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Improving SST reconstructions from coral Sr/Ca records: multiple corals from Tahiti (French Polynesia)

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Abstract We reconstruct SST from coral Sr/Ca ratios measured at three coral cores taken from the lagoon of Tahiti (French Polynesia). Two coral cores were drilled from the same coral colony (one horizontally and one vertically), and a third core was drilled vertically from another coral growing at a different site. We evaluate several Sr/Ca records as proxies for regional SST variations: (1) the three single-core records from Tahiti, (2) an average Sr/Ca record computed from the two cores drilled from the same coral colony, (3) an average Sr/Ca record computed from all three Tahiti cores, and (4) an average Sr/Ca record computed from the three Tahiti cores and a fourth core taken from a different island (Rarotonga). On a monthly scale, the average Sr/Ca record including the four coral cores from Tahiti and Rarotonga shows the best correlation with regional SST. The variance of the SST reconstruction is very realistic and the residual SST is low. This suggests that reconstructing SST from average proxy records gives a better representation of regional SST variations. Of the three Tahiti cores, the one that was drilled horizontally shows the best correlation with grid-SST on an annual mean scale. All three Tahiti corals show much larger interannual SST variations than that indicated by grid-SST.

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Introduction

Sea surface temperatures (SSTs) are the most important among climatic parameters. The strength of the relationship between coral Sr/Ca ratios with temperature is used as a basis for reconstructing past SST variations. In order to reconstruct past SSTs, the coral proxies must be calibrated with an instrumental SST dataset. The coral Sr/Ca–SST relationship is commonly estimated by linear regression of Sr/Ca against SST (e.g., Juillet-Leclerc and Schmidt 2001; Gagan et al. 2000; Linsley et al. 2000, 2004; Zinke et al. 2004; Pfeiffer et al. 2006). Past SST reconstructions are then based on this calibration (e.g., Corrège et al. 2004; Felis et al. 2004). Ideally, one should use a continuous time series of SST directly from the site where the coral grew. However, the available limited local SST measurements have forced most studies to use SST data from a distance in situ sampling site or grid-SST data from various sources. There is no general agreement on which SST dataset should be used (de Villiers et al. 1994; Schrag 1999; Linsley et al. 2000, 2004). Usually, however, a single Sr/Ca record is calibrated with grid-SST, chosen from the many different available SST products. A large number of SST datasets are available, each covering a different time period, having a different temporal/sampling resolution, and having a different spatial resolution as well as different amounts of interpolation. The data representing SST from the proxy is local and represents a point measurement.

Therefore using grid-SST (1° to 5° grids are used) may lead to a bias in reconstructed Sr/Ca-SST (Solow and Huppert 2004). However, SST series from global datasets also have uncertainties (Hurrell and Trenberth 1999). These are larger in regions with few in situ measurements. Nevertheless, a comparison with grid-SST is important to evaluate the quality of the proxy as a monitor of regional scale SST variations.

In this study, we present three new, monthly resolved coral Sr/Ca records from Tahiti, French Polynesia. We also use a published Sr/Ca record from Rarotonga (Linsley et al. 2000). The main objectives of our study are (1) to compare and evaluate different methods of age model development of the coral records, which are potential sources of error, (2) to compare single-core coral Sr/Ca-SST calibrations estimated with different SST datasets (in this context, we will also compare two cores drilled vertically and horizontally from the same coral colony, with another core drilled from a different coral colony growing at a different site), and (3) to evaluate multi-core, average Sr/Ca records and to discuss their quality as monitors of regional, grid-scale temperature variability on monthly and on annual mean time scales.

Climatic and oceanographic setting of the study area

Tahiti is located in the central Pacific (149°20′W 17°4′S) (Fig. 1), and is part of the Society Archipelago (French Polynesia). Tahiti Island measures around 1,042 sq km with a high mountain top (2,241 and 1,323 m). The trade winds flow around this mountain obstacle and largest rainfall is found on the windward side. Daytime convection on the leeward side leads to the development of clouds at the edges between the sea breeze and trade wind systems. In the central Pacific, in situ SST measurements are poor. Available grid-SST datasets in the region of Tahiti are averaged over large areas. This makes the calibration of coral Sr/Ca versus SST difficult, and may lead to inaccurate SST reconstructions (Solow and Huppert 2004).

Based on mean seasonal SST, the maximum (minimum) SST at Tahiti occurs in March (August) (Smith and Reynolds 2004). During the rainy season (November–April), climatological SSTs vary from 27° to 28°C and during the dry season (May–October) from 26 to 28°C. In the tropical Pacific, interannual SST anomalies are associated with the El Niño-Southern Oscillation (ENSO). However, at Tahiti, these anomalies are an order of magnitude smaller than the seasonal cycle (Delcroix et al. 2002). During an El Niño event, SST anomalies at Tahiti are close to zero. However, the SSTs stay warm during the austral winter of the following year and start cooling during the next austral summer. During ENSO events, air temperatures recorded at
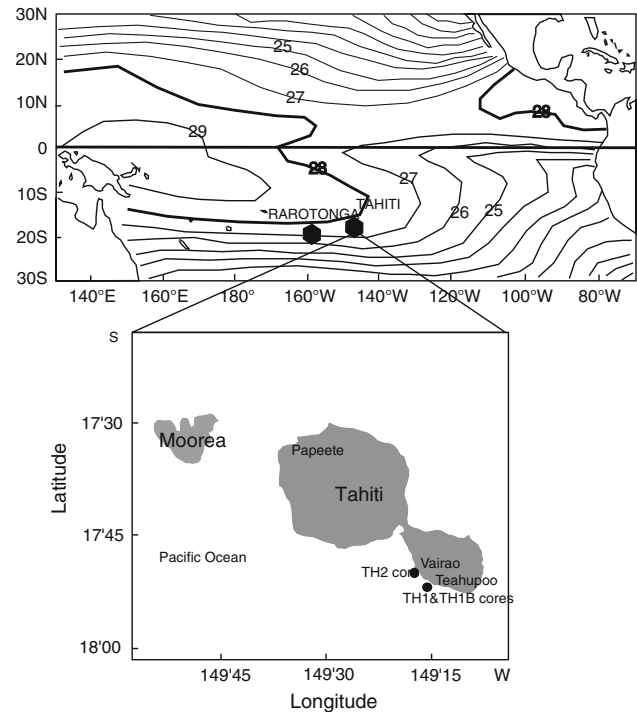

Fig. 1 *Top* Map of mean annual SSTs in the tropical Pacific and location of Tahiti and Rarotonga. *Bottom* Map of Tahiti with sampling locations of the coral cores

Faaa weather station increase from February to April in the following year (Boiseau et al. 1998).

Historical sea surface temperature datasets

In this study, we compare and use several SST datasets: grid-SST from the extended reconstructed global sea surface temperature (hereafter referred to as ERSST) of Smith and Reynolds (2004), grid-SST from the optimal interpolation SST from the National Centres for Environmental Prediction (hereafter referred to as NCEP SST) (Reynolds and Smith 1994), local SST from Tahiti obtained from *L'lnstitut français de Recherche scientifique pour le Développement en coopération* (hereafter referred to as IRD SST) (Boiseau et al. 1998), and a regional SST dataset based on ship measurements in the south western tropical Pacific published by Delcroix et al. (1996), Delcroix and McPhaden (2002), and Gouriou and Delcroix (2002) (hereafter referred to as Delcroix SST).

The ERSST is based on the SST data from the comprehensive ocean atmosphere data set (COADS) and uses improved statistical methods that allow a stable reconstruction using sparse data. This dataset covers the time period from January 1854 until present. Because of sparse data, the analyzed signal is heavily damped before 1880. Afterwards the strength of the signal is more consistent

over time. The standard deviation of monthly SST (ERS-ST) in the grid including Tahiti is large (more than 0.1°C) and increases from 1950 to the present (Smith and Reynolds 2004). Over the period of 1982–1997, the standard deviation of monthly SST ranges from 0.2 to 0.6°C (for a detailed discussion see Smith and Reynolds 2004).

The NCEP SST uses optimal interpolation to combine in situ and satellite-derived SST data. This method was described by Reynolds and Smith (1994). The dataset extends from November 1981 until present. The standard deviation of monthly SST anomalies from NCEP is larger in the equatorial Pacific, where large interannual variations that are associated with ENSO occur (Hurrell 1999). These anomalies are well captured in the NCEP analysis. In contrast, for the remaining tropical oceans, the SST variations are much smaller and the noise level is larger (Hurrell and Trenberth 1999).

The IRD SST is measured at Papeete, Tahiti (Boiseau et al. 1998). The SST measurements extend from 1979 until 1990. The mean SST, averaged from 1979 to 1990, is 27.1°C. The Delcroix SST (Delcroix et al. 1996; Delcroix and McPhaden 2002; Gouriou and Delcroix 2002) is obtained from bucket measurements along regular shipping routes in the south western tropical Pacific. The dataset extends from 1976 until 2000. For Tahiti, the SST record is available in the grid box 150°W–140°W 16°S–18°S.

The mean seasonal cycles of the SST datasets used in this study are compared in Fig. 2 for the time period 1981–1990. Delcroix SST and ERSST are more or less consistent, while the IRD SST has a lower seasonal amplitude of only 2°C. Figure 2b compares the interannual variations of the SST datasets. The records have been smoothed with a 12 point running average. The IRD SST that is measured close to our study area shows somewhat different trends compared to the other SSTs datasets.

Ideally the IRD SST, which is measured close to the coral site, should be used for calibration. However, the IRD SST (11 years) is too short for calibration on an annual mean scale. The ERSST provides a much longer time series (1854–present), which is long enough for an annual mean calibration. However, the ERSST is a reanalysis data, interpolated from sparse data. To check whether the ERSST is reliable enough for proxy calibration, we correlate the ERSST with the IRD SST and the Delcroix SST. We find that the correlation of the ERSST with IRD SST and Delcroix SST is high ($R = 0.87$ and $R = 0.89$, respectively). The NCEP SST has the highest correlation with the IRD SST ($R = 0.89$), however, the NCEP SST (13 years) is also too short for a Sr/Ca calibration on an annual mean scale. We therefore conclude that it is appropriate to use the ERSST for a calibration of our coral Sr/Ca time series. We will perform monthly calibrations of coral Sr/Ca and SST, and then compare the annual mean temperatures inferred
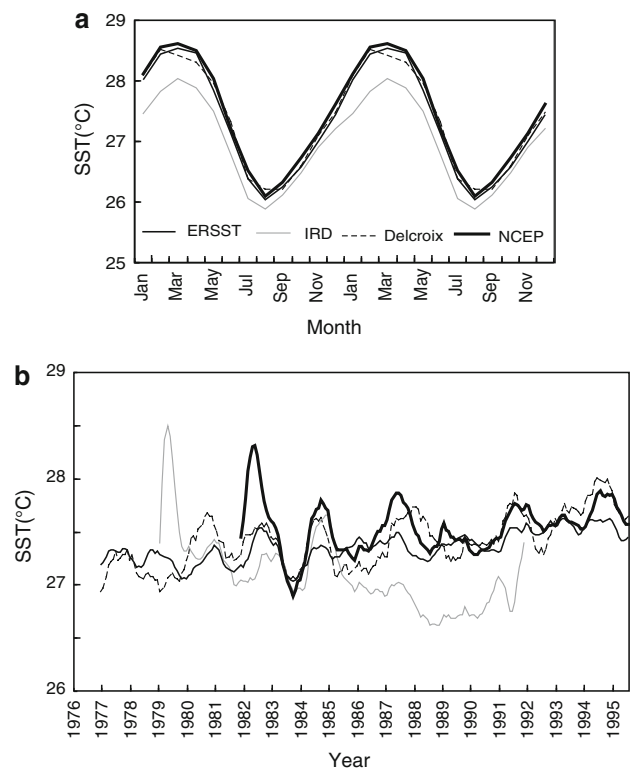

Fig. 2 a Climatological SST at Tahiti. b Annual mean SST variability (highlighted by 12 point running averages) from various instrumental datasets. *Thin black line* ERSST, *thick black line* NCEP SST, *gray line* IRD SST, *dashed line* Delcroix SST

from Sr/Ca with instrumental temperature. However, please note that the calibrations of monthly SST and coral Sr/Ca series will have inflated R-values due to the matching of two annual cycles. Table 1 compares basic statistics of the SST datasets used in this study.

Material and methods

On July 1995, three cores from massive colonies of the genus *Porites* were collected at Teahupoo and Vairao, in the south-eastern part of Tahiti (French Polynesia) (Fig. 1). Core TH1 and TH1B were drilled from a single colony growing in the lagoon of Teahupoo. The living surface of the coral almost reached the sea surface. The base is at 2.40-m water depth. Core TH1 was drilled vertically and core TH1B was drilled horizontally. The vertical core is 180 cm long and the horizontal core is 26 cm long. Core TH2 was drilled vertically in a colony within the lagoon of Vairao and the base of the coral is at 3.80-m water depth. Core TH2 is 342 cm long and the uppermost 110 cm of this core is analyzed for Sr/Ca.

The three cores were cut into 4 mm thick slabs. The slabs were cleaned in an Ultrasonic bath, rinsed with

Table 1 Basic statistics of the SST datasets used in this study

	Variance 1981–1990	Average 1981–1990	Maximum (minimum)	Range datasets available
ERSST	0.81	27.3	28.88 (25.69)	1854–present
NCEP	0.93	27.0	29.41 (25.65)	1981–present
IRD	0.71	27.5	29.4 (25.65)	1979–1990
Delcroix	0.95	27.4	29.4 (25.4)	1976–2000

See text for discussion

distilled water, and dried at 50°C for 24 h. Then they were X-rayed using 35 kvp and an exposure time of 12 min to reveal the annual density bands. All cores show clear annual density bands. The mean growth rate of the three cores is 2 ± 0.5 cm/year. We note that the core top of TH1 has slightly higher extension rates (1.34 cm/year) than the corresponding section of core TH1B (0.97 cm/year), which was drilled horizontally from the same coral colony.

Powdered samples for Sr/Ca analysis were taken every 1 mm following the main growth axis, using a drilling bit of 1 mm in order to get monthly resolution. The Sr/Ca ratios were measured in an inductively coupled plasma atomic emission sprectro-photometer (ICP-OES) at the Geological Institute of the University of Kiel following a combination of the techniques described in detail by Schrag (1999) and de Villiers (2002). Sr and Ca lines, which were used for this measurement, are 407 and 317 nm, respectively. The sample solution was prepared by dissolving ± 0.5 mg of coral powder in 1.00 ml HNO_3 2%. The working solution is prepared by a serial dilution of the sample solution with HNO_3 2% to get a concentration of about 5 ppm Ca. The standard solution was prepared by dilution of 1.00 ml of the stock solution (0.52 g coral powder from Mayotte sample in 250 ml HNO_3 2–3% with 2 ml HNO_3 2%). The relative standard deviation (RSD) of multiple measurements on the same day and on different days is about 0.15%.

Age model development

Monthly coral Sr/Ca time series

The chronology of our coral proxy data is developed using anchor points (e.g., Charles et al. 1997), which are fixed at the climatological SST maximum and minimum. It is assumed that the measured Sr/Ca minimum (maximum) corresponds to the seasonal SST maximum (minimum). Based on the SST climatologies for Tahiti (149.2°W 17.4°S) (Fig. 2a), the warmest temperatures (SST maximum) occur in March and the coolest temperatures (SST minimum) occur in August. To obtain age assignments for all Sr/Ca values, we linearly interpolated between the

anchor points. A second interpolation was performed to obtain an equidistant time series, with 12 monthly values per year. Based on this chronology, core TH1 extends from February 1923 to July 1995, core TH1B from January 1974 to July 1995 and core TH2 from July 1903 to July 1995 (Fig. 3).

We also use a monthly coral Sr/Ca record from Rarotonga (for detailed descriptions of the analytical procedures and data treatment see Linsley et al. 2000). In this paper, we only consider the time period from July 1903 to July 1995, which is also covered by the longest coral Sr/Ca record from Tahiti (Fig. 3). Average Sr/Ca records are
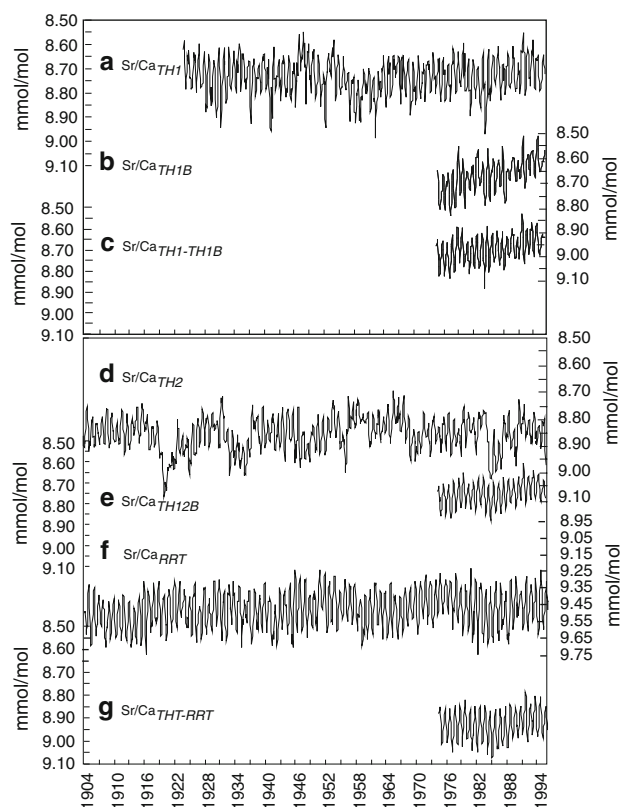

Fig. 3 Monthly coral Sr/Ca records from Tahiti and Rarotonga: **a** Sr/Ca_{TH1}, **b** Sr/Ca_{TH1B}, **c** average Sr/Ca record of TH1 and TH1B ($Sr/Ca_{TH1 - TH1B}$), **d** Sr/Ca_{TH2}, **e** average Sr/Ca record of TH1, TH2, TH1B (Sr/Ca_{TH12B}), **f** Rarotonga (Sr/Ca_{RRT}) and **g** average Sr/Ca record of all three Tahiti cores and the Rarotonga core ($Sr/Ca_{THT - RRT}$). See text for discussion

computed by calculating the arithmetic means between (1) TH1 and TH1B, (2) TH1, TH1B and TH2, and (3) TH1, TH1B, TH2 and Rarotonga. The proxy records are averaged after conversion into time. Hereafter, the coral Sr/Ca time series will be referred to as Sr/Ca$_{TH1}$ (TH1), Sr/Ca$_{TH1B}$ (TH1B), Sr/Ca$_{TH2}$ (TH2), Sr/Ca$_{RRT}$ (Rarotonga), Sr/Ca$_{TH1-TH1B}$ (average of TH1 and TH1B), Sr/Ca$_{TH12B}$ (average of TH1, TH1B and TH2), and Sr/Ca$_{THT-RRT}$ (average of TH1, TH1B, TH2 and Rarotonga).

Chronology development and age model uncertainties

To evaluate potential errors resulting from the age model development of the Sr/Ca chronologies, we also applied the peak matching method (Quinn et al. 1996; Felis et al. 2004) between monthly Sr/Ca and SST, that is, peak matching Sr/Ca with ERSST (used data period: 1923–1995) and peak matching Sr/Ca with NCEP SST (used data period 1981–1995). By matching measured Sr/Ca maxima (minima) directly with SST minima (maxima), the resulting age model uncertainty should be lower than that of the anchor point method, as the timing of maximum/minimum SST varies from year to year, and the correlation between the proxy and SST should improve. For this comparison we used the time period from November 1981 until July 1995.

To check whether the peak matching method yields a better correlation between the coral proxy and SST than the anchor point method, we compared the correlation coefficients obtained by linear regression of monthly SST versus the proxy data. The chronology of the proxy data was developed by: (1) peak matching of the proxy with the ERSST (PM ERSST), (2) peak matching of the proxy with the NCEP SST (PM NCEP) and (3) fixing anchor points at maximum and minimum Sr/Ca values (AP MinMax). Methods (1) and (3) were used to construct an age model

from 1923 to 1995 and method (2) was used to construct an age model from 1981 to 1995. We use the coral Sr/Ca ratios from TH1 to evaluate the two methods of age model development. The results are shown in Table 2.

By comparing the R values of those three approaches for the period 1981–90 (see Table 2 values in italics), we observe that matching coral Sr/Ca with the ERSST results in a lower correlation coefficient (R) than that of the anchor point method. In contrast, matching coral Sr/Ca with the NCEP SST resulted in a higher R value than that with the anchor point method. We conclude that coral Sr/Ca chronologies based on peak matching do not always have a higher correlation with SST. The generally lower correlation coefficient between the proxy and the ERSST may reflect the larger uncertainty of the SST data on longer time scales, particularly prior to the 1950, where in situ measurements are few. The NCEP record only ranges from 1981 until present, when data coverage is good. Therefore, the PM-NCEP method may result in slightly better correlations between the proxy and SST. For longer time scales, the anchor point method (AP MinMax) seems to be the most appropriate.

Monthly coral Sr/Ca versus sea surface temperature

Single-core records of coral Sr/Ca ratios versus SST

Sr/Ca ratios in corals are believed to be a function of temperature only (Beck et al. 1992; McCulloch et al. 1994; Marshall and McCulloch 2002; Alibert et al. 2003) and the regression equation of Sr/Ca versus SST is used to reconstruct past SSTs. However, there are still differences in the Sr/Ca-temperature equations published in different studies. Many studies use different SST datasets. Beck et al. (1992)

Table 2 The correlation coefficients (R) and slopes of the regressions of monthly coral Sr/Ca ratios from TH1 versus SST (ERSST, NCEP SST, IRD SST and Delcroix SST) for different methods of chronology development

	ERSST		IRD		NCEP		Delcroix	
Chronology (method)	1923–1995	*1981–1990*	1979–1990	*1981–1990*	1981–1995	*1981–1990*	1976–1995	*1981–1990*
1-PM ERSST	$S = -0.051$	*$S = -0.051$*	$S = -0.046$	*$S = -0.041$*	$S = -0.045$	*$S = -0.044$*	$S = -0.045$	*$S = -0.041$*
	$R = 0.624$	*$R = 0.638$*	$R = 0.550$	*$R = 0.482$*	$R = 0.636$	*$R = 0.592$*	$R = 0.605$	*$R = 0.552$*
	$\sigma = 0.059$	*$\sigma = 0.056$*	$\sigma = 0.061$	*$\sigma = 0.064$*	$\sigma = 0.056$	*$\sigma = 0.059$*	$\sigma = 0.058$	*$\sigma = 0.061$*
2-PM NCEP	–	*$S = -0.065$*	–	*$S = -0.054$*	$S = 0.058$	*$S = -0.060$*	–	*$S = -0.055$*
		$R = 0.789$		**$R = 0.619$**	**$R = 0.779$**	**$R = 0.782$**		**$R = 0.717$**
		$\sigma = 0.046$		*$\sigma = 0.058$*	$\sigma = 0.046$	*$\sigma = 0.046$*		*$\sigma = 0.051$*
3-AP MinMax	$S = -0.054$	*$S = -0.056$*	$S = -0.050$	*$S = -0.049$*	$S = -0.049$	*$S = -0.046$*	$S = -0.046$	*$S = -0.042$*
	$R = 0.687$	*$R = 0.732$*	$R = 0.617$	*$R = 0.600$*	$R = 0.686$	*$R = 0.650$*	$R = 0.656$	*$R = 0.605$*
	$\sigma = 0.053$	*$\sigma = 0.047$*	$\sigma = 0.055$	*$\sigma = 0.055$*	$\sigma = 0.051$	*$\sigma = 0.051$*	$\sigma = 0.052$	*$\sigma = 0.051$*

PM peak matching method, *AP* anchor point method. $S =$ slope of the regression equation of Sr/Ca versus SST, $\sigma =$ error of the regression equation

$P < 0.001$ for all analysis (see text for discussion)

calibrated Sr/Ca not against the in situ instrumental SST record but used $\delta^{18}O$-derived SST from the same sample. Other studies calibrated coral Sr/Ca with local SST records that were up to 100 km away from the actual site where the coral grew (de Villiers et al. 1994).

In this study, we decided to use the ERSST to calibrate the monthly Sr/Ca records. Table 3 compares the Sr/Ca-SST regression equations of the three single-core records (Sr/Ca$_{TH1}$, Sr/Ca$_{TH2}$ and Sr/Ca$_{TH1B}$). The slopes of the calibrations range from -0.04 to -0.05 mmol/mol per °C (Table 3), which is in a good agreement with published slopes of the Sr/Ca-SST relationship, which range from -0.04 to -0.08 mmol/mol per °C (e.g., Beck et al. 1992; de Villiers et al. 1994, 2002; Shen et al. 1996; Alibert et al. 2003; Marshall and McCulloch 2002; Mitsuguchi et al. 2003). The differences in the published Sr/Ca-SST calibrations can be dismissed as not being precise enough either with relation to Sr/Ca measurements or with relation to the instrumental SST data (Marshall and McCulloch 2002). The linear regressions of Sr/Ca versus SST obtained in this study are shown in Fig. 4. The differences between the calibrations may be attributed either to the quality of the coral records, or to local site-specific problems.

As corals grow upward, they extend into shallow water. This could bias the Sr/Ca-derived SST record (Heiss and Dullo 1997). Therefore, core TH1B was drilled horizontally from the same colony as core TH1. Based on the age model that was developed using anchor points, core TH1B extends from January 1974 to July 1995 (Fig. 3e). The difference in the intercept values between the coral Sr/Ca records from relevant time interval of TH1 (vertical core) and TH1B (horizontal core) is ±0.05 mmol/mol. Core TH1B has lower Sr/Ca ratios (8.51–8.84 mmol/mol) than core TH1 (8.85–8.97 mmol/mol). In the past, such discrepancies have frequently been attributed to vital effects, with higher mean Sr/Ca ratios being associated with lower extension/calcification rates (e.g., de Villiers et al. 1994). However, we note that core TH1B has lower skeletal extension rates and lower Sr/Ca ratios. We therefore believe that this problem still requires further investigation, using a larger set of coral cores and including the analysis of calcification rates (=linear extension × skeletal density).
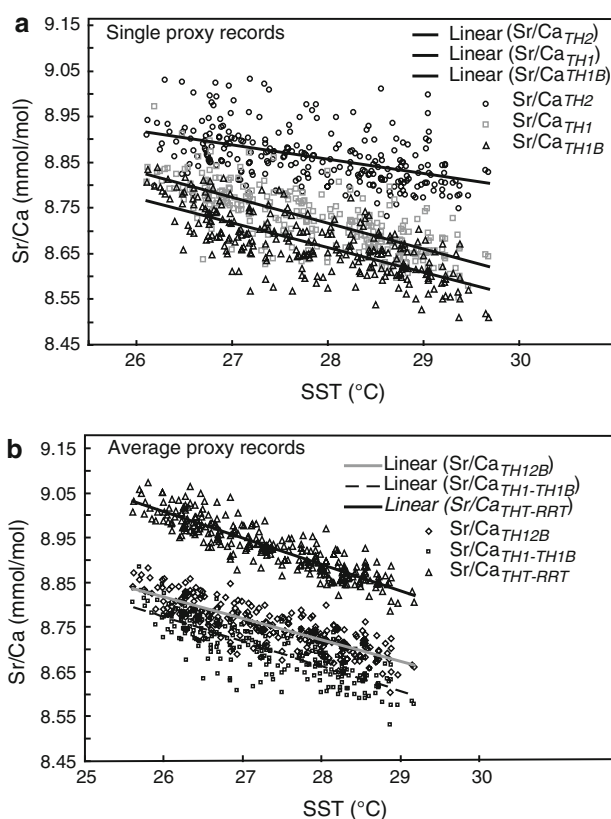

Fig. 4 Linear regression of **a** single-core Sr/Ca records versus ERSST: Sr/Ca$_{TH1}$, Sr/Ca$_{TH2}$ and Sr/Ca$_{TH1B}$, and **b** average Sr/Ca records versus ERSST: Sr/Ca$_{TH1 - TH1B}$ (average of TH1 and TH1B), Sr/Ca$_{TH12B}$ (average of TH1, TH1B and TH2), and Sr/Ca$_{THT - RRT}$ (average of TH1, TH1B, TH2 and Rarotonga)

Average monthly coral Sr/Ca records versus SST

We assume that coral cores taken from different colonies in the same area are influenced concomitantly by environmental changes (e.g., SST variations) while other potential influences on coral Sr/Ca (e.g., "vital effects", site specific problems) should differ for each core. Hence, an average proxy record calculated from multiple cores should better record regional environmental changes than a single core. This should reduce the noisiness of the proxy records as, for example, site-specific effects may bias single-core reconstructions. Since grid-SST represents a large region and not a spot measurement, the regression with an average

Table 3 Regression equations of the three monthly Sr/Ca records from Tahiti (Sr/Ca$_{TH1}$, Sr/Ca$_{TH2}$ and Sr/Ca$_{TH1B}$) versus ERSST ($P < 0.001$ for all analysis)

	Regression equation	R
Sr/Ca$_{TH1}$	Sr/Ca $= -0.05 \pm 0.002$ SST $+ 10.22 \pm 0.05$ ($n = 870$, $\sigma = 0.053$)	0.69
Sr/Ca$_{TH2}$	Sr/Ca $= -0.04 \pm 0.002$ SST $+ 9.815 \pm 0.05$ ($n = 1105$, $\sigma = 0.055$)	0.51
Sr/Ca$_{TH1B}$	Sr/Ca $= -0.05 \pm 0.03$ SST $+ 10.144 \pm 0.09$ ($n = 259$, $\sigma = 0.046$)	0.73

intercolony proxy record should result in a better correlation with SST than the regression with a single record (or an average proxy record computed from cores taken from the same colony).

Averaging the monthly Sr/Ca records of core TH1 and TH1B ($Sr/Ca_{TH1-TH1B}$), both drilled from the same coral colony, improves the correlation with SST (compare Tables 3 and 4). Core TH2 was drilled in the lagoon of Vairao and was derived from a coral colony different from that of the cores TH1and TH1B (drilled in the lagoon of Teahupoo). However, all cores are located within the same grid (Fig. 1). The single-core Sr/Ca record of TH2 has a lower correlation with SST than with either TH1 or TH1B (Table 3).

By averaging the monthly Sr/Ca records from TH1, TH1B and TH2 (Sr/Ca_{TH12B}), we obtain a better correlation with SST than with any of the three single-core Sr/Ca records (compare Tables 3 and 4). The three Sr/Ca records from Tahiti are also averaged with a published coral Sr/Ca record from Rarotonga ($Sr/Ca_{THT-RRT}$) (Linsley et al. 2000) that is located to the west of Tahiti, although it is not located in the same SST-grid. We average the relevant ERSST data from the grids including Rarotonga (159.82°W; 21.23°S) and Tahiti (149.2°W;17.4°S), and regress this record against the average Sr/Ca record from Tahiti and Rarotonga. We find that averaging the Tahiti and Rarotonga records improves the correlation with SST (Table 4). The regression slope of the averaged proxy records (−0.04 to −0.06 mmol/mol per °C) is in agreement with published estimates of the Sr/Ca-SST relationship (−0.04 to −0.08 mmol/mol per °C).

Although it is difficult to assess the significance of the differences between the R-values obtained for single-core records and multi-core averages due to the matching of the seasonal cycle in the monthly proxy and SST series, our results suggest that regional SST variations can be more adequately captured by multi-core averages from different sites.

Monthly coral Sr/Ca-SST reconstructions

To further explore the fidelity of multi-core Sr/Ca records as recorders of regional SST variations, we have compared the SST residual of the monthly SST reconstructions derived from single-core and multi-core Sr/Ca records (Fig. 5). The average Sr/Ca record of Tahiti and Rarotonga was converted to SST using the $Sr/Ca_{THT-RRT}$–ERSST regression listed in Table 4. Figure 5a compares monthly reconstructed SST from $Sr/Ca_{THT-RRT}$ and the relevant ERSST data. The SST residual is obtained by subtracting instrumental SST from reconstructed SST (Fig. 5b). This residual is suggested to be noise. Figure 5b–d compares the SST residual of the linear regression equations of (1) $Sr/Ca_{THT-RRT}$ versus ERSST, (2) $Sr/Ca_{TH1-TH1B}$ versus ERSST and (3) Sr/Ca_{TH1} versus ERSST. For the average Sr/Ca record from Tahiti and Rarotonga ($Sr/Ca_{THT-RRT}$), the residual SST varies only from −1 to 1°C (Fig. 5b). For the intercolony average proxy record ($Sr/Ca_{TH1-TH1B}$), the residual SST varies from −2 to 1°C (Fig. 5c). For the single core record of Sr/Ca_{TH1}, the variation of the residual SST is largest (−2 to 2°C) (Fig. 5d). These findings further support our conclusion that regional SST variations are better captured by multi-core averages, preferably from different sites.

Annual mean coral Sr/Ca versus sea surface temperature

In order to perform a mean annual calibration, the mean annual Sr/Ca records are regressed against mean annual SST data. We use the time period of 1974–1995 only, so that all three Tahiti cores cover the same time period. The annual mean is calculated by averaging the monthly Sr/Ca (SST) data from August to July in the following year. Table 5 compares the mean annual regression equations of the three single-core Sr/Ca records (TH1, TH1B and TH2) versus ERSST.

The correlation coefficients obtained for the annual mean calibration of the Sr/Ca records from TH1 and TH2 are low (Table 5; eq.1 and eq.3). In contrast, the horizontal core TH1B has a high correlation with ERSST ($R = 0.79$). However, the slope of the Sr/Ca-SST relationship (−0.22 ± 0.04 mmol/mol per °C) is much higher than the published slope estimates. The average proxy record computed from all three Tahiti corals does not show a better correlation with annual mean ERSST than the TH1B record alone (see equations 4 and 5, Table 5). This

Table 4 Regression equations of average monthly Sr/Ca records from Tahiti ($Sr/Ca_{TH1 - TH1B}$, Sr/Ca_{TH12B}) and Tahiti and Rarotonga ($Sr/Ca_{THT - RRT}$) versus ERSST for the time period of 1974–1995 ($P < 0.001$ for all analysis)

Proxy	Regression equation	R
(1) $Sr/Ca_{TH1 - TH1B}$	$Sr/Ca = -0.06 \pm 0.002$ SST $+ 10.213 \pm 0.07$ ($n = 259$ $\sigma = 0.04$)	0.82
(2) Sr/Ca_{TH12B}	$Sr/Ca = -0.05 \pm 0.002$ SST $+ 10.050 \pm 0.05$ ($n = 259$ $\sigma = 0.03$)	0.83
(3) $Sr/Ca_{THT - RRT}$	$Sr/Ca = -0.04 \pm 0.002$ SST $+ 10.088 \pm 0.05$ ($n = 259$ $\sigma = 0.03$)	0.88

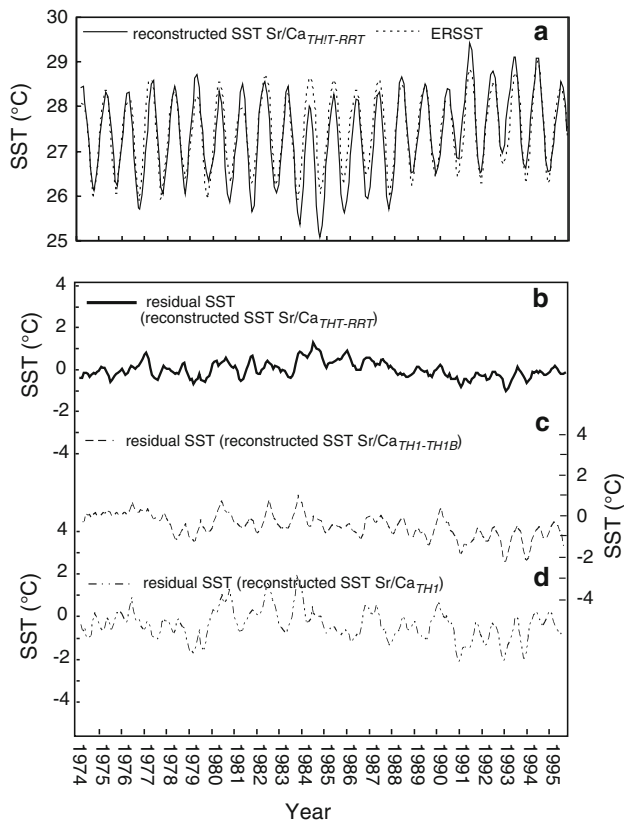**Fig. 5** **a** Reconstructed SST from the average Tahiti and Rarotonga record (Sr/Ca$_{THT - RRT}$) based on the monthly regression against ERSST (Sr/Ca = − 0.04 ± 0.002 SST + 10.088 ± 0.05, R = 0.88). Comparison of the residual SST of the regression Sr/Ca$_{THT - RRT}$ versus ERSST (**b**), Sr/Ca$_{TH1 - TH1B}$ versus ERSST (Sr/Ca = − 0.06 ± 0.002 SST + 10.213 ± 0.07) (**c**), and Sr/Ca$_{TH1}$ versus ERSST (Sr/Ca = − 0.05 ± 0.002 SST + 10.22 ± 0.05) (**d**). See text for discussion

suggests that horizontal cores from large *Porites* colonies may actually provide very valuable records of past SST variations. At present, most studies use vertical coral cores only, as horizontal cores were suggested to be biased due to vital effects (e.g., de Villiers et al. 1994). This issue clearly requires a more thorough investigation.

To further explore the differences between the monthly and annual mean Sr/Ca-SST calibrations, we used the

monthly coral Sr/Ca-SST regression equations to convert the proxy records to SST. This approach is justified, because the incorporation of Sr/Ca in the coral skeleton is governed by thermodynamic principles on monthly as well as on annual time scales, that is, the Sr/Ca-SST relationship should remain the same. As the correlation between monthly Sr/Ca and SST series is high, the slope estimates are also more accurate (compare Tables 3, 4 and 5). Figure 6 compares annual mean SST estimated from coral Sr/Ca (based on the monthly Sr/Ca-SST regression equations listed in Tables 3, 4) with annual mean ERSST. We find that on an annual mean scale, the standard deviation of reconstructed SST is much larger than indicated by grid-SST (Fig. 6). The three single-core records show larger standard deviations (Sr/Ca$_{TH2}$: $\sigma = 1.14°C$, Sr/Ca$_{TH1}$: $\sigma = 0.6°C$, Sr/Ca$_{TH1B}$ $\sigma = 0.79°C$) than the average Sr/Ca records (Sr/Ca$_{TH1-TH1B}$: $\sigma = 0.58°C$, Sr/Ca$_{TH12B}$: $\sigma = 0.53°C$). Importantly, differences in the standard deviations between the proxy records and grid-SST do not seem to depend on the strength of the correlation between the proxies and SST.

Grid-SST usually has a lower standard deviation than local SST at a given site, as averaging SST observations within a grid box tends to reduce the variance. As coral Sr/Ca series provide a record of local SST, they tend to show larger temperature variations than grid-SST. This appears to be particularly problematic on interannual time scales. However, our results suggest that averaging coral proxy records from different locations reduces the standard deviation of reconstructed temperature, so that the inferred temperature variations may eventually approach grid-SST, provided that a sufficiently large number of proxy records are averaged.

Summary of conclusions

We have generated three monthly resolved Sr/Ca records from Tahiti (French Polynesia): Sr/Ca$_{TH1}$ and Sr/Ca$_{TH1B}$ derive from the same coral colony growing in the lagoon of Teahupoo. The cores were drilled vertically (TH1) and

Table 5 Annual mean calibration equations of the three Tahiti Sr/Ca records for the time period of 1974–1995: single-core records Sr/Ca$_{TH1}$, Sr/Ca$_{TH1B}$ and Sr/Ca$_{TH2}$ versus ERSST (1–3) and average Sr/Ca records Sr/Ca$_{TH1 - TH1B}$, Sr/Ca$_{TH12B}$ and Sr/Ca$_{THT - RRT}$ versus ERSST (4–5) (P < 0.001 for all analysis)

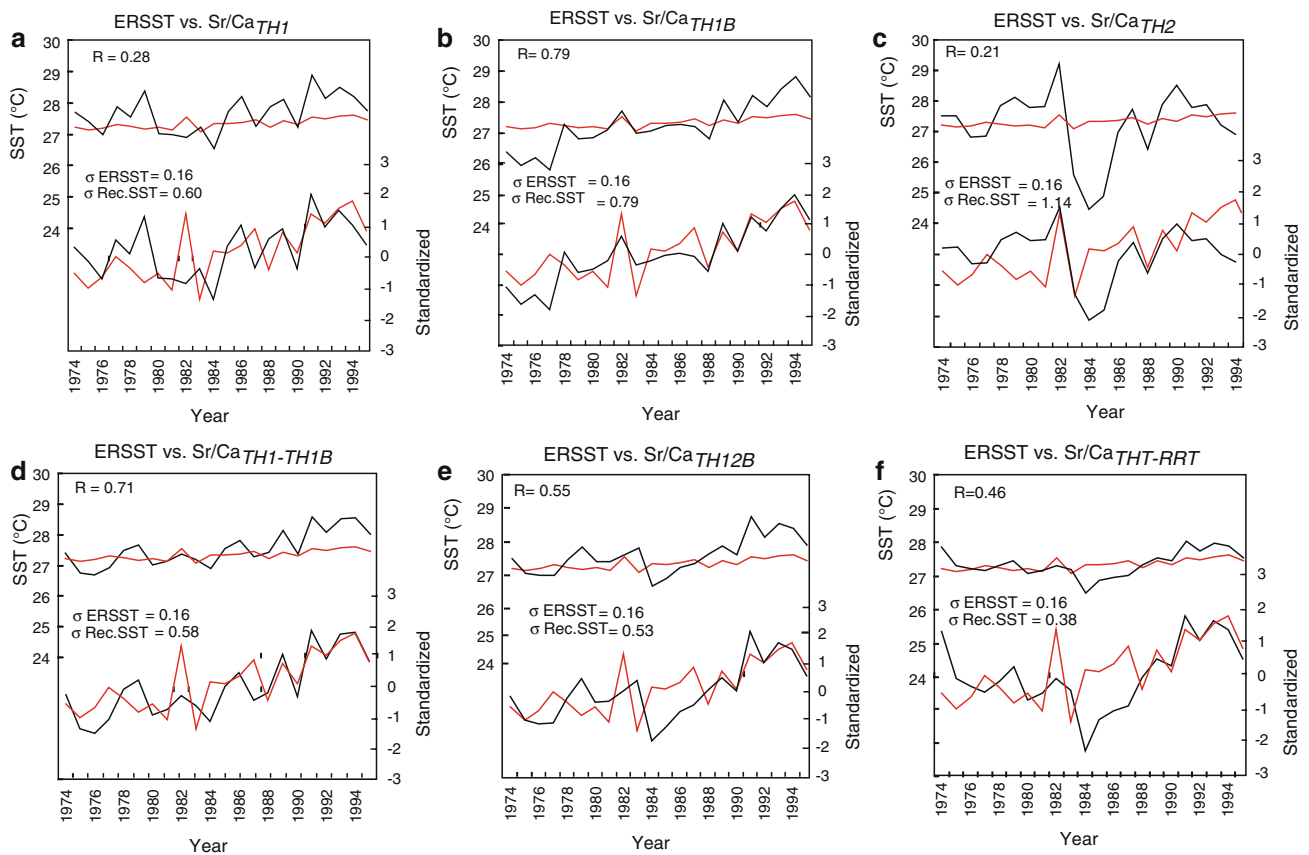| Proxy	Regression equation	R
1. Sr/Ca$_{TH1}$	Sr/Ca = − 0.08 ± 0.04 SST + 11.18 ± 1.15 $\sigma = 0.03$	0.28
2. Sr/Ca$_{TH1B}$	Sr/Ca = − 0.22 ± 0.04 SST + 14.62 ± 1.01 $\sigma = 0.03$	**0.79**
3. Sr/Ca$_{TH2}$	Sr/Ca = −0.05 ± 0.06 SST + 10.27 ± 1.55 $\sigma = 0.04$	0.21
4. Sr/Ca$_{TH1 - TH1B}$	Sr/Ca = − 0.15 ± 0.03 SST + 12.82 ± 0.91 $\sigma = 0.02$	**0.71**
5. Sr/Ca$_{TH12B}$	Sr/Ca = − 0.09 ± 0.03 SST + 11.17 ± 8.2 $\sigma = 0.02$	0.55
6. Sr/Ca$_{THT - RRT}$	Sr/Ca = − 0.03 ± 0.06 SST + 10.63 ± 0.79 $\sigma = 0.02$	0.46

Fig. 6 Annual mean ERSST (*red solid line*) and annual mean reconstructed SST based on coral Sr/Ca (*dark solid line*) in °C (*top panels*) and after normalizing to unit variance (*bottom panels*): **a** Sr/Ca$_{TH1}$, **b** Sr/Ca$_{TH1B}$, **c** Sr/Ca$_{TH2}$, **d** Sr/Ca$_{TH1 - TH1B}$, **e** Sr/Ca$_{TH12B}$, **f** Sr/Ca$_{THT - RRT}$. Reconstructed SST is based on the monthly coral Sr/Ca-ERSST regression equations listed in Table 3 (Sr/Ca$_{TH1}$, Sr/Ca$_{TH1B}$, and Sr/Ca$_{TH2}$) and Table 4 (Sr/Ca$_{TH1 - TH1B}$, Sr/Ca$_{TH12B}$ and Sr/Ca$_{THT - RRT}$). $\sigma = 1$ standard deviation (in °C). See text for discussion

horizontally (TH1B). Sr/Ca$_{TH2}$ derives from a second colony growing in the lagoon of Vairao. Analysis of the three proxy time series led us to the following conclusions:

(1) Different methods of chronology development (peak matching and anchor points) were tested. Our results show that coral Sr/Ca chronologies based on peak matching do not always have a higher correlation with instrumental SST. Particularly on longer time scales, when the uncertainties in instrumental SST become larger because of fewer measurements, the anchor point method appears to be more appropriate.

(2) Monthly coral Sr/Ca records from Tahiti are a good proxy for monthly temperature variations. The slope of Sr/Ca-SST relationship (−0.04 to −0.05 mmol/mol per °C) is in agreement with published slope estimates. However, the residual temperature of the single-core SST reconstructions is fairly large (−2 to 2°C). We speculate that grid-SST cannot capture the small-scale SST variations at a given coral site (that are portrayed by coral Sr/Ca), as grid-SSTs are typically regional averages over a large area.

(3) In order to improve the correlation between monthly coral Sr/Ca and grid-SST, to obtain more realistic standard deviations of the Sr/Ca-SST reconstruction and to minimize the residual SST, we propose to average Sr/Ca measurements from multiple coral colonies taken from different locations in a given region. We believe that SST reconstructions from average proxy records are more representative of regional SST variations. The Sr/Ca-SST reconstruction of the average Sr/Ca record comprising all three Tahiti cores resulted in a better correlation with grid-SST and a lower residual SST compared to any of the single-core Sr/Ca records. The average Sr/Ca record calculated from multiple coral colonies taken from two different islands (Tahiti and Rarotonga) has a better correlation with grid-SST and a lower residual SST than the average coral Sr/Ca record from Tahiti alone.

(4) Of the three Tahiti cores, the one that was drilled horizontally shows the best correlation with grid-SST on an annual mean scale. The average proxy record computed from all three Tahiti corals does not show a better correlation with annual mean SST than the

horizontal core alone. This suggests that horizontal cores drilled from large *Porites* colonies may provide very valuable archives of past SST variations.

(5) On an annual mean scale, the Sr/Ca-SST reconstructions from all three Tahiti corals show much larger interannual variations than indicated by grid-SST (i.e., the standard deviation of annual mean Sr/Ca-SST is much larger than the standard deviation of annual mean grid-SST). These discrepancies do not depend on the strength of the correlation between coral Sr/Ca and grid-SST. This poses a serious problem to any attemps to assess the magnitude of interannual SST variations from fossil corals taken at Tahiti. Besides calibrating coral Sr/Ca with local SST measurements, the development of multi-core coral Sr/Ca records is necessary in order to improve the quality of proxy-based SST reconstructions.

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