1	Changes in productivity and intermediate circulation in the
2	northern Indian Ocean since the last deglaciation: new
3	insights from benthic foraminiferal Cd/Ca records and
4	benthic assemblage analyses
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17	Abstract. We have measured Cd/Ca ratios of several benthic foraminiferal species and studied benthic
18	foraminiferal assemblages on two cores from the northern Indian Ocean (Arabian Sea and northern Bay of
19	Bengal, BoB), in order to reconstruct variations in intermediate water circulation and paleo-nutrient content
20	since the last deglaciation. Intermediate water Cd_w records estimated from the benthic Cd/Ca reflect past changes
21	in surface productivity and/or intermediate-bottom water ventilation. The benthic foraminiferal assemblages are
22	consistent with the geochemical data. These results suggest that during the last deglaciation, the Heinrich Stadial
23	1 and Younger Dryas (HS1 and YD, respectively) millennial-scale events were marked by a decrease in $\ensuremath{\text{Cd}}_w$
24	values, indicating an enhanced ventilation of intermediate-bottom water masses. During the early Holocene
25	(from 10 to 6 cal kyr BP), benthic foraminiferal assemblages indicate that surface primary productivity was low,
26	resulting in low intermediate water Cd_w at both sites. Then, from ~ 5.2 to 2.4 cal kyr BP, the benthic
27	foraminiferal assemblages indicate meso- to eutrophic intermediate water conditions, which correspond to high
28	surface productivity. This is consistent with a significant increase in the intermediate water Cd_{w} in the
29	southeastern Arabian Sea and the northeastern BoB. The comparison of intermediate water \ensuremath{Cd}_w records with
30	previous reconstructions of past Indian monsoon evolution during the Holocene suggests a direct control of
31	intermediate water Cd_{w} by monsoon-induced changes in upper water stratification and surface primary
32	productivity.
33	
34	1. Introduction
35	During the last deglaciation, a two-step rapid increase in atmospheric CO ₂ occurred during the 18-14.7 and

During the last deglaciation, a two-step rapid increase in atmospheric CO_2 occurred during the 18-14.7 and 12.8-11.7 cal kyr BP time intervals (e.g., Monnin et al., 2001). Several studies suggest that variations in the Southern Ocean circulation contributed to these increases in atmospheric CO_2 by transferring deep ocean carbon to the upper ocean and atmosphere, through enhanced upwelling and increased northward penetration of the Antarctic Intermediate Water (AAIW) in all ocean basins (e.g., Marchitto et al., 2007; Anderson et al., 2009;

40 Skinner et al., 2014). Different proxies have been used to reconstruct past changes in intermediate circulation,

such as radiocarbon activity (Δ^{14} C) (e.g., Marchitto et al., 2007; Bryan et al., 2010), benthic δ^{13} C (e.g., Pahnke and Zahn, 2005; Jung et al., 2009; Ma et al., 2019), foraminiferal ε_{Nd} (e.g., Pahnke et al., 2008; Xie et al., 2012;

- 43 Yu et al., 2018) and benthic foraminifera Sr/Ca (Ma et al., 2020). These studies have focused on the close
- 44 relationship between enhanced ventilation in the Southern Ocean and rising atmospheric CO₂ during the last
- 45 deglaciation period. Furthermore, it has been shown that glacial-interglacial transfer of CO_2 between the oceans
- 46 and the atmosphere could also be linked to changes in the efficiency of the oceanic biological pump (Pichevin et
- 47 al., 2009; Ziegler et al., 2013; Bauska et al., 2016; Hertzberg et al., 2016; Jaccard et al., 2016; Yu et al., 2019),
- 48 which may contribute up to half of the observed CO_2 flux (Kohfeld, 2005).
- 49 The oceanic biological pump and nutrient upwelling are at least partly controlled by intermediate-deep water 50 circulation, contributing to the observed CO₂ changes (e.g., Toggweiler, 1999; Marchitto and Broecker, 2006). 51 To track past changes in the nutrient concentration of intermediate water masses, benthic foraminifera Cd/Ca has 52 been used in many recent studies (e.g., Came et al., 2008; Poggemann et al., 2017; Valley et al., 2017; Umling et 53 al., 2018); indeed, the benthic foraminifera Cd/Ca is a robust proxy of seawater cadmium concentrations (Cd_w) 54 (Boyle, 1988; 1992), which shows a positive linear correlation with labile nutrients (phosphate and nitrate) in the 55 modern ocean (e.g., Boyle et al., 1976; Boyle, 1988; Elderfield and Rickaby, 2000). The benthic foraminifera 56 incorporate Cd as a function of Cd_w with a species-dependent partition coefficient (e.g., Tachikawa and 57 Elderfield, 2002). Thus, the Cd measured in the fossil tests reflects the paleo-nutrient concentrations of the 58 surrounding water masses, and can be used to investigate past changes in intermediate-to-deep ocean properties 59 (e.g., Boyle and Keigwin, 1982; Oppo and Fairbanks, 1987; Came et al., 2008; Poggemann et al., 2017; Valley et 60 al., 2017; Umling et al., 2018).
- 61 Complementary to the geochemical proxies, the type of benthic foraminifers and their abundance, both of 62 which are related to organic flux and ecosystem oxygenation, make benthic foraminifer assemblages a powerful 63 proxy for estimating past variations in bottom water conditions (e.g., Corliss et al., 1986; Schmiedl et al., 1998; 64 Almogi-Labin et al., 2000) in conjunction with organic matter fluxes to the seafloor (e.g., Altenbach et al., 1999; 65 Van der Zwaan et al., 1999; Fontanier et al., 2002; Caulle et al., 2015). Benthic foraminifera have been 66 successfully used as indicators of surface productivity, especially in high carbon flux regions (Schnitker, 1994). 67 By comparing past benthic foraminiferal assemblages to modern ones, changes in food supply and oxygen 68 concentrations of the bottom water can be reconstructed (e.g., Corliss, 1979; Peterson, 1984; Murgese and De 69 Deckker, 2005). Recently, the combining of benthic foraminiferal assemblages and geochemical proxies has 70 received increasing attention and have been used to reconstruct the evolution of surface productivity and 71 upwelling intensity in the Indian Ocean (e.g., Hermelin 1991, 1992; Hermelin and Shimmield, 1995; Den Dulk 72 et al., 1998; Murgese and De Deckker, 2005).
- The Arabian Sea is one of the most productive regions of the ocean today (Banse, 1987; Marra and Barber, 2005). Surface productivity is dominated by the monsoon system, which has a strong impact on the distribution and dynamics of stratification and vertical mixing (Lévy et al., 2007). Numerous studies have focused on the reconstruction of the paleo-productivity of the Arabian Sea in relation to past changes in monsoon intensity (e.g., Prell and Kutzbach, 1987; Naidu and Malmgren, 1996; Gupta et al., 2003; Singh et al., 2006; 2011; Bassinot et al., 2011; Saraswat et al., 2014). By contrast, little is known about the paleoproductivity of the BoB, especially
- 79 its links to changes in monsoon precipitation (Phillips et al., 2014; Zhou et al., 2020). Consequently, studying
- 80 paleoproductivity and past nutrient concentration of intermediate water masses in the northeastern Indian Ocean

81 will also allow us to completely understand the influence of monsoon climate changes in tropical ocean ecology 82 at different timescales. Besides, as the benthic foraminiferal Cd/Ca is a promising proxy to reconstruct the 83 intermediate-deep water nutrient content (e.g., Boyle and Keigwin, 1982; Tachikawa and Elderfield, 2002; Came 84 et al., 2008; Poggemann et al., 2017; Valley et al., 2017), most of the studies referred to above have 85 reconstructed deep-intermediate water masses in the past (e.g., Came et al., 2008; Bryan and Marchitto, 2010; 86 Poggemann et al., 2017; Valley et al., 2017), and only few works indicate the relationship between the 87 intermediate water masses nutrient and surface productivity (Bostock et al., 2010; Olsen et al., 2016). 88 Furthermore, the evolution of the nutrient content of intermediate water masses since the last deglaciation has 89 never been reconstructed in the Indian Ocean, where only two low-resolution Cd/Ca records are available for 90 deep-water depths (Boyle et al., 1995), and, to our knowledge, none are available for intermediate water depths.

91 In this study, we provide, for the first time, two benthic foraminifera Cd/Ca records at intermediate water 92 depths in the northern Indian Ocean (Arabian Sea and northern Bay of Bengal). These data make it possible to 93 estimate past changes in the nutrient content since the last deglaciation. We have also investigated benthic 94 foraminiferal assemblages obtained from core MD77-191 (southeastern Arabian Sea) to help us reconstructing 95 the conditions at the seafloor. Combined with planktonic foraminiferal δ^{18} O, benthic δ^{13} C, and Cd/Ca records 96 obtained from the same core, as well as with results already published in the Bay of Bengal (Ma et al., 2019; 97 2020), this study aims to document past variations in intermediate- and deep-water conditions and to decipher 98 their links with surface paleo-productivity and intermediate water ventilation.

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100 2. Material and modern hydrological setting

We analyzed sediment core MD77-191 (07°30'N-76°43'E, 1254m) located in the Arabian Sea (off the southern tip of India), and core MD77-176 (14°30'5N-93°07'6E, 1375m) retrieved in the northeastern Bay of Bengal (BoB). These cores were collected in 1977 during the OSIRIS III cruise of the French N/O Marion Dufresne (Fig. 1).

The age model of core MD77-191 was established by using accelerator mass spectrometry (AMS) ¹⁴C dates obtained on 9 monospecific samples of planktonic foraminifera *Globigerinoides bulloides* (Bassinot et al., 2011), one sample of pteropods (Ml éneck, 1997), and three samples of the planktonic foraminifera *Globigerinoides ruber* (Ma et al., 2020). The average sedimentation rate of core MD77-191 is about 53 cm/kyr and up to 90 cm/kyr during the Holocene, providing a high-resolution, continuous record since 17 cal kyr BP.

The age model of core MD77-176 was previously established by using 31 planktonic foraminifer (*G. ruber*)
 AMS ¹⁴C dates combined with the core MD77-176 oxygen isotope record obtained on planktonic foraminifera *G.*

113 *ruber*, which were correlated to the GISP2 Greenland ice core record (Marzin et al., 2013). Core MD77-176

displays high accumulation rates (average ~25 cm.kyr⁻¹ and up to 40 cm.kyr⁻¹ during the Holocene).

In the modern ocean, the surface waters of the Arabian Sea and BoB are characterized by seasonally reversing currents that are driven by the monsoon winds (Fig1.a). The surface water masses shallower than 150 m in the Arabian Sea are mainly Arabian Sea High Salinity Water (ASHS, 36.5 psu) (Talley et al., 2011). In the BoB, the surface waters above 100 m are designated Bay of Bengal surface waters (BoBSW), which have a low salinity (31 psu) due to large river inputs (Talley et al., 2011). Today, the northward extension of AAIW in the Indian Ocean rarely reaches beyond 10 °S (Lynch-Stieglitz et al., 1994). The sites of cores MD77-191 and MD77-176 are mainly bathed, therefore, by the North Indian Intermediate Water (Olson et al., 1993; Reid, 2003) with a
potential contribution from the Red Sea Outflow Water (RSOW) for the site MD77-191 (Beal et al., 2000).
Between 1500 and 3800m, the dominant deep water in the North Indian Ocean is Indian Deep Water (IDW),
originating from the Circumpolar Deep Water and North Atlantic Deep Water (NADW) (Talley et al., 2011).

125 As far as surface waters are concerned, during the summer monsoon, the clockwise circulation in the 126 Arabian Sea drives high salinity waters from the northern to the southeastern Arabian Sea. By contrast, during 127 the winter monsoon, the northeastern winds bring low salinity water (BoBSW) from the BoB. The northern 128 Indian Ocean, especially the Arabian Sea, is characterized by highly variable seasonal productivity (Shankar et 129 al., 2002). Southwest winds during the summer season induce a strong Ekman pumping resulting in very active 130 upwelling along the western coasts of the Arabian Sea and thus promoting strong surface productivity (Shankar 131 et al., 2002; Fig. S1). By contrast, the surface productivity in the BoB is generally weak compared with the 132 Arabian Sea (e.g., Prasanna Kumar et al., 2001; Thushara and Vinayachandran, 2016; O'Malley, 2017; Fig. S1). 133 In the BoB, large river inputs of fresh water and direct monsoon precipitation lead to more stable stratification in 134 the upper ocean (Vinayachandran et al., 2002), and hence the vertical mixing of nutrients from the subsurface to 135 the euphotic zone is generally limited (Gomes et al., 2000). However, the primary productivity of the western 136 BoB shows a slight increase during the winter monsoon, as indicated by the distribution of chlorophyll in the 137 surface water (Thushara and Vinayachandran, 2016; O'Malley, 2017; Fig. S1).

Modern data indicate that the southern-sourced intermediate water (AAIW) in the Indian Ocean has a phosphate concentration of about 2-2.5 µmol/kg (Figs. 1b and c). In the Northern Intermediate Indian Ocean, the phosphate concentration is significantly higher, ranging from 2.75 to 3 µmol/kg in the Arabian Sea during the summer monsoon, and from 2.5 to 2.75 µmol/kg in the BoB during the winter monsoon (Figs. 1b and c). The higher phosphate in the northern Indian Ocean can been linked to primary productivity (Banse, 1987; Marra and Barber, 2005).

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145 **3. Methods**

146 **3.1. Cd/Ca analysis** 147

In order to improve understanding of possible species level differences and microhabitat effects on the benthic Cd/Ca records, we analyzed Cd/Ca in three calcite (*Cibicidoides pachyderma, Uvigerina peregrina*, and *Globobulimina* spp.) and one aragonite (*Hoeglundina elegans*) benthic foraminiferal species from core MD77-191. *C. pachyderma* is a shallow infaunal species, *U. peregrina* and *Globobulimina* spp. are endobenthic species with intermediate and deep microhabitats, respectively (Fontanier et al., 2002). In core MD77-176, due to the limitation of calcitic species, we only measured Cd/Ca ratios in *H. elegans* shells.

Each sample contained between 10 and 15 individuals picked from the 250-315μm size fraction. Samples
were gently crushed, cleaned to remove clays, organic matter and elemental oxides by using reductive and
oxidative cleaning following previously published methods (Boyle and Keigwin, 1982; Barker et al., 2003).
Each sample was dissolved in 0.075N HNO₃ and analyzed using a single collector sector field high resolution
inductively coupled plasma mass spectrometer (HR-ICP-MS) Thermo Element XR hosted at the GEOPS
Laboratory (University Paris-Saclay, France).

160 The detailed instrumental settings and mother standard solutions are described in Ma et al., (2020). A blank 161 consisting of the same 0.1N HNO₃ used to dilute the standards and samples was also analyzed. We removed the blank intensity values from all the raw intensities (including standards), and raw data were linearly driftcorrected by interspersing a drift standard every four samples. Standard curves were used to calculate elemental concentrations, coefficients of determination (r^2) always being >0.9999 for all elemental ratios. The mean reproducibility and accuracy are 3.6% and 7.5%, respectively.

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167 **3.2 Faunal analysis**168

169 Benthic foraminiferal assemblages from core MD77-176 have already been published in Ma et al. (2019). For 170 core MD77-191, a total of 72 samples were collected for benthic foraminiferal assemblage determinations. In 171 each sample, benthic foraminifera (>150µm) were extracted, counted and identified to species level following 172 the taxonomical descriptions of various authors (e.g., Loeblich and Tappan, 1988; Jones, 1994; Holbourn et al., 173 2013). For core MD77-191, there is no material left in this old, low diameter core and so we used samples 174 obtained earlier for stable isotope studies. Since the bulk weights of these samples were not recorded prior to 175 sieving, we could not perform the calculation of absolute abundance of foraminifera or accumulation rates. Thus, 176 we only converted the individual counts to percentages with respect to the total benthic foraminifera present in 177 each sample. In order to describe major faunal variations, we performed principal component analysis (PCA) on 178 the variance-covariance matrix using the PAST software (Version 3.0, Hammer et al., 2001). Species present 179 with a percentage >1% in at least 1 sample were used for statistical analysis and diversity calculation.

180

181 **4. Results** 182

1834.1. Elemental ratios results184

185 To check the influence of oxide contaminants on the elemental ratios, Mn/Ca was systematically measured. 186 The Mn/Ca of H. elegans from cores MD77-191 and MD77-176 ranges between 6.5-10 µmol/mol and 1-30 187 µmol/mol, respectively. Such ranges are much lower than the 100 µmol/mol limit proposed by Boyle (1983). 188 The Mn/Ca obtained on the three calcite benthic foraminifera species from core MD77-191 - C. pachyderma (5-189 18 µmol/mol), U. peregrina (3-23 µmol/mol) and Globobulimina spp. (4-69 µmol/mol) - are also all below 100 190 µmol/mol (Boyle, 1983). The Fe/Ca ratios are also lower than 1 mmol/mol in all samples from cores MD77-191 191 and MD77-176, in agreement with the limit proposed by Barker et al. (2003). In addition, Barker et al. (2003) 192 concluded that no significant pollution by clay minerals would be expected when Al/Ca is <0.5 mmol/mol. In all 193 our samples, Al/Ca is below 0.5 mmol/mol, indicating that the sample cleaning procedure was efficient.

All of the above results indicate that our samples were not affected by contamination.

196 **4.1.1 Cd/Ca** 197

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The Cd/Ca records of *C. pachyderma*, *U. peregrina* and *Globobulimina* spp. from core MD77-191 range
between 0.07-0.2 μmol/mol, 0.07-0.14 μmol/mol and 0.03-0.09 μmol/mol, respectively (Fig. 2d; supplementary
Table S1).

The Cd/Ca records for the calcite benthic species *C. pachyderma* and *U. peregrina* have very low time resolutions during the last deglaciation. However, some common patterns can be observed. The Cd/Ca records of *C. pachyderma* and *U. peregrina* show lower values during the Heinrich stadial 1 (HS1, 17-15.2 cal kyr BP) and Younger Dryas (YD, 13-11 cal kyr BP) cold periods, with average values of ~0.08 µmol/mol for *C. pachyderma*

- and ~0.09 µmol/mol for *U. peregrina*. By contrast, these two species display higher Cd/Ca ratios (~0.12 µmol/mol) during the Bølling-Aller ød warm period (B-A, 15-13.3 cal kyr BP) compared with the HS1 and YD.
- 207 Then, lower values (~0.1 µmol/mol for *C. pachyderma*; 0.11 µmol/mol for *U. peregrina*) are observed during the
- 208 early Holocene (10-5 cal kyr BP) compared to larger variations occurring in the late Holocene (5.2-2.4 cal kyr
- 209 BP). The Cd/Ca record of deep infaunal *Globobulimina* spp., obtained at a lower time resolution, shows different
- 210 variations compared with the two other taxa without any clear trend during the Holocene.
- The *H. elegans* Cd/Ca values of core MD77-191 range from 0.05 to 0.31 μ mol/mol since 17 cal kyr BP (Fig. 2d; supplementary Table S1). Depleted values at about 0.07 μ mol/mol are recorded from the last deglaciation to the early Holocene (17-5 cal kyr BP time interval). During the HS1 and the YD time intervals, a significant decrease of about ~0.06 μ mol/mol occurred (even when taking into consideration the analytical error bar of ± 0.02 , 2σ), and a slight increase (0.09 μ mol/mol) is observed between 15 and 13.3 cal kyr BP (B-A period). A rapid increase in the Cd/Ca values beginning at 5.2 cal kyr BP reaches a maximum (0.31 μ mol/mol) during the late Holocene.
- For core MD77-176, the *H. elegans* Cd/Ca records range between 0.06 and 0.17 μ mol/mol over the past 18 cal kyr BP (Fig. 2e; supplementary Table S1), without no clear trends and average benthic Cd/Ca values of ~0.09 μ mol/mol during the different periods (HS1, YD and Holocene). However, the benthic Cd/Ca record during the Holocene seems to exhibit a slight increase both in value and range of variations after 6 cal kyr BP.
- 222
- 223 4.2. Foraminifera assemblages of core MD77-191
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225 Benthic foraminiferal species richness ranges between 16 and 36, and the total abundance fluctuates between 226 82 and 642 specimens (supplementary Table S2). Hyaline species are the dominant constituents (>80%), and 227 mainly consist of Bulimina aculeata, H. elegans, C. pachyderma, Uvigerina spp., Gyroidina broeckhiana, 228 Globocassidulina subglobosa, Sphaeroidina bulloides, Gyroidinoides spp., Lenticulina spp., Melonis 229 barleeanum, and Globobulimina spp. (including Praeglobobulimina spp.) (in decreasing order of relative 230 average abundance). Agglutinated taxa reach on average about 1.6%, and consist of Textularia sp., 231 Martinottiella communis, and Eggerella bradyi. The average percentage of porcelaneous species, characterized 232 by Pyrgo elongata, Pyrgo murrhina, Pyrgo depressa, Pyrgoella irregularis, Quinqueloculina spp., Sigmoilopsis 233 schlumbergeri, and Spiroloculina spp., is about 5.1%.

Furthermore, we merged species that share an ecological similarity, such as *Globobulimina affinis*, *Globobulimina pacifica*, and *Praeglobobulimina* spp. into *Globobulimina* spp. A total of 74 samples and 55 groups/species were adopted to perform principal component analysis (PCA) in order to identify major faunal trends. The PCA analysis suggests that the benthic foraminifera could be grouped into three assemblages, and represent about 61% of the total variance (Table 1).

The combination of *Bulimina aculeata* and *C. pachyderma*, together with *Pullenia bulloides* and *Ehrenbergina trigona* (Figs. 3 and S2), display high positive PC1 loadings. This assemblage, referred hereafter as assemblage 1, dominated the foraminiferal record during the late Holocene (between 6 and 1.4 cal kyr BP). By contrast, *H. elegans* and *Bulimina manginata* exhibit high negative PC1 loadings, and dominate assemblage 2, which corresponds to the record during the early Holocene (Figs. 3 and S2). Other quantitatively important contributors are *C. wuellerstorfi* and *Globocassidulina subglobosa* (Fig. S2). 245 The total variance of PC2 is 19%; for the positive loadings of PC2, Sphaeroidina bulloides and Gyroidinoides 246 orbicularis dominate assemblage 3, which is more important during the last deglaciation (Figs. 3 and S2). The 247 main associated species of assemblage 3 are Bulimina mexicana and Gyroidinoides soldanii (Fig. S2). However, 248 the main species from negative loadings consist of Bulimina aculeata, H. elegans and C. pachyderma, which 249 dominated the Holocene. The main composition of PC2 negative loadings is dominated by the same benthic 250 species as assemblages 1 and 2, which, as we have seen above, correspond to the Holocene; it is difficult, 251 therefore, to glean any additional information from this regarding bottom conditions. For this reason we only 252 recognize three assemblages in this paper.

253

254 **5.** Discussion

5.1. Past intermediate water Cd_w concentrations from the Northern Indian Ocean

In the modern ocean, benthic foraminifera Cd/Ca shows a positive correlation with Cd_w and dissolved nutrients (phosphate and nitrate) (Boyle et al., 1976; Hester and Boyle, 1982). As aragonitic benthic foraminifera *H. elegans* faithfully records the bottom water Cd concentrations (Cd_w), Cd/Ca ratios can be converted to seawater Cd_w with the appropriate relationship (Eq.1), where the partition coefficient $D_p \approx 1$ for all water depths (Boyle et al., 1995; Bryan and Marchitto, 2010).

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 $Dp = \frac{(Cd/Ca)_{foram}}{(Cd/Ca)_{water}}$ (Eq.1)

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In contrast, the partition coefficient for calcite species changes with water depth. For water depths between 1150-3000 m, D_p was calculated based on the equation of Boyle, (1992; Eq. 2). The seawater Ca concentration is assumed to be at a constant, mean value of 0.01 mol/kg (Boyle, 1992).

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 $D_p = 1.3 + (\text{depth} - 1150) \times (1.6/1850)$ (Eq.2)

271 The intermediate Cd_w results based on the *H. elegans* Cd/Ca values of core MD77-191, range from 0.5 to 3.1 272 nmol/kg since 17 cal kyr BP (Fig. 4a), with a core top value of 0.80 nmol/kg in agreement with the estimated 273 intermediate water depth modern Cdw (~0.83 nmol/kg) in the northern Indian Ocean (Boyle et al., 1995). The 274 intermediate Cd_w was also calculated from calcite benthic species C. pachyderma, U. peregrina and 275 Globobulimina spp. from core MD77-191, with values ranging between 0.53-1.48 µmol/mol, 0.52-1.04 276 µmol/mol and 0.26-0.65 µmol/mol, respectively (Fig. 4a). The Cd_w values of C. pachyderma and U. peregrina 277 are within the same range. However, the H. elegans Cdw values are higher than those from the two calcite 278 species, especially during the Late Holocene. Moreover, the core top data of C. pachyderma and U. peregrina 279 are also lower (~ 0.7 and 0.69 nmol/kg, respectively) than the modern estimated Cdw data (~ 0.83 nmol/kg) in the 280 northern Indian Ocean (Boyle et al., 1995) (Fig. 4a). These depleted Cd_w values may be related to the benthic 281 foraminiferal microhabitat effect; indeed, U. peregrina is known to be strictly a shallow infaunal species, as well 282 as C. pachyderma (Fontanier et al., 2002), differing from strictly epifaunal taxa, such as Cibicidoides 283 wuellerstorfi (Mackensen et al., 1993).

284 Besides, the deep infaunal *Globobulimina* spp. Cd_w displays relatively much lower values and does not

- exhibit strong variations compared to the other species investigated in this study, displaying a general increasing trend from the last deglaciation to the Holocene. As *Globobulimina* spp. correspond to deep benthic infaunal species, this result may indicate a stable nutrient content of pore water, as compared to other benthic taxa associated with bottom water (Fig. 4a). Thus, when tracking past changes in the bottom water Cd_w concentrations, the use of a strictly epifaunal species living at the water-sediment interface such as *H. elegans* appears to be more robust than using endofaunal species that live in contact with pore water.
- Relative variations in the Cd_w obtained from *C. pachyderma* and *U. peregrina* are in good agreement with the records obtained on *H. elegans*. Variations of *H. elegans* Cd_w during the last deglaciation indicate a decrease of about ~0.6 nmol/kg in the HS1 and YD periods, with a slight increase (0.9 nmol/kg) during the warm B-A. Cd_w results from core MD77-191 indicate a shift from the last deglaciation (~0.7 nmol/kg) to the late Holocene (~1.59 nmol/kg). During the Holocene, the Cd_w records display relatively low values of around 0.9 nmol/kg in the 10-6 cal kyr BP time interval, and show a major shift at around 6.4 cal kyr BP with values rising up to 3.1 nmol/kg.
- For core MD77-176, the intermediate water Cd_w calculated from the *H. elegans* Cd/Ca records ranges between 0.6 and 1.7 nmol/kg over the past 18 cal kyr BP (Fig. 4b). Compared with intermediate Cd_w from MD77-191, the Cd_w record of core MD77-176 does not display any clear trend from the last deglaciation to the Holocene. However, a slight increase is observed since 6 cal kyr BP, in agreement with the MD77-191 intermediate Cd_w records. In addition, even though the MD77-176 record has a lower time resolution, it displays a shorter maximum (1.3 nmol/kg) during the 13.4-11 cal kyr BP time interval.
- To summarize, among the three calcite benthic taxa and the aragonitic benthic species *H. elegans*, the Cd/Ca records of *H. elegans* appear to be the most suitable for tracking past Cd_w changes at intermediate water depth through time. Thus, in the following discussion, we will only focus on the intermediate Cd_w calculated from the *H. elegans* Cd/Ca from both studied cores.
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3095.2. Comparison between geochemical records and benthic foraminiferal assemblages310

311 Comparing the geochemical records to the benthic assemblages, we can observe similar patterns. For core 312 MD77-191 from the southeastern Arabian Sea, three benthic assemblages were identified since the last 313 deglaciation. S. bulloides and Gyroidinoides orbicularis are major components of assemblage 3 (during the last 314 deglaciation), together with B. mexicana and Gyroidinoides soldanii (Figs. 3 and S2). S. bulloides and B. 315 mexicana are found in intermediate to high organic carbon flux rate regions (e.g., Schmiedl et al., 2000; 316 Eberwein and Mackensen, 2006, 2008), while G. orbicularis and G. soldanii are associated with well-317 oxygenated and oligotrophic environments (Peterson, 1984; Burmistrova and Belyaeva, 2006; De and Gupta, 318 2010). Thus, assemblage 3 reflects mesotrophic environments and/or well-ventilated conditions during the last 319 deglaciation. Although millennial-scale changes in the benthic foraminiferal assemblages during the last 320 deglaciation could not be observed, benthic fauna 3 seems at least partly consistent with previous studies in the 321 northern Indian Ocean based on multiple geochemical proxies (e.g., benthic δ^{13} C, intermediate water [CO₃²⁻] and 322 $\varepsilon_{\rm Nd}$ records); these studies have revealed the presence of better-ventilated waters, which might correspond to 323 AAIW, during the HS1 and YD (e.g., Yu et al., 2018; Ma et al., 2019; 2020).

Benthic foraminiferal assemblage 2 predominates during the early Holocene and is characterized by *H*. *elegans* and *B. manginata* as major contributors (Figs. 3 and S2). The other important contributors are *C*. 326 wuellerstorfi and G. subglobosa. B. manginata is found in high organic carbon flux rate conditions (De Rijk et 327 al., 2000; Eberwein and Mackensen, 2006, 2008). However, previous studies on H. elegans, C. wuellerstorfi and 328 G. subglobsa indicate that these species correspond to high levels of dissolved oxygen and oligotrophic settings 329 (e.g., Altenbach et al., 1999; Fontanier et al., 2002; Murgese and De Deckker, 2005, 2007; De and Gupta, 2010). 330 Periods dominated by these taxa probably indicate high oxygen levels and an oligotrophic environment. 331 Additionally, glacial to Holocene benthic δ^{13} C shifts (0.35-0.4‰, vs. PDB) at intermediate-deep water depth in 332 the northern Indian Ocean are interpreted as reflecting an increased contribution of better-ventilated deep water 333 NADW, during the Holocene (e.g., Naqvi et al., 1994; Ma et al., 2019) (Fig. S3). Futhermore, the increased B-P 334 age offsets and depleted ε_{Nd} records obtained from the same core site could reflect the enhanced influence of 335 NADW during the Holocene, which is characterized by the well-ventilated and depleted nutrient (modern 336 Cd_w, ~0.2 nmol/kg) (Poggemann et al., 2017; Yu et al., 2018; Ma et al., 2019). Although the intermediate 337 benthic δ^{13} C record from core MD77-191 is missing for the LGM, the average value for the Holocene (~0.31‰, 338 vs. PDB) is consistent with previous studies carried out in the northern Indian Ocean; combined with the 339 opposite trend between $\delta^{18}O_{ivc}$ records and intermediate water temperature from MD77-191 (Ma et al., 2020), all 340 these records suggest well-ventilated conditions (Fig. S3). The predominance of Benthic foraminifera assemblage 2 in the early Holocene seems be in agreement with the higher values of benthic $\delta^{13}C$, reflecting 341 342 better-ventilated water masses, associated with NADW, at the core site.

- 343 By contrast, B. aculeata and C. pachyderma are major components of assemblage 1 (during the late Holocene), 344 together with P. bulloides and E. trigona (Figs. 3 and S2). Living B. aculeata have a widespread distribution, 345 with a preference for water depths ranging from 1500 to 2500m, and are typically associated with high organic 346 carbon fluxes (Mackensen et al., 1995; Almogi-Labin et al., 2000; Caulle et al., 2015). P. bulloides is a shallow 347 infaunal species, which prefers mesotrophic environments and shows adaptability with respect to oxygen 348 concentration in the Arabian Sea (Gupta and Thomas, 1999; Caulle et al., 2015). E. trigona is commonly 349 recorded in low oxygen habitats (Caulle et al., 2015). We thus interpret assemblage 1 as indicating relatively 350 low-oxygen and meso- to eutrophic bottom water conditions during the late Holocene (6-1.4 cal kyr BP). 351 However, the lower oxygen concentrations reflected by benthic fauna 1 seem to be the opposite of what would 352 be expected under an enhanced influence of better ventilated NADW during the Holocene in the northern Indian 353 Ocean. The higher relative abundances of *Globigerina bulloides*, a proxy of upwelling activity, observed in the 354 late Holocene of the same core, MD77-191, suggest increased productivity in the southeastern Arabian Sea 355 (Bassinot et al., 2011) (Fig. 5). This record is synchronous with the benthic foraminiferal assemblage 1 (during 356 the late Holocene). Thus, increased surface productivity during the late Holocene could result in more organic 357 matter in the bottom water, leading to depleted oxygen conditions in bottom water.
- 358 When we compare benthic assemblages 2 and 3 (during the last deglaciation and early Holocene; 17-6 cal kyr 359 BP) to the Assemblage 1 (during the late Holocene), assemblages 2 and 3 indicate that intermediate water 360 masses were characterized by higher bottom water oxygen conditions and a lower flux of organic matter. This is 361 associated with low Globigerina bulloides abundances during the same time interval compared with the late 362 Holocene, suggesting lower productivity in the southeastern Arabian Sea in the period from the last deglaciation 363 to the Holocene (Bassinot et al., 2011) (Fig. 5). Therefore, all of these elements suggest that changes in primary 364 productivity seem to be the main factor impacting on the distribution of benthic assemblages at core MD77-191 365 site, especially during the Holocene, rather than changes in intermediate-water circulation.

- 366 In addition, the total organic carbon (C_{org}) could also be used as a qualitative indicator of past productivity 367 and/or bottom water ventilation changes (Naidu et al., 1992; Canfield, 1994; Calvert et al., 1995; Naik et al., 368 2017). In order to examine the relationships between intermediate Cd_w and these different processes (surface 369 productivity and/or water mass ventilation) since the last deglaciation in the eastern Arabian Sea, we compared 370 the MD77-191 Cd_w values with the relative abundance of G. bulloides and benthic foraminiferal assemblage 371 analyses from the same core MD77-191, together with the records for C_{org} and the G. bulloides percentage 372 obtained from core SK237 GC04 (1245m, southeastern Arabian Sea, Naik et al., 2017) (Fig. 5). Despite a lower 373 resolution for MD77-191 H. elegans Cdw records, when compared to the Corg and the G. bulloides percentage 374 from core SK237 GC04, all of them seem to exhibit similar trends at the long-time scale from the last 375 deglaciation to Holocene; however, some little discrepancies can be observed at millennial time scales, 376 especially during the late Holocene (Fig. 5). In addition, the Cd_w records display a significant shift from the last 377 deglaciation (~ 0.5 nmol/kg) to the late Holocene (~1.59 nmol/kg), and the intermediate Cd_w values are 378 extremely high during the late Holocene. As mentioned before, increased influence of NADW was observed 379 during the Holocene in the northern Indian Ocean (Yu et al., 2018; Ma et al., 2019; 2020). However, NADW is 380 characterized by the depleted nutrient content (modern Cd_w , ~ 0.2 nmol/kg; Poggemann et al., 2017), and thus 381 this should indicate that deep-intermediate water masses variations does not seem to play an important role 382 during the Holocene in this area. Besides, previous studies have suggested that increased Cdw values (>1 383 nmol/kg) could correspond to elevated surface productivity (Bostock et al., 2010; Olsen et al., 2016). Thus, we 384 suggest the intermediate Cd_w at core MD77-191 site may be mainly influenced by surface productivity, 385 especially during the Holocene. Compared with benthic foraminifera fauna analysis from MD77-191 in the 386 Arabian Sea (Figs. 3 and S2), the benthic assemblages of core MD77-176 suggest that the intermediate water 387 masses were characterized by oligotrophic to mesotrophic conditions and/or well-ventilated environments during 388 the Holocene (Ma et al., 2019), associated with much lower surface productivity (Fig. S4). This observation is in 389 agreement with low primary productivity during the Holocene reconstructed by the relative abundance of 390 coccolith species Florisphaera profunda from the same core MD77-176 in the northeastern BoB (Zhou et al., 391 2020). In the modern ocean, Prasanna Kumar et al. (2001) indicate that primary productivity in the BoB is much 392 lower than in the Arabian Sea, the lower surface productivity resulting from the large freshwater input from river 393 and direct rainfall resulting from enhanced Indian Summer Monsoon precipitation (e.g., Vinayachandran et al., 394 2002; Madhupratap et al., 2003; Gauns et al., 2005). Moreover, when we compare the average Cd_w value of core 395 MD77-176 from the BoB (~0.9 nmol/kg) with results from core MD77-191 in the Arabian Sea (~1.2 nmol/kg), 396 lower values, especially during the late Holocene, are in agreement with the benthic assemblages. 397 To sum up, variations in the benthic assemblages seem to be associated with changes in the organic matter
- 398 flux, linked to surface productivity, especially in the Arabian Sea (Schnitker, 1994). The benthic foraminiferal 399 fauna are consistent with the Cd_w record of core MD77-191 particularly during the late Holocene (6-1.4 cal kyr 400 BP). Thus, our results seem to show that the Cd_w record is mainly controlled by changes occurring at the surface, 401 especially during the Holocene. However, at millennial time scales, such during the HS1 and YD, the 402 percentages of planktonic species G. bulloides from cores MD77-191 and SK237 GC04 all indicate modest 403 paleo-productivity, the opposite of what is suggested by the results of core MD77-191 Cdw and Core obtained 404 from core SK237 GC04. This interval is also marked by enriched G. ruber δ^{18} O values, indicating a weaker 405 monsoon and reduced freshwater inputs (Naik et al., 2017). This apparent discrepancy may be related to changes

406 in the intermediate water mass sources and/or ventilation during the last deglaciation. Therefore, we will discuss

- 407 these issues in greater detail below in order to decipher these different processes.
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5.3. Relationships between primary productivity and monsoon intensity

411 During the Holocene, the intermediate Cd_w records obtained from cores MD77-191 and MD77-176 display 412 depleted values in the early Holocene, followed by an abrupt increasing trend at the middle Holocene, and then 413 reach a maximum during the late Holocene.

414 Of the two cores, core MD77-176, located in the northeastern BoB, shows the lowest intermediate Cd_w (down 415 to ~ 0.83 nmol/kg) during the 10-6 cal kyr BP time interval. Observations described above suggest that this low 416 in Cd_w resulted from low primary productivity and thus reduced fluxes of organic matter to the intermediate 417 depths. We attribute this evolution to monsoon variation. The early Holocene Climate Optimum (10-6 cal kyr BP) 418 is characterized by enhanced monsoon precipitation (Marzin et al., 2013; Contreras-Rosales et al., 2014) (Figs. 419 6d-f) that resulted in increased freshwater discharge from the Ganges-Brahmaputra river system and from the 420 Irrawaddy River. However, the distribution of chlorophyll in surface water of the western BoB suggests a low 421 annual productivity, indicating that the BoB is not significantly influenced by the riverine nutrient input (Zhou et 422 al., 2020). Thus, it is likely that this increase in fresh water drove pronounced ocean stratification in the northeast 423 BoB, which could impede the nutrient transfer from deep layer to the euphotic upper seawater column, and then 424 inducing low productivity. A similar low in Cd_w is observed in the reconstructed intermediate water Cd_w record 425 from core MD77-191 during the early Holocene, with values descending to ~ 0.92 nmol/kg, in the 10-6 cal kyr 426 BP time interval. These low values of intermediate Cd_w are coeval with low surface productivity as recorded by 427 the G. bulloides percentage and low values in Corg content from SK237 GC04 in the Arabian Sea. Off the 428 southern tip of India, we cannot reject the possibility that increased monsoon precipitation and enhanced 429 freshwater runoffs in the BoB during the early Holocene, inducing a stronger stratification, could explain part of 430 the decrease in surface primary productivity. Yet, at this site, another explanation prevails which is related to the 431 decrease of summer monsoon wind intensity that drives local Ekman pumping. As shown by Bassinot et al. 432 (2011), the productivity variations at the southern tip of India are inversely related to the evolution of upwelling 433 activity along the Oman Margin, to the west of the Arabian Sea. Based on a data/model comparison, Bassinot et 434 al. (2011) showed that this anti-correlation can be attributed to the northward shift of the ITCZ when boreal 435 summer insolation reached a maximum in the early Holocene (Fig. 6a); this ITCZ location results in enhanced 436 summer monsoon wind intensity and an increase in the associated Ekman pumping in the west of the Arabian 437 Sea, and along the Oman margin, while it weakens at the southern tip of India. This process may thus induce a 438 decrease in surface productivity in the southeastern Arabian Sea. 439 In addition, Naik et al. (2017) pointed out the co-existence of low productivity during the early Holocene in

440 the BoB and to the South of India, in agreement with our data that clearly show the impact of such a reduction of 441 surface primary productivity on the intermediate water Cdw. These authors suggested a direct relationship 442 between intense monsoon rainfall and reduced surface productivity. However, the northeastern BoB received a 443 much larger amount of river input than the southern tip of India during the early Holocene (Marzin et al., 2013). 444 Thus, it seems reasonable to propose that the northeastern BoB is more affected by the salinity-related 445 stratification effect, while the southern tip of India is more affected by the decrease in wind intensity (Bassinot et al., 2011) with enhanced stratification being potentially made stronger by an additional fresh-water effect,
although weaker than in the BoB. Ultimately, both climatic features (summer wind intensity and precipitation)
are directly under the control of monsoon evolution resulting from the orbital forcing of low latitude boreal
summer insolation.

450 By contrast, higher intermediate Cd_w values from core MD77-191 associated with higher G. bulloides relative 451 abundances and Corg from core SK237 GC04 during the 5.2-2.4 cal kyr BP time interval could indicate enhanced 452 productivity during the mid to late Holocene (Naik et al., 2017) (Fig. 5). To a lesser extent, this is also observed 453 in the records from the Northern BoB for the same time-period. These changes are consistent with the weakened 454 summer monsoon intensity, with less rainfall during the late Holocene, as observed in the BoB using core 455 MD77-176 seawater δ¹⁸O and core SO188-342KL δD_{Alk-ic} records (Marzin et al., 2013; Contreras-Rosales et al., 456 2014; Figs. 6e-f). In addition, this is also strongly supported by the $\delta^{13}C_{wax}$ records from the Lonar Lake over the 457 Indian continent (Sarkar et al., 2015; Fig. 6d) and a progressive increase in monsoon summer winds to the South 458 of India (Bassinot et al., 2011). These observations could also strongly support the hypothesis that the major 459 control on surface productivity is linked to monsoon evolution in the BoB and at the southern tip of the Arabian 460 Sea during the Holocene (Bassinot et al., 2011; Naik et al., 2017; Zhou et al., 2020).

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462 5.4. Millennial-scale changes in intermediate water circulation during the deglaciation

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464 During the last deglaciation, short events have been recorded at the site of core MD77-191 during the 16-15.2 465 (HS1) and 12.6-11 cal kyr BP (YD) time intervals (Fig. 5). The low Cd_w values in the MD77-191 record are 466 coeval with reductions of Corg in core SK237 GC04 during the HS1 and YD periods (Fig. 5). According to 467 previous studies, extremely high Cd_w values (>1 nmol/kg) were reported to have been associated with enhanced 468 surface productivity (Bostock et al., 2010; Olsen et al., 2016). However, the range of values of intermediate Cd_w 469 (0.58-0.85 nmol/kg, HS1; 0.5-0.8 nmol/kg, YD) from core MD77-191 during the last deglaciation is much lower 470 compared with the Holocene Cd_w values (>1 nmol/kg), and thus may be associated with other processes such as 471 a better ventilation, changes in the water mass source, and/or depleted surface productivity (Fig. 6). Significant 472 decreases in G. bulloides relative abundance of cores SK237 GC04 (Naik et al., 2017) and MD77-191 records 473 were observed from the HS1 to B-A (Bassinot et al., 2011), and thereafter slight increases occurred in the YD 474 (Fig. 5). These high values at both core sites during the HS1 and YD may indicate an enhanced surface 475 productivity during these intervals (Fig. 5). This should have led to increased intermediate Cd_w and organic 476 matter preservation under low oxygen concentration conditions during the HS1 and YD. However, despite a low 477 resolution for the MD77-191 Cdw record during the last deglaciation, we do not observe high values of 478 intermediate Cd_w during the HS1 and YD (~ 0.6 nmol/kg) compared with the late Holocene (~ 1.59 nmol/kg), 479 especially at 16.5-16 cal kyr BP. Although we cannot fully discard the influence of surface productivity on the 480 intermediate Cd_w in these time intervals, this apparent discrepancy seems to provide another evidence for the 481 influence of changes in water masses and/or ventilation during the HS1 and YD, as already demonstrated by 482 previous studies and proxies in the northern Indian Ocean (Bryan et al., 2010; Yu et al., 2018; Ma et al., 2019; 483 2020).

484 Moreover, an increase in benthic δ^{13} C values is observed during the HS1 and YD in the northern Indian Ocean 485 (e.g., Duplessy et al., 1984; Curry et al., 1988; Naqvi et al., 1994; Jung et al., 2009; Ma et al., 2019). The

- 486 increase in the different benthic δ^{13} C records during the HS1 and YD in the western Arabian Sea, Pacific Ocean
- 487 and BoB is interpreted as reflecting the northward expansion of AAIW (Pahnke and Zahn, 2005; Jung et al.,
 488 2009; Ma et al., 2019). The decreased benthic-planktonic foraminiferal ¹⁴C offset (B-P age) obtained from
- 489 marine sediment cores from the Arabian Sea and the Bay of Bengal during the same intervals could confirm
- 490 enhanced vertical mixing in the Southern Ocean (Bryan et al., 2010; Ma et al., 2019). The transition in the ε_{Nd}
- 491 and Δ^{14} C records during the deglaciation also indicates a strong northward penetration of AAIW within the
- 492 North Atlantic and Bay of Bengal (e.g., Cao et al., 2007; Pahnke et al., 2008; Pena et al., 2013; Yu et al., 2018).
- 493 In addition, during the HS1 and YD, a decrease in the $[CO_3^{2-}]$ record from core MD77-191 also suggests the
- release of CO₂ from the deep ocean in the deglacial period through the expansion of AAIW (Ma et al., 2020).
 These time intervals are associated with better ventilation in the Southern Ocean (e.g., Anderson et al., 2009;
 Skinner et al., 2010), which led to enhanced vertical ventilation resulting in increased production of intermediate
 water masses (AAIW) (Anderson et al., 2009).
- 498 As mentioned before, previous studies have suggested an enhanced northward flow of southern sourced 499 intermediate water mass AAIW both in the Atlantic, Pacific and Indian Oceans during the last deglaciation (e.g., 500 Pahnke et al., 2008; Bryan et al., 2010; Poggemann et al., 2017; Yu et al., 2018; Ma et al., 2019, 2020), 501 indicating that the source of intermediate water masses may be partly the same in these oceans. Thus, as the 502 benthic δ^{13} C values collected from the north Indian Ocean could better constrain the influence of AAIW in the 503 two studied cores (Naqvi et al., 1994; Jung et al., 2009; Ma et al, 2019; 2020), we can also compare the range 504 values of AAIW Cdw from both studied cores with data from Atlantic and Pacific Oceans at intermediate water 505 depth during the HS1 and YD (Cd_w, 0.3-0.9 nmol/kg; Umling et al., 2018; Valley et al., 2017). Unfortunately, 506 the resolution of both intermediate Cd_w and benthic $\delta^{13}C$ from core MD77-176 (northeastern BoB) are very low 507 for the HS1 and YD events, making it difficult to extract reliable information. Thus, we have decided to focus on 508 the results from core MD77-191 (0.5-0.85 nmol/kg) during these two time-intervals; these results are in good 509 agreement with the collected dataset (Fig. 7). Thus, the benthic Cd_w results provide new evidence for tracking 510 the northern flow of AAIW in the northern Indian Ocean, which increased during HS1 and the YD.
- 511 Taken together, Cd_w, B-P age offset, benthic δ^{13} C, ε_{Nd} and Δ^{14} C records reported from the northern Indian 512 Ocean all suggest strong upwelling and enhanced northern flow of AAIW from the Southern Ocean during HS1 513 and the YD. Thus, the variations in these records can provide strong evidence for the hypothesis that Southern 514 Ocean upwelling played a vital role in the increase of atmospheric CO_2 in the deglacial period (Anderson et al., 515 2009; Skinner et al., 2010, 2014). However, Kohfeld et al. (2005) suggested that although physical processes 516 (such as ventilation) are involved in the glacial-interglacial atmospheric CO_2 change, the biological pump may 517 also contribute nearly half of the observed changes of CO₂ during the glacial-interglacial transitions. As shown 518 above, the HS1 event is characterized by reduced surface productivity, as revealed by the lower percentage 519 values of G. bulloides in core MD77-191 (Bassinot et al., 2011) and by several studies of cores located in the 520 eastern and western Arabian Sea within the Oxygen Minimum Zone (e.g., Schulz et al., 1998; Altabet et al., 521 2002; Ivanochko et al., 2005; Singh et al., 2006, 2011; Naik et al., 2017). This reduced productivity at a 522 millennial timescale suggests that the entire biological factory was related to the reduced monsoon intensity 523 during the North Atlantic Heinrich events (e.g., Singh et al., 2011; Naik et al., 2017). Thus, a weaker biological 524 production could also have contributed to the two-step increase of atmospheric CO₂ during the last deglaciation, 525 at least for the HS1 period.

527 6. Conclusions

Changes in benthic foraminiferal Cd/Ca and assemblages were reconstructed on core MD77-191 (1254 m water depth) located off the southern tip of India, as well as on core MD77-176 (1375 m water depth) from the northern BoB, in order to reveal the evolution of intermediate water circulation and paleo-nutrient changes in the northern Indian Ocean since the last deglaciation. We reconstructed seawater Cd_w concentration by converting *H. elegans* Cd/Ca. Benthic Cd/Ca ratios are mainly influenced by changes in surface productivity and intermediatebottom water ventilation.

- 535 Results indicate that assemblages 2 and 3, reflecting high bottom water oxygen conditions and a low flux of 536 organic matter, dominated between 17 and 6 cal kyr BP, corresponding to a poor productivity time-period. The 537 typical late Holocene assemblage indicates a relatively low-oxygen level and meso- to eutrophic deep-water 538 conditions, associated with high surface productivity. The early Holocene (10-6 cal ka BP) corresponds to a low 539 in productivity associated with depleted Cdw in intermediate water. These observations seem to result from 540 enhanced monsoon precipitation and increased river inputs from the Himalayan Rivers, which led to more 541 marked stratification in the BoB and a reduction in primary and export productivity. At the southern tip of India, 542 the decrease in vertical mixing is also associated with a reduction in summer wind forcing resulting from the 543 northward displacement of ITCZ during summer (Bassinot et al., 2011). During the late Holocene (5.2-2.4 cal 544 kyr BP), the increased intermediate Cd_w concentrations of cores MD77-191 and MD77-176 indicate enhanced 545 surface productivity in the southeastern Arabian Sea and in the northeastern BoB, corresponding to weakened 546 monsoon intensity and rainfall, in agreement with other local records and reconstructions of the paleo-monsoon 547 strength. Thus, our results clearly show the strong control of intermediate water Cd_w during the Holocene by 548 orbitally-driven changes in summer monsoon productivity.
- 549 As far as millennial-scale variability is concerned, during the last deglaciation, decreased intermediate Cd_w 550 concentrations during HS1 and the YD are coeval with increased benthic $\delta^{13}C$, depletion in $[CO_3^{2-}]$ and 551 decreased B-P age offsets. These observations indicate that the low Cd_w values in intermediate water mainly 552 resulted from the increased northward flow of AAIW during HS1 and YD intervals. These signals also provide 553 strong evidence for the important role of enhanced Southern Ocean ventilation in the CO₂ increase during the 554 last deglaciation. The declined intermediate Cd_w obtained from southeastern Arabian Sea (Core MD77-191), 555 combined with the published eastern and western Arabian Sea paleo-productivity results, together provide 556 evidence for the important influence of decreased monsoon intensity at a millennial time scale during cold events 557 in the North Atlantic region, associated with the increase in atmospheric CO_2 during the last deglaciation.
- 558
- 559 Data availability
- All data are given in Table 1 and supplementary materials Tables S1-S2.
- 561
- 562 Supplement
- 563 The supplement related to this paper is available online.
- 564

565 Author contribution

566 RM, SS, FB and CC developed the idea and interpreted the results. CC and FB supplied foraminifera samples.

567	RM did benthic foraminifera assemblage and geochemical analyses with the aide of FH and LL. ZY and LL
568	joined the discussion. All co-authors helped to improve the article.
569	
570	Competing interests
571	The authors declare that they have no conflict of interest.
572	
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- 24 -

	Dominant species		Important associated species		Variance (%)
PC1					42
Positive loadings	Bulimina aculeata	0.84	Pullenia bulloides	0.18	
	Cibicidoides pachyderma	0.19	Ehrenbergina trigona	0.13	
Negative loadings	Hoeglundina elegans	-0.14	Cibicidoides wuellerstorfi	-0.04	
	Bulimina manginata	-0.07	Globocassidulina subglobosa	-0.06	
PC2					19
Positive loadings	Sphaeroidina bulloides	0.42	Gyroidinoides orbicularis	0.17	
	Bulimina mexicana	0.11	Gyroidinoides soldanii	0.07	
Negative loadings	Bulimina aculeata	-0.14	Hoeglundina elegans	-0.62	
- 0	Cibicidoides pachyderma	-0.07			

Table 1. Species composition of benthic foraminiferal assemblages from core MD77-191.



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890 Fig. 1. (a) Oceanographic setting and locations of core MD77-191 in the Arabian Sea (red star), core MD77-176 891 in the Bay of Bengal (red star) and reference site SK237 GC04 (red circle, Naik et al., 2017). The black arrows 892 represent the general surface circulation direction in the Northern Indian Ocean during the summer, Southwest 893 Monsoon (Schott and McCreary, 2001). (b) and (c) Phosphate distribution along depth-latitude sections during 894 the Southwest Monsoon and Northeast Monsoon periods, for the Arabian Sea and the Bay of Bengal, 895 respectively. Data (in µmol/kg, colored scale) were contoured and plotted using the Ocean Data View (ODV) 896 software (Schlitzer, 2015). On these two figures are shown the distribution and circulation of water masses in the 897 Arabian Sea and Bay of Bengal (black arrows). ASHS: Arabian Sea High Salinity Water, EIOW: Eastern Indian 898 Ocean Water, BoBSW: Bay of Bengal surface waters, AAIW: Antarctic Intermediate Water, RSOW: Red Sea 899 Overflow Water, AABW: Antarctic Bottom Water, IDW: Indian Deep Water.



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Fig. 2. (a) GISP2 Greenland ice core δ^{18} O signal (Stuiver and Grootes, 2000). (b)-(c) *Globigerinoides ruber* δ^{18} O records of cores MD77-191and MD77-176, respectively (Marzin et al., 2013; Ma et al., 2020). (d) Cd/Ca records of the benthic foraminifera *Hoeglundina elegans* (black), *Cibicidoides pachyderma* (green), *Uvigerina peregrina* (blue), and *Globobulimina* spp. (orange) obtained from core MD77-191; (e) Cd/Ca records of the benthic foraminifera *H. elegans* from core MD77-176. EHCO for Early Holocene Climate Optimum, YD for Younger Dryas, B-A for B øling-Aller ød and HS1 for Heinrich stadial 1.



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911 Fig. 3. Down core variations of PC scores and the percentages of major species. The color shaded intervals and

912 abbreviations are the same as in Figure 2.



916Fig. 4. (a) Cd_w records calculated based on the Cd/Ca of benthic foraminifera *Hoeglundina elegans* (black),917*Cibicidoides pachyderma* (green), *Uvigerina peregrina* (blue), and *Globobulimina* spp. (orange) obtained from918core MD77-191, (b) Cd_w record from core MD77-176 reconstructed using *H. elegans* Cd/Ca, the red line is the919smoothed curves using a five-point average. The red stars represent the modern Cd_w (~0.83 nmol/kg) in the920northern Indian Ocean (Boyle et al., 1995). The color shaded intervals and abbreviations are the same as in921Figure 2.

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Fig. 5. (a) Organic carbon weight percentage (%C_{org}) and (b) *G. bulloides* percentage from core SK237 GC04
(1245m, Arabian Sea, Naik et al., 2017). (c) Relative abundance of *G. bulloides* (Ml éneck, 1997; Bassinot et al.,

2011) and (d) Cd_w records from core MD77-191 (Arabian Sea). The color shaded intervals and abbreviations are

- 945 the same as in Figure 2.
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Fig. 6. (a) The solar insolation at 10 % in summer (Laskar et al., 2004). (b) and (c) intermediate Cd_w calculated from *H. elegans* obtained from MD77-176 and MD77-191, respectively. (d) Lonar Lake $\delta^{13}C_{wax}$ record (Sarkar et al., 2015). (e) δD_{Alk-ic} record from core SO188-342KL (Contreras-Rosales et al., 2014). (f) Seawater $\delta^{18}O$ anomaly obtained from MD77-176 (Marzin et al., 2013). The color shaded intervals and abbreviations are the same as in Figure 2.

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Fig. 7. Intermediate Cd_w versus benthic $\delta^{13}C$ obtained from core MD77-191 located off the southern tip of India. The yellow shaded area represents the ranges of $Cdw - \delta^{13}C$ values of AAIW during the HS1 and YD, which were reconstructed in the Indian Ocean (benthic $\delta^{13}C$, Naqvi et al., 1994; Jung et al., 2009; Ma et al, 2019; 2020), Pacific and Atlantic Oceans (benthic Cd_w , Valley et al., 2017; Umling et al., 2018) at intermediate water depths.

964 The abbreviations are the same as in Figure 2.