

RESEARCH ARTICLE

10.1002/2015JC010821

Key Points:

- First coral-Sr/Ca record from this region, which has strong monsoonal influence
- Coral-Sr/Ca records monsoon-induced summer cooling of surface water temperatures
- Thermal-stress during some major El Niño years suppresses the summer Sr/Ca peaks

Supporting Information:

- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4

Correspondence to:

N. Sagar,
n.sagar@ngri.res.in

Citation:

Sagar, N., S. Hetzinger, M. Pfeiffer, S. Masood Ahmad, W.-C. Dullo, and D. Garbe-Schönberg (2016), High-resolution Sr/Ca ratios in a *Porites lutea* coral from Lakshadweep Archipelago, southeast Arabian Sea: An example from a region experiencing steady rise in the reef temperature, *J. Geophys. Res. Oceans*, 121, 252–266, doi:10.1002/2015JC010821.

Received 11 MAR 2015

Accepted 7 DEC 2015

Accepted article online 13 DEC 2015

Published online 10 JAN 2016

High-resolution Sr/Ca ratios in a *Porites lutea* coral from Lakshadweep Archipelago, southeast Arabian Sea: An example from a region experiencing steady rise in the reef temperature

Netramani Sagar¹, Steffen Hetzinger², Miriam Pfeiffer³, Syed Masood Ahmad¹, Wolf-Christian Dullo², and Dieter Garbe-Schönberg⁴

¹CSIR-National Geophysical Research Institute, Hyderabad, Telangana, India, ²GEOMAR Helmholtz Centre for Ocean Research, Kiel, Germany, ³Institute of Geology and Paleontology, RWTH Aachen University, Aachen, Germany, ⁴Department of Geology, Institute of Geosciences, University of Kiel, Kiel, Germany

Abstract Here we present the first record of Sr/Ca variability in a massive *Porites lutea* coral from the Lakshadweep Archipelago, Arabian Sea. The annual mean sea surface temperature (SST) in this region and the surrounding areas has increased steadily in the recent past. During some major El Niño events, SSTs are even higher, imposing additional thermal-stress on corals, episodically leading to coral bleaching. We infer from the coral-Sr/Ca record (1981–2008) that during some of these events high and persistent SSTs lead to a dampening of the temperature signal in coral-Sr/Ca, impairing the coral's ability to record full scale warming. Thus, coral-Sr/Ca may provide a history of past El Niño Southern-Oscillation (ENSO) induced thermal-stress episodes, which are a recurrent feature also seen in cross-spectral analysis between coral-Sr/Ca and the Nino3.4 index. Despite the impact of episodic thermal-stress during major El Niño events, our coral proxy faithfully records the seasonal monsoon-induced summer cooling on the order of $\sim 2.3^{\circ}\text{C}$. Calibration of coral-Sr/Ca with instrumental grid-SST data shows significant correlation to regional SST and monsoon variability. Hence, massive *Porites* corals of this region are highly valuable archives for reconstructing long-term changes in SST, strongly influenced by monsoon variability on seasonal scales. More importantly, our data show that this site with increasing SST is an ideal location for testing the future effects of the projected anthropogenic SST increase on coral reefs that are already under thermal-stress worldwide.

1. Introduction

Coral reefs are becoming increasingly vulnerable due to rising global sea surface temperatures (SSTs) resulting from a combination of global climate change and human impacts [Donner *et al.*, 2005, 2007; Eakin *et al.*, 2008; van Hooidonk *et al.*, 2012]. Most of the reef-building corals grow optimally when SSTs are between 25 and 29°C [Kinsman, 1964]; with an average distribution of corals between 23 and 29°C [Lalli and Parsons, 1995]. However, the upper SST limit for coral growth depends on local conditions and may not be fixed in time and space for any given species [Berkelmans, 2001]. In addition, the upper thermal limit may vary due to taxonomic differences, adaptation or regional differences [Berkelmans and Willis, 1999]. Kinsman [1964] found 11 coral species (including *Porites lutea*) surviving temperatures up to 36°C in the reefs along the Trucial Coast, Persian Gulf where the maximum SST rose as high as 40°C. However, major bleaching events resulting from elevated SSTs have been reported from this region in recent years [Burt *et al.*, 2013; Coles and Riegl, 2013]. Thus, in settings where the local summer surface water temperatures are already close to the upper limit, a further increase of 1°C in SST above the average summer maximum can cause coral bleaching [Goreau and Hayes, 1994; Donner *et al.*, 2005], endangering these rich ocean ecosystems. The steady increase in global SSTs since the 1980s [Hansen *et al.*, 2006] and the occurrence of more frequent El Niño events have increased the frequency of wide-spread coral bleaching episodes across the tropics [Wilkinson and Souter, 2008]. For example, the El Niño event of 1997/1998 caused mass bleaching of corals in the Great Barrier Reef [Baird and Marshall, 1998] and also severely affected corals in the Indian Ocean [Wilkinson, 1998]. It resulted in wide spread coral bleaching (around 82% of the coral cover) in lagoonal reefs of Lakshadweep Archipelago in the Arabian Sea [Arthur, 2000]. Coral bleaching and its influence on coral-Sr/Ca (anomalous low Sr/Ca-derived SSTs) have been reported by Marshall and McCulloch [2002]. Thermal stress

and/or bleaching associated hiatuses in coral growth have been reported by Suzuki *et al.* [2003]; Lough [2008]; Cantin *et al.* [2010]; D'Olivo *et al.* [2013]; and others. Several studies have also documented the influence of interannual SST anomalies associated with both the warm and cold phases of the ENSO on coral geochemistry in the Pacific and Indian Oceans [e.g., Evans *et al.*, 1999; Marshall and McCulloch, 2001, 2002]. The annual mean SST in the Lakshadweep Sea has increased from 28.5°C in 1985 to 28.9°C in 2005 [Vivekanandan *et al.*, 2008]. Considering a broader region, a steady SST warming of the tropical Indian Ocean during the last five decades has been reported by various researchers at a rate of about 0.5–1°C [Alory *et al.*, 2007; Alory and Meyers, 2009; Yu *et al.*, 2007; and others]. A recent study by Roxy *et al.* [2014] reveals that the western tropical Indian Ocean has been warming, at a faster rate than any other tropical region of the oceans.

The Indian subcontinent has a distinct monsoon pattern; the SW monsoon and the Northeast (NE) monsoon. The SW monsoon occurs from June through September accounting for about 80% of rainfall in India and is a prime requirement for Indian agriculture. A delay of a few days in the monsoon arrival or early withdrawals can result in drought episodes, which negatively affect the economy [Aijaz, 2013]. During mid-October to December there is a reversal of winds from SW to NE directions accompanied by rainfall activity. Dry cold winds from the NE directions pick up moisture from the Bay of Bengal and release it over the southeast Indian Peninsula, which generally receives less rainfall during the SW monsoons. These are known as the NE or retreating monsoons. The SW monsoon passes over the Arabian Sea during its journey from the Indian Ocean to the Indian subcontinent, affecting the islands of the Lakshadweep Archipelago. In the western equatorial Indian Ocean and Arabian Sea, the SW monsoon causes summer cooling of surface and subsurface waters due to wind induced upwelling [Rao and Sivakumar, 2000; Vinayachandran, 2004; Pfeiffer and Dullo, 2006]. Pillai [2001] reports upwelling in certain localities of these islands during the period from November to March due to diverging current systems. Wiggert *et al.* [2005] observed increased rate of primary productivity in the Arabian Sea as a result of surface layer nutrient enrichment during the monsoons. More importantly, the summer surface water temperatures in the Arabian Sea are reduced by an order of 3–4°C resulting from SW monsoon induced vertical mixing [Chakraborty and Ramesh, 1993; Luis and Kawamura, 2004]. This reduction in temperature is recorded in corals from this region, as evidenced from previous isotopic studies ($\delta^{18}\text{O}$) of *Porites* sp. [Chakraborty and Ramesh, 1992, 1993, 1997; Ahmad *et al.*, 2011] and *Favia speciosa* [Chakraborty and Ramesh, 1998].

Although the Lakshadweep Archipelago is a climatologically active region with strong monsoonal influence, little is known about the climate variability in this region on longer time scales. Amongst the various coral colonies found around these islands, *Porites* sp. are the most common, which grow at a rate of 1–2 cm/yr and form massive colonies. Massive *Porites* sp. corals have frequently been used as archives for high-resolution paleoclimatic reconstructions [Smith *et al.*, 1979; Pätzold, 1984; Beck *et al.*, 1992; Chakraborty and Ramesh, 1993; Pfeiffer and Dullo, 2006; Ahmad *et al.*, 2011; Cahyarini *et al.*, 2014]. As instrument-derived observations cover only the last few decades, scleractinian *Porites* sp. corals are an ideal archive to retrieve much longer paleoclimatic and paleomonsoonal records from this region on high-resolution (~monthly) time scales. The most important parameter for paleoclimatic studies is the seasonal- to decadal-scale variation of SST in the past, which is a crucial input variable for climate models.

The oxygen isotopic composition of coral skeletons depends on both, the temperature as well as the isotopic composition of surrounding seawater. The oxygen isotopic composition of seawater is affected by evaporation and precipitation and covaries with salinity [Weber and Woodhead, 1970, 1972]. To overcome this problem it has been demonstrated that Sr/Ca ratios in corals can be used as a proxy for SST independent of salinity [Weber, 1973; Smith *et al.*, 1979; Beck *et al.*, 1992]. The basic assumption is that coral-Sr/Ca varies with temperature and that the composition of Sr and Ca in seawater is invariant on millennial time-scales due to their long residence times in the ocean [Beck *et al.*, 1992]. Hence, the Sr/Ca ratio in coral skeletons is considered a reliable proxy for deriving high-resolution records of past SST [Shen *et al.*, 1992, 1996; McCulloch *et al.*, 1994; Alibert and McCulloch, 1997; Wei *et al.*, 2000; Swart *et al.*, 2002; Zinke *et al.*, 2004; Yu *et al.*, 2005; Hetzinger *et al.*, 2006, 2010; Pfeiffer and Dullo, 2006; DeLong *et al.*, 2007, 2011; Pfeiffer *et al.*, 2009; Cahyarini *et al.*, 2009]. Other than temperature, biological controls and other environmental factors can also influence coral-Sr/Ca ratios [de Villiers *et al.*, 1994, 1995]. However, to date, Sr/Ca ratios are considered to be the most reliable temperature proxy in tropical corals [Corrége, 2006].

Here we present the first monthly Sr/Ca record from a massive *Porites* coral from the Lakshadweep Archipelago. This record extends from 1981 to 2008 and was used to test the influence of local and regional

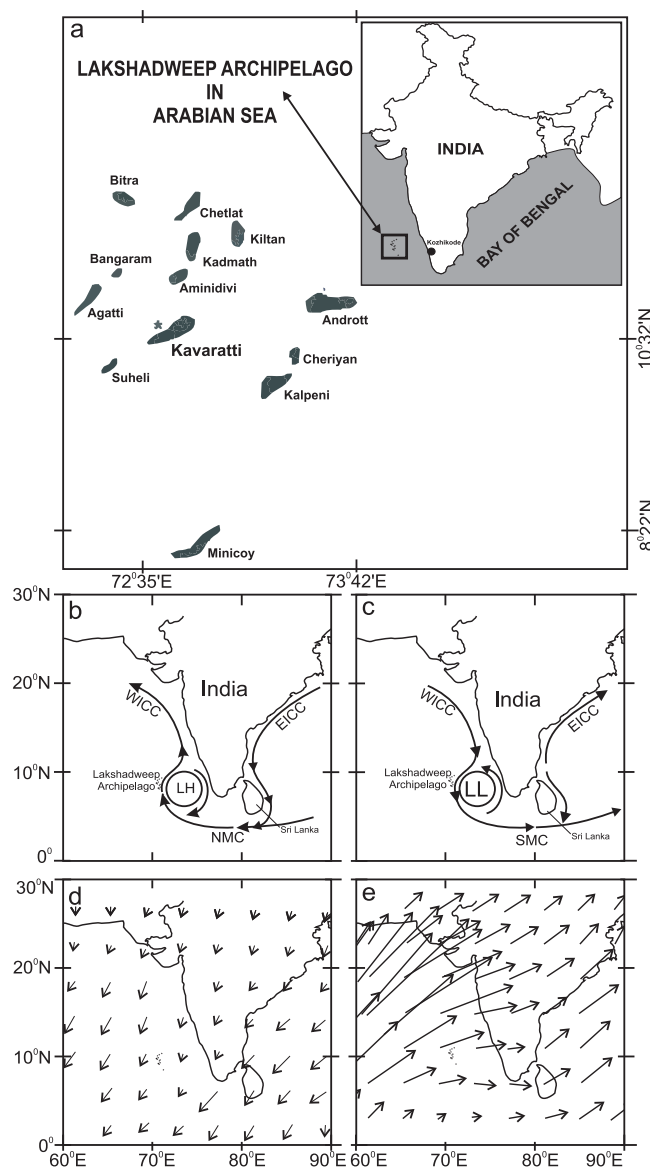


Figure 1. (a) Location map of the studied coral site at the lagoon of Kavaratti (*) Island, Lakshadweep Archipelago, Arabian Sea. (b) The Lakshadweep High (LH) and (c) Low (LL). Wind directions associated with the (d) North East (NE) and (e) South West (SW) monsoon.

is one of the world's most spectacular tropical island ecosystems and is located at a distance of about 200–400 km from Kozhikode on the Malabar Coast in the Kerala state, Southwest (SW) India [James, 2011]. The archipelago consists of 36 small islands [James, 2011] and a total of 103 species of corals were identified by Pillai and Jasmine [1989] from the lagoon area of these islands. This region is climatologically dynamic with major surface ocean currents in its vicinity, i.e., the West India Coastal Current (WICC), the Northeast Monsoon Current (NMC), and the Southwest Monsoon Current (SMC). The flow regime of the WICC along with the NMC away from the equator in the month of January (maximum) forms the Lakshadweep High (LH) (Figure 1b), and the movement of the WICC along with the SMC toward the equator in the month of July (maximum) forms the Lakshadweep Low (LL) (Figure 1c) [Shankar et al., 2002]. The NE and SW monsoon in this region are associated with distinct wind patterns (Figures 1d and 1e) blowing from NE and SW directions, respectively.

Kavaratti Island, the capital of the Union Territory of Lakshadweep, lies between 10°32' and 10°35' N latitude and 72°35' and 72°40' E longitude (Figure 1a). It has a surface area of 4.22 sq km and a lagoon area of 4.96

(monsoon-induced summer cooling and paleo SW monsoon activity) as well as large-scale climate dynamics, in particular the influence of ENSO. The rapid warming documented in the area [Vivekanandan et al., 2008] over the last decades makes it an ideal location to study the effects of anthropogenic related thermal stress on corals. First, we assess the robustness of our proxy by comparing coral-Sr/Ca with gridded SST products to derive proxy-temperature calibrations. Second, we explore the relationship between coral-Sr/Ca and the SW monsoon, which directly affects the study site by monsoon-induced summer cooling. Additionally, coral-Sr/Ca is compared with the Arabian Sea SST to check the ability of the coral to record large scale cooling in the Arabian Sea during the SW monsoon months. We compare our new coral-Sr/Ca record with a published coral proxy record from the Seychelles that also records the cooling of the Arabian Sea following the SW monsoon. Time series analysis of Sr/Ca proxy data are carried out to evaluate the ability of the coral to capture large scale climate signals originating from the tropical Pacific, as well as to investigate links with episodic ENSO events that often lead to anomalously high SSTs in the region causing thermal stress.

2. Material and Methods

2.1. Study Area and Coral Sampling

The Lakshadweep Archipelago in the Arabian Sea, our study area (Figure 1a)

Table 1. Basic Statistics of Instrumental Temperature Data Sets Used in the Study

	Spatial Resolution	Time Frame	Seasonal Cycle		
			Maximum (°C)	Minimum (°C)	Range (°C)
ERSST. v3b	2 degree	1981–2008	30.07	27.82	2.25
Reynolds OI v2 SST	1 degree	1982–2008	30.10	27.71	2.39
ICOADS SST 2.1	2 degree	1981–2008	30.15	28.07	2.08
HadISST1	1 degree	1981–2008	30.17	27.88	2.29
MODIS-Terra SST	4 km	2000–2008	30.02	27.23	2.79
Amini AT	Point data ^a	1981–2008	30.20	27.56	2.64

^aInstrumental air temperature data from a nearby island; Aminidivi (11.12°N and 72.73°E obtained from India Meteorological Department (WMO Station code: 43311). The maximum and minimum temperatures represent climatological highest and lowest temperatures for the mentioned time frame for each data set.

sq km. A coral core was recovered (by vertical drilling) in February 2009 from a live *Porites lutea* colony from the lagoon of Kavaratti Island in a water depth of 1.2 m during low tide. The core measuring 353 mm in length and 50 mm in diameter was cut longitudinally into two equal halves and split further to generate slabs measuring 7 mm in thickness. The working slab was first rinsed with fresh water and then ultrasonically cleaned (three times) using deionized water for 15 min. It was then chemically treated overnight to remove organic materials by using 1:1 mixture of Milli-Q water and Sodium Hypochlorite (NaOCl) in a closed plastic box kept under a laminar flow hood. Afterward, the samples were rinsed again with free flowing Milli-Q water, then cleaned ultrasonically (using Milli-Q water) 3 times for 10 min to remove any remnant solution. Finally, the samples were dried in an oven at 40°C for 15 h. The slab was x-rayed in order to expose the annual density banding couplets related to the non-monsoon and monsoon seasons. Powder samples were recovered along the major growth axis using a low-speed micro drill (Proxxon) with 0.8 mm diameter drill bit with a sampling resolution of 14–16 samples/growth year.

2.2. Instrumental Data Sets Used in This Study

The various SST data products used in this study are: Improved Extended Reconstruction of SST (ERSST. v3b) [Smith *et al.*, 2008], Reynolds OI v2 SST [Reynolds *et al.*, 2002], International Comprehensive Ocean-Atmosphere Data Set SST (ICOADS SST 2.1) [Worley *et al.*, 2005] and the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST1) [Rayner *et al.*, 2003]. The ERSST (2° grid), Reynolds (1° grid), ICOADS (2° grid) and HadISST (1° grid) data were obtained using the online tool Climate Explorer (<http://climexp.knmi.nl>). High-resolution MODIS-Terra SST (4 km spatial resolution) was obtained for the available time period of 2000–2008 (data source: http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=ocean_month). The NOAA AVHRR daily SST data sets used to calculate the degree heating weeks (DHW) in the study region were obtained from the online source: <http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.OISST/.version2/.AVHRR/>. Local air temperature data from Aminidivi Island (Amini AT), located ~60 km from the coral sampling site, were used for comparisons with the regional SST records. Table 1 summarizes the basic statistics of all temperature products. The Nino3.4 index was obtained from NOAA National Weather Service, Climate Prediction Center (<http://www.cpc.ncep.noaa.gov>) based on Kaplan SST data: Kaplan *et al.* [1998]. The precipitation data set was also obtained from the online tool Climate Explorer (<http://climexp.knmi.nl>) [Schneider *et al.*, 2014]. The All India Rainfall (AIR) and Western Peninsular Indian Rainfall (WPIR) data sets were downloaded from the website of the Indian Institute of Tropical Meteorology, Pune (<http://www.tropmet.res.in>) [Sontakke *et al.*, 2008].

2.3. Analytical Method for Coral-Sr/Ca

The powdered samples were analyzed for molar (Sr/Ca) ratios using an ICP-OES (SPECTRO Ciros SOP) at the University of Kiel following the analytical techniques by Schrag [1999] and de Villiers *et al.* [2002]. The sample solution was prepared by dissolving approximately 300 µg of coral powder in 1 ml subboiled 2% HNO₃ (v/v). The working solution was prepared by serial dilution of the sample with 2% HNO₃ to get a Ca concentration of 8 ppm. The Sr and Ca lines used for this study were 407 and 317 nm, respectively. An in-house coral standard (*Mayotte 5a*, 8.9916 mmol/mol Sr/Ca), bracketing batches of 6 samples, was used for instrumental drift correction which was typically <2%. Average internal error of 5 replicate Sr/Ca determinations per sample was <0.08% relative standard deviation (RSD) or <0.01 mmol/mol (1σ, n=440). External error of Sr/Ca ratios estimated from replicate measurements on the same day and on consecutive days is <0.08%

Table 2. Correlation Value “R” Amongst the Various Temperature Data Sets Used in This Study^a

	MODIS-Terra SST	ERSST	Reynolds SST	ICOADS SST	HadISST	Amini AT
MODIS-Terra SST		0.75	0.73	0.74	0.71	
ERSST	0.75		0.95	0.98	0.96	0.81
Reynolds SST	0.73	0.95		0.93	0.94	0.78
ICOADS SST	0.74	0.98	0.93		0.96	0.81
HadISST	0.75	0.96	0.94	0.96		0.51
Amini AT	0.51	0.79	0.81	0.78	0.81	

^aSee text for details.

RSD (1σ , $n=44$). Accuracy was monitored by analyzing the *Porites* coral standard JCp-1 as an unknown giving Sr/Ca 8.86 ± 0.01 mmol/mol ($n=4$) which compares to 8.84 ± 0.09 mmol/mol as average from an international inter-laboratory comparison [Hathorne *et al.*, 2013].

2.4. Coral Chronology

The coral-Sr/Ca raw data (supporting information Figure S1a) show two seasonal extremes, which correspond to the maximum and minimum temperature in the study region. The age chronology was developed in a two-step approach. In the first step, years were assigned to the raw Sr/Ca data based on the time of recovering the coral core (February 2009). The first summer peak was assigned 2008 and sequentially counted backward in time until 1981 (the last peak of this core). To accomplish the first step we referred to the annual density banding couplets from the x-radiography (supporting information Figure S1b). For comparing and correlating our Sr/Ca data (which has varying sampling points in different years) with various climatological data on a monthly scale, we performed a simple linear interpolation using the commonly used peak matching method [Cahyarini *et al.*, 2014] in the Analyseries software [Paillard *et al.*, 1996]. The ERSST [Smith *et al.*, 2008] was used as reference, due to the nonavailability of point SST data from the Kavaratti Island. The lowest and highest Sr/Ca values were peak-matched with the highest and lowest ERSST values (for any particular year) for the whole time series and the proxy-Sr/Ca chronology was built on a monthly scale. The uncertainty of this age model is approximately 1–2 months in any given calendar year as the instrumental (ERSST) highest and lowest temperature peaks vary between April–May and August–September, respectively. We present here 27 years of coral-Sr/Ca ratios extending from March 1981 to June 2008.

3. Results

3.1. SST Variability in the Study Region

Significant correlations were observed between the different temperature data sets ($R = 0.51$ – 0.98 ; $p < 0.001$; Table 2). The gridded SSTs are lagging the Amini AT by 1–2 months (Figure 2a). All the above data sets show climatological summer maximum values above 30°C (Table 1). The highest and lowest temperatures for gridded SSTs are observed in the months of May and August respectively (Figure 2a). The highest climatological seasonal range of 2.8°C is observed in MODIS-Terra SST, which has the highest spatial resolution of 4 km amongst the various SST data sets used in this study (Table 1). We notice, a gradual increase in temperature from August of any particular year to May of the next year (a total of 9 months), and a sharp fall from May to August of the same year. Additionally, the temperature data sets show intraseasonal secondary highs and secondary lows (SHSL) between August and January (period of 5 months) in both the climatological data (Figure 2a) as well as in individual years (Figure 2b). The secondary positive and negative excursions occur in the months of November and January, respectively (Figures 2a and 2c), and have amplitudes $>0.65^\circ\text{C}$ for gridded SST data sets and 0.25°C for the Amini AT.

3.2. Coral-Sr/Ca Records and Calibration With SST

In spite of the occurrence of the SHSL in all years in the SST records (Figure 2b), the coral-Sr/Ca shows only a subtle SHSL peak in any given year except for the years 1988, 2006, and 2007, where it is clearly visible (supporting information Figures S1a and S1c). As demonstrated by Gagan *et al.* [2012] coral proxy records are often attenuated during skeletogenesis, which extends over the entire living tissue layer, and this may limit their temporal resolution on subseasonal time scales. However, the raw coral-Sr/Ca record displays clear seasonal cycles (in any given year) with a prominent minimum and a maximum value (supporting information Figure S1a) corresponding to the highest and lowest SSTs respectively (supporting information

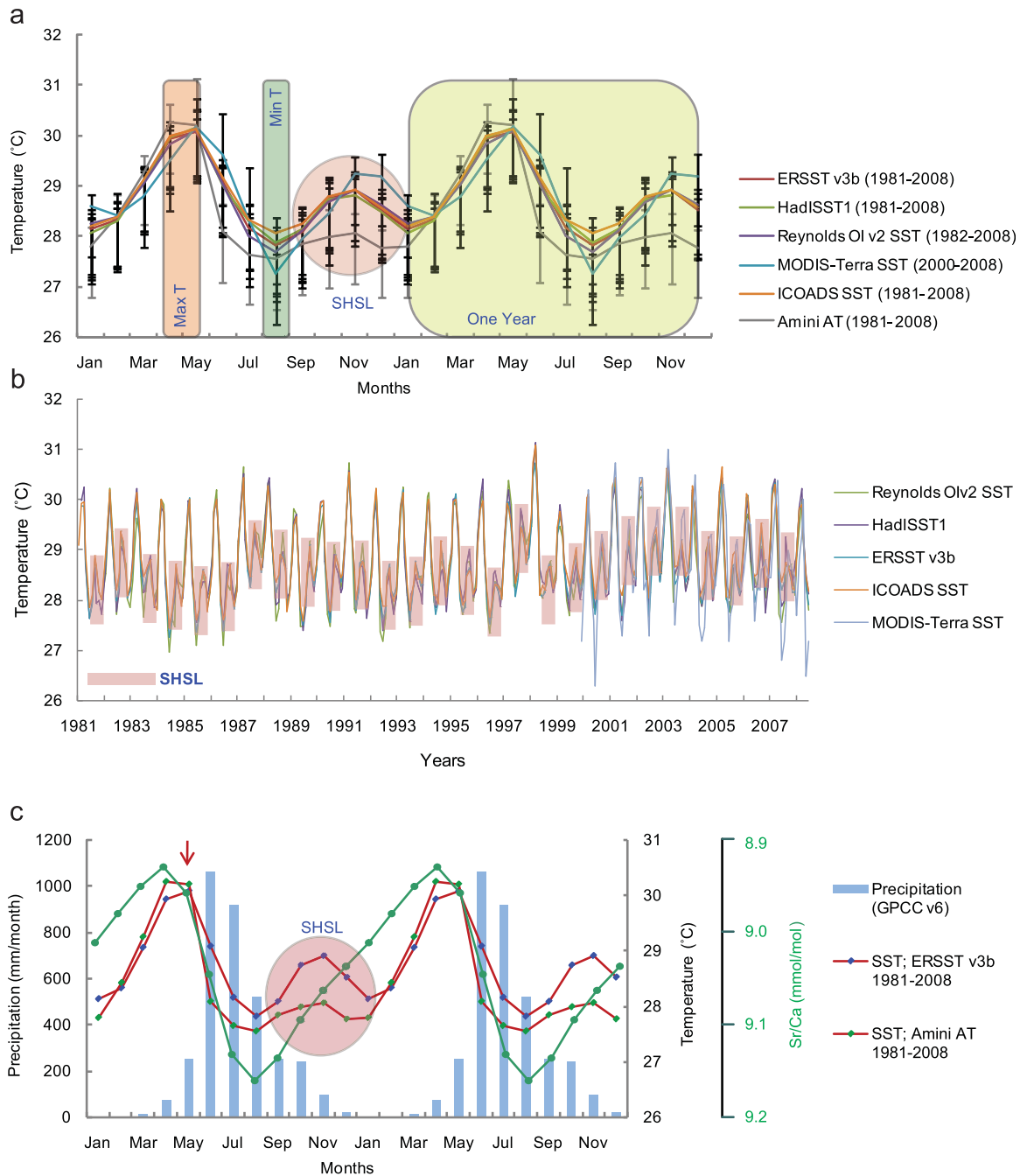


Figure 2. (a) Seasonal SST variability derived from various instrumental data sets in the study region of Lakshadweep Archipelago (The climatological data set from January to December is repeated; highlighted in light green). The maximum (Max T) and minimum temperature (Min T) months are highlighted. The area inside the circle shows the secondary highs and secondary lows (SHSL) occurring between August and January (period of 5 months). Different SSTs used are ERSST.v3b, [Smith et al., 2008]; HadISST1 [Rayner et al., 2003]; ReynoldsOIV2SST [Reynolds et al., 2002]; MODIS (http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=ocean_month); ICOADS [Worley et al., 2005]; and Amini AT, India Meteorological Department, Pune, India. (b) Intraseasonal variability (SHSL) in all years for all temperature data sets. (c) Climatological* precipitation, temperature and Sr/Ca variability. The red arrow shows the point where sea surface temperature drops sharply with the onset of Southwest (SW) monsoon in May/June. Precipitation data source from Schneider et al. [2014]. *Monthly average data from 1981 to 2008 of the study area.

Figure S1c; proxy Sr/Ca data). Table 3 compares the calibration equations between coral-Sr/Ca ratios and several SST data sets on monthly and annual mean scale and for extreme values. All the equations have been computed using Ordinary Least Squares (OLS) regression, as this approach is commonly used for asymmetric relationships [Smith, 2009]. The coral-Sr/Ca bears an asymmetric relationship with the SST, as it

Table 3. Regression Equations (With SE, Standard Error) Between Coral Sr/Ca Ratios and Instrumental SST Data Sets for the Time Period 1981–2008^a

Data Set		Slope (m)	SE-slope	Intercept (b)	SE-Intercept	R ²	R; p Value
ERSST v3b	monthly	−0.073	0.007	11.16	0.19	0.27	−0.52; <0.001
	extreme values	−0.104	0.009	12.08	0.25	0.73	−0.85; <0.001
	annual mean	0.003	0.044	8.96	1.28	0.00	0.02
Reynolds OI v2 SST	monthly	−0.073	0.006	11.16	0.18	0.30	−0.55; <0.001
	extreme values	−0.101	0.009	11.98	0.25	0.73	−0.85; <0.001
	annual mean	−0.01	0.039	9.35	1.12	0.00	−0.05
HadISST1	monthly	−0.069	0.007	11.04	0.19	0.25	−0.50; <0.001
	extreme values	−0.104	0.009	12.09	0.26	0.72	−0.85; <0.001
	annual mean	−0.006	0.038	9.25	1.09	0.00	−0.03
ICOADS SST	monthly	−0.069	0.007	11.07	0.20	0.24	−0.49; <0.001
	extreme values	−0.089	0.01	11.67	0.28	0.61	−0.78; <0.001
	annual mean	−0.009	0.04	9.34	1.11	0.00	−0.05
MODIS-Terra SST	monthly	−0.042	0.01	10.30	0.30	0.15	−0.38; <0.001
	extreme values	−0.088	0.01	11.59	0.41	0.72	−0.85; <0.001
	annual mean	0.028	0.05	8.27	1.59	0.04	0.19

^aTime period: Reynolds OI v2 SST: 1982–2008; MODIS-Terra SST: 2000–2008. All equations are computed using ordinary least squares regression with zero-lag. Equations are in the form Sr/Ca = m*SST + b.

depends on the SST. The OLS regression method is commonly used for deriving the coral Sr/Ca-SST regressions [Corrége, 2006; Hetzinger et al., 2006; Inoue et al., 2007; Cahyarini et al., 2011, 2014].

All of the gridded SST data sets correlate negatively with the Sr/Ca proxy record for monthly as well as extreme values (the highest and lowest SSTs are correlated with the lowest and highest Sr/Ca for all years of the studied time interval). The highest monthly correlation is observed with Reynolds OI v2 SST (R = −0.55, p < 0.001; Table 3). The extreme values of coral-Sr/Ca are significantly correlated with the extreme values of the gridded SST products with correlation coefficients ranging between −0.78 and −0.85 (p < 0.001). The slope of the linear regression between the various SST data sets and the coral-Sr/Ca, generated from monthly correlation studies (−0.042 to −0.073; Table 3) fall within the range of earlier data sets compiled by Swart et al. [2002] and Corrége [2006]. The annual coral-Sr/Ca record is not significantly correlated with the annual SST gridded data, which have coarse spatial resolution, but shows a weak correlation with Amini AT (R = −0.22), the nearest available local air temperature data set. The lack of annual correlation of coral-Sr/Ca with the gridded SSTs is discussed in section 4.2.

3.3. Southwest Monsoon Cooling

The climatological (1981–2008) ERSST data show a sharp drop of 2.3°C from May to August, which coincides with the onset and continuation of the SW monsoon in the study region (Figure 2c). The coral-Sr/Ca record follows the same trend indicated by increasing values from May to August (Figure 2c). We investigated the potential of this coral to track monsoon-induced summer cooling in this region by comparing the relationships between coral-Sr/Ca and rainfall data from India for the SW monsoon months; June–September [Sontakke et al., 2008]. The correlation coefficient between coral-Sr/Ca and All India Rainfall (AIR) is −0.39; p < 0.05 (Figure 3a). As the AIR is an average over entire India (total rainfall from both SW and NE monsoons), we decided to additionally use Western Peninsular India Rainfall (WPIR) data. The WPIR region is located in the direct pathway of the SW monsoon from the Indian Ocean to the Indian subcontinent and is closer to the Lakshadweep Archipelago. The correlation increases (R = −0.61, p < 0.01, Figure 3a) when using the WPIR. Additionally, we checked the potential of this coral to track SST changes in the whole Arabian Sea (5°S to 20°N and 50°E to 72°E) resulting from SW monsoon precipitation. We compared the climatological SST (calculated from Reynolds OISST) of the Arabian Sea with coral-Sr/Ca for the time period 1982–2008 (Figure 3b). A significant correlation (R = −0.98, p < 0.05) is observed for the time period from April to September, which covers the peak summer (April–May) and the SW monsoon months (from end of May or early June–September).

Finally, we compared our coral-Sr/Ca to a coral δ¹⁸O record published by Pfeiffer and Dullo [2006] (here after PD2006) from the Seychelles; 55°E, 4°S. We have 12 years of data (1981–1993) in common. In the first step, we compared the climatological SST for the time period 1981–1993 obtained from ICOADS for both regions (Kavaratti: 71–73°E and 9–11°N; Seychelles: 54–56°E and 3–5°S). The correlation coefficient between the SST from the two regions is 0.75; p < 0.01 (Figure 3c). The annual correlation value between the coral δ¹⁸O of

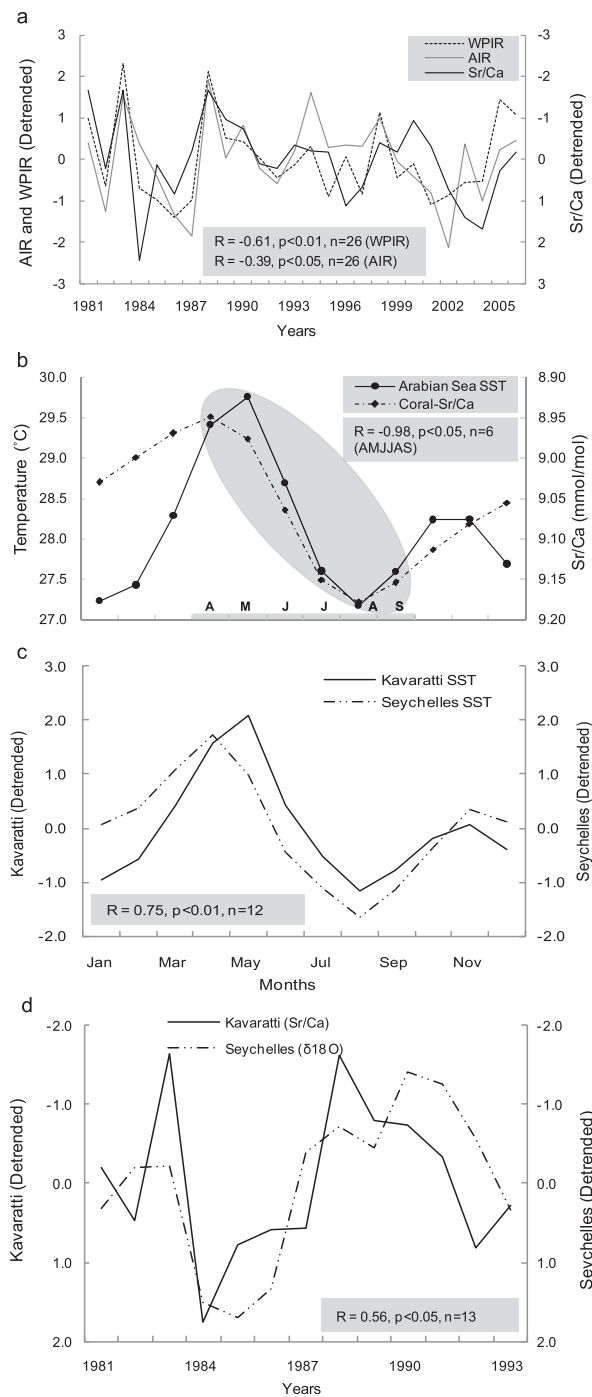


Figure 3. (a) Correlation between All India Rainfall (AIR, grey line), Western Peninsular Indian Rainfall (WPIR, black dashed line) and coral-Sr/Ca (black line). All data are from the SW monsoon months (June–September). All data series were detrended and normalized by subtracting the mean and dividing by the standard deviation. Rainfall data source: Sontakke et al. [2008]. (b) Climatological (average of 1981–2008) Arabian Sea surface temperature with coral-Sr/Ca. The grey shaded oval area comprises the peak-summer (April, May) and monsoon months (June, July, August, September). (c) Climatological ICOADS SST (average of 1981–1993) from Kavaratti (10.57°N, 72.62°E) and Seychelles (4.63°S, 55.46°E) regions. (d) Kavaratti; coral Sr/Ca with Seychelles; coral $\delta^{18}O$ [Pfeiffer and Dullo, 2006] time series: annual averages. All data series were detrended and normalized by subtracting the mean and dividing by the standard deviation.

PD2006 and our coral-Sr/Ca time series for the period 1981–1993 is 0.56; $p < 0.05$ (Figure 3d). We note that the strong cooling event of 1984 is prominently recorded in coral data sets of both regions: Kavaratti (this study) and the Seychelles record (studied by PD 2006) (Figure 3d).

3.4. Anomalous Coral-Sr/Ca Values in Some Years

The raw coral-Sr/Ca summer-peak data of years 1987, 1992, 1993, 1998, 1999, and 2008 (corresponding to peak numbers 22, 17, 16, 11, 10, and 1 in supporting information Figure S1a) show the highest values on the record. It is noted here that we are not relying on the coral-Sr/Ca data of peak 1, which represents the last summer peak before the coral was sampled in February 2009. We looked into more details by overlapping the average summer (March, April, May) SST (obtained from Reynolds OISST), and average summer (March, April, May) coral-Sr/Ca data sets (Figure 4a). In addition, Nino3.4 positive temperature anomalies were also plotted in the same figure (Figure 4a) as the western Indian Ocean normally warms during El Niño years and this warming has been reported to be more persistent compared to non-El Niño years [McClanahan et al., 2007]. Studies by Zhang et al. [2013] reveal that grid-SST alone may sometimes underestimate the SST warming on a reef scale during major climate anomalies. We observe that the average-summer-SST of the years, 1992, 1993, and 1999 (Figure 4a) are relatively cool and remain below the summer-average (29.7°C) of the studied time interval. Hence the higher summer-coral-Sr/Ca values are indicating relatively cold SSTs in those years (supporting information Figure S1a and Figure 4a). In addition, a positive Sr/Ca anomaly is seen in the year 1998, which is significant, and also possibly in the years 1987 and 2003 (Figure 4a). The year 1987 shows a reduced seasonality in coral Sr/Ca (supporting information Figure S3) whereas the year 2003 has an above average seasonal range (supporting information Figure S3). In spite of this above average seasonal range in 2003, the coral Sr/Ca (summer-average), in this year, indicates colder conditions, which is in contrast to the high summer-average SST

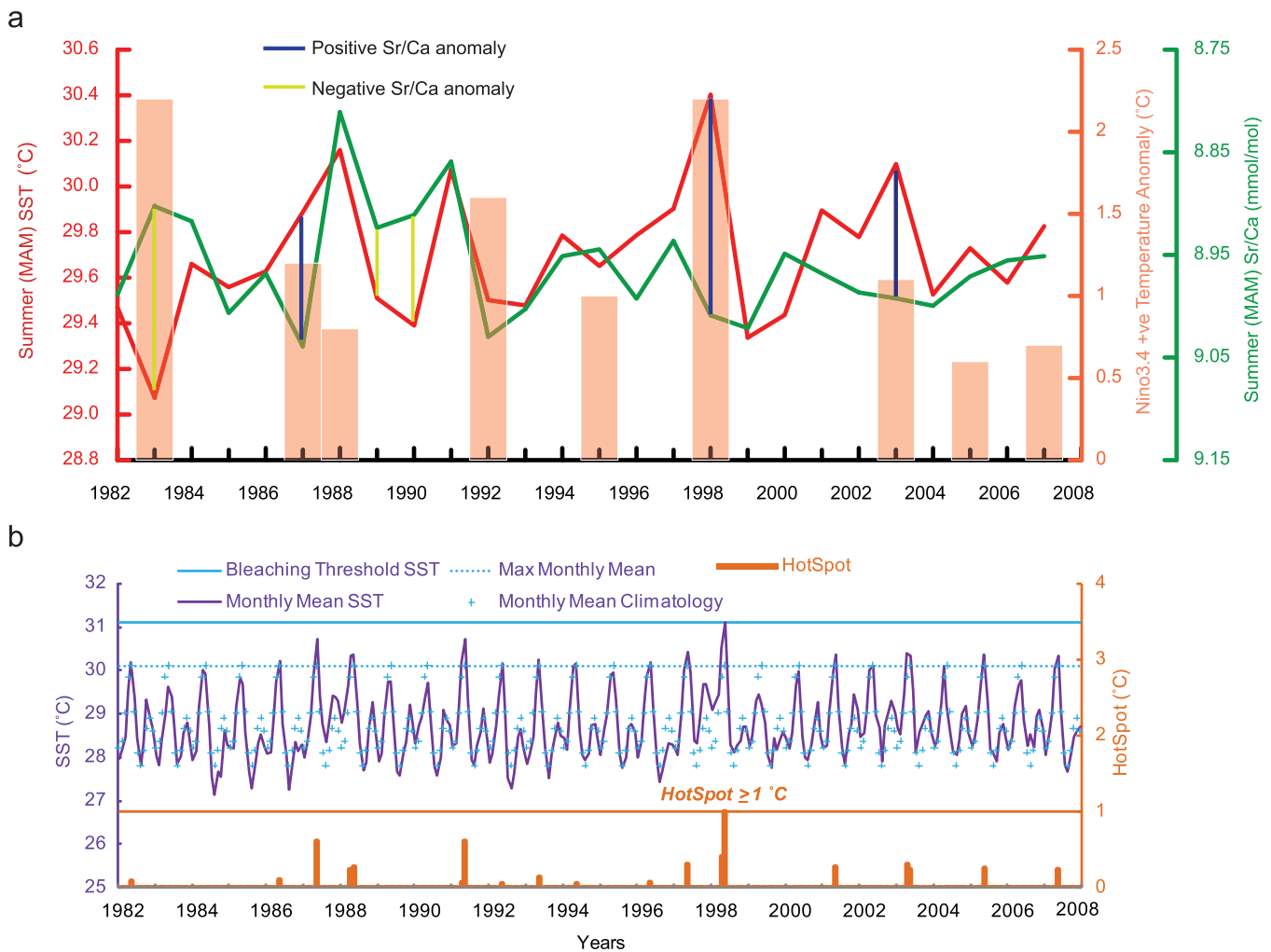


Figure 4. (a) Local summer (March, April, May) average SST from Reynolds OISST with coral-Sr/Ca (summer average: March, April, May). The bright orange bars represent the positive temperature anomaly in the Nino3.4 region. Blue vertical bars represent the positive Sr/Ca anomalies (in the years 1987, 1998, and 2003). The light-green vertical bars represent the negative Sr/Ca anomalies (in the years 1983, 1989, and 1990). The year 1998 marks the highest summer-average SST of 30.4°C. (b) HotSpot values (red vertical bars) calculated from Reynolds OISST monthly data sets. The year 1998 has the highest HotSpot value ($>1^{\circ}\text{C}$). The maximum monthly mean and the bleaching threshold SST of this region is 30.1 and 31.1°C , respectively.

(Figure 4a). Interestingly, these years (1987, 1998, and 2003) have high summer-average SSTs, which are above the local summer-average of the time interval studied (Note that the March–May average shown in Figure 4a appears relatively low during 1987, as March SSTs were low: in the following April and May SSTs rose above the maximum monthly mean (MMM) (Figure 4b)). The 1987, 1998, and 2003 warming coincides with positive temperature anomalies ($>1^{\circ}\text{C}$) of the Nino3.4 region (Figure 4a). The other years marked by similar ENSO positive temperature anomalies are 1983, 1992, and 1995. However, in these years, the local summer-average SSTs at Kavaratti Island are below the summer-average of the studied time interval (Figure 4a). 1998 shows a clear stress band in the coral core and the annual growth rate is very low (supporting information Figures S2 and S1d, respectively). To investigate further and to identify years with thermal stress, we generated the coral bleaching HotSpots [NOAA Coral Reef Watch, 2000] using Reynolds OISST data sets (Figure 4b). The HotSpot index crosses 1°C in 1998, the highest value in the studied time interval (Figure 4b). Finally, we calculated the coral bleaching degree heating weeks (DHW) [NOAA Coral Reef Watch, 2000], and degree heating months (DHM) [Donner *et al.*, 2005] plots using NOAA AVHRR daily and Reynolds monthly SST data sets (supporting information Figures S4a and S4b) to assess the degree of stress that the coral is undergoing during the studied time interval. Both cases indicate high stress in 1998: the maximum DHW and DHM values reached $3.5^{\circ}\text{C}\text{-week}$, and $1.4^{\circ}\text{C}\text{-month}$, respectively (supporting information Figures S4a and S4b) and the positive temperature anomaly (HotSpot) crossed 1°C (Figure 4b). In 1987 and 2003,

maximum summer SSTs were also elevated relative to the mean, but they remained below the threshold of coral bleaching. In addition to the positive Sr/Ca anomalies, we observe negative Sr/Ca anomalies in the years 1983, 1989, and 1990 (Figure 4a). The seasonality of all the above mentioned years with negative Sr/Ca anomalies is below the average (supporting information Figure S3).

4. Discussion

4.1. Monsoon Dynamics Recorded by the Coral

The SW monsoon accounting for about 80% rainfall over India is highly important to Indian agriculture and society. At Lakshadweep Archipelago, our study site, the onset of the SW monsoon in June causes a sharp decrease in summer temperature on the order of 2–4°C [Chakraborty and Ramesh, 1993; Ahmad et al., 2011]. The increasing values of our coral-Sr/Ca record from May to August (Figure 2c), following the ERSST trend and coinciding with the SW precipitation months, are a robust indicator of monsoon-induced sea surface temperature cooling in the study region. The significant correlation of the coral-Sr/Ca and the WPIR (Figure 3a) for the SW monsoon months (from June to September) indicates the strong potential of *Porites* from this region to track SW monsoon activity. Our findings are in agreement with the results of Vecchi and Harrison [2004], who indicated a strong relationship between Western Ghats rainfall and Arabian Sea SST. Additionally, we observe that coral-Sr/Ca also faithfully captures the monsoon-induced summer temperature cooling in the whole of Arabian Sea (Figure 3b), a feature observed by Pfeiffer and Dullo [2006] in their Seychelles coral record. Considering a broader region, using our results from Kavaratti (this study) and Seychelles (PD2006), we notice that the Kavaratti SST is lagging the Seychelles SST by ~1 month (Figure 3d), which is a direct result of the variation in the onset of SW monsoon in India, which is known as the Southeast monsoon in Seychelles [Payet and Agricole, 2006]. Interestingly, the significant correlation observed between the coral records of Kavaratti and Seychelles [Pfeiffer and Dullo, 2006] (Figure 3d) on interannual time scales, confirms that our coral-Sr/Ca does record large-scale climate variability induced by the SW monsoon. Based on these results we suggest that larger *Porites* coral colonies in this region have the potential to record local, regional and longer paleo-monsoon variability, possibly extending back in time for several centuries.

4.2. Influence of Thermal Stress Events on Coral Proxies

The study site is located in a region where the annual mean SSTs have warmed at a rate of 0.2°C per decade from 1985 to 2005 [Vivekanandan et al., 2008]. It was observed by PD2006 that the present mean SSTs in the western Indian Ocean are highest ever since at least the 1950s, and probably since the 1840s. Recently, Roxy et al. [2014] have reported warming of 1.2°C in the western Indian Ocean for the time period 1901–2012. The steady warming of SST at the study site and adjacent regions might be inducing thermal stress on corals, which grow in the lagoon areas of these islands. In addition, prolonged higher temperatures during El Niño years might induce additional thermal-stress that may lead to episodic coral bleaching. Coral bleaching in the Lakshadweep Sea has been reported in the year 1998 due to abnormally high SST associated with the strong 1998 El Niño event [Wilkinson et al., 1999; Vivekanandan et al., 2008]. The bleaching event associated with this strong El Niño event is clearly recorded in the coral as a stress band (supporting information Figure S2) with exceptionally low annual growth of only 4 mm in this year (compared to average annual growth of 13 mm for the entire record, supporting information Figure S1d). Thus, it is evident that some (major) El Niño events have a larger effect on the coral growth (supporting information Figures S1d and S3) and geochemistry (Figure 4a) than others, which are less well recorded. The monthly SST in May 1998 reached a record high of 31.1°C, which is 1°C above the MMM of 30.1°C in the study region (Figure 4b). The highest HotSpot value of >1°C in the month of May 1998 (Figure 4b) apparently stressed the coral, which resulted in the dampening of the Sr/Ca signal (Figure 4a and supporting information Figure S1a). The other years with positive Sr/Ca anomalies, 1987 and 2003 (Figure 4a), are also influenced by SSTs that are higher than the MMM in the study region (Figure 4b). The x-ray of the coral core does not show any evidence of bleaching in these years. However, Cantin et al. [2010] have shown that even apparently healthy corals respond to elevated SSTs with reduced growth. Based on our studies we suggest the following: (A) The coral-Sr/Ca is affected by the increasing SSTs in this region that are often associated with strong and persistent El Niño events. We therefore argue that warm El Niño years are primarily responsible for the weak correlation between coral-Sr/Ca and grid-SST on an annual mean scale. Our coral Sr/Ca record misses three prominent SST maxima and tends to show a relationship opposite to the normally negative Sr/Ca-SST correlation in these years. A similar loss of reconstruction skill was also reported by Damassa et al. [2006] for a

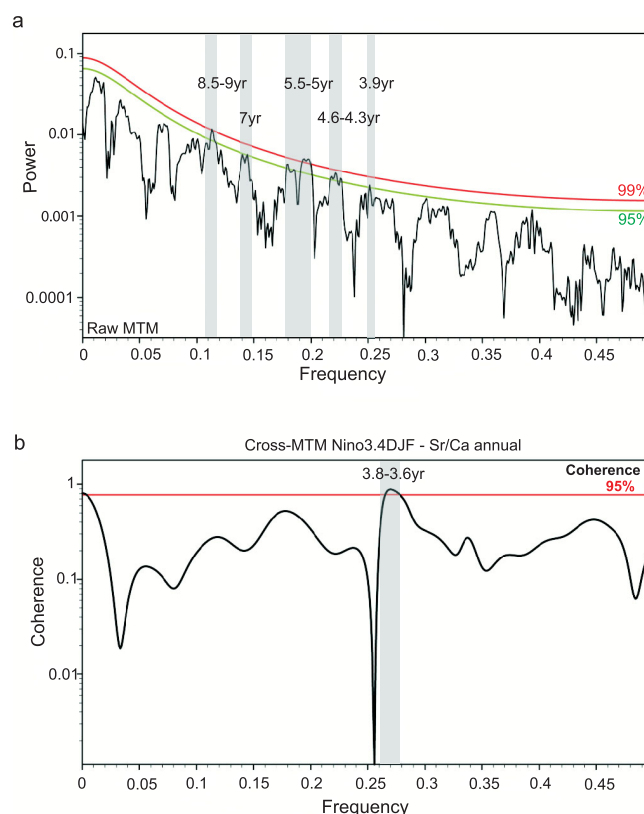


Figure 5. (a) Multi-Taper-Method (MTM) spectrum for coral-Sr/Ca proxy data (red: 99% significance level, green: 95% significance level). In the MTM analysis we used 3 tapers, resolution is 2 and significance is tested against red noise. The rectangular transparent boxes mark the dominant variability time periods. (b) Cross-spectral analysis between Sr/Ca (annual) and Nino 3.4 (DJF) shows coherence at 3.6–3.8 year band (significant at the 95% level). Nino 3.4 index from NOAA National Weather Service, Climate Prediction Center (<http://www.cpc.ncep.noaa.gov>) based on Kaplan SST data: Kaplan et al. [1998].

et al., 2000; Marshall and McCulloch, 2001; McClanahan et al., 2007; Izumo et al., 2012]. This means that thermal stress due to ENSO events is a recurrent problem for western Indian Ocean corals and coral reefs [McClanahan et al., 2007]. We test this by performing spectral analysis of our coral-Sr/Ca data, which was carried out using the Multi Taper Method (MTM) in order to visualize the dominant frequencies in the proxy time series [Vautard et al., 1992] (Figure 5a). Sr/Ca proxy data were detrended and the monthly mean was removed before spectral analysis. It appears that interannual variability in coral-Sr/Ca is dominant at the 5–5.3 and 8.5–9 year bands (99% significance level (SL)) and at 3.9, 4.3–4.6, 5.3–5.5, and 7 year bands (95% SL, Figure 5a). Additionally, cross-MTM spectra between the Nino3.4 index (DJF) [Kaplan et al., 1998] and coral-Sr/Ca (annual) shows coherence between time series at the 3.6–3.8 year band (95% SL, Figure 5b). This may indicate that there could be a persistent relationship between the coral-Sr/Ca and ENSO, in the sense that the El Niño-induced warming coincides with anomalously high Sr/Ca, e.g., El Niño warming is missed by the coral on a regular basis (note that spectral coherence is not affected by the sign of a relationship), albeit the relationship is weak. The observed variability in coral-Sr/Ca and coherence to the Nino3.4 index provides additional evidence that the adverse affect of El Niño on coral geochemistry is a recurrent feature over the time period covered by our coral-Sr/Ca record. It appears that El Niño-related warming regularly biases summer coral-Sr/Ca toward higher values.

5. Conclusion

We present the first high-resolution monthly resolved coral-Sr/Ca record from the southeastern Arabian Sea, a region with strong influence of the SW monsoon. The record extends from 1981 to 2008 and coral-Sr/Ca ratios, an established geochemical proxy, allow us to reconstruct past climate variability.

Kenya coral $\delta^{18}\text{O}$ record, where a breakdown of the coral $\delta^{18}\text{O}$ -SST relationship in the warmest years of the coral record was reported and the loss of the ENSO signal. (B) The coral is prone to bleaching when the monthly mean SST crosses the bleaching threshold SST in this region, which is possible when the HotSpot value is $\geq 1^\circ\text{C}$ (Figure 4b). The bleaching threshold SST in our study area is 31.1°C (Figure 4b: calculated using Reynolds OISST monthly data sets). A total of 15 years out of the studied 26 years have HotSpot values ranging between 0 and 1 (Figure 4b), indicating that the region is under stress (level: “bleaching watch”) [NOAA Coral Reef Watch, 2000]. The year 1998 was highly stressed reaching the stress level “possible bleaching” [NOAA Coral Reef Watch, 2000], which is defined by: $1 \leq \text{HotSpot}$ and $0 < \text{DHW} < 4$ (Figure 4b and supporting information Figure S4a).

4.3. Temporal Stability of ENSO Dampening in Coral-Sr/Ca

Previous studies have suggested that external forcing from the tropical Pacific has a persistent influence on interannual-scale SST variability in the Indian Ocean: El Niño causes basin wide warming in the western Indian Ocean following peak El Niño conditions [e.g., Hastenrath and Greischar, 1993; Cole

Acknowledgements

We are thankful to the Deutscher Akademischer Austauschdienst (DAAD) grant (A/11/75235) to NS, and financial support from CSIR-NGRI 12th plan projects, INDEX and INDIA IDEA. NS thanks SH and DGS for partial financial assistance for sample analysis. Several data sets from various sources have been used in the preparation of this manuscript, which are mentioned below and duly thanked. ERSST.v3b, HadISST1, Reynolds OIV2 SST, ICOADS SST 2.1, Precipitation GPCCv6, Cloud cover ICOADS v2.5, and Surface solar insolation FRESKO v6 were downloaded from the KNMI Climate Explorer (<http://climexp.knmi.nl/>; oldenborgh@knmi.nl). MODIS-Terra SST and MODIS-Aqua Chlorophyll a were obtained online from NASA Giovanni (http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=ocean_month). The NOAA AVHRR daily SST data sets were obtained online from IRI/LDEO Climate Data Library (<http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.OISST/.version2/.AVHRR>). Aminidivi temperature (Amini AT) was obtained from the Additional Director General of Meteorology (Research) India Meteorological Department Pune (NDC-057/VE/138/0114/527: Date 2 November 2014; ndcsupply@imd.gov.in). All India Rainfall (AIR) and Western Peninsular Indian Rainfall (WPIR) were obtained online (from IITM Pune (<http://www.tropmet.res.in>)). Nino3.4 index was obtained from NOAA National Weather Service, Climate Prediction Center (<http://www.cpc.ncep.noaa.gov>). Seychelles coral- $\delta^{18}\text{O}$ data for the common time period was provided by Miriam Pfeiffer (pfeiffer@geol.rwth-aachen.de). Thanks to Craig A Grove from NIOZ for X-radiography. We thank Venkatesh, Waseem for field assistance; G Suseela, K Bremer, and J von Reumont for lab assistance; S Ali and team for recovering the core. NS thanks the Lakshadweep Administration (Department of Science and Technology, Kavaratti Island) for permitting CSIR-NGRI to obtain coral samples from Lakshadweep Islands. We would also like to thank the anonymous reviewers for their comments, which led to several improvements in this manuscript. Finally, we thank the Director, CSIR-NGRI, for permitting to publish this research work.

The coral Sr/Ca-based SST reconstruction shows that *Porites lutea* corals faithfully capture the SW monsoon-induced summer temperature cooling of the order of $\sim 2.3^\circ\text{C}$ at the study site. Coral-Sr/Ca also shows a strong and significant relation with the Arabian Sea SST for the combined peak-summer and SW monsoon months implying the coral's ability to track SW monsoon-induced summer temperature cooling on a larger scale. Additionally, coral-Sr/Ca shows a strong and significant correlation with the Western Peninsular Indian Rainfall, suggesting that longer coral records from this region might be potentially used for the long-term reconstruction of past monsoon dynamics.

During some years, which coincide with major El Niño events, anomalously warm SSTs impair the coral's ability to record full scale warming, leading to a dampening of the temperature signal in coral-Sr/Ca, i.e., suppressed summer peaks. Modern geochemical proxy records from corals across the tropics that survived the strong 1998 bleaching event or similar past events might have been affected by similar cold biases. Areas historically more often affected by thermal stress could have potentially accumulated a history of past bleaching related growth perturbations in geochemical profiles far earlier than 1998. This, in turn, could have led to false identifications of long term cooling trends in coral proxy SST reconstructions.

The frequent occurrence of HotSpot values ranging between 0 and 1 indicates that this region is under thermal stress conditions (level: "bleaching watch"). The bleaching threshold SST in this region is 31.1°C , which is 1°C higher than the maximum monthly mean of the study area.

Generating and understanding longer paleoclimatic and paleo-monsoon records from this region that may extend further back in time into the preindustrial era would be highly useful to assess the regional variability of monsoonal changes and impact. In addition, longer coral records from this particular region, where the SSTs show a steady upward trend may help to study the effects of rising temperatures on massive corals at other sites that will be increasingly affected by global warming in the near future.

References

- Ahmad, S. M., V. M. Padmakumari, W. Raza, K. Venkatesham, G. Suseela, N. Sagar, A. Chamoli, and S. Rajan (2011), High-resolution carbon and oxygen isotope records from scleractinian (*Porites*) coral of Lakshadweep Archipelago, *Quat. Int.*, 238, 107–114, doi:10.1016/j.quaint.2009.11.020.
- Aijaz, R. (2013), Monsoon variability and agricultural drought management in India, *Observer Research Foundation (ORF)*, Issue Brief (53), New Delhi. [Available at www.orfonline.org]
- Alibert, C., and M. McCulloch (1997), Strontium/calcium ratios in modern *Porites* corals from the Great Barrier Reef as a proxy for sea surface temperature: Calibration of the thermometer and monitoring of ENSO, *Paleoceanography*, 12, 345–363, doi:10.1029/97PA00318.
- Alory, G., and G. Meyers (2009), Warming of the upper equatorial Indian Ocean and changes in the Heat Budget (1960–1999), *J. Clim.*, 22(1), 93–113, doi:10.1175/2008JCLI2330.1.
- Alory, G., S. Wijffels, and G. Meyers (2007), Observed temperature trends in the Indian Ocean over 1960–1999 and associated mechanisms, *Geophys. Res. Lett.* 34, L02606, doi:10.1029/2006GL028044.
- Arthur, R. (2000), Coral bleaching and mortality in three Indian reef regions during an El Niño southern oscillation event, *Curr. Sci.*, 79(12), 1723–1729.
- Baird, A. H., and P. A. Marshall (1998), Mass bleaching of corals on the Great Barrier Reef, *Coral Reefs*, 17, 376–376, doi:10.1007/s003380050142.
- Beck, J. W., E. Edwards, F. Ito, J. Taylor, F. Recy, P. Rougerie, and H. C. Joannot (1992), Sea surface temperature from coral skeletal strontium/calcium ratios, *Science*, 257(5070), 644–647, doi:10.1126/science.257.5070.644.
- Berkelmans, R. (2001), Bleaching, upper thermal limits and temperature adaptation in reef corals, PhD thesis, James Cook University, Australia.
- Berkelmans, R., and B. L. Willis (1999), Seasonal and local spatial patterns in the upper thermal limits of corals in the inshore central Great Barrier Reef, *Coral Reefs*, 18, 219–228, doi:10.1007/s003380050186.
- Burt, J. A., K. Al-Khalifa, E. Khalaf, B. Alshuwaikh, and A. Abdulwahab (2013), The continuing decline of coral reefs in Bahrain, *Mar. Pollut. Bull.*, 72, 357–363, doi:10.1016/j.marpolbul.2012.08.022.
- Cahyarini, S. Y., M. Pfeiffer, and W.-C. Dullo (2009), Improving SST reconstructions from coral Sr/Ca records: Multiple corals from Tahiti (French Polynesia), *Int. J. Earth Sci.*, 98, 31–40, doi:10.1007/s00531-008-0323-2.
- Cahyarini, S. Y., M. Pfeiffer, W.-C. Dullo, J. Zinke, S. Hetzinger, S. Kasper, C. Grove, and D. Garbe-Schönberg (2011), Comment on "A snapshot of climate variability at Tahiti at 9.5 ka using a fossil coral from IODP Expedition 310" by Kristine L. DeLong, Terrence M. Quinn, Chuan-Chou Shen, and Ke Lin, *Geochem. Geophys. Geosyst.*, 12, Q03012, doi:10.1029/2010GC003377.
- Cahyarini, S. Y., M. Pfeiffer, I. S. Nurhati, E. Aldrian, W.-C. Dullo, and S. Hetzinger (2014), Twentieth century sea surface temperature and salinity variations at Timor inferred from paired coral $\delta^{18}\text{O}$ and Sr/Ca measurements, *J. Geophys. Res. Oceans*, 119, 4593–4604, doi:10.1002/2013JC009594.
- Cantin, N. E., A. L. Cohen, K. B. Karnauskas, A. M. Tarrant, and D. C. McCorkle (2010), *Science*, 329(5989), 322–325, doi:10.1126/science.1190182.
- Chakraborty, S., and R. Ramesh (1992), Climatic significance of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ variations in a banded coral (*Porites*) from Kavaratti, Lakshadweep Islands, in *Oceanography of the Indian Ocean*, edited by B. N. Desai, pp. 473–478, Oxford and IBH Publ. (P) Ltd., New Delhi.
- Chakraborty, S., and R. Ramesh (1993), Monsoon-induced sea surface temperature changes recorded in Indian corals, *Terra Nova*, 5, 545–551, doi:10.1111/j.1365-3121.1993.tb00303.x.

- Chakraborty, S., and R. Ramesh (1997), Environmental significance of carbon and oxygen isotope ratios of banded corals from Lakshadweep, India, *Quat. Int.*, *37*, 55–65, doi:10.1016/1040-6182(96)00028-6.
- Chakraborty, S., and R. Ramesh (1998), Stable isotope variations in a coral (*Favia speciosa*) from the Gulf of Kutch during 1948–1989 environmental implications, *Proc. Indian Acad. Sci. Earth Planet. Sci.*, *107*(4), 331–341.
- Cole, J. E., R. B. Dunbar, T. R. McClanahan, and N. A. Muthiga (2000), Tropical Pacific forcing of decadal SST variability in the Western Indian Ocean over the past two centuries, *Science*, *287*(5453), 617–619, doi:10.1126/science.287.5453.617.
- Coles, S. L., and B. M. Riegl (2013), Thermal tolerances of reef corals in the Gulf: A review of the potential for increasing coral survival and adaptation to climate change through assisted translocation, *Mar. Pollut. Bull.*, *72*, 323–332, doi:10.1016/j.marpolbul.2012.09.006.
- Corrège, T. (2006), Sea surface temperature and salinity reconstruction from coral geochemical tracers, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *232*, 408–428, doi:10.1016/j.palaeo.2005.10.014.
- Damassa, T. D., J. E. Cole, H. R. Barnett, T. R. Ault, and T. R. McClanahan (2006), Enhanced multidecadal climate variability in the seventeenth century from coral isotope records in the western Indian Ocean, *Paleoceanography*, *21*, PA2016, doi:10.1029/2005PA001217.
- D'Olive, J. P., M. T. McCulloch, and K. Judd (2013), Long-term records of coral calcification across the central Great Barrier Reef: Assessing the impacts of river run off and climate change, *Coral Reefs*, *32*, 999–1012, doi:10.1007/s00338-013-1071-8.
- DeLong, K. L., T. M. Quinn, and F. W. Taylor (2007), Reconstructing twentieth-century sea surface temperature variability in the southwest Pacific: A replication study using multiple coral Sr/Ca records from New Caledonia, *Paleoceanography*, *22*, PA4212, doi:10.1029/2007PA001444.
- DeLong, K. L., J. A. Flannery, C. R. Maupin, R. Z. Poore, and T. M. Quinn (2011), A coral Sr/Ca calibration and replication study of two massive corals from the Gulf of Mexico, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *307*, 117–128, doi:10.1016/j.palaeo.2011.05.005.
- de Villiers, S., G. T. Shen, and B. K. Nelson (1994), The Sr/Ca temperature relationship in coralline aragonite: Influence of variability in (Sr/Ca) sea water and skeletal growth parameters, *Geochim. Cosmochim. Acta*, *58*, 197–208, doi:10.1016/0016-7037(94)90457-X.
- de Villiers, S., B. K. Nelson, and A. R. Chivas (1995), Biological controls on coral Sr/Ca and $\delta^{18}\text{O}$ reconstructions of sea surface temperatures, *Science*, *269*(5228), 1247–1249, doi:10.1126/science.269.5228.1247.
- de Villiers, S., M. Greaves, and H. Elderfield (2002), An intensity ratio calibration method for the accurate determination of Mg/Ca and Sr/Ca of marine carbonates by ICP-AES, *Geochem. Geophys. Geosyst.*, *3*(1), 1001, doi:10.1029/2001GC000169.
- Donner, S. D., W. J. Skirving, C. M. Little, M. Oppenheimer, and O. Hoegh-Guldberg (2005), Global assessment of coral bleaching and required rates of adaptation under climate change, *Global Change Biol.*, *11*(12), 2251–2265, doi:10.1111/j.1365-2486.2005.01073.x.
- Donner, S. D., T. R. Knutson, and M. Oppenheimer (2007), Model-based assessment of the role of human-induced climate change in the 2005 Caribbean coral bleaching event, *Proc. Natl. Acad. Sci. U. S. A.*, *104*, 5483–5488, doi:10.1073/pnas.0610122104.
- Eakin, C. M., J. Kleypas, and O. Hoegh-Guldberg (2008), Global climate change and coral reefs: Rising temperatures, acidification and the need for resilient reefs, in *Status of Coral Reefs of the World: 2008*, edited by C. R. Wilkinson, Global Coral Reef Monit. Network and Reef and Rainforest Res. Cent., Townsville, Queensland, Australia.
- Evans, M. N., R. G. Fairbanks, and J. L. Rubenstone (1999), The thermal oceanographic signal of El Niño reconstructed from a Kiribati Island coral, *J. Geophys. Res.*, *104*, 13,409–13,421, doi:10.1029/1999JC900001.
- Gagan, M. K., G. B. Dunbar, and A. Suzuki (2012), The effect of skeletal mass accumulation in *Porites* on coral Sr/Ca and $\delta^{18}\text{O}$ paleothermometry, *Paleoceanography*, *27*, PA1203, doi:10.1029/2011PA002215.
- Goreau, T. J., and R. L. Hayes (1994), Coral bleaching and ocean hot spots, *Ambio*, *23*, 176–180.
- Hansen, J., M. Sato, R. Ruedy, K. Lo, D. W. Lea, and M. A. Medina-Elizalde (2006), Global temperature change, *Proc. Natl. Acad. Sci. U. S. A.*, *103*(39), 14288–14293, doi:10.1073/pnas.0606291103.
- Hastenrath, S., and L. Greischar (1993), Changing predictability of Indian monsoon rainfall anomalies?, *J. Earth Syst. Sci.*, *102*(1), 35–47.
- Hathorne, E. C., et al. (2013), Inter-laboratory study for coral Sr/Ca and other element/Ca ratio measurements, *Geochem. Geophys. Geosystems*, *14*, 3730–3750, doi:10.1002/ggge.20230.
- Hetzinger, S., M. Pfeiffer, W.-C. Dullo, E. Ruprecht, and D. Garbe-Schönberg (2006), Sr/Ca and $\delta^{18}\text{O}$ in a fast-growing *Diploria strigosa* coral: Evaluation of a new climate archive for the tropical Atlantic, *Geochem. Geophys. Geosyst.*, *7*, Q10002, doi:10.1029/2006GC001347.
- Hetzinger, S., M. Pfeiffer, W.-C. Dullo, D. Garbe-Schönberg, and J. Halfar (2010), Rapid 20th century warming in the Caribbean and impact of remote forcing on climate in the northern tropical Atlantic as recorded in a Guadeloupe coral, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *296*, 111–124, doi:10.1016/j.palaeo.2010.06.019.
- Inoue, M., A. Suzuki, M. Nohara, K. Hibino, and H. Kawahate (2007), Empirical assessment of coral Sr/Ca and Mg/Ca ratios as climate proxies using colonies grown at different temperatures, *Geophys. Res. Lett.*, *34*, L12611, doi:10.1029/2007GL029628.
- Izumo, T., M. Lengaigne, J. Vialard, J. Luo, T. Yamagata, and G. Madec (2012), Influence of Indian Ocean dipole and Pacific recharge on following years El Niño: Interdecadal robustness, *Clim. Dyn.*, *42*(1), 291–310, doi:10.1007/s00382-012-1628-1.
- James, P. S. B. (2011), Lakshadweep: Islands of ecological fragility, environmental sensitivity and anthropogenic vulnerability, *J. Coastal Environ.* *2*(1), 9–25.
- Kaplan, A., M. A. Cane, Y. Kushnir, A. C. Clement, M. B. Blumenthal, and B. Rajagopalan (1998), Analyses of global sea surface temperature 1856–1991, *J. Geophys. Res.* *103*, 18,567–18,589, doi:10.1029/97JC01736.
- Kinsman, D. J. J. (1964), Reef coral tolerance of high temperatures and salinities, *Nature*, *202*, 1280–1282, doi:10.1038/2021280a0.
- Lalli, C. M. and T. R. Parsons (1995), *Biological Oceanography: An Introduction*, pp. 213, Elsevier Butterworth-Heinemann Ltd., Oxford, U. K.
- Lough, J. M. (2008), Coral calcification from skeletal records revisited, *Mar. Ecol. Prog. Ser.*, *373*, 257–264, doi:10.3354/meps07398.
- Luis, A. J., and H. Kawamura (2004), Air-sea interaction, coastal circulation and primary production in the eastern Arabian Sea: A review, *J. Oceanogr.*, *60*(2), 205–218, doi:10.1023/B:JOCE.0000038327.33559.34.
- Marshall, J. F., and M. T. McCulloch (2001), Evidence of El Niño and the Indian Ocean Dipole from Sr/Ca derived SSTs for modern corals at Christmas Island, Eastern Indian Ocean, *Geophys. Res. Lett.*, *28*, 3453–3456, doi:10.1029/2001GL012978.
- Marshall, J. F., and M. T. McCulloch (2002), An assessment of the Sr/Ca ratio in shallow water hermatypic corals as a proxy for sea surface temperature, *Geochim. Cosmochim. Acta*, *66*, 3263–3280, doi:10.1016/S0016-7037(02)00926-2.
- McClanahan, T. R., M. Ateweberhan, C. A. Muhando, J. Maina, and M. S. Mohammed (2007), Effects of climate and sea water temperature variation on coral bleaching and mortality, *Ecol. Monogr.*, *77*(4), 503–525, doi:10.1890/06-1182.1.
- McCulloch, M. T., M. Gagan, G. Mortimer, A. Chivas, and P. Isdale (1994), A high resolution Sr/Ca and $\delta^{18}\text{O}$ coral record from the Great Barrier Reef, Australia and the 1982–1983 El Niño, *Geochim. Cosmochim. Acta*, *58*, 2747–2754, doi:10.1016/0016-7037(94)90142-2.
- NOAA Coral Reef Watch (2000), NOAA Coral Reef Watch Operational 50-km Satellite Coral Bleaching Degree Heating Weeks Product. Silver Spring, Md. [Available at <http://coralreefwatch.noaa.gov/satellite/hdf/index.php>, last accessed 5 Jan 2011.]
- Paillard, D., L. Labeyrie, and P. Yiou (1996), Macintosh program performs time-series analysis, *Eos Trans. AGU*, *77*(39), 379, doi:10.1029/96EO00259.

- Pätzold, J. (1984), Growth rhythms recorded in stable isotopes and density bands in the reef coral *Porites lobata* (Cebu, Philippines), *Coral Reefs*, 3(2), 87–90, doi:10.1007/BF00263758.
- Payet, R., and W. Agricole (2006), Climate change in the Seychelles: Implications for water and coral reefs, *Ambio*, 35(4), 182–189, doi:10.1579/0044-7447(2006)35[182:CCITSI]2.0.CO;2.
- Pfeiffer, M., and W.-C. Dullo (2006), Monsoon-induced cooling of the western equatorial Indian Ocean as recorded in coral oxygen isotope records from the Seychelles covering the period of 1840–1994 AD, *Quat. Sci. Rev.*, 25, 993–1009, doi:10.1016/j.quascirev.2005.11.005.
- Pfeiffer, M., W.-C. Dullo, J. Zinke, and D. Garbe-Schönberg (2009), Three monthly coral Sr/Ca records from the Chagos Archipelago covering the period of 1950–1995 A.D.: Reproducibility and implications for quantitative reconstructions of sea surface temperature variations, *Int. J. Earth Sci.*, 98, 53–66, doi:10.1007/s00531-008-0326-z.
- Pillai, C. S. G., and S. Jasmine (1989), The coral fauna of Lakshadweep, in *Central Marine Fisheries Research Institute (CMFRI) Bulletin 43: Marine Living Resources of the Union Territory of Lakshadweep - An Indicative Survey With Suggestions for Development*, edited by C. Sus-eelan, pp. 179–195, P. S. B. R. James, Cochin, India.
- Pillai, V. N. (2001), Oceanographic aspects of Lakshadweep waters in relation to Skipjack tuna fisheries, *Geol. Surv. India Spec. Publ.*, 56, 125–128.
- Rao, R. R., and R. Sivakumar (2000), Seasonal variability of near-surface thermal structure and heat budget of the mixed layer of the tropical Indian Ocean from a new global ocean temperature climatology, *J. Geophys. Res.*, 105, 995–1015, doi:10.1029/1999JC900220.
- Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan (2003), Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *J. Geophys. Res.*, 108 (D14), 4407, doi:10.1029/2002JD002670.
- Reynolds, R. W., N. A. Rayner, T. M. Smith, D. C. Stokes, and W. Wang (2002), An improved in situ and satellite SST analysis for climate, *J. Clim.*, 15, 1609–1625, doi:10.1175/1520-0442(2002)015 <1609:AISAS>2.0.CO;2.
- Roxy, M. K., K. Ritika, P. Terray, and S. Masson (2014), The curious case of Indian Ocean warming, *J. Clim.*, (27), 8501–8509, doi:10.1175/JCLI-D-14-00471.1.
- Schneider, U., A. Becker, P. Finger, A. Meyer-Christoffer, M. Ziese, and B. Rudolf (2014), GPCP's new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle, *Theoretical and Applied Climatology*, 115(1), 15–40, doi:10.1007/s00704-013-0860-x.
- Schrag, D. P. (1999), Rapid determination of high-precision Sr/Ca ratios in corals and other marine carbonates, *Paleoceanography*, 14, 97–102, doi:10.1029/1998PA900025.
- Shankar, D., P. N. Vinayachandran, and A. S. Unnikrishnan (2002), The monsoon currents in the north Indian Ocean, *Prog. Oceanogr.*, 52(1), 63–120, doi:10.1016/S0079-6611(02)00024-1.
- Shen, C., T. Lee, C. Chen, C. Wang, C. Dai, and A. Li (1996), The calibration of D[Sr/Ca] versus sea surface temperature relationship for *Porites* coral, *Geochim. Cosmochim. Acta*, 60(20), 3849–3858, doi:10.1016/0016-7037(96)00205-0.
- Shen, G. T., J. E. Cole, S. W. Lea, L. J. Linn, T. A. McConnaughey, and R. G. Fairbanks (1992), Surface ocean variability at Galapagos from 1936–1982: Calibration of geochemical tracers in corals, *Paleoceanography*, 7, 563–588, doi:10.1029/92PA01825.
- Smith, R. J. (2009), Use and misuse of the reduced major axis for line-fitting, *Am. J. Phys. Anthropol.*, 140(3), 476–486, doi:10.1002/ajpa.21090.
- Smith, S., R. Buddemeier, R. Redale, and J. Houck (1979), Strontium-calcium thermometry in coral skeletons, *Science*, 204(4391), 404–406, doi:10.1126/science.204.4391.404.
- Smith, T. M., R. W. Reynolds, T. C. Peterson, and J. Lawrimore (2008), Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880–2006), *J. Clim.*, 21, 2283–2296, doi:10.1175/2007JCLI2100.1.
- Sontakke, N. A., S. Nityanand, and H. N. Singh (2008), Instrumental period rainfall series of the Indian region (1813–2005): Revised reconstruction, update and analysis, *Holocene*, 18(7), 1055–1066, doi:10.1177/0959683608095576.
- Suzuki, A., Gagan, M. K., Fabricius, K., Isdale, P. J., Yukino, I., and H. Kawahata (2003), Skeletal isotope microprofiles of growth and perturbations in *Porites* corals during the 1997–1998 mass bleaching event, *Coral Reefs*, 22, 357–369, doi:10.1007/s00338-003-0323-4.
- Swart, P. K., H. Elderfield, M. J. Greaves (2002), A high-resolution calibration of Sr/Ca thermometry using the Caribbean coral *Montastrea annularis*, *Geochem. Geophys. Geosyst.* 3(11), 8402, doi:10.1029/2002GC000306.
- van Hooidonk, R. J., D. P. Manzello, J. Moye, M. E. Brandt, J. C. Hendee, C. McCoy, and C. Manfrino (2012), Coral bleaching at Little Cayman, Cayman Islands 2009, *Estuarine Coastal Shelf Sci.*, 106, 80–84, doi:10.1016/j.jecss.2012.04.021.
- Vautard, R., P. Yiou, and M. Ghil (1992), Singular-spectrum analysis: A toolkit for short, noisy chaotic signals, *Physica D*, 58 (1–4), 95–126, doi:10.1016/0167-2789(92)90103-T.
- Vecchi G. A., and D. E. Harrison (2004), Interannual Indian Rainfall variability and Indian Ocean sea surface temperature anomalies, in *Earth Climate: The Ocean-Atmosphere Interaction*, edited by C. Wang, S. P. Xie, and J. A. Carton, *AGU Geophys. Monogr. Ser.*, 147, 247–259.
- Vinayachandran, P. N. (2004), Summer cooling of the Arabian Sea during contrasting monsoons, *Geophys. Res. Lett.*, 31, L13306, doi:10.1029/2004GL019961.
- Vivekanandan, E., M. Hussain Ali, B. Jasper, and M. Rajagopalan (2008), Thermal thresholds for coral bleaching in the Indian seas, *J. Mar. Biol. Assoc.*, 50(2), 209–214.
- Weber, J. N. (1973), Incorporation of strontium into reef coral skeletal carbonate, *Geochim. Cosmochim. Acta*, 37, 2173–2190, doi:10.1016/0016-7037(73)90015-X.
- Weber, J. N., and P. M. Woodhead (1970), Carbon and Oxygen Isotope Fractionation in Skeletal Carbonate of Reef-Building Corals, *Chem. Geol.*, 6, 93–117, doi:10.1016/0009-2541(70)90009-4.
- Weber, J. N., and P. M. Woodhead (1972), Temperature dependence of oxygen-18 concentration in reef coral carbonates, *J. Geophys. Res.*, 77, 463–473, doi:10.1029/JC077i003p00463.
- Wei, G., M. Sun, X. Li, and B. Nie (2000), Mg/Ca, Sr/Ca and U/Ca ratios of a *Porites* coral from Sanya Bay, Hainan Island, South China Sea and their relationship to sea surface temperature, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 162(1–2), 59–74, doi:10.1016/S0031-0182(00)00105-X.
- Wiggert, J. D., R. R. Hood, K. Banse, and J. C. Kindle (2005), Monsoon-driven biogeochemical processes in the Arabian Sea, *Prog. Oceanogr.*, 65(2–4), 176–213, doi:10.1016/j.pocan.2005.03.008.
- Wilkinson, C. (Ed.) (1998), *Status of the Coral Reefs of the World: 1998*, Global Coral Reef Monit. Network, Aust. Inst. of Mar. Sci., Townsville, Queensland, Australia.
- Wilkinson, C., and D. Souter (2008), *Status of Caribbean Coral Reefs After Bleaching and Hurricanes in 2005*, Global Coral Reef Monit. Network, and Reef and Rainforest Res. Cent., Townsville, Queensland, Australia.

- Wilkinson, C., O. Lindén, H. Cesar, G. Hodgson, J. Rubens, and A. E. Strong (1999), Ecological and socioeconomic impacts of 1998 coral mortality in the Indian Ocean: An ENSO impact and a warning of future change?, *Ambio*, *28*, 188–196.
- Worley, S. J., S. D. Woodruff, R. W. Reynolds, S. J. Lubker, and N. Lott (2005), ICOADS Release 2.1 data and products, *Int. J. Climatol.*, *25*, 823–842, doi:10.1002/joc.1166.
- Yu, K. F., J. X. Zhao, G. J. Wei, X. R. Cheng, T. G. Chen, T. Felis, P. X. Wang, and T. S. Liu (2005), $\delta^{18}\text{O}$, Sr/Ca, and Mg/Ca of *Porites lutea* corals from Leizhou Peninsula, northern South China Sea, and their applicability as paleoclimatic indicators, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *218*(1–2), 57–73, doi:10.1016/j.palaeo.2004.12.003.
- Yu, L., X. Jin, and R. A. Weller (2007), Annual, seasonal, and interannual variability of air-sea heat fluxes in the Indian Ocean, *J. Clim.*, *20*, 3190–3209, doi:10.1175/JCLI4163.1.
- Zhang, Z., J. Falter, R. Lowe, G. Ivey, and M. T. McCulloch (2013), Atmospheric forcing intensifies the effects of regional ocean warming on reef-scale temperature anomalies during a coral bleaching event, *J. Geophys. Res. Oceans*, *118*, 4600–4616, doi:10.1002/jgrc.20338.
- Zinke, J., W.-C. Dullo, G. A. Heiss, and A. Eisenhauer (2004), ENSO and Indian Ocean subtropical dipole variability is recorded in a coral record off southwest Madagascar for the period 1659 to 1995, *Earth Planet. Sci. Lett.*, *228*(1–2), 177–194, doi:10.1016/j.epsl.2004.09.028.