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Geochemical evidence from corals for changes in the amplitude and spatial pattern of South Pacific interdecadal climate variability over the last 300 years

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Abstract In the Pacific Ocean, the coherent pattern of interdecadal variations in sea surface temperature (SST) over the last ∽100 years has been termed the Interdecadal Pacific Oscillation (IPO). To examine past variations in the IPO we have generated time series of Sr/Ca and oxygen isotopes (δ^{18}O) from South Pacific *Porites* coral colonies growing at Rarotonga (1997 to 1726) and Fiji (1997 to 1780). At both sites skeletal Sr/Ca is highly correlated with instrumental SST at least back to ∽1970 and δ^{18}O appears to reflect both SST and South Pacific Convergence Zone (SPCZ) effects on seawater δ^{18}O. Comparison of our results to a New Caledonia coral δ^{18}O record and to indices of interdecadal Pacific climate variability demonstrates that these South Pacific corals have accurately recorded twentieth century variations in the IPO and SPCZ. The coral records also indicate that higher amplitude and more spatially coherent IPO-related variability existed from 1880 to 1950 with notably poor between-site correlations in the mid-1800s. These observations suggest that the spatial IPO pattern in South Pacific SST was significantly more complex and/or poorly defined in the mid-1800s compared to that observed in the twentieth century. Comparison with North Pacific IPO indices also indicates that the degree of cross-hemispheric symmetry of interdecadal oceanographic variability has changed over time with a lower correlation between the North and South Pacific in the mid-1800s. This evidence suggests that the spatial pattern of the IPO at least in the South Pacific has varied over the last 300 years, with a major reorganization occurring after ∽1880 A.D.

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1 Introduction

Instrumental sea surface temperature (SST) data now clearly indicate that interdecadal climatic variability over much of the Pacific Ocean was coherent in the twentieth century. In the North Pacific this variability is generally termed the Pacific Decadal Oscillation (PDO) (Ware 1995; Mantua et al. 1997; Zhang et al. 1997). Including data from the South Pacific, Power et al. (1999) refer to the variability as the Interdecadal Pacific Oscillation (IPO). Recently, Folland et al. (2002) have demonstrated that the IPO can be regarded as the quasi-symmetric Pacific-wide manifestation of the PDO and Salinger et al. (2001) and Folland et al. (2003) have identified significant climate impacts in the South Pacific, including IPO related variability of the South Pacific Convergence Zone (SPCZ). The spatial structure of this variability is similar to that of the El Niño Southern Oscillation (ENSO), with the notable difference that the variability has greater amplitude at mid-latitudes with a reduced tropical expression (see Fig. 1). This interdecadal mode of climatic variability has been linked to significant climate "events" such as the catastrophic 1930s drought in the USA and the ENSO recurrence interval shift after 1976.

Prior to ∽1950 AD there remain large uncertainties as to the nature and spatial coherence of this interdecadal variability due to the lack of instrumental data in large regions of the Pacific. Questions include whether the IPO is a recent phenomenon, or whether this mode

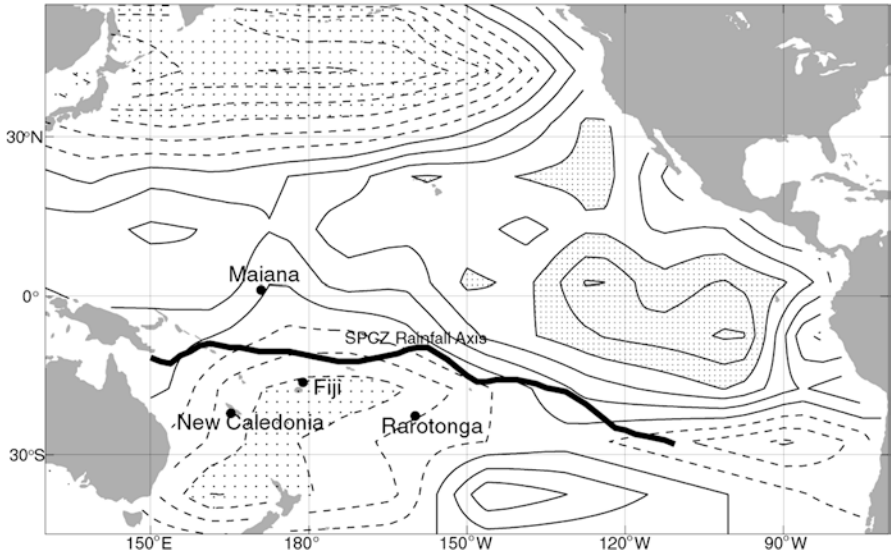

Fig. 1 Location of New Caledonia, Fiji, and Rarotonga in relationship to the South Pacific Convergence Zone Axis and pattern of the IPO (from Folland et al. 2002a). *Background contours* show the IPO as a covariance map of the third empirical orthogonal function (EOF3) of 13 year low-pass filtered SST anomalies for 1911–1995. The contour interval is 0.04 °C, *negative contours* are *dashed*, values <-0.12 °C *lightly stippled* and those $>+0.12$ °C *heavily stippled*. The rainfall maximum axis of the SPCZ for 1958–1998 is also shown. Figure modified from Folland et al. (2002a)

of variability has always existed in the past? Was IPO variability different in earlier centuries over the past millennium and did the spatial pattern and temporal pacing of the IPO change with the advent of significant anthropogenic forcing in the twentieth century?

Paleoclimatic reconstructions using tree-rings and corals have been used to extend the record of IPO variability prior to the instrumental record. Several studies have developed reconstructions of past PDO and IPO variability by using tree-rings from multiple sites along the western margin of North and South America (Biondi et al. 2001; D'Arrigo et al. 2001; Evans et al. 2001; Gedalof and Smith 2001; Villalba et al. 2001). In the ocean, one subtropical coral Sr/Ca record from Rarotonga in the Southwestern Pacific clearly displays interdecadal variability that is coherent with the PDO and IPO indices (Linsley et al. 2000). Although these paleorecords all exhibit the twentieth century IPO oscillations to differing degrees, they show much less between-site agreement before 1900 AD (Evans et al. 2001; Gedalof et al. 2002; Labeyrie et al. 2003). It is possible that the individual IPO reconstructions are indicating that the IPO is both a spatially and temporally intermittent phenomenon. It is also possible that each reconstruction has a strong overprint of local climatic/environmental variability superimposed on the large-scale IPO patterns (Labeyrie et al. 2003). In an attempt to lengthen the record of past variations of the IPO, we have developed multi-century long, subannually resolved, time-series of oxygen isotopes (δ^{18}O) and Sr/Ca from specimens of the massive coral *Porites lutea* growing at the islands of Rarotonga and Fiji near the central node of South Pacific IPO variability (Fig. 1). This region is on the southern margin of the SPCZ where interdecadal changes in instrumental SST have been previously shown to co-vary with the subtropical North Pacific (Power et al. 1999; Folland et al. 2002, 2003). In this contribution we focus on the significance of interdecadal variability in these records and compare our results with IPO and PDO indices and to coral δ^{18}O records from New Caledonia (22°S, 166°E) also in the southwest Pacific (Quinn et al. 1998), and Maiana Atoll (1°N, 173°E) (Urban et al. 2000) in the equatorial western central Pacific.

2 Methodology

In April 1997 we retrieved a 3.5 m long section of continuous coral core from a colony of *P. lutea* growing on the southwest side of Rarotonga at a depth of 18.3 m (21°14′16″S and 159°49′40″W). A 2.3 m coral core was also recovered from a *P. 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). Coral slabs 7 mm thick were cut from the cores and cleaned in deionized water in an ultrasonic bath. Dry slabs were sampled with a low-speed micro-drill along tracks parallel to corallite traces as identified in X-ray positives with a 1 mm round diamond drill bit. The X-ray positive collage of the Rarotonga coral core was published in Ren et al. (2003) and the Fiji X-ray collage is shown in Fig. 2. For the results discussed here, Sr/Ca was measured at 1 mm resolution (∽12–13 samples per year) and δ^{18}O was measured at 2 mm resolution on the same samples (analyzing every other sample or ∽6–7 samples per year) in both the Rarotonga and Fiji cores. We measured oxygen isotope ratios on a Micromass Optima gas source mass spectrometer at the University at Albany-State University of New York with an individual acid reaction vessel system following procedures discussed in Linsley et al. (2000) and Ren et al. (2003). External precision for the Rarotonga and Fiji analyses is better than 0.04 per mil for δ^{18}O based on analyses of 657 (13.5%) replicate samples. Aspects of the δ^{18}O results for the longest Rarotonga core are also discussed in Ren et al. (2003). We used an inductively coupled plasma atomic emission spectro-photometer (ICP-AES) at Harvard University to measure coral skeletal Sr/Ca following a technique described in detail by Schrag (1999). The external precision is better than 0.15% (RSD) based on analyses of replicate samples (10% replicates). The Sr/Ca record from Rarotonga was previously published in Linsley et al. (2000a).

The chronology for the Rarotonga coral record is based on both skeletal δ^{18}O and Sr/Ca and is discussed in Ren et al. (2003) and is identical to the Sr/Ca based chronology used in Linsley et al. (2000a). Briefly, because δ^{18}O and Sr/Ca were phased locked at zero lag in the down-core series we constructed the chronology by setting the annual minima in Sr/Ca and δ^{18}O to February (on average the warmest month) and maximum Sr/Ca and δ^{18}O to

August/September (on average the coolest months). Based on this chronology the coral core spans 1997 to 1726. To examine the reproducibility of the δ^{18}O signal at Rarotonga we also analyzed subannual δ^{18}O (every other 1 mm resolution or 8/year on average) on two other Rarotonga coral cores collected in 1999 and 2000, one within 200 m of the first and at 18 m water depth spanning 1999 to 1906, and the second from a colony located on the north side of the island in 10 m of water near a small river outlet spanning 2000 to 1874.

To construct the Fiji chronology we also tied the annual minima in Sr/Ca and δ^{18}O to February (on average the warmest month) and maximum Sr/Ca and δ^{18}O to August/September (on average the coolest months). In comparing the Fiji δ^{18}O and Sr/Ca records to Niño3.4 (central equatorial Pacific region bounded by 5°S–5°N and 120°–170°W) SST anomaly (SSTa) (Kaplan et al. 1998), Maiana coral δ^{18}O, and Rarotonga coral δ^{18}O and Sr/Ca, we discovered three approximately 1 year long gaps in the original Fiji sample series (two at core breaks, and one at a sampling track change along a coral slab). At each break in the Sr/Ca and δ^{18}O series we inserted one average Sr/Ca and δ^{18}O year respectively. The average year was calculated as the average year of the data five years on each side of the gap (10 years total). The gaps occur between composite core depths 1201–1202 cm (core 1F3A2-1F4 break), 1327–1328 cm (sample track change in core 1F4), and 1454–1456 cm (core 1F4-1F5A1 break). This Fiji coral core spans 1997 to 1780.

3 Results

Running-average (3 year window) filtered versions of δ^{18}O and Sr/Ca for the longest cores from both Fiji and Rarotonga are shown in Fig. 3. The reproducibility of the interannual, interdecadal and trend components of the coral δ^{18}O signal at Rarotonga is demonstrated through our analysis of replicate cores at that site

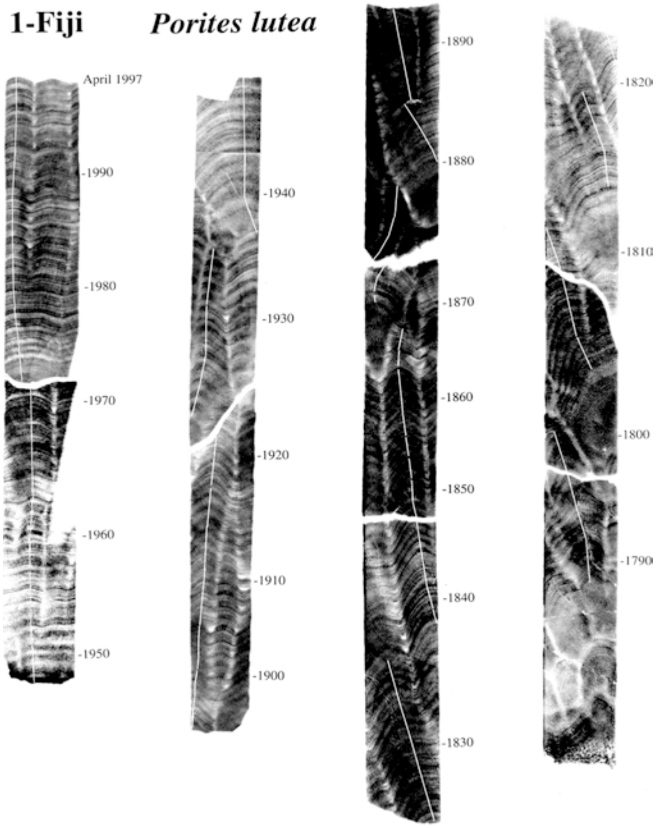

Fig. 2 X-radiograph of Fiji core 1F (*Porites lutea*). Thin *white line* indicates the sampling transect

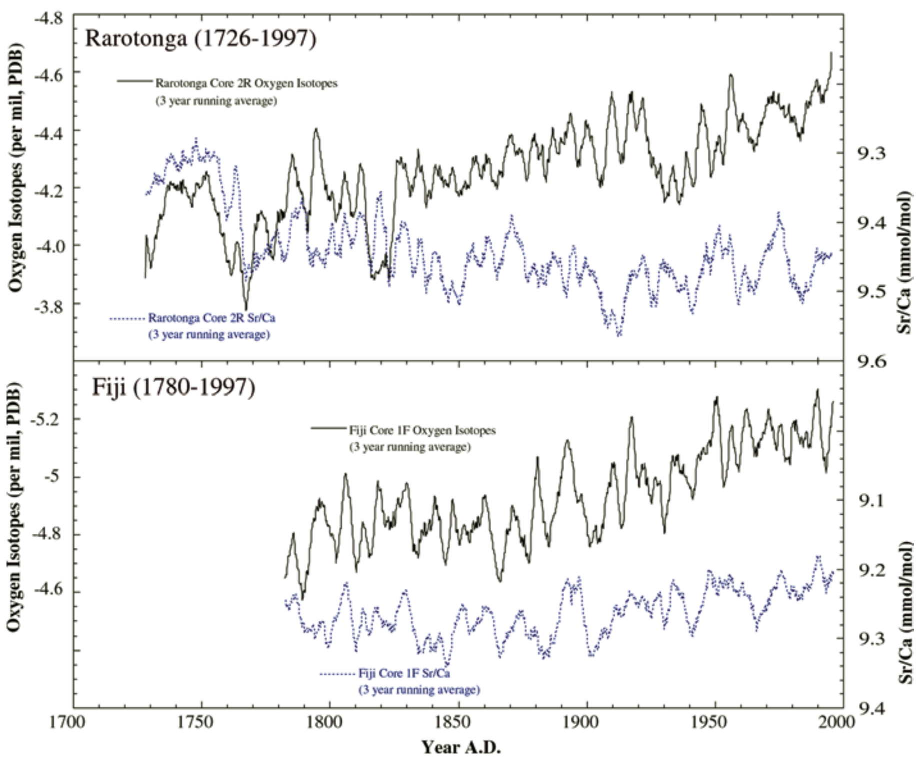

Fig. 3 Rarotonga and Fiji coral δ^{18}O and Sr/Ca: the results presented here have been smoothed with a 3 year running average filter in order to highlight the interannual, interdecadal and trend components of the data

(Fig. 4). After the annual cycle and the secular trend, interdecadal changes in these coral δ^{18}O and Sr/Ca records are the next largest component of variance in the unprocessed time series.

Bulk coral skeletal Sr/Ca at Rarotonga appears to be related to SST variability on annual through at least decadal time scales based on correlation with instrumental SST (Linsley et al. 2000a). We observed the same relationship for Fiji although it remains unclear whether multi-decadal and secular trends in coral Sr/Ca at both sites are entirely the result of SST change. At both Fiji and Rarotonga near-monthly coral Sr/Ca is highly correlated to monthly SST from the Integrated Global Ocean Service System Products (IGOSS) data (Reynolds and Smith 1994) over the period 1981 to 1997. The relationship at Fiji is: Sr/Ca * 10^3 = [10.65 – 0.053 (SST)], (r^2 = 0.77); and for Rarotonga is Sr/Ca * 10^3 = [11.12 – 0.065(SST)]; (r^2 = 0.75), as described in Linsley et al. (2000). Using the longer Climate Analysis Center (CAC) SST records for each site spanning 1970 to 1997 the relationship at Fiji is Sr/Ca * 10^3 = [11.73 – 0.055(SST)]; (r^2 = 0.70), and at Rarotonga is Sr/Ca * 10^3 = [11.07 – 0.063(SST)]; (r^2 = 0.64) (see Fig. 5A, B).

For δ^{18}O, the seasonal range (∼0.9 to 1.0‰) at both sites matches the expected range if annual water temperature change was the dominant influence on coral δ^{18}O. However, there are also intervals where δ^{18}O does not closely track SST and r^2 correlation coefficients between subannual δ^{18}O and IGOSS 1° × 1° SST are near 0.5 at both sites. This result is not unexpected as coral skeletal δ^{18}O is known to be affected by both SST and $\delta^{18}O_{seawater}$ and Rarotonga and Fiji are each located on the southwestern margin of the SPCZ. Interannual and decadal-scale variability in a 90 year instrumental record of rainfall (1901–1991) is clearly expressed in the replicated Rarotonga coral δ^{18}O record. Although the trends in coral δ^{18}O and instrumental rainfall at Rarotonga are different and it is not known whether Rarotonga rainfall is directly and/or linearly related to $\delta^{18}O_{seawater}$ around this island, the correspondence over interannual and decadal time scales further indicates that coral δ^{18}O in this region is in-part affected by the SPCZ (Fig. 4). We do not have a site-specific rainfall record from Savusavu Bay in Fiji where the coral core was collected. However, instrumental precipitation records from Suva and Nadi on the island of Viti Levu (Fiji) show the same degree of correlation on interannual time scales to our Fiji coral δ^{18}O record. This is expected because the Savusavu Bay site where the Fiji core was collected is known to be influenced by rainfall and river/groundwater discharge due to the hydraulic configuration of the bay. In addition, Le Bec et al. (2000) have found *Porites* skeletal δ^{18}O in colonies on the western side of the Island of Viti Levu (Fiji) to be strongly effected by salinity variations.

To quantify the variance in these coral δ^{18}O and Sr/Ca time series we processed each with singular spectrum analysis (SSA). A detailed description of SSA and its application is given by Vautard and Ghil (1989) and Vautard et al. (1992). SSA has been previously applied to coral time series (i.e., Dunbar et al. 1994; Linsley et al. 1994, 2000b; Charles et al. 1997). SSA is a fully nonparametric analysis technique based on principal component analysis of delay coordinates in vector space for a time series. It uses lagged copies of a centered time series to calculate eigenvalues and eigenvectors of their covariance matrix. Reconstructed components (RCs) are then calculated which allow a unique expansion of the signal into its different frequency components.

SSA of the Rarotonga, Fiji, and New Caledonia coral δ^{18}O and Sr/Ca records indicates that between 4 and 9% of the variance in each raw time series is in the interdecadal band with mean periods between ∼17 and 50 years. In each case this interdecadal variability is the third largest component of total variance behind the

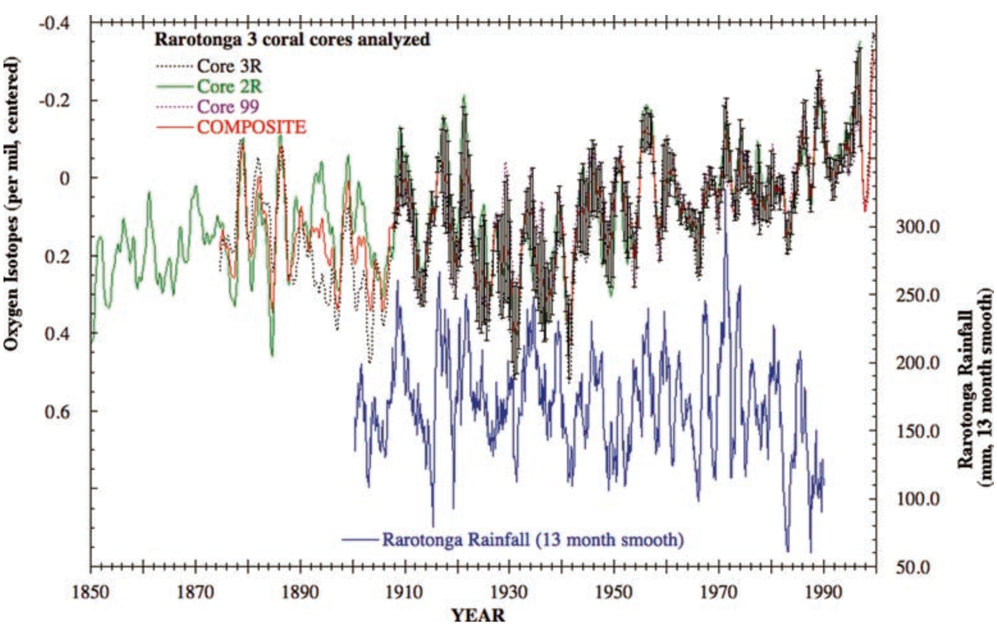

Fig. 4 Comparison of Rarotonga coral δ^{18}O from 3 different cores from *Porites lutea* coral colonies to instrumental rainfall. The average δ^{18}O over the interval from 1950 to 1997 was subtracted from each δ^{18}O record and the centered series was then filtered with a 2-year smoothing spline filter. The three cores were used to make a composite δ^{18}O record over the interval from 1997 to 1906 and a 2-core composite over the interval from 1906 to 1874. The composite δ^{18}O record is shown in *red*. The standard deviation of the 3-core composite is also shown. The rainfall data was smoothed with a 13 month running average filter to highlight interannual and interdecadal variability

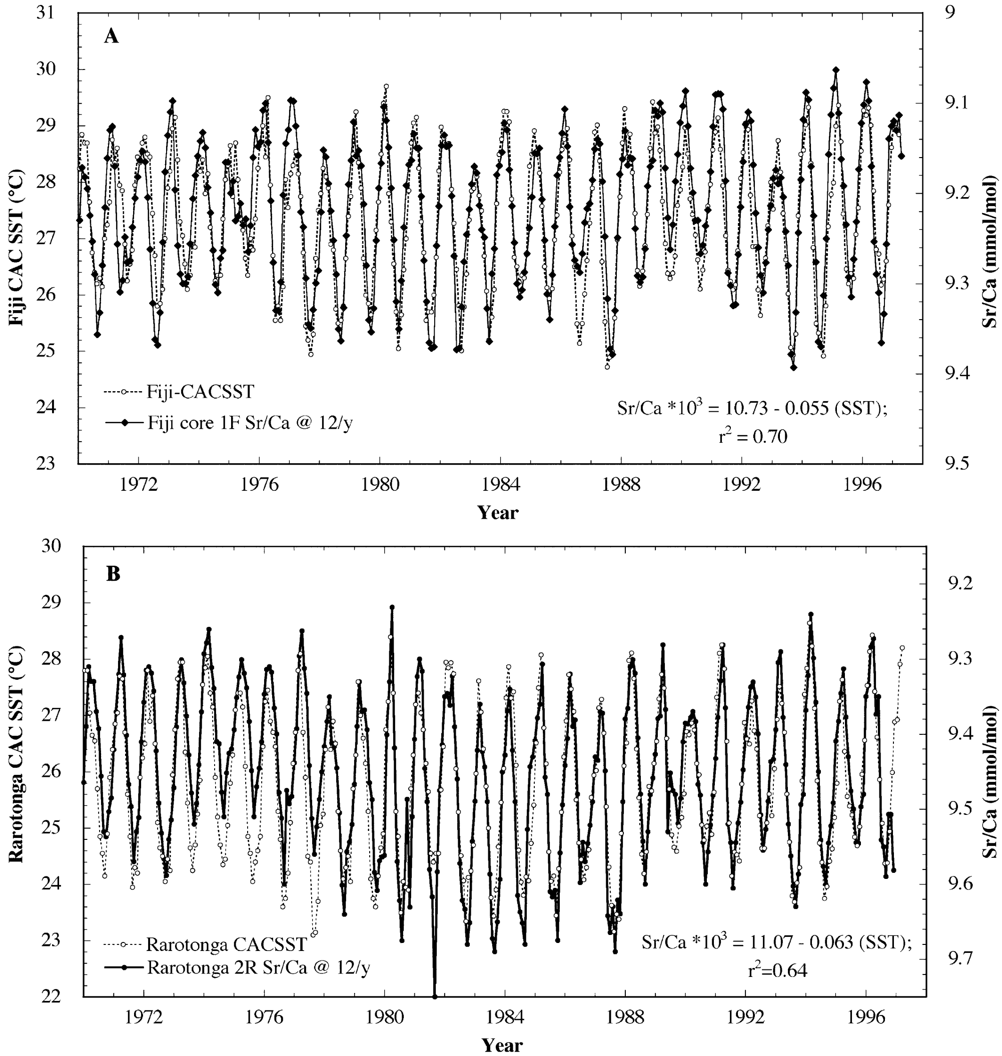

Fig. 5A, B Rarotonga and Fiji coral Sr/Ca and CACSST (Reynolds and Smith 1994). The Sr/Ca data has been interpolated to 12 points per year to allow calculation of correlation statistics with CACSST

annual cycle and the trend components. To more closely examine the interdecadal variability in the δ^{18}O and Sr/Ca time series we isolated variance with mean periodicities >17 years and <50 years. Subannual times series of coral δ^{18}O and Sr/Ca were generated at an interval of eight samples per year. Each data series was then filtered with a 10-year smoothing spline low-pass filter, and the low-pass fraction analyzed using SSA (software written by Dr. E. Cook of LDEO). For each time series all reconstructed components with mean frequencies between 17 and 50 years where then summed. The results are shown in Fig. 6. Note that essentially identical results were obtained by bandpass filtering with a Gaussian Filter (centered at 25 years between periods of 16.6 and 50 years). We also applied the same spline filtering-SSA treatment to the Maiana (Urban et al. 2000) and New Caledonia (Quinn et al. 1998) coral δ^{18}O records, and to the PDO (Mantua et al. 1997) and IPO (Folland et al. 2002) indices. In Fig. 6 we also display smoothing spline filtered versions of 2° × 2° SSTa anomaly data from the Hadley Centre Sea Ice and Sea Surface Temperature data set (HADISST1) and the 5° × 5° OS SSTa of Kaplan et al. (1998) for Rarotonga, Fiji, and New Caledonia. In addition, Fig. 6B shows the western North American tree-ring based PDO index of D'Arrigo et al. (2001). We elected to use the PDO reconstruction of D'Arrigo et al. (2001) rather than the reconstructions of Gedalof and Smith (2001) and Biondi et al. (2001). The D'Arrigo et al. (2001) results differ from the other studies by incorporating both ring width and density parameters from a range of species and by incorporating tree-ring records from both temperature-sensitive sites in coastal Alaska and the Pacific Northwest. In addition, D'Arrigo et al. (2001) demonstrated stronger calibration and verification results than the other studies. Their PDO index was also found to be correlated with reconstructed interdecadal changes in southern Sierran precipitation (Graumlich 1993), northern Sierran reconstructed discharge (Meko et al. 1999) and Mono Lake sedimentary inorganic carbonate δ^{18}O (Benson et al. 2003). This further supports the argument that the D'Arrigo et al. (2001) PDO index is representative of North Pacific and western North American interdecadal climatic variability.

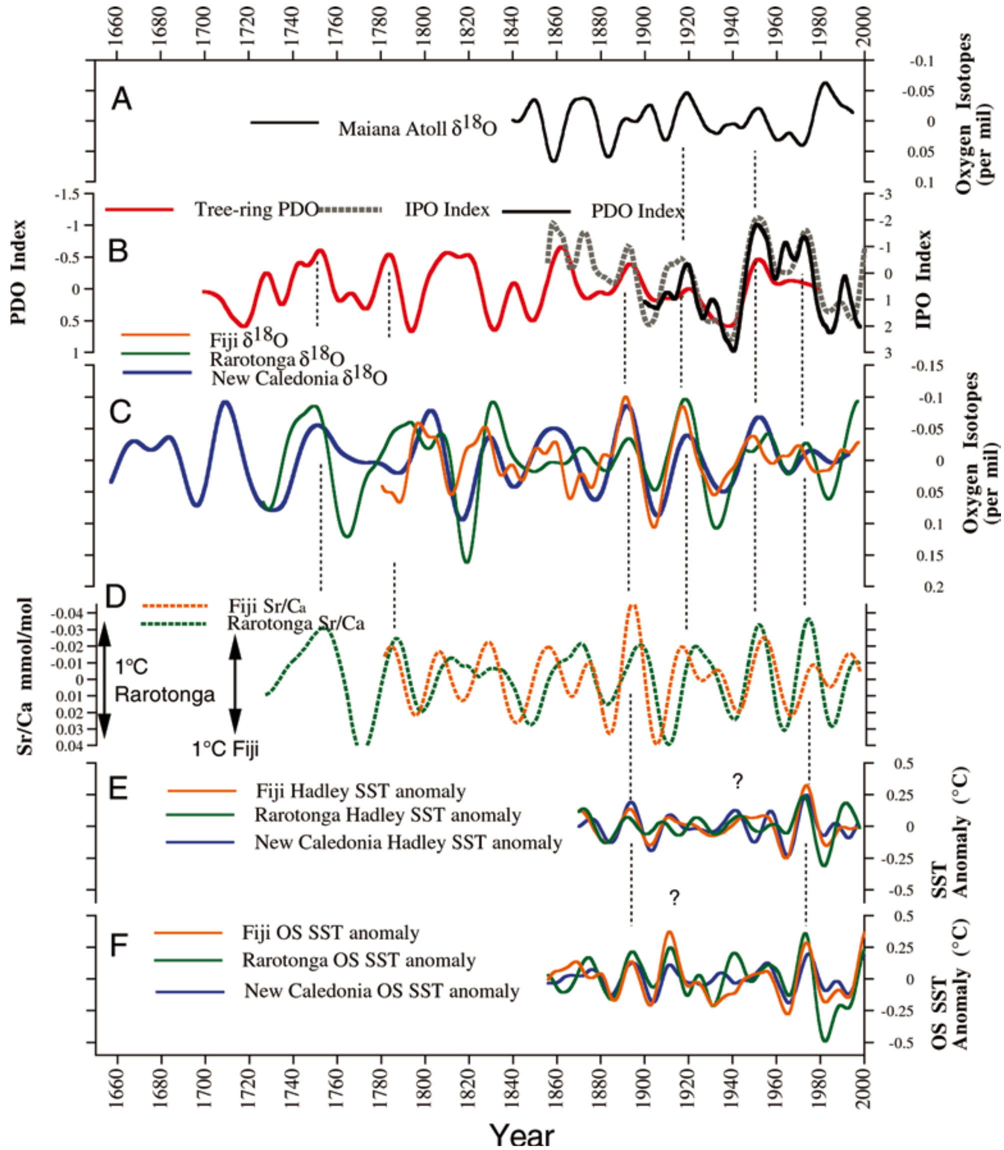

Fig. 6A–F Comparison of interdecadal variability in geochemical records from *Porites* corals from Rarotonga, Fiji, New Caledonia and Maiana Atoll. Also show are instrumentally based indices of the PDO and IPO, a tree-ring based index of the PDO, and sea surface temperature data from Rarotonga, Fiji, and New Caledonia from two different datasets. Interdecadal variability in each time series was isolated by first filtering with a 10 year smoothing spline low-pass filter. The low-pass fraction was next analyzed using singular spectrum analysis (SSA). All reconstructed components with mean frequencies between 17 and 50 years where then summed. **A** Maiana δ^{18}O. **B** IPO (Folland et al. 2002a) and PDO (Mantua et al. 1997) indices, along with the North American tree-ring based PDO index of D'Arrigo et al. (2001). Positive phases of the IPO and PDO indices corresponds to an El Niño-like mode and a negative phase corresponds to a La Niña-like mode. **C** Fiji, Rarotonga, and New Caledonia (Quinn et al. 1998) coral δ^{18}O. **D** Fiji and Rarotonga coral Sr/Ca. **E** Fiji, Rarotonga, and New Caledonia SSTa from the Hadley Centre Sea Ice and Sea Surface Temperature data set (HADISST1). **F** The 5° × 5° OS SSTa of Kaplan et al. (1998) for the regions around Fiji, Rarotonga, and New Caledonia. In this figure coral δ^{18}O and Sr/Ca, and SST have been scaled to approximately equal units based on the calibrations of Sr/Ca presented here and where 0.21 per mil δ^{18}O equals 1 °C. Note the *slightly different SST scales* for Fiji and Rarotonga coral Sr/Ca

4 Discussion

4.1 Interdecadal variability in coral Sr/Ca and δ^{18}O

From the comparison in Fig. 6 several observations are clear. In agreement with previous studies, interdecadal variability is more weakly expressed near the equator as represented by Maiana δ^{18}O and this variability is not synchronous with the South Pacific coral records. The subtropical South Pacific records indicate that most of the interdecadal transitions in coral δ^{18}O and Sr/Ca temporally align with each other and with comparable transitions in the PDO and IPO indices from the late twentieth century back to 1880. In Figs. 7 and 8 we used running averaged correlation coefficients (25 year win-

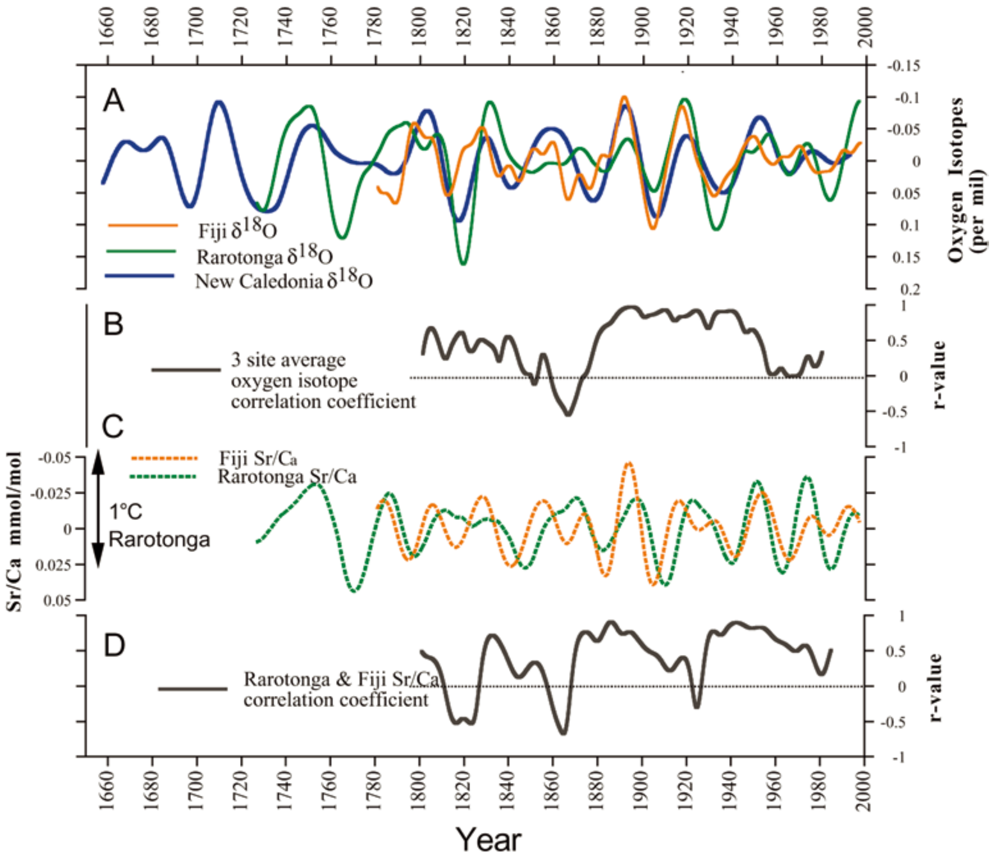

Fig. 7 **A** Fiji, Rarotonga, and New Caledonia coral δ^{18}O as in Fig. 6. **B** Average moving correlation coefficient (25 year window) between the three δ^{18}O series in **A**. **C** Fiji and Rarotonga Sr/Ca as in Fig. 6. **D** Moving correlation coefficient (25 year window) between Sr/Ca series in **C**

dow) to highlight intervals when the interdecadal modes temporally align and when they do not. Positive *r*-values indicate times of strong alignment. This is not a significance test, but rather a means of indicating when the signals are more strongly correlated.

Interdecadal variability in Fiji, New Caledonia and Rarotonga coral δ^{18}O is particularly well aligned from ~1880 to 1950 when the amplitude of interdecadal δ^{18}O variability was greater (Figs. 6, 7). Before the 1880s the interdecadal changes in each record are only intermittently or partially synchronous in these coral records (i.e., in the late 1700s and early 1800s). In addition, prior to 1880 the transitions in the NW North American tree-ring based PDO index of D'Arrigo et al. (2001) (see Fig. 6B) do not align with interdecadal transitions in these South Pacific coral δ^{18}O records, whereas they do align with Rarotonga Sr/Ca (but not with Fiji Sr/Ca) from ~1740 to 1810 (Fig. 8).

Potential chronological errors in the δ^{18}O and Sr/Ca data from the three coral sites cannot be responsible for

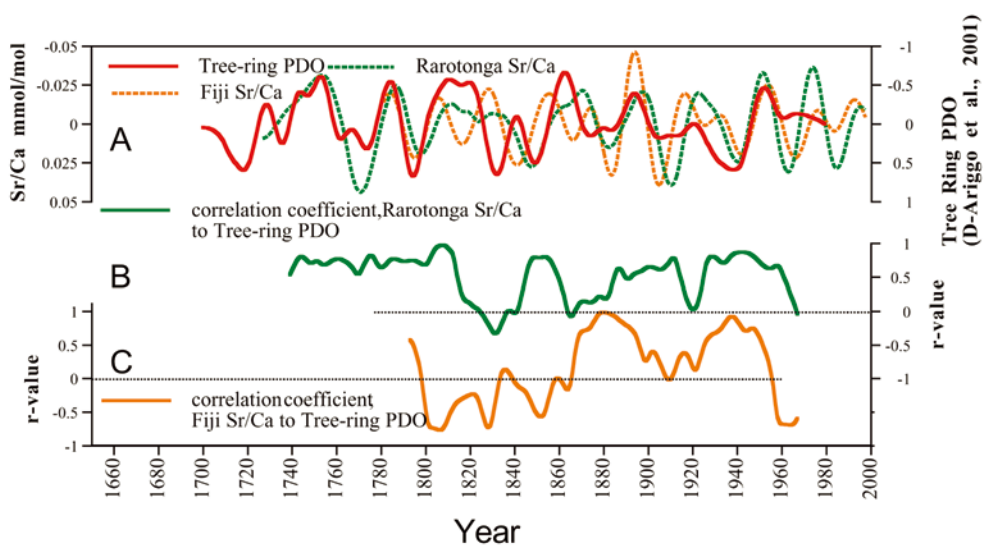

Fig. 8 **A** Detailed comparison of Fiji and Rarotonga Sr/Ca to the Tree-ring based PDO index of D'Arrigo et al. (2001). **B**, **C** moving correlation coefficients (25 year window) between Rarotonga and Fiji Sr/Ca and the tree ring PDO index in **A**

these observed changes in the timing of interdecadal variability. As discussed, ENSO-band (interannual) variability in coral $\delta^{18}O$ and Sr/Ca at each site is in agreement at the three sites and also in alignment with Maiana coral $\delta^{18}O$ and Niño3.4 SST variations. These observations indicate that the developed chronologies are accurate (BKL unpublished results). Although small (1-2 year) chronological errors are possible in these records, large errors that would effect the alignment of interdecadal variability are unlikely. Furthermore, the fact that the highest degree of correlation of interdecadal changes in coral $\delta^{18}O$ at Rarotonga, Fiji, and New Caledonia occurred from 1880 to ~1950 with reduced correlation after 1950 suggests that the source of this variability is interdecadal changes in oceanographic conditions. We would expect coral chronologies and proxy geochemical data calibrations to be more robust in the most recent portions of the records where certainty in the coral chronologies is the highest and where there is more continuous and accurate instrumental data to constrain and calibrate the coral tracers. We conclude that the observed changes in IPO-band variability in coral $\delta^{18}O$ and Sr/Ca at these three sites is primarily the result of SST and $\delta^{18}O_{seawater}$ variations related to the SPCZ and processes underlying the IPO.

However we also note that interdecadal variability in these SW Pacific coral $\delta^{18}O$ and Sr/Ca records has larger amplitudes than predicted from just interdecadal variability in instrumental SST. For $\delta^{18}O$ this can be explained by the combined influence of salinity and temperature on the interdecadal variations in $\delta^{18}O$ in these corals. For Sr/Ca, assuming the observed modern Sr/Ca-SST calibrations have remained constant over time, the larger amplitude suggests that interdecadal changes in coral Sr/Ca at Fiji and Rarotonga are in part related to additional local "island" effects on SST and/or salinity, or currently unknown environmental or biological factors that have apparently amplified the interdecadal Sr/Ca signal in these coral records. Alternatively, instrumental SST may not completely capture the full amplitude of interdecadal SST variability before the mid 1950s. Interdecadal changes in the optimally interpolated Hadley Centre SST anomaly (SSTa) data (Rayner et al. 1996) and optimally smoothed Kaplan et al. (1998) SSTa for these three sites do not agree perfectly. These differences in instrumental SST records may be due to the lack of measurements during the World Wars and also may be related to the low density of instrumental data before 1950, pointing to the need for more proxy records of SST in this region.

The interdecadal variability preserved in these South Pacific corals appears to be in part related to variations in the SPCZ. Rarotonga, Fiji, and New Caledonia are all located on the southwestern side of the current main axis of the SPCZ in a region climatically influenced by the Southeast Pacific trade winds and SPCZ related precipitation. Fiji and Rarotonga lie closer to the central axis of maximum rainfall. In the southwest Pacific the mean convergence axis of the SPCZ lies over the region with the largest SST gradient and not over the region of maximum SST (Folland et al. 2002). In addition, the surface convergence maximum axis in the SPCZ lies south of the axis of maximum precipitation, both of which are south of the axis of maximum SST (Vincent 1994). This appears to also be true on interdecadal time scales, where the SPCZ axis lies over the colder side of the region of maximum SST gradient (Folland et al. 2002). Thus the relationship between SST, precipitation, and $\delta^{18}O_{seawater}$ in this region is likely to be quite complex.

In an evaluation of instrumental South Pacific island temperature data, Salinger et al. (1995) used cluster and principle component analyses to determine sets of islands with similar trends over the period 1911–1990. Rarotonga, Fiji, and New Caledonia are located in the same zone (Salinger et al. 1995) where island temperature cools during El Niño events, and where temperatures trend upwards by 0.9 °C over the twentieth century. Additionally, in their analysis of instrumental data from the South Pacific, Folland et al. (2002) documented that the position of the SPCZ is significantly related to the phase of the IPO. During negative phases of the IPO (when SST reaches an interdecadal maximum in the SW Pacific), the SPCZ is displaced to the southwest. During positive phases of the IPO, the SPCZ is displaced to the northeast (Folland et al. 2002). To the northeast of the climatological SPCZ, island temperature and SST trends are opposite those in this region just southwest of the SPCZ (Salinger et al. 1995; Folland et al. 2003). Thus the SPCZ represents a major discontinuity for multi-decadal climate trends within the South Pacific (Salinger et al. 1995; Folland et al. 2003).

4.2 Reconstructed $\delta^{18}O_{seawater}$

Because the evidence indicates that our coral Sr/Ca records from Rarotonga and Fiji are at least correlated with annual and interannual SST changes, and because it appears that coral $\delta^{18}O$ from these two sites is primarily affected by both SST and $\delta^{18}O_{seawater}$ (and is reproducible), we have used the approach of Ren et al. (2003) to difference the two series and calculate down-core changes in $\delta^{18}O_{seawater}$ for both sites. This technique assumes that 100% of variations in coral Sr/Ca are due to SST changes and that variations in coral $\delta^{18}O$ are due to the combined influences of both SST and $\delta^{18}O_{seawater}$ (although we are uncertain if this is the case for multi-decadal and trend components of our Sr/Ca and $\delta^{18}O$ series). Briefly, the method separates the effects of $\delta^{18}O_{seawater}$ from SST by breaking the instantaneous changes of coral $\delta^{18}O$ into separate contributions by instantaneous SST and $\delta^{18}O_{seawater}$ changes respectively. Aspects of the Rarotonga $\delta^{18}O_{seawater}$ reconstruction are discussed in Ren et al. (2003). We applied the same technique to the Fiji coral Sr/Ca and $\delta^{18}O$ time series. We next applied the identical spline filtering-SSA treatment to the Rarotonga and Fiji reconstructed $\delta^{18}O_{seawater}$ series as described

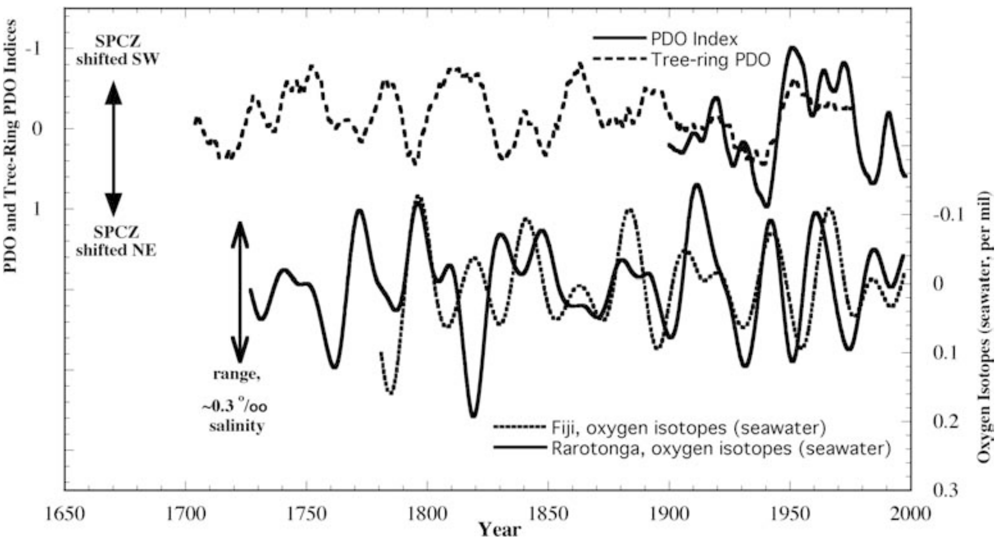

Fig. 9 Comparison of interdecadal components of Rarotonga and Fiji calculated $\delta^{18}O_{seawater}$ (see text and Fig. 6 caption) to PDO index (from Mantua et al. 1997) and Tree-ring PDO index of D'Arrigo et al. (2001). Note that Ren et al. (2003) report from their analysis of a Rarotonga *Porites* that there is a relative error of up to 27% on $\delta^{18}O_{seawater}$ calculated using their method on paired coral skeletal $\delta^{18}O$ and Sr/Ca measurements

above to isolate the interdecadal variability. The resulting $\delta^{18}O_{seawater}$ series and the PDO and tree-ring PDO series are shown in Fig. 9.

The average interdecadal range in $\delta^{18}O_{seawater}$ is approximately 0.2‰, which corresponds to a salinity change of ∽0.3‰ (Schmidt 1999; Ren et al. 2003). This range is approximately equal to the seasonal 0.35‰ salinity range for open ocean conditions at both sites (Levitus et al. 1994). Although the interdecadal amplitude is small, there is a fairly consistent relationship where lower reconstructed $\delta^{18}O_{seawater}$ (lower salinity) corresponds with positive phases of the PDO (and IPO) indices. In addition, there is reduced correlation between Fiji and Rarotonga $\delta^{18}O_{seawater}$ in the mid 1800s (see Fig. 9). Folland et al. (2002) found that during positive phases of the IPO the SPCZ is shifted to the northeast. Thus we expected to find the opposite relationship where relatively higher $\delta^{18}O_{seawater}$ (higher salinity) at Rarotonga and Fiji occurred during positive phases of the IPO. The fact that reconstructed interdecadal changes in $\delta^{18}O_{seawater}$ at each site are generally consistent from 1880 to 1997, as well as in the decade around 1800 suggests that our assumptions regarding interdecadal forcing of coral Sr/Ca and $\delta^{18}O$ at these sites are at least in-part valid and leads us to look for a climatic explanation.

To explain the relationship between reconstructed $\delta^{18}O_{seawater}$ and the IPO Index depicted in Fig. 9 requires that either changes in surface circulation allow a greater influx of lower salinity water probably from the northwest of Fiji and Rarotonga during positive phases of the IPO, and/or that evaporation effects predominate over precipitation in controlling the relatively small amplitude interdecadal $\delta^{18}O_{seawater}$ changes in this region. Figure 10 depicts annually averaged surface salinity in this region of the Pacific (from Levitus et al.

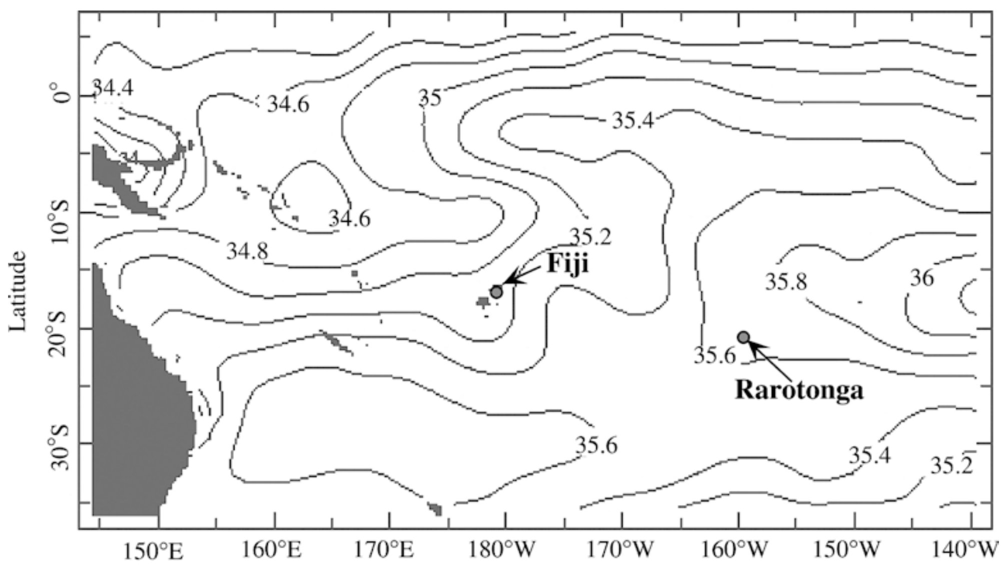

Fig. 10 Annually averaged surface ocean salinity in the Southwestern Pacific (data from Levitus et al. 1994). The location of *Rarotonga* and *Fiji* are indicated. Note the *region of lower salinity* to west and northwest of both study sites. The Levitus et al. (1994) salinity data was acquired from instrumental data spanning 1900 to 1992, but with a bias towards post-1950 when there is more instrumental data

1994). An eastward shift of the lower salinity water located to west and northwest of both sites during positive phases of the IPO could explain the relationship observed in Fig. 9. Lower $\delta^{18}O_{seawater}$ at Fiji and Rarotonga during positive phases of the IPO could also indicate reduced evaporation on the southwestern side of the SPCZ. We note that the zone of maximum wind convergence in the South Pacific lies along an axis parallel to the SPCZ rainfall axis but shifted ∽5 to 10° south (Vincent 1994). Another possible explanation for lower Rarotonga and Fiji $\delta^{18}O_{seawater}$ during positive phases of the IPO is that less evaporation at Fiji and Rarotonga occurs during this phase due to lower SST and reduced surface wind convergence (more divergence) when the zone of maximum convergence has shifted to the northeast. However it remains possible that one or more of the assumptions involved in calculating $\delta^{18}O_{seawater}$ from coral $\delta^{18}O$ and Sr/Ca are not valid. Thus, these observations and interpretations of reconstructed $\delta^{18}O_{seawater}$ interdecadal variability in this region must remain tentative until the coral Sr/Ca records can be replicated with additional cores and until a statistically significant network of coral records in this region can be developed.

4.3 Implications

Our results indicate that the timing of interdecadal transitions in SST in the south Pacific just southwest of the SPCZ has not always been consistent across the region. This indicates that the twentieth century IPO pattern in the South Pacific depicted in Fig. 1 has differed in the past. Interdecadal variability in this region was particularly disorganized and dampened in the mid-1800s in agreement with the results presented by Gedalof et al. (2002). In addition, the degree of correlation with North Pacific interdecadal climate changes has also varied over time. Combined, these coral records indicate that over the last 300 years interdecadal SST variations in the subtropical southwest Pacific alternated between times of larger amplitude and more geographically widespread interdecadal changes and times of lower amplitude and less geographically organized interdecadal changes. The observation that interdecadal SST and $\delta^{18}O_{seawater}$ variability in the South Pacific was less spatially organized and more complex before the 1880s agrees with the tree-ring based PDO and IPO indices (Biondi et al. 2001; D'Arrigo et al. 2001; Evans et al. 2001; Gedalof and Smith 2001; Villalba et al. 2001) that also show a general lack of agreement in the mid-1800's and a higher degree of correlation to the IPO in the twentieth century (Evans et al. 2001; Labeyrie et al. 2003).

It is possible that the observed changes in the spatial pattern of South Pacific interdecadal climate variability in the 1880s is related to interdecadal changes in trade wind strength coupled with SPCZ position. In evaluating trends in coral tracer data from the South Pacific, Hendy et al. (2002) concluded that a regional freshening of the southwest Pacific occurred after ∽1870. They suggested that this freshening was forced by a reduction in trade wind strength and South Equatorial Current influence in the region after ∽1870 AD. Such changes would have affected or been modulated by the SPCZ. Our results now point to a major reorganization of interdecadal climate variability in the South Pacific at approximately the same time as this inferred reduction in trade wind strength. It may also be note-worthy that coincident with this inferred 1880s change in the behavior of interdecadal climatic variability in the South Pacific, the late 1800s is also the generally accepted time of the end of a particularly cool period in the last millennium, in some regions identified as the Little Ice Age (LIA) (Grove 1988; Crowley and North 1991; Bradley and Jones 1993).

Although the ultimate cause of the 1880s change in the amplitude and spatial pattern of interdecadal variability in the South Pacific remains to be precisely determined, it does not appear to be directly related to anthropogenic warming in the Southern Hemisphere which began at ∽1910 (Jones et al. 1999). In fact in these reconstructions the general pattern of IPO variability during the warming of the twentieth century is similar to that in the preceding two centuries.

Our observation that both the South Pacific spatial pattern of the IPO and the degree of hemispheric symmetry of the IPO has varied over time requires corroboration for other proxy sources. If this observation proves correct it would indicate that the IPO phenomenon varies over time which we believe would suggest complex and temporally varying forcing mechanisms perhaps from both the tropics and extra-tropics.

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References

Benson L, Linsley BK, Smoot J, Mensing S, Lund S, Stine S, Sarna-Wojcicki A (2003) Influence of the Pacific Decadal Oscillation (PDO) on the climate of the Sierra Nevada, California and Nevada. Quat Res 59: 151–159

Biondi F, Gershunov A, Cayan DR, (2001) North Pacific decadal climate variability since 1661. J Clim 14(1): 5–10

Bradley RS, Jones PD (1993) 'Little Ice Age' summer temperature variations: their nature and relevance to recent global warming trends. The Holocene 3: 367–376

Charles CD, Hunter DE, Fairbanks RG (1997) Interaction between the ENSO and the Asian Monsoon in a coral record of tropical climate. Science 277: 925–928

Crowley TJ, North GR (1991) Paleoclimatology. Oxford University Press, New York

D'Arrigo R, Villalba R, Wiles G (2001) Tree-ring estimates of Pacific decadal climate variability. Clim Dyn 18: 219–224

Dunbar RB, Wellington GM, Colgan MW, Glynn PW (1994) Eastern Pacific sea surface temperature since 1600 A.D.: The $\delta^{18}O$ record of climate variability in Galapagos corals. Paleoceanography 9(2): 291–315

Evans MN, Cane MA, Schrag DP, Kaplan A, Linsley BK, Villalba R, Wellington GM (2001) Support for tropically-driven Pacific decadal variability based on paleoproxy evidence. Geophys Res Lett 28(19): 3689–3692

Folland CK, Renwick JA, Salinger MJ, Mullan AB (2002) Relative influences of the Interdecadal Pacific Oscillation and ENSO on the South Pacific Convergence Zone. Geophys Res Lett 29(13): 10.1029/2001GL014201

Folland CK, Salinger MJ, Jiang N, Rayner N (2003) Trends and variations in South Pacific island and ocean surface temperatures. J Clim 16:2859–2874

Gedalof Z, Smith DJ (2001) Interdecadal climate variability and regime-scale shifts in Pacific North America. Geophys Res Lett 28(8): 1515–1518

Gedalof Z, Mantua NJ, Peterson DL (2002) A multi-century perspective of variability in the Pacific Decadal Oscillation: new insights from tree rings and coral. Geophys Res Lett 29(24) 10.1029/2002GL015824

Graumlich LJ (1993) A 1000-year record of temperature and precipitation in the Sierra Nevada. Quat Res 39: 249–255

Grove JM (1988) The Little Ice Age Methuen, London

Hendy EJ, Gagan MK, Alibert C, McCulloch MT, Lough JM, Isdale PJ (2002) Abrupt decrease in tropical Pacific sea surface salinity at the end of the Little Ice Age. Science 295: 1511–1514

Jones PD, New M, Parker DE, Martin S, Rigor IG (1999) Surface air temperature and its changes over the past 150 years. Rev Geophys 37: 173–185

Kaplan A, Cane MA, Kushnir Y, Clement AC, Blumenthal MB, Rajagopalan B (1998) Analysis of global sea surface temperature. J Geophys Res 103: 18,567–18,589

Labeyrie L, Cole JE, Alverson K, Stocker T (2003) The history of climate dynamics. In: Alverson K, Bradley RS, Pedersen T (eds) Paleoclimate, global change and the future. Springer, Berlin Heidelberg New York, pp 33–61

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

Levitus S, Burgett R, Boyer TP (1994) World Ocean Atlas 1994, vol. 3: salinity, (1994) NOAA Atlas NESDIS 3, 3. US Department of Commerce, Washington D.C., pp 99

Linsley BK, Wellington GM, Schrag DP (2000a) Decadal sea surface temperature variability in the subtropical South Pacific from 1726 to 1997 AD. Science 290(5494): 1145–1148

Linsley BK, Ren L, Dunbar RB, Howe SS (2000b) ENSO and decadal-scale climate variability at 10°N in the Eastern Pacific from 1893 to 1994: a coral-based reconstruction from Clipperton Atoll. Paleoceanography 15(3): 322–335

Linsley BK, Dunbar RB, Wellington GM, Mucciarone DA (1994) A coral-based reconstruction of intertropical convergence zone variability over Central America since 1707. J Geophys Res 99(C5): 9977–9994

Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC (1997) A Pacific interdecadal oscillation with impacts on salmon production. Bull Am Meteorol Soc 78: 1069–1079

Meko DM, Therrell MD, Baisan CH, Hughes MK (2001) Sacramento River flow reconstructed to A.D. 869 from tree rings. J Am Water Res Assoc 37: 1029–1040

Power S, Casey T, Folland C, Colman A, Mehta V (1999) Interdecadal modulation of the impact of ENSO on Australia. Clim Dyn 15(5): 319–324

Quinn TM, Crowley TJ, Taylor FW, Henin C, Joannot P, Join Y (1998) A multicentury stable isotope record from a New Caledonia coral: Interannual and decadal sea surface temperature variability in the southwest Pacific since 1657 A.D. Paleoceanography 13(4): 412–426

Rayner NA, Horton EB, Parker DE, Folland CK, Hackett RB (1996) Version 2.2 of the Global sea-ice and Sea Surface Temperature Data Set, 1903–1994. Climate Research Technical Note 74, unpublished document available from Hadley Centre, UK

Ren L, Linsley BK, Wellington GM, Schrag DP, Hoegh-Guldberg O (2003) 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 1726–1997. Geochim Cosmochim Acta 67(9): 1609–1621

Reynolds RW, Smith TM (1994) Improved global sea surface temperature analyses, J Clim 7: 929–948

Salinger MJ, Fitzharris BB, Hay JE, Jones PD, MacVeigh JP, Schmidely-Leleu I (1995) Climate trends in the south–west Pacific. Int J Climatol 15: 285–302

Salinger MJ, Renwick JA, Mullan AB (2001) Interdecadal Pacific Oscillation and South Pacific climate. Int J Climatol 21: 1705–1721

Schmidt GA (1999) Error analysis of paleosalinity calculations. Paleoceanography 14: 422–429

Schrag DP (1999) Rapid analysis of high-precision Sr/Ca ratios in corals and other marine carbonates. Paleoceanography 14(2): 97–102

Urban FE, Cole JE, Overpeck JT (2000) Modification of tropical Pacific variability by its mean state inferred from a 155 year coral record. Nature 407: 989–991

Vautard R, Ghil M (1989) Singular spectrum analysis in nonlinear dynamics, with applications to paleoclimatic time series. Physica D 35: 395–424

Vautard R, Yiou P, Ghil M (1992) Singular-spectrum analysis: a toolkit for short, noisy chaotic signals. Physica D 58: 95–126

Villalba R, D'Arrigo RD, Cook ER, Jacoby GC, Wiles G (2001) Decadal-scale climate variability along the extratropical western coast of the Americas: evidence from tree-ring records. In: Markgraf V (ed) Interhemispheric climate linkages, Academic Press, San Diego, pp 155–172

Vincent DG (1994) The South Pacific Convergence Zone (SPCZ): a review. Mon Weather Rev 122: 1949–1970

Ware DM (1995) A century and a half of change in the climate of the NE Pacific Fish Oceanogr 4: 267–277

Ware DM, Thomson RE (2000) Interannual to multidecadal timescale climate variations in the northeast Pacific. J Clim 13: 3209–3220

Zhang Y, Wallace JM, Battisti DS (1997) ENSO-like interdecadal variability: 1900–93. J Clim 10: 1004–1020