El Niño–Southern Oscillation–related salinity variations recorded in the skeletal geochemistry of a *Porites* coral from Espiritu Santo, Vanuatu

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[1] Coral skeletal geochemistry offers the potential to reconstruct the sea surface salinity (SSS) history of the tropical oceans on seasonal to interannual and perhaps centennial timescales because of the strong link between variation in SSS and seawater $\delta^{18}O$ in tropical regions. We explore this potential using a monthly resolved, 65-year record of skeletal $\delta^{18}O$ and Sr/Ca variations in a *Porites* coral from Espiritu Santo, Vanuatu. We demonstrate that El Niño–Southern Oscillation–related climate variability strongly influences coral $\delta^{18}O$ at Santo through local salinity changes associated with the position of the South Pacific Convergence Zone and the movement of its associated salinity front. Such a demonstration provides the "ground truth" data that can be used to place paleoclimate variability estimated using existing fossil coral records from this region into a modern conceptual framework. We also evaluate different methods of combining coral $\delta^{18}O$ and Sr/Ca to reconstruct SSS and conclude that the coral $\delta^{18}O$ anomaly time series provides the best fit to recent in situ SSS data at Santo. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 4215 Oceanography: General: Climate and interannual variability (3309); 4267 Oceanography: General: Paleoceanography; 4522 Oceanography: Physical: El Nino; 4825 Oceanography: Biological and Chemical: Geochemistry; *KEYWORDS:* El Niño–Southern Oscillation variability, salinity, coral geochemistry

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1. Introduction

[2] Variations in sea surface salinity (SSS) and sea surface temperature (SST) are integral components of tropical climate dynamics, especially in the El Niño–Southern Oscillation (ENSO) phenomenon [e.g., *Lukas and Lindstrom*, 1991; *Vialard and Delecluse*, 1998; *Delcroix and McPhaden*, 2002; *Vialard et al.*, 2002]. Unlike instrumental SST records, some of which begin in the late 1800s and have rather good spatial coverage for the latter half of the 20th century, instrumental salinity records are exceedingly rare and the few that do exist are usually only a few decades long [e.g., *Gouriou and Delcroix*, 2002]. Longer records are necessary for assessing possible relationships between tropical Pacific SSS and low-frequency phenomena that might modulate ENSO, such as the Pacific Decadal Oscillation [*Mantua et al.*, 1997; *Salinger et al.*, 2001; *Folland et al.*, 2002].

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[3] Corals show great promise for extending instrumental SSS records. Corals incorporate $\delta^{18}O$ into their skeletal aragonite as a function of temperature and the oxygen isotopic composition of the surrounding seawater (δ_w; e.g., *McConnaughey* [1989]). Tropical δ_w is primarily controlled by evaporation and precipitation, which in turn partly control salinity. A strong correlation has been demonstrated between surface δ_w and SSS in regions of the tropical Pacific dominated by strong atmospheric convection [*Fairbanks et al.*, 1997; *Morimoto et al.*, 2002]. Coral $\delta^{18}O$ has been used to reconstruct salinity-driven climate signals at a few localities [*Cole and Fairbanks*, 1990; *Linsley et al.*, 1994; *Tudhope et al.*, 1995; *Le Bec et al.*, 2000]. Strong dependence of coral Sr/Ca on SST [*Beck et al.*, 1992, 1997] has led to two proposed methods of reconstructing past δ_w (and by extension SSS), both of which remove the Sr/Ca-derived temperature from the skeletal $\delta^{18}O$ signal [*McCulloch et al.*, 1994; *Gagan et al.*, 1998; *Ren et al.*, 2002].

[4] Evaluating the different methods of SSS reconstruction requires comparisons of each in a variety of environmental/climatic settings. Espiritu Santo is a good place to start such a comparison because SSS data are available for this region from the 2 by 10 degree gridded ship of opportunity data set of *Gouriou and Delcroix* [2002] (hereafter referred to as G&D-SSS). The primary regional salinity dynamics are also well understood. Salinity variations on seasonal timescales are ~0.35 psu and are inversely corre-

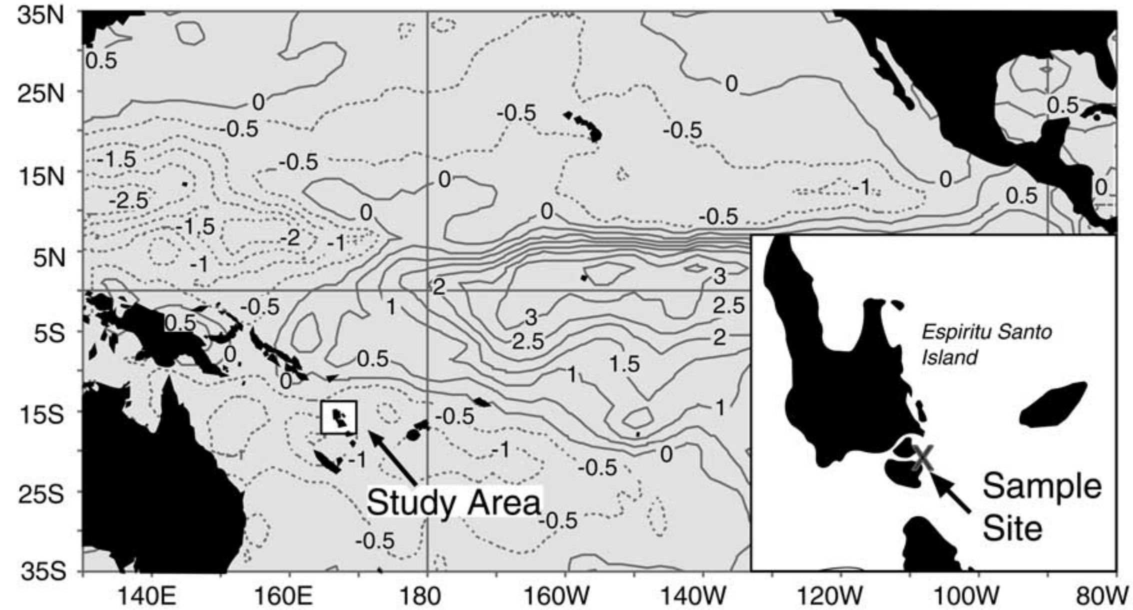

Figure 1. Sample site map superimposed on a contour map of March–November average precipitation rate anomaly (mm/day) during ENSO warm phase years shows that Vanuatu is well situated to experience precipitation anomalies during El Niño events. Data from the NCEP/NCAR reanalysis model [*Kalnay et al.*, 1996] were provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, from their Web site at http://www.cdc.noaa.gov/. ENSO years considered are 1958, 1966, 1969, 1973, 1983, 1992, and 1998, compared against the 1968–1996 average.

lated with rainfall at Santo (*Gouriou and Delcroix* [2002]; NOAA Climate Prediction Center rainfall data). Salinity variations on interannual timescales can exceed 1 psu in response to the dynamics of the South Pacific Convergence Zone (SPCZ) and its associated salinity front [*Gouriou and Delcroix*, 2002]. The SPCZ is the upward component of the west Pacific Walker circulation cell, and is an integral part of the Southern Oscillation, thus providing a direct link to ENSO [*Vincent*, 1994].

[5] Vanuatu is also the site of several paleoclimate studies using fossil corals [*Beck et al.*, 1992, 1997; *Corrège et al.*, 2000, 2004; *Kilbourne et al.*, 2004]. Interpreting fossil coral records requires a thorough understanding of the climate dynamics in the region, and demonstrating that modern corals from the same area are faithful recorders of those dynamics lends further credence to fossil coral interpretations. Currently, the only published multidecadal modern coral record from Santo is based on a *Platygyra* sp. [*Quinn et al.*, 1993, 1996], a coral genus not commonly used in coral paleoclimatology. The seasonally resolved stable isotopic records from this coral present a complex climate signal in part because *Platygyra* is a structurally complex coral genus that is difficult to physically sample. Interpretations of fossil *Porites* records from Vanuatu may be strengthened by demonstrating the robust nature of coral-based records of climate variability in this region from a modern *Porites* coral.

[6] In this study we use a monthly resolved, 65-year record of skeletal $\delta^{18}O$ and Sr/Ca variations in a *Porites* coral from Espiritu Santo, Vanuatu to demonstrate that $\delta^{18}O$ variations primarily respond to changes in SSS, which are driven by ENSO/SPCZ dynamics. We also evaluate several methods with which to extract a SSS record from a coral-based geochemical record. The results of our study can be used to fortify paleoclimate interpretations based on fossil *Porites* corals from this area.

2. Methods

[7] The Santo coral core was recovered in October 1992 from a *Porites lutea* living in 1.5 m of water in the passage between Malo Island and Espiritu Santo Island (15.7°S, 167.2°E; Figure 1). Stable isotopes and elemental ratios were analyzed on paired subsamples at the Paleoceanography, Paleoclimatology, and Biogeochemistry laboratory in the College of Marine Science at the University of South Florida (Figure 2). Analytical precision (1σ) on carbon and oxygen isotopic determinations is 0.04‰ and 0.08‰, respectively (standardized against Vienna Peedee belemnite (VPDB)). Analytical precision on Sr/Ca determinations is 0.16% RSD or 0.014 mmol/mol (1σ).

[8] Time was assigned to the Sr/Ca and coral $\delta^{18}O$ depth series by matching Sr/Ca minima with SST maxima (and vice versa), using AnalySeries software [*Paillard et al.*, 1996]. The SST record was extracted from a 1 × 1° grid box centered on 15.5°S and 166.5°E from the HadISST1.1 data set [*Rayner et al.*, 2003]. A visual comparison between the density band years and geochemical years confirmed the accuracy of the age conversion. The time series were also band-pass filtered to isolate the variance close to 1 year and phase differences between the two filtered time series were minimized.

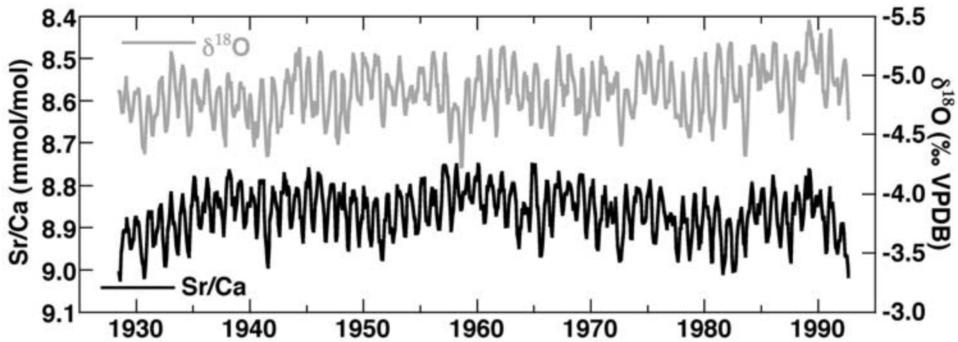

Figure 2. Sr/Ca and δ^{18}O variations in a *Porites lutea* from Malo Channel, Vanuatu. Clear annual cycles in the geochemistry and cross-referencing the geochemistry with the annual density bands ensures a robust age model.

[9] In this study we use the G&D-SSS data [*Gouriou and Delcroix*, 2002] rather than a hindcast model SSS such as that available from NCEP in 1 by 1 degree grid boxes (*Behringer et al.* [1998]; hereafter referred to as NCEP-SSS) because the former consists of actual salinity measurements. A comparison of the G&D-SSS data for the grid box nearest to Santo and the NCEP-SSS data for the same grid area illustrates large differences between the two data sets (Figure 3). Average SSS values are very similar for G&D-SSS and NCEP-SSS (cf., 34.99 versus 34.95), whereas the standard deviation in G&D-SSS is four times larger than in the NCEP-SSS (cf., 0.32 versus 0.08). The seasonal cycle is also five times larger in the G&D-SSS data relative to the NCEP-SSS (cf., 0.36 versus 0.07). Lastly, total salinity range over a 20-year period is >3 times larger in G&D-SSS than in NCEP-SSS model output (cf., 1.91 versus 0.51). Such large differences in the SSS between these two data sets imply that the SSS data set used for calibrating a measured coral proxy can strongly affect the outcome of the calibration.

[10] Three different methods for reconstructing SSS-related δ_w variations are compared in this paper. The first method involves removing the mean seasonal δ^{18}O cycle (average January coral δ^{18}O, average February coral δ^{18}O, etc.) from the coral δ^{18}O time series to obtain a δ^{18}O anomaly curve (δ^{18}OA). Vanuatu is a particularly appropriate location to apply an anomaly method because interannual SSS variations greatly exceed seasonal SSS variations, whereas for SST, seasonal variations exceed interannual variations. Thus removing the seasonal cycle from the Santo coral δ^{18}O record effectively removes the SST signal and leaves the SSS signal unaffected. This method was successfully applied at Fiji [*Le Bec et al.*, 2000], where SSS and SST variations behave similarly to those at Vanuatu.

[11] The second and third methods for reconstructing SSS-related δ_w variations use paired coral δ^{18}O and coral Sr/Ca analyses. *Gagan et al.* [1998] applied the method initially put forth by *McCulloch et al.* [1994] to reconstruct SSS changes at the Great Barrier Reef, a site where fluvial input associated with extreme hydrologic events influences

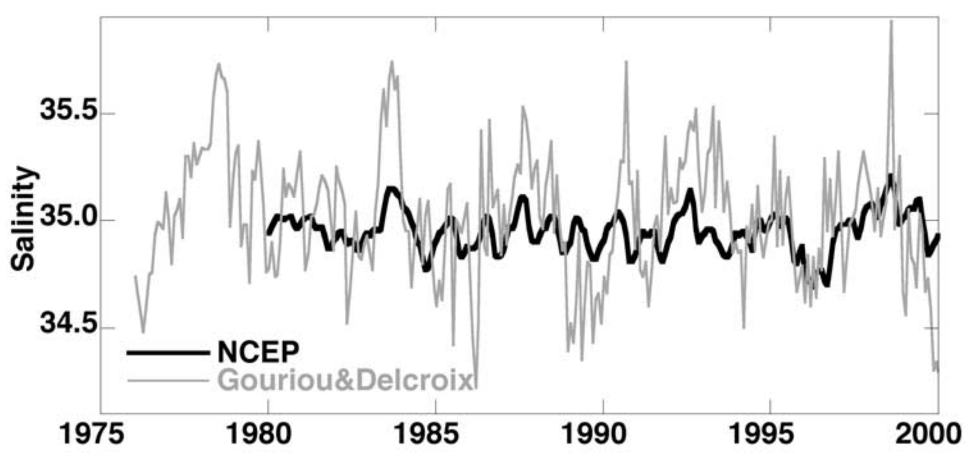

Figure 3. A comparison of monthly hindcast model salinity (NCEP; *Behringer et al.* [1998]) and monthly gridded ship of opportunity data [*Gouriou and Delcroix*, 2002]. Note the large difference in variability between the two SSS data sets from the same region of the surface ocean. Such differences have the capability to introduce nontrivial confusion in climate proxy interpretations.

seawater δ^{18}O. Their method (henceforth referred to as the Gagan method) relies mathematically on having two equations (Sr/Ca-SST calibration, and coral δ^{18}O-δ_w-SST calibration) and two unknowns (SST and δ_w) to simultaneously solve the equations for both variables. *Gagan et al.* [1998] merge the two calibration equations first, then calculate the δ_w, all at once instead of solving the two calibration equations sequentially by first using Sr/Ca to solve for temperature, then inputting that temperature into the δ^{18}O-δ_w-SST calibration, as is commonly done for foraminiferal studies using Mg/Ca and δ^{18}O [e.g., *Bemis et al.*, 1998]. Given the same calibrations, the sequence of calculation makes no difference in the final answer.

[12] An alternate method put forth by *Ren et al.* [2002] calculates the instantaneous rate of change in δ_w by simultaneously solving two equations derived from the partial derivatives of the above two calibration equations and then obtains the δ_w changes by integrating the result. The integration is done discretely by adding up all of the instantaneous rates of δ_w change to an arbitrary reference (ideally the mean δ_w value). This method (henceforth referred to as the Ren method) purportedly bypasses the uncertainty related to the intercepts of both the Sr/Ca-SST and coral δ^{18}O-δ_w-SST calibrations.

[13] The calibration equations used in the present study come from *Stephans et al.* [2004]. We hope to minimize the number of calibration uncertainties by using calibration equations generated by comparing multiple coral time series from the same reef analyzed in one lab with in situ SST measurements. Significance for all correlation coefficients reported in this paper are calculated with an effective number of data points determined using *Chelton* [1983, equation (1)].

3. Results and Discussion

3.1. Comparing Three SSS Reconstruction Methods

[14] The three methods of reconstructing SSS-related δ_w are applied to coral data from Vanuatu and compared to the salinity time series of the appropriate grid box from the *Gouriou and Delcroix* [2002] data set (Figure 3). The strongest correlation is between SSS and δ^{18}OA. This result is especially impressive given that the δ^{18}OA is from a single coral head from one reef and the SSS data is from a $2 \times 10°$ grid box. Clearly, the coral δ^{18}OA time series from a modern coral at Vanuatu is a good proxy for regional SSS. This method actually produces a SSS anomaly record because the annual cycle is removed explicitly, though this compares well to the monthly SSS because the annual cycle is small, and thus has little influence on the outcome.

[15] The value of both the Ren and Gagan methods lies in the fact that the seawater δ_w changes are explicitly separated from SST influence. Changes in the δ_w seasonal cycle or mean SST can be resolved theoretically, although the Ren and Gagan methods seem to work best in areas where both SSS and SST contribute a considerable amount of variance to the climatology. If SST anomalies are much larger than the SSS anomalies, the signal-to-noise ratio decreases and SSS is not well resolved by the δ_w calculations. In Figure 4, the Ren and Gagan reconstructions have more noise in them than the reconstruction based on the δ^{18}OA method. One explanation for this observation is that both the Ren and Gagan methods contain error associated with two variables (each Sr/Ca and δ^{18}O), whereas the δ^{18}OA has less error because only one variable is used. The decreased signal-to-noise ratio is not due to the inability of Sr/Ca to accurately predict temperature, as the coral Sr/Ca is well correlated to a 1×1 degree grid temperature record from this area (r = −0.78; *Kilbourne et al.* [2004]).

[16] The δ_w curves generated from the Ren and Gagan methods have the same shape. Calculations using the Gagan and Ren methods differ by a constant, and are mathematically related by the following equation:

$$\delta_{wRn} = \overline{\delta_w} + \delta_{wGn+1} - \delta_{wG1},$$

where δ_{wRn} is the *n*th value of seawater δ^{18}O using the Ren method, $\overline{\delta_w}$ is the average seawater δ^{18}O value used to integrate the $\Delta\delta^{18}O^{sw}$ of *Ren et al.* [2002], δ_{wGn+1} is the *n*th plus one seawater δ^{18}O value ($\Delta\delta^{18}$O as defined by *Gagan et al.* [1998]), and δ_{wG1} is the first value of seawater δ^{18}O using the Gagan method. The two methods (Gagan and Ren) result in equivalent seawater δ^{18}O changes if the same equation slopes are used, and are offset from each other in a predictable way.

3.2. ENSO and δ^{18}O Anomaly

[17] A robust signal of interannual climate variability can be reconstructed from the skeletal geochemistry records of the Santo coral as demonstrated via the goodness of fit between geochemical time series and instrumental records of ENSO and SOI variability. We also demonstrate that changes in mean climate state observed in instrumental records are also observable in coral proxy time series.

[18] A correlation matrix consisting of monthly values of SSS, coral δ^{18}OA, and ENSO indices confirms the relevance of corals from Santo for reconstructing regional climate changes (Table 1). The indices used to define ENSO are the Niño 3.4 grid box SST anomaly (referred to as simply Niño 3.4; 5S–5N, 170W–120W extracted from the HadISST1.1 data set; *Rayner et al.* [2003]), and the Southern Oscillation Index (SOI). As one would expect from Figure 4, δ^{18}OA correlates well (r = 0.71; p = 0.02) with SSS at zero lags (δ^{18}OA also correlates well with SSS anomaly, r = 0.64, p = 0.037, 12 independent data points). Salinity in turn correlates well with both the SOI and the Niño 3.4 index. Salinity lags the SOI by six months and the Niño 3.4 index by seven months. The difference in phasing is expected since the SOI leads the Niño 3.4 SST index by one month. δ^{18}OA follows the SOI and Niño 3.4 index almost as well as SSS and has similar phasing relationships during 1976–1992, when the coral δ^{18}OA record overlaps with the SSS record. The stationarity of these relationships is the test of the proxy. Indeed the correlations between δ^{18}O, SOI and Niño 3.4 remain high for the period prior to the availability of SSS data (1928–1975).

[19] The ordinary least squares regression of coral δ^{18}OA on SSS anomaly gives a slope of 0.36‰ VPDB psu^{-1} (0.37‰ VSMOW psu^{-1}). This slope is higher than the 0.273‰ VSMOW psu^{-1} determined by *Fairbanks et al.*

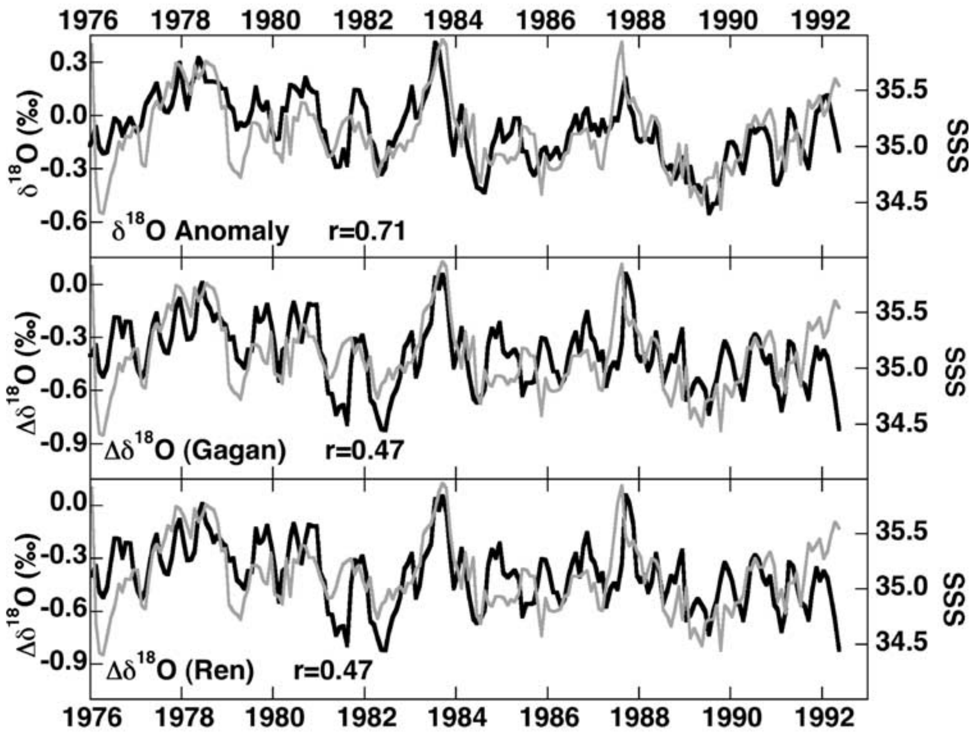

Figure 4. Comparison of three coral-based reconstructions of seawater δ^{18}O (heavy black lines) and instrumental SSS (thin gray line; *Gouriou and Delcroix* [2002]). The top panel is the δ^{18}O anomaly (monthly averages 1928–1992 subtracted out), the middle panel uses the method proposed by *McCulloch et al.* [1994] and expanded by *Gagan et al.* [1998], and the bottom panel uses the method of *Ren et al.* [2002]. The correlation coefficients (r) for each proxy of salinity are calculated after detrending the data and normalizing by the standard deviations of each time series.

[1997] from the equatorial Pacific. However it is less than the 0.42‰ VSMOW psu^{-1} obtained by *Morimoto et al.* [2002] for Malakal, Palau. A water sampling and analysis program at Santo is required to identify the factors responsible for the intermediate slope value of the seawater δ^{18}O/SSS relationship estimated in this study.

[20] A strong (r = 0.48) and statistically significant (p = 0.0026) relationship exists between monthly δ^{18}O anomaly at Santo and the Niño 3.4 index for the length of the record, 1928 to 1992 (Figure 5). The maximum correlation for the entire data set is at a 4-month lag where western equatorial Pacific seawater δ^{18}O lags behind the eastern equatorial Pacific SSTA. The mechanism for the time lag likely reflects the time it takes for precipitation anomalies to affect SSS (2–3 months; *Delcroix et al.* [1996]) and with the time it takes the western Pacific Ocean to be affected by an ENSO warm phase event, because local SSS anomalies are driven by both SPCZ precipitation and advection of the "fresh pool" salinity front.

[21] Specific ENSO events are readily identified in the Santo δ^{18}OA record. ENSO cool phase events at Santo are characterized by increased precipitation, decreased salinity, and decreased δ^{18}O, whereas ENSO warm phase events are characterized by decreased precipitation, increased salinity and increased δ^{18}O. All of the ENSO events since 1950, as defined by *Trenberth* [1997], can be visually distinguished by the δ^{18}O signal in Figure 5. All but one of the ENSO events can be distinguished objectively when δ^{18}OA exceeds a threshold of ±0.1‰ for several months, minus 0.1‰ during warm phase events and plus 0.1‰ during cool phase events.

[22] Other analyses support our interpretation that the Santo coral δ^{18}O reflects ENSO-driven salinity changes. Cross-spectral analysis (not shown) between δ^{18}O and the SOI, and δ^{18}O and the Niño 3.4 index shows highly significant ($p < 0.05$) coherency in the ENSO bandwidth. Interannual δ_w changes, as recorded by coral δ^{18}O, also

Table 1. Linear Correlations Between Salinity in the Vanuatu Region, Coral δ^{18}O, and Indices of ENSO[a]

	δ^{18}O Anomaly		SOI		Niño 3.4	
	76–92	28–75	76–92	28–75	76–92	28–75
G&D-SSS	0.71	N/A	−0.59	N/A	0.60	N/A
δ^{18}O Anomaly			−0.54	−0.32	0.59	0.51
SOI					−0.71	−0.60

[a]All of the data have monthly resolution and the correlations are significant to the 95% confidence level or greater. Each correlation coefficient is the maximum or minimum of the correlation function and the lead-lag relationships are noted in the text. The 1976–1992 interval is the period of overlap for all four data sets. The interval between 1928–1975 is the period prior to the availability of SSS data. N/A, not applicable.

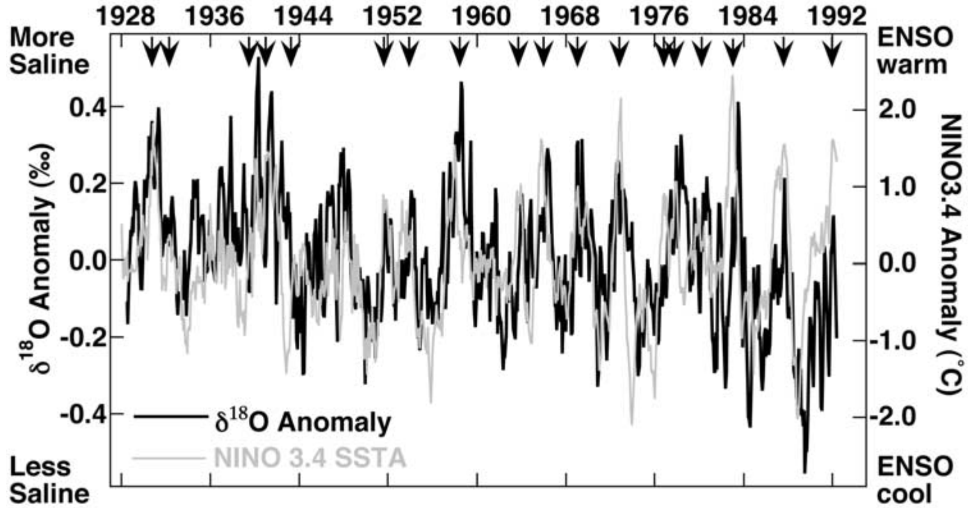

Figure 5. Santo coral δ^{18}O anomaly plotted versus Niño 3.4 region SSTA. The δ^{18}O curve has been shifted forward in time by 6 months to compensate for a 6 month lag time between the salinity response at Vanuatu to changes in temperature in the Niño 3.4 region. ENSO warm phase events (El Niño) in the eastern Pacific are correlated with increased salinity in the western Pacific and are noted by arrows along the top of the graph.

relate to regional rainfall changes associated with SPCZ dynamics. There is covariance between the SPCZ index, derived from December–January–February seasonal rainfall at Pacific island rain gauge stations [*Deser et al.*, 2004], and seasonal averages of the Santo coral δ^{18}OA. The correlation between the SPCZ index with δ^{18}OA from the most highly correlated season (April, May, June) shows a clear correlation peak at the zero lag point and very little correlation at greater and lesser lags, indicating that the correlation is not just a statistical artifact. However, the correlation is not statistically significant ($r = -0.42$, $p = 0.165$), because serial correlation reduces the number of effective data points from $N = 65$ to $N^* = 11.4$.

[23] The Santo coral time series also captures a decreasing trend in δ^{18}O since the late 1970s (Figure 6). Similar trends appear in the δ^{18}O of Pacific corals from Tarawa (1°N, 172°E; *Cole et al.* [1993]), Palmyra (5°52′N, 162°8′W; *Cobb et al.* [2001]), Maiana (1°N, 173°E, *Urban et al.* [2000]), and Nauru (0.5°S, 166°E; *Guilderson and Schrag* [1999]). The Santo coral δ^{18}O trend amounts to a decrease of about 2.1‰ between 1977 and 1992, too much to be interpreted as temperature alone (it is equivalent to ~10°C warming), and no significant shift in coral extension rates occurs in the Santo coral to explain such a trend. Recent analyses show that surface freshening has occurred in the tropics [*Antonov et al.*, 2002], and it is likely that the decreasing δ^{18}O trend is related to surface ocean freshening under the convergence zones. Increased precipitation under the convergence zones could decrease the δ^{18}O of precipitation through the amount effect [*Craig and Gordon*, 1965]. The slope of consecutive 4-yearlong δ^{18}O-SSS regressions of the δ^{18}OA and SSS anomaly data indicate an increasing trend in slope during the period 1976–1992, supporting this inference. Ensemble modeling predicts an increase in precipitation under the convergence zones as global warming progresses [*Allen and Ingram*, 2002], and this theory is further supported by data indicating increased intensity in Hadley and Walker circulation during the 1990s [*Chen et al.*, 2002]. The fact that five Pacific corals show similar δ^{18}O trends that track changes observed in the instrumental record, increases our confidence that our Santo coral is a robust recorder of large-scale, long-term changes in mean climate state as well as interannual variability associated with ENSO.

[24] Understanding the modern relationships between climate processes and Santo coral geochemistry provides the basis for interpreting fossil coral records from the same region. Previous work on coral climate records from Vanuatu has mainly focused on Sr/Ca and SST changes [*Beck et al.*, 1992, 1997; *Corrège et al.*, 2000]. Analyzing δ^{18}O in existing coral samples might help to shed light on remaining questions, such as what happened to the annual δ_w cycle when the annual temperature cycle changed in the mid Holocene [*Corrège et al.*, 2000], or how much interannual salinity changes were associated with the large temperature variations previously recorded [*Beck et al.*, 1997]. New, longer coral records from this area could provide evidence for SPCZ migrations [e.g., *Corrège et al.*, 2004] or ENSO frequency variations in the geologic past.

4. Conclusions

[25] We have used a monthly resolved, 65-year record of skeletal δ^{18}O and Sr/Ca variations in a *Porites* coral from Espiritu Santo, Vanuatu to demonstrate that δ^{18}O variations are well correlated to regional SSS changes on interannual timescales, which reflect the strong regional signature of ENSO dynamics. Our analysis also provides a cautionary note to others that some discrepancies may exist between

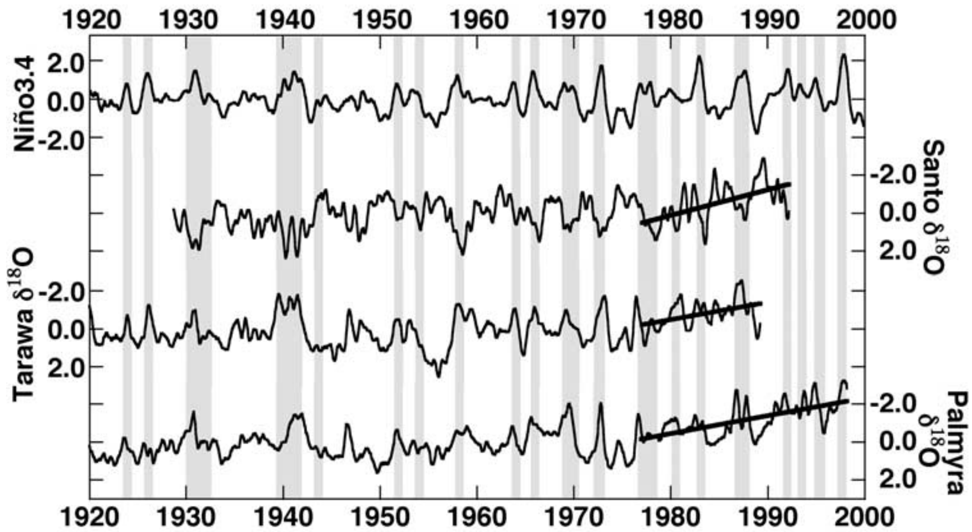

Figure 6. Coral $\delta^{18}O$ records from Santo (this study), Tarawa [*Cole et al.*, 1993] and Palmyra [*Cobb et al.*, 2001] record interannual climate variations due to ENSO and decadal-scale changes in SSS. ENSO warm phase events since 1950 are indicated in the figure by gray bars. Tarawa and Palmyra experience warmer and wetter conditions during ENSO warm phase events, while Santo experiences cooler and drier conditions during these events. All three tropical Pacific corals record a decrease in coral $\delta^{18}O$ since 1976 that is consistent with a documented freshening trend in seawater under the convergence zones.

model salinity output and measured salinity. We demonstrated that previously proposed methods of estimating seawater $\delta^{18}O$ using paired coral $\delta^{18}O$ and Sr/Ca are functionally equivalent and that the coral $\delta^{18}O$ anomaly time series provides the best fit between instrumental salinity variations and coral proxy data at Santo. We also document that the coral time series at Santo captures a freshening trend in surface ocean salinity in the western tropical Pacific since the climate regime shift of 1976–1977 [e.g., *Mantua et al.*, 1997]. The results of our study can be used to fortify paleoclimate interpretations based on fossil *Porites* corals from this area.

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References

Allen, M., and W. Ingram (2002), Constraints on future changes in climate and the hydrologic cycle, *Nature*, *419*, 224–232.

Antonov, J. I., S. Levitus, and T. P. Boyer (2002), Steric sea level variations during 1957–1994: Importance of salinity, *J. Geophys. Res.*, *107*(C12), 8013, doi:10.1029/2001JC000964.

Beck, J. W., R. L. Edwards, E. Ito, F. W. Taylor, J. Recy, F. Rougerie, P. Joannot, and C. Hénin (1992), Sea-surface temperature for coral skeletal strontium/calcium ratios, *Science*, *257*, 644–647.

Beck, J. W., J. Recy, F. Taylor, R. L. Edwards, and G. Cabioch (1997), Abrupt changes in early Holocene tropical sea surface temperature derived from coral records, *Nature*, *385*, 705–707.

Behringer, D. W., M. Ji, and A. Leetmaa (1998), An improved coupled model for ENSO prediction and implications for ocean initialization. Part I: The ocean data assimilation system, *Mon. Weather Rev.*, *126*, 1013–1021.

Bemis, B. E., H. J. Spero, J. Bijma, and D. W. Lea (1998), Reevaluation of the oxygen isotopic composition of planktonic foraminifera: Experimental results and revised paleotemperature equations, *Paleoceanography*, *13*(2), 150–160.

Chelton, D. B. (1983), Effects of sampling errors in statistical estimation, *Deep Sea Res. Part A*, *30*(10), 1083–1103.

Chen, J., B. E. Carlson, and A. D. Del Genio (2002), Evidence for strengthening of the tropical general circulation in the 1990's, *Science*, *295*, 838–841.

Cobb, K. M., C. D. Charles, and D. E. Hunter (2001), A central tropical pacific coral demonstrates Pacific Indian, and Atlantic decadal climate connections, *Geophys. Res. Lett.*, *28*(11), 2209–2212.

Cole, J. E., and R. G. Fairbanks (1990), Southern Oscillation recorded in the $\delta^{18}O$ of corals from Tarawa atoll, *Paleoceanography*, *5*(5), 669–683.

Cole, J. E., R. G. Fairbanks, and G. T. Shen (1993), The spectrum of recent variability in the Southern Oscillation: Results from a Tarawa Atoll coral, *Science*, *260*, 1790–1793.

Corrège, T., T. Delcroix, J. Récy, W. Beck, G. Cabioch, , and F. Le Cornec (2000), Evidence for stronger El Niño-Southern Oscillation (ENSO) events in a mid-Holocene massive coral, *Paleoceanography*, *15*(4), 465–470.

Corrège, T., M. K. Gagan, W. Beck, G. S. Burr, G. Cabioch, and F. Le Cornec (2004), Interdecadal variation in the extent of South Pacific tropical waters during the Younger Dryas event, *Nature*, *428*, 927–929.

Craig, H., and L. I. Gordon (1965), Deuterium and oxygen 18 variations in the ocean and the marine atmosphere, in *Stable Isotopes in Oceanographic Studies and Paleotemperatures*, edited by E. Tongiorgi, pp. 9–130, Cons. Naz. delle Ric. Lab. di Geol. Nucl., Pisa, Italy.

Delcroix, T., and M. McPhaden (2002), Interannual sea surface salinity and temperature changes in the western Pacific warm pool during the 1992–2000, *J. Geophys. Res.*, *107*(C12), 8002, doi:10.1029/2001JC000862.

Delcroix, T., C. Henin, V. Porte, and P. Arkin (1996), Precipitation and sea-surface salinity in the tropical Pacific Ocean, *Deep Sea Res. Part I*, *43*(7), 1123–1141.

Deser, C., A. S. Phillips, and J. W. Hurrell (2004), Pacific interdecadal climate variability: Linkages between the tropics and North Pacific during boreal winter since 1900, *J. Clim.*, *17*(16), 3109–3124.

Fairbanks, R. G., M. N. Evans, J. L. Rubenstone, R. A. Mortlock, K. Broad, M. D. Moore, and C. D. Charles (1997), Evaluating climate indices and their geochemical proxies measured in corals, *Coral Reefs*, *16*(suppl.), S93–S100.

Folland, C. K., J. A. Renwick, M. J. Salinger, and A. B. Mullan (2002), Relative influences of the Interdecadal Pacific Oscillation and ENSO on the South Pacific Convergence Zone, *Geophys. Res. Lett.*, *29*(13), 1643, doi:10.1029/2001GL014201.

Gagan, M. K., L. K. Ayliffe, D. Hopley, J. A. Cali, G. E. Mortimer, J. Chappell, M. T. McCulloch, and M. J. Head (1998), Temperature and surface-ocean water balance of the mid-Holocene tropical western Pacific, *Science*, *279*, 1014–1018.

Gouriou, Y., and T. Delcroix (2002), Seasonal and ENSO variations of sea surface salinity and temperature in the South Pacific Convergence Zone during 1976–2000, *J. Geophys. Res.*, *107*(C12), 3185, doi:10.1029/2001JC000830.

Guilderson, T. P., and D. P. Schrag (1999), Reliability of coral isotope records from the western Pacific warm pool: A comparison using age-optimized records, *Paleoceanography*, *14*, 457–464.

Kalnay, E., et al. (1996), The NCEP/NCAR Reanalysis 40-year Project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471.

Kilbourne, K. H., T. M. Quinn, and F. W. Taylor (2004), A fossil coral perspective on western tropical Pacific climate ~350 ka, *Paleoceanography*, *19*, PA1019, doi:10.1029/2003PA000944.

Le Bec, N., A. Juillet-Leclerc, T. Corrège, D. Blamart, and T. Delcroix (2000), A coral $\delta^{18}O$ record of ENSO driven seas surface salinity variability in Fiji (south-western tropical Pacific), *Geophys. Res. Lett.*, *27*(23), 3897–3900.

Linsley, B. K., R. B. Dunbar, G. M. Wellington, and D. A. Mucciarone (1994), A coral-based reconstruction of intertropical convergence zone variability over Central America since 1707, *J. Geophys. Res.*, *99*(C5), 9977–9994.

Lukas, R., and E. Lindstrom (1991), The mixed layer of the western equatorial Pacific Ocean, *J. Geophys. Res.*, *96*, 3343–3358.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis (1997), A Pacific decadal climate oscillation with impacts on salmon, *Bull. Am. Meteorol. Soc.*, *78*, 1069–1079.

McConnaughey, T. (1989), 13C and 18O isotopic disequilibrium in biologic carbonates: I. Patterns, *Geochim. Cosmochim. Acta*, *53*, 151–162.

McCulloch, M. T., M. K. Gagan, G. E. Mortimer, A. R. Chivas, and P. J. Isdale (1994), A high-resolution Sr/Ca and $\delta^{18}O$ coral record from the Great Barrier Reef, Australia, and the 1982–1983 El Niño, *Geochim. Cosmochim. Acta*, *58*(12), 2747–2754.

Morimoto, M., O. Abe, H. Kayanne, N. Kurita, E. Matsumoto, and N. Yoshida (2002), Salinity records for the 1997–98 El Niño from Western Pacific corals, *Geophys. Res. Lett.*, *29*(11), 1540, doi:10.1029/2001GL013521.

Paillard, D., L. Labeyrie, and P. Yiou (1996), Macintosh program performs time series analysis, *Eos Trans. AGU*, *77*(39), 379.

Quinn, T. M., F. W. Taylor, and T. J. Crowley (1993), A 173-year stable isotope record from a tropical South Pacific coral, *Quat. Sci. Rev.*, *12*, 407–418.

Quinn, T. M., T. J. Crowley, and F. W. Taylor (1996), New stable isotope results from a 173-year coral from Espiritu Santo, Vanuatu, *Geophys. Res. Lett.*, *23*(23), 3413–3416.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan (2003), Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *J. Geophys. Res.*, *108*(D14), 4407, doi:10.1029/2002JD002670.

Ren, L., B. K. Linsley, G. M. Wellington, D. P. Schrag, and O. Hoegh-Guildberg (2002), Deconvolving the $\delta^{18}O$ seawater component from subseasonal coral $\delta^{18}O$ and Sr/Ca at Rarotonga in the southwestern subtropical Pacific for the period 1726 to 1997, *Geochim. Cosmochim. Acta*, *67*(9), 1609–1621.

Salinger, M. J., J. A. Renwick, and A. B. Mullan (2001), Interdecadal Pacific Oscillation and South Pacific Climate, *Int. J. Climatol.*, *21*, 1705–1721.

Stephans, C. L., T. M. Quinn, F. W. Taylor, and T. Corrège (2004), Assessing the reproductibility of coral-based climate records, *Geophys. Res. Lett.*, *18*, L18210, doi:10.1029/2004GL020343.

Trenberth, K. E. (1997), The definition of El Niño, *Bull. Am. Meteorol. Soc.*, *78*(12), 2771–2777.

Tudhope, A. W., G. B. Shimmield, C. P. Chilcott, M. Jebb, A. E. Fallick, and A. N. Dalgleish (1995), Recent changes in climate in the far western equatorial Pacific and their relationship to the Southern Oscillation: Oxygen isotope records from massive corals, Papua New Guinea, *Earth Planet. Sci. Lett.*, *136*, 575–590.

Urban, F. E., J. E. Cole, and J. T. Overpeck (2000), Influence of mean climate change on climate variability from a 155-year tropical Pacific coral record, *Nature*, *407*, 989–993.

Vialard, J. M., and P. Delecluse (1998), An OGCM study for the TOGA decade. Part I: Role of salinity in the physics of the western Pacific fresh pool, *J. Phys. Oceanogr.*, *28*, 1071–1088.

Vialard, J. M., P. Delecluse, and C. Menkes (2002), A modeling study of salinity variability and its effects in the tropical Pacific Ocean during the 1993–1999 period, *J. Geophys. Res.*, *107*(C12), 8005, doi:10.1029/2000JC000758.

Vincent, D. G. (1994), The South Pacific Convergence Zone (SPCZ): A review, *Mon. Weather Rev.*, *122*, 1949–1970.

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