Potential of reef building corals to study the past Indian monsoon rainfall variability

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Reef building corals are known to provide high resolution records of ocean–atmospheric variables for the last several centuries. The most important parameter is the sea surface temperature, which is accurately recorded by the oxygen isotopic composition as well as by a few trace elemental ratios such as, Sr/Ca, Mg/Ca, U/Ca, etc. Determination of the sea surface temperature has enabled the palaeocenographers to study a variety of oceanic processes, such as the El Niño and Southern Oscillation, ocean circulation, air–sea gas exchange, Indian Ocean dipole, etc. Monsoon is an important atmospheric process in which sea surface temperature plays an active role in governing the moisture production and modulation of the wind circulation. Apart from temperature reconstruction, the corals have also been used to study the monsoon processes by some investigators, viz. the estimation of rainfall. In this article, we review the available coral records, specifically for studying the Indian summer monsoon rainfall variability. The study reveals that the coral records only from a few specific regions show promise in this endeavour.

Keywords: Arabian Sea, coral, ISM, Lakshadweep, SST, δ^{18}O.

Introduction

REEF building corals are known to provide a wealth of information on the physical and chemical condition of the environment in which they live. The oxygen isotopic composition of the coral skeleton is a function of sea surface temperature (SST) and the oxygen isotopic values of the surface seawater[1–7]. Hence the isotopic analysis of long lived corals is potentially useful to derive these parameters for geological past[8–11]. During the carbonate precipitation a variety of metals, albeit in trace quantity, get incorporated into the lattice structure of the carbonate mineral. Some of these metals, namely Sr, Mg, U, etc. when get incorporated into the carbonate matrix, their proportion is determined by the ambient temperature. So the elemental ratios, i.e. Sr/Ca, Mg/Ca and U/Ca in the coral skeleton will be largely determined by the temperature dependent distribution coefficients of Sr/Ca, Mg/Ca and U/Ca between aragonite and sea water[12]. Since these ratios are independent of the oxygen isotopic composition of the sea water, analysis of trace metal concentrations has been widely used to reconstruct the SST[13–23]. On the other hand, paired analysis of the oxygen isotopes and trace metal abundance provide a means to estimate the salinity of the ocean surface[12,24]. Since both the isotopic values and the sea surface salinity are governed by the evaporation and precipitation, the salinity could also be estimated. So the combined analysis of isotope and trace metal is useful to reconstruct the past history of the temperature and salinity of the surface ocean[12]. A large number of studies are available across the world's oceans. In the absence of the elemental records, the isotopic analysis has also been used to study the long-term behaviour of the SST. Cole *et al.*[25] established a 194-year record of coral δ^{18}O from the equatorial coastal region of Africa in the Indian Ocean. From this record, the authors demonstrated that the western equatorial Indian Ocean experienced a warming trend ca. 1.3°C since the early 1800s, if the salinity change was considered to be minimal. Carbon isotopes have also been attempted by some investigators[26]. But the controlling mechanism, especially on the stable carbon isotopic composition is numerous and the pathways are not well understood. Hence, the study of stable carbon isotopes in coral as environmental indicator got limited success. However, the radioactive carbon, basically the ^{14}C/^{12}C ratio in annual bands of corals has widely been used to study a variety of processes. For example, estimation of CO_2 exchange rate across the air–water boundary[27–29], surface ocean circulation[30], surface–subsurface mixing[31,32], changes in thermocline depth[33], major current shift[34], to study the meridional transport in the Indian Ocean[35], etc.

Corals have also been used for high resolution pH reconstruction. Boron isotopes (δ^{11}B) in coral skeleton provide an excellent means in understanding the bleaching effect due to enhance acidity of surface water[36–42]. Unlike the Pacific and the Atlantic Ocean, coralline records of oceanic pH, to our knowledge are not available from the Indian Ocean. But model simulation studies show that the acidification trends, especially in the western Arabian Sea have intensified in the recent decades[43].

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The above discussion shows that the isotopic and elemental tracers in coral carbonate have provided information about a variety of ocean atmospheric processes. However, despite it being a myriad source of information, application of coral tracers in deriving the information on rainfall variability is limited. The carbonate bearing materials, both biogenic and abiogenic, are known for their potential in reconstructing different attributes of monsoon. For example, the isotopic analysis of foraminifera from the ocean sediments has provided immense information on the strength of the monsoon[44], upwelling history[45], quantification of the evaporation and precipitation processes in specific areas[46], ocean circulation parameters on glacial–interglacial time scales, etc. Carbonate analysis of the terrestrial environment has also been shown to be a reliable indicator of past monsoon strength[47]. The oxygen isotopic analysis of speleothem has provided information on monsoon variability on millennial time scales[48–57]. The carbonate analysis of lake sediments has also provided a variety of information[58,59]. However, despite being a member of the same carbonate family, corals apparently could not show great potentials to be a proxy for monsoon rainfall. Several investigators have reviewed the merits of coral study in extracting palaeoclimatic information in the Pacific[60] in the Indian Ocean[61–63], but a discussion focussed on rainfall reconstruction using the coralline proxy, especially in the context of the Indian summer monsoon (ISM) rainfall seems to be lacking. In this article, we discuss the potentials of coralline proxies as a means to reconstruct the Indian monsoon rainfall, their merits and limitations. Finally, we explore whether there are any alternative means that may provide promise in this endeavour.

Oxygen isotope as a proxy for environmental parameters

Temperature is the primary driver that determines the heavy to light isotopic ratios say, oxygen (i.e. ^{18}O versus ^{16}O) in case of condensation of cloud water, precipitation of organic and inorganic carbonates, etc.[64]. If the isotopic distribution takes place between the co-existing phases under equilibrium condition, then the oxygen isotope ratio maintains a linear relation with the temperature. In case of marine carbonate, such as foraminifera, the equilibrium condition is believed to be maintained. Speleothem, a typical form of cave deposit, also precipitates under equilibrium condition enabling a means to reconstruct the past rainfall variations. A recent study shows that the fresh water mollusc, if characterized by high growth rate, is potentially useful in delineating the active and break phases of rainfall within a given season[65]. This is seemingly possible because the active period is characterized by heavy rainfall, while the break periods receive scanty rainfall. This makes the soil water depleted (enriched) in isotopic values as a result of weakened (strengthened) soil evaporation[66]. Biogenic or abiogenic carbonate in a fresh water environment could record the isotopic values of soil water in its carbonate matrix, enabling the reconstruction of active and break condition of a monsoon season. But, whether such kind of mechanism is feasible in a marine environment is yet to be investigated. On the other hand, the reef building corals do not form their carbonates under isotopic equilibrium, since the process is mediated by a particular form of algae, the zooxanthelae. The biological process, known as the 'vital effect' is believed to be responsible for creating isotopic disequilibrium[67]. However, despite this apparent disequilibrium, the oxygen isotopic values of coral carbonate have been shown to maintain a 'constant offset' from the equilibrium value[68], and hence the coralline isotopic values have been proven to be a reliable indicator of ocean surface temperature[10,69]. Hence the physical principle, in this case, the temperature dependency of the stable isotope distribution in coral skeleton is assumed to be obeyed. This characteristic feature makes it possible to establish an empirical relation between the coral δ^{18}O (henceforth written as $\delta^{18}O_C$) and SST. However, unlike the SST, some meteorological variables, such as, precipitation do not follow a well constrained relation with $\delta^{18}O_C$. An event of precipitation, in principle, will deplete the isotopic composition of the surface sea on a local scale. If the SST does not change significantly in a specific area of a sea, the change in surface water isotopic values would be recorded in coralline δ^{18}O, which subsequently could be used as a measure of fresh water input. The fresh water may be contributed both by the rainwater as well as by the river discharge. Cole *et al.*[2] exploited this characteristic feature of corals in the Tarawa Atoll (1°N, 172°E) in the Pacific Ocean and demonstrated that coralline isotope provided a means to quantify the fresh water discharge, as the SST in this region did not have significant variability. A similar kind of application has also been reported in the Indian Ocean context. Pfeiffer *et al.*[70] demonstrated that corals from the Chagos Island (the geographical centre of the Indian Ocean) strongly responded to the intense precipitation associated with the ITCZ movement especially during the boreal winter (October to March). But unlike the Tarawa atoll, the SST in Indian Ocean also played an important role in modulating the $\delta^{18}O_C$. Decoupling the effects of rainfall and SST seems to be a daunting task, hence the $\delta^{18}O_C$ in this case may not be suitable for rainfall reconstruction, but could be a reliable proxy for the ITCZ movement. Despite this limitation, the corals from the Indian seas have indeed been used to study the monsoon rainfall variability.

Indian monsoon and corals

Unlike the other major ocean basins, such as the Pacific and the Atlantic, the Indian Ocean is landlocked from the North due to the presence of the Himalayan mountain chain. As a consequence, it experiences the seasonal reversal of circulation due to differential heating of the land and ocean surfaces. The seasonal reversal of wind pattern, or the so-called monsoon circulation carries abundant moisture from the Indian Ocean to the Indian subcontinent during the summer (June–September), which comprises more than 70% of annual rainfall in India. A strong circulation drives intense upwelling resulting in sea surface cooling at several places in the Arabian Sea. The extent of cooling (ca. 2°C to 4°C)[71,72] in the southeast part of the Arabian Sea could increase δ^{18}O by 1‰ in coral aragonite that are abundantly available in this region[73,74]. Though the signal is created primarily by the drop in SST, the reduction in SST is strongly associated with the monsoon circulation. Hence, the change in coral oxygen isotope is indirectly related to the monsoon as well, which in principle, helps establish an empirical relationship between $\delta^{18}O_C$ and the monsoon system. Wind circulation and precipitation, both are essential components of the monsoon system. Some organisms, such as the foraminifera, which float freely in the ocean waters strongly respond to the ocean circulation and in turn to the atmospheric circulation. Hence the abundance of different foraminiferal species has been shown to be a good proxy for the circulation system[75]. But the reef building corals being rigid systems are not subjected to the same mechanism. With this perspective, the coralline proxies are analysed to study the ocean–atmospheric processes, such as changes in SST, oceanic upwelling, fresh water discharge, estimation of CO_2 exchange, etc.

The Lakshadweep Archipelago in the Arabian Sea and the Andaman and Nicobar Islands in the Bay of Bengal are known to harbour a diverse marine ecosystem that contains a variety of massive corals. Several investigators have carried out geochemical analysis of corals collected from these two coral reef ecosystems[6,71,72,74,76,77]. Chakraborty and Ramesh[71,73] demonstrated that the coral oxygen isotopes in the Lakshadweep region strongly respond to the upwelling induced cooling resulting in a rise in δ^{18}O by about 0.9‰. These authors also showed that they have the potential to reconstruct the SST though the uncertainty level was relatively high (±1.9°C). Further work of Sr/Ca analysis of corals from this region[77] showed that the monsoon induced cooling of the order of 2.3°C could be accurately tracked by the corals growing in this region. Other than tracking the sea surface cooling, Sagar *et al.*[77] also demonstrated that the coralline Sr/Ca ratio is also associated with the Indian rainfall. Though they found a weak correlation ($r = –0.39$) with the all India rainfall, which included rainfall in the summer and winter seasons, the correlation was significantly improved ($r = –0.61$, $P < 0.01$) when the rainfall was considered only for the western peninsular India. The connection between Sr/Ca ratio and the rainfall stems from the fact that the two processes, like sea surface cooling and the monsoon precipitation are nearly synchronous.

But most of the studies connecting the Indian monsoon rainfall and coral rely on the coralline oxygen isotopic records. For example, Charles *et al.*[3] analysed Indian Ocean corals (collected from the Mahe Island; 4°379′S, 55°49′E) to examine its isotopic variability in relation to the Indian monsoon. These authors noted that the long term trend in coral δ^{18}O matched reasonably well with the Webster and Young (WY) monsoon index[78]. However, the WY monsoon index characterizes the monsoon circulation, and not necessarily the monsoon precipitation. Hence the effort of Charles *et al.*[3] in reconstructing the monsoon rainfall did not meet with much success.

One of the intriguing aspects of the monsoon rainfall is its relationship with the SST, particularly at lead times greater than 1–2 months before the boreal summer monsoon[79]. Based on the instrumental data and model simulation, a large number of studies attempted to correlate these two parameters and their lead lag relationship. It has been shown that a low Arabian Sea SST leads to a reduced Indian rainfall and vice versa[80,81]. Since many reef building corals are characterized by high growth rate (up to 2 cm $year^{-1}$), they are potentially useful in resolving events that happen in 2–3 week timescale. As coral oxygen isotope ratios are inversely related to temperature, a rise in SST would reduce the $\delta^{18}O_C$ but likely to increase the precipitation. Tudhope *et al.*[82] indeed found such a correlation by analysing corals collected from Marbat, Oman coast (16°50′N; 54°45′E). The $\delta^{18}O_C$ of this site was shown to be inversely related to the all India annual rainfall ($r = –0.5$, $P = 0.01$). However, despite this apparent robust relationship, similar behaviour was not found in case of a coral collected from a nearby location of WadyAyn (16°48′N; 54°50′E) either in isolation or as a composite δ^{18}O time series of these two sites[82]. Only a detrended time series of the composites coral δ^{18}O showed a relationship with the annual rainfall ($r = –0.5$ at the 95% level). However, different response of two nearly co-located corals with the monsoon rainfall demonstrated its limitation in deriving the past summer monsoon information using the $\delta^{18}O_C$.

Further evidence of the monsoon – $\delta^{18}O_C$ connection comes from the work of Klein *et al.*[83]. These authors collected coral samples from the Dahlak Archipelago (16°N, 40°E) in the southern Red Sea. Two cores of coral were retrieved from a colony that yielded 63-year and 34-year records of coral δ^{18}O and δ^{13}C respectively. The NE monsoon coral $\delta^{18}O_{DJF}$ (i.e. December–January–February) showed a significant inverse correlation (at the 99.9% level) with the Indian Ocean and southern Red Sea annual SSTs. The significance level decreased to 99% when the coral $\delta^{18}O_{JJA}$ for the SW monsoon season (June–July–August) was compared with the Indian Ocean annual SST. But the correlation was lost when the coral $\delta^{18}O_{JJA}$ was compared with the southern Red Sea annual SST, implying that summer monsoon SST had a minor effect on $\delta^{18}O_C$. Though Klein *et al.*[83] got some success in establishing the relationship between $\delta^{18}O_C$ from the southern Red Sea with the Indian Ocean annual SST, the relationship, however, could not show potential to reconstruct the monsoon rainfall.

Felis *et al.*[84] reported a 245-year coral $\delta^{18}O$ record from the northern Red Sea (Ras Umm Sidd in Egypt; 28°N, 35°E). The oxygen isotopic composition of this coral showed a somewhat weak correlation with the precipitation record of Alexandria and Cairo ($r = 0.35$ at 99.5% level). But this relationship did not seem to be promising in rainfall reconstruction. First, the coral record did not show any relation with the Indian monsoon rainfall, and secondly, a positive correlation between $\delta^{18}O_C$ and the Mediterranean rainfall does not follow the conventional dynamical behaviour of $\delta^{18}O_C$ and rainfall as observed in the other Indian Ocean corals. For example, Chakraborty and Ramesh[85] collected a coral from the Gulf of Kutch in the northwestern coastal region of India. These authors demonstrated that the oxygen isotope minima (i.e. SST maxima) and the total monsoon rainfall in the neighbouring state were strongly anti-correlated ($r = -0.56$ at the 99% level). However, the isotopic record did not show any reasonable correlation with the all India summer monsoon rainfall in this case. Hence it showed only limited applicability in reconstructing rainfall on a local to regional scale.

Other than the isotopic proxies, rainfall reconstruction was also attempted by means of coral extension rate, a method often practised by the dendrochronologists to decipher the climatic variables in the terrestrial environment using the ring width of trees[86–91]. With the advent of monsoon, the hydrodynamic energy increases as a result of enhanced circulation. Increased circulation and turbidity could reduce the coral extension rate, relative to the non-monsoon season. Stortz and Gischler[92] indeed observed an inverse correlation between the extension rates of corals growing in the Rasdhoo Atoll (4°N, 73°W) in the central Maldives and the rainfall over the Western Ghats region of the west peninsular India. A five year running mean of the coral extension rates yielded a strong correlation ($r = -0.82$, $P < 0.01$) with the rainfall records from the Western Ghats (an area covering 13–15°N, 73–76°E) for the period of 1958–2006.

The sensitivity test of the coralline proxies with the Indian monsoon rainfall as discussed above, are entirely based on corals from the Indian Ocean. But it has also been reported that the corals from the Pacific Ocean could also be useful in tracking the past Indian monsoon rainfall. It is widely known that the tropical Pacific plays an important role in modulating the Indian monsoon through the atmospheric teleconnection[93]. The periodic warming of the equatorial Pacific, manifested in the form of El Niño and Southern Oscillation (ENSO) imparts a negative influence on the Indian summer monsoon rainfall[94]. This part of the Pacific also harbours a variety of corals, and many investigators have shown that they are excellent archives of the ENSO variability[7]. Chakraborty *et al.*[95] have exploited this characteristic feature of the Pacific corals and attempted to establish a link between the coral oxygen isotope and the Indian monsoon. The link, however, is established by means of a different mechanism. Xavier *et al.*[96] proposed that it is the tropospheric temperature (TT) gradient, rather than the conventional land-sea surface temperature gradient actually drives the monsoon circulation. According to Xavier *et al.*[96] the ENSO influences the Indian monsoon by modifying the TT gradient over this region. Chakraborty *et al.*[95] demonstrated that $\delta^{18}O$ of corals from several sites in the equatorial Pacific responded to the TT gradient variability over the Indian monsoon region, and are strongly correlated to monsoon precipitation (correlation coefficient between $\delta^{18}O_C$ and all India summer monsoon rainfall ranged from 0.33 to 0.56). Using this correlation these authors reconstructed the past Indian monsoon rainfall variability in the first half of the 20th century, which agreed well with the instrumental record. Further, they have used the isotopic record of an older coral to reconstruct seasonally resolved summer monsoon rainfall variability of the latter half of the 17th century. The reconstructed rainfall showed that the average annual rainfall during this period was similar to that during the 20th century.

One of the important parameters characterizing the monsoon season is the length of the rainy season (LRS) which is defined as the duration between the monsoon withdrawal and the monsoon onset dates[96]. Since the LRS and the TT gradient are intricately related, the $\delta^{18}O_C$ is also strongly connected to the LRS, implying that the parameter could also be reconstructed using the coral proxies. In this context, it may be mentioned that the connection between the TT gradient and the $\delta^{18}O$ of corals from the equatorial Indian Ocean has also been examined by Chakraborty *et al.*[95]. However, unlike their Pacific counterpart, the Indian Ocean corals showed poor correlation (r varied from –0.03 to 0.12). This provides indirect evidence that the equatorial Pacific, rather than the equatorial Indian Ocean plays a greater role in modulating the Indian monsoon, and secondly, offers an explanation why the equatorial Indian Ocean corals, unlike their Pacific counterparts may not have good potentials in reconstructing the Indian monsoon rainfall.

Discussion

From the available information as presented above, it is evident that the coralline proxies, such as the oxygen isotopes and the trace metal abundance may not have strong potential, especially that grow in the equatorial Indian Ocean for reconstructing the Indian monsoon precipitation, but the corals from the equatorial Pacific may have good potential in this regard. Apart from this,

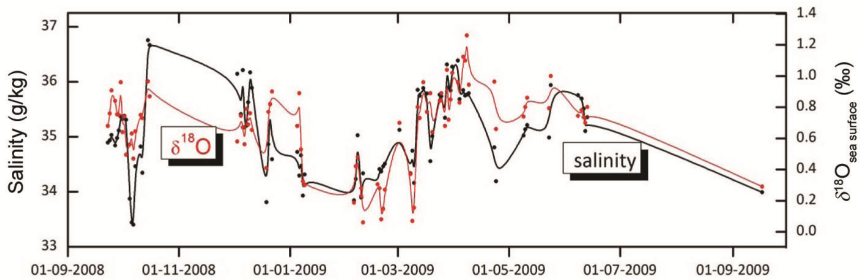

Figure 1. Time profile of sea surface salinity (black line) and sea water $\delta^{18}O$ (red line) in the southeastern part of the Arabian Sea (5°–15°N, 65°–75°E) illustrating a strong link between these parameters. The data were obtained from ref. 98.

another possibility that seems to be emerging from this discussion is that the corals from the Lakshadweep and the Maldives region may also be potentially useful in providing past rainfall information, especially for the western peninsular India. The trace metal analysis of corals[77] and the coral growth rate analysis[92] show that the corals from this region are sensitive to the rainfall of the western peninsular India. This aspect prompts us to examine the characteristics of the corals from this region to explore their potential for the palaeomonsoon study.

As mentioned earlier, $\delta^{18}O_C$ depends on both SST and the oxygen isotopic composition of the surface water ($\delta^{18}O_{SW}$). Though the temperature coefficient of $\delta^{18}O_C$ is well constrained (varies between –0.18 to –0.21‰ °C^{-1}), its dependency on $\delta^{18}O_{SW}$ is not well established. It is generally believed that for every one permil increase in $\delta^{18}O_{SW}$, $\delta^{18}O_C$ would increase by a similar amount, if the temperature remains constant. To quantify this parameter, the on-site calibration process is required. Such kind of effort is rare[97], and in the Indian context, it is not available. In most situations its variability is assumed to be small and hence its effect on $\delta^{18}O_C$ is thought to be negligible. Though there is no systematic measurement of $\delta^{18}O_{SW}$ available for the Lakshadweep region, Deshpande *et al.*[98] analysed a large number of sea water samples during an oceanographic expedition programme over a large area in the southeastern Arabian Sea. From their dataset, we compile the salinity and $\delta^{18}O_{SW}$ for an area of 5–15°N and 65–75°E. Figure 1 shows the variation of these two parameters which covers a period approximately from October 2008 to July 2009. From this figure, it is obvious that from early March to late May, the $\delta^{18}O_{SW}$ increased by about 1‰. Though this dataset belongs to a very large area, it may not be strictly representative of a given coral site in the Lakshadweep region. Nevertheless, this gives an indication of the $\delta^{18}O_{SW}$ and the salinity variability. Since $\delta^{18}O_{SW}$ is closely associated with the surface salinity all over the ocean, including the northern Indian Ocean[98,99] we use it as a proxy for $\delta^{18}O_{SW}$ for the sites where from the coral records were reported. We use observational records of these two parameters available from the NOAA/OAR/ESRL PSD website (https://www.esrl.noaa.gov/psd/) in order to calculate the monthly climatology of the SST and salinity variation in this region[100]. Two sites representing the northern portion (the Amini Island; 11–12°N, 72–73°E) and a southern portion (the Minicoy Island 8–9°N; 72.5–73.5°E) of the Lakshadweep region have been chosen to calculate the long-term climatological variations of SST and salinity (1900–1990) on a monthly scale. Figure 2 *a* and *b* shows these profiles for Amini and Minicoy respectively. A careful observation of this figure shows that these two parameters nearly co-vary from Jan to May, albeit salinity has a small phase lag (Figure 2 *a* and *b*). This kind of salinity profile, i.e. co-variation with the SST in the early year, but out of phase behaviour in the later part of the year is a characteristic feature, specifically for this region. Such kind of salinity behaviour in the Arabian Sea is largely controlled by the low saline surface water flux from the Bay of Bengal in the south, and high salinity water intrusion from the northern Arabian Sea is well documented in the oceanographic literature[101]. But the same profiles look quite different in the case of the Bay of Bengal. To illustrate this behaviour, we have also plotted the salinity and SST profiles for the Andaman region (Figure 2 *c*) from where a coral isotopic record was reported[76]. Additionally, two more plots are also shown. One is Chagos, an equatorial Indian Ocean site[70] and Marbat, a site near the Oman coast[82]; corals from both the sites have been shown to have some link with the movement of the ITCZ and Indian monsoon rainfall respectively.

From Figure 2 *c* it is obvious that the difference in salinity and SST (June–September) in Andaman area is smaller than that of the Lakshadweep region, which would yield a lower seasonal amplitude in $\delta^{18}O_C$. In fact, Rixen *et al.*[76] observed seasonal amplitude ca. 0.15‰. In the case of the Arabian Sea, the monsoon onset takes place typically in the first week of June. The SST drops sharply as a result of vertically advected cool upwelled water, but salinity continues to increase and achieves a maximum value, sometime in August (Figure 2 *a* and *b*). This characteristic behaviour of salinity and SST is especially useful as far as $\delta^{18}O_C$ is concerned. $\delta^{18}O_C$ is inversely correlated with the SST, but varies directly with the sea water $\delta^{18}O_{SW}$, and in turn with the salinity. Hence, an out of phase behaviour of salinity and SST during the summer monsoon season would enhance the isotopic signal in coral. On the other hand, after the end of the monsoon season, usually in late September SST starts rising and by October the salinity declines[101]. This period actually coincides with the monsoon withdrawal phase. So the rise in SST and consequent fall in salinity would greatly diminish the $\delta^{18}O_C$, enabling a means to record the withdrawal phase. This characteristic feature is most pronounced in the case of Lakshadweep region. Though the process may not provide a means to quantify the southwest or the northeast monsoon rainfall, it may offer an opportunity to estimate the southwest monsoon onset and the withdrawal dates, probably with an uncertainty of 1–2 weeks depending on the coral growth rate. Corals with high growth are abundantly available in the Lakshadweep region[102], hence long-term records of monsoon onset and withdrawal information are likely to be retrieved. As mentioned earlier, this parameter, the LRS, is an important attribute of the monsoon and a long-term record of the LRS variability is essential to study the monsoon dynamics[96]. But one of the characteristics of the Andaman corals could be the detection of severe cyclonic events. It is known that the Bay of Bengal is subjected to intense convective activity[103], as a result the precipitation isotopes possess distinct isotopic signature[104,105]. Intense cyclonic events, especially during the post-monsoon season, cause large depletions in rain $\delta^{18}O$ (ref. 106). The anomalously low $\delta^{18}O$ is likely to deplete the surface water $\delta^{18}O_{SW}$ which in turn may get incorporated in the coralline matrix.

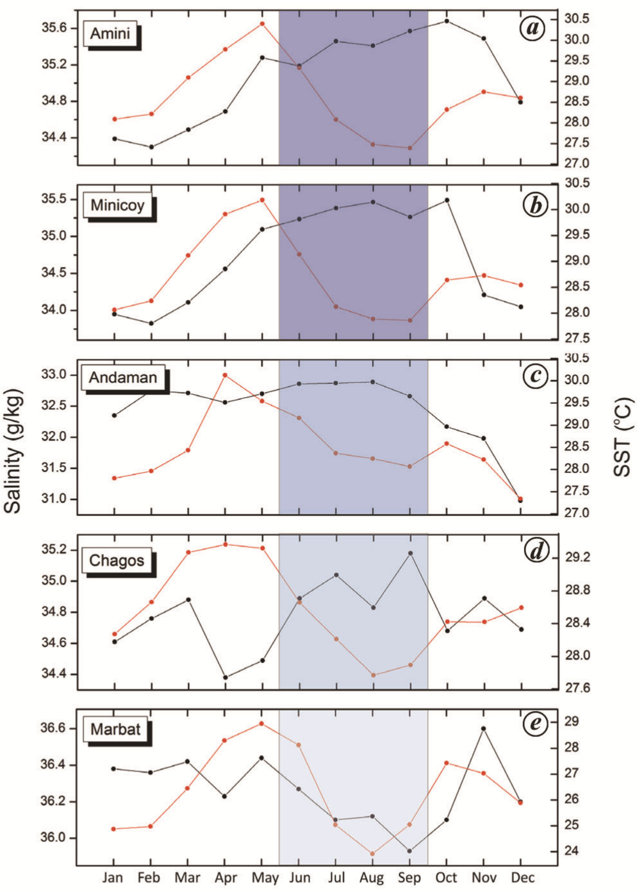

Figure 2. Long-term (1900–1990) variations of sea surface temperature (red line) and salinity (black line) on a monthly scale for a few coral sites in the Indian Ocean. ***a***, Amini (8–9°N, 72.5–73.5°E; Sagar *et al.*[77]); ***b***, Minicoy (8–10°N, 72.5–73.5°E; Fousiya *et al.*[74]); ***c***, Andaman (92°42′E; 11°30′N); Rixen *et al.*[76]); ***d***, Chagos (5°20′S, 71°55′E; Pfeiffer *et al*. 2006); ***e***, Marbat (16°50′N; 54°45′E; Tudhope *et al.*[81]). The blue shading shows a period approximately representing the Indian summer monsoon season. Relatively dark shading in the case of (***a***) and (***b***) implies that the corals from these regions are likely to be more sensitive to the monsoon onset and withdrawal phases, while corals from the other regions may not hold that potential. Salinity and the SST data were obtained from the NOAA website[99].

In this context, it may also be mentioned that the Chagos in the equatorial Indian Ocean also shows a similar behaviour in its salinity and SST profile as that of the Lakshadweep region, but this site may not be suitable for retrieving the monsoon onset and demise information because of its geographical location, which is not sensitive to these kind of monsoon attributes. That is, due to the absence of seasonality, the rainfall is not characterized by sharp changes anytime during the year. On the other hand, the Marbat region shows nearly a co-variation of salinity and SST, making it an unsuitable candidate for monsoon onset/withdrawal study. So, it appears that the corals from the Lakshadweep region may hold good potential to infer about monsoon onset/withdrawal as well as rainfall reconstruction at least for the western peninsular India. However, as the corals from the Pacific is also good for the ISM reconstruction, a better strategy, such as time-synchronous analysis of corals collected from both the equatorial Pacific as well as from the Lakshadweep region is likely to yield a better result in pursuit of palaeo-monsoon study.

Conclusions

A large number of coral oxygen isotopic records are available from across the Indian Ocean. Though they have been used to infer various ocean–atmospheric processes, monsoon rainfall reconstruction was not well established. It has been shown that corals from the equatorial Pacific hold good potential in studying the Indian summer monsoon rainfall, but their Indian Ocean counterparts have little sensitivity in this regard. However, corals from the northern Indian Ocean, especially from the Lakshadweep region are likely to hold strong potential in this endeavour. It is proposed that a time synchronous analysis of coral isotopic data from the Lakshadweep region as well as from the equatorial Pacific Ocean would provide long-term records of monsoon variability including the monsoon onset and withdrawal information.

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