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ORIGINAL PAPER

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

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Abstract In order to assess the fidelity of coral Sr/Ca for quantitative reconstructions of sea surface temperature variations, we have generated three monthly Sr/Ca time series from *Porites* corals from the lagoon of Peros Banhos (71°E, 5°S, Chagos Archipelago). We find that all three coral Sr/Ca time series are well correlated with instrumental records of sea surface temperature (SST) and air temperature. However, the intrinsic variance of the single-core Sr/Ca time series differs from core to core, limiting their use for quantitative estimates of past temperature variations. Averaging the single-core data improves the correlation with instrumental temperature ($r > 0.7$) and allows accurate estimates of interannual temperature variations (~0.35°C or better). All Sr/Ca time series indicate a shift towards warmer temperatures in the mid-1970s, which coincides with the most recent regime shift in the Pacific Ocean. However, the magnitude of the warming inferred from coral Sr/Ca differs from core to core and ranges from 0.26 to 0.75°C. The composite Sr/Ca record from Peros Banhos clearly captures the major climatic signals in the Indo-Pacific Ocean, i.e. the El Niño–southern oscillation and the Pacific decadal oscillation. Moreover, composite Sr/Ca is highly correlated with tropical mean temperatures ($r = 0.7$), suggesting that coral Sr/Ca time series from the tropical Indian Ocean will contribute to multi-proxy reconstructions of tropical mean temperatures.

Keywords *Porites* · Indian Ocean · Trace elements · El Niño–southern oscillation · Pacific decadal oscillation

Introduction

The Sr/Ca ratio of coral aragonite is a widely used tool for deriving high-resolution proxy records of past sea surface temperatures. Coral Sr/Ca measurements have been employed to study many key periods of past climates, including the Little Ice Age (e.g., Watanabe et al. 2001; Zinke et al. 2004), the Holocene (e.g., Beck et al. 1997; Correge et al. 2000), the Younger Dryas (Correge et al. 2004), and glacial/interglacial cycles (e.g., Hughen et al. 1999; Tudhope et al. 2001; Felis et al. 2004). Application of the Sr/Ca paleothermometer relies on the assumption that coral Sr/Ca varies predictably with temperature, and that seawater Sr/Ca is invariant on millennial timescales due to the long residence time of Sr and Ca in the ocean (e.g., Beck et al. 1992). Thus, unlike the oxygen isotope ratios (δ^{18}O) of coral aragonite, which vary in response to temperature and changes in the δ^{18}O of seawater, coral Sr/Ca should be sensitive to temperature only.

However, the accuracy of quantitative SST estimates derived from coral Sr/Ca has been challenged recently by evidence that physiological processes influence skeletal chemistry (e.g., Cohen et al. 2001, 2002; Meibom et al.

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2003, 2006; Sinclair et al. 2006). Ion microprobe analysis has documented large trace element heterogeneities in corals that cannot be explained by SST variations and are believed to be metabolic in origin (Cohen et al. 2001, 2002; Meibom et al. 2003). Meibom et al. (2003) argue that this will also severely limit the accuracy of Sr/Ca thermometry by conventional sampling techniques.

At present, there are few long-term reproducibility studies of monthly coral Sr/Ca records employing conventional sampling techniques, and those that exist do not cover more than the past 25 years (e.g., Alibert and McCulloch 1997; Marshall and McCulloch 2002; Stephans et al. 2004; Felis et al. 2004). Also, real in situ calibrations of coral Sr/Ca are at present limited to about ten years (see Alibert and McCulloch 1997; Marshall and McCulloch 2002; Swart et al. 2002; Felis et al. 2004; Ourbak et al. 2006). This is too short to assess the ability of coral Sr/Ca as a proxy for year-to-year SST variations, let alone decadal to interdecadal SST changes. Recently published coral Sr/Ca records covering the past hundreds of years indicate some problems with the Sr/Ca thermometer, particularly on decadal to secular time scales (e.g., Linsley et al. 2004, 2006; Quinn et al. 2006).

In the Indian Ocean, time-dependent variations in coral δ^{18}O are often dominated by the freshwater cycle associated with the monsoon circulation, so that quantitative temperature variations cannot be inferred (e.g., Pfeiffer et al. 2004a, b; Timm et al. 2005). Hence, additional paleotemperature estimates using elemental indicators such as Sr/Ca are extremely important (e.g., Zinke et al. 2004, 2005; Pfeiffer et al. 2006).

Here, we compare three monthly resolved Sr/Ca time series covering the time period of 1950–1995. The Sr/Ca time series were generated from three different coral cores drilled in the lagoon of Peros Banhos (Chagos Archipelago; 71°E, 5°S), an atoll situated in the central Indian Ocean, where rainfall is high. Previous analysis of δ^{18}O and Sr/Ca measured in one of the cores from Peros Banhos has shown that δ^{18}O primarily records rainfall variations (Pfeiffer et al. 2004a, b, 2006; Timm et al. 2005), while Sr/Ca shows a stable relationship with local sea surface temperature and appears to be a good temperature proxy. In this study, we will explore the reproducibility and fidelity of the Sr/Ca thermometer on interannual to interdecadal time scales. We will demonstrate that single-core data are generally reproducible, despite uncertainties, and that quantitative reconstructions of long-term SST variations are possible using a composite, multi-core Sr/Ca reconstruction. Furthermore, a comparison with both instrumental and proxy-based indices of major climatic modes such as the El Niño–southern oscillation (ENSO) and the Pacific decadal oscillation (PDO) demonstrates that coral Sr/Ca captures large-scale climate variations in the Indo-Pacific sector.

Regional setting

The Chagos Archipelago, also known as the British Indian Ocean Territory (BIOT), is situated on the southernmost part of the Chagos–Laccadive Ridge, in the geographical centre of the Indian Ocean. The archipelago includes five true atolls (Blenheim Reef, Diego Garcia, Egmont, Peros Banhos and Salomon), a mostly submerged atoll (Great Chagos Bank), and a number of submerged banks (including Speakers Bank, Pitt Bank and Centurion Bank) (Fig. 1) (Spalding et al. 2001). Peros Banhos is the most

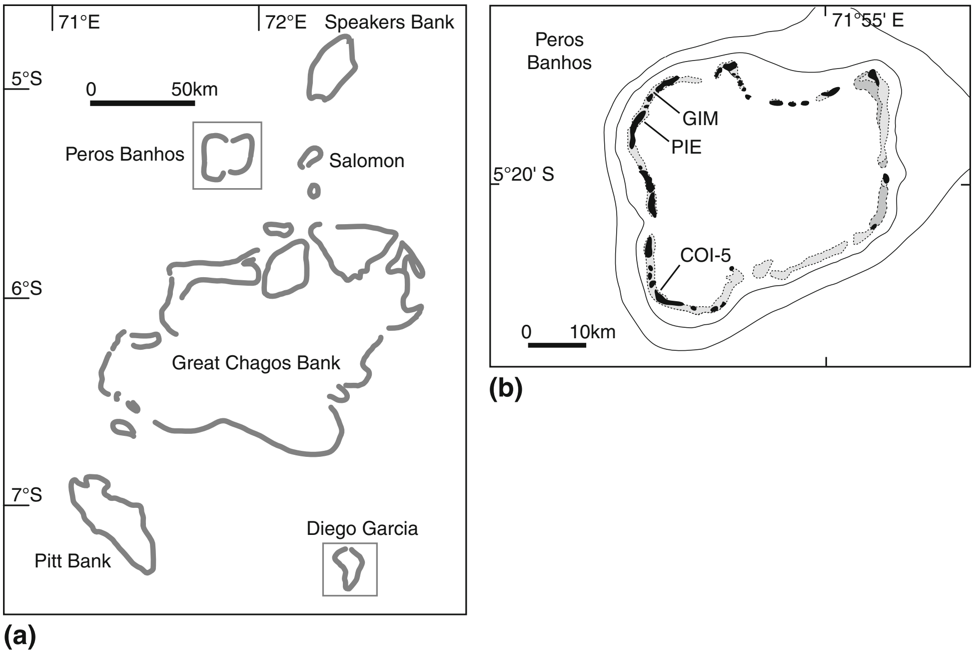

Fig. 1 **a** The Chagos Archipelago. *Grey squares* mark Peros Banhos and Diego Garcia, where air temperature data is available (WMO Station ID 6196700). **b** Map of Peros Banhos Atoll showing the location of the coral cores

north-westerly Chagos Atoll, located at 71.5°E and 5.2°S (Fig. 1b). The atoll covers an area of 463 km^2 and rises steeply from 2 km depth. Numerous islands are scattered around the rim, separated by channels that afford good water exchange with the open ocean (Spalding et al. 2001).

The climate of the Chagos Archipelago is dominated by the seasonal reversal of the monsoon. From October to April, winds are light or moderate and generally from the north-west (Sheppard et al. 1999). The Chagos then lies in the intertropical convergence zone (ITCZ) which forms in a narrow band across the tropical Indian Ocean, and precipitation is high. During the rest of the year, the south-east trade winds blow strongly (Sheppard et al. 1999). SST has an approximately bimodal distribution with maxima in December–January and March–April (Sheppard et al. 1999).

Historical temperature data

The optimal interpolation SST (OISST), version 2 (Reynolds et al. 2002) includes satellite-based SST measurements and provides a continuous time series of global SSTs since 1982. In the 1° × 1° grid centred at 70.5°E, 5.5°S, which includes Peros Banhos, the OISST indicates mean temperatures of 28.40°C. The average annual cycle is 1.85°C. Recent El Niño events lead to a warming of 0.5–1.5°C. The magnitude of these anomalous SST variations is small, and lies within the range of observational errors (Annamalai et al. 1999), resulting in a poor signal-to-noise ratio of Indian Ocean SST data.

Local air temperature data are only available from Diego Garcia (72.4°E, 7.3°S; WMO Station ID 6196700), an atoll in the south-west of the Chagos Archipelago (Fig. 1a). The data has been quality controlled (Baker et al. 1994), but it is not continuous. In total, 25 years of data are available over the past 50 years. Mean air temperatures measured at Diego Garcia are 27.14°C, with an average annual cycle of 1.99°C.

Historical SST data collected primarily by ships-of-opportunity has been summarized in the comprehensive ocean atmosphere data set (COADS) to produce monthly averages on a 2° × 2° grid basis (Woodruff et al. 1998). COADS only contains actual historical SST measurements. In the grid including Peros Banhos, the data is discontinuous, and prior to 1968, there is not a single year with at least one SST observation per month. We therefore extracted SST data from the extended reconstructed SST (ERSST), version 2 (Smith and Reynolds 2004). The ERSST is based on the available COADS data, and uses sophisticated statistical methods to reconstruct SST in times of sparse data. From the ERSST, we extract data in the grid centred at 70°E, 6°S. Over the 1950 to 1995 period, the ERSST averages 28.13°C, with an average annual cycle of 1.91°C. SST time series from other gridded SST products (HadISST, Rayner et al. 2003; OS SST, Kaplan et al. 1998) agree well with the ERSST time series in the grid including Peros Banhos (note that all gridded SST products are mainly based on COADS data).

Materials and methods

Coral sampling

The coral cores were collected in February 1996 from three massive *Porites* corals growing in the lagoon of Peros Banhos Atoll (Fig. 1b; Table 1). Core GIM derives from a *Porites solida* colony living in a water depth of 3 m in a channel between Ile Diamant and Grand Ile Mapou, where tidal currents afford good water exchange with the open ocean. Core COI-5 was retrieved from a *Porites lobata* coral living on the lagoon side of Ile du Coin, in very shallow water (1.8 m water depth). Core PIE was taken from a *Porites solida* colony growing in a water depth of 2.6 m on the lagoon side of Ile Pierre.

After drilling, the cores were washed with freshwater, air dried, and then cut into 5 mm thick slabs. The slabs were cleaned in an ultrasonic bath with de-ionized water for 15 min and then oven dried at 40°C. X-ray images of core GIM and core PIE show very distinct annual density bands, while the density bands of COI-5 are not very clear.

For Sr/Ca analysis, we chose a physical sample spacing of 1 mm, which yielded on average 12–13 samples per year (Table 1). Samples were taken along the maximum axis of growth using a 0.6 mm dental drill. All cores were sampled from August 1949 to February 1996.

Analytical procedures

Sr/Ca ratios were measured at the University of Kiel with a Spectro Ciros CCD SOP inductively coupled plasma

Table 1 The Chagos corals

Core	Coral species	Longitude	Latitude	Water depth (m)	Samples per year
GIM	*Porites solida*	71°45.51′E	5°15.08′S	3	13.2 (±3.8)
COI-5	*Porites solida*	71°45.86′E	5°26.04′S	1.8	12.4 (±4.9)
PIE	*Porites lobata*	71°44.66′E	5°16.66′S	2.6	13.6 (±3.8)

All cores were drilled in the Lagoon of Peros Banhos Atoll

GIM Grand Ile Mapou, *COI-5* Ile du Coin, *PIE* Ile Pierre optical emission spectrometer (ICP-OES), which simultaneously collects the respective elemental emission signals, following a combination of the techniques described by Schrag (1999) and de Villiers et al. (2002). The sample solution is prepared by dissolving approximately 0.5 mg of coral powder in 1.00 mL HNO_3 70%. The working solution is prepared by serial dilution of the sample solution with HNO_3 2% to get a concentration of ca. 8 ppm Ca. Standard solution is prepared by dilution of 1.00 mL of the stock solution (0.52 grams of homogenized coral powder from an in-house standard in 250 mL HNO_3 2%) with 2.00 mL HNO_3 2%. Sr and Ca lines, which are used for this measurement, are 407 and 317 nm, respectively. Analytical precision on Sr/Ca determinations is 0.15% RSD or 0.01 mmol/mol (1σ).

Coral chronology

The coral chronologies were developed based on the seasonal cycle in Sr/Ca. We assigned 15 August to the highest Sr/Ca ratios measured in any given year, because August is on average the coldest month at Chagos. We then interpolated linearly between these anchor points to obtain age assignments for all other Sr/Ca measurements. In a second step, the Sr/Ca data was interpolated to 12 equidistant points per year to obtain monthly time series. This approach creates a non-cumulative time scale error of 1–2 month in any given year, because the exact timing of lowest (highest) SST varies. However, with this method the coral age model is independent from instrumental data, and at Peros Banhos, actual SST measurements are sparse prior to 1968. Annual mean values of coral Sr/Ca were computed from the 12 monthly values of each year (January to December averages, with the year labelled according to January).

Results

Monthly Sr/Ca time series of GIM, COI-5 and PIE are shown in Fig. 2. All Sr/Ca series display clear seasonal cycles, as well as significant interannual to interdecadal variability. Basic statistics (means and standard deviations) are indicated in Fig. 2. GIM and COI-5 have more or less identical mean values (8.744 and 8.747 mmol/mol, respectively), while the mean value of PIE is higher (8.832 mmol/mol). Standard deviations (1σ) range from 0.042 (GIM) to 0.061 mmol/mol (PIE) for monthly time series, and from 0.025 (GIM) to 0.042 mmol/mol (COI-5) for annual means. Correlation coefficients between the annual mean Sr/Ca time series are: $r = 0.38$, $P < 0.05$ (GIM vs. COI-5), $r = 0.54$, $P < 0.001$ (GIM vs. PIE), and $r = 0.54$, $P < 0.001$ (COI-5 vs. PIE).

The individual time series have been stacked to form a composite Sr/Ca series (Fig. 2d). The composite is the arithmetic mean of GIM, COI-5 and PIE. Composite Sr/Ca has a mean value of 8.774 mmol/mol and a standard deviation (1σ) of 0.043 (monthly data) and 0.028 mmol/mol (annual means).

Table 2 summarizes linear regression equations between the annual mean Sr/Ca time series and instrumental temperature data (ERSST from the grid including Peros Banhos and air temperature measured at Diego Garcia). All Sr/Ca time series are significantly correlated with the instrumental temperature records, with r values ranging between 0.5 (COI-5 vs. ERSST) and 0.84 (composite Sr/Ca vs. air temperature). The estimated Sr/Ca–temperature relationship ranges between −0.035 (±0.01) (GIM vs. air temperature) and −0.100 (±0.02) mmol/(mol °C) (PIE vs. ERSST). With the exception of core PIE, all Sr/Ca time series correlate better with air temperature (Table 2).

Discussion

Single-core Sr/Ca time series

While the mean Sr/Ca values of GIM and COI-5 agree well, Sr/Ca of core PIE, taken less than 10 km to the south of core GIM, is offset by more than 0.08 mmol/mol. Based on published Sr/Ca–temperature relationships that typically range from −0.04 to −0.08 mmol/(mol °C) (e.g., Marshall and McCulloch 2002; Swart et al. 2002), this would indicate a temperature difference of 1–2°C between the two sites. As PIE derives from the inner lagoon of Peros Banhos, while GIM is from a channel connecting the lagoon and the open ocean, we cannot rule out this possibility. However, absolute offsets in mean Sr/Ca ratios of different coral samples from the same reefs have been found at other locations (e.g., Linsley et al. 2006). While it is not clear what causes these offsets, they are often attributed to non-environmental factors (e.g., de Villiers et al. 1995; Linsley et al. 2006), in analogy to coral $\delta^{18}O$, which typically shows different absolute values in individual coral colonies that are attributed to ‘vital’ effects (e.g., McConnaughey 1989; Linsley et al. 1999).

The correlation between the three annual mean Sr/Ca time series from Peros Banhos indicates that time-dependent variations of Sr/Ca are generally reproducible. However, the Sr/Ca time series also show different standard deviations, e.g., their intrinsic variance differs.

A rigorous test for the fidelity of coral proxies as indicators of anomalous temperature changes is the calibration of the annual mean proxy time series (e.g., Quinn et al. 1998; Crowley et al. 1999). This procedure effectively removes the seasonal cycle, which tends to inflate the

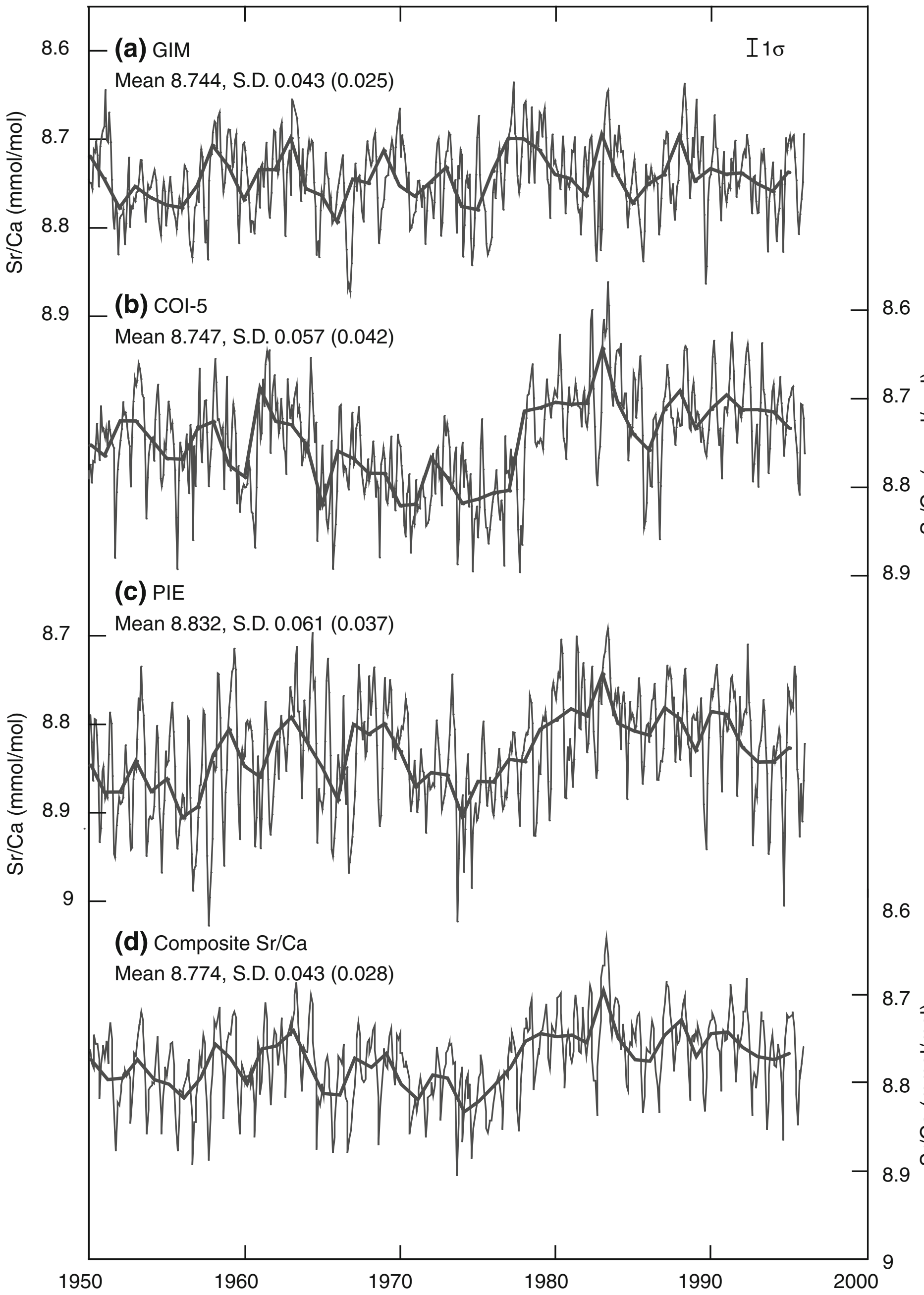

Fig. 2 **a** Monthly Sr/Ca time series of GIM (*thin line*) and annual means (*thick line*). **b** Monthly Sr/Ca time series of COI-5 (*thin line*) and annual means (*thick line*). **c** Monthly Sr/Ca time series of PIE (*thin line*) and annual means (*thick line*). **d** Monthly Sr/Ca time series of composite Sr/Ca (*thin line*) and annual means (*thick line*). Means and standard deviation of monthly (annual mean) time series are indicated in the figure. *Error bar* analytical uncertainty of Sr/Ca (0.15% RSD or 0.01 mmol/mol)

correlation between the proxy and instrumental temperature, and the resulting correlation only reflects the ability of the coral proxies as recorders of interannual and long-term temperature variability. In the central Indian Ocean, interannual SST variations are small (Annamalai et al. 1999). As a result, the signal-to-noise ratio of both instrumental temperature and Sr/Ca proxy data is low. Despite these problems, all three single-core Sr/Ca time series from Peros Banhos are significantly correlated with instrumental temperature (Table 2).

The three single-core Sr/Ca time series from Peros Banhos show fairly large variations in the estimated Sr/Ca–temperature relationship (Table 2). Clearly, the slope of the Sr/Ca temperature relationship depends on (1) the temperature data, and (2) the proxy time series. This is to be expected, as all time series presented in this study, instrumental and proxy, have different standard deviations around their mean, i.e., their intrinsic variance differs. Nevertheless, taking into account the statistical uncertainties, the estimated Sr/Ca–temperature slope values presented in Table 2 are all consistent with previously published values, which range from −0.033 to −0.090 mmol/(mol °C) (see Swart et al. 2002, their Table 1 for a summary). Few of these calibration studies, however,

Table 2 Linear regression equations and correlation coefficients between annual mean coral Sr/Ca, ERSST from the grid including Peros Banhos and air temperature measured at Diego Garcia

Coral core	Regression equation	*r*	*P*	*σ*
ERSST (70°E/6°S)				
GIM	Sr/Ca = −0.050(±0.01) × SST + 10.15(±0.35)	−0.52	<0.001	0.02
COI-5	Sr/Ca = −0.083(±0.02) × SST + 11.08(±0.60)	−0.50	<0.001	0.04
PIE	Sr/Ca = −0.100(±0.02) × SST + 11.59(±0.44)	−0.68	<0.001	0.03
Composite Sr/Ca	Sr/Ca = −0.077(±0.01) × SST + 10.94(±0.34)	−0.70	<0.001	0.02
Air temperature				
GIM	Sr/Ca = −0.035(±0.01) × *T* + 9.70(±0.25)	−0.63	<0.001	0.02
COI-5	Sr/Ca = −0.076(±0.01) × *T* + 10.81(±0.31)	−0.81	<0.001	0.03
PIE	Sr/Ca = −0.053(±0.01) × *T* + 10.27(±0.36)	−0.64	<0.001	0.03
Composite Sr/Ca	Sr/Ca = −0.055(±0.01) × *T* + 10.26(±0.20)	−0.84	<0.001	0.02

Time period 1950–1995. *σ*, error of regression (1*σ*). See text for discussion

actually use real in situ SST measurements. Instead, most rely on other temperature data sets for calibration, either local SST records measured in nearby reefs (e.g., de Villiers et al. 1995; Marshall and McCulloch 2002), or grid-scale SST data extracted from various global SST products (e.g., Gagan et al. 1994; Marshall and McCulloch 2001). Therefore, it is difficult to assess whether the observed spread in the Sr/Ca–SST relationship is due to (1) metabolic effects (e.g., de Villiers et al. 1995; Cohen et al. 2001, 2002; Meibom et al. 2003), (2) local environmental conditions, e.g., site specific differences in temperature variability, or (3) a combination of the two.

Alibert and McCulloch (1997) published in situ calibrations for *Porites* sp. corals from the Great Barrier Reef, and estimated a Sr/Ca–temperature relationship of −0.061 mmol/(mol °C). Later, Marshall and McCulloch (2002) found slightly lower values (−0.58 and −0.59 mmol/(mol °C), respectively), but noted that all calibrations are within the error limits of each other. Felis et al. (2004) performed an in situ calibration for *Porites* sp. corals from the northern Red Sea, and obtained a coral Sr/Ca–temperature relationship of −0.0597 mmol/(mol °C). To further evaluate our Sr/Ca time series, we therefore decided to use a Sr/Ca–temperature dependence of −0.06 mmol/(mol °C), rather than arbitrarily choosing one of our own calibrations. Thus, we practically assume that −0.06 mmol/(mol °C) reflects the "true" Sr/Ca–temperature relationship, while the range of slope values observed in our study (and many others) is either due to inadequate instrumental data or other unknown factors that lead to a bias in coral Sr/Ca. Furthermore, as the absolute values appear uncertain, we will centre the Sr/Ca time series by subtracting the mean value over the 1950–1995 period.

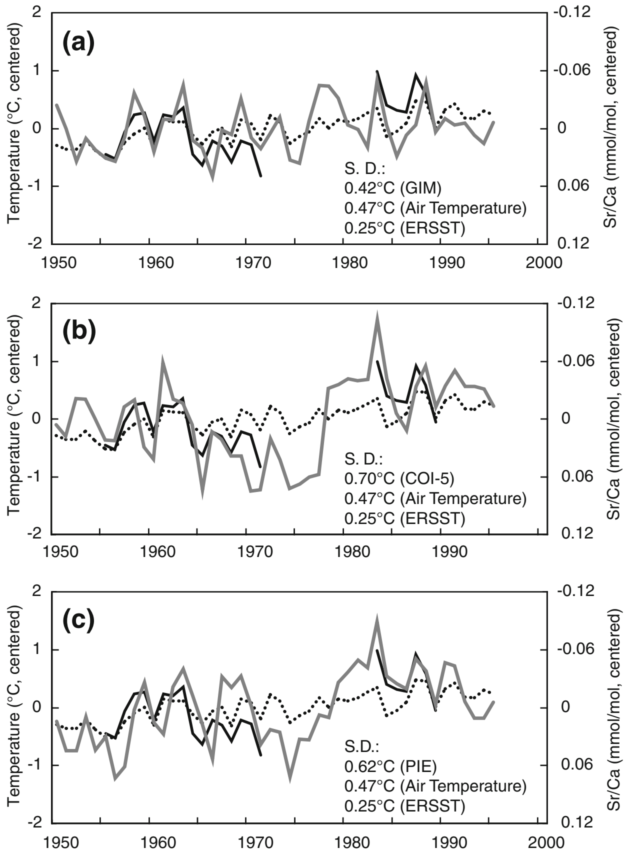

Fig. 3 **a** Annual mean Sr/Ca time series of GIM (*thick grey line*), SST (*stippled line*) and air temperature (*black solid line*). **b** Annual mean Sr/Ca time series of COI-5 (*thick grey line*), SST (*stippled line*) and air temperature (*black solid line*). **c** Annual mean Sr/Ca time series of PIE (*thick grey line*), SST (*stippled line*) and air temperature (*black solid line*). Sr/Ca has been scaled so that −0.06 mmol/mol correspond to 1°C. The standard deviation (1*σ*) of all time series is given in °C

Figure 3 compares the annual mean Sr/Ca time series of GIM, COI-5 and PIE with ERSST and air temperature, scaled so that −0.06 mmol/mol corresponds to a warming of 1°C. Of all three single-core time series, GIM shows the best agreement with instrumental temperature variations (Fig. 3a). The standard deviation of GIM (0.025 mmol/mol, which would translate to 0.42°C) more or less equals the standard deviation of air temperature measured at Diego Garcia (0.47°C), but is larger compared to the ERSST (0.25°C). In contrast, COI-5 and PIE indicate larger temperature variations (0.7 and 0.62°C, respectively) than either of the instrumental temperature series (Fig. 3b, c).

Thus, assuming that a “true” and universally applicable Sr/Ca–temperature relationship exists, differences in the intrinsic variance of the three Sr/Ca time series from Peros Banhos would translate into different estimates of local temperature variability. We do not know whether this reflects actual differences in local temperature variability at the sites where the corals were drilled, or time-varying metabolic influences that bias the Sr/Ca thermometer (e.g., Cohen et al. 2001, 2002; Meibom et al. 2003). However, similar difficulties also occur in other Sr/Ca time series from other regions (e.g., Linsley et al. 2004, 2006), and we therefore believe that the calibration problems we encountered go well beyond this particular site in the Indian Ocean. We conclude that the use of single-core Sr/Ca records for quantitative estimates of past temperature variations is not free of problems.

Composite Sr/Ca

The annual composite Sr/Ca time series correlates much better with instrumental temperature data than each of the single-core records alone (Table 2), suggesting that averaging single-core time series effectively reduces the noisiness of the Sr/Ca data. Taking into account the statistical uncertainties, the relationship between composite Sr/Ca and air temperature measured at Diego Garcia is consistent with the slope estimates of Alibert and McCulloch (1997) and Marshall and McCulloch (2002) (Table 2).

Figure 4 compares the centred composite Sr/Ca record, scaled so that −0.06 mmol/mol corresponds to a warming of 1°C, with instrumental temperature data. We have computed error bars by calculating the standard deviation of the three single-core Sr/Ca series (Fig. 4). We note that within these uncertainty limits, composite Sr/Ca agrees very well with air temperature measured at Diego Garcia, and is fairly consistent with the ERSST data from the grid including Peros Banhos (Fig. 4a). The temperature variations inferred from composite Sr/Ca are remarkably accurate: the standard deviation of the residual calculated by subtracting temperature variations inferred from Sr/Ca and instrumental temperatures is 0.28 (air temperature) and 0.35°C (ERSST) (Fig. 4b). However, assuming a Sr/Ca–temperature relationship of −0.06 mmol/(mol °C), the standard deviation of composite Sr/Ca (0.028 mmol/mol, Fig. 2) is identical with the standard deviation of air temperature (0.47°C), but almost twice as large as expected based on the ERSST.

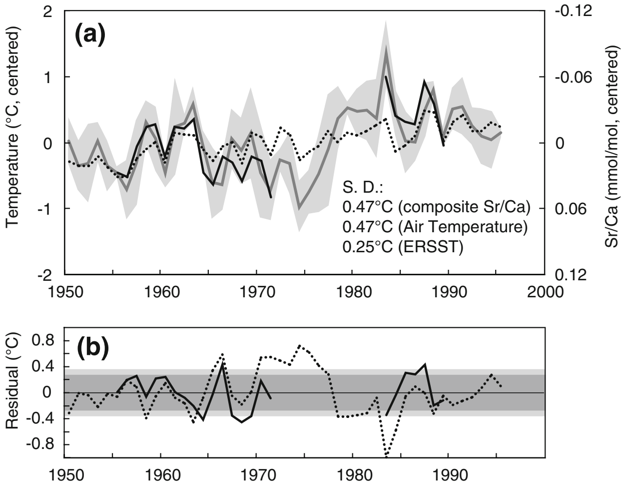

Fig. 4 **a** Annual mean, composite Sr/Ca time series (*thick grey line*), SST (*black stippled line*) and air temperature (*solid black line*). Composite Sr/Ca is the arithmetic mean of GIM, COI-5 and PIE. *Shading* indicates ±1 SD of GIM, COI-5 and PIE. The standard deviation (1σ) of all time series is indicated in the figure (in °C). **b** Temperature residual (*solid line* air temperature; *stippled line* ERSST). *Shading* indicates ±1 SD of the residual (*dark* shading: air temperature; *light* shading: ERSST). Sr/Ca has been scaled so that −0.06 mmol/mol correspond to 1°C

To further explore this problem, we have computed scatter plots of composite Sr/Ca, air temperature and ERSST (Fig. 5). Figure 5 a compares annual mean air temperature from Diego Garcia with annual mean ERSST from the grid including Peros Banhos. Clearly, the intrinsic variance of the air temperature series is larger (Fig. 5a). Figure 5b compares composite Sr/Ca and ERSST. Composite Sr/Ca has been scale so that −0.06 mmol/mol corresponds to a warming of 1°C. Again, the intrinsic temperature variance indicated by Sr/Ca is higher than expected based on the ERSST data (Fig. 5b). However, composite Sr/Ca shows almost exactly the same relationship with ERSST as the air temperature data from Diego Garcia (the two regression lines are within the error limits of each other) (compare Fig. 5a, b). Composite Sr/Ca and annual mean air temperature are highly correlated (r = 0.84), and the estimated Sr/Ca–temperature relationship is not significantly different from the estimates of Alibert and McCulloch (1997) and Marshall and McCulloch (2002) (Table 2; Fig. 5c). This excellent match between temperatures inferred from our composite Sr/Ca record and measured air temperatures from Diego Garcia is remarkable, as Diego Garcia and Peros Banhos are separated by almost 2° of latitude. Thus, we conclude that despite the problems described in our study, coral Sr/Ca is generally under strong thermodynamic control and mainly sensitive to temperature. The uncertainties of single-core Sr/Ca time series can be effectively minimized by averaging a few independent proxy series. We would not expect this if temporal Sr/Ca variations were dominated by metabolic influences. For example, interannual to decadal δ^{13}C variations in hermatypic corals, which are known to be primarily affected by metabolic processes, are neither

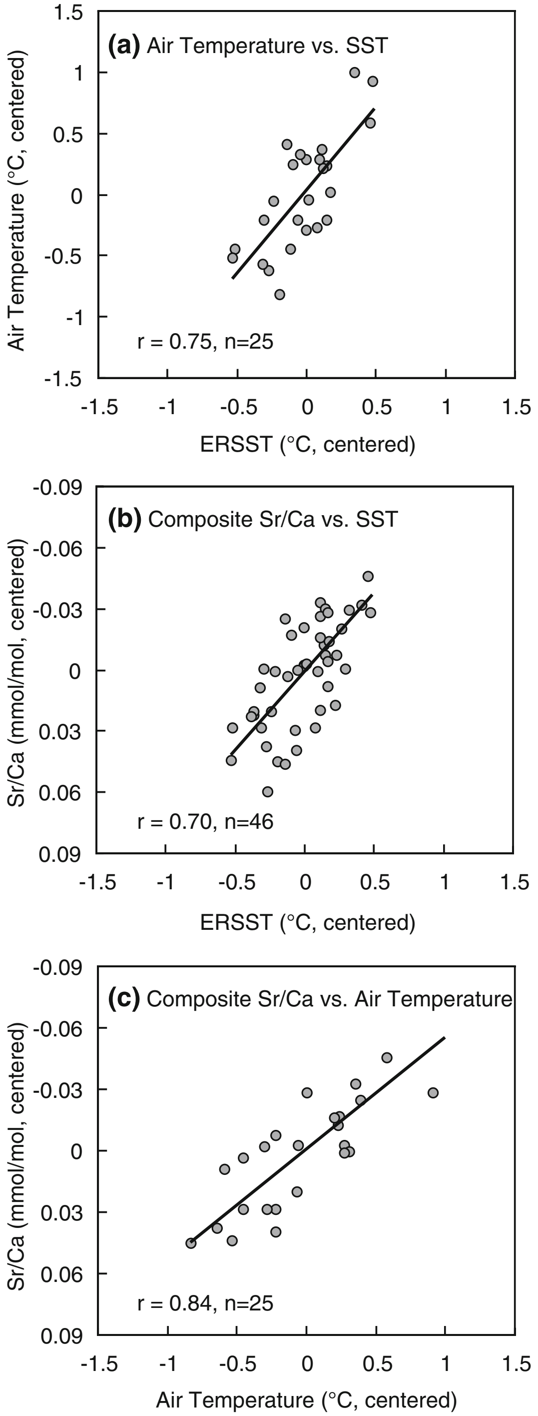

Fig. 5 Scatter plots of annual mean **a** air temperature and SST, **b** composite Sr/Ca and SST, **c** composite Sr/Ca and air temperature. Sr/Ca has been scaled so that −0.06 mmol/mol correspond to 1°C

reproducible, nor can they be unequivocally related to any environmental parameter (e.g., Guilderson and Schrag 1999). At Peros Banhos, we encountered similar problems with Mg/Ca variations, also believed to be under strong metabolic control (e.g., Sinclair et al. 2006): Mg/Ca ratios measured at the same sub-samples as the Sr/Ca data presented here (not shown) are neither reproducible, nor can they be related to temperature or other environmental parameters.

Furthermore, although it is very likely that some uncertainties of the Sr/Ca thermometer result from problems of the coral proxy, our study also shows that gridded SST products are not ideal for proxy calibration (Fig. 5). It appears that grid-SST may not adequately represent the interannual to decadal temperature variability recorded by the coral proxy. While this may be due to the large spatial scales represented by grid-data, we speculate that many shallow-water corals may also experience larger local temperature variations compared to open ocean sea surface temperatures. In this case, grid-SST should not be used as a substitute for coral Sr/Ca measurements. For example, if the actual temperature variability at a coral site is larger than the variability of grid-SST, δ^{18}O seawater reconstructions calculated by subtracting grid-SST from measured coral δ^{18}O (e.g., Asami et al. 2004; Linsley et al. 2006) would systematically overestimate δ^{18}O seawater variability.

The temperature shift in the mid-1970s

In the mid-1970s, a major climatic shift occurred in the northern and tropical Pacific Ocean (e.g., Mantua et al. 1997; Cobb et al. 2001). This so-called Pacific regime shift had important socio-economic impacts, particularly for the fishing industry (Mantua et al. 1997). Previous analysis of the stable oxygen isotope and Sr/Ca time series of core GIM has shown that in the same time interval, tropical Indian Ocean SSTs reached a critical threshold beyond which small SST anomalies may have a significant impact on atmospheric convection and rainfall variability (Timm et al. 2005; Pfeiffer et al. 2006). However, recent studies have indicated significant problems regarding the fidelity of coral Sr/Ca ratios as recorders of decadal to interdecadal temperature changes (e.g., Linsley et al. 2006). Here, we compare the magnitude of the temperature changes inferred from the Sr/Ca time series of the Peros Banhos corals associated with the regime shift in the tropical Indian Ocean during the mid-1970s.

Composite Sr/Ca indicates a pronounced shift towards warmer temperatures in the mid-1970s (Fig. 4), while the ERSST data from the grid including Peros Banhos shows a uniform, linear warming trend since 1950, and a comparably small temperature shift in the mid-1970s. Composite Sr/Ca and ERSST show large deviations in the 1970s and early 1980s, when air temperature data is lacking. In this time period, the temperature residual clearly exceeds the ±1σ level (Fig. 4b). The origin of these differences could be either climatic or poor data. In the 2° × 2° grid including Peros Banhos, the average number of observations in COADS decreases by more than a factor of two prior to 1980, from 7.7 (1980–1992) to 3.6 observations per month (1970–1979). A similar decrease in the number of observations is found in nearby grids.

We have estimated the magnitude of the temperature shift in the mid-1970s by subtracting the mean temperatures of 1950–1975 from the mean temperatures of 1995–1975 (Fig. 6). Again, coral Sr/Ca is converted to temperature by assuming that −0.06 mmol/mol corresponds to a warming of 1°C. However, we have also used slope values of −0.04 and −0.08 mmol/(mol °C) in order to obtain error estimates for the coral Sr/Ca–temperatures. These slope values broadly cover the observed spread of the Sr/Ca–temperature relationship (e.g., Marshall and McCulloch 2002; Swart et al. 2002). We note that due to these uncertainties, the absolute error of changes in mean temperature inferred from coral Sr/Ca increases with increasing changes in mean Sr/Ca (the relative error remains constant: 0.06/0.02 = 33%) (Fig. 6).

Of all Sr/Ca time series, core GIM shows the smallest increase in mean temperatures (0.26°C), and is within error of the ERSST data. PIE, COI-5 and composite Sr/Ca all suggest a larger temperature increase, but the magnitude of the inferred warming is consistent with the increase in mean air temperatures recorded at Diego Garcia. Thus, we are facing a dilemma: we cannot reject either of the two temperature records, or any of the three Sr/Ca series, as erroneous. One out of three coral Sr/Ca series shows better agreement with ERSST, while two show better agreement with measured air temperatures (as a consequence, the composite Sr/Ca record is also expected to agree better with air temperature). Based on coral Sr/Ca, the sea surface temperature shift in the mid-1970s could range anywhere between 0.25 and 0.75 C.

We believe the a likely cause for these discrepancies are differences in the intrinsic variance at the coral sites, as core GIM derives from a channel where currents are strong, while COI-5 and PIE are from shallow water settings within the lagoon of Peros Banhos (Fig. 1b). We would actually expect small-scale, local differences in temperature variability in shallow-water reef environments. Lacking in situ temperature data from the three coral sites, these conclusions remain speculative, and underline the need for long-term monitoring studies spanning several decades rather than years. Nevertheless, the three Sr/Ca records from Peros Banhos provide clear evidence of a major climatic shift in the equatorial Indian Ocean that coincides with the regime shift in the tropical and northern Pacific Ocean (despite large uncertainties regarding the magnitude of the actual temperature change).

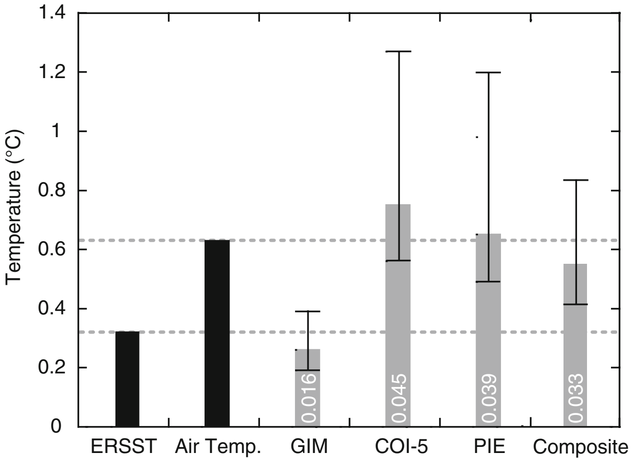

Fig. 6 Mean temperature change in 1975: (1976–1995) − (1950–1975). Coral Sr/Ca was converted to temperature units assuming that −0.06 mmol/mol correspond to a warming of 1°C. *Error bars* on Sr/Ca-temperatures are computed using −0.04 and −0.08 mmol/mol per 1°C, respectively. The decrease in mean Sr/Ca is also indicated (in mmol/mol). See text for discussion

Correlation with large-scale climate indices

The El Niño–southern oscillation

On interannual time scales, ENSO is the most important driver of anomalous SST variations in the Indo-Pacific sector (e.g., Latif et al. 1999; Reason 2000). However, in the Indian Ocean the magnitude of ENSO-induced SST anomalies is small compared to the seasonal cycle of SST. El Niño typically leads to a warming of 0.5–1°C (Reason 2000). Moreover, the impact of ENSO on Indian Ocean SSTs varies seasonally and is strongest in boreal winter (December to February), but weaker during other times of the year (e.g., Webster and Yang 1992). The seasonality of the ENSO teleconnection should further complicate the detection of ENSO in the Sr/Ca time series from Peros Banhos: the seasonal-scale age-model error is 1–2 month in any year, increasing the noisiness of seasonal proxy time series compared to instrumental data. Hence, it is often difficult to get a clear ENSO signature from single-core proxy records from the tropical Indian Ocean (Pfeiffer and Dullo 2006). A composite Sr/Ca record should provide a much better record of past ENSO variability in the Indian Ocean.

Figure 7 displays mean December to February time series calculated from the ERSST data in the grid including Peros Banhos and composite Sr/Ca along with three major indices of ENSO variability: Nino 3.4, the southern oscillation index (SOI) and Palmyra coral δ^{18}O. The Nino 3.4 Index is a SST anomaly index averaged over 5°N–5°S, 120°–170°W (we use the ERSST data set), and provides a measure of ENSO-related SST anomalies in the equatorial Pacific (e.g., Trenberth 1997). The SOI is the standardized atmospheric pressure difference between Darwin and Tahiti and captures the atmospheric component of ENSO (the index is available at the web page of the National Centers for Environmental Prediction, NCEP, using the URL: ftp://ftp.ncep.noaa.gov/pub/cpc/wd52dg/data/indices/soi.his). Palmyra δ^{18}O is a coral proxy reconstruction from the “centre of action” of ENSO-induced SST and rainfall anomalies in the equatorial Pacific (Cobb et al. 2001). A summary of correlation coefficients between all time series is given in Table 3. The composite Sr/Ca record clearly captures ENSO-related SST variations in the tropical Indian Ocean (Fig. 7), although the correlation coefficients are slightly lower when compared to the ERSST data from Peros Banhos (this should be expected due to the greater noisiness of the proxy data). More importantly, the ENSO teleconnection can be traced using coral proxy time series alone: the correlation between composite Sr/Ca from Chagos and Palmyra δ^{18}O is high and statistically significant ($r = 0.52$, $P < 0.001$). Thus, it should be possible to use coral-based SST reconstructions alone to investigate the impact of ENSO in the tropical Indian Ocean during pre-instrumental times. Also, we note that composite Sr/Ca from Peros Banhos shows a large and distinct negative anomaly during the strong El Niño event of 1982/83, while this event is not as clearly recorded in Palmyra δ^{18}O (Fig. 7). This suggests that composite Indian Ocean Sr/Ca records may actually contribute to proxy-based reconstructions of ENSO.

The Pacific Decadal Oscillation (PDO) and mean tropical temperatures

The most important mode of low-frequency, interdecadal climate variability in the Indo-Pacific Ocean is the so-called PDO, a recurring pattern of ocean–atmosphere climate variability centred over the midlatitude North Pacific basin (Mantua et al. 1997). In a later study, Deser et al. (2004) found clear linkages between tropical climate and interdecadal fluctuations over the North Pacific, supporting the notion that the tropics play a key role in North Pacific interdecadal variability. In particular, SST anomalies in the tropical Indian Ocean were found to exhibit prominent interdecadal fluctuations coherent with those over the North Pacific (Deser et al. 2004).

Evans et al. (2001) found evidence for Pacific decadal variability in a coral Sr/Ca record from the South Pacific (Rarotonga). However, subsequent replication studies revealed large uncertainties regarding decadal and interdecadal temperature variations inferred from Sr/Ca ratios measured in corals from Rarotonga (Linsley et al. 2006). Here, we evaluate the fidelity of the composite Sr/Ca record from Peros Banhos Atoll as a recorder of Pacific decadal variability in the tropical Indian Ocean.

Figure 8 compares annual mean time series of the ERSST data from the grid including Peros Banhos, composite Sr/Ca, the PDO index (Mantua et al. 1997), and a growth index derived from long-lived geoduck clams from the eastern North Pacific (122°W, 48°N), which provides an annually resolved proxy of SST in one of the “centres of action” of the PDO (Strom et al. 2004). Mean tropical surface temperatures averaged over 30°N–30°S, 0°–360°E are also shown for comparison (data from HadCRUT3; Brohan et al. 2006). A summary of correlation coefficients between all time series is given in Table 3. As expected based on the analysis of historical data (e.g., Deser et al. 2004), our composite Sr/Ca record clearly captures the most recent regime shift of the PDO that occurred in the mid-1970s (Fig. 8). The correlation between composite Sr/Ca and the PDO further confirms that Sr/Ca is an accurate recorder of climate variability on decadal to interdecadal timescales. Moreover, we find that the linkage between interdecadal SST variations in the tropical Indian Ocean and the North Pacific can be captured using proxy records from biogenic archives alone: the correlation between composite Sr/Ca from Chagos and the geoduck clam growth index is high and statistically significant ($r = 0.50$, $P < 0.001$) (Table 4). This finding demonstrates that different climatic archives and proxies can be used to investigate large-scale climatic teleconnections, provided that they have comparable temporal resolution and accurate chronological control.

The spatial correlation patterns of the PDO index and annual mean composite Sr/Ca from Chagos are compared

Table 3 Summary of correlations between mean December–February ERSST from the grid including Peros Banhos, composite Sr/Ca and various ENSO indices

	ERSST (70°E/6°S)	Composite Sr/Ca	Nino 3.4	SOI	Palmyra δ^{18}O
ERSST (70°E/6°S)	×				
Composite Sr/Ca	−0.63	×			
Nino 3.4	0.64	−0.54	×		
SOI	−0.64	0.56	0.88	×	
Palmyra δ^{18}O	−0.67	0.52	−0.66	0.59	×

Nino 3.4 is taken from ERSST, version 2. The SOI index is provided by NCEP. The Palmyra δ^{18}O data is from Cobb et al. (2001). For all correlations $P < 0.001$

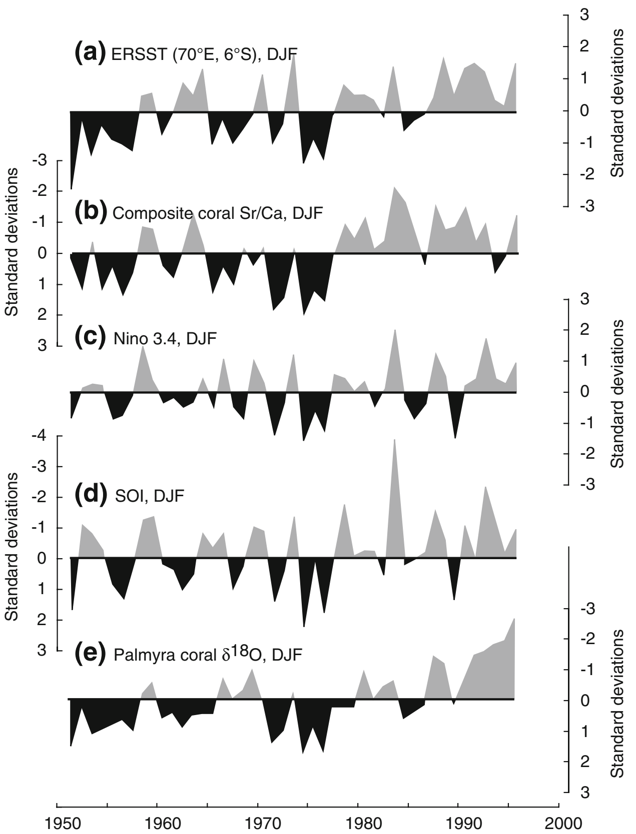

Fig. 7 Mean December–February time series of **a** ERSST (70°E, 6°S), **b** composite Sr/Ca, **c** Nino 3.4 SST anomalies, **d** the southern oscillation index (*SOI*), **e** Palmyra coral δ^{18}O (from Cobb et al. 2001). All time series are normalized by subtracting the mean and dividing by their standard deviation. The *y*-axis of the SOI, composite Sr/Ca and Palmyra δ^{18}O are reversed to facilitate comparison

in Fig. 9 (note that the correlations of composite Sr/Ca are opposite in sign due to the inverse Sr/Ca–temperature relationship). The correlation patterns are broadly similar, with high correlations throughout much of the Indian and equatorial Pacific Oceans, and a dipole pattern in the North Pacific with opposite values in the east and the centre. However, some differences in spatial emphasis exist. In particular, a stronger weighting of the tropical Indian Ocean relative to the equatorial and northern Pacific Ocean is apparent. Figure 9 c shows the spatial correlation patterns of annual mean tropical surface temperatures (Fig. 8d) for comparison. The correlation patterns are remarkably similar to the patterns obtained with our composite Sr/Ca record from Peros Banhos (compare Fig. 9b, c), with a coherent positive correlation in the entire tropical Indian Ocean. Hence, the strong correlation between composite Sr/Ca from Peros Banhos and tropical mean temperatures is not surprising (Table 4). We conclude that century-long coral Sr/Ca records from the tropical Indian Ocean will not only help to investigate large-scale climatic teleconnections in the Indo-Pacific Ocean, but also provide invaluable data for reconstructions of tropical mean temperatures from corals (e.g., Wilson et al. 2006).

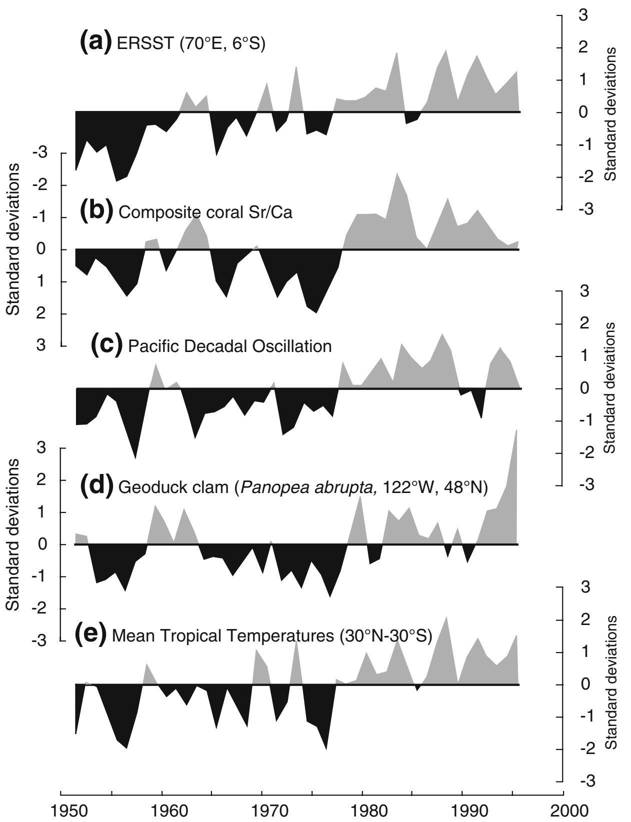

Fig. 8 Mean annual time series of **a** ERSST (70°E, 6°S), **b** composite Sr/Ca, **c** the Pacific Decadal Oscillation (PDO, Mantua et al. 1997), **d** a geoduck clam (*Panopea abrupta*) growth index from the north-eastern Pacific (Strom et al. 2004), **e** mean tropical temperatures averaged over 30°N–30°S (data from HadCRUT3, Brohan et al. 2006). All time series are normalized by subtracting the mean and dividing by their standard deviation. The *y*-axis of the composite Sr/Ca series is reversed to facilitate comparison

Summary and conclusions

We have generated three monthly resolved Sr/Ca records, each covering the time period of 1950–1995, from Peros Banhos (Chagos Archipelago), an atoll situated in the geographical centre of the Indian Ocean. Analysis of these proxy time series led us to the following conclusions:

(1) The intrinsic variability of single-core Sr/Ca time series differs from core to core. While it is not clear whether this is due to biological effects or local climatic factors, this limits the use of single-core reconstructions for quantitative estimates of sea surface temperature variations.

(2) Despite their uncertainties, all single-core Sr/Ca time series are significantly correlated with each other and

Table 4 Summary of correlations between annual mean ERSST from the grid including Peros Banhos, composite Sr/Ca, and various climate indices

	ERSST (70°E/6°S)	Composite Sr/Ca	PDO	Geoduck clam	Mean tropical T
ERSST (70°E/6°S)	×				
Composite Sr/Ca	−0.70	×			
PDO	0.56	−0.56	×		
Geoduck clam	0.39*	−0.50	0.45*	×	
Mean tropical T	0.85	−0.70	0.68	0.44*	×

The PDO index is provided by Mantua et al. (1997). The Geoduck Clam data are from Strom et al. (2004). Mean tropical temperatures are taken from HadCRUT3 (Brohan et al. 2006), averaged over 30°S–30°N. For all correlations $P < 0.001$ (*$P < 0.01$). See text for discussion

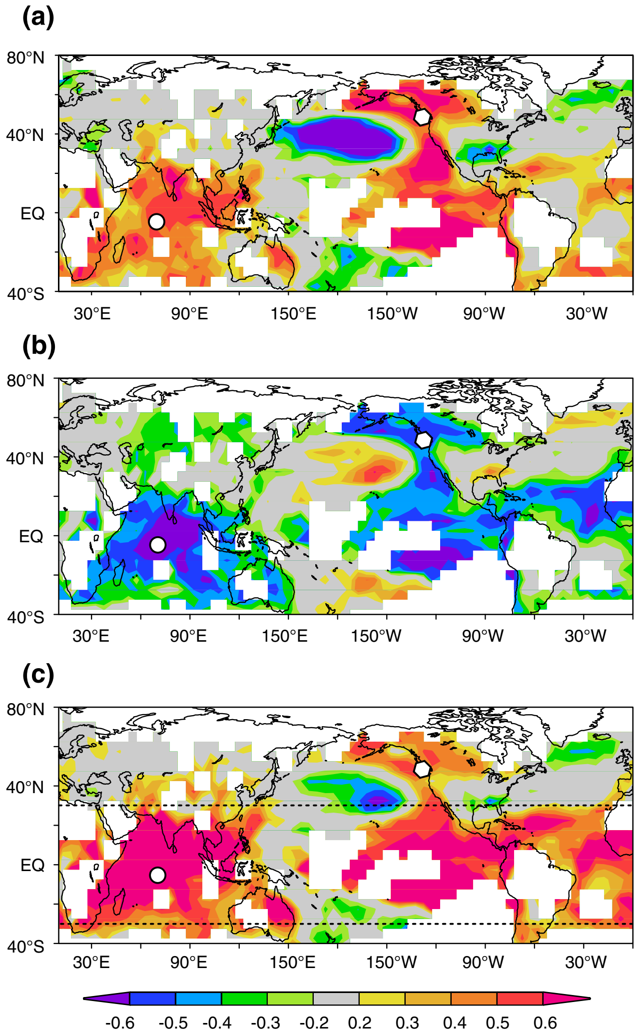

Fig. 9 **a** Spatial correlations of the PDO index (Mantua et al. 1997) with global surface temperatures (HadCRUT3, Brohan et al. 2006). **b** Same as Fig. 9**a** but for mean annual composite Sr/Ca from Chagos (*open circle*) with global surface temperatures (**b**). Same as Fig. 9**a** but for mean tropical temperatures averaged over 30°N–30°S (HadCRUT3, Brohan et al. 2006). The location of the Geoduck clam growth index is also indicated (*rectangle*). *White squares* indicate missing data.

with instrumental temperature data. Coral Sr/Ca generally correlates better with air temperature measured at Diego Garcia, situated almost 2° south of Peros Banhos, than with grid-SST reconstructed from sparse historical data. The observed spread of estimated Sr/Ca–temperature relationships reflects the differences in the intrinsic variance of the single-core Sr/Ca time series, as well as the instrumental temperature data. We speculate that this may also partly explain the large spread of Sr/Ca–temperature relationships estimated from corals, as most Sr/Ca time series are not calibrated with in situ temperature data.

(3) Averaging the single-core data to a composite Sr/Ca record improves the correlation with instrumental temperature and allows the reconstruction of relative temperature variations with considerable accuracy. This shows that despite possible biological influences, thermodynamics exert a strong control on skeletal Sr/Ca ratios in corals.

(4) All three single-core Sr/Ca time series indicate a shift towards warmer temperatures in the mid-1970s. COI-5 and PIE suggest a warming of 0.65 and 0.75°C, respectively. This is within error of the warming indicated by the air temperature data from Diego Garcia. GIM shows a warming of only ~0.26°C, and is consistent with grid-SST. Our results indicate that the magnitude of interdecadal temperature changes inferred from single-core Sr/Ca time series may differ by a factor >2.5.

(5) Coral Sr/Ca measured in the Chagos corals is a robust recorder of large-scale climatic signals in the Indo-Pacific. Interannual SST variations are clearly related to ENSO, while the shift towards warmer temperatures in the mid-1970s coincides with the most recent shift of the PDO. These large-scale climatic teleconnections can also be captured using suitable proxy records from the Pacific Ocean.

(6) Century-long coral Sr/Ca time series from the Indian Ocean should contribute significantly to proxy reconstructions of tropical mean temperatures.

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