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## Rapid switch in monsoon-wind induced surface hydrographic conditions of the eastern Arabian Sea during the last deglaciation

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**Title: Rapid switch in monsoon-wind induced surface hydrographic conditions of the eastern Arabian Sea during the last deglaciation.**

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1 **Rapid switch in monsoon-wind induced surface hydrographic conditions of the eastern**  
2 **Arabian Sea during the last deglaciation**

3  
4 **ABSTRACT**

5  
6 Surface water hydrography in the Arabian Sea is primarily governed by the Asian monsoon  
7 wind system. Changes in the composition of fossil planktic foraminiferal assemblages and sea  
8 surface temperatures (SST) in sediment core SK17, retrieved from offshore of central India, are  
9 used to decipher past changes in sea-surface hydrographic conditions linked mainly to the winter  
10 monsoon winds. The planktic foraminiferal assemblage and the SST records indicate a rapid  
11 switch in sea-surface hydrographic conditions around 17.5 ka BP marking the end of last glacial  
12 period. The data show that intensified winter winds during 17.5 to 23.5 ka BP, resulted in  
13 nutrient injection into surface waters and eutrophic conditions, mainly through deep vertical  
14 mixing and/or moderate upwelling; and reduction in winter wind intensity caused stratification  
15 characterized by the high tropical SST since 17.5 ka BP. The timing of the rapid switch in  
16 seawater conditions caused by a drop in strength of winter monsoon winds is coeval with the  
17 cold climate excursion in the northern hemisphere (Heinrich Event 1), suggesting that the two  
18 areas are climatically linked.

19  
20 *Keywords:* Arabian Sea; hydrography; winter monsoon; last deglaciation; Heinrich Event

21  
22 **1. Introduction**

23  
24 In the Arabian Sea, seasonally reversing air flow of the Asian monsoon produces spatial  
25 changes in surface circulation, hydrography and biological productivity. Through time, changes  
26 in the composition of planktic foraminiferal assemblages and sea surface temperatures largely  
27 reflect the history of upper water column conditions in response to changes in direction and/or  
28 strength of seasonal monsoon winds. Previous paleoceanographic studies using fossil planktic  
29 foraminifera were focused mainly on the western and northern regions predominantly influenced  
30 by the southwest (summer) monsoon. These studies have provided crucial insights into the

31 processes controlling summer monsoon variability on orbital and sub-orbital scales (eg. Clemens  
32 et al., 1991; Anderson and Prell, 1993; Venec-Peyre et al., 1995; Naidu and Malmgren, 1996;  
33 Reichart et al., 1998; von Rad et al., 1999; Venec-Peyre and Caulet, 2000; Jung et al., 2002;  
34 Gupta et al., 2003). However, high resolution planktic foraminiferal records from the eastern  
35 Arabian Sea, a region sensitive to the winter (northeast) monsoon circulation, are scarce.  
36 Therefore, our understanding of winter monsoon variability and associated changes in sea-  
37 surface hydrography particularly remains poor.

38 Previous studies have shown that wind driven changes in productivity and sea surface  
39 temperatures (SST) occurred at the millennial-scale in the western and northern Arabian Sea  
40 (e.g. Schulz et al., 1998; Ivanochko et al., 2005). Summer monsoon wind-induced upwelling  
41 generally reduced in the western and northern Arabian Sea during the glacial period, and  
42 particularly during extreme cold phases (Heinrich Events) in the northern hemisphere (Sirocko et  
43 al., 1993; Schulz et al., 1998; Ivanochko et al., 2005; Anand et al., 2008; Singh et al., 2011). The  
44 pattern of changes in surface hydrography of the eastern Arabian Sea, however, may well be  
45 different from those in the western and northern Arabian Sea, because of the dominant influence  
46 of winter monsoon winds in this area. At present, the winter winds cause shallow vertical mixing  
47 and sporadic upwelling along the central coast of India (Colborn, 1975; Zhang, 1985;  
48 Madhupratap et al., 1996; Schott and McCreary, 2001). Stratification of the surface waters  
49 occurs in summer because of increased fluvial runoff over the eastern Arabian Sea during the  
50 rainy summer season. In recent years, attempts have been made to study millennial-scale  
51 productivity variations in the eastern Arabian Sea influenced by seasonal monsoon air flow  
52 intensities, based on changes in the planktic foraminifera (Singh et al., 2006, 2011) and  
53 coccolithophore assemblages (Cabarcos et al., 2014). Changes in the upper water column  
54 structure through time, however, relating to millennial-scale variations in monsoon winds have  
55 not been studied in detail for the late glacial – Holocene.

56 We present planktic foraminiferal assemblage and Mg/Ca based SST records from  
57 sediment core SK 17 retrieved off Goa. This core provides a continuous record of upper ocean  
58 conditions in the eastern Arabian Sea during the last 30 ka BP. In particular, the reconstructions  
59 reveal millennial- scale changes in trophic conditions of the upper water column influenced by  
60 seasonal monsoon (summer vs winter) air flow intensities since the Last Glacial Maximum

61 (LGM). We explore links between these monsoon-induced air flow changes, global climate and  
62 deep-sea circulation.

63

## 64 **2. Oceanographic Setting**

65

66 Surface ocean circulation along the west coast of India is driven by seasonally reversing  
67 monsoon winds. Between June and September, SW monsoon winds prevail over the Arabian Sea  
68 (Fig. 1a). During this season, the West Indian Coastal Current (WICC) flows southward along  
69 the eastern margin of the Arabian Sea and joins the eastward flowing Southwest Monsoon  
70 Current (SMC) in the southeastern Arabian Sea (Schott and McCreary, 2001). Locally, high  
71 precipitation and runoff from the Western Ghats during the summer leads to a stratified surface  
72 water (Joseph and Freeland, 2005). The fluvial runoff supplies nutrient into surface waters,  
73 which can induce a local increase in productivity (Cabarcos et al., 2014). Further south, weak  
74 upwelling occurs along the southwest coast of India (south of 10° N) during this season (Sharma,  
75 1966; Wyrтки, 1973; Naidu et al., 1999) resulting in the presence of moderately cold, nutrient-  
76 rich surface water in the region (Fig. 1a,b) .

77 During winter (December to March), the wind flow reverses and the NE monsoon prevails  
78 (Fig. 1a). Because of the reversed air flow, a cyclonic circulation develops causing weak and  
79 sporadic upwelling along the coasts off Pakistan and India (Colborn, 1975; Zhang, 1985; Bauer  
80 *et al.*, 1991). The cool and dry NE monsoon winds intensify evaporation, leading to surface  
81 cooling and vertical mixing in the eastern Arabian Sea, north of 10° N (Fig. 1b) [Banse and  
82 McClain, 1986; Madhupratap et al., 1996; Kumar et al., 2000]. The vertical mixing leads to a  
83 mild increase in primary productivity (Shalin, 2017). During this time, the WICC reverses and  
84 the Northeast Monsoon Current (NMC) transports waters from the Bay of Bengal (BOB) into the  
85 southeastern Arabian Sea up to 13° N (Sarma, 2003).

86

## 87 **3. Material and Methods**

88

89 Gravity core SK17 was retrieved from the sea bed off the central western Indian margin off  
90 Goa from 840 m water depth (Lat. 15° 15 ' N and Long. 72° 58 ' E; core length 470 cm) during the  
91 ORV Sagar Kanya Cruise in 1999 (Fig.1). The sediment sequence is characterized by alternating

92 dark-coloured laminated and light-coloured bioturbated layers, free of gravity flows (Singh et al.,  
93 2006). Today the core site is well above the Calcite Compensation Depth (Belyaeva and  
94 Burmistrova, 1984). Singh et al. (2006) have evaluated dissolution effects on planktic  
95 foraminiferal tests in sediments of core SK 17. The results indicate that there is no evidence of  
96 significant dissolution of the tests over the last 30 ka BP.

97 The core was sampled every 1 cm interval up to one meter and further at 2 cm regular  
98 intervals. Alternate samples at 2 to 4 cm intervals were used in this study for planktic  
99 foraminiferal census counts. Dried sediments were washed over a 63  $\mu\text{m}$  screen. The resulting  
100 dry residues were sieved over a 125  $\mu\text{m}$  screen. Census counts of planktic foraminifera were  
101 made on the  $>125 \mu\text{m}$  fraction. The taxonomy of the planktic foraminifera is based on Kennett  
102 and Srinivasan (1983) and Hemleben et al. (1989). The relative abundance (%) of each species  
103 was calculated and plotted against depth to illustrate the down-core distribution patterns. In order  
104 to explain interrelationships in a multivariate database by the presence of a few key factors, we  
105 carried out Q mode factor analysis on the planktic foraminiferal relative abundances, using the  
106 SPSS 10.0. All species with a relative abundance  $> 2 \%$  were included in this analysis (Table 1).  
107 Nitrogen isotopes ( $\delta^{15}\text{N}$ ) were measured using a CE Instruments NA 2500 Elemental Analyser  
108 interfaced with a VG PRISMIII stable isotope spectrometer in continuous flow mode with  
109 helium carrier gas. The standard used is atmospheric nitrogen. The precision of measurement is  
110  $\pm 0.2$  per mil. In addition to our new data (foraminiferal assemblage and  $\delta^{15}\text{N}$  records), we also  
111 include previously published Mg/Ca -SST and  $\delta^{18}\text{O}_{\text{w}}$  time series (Anand et al., 2008), the  $C_{\text{org}}$   
112 record (Singh et al., 2006) and the aragonite record (Singh, 2007) of the same core SK 17. A  
113 section of the foraminiferal data (abundance ratio of *Globigerinoides ruber* and *Globigerina*  
114 *bulloides* and abundance total of fertile species viz. *G. bulloides*, *G. falconensis*, *G. glutinata*  
115 and *Neogloboquadrina dutertrei*) has been published earlier (Singh et al., 2011). The age model  
116 for core SK 17 is based on 26 AMS  $^{14}\text{C}$  dates and has been published previously (Singh et al.,  
117 2011). The AMS $^{14}\text{C}$  dates are based on monospecific samples of *Globigerinoides ruber*.  
118 Further details on the chronology are given in Singh et al. (2011).

119

## 120 **4. Results**

121

### 122 *4.1. Planktic foraminiferal census counts*

123

124 In total, 27 planktic foraminiferal species were found in core SK 17. The most abundant  
125 species, accounting on average for more than 80 % of the assemblage are: *Globigerinoides ruber*  
126 (26 %), *Globigerinita glutinata* (14.5 %), *Globigerina bulloides* (9.5 %), *Neogloboquadrina*  
127 *dutertrei* (9 %), *Globigerinoides quadrilobatus* (6 %), *Gobigerina falconensis* (5.5 %),  
128 *Globigerinoides sacculifer* (4 %), *Globorotalia menardii* (4 %), and *Pulleniatina obliquiloculata*  
129 (4 %). The relative abundance records of these species are shown in Fig. 2. The faunal record  
130 reveals that the planktic foraminiferal assemblages of the core are generally characterized by  
131 predominance of the *G. ruber* - *quadrilobatus* - *sacculifer* group (> 40 %). The cumulative  
132 abundance of these three species shows minima in the period 17.5 – 23.5 ka BP and the late  
133 Holocene (Fig. 2).

134 *G. bulloides* is an important species of the faunal assemblages of core SK17 with  
135 minimum concentrations of 4 % and maximum concentrations of up to 21 %. Its abundance  
136 maxima occur during the periods 22.5 - 23.5 ka BP and 18 -19 ka BP (Fig. 2). The abundance  
137 pattern of *G. falconensis* generally follows that of *G. bulloides* (Fig. 2). *G. glutinata* is another  
138 significant species, its relative abundance varies between 2 and 25 % (Fig. 2). This species shows  
139 high abundances during the periods 18 - 22 ka BP and 27 - 28 ka BP, and in the late Holocene  
140 (Fig. 2).

141 Other important taxa of the assemblages are *N. dutertrei*, *G. menardii* and *P.*  
142 *obliquiloculata*. The relative abundance of *N. dutertrei* varies between 4 % and 17 %. This  
143 species shows its maximum abundance during the period 17.5 – 23.5 ka BP. Its abundance  
144 decreases rapidly from 17.5 ka BP, followed by an increase at around 14 ka BP (Fig. 2). The  
145 relative abundance pattern of *G. menardii* broadly follows that of the *N. dutertrei* pattern,  
146 although it shows a more gradual decline in abundance from 17.5 ka BP onward, eventually  
147 disappearing around 15 ka BP. *P. obliquiloculata* shows a broad abundance maximum in the  
148 period 10.5 - 14 ka BP (Fig. 2).

149

#### 150 4.2. *Q* mode factor analysis on planktic foraminifera

151

152 Multivariate analysis provides information on interspecies relationships and their  
153 dependency on varying environmental factors (e.g. Kroon, 1988; Caulet et al., 1992; Venec-

154 Peyre et al., 1995; Cayre et al., 1999; Venec-Peyre and Caulet, 2000). The factor analysis of  
155 planktic foraminiferal assemblages of core SK 17 results in three distinct groups of species,  
156 together accounting for 93 % of the total variance (Table 1). Factor 1 describes almost 40 % of  
157 the variance.

158 The highest-positive score of Factor 1 is attributed to *G. ruber*. Other important species  
159 having positive scores are *P. obliquiloculata* and *G. quadrilobatus*. These species are common in  
160 warm tropical surface waters and have adapted to nutrient-poor, oligotrophic water conditions  
161 (Bé and Tolderlund, 1971; Cullen, 1981; Cullen and Prell, 1984; Kroon, 1988). Factor 2  
162 describes 35 % of the total variance. High positive scores of *G. bulloides*, *G. glutinata*, *G.*  
163 *falconensis* and *N. dutertrei* characterise Factor 2. These species prefer nutrient-rich, eutrophic  
164 water conditions, such as in a tropical upwelling environment (Bé and Tolderlund, 1971; Cullen,  
165 1981; Cullen and Prell, 1984; Kroon, 1988). These species live mainly in the mixed layer except  
166 for *N. dutertrei* that lives in the thermocline during the adult phase (Sautter and Thunell, 1991;  
167 Ravelo and Fairbanks, 1992). Factor 3 describes 18 % of the total variance. This factor is  
168 dominated by positive scores of *G. glutinata*, with secondary contributions from *G. ruber*, *G.*  
169 *menardii* and *G. sacculifer*. Significantly, *G. bulloides*, *G. falconensis* and *N. dutertrei*  
170 (important contributors of Factor 2) have negative scores in Factor 3. We interpret the  
171 assemblage that contributes with positive scores to Factor 1 as the ‘assemblage representing  
172 oligotrophic conditions in the mixed layer associated with surface water stratification’ and the  
173 assemblage that contributes with positive scores to Factor 2 as the ‘assemblage representing  
174 eutrophic conditions in the mixed layer associated with vertical mixing and/or upwelling’ (eg.  
175 Venec-Peyre et al., 1995; Venec-Peyre and Caulet, 2000). The assemblage of Factor 3 appears to  
176 characterise small variations in mixed layer trophic conditions. These are of minor importance,  
177 because the assemblages of Factors 1 and 2 account for most of the total variance.

178

## 179 **5. Discussion**

180

### 181 *5.1. Planktic foraminifera reflect mixed layer nutrient status and productivity*

182

183 The multivariate statistical approach, employing abundance records of planktic  
184 foraminifera, provides a way of connecting groups of species to environmental parameters. In the



185 case of core SK17, the first two factors describe 75% in the data set, where two distinct planktic  
186 foraminiferal assemblages connect to two modes of ocean conditions related to the nutrient state  
187 of the mixed layer with implications for productivity. The species, dominant on the positive side  
188 of the first factor are *G. ruber*, *P. obliquiloculata*, *G. quadrilobatus* and *G. sacculifer*. These  
189 species are common in nutrient-poor, oligotrophic conditions, mainly in the mixed layer of  
190 highly stratified waters, such as in tropical gyre systems (Bé and Tolderlund, 1971; Ravelo and  
191 Fairbanks, 1992). The species *G. bulloides*, *G. glutinata*, *G. falconensis* and *N. dutertrei*,  
192 dominate on the positive side of Factor 2. These species are common in nutrient-rich, eutrophic  
193 conditions in highly mixed waters, such as tropical upwelling areas and regions of deep vertical  
194 mixing. Therefore, the two planktic foraminiferal assemblages dominant in the first two factors  
195 describe perfectly two contrasting water mass conditions regarding upper water column structure  
196 and nutrient concentration in the tropical Arabian Sea. Distribution patterns of these two  
197 assemblages in core SK 17 reveal monsoon driven periods of alternating oligotrophic and  
198 eutrophic surface waters in the region resulting from changes in the upper water column structure  
199 from a stratified to a mixed surface ocean. Today, seasonal productivity patterns in the eastern  
200 Arabian, particularly north of 10<sup>0</sup> latitude near the location of core SK 17 are governed by the  
201 seasonal winter monsoon winds that induce vertical mixing and sporadic upwelling and summer  
202 monsoon precipitations that induce surface water stratification ( Madhupratap et al., 1996;  
203 Joseph and Freeland, 2005). Therefore, the alternating planktic foraminiferal assemblages,  
204 described by Factors 1 and 2, should reflect oceanic conditions associated with changes mainly  
205 in the intensity of the winter monsoon winds through time (Fig. 3) given the position of core SK  
206 17 in the eastern Arabian Sea.

207

208 *5.2. Changes in water column structure during key periods over the last 30 ka BP*

209

210 The last glacial period 17.5 - 23.5 ka BP

211

212 High abundance of the eutrophic species assemblage (*G. bulloides*, *G. glutinata*, *G.*  
213 *falconensis*, *N. dutertrei*), described by the Factor 2, in the period 17.5 - 23.5 ka BP (Fig. 3),  
214 suggests not only nutrient-rich conditions in the surface mixed layer but also in the thermocline,  
215 where adult populations of *N. dutertrei* reside. Presence of this assemblage strongly indicates

216 periods of high productivity associated with nutrient supply to surface waters either due to deep  
217 vertical mixing or upwelling or a combination of both, which is further corroborated by the  
218 remarkably low SST based on Mg/Ca ratios in shells of *G. bulloides* (Anand et al., 2008) and  
219 high C<sub>org</sub> content (Singh et al., 2006)[Fig. 3]. Heavier  $\delta^{15}\text{N}$  values during this interval also  
220 suggest high productivity conditions coupled with sluggish eastern boundary circulation and  
221 denitrification (Fig. 4) (Naqvi et al., 1998; Ivanochko et al., 2005). The combined set of data  
222 supports the notion that strengthened winter monsoon winds caused intense vertical mixing (eg.  
223 Emeis et al., 1995) leading to nutrient –rich subsurface water into the photic zone, which in turn  
224 fueled high productivity between 17.5 and 23.5 ka BP. Moreover, upwelling may have also been  
225 enhanced during this interval. Today, the convective vertical mixing is the dominant driver of  
226 eutrophic conditions in winter monsoon season, and it was probably the main driver in the glacial  
227 period; but possibility of somewhat enhanced upwelling cannot be ruled out. At this stage,  
228 however, it is difficult to separate the two physical processes resulting in eutrophic conditions.  
229 This finding is in line with earlier publications (eg. Rostek et al., 1997; Ivanova et al., 2003;  
230 Singh et al., 2011; Cabarcos et al., 2014). ). It is intriguing to note that within the period 17.5 -  
231 23.5 ka BP, *G. bulloides* concentrations declined for a short spell around 20 - 21 ka BP (Fig. 2).  
232 This decline of *G. bulloides* abundance probably does not indicate a complete loss of  
233 productivity, because concomitant increases in abundances of other nutrient loving species like  
234 *G. glutinata* and *N. dutertrei* occurred. This finding probably suggests that nutrient availability in  
235 surface waters remained relatively high during this period but perhaps subsurface waters,  
236 brought to the surface, were not sufficiently enriched in nutrients for *G. bulloides* populations to  
237 thrive, whilst the other eutrophic species flourished. The process of nutrient injection was  
238 probably related to shallow winter convective mixing rather than upwelling, which generally  
239 brings nutrient from deeper thermocline levels. Interestingly, such subtle changes in the  
240 eutrophic species assemblage seem to support the notion that each species within the assemblage  
241 has a unique response to changes in environmental conditions. Further studies in the modern  
242 ocean will be able to shed more lights in our understanding of planktic foraminiferal responses,  
243 leading to improved interpretation of species abundance records in paleoceanographic  
244 reconstructions.

245

246 Rapid change in hydrographic conditions during the last deglaciation 15 – 17.5 ka BP

247

248         The planktic foraminiferal record of core SK 17 shows major changes during the last  
249 deglaciation commencing around 17.5 ka BP. The abundances of species, indicative of eutrophic  
250 waters (Factor 2), declined rapidly accompanied by concomitant increase in mixed layer  
251 oligotrophic species (Factor 1), implying a change to oligotrophic waters prevailing during the  
252 deglaciation (17.5 - 15 ka BP). This finding suggests a shift from a dominant nutrient-rich  
253 productive environment to one characterized by relatively nutrient-poor stratified surface waters .  
254 The new data are in line with a significant increase in surface temperatures of the mixed layer  
255 (Anand et al., 2008) and lower  $C_{org}$  concentration (Singh et al., 2006), jointly supporting the  
256 notion of low productivity during the deglaciation between 17.5 and 15 ka BP (Figs. 3,4). The  
257 lighter values of  $\delta^{15}N$  during this interval also imply low productivity related to nutrient  
258 depletion in subsurface water, as compared to that of during the LGM (Fig 4). Thus, the changes  
259 in planktic foraminiferal assemblage composition, SST,  $C_{org}$  content and  $\delta^{15}N$  suggest a rapid  
260 change in surface oceanic conditions, probably triggered by a change in strength of winter  
261 monsoon winds around 17.5 ka BP: strong winter monsoon winds were replaced by moderate or  
262 weak winter monsoon winds, reducing nutrient availability in surface waters.

263         The timing of this switch in intensity of winter monsoon winds is synchronous with  
264 Heinrich Event 1 (H1), a cold event in the northern hemisphere, when the large-scale deposition  
265 of ice rafted sediments occurred (Bond and Lotti, 1995). We are confident that the timing of the  
266 winter monsoon weakening around 17.5 ka BP is well constrained by AMS  $^{14}C$ -dates in core SK  
267 17 and matches the timing of H1 within the uncertainties associated with radiocarbon dating.  
268 Reichert et al. (1998) inferred intensified winter northeasterly wind induced convective mixing  
269 in the northern Arabian Sea during this time. In such scenario, productivity would be maintained  
270 during H1, but, in contrast, the planktic foraminiferal record from core SK 17 suggests reduced  
271 productivity. Others suggest that variations in nutrient supply through intermediate waters may  
272 have played a role in this reduction of productivity (e.g. Ziegler et al., 2010). However, this  
273 would still require a mechanism that transfers intermediate waters across the thermocline to the  
274 surface. The SST data from core SK 17 show evidence of a change from cold to warm surface  
275 waters during the time period of H1, confirming a change from deep vertical mixing and/or  
276 upwelling to stratified waters. Thus, although nutrient content of deeper waters may have played

277 some role in productivity changes (Ziegler et al., 2010), strength of winter monsoon winds likely  
278 dropped during H1.

279 Similarly, reduced strength of winter monsoon winds resulting in stratified surface  
280 waters and low productivity conditions during H1, can also be observed in the period 23.5 –  
281 24.5 ka BP (equivalent to the North Atlantic H2), at least in this part of the Arabian Sea. The  
282 reduction in productivity, however, was less prominent than during H1. The coupled cooling in  
283 the northern hemisphere, reduction of productivity and warming of surface waters in the eastern  
284 Arabian Sea occurred repeatedly during Heinrich Events in the glacial period (see also Singh et  
285 al., 2011).

286 In contrast to our conclusion of a more stratified upper water column, low productivity and  
287 weaker winter monsoon winds in the period 15-17.5 ka BP based on foraminifer assemblages,  
288 SST and  $\delta^{15}\text{N}$  records (Fig. 4), Cabarcos et al. (2014) suggested increased productivity and  
289 stronger winter monsoon winds in this period based on coccolith assemblage data in the same  
290 core (Fig.4). Indeed, the coccolith assemblage data (Factor 1, the productivity proxy as defined  
291 by Cabarcos et al., 2014) indicate relatively high productivity in the prolonged period 17.5-10 ka  
292 BP. Thus, the coccolithophore driven productivity remained largely unaffected during the cold  
293 H1 event. A wider discussion on the coupling of low productivity events in the Arabian Sea and  
294 cold events (Heinrich Events) in the northern hemisphere may be useful to speculate why the  
295 coccolith and the foraminifer assemblage results are different. The changes in the planktic  
296 foraminifer assemblage, SST and  $\delta^{15}\text{N}$  records are in concert with northern hemisphere climate  
297 events, not only during H1, but also during H2, and in the period LGM to H1 (Fig. 4). The low  
298 productivity Arabian Sea events are clearly linked with the Heinrich cold periods in the northern  
299 hemisphere. This is not necessarily new, because this pattern of coupling between Arabian Sea  
300 low productivity and northern hemisphere cold climate events has been previously reported using  
301 a wide variety of proxy data series in cores from across the Arabian Sea (Schulz et al., 1998;  
302 Altabet et al., 2002; Ivanochko et al., 2005; Singh et al., 2006, 2011). It is intriguing to note that  
303 a record of changes in dinoflagellate assemblage data, from another deep core offshore Goa  
304 (water depth; 1807 m), suggested also low productivity during H1 (Narale et al., 2015). The  
305 weak response of coccolithophores to millennial-scale climate change as evident in figure 4 is  
306 anomalous. The coccolithophores dwelling in the mixed layer may have a specific response to  
307 nutrient supply (Tarran et al., 1999; Le Mézo et al., 2017). Perhaps coccolithophore abundances

308 and assemblage composition are sensitive to nutrient supply from the continent either by  
309 runoff/river or wind (Patil and Singh, 2013, Cabarcos et al., 2014), much more so than other  
310 primary producers. Furthermore, coccolithophores are also known to be sensitive to salinity and  
311 turbidity of surface waters (McIntyre and Bè, 1967; Baumann et al., 2005). The location of core  
312 SK 17 is close to the coast where large variability in salinity and turbidity occurs. Intriguingly,  
313 the reconstructed  $\delta^{18}\text{O}_w$  values (salinity related) show large swings in the glacial-deglaciation  
314 period (Fig 4), which may have played a role in the abundance changes of the coccolithophores.  
315 Although nutrients, salinity and turbidity may explain the anomalous behavior of  
316 coccolithophores ecology, the precise reason for this remains unclear.

317

### 318 The Holocene surface hydrography

319

320 Low abundances of planktic foraminifera that contribute positively to Factor 2, and  
321 corresponding high abundances of species that contribute positively to Factor 1 in conjunction  
322 with low  $C_{\text{org}}$  content and high Mg/Ca-based SST collectively suggest that a strongly stratified  
323 upper water column prevailed during most of the Holocene except for the last 2.5 ka BP (Fig. 3).  
324 A moderate increase in productivity over the last 2.5 ka BP probably marks the establishment of  
325 modern conditions of weak winter vertical mixing and /or sporadic upwelling, driven by slightly  
326 enhanced northeasterly winter monsoon winds in the eastern Arabian Sea. The coccolithophore  
327 record of Cabarcos et al. (2014) indicates stratified surface water and relatively low productivity  
328 during the Holocene.

329

### 330 *5.3. Abundance variations of G. menardii : implications for changes in thermocline ventilation*

331

332 Deep dwelling planktic foraminifera may reveal thermocline conditions in the eastern  
333 Arabian Sea over the last 30 ka BP. Populations of *G. menardii*, *N. dutertrei*, and *P.*  
334 *obliquiloculata* tend to flourish in areas where a deep chlorophyll maximum occurs (Sexton et al,  
335 2011), although each of these species has adapted to slightly different ecological niches which  
336 are yet to be fully deciphered. Despite this principle limitation, there is agreement that *G.*  
337 *menardii* thrives in thermocline waters associated with the so-called deep chlorophyll maximum

338 where oxygen levels are relatively low and nutrient levels are high (Karstensen et al., 2008;  
339 Sexton et al, 2011).

340 In core SK 17, the abundance pattern of *G. menardii* is broadly similar to that of  
341 *N. dutertrei*, a thermocline, eutrophic species flourishing in upwelling conditions (Fig. 2). During  
342 the periods of monsoon winds induced high surface productivity, upper thermocline waters are  
343 enriched in nutrients and depleted in oxygen, a condition favourable for *G. menardii*. A change  
344 in ventilation conditions of intermediate waters may lead to variation in oxygen levels at lower  
345 thermocline depth, thus affecting *G. menardii* abundance. Hence, *G. menardii* populations in the  
346 eastern Arabian Sea, though primarily governed by the productivity, may have been significantly  
347 influenced by intermediate water ventilation influencing lower thermocline conditions in the  
348 eastern Arabian Sea (Naidu et al., 2014).

349 High concentrations of *G. menardii* between 17.5 and 23.5 ka BP suggest poorly  
350 ventilated thermocline waters, enriched in nutrients (Fig. 2 and Fig. 5). Notably, the abundance  
351 of *G. menardii* declined conspicuously during 15- 17.5 ka BP, but more intriguingly, the *G.*  
352 *menardii* population almost disappeared just after the H1. It appears that these changes are  
353 related to the ventilation history of intermediate waters combined with the productivity  
354 variations. Interestingly, during other North Atlantic cold phases (Younger Dryas and Heinrich 2  
355 Events) *G. menardii* disappeared (Fig. 5). Other evidence for ventilation of the thermocline can  
356 be found in geochemical data. For instance, aragonite concentrations can be very indicative of  
357 changes in the ventilation state of the intermediate waters (Singh, 2007; Naidu et al., 2014). Old  
358 water becomes more corrosive and dissolves aragonite, due to increased CO<sub>2</sub> content that lowers  
359 the pH of the waters. The intervals of *G. menardii* abundance minima correspond very well with  
360 the maxima in aragonite content in the core SK17 (Fig. 5). This finding suggests that *G.*  
361 *menardii* disappeared during phases of enhanced ventilation pointing to periods of repeated  
362 collapses of the oxygen minimum zone. Most likely increased ventilation of the deep waters in  
363 the Arabian Sea during Heinrich events was triggered by world-wide global climate changes.  
364 Jung et al. (2010) showed profound evidence of changes in ventilation state of the intermediate  
365 waters in the western Arabian Sea. They concluded that intensified inflow of Antarctic  
366 Intermediate Water to Arabian Sea probably ventilated the thermocline waters during northern  
367 hemisphere cold phases. Thus, this likely happened in the eastern Arabian Sea in a similar way,  
368 which caused the demise of the *G. menardii* populations. Interestingly, reduction in *G. menardii*

369 populations occurred during the Heinrich events, but complete collapse of these populations  
370 occurred slightly later when the northern hemisphere was still cold, and the populations  
371 recovered again during the warming phase.

372

## 373 **6. Conclusions**

374

375 Variations in the composition of planktic foraminiferal assemblages in core SK 17 from the  
376 eastern Arabian Sea are used to reconstruct changes in upper water column structure over the last  
377 30 ka BP. Down-core variations in faunal records (species abundances, factor loadings) correlate  
378 with fluctuations of  $C_{org}$  % and SST. While strong monsoon winter winds drove deep vertical  
379 mixing and/or moderate upwelling, in the period 17.5 - 23.5 ka BP, high abundance of *G.*  
380 *menardii* during this period suggests that thermocline waters were poorly ventilated.

381 At 17.5 ka BP, a rapid decline in productivity and nutrient availability occurred with a  
382 concomitant increase in SST, implying a change towards stratification of surface waters and  
383 reduced winter monsoon winds. The *G. menardii* abundance record supports the notion that the  
384 upper thermocline waters became ventilated during this period, but ventilation improved further  
385 between 15 and 17.5 ka BP. These changes are synchronous with northern hemisphere climate  
386 changes. Notably, the reduction in winter monsoon intensity, increased SST's, and better  
387 ventilation occurred simultaneously with the onset of Heinrich event (H1), showing climate  
388 connections between the two areas, through wind systems but also through flow regimes of  
389 intermediate waters.

390 The faunal data further suggest a moderate increase in winter wind induced vertical mixing  
391 and/or sporadic upwelling to modern levels since 2.5 ka BP.

392

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394

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398

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