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# Timing, cause and consequences of mid-Holocene climate transition in the Arabian Sea

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ABSTRACT

We reconstruct centennial scale quantitative changes in surface seawater temperature (SST), evaporation-precipitation (from Mg/Ca and $\delta^{18}O$ of surface dwelling planktic foraminifera), productivity (from relative abundance of *Globigerina bulloides*), carbon burial (from %$CaCO_3$ and organic carbon [%$C_{org}$]) and dissolved oxygen at sediment–water interface, covering the entire Holocene, from a core collected from the eastern Arabian Sea. From the multi-proxy record, we define the timing, consequences and possible causes of the mid-Holocene climate transition (MHCT). A distinct shift in evaporation-precipitation (E-P) is observed at 6.4 ka, accompanied by a net cooling of SST. The shift in SST and E-P is synchronous with a change in surface productivity. A concurrent decrease is also noted in both the planktic foraminiferal abundance and coarse sediment fraction. A shift in carbon burial, as inferred from both the %$CaCO_3$ and %$C_{org}$, coincides with a change in surface productivity. A simultaneous decrease in dissolved oxygen at the sediment–water interface, suggests that changes affected both the surface and subsurface water. A similar concomitant change is also observed in other cores from the Arabian Sea as well as terrestrial records, suggesting a widespread regional MHCT. The MHCT coincides with decreasing low-latitude summer insolation, perturbations in total solar intensity and an increase in atmospheric $CO_2$.

## Introduction

Early research suggested that the Holocene was an epoch of relatively stable climate due to limited changes in climatic forcing, which apparently facilitated the rise of civilizations. Recent high-resolution centennial records, however, reveal distinct climatic events in the Indian subcontinent and adjoining seas during the Holocene (Staubwasser et al., 2003a,b; Gupta et al., 2005; Dykoski et al., 2005; Yadav et al., 2011). Such climatic changes during times of limited natural boundary conditions can help in the understanding of Earth's response to increasing anthropogenic influences (Schewe and Levermann, 2012; Cook et al., 2015). The mid-Holocene climatic transition (MHCT) is a very prominent feature of the present interglacial (deMenocal et al., 2000; Weldeab et al., 2005; Roberts et al., 2011; Dixit et al., 2014; Vincenzo and Massimo, 2015). Defining the timing of the MHCT is important as it coincides with distinct changes in human civilizations and has been linked with anthropogenic activities (Ruddiman and Ellis, 2009; Kelly et al., 2013). Previous studies show that the MHCT in the Arabian Sea dates to between 7 and 5 ka (Sarkar et al., 2000; Govil and Naidu, 2010; Singh et al., 2011; Kessarkar et al., 2013; Naik et al., 2014). A centennial-scale multi-proxy record covering the entire Holocene can help better define the timing of the MHCT. A precisely dated MHCT can then be used to help understand the lead–lag relationship between different processes during major climate transitions in the eastern Arabian Sea. Such a record can further help to understand land-ocean interaction and to compare regional climatic events in the context of various global climatic changes. In this paper, we develop a record of mid-Holocene climate changes by using a gravity sediment core (SK237 GC04, hereafter referred as Malabar core) from the continental slope of southeastern Arabian Sea (10°58.65′ N, 74°59.96′ E, water depth 1245 m). The core had centennial scale resolution and covered the last glacial-interglacial transition (Fig. 1). The stable isotopic and trace element analysis of surface dwelling planktic foraminifera from this core was used to define the timing of deglacial warming and precipitation-evaporation changes during the last glacial-interglacial transition (Saraswat et al., 2013). We use multi-proxy analysis on the Holocene section of this core to reconstruct both the surface and sediment–water interface conditions at centennial-scale resolution,

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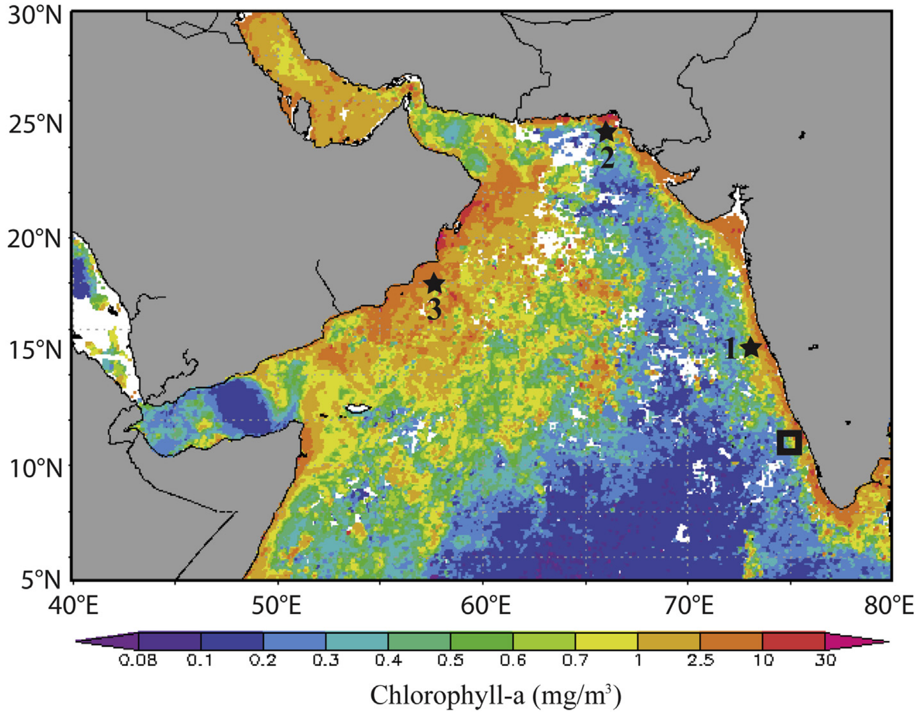

**Fig. 1.** The core location in the southeastern Arabian Sea is marked by an open black rectangle. Other cores discussed in the text are marked by filled black star (1. SK17, Anand et al., 2008; 2.63KA-41KL, Staubwasser et al., 2003a,b; 3. RC27-23, Altabet et al., 2002). The template is surface primary productivity (chlorophyll-a, mg/m$^3$) in the Arabian Sea during the southwest monsoon season (June-July-August-September; Acker and Leptoukh, 2007).

throughout the Holocene, to define the timing, possible cause and consequences of the MHCT in the eastern Arabian Sea.

## Oceanographic setting

The eastern Arabian Sea is characterized by a seasonal reversal of surface currents in response to winds (Shankar et al., 2002). The equatorward West India Coastal Current brings relatively more saline water to the eastern Arabian Sea prior to and during the southwest monsoon, whereas the poleward winter monsoon current transports low salinity water from the western Bay of Bengal into the eastern Arabian Sea during boreal winter (Prasanna Kumar et al., 2004). Increased productivity in this region is observed during the summer monsoon season (Levy et al., 2007, Fig. 1). The sea surface temperature (SST) in the eastern Arabian Sea increases during the pre-summer monsoon season, leading to the development of a small warm pool that peaks in April. The eastern Arabian Sea warm pool dissipates prior to the onset of summer monsoon precipitation as a result of upwelling (Shenoi et al., 1999). The region is also marked by both seasonal shallow water hypoxic zone (Naqvi et al., 2000) as well as a perennial intermediate water-depth oxygen minimum zone (OMZ) that extends from ~150 to ~1200 m below sea level (Naqvi, 1991; Naqvi et al., 2003).

## Materials and methodology

The Holocene section (top 100 cm, subsampled at 1 cm intervals) of the Malabar core was used to reconstruct centennial-scale changes. The section was dated by using five Accelerator Mass Spectrometer $^{14}$C ages on mixed planktic foraminifera measured at the Center for Applied Isotope Studies, the University of Georgia, USA (Table 1; Saraswat et al., 2013). Marine09 (Reimer et al., 2009) and Calib6.0 version (Stuiver and Reimer, 1993) were used to calibrate the $^{14}$C ages. A reservoir correction (ΔR) of 138 ± 68 yr for the eastern Arabian Sea was applied (Southon et al., 2002). The age model utilizes the calibrated ages as tie-points and assumes a linear sedimentation rate (Fig. 2). A minimum of 300 benthic foraminifera were picked and examined from each sample of the coarse sediment fraction (>63 μm). The relative abundance of angular asymmetrical benthic foraminifera (AABF) was counted following the methods of Nigam et al. (1992, 2007). Planktic foraminifera were picked from the >125 μm sediment fraction. Changes in relative abundance of planktic foraminifera *Globigerina bulloides* (an indicator of high productivity), coarse sediment fraction (CF), organic carbon weight percentage (%$C_{org}$) and calcium carbonate weight percentage (%$CaCO_3$) were used to reconstruct past monsoon strength and associated changes (Fig. 3). The total %C was measured with a CNS analyzer and inorganic carbon was measured with a coulometer. The precision of total carbon measurements was better than ±0.49%. The precision of total inorganic carbon measurements, based on repeat analysis of laboratory standard after every ten samples, was better than ±0.22%. The %$CaCO_3$ was calculated from the total inorganic carbon. Total %$C_{org}$ was calculated by subtracting total inorganic carbon from the total carbon. The cumulative error associated with %$C_{org}$ estimates was ±0.54%. Seawater paleotemperature was reconstructed from changes in the Mg/Ca ratio of the white variety of planktic foraminifera *Globigerinoides ruber* (Saraswat et al., 2013), which is a very robust method to quantify paleotemperatures (Lea et al., 1999; Saraswat et al., 2005; Weldeab et al., 2005). The error in seawater temperature estimated from Mg/Ca in *G. ruber* is ±1.3 °C. The cumulative error was calculated from the standard deviation of replicate analyses of the samples, when available, combined with the standard deviation of consistency standards during the sample run, as well as the error associated with the calibration equation. The Malabar core data was compared with other records published from the Arabian Sea as well as Indian subcontinent (Fig. 4). Additionally, local evaporation-precipitation changes have been reconstructed by subtracting

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