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Assessing the reproducibility of coral-based climate records

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[1] We perform replication tests using monthly variations in Sr/Ca and $\delta^{18}O$ in four cores from three *Porites lutea* coral heads from New Caledonia to assess the reproducibility of coral-based climate records. Coral Sr/Ca ($\delta^{18}O$) records are well correlated to each other and to the instrumental SST record (1967–1992), especially in terms of differences in the mean values of 25-year SST records (~0.2°C, Sr/Ca-SST; 0.6°C, $\delta^{18}O$-SST). The average error associated with the coral Sr/Ca-SST ($\delta^{18}O$-SST) of any particular month, season or year is ~0.8°C (1.1°C), 0.6°C (0.8°C) and 0.5°C (0.6°C), respectively. "Stacking" or averaging the individual proxy records reduces the error between observed and predicted SST, although the reduction is small for coral Sr/Ca. Excellent reproducibility among the coral proxies implies that reliable climate records can be generated from a single coral core and that coral Sr/Ca-SST records are not compromised, beyond the errors stated herein, by non-temperature-related biological effects. *INDEX TERMS:* 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 1620 Global Change: Climate dynamics (3309); 4215 Oceanography: General: Climate and interannual variability (3309); 4267 Oceanography: General: Paleoceanography; 4825 Oceanography: Biological and Chemical: Geochemistry. **Citation:** Stephans, C. L., T. M. Quinn, F. W. Taylor, and T. Corrège (2004), Assessing the reproducibility of coral-based climate records, *Geophys. Res. Lett.*, *31*, L18210, doi:10.1029/2004GL020343.

1. Introduction

[2] Coral-based climate reconstructions are increasingly being used to assess environmental variability in the tropical surface oceans [e.g., *Cole and Fairbanks*, 1990; *Dunbar et al.*, 1994; *Charles et al.*, 1997; *Quinn et al.*, 1998; *Le Bec et al.*, 2000; *Linsley et al.*, 2000; *Cobb et al.*, 2003]. The majority of coral-based climate reconstructions are based on geochemical variations from a single coral head from a single locality. The need for replication to document the fidelity of the coral-climate signal from multiple corals from the same reef has been recognized for some time [e.g., *Briffa*, 1995; *Cook*, 1995; *Barnes and Lough*, 1996; *Crowley et al.*, 1997], but has not routinely been performed because of sample availability, sample throughput and cost constraint issues. Previous coral replication studies using coral $\delta^{18}O$, which varies as a function of sea surface temperature (SST) and seawater $\delta^{18}O$ composition, have documented mean $\delta^{18}O$ differences of 0.2‰–0.4‰ (~1 to 2°C) among coral cores recovered from the same reef, which are unlikely to reflect true temperature variability at a single reef site [*Tudhope et al.*, 1996; *Gagan et al.*, 1998; *Guilderson and Schrag*, 1999; *Linsley et al.*, 1999]. Initial replication studies using coral Sr/Ca, which varies as a function of SST, demonstrate a strong level of agreement in terms of SST (~±0.3°C [*Alibert and McCulloch*, 1997; *Gagan et al.*, 1998; *Hendy et al.*, 2002]).

[3] In this study we conduct a replication study to determine the degree of reproducibility among records of monthly variations in $\delta^{18}O$ and Sr/Ca derived from four cores from three *Porites lutea* coral heads from offshore of Amédée Island, New Caledonia (22°29′S, 166°27′E). The Amédée reefs are ideally situated for this study because daily SST and sea surface salinity (SSS) measurements are available for the last ~25 years [*Delcroix and Lenormand*, 1997].

2. Material and Methods

[4] Coral cores were collected within 0.5 km of each other near the Amédée lighthouse in <3 m of water depth and far removed from freshwater input from the mainland. The numeric prefix in the core names refers to the year that the core was recovered. Coral core 99-PAA was drilled from the same large *Porites lutea* coral head that yielded core 92-PAA, which has been extensively studied [*Quinn et al.*, 1996; *Crowley et al.*, 1997; *Quinn et al.*, 1998; *Corrège et al.*, 2001; *Quinn and Sampson*, 2002].

[5] Powdered samples were generated every 0.625 mm (~11–20 samples/year of growth) from coral cores 92-PAC, 92-PAD and 99-PAC. Sampling resolution in coral core 92-PAA is 1.03 mm/sample (~monthly). Stable isotopic and elemental ratio determinations were made on splits of the same powder using instrumentation at the University of South Florida. Analytical precision, based on daily measurements of laboratory standards, is ±0.08‰ (1σ) for $\delta^{18}O$ and ±0.2% (2σ; 0.018 mmol/mol; ~0.3°C) for Sr/Ca. The absolute value of Sr/Ca in the coral standard solution has been confirmed using thermal ionization mass spectrometry (TIMS) at the University of Minnesota Isotope Laboratory. Sr/Ca and $\delta^{18}O$ data from coral core 92-PAA were generated on different analytical instruments and were subjected to different sample pre-treatment processes [*Quinn et al.*, 1996; *Quinn and Sampson*, 2002] than other samples in this study.

[6] Age models for each core were constructed by correlating the lowest (highest) Sr/Ca values to the warmest (coolest) SST to define each year. The data were linearly interpolated to give monthly Sr/Ca values (and corresponding paired $\delta^{18}O$ values) to compare to the instrumental SST and SSS data. We estimate potential chronology errors of 1–2 months. Cross-validation or verification tests were

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Table 1. Linear, Zero-Lag Correlations Among Monthly (Bold) and Seasonal (Italics) Coral and Climate Records, 1967–1992[a]

	IRD SST	92-PAC Sr/Ca	92-PAD Sr/Ca	99-PAA Sr/Ca	Stack 3 Sr/Ca	92-PAA Sr/Ca	Stack 4 Sr/Ca
IRD SST[b]	1.00	**−0.90**	**−0.83**	**−0.86**	**−0.91**	**−0.91**	**−0.94**
92-PAC Sr/Ca	*−0.89*	1.00	**0.87**	**0.85**	**0.96**	**0.82**	**0.95**
92-PAD Sr/Ca	*−0.85*	*0.87*	1.00	**0.80**	**0.80**	**0.79**	**0.93**
99-PAA Sr/Ca	*−0.85*	*0.87*	*0.80*	1.00	**0.93**	**0.85**	**0.93**
Stack 3 Sr/Ca	*−0.91*	*0.96*	*0.94*	*0.93*	1.00	**0.86**	**0.86**
92-PAA Sr/Ca	*−0.89*	*0.81*	*0.80*	*0.93*	*0.85*	1.00	**0.92**
Stack 4 Sr/Ca	*−0.93*	*0.81*	*0.80*	*0.83*	*0.85*	*0.92*	1.00
	IRD SST	92-PAC δ^{18}O	92-PAD δ^{18}O	99-PAA δ^{18}O	Stack 3 δ^{18}O	92-PAA δ^{18}O	Stack 4 δ^{18}O
IRD SST	1.00	**−0.89**	**−0.70**	**−0.78**	**−0.87**	**−0.93**	**−0.90**
92-PAC δ^{18}O	*−0.87*	1.00	**0.70**	**0.82**	**0.93**	**0.89**	**0.93**
92-PAD δ^{18}O	*−0.72*	*0.72*	1.00	**0.70**	**0.70**	**0.72**	**0.86**
99-PAA δ^{18}O	*−0.78*	*0.72*	*0.71*	1.00	**0.93**	**0.85**	**0.92**
Stack 3 δ^{18}O	*−0.87*	*0.93*	*0.88*	*0.92*	1.00	**0.90**	**0.90**
92-PAA δ^{18}O	*−0.91*	*0.87*	*0.73*	*0.92*	*0.88*	1.00	**0.94**
Stack 4 δ^{18}O	*−0.90*	*0.93*	*0.87*	*0.92*	*1.00*	*0.92*	1.00

[a] All correlations are significant at more than 95%; stack 3 refers to the average of cores 92-PAC, 92-PAD and 99-PAA; stack 4 refers to the average of 92-PAC, 92-PAD, 99-PAA and 92-PAA.

[b] In situ sea-surface temperature data (http://www.ird.nc/ECOP/siteecopuk/cadres.htm).

performed with each time series by calibrating over the interval 1992.65–1979.46 (148 monthly values) and verifying over the interval 1979.38–1967.04 (148 monthly values). Correlation coefficients for calibration and verification intervals are similar, and range from −0.86 to −0.95 for Sr/Ca and −0.75 to −0.92 for δ^{18}O. A 3% bias correction (λ = 0.97 [*Solow and Huppert*, 2004]) was determined for the coral-based SST reconstructions.

3. Results

[7] The four monthly Sr/Ca (δ^{18}O) time series are well correlated to each other (Table 1 and Figures 1a and 1b). The strong relationship among records at Amédée is consistent with previous studies of four coral δ^{18}O records from the central equatorial Pacific [*Urban et al.*, 2000]. The four monthly δ^{18}O records and Sr/Ca records are also well correlated to each other, a result that is consistent with the results of previous studies [e.g., *Beck et al.*, 1992; *Mitsuguchi et al.*, 1996]. The four monthly Sr/Ca time series have equivalent means and variances, but the monthly δ^{18}O time series fall into two distinct groups (92-PAA and 92-PAD vs. 92 PAC and 99-PAA), which are separated by ~0.15‰.

[8] Bias-corrected regression equations for Sr/Ca-SST and δ^{18}O-SST using the stacked data from all four cores (n = 308) are:

$$\mathrm{Sr/Ca(mmol/mol)} = 10.331(\pm 0.055, 2\sigma) - 0.0504(\pm 0.002, 2\sigma) * \mathrm{SST}(r = -0.93) \quad (1)$$

$$\delta^{18}\mathrm{O}(\text{‰ VPDB}) = 1.24(\pm 0.180, 2\sigma) - 0.133(\pm 0.008, 2\sigma) * \mathrm{SST}(r = -0.90) \quad (2)$$

[9] The standard error of these regression equations is 0.67°C (Sr/Ca) and 0.81°C (δ^{18}O). These bias-corrected equations are modestly different than previous calibration equations for *Porites* [*Gagan et al.*, 1998, 2000; *Quinn et al.*, 1998; *Marshall and McCulloch*, 2002; *Quinn and Sampson*, 2002].

3.1. Coral Sr/Ca as an SST Proxy

[10] The coral Sr/Ca-SST proxy, after comparison with the instrumental SST record at New Caledonia at various timescales, is judged to be a robust and accurate recorder of SST variations. Sr/Ca-SST estimates of mean SST determined from each of the ~25-year, monthly resolved time series (n=308) differs from the instrumental mean annual SST by ~0.2°C (Figure 2a). This difference is on the same order as the two-sigma analytical error associated with the determination of Sr/Ca and is not statistically significant. The seasonal Sr/Ca-SST cycle matches well the observed seasonal SST cycle between 1992–1967 (Figure 2b). The average error associated with the coral Sr/Ca-based prediction of the SST of any particular month, season or year is ~0.8°C, 0.6°C and 0.5°C, respectively. The source of this monthly misfit most likely resides in the difficulty

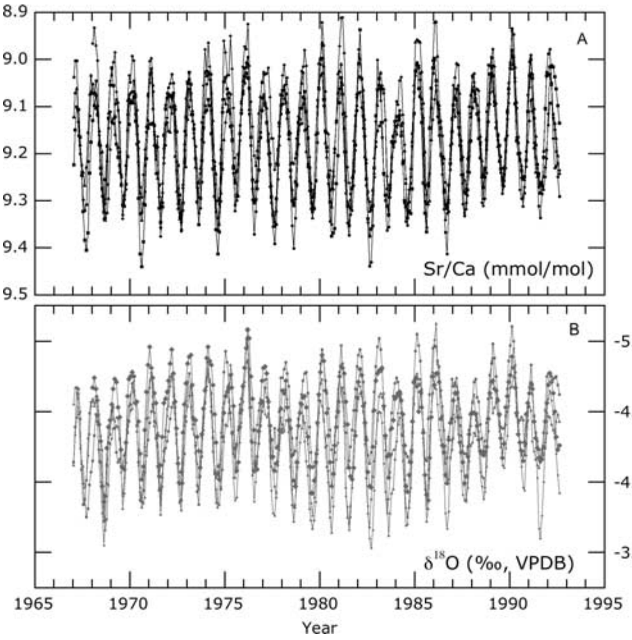

Figure 1. (a) Coral Sr/Ca variations versus time in four coral cores from New Caledonia (closed circle, 92-PAC; closed square, 92-PAD; closed triangle, 99-PAA; closed diamond, 92-PAA). (b) Coral δ^{18}O variations versus time in four coral cores from New Caledonia (symbols as in Figure 1a). Note the high degree of reproducibility in both sets of time series.

associated with assigning time precisely to each sample and with the sampling resolution (11–20 samples/year) used in this study. Stacking the individual time series to form a composite time series reduces the misfit between the Sr/Ca-SST proxy and the observed SST at all timescales; however the improvement is small and must be weighed against the time and cost required to generate the replicate time series. The sense and magnitudes of the differences between observed and predicted Sr/Ca-SST are confirmed using split-sample period calibration and verification tests.

[11] Our results contrast with conclusions reached by other workers [*Cohen et al.*, 2002; *Meibom et al.*, 2003] that non-temperature related biological effects compromise the veracity of the coral Sr/Ca paleothermometer. The high level of reproducibility of the monthly Sr/Ca variations in four corals from offshore of Amédée Island, New Caledonia, added to previous results from the Great Barrier Reef (GBR) implies that coral Sr/Ca-SST records are not compromised, outside of the errors stated herein, by non-temperature-related biological effects.

3.2. Coral $\delta^{18}O$ as an SST Proxy

[12] The mean predicted $\delta^{18}O$-SSTs based on the 25-year time series from cores 92-PAC and 99-PAA (n=308) are not statistically different from each other, however they are different from those calculated from cores 92-PAD and 92-PAA (Figure 2a). The mean SST values for these two groups (92-PAD and 92-PAA versus 92-PAC and 99-PAA) differ by ~0.6°C from the observed mean SST of the instrumental record, which is a greater difference than that derived from the mean Sr/Ca-SST reconstructions (Figure 2a). The seasonal $\delta^{18}O$-SST cycle matches the observed seasonal SST cycle between 1992–1967 (Figure 2c), although not as well as the seasonal Sr/Ca-SST cycle (Figure 2b). The average error associated with the coral $\delta^{18}O$ proxy-based prediction of the SST of any particular month, season or year is ~1.1°C, 0.8°C and 0.6°C, respectively.

[13] Stacking the individual coral $\delta^{18}O$ time series reduces the error between coral $\delta^{18}O$-predicted SST and the observed SST at all timescales. The sense and magnitudes of the differences between observed and predicted $\delta^{18}O$-SST are confirmed using split-sample period calibration and verification tests. The greater magnitude of misfit between coral $\delta^{18}O$ and SST relative to the comparisons between coral Sr/Ca and SST is not surprising given the influence of both SST and seawater $\delta^{18}O$ on the coral $\delta^{18}O$ signal.

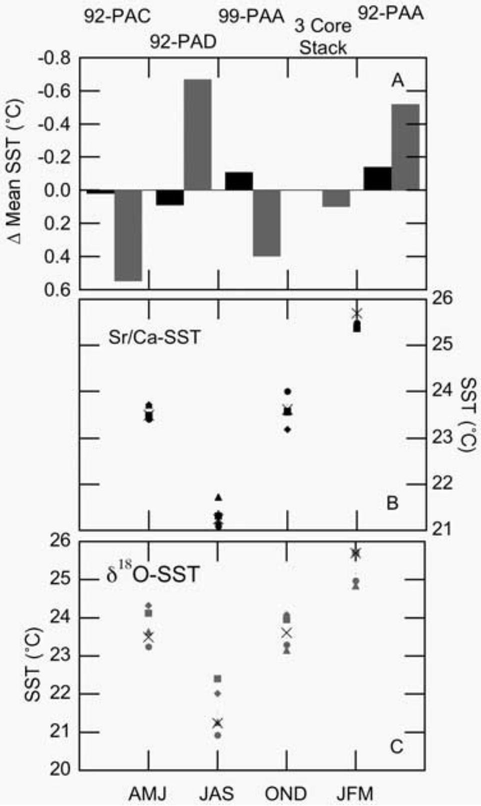

Figure 2. (a) Difference in mean SST between the 25-year instrumental SST record and 25-year proxy time series (Sr/Ca-SST, black bars; $\delta^{18}O$-SST, gray bars) from four coral cores, a stack or average of data from cores 92-PAC, 92-PAD and 99-PAA. Proxy-based estimates of SST and observed SST agree well, especially for coral Sr/Ca-SST. (b–c) Comparison of the seasonal SST averages based on coral Sr/Ca-SST (Figure 2b) and $\delta^{18}O$-SST (Figure 2c) from the four cores (symbols are the same as in Figure 1) and the instrumental SST record (X). The average error associated with the coral Sr/Ca-SST ($\delta^{18}O$-SST) of any particular season is 0.6°C (0.8°C).

3.3. Coral-Based $\delta^{18}O_{seawater}$ Reconstructions as a SSS Proxy

[14] Paired coral $\delta^{18}O$ and Sr/Ca determinations have been used to exploit the link between variations in SSS and seawater $\delta^{18}O$ to directly solve for seawater $\delta^{18}O$ in two ways: 1) seawater $\delta^{18}O$ ($\Delta\delta^{18}O$) is determined as a residual after the effects of SST, as estimated using coral Sr/Ca, are directly subtracted from coral $\delta^{18}O$ [*McCulloch et al.*, 1994; *Gagan et al.*, 1998, 2000] and 2) the effects of seawater $\delta^{18}O$ are separated from SST by breaking the instantaneous changes in coral $\delta^{18}O$ into separate contributions by instantaneous SST and seawater $\delta^{18}O$ [*Ren et al.*, 2002]. *Ren et al.* [2002] reconstructed salinity variations at Rarotonga after calibrating their reconstructed seawater $\delta^{18}O$ time series with SSS derived from a model-based ocean analysis [*Ji et al.*, 1995].

[15] We assess the fidelity of inferring SSS variations from seawater $\delta^{18}O$ reconstructions using our coral time series and the instrumental SSS time series from Amédée. We use equations 1 and 2 from this study to calculate $\Delta\ \delta^{18}O$, but the use of other equations for Sr/Ca-SST and $\delta^{18}O$-SST does not change the sense of the results. Overall there is a modest fit between predicted seawater $\delta^{18}O$ and observed SSS variations using both the aforementioned approaches ($r < 0.33$, $p < 0.05$). A similarly modest correlation also exists between coral-based seawater $\delta^{18}O$ and the NCEP SSS records (22°S, 165.75°E [*Ji et al.*, 1995]) and between the Amédée SSS and the NCEP SSS records ($r = 0.38$; $p < 0.05$).

[16] The misfit between the reconstructed seawater $\delta^{18}O$ and Amédée SSS records is likely related to hydrologic differences between the GBR, Rarotonga and New Caledonia. Salinity at the GBR varies between ~32 to 36 [*Marshall and McCulloch*, 2002], in part reflecting Burdekin River input, whereas at Amédée and Rarotonga [*Ren et al.*,

2002] have a much smaller range in SSS (~35 to 36). The observed misfit may also be a reflection of a small seawater δ^{18}O signal relative to the magnitude of the error in the proxy estimation of this variable.

4. Conclusions

[17] Our replication study of coral-based climate proxies at New Caledonia yields the following conclusions, which are confirmed by calibration-verification testing: 1) coral Sr/Ca is an accurate recorder of SST variations; coral δ^{18}O is a less accurate recorder of SST, 2) generating and stacking multiple proxy SST records improves the fit between predicted and observed SST, but requires additional time and cost, 3) coral-based reconstructions of seawater δ^{18}O at New Caledonia have only a modest correlation with the instrumental SSS record, and 4) the high level of reproducibility of Sr/Ca variations in all four corals implies that coral Sr/Ca-SST records are not compromised, beyond the errors stated herein, by non-temperature-related biological effects.

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