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Monsoon related changes in sea surface productivity and water column denitrification in the Eastern Arabian Sea during the last glacial cycle

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Abstract

Sea surface salinity reconstruction for the Holocene and the Last Glacial Maximum (LGM) suggests that the LGM-Eastern Arabian Sea was more saline (by ~1.5 psu) than the Holocene due to weakened freshwater flux to the region, and intensified winter monsoons. Time-series of sedimentary organic-carbon (C_{org}), $\sum$alkenone and $\delta^{13}C_{org}$ for the last 100 kyr, together, indicate increased glacial productivity. Significantly reduced sedimentary-$\delta^{15}N$ during the LGM indicates, however, diminished water column denitrification in spite of increased productivity. The distinct decoupling of denitrification from productivity during the LGM can be explained by vigorous ventilation of the thermocline as a result of simultaneously intensified formation of high-salinity water and deep-winter mixing in northern-Arabian Sea related to the extreme cold climate. The closely comparable time-series $\delta^{15}N$ records across the Arabian Sea suggest basin-wide homogenisation of the isotopic signal. This probably resulted from combined monsoon-dependent surface water mixing, due to changes in the relative strength of reversing surface circulations, and intermediate water mixing, due to changes in north–south salinity gradient.

Keywords: Arabian Sea; stable isotopes; palaeoclimate; monsoons; productivity; denitrification

1. Introduction

The Arabian Sea (AS) sedimentary records have shown contrasting monsoon driven productivity on a glacial–interglacial time-scale. On one hand, the LGM productivity was shown to have decreased in the western-AS (Emeis et al., 1995; Spaulding and Oba, 1992 and references therein) and southeastern-AS (Pattan et al., 2003). On the other hand, the northern and eastern regions of the basin exhibited increased LGM-productivity (Cayre and Bard, 1999; Rostek et al., 1997; Schulte et al., 1999; Thamban et al., 2001).

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The decreased LGM-productivity hinges on the weakened summer monsoons (Anderson and Prell, 1993) leading to reduced upwelling (Naidu and Malmgren, 1996 and references therein). Whereas, the increased LGM-productivity hinges on the hypothesised intensification of winter monsoons (Duplessy, 1982; Rostek et al., 1997) leading to an increased deep-water nutrient injection in to the photic zone (Cayre and Bard, 1999). There is no agreement even in regard to past-denitrification in the basin, where two views have been propounded. According to one view, the past changes in denitrification intensity were due to climate-linked variations in hydrography and productivity (Altabet et al., 1995), while the other view proposes that the changes in upwelling intensity were responsible (Ganeshram et al., 2000). These opposing views render the AS an interesting basin to investigate the responses of biogeochemical processes to the past climate. In that, the Eastern-AS (EAS) is least explored region when compared to the voluminous information available from the western-AS.

The modern surface hydrography in the northern Indian Ocean is governed by the monsoon wind system (Wyrtki, 1973). The summer monsoons not only cause heavy precipitation but also induce significant oceanic upwelling and associated increased productivity across the basin (Kabanova, 1968). Whereas, the winter monsoons enhance the evaporation in the northern-AS, leading to the formation of Northern Arabian Sea High Salinity Water (ASHSW) (Prasannakumar and Prasad, 1999). The influx of low salinity Bay of Bengal (BOB) water drawn by the winter monsoon currents (WMC) and the poleward coastal currents (PCC) along the western margin of India (Shetye et al., 1991) maintain the salinity balance in the basin. The PCC is driven by the long-shore pressure gradient developed with the decay of summer monsoons between the low-salinity southern region and the high-salinity northern region (Shetye et al., 1991), and is part of the WMC connecting the EAS to the BOB. Salinity of the BOB itself depends upon the summer monsoon related freshwater flux through the world's largest river system viz., Ganges–Brahmaputra and regional precipitation. Thus, the characteristic Indian monsoon system not only governs the productivity and particle flux (Haake et al., 1993) but also the evaporation–precipitation balance (E–P) (Sarkar et al., 2000). The modern-AS sustains an intense oxygen minimum zone (OMZ) due to basin-wide high productivity and inflow of low oxygen intermediate water (Olson et al., 1993), making it one of the world's largest marine denitrification regions (Codispoti, 1995). Marine denitrification produces significant enrichment of $\delta^{15}N$ in subsurface nitrates, which is reflected in the sinking organic particulates (Altabet et al., 1995).

The sediment of the AS provides an excellent record to understand past monsoon climate and its impact on marine biogeochemistry. In this study, we utilize multiple proxies from a single sediment core from the EAS and demonstrate that (a) productivity was higher during the cold and dry glacial climate than during the warm and wet Holocene climate due to weakened summer monsoons and strengthened winter winds, and (b) the water column denitrification was decoupled from local productivity during the extreme cold climate of the LGM.

2. Material and methods

A 410 cm long sediment core (SK117-GC8: hereafter referred as the 'core') was raised from the EAS (off Goa, India) at 15°29′N latitude and 72°51′E longitude from a water depth of 2500 m (Fig. 1). This water depth is well below the modern OMZ that occurs between 200 m and 1500 m. The recovered thin fluffy top of the core suggests an undisturbed core-top. Around 30 clean tests of *G. sacculifer* (without terminal sac), an upper mixed layer dwelling foraminifer, were handpicked under a microscope from 2 cm subsections of the core from the 250–350 μm size fraction for $\delta^{18}O$ measurements. The $^{18}O/^{16}O$ measurements were performed on a Finnigan MAT-251 MS using the purified CO_2 generated by the reaction of crushed and cleaned *G. sacculifer* tests with 100% H_3PO_4 at a constant reaction temperature of 60 °C. The results of the isotopic ratios are expressed as $\delta^{18}O$ and in per mil (‰) unit on PDB scale. Six replicate measurements show precision to be better than ± 0.04‰. The chronology for the core was obtained by tuning the down-core *G. sacculifer*-$\delta^{18}O$ to the low-latitude stacked SPECMAP marine oxygen isotope events (MIS) (Bassinot et al., 1994). The presence of Youngest Toba Tuff (YTT) ~72 Ka identified by the characteristic bubble-wall-junction