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Impact of monsoon-driven surface ocean processes on a coral off Port Blair on the Andaman Islands and their link to North Atlantic climate variations

Tim Rixen [a,*], Purvaja Ramachandran [b], Laura Lehnhoff [a], Dorothee Dasbach [a], Birgit Gaye [c], Brigitte Urban [d], Ramesh Ramachandran [b], Venugopalan Ittekkot [a]

[a] Leibniz-Zentrum für Marine Tropenökologie, Fahrenheitstr. 6, D-28359 Bremen, Germany
[b] Institute for Ocean Management, Anna University, Chennai 600 025, India
[c] Institut für Biogeochemie und Meereschemie, Universität Hamburg, Bundesstraße 55, D-20146 Hamburg, Germany
[d] Leuphana University Lüneburg, Faculty of Environmental Science and Engineering, Herbert-Meyer-Str. 7, D-29556 Suderburg, Germany

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ABSTRACT

North Atlantic climate variations are reflected in sedimentary records from the northern Indian Ocean in which two basins, the Arabian Sea and the Bay of Bengal, are strongly affected by the monsoon. Contrary to the Bay of Bengal the Arabian Sea plays an important role in the global marine nitrogen cycle. In its mid-water oxygen minimum zone (OMZ) bioavailable fixed nitrogen is reduced to nitrogen gas (NO_3^- ->N_2), whereas oxygen concentrations are slightly above the threshold of nitrate reduction in the OMZ of the Bay of Bengal. A coral colony (*Porites lutea*) growing south of Port Blair on the Andaman Islands in the Bay of Bengal was studied for its response to changes in the monsoon system and its link to temperature changes in the North Atlantic Ocean, between 1975 and 2006. Its linear extension rates, $\delta^{13}C$ and $\delta^{18}O$ values measured within the coral skeleton reveal a strong seasonality, which seems to be caused by the monsoon-driven reversal of the surface ocean circulation. The sampling site appears to be influenced by low salinity Bay of Bengal Water during the NE monsoon (boreal winter) and by the high salinity Arabian Sea Water during the SW monsoon in summer. The high salinity Arabian Sea Water circulates along with the Summer Monsoon Current (S-MC) from the Arabia Sea into the Bay of Bengal. Decreasing $\delta^{18}O$ and reconstructed salinity values correlate to the increasing SSTs in the North Atlantic Ocean indicating a reduced influence of the S-MC at the sampling site in the course of northern hemispheric warming. During such periods oxygen depletion became stronger in the OMZ of the Arabian Sea as indicated by the sedimentary records. A reduced propagation of oxygen-depleted high salinity Arabian Sea Water into the Bay of Bengal could be a mechanism maintaining oxygen concentration above the threshold of nitrate reduction in the OMZ of the Bay of Bengal in times of global warming.

1. Introduction

Fertility of the ocean, and the sequestration of CO_2 from the atmosphere by marine organisms is strongly influenced by the marine nitrogen cycle which is mainly driven by nitrate reduction and nitrogen fixation (N_2 –>$2NH_3$) (Dugdale and Goering, 1967; McElroy, 1983; Brandes and Devol, 2002; Deutsch et al., 2007). The Arabian Sea in the northern Indian Ocean plays an important role in the global nitrogen cycle because ~30% of the global water-column nitrate reduction occurs in its OMZ (Naqvi, 1987; Bange et al., 2000; Codispoti et al., 2001). The Bay of Bengal also reveals a pronounced OMZ which is strongly influenced by the propagation of oxygen-depleted, high salinity Arabian Sea Water into the Bay of Bengal (Rao et al., 1994). Since oxygen concentrations are slightly higher in Bay of Bengal than in the Arabian Sea mid-water nitrate reduction, which is generally assumed to occur at oxygen concentrations<~ 3–5 µM, is so far absent in the Bay of Bengal (Rao et al., 1994; Codispoti et al., 2001). On centennial to glacial interglacial time scales nitrate reduction rates in the Arabian Sea were very sensitive to northern hemispheric climate variations and increased during times of northern hemispheric warming (Altabet et al., 1995; Suthhof et al., 2001; Agnihotri et al., 2008).

Temperature reconstructions (Levitus et al., 2000; Smith et al., 2008; Banzon et al., 2010) in line with records derived from century old coral colonies indicate a general warming of the entire tropical/subtropical oceans during the last ~100 to 150 years (Cole et al., 2000; Pfeiffer et al., 2006; Grottoli and Eakin, 2007). A declining Eurasian snow cover, increasing wind stress over the Arabian Sea in line with other satellite-derived information, suggests an intensification of the Asian summer monsoon and the monsoon-driven upwelling in the

* Corresponding author.
E-mail address: trixen@uni-bremen.de (T. Rixen).

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western Arabian Sea since 1997 (Goes et al., 2005). Monsoon-driven upwelling and thermohaline mixing are assumed to be the main processes linking monsoon intensity to mid-water oxygen concentration and nitrate reduction rates because of their impacts on the biological production and the ventilation of the OMZ (Schulz et al., 1998; Altabet et al., 2002; Rixen and Ittekkot, 2005; Rixen et al., 2009). Due to the propagation of oxygen-depleted, high salinity Arabian Sea Water into the Bay of Bengal and its already intense OMZ, a strengthening of the monsoon-driven upwelling might have a large impact on the global marine nitrogen cycle. In order to investigate links between the Arabian Sea and the Bay of Bengal in times of global warming and the response of a *Porites* coral to the monsoon, we studied a ~37 cm long coral core taken from a *Porites lutea* colony growing in a reef south of Port Blair on the Andaman Island in the Bay of Bengal (Fig. 1).

2. Study area

The Bay of Bengal and the Arabian Sea, the two semi-enclosed basins of the northern Indian Ocean, are strongly influenced by the Asian monsoon (Fig. 1). The monsoon is driven by the sea-level pressure difference between Asia and the Indian Ocean (Ramage, 1971, 1987) that is mainly caused by summer warming and winter cooling of the Asian landmass. Following the pressure gradient and deflected by the Coriolis effect, the wind blows from the NE over the Bay of Bengal and the Arabian Sea between December and March (NE monsoon, Currie et al., 1973). During summer (June–September) the warming of the Asian landmass forms a low pressure cell forcing the SE trade winds to cross the equator. After crossing the equator, the SE trade winds blow as SW winds over the Arabian Sea and the Bay of Bengal where they gather water vapor, sustaining the heavy rainfall over the Indian subcontinent and the Bay of Bengal (Fig. 2a; Ramesh Kumar and Prasad, 1997; Ramesh Kumar and Schlüssel, 1998). The heavy monsoon clouds reduce the incoming solar radiation which peaks in March/April prior to the onset of the SW monsoon (Fig. 2b). The monsoon rains feed the Ganges-Brahmaputra, the Irrawaddy and the smaller SE Asian rivers discharging into Bay of Bengal and thereby lowering the salinity of the Bay (Milliman and Meade, 1983; Milliman et al., 1984; Subramanian et al., 1985; Ludwig et al., 1996).

The surface ocean circulation in the Bay of Bengal is characterized by the seasonal reversing Monsoon Current (MC) and the East Indian Coastal Current (EICC; Fig. 1, Eigenheer and Quadfasel, 2000; Schott and McCreary, 2001; Shankar et al., 2002). During the NE monsoon the EICC carries colder, low salinity surface water from the northern Bay of Bengal southwards along the Indian coast and the west-flowing Winter-Monsoon Current (W-MC) is formed in the southern Bay of Bengal. The east-flowing S-MC occurs in May and lasts until September (Shankar et al., 2002). In April/May, the monthly mean

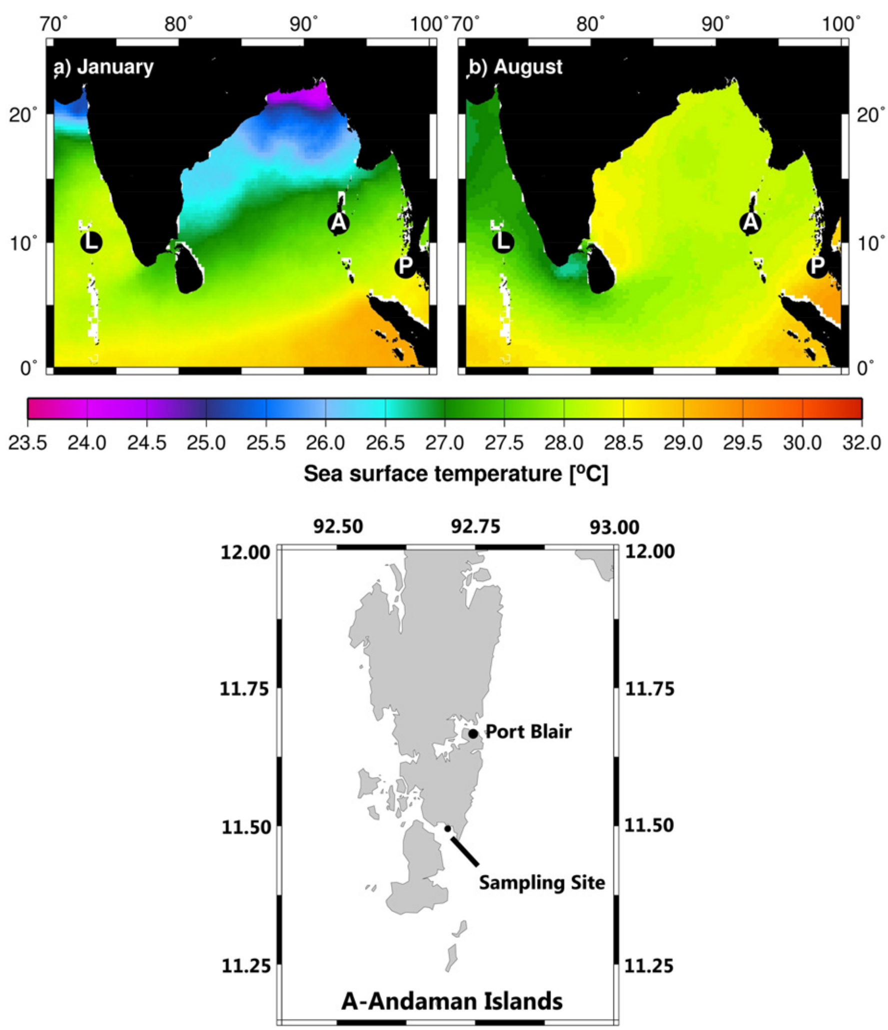

Fig. 1. Study area showing the mean sea surface temperatures in January (a) and August (b) as well as the mean NE (a) and SW monsoon currents (b). EICC and SD indicate the East Indian Coastal Current and the Sri Lanka Dome. The black circles labeled "A" show the sampling site on the Andaman Islands (see also the detailed map below), "L" and "P" indicate sampling sites from other studies at the Lakshadweep Islands and Phuket, South Thailand. The sea surface temperatures were obtained from the "Physical Oceanography Distributed Active Archive Centre at the Jet Propulsion Laboratory, California". For more detailed information see Rixen et al. (1996).