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A multicoral calibration method to approximate a universal equation relating Sr/Ca and growth rate to sea surface temperature

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[1] Combining strontium-to-calcium ratios (Sr/Ca) with mean annual growth rates in Bermuda *Diploria labyrinthiformis* (brain corals) is shown to improve sea surface temperature (SST) calibrations relative to instrumental data. Growth-corrected Sr/Ca–SST calibrations based on single-coral colonies over the same calibration interval, however, are found to be poorly suited for application to data from different coral colonies. This raises concerns about the accuracy of SST reconstructions from fossil coral measurements that involve extrapolation beyond the range of values seen during the calibration period. Here we pursue a novel approach to this problem by incorporating data from multiple coral colonies into a single growth-corrected Sr/Ca–SST calibration equation, effectively expanding the range of modern values constraining the model. The use of a multiple-colony calibration model for reconstructing SST yields greater precision and accuracy relative to instrumental data than single-colony models, providing greater confidence for applications to fossil coral samples.

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1. Introduction

[2] Understanding long-term climate variability requires the reconstruction of key climate parameters, such as sea surface temperature (SST), in records extending beyond the relatively short instrumental period. The high accretion rates, longevity, and annual growth bands found in coral colonies make this an ideal resource for well-dated, seasonal-resolution climate reconstructions. One method used for quantifying past temperature changes from corals involves the inverse relationship between SST and the strontium (Sr) to calcium (Ca) ratio in coral skeleton [*Smith et al.*, 1979]. Typically, this method relies on obtaining a linear regression of Sr/Ca on SST from a modern coral colony and then applying this calibration to Sr/Ca measurements from fossil samples [*Beck et al.*, 1992, 1997; *Correge et al.*, 2004; *McCulloch et al.*, 1999]. However, in many cases reconstructions of past SST from coral Sr/Ca ratios are several degrees cooler than other marine proxies such as alkenones or foraminiferal Mg/Ca [e.g., *Lea et al.*, 2000; *Pelejero et al.*, 1999; *Rosenthal et al.*, 2003]. Part of this discrepancy may be due to differences in seasonality, differences in the depth at which various proxies record SST, or influences from other environmental factors.

[3] Nevertheless, it has been observed that correlations of coral Sr/Ca to SST vary between individual colonies, time periods, and species [*Alibert and McCulloch*, 1997; *deVilliers et al.*, 1995; *Marshall and McCulloch*, 2002; *Swart et al.*, 2002]. Differences between coral colony Sr/Ca–SST calibrations have been previously investigated, and proposed sources of error include variations in Sr and Ca concentrations of seawater, particularly in areas of upwelling [*Alibert and McCulloch*, 1997; *deVilliers et al.*, 1994; *Marshall and McCulloch*, 2002; *Shen et al.*, 1996]; the veracity of the instrumental or calibration SST record [*Crowley et al.*, 1999; *Marshall and McCulloch*, 2002]; imprecise age models [*Swart et al.*, 2002]; biological and symbiotic effects [*Cohen et al.*, 2002; *deVilliers et al.*, 1995; *Ferrier-Pages et al.*, 2002]; and the length of the calibration period [*Goodkin et al.*, 2005]. In addition, several studies have indicated that growth rate and/or calcification rate may act as an additional influence on Sr/Ca ratios [*Alibert and McCulloch*, 1997; *Cohen and Hart*, 2004; *deVilliers et al.*, 1995; *Ferrier-Pages et al.*, 2002; *Goodkin et al.*, 2005; *Weber*, 1973]. In a recent study of corals with slow growth rates, the use of a multivariant regression of Sr/Ca to SST and extension (growth) rate was shown to improve SST reconstructions over the instrumental calibration period [*Goodkin et al.*, 2005]. In addition, applying this regression to a record back to 1775 AD resulted in SST changes consistent with other marine proxies [e.g., *Keigwin*, 1996]. These studies indicate that growth rate can be an important factor to consider when examining Sr/Ca in modern and fossil corals. However, the concern remains that measurements of past coral growth rates often fall well outside the range seen during the instrumental interval, and thus require extrapolation beyond the constraints of the observed modern calibration relationship. One way to minimize uncertainties due to extrapolating beyond the calibration range is to utilize data simultaneously from several coexisting corals with different growth rates. In addition to extending the range of modern values for comparison, using multiple colonies for calibration can also serve to average

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away uncertainties due to dating errors and individual metabolic effects. For example, averaging Sr/Ca measurements from multiple corals prior to calibration [*Stephans et al.*, 2004] or averaging coefficients from two or more single-colony calibrations [*Alibert and McCulloch*, 1997; *Smith et al.*, 1979] have previously been shown to reduce errors in reconstructed SSTs.

[4] Here we present a unique approach to coral Sr/Ca–SST calibration, combining data from multiple corals into a single multivariate regression in an effort to derive a universal equation that can be applied with equal confidence to any modern or fossil coral from the same location. Combining multiple colonies into a single SST calibration expands the range of Sr/Ca and growth rate values applied to the calibration, minimizing extrapolation beyond modern coral values during reconstructions of past SST. We demonstrate that a calibration using multiple colonies results in increased accuracy and precision for Sr/Ca–based SST reconstructions. In this study, multivariate regressions of Sr/Ca to SST and growth rate ("single-colony" growth-corrected model) were performed on several colonies of massive *Diploria labyrinthiformis* from Bermuda, following the method of *Goodkin et al.* [2005]. In addition, a similar multivariate regression was performed using measurements from multiple colonies simultaneously ("multicolony" model) to provide a single calibration equation. The multicolony and single-colony calibration models were applied to data from each individual colony, and reconstructed SST was compared to instrumental SST over the calibration interval to determine the method that provides the most accurate and precise reconstruction.

2. Methods

2.1. Study Site

[5] In April 1999, three 30–50 year old brain corals (*Diploria labyrinthiformis*) (BER 002, BER 003, and BER 004) were sampled live off John Smith's Bay (JSB) on the southeastern edge of the Bermuda platform at 16-m depth. A fourth, ~230 year old coral (BB 001) was sampled live from the same location in May of 2000. *Diploria labyrinthiformis* was chosen for this study because slow growth rates combined with multicentury life spans and large geographical distribution from tropical to subtropical waters makes this species a promising source of paleoceanographic information. Growth rates from brain corals in this region vary from 2–6 mm/yr [*Dodge and Thomson*, 1974; *Goodkin et al.*, 2005; *Logan and Tomascik*, 1991], much slower than more commonly used species such as *Porites*, which exhibits growth rates from 8–20 mm/yr [*Alibert and McCulloch*, 1997; *Hughen et al.*, 1999; *Shen et al.*, 1996].

[6] The south terrace of Bermuda provides exposure to open ocean waters and proximity to instrumental data from Hydrostation S, located 30 km to the southeast. At Hydrostation S, SST from 0–16 m depth has been recorded biweekly since 1954. Over that time, monthly averaged SST ranged from 18.0 to 28.9°C with annual averages between 22.4 and 24.3°C. The calibration period of this study (1976–1997) has mean annual SST ranging from 22.8 to 23.5°C with a seasonal range of 18.3 to 28.9°C. The SST record is incomplete over different intervals including two or more months of missing data in the years 1978–1980, 1986, and 1989, and subsequently these years are omitted from the mean annual calibrations.

2.2. Subsampling and Analysis of Coral

[7] Corals were sliced into ~1 cm thick slabs along the growth axis using a diamond blade rock saw and cleaned in an ultrasonic bath [*Goodkin et al.*, 2005]. X radiographs were performed at Falmouth Hospital (Falmouth, Massachusetts) with machine settings of 50kV and 1.6 mAs, a film focus distance of 1 m and exposure time of 0.2 s. X rays for BB 001 and BER 002 are given by *Goodkin et al.* [2005] and *Cohen et al.* [2004], respectively. X radiographs for BER 003 and BER 004 are shown in Figure 1.

[8] Samples for Sr/Ca analysis were drilled along the solid thecal wall separating the ambulacrum from the calyx following the methods of *Goodkin et al.* [2005]. For the calibration period (1976–1997), BER 002, 003, and 004 were sampled every 0.25 mm and BB 001 was sampled every 0.33 mm, using a drill press and micrometer controlled stage. An Inductively Coupled Plasma–Atomic Emission Spectrometer (ICP-AES) at the Woods Hole Oceanographic Institution (WHOI) was used to measure Sr and Ca simultaneously, applying solution standards to correct for drift and matrix effects related to interference from varying Ca concentrations following the methods of *Schrag* [1999]. The unknowns, blanks and samples of external standard (a homogenized, powdered *Porites* coral) were prepared simultaneously. Repeat measurements on the coral external standard over 12 months showed good reproducibility (RSD = 0.3%, n = 847).

[9] Over the calibration interval, age models and annual extension rates for all corals were developed using density banding visible in the X radiographs (Figure 1), followed by assigning Sr/Ca to monthly averaged SSTs at maxima, minima and inflection points [*Goodkin et al.*, 2005]. Sr/Ca was then interpolated in order to resample at even monthly increments, and mean annual Sr/Ca was calculated by averaging the interpolated monthly values. Average extension rates for each colony used in the multicolony correlation exercises were calculated based on the entire length of the colony (Table 1).

3. Results

3.1. Seasonal Cycle

[10] All four corals show strong seasonal cycles in Sr/Ca (Figure 2). Type-I linear regressions of monthly resolved Sr/Ca ratios to SSTs yield relatively consistent correlations among the four corals:

Table 1. Average Extension Rates for the Colony and the Period of Calibration

Coral	Average Extension Rate, mm/yr	Time Period of Calibration
BB 001	3.8	1977–1997
BER 002	3.2	1976–1996
BER 003	4.2	1976–1997
BER 004	2.1	1976–1997

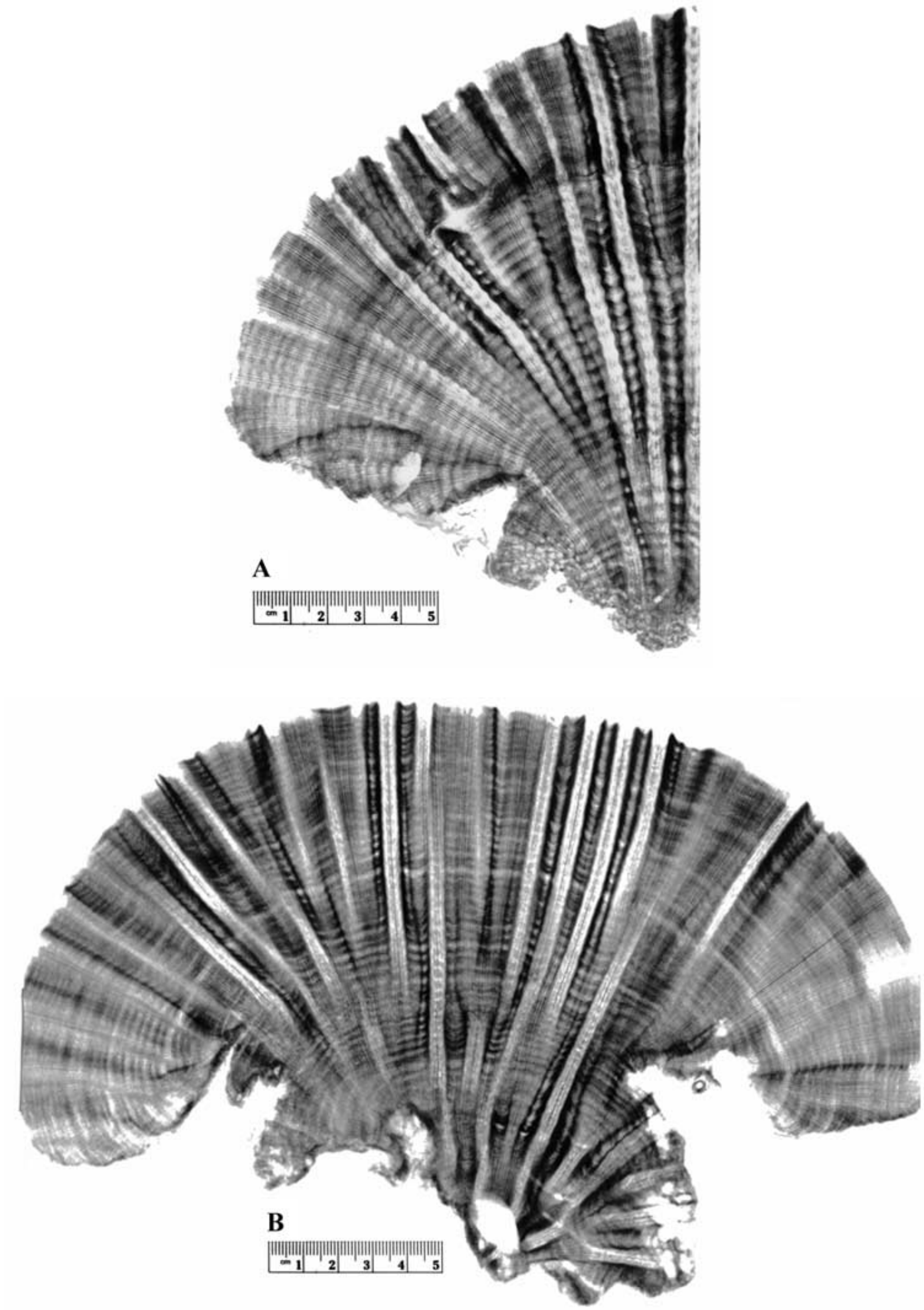

Figure 1. X-radiograph positive image of (a) BER 003 and (b) BER 004. X rays show clear annual banding made up of a low- and high-density band.

BB 001
Sr/Ca = 10.1 (±0.04) − 0.0358 (± 0.0018) * SST [*Goodkin et al.*, 2005]
(2σ, 95% conf., $r^2 = 0.86$, $F_{sig} \ll 0.0001$)

BER 002
Sr/Ca = 10.1 (±0.07) − 0.0376 (±0.0030) * SST
(2σ, 95% conf., $r^2 = 0.73$, $F_{sig} \ll 0.0001$)

BER 003
Sr/Ca = 10.3 (±0.06) − 0.0436 (±0.0024) * SST
(2σ, 95% conf., $r^2 = 0.85$, $F_{sig} \ll 0.0001$)

BER 004
Sr/Ca = 10.3 (±0.07) − 0.0429 (±0.0029) * SST
(2σ, 95% conf., $r^2 = 0.76$, $F_{sig} \ll 0.0001$)

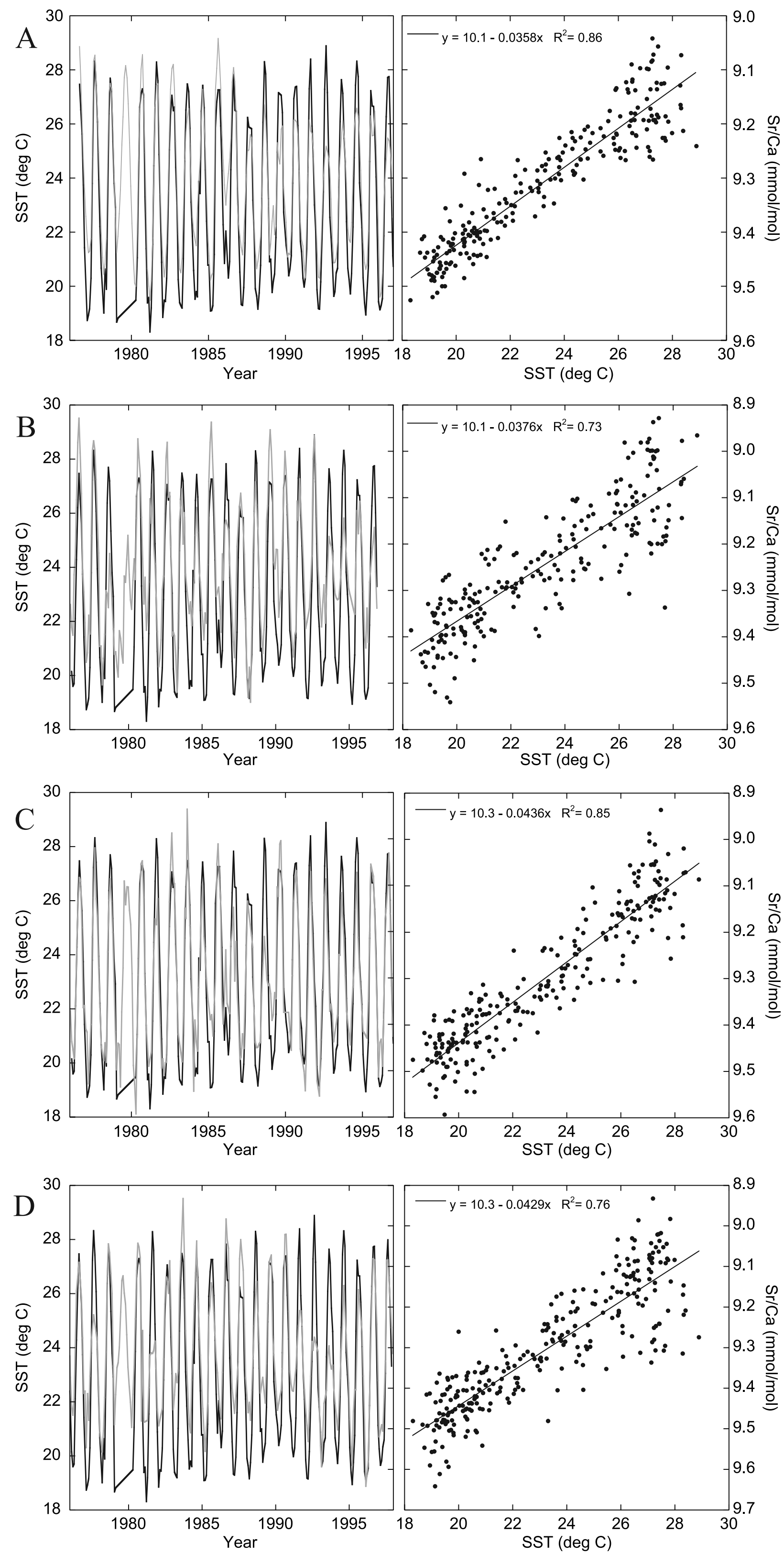

Figure 2. Coral Sr/Ca (shaded) and Hydrostation S SST (solid) at monthly resolution plotted versus (left) year and correlated (right) using linear regression. Calibration results for (a) BB 001 (r^2 = 0.86), (b) BER 002 (r^2 = 0.73), (c) BER 003 (r^2 = 0.85), and (d) BER 004 (r^2 = 0.76).

These results are consistent to one another and to other slow to moderately growing corals [*Bagnato et al.*, 2004; *Cardinal et al.*, 2001; *Swart et al.*, 2002]. A larger variance in summer Sr/Ca values than in winter in all four corals suggests a growth effect on the summer Sr/Ca values, as previously found for BB 001 [*Goodkin et al.*, 2005]. Smoothing of the seasonal cycle, as previously identified for bulk sampling methods in slow growing corals, is seen in these colonies, rendering the seasonal calibration ineffective for reconstructing SST back through time [*Cohen and Hart*, 2004; *Cohen et al.*, 2004; *Goodkin et al.*, 2005].

3.2. Interannual Calibrations

[11] Mean annual Sr/Ca regressed (type I) upon mean annual SST shows a significantly reduced correlation coefficient for all four corals relative to the seasonal correlations (Figure 3):

BB 001
$$Sr/Ca = 10.4\ (\pm 1.2) - 0.0481\ (\pm 0.0503) * SST$$
$(2\sigma$, 95% conf., $r^2 = 0.21$, $F_{sig} = 0.0766$, RMSR = 0.5°C)

BER 002
$$Sr/Ca = 11.2\ (\pm 1.5) - 0.0844\ (\pm 0.0666) * SST$$
$(2\sigma$, 95% conf., $r^2 = 0.31$, $F_{sig} = 0.0238$, RMSR = 0.4°C)

BER 003
$$Sr/Ca = 10.3\ (\pm 1.3) - 0.0451\ (\pm 0.0544) * SST$$
$(2\sigma$, 95% conf., $r^2 = 0.15$, $F_{sig} = 0.1180$, RMSR = 0.6°C)

BER 004
$$Sr/Ca = 9.33\ (\pm 2.23) - 0.00005467\ (\pm 0.0964689) * SST$$
$(2\sigma$, 95% conf., $\ll 0.0001$, $F_{sig} = 0.9991$, RMSR = not relevant)

where RMSR is the root-mean-square of the residual.

[12] Previous work has demonstrated that growth rate influences do not impact the summer and winter season equally [*Goodkin et al.*, 2005]. In that work, changes in mean annual growth rates were shown to correlate strongly with anomalous summer and mean annual Sr/Ca values. Incorporating annual growth rate data into a single-colony, multivariate regression of mean annual Sr/Ca onto SST resulted in an improved calibration with reduced residual SSTs. The poor correlation observed here in the mean annual calibrations for each of these corals, combined with the larger spread in summer Sr/Ca relative to winter Sr/Ca values (Figure 2), implies that a similar effect may be impacting the Sr/Ca–SST relationship.

[13] A growth corrected mean annual model following the method of *Goodkin et al.* [2005], was therefore fit to each of the four corals to evaluate the influence of growth on the calibration of Sr/Ca versus SST. The following correlations were found:

BB 001
$$Sr/Ca = -0.0529\ (\pm 0.0334) * SST - 0.00170\ (\pm 0.00078) * (\text{growth rate}) * SST + 10.7\ (\pm 0.8)$$
$(2\sigma$, 95% conf., $r^2 = 0.68$, $F_{sig} = 0.0006$, RMSR = 0.2°C)

BER 002
$$Sr/Ca = -0.0906\ (\pm 0.0679) * SST - 0.000522\ (\pm 0.001060) * (\text{growth rate}) * SST + 11.4\ (\pm 1.6)$$
$(2\sigma$, 95% conf., $r^2 = 0.36$, $F_{sig} = 0.0538$, RMSR = 0.3°C)

BER 003
$$Sr/Ca = -0.0502\ (\pm 0.0573) * SST + 0.000543\ (\pm 0.001584) * (\text{growth rate}) * SST + 10.4\ (\pm 1.3)$$
$(2\sigma$, 95% conf., $r^2 = 0.18$, $F_{sig} = 0.2441$, RMSR = 0.5°C)

BER 004
$$Sr/Ca = -0.000201\ (\pm 0.092689) * SST - 0.00194\ (\pm 0.00259) * (\text{growth rate}) * SST + 9.4\ (\pm 2.1)$$
$(2\sigma$, 95% conf., $r^2 = 0.14$, $F_{sig} = 0.3525$, RMSR = 8.2°C)

BER 004 fails to show enough improvement in the growth corrected model to be used to reconstruct SST. BER 004 has the slowest average annual extension rate (2.1 mm/yr) by more than one mm/yr. A correlation of mean annual Sr/Ca to average annual extension in BER 004, with an r^2 of 0.21 and an F_{sig} of 0.0337, shows a stronger correlation than does Sr/Ca to SST, with an r^2 of $\ll 0.0001$ and an F_{sig} of 0.9991. The inability to model the Sr/Ca–SST thermometer at the mean annual level in BER 004 is an indication that extremely slow growing corals are not suitable for bulk sampling of this resolution and should be avoided when both calibrating and reconstructing SST by this sampling method. These results warrant further study of corals growing consistently at or below 2mm/yr, as BER 004 does in the last 10 years of the calibration.

[14] In contrast to BER 004, the growth-corrected models of BB 001, BER 002, and BER 003 more accurately reconstruct SST, decreasing the root-mean-squares of the residuals in all cases (Table 2). BB 001 shows increased significance for the relationship ($F_{sig} = 0.0006$, growth, and 0.0766, nongrowth), an improved r^2 (0.68 compared to 0.21) and a strong significance for the added term (p = 0.00078). For BER 002 and 003, the explained variance (r^2) in Sr/Ca for the growth-corrected model increases slightly from 0.31 to 0.36 and 0.15 to 0.18, respectively. The significance of the equations, however, do not improve in either case from the mean annual model to the growth-corrected model, and neither coral shows statistical significance for the added term accounting for interannual growth rate (p = 0.34 and 0.50 for 002 and 003, respectively).

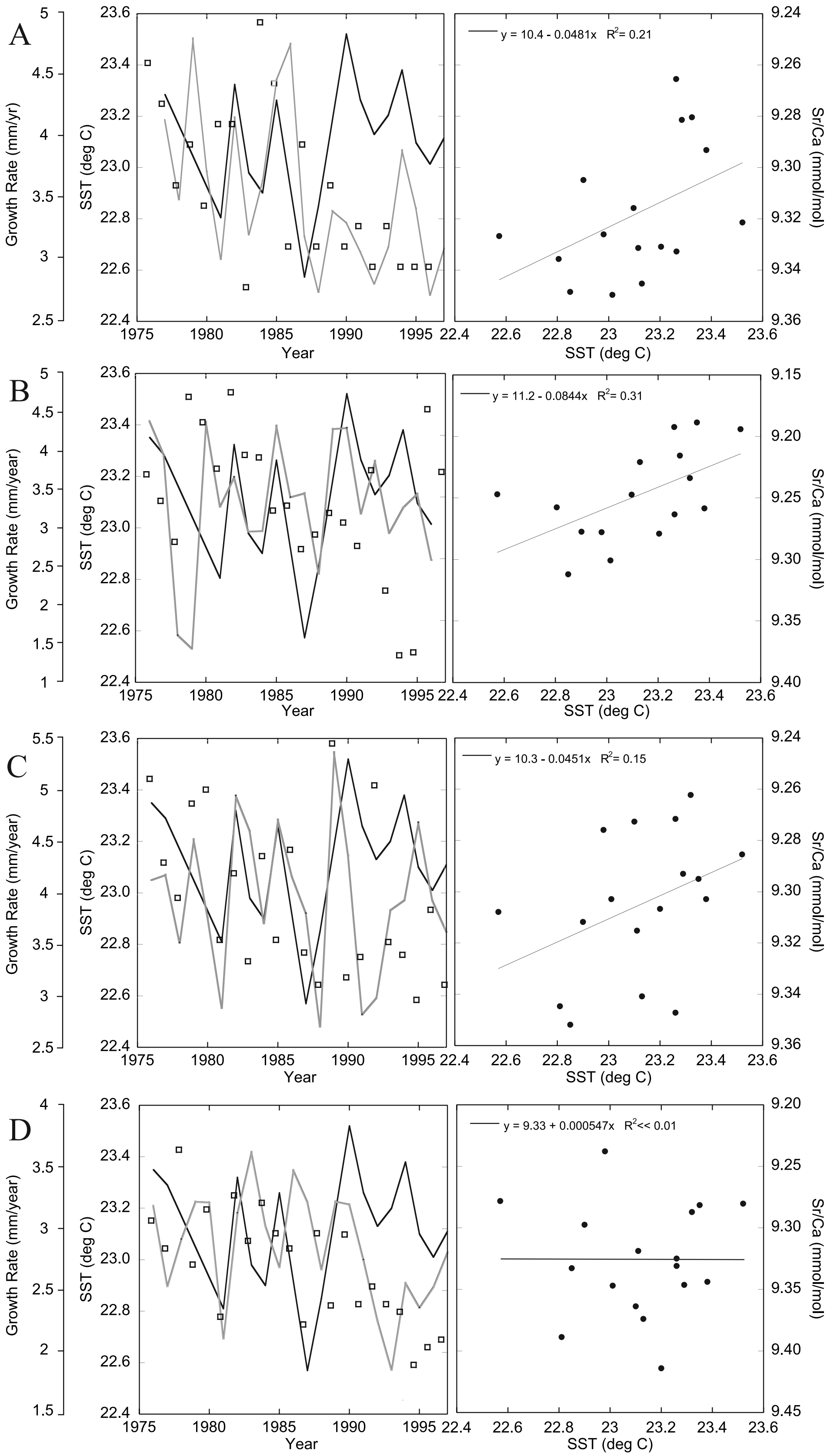

Figure 3. Coral Sr/Ca (shaded) and Hydrostation S SST (solid) at mean annual resolution plotted versus (left) year and correlated (right) using linear regression. Calibration results for (a) BB 001 ($r^2 = 0.21$), (b) BER 002 ($r^2 = 0.31$), (c) BER 003 ($r^2 = 0.15$), and (d) BER 004 ($r^2 \ll 0.01$).

Table 2. Root Mean Squares of the Residuals Generated by Each Calibration/Model Applied to Each Coral and to the Group as a Whole[a]

Calibration	BB 001	BER 002	BER 003	Group
MultiColony	0.43	0.47	0.47	0.46
BB 001				
Growth corrected	0.24	1.53	0.53	0.94
Mean annual	0.46	1.59	0.58	1.00
Monthly	0.65	2.00	0.72	1.28
BER 002				
Growth corrected	0.81	0.32	0.77	0.67
Mean annual	0.88	0.43	0.74	0.71
Monthly	1.89	0.88	1.60	1.52
BER 003				
Growth corrected	0.65	1.24	0.51	0.86
Mean annual	0.56	1.45	0.55	0.95
Monthly	0.62	1.40	0.57	0.94

[a]Root mean squares of the residuals are given in °C. Values are reported to the 100th decimal place for comparison purposes.

[15] More importantly, the growth-corrected model, when applied to corals 001, 002, and 003, fails to establish a single equation that can be applied reliably for all modern and, by inference, fossil corals; that is, the slopes and intercepts of the three equations are not consistent (Figure 4). This leads to the conclusion that interannual growth rate is not accounting for all of the differences found between these individual corals. An alternate hypothesis is required in order to link the different corals together into a single relationship.

[16] Following the general form of the growth-corrected model,

$$Sr/Ca = m_1 * (\text{interannual growth}) * SST + m_2 * SST + b_0 \quad (1)$$

We observe that m_2 (the SST slope) reveals a correlation to the average growth rate (r^2 = 0.89) for the three colonies (Figure 4a), which in turn influences the values of the intercepts (b_0) (Figure 4b). Thus the intercept also shows a strong correlation to average growth rate (r^2 = 0.98). M_1, which already accounts for a growth rate influence, shows relatively little correlation to average growth rates (Figure 4c) (r^2 = 0.13). Three points do not allow for a statistical evaluation of these observed relationships or determination of the nature (linear, exponential etc.) of these relationships. However, this illustrative result implies that developing a general model applicable to different coral colonies requires incorporation of the average growth rate of each colony. We therefore adopt the simplest hypothesis that a multicolony calibration model will assume that m_2 (the SST slope) changes as a linear function of growth rate, such that

$$m_2 = d_0 * (\text{average growth}) + d_1 \quad (2)$$

The net regressed equation is

$$Sr/Ca = m_1 * (IG) * SST + d_0 * (AG) * (SST) + d_1 * (SST) + b_0 \quad (3)$$

where (IG) is interannual growth and (AG) is average growth for each colony. The linear least squares (type I) multiple regression performed on all three data sets simultaneously returns the following equation:

$$\begin{aligned} Sr/Ca = &-0.000697\ (\pm 0.000751) * (IG) * SST \\ &+ 0.00304\ (\pm 0.00102) * (AG) * SST \\ &- 0.0738\ (\pm 0.0374) * SST + 10.8\ (\pm 0.9) \\ &(2\sigma,\ 95\%\ \text{conf.},\ r^2 = 0.51,\ F_{sig} \ll 0.0001, \\ &RMSR = 0.5°C) \end{aligned}$$

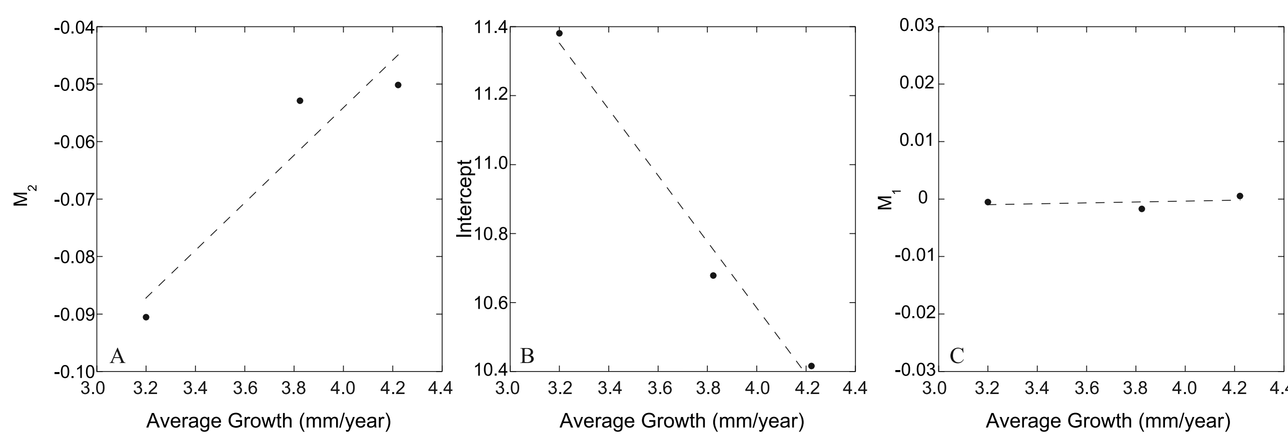

Figure 4. Single-colony, growth-corrected model intercepts and slopes from each coral model to average growth (mm/year) of the individual coral colony: (a) M_2, (b) intercept (b_o), and (c) M_1 versus average growth.

Table 3. Covariance (σ^2) Among the Slopes and Intercept of the Multicolony Model[a]

	Intercept	SST	AG * SST
SST	−8.01 E-03		
AG * SST	9.57 E-06	−1.09 E-06	
IG * SST	−1.66 E-05	5.48 E-07	−8.79 E-08

[a]Read, for example, −8.01 E-03 as -8.01×10^{-3}. SST is sea surface temperature; AG is average growth; IG is interannual growth.

Covariance among the slopes and intercepts are reported in Table 3. The interannual growth term (m_1) which previously showed significance only in the individual colony model for coral BB 001, is now significant in this model including data from all three colonies (p = 0.0800). The inclusion of the average growth term and the utilization of all three colonies in one regression lead to a highly significant model ($F_{sig} \ll 0.0001$), a strong significance of the added average growth term ($p \ll 0.0001$), and a low root-mean-square of the residual (0.5°C).

4. Discussion: Testing the Multicolony Regression

[17] In order to evaluate the accuracy and precision of the different calibration methods presented here, each single-colony calibration (monthly, mean annual, and growth-corrected) for the three corals, as well as the multicolony calibration, was applied to all of the corals such that there are ten SST reconstructions for each coral (Figure 5). In Figure 5a, the monthly calibrations for coral 001, 002, and 003 (top to bottom) are applied to mean annual Sr/Ca from each coral and compared to mean annual instrumental SST. In these scenarios, neither the accuracy nor the precision are

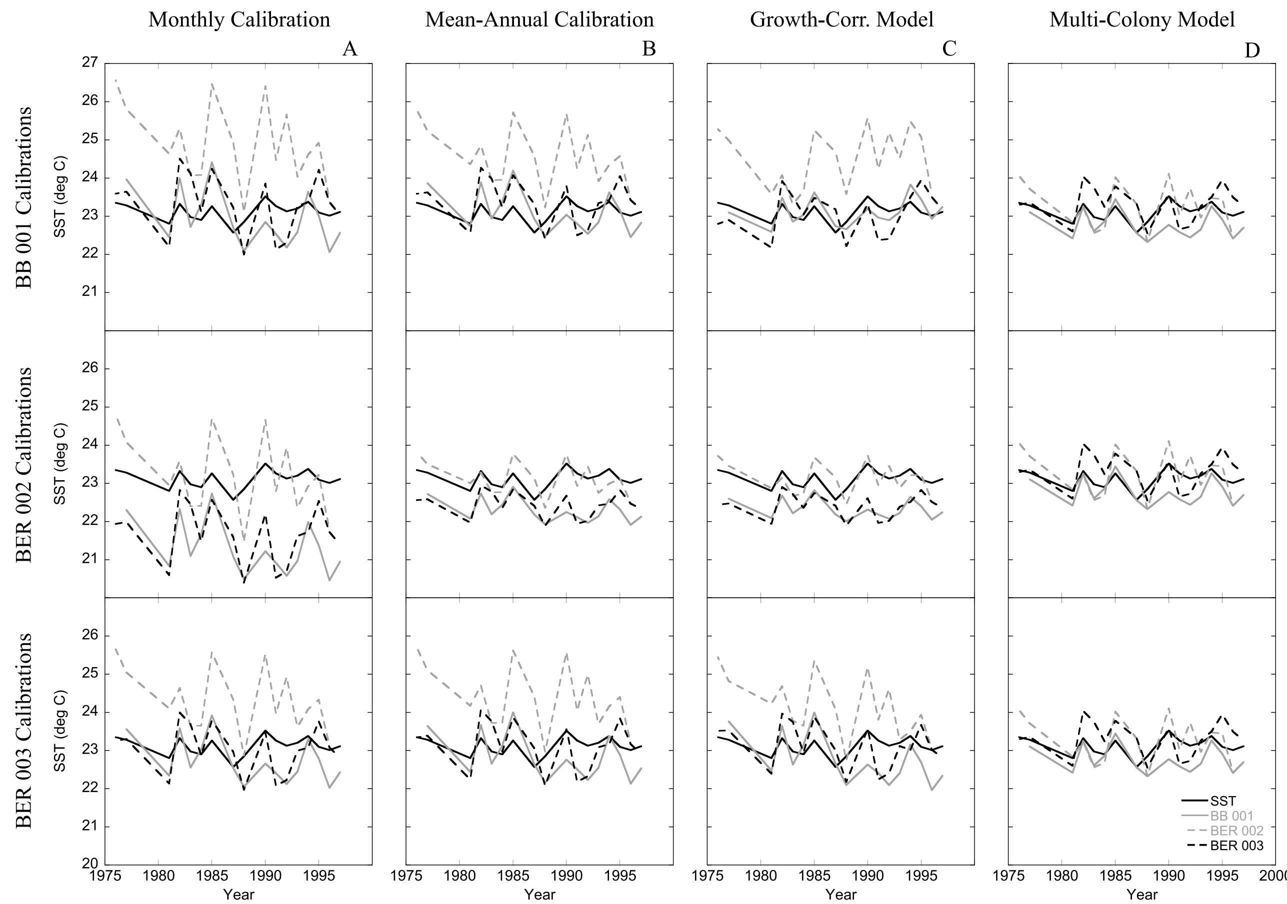

Figure 5. Hydrostation S (solid line) and reconstructed mean annual SST for BB 001 (shaded line), BER 002 (shaded dashed line) and BER 003 (dashed line) plotted versus year. Reconstructed SSTs from (a) monthly calibration of (top) BB 001, (middle) BER 002, and (bottom) BER 003; (b) mean annual calibration of (top) BB 001, (middle) BER 002, and (bottom) BER 003; (c) growth-corrected model of (top) BB 001, (middle) BER 002, and (bottom) BER 003; and (d) the multicolony model. The multicolony model shows the most accurate reconstruction of SST for the colonies as a group with a RMSR of 0.46°C and a minimal offset from the mean instrumental SST over the period of 0.24°C.

Table 4. Difference Between the Mean of the Reconstructed SST and the Mean of the Instrumental SST Over the Calibration Period for Each Individual Colony Growth-Corrected Model and the Multicolony Model[a]

	BB 001	BER 002	BER 003	RMSR
BB 001 growth-corrected model	0.00	1.38	−0.04	0.80
BER 002 growth-corrected model	−0.78	0.00	−0.70	0.61
BER 003 growth-corrected model	−0.35	−0.36	0.00	0.29
MultiColony model	−0.34	0.13	0.20	0.24

[a]Values are given in °C and reported to the 100th decimal place for comparison purposes. RMSR is root-mean-square of the residual.

good. In a single year, the difference between the three records can be as large as 2.5°C and the records on average are also significantly offset from one another and the instrumental record. In addition, the root-mean-squares of the SST residuals when applied to the group as a whole are 1.3, 1.5, and 0.9°C (top to bottom, Table 2). If a reconstructed paleotemperature record was compiled from multiple corals using a monthly calibration from any single colony, it would be likely to significantly overestimate or underestimate SST changes through time.

[18] In Figure 5b, the mean annual calibrations of 001, 002, and 003 (top to bottom) are applied to mean annual Sr/Ca from each coral and compared to instrumental SST. Although minimizing the known artifacts of smoothing from bulk sampling of monthly calibrations [e.g., *Goodkin et al.*, 2005], the mean annual calibrations still lead to significant offsets from the instrumental record (Figure 5b). The mean annual calibration from BER 003 performs as poorly as the monthly calibration when applied to all three corals, returning a root-mean-square of the residuals for the group of 1.0°C, while mean annual calibrations for BB 001 and BER 002 show improvement (group RMSR of 1.0 and 0.7°C respectively) (Table 2).

[19] In Figure 5c, the single-colony growth-corrected calibrations for corals 001, 002, and 003 (top to bottom) are again applied to mean annual Sr/Ca from each coral and compared to mean annual SST. These models attempt to account for some of the variability between different coral colonies, but still result in significant errors in SST reconstructions (Figure 5c). The growth-corrected model for BB 001 reconstructs SST well for itself (RMSR = 0.2°C). However, it does relatively worse for BER 003 (RMSR = 0.5°C), and it does poorly for BER 002 (RMSR = 1.5°C; group RMSR = 0.8°C). Similarly, single-colony growth-corrected models for BER 002 and 003 result in poor SST reconstructions when applied to other colonies. The BER 002 growth-corrected model provides the most precise reconstruction across the group (RMSR of 0.7°C) of the three single-colony models, with RMSR of 0.8, 0.3 and 0.8°C when applied to BB 001, BER 002, and BER 003, respectively. The growth-corrected model of BER 003 reconstructed SST with an RMSR of 0.7, 1.2 and 0.5°C for the three colonies respectively, and a group RMSR of 0.9°C. In general, the single-colony, growth-corrected models when applied to other colonies still result in SST reconstructions with significant offsets of the mean from instrumental data (Figure 5c and Table 4), and demonstrate that reconstructions from fossil corals could possibly overestimate or underestimate mean SST by as much as 1.4°C (Table 4).

[20] Finally, shown in triplicate in Figure 5d and in the top row of Table 2 are the results of SST reconstructions using the multicolony model. With the multicolony model, both precision and accuracy of reconstructed SSTs are improved over the single-colony models. Although reconstructed SSTs for BB 001 and BER 002 (but not BER 003) fit best using their own single-colony growth-corrected model (Table 2), each single-colony model performs poorly when applied to the other colonies. The group RMSR of reconstructed SSTs for the three colonies equal 0.9, 0.7 and 0.9°C for the single-colony models, compared to only 0.5°C using the multicolony model (Table 2). Similarly, the means for reconstructed SSTs using single-colony calibrations show greater offsets from instrumental SST (group offsets of 0.8, 0.6 and 0.3°C) than the multicolony model (average offset 0.2°C) (Table 4). When reconstructing SST for the group as a whole, the best fit is clearly achieved using the multicolony calibration. Applying the multicolony calibration to all three corals shows reconstructed SSTs evenly distributed above and below the instrumental record, with diminished offsets and greatly reduced scatter compared to single-colony monthly, mean annual, and growth-corrected methods (Figure 5). This implies that the multicolony calibration approximates a universal equation that may potentially be applied to any individual modern or fossil *Diploria labyrinthiformis* colony from this area with equal confidence.

5. Conclusion

[21] Individual modern coral colonies often provide distinct independent calibrations of Sr/Ca to SST. Choosing an equation to apply to a fossil coral or even to the nonmodern portion of a living coral can be problematic, as the variation in slopes from one calibration to another can have significant implications for reconstructed SST. The application of a single-colony Sr/Ca–SST calibration to different corals can lead to significant offsets between independent records covering the same time interval. Such discrepancies can pass unnoticed when a modern calibration is applied to a fossil coral, particularly if the fossil record shows no overlap with more recent values. In slow-to-moderate growing corals, growth rate can explain some of the differences in the calibrations of individual corals. However, even growth-corrected Sr/Ca–SST calibrations based on a single colony yield large anomalies in reconstructed SST when applied to other colonies.

[22] For this study, data from multiple corals were used simultaneously in a multivariate regression to develop a single multicolony growth-corrected Sr/Ca–SST calibra-

tion. Applying the multicolony calibration for reconstructing SST reduces the root-mean-square of the residual as well as mean offsets for three colonies evaluated independently and together as a group, compared to single-colony growth-corrected calibration models. In general, incorporating quantitative interannual and average growth rate information and expanding the calibration range through the inclusion of multiple coral colonies improves the coral Sr/Ca thermometer and provides more accurate reconstructions of SST. Investigating growth influences on other slow-to-moderate growing corals and using multiple colonies in Sr/Ca–SST calibrations may improve the reliability of past SST reconstructions and serve to diminish anomalies relative to other paleotemperature proxies.

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