New stable isotope records of sediment cores from the SE Arabian Sea – Inferences on the variations in monsoon regime during the late Quaternary

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We reconstruct here the changes in regional hydrography related to the fluctuations in Indian monsoons during the late Quaternary based on the stable isotope composition of the foraminifers and organic matter in three sediment cores from the upper continental slope of western India. The planktic foraminiferal d^{18}O contrast between the Last Glacial Maximum (LGM) and Holocene (Δd^{18}O), after correcting for the global 'ice effect' is relatively high (0.8–1.0‰), suggesting notable changes in the sea surface conditions. This includes a moderate sea surface cooling (~ 2°C) and an enhanced evaporation (increasing salinity by ~ 2.5 p.s.u.) during the LGM and/or increased precipitation during the early Holocene. The diminished Δd^{18}O value of benthic records (~ 1.0‰) appears to be a basin-wide phenomenon along the shallow depths of the upper continental slope and is related to the eustatic sea level fluctuations. Carbon isotope composition of the organic matter suggests that primary productivity was the main source of organic carbon along this margin throughout the late Quaternary.

THE modern surface circulation and hydrography in the northern Indian Ocean and rainfall over Indian subcontinent are intimately related to the seasonal variations in the Indian monsoon system. The strong seasonality in monsoons also leads to large changes in the marine productivity, with highest productivity values observed during the summer monsoons[1,2]. Information on the late Quaternary (past ~ 130,000 years) variations in Indian monsoons is important in assessing the natural environmental changes that have taken place in the past and that may occur in the

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future. Palaeoclimatic records provide the only way to assess the reliability and reproducibility of state-of-the-art climate models that simulate the monsoon conditions different from present day. Valuable information related to the monsoon history is preserved in the sediments of northern Indian Ocean in the form of microfossil abundance, pollens, organic carbon and the elemental and isotopic compositions of shells and other sediment components. These parameters have been universally used as 'proxies' for inferring the climatic and ocean characteristics during the time of their preservation. Several such proxy records from the Arabian Sea indicated that the late Quaternary monsoon fluctuations were largely in response to the global and regional climate forcing mechanisms[3–11].

More recent data on past climate change from the Arabian Sea and Indian subcontinent point to the diverse nature of monsoon variations[12–17]. Most of the Arabian Sea records come from the north-western margin, where monsoon-induced upwelling basically controls both the surface productivity and hydrographic structure. Records from the SE Arabian Sea (south-western margin of India) suggest a more complex scenario. Although a few studies indicate similar productivity patterns throughout the Arabian Sea[15], mounting evidences from multi-proxy records suggest that the winter monsoon had significant influence on primary productivity along the SE Arabian Sea in the past[16–20]. Further, it has been suggested that mixing with monsoon-related freshwater containing lighter isotopes is a dominant factor influencing the oxygen isotope composition of the sea water in this region[3,17,21]. In this study we report the oxygen and carbon isotope records in three gravity cores from the SE Arabian Sea and discuss their regional climatic implications. This is an extension of our earlier studies in this area.

The three sediment cores selected for this study were raised from shallow depths (335–355 m water depth) of the upper continental slope of western India (Figure 1). These cores were collected during the 6th cruise of *A. A. Siderenko*, a vessel chartered by the Department of Ocean Development (DOD), New Delhi. Although all cores fall within the oxygen minimum zone (OMZ ~ 150–1200 m), they depict diverse depositional settings and contrasting sedimentation patterns[22,23]. The stable oxygen isotope (d^{18}O) composition of the surface-dwelling planktic foraminifers *Globigerinoides sacculifer* and/or *Globigerinoides ruber* (400–450 μm size) was used to reconstruct the past surface water conditions at two sites (GC-3 and GC-6). Benthic foraminifer *Uvigerina peregrina* was used for stable isotope studies in core GC-4. All measurements were made at the Isotope laboratory of University of Bremen using a Finnigan MAT 252 mass spectrometer with a measurement precision better than ± 0.07‰. Calibration to the international standard Pee Dee Belemnite (PDB) was achieved through NBS 19. Stable carbon isotope composition of the organic matter ($d^{13}C_{org}$) was also determined in core GC-4 using a Finnigan Delta-E mass spectrometer. Details of isotope measurements and calibration can be found elsewhere[17]. The analytical precision of the measurements was better than ± 0.1‰.

Chronology for these cores was obtained by correlating the oxygen isotope records with the stacked SPECMAP d^{18}O record of Imbrie *et al*.[24]. Additionally, the core GC-4 has three bulk carbonate ^{14}C dates (Figure 2). Of the three d^{18}O records, GC-3 record is better resolved and the data are available for the upper ~ 200 cm of the core. As the oxygen isotope records of core GC-4 for the upper ~ 240 cm interval are of low resolution, it is difficult to define the precise stage boundaries and age beyond the ^{14}C dating points. The GC-6 d^{18}O record spans nearly 300 cm interval and the uppermost Holocene sediments appear to have eroded (Figure 2).

Stable oxygen isotope records on planktic/benthic foraminifers of the studied cores are shown in Table 1 and Figure 2. It is well known that the d^{18}O composition of the marine calcareous shells mainly depends on the temperature of shell calcification and local variations in salinity, in addition to changes in the composition of sea water itself[25]. Variations of surface salinity in the tropical oceans are strongly related to the evaporation–precipitation (E–P) balance and thus represent a sensitive climate indicator. At present the south-western continental margin of India is a region of relatively low salinity compared to other parts of the Arabian Sea and does not follow the normal latitudinal salinity variations[26]. This is mainly because of the large influx of freshwater from hinterland during the summer monsoon and transport of low-salinity waters from Bay of Bengal during the winter monsoon. Therefore, the planktic d^{18}O composition from this region may have varied in the past as a function of local

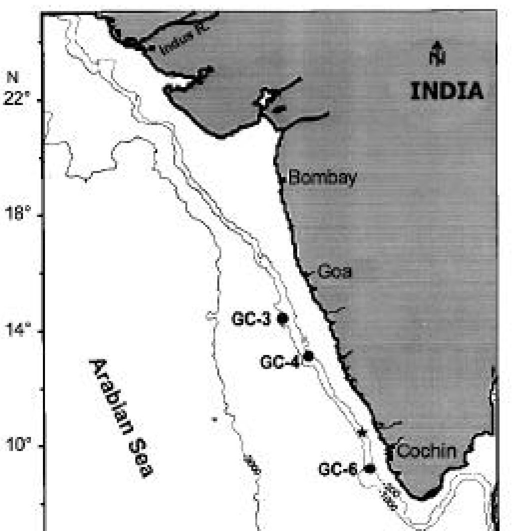

Figure 1. Location map and core sites. ★ indicates the location of GC-5 site described by Thamban *et al*.[17].

precipitation. Recently, the down core variations of planktic δ^{18}O values from the SE Arabian Sea were interpreted in terms of past changes in E–P (ref. 21).

The *d*^{18}O record of *G. ruber* and *G. sacculifer* in core GC-3 fluctuated between – 2.65 to – 0.52‰ and – 2.31 to – 0.18‰, respectively (Figure 2 *a*). The heaviest *d*^{18}O values occur at 80–100 cm interval, which may correspond to the last glacial maximum (LGM around ~ 18,000 ^{14}C year B.P.). The *G. sacculifer* *d*^{18}O records showed the classical two-step deglaciation with a brief plateau around

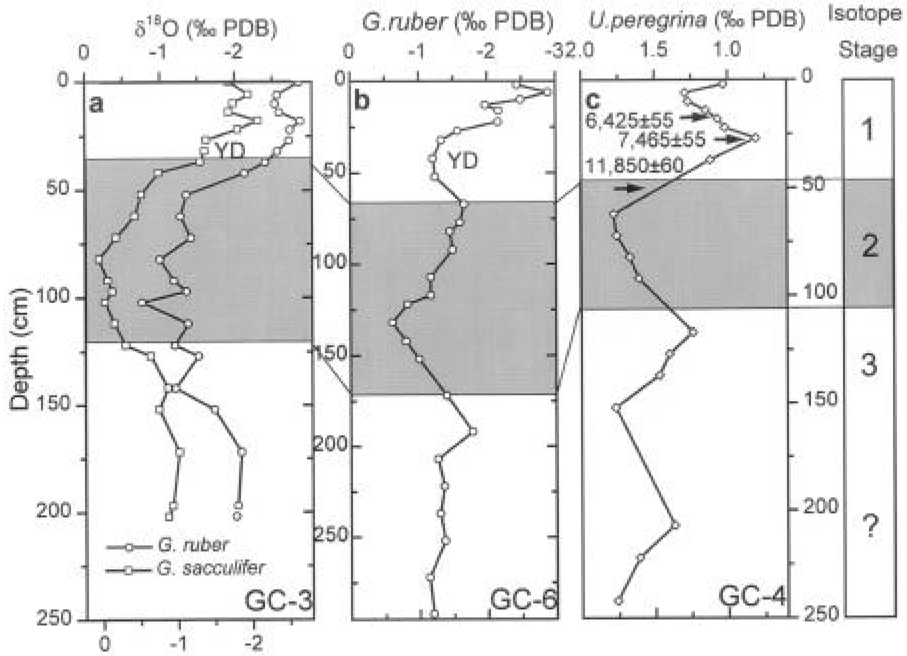

Figure 2. Oxygen isotope records of planktic/benthic foraminifers. Bulk carbonate ^{14}C dates are shown by arrows.

Table 1. Stable isotope data in three sediment cores

Core GC-3			Core GC-6		Core GC-4		
Depth (cm)	δ^{18}O ‰ *G. ruber*	δ^{18}O ‰ *G. sacculifer*	Depth (cm)	δ^{18}O ‰ *G. ruber*	Depth (cm)	δ^{18}O ‰ *U. peregrina*	δ^{13}C$_{org}$ ‰
0	– 2.63	– 1.92	2	– 2.44	2	1.03	– 20.45
6	– 2.34	– 2.18	6	– 2.89	6	1.29	– 20.31
10	– 2.31	– 1.98	10	– 2.49	10	1.27	– 20.38
14	– 2.37	– 1.92	13	– 1.98	14	1.15	– 20.36
18	– 2.65	– 2.31	16	– 2.17	18	1.07	– 20.25
22	– 2.51	– 2.04	22	– 2.16	22	1.02	–
27	– 2.50	– 1.62	27	– 1.57	27	0.81	– 20.30
32	– 2.34	– 1.60	32	– 1.33	37	1.12	–
37	– 2.18	– 1.54	42	– 1.21	42	–	– 20.34
42	– 1.90	– 0.98	52	– 1.24	52	–	– 20.29
52	– 1.12	– 0.75	67	– 1.66	62	1.78	– 20.34
62	– 1.04	– 0.66	77	– 1.60	72	1.76	– 20.39
72	– 1.18	– 0.41	82	– 1.45	82	1.67	– 20.27
82	– 0.76	– 0.18	92	– 1.49	92	1.61	– 20.33
92	– 0.95	– 0.30	107	– 1.17	107	–	– 19.86
97	– 1.12	– 0.36	117	– 1.17	117	1.24	– 20.29
102	– 0.52	– 0.26	122	– 0.83	127	1.40	– 19.92
112	– 1.14	– 0.39	132	– 0.61	137	1.47	– 20.07
122	– 0.96	– 0.54	142	– 0.81	152	1.77	– 20.15
127	– 1.28	– 0.87	152	– 1.00	172	–	– 20.12
142	– 0.97	– 1.10	172	– 1.40	192	–	– 19.99
152	– 1.49	– 0.98	192	– 1.78	207	1.37	– 19.81
172	– 1.85	– 1.25	207	– 1.27	222	1.61	– 19.83
197	– 1.80	– 1.16	222	– 1.36	242	1.76	– 19.96
202	– 1.78	– 1.10	237	– 1.30			
			252	– 1.37			
			272	– 1.14			
			292	– 1.20			

~ 11,000 ^{14}C year B.P., which is attributed to the global Younger Dryas event. The *G. ruber* d^{18}O record of core GC-6 varied between – 0.6‰ and – 2.9‰ (Figure 2 *b*). The LGM, as inferred from d^{18}O record is placed at 145–120 cm interval and the d^{18}O values again returned to near-glacial values between 55 and 30 cm interval, possibly corresponding to the Younger Dryas event. For core GC-4, the d^{18}O measurements were carried out on benthic species *U. peregrina* and the values fluctuated between 1.8‰ during the LGM and 0.81‰ in the Holocene (Figure 2 *c*). Even though the sampling resolution is poor in this core, the d^{18}O records show the broad glacial–interglacial isotope stages. The LGM is indicated by the heaviest d^{18}O value at 70–75 cm interval and the Holocene maxima towards lighter d^{18}O values occur at 25–30 cm interval corresponding to 7500 ^{14}C yr B.P. (Figure 2 *c*). The $d^{13}C_{org}$ record of GC-4 (Figure 3) is remarkably consistent throughout the core with values varying between – 19.71 and – 20.45‰ (av. – 20.1‰). Although there appears to be a slight decrease towards lighter values from the bottom to the top, the difference is < 1‰ and no significant variation was obtained between the glacial and interglacial stages (Figure 3).

The estimated LGM to Holocene d^{18}O amplitude (Δd^{18}O; difference between the d^{18}O values representing LGM and Holocene) for GC-3 is consistent for both the planktic species (~ 2.1‰) and is comparable with that of GC-6 (~ 2.2‰). These values also compare exceptionally well with the Δd^{18}O value of ~ 2.1‰ obtained for the high-resolution planktic d^{18}O records of core GC-5 from the south-western continental margin of India (Figure 1; ref. 17). In order to quantify the past sea surface conditions at the core sites, we have computed the residual Δd^{18}O values ($\Delta d^{18}O_{res}$) by subtracting 1.2‰ (global 'ice effect')[27,28] from the estimated Δd^{18}O. The $\Delta d^{18}O_{res}$ values thus obtained (0.9‰ and 1.0‰ for GC-3 and GC-6, respectively) can solely be ascribed to the fluctuations in sea surface temperature (SST) and/or salinity (SSS).

The improved palaeo-SST estimations using alkenones and foraminferal transfer functions (TF) from the eastern Arabian Sea indicate that the LGM was indeed cooler by at least 2°C than at present[18–20]. This is in contrast with the findings of CLIMAP[29] that the tropical Arabian Sea experienced no cooling or even slight warming during LGM. It was estimated that a 1°C change in temperature would lead to a d^{18}O variation equivalent to 0.25‰ (ref. 30). Thus the LGM cooling of sea surface would account for a $\Delta d^{18}O_{res}$ value of ~ 0.5‰, leaving local salinity variations as a significant contributor for the planktic Δd^{18}O.

Duplessy[3] suggested that the large glacial–interglacial d^{18}O variations along the eastern Arabian Sea are mainly related to the precipitation-related salinity variations, with little or no variations in SST. Based on the recent palaeotemperature database for eastern Arabian Sea, we believe that the planktic d^{18}O records contain signatures of both temperature and salinity. If the $\Delta d^{18}O_{res}$ values were influenced by the freshwater discharge from rivers, this would require large changes in salinity as the variations in evaporation and precipitation cause only small oxygen isotope fractionation in tropical regions that are influenced by strong river discharge. Using the d^{18}O surface seawater–salinity relationship from eastern Arabian Sea[21], the remaining $\Delta d^{18}O_{res}$ value of 0.4–0.5‰ after accounting for the temperature effect of ~ 0.5‰, can be attributed to a salinity variation of ~ 2 p.s.u. Major hydrographic changes thus inferred in the study area are a moderate cooling (~ 2ºC) and an increased evaporation during the LGM (enhancing salinity by ~ 2.5 p.s.u.) and/or an increased precipitation during the early Holocene. Our interpretation is consistent with the inferred moderate LGM cooling[19], increased evaporation and/or decreased precipitation during the LGM[3] and a low E–P value during the early Holocene for the eastern Arabian Sea[21]. The SW monsoon intensity was very weak and the dry NE monsoon was the dominant feature during the LGM in the Arabian Sea[3]. The cool winds of the north-easterly winter monsoon could have kept the SST of eastern Arabian Sea low, well into spring and early summer, decreasing the mean SST during LGM. Also the dry winds which blew from the continent to the ocean could have increased the evaporation leading to an increase in salinity of the surface water.

Although the benthic LGM–Holocene amplitude reported here (Δd^{18}O ~ 1.0‰) is lower than that of several other intermediate depth Indian Ocean sites[31–33], it is comparable with the upper slope records[17] from the SE Arabian Sea (Δd^{18}O ~ 0.8‰). This has been mainly attributed to changes in hydrography related to the sea level oscillations[17]. Due to the shallow depth of the core sites (< 350 m), a sea level lowering by 120 m during the

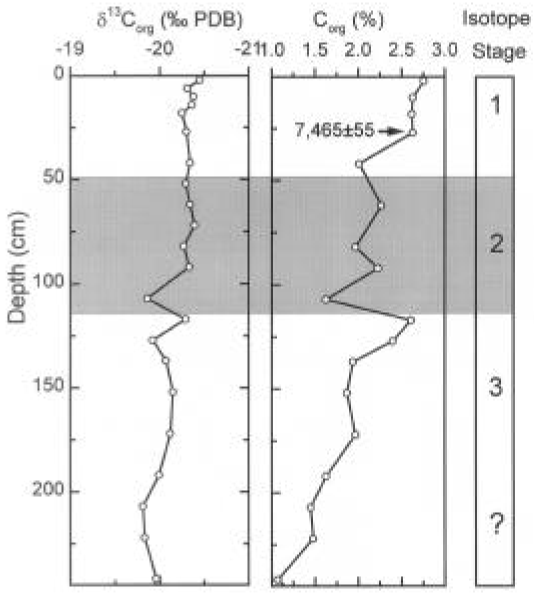

Figure 3. Carbon isotope record of organic matter and organic carbon content in core GC-4.

LGM would lead to large difference in ambient water temperature at these depths. The estimated $\Delta d^{18}O_{res}$ values at GC-5 and GC-4 sites corroborate this. The $\Delta d^{18}O_{res}$ value is ~ 0.8‰ in GC-5, which is from 280 m water depth, whereas it is 1.0‰ in GC-4 which is from 335 m water depth. We therefore suggest that the diminished LGM–Holocene amplitude in benthic $d^{18}O$ records is a basin-wide phenomenon along the upper continental slopes (< 500 m water depth) of the Arabian Sea and has direct relevance to the late Quaternary sea level oscillations.

The consistently heavy $d^{13}C_{org}$ values (– 19.71 to – 20.45‰) throughout the core GC-4 are within the range ascribed for marine planktic organic matter (– 18 to – 21‰) in tropical waters[34]. This suggests that the organic matter was mainly of marine origin throughout the late Quaternary, with little influence from the terrestrial sources. Due to the poor chronological control, we have not estimated the mass accumulation rates of organic carbon, which is the more direct proxy to interpret the palaeoproductivity[17]. Nevertheless the apparent low sedimentation rate throughout the core indicates that the observed variations within the C_{org} record of this core can be attributed to the palaeoproductivity variations. The increased C_{org} values during the past ~ 7.5 ka may suggest that the Holocene surface productivity increased around ~ 7.5 ^{14}C ka B.P., but not during the early Holocene, as suggested by others from the records of north-western Arabian Sea[8,35]. A low productivity during the early Holocene and its increase towards late Holocene are in conformity with the findings of Thamban *et al.*[17].

Based on this study and our earlier investigations[17, 23], it is suggested that the main source of organic matter to the eastern Arabian Sea is surface water productivity. The near absence of any terrigenous organic matter supply to the upper continental slope is remarkable, because the numerous rivers draining to the eastern Arabian Sea carry large amount of freshwater that can be traced in the surface hydrography[26]. It is therefore likely that the numerous backwater systems, characteristic of the rivers draining to the western margin of India, act as sinks for the terrigenous river-bound organic fluxes. On a regional and global perspective, the influence of terrigenous organic carbon supply on the carbon cycling in Arabian Sea appears negligible.

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ACKNOWLEDGEMENTS. We thank Dr E. Desa, Director, National Institute of Oceanography, Goa for encouragement. We are grateful to Professors G. Wefer, R. R. Schneider and P. J. Müller of University of Bremen, Germany, for the mass spectrometer facilities and Professors S. Krishnaswami and R. Bhushan of Physical Research Laboratory, Ahmedabad for the ^{14}C dates. Financial support from CSIR, New Delhi and DAAD, Germany in the form of research fellowships is gratefully acknowledged. This is NIO contribution No. 3646.

Received 12 August 2000; revised accepted 16 February 2001