



## A multi-proxy analysis of late Quaternary Indian monsoon dynamics for the Maldives, Inner Sea

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**Abstract.** We present a detailed multi-proxy data record to reveal the late Quaternary changes in marine sedimentation and biogeochemical processes of the upper bathyal Maldives (equatorial Indian Ocean) and how they are related to the benthic ecosystem dynamics. We investigated the sediment core SO-236-052-4 from the central part of the Inner Sea, Maldives, focusing on Fe/Ca and Si/Ca ratios as proxies for terrigenous sediment delivery, as well as Total Organic Carbon (TOC) and

15 Ba/Ca ratios as proxies for marine productivity. Benthic foraminiferal fauna distributions, sortable silt records and stable oxygen and carbon isotope analyses were used for reconstructing the past ecosystem, as well as changes in the intermediate water circulation, bottom water current velocity and oxygenation.

This multi-proxy data record shows an enhanced dust supply during the glacial intervals, represented by increased Fe/Ca and Si/Ca ratios, an overall coarsening of the sediment and increasing amount of agglutinated benthic foraminifera. The

20 enhanced dust fluxes can be attributed to higher dust availability in the Asian desert and loess areas and its transport by intensified winter monsoon winds during glacial conditions. These combined effects of wind-induced mixing of surface waters and dust fertilisation during the cold phases resulted in increased surface water productivity and related organic carbon fluxes. Thus, the development of highly diverse benthic foraminiferal faunas and the distribution of certain detritus and suspension feeders were fostered.

25 The difference in the stable carbon isotope signal between epifaunal and deep infaunal benthic foraminifera reveals intermediate water oxygen concentrations between approximately 40 and 100  $\mu\text{mol kg}^{-1}$ . The pattern of oxygen changes resembles that from the deep Arabian Sea suggesting an expansion of the Oxygen Minimum Zone (OMZ) from the Arabian Sea into the tropical Indian Ocean, further controlled by the inflow of the Antarctic Intermediate Water (AAIW). The precessional circulation pattern of the bottom water oxygenation is overprinted by glacial-/interglacial changes resulting in a

30 long phase of reduced ventilation during the last glacial period. The latter process is likely linked to the combined effects of generally enhanced oxygen consumption rates during high-productivity phases, reduced AAIW production and restriction of bathyal environments of the Inner Sea of the Maldives during sea-level lowstands. Thus, this multi-proxy record provide a close linkage between the Indian monsoon oscillation, intermediate water circulation, productivity and sea-level changes on orbital time-scale.



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## 1 Introduction

Sedimentation and biogeochemical processes of the tropical and subtropical northern Indian Ocean are closely linked to the intensity and seasonal changes of the Indian monsoon system. From June to October, the region is dominated by the SW monsoon, while the NE monsoon operates from December to April (Wyrski, 1973; Schott and McCreary, 2001). During the SW monsoon, coastal and open-ocean upwelling in the Arabian Sea results in maximum surface water productivity and related organic matter fluxes (Nair et al., 1989, Rixen et al., 1996). At the same time, the Southwest Monsoon Current (SMC) transports high-saline surface waters from the Arabian Sea into the equatorial region (Schott and McCreary, 2001). During the NE monsoon, the current system reverses and the Northeast Monsoon Current (NMC) transports lower-saline surface waters from the Bay of Bengal into the western Indian Ocean. While chlorophyll concentrations strongly decrease in the Arabian Sea during the NE monsoon, elevated concentrations are mainly restricted to the Indian west coast. In the Maldives area, mean chlorophyll concentrations reach their maximum during the NE monsoon (Sasamal, 2007; de Vos et al., 2014; NASA MODIS-Aqua, 2014).

The decay of organic matter in the water column and the generally reduced ventilation of regional subsurface waters in the Indian Ocean result in the development of a strong Oxygen Minimum Zone (OMZ) between 200 and 1200 m water depth (Reid, 2003; Stramma et al., 2008). The oxygen depletion is fostered by the semi-enclosed nature of the northern Indian Ocean, the long pathway of intermediate water from its main formation sites at 40°S in the central South Indian Ocean (Antarctic Intermediate Water, AAIW) and Indonesia (Indonesian Intermediate Water, IIW) (Olson et al., 1993; You, 1998), and the contribution of low-oxygen outflow waters from the Red Sea and the Persian Gulf (Jung et al., 2001; Prasad and Ikeda, 2001). The OMZ extends from the Arabian Sea into the equatorial Indian Ocean. While oxygen concentrations in the Arabian Sea can be as low as 0.1 ml l<sup>-1</sup> (or 5 μmol kg<sup>-1</sup>) (Reid, 2003), they still reach low oxic values around 1 ml l<sup>-1</sup> (or 45 μmol kg<sup>-1</sup>) in 500 to 1000 m water depths of the Maldives region (Weiss et al., 1983; Reid, 2003).

The evaluation of deep-sea sediment archives from the Arabian Sea delivered comprehensive information on the pacing and intensity of the Indian summer monsoon and response of deep-sea environments on orbital (Clemens and Prell, 1990; Clemens et al., 1991) and suborbital (Schulz et al., 1998; Gupta et al., 2003) time scales. Summer monsoon changes are strongly coherent over the precessional band and reveal a close but lagged response to maxima in northern hemisphere summer insolation (Clemens and Prell, 2003). Phases of intensified OMZ are related to increased organic matter fluxes and microbial oxygen consumption rates during summer monsoon maxima (Den Dulk et al., 2000). In contrast, deep vertical mixing and erosion of the OMZ occurred during phases of intensified winter monsoon (Reichart et al., 1998). More recent studies revealed that the intensity of the OMZ and dynamics of deep-sea benthic ecosystems are paced by the superposition of regional monsoon dynamics and super-regional changes of intermediate and deep-water ventilation (Schmiedl and Leuschner, 2005; Pattan and Pearce, 2009; Das et al., 2017).



Records from the equatorial Indian Ocean provide a more diverse and partly contradictory picture since this region is not only influenced by the summer and winter monsoons but also by the strength of Indian Ocean Equatorial Westerlies (IEW) which are strongest during the intermonsoon seasons in spring and fall and are inversely related to the Indian Ocean Dipole (Hastenrath et al., 1993; Beaufort et al., 2001). Variations in surface water properties in the southeastern Arabian Sea at a site close to the Maldives platform revealed maximum productivity at times of enhanced winter monsoon winds associated with precessional maxima in ice volume (Rostek et al., 1997). An upper bathyal benthic foraminiferal record from the Maldives Ridge suggests that late Quaternary changes in organic matter fluxes are either driven by summer monsoon winds (Sarkar and Gupta, 2009) or linked to changes in the IEW strength (Sarkar and Gupta, 2014). The precessional variability in productivity records from the equatorial Indo-Pacific Ocean has been attributed to the influence of low-latitude insolation on the IEW strength and on long-term dynamics of the El Niño-Southern Oscillation (ENSO) (Beaufort et al., 1997, 2001).

Here we present a multi-proxy data set on the links between climate variability, ocean circulation, sedimentation and biogeochemical processes of the Maldives Inner Sea. Specifically, our study addresses the following questions: (1) Which impact did orbital-scale changes of the Indian monsoon have on dust fluxes and marine environments of the Maldives? (2) How did global sea-level changes influence the sedimentation processes and benthic ecosystems of the Maldives Inner Sea? (3) Can we trace the influence of changes in the configuration of intermediate waters and how are these changes related to super-regional oceanographic processes?

The sediment archive of the Maldives Inner Sea is ideally situated to answer the above questions because it lies in the central part of the Indian Ocean and therefore it is in the zone where the different processes introduce above acts. The Maldives also appear as an ideal place to trace back paleoceanographic variations in time, as seismic surveys (Betzler et al. 2009, 2013a, 2013b, 2016; Lüdmann et al., 2013) have shown that the Maldives are comparable to a large natural sediment trap with a continuous Neogene succession.

## 2 Material and Methods

### 2.1 Sediment cores and material descriptions

For this study, two sediment cores were retrieved from different sites in the Inner Sea of the Maldives (Fig. 1). The 5.97 m long sediment core SO-236-052-4 was obtained by means of a gravity corer in the framework of R/V SONNE cruise SO236 in August 2014, E of the North Ari Atoll in the central part of the Inner Sea (03°55.09'N; 73°08.48'E) and from a water depth of 381.9 m. The 12.94 m long sediment core M74/4-1143 is a piston core from R/V METEOR cruise M74/4, obtained in 2007 from E of the Goidhoo Atoll (04°49.50'N; 73°05.04'E) at a water depth of 386.8 m (Fig. 1). This study is focused on the first 6.00 m of core M74/4-1143.

The sediment of core SO-236-052-4 consists of an alternation of non-lithified fine-grained ooze with abundant pteropods, sponge spicules, planctonic and benthic foraminifera, and echinoid remains, with minor otolites and fragments of gastropods and bivalves. There are locally some intervals that present up to 4 cm bioclast including solitary corals and thin-shelled



100 bivalves. The entire succession is intensely reworked by bioturbation. Just a few primary structures, usually main boundaries  
between facies are preserved (i.e. the sharp contacts at 2.35 mbsf and at 3.90 mbsf). Discrete burrows are scarce. The  
succession recovered at site M74/4-1143 has been described by Betzler et al. (2013b). The core consists mainly of  
periplatform ooze with planktic foraminifers, pteropods, otoliths, mollusc remains, benthic foraminifers, sponge spicules,  
and echinoid debris. Down the core, light and dark colored greenish to olive gray intervals alternate, with the light colored  
105 intervals correlating to isotopically lighter intervals and the darker colored intervals correlating to isotopically heavier  
intervals (Betzler et al., 2013b).

## 2.2 Geochemical analyses

Scanning X-Ray Fluorescence (XRF) element analysis of core SO-236-052-4 was carried out at the MARUM, University of  
110 Bremen, using an Avaatech XRF Core Scanner II. Element analysis was performed at 1 cm intervals, using generator  
settings of 50 kV (1.0 mA current), 30 kV (1.0 mA) and 10 kV (0.2 mA), and a sampling time of 20 seconds per  
measurement. Raw data spectra were processed using the software package WIN AXIL. Element ratios (Ba, Fe, Si, Sr  
against Ca) were calculated and used for environmental interpretations following Croudace and Rothwell (2015).

The calcium carbonate and Total Organic Carbon (TOC) content of core SO-236-052-4 was measured at 5 cm spacing.  
115 The carbon content of the grain-size fraction < 63 µm was determined using a LECO DR144 carbon analyser. All samples  
were freeze dried. Subsequently, one subsample was measured at 1350 °C to obtain the total carbon content. A second  
subsample was heated to 550 °C for 5 hours to remove the organic carbon prior to measurement in the LECO; this gave the  
inorganic carbon content. The difference between total carbon- and inorganic carbon- is regarded as the organic-carbon  
content. Calcium carbonate contents were calculated from the inorganic carbon content.

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## 2.3 Grain-size analyses

For bulk grain size analysis core SO-236-052-4 was sampled equidistantly (1.5 cm<sup>3</sup> each 1 cm). Samples were wet-sieved  
(2000 µm) to remove very coarse particles, and subsequently suspended in water with addition of a 0.05 % solution of Tetra-  
Sodium Diphosphate Decahydrate as dispersant.

125 The mean grain size of the non-carbonate fraction between 10 to 63 µm, the sortable silt, has been shown to be a reliable  
proxy for palaeocurrent strength in predominantly siliciclastic sediments (Manighetti and McCave, 1995; McCave et al.,  
1995a, 1995b; Hall et al., 1998; Bianchi et al., 1999; McCave and Hall, 2006). The method makes use of the non-carbonate  
fraction only and is therefore expected to be unaffected by primary carbonate production and burial diagenesis. Samples for  
the determination of the sortable silt component (c. 20 cm<sup>3</sup> each) were taken equidistantly (at 5 cm intervals down to 1 m  
130 below the sea floor and at 10 cm intervals underneath for core M74/4-1143 and at 5 cm downcore intervals for core SO-236-  
052-4). Subsequently to wet-sieving, the fraction < 63µm was cooked in H<sub>2</sub>O<sub>2</sub> to remove the organic portion, and treated



with 1M Ca<sub>3</sub>COOH to dissolve the carbonate. Biogene opal was removed with 2M NaHCO<sub>3</sub>. The remainder was dispersed in water for grain-size determination.

All grain-size measurements were done using a Helos KFMagic Laser particle size analyzer and measuring ranges of  
135 either 0.5/18-3500 μm (for bulk grain size) or 0.25/87.5 μm (for the non-carbonate fraction). To ensure accuracy of measurements and absence of a long-term instrumental drift, an in-house grain-size standard was measured regularly. Grain size statistics are based on the graphical method (Folk and Ward, 1957) and were calculated using the software GRADISTAT (Blott and Pye, 2001).

#### 140 **2.4 Foraminiferal faunal and stable isotope analyses**

For stable isotope analyses core SO-236-052-4 was sampled at 5 cm spacing and for benthic foraminiferal faunal analysis at 10 cm spacing. All Samples were wet-sieved over a 63 μm screen and the residues subsequently dried at 38 °C. The benthic foraminiferal analysis was carried out on the > 125 μm size fraction and based on allocate splits in order to obtain approximately 300 tests. Genus and species identifications mainly based on Loeblich and Tappan (1988), Hottinger et al.  
145 (1993), Jones (1994), Debenay (2012), Milker and Schmiedl (2012) and Holbourn et al. (2013). The genera *Cymbaloporeta* and *Tretomphaloides* were summarized as meroplanktonic benthic foraminifera (BF) since they are known to have planktonic drift phases as part of their dispersal strategy (Banner et al., 1985; Alve, 1999). For analysis based on the test material all individuals of the foraminiferal orders Astrorhizida, Lituolida and Textulariida were summarized as agglutinated BF.

Benthic foraminiferal assemblages were defined by Q-mode Principal Component Analysis (PCA) with varimax rotation using the software SYSTAT, version 5.2.1. Following Schmiedl et al. (1997) only foraminiferal taxa with percentages ≥ 1 % in at least one sample and/or taxa, which occur at least in two samples were used for the statistical analysis. Loadings ≥ 0.5 were defined as significant (Backhaus et al., 2008). The Shannon-Wiener diversity index H(S) was calculated after Murray (2006) based on the function  $H(S) = (-1) \sum_{i=1}^S p_i \times \ln(p_i)$ , where S is the species number and p<sub>i</sub> the relative abundance of  
155 the i-th species.

Stable oxygen and carbon isotope records were generated for planktonic and benthic foraminifera. Approximately 10 tests of the planktonic foraminifer *Globigerinoides ruber* (white) were selected from the 250-350 μm size fraction of core SO-236-052-4. Stable isotope data of *G. ruber* (white) of core M74/4-1143 were taken from Betzler et al. (2013b).

In addition, approximately 2-5 tests of the epibenthic foraminifera *Cibicides mabahethi* and of the deep infaunal species  
160 *Globobulimina affinis* s.l. were selected from the size fraction > 125 μm of core SO-236-052-4. Stable oxygen and carbon isotope analyses were performed with Finnigan MAT 253 gas mass spectrometers coupled to automatic carbonate preparation devices Kiel II or IV, respectively. The mass spectrometers were calibrated to the PDB scale via international standard NBS19, and results are given in δ-notation versus VPDB. Based on measurements of an internal laboratory standard



(Solnhofen limestone) together with samples over a 1-year period, precision was better than 0.08 ‰ for  $\delta^{18}\text{O}$  and 0.06 ‰ for  $\delta^{13}\text{C}$ , respectively.

For site SO-236-052 changes in bottom water oxygen concentrations were estimated based on the  $\delta^{13}\text{C}$  difference between the epifaunal (*C. mabahethi*) and deep infaunal (*G. affinis* s.l.) benthic foraminifera using the function  $\Delta\delta^{13}\text{C} = 0.00772 \times [\text{O}_2] + 0.41446$ , wherein concentrations  $[\text{O}_2] < 235 \mu\text{mol kg}^{-1}$  are considered as significant (Hoogakker et al., 2015). For comparison, oxygen concentration changes of a deep sea sediment core from an Arabian Sea site (GeoB3004, 1803 m water depth) were taken from Schmiedl and Mackensen (2006). These data based on the difference between the epifaunal *Cibicides wuellerstorfi* and *G. affinis*. Further, the  $\delta^{13}\text{C}$  gradient between *G. ruber* (white) and *C. mabahethi* of core SO-236-052-4 was estimated for assess the sea surface and bottom-water stable carbon isotope difference and water column mixing.

## 2.5 Radiocarbon dating and compilation of the age model

Accelerator Mass Spectrometry (AMS) radiocarbon dating was carried out at the Beta Analytic Radiocarbon Dating Laboratory on mixed surface-dwelling planktonic foraminifera from 35 cm, 80 cm and 140 cm depth of core SO-236-052-4 (Table 1). Conventional radiocarbon ages were calibrated using the radiocarbon calibration program CALIB (version 7.0.4; Stuiver and Reimer, 1993) and the calibration curve Marine13 (Reimer et al., 2013). Local reservoir corrections were not applied. Additional age tie points were derived from graphical correlation of the benthic  $\delta^{18}\text{O}$  record of core SO-236-052-4 with the LR04 standard benthic stack (Lisiecki and Raymo, 2005) using the software AnalySeries 2.0 (version 5/2005; Paillard et al., 1996). The age model of core M74/4-1143 (Betzler et al., 2013b) was revised by graphical correlation with the planktonic  $\delta^{18}\text{O}$  record of core SO-236-052-4 (Fig. 2).

## 3 Results

### 3.1 Age model and sedimentation rate

Based on the radiocarbon ages and the alignment of the stable oxygen isotope stratigraphy, core SO-236-052-4 comprises sediments of the past 207.7 ka, respectively (Fig. 2). The top 6 m of sediment core M74/4-1143 comprise the past 242.3 ka. Average sedimentation rates varied between 3.5  $\text{cm ka}^{-1}$  in SO-236-052-4 and 4.4  $\text{cm ka}^{-1}$  in M74/4-1143. Maximum sedimentation rates occurred during interglacial intervals, with 6.8  $\text{cm ka}^{-1}$  (SO-236-052-4) and 8.4  $\text{cm ka}^{-1}$  (M74/4-1143) for the Eemian, and 7.1  $\text{cm ka}^{-1}$  (SO-236-052-4) to 3.0  $\text{cm ka}^{-1}$  (M74/4-1143) for the Holocene (Fig. 2).

### 3.2 Foraminiferal stable oxygen and carbon isotope records

The  $\delta^{18}\text{O}$  values of core SO-236-052-4 vary between -3.09 and -0.68 ‰ in the planktonic *G. ruber*, between 0.91 and 2.51 ‰ in the epibenthic *C. mabahethi*, and between 1.10 and 5.02 ‰ in the deep infaunal *G. affinis* (Fig. 3). Generally, the  $\delta^{18}\text{O}$



records reveal a consistent picture with relatively higher values during glacial intervals and lower values during interglacial intervals.

The  $\delta^{13}\text{C}$  values of core SO-236-052 vary between 0.12 and 1.25 ‰ in *G. ruber*, between 0.22 and 0.91 ‰ in *C. mabahethi*, and between -0.84 to 0.27 ‰ in *G. affinis* (Fig. 3). Despite considerable short-term variability, all records reveal a stepwise increase of  $\delta^{13}\text{C}$  values with lowest values during the Marine Isotope Stage (MIS) 6 and highest values during the Holocene (Fig. 3).

Considering the past bottom-water oxygen concentration reconstruction for core SO-236-052-4 by using the  $\Delta\delta^{13}\text{C}_{\text{Cm-Ga}}$  estimation, the values varied between 10.43 and 139.45  $\mu\text{mol kg}^{-1}$  with average values of approximately 65.50  $\mu\text{mol kg}^{-1}$ . In addition, a long-lasting oxygen depletion was observed, starting from the end of MIS 5 to the end of MIS 3 (duration of ~50 ka), and with average oxygen concentrations of approximately 52.50  $\mu\text{mol kg}^{-1}$ . The oxygen concentration of sediment core GeoB3004 (W Arabian Sea) showed an average oxygen content of approximately 81.75  $\mu\text{mol kg}^{-1}$  (Schmiedl and Mackensen, 2006). In comparison both cores represented a precessional pattern during MIS 6 to late MIS 5, in which they were almost in phase. A comparable long lasting oxygen depletion, as documented at site SO-236-052, could not be identified for GeoB3004.

The  $\Delta\delta^{13}\text{C}_{\text{Cm-Ga}}$  calculation for site SO-236-052 showed maximum differences of the planktic and epibenthic stable  $\delta^{13}\text{C}$  values during the full interglacial periods of MIS 7, 5 and 1, coinciding with the global sea-level highstands. Accordingly, minimum differences were documented for the glacial periods MIS 6 and 2 and sea-level lowstands.

### 3.3 Sedimentological and geochemical records

The detailed sedimentological and geochemical data of core SO-236-052-4 reveal a glacial-interglacial pattern but also considerable short-term variability (Figs. 4a-d). Sortable silt records are available for both sites and in general they show coarser means in interglacial times (Figs. 4a, 5). However, absolute values and variability are much greater in core M74/4-1143 which is located in the drift of the Kardiva Channel (Betzler et al., 2013b) compared to core SO-236-052-2 from the more sheltered southern part of the Inner Sea. In core M74/4-1143, sortable silt shows an increase towards the MIS 6/5 transition (Termination II) followed by generally elevated values during the MIS 5.5, whereas there is much less variability at the same time in the data from core SO-236-052-4. Both cores show a coarsening of the sortable silt towards the MIS 1.

Bulk mean grain size shows a pronounced glacial-interglacial variability with up to 57  $\mu\text{m}$  during the MIS 2 and MIS 6 and values between 10 and 30  $\mu\text{m}$  for the remainder (Fig. 4a). Finest sediments occur during the early MIS 5 and the MIS 1.

Total Organic Carbon (TOC) and carbonate ( $\text{CaCO}_3$ ) content of core SO-236-052-4 reveal reverse glacial-interglacial trends with maximum TOC content during glacial- and maximum carbonate contents during interglacial periods. TOC varies between 0.85 wt. % (interglacial) and 2.06 wt. % (glacial), whereas the carbonate content varies between 77.03 wt. % (glacial) and 89.40 wt. % (interglacial) (Fig. 4b).



The Fe/Ca and Si/Ca records reveal generally higher values during glacial and lower values during interglacial periods. Both Fe/Ca and Si/Ca records are characterized by an abrupt and short-lasting maximum at Termination II (Fig. 4c). The Ba/Ca ratio is comparatively low but shows a similar glacial-interglacial pattern, such as the Fe/Ca and Si/Ca records, with generally higher ratios during glacial periods and lower ratios during interglacial periods, but with additional variability on orbital time scales (Fig. 4d). Inverse patterns are observed for the Sr/Ca record, which follows the inversed  $\delta^{18}\text{O}$  curve and shows higher values during interglacial and lower values during glacial periods (Fig. 4d).

### 3.4 Benthic foraminiferal record

In sediment core SO-236-052-4, a total of 256 different benthic foraminiferal species were distinguished, with 51 to 93 different species per sample. The diversity  $H(S)$  of core SO-236-052-4 is relatively high and varies between 3.3 and 4.0, with a slight long-term decrease towards today (Fig. 6a). The three-component model of the Q-mode PCA explains 89.14 % of the total variance (Fig. 6, Table 2). Assemblage 1 (PC1) explains 31.54 % of the total variance and is dominated by *N. proboscidea* and *D. araucana*, with *Hyalinea inflata*, *Cymbaloporeta squamosa*, *Bulimina marginata* and *Rosalina vilardeboana* as associated taxa. This assemblage occurred mainly during the late MIS 7 and 5 and is less pronounced during MIS 4 to early MIS 2 (Fig. 6b). Assemblage 2 (PC2) explains 30.54 % of the total variance and is dominated by *C. mabahethi*, with *Discorbinella bertheloti*, *Siphogenerina columellaris*, *Gyroidina umbonata*, *Reophax* sp., *H. inflata*, and *D. araucana* as associated taxa (Table 2). The assemblage 2 occurred mainly during MIS 6 and 1 (Fig. 6c). Assemblage 3 (PC3) explains 27.06 % of the total variance and is dominated by *N. proboscidea* and *Hoeglundina elegans*, with *D. bertheloti*, *Cibicidoides subhaidingeri*, *Discorbis* sp., *Spiroplectinella sagittula* s.l., and *C. mabahethi* as associated taxa (Table 2). Assemblage 3 occurred during MIS 4 to 2 (Fig. 6d).

The distribution of the most important benthic foraminiferal species, which characterize the three faunal assemblages, are displayed in Figs. 6e-g. The most abundant species include *C. mabahethi* (maximum relative abundance of ~17 % during MIS 6), the weakly hispid *N. proboscidea* (maximum of ~16 % at the end of MIS 5) and *D. araucana* (maximum of ~11 % during the onset of MIS 5). Meroplanktonic benthic foraminifera (genera *Cymbaloporeta* and *Tretomphaloides*) occurred in elevated numbers during interglacial periods, particularly during MIS 5 (Figs. 5d and 6e).

The foraminiferal fauna at the Inner Sea is dominated by hyaline taxa. In comparison, agglutinated individuals were less abundant, but with increasing relative abundances up to approximately  $\geq 20$  % of the entire fauna during the glacial periods.

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## 4 Discussion

### 4.1 Monsoon variability, dust fluxes and marine productivity

The Fe/Ca and Si/Ca ratios at site SO-236-052 were interpreted as proxies for terrigenous sediment delivery, deposited by aeolian dust fluxes in the Maldives Inner Sea. Local sources of Fe-rich sediments can be excluded since the sediments of the Maldives islands and adjacent deep-water environments are characterized by carbonates comprising reef and lagoon

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carbonates of the islands and pelagic deep-water carbonates (Betzler et al., 2013b; Reolid et al., 2017). Calcite content is also very high at site SO-236-052 throughout the past 200 ka (Fig. 4b). Studies on modern aerosols of the North Pacific region indicate that most of the oceanic iron input is derived from atmospheric transport after mobilisation from the central Asian deserts and Chinese loess plateau (Duce and Tindale, 1991). Accordingly, the most likely dust sources for the observed Fe in  
265 the sediments of the Maldives are the Indian subcontinent and the Asian desert and loess areas (Roberts et al., 2011), although a minor contribution from Africa and Arabia cannot be excluded (Sirocko and Lange, 1991; Chauhan and Shukla, 2016). Coincident to the prevailing wind system, the majority of dust is transported via the NE monsoon, which blows during northern hemisphere winter. Elevated Fe/Ca ratios during the glacial intervals of MIS 6 and MIS 4-2 indicate the combined effects of enhanced glacial dust availability in the source areas and dust transport to the Maldives with generally  
270 strengthened NE monsoon winds. Enhanced glacial dust fluxes were also observed in the Arabian Sea associated with a strengthening of northwesterly winds, which blow dust from the Arabian peninsula into the marine areas (deMenocal et al., 1991; Sirocko and Lange, 1991). On a global scale, the generally colder and drier glacial conditions resulted in a two- to fivefold increase of dust fluxes (Maher et al., 2010). Enhanced glacial dust concentrations were also detected in polar ice cores (Ruth et al., 2003; EPICA Community Members, 2004) and a multitude of marine records (deMenocal et al., 1993; Liu  
275 et al., 1999; Zhang et al., 1999; Winckler et al., 2008; Maher et al., 2010).

The observed response of the winter circulation of the Maldives to glacial conditions is in line with the finding of a general strengthening of the NE Indian monsoon after initiation of the northern hemisphere glaciation (Gupta and Thomas, 2003). However, our Fe/Ca record lacks significant variability on the precessional band, which should be expected if the dust fluxes were directly proportional to the intensity of the winter monsoon (Caley et al., 2011a, b). Therefore the dust record of  
280 the Maldives Inner Sea is mainly driven by the generally enhanced dust availability during glacial intervals. As a major dust source, the Chinese loess plateau is strongly influenced by the East Asian Monsoon (EAM). During the late Quaternary, EAM and related vegetation changes are characterized by predominant excentricity cycles associated with the advance and retreat of the boreal ice sheets (Ding et al., 1995; Liu et al., 1999; Sun et al., 2006; Hao et al., 2012). On the Chinese loess plateau the onset of glacial conditions led to an abrupt increase of atmospheric dust loadings (Zhang et al., 2002) suggesting  
285 the operation of climate-vegetation feedbacks. Enhanced deposition of dust particles at site SO-236-052 led to a generally coarsening of the glacial sediment (Fig. 4a) and fostered the distribution of agglutinated benthic foraminifera, which reach a relative abundance of up to ~20 % during the last glacial period (Fig. 7e). Most agglutinated foraminifera in core SO-236-052-4 belong to the Textulariida, such as *Spiroplectammina sagittula*, *Textularia calva* or *Textularia pala*. These and related taxa are often associated with relatively coarse-grained substrates and preferentially use siliciclastic grains for test  
290 construction (Allen et al., 1999; Murray, 2006; Armynot du Châtelet et al., 2013).

The equatorial Indian Ocean is limited in the micronutrient iron (Wiggert et al., 2006; Maher et al., 2010) and therefore, enhanced Fe fluxes during glacial periods may have resulted in increased surface water productivity, similar to observations from the Southern Ocean (Anderson et al., 2014; Martínez-García et al., 2014) and the equatorial Pacific Ocean (Costa et al.,



295 2016). The TOC and Ba contents of marine sediments are widely used as proxies for organic matter fluxes and surface water productivity (Müller and Suess, 1979; Gingele et al., 1999; McManus et al., 1999; Rühlemann et al., 1999). But the applicability of both proxies in quantitative reconstructions is limited by the specific sedimentological and biogeochemical processes at the sediment-water interface, including the bulk accumulation rate and bottom water oxygenation (Möbius et al., 2011; Schoepfer et al., 2015; Naik et al., 2017).

Elevated TOC and Ba/Ca values in core SO-236-052-4 suggest generally enhanced organic matter fluxes during glacial  
300 periods, which may reflect the influence of Fe fertilisation (Fig. 7b-d). The benthic foraminiferal faunas at site SO-236-052 reveal a marked glacial-interglacial pattern (Figs. 6, 7f). The diversity, microhabitat partitioning and species composition of deep-sea benthic foraminiferal faunas is mainly controlled by the combined influences of quantity and quality of food supply and oxygen content of the bottom and pore waters (Jorissen et al., 1995; Fontanier et al., 2002). The diversity of the faunas is high, with H(S) values always > 3.2, throughout the studied time interval, suggesting the absence of extreme environmental  
305 conditions at the sea floor of the study site. Therefore, the observed faunal changes likely reflect variations in the amount and quality of food supply.

The most abundant species of the three benthic foraminiferal assemblages comprise *C. mabahethi*, *N. proboscidea* and *D. araucana*, all with PC scores > 3 in at least one assemblage (Table 2). Microhabitat studies demonstrated that most species of the genera *Cibicides* and *Ciccidoides* live as suspension feeders on or elevated above the sea floor (Lutze and Thiel,  
310 1989; Linke and Lutze, 1993), therefore we assume a similar microhabitat preference for *C. mabahethi*. In the Red Sea this species is adapted to relatively high oxygen contents and low organic matter fluxes (Edelman-Furstenberg et al., 2001; Badawi et al., 2005). The cosmopolitan *N. proboscidea* inhabits an epifaunal to very shallow infaunal microhabitat (Fontanier et al., 2002; Licari et al., 2003) and has been described as detritus feeder from various bathyal and abyssal environments. In the South Atlantic Ocean, *N. proboscidea* is associated with well-ventilated and oligotrophic conditions  
315 (Schmiedl et al., 1997). Whereas this species thrives under moderate to high organic matter fluxes and oxygen-depleted intermediate waters in the Indian Ocean (Murgese and De Deckker, 2007; De and Gupta, 2010) and was used as a proxy for the strength of the SW monsoon (Gupta and Srinivasan, 1992; Gupta and Thomas, 2003; Sarkar and Gupta, 2014). These observations and the high relative abundance of *N. proboscidea* in core SO-236-052-4 during the last glacial intervals MIS 4-2, as well as the interglacial interval MIS 5 suggest an adaptation to a wide range of trophic conditions and confirms its  
320 tolerance to moderate oxygen depletion. Little information is available on the ecology of *D. araucana* but its flat trochospiral morphology and distribution in the North Atlantic Ocean suggest an epifaunal microhabitat and adaptation to suspended food sources (Corliss and Chen, 1988; Koho et al., 2008). Similar to the closely related *D. bertheloti* it may prefer mesotrophic and oxic conditions (De, 2010) with a tolerance to moderate oxygen depletion (Edelmann-Furstenberg et al., 2001). The shallow infaunal *Hoeglundina elegans* is commonly associated with low to moderate organic matter fluxes, fresh  
325 phytodetritus and high oxygen contents (Corliss, 1985; Koho et al., 2008).



The ecological preferences of the dominant taxa suggest that faunal changes at site SO-236-052, although pronounced, were driven by rather subtle changes in the amount of organic matter fluxes. Instead, the faunal changes likely reflect variations in lateral suspension of food particles, substrate-specific development of infaunal niches, and the influence of oxygen changes on the quality of the organic matter. The high dominance of the detritus feeders *N. proboscidea* and *H. elegans* in assemblage 3 suggest highest organic matter fluxes during the last glacial MIS 4-2 (Fig. 7f). In contrast, the dominance of the epifaunal suspension feeder *C. mabahethi* in assemblage 2 during the penultimate glacial (MIS 6) suggests relatively lower organic matter fluxes. The *N. proboscidea/D. araucana* assemblage 1 of MIS 5 reveals some similarity to assemblage 3 but the high abundance of *D. araucana* suggests an overall lower food flux with a considerable amount of suspended particles. In addition, the relatively finer-grained substrate likely opened infaunal niches as indicated by the presence of the shallow to deep infaunal *Bulimina marginata* during the MIS 5 (Jorissen and Wittling, 1999) (Fig. 6e).

While the benthic foraminiferal fauna preliminary show changes on glacial-interglacial time scale, the TOC content and Ba/Ca ratio are characterized by additional variability in the precessional band. The surface water productivity of the northern Indian Ocean is strongly linked to wind-induced mixing of the upper water column and upwelling of nutrient-rich subsurface waters and thus reveals a close association with seasonal changes of the monsoonal wind system (Nair et al., 1989). Accordingly, productivity changes in the northern and northwestern Arabian Sea are coherent to the strength of the SW monsoon (Ivanova et al., 2003; Leuschner and Sirocko, 2003; Singh et al., 2011), and along the Indian west coast to the strength of the NE monsoon (Rostek et al., 1997; Singh et al., 2011). Elevated TOC and Ba/Ca ratios at site SO-236-052 during phases of reduced northern hemisphere summer insolation suggest a direct influence of the Indian winter monsoon on productivity and related organic matter fluxes of the Maldives Inner Sea during the past 200 ka, which is consistent with the present-day situation (de Vos et al. 2014). The close link between the winter monsoon intensity and surface water productivity in the study area is confirmed by the difference between the  $\delta^{13}\text{C}$  values of the epipelagic *G. ruber* (Gr) and the epibenthic *C. mabahethi* (Cm) (Figs. 3, 8). Low  $\Delta\delta^{13}\text{C}_{\text{Gr-Cm}}$  values indicate enhanced vertical mixing of the water column, which is associated with increased supply of nutrients from subsurface waters into the photic zone, based on enhanced surface water productivity.

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#### 4.2 Sea-level changes, sedimentation processes and benthic ecosystem dynamics

The close association of changes in sediment composition (i.e. bulk grain size, carbonate content) at site SO-236-052 with the LR04 stable benthic isotope stack (Lisiecki and Raymo, 2005) suggest a dominant influence of sea-level changes on the depositional environments of the Maldives Inner Sea. This is also corroborated by the Sr/Ca variations in the core. In periplatform ooze, i.e. areas around shallow water carbonate banks, higher Sr contents are a consequence of higher input of shallow water aragonite (Dunbar and Dickens, 2003), which is produced in the neritic parts of the platforms and exported to the areas around the platform by currents.

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The observed changes in bottom currents likely influenced the lateral transport of suspended organic particles as is suggested by variations in the relative abundance of suspension feeders in the different benthic foraminiferal assemblages (Figs. 6, 7, Table 2). The dominance of *D. araucana* during MIS 5 and *C. mabahethi* during MIS 6 and MIS 1 indicate phases of enhanced lateral food supply, which for the interglacial periods (MIS 5, MIS 1) correlate with reconstructed higher current velocities (Fig. 5). The interglacial intervals of SO-236-052-4 (mainly MIS 5 and MIS 7, Fig. 5) contain high abundances of meroplanktonic benthic foraminifera (*Cymbaloporeta*, *Tretomphaloides*), which build floating chambers for dispersal (Banner et al., 1985; Alve, 1999). These taxa are commonly found in shelf environments (Milker and Schmiiedl, 2012). Their acme during the last interglacial maximum at bathyal depth of the Maldives Inner Sea coincides with almost absence of other displaced species from reef and lagoon environments, such as *Elphidium*, *Amphistegina* or *Operculina* (Parker and Gischler, 2011). This implies a repeated colonization of bathyal environments with meroplanktonic taxa from submerged neritic environments during sea-level highstands and strengthened bottom water velocity.

#### 370 4.3 Changes in intermediate water circulation and oxygenation

The epibenthic stable carbon isotope record of core SO-236-052-4 lacks a coherent glacial-interglacial pattern but reveals an overall  $\delta^{13}C_{Cm}$  increase of  $\sim 0.5$  ‰ over the past 200 ka (Fig. 3). Long-term trends of similar magnitude have been recorded from sites bathed by the Antarctic Intermediate Water mass (AAIW) in the southwestern Pacific Ocean (Pahnke and Zahn, 2005; Elmore et al., 2015; Ronge et al., 2015). The general resemblance of the various epibenthic  $\delta^{13}C$  records suggests a significant role of AAIW in ventilation of bathyal environments of the Maldives Inner Sea, which is consistent with the modern oceanographic situation (You, 1998).

Following the approach of Hoogakker et al. (2015) we estimated changes in the oxygen content of the intermediate water mass of the Maldives Inner Sea based on the  $\Delta\delta^{13}C_{Cm-Ga}$  signal, i.e. the difference between the  $\delta^{13}C$  values of the epifaunal *C. mabahethi* and the deep infaunal *G. affinis* s.l. The resulting  $O_2$  concentrations never dropped substantially below  $45 \mu\text{mol kg}^{-1}$  ( $\sim 1 \text{ ml l}^{-1}$ ) (Fig. 8). Moreover, the oxic to low oxic conditions ( $O_2 > 1 \text{ ml l}^{-1}$ ) did not seem to pose stress to the benthic foraminiferal fauna. Instead, the proportion of the deep infauna increases exponentially under dysoxic conditions, i.e. at  $O_2$  values significantly below  $1 \text{ ml l}^{-1}$  (Jorissen et al., 2007). The lack of dysoxic conditions at site SO-236-052 at any time of the past 200 ka is corroborated by the persistent high diversity across glacial and interglacial periods and the low abundance of deep infaunal taxa.

The reconstructed  $O_2$  record reveals precessional changes between oxic and low oxic conditions during northern hemisphere insolation maxima and minima, respectively. Detailed stable isotope records from the southwestern Pacific Ocean indicate enhanced AAIW formation during warm intervals (Pahnke and Zahn, 2005; Elmore et al., 2015; Ronge et al., 2015). Accordingly, the strength of the Oxygen Minimum Zone (OMZ) at the Maldives Inner Sea, which is preconditioned by the southward expansion of the OMZ from the Arabian Sea (Reid, 2003), is controlled by the inflow of the AAIW from the Subantarctic Southern Ocean and thus contains a strong southern hemisphere climate signal. The reconstructed  $O_2$



changes in intermediate waters at site SO-236-052 resemble those from the deep OMZ of the western Arabian Sea, which is influenced by the advection of oxygen-rich North Atlantic Deep Water (NADW) (Schmiedl and Mackensen, 2006). The dependence of oxygen changes in Indian Ocean intermediate and deep-water masses from the inflow of Atlantic and Antarctic water masses is corroborated by a number of recent observations from the northwestern and southeastern Arabian Sea (Pattan and Pearce, 2009; Das et al., 2017; Naik et al., 2017).

The long period of lowered O<sub>2</sub> values below 60 μmol kg<sup>-1</sup> centred at MIS 4-3 coincides with a marked monsoon and upwelling maximum in the Arabian Sea (Hermelin and Shimmiedl, 1995; Clemens and Prell, 2003; Leuschner and Sirocco, 2003; Caley et al., 2011a, b), which caused a strengthening and deepening of the OMZ (Almogi-Labin et al., 2000; Den Dulk et al., 2000; Schmiedl and Leuschner, 2005). The expansion of the Arabian Sea OMZ southward into the equatorial region likely preconditioned the oxygen levels of intermediate waters of the Maldives Inner Sea. There, oxygen changes were further lowered by the reduced glacial advection of oxygen-rich AAIW and enhanced regional microbial oxygen consumption reflecting a superposition of high and low-latitude climate signals. The resulting changes in biogeochemical processes at site SO-236-052 are illustrated by the establishment and long-term persistence of the benthic foraminiferal assemblage 3 underlining the positive response of *N. proboscidea* and associated species such as *H. elegans* and *D. bertheloti* to moderately reduced oxygen and increased food levels.

Abrupt O<sub>2</sub> drops occur at the end of the last two glaciations suggesting short phases of reduced AAIW advection or increased surface water productivity and related oxygen consumption at depth (Fig. 8). The recorded events correlate with phases of increased Agulhas leakage, which have been linked to a strengthening of the Indian monsoon and Indian Ocean equatorial winds (Peeters et al., 2004). Accordingly, an additional impact of changes in the strength of the Indian Ocean Equatorial Westerlies (IEW) on environmental changes of the Maldives Inner Sea appears likely (Beaufort et al., 1997, 2001). However, our new results imply that on orbital time scales changes of the winter monsoon and AAIW advection seem to play the dominant role.

## 5 Conclusions

The integrated evaluation of sedimentological, geochemical and micropaleontological proxy records from the Maldives Inner Sea (tropical Indian Ocean) furthers our understanding of links between equatorial climate variability, sea-level changes, changes in intermediate water ventilation and benthic ecosystem dynamics on orbital time scales during the past 200 ka. The main conclusions are:

(1) Aeolian dust fluxes were considerably enhanced during glacial intervals (MIS 6 and MIS 4-2) as indicated by increased Fe/Ca and Si/Ca ratios, generally coarsening of the bulk sediment, and increased abundance of agglutinated benthic foraminiferal taxa, which use siliciclastic grains for test formation. The enhanced dust input was linked to phases of



generally increased atmospheric dust loads and northeast winds, suggesting a close link of Maldives marine environments to the aridity of the central Asian loess areas and the strength of the Indian winter monsoon.

(2) Increased vertical mixing during glacial phases of intensified winter monsoon resulted in enhanced surface water productivity and associated organic carbon fluxes to the sea-floor as indicated by TOC values and composition of the benthic foraminiferal fauna. The *Cibicidoides mabahethi* (assemblage 2) and *Neouvigerina proboscidea* (assemblage 3) faunas dominate during MIS 6 and MIS 4-2 respectively, suggesting differences in the amount and quality of the food delivery for the two glacial intervals. The  $\Delta\delta^{13}C_{Gr-Cm}$ , Ba/Ca and TOC records reveal additional changes on the precessional band, which are inversely correlated to northern hemisphere summer insolation underlining a close link of regional vertical mixing of the water column and marine productivity to the Indian winter monsoon.

(3) Glacial-interglacial changes in sea level controlled the downslope transport of sediment from the Maldives islands to the deep-sea environments and influenced the current strength at the benthic boundary layer of the Inner Sea resulting in different grain size and substrates. Hand in hand with sea level changes there was a change in the bottom current regime. The drift deposits recovered by core M74/4-1143 show that highest current intensities occurred during and after the glacial terminations (Fig. 5). Bottom currents in general were stronger during interglacials than during glacials, although core SO-236-052-4 records lower current velocities and lower amplitude of change. Strongest current intensities at the sea floor likely favoured the distribution of certain suspension feeding benthic foraminiferal taxa, such as *D. araucana*.

(4) The long-term trend in the benthic  $\delta^{13}C$  record mirrors the basin-wide change in the composition of intermediate waters, implying a close linkage to the main formation sites of the AAIW in the Southern Ocean. The precessional changes of estimated oxygen concentrations of intermediate waters are coherent with changes in the deep Arabian Sea. This suggests an influence of the lateral expansion of oxygen minimum waters from the Arabian Sea into the equatorial intermediate Indian Ocean and modulation by inflowing AAIW from the south. The predominance of *N. proboscidea* during a long phase of reduced oxygen concentrations (with average oxygen concentrations around  $50 \mu\text{mol kg}^{-1}$ ) during late MIS 5 to late MIS 3 suggests an adaption of this species to the particular biogeochemical conditions and food quality associated with low oxie conditions.

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### Table Captions

**Table 1:** Accelerator Mass Spectrometry (AMS) radiocarbon dating results based on mixed surface-dwelling planktonic foraminifera (*Gr* = *Globigerinoides ruber*, white; *Gs* = *Globigerinoides sacculifer*) from 35 cm, 80 cm and 140 cm sediment depth of core SO-236-052-4. Conventional radiocarbon ages were calibrated using the radiocarbon calibration program CALIB (version 7.0.4; Stuiver and Reimer, 1993) and the calibration curve Marine13 (Reimer et al., 2013).

No.	Sample ID	Lab ID	Material	Core depth [mbsf]	<sup>12</sup> C/ <sup>13</sup> C o/oo	<sup>14</sup> C age ya BP	Calibrated age (ΔR 0)		
							cal BP (2s ranges, 95.4 % probability)		
							range [years]	rel. area u. distr.	median of prob. [ka]
1	SO236-052-035	Beta-418574	Gr, Gs	0.35	+1.4	7940 ±30	8330 - 8480	1.00	8.4 ± 0.08
2	SO236-052-080	Beta-418575	Gr, Gs	0.80	+1.6	12890 ±40	14310 - 15020	1.00	14.7 ± 0.36
3	SO236-052-140	Beta-418576	Gr, Gs	1.40	+1.8	23930 ±100	27480 - 27850	1.00	27.7 ± 0.19

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**Table 2:** Species composition of benthic foraminiferal assemblages. Principal component number, dominant and important associated species with principal component scores (Q-mode) and explained variance in percent of total variance are given.

Q-mode Principal Components	Species	Scores	Explained variance [%]
PC1	<i>Neouvigerina proboscidea</i>	5.812	31.54
	<i>Discorbinella araucana</i>	3.948	
	<i>Hyalinea inflata</i>	2.562	
	<i>Cymbaloporeta squamosa</i>	1.913	
	<i>Bulimina marginata</i>	1.729	
	<i>Rosalina vilardeboana</i>	1.595	
PC2	<i>Cibicides mabahethi</i>	7.466	30.54
	<i>Discorbinella bertheloti</i>	1.756	
	<i>Siphogenerina columellaris</i>	1.622	
	<i>Gyroidina umbonata</i>	1.589	
	<i>Reophax</i> sp.	1.387	
	<i>Hyalinea inflata</i>	1.214	
	<i>Discorbinella araucana</i>	1.109	
PC3	<i>Neouvigerina proboscidea</i>	4.608	27.06
	<i>Hoeglundina elegans</i>	3.952	
	<i>Discorbinella bertheloti</i>	3.004	
	<i>Cibicoides subhaidingeri</i>	2.311	
	<i>Discorbis</i> sp.	2.161	
	<i>Spiroplectinella sagittula</i> s.l.	1,808	
	<i>Cibicides mabahethi</i>	1,084	

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### Figure Captions

**Figure 1:** Location maps of the Maldives archipelago in the Indian Ocean (a, b) and the setting of the study area (c) (modified after Betzler et al., 2013a), showing the location of sediment core M74/4-1143 in the Kardiva Channel and core SO-236-052-4 in the central part of the Inner Sea (red circles).

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**Figure 2:** Full resolution stable oxygen isotope records of the planktonic foraminifer *G. ruber* (a) and age-depth plots for the sediment cores SO-236-052 (light blue) and M74/4-1143 (grey). Orange triangles indicate radiocarbon dates and circles indicate age control points derived from correlation with the LR04 benthic isotope stack of Lisiecki and Raymo (2005). Sedimentation rates are derived from linear interpolation between age data. MIS denotes the Marine stable oxygen isotope stages.

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**Figure 3:** Stable oxygen and carbon isotope records of planktonic and benthic foraminifera of sediment core SO-236-052. Displayed are the planktonic species *G. ruber* (light blue), the epibenthic species *C. mabahethi* (dark blue) and the deep infaunal species *G. affinis* s.l. (red). MIS denotes the Marine stable oxygen isotope stages.

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**Figure 4:** Sedimentological and geochemical records of sediment core SO-236-052-4 from the central part of the Maldives Inner Sea. a) Sortable silt (black) and bulk sediment (grey) MEAN values, b) Total Organic Carbon (TOC) (dark green) and calcium carbonate (light green) content of the sediment, c) iron (dark blue) and silicium (light blue), and d) barium (pink) and strontium (purple). All element count rates are given in relation to the calcium counts of the XRF core scans. Thin lines represent full-resolution data, bold lines indicate five-point running averages. Only the Ba/Ca ratio is displayed with a fifteen-point running average. MIS denotes the Marine stable oxygen isotope stages.

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**Figure 5:** a) Epibenthic stable oxygen isotope record of core SO-236-052-4 (dark blue) in comparison with the LR04 benthic stable isotope stack (dashed grey line; Lisiecki and Raymo 2005). b-c) Comparison of the sortable silt records of sediment cores M74/4-1143 and SO-236-052-4, and d) relative abundance of meroplanktonic Benthic Foraminifera (BF; including the genera *Cymbaloporeta* and *Tretomphaloides*) in sediments of core SO-236-052-4. Thin lines represent full-resolution data, bold lines indicate five-point running averages. MIS denotes the Marine stable oxygen isotope stages.

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**Figure 6:** Comparison of benthic foraminiferal faunal records of core SO-236-052-4 from the central part of the Maldives Inner Sea. a) Shannon-Wiener diversity index  $H(S)$ , b-d) Q-mode benthic foraminiferal assemblages, including the *N. proboscidea*-*D. araucana*-fauna (assemblage 1), the *C. mabahethi*-fauna (assemblage 2), and the *N. proboscidea*-*H. elegans*-fauna (assemblage 3). Loadings  $\geq 0.5$  are defined as significant after Backhaus et al. (2008). e-g) Distribution of

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selected important and associated benthic foraminiferal taxa, given in percent. The meroplanktonic Benthic Foraminifera (BF) comprise the genera *Cymbaloporeta* and *Tretomphaloides*.

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**Figure 7:** Variation of the insolation difference between the June and December solstice at 30° N (after Laskar, 2004; calculated with AnalySeries 2.0: Paillard et al. 1996) (a) in comparison with geochemical and benthic foraminiferal productivity records of core SO-236-052-4. b) Total Organic Carbon (TOC) content and c) Ba/Ca ratio as derived from XRF scanning count rates as indicator for surface water productivity. d) Fe/Ca ratio and e) relative abundance of agglutinated benthic foraminifera as indicator for enhanced dust supply. f) Principal Components (PC) show the *C. mabahethi*-fauna (assemblage 2) and *N. proboscidea*-*H. elegans*-fauna (assemblage 3). Thin lines represent full-resolution data, bold lines in b), d) and e) indicate five-point running averages, the bold line in c) indicate a fifteen-point running average. MIS denotes the Marine stable oxygen isotope stages.

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**Figure 8:** Water mass circulation changes obtained from stable  $\delta^{13}\text{C}$  data of core SO-236-052-4 (Indian Ocean) in comparison to ventilation changes in the Arabian Sea. a)  $\delta^{13}\text{C}$  records of the planktonic *G. ruber* (light blue) and the epibenthic *C. mabahethi* (dark blue), b) difference between the planktonic and epibenthic stable carbon records ( $\Delta\delta^{13}\text{C}_{Gr-Cm}$ ), c) differences between epibenthic and deep endobenthic  $\delta^{13}\text{C}$  records of SO-236-052-4 (dark blue) from the intermediate Maldives Inner Sea in comparison to that of GeoB3004 (purple) from the deep Arabian Sea (Schmiedl and Mackensen, 2006). Changes in intermediate- and deep-water oxygen concentrations are calculated by the linear regression between the  $\Delta\delta^{13}\text{C}$  and  $\text{O}_2 < 235 \mu\text{mol kg}^{-1}$  after Hoogakker et al. (2015). Variation of the insolation difference between the June and December solstice at 30° N (yellow) were estimated after Laskar (2004) with AnalySeries 2.0 (Paillard et al., 1996). All lines indicate five-point running averages. MIS denotes the Marine stable oxygen isotope stages. *Cib.* = *Cibicides*, *Cm* = *Cibicides mabahethi*, *Cw* = *Cibicides wuellerstorfi*, *Ga* = *Globobulimina affinis*, *Gr* = *Globigerinoides ruber*.

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830 Figure 1

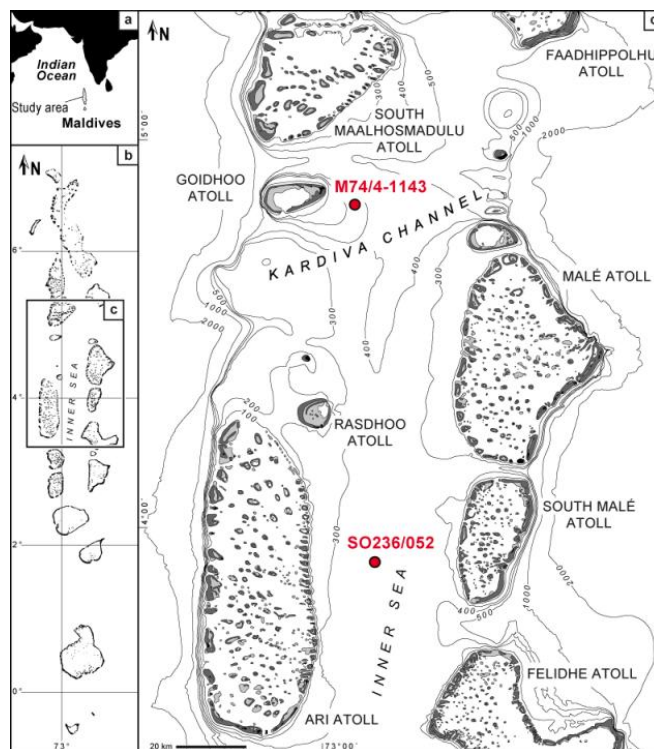




Figure 2

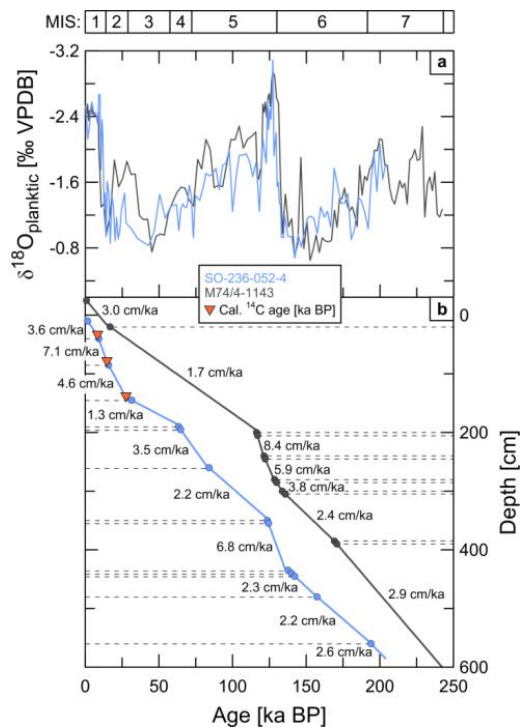




Figure 3

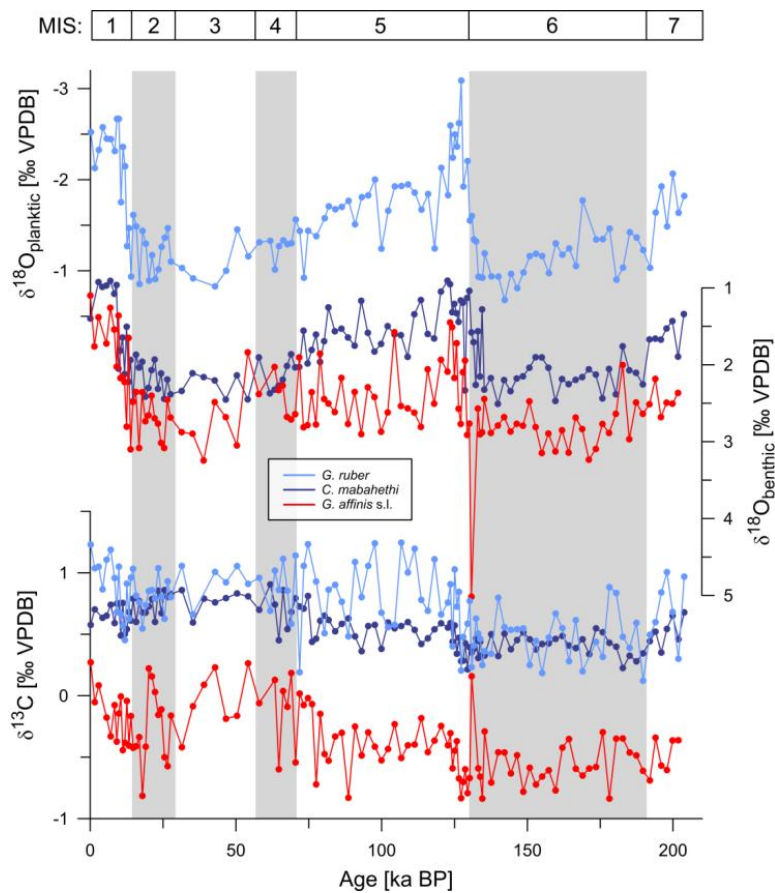




Figure 4

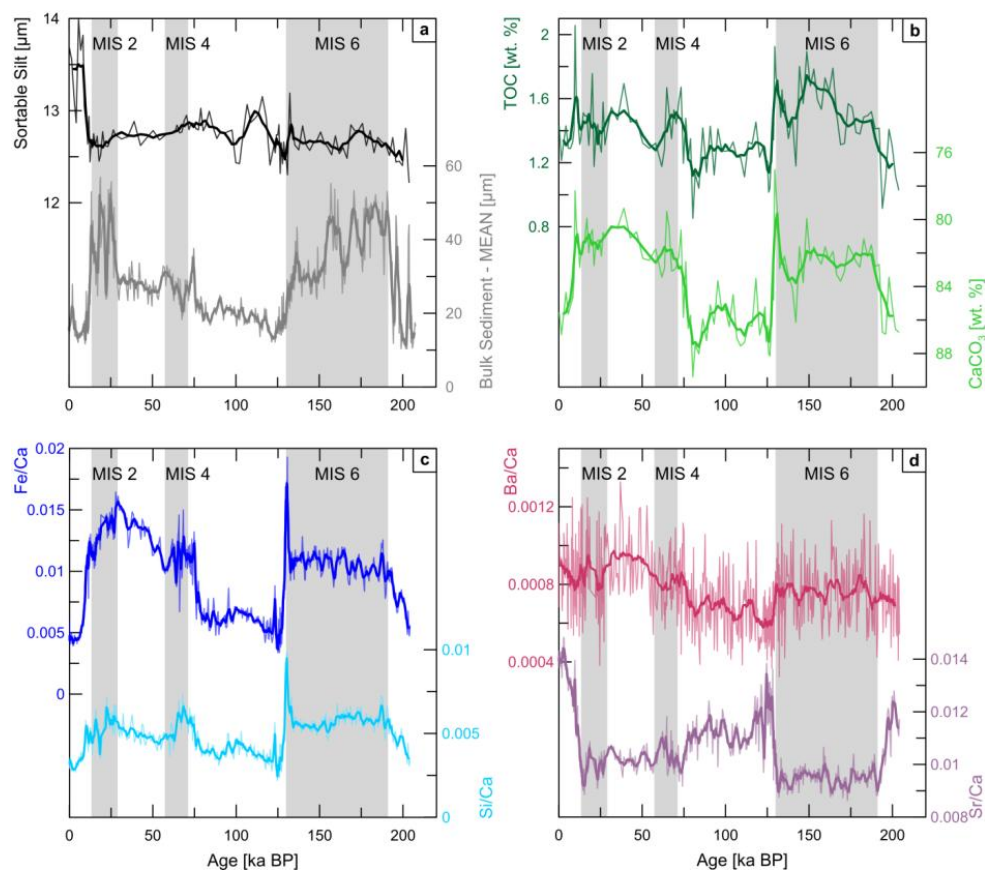
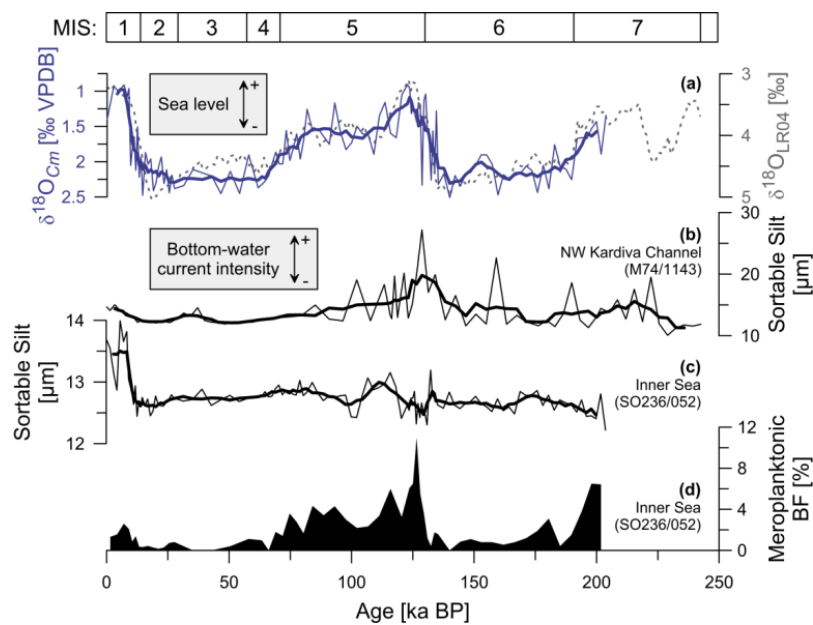




Figure 5







835 Figure 6

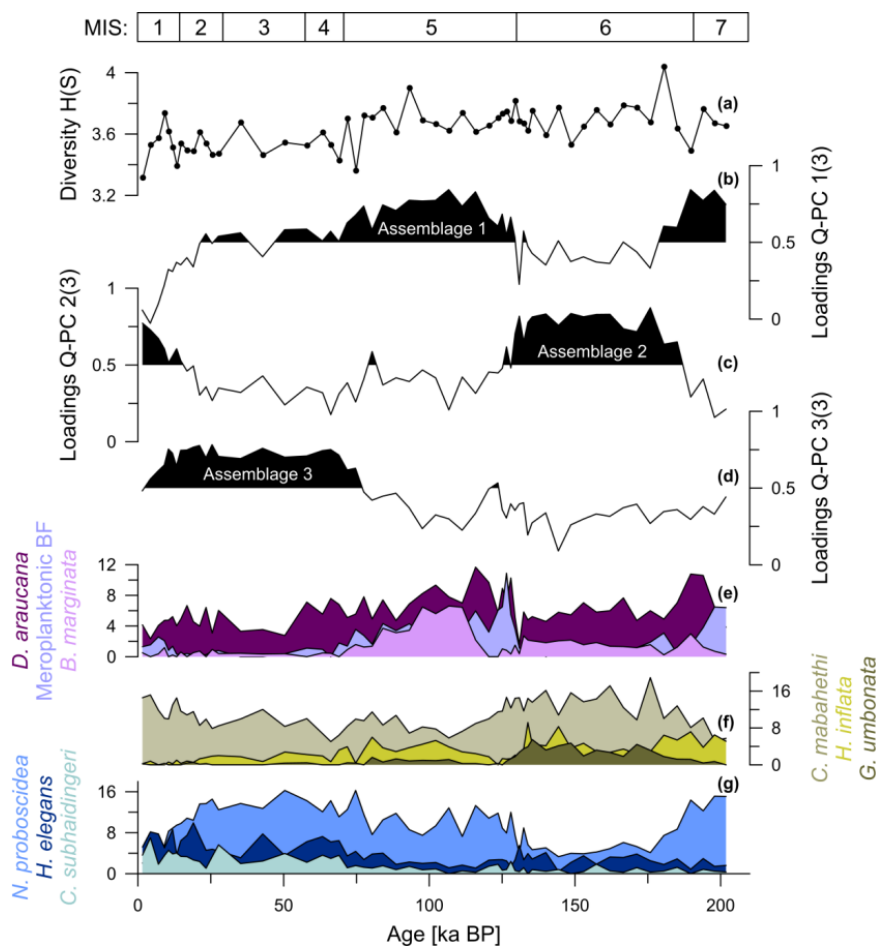




Figure 7

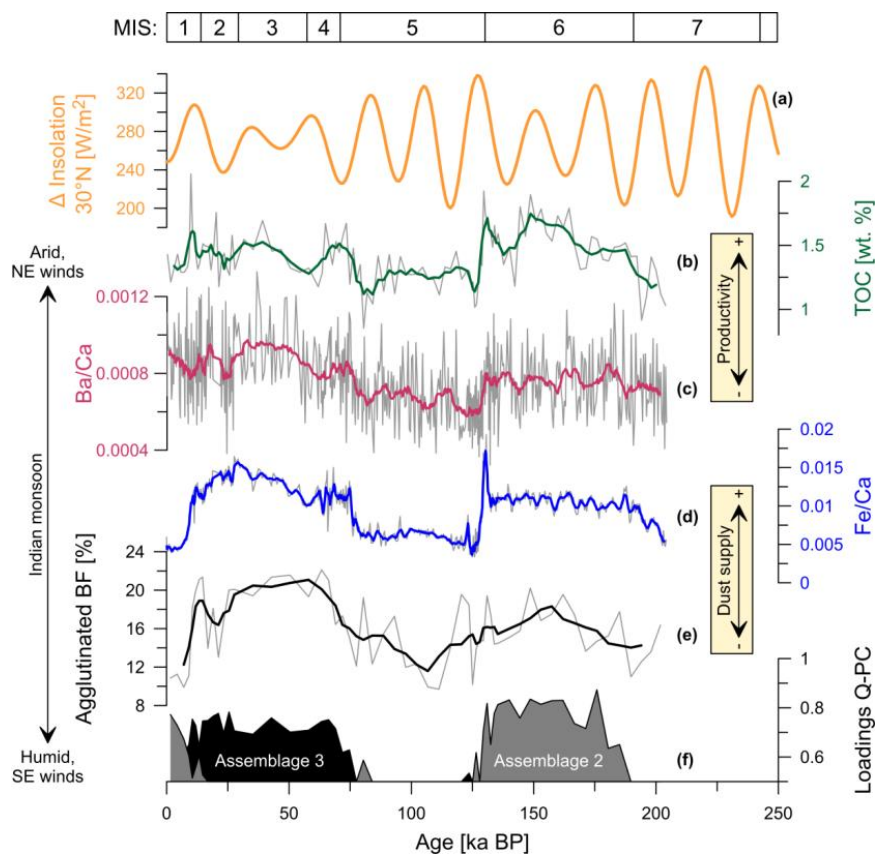




Figure 8

