table 1). AMS^{14}C ages were converted to calendar ages on the Calib 4.4 software package using the Marine98 calibration dataset and a reservoir age of 640 years (Southon et al., 2002; Singh et al., 2011). According to the age model, the time interval between samples varies from 0.02 to 0.59 ka, depending on the spacing of the sampling and the sedimentation rate.

3.2. Preparation and microscopy techniques

A total of 222 samples were studied for the last 30 ka. Samples were prepared following the technique of decanting of Flores and Sierro (1997) and coccolithophores were counted with a Leica Petrographic Microscope (Light Microscope, LM) (1000×). In each sample we counted at least 500 coccoliths, which assures that all species with an abundance greater than 1% (with paleontological significance) are represented in the count (Dennison and Hay, 1967; Fatela and Taborda, 2002). A second counting was carried out extending the number of visual fields in order to control the abundance of minority taxa. In order to obtain additional morphological information, some of the samples were observed under the Scanning Electron Microscope (SEM) at Bremen University. For that, these samples were prepared following the technique of dilution and filtering of Boeckel et al. (2006).

Coccolithophore absolute abundances (coccoliths/g of sediment) were calculated using the formula given by Flores and Sierro (1997): $[Abs.\ Ab. = (n\,R^2\,V)/(r^2\,g\,v)]$, where n is the number of coccoliths counted in a random visual field; R is the radius of the Petri dish where the sample was prepared; V is the volume of the water added to the dry sediment; r is the radius of the visual field; g is the dry sediment weight; and v is the volume of mixture withdrawn with the micropipette.

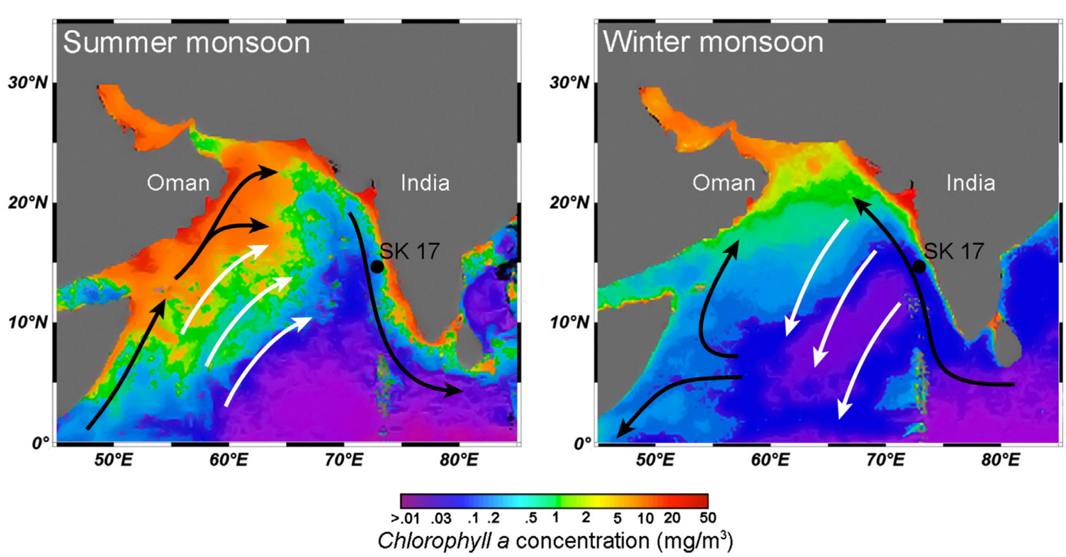

Fig. 1. SK 17 site location and schematic patterns of oceanographic and atmospheric circulation during the winter and summer monsoons. Chlorophyll concentration during both seasons (source NASA/Sea WiFS), main ocean circulation during the summer monsoon and winter monsoon (black lines), and dominant direction of the winds during both seasons (white lines) (Schott et al., 2002; Singh et al., 2011).

Table 1
AMS^{14}C dates for core SK 17 used in this work (Singh et al., 2011).

Depth (cm)	^{14}C Age (ka)	Error (±) (ka)	Calendar Age (ka)
1.5	1.524	0.068	0.875
32.5	2.441	0.045	1.856
40.5	2.96	0.045	2.498
46.5	3.334	0.046	2.922
50.5	3.494	0.146	3.149
54.5	3.908	0.046	3.634
60.5	4.093	0.047	3.875
66.5	4.688	0.047	4.694
70.5	4.775	0.048	4.8
74.5	5.146	0.052	5.302
80.5	5.172	0.149	5.34
90.5	6.873	0.052	7.216
101	7.689	0.054	7.949
117	8.451	0.058	8.764
125	8.885	0.059	9.24
169	10.068	0.061	10.657
193	10.771	0.065	11.668
209	11.639	0.070	12.983
237	12.59	0.142	13.936
261	12.803	0.087	14.171
321	15.678	0.099	17.939
381	18.87	0.132	21.61
417	21.05	0.152	23.74
433	21.91	0.221	23.886
469	25.56	0.231	29.168

Coccolithophore preservation was estimated with the scale reported by Roth and Thierstein (1972) and Flores and Marino (2002), which establishes several degrees of preservation according to visual estimations. Another method to estimate the dissolution used in this work, was the CEX' index (Boeckel and Baumann, 2004), derived from the CEX index from Dittert et al. (1999), which represents the relationship between small and delicate placoliths and strongly calcified coccoliths: *[CEX' = (% small placoliths)/(% small placoliths + % Calcidiscus leptoporus)].*

3.3. Statistics

A Principal Component Analysis (PCA) was performed, including a varimax normalized rotation with the Statistica 7.0® software. These techniques are generally used to reduce the number of variables and even to join variables into a smaller set of dimensions (components or factors) with a minimum loss of information (Hair et al., 1992). Previously, a log-transformation of $\log(x + 1)$ was applied to the dataset to obtain a normal distribution, which amplifies the importance of less abundant species, and thus minimizes the dominance of few abundant species (Mix et al., 1999). Our analysis included 12 species which showed a varying presence in the sedimentary record, from minority to abundant and accounting for 100% of the assemblage, but excluded the reworked taxa and species which only appeared rarely (e.g. *Coccolithus pelagicus*, *Neosphaera coccolithomorpha*, etc.).

To investigate the relationship between tropical variability in the Arabian Sea and the high latitudes dynamics, we implemented a correlation analysis between the main proxies used in the present work and δ^{18}O data from EPICA Dome C (Jouzel et al., 2001; Schwander et al., 2001; Stenni et al., 2001) and GISP2 (Meese et al., 1997; Blunier et al., 1998; Blunier and Brook, 2001) ice cores in Antarctica and Greenland, respectively, by using the Pearson linear correlation coefficient (r).

4. Coccolithophores as paleoproductivity indicators

4.1. High productivity proxies

The most abundant taxa in the assemblages are the group of small placoliths (SP). In the SP we included small *Gephyrocapsa* and *Emiliania huxleyi*, with cocoliths < 3 µm. The small *Gephyrocapsa* group often includes several species. Using SEM we identified three species: *G. aperta*, *G. ericsonii* and *G. ornata*. We only used the term small placoliths or SP, as the discrimination between these species under LM becomes complex because of their small sizes. SP and *Gephyrocapsa oceanica* live in the upper photic zone and their abundances in upwelling areas have been linked to high primary productivity conditions (Kleijne et al., 1989; Giraudeau, 1992; Young, 1994; Okada and Wells, 1997; Bollmann et al., 1998; Flores et al., 1999, 2000, 2003; Baumann and Freitag, 2004; López-Otálvaro et al., 2009; Amore et al., 2012). Andruleit and Rogalla (2002) observed a positive response of *G. oceanica* to an increase in nutrient supply in the Arabian Sea. Based on results of trap studies in the upwelling area off Somalia, Broerse et al. (2000) proposed this species as indicator of maximum upwelling conditions.

4.2. Stratification proxies

Florisphaera profunda is a characteristic species of the lower photic zone in middle or low latitudes (Okada and Honjo, 1973). It is a good indicator of the thermocline/nutricline position, such that when nutricline deepens, total primary production is low and *F. profunda* becomes the dominant coccolithophore (Molfino and McIntyre, 1990). When primary productivity increases, the relative abundance of *F. profunda* decreases (Beaufort et al., 2001). The distribution pattern of *F. profunda* in the Arabian Sea showed a positive correlation to the mean annual mixed layer depth (Andruleit and Rogalla, 2002). *Oolithotus* spp. is also a taxon inhabiting the lower photic zone, or the bottom of the upper photic zone, in oligotrophic areas, with low-nutrient waters (Brand, 1994).

4.3. N ratio

The relationship between the main upper photic zone species (SP and *Gephyrocapsa oceanica*) and the main lower photic zone species (*Florisphaera profunda* and *Oolithotus* spp.), can be used as indicator of primary productivity (Beaufort et al., 1997; Flores et al., 2000; Beaufort et al., 2001). This ratio was calculated using the formula given by Flores et al. (2000), with a slight modification, in which *Oolithotus* spp. was added: *[N ratio = (G. oceanica + SP)/(G. oceanica + SP + F. profunda + Oolithotus* spp.*)]*. High values in this ratio indicate a prevalence of the upper photic zone species, and likely respond to the presence of a shallow nutricline, with a high availability of nutrients in the surface waters. On the contrary, lower values of N ratio point to a higher development of the lower photic zone species, suggesting the presence of a deep nutricline, and a low productivity in the surface waters.

5. Results

5.1. Coccolithophore assemblage

Fig. 2 shows the relative and the absolute abundances for the main coccolithophore species. The coccolithophore assemblage was dominated by the SP, *Gephyrocapsa oceanica*, and *Florisphaera profunda* (Fig. 2a, b and c). The SP and *G. oceanica* together dominated the assemblage during the LGM and remain moderately high up to ~11 ka, and then the assemblage was dominated by *F. profunda* in the Holocene. Relatively low values in the percentages of SP were observed during the LGM (23–18 ka) coinciding with maximum relative abundances of *G. oceanica*. However, high values in the percentages of the SP were recorded between ~16 and 14 ka corresponding to low values in *G. oceanica*. A sharp drop was recorded in the relative abundance of SP at around 14 ka, which matches with a marked increase in the percentages of *G. oceanica* and *F. profunda*. Additionally, a marked decline in the relative abundance of *G. oceanica* was recorded at around 17.5 ka.

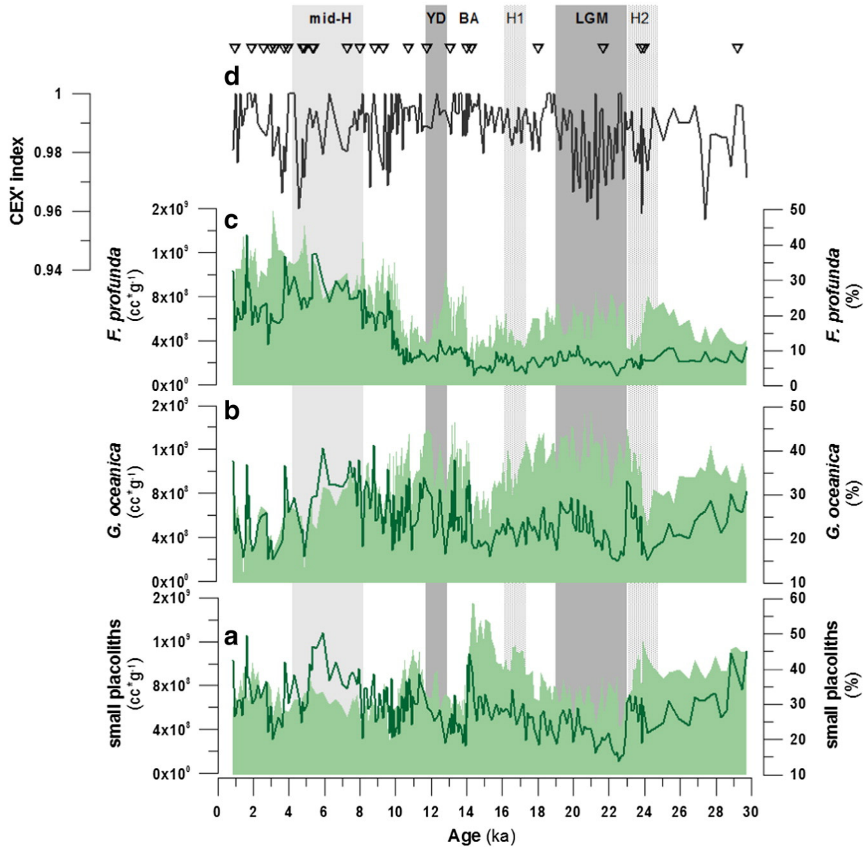

Fig. 2. Relative (shaded area) and absolute abundances (green line) of the most significant coccolithophore: (a) Small placoliths; (b) *G. oceanica*; and (c) *F. profunda*. (d) CEX' index (preservation). H2, Heinrich 2 event; LGM, Last Glacial Maximum; H1, Heinrich 1 event; BA, Bolling Allerod; YD, Younger Dryas; and mid-H, middle Holocene.

The absolute abundances of SP and *Gephyrocapsa oceanica* exhibited a gradual fall up to ~24 ka (Fig. 2a and b) and a subsequent rise, especially in the *G. oceanica* record. After a progressive increase (22.5–14 ka), the absolute abundance of SP displayed a sharp drop followed by a gradual increase up to 6 ka (Fig. 2a). The absolute abundance of *G. oceanica* showed relatively lower values up to 13.5 ka, with a brief increase during the LGM (Fig. 2b). Between 14 and 11 ka, this record registered large fluctuations and a subsequent increase up to 6 ka. Meanwhile, the absolute abundance of *Florisphaera profunda* remained very low with no significant changes until the Holocene, when its maximum values were recorded (Fig. 2c). A marked decrease occurred in the absolute abundance of the main species between 6 and 3 ka, followed by a slight increase between 3 and 1 ka (Fig. 2a, b and c).

5.2. Preservation

The degree of preservation of coccoliths varies from moderate to good, according to the visual scale given by Roth and Thierstein (1972) and Flores and Marino (2002). All the specimens are well preserved and can be identified at species level, and only in some samples appeared irrelevant signs of dissolution or fragmentation. This is reflected in the CEX' index (Boeckel and Baumann, 2004), which showed high values (>0.95) in the entire core (Fig. 2d). It is important to note that this allows us to be confident that the dissolution did not bias our results.

5.3. N ratio and total absolute abundance

The record of the N ratio showed higher values during the glacial stage and deglaciation (~0.8) as compared to the Holocene, except significant low values during the second half of the Bolling Allerod (BA) (Fig. 3c). A marked decrease occurred between 10.5 and 9.5 ka, and relatively low values (~0.65) were observed until 6 ka. Additionally, a gradual decrease was recorded, reaching minimum at around 3 ka (~0.5). Also, a slight increase occurred in the N ratio at around 1 ka. The total absolute abundance of coccoliths recorded a gradual decrease until up to 22.5 ka (with a slight increase between 24 and 23 ka) (Fig. 3b). Relatively lower values were recorded during the LGM and deglaciation, and a marked shift to high coccoliths content was observed at around 10 ka. Maximum values occurred at 6 ka, followed by a marked increase up to 3 ka, and a slight increase between 3 and 1 ka.

5.4. Principal component analysis

The PCA indicated the existence of three main factors. Factor 1 was defined by SP and *Gephyrocapsa oceanica* (Table 2), explaining the 35.3% of the total variance. According to the description given in Section 4.1, this factor was interpreted as indicator of high productivity. Henceforth, we will refer to this factor as the Productivity Factor (PF). Factor 2, represented mostly by *Florisphaera profunda*, explained the 38.1% of the total variance and was interpreted as indicator of a deep nutricline, according to Section 4.2. We will call this factor as the Stratification Factor (SF). Factor 3 was defined by *Umbilicosphaera* spp. and explained the 24.9% of the total variance. This genus was normally associated with temperate and oligotrophic waters (Okada and McIntyre, 1979), but Andruleit and Rogalla (2002) observed a positive response of *U. sibogae* (the predominant species of the genus) to an increase in nutrient supply in a study of surface sediments along the Arabian Sea. For this reason, the meaning of this factor was not well established.

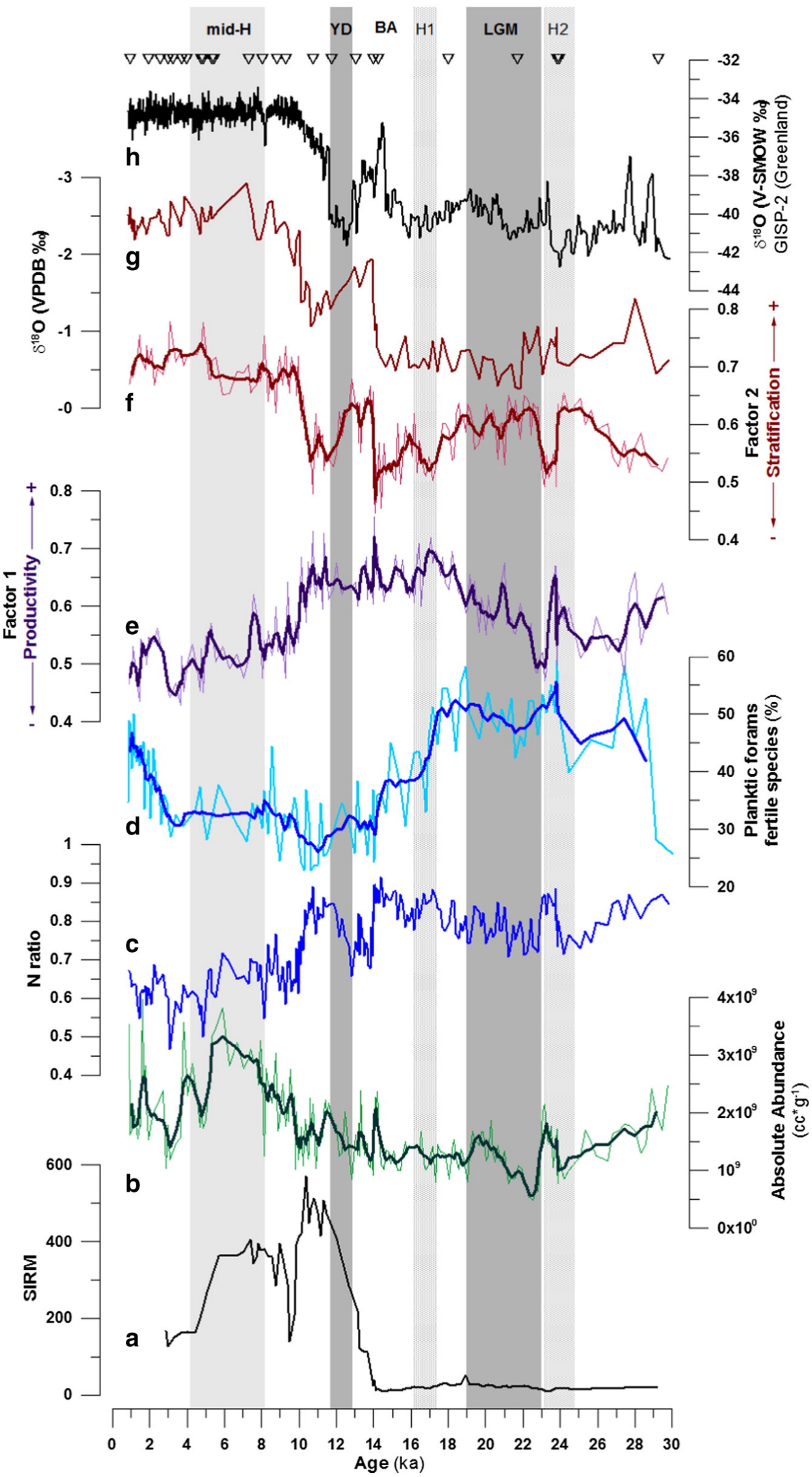

Fig. 3. Comparison of paleoproductivity proxies for the core SK 17. (a) Magnetic susceptibility record (SIRM, Saturation Isothermal Remanent Magnetization) (Patil and Singh, 2013); (b) Total absolute abundance of coccolithophores. Dark green line represents a smoothing of five points; (c) N ratio; (d) Relative abundance of the planktic foraminifera fertile species (Singh et al., 2011). Dark blue line represents a smoothing of five points; Factor loadings for (e) Factor 1 (Productivity proxy) and (f) Factor 2 (Stratification proxy). Thick lines represent a smoothing of five points; (g) δ^{18}Oc of *G. ruber* from SK 17 core, referred to the scale V-PDB (Vienna Pee Dee Belemnite) (Anand et al., 2008); (h) Greenland ice core δ^{18}O record from GISP2, referred to the scale V-SMOW (Vienna Standard Mean Ocean Water) (Meese et al., 1997; Blunier et al., 1998; Blunier and Brook, 2001). H2, Heinrich 2 event; LGM, Last Glacial Maximum; H1, Heinrich 1 event; BA, Bolling Allerod; YD, Younger Dryas; and mid-H, middle Holocene.

The PF exhibited a declining trend until up to 25 ka and a subsequent increase at around 24 ka (Fig. 3e). A sharp drop was recorded between 24 and 23 ka followed by a gradual rise during the LGM (23–19 ka). This record reached its maxima values during the deglaciation (especially at around 17 and 14 ka). During the Holocene, there was a declining trend in the PF, similar to the record of the N ratio (Fig. 3c and e). Regarding

Table 2
Factor scores obtained in the Principal Component Analysis.

	Factor 1	Factor 2	Factor 3
Small placoliths	**1.72**	0.25	1.07
Gephyrocapsa oceanica	**1.90**	0.06	1.03
Gephyrocapsa muellerae	−0.46	−0.58	−0.39
Florisphaera profunda	−0.43	**3.02**	−0.59
Oolithotus	0.19	−0.01	−0.94
Umbilicosphaera	−1.34	−0.06	**2.04**
Calcidiscus leptoporus	−0.67	−0.53	0.12
Helicosphaera carteri	−1.18	−0.10	0.76
Syracosphaera	0.45	−0.53	−0.67
Calciosolenia	0.14	−0.25	−1.14
Rhabdosphaera clavigera	−0.36	−0.59	−0.44
Umbellosphaera	0.03	−0.67	−0.84

Rotation, varimax normalized; extraction, principal components. Bold values indicate the species which define each factor.

the SF, it showed and opposite trend to PF, with a marked decrease around 24 ka, and a clearly declining trend during the LGM and most of the deglaciation (Fig. 3f). A sharp increase was observed in the SF during the BA (~14 ka) and a subsequent decrease during the YD. Maxima values in this record was recorded during the Holocene (Fig. 3f).

6. Discussion

6.1. Productivity variations in the eastern Arabian Sea

Coccolithophores reflect oceanic productivity, and their fossil assemblages were used successfully for the reconstruction of the primary productivity in the equatorial Indian Ocean during the Late Quaternary with an orbital scale (Beaufort et al., 1997). The results from the EAS core SK 17 provide valuable data of the primary productivity evolution in the region. The surface water productivity conditions in the EAS are controlled primarily by the winter wind induced vertical mixing and/or upwelling invoking injection of nutrient to the photic layer. Productivity is also influenced by summer monsoon related to fluvial runoff that causes stratification of surface waters and, consequently, an oligotrophic environment. However, high supply of terrigenous material through runoff can be a source of nutrients to the photic zone that can induce a local increase of productivity, as has been reported from other areas (e.g. Portuguese coast; Guerreiro et al., 2013). We compare our data with other proxies related to oceanographic information such as census of planktonic foraminfera, magnetic susceptibility and isotope records of the core, published elsewhere (Anand et al., 2008; Singh et al., 2011; Patil and Singh, 2013). We recorded major changes in primary productivity and related surface hydrohraphic patterns during glacial, deglacial and Holocene periods, discussed in next sections.

6.1.1. Glacial period

Absolute and relative abundances of SP, *Gephyrocapsa oceanica* and *Florisphaera profunda* indicate high productivity in the late glacial period (Figs. 2a, b, c and 3c). Relatively low values of Factor 2 (SF, Stratification Factor) during these periods suggest less stratified surface waters, pointing towards high vertical mixing and/or upwelling associated with the intensified winter monsoon winds (Fig. 3f). Furthermore, Factor 1 (PF, Productivity Factor), an indicator of eutrophic conditions, agrees with the other alternative records (Fig. 3e). However, note that our proxies indicated a lower productivity between 27 and 25 ka and around 23 ka (Fig. 3c and e) with an increased stratification in the water column (Fig. 3f). A marked increase in the productivity of the EAS is recorded during the LGM. Increases in the productivity of the EAS likely responded to intensified winter monsoon winds. Our interpretation that winter monsoon controls glacial productivity in EAS, gains support from planktic foraminiferal and geochemical productivity proxy data of the core SK 17 (Singh et al., 2006, 2011). The planktonic foraminifers fertile species record suggested an increased productivity in the EAS during the last glacial stage (Fig. 3d), and this has been attributed to an enhanced vertical mixing and upwelling due to the intensification of the winter monsoon (Singh et al., 2011). The strong, cold and dry winter winds during the glacial time would have resulted in enhanced evaporation, provoking the increase of sea surface salinity and convective mixing. Additionally, strong winds might caused upwelling in this region. Thus, intensified winter winds produced upwelling of nutrient-rich waters into the euphotic zone, which promoted an increase on phytoplankton and in the productivity of the EAS (Wiggert et al., 2002). Similar patterns have been showed in other studies in the area (e.g. Rostek et al., 1997; Banakar et al., 2005) pointing that the increased primary productivity in this region was associated with intensified winter monsoons.

Studies from the western and northern Arabian Sea indicated lower productivity during the LGM as compared to the Holocene (e.g. Anderson and Prell, 1993; Reichart et al., 1997; Naidu and Malmgren, 1999). These studies mentioned this lower productivity during the LGM with decreased summer monsoon winds, the main factor driving upwelling in the western Arabian Sea (WAS). Anderson and Prell (1993) recorded lower productivity during the LGM, as well as a decreased precipitation over the WAS, related to a weakened summer monsoon. Therefore, although a weakened summer monsoon reduced productivity in the WAS, the presence of enhanced winter monsoon winds invoked an increased vertical mixing and/or upwelling in the EAS, which substantially increased the productivity in most of the late glacial period, particularly during the LGM.

6.1.2. Deglaciation

Our productivity proxy records indicate a higher primary productivity during the deglaciation. High values of PF and lower values in SF at around 17 ka can be an indicative of enhanced productivity (Fig. 3e and f). Increased in stratification is suggested by the SF during the BA, and our proxies showed relatively lower productivity during 14 to 12.5 ka followed by a marked rise between 12.5 and 10 ka (Fig. 3c, e and f). Increased stratification in the water column of the EAS can be explained by weak winter monsoon winds. However, the explanation of a mechanism to explain high productivity during 10 to 12.5 ka does not seem to be straight forward because the foraminifera record does not support clearly this conclusion (Fig. 3d). Interestingly, the magnetic susceptible record (Patil and Singh, 2013) provides a clue to explain this interval of productivity maximum which coincides with the high content of ferromagnetic minerals (Fig. 3a). It has been suggested that there was high terrigenous supply to the core site during 12.5 to 10 ka and early Holocene (Patil and Singh, 2013) as showed the high content of ferromagnetic minerals (high SIRM values) (Fig. 3a). There could be two probable sources of terrigenous: eolian and fluvial.

So, planktonic foraminifera records, which suggested a rapid switch to lower productivity conditions during the deglaciation (Singh et al., 2011), may be indicative of the open ocean vertical mixing during the winter monsoon. However, our coccolithophore records may indicate changes on primary productivity and nutrient availability, which are controlled by the vertical mixing but also the supply from the continent. During most of the deglaciation winter monsoon winds were weak, reducing vertical mixing, but the presence of enhanced summer monsoons provided nutrients to the EAS from land. An intensification of the summer monsoon was recently documented around 15.2 ka in the EAS (Kessarkar et al., 2013). This situation can induce an increase of primary productivity during the summer monsoon, particularly productivity of coccolithophores, as total absolute abundances suggest (Fig. 3b). This assumption finds support from a good concordance between the absolute abundance of coccolithophores and the SIRM record (Fig. 3a and b). The good concordance between SF and δ^{18}O record in the EAS (Anand et al., 2008) supports our assumptions, showing an increased stratification/oligotrophy when sea surface temperature was warmer (Fig. 3f and g).

6.1.3. Holocene

PF and SF in the EAS indicate high primary productivity at the beginning of the Holocene (Fig. 3e and f). This scenario may respond to a high nutrient availability due to the supply from the continent, as would have occurred during deglaciation. A sharp decrease in the primary productivity occurred around 10 ka, which match with a marked decrease in the SIRM values (Fig. 3a). These observations suggest a significant reduction of the summer monsoon, which are in agreement with other studies in the Arabian Sea (Bassinot et al., 2011). Primary productivity dropped again around ~6 ka (Fig. 3c and d) coinciding with a sharp decrease in the SIRM record and around 3.2 ka PF and SF reached its minima and maxima values, respectively. The sharp drop observed in the SIRM record indicates a reduction in the supply from the continent, associated with a weakening of the summer monsoon. This assumption is consistent with data from Rampelbergh et al. (2013) that interpreted a reduction in the summer monsoon intensity and a change toward drier conditions in the Arabian Sea around 6 ka, which would reduce the nutrient supply due to the fluvial runoff into the EAS. However, a moderate increase in the productivity is marked by the foraminifera record between 3 and 1 ka (Fig. 3d), suggesting an enhancement of the winter monsoon in the EAS. This increase in productivity inferred by planktonic foraminifers is not evident in our coccolithophorid census, although a slight increase was recorded in the PF (Fig. 3e). The reduction of the nutrients supply from the continent, via fluvial runoff, may be the explanation, limiting the nutrient availability in the EAS despite the increased vertical mixing during winter.

6.2. Interhemispheric connections

The comparison between our records (N ratio, PF and SF) and isotopic ice core records from high latitudes, allowed us to observe an evident parallelism with the GISP2 $\delta^{18}O$ ice core record (Greenland) (Fig. 3c, e, f and h) and the millennial events referred in the ice core (e.g. Dansgaard et al., 1993). The parallelism was more obvious between SF and Greenland record (Fig. 3f and h), showing a high correlation ($r = 0.73$) (Table 3). The parallelism was also observed with the $\delta^{18}Oc$ record in core SK 17 (Anand et al., 2008) (Fig. 3g). Therefore, the dynamics of high-latitude in the northern hemisphere may have played a crucial role over the oceanographic conditions in the Arabian Sea along the last 30 ka. Productivity in the EAS would be lower during the warmer events in the north Atlantic region, while coinciding with the north Atlantic cold events productivity in the EAS would be higher.

Our coccolithophore record suggests an increased productivity coinciding with the extremely cold events well described in high latitudes of the northern hemisphere (Heinrich 2-1) (Fig. 3e and f). According to previous studies, the existence of an extensive snow/ice cover in the Tibetan Plateau during these cold events would increase the albedo of the region. This fact could diminish the establishment of the low surface pressure above the Tibetan Plateau and reduce the land–sea pressure gradient, which would weaken the summer monsoon but reinforce the winter monsoon (e.g. Colin et al., 1998). Nevertheless, the foraminifera data showed a rapid switch to oligotrophic waters in the EAS coinciding in time with the H1 (Fig. 3d), responding to a decreasing winter monsoon (Singh et al., 2011). Our data support the idea of strengthened winter monsoon, while planktonic foraminifera suggest an increased stratification in the water column of the EAS during the H1 event. These discrepancies will require the analysis of new proxies.

Table 3
Correlation matrix between N ratio, Factor 1, Factor 2, Dome C $\delta^{18}O$ and GISP2 $\delta^{18}O$ records.

	N ratio	Factor 1	Factor 2	Dome C	GISP2
N ratio	1	**0.69**	**−0.76**	**−0.58**	**−0.71**
Factor 1	**0.69**	1	**−0.76**	**−0.54**	**−0.62**
Factor 2	**−0.76**	**−0.76**	1	**0.60**	**0.73**
Dome C	**−0.58**	**−0.54**	**0.60**	1	**0.86**
GISP2	**−0.71**	**−0.62**	**0.73**	**0.86**	1

Bold values correspond to significant correlations at $p < 0.05$.

7. Conclusions

Our data offer a high-resolution reconstruction of the productivity and coccolithophorid production in the EAS for the last 30 ka. The intensity of the winter monsoon winds played a crucial role over the productivity in the EAS, and during the glacial period, with enhanced winter monsoon, surface waters were less stratified in the EAS, and productivity was higher as compared to the Holocene. The nutrient supply from land, due to an intensified summer monsoon, would have maintained a high productivity during deglaciation. However, planktonic foraminifera data suggest a rapid switch to increased stratitification conditions during deglacial time, which may respond to a cease of the mixing during winter, due to a weakening of the winter monsoon. An abrupt switch to stratified and/or less productive waters occurred during the early Holocene at around 10 ka. Productivity in the EAS seems to be controlled by the dynamics of high latitudes in the northern hemisphere. An opposite interpretation is expressed during Heinrich events: whereas coccolithophore data suggest an intensification of the winter monsoon, planktonic foraminifera support the idea of an increased stratification. New studies and new proxies will help to solve this controversy

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