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Research

Coral Sr/Ca-SST calibration: SST records from Kenyan corals

Nyinge N. Mwadzombo¹ · Mwakio P. Tole² · Guyo P. Mwashimba¹ · Florence Le Cornec³

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Abstract

To better understand the seasonal variability in SST in Kenyan coral reef ecosystems, Sr/Ca ratios have been measured in Kenyan coral skeletons as proxies of SST, and a new Sr/Ca = f(SST) calibration was established: $Sr/Ca = -0.053 (\pm 0.006) *SST + 10.43 (\pm 0.16)$. The slope was within the margins of -0.04 and -0.08 mmolmol⁻¹ °C of previously published Sr/Ca-SST calibration equations. A reliability test revealed that the present calibration equation reproduces a previously published calibration equation developed for Kenyan corals. This calibration was applied to corals collected in reef ecosystems under different natural and anthropogenic influences: Tana Delta Ziwayu Island, Watamu National Marine Park, and Shimon Mupunguti Marine Reserve. Using the developed Sr/Ca-thermometry, the reconstructed Sr/Ca-SST revealed that reefs from the southern basin of the Kenyan Indian Ocean are exposed to warmer SSTs than reefs in the northern Basin are. Additionally, the results revealed that the seasonal variability on SST increased moving toward the southern basin of the Kenyan Indian Ocean. We use the local instrument SST as an SST reference, which is aligned against the Sr/Ca seasonal signals recorded in SMR3-18 (the nearest coral site), and the intensity of the third global coral bleaching (April and May 2016) is affirmed.

Keywords Sr/Ca-Sclero thermometry · Kenyan reefs · Coral bleaching · Seasonal variability

1 Introduction

Studies have shown that there is an inverse correlation between strontium (Sr) to calcium (Ca) ratios measured in the coral skeleton and seawater surface temperatures [3, 6, 8, 48, 76, 81]. Importantly, massive *Porites* spp. corals are relatively resilient to both natural and human-induced stressors and are therefore capable of living for up to a century or more [81]. Because massive *Porites* spp. corals can encode climatic records during their lifetime without any alteration, SST proxies preserved in coral skeletons have been used to develop sclerothermometers [3, 48, 76]. For example, thermometers developed from Sr/Ca proxies preserved in coral skeletons can retrospectively reconstruct SST seasonal variability [22] when SST-monitored instrument data are limited (see [15, 41, 81–83]). To obtain quantitative data on SST anomalies, for example, it is first necessary to establish calibration curves linking Sr/Ca ratios measured in healthy modern corals to physical temperature data [15, 76]. However, calibration equations developed from Sr/Ca have their own limitations in climatic studies [7, 15, 30, 53–56]. Today, several Sr/Ca vs. SST calibration equations have been published with different

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slopes and intercepts [8, 41, 58, 83], with coefficients varying according to coral species, the region where it was collected, and/or the SST data used for calibration (e.g., in situ, local or satellite SSTs as the IOSST dataset) [17].

With new advances in paleo-studies, concern has been raised regarding the reliability and applicability of Sr/Ca thermometers in SST variability studies [12, 13, 20, 58]. For example, an inappropriate analytical protocol for sampling [58], e.g., continuous milling of aragonite powder samples, compromises climate variability signals because of time averaging [11]. Other factors, such as biological factors [13, 53, 54], physiological factors [56], e.g., the coral growth rate [56, 72], and vital effects [14, 55], have also been associated with seasonal variations in the Sr/Ca ratios in the coral skeleton [21, 25, 42], which can otherwise affect the accuracy of paleoclimatic records from corals [20]. In addition, Sr/Ca proxies are susceptible to non-SST influences [72] and variations in seawater Sr/Ca proxies [2]. A study by [58, 76] implicated seasonal phenomena such as upwelling, riverine discharge, and coastal runoff with spatial seasonal variability in the Sr/Ca concentration in the ocean, which in turn influences the seasonal mean concentration of Sr/Ca in a coral skeleton. Other researchers [57, 75] associated early diagenesis in a coral skeleton with variations in Sr/Ca proxies.

Besides Sr/Ca-SST, another proxy of interest is ($^{18}\text{O}/^{16}\text{O}$), and like the former, the accuracy of ($^{18}\text{O}/^{16}\text{O}$)-SST thermometry is influenced by several temporal environmental parameters [15, 70]. For example, the incorporation of ^{18}O in the coral skeleton depends not only on the SST [55] but also on the heavy ^{18}O isotopes of seawater [15, 55, 80], therefore with a paired ($^{18}\text{O}/^{16}\text{O}$)-Sr/Ca-SST thermometry, one can reconstruct both the seasonal variability of ^{18}O seawater and salinity [67, 70]. In fact, [15, 30, 55] reported the influence of seasonal variability in freshwater inputs on the sensitivity of the ($^{18}\text{O}/^{16}\text{O}$)-SST thermometer developed from Kenyan corals. Since ($^{18}\text{O}/^{16}\text{O}$)-SST thermometry is influenced by an array of spatiotemporal environmental factors in addition to the SST, the heavy ($^{18}\text{O}/^{16}\text{O}$)-SST thermometer is less robust than the Sr/Ca thermometer is and therefore unreliable [67]. However, based on earlier climatic studies, e.g., [13, 15, 25, 42, 55, 58, 67, 76], it is evident that there is no universal ($^{18}\text{O}/^{16}\text{O}$)-SST or Sr/Ca-SST calibration equation that is deemed appropriate, as calibration equations developed from corals are highly variable among individual corals [80–83].

In Kenya, a few calibration curves have been developed for $\delta^{18}\text{O}$ -SST [15, 30] and Sr/Ca-SST [41] thermometry, but much attention has been given to addressing the limited instrument data on seasonal variability in SST for East Africa. In fact, spatiotemporal Sr/Ca-SST sclero-thermometry coral records in Kenya remain sparse and poorly documented, especially in remote areas of Kenyan coral reef ecosystems (see [15, 30, 41]). Undoubtedly, calibration equations (Sr/Ca-SST) developed from coral records in remote areas (e.g., Tana Delta Ziwayu Island) of Kenyan coral reef ecosystems where monitoring of the seasonal variability in SST is a challenge (see [15, 30, 41]) are currently lacking. Thus, there is an urgent need to increase the number of calibration equations, particularly from coral records in unprotected remote coral reef ecosystems in the Kenyan Indian Ocean. Increasing the number of calibration equations in unprotected coral reef areas will help improve spatiotemporal coral-climate studies in these neglected fragile ecosystems [52, 65, 66].

The present study attempts to achieve the following objectives: (1) to establish a calibration that links Sr/Ca measured in the coral skeleton to SST from Kenyan corals (unprotected) and uses it to reconstruct SST seasonal variability in three different coral reef ecosystems; (2) to compare the means and seasonal Sr/Ca-SST variabilities derived from three coral sites under different natural and anthropogenic influences along the Kenyan coast; (3) to test the reliability of the developed Sr/Ca-SST calibration curves from *Porites lutea* coral in the WIO region by comparing the reconstructed SST seasonal variability (SMR3-18) with local monitored SST seasonal data; and (4) to discuss the influences of SST, environmental, and anthropogenic factors on the annual growth rate.

2 Materials and methods

2.1 Climatic conditions of the study area

The study was restricted to [2° 35' 0" and 4° 42' 0" S] and [39° 22' 0" and 40° 35' 03" E] of the Kenyan marine environment (Fig. 1). The air temperature of the Kenyan coastal region (study area) is influenced by seasonal monsoons [79]. The air temperature varies from 25 to 30 °C during the south-easterly and north-easterly monsoons, respectively [79]. Because of the influence of the monsoons, there is a bimodal seasonal pattern in the SST variation with two SST maxima: April and November or December and one minimum SST in July or August (Fig. S1a). The sea surface temperature (SST) in this region ranges between 26.5 and 30.0 °C [79], and between summer and winter, the Kenyan coastal environment experiences a very small temperature difference.

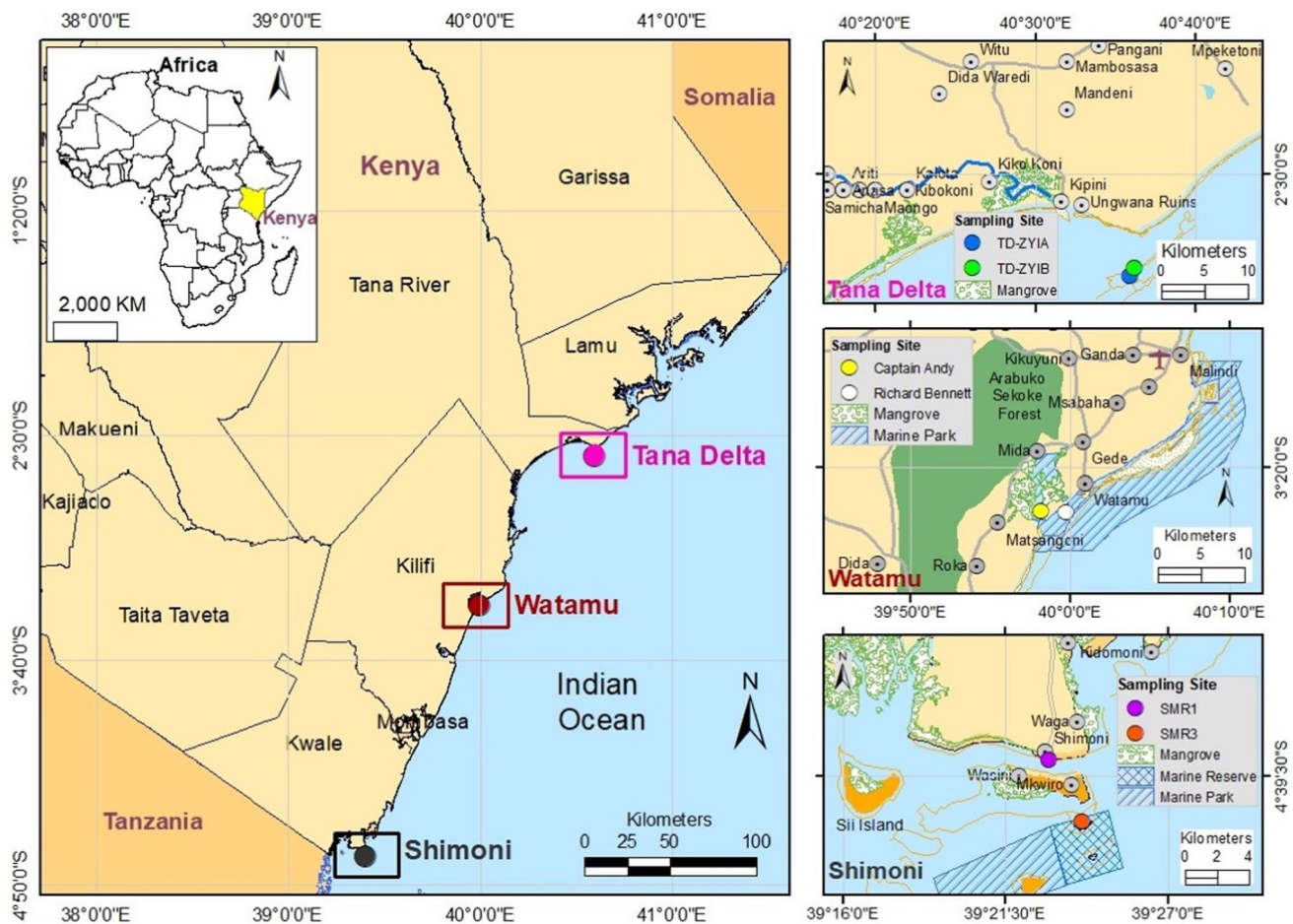


Fig. 1 Map showing the sampling sites

2.2 Study area

A recent study by [35] reported a direct link between seasonal monsoons and sea surface temperature (SST) along the Kenyan Indian Ocean. During the southeasterly monsoons (rainy and cloudy), the SST is lowest, and during the northeasterly monsoon, the SST is highest [49]. In addition, between December and February, there are seasonal upwelling events that occur in the northern part of the Kenyan Indian Ocean ($2^{\circ} 42' S, 40^{\circ} 47' 60'' E$), and the SST can then be lowered to $26^{\circ} C$ [34] (Fig. S1a). During the same period, there are downwelling events that originates from Tanzania water moving toward the southern Kenyan Indian Ocean Basin [38, 49]. The extent of the impact of these seasonal events (upwelling and downwelling) on coral reef ecosystems in the northern and southern Kenyan Indian Ocean basin, respectively, remains unknown.

Moreover, extreme seasonal events (e.g., heat waves) are frequently reported and are claimed to threaten fragile coral reef ecosystems in the region [52, 65, 66]. For example, in 2015 and 2016, the annual mean SST exceeded $29.5^{\circ} C$ (coral bleaching threshold) [31], which resulted in lower productivity of marine resources [31]. Therefore, monitoring SST seasonal variability in Kenya's coral reef ecosystems via SST tools developed from coral SST proxies in Kenyan coral reef ecosystems is critical. The use of such an approach has been recommended by several scientists (see [3, 5–7, 20, 27, 64, 69, 76, 80–83]). Coral SST proxies can be used retrogressively and can generate SST seasonal variability data that are equally reliable [41]. Such data can be relevant to coral reef stakeholders, especially for understanding past episodic heat wave events. Additionally, knowledge generated from such studies can be used to mitigate future coral reef threats through modeling.

2.3 Sample collection

Between 13th January and 21st August 2018, three pairs of small live *Porites lutea* coral colonies were collected, one pair per site, from three sampling sites. The first pair of coral samples, TD-ZYIA-18 and TD-ZYIB-18, was collected from the Tana Delta, Ziwayu Island, during February 2018, a site in the northern part of the Kenyan Indian Ocean, 11.7 km offshore (Fig. 1). This site is presumed to be influenced by seasonal monsoon winds [34–36], which are also associated with upwelling and are partly impacted by the seasonal River Tana plume [35]. The second pair was collected at Captain Andy (CA-18) and Richard Bennett (RB-18) in January and July 2018, respectively, at Watamu National Marine Park, a site located in the northern Kenya Indian Ocean. Unlike Richard Bennett (RB), which communicates with pelagic ocean circulations, Captain Andy is enclosed and restricted from pelagic circulations. Moreover, Watamu National Marine Park is threatened by human activities [61], e.g., the commercialized boat firm at Captain Andy and the expanding tourism industry [61]. In fact, the expanding tourism industry has consequently increased the number of tourist hotels and resort villages within the Watamu environment [18]. Additionally, since 1998, the park has experienced recurrent heat wave episodes [31, 65], in addition to threats from land-use practices [63]. Finally, the third pair of coral samples was collected in the Shimoni Mupunguti Marine Reserve on 21st August 2018 and was labeled SMR1-18 and SMR3-18. The coral reef ecosystems at the Shimoni Mupunguti Marine Reserve are also threatened by anthropogenic activities, especially maritime activities [61]. The Shimoni port is located within the Shimoni Mupunguti Marine Reserve. In addition, there is a residual effect of downwelling as mentioned earlier in this manuscript, which originates from Tanzania waters, during the North-easterly monsoons [38, 49]. Downwelling is a seasonal phenomenon that is associated with warmer SST water currents, and most likely, the coral reef ecosystems of the southern basin of the Kenyan Indian Ocean are exposed to warmer conditions. Importantly, the Shimoni Marine Reserve is one of the Kenyan coral reef ecosystems known for its rich biodiversity [66], and SST is among the crucial components of marine water quality parameters that determine overall coral reef health [31].

Samples of *Porites lutea* coral colonies were dislodged from the substrate with a mason's chisel from a depth of 1.6 to 4.1 m (Table 1), washed with distilled water, and dried at room temperature. The dried samples were then cut along the maximum growth axis via a water-lubricated diamond disc blade to produce 10 mm thick slabs (Fig. S2b). The obtained coral slabs were rinsed several times in an ultrasonic bath for 15 min with distilled water and then dried in an oven at 40 °C for 48 h.

The clean dried coral slabs were then X-rayed via a 49 kV X-ray machine, yielding X-rays showing alternating high- and low-density growth bands (Fig. S2b). These bands (the light and dark band doublet) generally have an annual periodicity and allow rapid chronological determination of coral growth. The X-rays were used (1) to estimate the age of the coral and establish a first chronology of coral growth, (2) to identify the sampling line along the maximum growth, and (3) to estimate the growth rate of the coral; thus, the sampling step for geochemical analysis was chosen to have approximately one sample per month.

2.4 Preservation status of coral samples

The reliability and credibility of past SST reconstructions from the Sr/Ca ratio measured in the coral skeleton require prior verification of the conservation status of the skeleton. As noted by [51], a well-preserved coral skeleton should have its aragonite fibers still intact, with no signs of dissolution or precipitation of calcite in the coral natural pore spaces or secondary aragonite [39]. Previous studies [39, 51, 75] have linked the degree of alteration of the aragonite constituting the

Table 1 Description of the collected Kenyan coral samples (*Porites lutea*)

Sampling site	Sample name	Latitude (S)	Longitude (E)	Depth (m)	Years (number)	Mean growth rate (cmyear ⁻¹)
Tana Delta Ziwayu Island	TD-ZYIA-18	2° 60' 42.4"	40° 59' 90.7"	2.00	2016 to 2017 (2)	1.08 ± 0.06
	TD-ZYIB-18	2° 59' 94.0"	40° 60' 15.1"	2.06	2015 to 2017 (3)	1.23 ± 0.26
Watamu Marine Park	CA-18	3° 22' 45"	39° 58' 8"	2.03	2015 to 2017 (3)	1.77 ± 0.06
	RB-18	3° 22' 48"	39° 59' 43"	4.10	2016 to 2017 (2)	1.65 ± 0.45
Shimoni Mupunguti Reef	SMR1-18	4° 23' 23"	39° 13' 46"	2.64	–	–
	SMR3-18	4° 41' 05.7"	39° 24' 04.2"	1.62	2015 to 2017 (3)	1.56 ± 0.52

coral skeleton directly to the error in the SST calculated from Sr/Ca measurements. A study by [57] reported an artifact of 4–5 °C drops in SST determined from Sr/Ca-thermometer calibration and indicated the presence of secondary aragonite in a poorly preserved coral sample.

The state of preservation of the studied coral colonies was assessed by scanning electron microscopy (SEM). In brief, small portions of coral were extracted from the coral slabs via a small diamond disc blade supported on an electric drive drill. Fragments (~ 1 cm²) were then manually broken, rinsed with deionized water and dried before being coated with gold. Observations were performed via a ZEISS Evo[®]-LS15 SEM.

2.5 Sampling for geochemical proxy analyses

The coral plates are usually sampled continuously via a computerized sampling bench, with the sampling lines identified on the basis of X-ray radiographs. Coral slabs were sampled continuously via a triaxial computerized sampling bench (ISEL Automation[®]), with the sampling lines identified on the basis of X-rays parallel to the maximum extension axis (Figs. S2a, b). The coral plates were milled using a mini drill with a 0.8 mm drill bit that moves in 3 dimensions. The mini drill sampled small consecutive cubes (depth 1.5 mm × height 0.7 mm × length: 0.8 to 1 mm). The length of the cube sampled, which represents the sampling step, depends on the growth rate of the coral and the temporal resolution chosen. For each slab, the growth rate was estimated from the X-rays, and a monthly resolution of Sr/Ca ratio values (approximately 12 samples/year) was applied: 0.8 mm (TD-ZYIA/B-18), 0.9 mm (SMR1/3–18 and RB-18), and 1 mm (CA-18) (Fig. S2a). From each drilled coral sample, ≈ 1 mg of aragonite powder was obtained.

2.6 Geochemical analysis

A procedure adapted from [40] was adopted to quantify Sr and Ca from coral samples via an Agilent Technologies 7500cx[®] ICP–MS. Digestion of aragonite powder was achieved by using 8 mL of a solution of 50 µg/L scandium and yttrium in 2-wt% HNO₃ ultrapure acid. Scandium and Yttrium were used as internal standards to correct the drift of the instrument. A calibration curve using external standards prepared from single-element solutions (SCP Science) was run each day to analyze the samples. The Sr and Ca contents in each standard are in the same proportions as those measured in the corals. The accuracy of the analyses was systematically checked and corrected where necessary, using the Hathorne et al. 2013 [32] robust average (8.84 mmol/mol), by measuring two samples of the *Porites spp.* coral reference material JCp-1 prepared by the Geological Survey of Japan (GSJ) [32, 33], with every 10 coral samples. The reproducibility was calculated by analyzing every 20 coral samples, one JCp-1 sample prepared in the same way as the coral samples and whose measured values were treated in the same way as the samples. The Sr/Ca reproducibility (standard deviation considering analyses carried out on several days over 2 years) was ± 0.05 mmol/mol (1σ, n = 254).

2.7 Coral chronology

The chronology of the coral slabs was first determined via coral slab X-ray images (Fig. S2a) and later confirmed via monthly Sr/Ca seasonal cycles. Since the relationship between Sr and Ca incorporation in the aragonite skeleton of massive coral is temperature dependent [76], four points/year of the Sr/Ca-ratio seasonal cycles (2 minima–2 maxima) were anchored with 2 maxima–2 minima of the monthly bimodal gridded IOSST time series using AnalySeries software [68] to assign time to the coral Sr/Ca. Between each successive maximum–minimum, it was assumed that coral growth was constant and thus assigned a date to each sample, starting with the most recent to oldest age (error margin = ± 1–2 months).

2.8 Sr/Ca vs. SST calibration equation

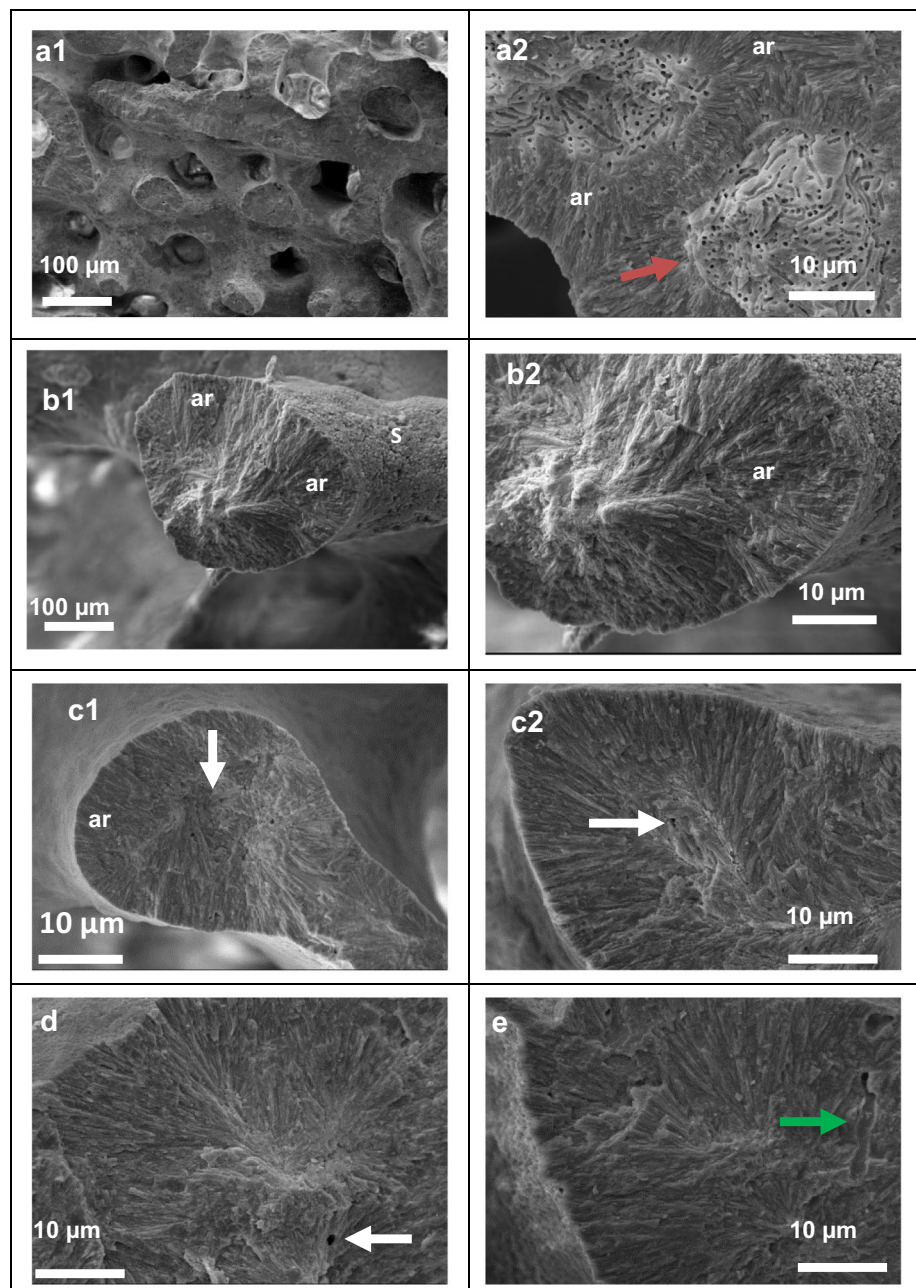
We did not have SST records very close to where our corals were collected (TD-ZYIB-18) to calculate a calibration curve from local SSTs, so we chose monthly 1° × 1° I (OISST) satellite SST data (centered at 2° 30' S and 40° 30' E) [71] (Fig. S1c). The measured Sr/Ca ratios were continuously resampled and aligned against Reyn_SmithOlv2 gridded 1° X 1° IOSST data [71] at monthly time intervals, followed by regression using the reduced least square method, as suggested in several publications, e.g., [26, 27, 58].

3 Results

3.1 Preservation status of coral samples

The preservation state of the coral samples was checked via SEM observations (Fig. 2). The interskeletal pore spaces of the coral skeleton (TD-ZYIA-18) are clean and empty, with no signs of secondary aragonite growth (Plate a-1). In all the images (Plate a-1 to e), the aragonite fibers presented by the letter (ar) are well preserved, and there are no signs of dissolution or calcite formation. Some microborer signatures are evident in very restricted areas in the corals TD-ZYIA-18, CA-18, RB-18, and SMR1-18 (Fig. 2b–d). As shown (image d) and as indicated by the bold white arrow, the microborer galleries are empty and clean, and there is no infilling of calcite. These SEM observations allow us to conclude that all the coral skeletons are well preserved. The Sr/Ca ratios incorporated in the corals were therefore analyzed.

Fig. 2 Plates showing the preservation status of coral slabs. Plates Images **a1** and **a2** show the preservation of TD-ZYIA-18, and as indicated on Plate **a1**, the natural coral pore spaces are clean and empty. In plate **a2**, aragonite fibers are intact, as indicated by the white bold small letters (ars). Additionally, signs of microborer invasion within the calcification centers are evident, as indicated by the bold brown arrow. Plates **b1** and **b2** are plates showing the preservation status of coral slab TD-ZYIB-18, and as indicated, the coral septum, which is represented by white letters, has well-preserved aragonite fibers. Plate **b2** is an enlargement of Plate **b1**. Plates **c1** and **c2** present the preservation status of the CA-18 coral slab, and as indicated, the aragonite fibers are intact, with restricted signatures of microborers, as indicated by the white bold arrows. The preservation status of the coral slab SMR3-18, as shown on Plate **d**, reveals well-preserved aragonite fibers. For the RB-18 coral slab, the aragonite fibers shown in Plate **e** are intact and well preserved, with microborer signatures that are evident in restricted areas, as indicated by the green bold arrow



3.2 Monthly concentration variation in the Sr/Ca ratios and chronology

The results of the minimum, mean, maximum and mean annual amplitudes of the Sr/Ca ratios (mmol/mol) measured for each coral slab from 2015 to 2017 or 2016 to 2017 are presented in Table 2, whereas the results for the monthly variations in the Sr/Ca ratios are shown in Fig. 3. The measured monthly Sr/Ca concentrations varied from site to site. The Sr/Ca ratios ranged between 8.42 and 9.30 mmol/mol for all the samples analyzed, and the sum of the monthly means was 8.98 ± 0.09 mmol/mol ($N = 267$) (Table 2). The mean annual Sr/Ca ratios are low, ranging between 0.25 and 0.37 mmol/mol.

The Sr/Ca ratio cycle records for coral from the Tana Delta reefs (TD-ZYIA-18 and TD-ZYIB-18) (Fig. 3a) reproduced the seasonal temperature cycles well (Fig. S1a), with each year having 2 maxima (Fig. S1b) and 2 minima. The Sr/Ca seasonal monthly cycles of the offshore coral slabs are clear and visible and reproduce bimodal seasonal SST cycles (refer to Fig. S1a), and it's attributed to natural ocean circulations. For the inshore reefs (CA-18 and RB-18) from Watamu Marine Park (Fig. 3b) and (SMR3-18) from Shimoni Mupunguti Marine Reserve (Fig. 3c), the Sr/Ca seasonal monthly cycles are visible and slightly noisier, whereas for the SMR1-18 coral slab (Shimoni Mupunguti Reef), which was collected closer to the shoreline, the Sr/Ca signals were noisy, distorted, and unclear (Fig. S3); thus, identifying the minima and maxima was difficult. For the rest of the coral slabs, their chronology was established. However, for SMR1-18 (Fig. S3), the Sr/Ca signals were too noisy, and the sclerobands on the radiograph were not clear enough to enable the assignment of the chronology for the SMR1-18 coral slab.

3.3 Calibration of Sr/Ca-SST

Because the TD-ZYIB-18 coral had well-preserved aragonite fibers and its Sr/Ca seasonal cycles agreed with the IOSST nmc Reyn_SmithOlv2 gridded $1^\circ \times 1^\circ$ SST variation (Fig. S2c), the calibration equation $Sr/Ca = f(SST)$ was calculated from these two records via the reduced least square regression method. The regression model between the Sr/Ca ratios and the gridded $1^\circ \times 1^\circ$ IOSST data covered the period from July 2014 to December 2017. The modal regression coefficient is $r = 0.81$ ($p < 0.05$, $N = 42$), and the adjusted $R^2 = 0.66$ is statistically significant ($F = 68.26$, $p < 0.05$) for the 3-year period. The standard error of the estimate is (± 0.043), and the slope of the calibration curve is -0.053 , corresponding to the following calibration equation: $Sr/Ca = -0.053(\pm 0.006) * SST + 10.43 (\pm 0.16)$ (Fig. 4).

3.4 Recalculated Sr/Ca-SST

To test the reliability of our calibration curve, we compared the reconstructed $SST_{Sr/Ca}$ from the SMR3-18 coral to local SST data. Closer local (instrument) SST data were recorded at the Kilindini Port Mombasa Meteorological weather station ($4^\circ 3' 3.76''$ S and $39^\circ 38' 43.47''$ E), almost 73 km from the sampling site where the SMR3-18 coral slab was collected. As shown (Table 3), the recalculated Sr/Ca-SST mean temperatures ranged from 25.2 to 31.8 °C, and the annual mean amplitude was (4.7 ± 0.2) °C. For the local instrument-SST, the mean was 28.3 °C, and the range was between 26.3 and 30.7 °C, resulting in an amplitude of (3.6 ± 0.4) °C.

Table 2 Descriptive statistical data for Sr/Ca-Proxy

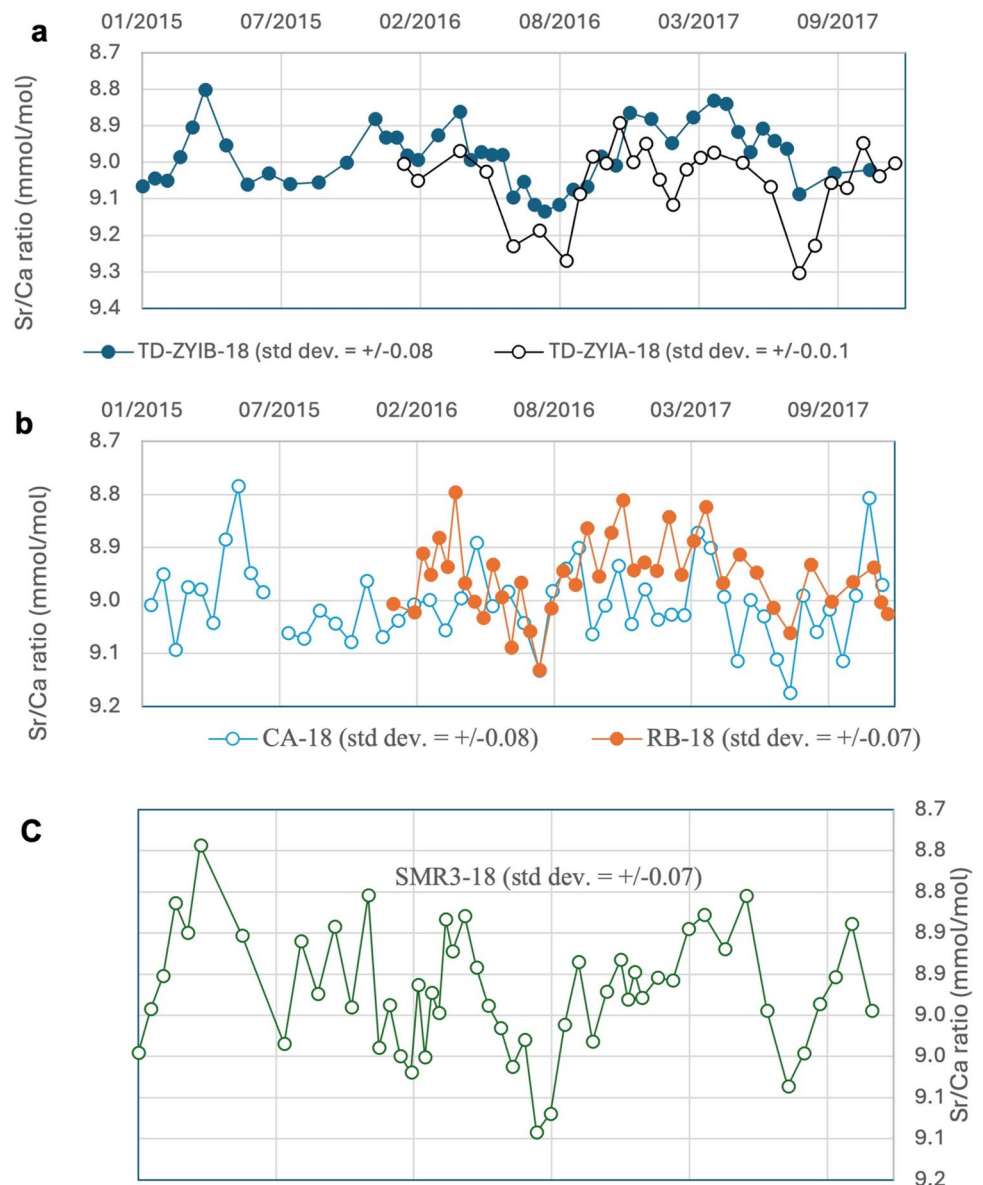
Sampling site	Sample name	Years ^a	N ^b	Min Sr/Ca ^c	Mean Sr/Ca ^{cd}	Max Sr/Ca ^c	Mean annual Sr/Ca amplitude
Tana Delta	TD-ZYIA-18	2016 to 2017	27	8.89	9.06 ± 0.10	9.30	0.37 ± 0.02
Ziwayu Island	TD-ZYIB-18	2015 to 2017	46	8.80	8.98 ± 0.08	9.13	0.26 ± 0.01
Watamu Marine Park	CA-18	2015 to 2017	54	8.78	9.00 ± 0.08	9.18	0.31 ± 0.06
	RB-18	2016 to 2017	41	8.80	8.96 ± 0.07	9.13	0.29 ± 0.07
Shimoni Mupunguti Reef	SMR1-18	–	34	8.77	8.96 ± 0.08	9.26	–
	SMR3-18	2015 to 2017	52	8.74	8.92 ± 0.07	9.09	0.25 ± 0.02
All sites		2015 to 2017	254	8.74	8.98 ± 0.09	9.30	0.29 ± 0.05

^aNo chronology could be established for SMR1-18

^bNumber of analyzed samples in the time period

^cUnit is mmol/mol

Fig. 3 Graphs (a) to (c) show the seasonal monthly cycles of Sr/Ca for TD-ZYIA/B-18 (a), CA-18 and RB-18 (b), and SMR3-18 (c), for the period between 2015 and 2017



The mean difference between the recalculated $SST_{Sr/Ca}$ and the local SST was $0.3\text{ }^{\circ}\text{C}$, and for the 3-year (2015 to 2017) monitoring period, there was no significant difference in the mean SST ($F=0.54$; $p>0.05$). On the other hand, the mean SST from IOSST nmc Reyn_SmithOlv2 gridded $1^{\circ}\times 1^{\circ}$ (02.5°S and 040.5°) satellite observations was $27.3\pm 1.2\text{ }^{\circ}\text{C}$ ($N=36$), and the range was between 25.4 and $29.5\text{ }^{\circ}\text{C}$. The mean offset between IOSST and the recalculated Sr/Ca-SST was $0.8\text{ }^{\circ}\text{C}$, and that between the satellite SST and the local instrument SST was $1\text{ }^{\circ}\text{C}$; both the satellite SST and the developed Sr/Ca-SST thermometer underestimated the local instrument SST.

For the entire coral slabs, the lowest SST minimum was $21.3\text{ }^{\circ}\text{C}$ and was recorded by the TD-ZYIA-18 coral slab (Tana Delta), whereas the highest SST minimum was $25.2\text{ }^{\circ}\text{C}$ and was recorded by the SMR3-18 coral slab (Shimoni). The minimum SSTs followed the order TD-ZYIA-18 < CA-18 < (TD-ZYIB-18 = RB-18) < SMR3-18. Similarly, the lowest maximum SST was $29.0\text{ }^{\circ}\text{C}$ and was reported from the TD-ZYIA-18 coral slab (Tana Delta), whereas the highest maximum SST was $31.8\text{ }^{\circ}\text{C}$ and was recorded from the SMR3-18 coral slab (Shimoni). The maximum SSTs followed the order TD-ZYIA-18 < TD-ZYIB-18 < RB-18 < CA-18 < SMR3-18 (Table 3). Among the reefs investigated, the Tana Delta coral reef ecosystems recorded the lowest Sr/Ca-SST [$26.8\pm 1.8\text{ }^{\circ}\text{C}$ ($N=84$)], whereas the Shimoni Mupunguti Marine Reserve recorded the highest mean SST [$28.5\pm 1.4\text{ }^{\circ}\text{C}$ ($N=52$)]. Interestingly, the mean recalculated Sr/Ca-SST that was recorded for coral in the Tana Delta coral reef ecosystem almost replicated the literature temperature of $26.5\text{ }^{\circ}\text{C}$ reported by [34] in the northern Kenyan Indian Ocean basin, implying that *Porites* spp. corals are faithful bioindicators of seasonal SST variability [81]. For the case

Fig. 4 Calibration curve $Sr/Ca = f(SST)$ calculated from the Sr/Ca values of TD-ZYIB-18 and IOSST

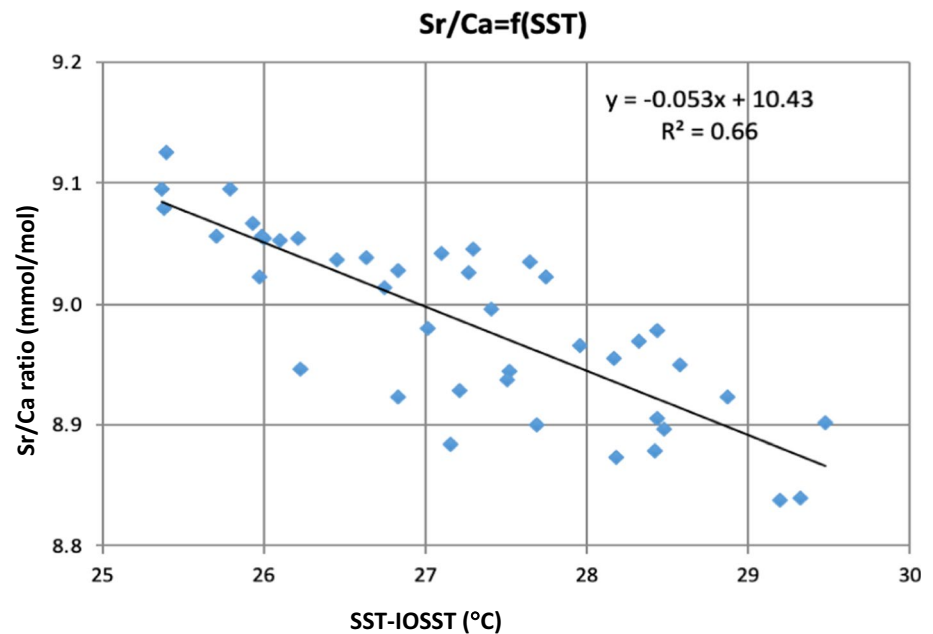


Table 3 Recalculated $SST_{Sr/Ca}$: mean, min, max and mean annual amplitude SSTs in °C

Sampling site	Sample name	Years	Min SST ^a	mean SST ^a	Max SST ^a	Mean annual SST amplitude ^a
Tana Delta	TD-ZYIA-18	2016 to 2017	21.3	25.9 ± 1.9	29.0	6.9 ± 0.3
Ziwayu Island	TD-ZYIB-18	2015 to 2017	24.5	27.3 ± 1.6	30.7	5.0 ± 0.2
Watamu	CA-18	2015 to 2017	23.7	26.9 ± 1.4	31.1	8.04 ± 2.40
Marine Park	RB-18	2016 to 2017	24.5	27.8 ± 1.4	30.8	5.43 ± 1.3
Shimoni	SMR3-18	2015 to 2017	25.2	28.5 ± 1.4	31.8	4.69 ± 0.18
Mupunguti Reef						
All sites		2015 to 2017	21.3	27.4 ± 1.7	31.8	5.47 ± 1.0
Reference SST	Source					
Satellite data	IO-SST	2015 to 2017	25.4	27.3 ± 1.2	29.5	3.6 ± 0.2
Local data	Mombasa (Kilindini)	2015 to 2017	26.3	28.3 ± 1.2	30.7	3.6 ± 0.4

^a present recalculated sea surface temperature (SST) (TD-ZYIA-18, TD-ZYIB-18, CA-18, RB-18, and SMR3-18)

of Watamu National Marine Park, the average Sr/Ca -SST was 27.5 ± 1.5 °C ($N = 95$). A comparison of the mean monthly Sr/Ca -SST values measured at the three sites between 2015 and 2017 revealed that Watamu National Marine Park was 0.7 °C warmer than the Tana Delta. Similarly, the Shimoni Mupunguti Reef ecosystems were 1.0 and 1.7 °C warmer than the SSTs measured in the Watamu and the Tana Delta reefs, respectively, implying that the SST variations increased toward the southern basin of the Kenyan Indian Ocean. ANOVA test of variance revealed that the recalculated monthly SST averages were statistically significant ($F = 8.89$, $p < 0.05$), with the mean SST variation across sites following the order $TD-ZYIA-18 < CA-18 < TD-ZYIB-18 < RB-18 < SMR3-18$ (Table 3).

We also evaluated the seasonal annual median SST, and the results are shown in Fig. S4, whereas the recalculated monthly SST variations are shown in Fig. 5. As shown (Fig. S4), the Sr/Ca -SST annual median varied across and within sites, and the variation was quite significant ($F \geq 4.17$, $p < 0.05$). Similar observations have been reported by several others [e.g., 14, 48, 81, 83]. But of interest, our SST monitoring time window (2015 to 2017), i.e., our coral chronology, coincides with that of the third global coral bleaching [see 31]. We retrogressively recalculated Sr/Ca -SST using the present developed calibration curve to estimate the impact of third global coral bleaching (2015 and 2016) in the investigated coral reef ecosystems by adopting a coral bleaching threshold of 29.5 °C, as used in the work of [31]. The recalculated Sr/Ca -SST results seem to overestimate the coral bleaching threshold SST (Fig. 5), especially in the summer seasons. However, the spatiotemporal variation in the impact of the third global coral bleaching event (2015 to 2017) (Fig. 5) agrees with the

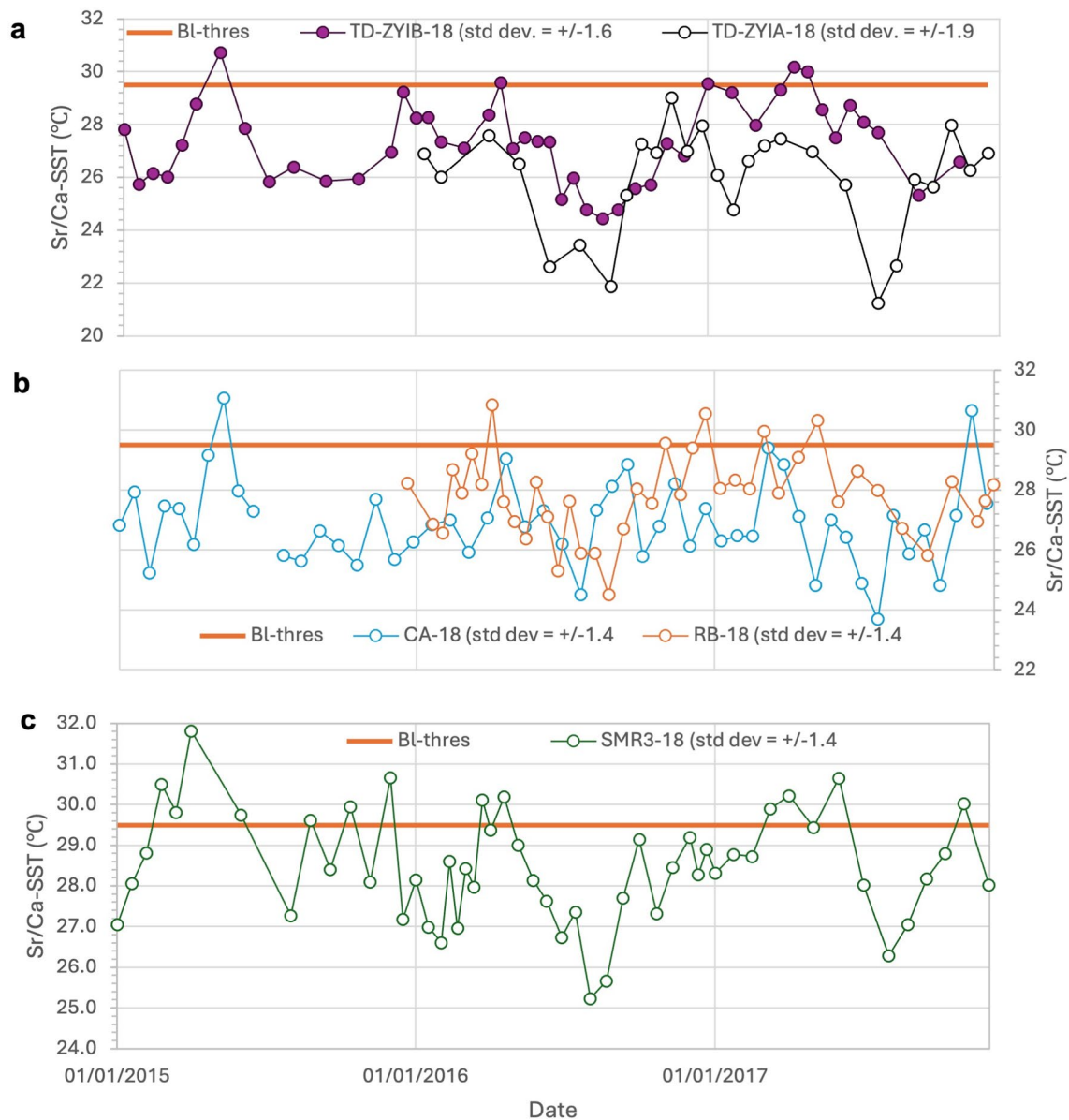


Fig. 5 Recalculated seasonal SSTs from measured Sr/Ca for TD-ZYIA-18 and TD-ZYIB-18 (a), CA-18 and RB-18 (b), and SMR3-18 (c) corals for the period between 2015 and 2017. *Bl-thres* Bleaching threshold temperature

findings reported by [31]. For example, (Fig. 5), the offshore reefs (Fig. 5a) seem to have been lesser impacted by the 2015 and 2016 heat wave episodes than the inshore reefs (Fig. 5b, c). Furthermore, the reefs in the northern basin (Tana Delta Ziwayu Island) were less exposed to extreme heat wave stress than were the reefs in the southern basin of the Kenyan Indian Ocean (Shimoni Mupunguti Marine Reserve). Further, the results on SST spatiotemporal seasonal variation (Fig. 5) agree with the results on the spatiotemporal third global bleaching trends reported by [31]. In support, a study by [31] revealed that, the severity of the third global coral bleaching in 2015 and 2016 was relatively high in the southern basin of the Kenyan Indian Ocean. But with time, the heat wave intensity progressively diminished moving toward the northern basin [31]. It is important to know that, in the northern basin of the Kenyan Indian Ocean, coral are consistently exposed to seasonal riverine discharge [35], especially during the south-easterly monsoon winds [35]. Also, unlike the inshore reefs (Shimoni and Watamu), offshore reefs (Tana Delta) are exposed to pelagic ocean circulation, and such circulations are likely to suppress extreme SST heat wave events. Additionally, the northern basin (Tana Delta) is under the influence of residual impulses of upwelling, especially during northeasterly monsoons [34]. In fact, upwelling is one

of the contributing factors controlling the seasonal SST in the Kenyan northern banks [34, 35], in addition to the seasonal riverine discharge during the south-easterly monsoons [35].

Since the recalculated Sr/Ca-SST overestimated the coral bleaching threshold SST, we further validated our findings by aligning the local monitored instrument SST data ($4^{\circ} 3' 3.76''$ S and $39^{\circ} 38' 43.47''$ E) obtained from the Kilindini Port Meteorological Weather Stations Mombasa with Sr/Ca proxies from the nearest sampling site (SMR3-18) (Fig. 6). As shown (Fig. 6), the severity of the third global bleaching occurred in April and May 2016 (Fig. 6) and agrees with the findings reported by [31]. In Fig. 6, the highest local SSTs were recorded in April 2015 (30.2°C) and 2016 (30.7°C), corresponding to SST anomalies of 0.7 and 1.2°C , respectively, above the coral bleaching threshold.

Although massive *Porites spp.* corals are resilient to extreme SSTs [48, 50], as shown (Fig. 6), the Sr/Ca ratio signals (SMR3-18) reveal a progressive anomalous on upward shift in the Sr/Ca ratio after the (April and May 2016) coral bleaching [31], which, according to [48], is a common observation reflecting extreme thermal stress in the coral skeleton. A study by [48], attributed the upward shift in Sr/Ca during extreme thermal stress with the impairment of the Ca-ATPase enzyme (although still an unresolved issue). According to [48], the enzyme Ca-ATPase under extreme thermal stress becomes inefficient in transporting Ca^{2+} relative to Sr^{2+} and, in turn, leads to an increase in skeletal Sr/Ca [48], which is normally reflected by an upward shift in Sr/Ca signals. Similarly, it has also been suggested that other than extreme SST anomalies, other coral stressors (e.g., sedimentation, nutrition, and impaired light intensity), which are capable of disrupting the total energy budget of the coral, can also alter the rate at which Sr^{2+} and Ca^{2+} ions are transported to the calcifying fluid and could otherwise cause an upward shift in Sr/Ca ratios in the coral skeleton [48].

3.5 Annual linear extension rate

The annual linear extension rate of each coral slab for the period from 2015 to 2017 was calculated from the seasonal cycles of the Sr/Ca ratios measured on each slab, and the results are presented in Table 4. As shown in Table 4, the annual linear extension rate of the investigated coral slabs varied from year to year. For example, from 2015–2017, the growth rate of the coral ranged between 1.0 and 2.2 cm yr^{-1} , and the average linear extension rate was $1.4 \pm 0.4\text{ cm yr}^{-1}$. The coral slabs RB-18, SMR3-18, and TD-ZYIB-18 recorded the highest annual extension rates in 2016, at 2.16 , 2.16 and 1.52 cm yr^{-1} , respectively. Comparing SMR3-18 and TD-ZYIB-18, the surface of the RB-18 coral slab was not always perfectly parallel

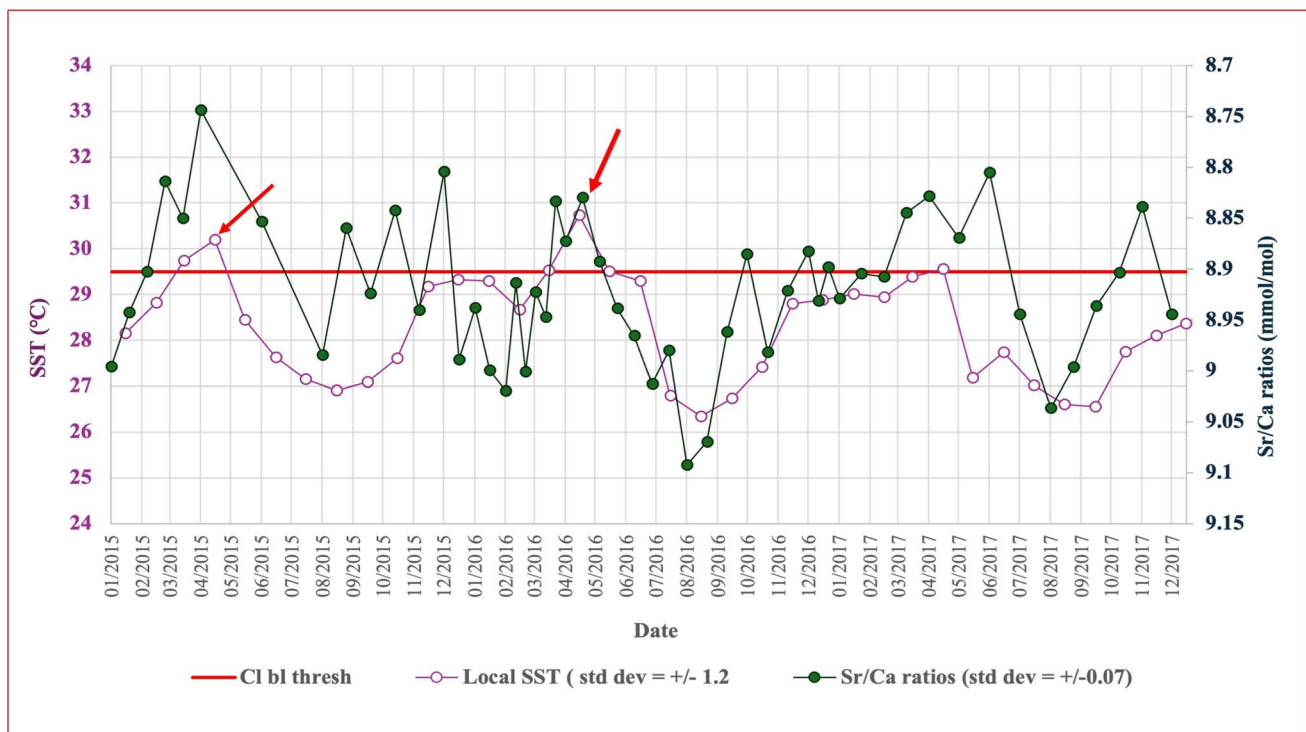


Fig. 6 Impulses of 2015 and 2017 episodic heat waves registered in the SMR3-18 coral slab

Table 4 Annual linear extension rate of each coral sample with the mean annual SST and annual amplitude

Sampling site	Sample name		2015	2016	2017
Tana Delta Ziwayu Island	TD-ZYIA-18	Linear extension rate (cm year ⁻¹)	–	1.04	1.12
		Mean annual SST (°C)	–	26.0	25.8
		Annual amplitude SST (°C)	–	7.1	6.7
	TD-ZYIB-18	Linear extension rate (cm year ⁻¹)	1.12	1.52	1.04
		Mean annual SST (°C)	27.2	27.0	27.9
		Annual amplitude SST (°C)	5.0	5.2	4.8
Watamu Marine Park	CA-18	Linear extension rate (cm year ⁻¹)	1.80	1.70	1.80
		Mean annual SST (°C)	27.0	26.9	26.8
		Annual amplitude SST (°C)	5.8	4.5	7.0
	RB-18	Linear extension rate (cm year ⁻¹)	–	1.76	1.53
		Mean annual SST (°C)	–	27.7	27.9
		Annual amplitude SST (°C)	–	6.3	4.5
Shimoni Mupunguti Reef	SMR3-18	Linear extension rate (cm year ⁻¹)	1.26	2.16	1.26
		Mean annual SST (°C)	29.1	28.0	28.7
		Annual amplitude SST (°C)	4.8	5.0	4.4

to the axis of growth (Fig. S2b). The end of the sampled line was not on the main axis of coral growth but was perhaps slightly inclined.

This may explain the relatively high growth rate of RB-18 corals in 2016, which was most likely overestimated. In contrast, the CA-18 and TD-ZYIA-18 corals presented no difference in their annual growth rates. Unlike the SMR3-18 and TD-ZYIB-18 corals, the CA-18 and TD-ZYIA-18 coral slabs presented no correlation between the yearly growth rate and the yearly SST amplitude for both the IOSST and locally monitored monthly SSTs, as indicated in Table 4, implying that, other than seasonal variability, other factors are in control.

4 Discussion

4.1 Sr/Ca ratio variations

The Sr/Ca ratios measured in coral skeletons from different slabs reproduce seasonal SST cycles quite distinctly (Fig. 3). Despite the small annual amplitudes recorded in Kenya (maximum of 4.5 °C), the characteristics of some years in which 2 minima and 2 maxima were recorded (Fig. S1b). The results confirm that even at low latitudes where seasonal temperature variations are small, the Sr/Ca ratio in corals is a robust proxy of SST [5, 24, 48]. The corals that were collected at the site farthest from the coastal shoreline (Tana Delta Ziwayu Island), approximately 12 km away, show low-noise annual cycles with well-marked maxima and minima (Fig. 3a). These corals are more influenced by natural seasonal ocean conditions and less impacted by local anthropogenic effects (see [61]). However, sometimes at other sites, the Sr/Ca signals measured in the coral skeleton are not as clear and are noisier, making it more difficult to distinguish annual cycles and making it difficult to establish coral chronologies, e.g., Sr/Ca ratio cycles of the coral SMR1-18 (Fig. S3).

SEM observations of the different slabs confirmed the perfect state of preservation of the coral skeletons (Fig. 2). Therefore, the differences in the relationships between Sr/Ca in coral and SST may have three different causes [69]: (i) local anthropogenic environmental conditions [69] (leading to different temperature variabilities compared with instrumental records in the open ocean) or seasonal variations in Sr/Ca ratios in seawater [58], (ii) biological [13, 55] and vital effects [21], or (iii) a combination of all these factors, in addition to other factors [13, 21, 55, 69]. For example, high tourist pressure at some sites, such as (i) the Captain Andy Reef site, located in the inner lagoon west of Mida Creek and near the shoreline, and Richard Bennett in Watamu Marine Park [18], or (ii) the Shimoni Mpunguti reef near the Kisite Mpunguti Marine National Park & Reserve, may have affected the Sr/Ca signals recorded in coral skeletons. In fact, maritime activities have been proven to have diverse sublethal impacts on coral reefs [23], and most likely, they could have been among the causes of noisier Sr/Ca signals. Similarly, industrial activity or intensive agricultural activities in locations sheltered from oceanic circulations tend to compromise the surrounding water quality and modify the SST variability. For example, agricultural chemicals, untreated domestic sewage, and industrial sewage are some of the sources of

Table 5 Published linear Sr/Ca-SST calibrations from regional *Porites* spp.: Sr/Ca (mmol mol⁻¹) = b + a * SST (°C)

Location	SST Product	A	B	r	Mean SST ± SD ^a	References
Kenya	IOSST	-0.053	10.43	0.81	28.6 ± 1.4	Present study
Kenya	AVHRR	-0.066	10.811	0.86	28.8 ± 1.1	[41]
Madagascar	ERSST	-0.048	10.13	0.82	25.2 ± 1.5	[29]
Rodrigues Island	AVHRR	-0.052	10.27	0.79	26.0 ± 1.4	[82]
Mozambique	ERSSTV4	-0.051	10.40	0.93	29.1 ± 1.3	[83]
Kenya	Local (Mombasa)				28.3 ± 1.2 ^b	

^aMean SSTs (°C) at the Shimoni Mupunguti Reef site for the period 2015–2017 calculated from Sr/Ca ratios measured on the SMR3–18 coral

^bMean Mombasa SSTs calculated from local instrument data obtained from Kilindi Port meteorological weather stations for the period from 2015–2017

Table 6 Sr/Ca vs. SST calibration equations published using *Porites* spp. corals from various tropical ocean basins

Location	SST Product	a	B	r ²	References
Pacific Ocean (New Caledonia)	IGOSS	-0.0465	10.19	0.85	[17]
Pacific Ocean (New Caledonia)	Local	-0.062	10.45	0.55	[67]
Pacific Ocean (Tonga)	IGOSS	-0.062	10.65	0.67	[81]
Pacific Ocean (Fiji)	IGOSS	-0.053	10.65	0.77	[42]
Pacific Ocean (GBR Australia)	Local	-0.058	10.40	0.85	[48]
Pacific Ocean (Tahiti)	Local	-0.057	10.53	0.69	[25]
Atlantic Ocean (Floride)	Local	-0.040	10.13	0.59	[5]
Red Sea	AVHRR	-0.055	10.61	0.72	[58]
Eastern Indian Ocean (Christmas Island)	IGOSS	-0.059	10.38	0.69	[47]

nutrients and other contaminants in shallow coral reef environments [10, 61]. Similarly, [63] indicated that Mida Creek, which communicates with Watamu National Marine Park to the west, is highly impacted by changes in land-use practices (e.g., crop farming and pastoralism). Such anthropogenic activities may have an impact on the total energy budget of the coral, and according to [48], and can lead to the impairment of the Ca-ATPase Ca²⁺ pumping mechanism resulting to imbalance of seasonal Sr/Ca signals, a possible reason for the hardly visible annual cycles witnessed in some coral slabs. For example, the amplitudes of the Sr/Ca profile measured in the skeleton of the CA-18 coral slab collected in a highly protected area near Captain Andy's factory, one of Kenya's major boat manufacturers, are very low, and to some extent, the annual temperature cycles are not consistent with the surrounding SST cycles (see Fig. S1a).

A second cause of nonenvironmental origin that is often mentioned to explain the poor inverse correlation between SST and the Sr/Ca ratio is metabolic effects [24, 53, 54, 69]. Thus, in addition to the SST-dependent relationship in the incorporation of Sr/Ca into the *Porites* spp. coral skeleton, studies have shown that biological [54] and physiological factors can impact the incorporation of Sr/Ca into the coral skeleton [13, 54, 68]. These factors are potentially more important in highly anthropized areas and may partly explain the noisy seasonal cycles of the Sr/Ca recordings (CA-18, SMR3-18 or SMR1-18).

4.2 Reliability of Sr/Ca-SST calibration

The Sr/Ca-SST calibration calculated from TDB-ZYIB-18 coral data has a correlation coefficient (*r*) of 0.82, implying that Sr/Ca is a robust paleothermometer. As shown (Tables 5 and 6), the regression slope of the developed calibration equation is within (0.04–0.08 mmol/mol/°C), whereas for the y-intercept, it is within (10 and 11) and is within the limits of the calibration equations published from *Porites* spp. corals from the WIO and other tropical regions [4, 48, 58, 82, 83]. However, when the present calibration equation is compared with that of [41] (Table 5), there is a slight disparity in both the slope and the intercept, which is a common observation reported by several others [3, 7, 32, 39, 48, 58, 81–83]. Such disparities have been associated with differences linked to interlaboratory bias (e.g., methodological differences such as the type of instrument and analytical procedures) [32] and calibration procedures [21]. Here, as in many publications, we opted for the reduced least squares method in developing the present calibration equation.

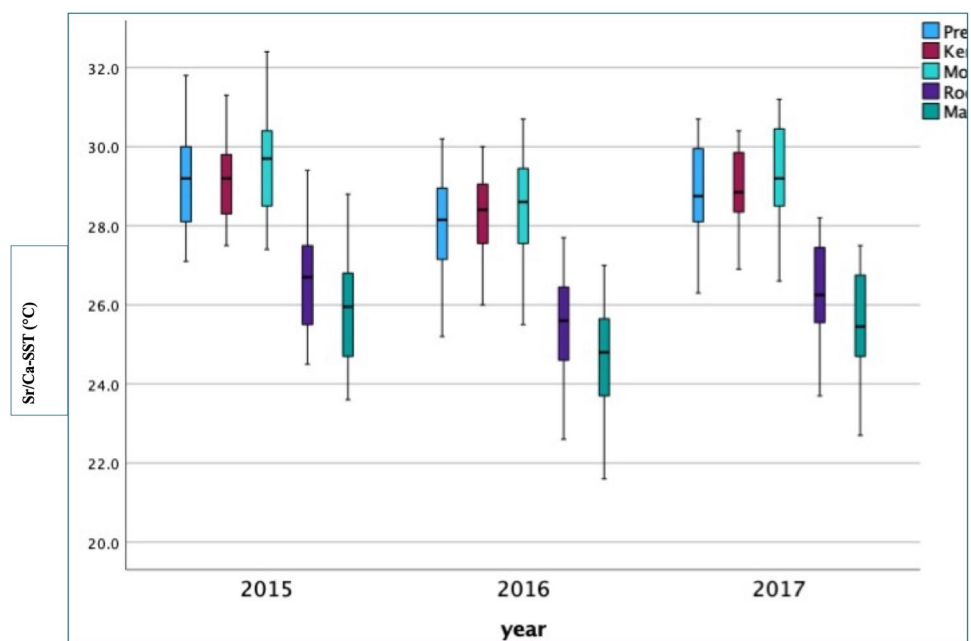
Worthy mentioning, the slope of a calibration curve also depends on (1) the temperature data and (2) the proxy time series [69]. As no in situ local SST measurements were available (Tana Delta Ziwayu Island), we chose gridded reconstructed values and satellite SST values smoothed over a $1^\circ \times 1^\circ$ grid, which may not reflect local temperature anomalies such as local currents, upwelling, or coastal effects [67]. In addition, we preferred to establish a calibration curve offshore (remote and unprotected reef) and less influenced by coastal impacts (TDB-ZYIB-18 coral).

The temperature sensitivity of the present Sr/Ca thermometer ($-0.053 \text{ mmol/mol } ^\circ\text{C}^{-1}$), as already mentioned, is within the range of -0.04 to $-0.08 \text{ mmol/mol } ^\circ\text{C}^{-1}$ of the already published slopes for *Porites* spp. corals in tropical regions [58]. In addition, it is slightly different from the slope reported by [41] but comparable to the temperature sensitivity of $-0.051 \text{ mmol/mol } ^\circ\text{C}^{-1}$ reported by [83] from a coral sampled in the Mozambique Channel (Indian Ocean) (Table 5). A comparison between Indian Ocean thermometers (Table 5) and thermometers from other tropical basins, such as the Atlantic basin, e.g., [5] ($-0.04 \text{ mmol/mol } ^\circ\text{C}^{-1}$) (Table 6), revealed that thermometers developed from coral collected from the Indian Ocean are less sensitive to SST. However, compared with Sr/Ca thermometers derived from the Red Sea, $0.055 \text{ mmol/mol } ^\circ\text{C}^{-1}$, [58] and the Pacific Basin, $-0.062 \text{ mmol/mol } ^\circ\text{C}^{-1}$ [67] and $-0.062 \text{ mmol/mol } ^\circ\text{C}^{-1}$ [81], respectively, are comparable but slightly different from the slope ($0.071 \text{ mmol/mol } ^\circ\text{C}^{-1}$) reported by [17] (Table 6).

To assess the reliability of our Sr/Ca-coral = $f(\text{SST})$ equation and the already published calibration equation in the WIO region. The seasonal Sr/Ca-SST for the SMR3-18 coral slab was reconstructed for the period from 2015 to 2017 using the present and previously published calibration equations from the WIO region. The results obtained were then compared with the local monitored instrumental SST from Mombasa, which was the closest SST for our study site (SMR3-18). As shown (Fig. 7), the present calibration model reproduces the calibration equation developed by [39, 82]. Additionally, the calibration equation from Madagascar [29] tends to reproduce the calibration equation developed by [81]. We conclude that calibration equations developed from similar coral species and geographical locations (latitude) are likely to reproduce each other (Fig. 7). In 2015, the median SST monitored was 27.4°C ; compared with the recalculated Sr/Ca-SST (Fig. 7), the calibration equations developed from coral from lower latitudes (Kenya and Mozambique) overestimated the monitored SST, whereas those from higher latitudes (Rodrigues Island and Madagascar) underestimated the monitored local instrument SST.

Similar observations were also made in 2016 and 2017, where the medians from the monitored SST data were 28.1 and 28.4°C , respectively. ANOVA test of variance for the 3-year monitoring period, revealed a significant seasonal variation in the Sr/Ca-SST ($F = 3.5$ to 3.66 , $P < 0.05$). Additionally, the means of the recalculated SST ($\text{Sr/Ca}_{\text{SMR3-18}}$) and measured local SST in Mombasa for the period from 2015–2017 were compared for all the calibration equations (refer to Table 5). As shown (Table 5), the mean SST calculated via the present calibration equation yielded a mean offset of 0.3°C , whereas the calibration equations developed by [39, 83] yielded mean offsets of 0.5°C and 1.1°C , respectively, relative to the reference SST (local instrument mean SST). More importantly, the mean offsets

Fig. 7 Boxplots showing the variation in the reconstructed Sr/Ca-SST from the SMR3-18 Sr/Ca proxy using the present and previously published coral slabs from the WIO region. *Pre* Present, *Ke* Kenya, *Mo* Mozambique, *Ro* Rodrigues Island, *Ma* Madagascar



posted by the calibration equations developed from the Kenyan coral are within the accuracy limit tolerated for month-resolved SST reconstructions in tropical regions. We conclude that the Kenyan coral reef ecosystems and those found in the Mozambique Channel are likely experiencing similar SST seasonal variability trends; therefore, the calibration curves are Regio specific. In fact, paleo-temperature reconstructions are more accurate if the calibration curve used has been calculated from corals of the same species and from the same region [58]. However, in some cases, slight differences in the calibration equation have been reported from corals obtained from the same colony [see 3, 48, 58].

4.3 SST reconstruction of five Kenyan coral reef ecosystems

The SSTs recalculated from the Sr/Ca records of the five coral reefs (refer to Fig. 5) exhibited different seasonal cycles. In addition to the seasonal variability in temperature, other factors may have played a significant role in influencing SSTs. The coral samples obtained from the offshore environment displayed well-defined SST seasonal cycles (Fig. 5a), which replicated the IOSST (02.5 S and 040.5 E) grid seasonal cycles (Fig. S1a). On the other hand, the inshore coral samples displayed sporadic seasonal monthly SST cycles (Fig. 5b, c). As shown (Fig. 5a), a bimodal seasonal pattern, marked by two distinct interannual seasonal maxima peaks in SST, was evident, with higher maxima occurring from March to April and lower maxima occurring from November to December. The coldest month generally appeared in August. Our results are similar to the results published by [36], with the warmest months observed in April and the coldest months in August from one cell $1^\circ \times 1^\circ$ grid (3.2° S, 40.1° E), implying that corals are faithful archives of climatic records.

However, (Fig. S4), the inshore coral reef ecosystems had the highest recalculated monthly median SSTs compared with those of the offshore reefs. For example, the Shimoni Mupunguti Marine Reserve, which is located near the shoreline, recorded the highest recalculated SST_{Sr/Ca} median for the three consecutive years, whereas the Tana Delta (TD-ZYIA-18), an offshore reef, had the lowest SST median. A close look at the seasonal monthly concentrations of Sr/Ca ratios at Tana Delta Ziwayu Island revealed consistency in the Sr/Ca ratios between the two coral slabs (TD-ZYIA/B-18) (Fig. 3a). Since coral reef environments are shallow (refer to Table 1), with a relatively small mass of water, the SST in such environments is relatively high compared with that in offshore reef environments. In some cases, reports on SSTs greater than 30 °C have been reported from shallow coral habitats. It's worth noting, SSTs above the coral bleaching threshold are likely to trigger coral bleaching [31]. However, in addition, there is the residual impact of downwelling [38] in the southern basin of the Kenyan Indian Ocean, whose magnitude remains to be determined. Downwelling is a seasonal phenomenon that is characterized by warmer SST conditions and could partly explain the variation in the increase in SST moving toward the southern basin of the Kenyan Indian Ocean.

In the case of the Tana Delta, reefs are under the influence of the seasonal freshwater plumes discharged by the Tana River, especially during the south-easterly [35, 60], when inland rainfall, runoff, and riverine discharge are at their highest peak [37, 38]. Additionally, there is a residual effect of upwelling during northeasterly monsoons [34, 35]. During upwelling, there is the upthrust of cold-water currents from the thermocline zone to the water surface, and through vertical mixing, the SST is suppressed; in most cases, this is reflected by an abrupt upward shift in the Sr/Ca ratio values (refer to Fig. 3a). In addition to upwelling and riverine discharge, [48] added that coral stressors that can disrupt the net energy budget in a coral can also cause an upward shift in the Sr/Ca ratios records in the coral skeleton. For example, a sharp decrease in the recalculated SST (< 25 °C) (Fig. 5a) is observed in the Tana Delta (TD-ZYIA-18) and coincides with the south-easterly monsoon. In support of these findings, a study by [35, 37, 38] implicated the southeasterly monsoon winds, with local runoff, floods and riverine discharge. These mentioned coral drivers are potential vectors controlling the sediment budget in the water column of River Tana [35, 37, 62], which in turn controls the nutrient levels in the same water columns [60, 62]. However, with the construction of dams along the Tana River, the seasonal river discharge regime has been modified and has shifted from May to June to early July and August [28]. Nevertheless, since corals are highly sensitive [74], in addition to solar radiation, human activities may also be a contributing factor influencing Sr/Ca-SST records in the coral skeleton and may be reflected by extreme sporadic signals in Sr/Ca-SST records [29].

For example, a large volume of sewage discharged in a shallow marine environment can consequently alter the water quality of the surrounding area by suppressing the sea surface temperature, especially during low tides or in a confined lagoon. In addition, the running of a boat engine in a shallow marine environment (leisure) is likely to radiate heat into the surrounding water, and these heat waves can certainly be recorded by the coral skeleton.

Such acute (pulse) records are likely to feature in coral records, especially in areas that are impacted by coastal city urbanization and tourism activities (Watamu and Shimoni coral reef ecosystems).

4.4 Linear extension rate

The mean annual growth rates calculated from the Sr/Ca cycles measured in our coral samples are between 1.12 and 1.85 cm/year (Table 1). These annual means are within the global mean value of 1.2 cm/year measured for massive corals [1] and close to the mean annual values measured for corals collected (1) on Europa Island, Mozambique Channel (1.23 and 1.28 cm/year, [83] or (2) East Madagascar (1.4 and 1.8 cm/year, [29]). Finally, they are also comparable to the growth rates estimated from X-rays by [30] between 0.6 and 1.5 cm/year from cores collected in 1997 along the Kenyan coast at depths between 1 and 4 m.

As shown in Table 4, there are inter- and intracolony variations in the linear extension rate, which is a common observation [e.g., 1, 9, 16, 26, 27, 59, 77]. Environmental parameters (SST, light, sediment level, upwelling) and anthropogenic impacts are the main factors affecting the linear extension rate of the coral skeleton [44]. Several studies have shown that the linear extension rate of corals depends on the SST [1, 59], revealing that the linear extension rate of a coral is higher in a warmer environment, i.e., the summer, than in a cold environment [9], i.e., the winter. As the areas where our corals were collected are close to the equator, the minimum temperatures recorded are most often above 24 °C. We can therefore assume that coral growth was regular throughout the year. Only the TD-ZYIA-18 coral, for which we measured relatively high Sr/Ca values and therefore minimum temperatures of approximately 21–22 °C, presented relatively low annual growth rates. The average annual SST can sometimes explain more than 70% of the variance in the linear extension rate [44]. SST is also mentioned as being able to have a positive [44, 45], a negative [78] or no influence on the growth rate of corals [83]. Furthermore, a thermal optimum of 26.7 °C was measured by [16] for *Porites* from the northern Great Barrier Reef; above this temperature, the positive effect of SST on the *Porites* growth rate can be reversed. The high SSTs, often greater than 27 °C, recorded at each of our coral collection sites in Kenya do not appear to have had any influence on the growth rates measured in the corals. Even maxima more than 30 °C did not slow their growth rates. Studies have shown that *Porites* spp. corals could be more resilient to elevated SSTs than other species [83].

In addition to the SST [77], other factors have been reported to control the linear extension rate in corals. For example, light intensity controls photosynthesis, the main source of energy required for calcification in coral [16, 43, 78]. A warmer environment with high light intensity is more favorable for algae photosynthesis processes [29]. A decrease in light intensity is often related to increasing depth, and several authors [9, 44] have evaluated the influence of this parameter on the mean annual growth rate of corals. According to [1], there is an inverse relationship between the linear extension rate and depth, which is associated with a decrease in the light intensity and photosynthesis activities of coral algae. Some studies have shown that for *Porites* spp. corals collected at depths of < 10 m or even < 20 m, depth has a limited impact on the annual growth rate, and an optimal extension rate is often observed between 5 and 10 m, where the water is still very clear and sometimes less turbulent [43]. Our coral samples were collected in shallow waters (< 4.5 m), and the results revealed no correlation between depth and the mean annual linear extension (Table 1). For example, RB-18, collected at a depth of approximately 4 m, grew at a relatively high rate or was comparable to other corals collected at relatively shallow depths.

Similarly, high levels of sediment particles [19], which also result in reduced light levels, can be stressful for corals and cause a decrease in their growth rate [9, 19, 73]. A study by [35] reported high sediment outflow (and turbidity) in water columns in the northern Kenyan Indian Ocean (Tana Delta), especially during the south-easterly monsoon winds, which are caused by seasonal river discharge by the Tana River, could partly explain the lower linear extension rates measured annually on the corals of the Tana Delta Ziwayu Island, TD-ZYIA-18 (1.08 cm year⁻¹) and TD-ZYIB-18 (1.23 cm year⁻¹).

As shown above (Fig. 1), the sampling site Captain Andy (CA) is highly protected by mangroves and is also enclosed compared with the Richard Bennett (RB) site. The buffer zone and the enclosed lagoon create a more microstatic environment at Captain Andy that is free from pelagic ocean circulation. Carbon recycling and enrichment of the surrounding marine water column with dissolved organic carbon (DOC) are important ecological benefits of mangrove buffer zones in catchment areas (e.g., creeks and estuaries) and shallow marine environments [4, 46]. A study by [56] reported a positive correlation between the linear extension rate and DOC from in vitro experiments. According to the findings of [56], high DOC induced 42% growth in massive corals. Thus, the high DOC in mangroves and the constant annual SST may explain the high and constant annual growth rates measured for the coral slab CA-18 between 2015 and 2017. Finally, on the basis of our 3-year records, determining the % impact of anthropogenic effects with

authority is slightly difficult. However, it is impossible to refute that the impact of (tourists, maritime activities, and coastal urbanization) influences the annual growth rates of RB-18, CA-18, and SMR-3-18 coral slabs.

5 Conclusion

The massive *Porites* spp. coral proves to be a reliable archive for high-resolution sea surface temperature reconstruction from Sr/Ca analysis of its skeleton, even at low latitudes, in regions where SSTs vary little throughout the year. Another Sr/Ca-SST calibration from Kenyan coral was established to monitor SSTs in coral reef ecosystems, with high resolution and greater accuracy. We checked and validated the accuracy of the developed Sr/Ca-SST calibration using *Porites* spp. coral slab SMR3-18 with locally monitored Mombasa instrument data, which yielded a mean offset of 0.3 °C. We also established that the reconstructed SST increases moving from the northern basin to the southern basin. Additionally, the southern reefs were more exposed to warmer conditions (above the coral bleaching threshold than were the reefs in the northern basin). The present Sr/Ca-SST calibration equation reproduces the calibration published by [42, 83] (lower latitude) (see Fig. 6). The thermometers developed by [29, 82] (higher latitudes, WIO) underestimated the local instrument SST and hence are unreliable.

The linear extension rates of the present corals were within the average measured range for *Porites* spp., although the Kenyan corals are often exposed to elevated seasonal SSTs greater than 28 °C or even 30 °C. Although the Sr/Ca thermometer seems to be a reliable tool for monitoring and deciphering climate variability, there is a need to reconstruct SST variability over a wider time window, especially from coral reef ecosystems in northern and southern China, where upwelling and downwelling are dominant, respectively. With increased coral records, monitoring the recurrent impact of episodic heat wave events in the general context of global warming, in addition to upwelling and downwelling, is more likely to be achieved.

5.1 Recommendation

There is already ongoing collaborative research between Pwani University and the Institute of Research and Development (IRD), France, whose main focus is to develop a Sr/Ca thermometer that can allow a more precise and elaborate assessment of upwelling (northern reefs), downwelling (southern reefs), and SST evolution in the Kenyan coral reef ecosystems over the past decades.

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Data availability We declare that the data of this research will be made available upon request or upon publication.

Declarations

Competing interests The authors declare no competing interests.

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