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

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**A B S T R A C T**

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 (\(\text{NO}_3^- \rightarrow \text{N}_2\)), 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.

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1. Introduction

Fertility of the ocean, and the sequestration of CO₂ from the atmosphere by marine organisms is strongly influenced by the marine nitrogen cycle which is mainly driven by nitrate and nitrogen fixation (\(N_2 \rightarrow 2\text{NH}_3\)) (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; Rane 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; Suthloff 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

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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 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).](image-url)
SSTs are at a maximum and decrease during the SW monsoon mainly due to upwelling off the south-west coast of India and the propagation of the cold nutrient-rich upwelled water along with S-MC into the Bay of Bengal (Figs. 1, 2b; Banse, 1987; Rixen et al., 1996). The transport of nutrient-rich upwelled water along with the S-MC increases the productivity and the export of photosynthesized organic matter into the deep southern Bay of Bengal (Fig. 2c; Banse, 1987; Rixen et al., 1996). The transport of cold nutrient-rich upwelled water along with S-MC into the Bay of Bengal (Unger et al., 2003).

On interannual times scales the Bay of Bengal (Singh et al., 2001) is similar to the western Indian Ocean influenced by anomalies of the ocean-atmospheric circulations such as El Niño Southern Oscillation (ENSO; Cole et al., 2000; Charles et al., 1997, 2003; Zinke et al., 2004; Pfeiffer and Dullo, 2006) and the Indian Ocean Dipole Mode (IODM, Saji et al., 1999; Webster et al., 1999). In 1997/98 the combined effect of ENSO and IODM caused an extremely strong upwelling and cooling in the eastern Indian Ocean which according to climate reconstructions derived from Porites corals occurred only four times during the last ~130 years (Abram et al., 2003). The western part of the Indian Ocean as well as the Andaman Islands which are the main reef sites in the Bay of Bengal experienced a strong warming that caused coral bleaching and mortality, damaging >60% of the reefs (Hoegh-Guldberg, 1999; Wilkinson et al., 1999).

3. Methods

3.1. Sampling

A P. lutea colony was sampled in March 2006 (92°42′E; 11°30′N) at a water-depth of ~6 m (Fig. 1). The core with a diameter of 6.4 cm and a length of ~37 cm was first rinsed in freshwater and then air-dried. It was then sectioned parallel to the axis of growth into ~5 mm thick slabs. X-rays of each slab were taken to delineate density banding and to identify the axis of growth (Fig. 3). On one slab, the theca of a single polyp was sampled continuously using a 0.6 mm diameter drill bit. On average this method produced 12 powdered samples (~1 mg carbonate powder/sample) per year of coral growth. The polyp’s transect had to be changed after the year 1983 because the axis of growth of the sampled polyp had terminated. Hence an overlapping transect between 1983 and 1978 was produced to ensure there was no offset between the sampled polyps.

3.2. Geochemical analysis

The δ18O and δ13C analyses were performed by treating the samples with phosphoric acid in an automated Finnigan carbonate device (Kiel IV carbonate device) attached to a mass spectrometer (Finnigan MAT-253). The δ18O and δ13C values were calibrated relative to NBS91 (δ18O = −2.20‰ and δ13C = 1.95‰) and are given in per mil deviation from the PDB. The reproducibility of the δ18O and δ13C values was ±0.05‰ and ±0.03‰, respectively.

3.3. Climatological data

For the discussion of the data derived from the coral additional environmental information were obtained from various sources. Precipitation rates on a 1-degree grid covering the period between 1986 and 2009 were obtained from the Global Precipitation Climatology Centre (Fig. 2, DWD, 2010). Monthly mean solar irradiances (July 1983–June 1991) were extracted from the cloudiness and solar radiation data set of the International Satellite Cloud Climatology Project (Fig. 2b, Climate Data Library, 2010). Salinity data were obtained from the World Ocean Atlas 2005 (WOA05, 2005) and the Simple Ocean Data Assimilation Reanalysis (Fig. 2a, CARTON-GIESE SODA v2p0p2-4, Climate Data Library, 2010). δ18O values of sea water (δ18Ow) from the Bay of Bengal, which was mostly based on data measured during a cruise with the German research vessel R/V Sonne in 1993/94 (Delaygue et al., 2001), were obtained from the Global Seawater δ18O database (http://data.giss.nasa.gov/cgi-bin/o18data/geto18.cgi). The ENSO indices based on SST variation in the tropical Pacific Ocean (Nina3.4), the sea level pressure difference between Darwin and Tahiti (SOI-Southern Oscillation Index) as well as sea-level pressure, surface wind, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky over the tropical Pacific (MEI-Multivariate ENSO Index) were obtained from NOAA and NASA websites (NASA, 2010; NOAA, 2010a,b).

The Indian Ocean Dipole Index (DMI) representing anomalies of the SST gradients between the western Indian Ocean (50°E–70°E and 10°S–10°N) and the eastern equatorial Indian Ocean (90°E–110°E and 10°S–0°N) were also included into our study (Rao, 2010). Furthermore four different SST products were used. The Optimum Interpolation Sea Surface Temperature (OI-SST) was derived from satellite AVHRR SSTs and in situ data which were obtained from ships and buoys (Reynolds and Smith, 1994; Reynolds et al., 2002).
The monthly mean 1° x 1° gridded data set is available from 1981 onwards. The OI-SST data were included in the Extended Reconstruction Sea Surface Temperature (ERSST) analysis which extended the SST data back to the year 1854 on a 2-degree grid (Smith et al., 2008; Banzon et al., 2010). The historical surface temperature data set HadCRUT is a merged SST and land–near-surface temperature (LST), 5-degree gridded data set covering the period from 1850 to present (Jones et al., 2009; Jones and Salmon, 2010). The LST were derived from weather stations and the SSTs from the data set HadSST2, which was made from in situ ship and buoy observations derived from the International Comprehensive Ocean-Atmosphere data set (Brohan et al., 2006; Rayner et al., 2006). Furthermore day and night SSTs derived from Moderate Resolution Imaging Spectroradiometer (MODIS) are available on a 9 km grid from February 2002 onwards (Kempler, 2010). The day and night SSTs were averaged. In order to compare all these environmental parameters to data derived from the coral core, time-series data for the sampling site were extracted from the global data sets. The different SST data sets correlate to each other and the HadCRUT-SSTs are ~1 °C lower than the other SSTs (Table 1).

3.4. Age models and growth rates

For developing the age model the OI-SSTs maxima occurring during the spring intermonsoon in May (I1) were assigned to the δ¹⁸O minima which are often associated with the onset of a distinct low density band (Fig. 3). In a second step OI-SSTs minima occurring during the NE and SW monsoon were paired to δ¹⁸O maxima. Finally the OI-SST maximum of the autumn intermonsoon in October/November was assigned to the δ¹⁸O minimum. Dating of all other
samples was carried out by a linear interpolation of the four anchored points mentioned above. Since the distance of the individual sample from the core top was recorded during the sampling, the distance of each sample could be plotted versus its age (Fig. 4a). The resulting plot shows an almost linear extension over time suggesting a mean annual extension rate of 11.9 mm year\(^{-1}\) between 1975 and 2006 (Fig. 4b).

In order to produce monthly and seasonal means we interpolated linearly between the dated samples (Fig. 5). The resulting mean linear extension rates during the NE and SW monsoon are 0.93 and 1.1 mm month\(^{-1}\) (3.7 and 4.4 mm season\(^{-1}\), Fig. 2c, 4b).

4. Results and discussion

4.1. Linear extension rates and SSTs

Intensive studies on Porites corals in the Great Barrier Reef (GBR) including data from Phuket, Thailand, and Hawaii indicate that the annual mean linear extension rates are strongly influenced by the annual mean SSTs (Fig. 7, Lough and Barnes, 2000). Mean annual extension rates derived from studies on Porites corals in the Indian Ocean (Scoffin et al., 1992; Chakraborty and Ramesh, 1993; Tudhope et al., 1996; Cole et al., 2000; Charles et al., 2003; Felis et al., 2003; Zinke et al., 2004; Pfeiffer and Dullo, 2006) do not deviate much from the trend seen in the Pacific Ocean (Fig. 6). Nevertheless, the spatial variability of linear extension rates determined in Porites corals off Phuket (9–35 mm year\(^{-1}\)) are much larger than those from Porites corals growing in the GBR between 12 and 22°S (Scoffin et al., 1992; Lough and Barnes, 2000). Annual mean extension rates of corals off Phuket are strongly influenced by hydraulic energy (Scoffin et al., 1992). In a more recent study from the Similan Islands (located off

### Table 1

<table>
<thead>
<tr>
<th>Product</th>
<th>OI-SST</th>
<th>ERSST</th>
<th>HadCRUT-SST</th>
<th>MODIS-SST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation</td>
<td>0.936; n = 300</td>
<td>0.733; n = 300</td>
<td>0.777; n = 52</td>
<td></td>
</tr>
<tr>
<td>SST Product</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SST Area</td>
<td>11–12°N, 92–93°E</td>
<td>10–12°N, 92–94°E</td>
<td>4.5–9.5°N, 89.5–94.5°E</td>
<td>11.48–11.51°N, 92.69–92.71°E</td>
</tr>
<tr>
<td>Mean SST [°C]</td>
<td>28.71 ± 0.84</td>
<td>28.78 ± 0.69</td>
<td>27.76 ± 0.60</td>
<td>28.82 ± 0.98</td>
</tr>
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</table>

Fig. 4. (a) Distance of each of the 379 samples from the core top versus its age. The resulting regression equation indicates a mean linear extension rate of 11.9 mm year\(^{-1}\). (b) Annual mean linear extension rates in mm year\(^{-1}\) (black squares), SW (black circles) and NE monsoon linear extension rate (open circle) in mm season\(^{-1}\) (4 months).

Fig. 5. δ\(^{18}\)O measured in the coral core (open circles) and the interpolated monthly mean δ\(^{18}\)O values (black circles) values versus time. The figure ’b’ shows the same for the last ~4 years.

Fig. 6. Linear extension rates derived from Porites corals in the Indian Ocean (black circles – references are given in the text), and the Andaman Islands (black star) versus annual mean SSTs selected from the OI-SST data set. Triangles indicate the range of linear extension rates measured in different Porites colonies off Phuket (Scoffin et al., 1992) and the Gulf of Aqaba (Felis et al., 2003). The broken line represents the relationship between SST and linear extension rates derived the Porites coral growing in the GBR and the solid line indicates the range covered by data from the GBR.
Phuket) by Schmidt (2010), it could be shown that the exposure of the reefs to the Large Amplitude Internal Waves (LAIW) strongly effects coral growth. These waves, generated mostly during the NE monsoon at the Andaman-Nicobar Island Arc, propagate across the Andaman Sea towards Thailand and carry subsurface water to the surface layer. Associated short term temperatures and pH drops of 10 °C and 0.6 pH units stress corals and might be responsible for the large variability seen in linear extension rates and the ambiguous banding in corals off Thailand. Annual linear extension rates of the *Porites* corals from the Andaman Islands is lower as one would expect from the SSTs (Fig. 6) which is probably caused by the high wave energy conditions and the impact of the LAIW prevailing in this area.

The linear extension reveals a pronounced seasonality with enhanced rates during the NE and SW monsoon which are the colder periods (Fig. 2b, c). This seasonality differs from that of the solar radiation (Fig. 2b) favoring the photosynthetic enhanced calcification of corals at other sites (Lough and Barnes, 2000; Sun et al., 2008b). In the southern Bay of Bengal the photosynthesis of organic matter and its export into the deep sea is controlled by the deep mixing during the NE and the advection of upwelled water along with S-MC during the SW monsoon (see above). Since both processes are indicated by lower SSTs at the sampling site (Fig. 2b) it is assumed that similar to Bermuda (Dodge and Vainsys, 1975) an enhanced nutrient supply increases the linear extension of the studied *Porites* coral during the SW and NE monsoon.

4.2. δ¹⁸O records

The oxygen isotope partitioning between carbonates (δ¹⁸O) and water is strongly influenced by SSTs (Urey, 1947; McIver, 1950; Epstein et al., 1953; O’Neil et al., 1969). If δ¹⁸O values of sea water (δ¹⁸Ow) are constant, the regression equations derived from the correlation between δ¹⁸O and SST often reveal slopes of ~0.2 ‰/°C suggesting that δ¹⁸O drops by 0.2 ‰ if the SST increases by 1 °C (McConnaughey, 1989, and references therein). Although δ¹⁸O measured in corals often follow this trend, their skeletons are depleted in ¹⁸O (McConnaughey, 1989; Guzman and Tudhope, 1998; Watanabe et al., 2001, 2002; Lough, 2004; Grottoli and Eakin, 2007) compared to

Fig. 7. Salinity versus oxygen isotopic ratios of sea water (δ¹⁸Ow) from surface waters (water depth ~20 m) of the Bay of Bengal (80°–100°E, 0°–30°N). The data were obtained from the Global Seawater δ¹⁸O database (http://data.giss.nasa.gov/cgi-bin/o18data.geto18.cgi).

Fig. 8. δ¹³C and chlorophyll-a (chl-a) measured in sea water along a transect from the upwelling region off Oman into the open Arabian Sea. The black circles indicate the sampling positions. The data were obtained during a cruise with the German research R/V Meteor in 2008.
calcite and aragonite precipitated at isotopic equilibrium (McCrea, 1950; Epstein et al., 1953; O'Neil et al., 1969). This offset from equilibrium referred to as the “vital effect” (Weber and Woodhead, 1972) is still not entirely understood (McConnaughey, 2003; Allemand et al., 2004) but assumed to be caused by the pH-dependent ratio between hydration and hydroxylation of CO₂ entering the calcifying fluid through diffusive transports across the cell membrane and kinetic effects (Spero et al., 1997; Bijma et al., 1999; Adkins et al., 2003; McConnaughey, 2003; Rollion-Bard et al., 2003). Day and night variation of the pH (8.1–9.3) within the calcifying fluid (Al-Horani et al., 2003) and the resulting pH-dependent disequilibrium precipitation could explain large short-term fluctuations of δ¹⁸O measured in a Porites coral (−10.6 to −0.2) (Rollion-Bard et al., 2003). These short-term changes are averaged by the conventional millimeter scale sampling method (Rollion-Bard et al., 2003) which was also applied by us. On monthly and interannual time scale kinetic fractionation effects are assumed to be of minor importance if linear extension rate rates exceed 6 mm year⁻¹ (McConnaughey, 1989; Felis et al., 2003) as it is the case within the studied coral.

The monthly δ¹⁸O values derived for the studied coral correlate to the OI-SST \((r = -0.503, n = 291, p < 0.001)\), the ERSST, \((r = -0.454, n = 373, p < 0.001)\), the HadCRUT-SSTs \((r = -0.389, n = 373, p < 0.001)\), and the MODIS-SST \((r = -0.677, n = 44, p < 0.001)\). Considering the periods during which MODIS data are available, the correlation coefficients derived from the correlation between OI-SST, ERSST, HadCRUT-SSTs and δ¹⁸O values are similar \((-0.656, -0.669, -0.435)\) to those derived from the correlation between MODIS-SSTs and δ¹⁸O. This implies that δ¹⁸O values measured in the sampled corals reflect regional changes in SSTs and are hardly affected by small scale local oceanographic features.

The annual mean δ¹⁸O derived from the Andaman coral correlate also to the SSTs and the resulting slopes of the regression equations

![Fig. 9. Pearson correlation coefficient obtained from the correlation between the annual mean SST time-series data derived from the coral sampling site (black circle) and all other annual mean SST times-series data extracted from degree gridded SST fields. The black square indicates the sediment trap sampling site in the southern Bay of Bengal. Pearson correlation coefficients between −0.84 and 0.84 are not shown (appear white).](image-url)
almost equal those derived from precipitation of aragonite at isotopic equilibrium.

\[ \delta^{18}O[\%e] = -0.2070 \times \text{OI} - \text{SST}[^\circ C] + 0.2345; \quad r = -0.44; \quad n = 24. \]  
\[ p = 0.0185 \]  

\[ \delta^{18}O[\%e] = -0.1560 \times \text{ERSST}[^\circ C] - 2.055; \quad r = -0.383; \quad n = 29, \]  
\[ p = 0.0406 \]  

\[ \delta^{18}O[\%e] = -0.1955 \times \text{HadCRUT}[^\circ C] - 0.2781; \quad r = -0.509; \quad n = 29, \]  
\[ p = 0.0048 \]  

Accordingly, it is assumed that the vital effect was almost constant over time in the Andaman coral and that variations of \( \delta^{18}O \) determined in the corals are mainly caused by changes in SST and \( \delta^{18}O_w \). Based on studies on Porites corals from the Lakshadweep Islands (Chakraborty and Ramesh, 1993) the relationship between \( \delta^{18}O \) from corals, \( \delta^{18}O_w \) and SST was described similar to other studies (McConnaughey, 1989; Grottoli and Eakin, 2007) as follows:

\[ \delta^{18}O[\%e] - \delta^{18}O_w[\%e] = -0.214 \times \text{SST}[^\circ C] + 0.641 \]  

\( \delta^{18}O \) and \( \delta^{18}O_w \) referred to the PDB (Pee Dee Belemnite) and SMOW (Standard Mean Ocean Water), respectively. The \( \delta^{18}O_w \) values and the salinity (SSS) data obtained from the Global Seawater \( \delta^{18}O \) database correlate with each other (Fig. 7) and the resulting regression equation could be used to translate \( \delta^{18}O_w \) into SSS:

\[ \text{SSS} = 5.1709 \times \delta^{18}O_w[\%e] + 32.673 \]  

Based on Eqs. (4) and (5), the different SSTs data sets and the measured \( \delta^{18}O \), SSS were calculated. Direct measurements for validating the reconstructed SSS are not available but ARGO floats which are a part of “The Global Ocean Observing System” (GOOS), provide some real-time data on SST and SSS around the Andaman Islands (12–18°N and 86–93°E) between 2003 and 2006. The ARGO

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**Fig. 10.** (a) Spectral densities of the annual mean MEI index (solid line) and the annual mean ERSSTs (broken line; 1950–2009) and (b) their coherency spectra. (c) Spectral densities of the annual mean MEI index (solid line) and annual mean linear extension rates (1976–2005) and (d) their coherency spectra. Hamming weights: 0.035714, 0.241071, 0.446429, 0.241071, 0.035714.

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**Fig. 11.** ERSSTs, reconstructed SSS, monthly mean \( \delta^{13}C \) and \( \delta^{18}O \) values derived from the Andaman coral versus time. The bold black lines indicate the annual mean values. The grey bars indicate the year 1990 and the combined ENSO/IODM event in 1997/98.
data agree quite well the SSS reconstructed from the OI-SSTs and ERSSTs if the constant in Eq. (4) is reduced 0.641 to 0.441 (Fig. 2a). Contrary to the SODA and the WOA05 data which based on <20 observations, the ARGO and the reconstructed SSS decrease during the SW monsoon due to the heavy monsoon rains (Fig. 2a). Despite the much lower rainfall the ARGO as well as the reconstructed SSSs show the SSS minimum during the NE monsoon. This NE monsoon minimum indicates a decoupling between the monsoon-driven hydrological cycle and the salinity at the sampling site which might be associated with seasonal reversing MC. During the NE monsoon the W-MC seems to lower the salinity by carrying cold, low salinity water from the northern and western Bay of Bengal towards the sampling site (Fig. 1). During the SW monsoon the S-MC appears to reduce the effect of the heavy monsoon rains on the SSS at the sampling site by carrying high salinity Arabian Sea Water into the Bay of Bengal. The salinity maxima in April/May could result from an enhanced evaporation due to the high solar radiation (Fig. 2b) and the increasing influence of high salinity Arabian Sea prior to the onset of the monsoon rains.

4.3. δ13C records

The δ13C values measured in the Andaman corals (−1.2 to −3.4‰) were on average lower than those determined in the corals of Lakshadweep Islands (−0.05 to −1.25‰) and fall within the upper range of δ13C values measured in corals from Phuket (−1.73 to −5.29‰) (Chakraborty and Ramesh, 1992; Allison et al., 1996). δ13C values in corals could be influenced by the pH of the calcifying fluid and its impact on the diffusive transport of CO2 across the cell membrane, kinetic and metabolic effects as well as by the δ13C in sea water (Spero et al., 1997; Bijma et al., 1999; Adkins et al., 2003; McConnaughey, 2003). Metabolic effects and the δ13C in sea water are furthermore influenced by a variety of environmental factors such as availability of light, water depth, solar radiation, inputs of carbon from terrestrial sources, the emission of 13C depleted anthropogenic CO2, etc (e.g., Suess, 1955; Pelejero et al., 2005; Grottoli and Eakin, 2007).

δ13C values measured in the studied coral do not correlate with linear extension rates suggesting that metabolic effects associated
with the photosynthetic enhanced calcification as seen in other studies (Sun et al., 2008a), are of minor importance. $\delta^{13}C$ of sea water has, as far as we know, not been measured at the sampling site but there are data available of a transect from the coastal upwelling system off Oman into the open Arabian Sea (Fig. 8). These data show that $^{13}C$-depleted water that wells up along the coast becomes heavier as it gets advected offshore due to an enhanced productivity in the surface water and an increased export of $^{13}C$-depleted, photosynthetic organic matter into the deep sea (Rixen et al., 2006). Such a $^{13}C$-enrichment could also be caused by the high export fluxes in the southern Bay of Bengal which could explain the $\delta^{13}C$ maxima occurring during SW monsoons (Fig. 2c).

4.4. Interannual variability

The liner extension rates, $\delta^{18}O$ and the $\delta^{13}C$ values reveal a strong monsoon-driven seasonality which appears to be caused by the seasonal reversal of the surface ocean circulation. In order to test this hypothesis a field correlation was carried out where SSTs from the sampling site were correlated with time-series data on SSTs derived from all other grids cells. The resulting high correlation coefficients indicate the strong link between SSTs from the sampling site and those from the southern Bay of Bengal (Fig. 9).

During El Niño periods there seems to be prevalence of enhanced SSTs in the central Bay of Bengal (Singh et al., 2001). This seems also to be the case at the sampling site as indicated by the correlation between the annual mean ERSSTs and the HadCRUT-SSTs and the Nino3.4 and MEI indices ($p<0.05$) which show a periodicity similar to those of the SSTs at the sampling site (Fig. 10a, b). The enhanced SSTs are reflected in lower $\delta^{18}O$ values in the studied Porites coral during the strong warming and coral bleaching event in 1997/98 (Fig. 11, Hoegh-Guldberg, 1999; Wilkinson et al., 1999). At the beginning of this combined ENSO/IODM event during the NE monsoon 1996/97, the linear extension rate (0.59 mm month$^{-1}$) fall below the average NE monsoon linear extension rate of 0.93 mm month$^{-1}$. Towards the end of this event during NE monsoon 1997/98 the extension rates (1.11 mm month$^{-1}$) exceed the average by ~20% but the annual mean linear extensions rate 1997
remained below average (8.9 mm year⁻¹; Fig. 3). The mean annual extension rates reveal, as ENSO, a periodicity of ~5 years suggesting that thermal stress (e.g., Brown et al., 1996) caused by ENSO induced-warming is a factor lowering linear extension of the Andaman coral during El Niño periods. The lowest linear extension rates were determined during the NE monsoon 2004/05 (0.3 mm month⁻¹; Fig. 3) as the corals of the Andaman Island were affected by the mega Tsunami that occurred in December 2004 (Ramesh et al., 2010). The coral recovered also from this impact and the annual mean linear extension rate of 10.2 mm year⁻¹ hardly deviates from the average of 11.9 mm year⁻¹.

As elsewhere in the tropical/subtropical oceans the generally decreasing annual mean δ¹⁸O and δ¹³C values determined in the Andaman coral seem to reflect increasing SSTs as well as an enhanced incorporation of ¹³C-depleted carbon (Fig. 11). Both could be caused by the enhance burning of fossil fuel which results in global warming and enriches the environment with ¹³C-depleted CO₂ (Suess, 1955; Pelejero et al., 2005). An additional process explaining the decreasing δ¹⁸O and δ¹³C values as well as pronounced decrease of the SSS since ~1990 could be a reduced influence of the S-MC at the sampling site. This might be associated with the assumed intensification of the monsoon-driven upwelling in the Arabian Sea which could only be observed from 1997 onwards due to availability of the satellite-derive chlorophyll a data (Goes et al., 2005). To which extend these recent changes are caused by global warming or are a part of, e.g. decadal oscillation as indicated by SSSS (Fig. 11) is difficult to assess. However, coral data provide interesting hints to processes linking biogeochemical process in the northern Indian Ocean to the northern hemispheric climate changes not only on centennial to glacial/interglacial time scales as seen in sedimentary records (Schulz et al., 1998; Kudrass et al., 2001; Suthoff et al., 2001; Agnihotri et al., 2002; Altabet et al., 2002; Wang et al., 2005), but also on an inter-annual time scale.

The annual mean δ¹⁸O and the reconstructed SSS correlate to SSTS in the North Atlantic Ocean and the obtained correlation coefficients are even higher than those derived from the correlation with local SSTs (Figs. 12, 13). This shows that the northern hemispheric warming is associated with lower δ¹⁸O and SSS suggesting a reduced influence of the S-MC due to, e.g. a southward deflection of the S-MC in the course of global warming. A decreasing propagation of the oxygen-depleted, high salinity Arabian Sea Water into the Bay of Bengal could be a mechanism preventing nitrate reduction in the OMZ of the Bay of Bengal in times of North Atlantic warming.

5. Conclusion

The results derived from the Porites core sampled at the reef south of Port Blair indicate the following:

- The linear extension rates of the studied Porites coral are within the lower range of those determined elsewhere, suggesting the exposure of the reef to enhanced wave energy and/or large amplitude internal waves.
- The monthly δ¹⁸O values determined in the Andaman coral are mainly controlled by sea water temperatures and the oxygen isotopic composition of the sea water.
- The seasonal and inter-annual variability of sea water salinity, δ¹⁸O and δ¹³C appeared to be strongly affected by the advection of high salinity Arabian Sea Water into the fresh water influence Bay of Bengal along with the S-MC during the SW monsoon.
- Decreasing δ¹⁸O values and SSS correlate to the increasing SSTs in the North Atlantic suggesting in line with decreasing δ¹³C values a reduced influence of the S-MC at the sampling site in the course of global warming.
- A reduced propagation of oxygen-depleted high salinity Arabian Sea Water into the Bay of Bengal could the mechanism maintaining oxygen concentration in the OMZ of the Bay of Bengal above the threshold of nitrate reduction in times of North Atlantic warming when oxygen depletion and nitrate reduction becomes stronger in the OMZ of the Arabian Sea.

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Date derived form the coral are available at http://www.nccdc.noaa.gov/paleo/paleo.html and http://www.pangea.de.

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