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Coral oxygen isotope records of interdecadal climate variations in the South Pacific Convergence Zone region

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[1] The South Pacific Convergence Zone (SPCZ), a region of high rainfall, is a major feature of subtropical Southern Hemisphere climate and contributes to and interacts with circulation features across the Pacific, yet its past temporal variability and forcing remain only partially understood. Here we compare coral oxygen isotopic ($\delta^{18}O$) series (spanning A.D. 1997–1780 and A.D. 2001–1776) from two genera of hermatypic corals in Fiji, located within the SPCZ, to examine the fidelity of these corals in recording climate change and SPCZ interdecadal dynamics. One of these coral records is a new 225-year subannually resolved $\delta^{18}O$ series from the massive coral *Diploastrea heliopora*. *Diploastrea*'s use in climate reconstructions is still relatively new, but this coral has shown encouragingly similar interannual variability to *Porites*, the coral genus most commonly used in Pacific paleoclimate studies. In Fiji we observe that interdecadal $\delta^{18}O$ variance is also similar in these two coral genera, and *Diploastrea* contains a larger-amplitude interdecadal signal that more closely tracks instrumental-based indices of Pacific interdecadal climate change and the SPCZ than *Porites*. Both coral $\delta^{18}O$ series record greater interdecadal variability from ~1880 to 1950, which is consistent with the observations of Folland et al. (2002), who reported higher variability in SPCZ position before 1945. These observations indicate that *Diploastrea* will likely provide a significant new source of long-term climate information from the SPCZ region.

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1. Introduction

[2] The South Pacific Convergence Zone (SPCZ) is characterized by a band of low-level convergence, cloudiness, precipitation, and strong sea surface temperature (SST) gradients extending from the Western Pacific Warm Pool southeastward toward French Polynesia [*Kiladis et al.*, 1989; *Vincent*, 1994; *Folland et al.*, 2002]. The SPCZ is located at a major discontinuity in the tempera-

ture and precipitation responses in the South Pacific on annual through interdecadal timescales [*Salinger et al.*, 1995, 2001; *Folland et al.*, 2002, 2003]. The position and activity of the SPCZ are modulated by the El Niño Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) [*Folland et al.*, 2002]. Further, the SPCZ appears to play an important role in the cross-equatorial circulation over the western and central Pacific [*Vincent*, 1994]. The importance of the SPCZ in global-scale circulation and climate warrants a better understanding of the SPCZ dynamics, including how it interacts with low-frequency SST variations, the importance of tropical versus higher-latitude influences, and its link to circulation patterns over the Indian Ocean. Advances in any of these areas would lead to improvements in weather forecasting and climate prediction [*Vincent*, 1994].

[3] Perhaps the largest obstacle in addressing these questions about SPCZ variability is the availability of reliable continuous measurements of physical ocean properties in the tropical and subtropical Pacific, which generally do not span more than the past 50 years, a period likely already influenced by human activities. Such short and sparse instrumental data cannot begin to address long-term interannual variability or establish statistically significant conclusions about decadal-scale variability. However, developing a longer-term perspective on climatic variations in the Pacific is crucial for confirming the accuracy of climate models used to predict potential future change. Some scleractinian corals are uniquely suited for extending the instrumental record to preanthropogenic times because climate-driven variability in ocean conditions is in many cases recorded in the chemistry of their aragonite skeletons. Additionally, corals probably provide the best marine archive of changes in SST, sea surface salinity (SSS) and the δ^{18}O composition of seawater over the last several centuries [e.g., *Dunbar and Wellington*, 1981; *Cole et al.*, 1993; *Quinn et al.*, 1993; *Linsley et al.*, 1994; *Charles et al.*, 1997; *Linsley et al.*, 2000a; *LeBec et al.*, 2000] and have sufficient time resolution to study interannual through interdecadal climate phenomena.

[4] The coral genus *Porites* has been the primary Pacific coral archive of past climate variability. Despite previous success using the genus *Porites* for paleoclimate reconstructions, several significant limitations of using these archives remain including interpretation of decadal and trend modes of variance, potential biological artifacts, and an annual skeletal extension rate (generally ~1 cm/yr) which at best yields colonies only 300–400 years in age from typical cores. Examination of ENSO-scale variability has been the main success of coral proxy records to date, but there exist only a few multicentury long Pacific *Porites* records that can begin to address climate variability with decadal and lower frequencies [*Cole et al.*, 1993; *Quinn et al.*, 1993, 1998; *Linsley et al.*, 1994, 2000b, 2004; *Dunbar et al.*, 1994; *Boiseau et al.*, 1998; *Cole et al.*, 2000; *Urban et al.*, 2000]. The Indo-Pacific coral genus *Diploastrea*, however, has a slower annual skeletal extension rate (3–6 mm/yr), which in itself indicates that *Diploastrea* colonies may yield longer proxy records than *Porites* colonies from the same length of core. *Diploastrea* has a dense skeletal structure, rarely damaged by bioeroders, resulting in a lifespan longer than any other coral in the Faviidae family [*Veron*, 1986], up to 1000 years [*Watanabe et al.*, 2003]. Additionally, *Diploastrea*'s presence in the fossil record extends as far back as the Cretaceous [*Veron*, 1986], a full 10 million years before *Porites*. Such advantages in using *Diploastrea* corals may have already begun to reveal new insights into tropical South Pacific climate variability during the Younger Dryas [*Corrège et al.*, 2004].

[5] The SPCZ directly affects the climate of the Fijian Islands (Figure 1). The SPCZ Position Index (SPI), defining the north-south movement of the SPCZ, is calculated as the normalized November–April difference in sea level pressure between Suva, Fiji and Apia, Samoa, based on the period 1961–1990 [*Folland et al.*, 2002]. Briefly, positive (negative) values of the SPI correspond to northward (southward) displacement of the SPCZ to ward Samoa (Fiji) during El Niño (La Nina) events and the positive (negative) phase of the IPO [*Folland et al.*, 2002], with Fiji generally experiencing negative (positive) precipitation and SST anomalies [*Salinger et al.*, 1995] creating positive (negative) coral δ^{18}O anomalies. The correlation between movements of the SPI and precipitation and SST is shown in Figure 1, along with the location of the Fijian Islands. *Folland et al.* [2002] have shown that the SPI is highly correlated with the IPO, thus for the southwest Pacific area around Fiji, the correlation pattern in Figure 1 is thought to reflect IPO related variability of the SPCZ. Both ENSO and IPO-scale variability in the position of the SPCZ, and advection of low δ^{18}O seawater to the west of Fiji are predicted to alter seawater δ^{18}O in the region, although the interdecadal seawater

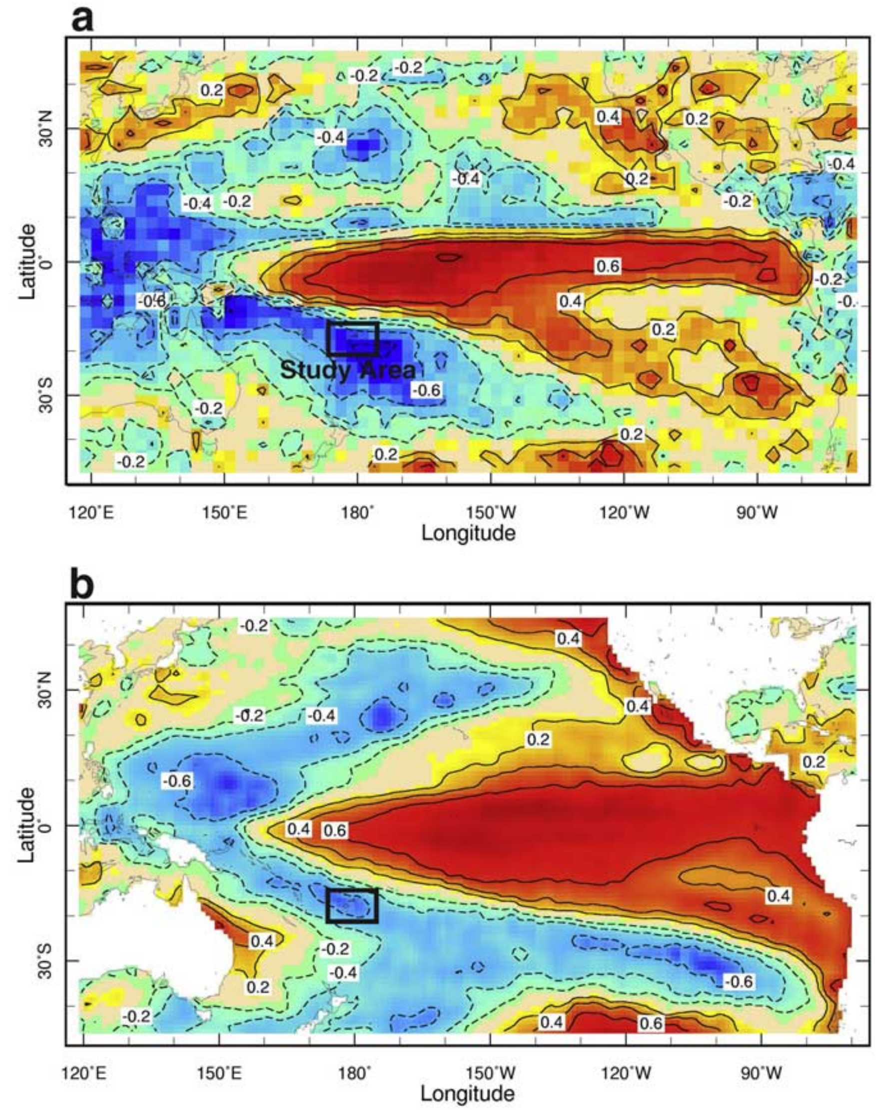

Figure 1. Location of study area in relationship to the spatial pattern of the correlation of the South Pacific Convergence Zone Index (SPI) [from *Folland et al.*, 2002] against precipitation and sea surface temperature in the tropical and subtropical Pacific over the last ~20 years. *Folland et al.* [2002] have found that the SPI is highly correlated with the Interdecadal Pacific Oscillation (IPO). (a) Correlation of SPI against precipitation over interval from 1979 to 2000 (r values). (b) Correlation of SPI against SST over interval from 1981 to 2000 (r values). August to July annual means of precipitation and SST are calculated from monthly analyses by *Xie and Arkin* [1996] and *Reynolds et al.* [2001], respectively.

δ^{18}O anomalies in this region could also be overprinted by evaporation [*Linsley et al.*, 2004]. Because interdecadal SST and SPCZ-related seawater δ^{18}O anomalies force coral skeletal δ^{18}O in the same direction in Fiji, corals from this location are ideally suited for reconstructing IPO-related climate variability [*Linsley et al.*, 2004; *Bagnato et al.*, 2004]. Here we compare our new 225-year *Diploastrea* δ^{18}O time series to regional instrumental data and to a neighboring 217-year-long *Porites* δ^{18}O record, which was shown to contain a regionally coherent interdecadal signal [*Linsley et al.*, 2004], to assess the paleoclimatic utility of *Diploastrea* skeletons in recording interdecadal variability within the SPCZ.

2. Methods

[6] In April 1997 a 30 cm core from a colony of *Diploastrea heliopora* [*Bagnato et al.*, 2004] and a 2.3 m core from a *Porites lutea* colony [*Linsley et al.*, 2004] were collected from the middle of Savusavu Bay on the south side of Vanua Levu,

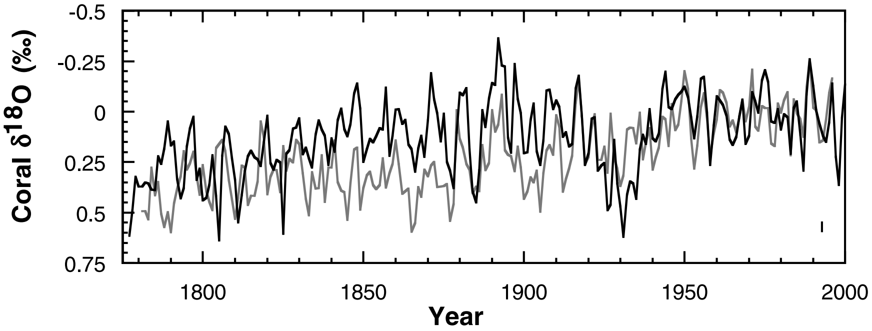

Figure 2. Annually averaged time series of Fiji coral δ^{18}O. The composite *Diploastrea* record is shown in black; *Porites* is in gray. All coral δ^{18}O data are reported as per mil deviations relative to the 1970–1996 mean from each record. Error bar in bottom right corner shows analytical precision (1σ).

Fiji (16°49′S, 179°14′E) from about 10 m water depth. In December 2001 a 1.3 m *Diploastrea* core was retrieved in 2 m of water from the outer edge of Savusavu Bay, approximately 0.5 km from the 1997 site, the upper 60 years of which have been previously described [*Bagnato et al.*, 2004]. Recent examination of *Diploastrea* skeletal δ^{18}O suggests that *Diploastrea* records interannual climate variability in a manner similar to *Porites* in Indonesia, New Caledonia, and Fiji [*Watanabe et al.*, 2003; *Bagnato et al.*, 2004]. Although these studies employed two different skeletal sampling strategies, it appears that either approach yields a comparable representation of the annual mean [*Bagnato et al.*, 2004], a key target for examination of climate frequencies at or below interannual [*Quinn et al.*, 1998]. Therefore we present here an annually averaged composite record (period of overlapping records 1941–1996) that spans the period 1776–2001, employing the sampling techniques and age model of *Bagnato et al.* [2004]. Briefly, coral cores were cut into 7-mm-thick slabs, which were cleaned in deionized water in an ultrasonic bath. The slabs were sampled with a low-speed micro drill, along tracks identified in X-ray positives, with a 1 mm round diamond drill bit. For the *Diploastrea* composite record presented here, septal skeleton was sampled continuously at 0.5 mm intervals along the axis of maximum growth within the upper 50 mm, after which the sampling density was changed to 1 mm intervals, yielding 5–6 samples per year. The Fiji *Porites* coral was sampled for δ^{18}O at a comparable (roughly bimonthly) resolution, and described elsewhere [*Linsley et al.*, 2004]. We measured oxygen isotopes on a gas source mass spectrometer with an individual acid reaction vessel system at the University at Albany Stable Isotope Laboratory following the procedures of *Linsley et al.* [2000a]. External precision for δ^{18}O, based on the repeated analysis of NBS-19 over the course of the project, is better than 0.04‰ (1σ). Fiji *Diploastrea* δ^{18}O data are archived at http://www.ngdc.noaa.gov/paleo/data.html.

3. Results

[7] Annually averaged Fiji coral δ^{18}O time series are shown in Figure 2 as anomalies relative to the 1970–1996 average δ^{18}O value from each core to demonstrate the inter-genus reproducibility of δ^{18}O at this site and to highlight lower frequency trends in the data. Although there is some offset in the mid 1800s, interannual variations in *Diploastrea* and *Porites* δ^{18}O are well aligned temporally, but the magnitude of interdecadal variability appears larger in *Diploastrea*, especially in the late 1800s and early 1900s.

[8] Annual average δ^{18}O records and instrumental data were filtered with a 10-year smoothing spline low-pass filter, and the low-pass fraction was analyzed using Singular Spectrum Analysis (SSA), as done by *Linsley et al.* [2004]. The interdecadal mode of variance in each Fiji coral δ^{18}O time series, in instrumental SST data, and in climate indices was isolated and examined by utilizing SSA to extract the components of variance with periods between ~17 and 50 years from all time series [*Linsley et al.*, 2004]. Note that essentially identical results are obtained by band-pass filtering with a Gaussian Filter (centered at 25 years between periods 17 and 50 years). For both Fiji corals this interdecadal band in δ^{18}O is the third largest component of variance behind the annual cycle and long-term trend. However, the interdecadal mode accounts for up to ~21% of the variance in the *Diploastrea* time series, while the

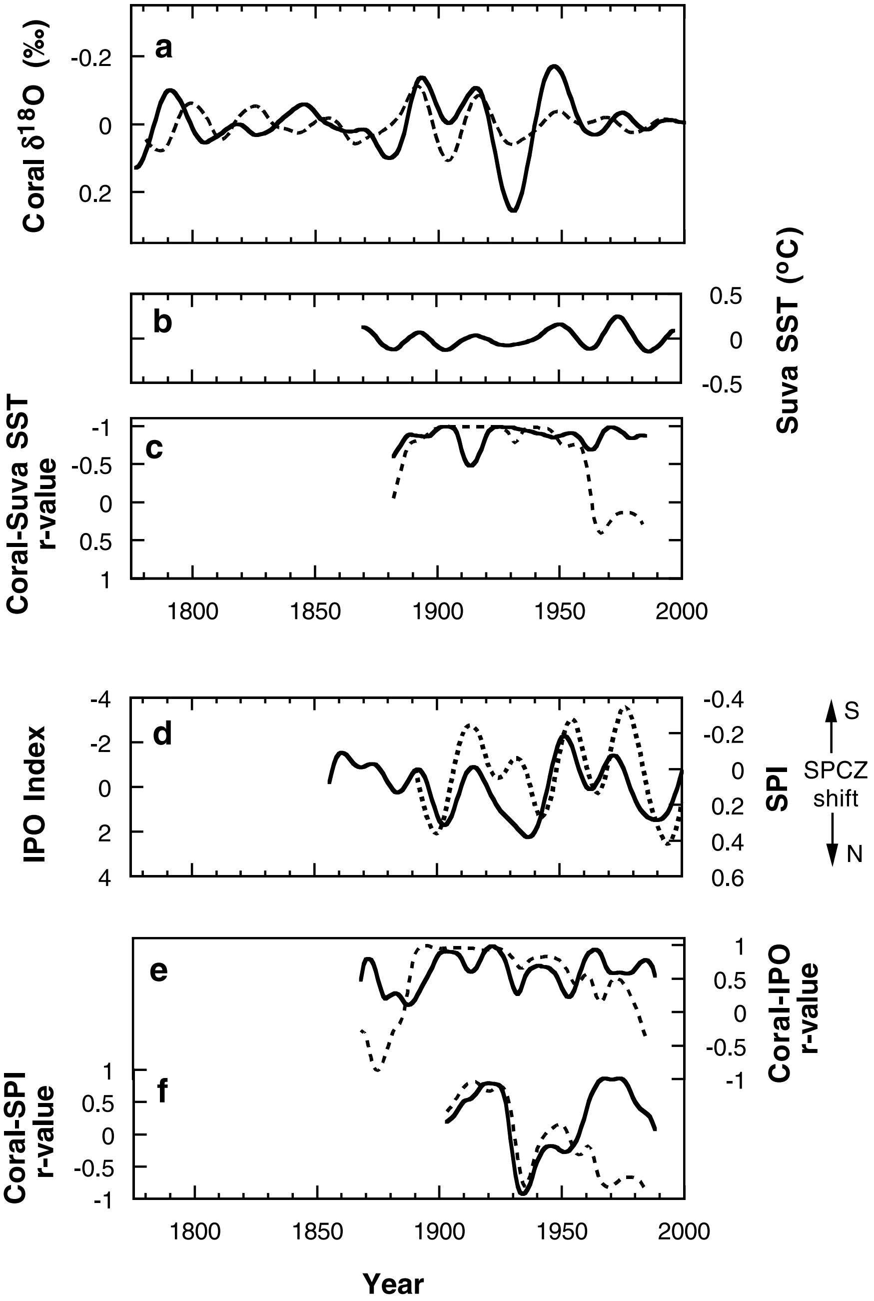

Figure 3. (a) Interdecadal variability in Fiji coral δ^{18}O, *Diploastrea* solid, *Porites* dashed, and (b) instrumental SST data from Suva, Fiji. (c) Running correlation coefficients between Fiji coral δ^{18}O and Suva SST, *Diploastrea* solid, *Porites* dashed (note that coral δ^{18}O and SST are negatively correlated). (d) The instrumental IPO (solid) and SPI (dashed) indices. Note that positive (negative) values of the SPI indicate northward (southward) displacement of the SPCZ. (e and f) Running correlation coefficients between Fiji coral δ^{18}O and the IPO and SPI indices, *Diploastrea* solid, *Porites* dashed.

interdecadal band in *Porites* accounts for ~9% of the total variance [*Bagnato*, 2003; *Linsley et al.*, 2004].

[9] To assess the interdecadal signal in each coral we compare the interdecadal band of coral δ^{18}O to that of instrumental SST data from Suva, Fiji [*Folland et al.*, 2003], the IPO index and the SPI [*Folland et al.*, 2002] in Figure 3. We applied the same spline filtering-SSA treatment to all data compared in Figure 3. Coral δ^{18}O faithfully records the timing of most major transitions of the IPO, which is coherent with Suva SST and the position of the SPCZ, although the SPCZ is also affected

independently by interannual (ENSO-related) variability [*Folland et al.*, 2002] (Figure 3). A running average correlation coefficient (25 year window) is calculated for each coral genus versus Suva SST (Figure 3c), the IPO Index (Figure 3e), and the SPI (Figure 3f) to highlight the time intervals of strongest interdecadal alignment. Both coral genera are well aligned with interdecadal SST variations, showing similar response both locally and regionally. The period of highest-amplitude δ^{18}O variability and greatest coherence with interdecadal climate variations in *Diploastrea* and *Porites* δ^{18}O is between ~1890 and 1950, which is consistent with the higher variability before 1945 seen in recent analysis of SPCZ position [*Folland et al.*, 2002] and also a time interval of lower interdecadal variability in SST. The only exception is a clear reduction in coherence with the SPCZ around 1935, when both corals are distinctly out of phase with the SPI. However, the degree of correlation between all indices and *Porites* δ^{18}O drops off sharply after ~1950, while *Diploastrea* δ^{18}O maintains greater correlation with interdecadal SST and SPCZ variations throughout the remainder of the 20th century, most noticeably with respect to the SPI (Figure 3f).

4. Discussion

[10] The observed differences in the amplitude of interdecadal δ^{18}O variations in these corals are likely not attributed to climate change since each grew in the same bay. To explore the potential source of this difference, we quantitatively separated the effects of SST from those of seawater δ^{18}O on each coral δ^{18}O record, for SST and seawater δ^{18}O both influence coral δ^{18}O in the same sense, however the relative contributions may vary in different regions and coral colonies. We used the technique of [*Ren et al.*, 2003] to difference our time series of Sr/Ca [*Linsley et al.*, 2004; *Bagnato et al.*, 2004] and δ^{18}O for the period 1965–1997. The technique assumes that all variations in coral Sr/Ca are due to SST changes, and that variations in coral δ^{18}O are due to the combined influences of SST and seawater δ^{18}O. With these assumptions we find that SST explains a maximum of 66% of the variance in *Porites* δ^{18}O, while seawater δ^{18}O explains a maximum of 34%. For *Diploastrea*, SST explains a maximum of 55% of the variance in δ^{18}O, while seawater δ^{18}O explains a maximum of 45%. Our local *Diploastrea* tracer-SST calibration slopes are below typical values for Pacific corals [*Ren et al.*, 2003] due to low resolution sampling [*Bagnato*, 2003; *Bagnato et al.*, 2004], although, when more typical slope values [*Ren et al.*, 2003] are substituted in our calculations, the seawater δ^{18}O and SST contributions each become very nearly 50%. These calculations suggest that, at least for the latter half of the 20th century, *Diploastrea*'s higher-amplitude interdecadal signal may be due to the coral's stronger response to SPCZ-forced seawater δ^{18}O variability, also evident in the stronger coherence between *Diploastrea* and the SPI after 1960 (Figure 3f). SPCZ variability is strongly related to the polarity of the IPO since at least 1891 [*Folland et al.*, 2002], which is consistent with our calculations and the strong interdecadal seawater δ^{18}O signal observed in the southwestern Pacific [*Salinger et al.*, 1995; *Hendy et al.*, 2002]. Therefore it appears that at this location a more balanced contribution from SST and seawater δ^{18}O on skeletal δ^{18}O has resulted in a stronger, more coherent interdecadal δ^{18}O mode. However, because Sr/Ca analyses were only made in the upper ~30 years of the *Diploastrea* record, we have not been able to reconstruct long-term seawater δ^{18}O variability and this explanation may not apply to the very large amplitude signal in the first half of the 20th century.

[11] Our *Diploastrea* and *Porites* interdecadal δ^{18}O records both contain larger amplitudes than predicted from instrumental SST and SPI data. Interdecadal variations in salinity are likely significant influences on skeletal δ^{18}O, however time series salinity data in the tropics before about 1970 are virtually nonexistent, making this factor difficult to evaluate. It has been argued that coral growth mechanisms may bias and distort environmental information recorded in coral skeletons [*deVilliers et al.*, 1995; *Barnes et al.*, 1995; *Allison et al.*, 1996; *Lough and Barnes*, 2000], and therefore the differences in growth rates, and thus kinetic isotope effects [*McConnaughey*, 1989] between *Diploastrea* and *Porites* must be acknowledged as a potential source of signal amplification. However, linear extension (one indicator of coral growth) does not correlate with δ^{18}O in these Fiji corals and such uncertainty on this issue likely precludes a growth rate explanation. Additionally, the *Porites* colony grew in ~10 m of water while *Diploastrea* grew in only ~2 m of water, and it is not known if the interdecadal SST response at this location may be dampened deeper in the water column. Clearly more process studies into how *Diploastrea* incorporates environmental tracers relative to *Porites* are needed to properly address exactly what the tracers

represent, a hurdle that confronts coral paleoclimate research as a whole [*Lough*, 2004].

5. Summary

[12] Skeletal δ^{18}O from two coral genera in Fiji indicate that within the SPCZ region, interdecadal climatic variations in SST and seawater δ^{18}O during the last two centuries were largest in the late 1800s through early 1900s. Interdecadal variability in *Diploastrea* δ^{18}O represents a larger fraction of the total variance, and is of greater amplitude than that in *Porites* δ^{18}O for much of the last two centuries. These differences suggest that each coral's skeletal δ^{18}O may have inherently different sensitivities to the overall climate field. Confirming our preliminary calculations and determining *Diploastrea*'s sensitivity to SST versus seawater δ^{18}O relative to *Porites* will require further long-term investigations possibly using coupled Sr/Ca (or another SST proxy) and δ^{18}O measurements. Nonetheless, *Diploastrea* will likely prove to be a valuable archive of past Pacific climate variability, as it shows a clear ability to record interdecadal variations in local and regional climate conditions at least as effectively as *Porites*. With its typical lifespan, *Diploastrea* holds tremendous future potential to provide longer proxy climate records than *Porites*, from a region that is recognized as playing a significant role in global-scale climate.

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