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A Fiji multi-coral δ18O composite approach to obtaining a more accurate reconstruction of the last two-centuries of the ocean-climate variability in the South Pacific Convergence Zone region

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Key Points:
- Regional network of five coral $\delta^{18}O$ time series from different locations in Fiji
- Water mass advection in controlling Fiji coral variability
- Re-organization of climatic variability in the SPCZ region around 1900

Supporting Information:
- Readme
- Figure S1
- Figure S5

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Abstract The limited availability of oceanographic data in the tropical Pacific Ocean prior to the satellite era makes coral-based climate reconstructions a key tool for extending the instrumental record back in time, thereby providing a much needed test for climate models and projections. We have generated a unique regional network consisting of five *Porites* coral $\delta^{18}O$ time series from different locations in the Fijian archipelago. Our results indicate that using a minimum of three *Porites* coral $\delta^{18}O$ records from Fiji is statistically sufficient to obtain a reliable signal for climate reconstruction, and that application of an approach used in tree ring studies is a suitable tool to determine this number. The coral $\delta^{18}O$ composite indicates that while sea surface temperature (SST) variability is the primary driver of seasonal $\delta^{18}O$ variability in these Fiji corals, annual average coral $\delta^{18}O$ is more closely correlated to sea surface salinity (SSS) as previously reported. Our results highlight the importance of water mass advection in controlling Fiji coral $\delta^{18}O$ and salinity variability at interannual and decadal time scales despite being located in the heavy rainfall region of the South Pacific Convergence Zone (SPCZ). The Fiji $\delta^{18}O$ composite presents a secular freshening and warming trend since the 1850s coupled with changes in both interannual (IA) and decadal/interdecadal (D/I) variance. The changes in IA and D/I variance suggest a re-organization of climatic variability in the SPCZ region beginning in the late 1800s to period of a more dominant interannual variability, which could correspond to a southeast expansion of the SPCZ.

1. Introduction

The response of the Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ) to global climate change is of high interest, mainly due to their impact on the global water budget. The SPCZ is the largest and most important spur of the Inter Tropical Convergence Zone (Figure 1a). It is a zone of maximum precipitation and low SSS that extends from the West Pacific Warm Pool (WPWP) southeastward toward French Polynesia [*Vincent*, 1994; *Folland et al*., 2002]. Interannual to long-term changes in the position of the SPCZ can result in severe droughts or floodings in many equatorial nations. Despite numerous modeling studies of the SPCZ, no real consensus has been reached about its future variability in the context of a warmer climate [e.g., *Brown et al*., 2013; *Borlace et al*., 2014]. The variability of the SPCZ is dependent on interannual but also decadal and interdecadal variability. A better understanding of those modes of variability and how they affect the SPCZ displacements will be a great asset to increase the reliability of climate projection.

At the eastern edge of the SPCZ, a salinity front (Figure 1a) separates the low-salinity water under SPCZ influence from the high-salinity waters of the South Central Pacific gyre. Tracking the displacement of this salinity front can help constrain the spatial movements of the SPCZ over time [*Gouriou and Delcroix*, 2002; *Linsley et al*., 2006]. The Fiji archipelago is located along the southeastern edge of the SPCZ (Figure 1a), therefore a key location to study SPCZ interannual and also decadal-interdecadal variability over time.

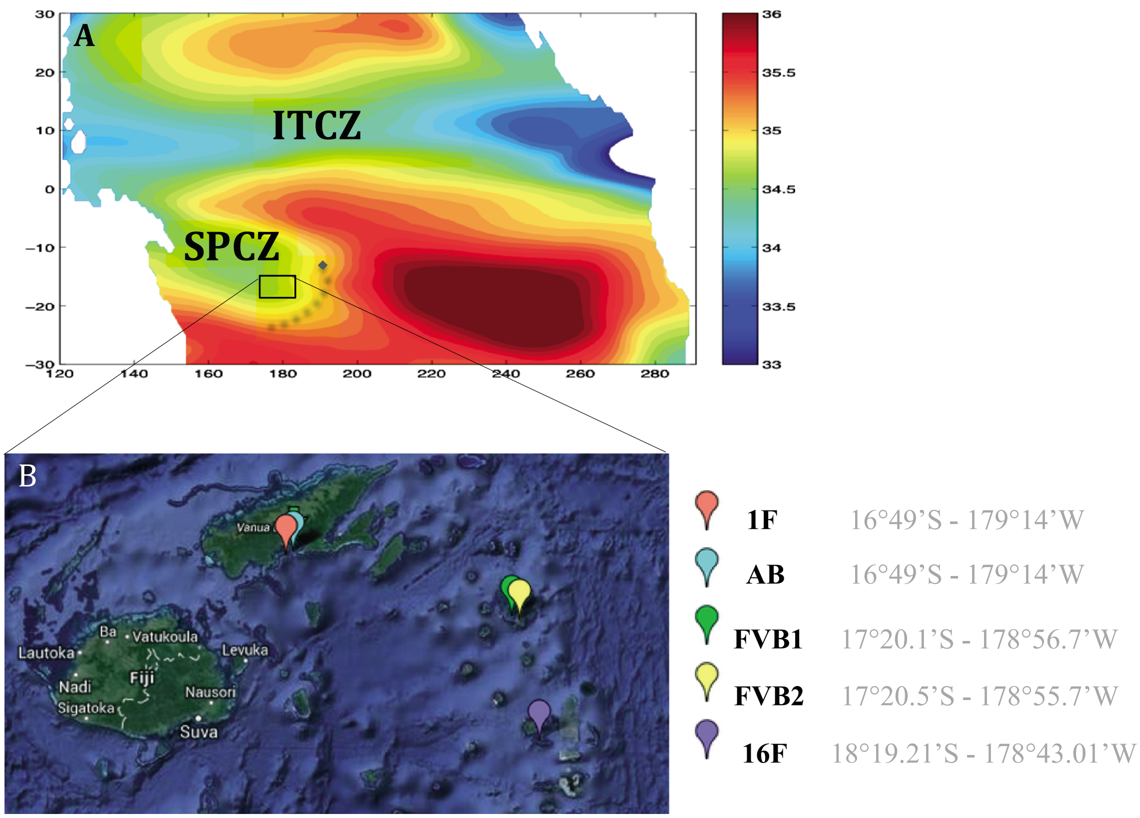

Figure 1. (a) Composite sea surface salinity map of the Pacific Ocean during the most recent La Niña events (1999, 1988, and 1975) from instrumental gridded sea surface salinity (SSS), 1° × 1° over the period 1950–2009 (http://www.legos.obs-mip.fr/observations/sss/datadelivery/productstime-gsss_tpo_5009_v1.0..nc). The South Pacific Convergence Zone (SPCZ), the Intertropical Convergence Zone (ITCZ), and the Salinity front (dotted line) are represented. (b) Detailed coral collection locations of colonies AB (16°49′ S; 179°14′ E), 1F (16°49′ S; 179°14′ E), FVB1 (17°20′S; 178°56′ W), FVB2 (17°20′ S; 178°55′ W), and 16F (18°19′ S; 178°43′ W).

The last 50 years of instrumental sea surface temperature (SST), sea surface salinity (SSS), and rainfall for the Fiji region are presented in Figure 2. SST in Fiji contains a distinct seasonal cycle (Figures 2b–2e) with high SST found during the austral summer, with February/March being on average the warmest months (~28.4°C), and annual minimum SST during the austral winter, with August/September being the coolest months (~25.2°C). The SSS signal (Figures 2a–2d) is, however, less regular with a minimum in March (~34.8 S_P) and a poorly defined maximum in August–September (~35.0 S_P). Rainfall (Figures 2c–2f) reaches its maximum during the austral summer, with March the rainiest month (~350 mm) and its minimum during the month of July (~105 mm).

Interannual SST, SSS, and precipitation variability in the Fiji area is mainly influenced by El Niño Southern Oscillation (ENSO) [e.g., *Folland et al*., 2002; *Gouriou and Delcroix*, 2002]. The amplitude of the interannual changes in SST and precipitation in this region (Figures 2b–2c) are an order of magnitude less than the amplitude of the seasonal cycle for each parameter. However, the interannual SSS signal of 1 to 1.3 S_P (Figure 2a) has double the amplitude of the seasonal SSS signal, as previously described for this area [*LeBec et al*., 2000; *Gouriou and Delcroix*, 2002; *Linsley et al*., 2006]. This pattern is due to the coupled relationship between the SPCZ and oceanographic variability in this area. During the warm phase of ENSO (El Niño), the SPCZ migrates to a more northeast position, and the salinity front moves northwestward, leaving Fiji drier, saltier, and cooler. During the austral summer and/or the cold phase of ENSO (La Niña), the opposite occurs: the SPCZ migrates to a more southwestern position, and the salinity front moves to a more southeastward position, leading to wetter, fresher, and warmer conditions in the Fiji area [*Vincent*, 1994; *Salinger et al*., 1995, 2001; *Delcroix*, 1998; *Gouriou and Delcroix*, 2002].

On longer time scales, another phenomenon, the Interdecadal Pacific Oscillation (IPO), influences climatic conditions in the Fiji archipelago. The IPO is the Pacific-wide manifestation of the Pacific Decadal Oscillation

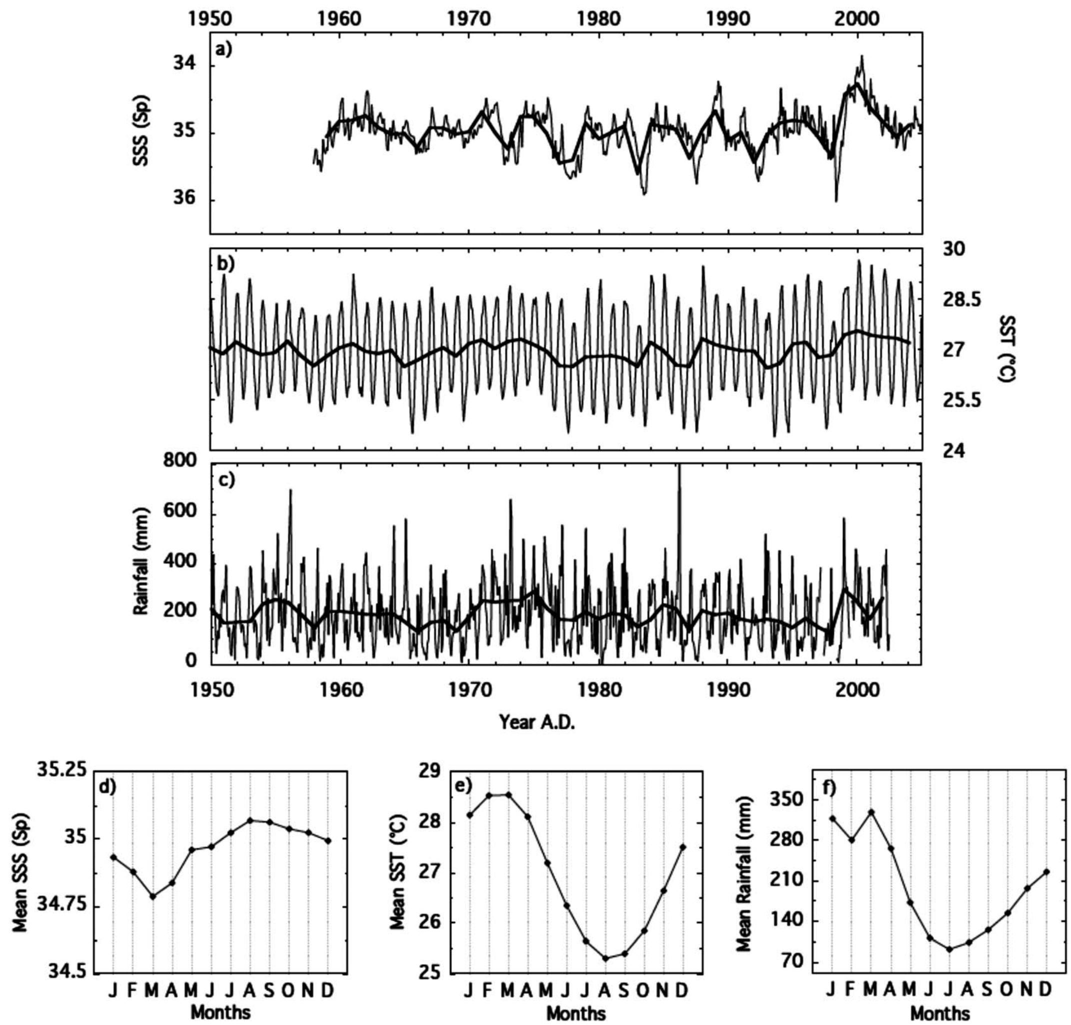

Figure 2. Gridded monthly (thin) and annually averaged (bold) Fiji climatology (a) sea surface salinity (Sp) centered on 17°S–179°E and extending from January 1958 to December 2004 [*Delcroix et al.*, 2011], (b) ERSST Sea Surface Temperature (°C)); data set centered on 178°W–18°S extending from January 1950 to December 2004 (LDEO Climate Data Library: http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.ERSST/.version3/.SST/) [*Smith et al.*, 2008], and (c) cumulative precipitation (mm) from various sites around Fiji from January 1950 to July 2002 (PACRAIN database retrieved from http://pacrain.evac.ou.edu). The long-term Fiji climatology (d) SSS, (e) SST, and (f) precipitation, over the common period of the three data sets (1958 to 2002).

(PDO) with displays as much SST variance in the Southern Pacific, from the Fiji area to 55°S, as in the Northern Hemisphere subtropics [*Mantua et al.*, 1997; *Power et al.*, 1999; *Folland et al.*, 2002; *Parker et al.*, 2007]. The SPCZ tends to move northeast during the warm phase of both interannual and decadal-scale oscillations (Positive IPO and PDO, and Negative SOI—El Niño event). Conversely, the SPCZ tends to move southwest during the cold phase of both oscillations (Negative IPO and Positive SOI—La Niña event) [*Mantua et al.*, 1997; *Power et al.*, 1999; *Pierce et al.*, 2000; *Salinger et al.*, 2001; *Folland et al.*, 2002]. However, recent studies have shown that the relationship between SPCZ variability and ENSO is not that straight forward [*Vincent et al.*, 2011; *Borlace et al.*, 2014]. The SPCZ displays different footprints under different ENSO regimes, which might also evolve under global climate change [e.g., *Cravatte et al.*, 2009; *Vincent et al.*, 2011; *Borlace et al.*, 2014]. The relatively short record of ENSO activity covered during the satellite era does not allow for a consensus to be reached about future ENSO or SPCZ variability.

Coral-based climate reconstructions provide essential information for extending the oceanographic instrumental record in the tropics. During calcification, massive scleractinian corals incorporate geochemical tracers such as

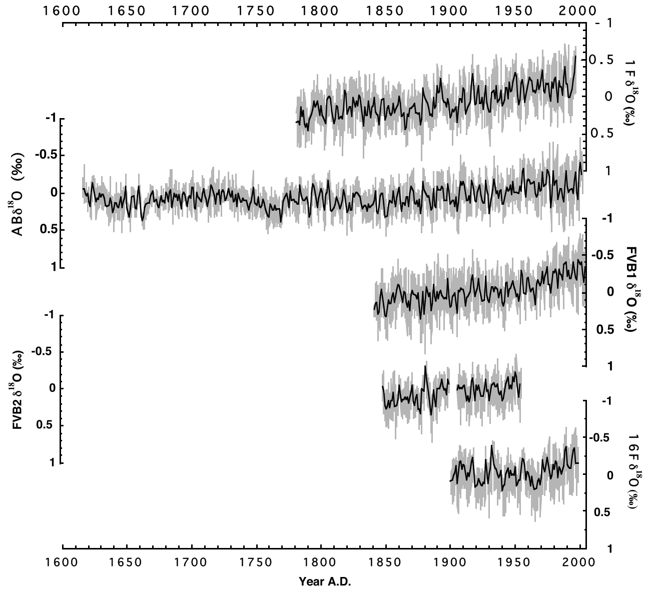

Figure 3. Centered monthly interpolated coral $\delta^{18}O$ data (‰) from the five Fiji coral cores in grey and annual average in black: 1F (1781–1997), AB (1617–2001), FVB1 (1841–2004), FVB2 (1847–2000 with a gap from 1899 to 1905), and 16F (1937–1998). The time series were centered over their common period of 1905–1954.

oxygen isotopes into their aragonitic skeleton. Studies of the oxygen isotopic composition ($\delta^{18}O$) of corals have demonstrated that the $\delta^{18}O$ of coral skeletal aragonite is primarily related to water temperature and the isotopic composition of seawater (which, at a regional scale, can be linearly correlated to surface salinity) at the time of calcification [e.g., *Epstein et al*., 1953; *Kim and O'Neil*, 1997; *Cole and Fairbanks*, 1990; *Fairbanks et al*., 1997]. However, paleoclimatic information extracted from massive scleractinian coral aragonite skeletons continues to have uncertainties related to the exact environmental significance of the geochemical tracers due to unconstrained biological factors ("vital effects"). Coral-based paleoclimatic time series are commonly calibrated from a single coral record between the most recent portion of coral growth and regional and/or local instrumental climatic parameters. As pointed out by *Lough* [2004] and *Grottoli and Eakin* [2007], among others, caution should be exercised when extrapolating a single coral isotope record to reflect basin-scale processes. The regional-scale significance of coral-based climate reconstructions can be assessed through replication of coral geochemical records at multiple sites [*Lough*, 2004; *Hendy et al*., 2007]. For coral studies, replication has not been routinely practiced due to the amount of time and resources involved in processing coral cores. Previous coral replication studies addressed the idea of using a network of corals, an approach commonly used in tree ring studies [*Tudhope et al*., 1995; *Gagan et al*., 1998; *Guilderson and Schrag*, 1999; *Linsley et al*., 1999, 2006, 2008; *Lough*, 2004; *Stephans et al*., 2004; *DeLong et al*., 2007].

We have generated and compiled a unique network of five coral oxygen isotopic ($\delta^{18}O$) time series from the Fiji archipelago (Figure 3). After evaluating the minimum number of replicate time series needed to most accurately reconstruct oceanographic variability in that region, interannual (IA) and decadal/interdecadal (D/I) modes are isolated and compared to other Pacific coral $\delta^{18}O$ records and various Pacific-wide IA and D/I indices. As part of the discussion we (1) determine the SST and SSS influences on the Fiji $\delta^{18}O$ composites through the examination of "pseudocorals" which are modeled $\delta^{18}O$ time series based on the expected coral $\delta^{18}O$ temporal variability, assuming exclusive influence of $\delta^{18}O$ seawater (linearly related to SSS) and of SST changes [*Thompson et al*., 2011], (2) examine the variability of both IA and D/I signals prior to instrumental records, and (3) discuss the climatic implications of the Fiji coral $\delta^{18}O$ composite secular trend.

2. Materials and Methods

2.1. Coral Collection and Sampling

Five coral cores from different regions of Fiji were utilized in this study (Figure 1b and Table 1). In April 1997, a coral core (designated 1F) was retrieved from a *Porites lutea* colony growing at a depth of 10 m in the middle of Savusavu Bay on the south side of the island of Vanua Levu, Fiji (16° 49′ S, 179° 14′ E). In December 2001, a second *P. lutea* colony (designated AB) was cored in Savusavu Bay about 200 m from the coral colony where core 1F was recovered. Results from these two cores have been previously published [*Linsley et al*., 2004, 2006, 2008]. In November 2004, two *P. lutea* coral colonies were cored near Susui Village on Vanua Balavu (designated cores FVB1 and FVB2). Core FVB1 was collected in an open lagoon north of Susui Village on the east side of an exposed reef (17° 20.055′ S; 178° 56.743′ W) in 6 m water depth at the top of

Table 1. Summary of the Completed Sub-Seasonal Resolution Fiji Coral $\delta^{18}O$ Time Series

Core ID	Species	Length[a] (in cm)	Years	Location	Latitude Longitude	Mean $\delta^{18}O$[b]	Reference
1F	*Porites lutea*	230	1781–1997	Savusavu Bay, Fiji	16°49′S 179°14′W	−5.0 (±0.24)	[*Linsley et al.*, 2004]
AB	*Porites lutea*	389	1617–2001	Savusavu Bay, Fiji	16°49′S 179°14′W	−4.6 (±0.19)	[*Linsley et al.*, 2006]
FVB1	*Porites lutea*	236	1841–2004	Vanua Balavu. Fiji	17°20.1′S 178°56.7′W	−5.0 (±0.21)	*This study*
FVB2	*Porites lutea*	294	1847–2000	Vanua Balavu, Fiji	17°20.5′S 178°55.7′W	−5.0 (±0.19)	*This study*
16F	*Porites lutea*	450	1900–1998	Aïwa Island, Fiji	18°19.21′S 178°43.01′W	−4.8 (±0.21)	*This study*

[a]Length of the coral core.
[b]Mean $\delta^{18}O$ and standard deviation of the monthly time series from the common time period (1954–1905).

the coral. Core FVB2 was collected in the lagoon east of Susui Village (17° 20.462′ S; 178° 55.716′ W) in 1 m water depth at the top of the coral. This colony had a partially dead top at the time of sampling and showed evidence of distressed growth in the upper ~30 cm of skeleton. The last coral core used in this study (designated 16F) came from Aïwa Island, south of the Lau Group (18° 19.21′ S; 178° 43.01′ W) and was retrieved by the Institut de Recherche pour le Dévelopement (IRD) during the Paleofiji cruise in June to July 1998.

The cores were cut into ~7 mm thick slabs with a modified tile saw. The slabs were X-rayed with an HP cabinet X-ray system at 35 kV for 90 s, and the X-ray negatives were scanned to generate X-ray positives (Supplements S1 for the three new cores presented FVB1, FVB2, and 16F). Density bands and growth axes were visible on the X-ray positives, which allowed the identification of sampling paths and possible signs of diagenesis. Prior to micro-sampling, the slabs were cleaned in deionized water in an ultrasonic bath for 30 min and then cleaned with a high-energy (500 W, 20 kHz) probe sonicator, also in a deionized water bath, for approximately 10 min on each slab face. The dried slabs were sampled using a low-speed micro-drill with a 1 mm round diamond drill bit along the maximum growth axis in tracks (U-shaped grooves) parallel to corallite traces as identified in X-ray positives. A ~3 mm deep by ~3 mm wide groove was excavated at 1 mm increments.

2.2. Stable Isotope Analysis

Approximately 100 μg of coral powder per sample was dissolved in ~100% H_3PO_4 at 90°C in a MultiPrep sample preparation device, and the generated CO_2 gas was analyzed by a Micromass Optima gas-source triple-collector mass spectrometer in the Stable Isotope Ratio Mass Spectrometry (SIRMS) Laboratory at the State University of New York at Albany. Every 1 mm sample in the first 14 years of growth (200 samples) was analyzed, followed by analyzing samples from every other 1 mm below this interval. The every other mm analysis resolution (about 6 to 7 samples per year) proved to be a sufficient sampling resolution to capture the full annual range of $\delta^{18}O$ variability in massive *Porites* corals [*Quinn et al.*, 1996]. For every 8 samples (16 samples below 200 mm), a replicate sample was analyzed. The average difference in $\delta^{18}O$ between duplicate analyses of 874 samples (all coral cores included) was 0.046‰. Samples of international standard NBS-19 were interspersed every ~10 samples. On this instrument, the long-term precision of NBS-19 $\delta^{18}O$ was 0.05‰ during the analysis period.

2.3. Chronology

Density bands for the corals analyzed in this study are not always distinct at every interval in a particular core. Thus, in this study, counting the number of growth bands [e.g., *Knutson et al.*, 1972] is ineffective in making an accurate chronology. However, the clear annual cycle in the mm-scale $\delta^{18}O$ data from Fiji *Porites* allows for the construction of an accurate down-core chronology [see *Linsley et al.*, 2004, 2006]. Individual coral chronologies were established by selecting semi-annual tie points, linking the lightest (most negative) $\delta^{18}O$ value in each seasonal cycle to the warmest month of the year and vice versa. For time prior to instrumental SST records, we determined what was on average the warmest and coldest months of the year for each records, then we assigned those months to the $\delta^{18}O$ minimum and maximum values, respectively, down the core.

Since the corals were alive when they were drilled, the top age is assumed to represent the month of collection. The first several millimeters of a coral core consists of the growth tissue layer that had anomalous $\delta^{18}O$ values similar to other studies [e.g., *Linsley et al.*, 1994, 2004]; thus, the time series for each core begins

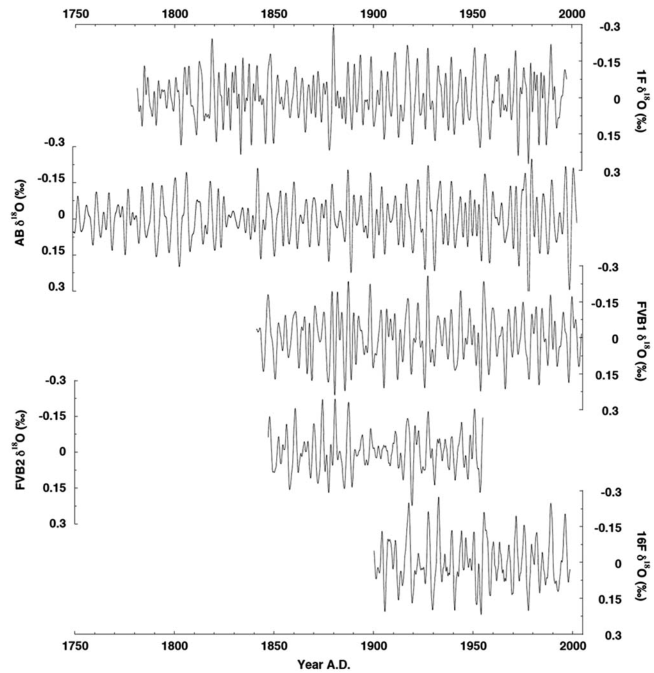

Figure 4. Interannual mode of variability (frequency from 2 to 9 years) is extracted from the five Fiji coral δ^{18}O records using a Singular Spectral analysis software [*Vautard and Ghil*, 1989]. The cumulative percentage variance of the interannual mode in the individual records is 1F (~16%), AB (~22%), FVB1 (~16%), FVB2 (~18%), and 16F (~23%).

a couple of months prior to the collection date. The top age is August 2004 for FVB1, November 2001 for AB, May 1997 for 1F, and October 1998 for 16F. The chronology for FVB2 begins in December 1954 due to the presence of an anomalous growth pattern at the top inducing both its skeletal extension rate and δ^{13}C values to present a peculiar pattern [*Dassié et al*., 2013]. This is possibly due to the extremely shallow depth habitat or the partially dead top of the colony.

Slab breaks and changes in the sampling track on a coral slab can present major issues for the chronology. For each slab break and sampling track change we overlapped the sampling paths by approximately one centimeter (about one year). Thanks to the high intra-colony δ^{18}O reproducibility, we could efficiently match the overlapping sections. To verify the chronologies and confirm the assumption of no time loss around the core breaks and/or sampling path changes, each individual chronology was fine-tuned by cross-dating them to the four other Fiji δ^{18}O series, at both seasonal and interannual time scales. The high correlation among the individual records gave us confidence in our chronologies. Additionally, we evaluated whether adding or removing years at slab breaks or track jumps increased or decreased the inter-colony correlations. We found that our original chronologies were best in all cases confirming their validity, since it is unlikely that we would have missed the same year in all five chronologies. The last method of chronology verification was to compare the individual coral records to known climate indices (e.g., Southern Oscillation Index (SOI), and Pacific Decadal Oscillation (PDO)), which show high correlations with not time gaps. FVB2 presented a peculiar growth pattern on slab #5. Therefore, this slab was not analyzed. The methodology described above allowed us to determine the complete FVB2 chronology for the section below slab #5.

Sample depths down core were transformed to time (years) using the "Ager" software in the ARAND software package [*Howell et al*., 2006]. Ager assigns ages to specific depth increments using an age model with depth-age relationships. In this case we used two anchor points per year based on the annual δ^{18}O cycle (SST maximum and minimum). The age assignments were then linearly interpolated into monthly intervals using "Timer" (also part of ARAND) in order to generate time series for statistical analysis.

2.4. Coral Inter-Colony Replication Approaches

We performed three statistical analyses to determine the interseries replication: (1) Absolute Deviation method (AD), (2) Root Mean Square (RMS) determination, and (3) the Expressed Population Statistic (EPS) method. The interseries replication might vary in relation to the time scale of the reconstruction; therefore, interseries correlations were tested for different time scales (seasonal variability, Interannual (IA) variability (2 to 9 years), and Decadal/Interdecadal (D/I) variability (10 to 50 years). The frequencies of IA and D/I in each monthly resolution coral δ^{18}O time series were extracted using singular spectrum analysis (SSA) software (Figures 4 and 5). A detailed description of this technique and its paleoclimate application is explained in *Vautard and Ghil* [1989] and *Vautard et al*. [1992]. SSA has been previously applied to coral time series [e.g., *Dunbar et al*., 1994; *Linsley et al*., 1994, 2000, 2008; *Charles et al*., 1997].

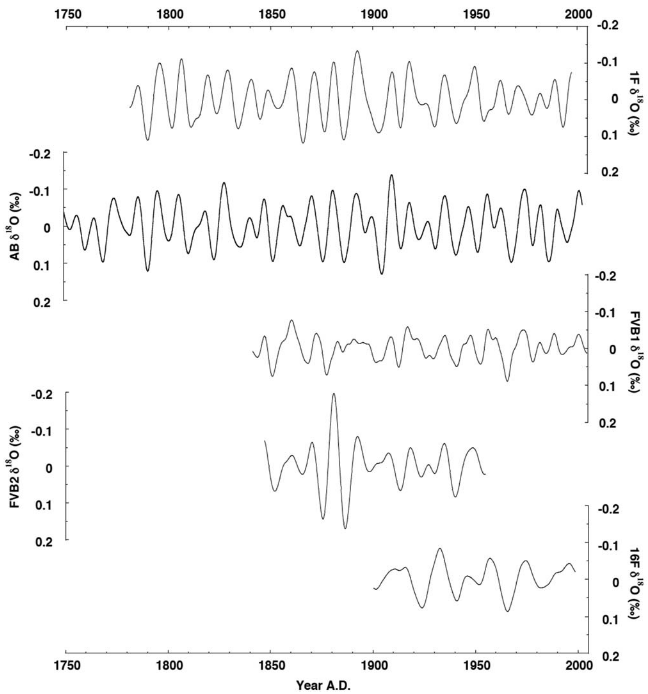

Figure 5. Decadal/interdecadal mode of variability (frequency from 10 to 50 years) is extracted from the five Fiji coral $\delta^{18}O$ records using a Singular Spectral analysis software [*Vautard and Ghil*, 1989]. The cumulative percentage variance of the decadal/interdecadal mode in the individual records is 1F (~7%), AB (~10%), FVB1 (~5%), FVB2 (~12%), and 16F (~11%).

2.4.1. Absolute Deviation (AD)

The Absolute Deviation (AD) method measures the discrepancy between two $\delta^{18}O$ records for a given month (equation (1)). The computations were done between individual time series as well as among different composites made from combinations of two, three, and four records. Results from this method (Table 2, bottom part) indicate that the average AD between two records is less than 1σ of the magnitude of analytical precision (0.045‰) for both IA and D/I signals. However, the AD created from seasonal variability time series, using individual records as well as combinations of two records, present values greater than 1σ but still less than 2σ of the magnitude of analytical precision. Additionally, this method shows that AD values are reduced by more than half when using a three-record composite compared to using individual records.

$$AD = 2^{-1/2}\left|\delta^{18}O_1 - \delta^{18}O_2\right| \quad (1)$$

2.4.2. Root Mean Squared Deviation (RMSD)

The Root Mean Squared Deviation (RMSD) method (equation (2)) measures the difference between the values predicted by an estimator, and the values actually observed. In this study the estimator is the Fiji coral $\delta^{18}O$ composite (arithmetic average of the five Fiji coral $\delta^{18}O$ time series), and the values actually observed are the individual times series as well as all the possible combinations using two to four records. Results from this method are detailed in Table 2, top part. As with the results using the AD method, the difference between predicted and observed values is less than 1σ of the magnitude of analytical precision (0.045‰) except for the

Table 2. Comparison Table for the Root Mean Square Deviation and Absolute Difference Values

Root Mean Square Deviation

	Individual Records[a]	Two Records[b]	Three Records[c]	Four Records[d]
Monthly	9.34	5.72	3.81	2.34
Interannual[e]	4.21	2.58	1.72	1.05
Decadal/interdecadal[f]	2.46	1.82	1.00	0.61

Absolute Difference

	Individual Records[a]	Two Records[b]	Three Records[c]	Four Records[d]
Monthly	8.85	5.05	3.36	2.21
Interannual[e]	3.98	2.27	1.51	0.99
Decadal/interdecadal[f]	2.33	1.54	0.89	0.58

[a]Average values multiplied by 100 for the individual time series 1F, AB, FVB1, FVB2, and 16F.
[b]Average values multiplied by 100 for the following combinations: 1F-AB, 1F-FVB1, 1F-FVB2, 1F-16F, AB-FVB1, AB-FVB2, AB-16F, FVB1-FVB2, FVB1-16F, and FVB2-16F.
[c]Average values multiplied by 100 for the following combinations: 1F-AB-FVB1, 1F-AB-FVB2, 1F-AB-16F, AB-FVB1-FVB2, AB-FVB1-16F, AB-FVB2-16F, 1F-FVB1-FVB2, 1F-FVB1-16F, 1F-FVB2-16F, and FVB1-FVB2-16F.
[d]Average values multiplied by 100 for the following combinations: AB-FVB1-FVB2-16F, 1F-FVB1-FVB2-16F, 1F-AB-FVB2-16F, 1F-AB-FVB1-16F, and 1F-AB-FVB1-FVB2.
[e]Interannual time scale with frequencies between 2 and 9 years.
[f]Decadal/interdecadal time scale with frequencies between 10 and 50 years.

Table 3. Comparison Table of $\bar{r}$, EPS, and SNR Using 2, 3, 4, and 5 Coral Records for Monthly, Interannual, and Decadal/Interdecadal Time Scales[a]

Monthly Data (1905–1954)					*Interannual (1905–1954)*					*Decadal/Interdecadal (1905–1954)*				
N[a]	Core ID	$\bar{r}$[b]	EPS[c]	SNR[d]	N[a]	Core ID	$\bar{r}$[b]	EPS[c]	SNR[d]	N[a]	Core ID	$\bar{r}$[b]	EPS[c]	SNR[d]
5	All	0.7	0.92	11.67	5	All	0.71	0.92	12.24	5	All	0.47	0.82	4.43
4	Without 1F	0.73	0.92	10.81	4	Without 1F	0.7	0.90	9.33	4	Without 1F	0.47	0.78	3.55
4	Without AB	0.67	0.89	8.12	4	Without AB	0.71	0.91	9.79	4	Without AB	0.38	0.71	2.45
4	Without FVB1	0.66	0.89	7.76	4	Without FVB1	0.68	0.89	8.50	4	Without FVB1	0.39	0.72	2.56
4	Without FVB2	0.70	0.90	9.33	4	Without FVB2	0.73	0.92	10.81	4	Without FVB2	0.42	0.74	2.90
4	Without 16F	0.72	0.91	10.29	4	Without 16F	0.72	0.91	10.29	4	Without 16F	0.69	0.90	8.90
			0.90[e]	**9.26**[e]				**0.9**[e]	**9.75**[e]				**0.77**[e]	**4.07**[e]
3	1F-AB-FVB1	0.73	0.89	8.11	3	1F-AB-FVB1	0.74	0.90	8.54	3	1F-AB-FVB1	0.68	0.86	6.38
3	1F-AB-FVB2	0.69	0.87	6.68	3	1F-AB-FVB2	0.70	0.88	7.00	3	1F-AB-FVB2	0.64	0.84	5.33
3	1F-AB-16F	0.66	0.85	5.82	3	1F-AB-16F	0.69	0.87	6.68	3	1F-AB-16F	0.37	0.64	1.76
3	1F-FVB1-FVB2	0.70	0.88	7.00	3	1F-FVB1-FVB2	0.72	0.89	7.71	3	1F-FVB1-FVB2	0.54	0.78	3.52
3	1F-FVB1-16F	0.65	0.85	5.57	3	1F-FVB1-16F	0.74	0.90	8.54	3	1F-FVB1-16F	0.36	0.63	1.69
3	1F-FVB2-16F	0.61	0.82	4.69	3	1F-FVB2-16F	0.69	0.87	6.68	3	1F-FVB2-16F	0.24	0.49	0.95
3	AB-FVB1-FVB2	0.76	0.90	9.50	3	AB-FVB1-FVB2	0.71	0.88	7.34	3	AB-FVB1-FVB2	0.69	0.87	6.68
3	AB-FVB1-16F	0.74	0.90	8.54	3	AB-FVB1-16F	0.74	0.90	8.54	3	AB-FVB1-16F	0.42	0.68	2.17
3	AB-FVB2-16F	0.7	0.88	7.00	3	AB-FVB2-16F	0.63	0.84	5.11	3	AB-FVB2-16F	0.39	0.66	1.92
3	FVB1-FVB2-16F	0.74	0.90	8.54	3	FVB1-FVB2-16F	0.71	0.88	7.34	3	FVB1-FVB2-16F	0.38	0.65	1.84
			0.87[e]	**7.15**[e]				**0.88**[e]	**7.35**[e]				**0.71**[e]	**3.22**[e]
2	1F-AB	0.75	0.86	6.00	2	1F-AB	0.73	0.84	5.41	2	1F-AB	0.62	0.77	3.26
2	1F-FVB1	0.67	0.80	4.06	2	1F-FVB1	0.71	0.83	4.90	2	1F-FVB1	0.75	0.86	6.00
2	1F-FVB2	0.62	0.77	3.26	2	1F-FVB2	0.74	0.85	5.69	2	1F-FVB2	0.77	0.87	6.70
2	1F-16F	0.53	0.69	2.26	2	1F-16F	0.71	0.83	4.90	2	1F-16F	0.14	0.25	0.33
2	AB-FVB1	0.78	0.88	7.09	2	AB-FVB1	0.77	0.87	6.70	2	AB-FVB1	0.66	0.80	3.88
2	AB-FVB2	0.69	0.82	4.45	2	AB-FVB2	0.64	0.78	3.56	2	AB-FVB2	0.54	0.70	2.35
2	AB-16F	0.71	0.83	4.90	2	AB-16F	0.71	0.83	4.90	2	AB-16F	0.36	0.53	1.13
2	FVB1-FVB2	0.79	0.88	7.52	2	FVB1-FVB2	0.65	0.79	3.71	2	FVB1-FVB2	0.70	0.82	4.67
2	FVB1-16F	0.74	0.85	5.69	2	FVB1-16F	0.81	0.90	8.53	2	FVB1-16F	0.24	0.39	0.63
2	FVB2-16F	0.69	0.82	4.45	2	FVB2-16F	0.61	0.76	3.13	2	FVB2-16F	0.36	0.53	1.13
			0.82[e]	**4.97**[e]				**0.83**[e]	**5.14**[e]				**0.65**[e]	**3.01**[e]

[a]*N* is the number of coral records used.
[b]$\bar{r}$ is the correlation coefficient between the different records.
[c]EPS is the expressed population statistic.
[d]SNR is the signal to noise ratio.
[e]The bold numbers are the mean EPS and SNR per different *N*.

seasonal variability using both individual records and two record composites. Additionally, a 50% reduction in the RMS values is also observed when using composite with three or more records.

$$\mathrm{RMS} = \left(\sum \left(\delta^{18}\mathrm{O}_I - \delta^{18}\mathrm{O}_{mean}\right)^2 \Big/ n \right)^{1/2} \tag{2}$$

2.4.3. Expressed Population Statistic (EPS)

The Expressed Population Statistic (EPS) approach has been extensively applied in tree ring studies and similar methods have been advocated in coral studies [*Linsley et al*., 2008; *Lough*, 2004; *Stephans et al*., 2004; *Cobb et al*., 2003, 2008; *DeLong et al*., 2007]. Here, this method consists of using the network of five coral time series (Table 1) to determine the number of replicates needed to increase the signal-to-noise ratio (SNR) with the purpose of improving the reliability of paleo-reconstructions. In dendroclimatology, EPS has been described by *Wigley et al*. [1984] and is used to determine the number of records (N) required to produce an average (composite) with an acceptable signal to noise ratio (SNR) for the calculated mean interseries correlation coefficient ($\bar{r}$).

$$\mathrm{EPS} = N(\bar{r}) \Big/ N(\bar{r}) + (1-\bar{r}) \cdot \quad \mathrm{SNR} = N(\bar{r}) \Big/ (1-\bar{r})$$

For dendroclimatologists, the acceptable EPS was set to ≥0.85 by *Wigley et al*. [1984]. The closer the EPS value is to one, the stronger the signal is [*Wigley et al*., 1984; *Briffa et al*., 1995]. Using this metric, a coral core composite can be considered statistically significant when its EPS value is ≥0.85. The EPS is dependent on

Table 4. Interseries Coral $\delta^{18}O$ Pearson Product-Moment Correlation Coefficient at Both Monthly (Bottom Left Side of the Table) and Annual Average (Top Right Side of the Table) Time Scales[a]

	1F	AB	FVB1	FVB2	16F
1F	*1*	*0.76*	*0.76*	*0.54*	*0.58*
AB	*0.75*	*1*	*0.73*	**0.34**	*0.63*
FVB1	*0.70*	*0.77*	*1*	*0.43*	*0.75*
FVB2	*0.39*	*0.48*	*0.63*	*1*	***0.21***
16F	*0.60*	*0.73*	*0.78*	*0.47*	*1*

[a]Most correlations are significant at 99% (italicized values), the value in bold italics is significant at 95%, and the value in boldface is not significant. Interseries correlations were established for the time period 1900–1997, except for those for the FVB2 time series, which were established for the time period 1905–1954.

both $\bar{r}$ and the number of coral records used. To obtain a significant signal when exploiting 2, 3, 4, or 5 records, the $\bar{r}$ value must be ≥0.74, ≥0.65, ≥0.59, or ≥0.53, respectively. When a record is added to a composite, both the EPS and the SNR values should increase. However, if the EPS or the SNR does not increase with the addition of a particular time-series, it can be assumed that the newly added record contains some anomalous patterns. $\bar{r}$, EPS and SNR values were determined over the corals common time period (1905–1954) for different time scales: seasonal, interannual, decadal/interdecadal (Table 3), and secular trend (frequency lower than 75 years).

3. Results

3.1. Fiji $\delta^{18}O$ Individual Records

Over the 50 year common period (1905–1954) of all five coral $\delta^{18}O$ time series, mean $\delta^{18}O$ values of 1F (-5.0 ± 0.24‰), FVB1 (-5.0 ± 0.21‰), and FVB2 (-5.0 ± 0.19‰) are similar (Table 1). Colonies AB and 16F have higher mean $\delta^{18}O$ values of -4.6 (±0.19) ‰ and -4.8 (±0.21) ‰, respectively. This offset has been previously observed in several replicated coral records [*Tudhope et al*., 1995; *Linsley et al*., 1999, 2004, 2006, 2008; *Cobb et al*., 2003]. The offsets between cores 1F, FVB1, and FVB2, and cores 1F and 16F are within the limit of the one standard deviation magnitude of analytical precision (0.045‰). Other studies have attributed $\delta^{18}O$ offsets to differences in the so-called "vital effect" offset (isotopic disequilibrium) that might be due to micro-environmental or genetic differences between coral colonies. Therefore, the individual time series were centered by removing their respective common period (1905–1954) mean $\delta^{18}0$ values, and only $\delta^{18}O$ anomalies are discussed in the rest of this paper.

All five Fiji coral $\delta^{18}O$ time series show similar seasonal and interannual variability (Figure 3). Pearson product moment correlation coefficients between the individual monthly and annually resolved Fiji coral $\delta^{18}O$ time series show high significance with most of them being significant at 99% (Table 4). The inter-colony correlation coefficients range from 0.39 to 0.78 (monthly) and 0.21 to 0.76 (annual), which is in agreement with studies demonstrating robust regional inter-colony reproducibility [*Wellington et al*., 1996; *Linsley et al*., 1999, 2004, 2006, 2008; *Watanabe et al*., 2002; *Stephans et al*., 2004; *DeLong et al*., 2007, 2012a, 2012b].

Using only one coral record or parts of records inhibit the identification of non-climatic factors that could have dominated the geochemical signal. *Lough* [2004] concluded that ideally three records of geochemical tracers would ensure accurate dating, identification of periods when non-climatic factors dominate, and enhance the reliability of the paleoclimatic record. Additionally, *DeLong et al*. [2012b] pointed out that "the lack of replication leads to questions about chronology accuracy and reliability of the inclusive geochemical variations to record climate viability". A quick assessment of the necessity of using a composite instead of individual records was done by looking at the differences in relationship strengths between individual Fijian coral $\delta^{18}O$ records and composite $\delta^{18}O$ records and climatic parameters (SST and SSS). As expected, the coral core composite (made from the arithmetic mean of the four Fiji coral cores 1F, AB, FVB1, and 16F) has higher regression coefficients, up to 20% increase for the composite compared to certain individual records [*Dassié*, 2012].

3.2. Statistical Assessment of the Optimal Number of Records Needed

The AD and RMSD methods, described in the method section, established that the individual Fiji coral $\delta^{18}O$ time series present a high coherency not only at seasonal, but especially at IA and D/I time scales. Those methods lead to the conclusion that using three or more Fijian records will ensure the fidelity of geochemical reconstructions.

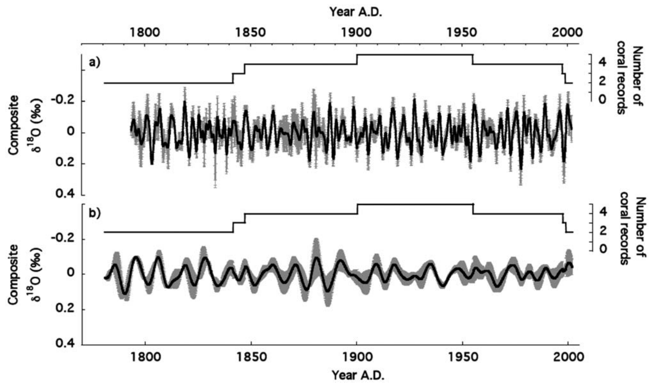

Figure 6. Fiji coral $\delta^{18}O$ composite record extracted for (a) interannual mode of variability (black) with 99% confidence interval (grey shading) and (b) the decadal/interdecadal mode of variability (black) with 95% confidence interval (grey shading). The coral $\delta^{18}O$ composite record is derived from the arithmetic mean of the five Fiji coral colonies FVB1, FVB2, 1F, AB, and 16F. Above each mode of variability is the total number of colonies used for the composite.

The EPS technique reveals the importance of choice in selecting (a) the geochemical record for compilation and (b) the time scale of investigation. Beginning with seasonal variability assessment, some combinations of two records (1F-AB, AB-FVB1, FVB1-FVB2, and FVB1-16F) can yield an EPS ≥0.85. For every combination of two records, adding a third record increased both the EPS and the SNR values; the climate signal is therefore enhanced with the combination of three records. All the combinations of three records (except 1F-FVB2-16F) obtained an EPS ≥0.85, which made them suitable to be used for reliable climatic interpretations. Last, when a fourth record is added to the 1F-FVB2-16F combination, both its EPS and the SNR values increase, making it a more robust composite.

For interannual climate reconstructions, the high inter-colony correlation reflects the dominant influence of ENSO variability in this area. Our result indicates that the use of at least three coral records is statistically sufficient to obtain a reliable signal (except AB-FVB2-16F combination) to reconstruct past ENSO activity. This result supports the finding that basin-scale ENSO variability can be reliably reconstructed from a limited number of three records [*Evans et al*., 2000; *Wilson et al*., 2006].

At decadal/interdecadal time scales, only two combinations of three records are found to be statistically significant while none of the combinations of two records are significant. This may in part be due to the lower amplitude SST and SSS decadal/interdecadal variability in Fiji relative to interannual variability. This is in agreement with previous studies concluding that the low signal to noise ratios of decadal time scale signals could present greater challenges for pattern identification [*Lough*, 2004; *Linsley et al*., 2008]. Additionally, the lack of a major IPO phase shift during the length of the common period (1905–1954) possibly influenced the low inter-series correlation. Combinations using coral core 16F $\delta^{18}O$ series obtain the lowest interseries correlation coefficients. One possibility for this low correlation is the relatively short length of the 16F record (98 years), which may not be enough to fully capture the decadal/interdecadal variability mode.

This study advocates some general rules to follow in future coral-based paleoclimatology studies. All the statistical methods (AD, RMSD, and EPS) presented in this study gave similar results; however, only the EPS method gives an actual threshold value above which, one could assume the composite is reliable for climatic interpretations. This study therefore recommends the use of the EPS and SNR techniques to verify that a coral composite time series in fact represents regional, and not local site-specific-climate variability. When a record is added to a composite, both the $\bar{r}$ and the EPS values should increase thus enhancing the climate signal. If the EPS and SNR values do not increase when a new time series is added to the composite, it can be assumed that all or part of the newly added record is anomalous and chronology and/or diagenesis re-assessments might be needed before a decision could be made concerning whether or not to include this record in the composite.

Using the EPS method, the significance of the composite was tested outside the common time period for the IA and D/I time scales as well as the secular trend (variability with a frequency inferior at 75 years). The reconstructed climate signal is significant from 1841 to 2001 for IA variability (Figure 6a) and the secular trend (Figure 10), and significant from 1781 to 2001 for the D/I time scale (Figure 6b).

3.3. Assessment of Fiji $\delta^{18}O$ Composite IA and D/I Regional Reliability

3.3.1. Comparison With Other Coral $\delta^{18}O$ Records

The Fiji $\delta^{18}O$ composite is compared to other coral $\delta^{18}O$ records from both the southwest Pacific (Vanuatu, New Caledonia), and central Pacific regions (Palmyra, Maiana, Tarawa, and Nauru). From the Fiji $\delta^{18}O$ composite we

Table 5. Pearson Product Correlation Between Fiji Coral $\delta^{18}O$ Composite at Interannual and Decadal/Interdecadal Time Scales and Other Coral $\delta^{18}O$ Records From the Pacific Ocean: Vanuatu [*Kilbourne et al.*, 2004], New Caledonia [*Stephans et al.*, 2004], Palmyra [*Cobb et al.*, 2003], Nauru [*Guilderson and Schrag*, 1999], Maiana [*Urban et al.*, 2000], and Tarawa [*Cole et al.*, 1993]

Interannual Time scale

	Vanuatu	New Caledonia	Palmyra	Nauru	Maiana	Tarawa
Fiji Coral $\delta^{18}O$ composite	0.74	0.24	−0.53	−0.55	−0.74	−0.52

Decadal/Interdecadal Time scale

	Vanuatu	New Caledonia	Palmyra	Nauru	Maiana	Tarawa
Fiji Coral $\delta^{18}O$ composite	0.33	0.32	−0.52	−0.45	−0.57	−0.48

extracted both IA and D/I modes using SSA (see method section 2.4) after varying the window length (M) to identify the stable eigenvectors (number of principal components). IA and D/I modes of variability were also extracted from Vanuatu [*Kilbourne et al.*, 2004], Nauru [*Guilderson and Schrag*, 1999], New Caledonia [*Stephans et al.*, 2004], Maiana [*Urban et al.*, 2000], Tarawa [*Cole et al.*, 1993], and Palmyra [*Cobb et al.*, 2003] records for comparison to the Fiji IA and D/I composites (see Supplement S2). Pearson product-moment correlation coefficients between Fiji composites and the other coral $\delta^{18}O$ data (Table 5) at both IA and D/I time scales are significant at more than 99‰ except between Fiji and Vanuatu at D/I time scale (>90%). As expected, Fiji $\delta^{18}O$ composites show positive correlations with the subtropical Vanuatu and New Caledonia sites and negative correlations with the other four equatorial records, for both IA and D/I time scales (Table 5). Vanuatu, New Caledonia, and Fiji are under similar climatic forcing (i.e., El Niño events make the region cooler and saltier), while Nauru, Maiana, Tarawa, and Palmyra are located in a more equatorial region where the response to El Niño events is warmer and lower salinity conditions. These relationships indicate that the Fiji $\delta^{18}O$ composite reconstruction successfully increased the signal to noise ratio compared to individual Fiji coral records, and is primarily reflecting regional changes in oceanographic conditions.

3.3.2. Comparison With Known Pacific Wide IA and D/I Indices

There are various remote climate modes influencing the greater Pacific. El Niño-Southern Oscillation is the main interannual mode of variability; the main index to represent this mode of variability across the Pacific is the Southern Oscillation Index (SOI), calculated as the standardized sea level air pressure difference between Tahiti and Darwin [*Trenberth*, 1984]. In addition, existing decadal and interdecadal modes of variability are represented in the Pacific by multiple indices: the Pacific Decadal Oscillation (PDO) index [*Mantua et al.*, 1997], derived as the leading principal component (PC) of monthly SSTA in the North Pacific Ocean, poleward of 20°N; the Southern Hemisphere Pacific Decadal Oscillation (SHPDO) [*Shakun and Shaman*, 2009] created from leading mode of sea surface temperature variability for the South Pacific; and the South Pacific (inter) Decadal Oscillation (SPDO) [*Hsu and Chen*, 2011], which is defined as the first Empirical Orthogonal Function (EOF) of the July–August–September–October-mean SSTA south of 20°S.

All correlations of Fiji IA and D/I composites and climatic indices (SOI, PDO, SDPO, and SHPDO) are significant at greater than 99% (Figure 7) except for the correlation between PDO and Fiji composite at the D/I time scale that is only significant at the 95% level. These high correlations between IA and D/I Fiji composites signals and the Pacific wide IA and D/I indices further support our contention that the Fiji $\delta^{18}O$ composite can be used to reconstruct past IA and D/I variability of the Pacific back in time.

Correlation between the Fiji composite and the SOI at interannual time scale reveals a maximum 4 ± 1 month lag, with the SOI leading interannual variability in the Fiji $\delta^{18}O$ composite. A similar 4 ± 1 month lag is found between the Fiji $\delta^{18}O$ composite and other indices at interannual time scale (except the PDO index that has a 0 month lag correlation). This finding is similar to the time lag found by *Kilbourne et al.* [2004] for their Vanuatu coral record. Sites influenced mostly by rainfall variability have their coral $\delta^{18}O$ reaching a maximum in correlation with the SOI index at a 9 month lag, a value consistent with the timing of negative rainfall anomalies in the area [*Ropelewski and Halpert*, 1987]. The fact that the maximum correlation between the Fiji $\delta^{18}O$ composite and the SOI has a 4 ± 1 month lag (and not a 9 month lag), further supports our contention that the rainfall variability is not the main factor influencing the Fiji composite $\delta^{18}O$ variability at interannual time scales. Due to possible chronology errors, one might be skeptical of the significance of the 4 month lag.

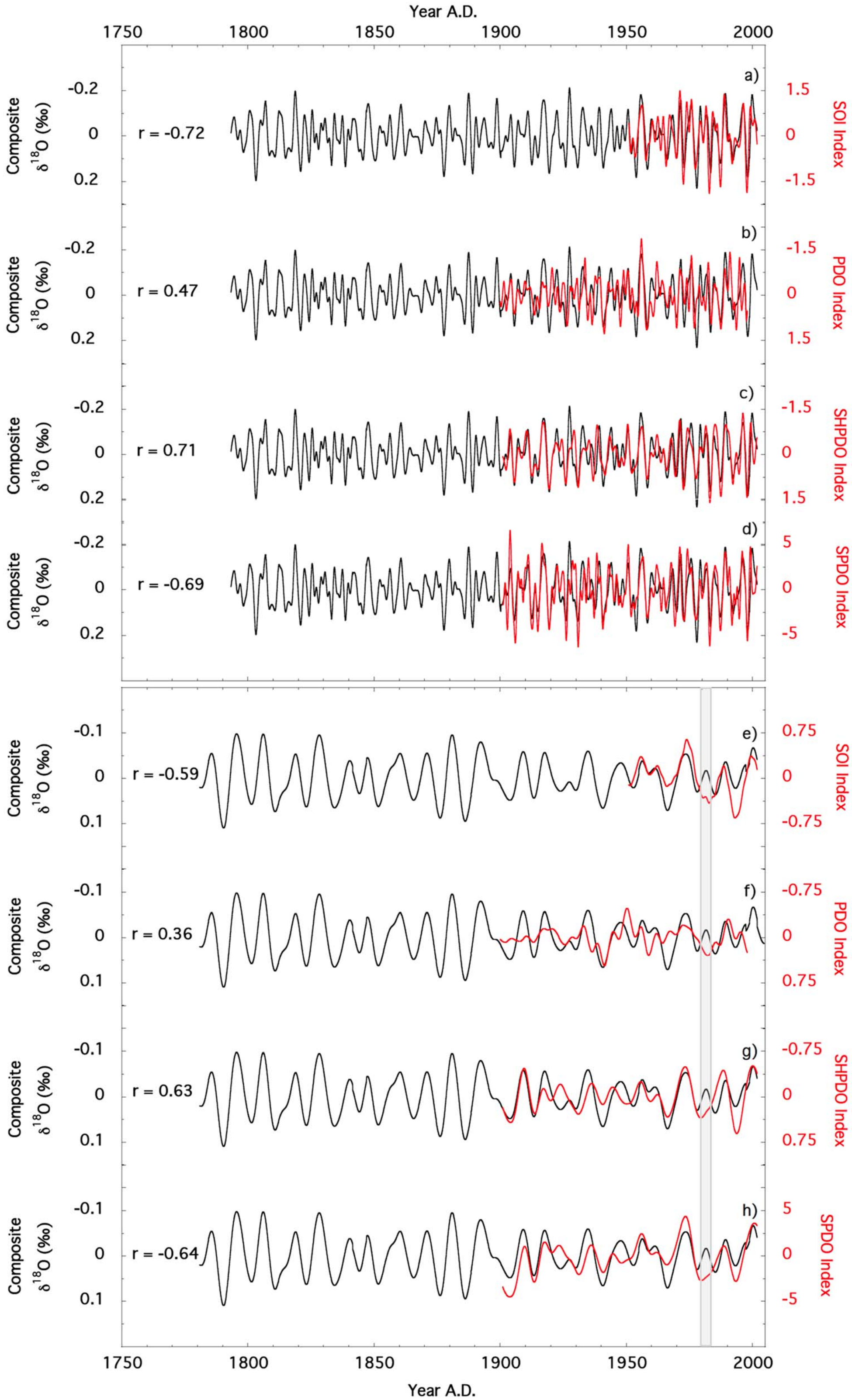

Figure 7. (a–d) Interannual and (e–h) decadal/interdecadal variability of both Fiji coral $\delta^{18}O$ composites (black lines) and Pacific indices (red lines): Southern Oscillation index (SOI) [*Trenberth*, 1984], Pacific Decadal oscillation Index (PDO) [*Mantua et al.*, 1997], the South Hemisphere Pacific Decadal Oscillation Index (SHPDO) [*Shakun and Shaman*, 2009], and the South Pacific Decadal Oscillation (SPDO) [*Hsu and Chen*, 2011]. Gray shading around 1980 indicates anomalously poor correlation (see text).

Table 6. Pearson Product Correlation Between Fiji Coral $\delta^{18}O$ Composite and the Various Pseudocoral ($PseudoCor_{SST}$, $PseudoCor_{SSS}$, and $PseudoCor_{Total}$) $\delta^{18}O$ Time Series for Both Monthly and Annual Average Values

Monthly Values	$PseudoCor_{SST}$	$PseudoCor_{SSS}$	$PseudoCor_{Total}$
Fiji Coral $\delta^{18}O$ Composite	0.75	0.38	0.85
Fiji Coral $\delta^{18}O$ composite	0.69	0.80	0.88

However, the correlation reaches maximum at a 4 month lag (20% higher than at a 0 month lag) and decreases toward higher month lags to a correlation value 50% lower for a 9 month lag. This gives us confidence in each coral chronology and supports our conclusion that there is a small rainfall influence on the coral $\delta^{18}O$ variability at interannual to decadal/interdecadal time scales. This same conclusion was reached by *Wu et al*. [2013] who discussed coral Sr/Ca and $\delta^{18}O$ results from Tonga (also in the SPCZ region). In summary, since the interannual oceanographic variability around Fiji is mainly dominated by SSS variability, coral $\delta^{18}O$ variability on interannual time scales is primarily related to horizontal advection of water with different SSS, rather than precipitation/evaporation.

We do note that a discrepancy is observed around 1980 between Fiji D/I composite and all the other D/I indices we compared to (Figures 7e–7h—grey shading). The Fiji composite pattern also shows a discrepancy with Nauru, Maiana, Tarawa, and Palmyra sites (Supplements S2) in this time interval. However, a similar pattern is observed in the Vanuatu and New Caledonia coral $\delta^{18}O$ records. Since the PDO, SPDO, and SHPDO indices are all based on SST, these results indicate that this D/I "event" around 1980 is related to a SSS event in the southwest Pacific, reinforcing the idea that there is additional D/I variability in SSS in this region possibly due to water masses advection.

4. Discussion

4.1. Influences of SST and SSS on the Coral Composite $\delta^{18}O$

Precisely quantifying the influence of SST and SSS on coral $\delta^{18}O$ is not an easy task given the limited spatial and temporal coverage of instrumental SSS databases in addition to possible local effects on coral $\delta^{18}O$. The new *Delcroix et al*. [2011] SSS database, despite its limitations, provides a unique opportunity to develop a "pseudocoral" $\delta^{18}O$ time series based on the method described by *Thompson et al*. [2011].

The $\delta^{18}O$ pseudocoral is a forward modeling exercise where the measured $\delta^{18}O$ time series represents the expected coral $\delta^{18}O$ temporal variability assuming that all the variability is the direct result of $\delta^{18}O_{seawater}$ (linearly related to SSS) and SST. A Fiji pseudocoral was created using the same instrumental SST and SSS data sets used to create the Fiji climatology (Figure 2). Instrumental SST were converted into $\delta^{18}O_{SST}$ time series by exploiting the most commonly used $\delta^{18}O$-SST slope of $-0.22‰\ °C^{-1}$ when comparing multiple locations [e.g., *Epstein et al*., 1953; *Evans et al*., 2000; *Lough*, 2004; *Thompson et al*., 2011]. For the $\delta^{18}O_{SSS}$ component, multiple iterations of the Fiji pseudocorals time series were created based on the range of commonly reported $\delta^{18}O$-SSS relationship for the Southwest Pacific [0.27 to 0.45‰ S_P^{-1}; *Fairbanks et al*., 1997; *Schmidt et al*., 2011; *Thompson et al*., 2011]. The minimum (0.27‰ S_P^{-1}) and maximum (0.45‰ S_P^{-1}) as well as the median (0.36‰ S_P^{-1}) were

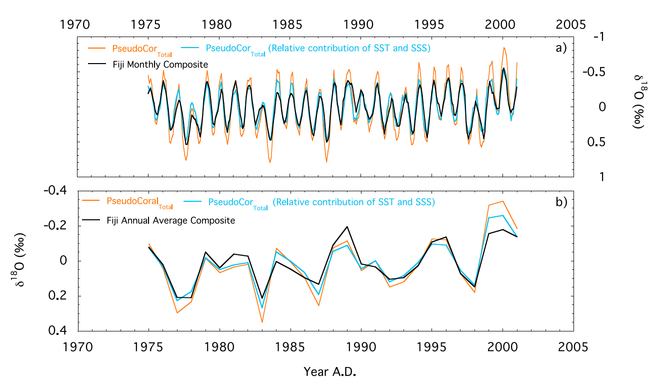

Figure 8. Fiji coral $\delta^{18}O$ composite at interannual time scale (black) plotted with the modeled $\delta^{18}O$ time series representing the expected coral $\delta^{18}O$ temporal variability assuming that all the variability is the direct result of $\delta^{18}O$ seawater (linearly related to SSS) and SST ($PseudoCor_{Total}$—orange), and the Pseudocoral of the relative contributions of SST and SSS made using the regression coefficient between the Fiji coral composite and instrumental SST and SSS (Table 6).

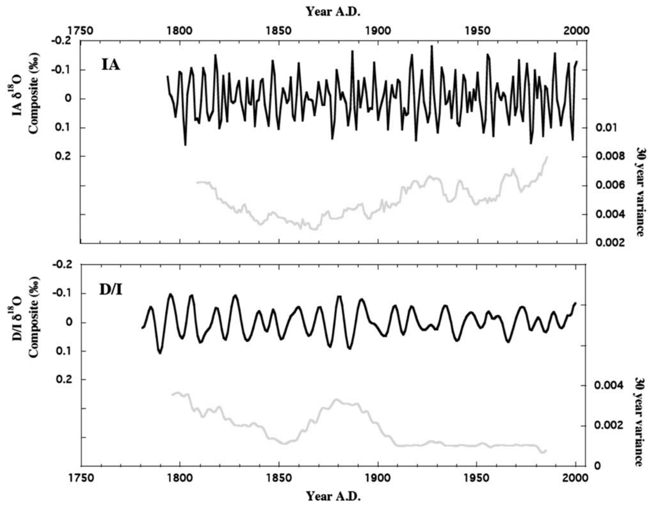

Figure 9. Fiji coral δ^{18}O composite at interannual (IA) and decadal/interdecadal (DI) time scales (black) plotted with their respective 30 year window running variance (grey).

calculated to show the disparity in δ^{18}O-SSS relationship of this region. The correlation between the Fiji coral δ^{18}O composite and pseudocorals using the three different δ^{18}O-SSS slopes are similar; thus, we retained the highest correlated δ^{18}O-SSS transfer function of 0.36‰ $S_P{}^{-1}$ for discussion.

Three renditions of a Fiji pseudocoral were created: one combining both the SST and SSS influences ($PseudoCor_{total}$), one with the SST alone ($PseudoCor_{SST}$), and one with the SSS alone ($PseudoCor_{SSS}$). These pseudocorals iterations were created with both monthly and annually averaged values from 1975 to 2001 [time period where the associated errors in SSS were less than 0.13 S_P; *Delcroix et al.*, 2011]. Statistically significant correlations (>99%) are found between Fiji coral δ^{18}O composite and $PseudoCor_{total}$ at both seasonal and interannual resolution (Table 6). Additionally, Fiji coral δ^{18}O composite is better correlated with $PseudoCor_{SST}$ at monthly time scales ($r = 0.75$) and with $PseudoCor_{SSS}$ at annual average time scales ($r = 0.80$). Our results confirm the reported sub-seasonal influence of SST on coral δ^{18}O, while annual average Fiji coral δ^{18}O variability is more closely correlated to SSS variability [*LeBec et al.*, 2000; *Linsley et al.*, 2004, 2006, 2008; *Gorman et al.*, 2012]. Furthermore, no significant change in the correlation coefficient is found between the pseudocorals and Fiji coral δ^{18}O composite when the contribution of the SSS or SST is increased as suggested by *Gorman et al.* [2012] for the pseudocoral created at Sabine Blank, Vanuatu. This further verifies the joint influence of SST and SSS on the coral δ^{18}O variability on seasonal and interannual time scales. However, if we use the r^2 regression coefficients presented in Tables 5 and 6 as representative of relative contributions of SST and SSS (i.e., $r^2 = 0.75$ for monthly SST and $r^2 = 0.38$ for monthly SSS; and $r^2 = 0.69$ for annual SST and $r^2 = 0.80$ annual SSS), the variance of those new pseudocorals are similar to the variance of the Fiji coral composites (Figure 8). This reinforces our conclusion that the variability in the Fiji coral δ^{18}O composite is due to changes in SST and SSS, but also that there is a shared contribution of SST and SSS to the coral δ^{18}O variability.

Monthly Fiji coral composite δ^{18}O variability seems to be influenced independently by SST and SSS due to relatively large annual cycle in SST and muted irregular annual cycle in SSS. These relationships are the result of the seasonal north-south movement of the SST gradient and the northeast-southwest movement of the salinity front following the SPCZ seasonal displacement [*Gouriou and Delcroix*, 2002]. Conversely, SST and SSS appear to have shared interannual variance; movements of water masses will simultaneously bring a change in both SST and SSS. On interannual time scales, Fiji coral δ^{18}O variability is influenced by changes in water mass displacement around the Fiji region. This hypothesis is verified by modeling studies showing that on interannual time scales, heavy precipitation in the SPCZ area is not the main factor influencing surface salinity in Fiji and that the zonal expansion/contraction of the South Equatorial Current (SEC) is the main factor influencing the salinity budget of the surface ocean of SPCZ region [*Hasson et al.*, 2013a; *Vialard and Delecluse*, 1998].

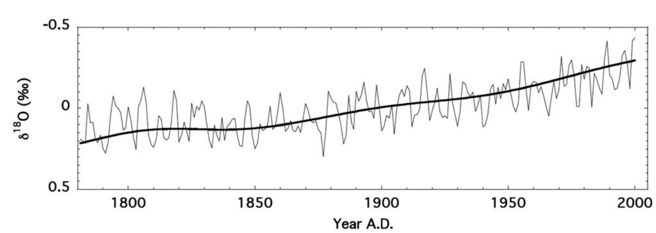

Figure 10. Fiji coral δ^{18}O composite made from the arithmetic average of the five individuals coral records (thin black line) and its extracted secular trend (SSA frequency lower than 75 years) (bold black line).

4.2. 20th Century and Long-Term Variability of the IA and DI Signals

Recent observational and modeling studies have pointed out that the different flavors of ENSO events generate distinct impacts on SPCZ movements with the SPCZ collapsing onto the equator during three notably large eastern Pacific warming events [*Vincent et al*., 2011; *Hasson et al*., 2013a; *Borlace et al*., 2014]. The same studies concluded that more extreme ENSO events as well as events generating a horizontal position of the SPCZ closer to the equator will be more likely to occur under the current global warming context. Being located under the SPCZ influence, the Fiji composite is most likely able to reconstruct canonical ENSO, such as the 1982–1983 and 1997–1998 events, while Central Pacific [*Larkin and Harrison*, 2005] or Modoki ENSO [*Ashok et al*., 2007], such as the 1991–1992, should be less represented [*Stevenson et al*., 2013]. Indeed, when looking at our Fiji IA composite, the 1991–1992 event is less distinct than the two other extreme ENSO events occurring during the satellite era. As *Stevenson et al*. [2013] pointed out, sites in the SPCZ area will allow for the reconstruction of the canonical ENSO events; however, to be able to look at the different flavors of ENSO events, one would need to combine sites from both the SPCZ and the Warm Pool area. Combining this Fiji coral composite record with Warm Pool records may prove to be a great asset for reconstructing previous events and identifying ENSO event types over longer time periods.

During the time period prior to instrumental records (prior to 1950) the amplitudes of both the IA and D/I signals fluctuate in our Fiji composite $\delta^{18}O$ record. To quantify this variability, we calculated a 30 year-window running variance for both signals (Figure 9). The IA variability decreases from the early part of the record to around 1850 when the variance increases to a maximum near 1880. After 1900 the D/I variance in the Fiji $\delta^{18}O$ composite decreases rapidly, reaching a stable low variance signal in the 20th century. This is in contrast with the interannual variance, which increases in the Fiji composite throughout the 20th century. Previous coral-based reconstructions in the central equatorial Pacific [*Urban et al*., 2000] also found an increase of interannual variability during the 20th century. This may suggest a re-organization of South Pacific climate variability in the late 1800s to a mode with increasing interannual variability.

4.3. Secular Trend of the Fiji Coral $\delta^{18}O$ Composite: Climatic Implications

The Fiji coral $\delta^{18}O$ composite made from the arithmetic average of the five individuals coral records and the extracted secular trend (SSA frequencies lower than 75 years) are plotted on Figure 10. The observed $\delta^{18}O$ long-term secular decreasing trend from 1781 to 2000 is 0.46‰; this linear trend is significant at the 99% level. While in the earlier part of the record the decrease is less pronounced, beginning around 1850, decadal mean $\delta^{18}O$ starts to decrease, reaching a nearly constant decrease of 0.0027‰ yr^{-1}. Between 1850 and 2001, the signal presents a total decrease of 0.41‰, which correspond to nearly 90% of the total secular decrease, assuming a linear trend through the length of the record.

If we interpret this secular trend in coral $\delta^{18}O$ as being solely a response to SST warming, assuming a linear trend through the length of the record, a decrease of 0.41‰ would correspond to a SST increase of about 2°C since 1850 and consequently 1°C since 1950. This is four times more than what the instrumental data recorded (0.2°C for the 20th century). Furthermore, if we interpret this trend as being solely influenced by surface ocean freshening, then salinity would have decreased ~0.5 S_P between 1950 and 2000. During the 1975–2000 period, period when the associated error on the instrumental SSS is less than 0.13 S_P, the SSS presents a 0.36 S_P decrease. For the same period we can observe a SSS derived-coral composite $\delta^{18}O$ decrease of similar amplitude. This reinforces our conclusion of the dominant influence of SSS on long-term variability. If we assume that the percentage contribution from SSS and SST to the secular $\delta^{18}O$ trend is the same as those determined over the last 25 years, the total $\delta^{18}O$ decrease of 0.41‰ (1850–2001) would correspond to a SST increase of slightly more than 1°C and a SSS decrease of about 1 S_P. Assuming a linear trend from 1850 to 2001, these values are comparable to those obtained by *Cravatte et al*. [2009] for their linear trends of SST and SSS from 1955 to 2003 for the Fiji area: +0.25°C and −0.3 S_P per 50 years.

This century-scale freshening and warming might be related to water mass advection variability possibly associated with a progressive expansion and/or intensification of the salinity front located at the southeastern edge of the SPCZ as proposed by *Linsley et al*. [2006]. However, we could not find any definite explanation for the cause of this century-scale trend. *Hasson et al*. [2013b] found a low frequency westward shift of the SSS maximum in the south Pacific, of 1400 km from the mid 1990s to the early 2010s. It could be possible that oceanographic conditions in the South Pacific began changing earlier than the mid-twentieth century and that this change is linked to the climatic variability switching around 1900 to a more interannual-focused variability as presented in the previous section.

5. Summary and Conclusions

Based on statistical criteria, we show that in order to reconstruct interannual, decadal-interdecadal, and secular climatic variability using Fiji *Porites* coral $\delta^{18}O$, three or more *Porites* coral $\delta^{18}O$ records ensure the fidelity of the geochemical reconstruction. The dendrochronology method (EPS and SNR techniques) is suitable to verify that a coral composite record does in fact represent regional, and not local site-specific, climate variability. We therefore recommend the use of this statistical method because it gives similar results as the other methods tested and additionally gives a threshold value for quantifying the reliability of a composite for climatic interpretations.

Both extracted modes (IA and D/I) from the Fiji $\delta^{18}O$ composite agree with records from other regions of the equatorial and southwest Pacific as well as with known Pacific-wide climatic indices. This supports our conclusion that the Fiji $\delta^{18}O$ composite time series records regional climatic variability and is a great asset for the reconstruction of large Pacific-wide features from preindustrial time.

From a comparison between modeled $\delta^{18}O$ (Pseudocoral) and Fiji coral $\delta^{18}O$, we found SST variability to be the primary driver of seasonal $\delta^{18}O$ variation with IA and D/I variability more closely correlated to SSS variability. Additionally, there is a shared variance of the SST and SSS influence on the coral $\delta^{18}O$ variability at an interannual time scale. This result suggests that on interannual time scales, Fiji *Porites* coral $\delta^{18}O$ variability is influenced by changes in water mass displacement around the Fiji region.

This study concluded that Fiji coral $\delta^{18}0$ composite secular decreasing trend was induced by a century-scale freshening and warming of the area that might be related to water mass advection variability possibly associated with a progressive expansion and/or intensification of the salinity front located at the southeastern edge of the SPCZ.

Both Fiji IA and D/I composite variance present a switch around 1900 that could be attributable to a re-organization of Pacific climate variability to more dominant interannual variability in the 20th century. Fiji IA seems to be more tightly coupled to canonical ENSO as already assessed by *Stevenson et al*. [2013]. While having a network of corals from the same site allows one to obtain a better assessment of the regional variability, combining this Fiji composite record with other coral proxy records from the central equatorial Pacific and Western Pacific Warm Pool may prove useful for reconstructing previous events and identifying ENSO event types over long periods of time.

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