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Pacific coral oxygen isotope and the tropospheric temperature gradient over the Asian monsoon region: a tool to reconstruct past Indian summer monsoon rainfall

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ABSTRACT: Having recognized that it is the tropospheric temperature (TT) gradient rather than the land–ocean surface temperature gradient that drives the Indian monsoon, a new mechanism of El Niño/Southern Oscillation (ENSO) monsoon teleconnection has been unveiled in which the ENSO influences the Indian monsoon by modifying the TT gradient over the region. Here we show that equatorial Pacific coralline oxygen isotopes reflect TT gradient variability over the Indian monsoon region and are strongly correlated to monsoon precipitation as well as to the length of the rainy season. Using these relationships we have been able to reconstruct past Indian monsoon rainfall variability of the first half of the 20th century in agreement with the instrumental record. Additionally, an older coral oxygen isotope record has been used to reconstruct seasonally resolved summer monsoon rainfall variability of the latter half of the 17th century, indicating that the average annual rainfall during this period was similar to that during the 20th century. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: coral oxygen isotope; ENSO; Indian Summer Monsoon; precipitation reconstruction.

Introduction

Knowledge of past variations of the Indian monsoon is crucial for evolving any adaptation or mitigation strategy to cope with the changing climate over the Indian monsoon region (Gupta *et al.*, 2006). Monthly instrumental records of Indian monsoon rainfall are, however, available only for about 196 years (Parthasarathy *et al.*, 1995; Sontakke *et al.*, 2008). There is therefore a need to reconstruct an annually resolved All India Summer Monsoon Rainfall (AISMR) or equivalent measure of monsoon variability using proxy records. Here we explore the possibility of reconstructing indices of monsoon variability from the oxygen isotope of corals in the equatorial Pacific. The ratios of ^{18}O and ^{16}O isotopes ($\delta^{18}O$) in coral skeletons are sensitive to the temperature and oxygen isotopic composition of the ambient seawater (see review by Druffel, 1997 and references therein). Our attempt to reconstruct the monsoon from coral records is based on the knowledge that $\delta^{18}O$ in corals of the equatorial Pacific is known to be a reliable recorder of sea surface temperature (SST) changes associated with the El Niño/Southern Oscillation (ENSO; Grottoli and Eakin, 2007), and that a strong relationship exists between the Indian monsoon and ENSO (Rassmusson and Carpenter 1983; Krishnamurthy and Goswami, 2000), although this relationship seems to have weakened in recent times (Kumar *et al.*, 1999; Goswami, 2005).

The conventional description of the negative correlation between the ENSO and Indian monsoon is described in terms of the large-scale east–west shift in the tropical Walker circulation. According to this, eastward shift of the Walker circulation with positive ENSO index decreases low-level divergence over the equatorial Indian Ocean leading to enhanced convection over the equatorial Indian Ocean and increased subsidence over continental India. The result is reduced monsoon rainfall (Krishnamurthy and Goswami, 2000). This classical explanation assumes that the Indian summer monsoon season is of fixed duration (June 1 to September 30). However, the Indian summer monsoon season is a segment of the annual cycle of the north–south migrating tropical convergence zone (TCZ; Gadgil, 2003; Goswami, 2005). This physical phenomenon, driven by large-scale heating gradients, can be modulated through ENSO teleconnections and vary in intensity and duration from year to year. Therefore, the actual length of the Indian monsoon season may vary from year to year. If 'onset' and 'withdrawal' of the Indian monsoon could be defined objectively, the length of the rainy season (LRS, as defined later) can be considered as another index of the Indian monsoon. An objective definition of 'onset' and 'withdrawal' dates and hence of LRS based on change in sign of the tropospheric temperature gradient over the Asian monsoon region has been proposed by Goswami and Xavier (2005) and Xavier *et al.* (2007). These authors show that 'onset' and 'withdrawal' dates and LRS of the Indian monsoon are strongly related to the ENSO. These findings prompted them to re-evaluate the ENSO–monsoon relationship from a new perspective and propose a new extra-tropical teleconnection mechanism through which the ENSO influences the Indian monsoon (Goswami and Xavier, 2005; Xavier *et al.*, 2007). Under this, the tropical Pacific heating anomalies in the atmosphere associated with the ENSO set up a stationary-wave response in the subtropics and influence the tropospheric temperature (TT) anomalies over Eurasia, thereby influencing the north–south gradient of TT over the Indian monsoon region and the Indian monsoon rainfall. Based on this hypothesis Xavier *et al.* (2007) formulated a new 'thermodynamic index of Indian summer monsoon' (TISM), and observed a significant correlation between the length of the rainy season and the ENSO, providing new insight into the ENSO–monsoon connection.

As mentioned earlier, oxygen isotopic records of corals are known to be a reliable recorder of the ENSO and its associated effects. Secondly, the ENSO plays a dominant role in the TT distribution over Eurasia and hence the monsoon (Xavier *et al.*, 2007). Therefore, it is expected that corals growing in the central Pacific (at the heart of the ENSO region) would show good correlation with TT gradient over the Indian monsoon region as well as with monsoon rainfall. Thirdly, if Xavier *et al.* (2007)'s assertion is correct then the coral isotopic record

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would show good correlation with the thermodynamic characteristics of monsoon variability vis-à-vis the conventional monsoon rainfall indices. One implication of the above hypothesis is establishment of an alternative means to reconstruct seasonally resolved past monsoon precipitation variability based on empirical relationships between the coral $\delta^{18}O$ and the indices of monsoon variability. As the Indian Ocean sea surface temperature (SST) shows a variability linked to the ENSO as well as variability independent of the ENSO such as the Indian Ocean dipole mode (Saji *et al.*, 1999), we also examine the relationship between Indian Ocean coral $\delta^{18}O$ and indices of AISMR variability. Our aim is to examine Xavier *et al.* (2007)'s hypothesis that predicts a possible relationship between coral oxygen isotope and the thermodynamic characteristics of the monsoon variability. Secondly, we investigate the potential of reconstruction of the Indian summer monsoon rainfall with seasonal/annual resolution.

Data and methods

Details of the methods of calculation of TT, LRS and TISM have been outlined in Xavier *et al.* (2007). A brief account is presented here for ease of reference. The tropospheric temperature (denoted as TT) is defined as the mean air temperature between the levels 600 and 200 hPa. The definition of large-scale monsoon onset and withdrawal is based on the reversal of TT between a northern box (40–100°E, 5–35°N) and a southern box (40–100°E, 15–5°N), denoted as ΔTT. The onset date is defined as the date when ΔTT changes sign from negative to positive, and the withdrawal date is defined as the date when ΔTT changes sign from positive to negative (see figure 2 in Xavier *et al.*, 2007). The NCEP/NCAR reanalysis daily data (Kalnay *et al.*, 1996; available since 1950) has been used to calculate the TT. LRS is the number of days between onset and withdrawal of monsoon while TISM is the integral of ΔTT during LRS.

The coral oxygen isotopic ($\delta^{18}O$) data sets were downloaded from the archive of the NOAA National Climatic Data Center (http://www.ncdc.noaa.gov/paleo/corals.html). Those records were chosen that span about 40 years starting from 1950 to 1990 or beyond. This period overlaps with the NCEP/NCAR reanalysis TT data that was used to determine the TISM and LRS. Only a select set of coral data was chosen that are known to carry the ENSO signature in their $\delta^{18}O$ values from the Pacific (Grotolli and Eakin, 2007) and also whose oxygen isotopic values are mostly controlled by SST rather than sea water oxygen isotopic composition. One such record from the central Pacific is the Palmyra Island coral (Cobb *et al.*, 2001), which is located at the heart of the ENSO region. This site provided a 112-year record of $\delta^{18}O$ with monthly resolution. Other coral records from the central Pacific were Nauru island (Guilderson and Schrag, 1999), Kiritimati Island (Evans *et al.*, 1998) and Maiana Atoll (Urban *et al.*, 2000). We have also considered one more coral record from this region, namely the Tarawa island coral, which is known to be significantly controlled by the isotopic composition of seawater apart from SST (Cole *et al.*, 1993). The Indian Ocean sites are Mahe Island, Seychelles (Charles *et al.*, 1997), Malindi (Cole *et al.*, 2000), Chagos Archipelago (Pfeiffer *et al.*, 2004) and Ras Umm Sidd in the Red Sea (Felis *et al.*, 2000). The locations of these coral sites are shown in Fig. 1, and are listed in Table 2 (see below). The coral $\delta^{18}O$ data that give monthly resolution were averaged annually as well as for the summer monsoon season (June–September, or JJAS). The mean values were then correlated with the monsoon parameters, i.e. thermodynamic indices of Xavier *et al.* (2007), namely TISM and LRS, and the conventional rainfall index representing JJAS mean precipitation (AISMR; Parthasarathy *et al.*, 1995; Sontakke *et al.*, 2008). The time period chosen was 1950–1990 +, during which the NCEP/NCAR Reanalysis data were available. We also attempted to use composite coral $\delta^{18}O$ index (simple mean of two coral records such as Palmyra-Kiritimati and Maiana-Nauru) instead of single time series; however, that did not improve the correlation coefficient significantly. Also the lack of time-contemporaneous coral records prevented us from following such a strategy. To compare the long-term relationship of monsoon variability with various ENSO indices, we have used Niño3 SST anomaly reconstruction for AD 1700–1950 (Mann *et al.*, 2000), Niño3.4 SST anomaly for AD 1950–2000 (Trenberth, 1997) and bimonthly Multivariate ENSO Index (MEI) since 1950 (Wolter and Timlin, 1998).

We have performed spectral analyses and determined the coherence and phase relationship between coral $\delta^{18}O$ records and some of the monsoon indices, using the multi-taper method (MTM) (Mann and Lees, 1996). The MTM spectra were obtained using SSA-MTM Toolkit (version 4.4, available at http://www.atmos.ucla.edu/tcd/ssa/). We produced a high-resolution MTM spectrum (time-frequency bandwidth product '$p' = 1$, number of tapers = 1), with red noise background assumption. To study the non-stationary behaviour of the

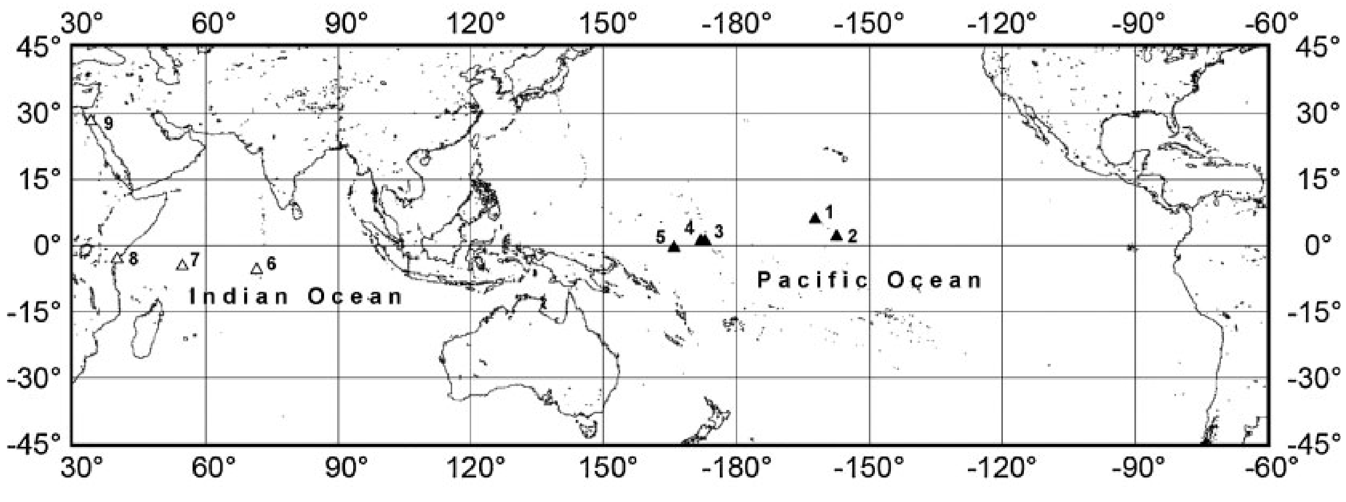

Figure 1. Location map of the coral sites whose records have been used in this paper. Pacific Ocean locations (filled triangles): 1, Palmyra; 2, Kiritimati; 3, Maiana; 4, Tarawa; 5, Nauru; Indian Ocean locations (open triangles): 6, Chagos Archipelago; 7, Seychelles; 8, Malindi; 9, Ras Umm Sidd.

coherence between monsoon and ENSO indices, we determined evolutive MTM coherence using FORTRAN codes available at http://holocene.meteo.psu.edu/Mann/tools/tools.html. We used a sliding window of 50 years with time steps of 1 year. The spectral coherence values were filtered at 50% level of significance.

Results

First, we present the physical basis by which the Pacific coral $\delta^{18}O$ could be linked to the Indian summer monsoon rainfall and its associated indices, such as TISM. Figure 2 shows the time series of MEI, and oxygen isotope records of Kiritimati, Palmyra, Maiana, Tarawa and Nauru coral of the Pacific Ocean, and of equatorial Indian Ocean corals, such as Chagos, Seychelles and Malindi; the bottom panel shows the temporal variation of AISMR and TISM. Strong and moderately strong ENSO years are shown as heavy and light shading, respectively. In each cases the JJAS values were averaged (except for Malindi coral) and Z-values were calculated. The climatological mean was calculated for a time duration of 40 years (1950–1989) during which all the data sets, namely AISMR, individual coral records and NCEP/NCAR reanalysis data, were available. The figure shows clearly that there is very good correspondence among these records; correlation coefficients are shown in Table 1. This table shows that coral records are strongly correlated among themselves (belonging to the same ocean basin) and inversely correlated with the ENSO index. However, correlation is poorer for coral $\delta^{18}O$ vs. AISMR and AISMR vs. MEI, probably indicating control of other factors than the ENSO on the Indian monsoon variability.

In this context would seem reasonable to establish a connection between coral oxygen isotopes and the land ocean temperature and pressure gradient, which are known to initiate the monsoon circulation. However, we feel this is not justified because of the following reasons. Analysis shows that the temperature of the Indian landmass actually drops after the monsoon sets in (see Supporting information, Fig. S1; B. N. Goswami, unpublished results). It is evident that the land temperature, except at the sub-Saharan and Arabian desert, is a few degrees cooler than the ocean temperature. Thus, the land–ocean surface temperature gradient during the monsoon season actually becomes negative. Therefore, even though the north–south gradient of surface temperature may play a role in the

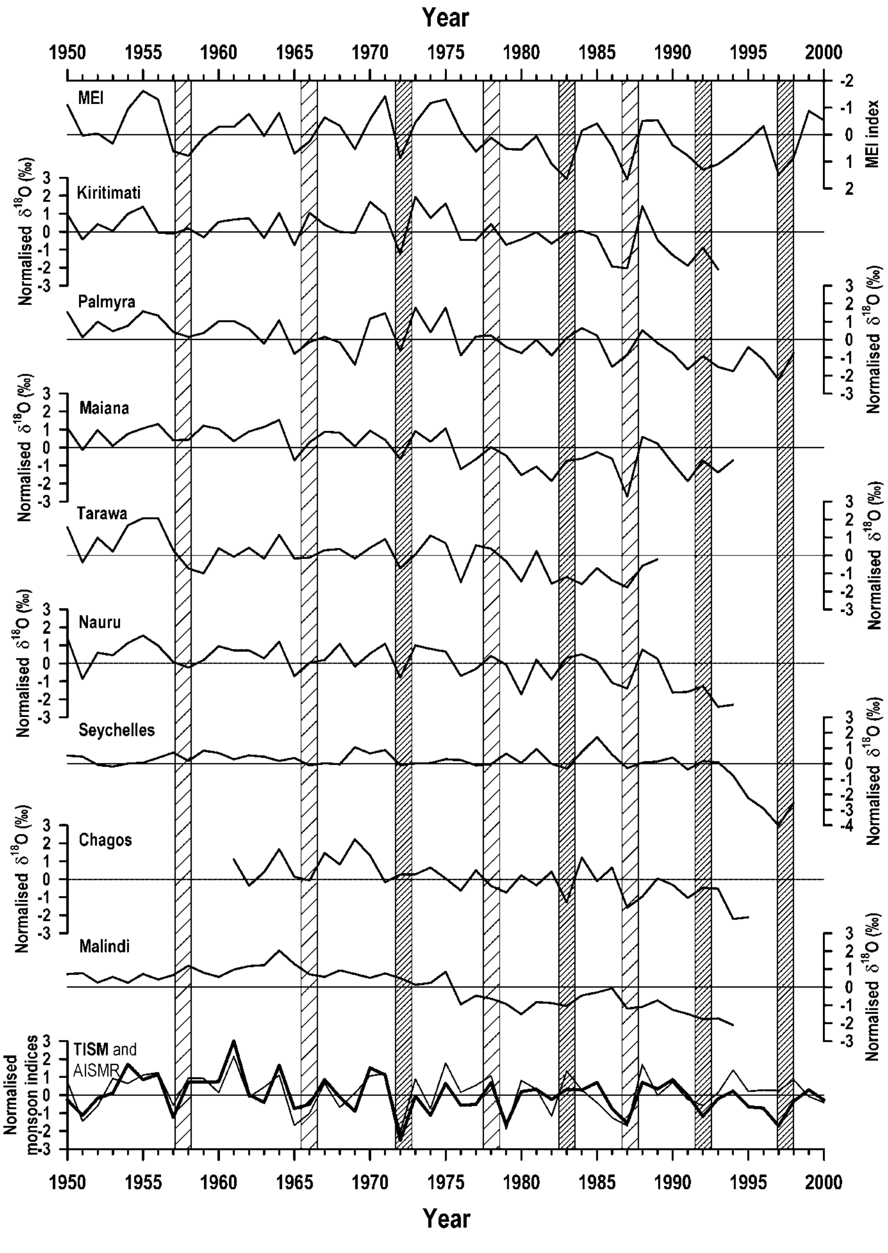

Figure 2. Time series of multivariate ENSO index, Pacific Ocean coral oxygen isotope records (Kiritimati, Palmyra, Maiana, Tarawa, Nauru), equatorial Indian Ocean coral isotope records (Seychelles, Chagos, Malindi), and TISM and AISMR representing the Indian summer monsoon rainfall indices. The multivariate ENSO index was plotted with an inverted *y*-axis. All the records were averaged for the boreal summer months (JJAS) except the Malindi coral record, which was available in annual resolution. The *y*-axis represents the normalized values of all the parameters. Strong and moderately strong ENSO years are indicated as dark grey and light grey cross-hatched columns, respectively.

Table 1. Correlation matrix showing the correlation coefficient among various coral records as well as with the ENSO (MEI) and monsoon indices, such as TISM and AISMR. The coral records are represented by their respective sites (locations given in Table 2). The numbers represent the Pearson correlation coefficients between two given parameters.

	MEI	Kiritimati	Palmyra	Maiana	Tarawa	Nauru	Seychelles	Chagos	Malindi	TISM	AISMR
MEI	1										
Kiritimati	−0.82	1									
Palmyra	−0.78	0.85	1								
Maiana	−0.76	0.75	0.75	1							
Tarawa	−0.73	0.60	0.68	0.71	1						
Nauru	−0.78	0.84	0.86	0.79	0.76	1					
Seychelles	−0.31	0.08	0.42	0.28	−0.02	0.26	1				
Chagos	−0.33	0.34	0.31	0.49	0.33	0.45	0.53	1			
Malindi	−0.50	0.65	0.63	0.77	0.46	0.67	0.41	0.60	1		
TISM	−0.64	0.50	0.55	0.43	0.34	0.42	0.29	0.10	0.20	1	
AISMR	−0.61	0.56	0.56	0.45	0.32	0.33	−0.07	0.12	0.06	0.75	1

MEI, multi ENSO index; TISM, thermodynamic index of summer monsoon; AISMR, all India summer monsoon rainfall.

onset phase of the monsoon, it cannot sustain the monsoon during the season.

On the other hand, the pressure on the land surface varies considerably with topography. Even though monsoon winds are triggered due to land–ocean pressure differences, the surface pressure rises soon after the monsoon is fully developed, as the land surface cools. Hence the data on surface pressure and in turn the land–ocean pressure gradient is not a reliable indicator of monsoon variability. This is also evident from the poor correlation with AISMR ($r = 0.05$). It has also been shown that SST of the Indian Ocean does not show a strong correlation with AISMR as compared with the SST of the Pacific (Rao and Goswami, 1988). Coral records also support this observation. The oxygen isotopic record of the Malindi coral (western equatorial Indian Ocean) shows strong coherence with the ENSO variability but is weakly correlated with AISMR (Cole *et al.*, 2000). Although the land–ocean pressure gradient shows strong correlation with the coral isotope records, such as with Malindi coral ($r = 0.7$), it does not appear to be a good representative of monsoon variability. In this context note that the TT gradient is calculated at the levels of 600 and 200 mbar, thereby almost eliminating the effect of topography.

One of the necessary conditions for establishing a link between Pacific coral $\delta^{18}O$ and the AISMR and/or TISM is to determine first the common periodicities between the AISMR/TISM and ENSO. We show that the TISM record possess a periodicity of ~4.92 years (close to 90%) at the ENSO bands, and exhibits strong coherence (>99%) with the Niño3.4 SST anomaly at this time scale (Fig. 3). On the other hand, the Palmyra coral $\delta^{18}O$ record also displays a strong periodicity at

Table 2. Pearson correlation coefficients (*r*) among coral $\delta^{18}O$ and the various monsoon indices.

Coral location	JJAS/AISMR (*r*)	*P*	LRS (*r*)	*P*	TISM (*r*)	*P*	*n*	Record period	Ref.
Pacific Ocean coral records									
Palmyra (5°52′N, 162°8′W)	0.422/	<0.005	0.588	<0.0001	0.547	<0.0001	49	1886–1998	A
	0.305	<0.05	0.517	<0.0005	0.458	<0.001			
Kiritimati (2°N, 157°18′W)	0.563/	<0.0001	0.379	<0.05	0.503	<0.001	44	1938–1993	B
	0.387	<0.01	0.343	<0.05	0.389	<0.01			
Nauru (0°30′S, 166°E)	0.354/	<0.05	0.483	<0.001	0.418	<0.005	45	1898–1995	C
	0.276	<0.1	0.493	<0.001	0.377	<0.05			
Maiana (1°N, 173°E)	0.424/	<0.005	0.474	<0.005	0.430	<0.005	45	1840–1994	D
	0.336	<0.05	0.479	<0.001	0.368	<0.05			
Tarawa (1°N, 172°E)	0.322/	<0.05	0.465	<0.005	0.342	<0.05	40	1959–1979	E
	0.324	<0.05	0.506	<0.001	0.339	<0.05			
Indian Ocean coral records									
Chagos (5°26′S, 71°46′E)	0.115/	NC	0.096	NC	0.104	NC	35	1961–1995	F
	0.029	NC	0.191	NC	0.206	NC			
Seychelles (4°37′S, 55°E)	−0.072/	NC	0.241	<0.1	0.29	<0.05	49	1846–1995	G
	−0.034	NC	0.290	<0.05	0.321	<0.05			
Malindi (3°S, 40°E)	0.061	NC	0.273	<0.1	0.202	NC	45	1801–1994	H
Ras Umm Sidd (27°51′N, 34°18′E)	0.060/	NC	0.110	NC	0.085	NC	46	1750–1995	I
	0.129	NC	0.320	<0.05	0.181	NC			

In each case (except for Malindi) the upper row shows the results for the JJAS-averaged coral record, while the lower row displays the same for the annually averaged coral record. Summer monsoon rainfall in India is represented by JJAS AISMR. LRS, length of rainy season; NC, no significant correlation; TISM, thermodynamic index of indian summer monsoon. The ninth column shows the duration of the coral records available for the respective site. *P* is the significance level and *n* is the number of data points. References: A, Cobb *et al.* (2001); B, Evans *et al.* (1998); C, Guilderson and Schrag (1999); D, Urban *et al.* (2000); E, Cole *et al.* (1993); F, Pfeiffer *et al.* (2004); G, Charles *et al.* (1997); H, Cole *et al.* (2000); I, Felis *et al.* (2000).

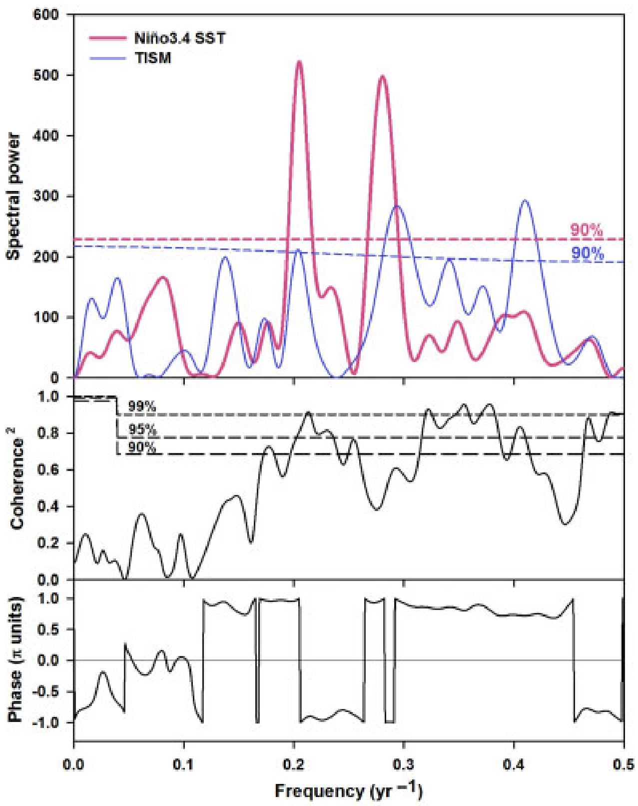

Figure 3. Periodicities (top) and spectral coherence (middle) of the anomalies of Niño3.4 SST (red) and (TISM, blue), obtained using the multi-taper method (MTM) for the period 1950–2000. Horizontal dashed lines of the MTM spectra indicate 90% levels of significance of the respective data; the dashed lines in the coherency plot indicate 90, 95 and 99% levels of confidence (bottom to top). Both time series show significant periodicities and strong coherencies (middle panel) at ~5- to 4-year bands. Phase lags between the two time-series (bottom panel); positive phase lags indicate Niño3.4 SST anomalies lead TISM anomalies, and vice versa. The two time series are ~180° out of phase at the periods of maximum coherencies, indicating general anti-correlation of the two variables at these frequencies. This figure is available in colour online at wileyonlinelibrary.com.

~5.5 years (Cobb *et al.*, 2001). Hence it is reasonable to expect that the Pacific coral oxygen isotope record such as for Palmyra coral would be correlated with the thermodynamic indices of the monsoon variability, such as TISM or its derivative (LRS). Hence we expect the coral records from the equatorial Pacific would be correlated with the AISMR by virtue of the ENSO–AISMR connection as mentioned above.

Figure 4 shows the evolutive MTM coherence plot between Niño3 SST and AISMR for the period 1813–1950. Temporal instability of the Niño3 SST–ISMR relationship is clear from this analysis. The coherence of the variabilities of Niño3 SST and AISMR was high at ~3.5-year time scales within a 50-year period centered between ~1855 and ~1875. The coherence shifted to longer periods of ~5–6 years from ~1875 to ~1920. Coherence at shorter periods (<4 years) emerge after ~1920. This result is similar to the analysis by Torrence and Webster (1999), who noted high coherence of ENSO–monsoon indices during the periods of high variance between 1875 and 1920. We have also noted high coherence at decadal or multi-decadal time scales (~15–20 years) during the later portion of the record, in a 50-year window centred at ~1910 to ~1920.

Table 2 summarizes the correlation coefficients between coral $\delta^{18}O$ and the monsoon indices. In each case the upper row represent the result for the JJAS-averaged coral record, while the lower row represents the same for the annually averaged coral record. The upper panel consists of the Pacific Ocean corals while the lower panel displays results for the Indian Ocean corals. From this table we make the following observations:

(1) Indian Ocean corals show little correlation with the Indian summer monsoon rainfall variability.
(2) Some of these coral $\delta^{18}O$ values are weakly correlated with the thermodynamic definition of monsoon rainfall indices (TISM/LRS).
(3) The Pacific Ocean corals show good correlation with the summer monsoon rainfall and with the thermodynamic definition of monsoon rainfall indices. Except in the case of the Kiritimati island coral, the coral $\delta^{18}O$ shows better correlation with the thermodynamic indices of rainfall rather than the traditional definition of monsoon rainfall index.
(4) The mean coral $\delta^{18}O$ during the summer monsoon season (JJAS) is in general better correlated (with the monsoon indices) than the annually averaged coral $\delta^{18}O$. However, both the seasonally averaged and annually averaged coral $\delta^{18}O$ show almost the same correlation (only) with LRS.
(5) The highest correlations were observed for Palmyra island coral $\delta^{18}O$ (JJAS average) vs. LRS (0.59) and TISM (0.55) and the Kiritimati island coral $\delta^{18}O$ vs. AISMR (0.56) with high significance ($P < 0.0001$) in all the cases.

Discussion

From these observations it is clear that central Pacific coral $\delta^{18}O$ is better correlated with the monsoon indices than their counterparts growing in the Indian Ocean. Secondly, except for the Kiritimati record the same coral isotopic record appears to show better correlation with the thermodynamic characteristics of monsoon variability as proposed by Xavier *et al.* (2007) than the conventional monsoon index (ISMR).

In this context it may be worth addressing why the Indian Ocean corals, especially those in the western Indian Ocean (teleconnected to the ENSO), do not show good correlation with the monsoon indices. This is apparent if we analyse the connection between SST of the Indian Ocean compared with the Pacific Ocean and the ENSO index. Figure 5(a) shows a correlation diagram between SST and ENSO variability. The plot clearly shows that the central Pacific Ocean SSTs are better correlated (mostly 0.8) than the Indian Ocean SSTs ($\leq$0.6) with MEI. Similarly, Fig. 5(b) shows how the TISM is correlated with the SST of these two ocean basins. As before, TISM shows a strong (inverse) correlation with the Pacific Ocean SST as compared with the Indian Ocean SST. As coral oxygen isotope primarily responds to changes in SST, it may be argued that corals from the Indian Ocean would be less sensitive (relative to their Pacific Ocean counterparts) to changes in ENSO characteristics and hence with variations in the monsoon.

Pfeiffer *et al.* (2004) observed that the coral from the Chagos Archipelago at the equatorial Indian Ocean responds strongly to the north-east monsoon rainfall but not to the summer monsoon rain. It shows a strong inverse correlation with north-east monsoon precipitation and outgoing longwave radiation (OLR) during December–March. This most probably implies that this coral responds to local rain and not to the broad-based Indian summer monsoon rain. Observational data from the past two to three decades show that, in contrast to the tropical Pacific, SST and OLR are weakly correlated in the Indian Ocean (Webster *et al.*, 1998). According to Pfeiffer *et al.* (2004) this has two important implications: (i) SST in the tropical Indian Ocean

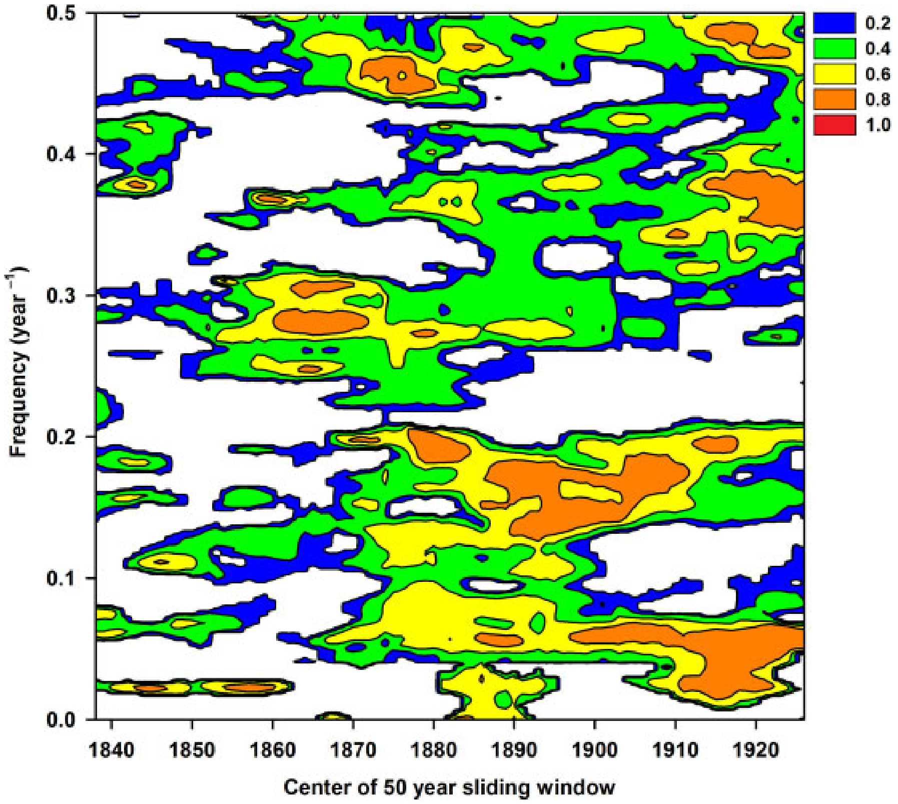

Figure 4. Evolutive coherence using the multi-taper method (MTM) between Niño3 SST index and AISMR (1813–1950). Coherencies determined for a sliding window of 50 years at intervals of 1 year. The red regions indicate the periods of maximum coherence. Only coherencies with significance levels >50% are shown.

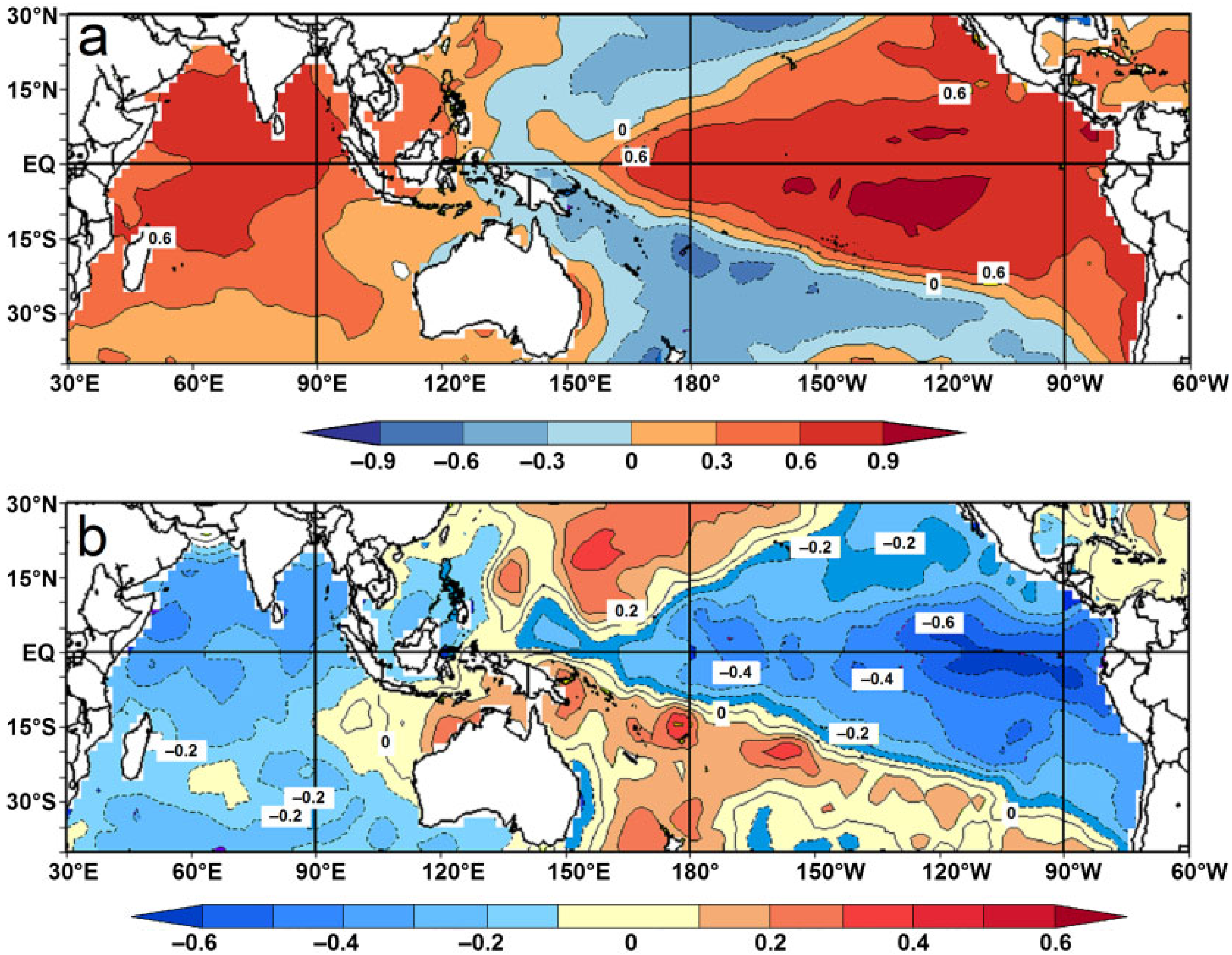

Figure 5. Seasonal correlations of annual SST (January–December, 1950–000) with: (a) multivariate El Niño/Southern Oscillation Index (MEI), and (b) thermodynamic index of Indian summer monsoon (TISM). The contours indicate linear correlation coefficients (*r*) among the variables.

is not regulated by deep atmospheric convection, as has been proposed for the tropical Pacific (Ramanathan and Collins, 1991; Lindzen *et al.*, 2001); and (ii) atmospheric convection is governed by processes other than ocean–atmosphere interactions (Webster *et al.*, 1998). Hence it is apparent that ocean–atmosphere processes in the Indian Ocean determine the coral $\delta^{18}O$–monsoon relationship, which is weaker compared with the Pacific Ocean. However, long coral records from the western and the eastern Indian Ocean have been used to reconstruct dipole mode index (Abram *et al.*, 2008), which shows a close relationship with the Asian monsoon.

Returning to the Pacific Ocean corals and examining their relationship with the monsoon indices, the strong connection between the Palmyra coral $\delta^{18}O$ and the LRS can be used to reconstruct the past length of rainy season. By contrast, a good correlation between Kiritimati coral $\delta^{18}O$ and AISMR has the potential to quantify past precipitation.

To achieve this we first fit a straight line between these two time series for the time period 1950–1998. The following equation yields the relationship between the Palmyra coral $\delta^{18}O$ and LRS:

$$\mathrm{LRS} = (280.246 \pm 31.68) + (30.853 \pm 6.19) \times \delta^{18}\mathrm{O}_{\mathrm{Palmyra}} \quad [r = 0.59,\ n = 49,\ P < 0.0001]. \tag{1}$$

As the Palmyra coral record is available from 1886 this equation was then used to reconstruct the LRS for the period 1886–1949. The predicted LRS and the instrumental rainfall record show a very significant correlation ($r = 0.58$, $n = 64$, $P < 0.0001$), similar to that observed ($r = 0.49$) by Xavier *et al.* (2007) for the period 1950–2003. Similarly, the Kiritimati coral $\delta^{18}O$ data have been calibrated with the instrumental rainfall data for the period 1950–1993, and the following equation was obtained:

$$\mathrm{AISMR} = (2063.736 \pm 261.89) + (252.036 \pm 57.06) \times \delta^{18}\mathrm{O}_{\mathrm{Kiritimati}} \quad [r = 0.563,\ n = 44,\ P < 0.0001]. \tag{2}$$

This equation was then used to reconstruct the rainfall time series for the period 1938–1949, as the Kiritimati coral $\delta^{18}O$ record is available only from 1938. Figure 6(a) shows the reconstructed rain and the instrumental record of rainfall variability.

The reconstructed rainfall record shows very good agreement with the instrumental data ($r = 0.71$, $n = 12$, $P < 0.01$). The Palmyra coral $\delta^{18}O$ has also been used to reconstruct past rainfall variability, even though its $\delta^{18}O$ is relatively less strongly correlated with rainfall variability than with LRS, although it provides a much longer record than any other coral growing in the equatorial Pacific. This may be done in two ways. First, the coral $\delta^{18}O$ is calibrated with the instrumental rainfall data for the period 1950–1993 and use the calibration equation to reconstruct the rainfall for the period 1888–1949. The reconstructed time series shows a good correlation ($r = 0.57$, $n = 64$, $P < 0.0001$) with the instrumental record. We also compare the observed rainfall and coral-derived rainfall over decadal time scales. Figure 6(b) shows the plots of these two time series (normalized), namely a 9-year moving average of coral-derived precipitation and the same for the instrumental record. It is clear that these two time series show strong coherence on decadal time scales.

The second method uses the entire 112-year coral record to calibrate the coral $\delta^{18}O$ and the corresponding instrumental rainfall variability. Although in this case the calibration may not be validated, it is likely to give a better constrained calibration function because of the larger number of data points. The regression equation is given by:

$$\mathrm{AISMR} = (1911.05 \pm 187) + (199.7 \pm 37) \times \delta^{18}\mathrm{O}_{\mathrm{Palmyra}} \quad [r = 0.45,\ n = 112,\ P < 0.0001], \tag{3}$$

and may be applied to fossil coral data to reconstruct the past monsoon precipitation variability. Palmyra coral data are available in different time intervals and one of the longest intervals is AD 1635–1702. Applying Equation (3) we reconstruct the AISMR variability for this time period, which is presented in the form of a bar diagram in Fig. 6(c). During the reconstruction period the rainfall variability shows an increasing trend, and the period 1635 to about 1670 shows a large variability with some of the years showing rainfall as low as 820 mm (AD 1657) and 830 mm (AD 1653). The mean precipitation during this period was 916.0 ± 41.3 mm while that during AD 1671–1702 was 932.0 ± 25.5 mm. The entire period shows a mean of 923.6 ± 35.5 mm. This period is believed to have witnessed significantly enhanced ENSO activities, as evidenced from the Palmyra coral oxygen isotope record in terms of both intensity and frequency (Cobb *et al.*, 2003). As monsoon rainfall and ENSO are inversely correlated, this reduction in rainfall during the beginning of this reconstruction period was most probably due to the intense ENSO activities. This period also coincides with the Maunder Minimum period centred around AD 1658 (AD 1645–1710), a period of decreased monsoon precipitation due to reduced solar irradiance (Agnihotri *et al.*, 2002; Liu *et al.*, 2009).

A large number of marine and terrestrial climate records exist that attempt to reconstruct Indian/Asian monsoon rainfall variability (for a succinct description of Holocene monsoon variability see Fleitmann *et al.*, 2007, Fig. 1). However, comparison of our coral-based reconstruction for testing the reliability of this method is difficult due to the lack of availability of well-dated annually resolved proxy rainfall record in this time range. So we make only qualitative comparison of our coral-based reconstruction with other proxy records. One such record is a 780-year (AD 1220–2000) $\delta^{18}O$ speleothem data collected from southern Oman (Burns *et al.*, 2002). However, we have reservation on the authors' claim that this speleothem $\delta^{18}O$ record is a reliable recorder of the ISMR variability. This is based on the observation that, during the Indian monsoon season (JJAS), cooling of the western Arabian Sea due to upwelling confines the organized convection to stay east of 60°E (Webster *et al.*, 1998). The $\delta^{18}O$ record of spelothems from Oman may therefore represent rains associated with the tropical convergence zone during the premonsoon, but is unlikely to be related to JJAS rainfall over the Indian continent.

A large number of coral-based SST proxies (oxygen isotopic records) are also available from the Indian Ocean (Ramesh *et al.*, 2010; Chakraborty, 2006); however, these records reveal no significant statistical link to the AISMR index (Storz and Gischler, 2011). Nevertheless, the latter authors report a strong anti-correlation ($r = -0.82$, $P < 0.05$) between coral extension rates from the Maldives (Rasdhoo Atoll, 4°N, 73°W) and monsoon rain in the Western Ghats (73–76°E/13–15°N). According to Storz and Gischler (2011) corals from this region could be used to reconstruct past monsoon variations of the India monsoon system. However, the observed correlation was with monsoon rainfall of a particular grid, rather than AISMR. Incidentally, the JJAS rainfall of the western peninsular India is characterized by heavy precipitation and large variability

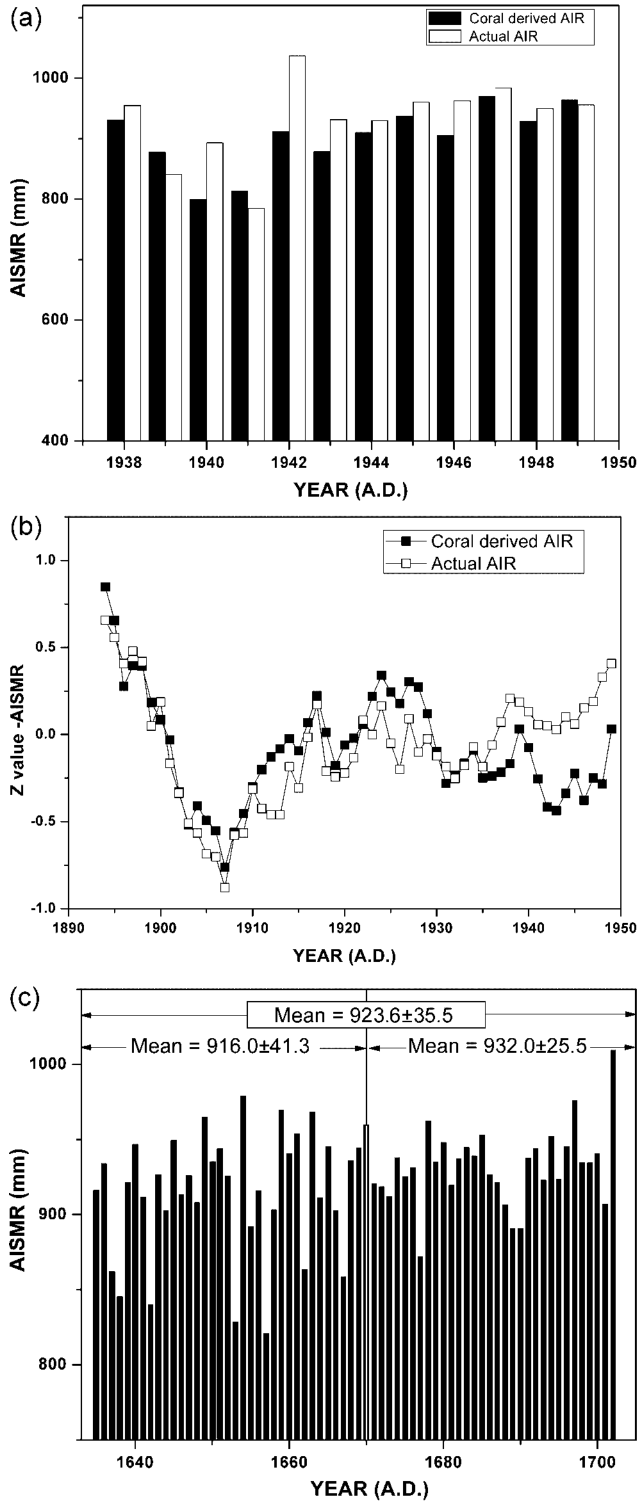

Figure 6. (a) Rainfall reconstruction based on Kiritimati coral $\delta^{18}O$ between 1938 and 1949. (b) Nine-year moving average of the *z*-scores of the coral-derived summer monsoon rainfall (black) and observed rainfall (grey) between 1893 and 1849. (c) Reconstruction of the 17th century summer monsoon rainfall (mm) based on Palmyra coral $\delta^{18}O$. The rainfall is for the area defined by the present-day political boundary of India. The vertical line divides the period showing lower rainfall but higher variability during 1635–1670 and the latter half showing relatively higher rainfall but lower variability.

(mean = 921 ± 162 mm), meaning that it is unrealistic to regard it as a representative of the AISMR.

Other proxy records on monsoon intensity are available; however, the comparisons are not very effective due to the mismatch in temporal resolution of those records. For example, Thompson *et al.* (2000) analysed oxygen isotopic ratio, dust concentration and chemical composition (chloride content) of an ice core from Dasuopu, Tibet (28°23′N, 85°43′E), in order to reconstruct the south Asian monsoon variability for the period AD 1400–2000, which gave a relative estimate of monsoon variation in decadal timescales. These authors observed strong peaks of dust, chloride and oxygen isotopic ratios in the years of 1790–1796 and 1876, which they attributed to severe droughts in the northern Indian region. The dust record shows another peak at AD 1650 (Thompson *et al.*, 2000, Fig. 3), which is accompanied by a somewhat smaller peak of chloride content. This is probably another drought year of relatively low intensity. Our coral-derived rainfall reconstruction shows two reduced rainfall year, 1653 and 1657. Within the limits of chronological uncertainties (±3 years for ice cores and ±5 years for coral band) this seems to agree with the ice core record of rainfall variability. Other proxy-based reconstructions, such as the varve record from the coastal region of Pakistan, also indicated reduced rainfall during the period 650–450 BP (von Rad *et al.*, 1999).

To check the credibility of this rainfall reconstruction we also reconstruct the LRS using Equation (1) but using a different slice of Palmyra coral $\delta^{18}O$ available for the period 1653–1695 (sample B13 of Cobb *et al.*, 2003). Reconstructed AISMR and LRS for the respective periods are detailed in Supporting information, Table S1. The values reveal a strong correlation of 0.68 ($n = 43$, $P < 0.0001$) for the period 1653–1695. This is similar to the one obtained during the modern period (Goswami and Xavier, 2005) and hence gives credence to these reconstructions of past LRS and monsoon rainfall variability.

Although the coral-derived rainfall and LRS reconstruction provide a reliable means of studying the past monsoon characteristic, they suffer from some limitations. First, this method is based on the assumption that the Indian summer monsoon rainfall is by and large controlled by ENSO variability and the AISMR–ENSO inverse relationship remains valid throughout the reconstruction period. The Indian monsoon is also affected by non-ENSO parameters and may not be entirely explained by ENSO variability. Hence this method of precipitation reconstruction remains valid as long as ENSO–monsoon is strongly connected. Secondly, the coral-derived rainfall reconstruction seems to underestimate the large variance in precipitation. For example, the reconstructed rainfall during 1886–1949 based on Palmyra coral $\delta^{18}O$ has a mean of 939 ± 23 mm while the actual mean and variance are 908 ± 87 mm. Similarly, the reconstructed LRS has a mean of 128 ± 5 days while that of the estimates of Xavier *et al.* (2007) for the same period was 123 ± 11 days. This appears to be an inherent problem of coral $\delta^{18}O$ that is primarily controlled by SST, which itself has relatively small variations especially in the tropics. This makes the coral isotopic record less sensitive to extreme rainfall variability.

Conclusions

The classical theory of monsoon circulation that relies on the land–ocean temperature gradient suffers from some limitations, most important being the fall in temperature gradient after the onset of the monsoon. Xavier *et al.* (2007) proposed that the TT gradient rather than the land–ocean surface temperature gradient is responsible for sustaining the deep monsoon circulation. So far, no proxy record has been shown to give credence to this hypothesis. Our re-analysis of the equatorial Pacific coral oxygen isotopic record appears to support this hypothesis. As the tropospheric temperature gradient is a large-scale process and the coralline oxygen isotope responds to this process mediated by SST, it may have immense potential in reconstructing past rainfall variability. Proxy records that give annual resolution often represent local or regional climate. This limitation is to a great extent overcome using Pacific Ocean coral $\delta^{18}O$ and its relationship with monsoon as described in this paper. Unlike other proxy records that mostly deal with the intensity of the monsoon rainfall, this method of investigation also quantifies another degree of freedom of monsoon variability, namely LRS. On the other hand, most of the isotope-based rainfall reconstructions (Sinha *et al.*, 2007; Thompson *et al.*, 2000) provide only a relative measure of annual rainfall variability, whereas this method actually quantifies the summer monsoon rainfall variability over the Indian region. Another plausible merit of this method is that the reconstruction is mainly for the summer monsoon rainfall and the seasonality in rainfall variation (that is summer versus winter precipitation) is unlikely to affect the reconstruction. Study of past monsoon variability to a great extent relies on the oxygen isotopes of speleothems (Fleitmann *et al.*, 2003), although this method suffers from several limitations, the most important being the variability in rainfall seasonality and the source of moisture (Maher, 2008). The coral-based monsoon reconstruction described in this paper is independent of the isotopic composition of the moisture source or of the precipitation, and hence seems to overcome these problems. Our analysis shows that multiple regression analysis between rainfall variability (predictand) and TISM and LRS (predictors) yields stronger correlation than simple regression between rainfall/LRS and coral $\delta^{18}O$. It is, in principle, possible to reconstruct LRS and TISM from two different coral records and then rainfall variability from the reconstructed LRS and TISM records. Currently this is not possible due to the lack of long records. When longer coral records are made available from the equatorial Pacific Ocean this potential could be realized. Another possible application of this study is to reconstruct past TT gradient over Eurasia. Reliable estimation of these parameters is likely to help understand the atmospheric processes that were operative during the past several centuries and understand the physical basis for observed past teleconnection between the Indian monsoon and other regional climates.

Supporting information

Additional supporting information can be found in the online version of this article:

Table S1. Coral-derived reconstructed all India summer monsoon rainfall and length of the rainy season based on two different slices of Palmyra coral.

Figure S1. Skin temperature NCEP/reanalysis average of all Julys (1949–2002).

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Abbreviations. AISMR, All India Summer Monsoon Rainfall; ENSO, El Niño/Southern Oscillation; LRS, length of the rainy season; MEI, Multivariate ENSO Index; JJAS, June–September; OLR, outgoing longwave radiation; SST, sea surface temperature; TCZ, tropical convergence zone; TISM, thermodynamic index of Indian summer monsoon; TT, tropospheric temperature.

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