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## Deconvolving the $\delta^{18}\text{O}$ seawater component from subseasonal coral $\delta^{18}\text{O}$ and Sr/Ca at Rarotonga in the southwestern subtropical Pacific for the period 1726 to 1997

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**Abstract**—To reconstruct oceanographic variations in the subtropical South Pacific, 271-year long subseasonal time series of Sr/Ca and  $\delta^{18}\text{O}$  were generated from a coral growing at Rarotonga (21.5°S, 159.5°W). In this case, coral Sr/Ca appears to be an excellent proxy for sea surface temperature (SST) and coral  $\delta^{18}\text{O}$  is a function of both SST and seawater  $\delta^{18}\text{O}$  composition ( $\delta^{18}\text{O}_{\text{sw}}$ ). Here, we focus on extracting the  $\delta^{18}\text{O}_{\text{sw}}$  signal from these proxy records. A method is presented assuming that coral Sr/Ca is solely a function of SST and that coral  $\delta^{18}\text{O}$  is a function of both SST and  $\delta^{18}\text{O}_{\text{sw}}$ . This method separates the effects of  $\delta^{18}\text{O}_{\text{sw}}$  from SST by breaking the instantaneous changes of coral  $\delta^{18}\text{O}$  into separate contributions by instantaneous SST and  $\delta^{18}\text{O}_{\text{sw}}$  changes, respectively. The results show that on average  $\delta^{18}\text{O}_{\text{sw}}$  at Rarotonga explains ~39% of the variance in  $\delta^{18}\text{O}$  and that variations in SST explains the remaining ~61% of  $\delta^{18}\text{O}$  variance. Reconstructed  $\delta^{18}\text{O}_{\text{sw}}$  shows systematic increases in summer months (December–February) consistent with the regional pattern of variations in precipitation and evaporation. The  $\delta^{18}\text{O}_{\text{sw}}$  also shows a positive linear correlation with satellite-derived estimated salinity for the period 1980 to 1997 ( $r = 0.72$ ). This linear correlation between reconstructed  $\delta^{18}\text{O}_{\text{sw}}$  and salinity makes it possible to use the reconstructed  $\delta^{18}\text{O}_{\text{sw}}$  to estimate the past interannual and decadal salinity changes in this region. Comparisons of coral  $\delta^{18}\text{O}$  and  $\delta^{18}\text{O}_{\text{sw}}$  at Rarotonga with the Pacific decadal oscillation index suggest that the decadal and interdecadal salinity and SST variability at Rarotonga appears to be related to basin-scale decadal variability in the Pacific. Copyright © 2002 Elsevier Science Ltd

### 1. INTRODUCTION

It has now been recognized that the western subtropical South Pacific is a dominant source region for water transport to the equatorial thermocline, in part because of its relatively high salinity (Tsuchiya, 1968, Tsuchiya, 1989; Wyrski and Kilonky, 1984; Knuass, 1996). In addition, this region is also identified as an important source region for interannual sea surface temperature (SST) anomalies propagating into higher latitudes of the Southern Hemisphere and the Antarctic Circumpolar Current (White and Peterson, 1996; Peterson and White, 1998). The South Pacific Convergence Zone (SPCZ) also extends northwest to southeast across this region, and SPCZ rainfall plays a potentially important role in the hydrologic balance and on the seawater oxygen isotopic composition ( $\delta^{18}\text{O}_{\text{sw}}$ ) in this region. However, the historical record of past climate variations in this region remains limited, necessitating the development of techniques to extract a paleoclimatic record from natural archives of past climate variability. Here we focus on utilizing coral records from Rarotonga (21.5°S, 159.5°W) in the western subtropical South Pacific.

Massive hermatypic corals have proven in many cases to contain geochemical records of past climate variability on interannual and interdecadal timescales (Dunbar et al., 1994; Wellington et al., 1996; Linsley et al., 2000b, among others). Many of these studies have focused on examining past SST

variations. Besides SST,  $\delta^{18}\text{O}_{\text{sw}}$  is another important parameter that can potentially be reconstructed by using corals.  $\delta^{18}\text{O}_{\text{sw}}$  is of climatic importance because it is closely related to the balance between precipitation and evaporation, and so its reconstruction could yield important information about past changes in hydrologic balance and oceanographic circulation. However, because the  $\delta^{18}\text{O}$  composition of coral skeletons is at least a function of both SST and  $\delta^{18}\text{O}_{\text{sw}}$  (Weber and Woodhead, 1972), it is generally difficult to separate the effects of SST and  $\delta^{18}\text{O}_{\text{sw}}$  by using coral  $\delta^{18}\text{O}$  alone. One great advantage of corals for paleoclimatic studies is that they possess a remarkable array of chemical tracers that contain information on past environmental variations. Although coral  $\delta^{18}\text{O}$  reflects the effects of both SST and  $\delta^{18}\text{O}_{\text{sw}}$ , the skeletal Sr/Ca ratio in many corals appears to be mainly influenced by SST, and it appears that coral Sr/Ca is linearly related to SST (Smith et al., 1979; Beck et al., 1992; Gagan et al., 1998; Linsley et al., 2000a). By using both  $\delta^{18}\text{O}$  and Sr/Ca, it is therefore potentially possible to separate the different effects of  $\delta^{18}\text{O}_{\text{sw}}$  and SST in a coral  $\delta^{18}\text{O}$  time series (McCulloch et al., 1994; Gagan et al., 1998; Gagan et al., 2000).

McCulloch et al. (1994) made the first attempt to quantitatively separate the effects of SST from those of  $\delta^{18}\text{O}_{\text{sw}}$  on skeletal  $\delta^{18}\text{O}$  by using paired coral  $\delta^{18}\text{O}$  and Sr/Ca analysis on the same samples. Gagan et al. (1998, 2000) used a similar method by which the effects of SST are directly subtracted from the observed skeletal  $\delta^{18}\text{O}$  to obtain the residual effects of  $\delta^{18}\text{O}_{\text{sw}}$ . To do so, they first converted coral  $\delta^{18}\text{O}$  into units of temperature ( $T_{\delta^{18}\text{O}}$ ) by using an empirical SST- $\delta^{18}\text{O}$  equation

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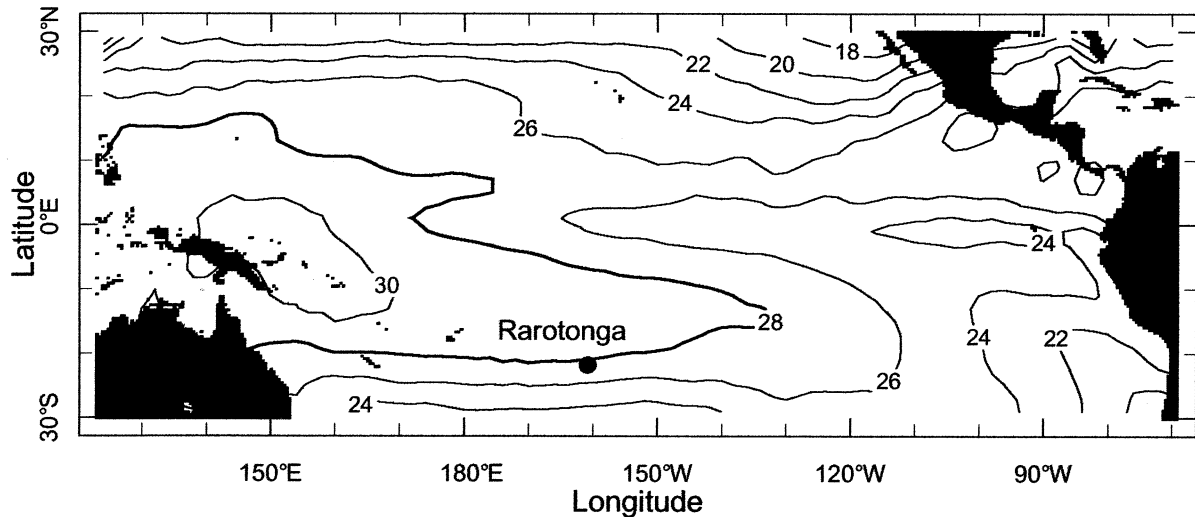


Fig. 1. Geographic location of Rarotonga. The contours shown are monthly averaged SST in the Pacific. SST data are from IGOSS SST (Reynolds and Smith, 1994). The warm pool is indicated by the 28°C isotherm.

and then subtracted this from the reconstructed SST ( $T_{Sr/Ca}$ ) obtained from the Sr/Ca record. The residual  $\delta^{18}O$ , they argued, reflects the effects of seawater  $\delta^{18}O$  composition. The idea underlying the methods of both McCulloch et al and Gagan et al is to use a linear  $\delta^{18}O$ -SST equation (i.e.,  $\delta^{18}O = k \times SST + b$ ) as the reference to obtain the discrepancies of coral  $\delta^{18}O$  as the result of variations of  $\delta^{18}O_{sw}$ . However, the equation they used was obtained by linear regression of the  $\delta^{18}O$  data against the instrumental SST data from McConnaughey (1989) and Gagan et al. (1994), respectively. The equation obtained in this way may not represent the true  $\delta^{18}O$ -SST relationship because there may also be effects of  $\delta^{18}O_{sw}$  variation, which could alter the relationship. Such empirical equations therefore do not appear to be applicable unless  $\delta^{18}O_{sw}$  is known or assumed to be constant in the study area in question. Furthermore, even if the SST calibration equation used is correct (i.e.,  $\delta^{18}O_{sw}$  is roughly constant so that  $k$  and  $b$  values are correct), the magnitude of  $\delta^{18}O_{sw}$  at the calibration site will still influence the value of the constant  $b$  in the equation above, which will directly affect the result of the  $\delta^{18}O_{sw}$  reconstruction.

To minimize these potential problems, in this article, we present a revised method of retrieving  $\delta^{18}O_{sw}$  by using instantaneous changes in paired measurements of  $\delta^{18}O$  and Sr/Ca in corals. We apply this technique to the Rarotonga coral Sr/Ca and  $\delta^{18}O$  records spanning 1726 to 1997. The derived  $\delta^{18}O_{sw}$  time series is then examined and discussed in terms of how paleosalinity and rainfall varied in this region during the past three centuries.

## 2. STUDY AREA

The island of Rarotonga is located at 21.5°S and 159.5°W in the Cook Islands of the western subtropical South Pacific (Fig. 1). Over the last two decades, SST in the grids measuring 2° by 2° (CAC SST) and 1° by 1° (IGOSS SST) (Reynolds and Smith, 1994) surrounding Rarotonga has ranged between 23 to 27°C, with an average annual variation of  $\sim 4^\circ\text{C}$  (Fig. 2). On average, the highest SST occurs in February and lowest in

August–September. Precipitation is also generally highest in February–March of each year, when SSTs peak near  $\sim 27^\circ\text{C}$  (NOAA NCDC GPCP monthly station precipitation) (Baker et al 1994).

In this region, instrumental salinity measurements are very limited, and a satellite-derived salinity record is available only

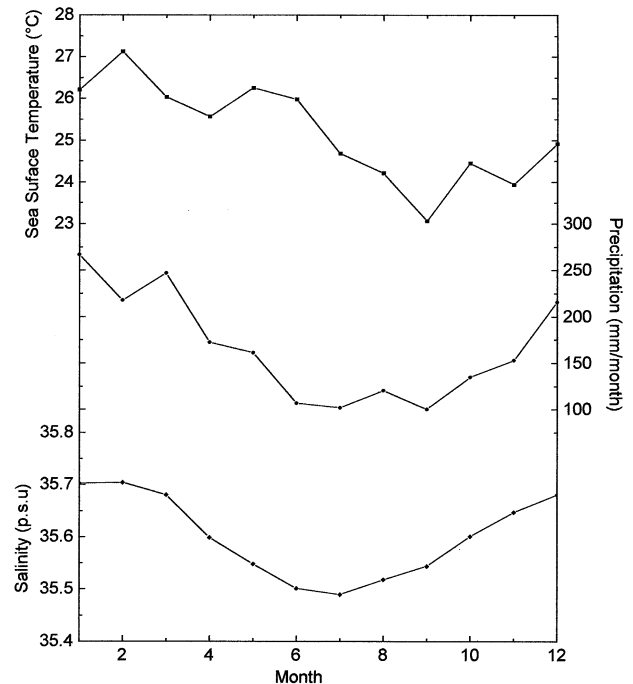


Fig. 2. Composite annual curves calculated by averaging monthly SST, rainfall, and salinity (at 20-m depth) in the vicinity of Rarotonga for the period 1981 to 1997. The SST data are from IGOSS SST (Reynolds and Smith, 1994), whereas rainfall and salinity data are from NOAA NCDC GPCP monthly precipitation (Baker et al 1994) and NOAA NCEP EMC CMB Pacific monthly salinity (Ji et al., 1995; Ji and Smith, 1995; Behringer et al., 1998), respectively.

after 1980 (NOAA NCEP EMC CMB Pacific monthly salinity) (Ji et al., 1995; Ji and Smith, 1995; Behringer et al., 1998). This salinity record is derived from a model-based ocean analysis that assimilated the observed surface and subsurface ocean temperatures as well as satellite altimetry sea-level data from TOPEX/POSEIDON into a Pacific basin ocean general circulation model. The model is configured for the Pacific Ocean from 45°S to 55°N and 120°E to 70°W (Ji et al., 1995). The horizontal resolution in the zonal direction is 1.5°. The resolution in the meridional direction is 1/3° within 10° of the equator, which is continuously changed to 1° poleward of 20° latitude. The resultant error estimates are in the range of 0.5 to 1.0 psu (Ji et al., 1995; Behringer et al., 1998). The annual salinity maxima (at 20-m depth) occur in February of each year at the time of the highest SST and rainfall at Rarotonga. This apparent contradiction may be related to dynamics in the South Pacific subtropical gyre. During the summer months, the core of high salinity in the center of the South Pacific subtropical gyre appears to shift to a position further to the west near Rarotonga, resulting in higher salinity in summer months (Levitus et al., 1982).

### 3. METHODS AND RESULTS

In April 1997, several coral cores were collected from a large colony of *Porites lutea* in 18.3 m (60 feet) of water on the southwest side of the Island of Rarotonga. This coral colony was not influenced by shading or other microenvironmental factors. Slabs of coral (7 mm thick) cut along the major axis of growth were cleaned with deionized water to remove saw cutting and were then oven dried at 40°C. Samples were continuously drilled at 1-mm intervals by using a low-speed microdrill along tracks parallel to corallite traces, as identified in X-ray positives (Fig. 3). Splits from the same sample powder were used for both  $\delta^{18}\text{O}$  and Sr/Ca analyses. The total usable length of core B is 1.4 m, whereas core C is 3.5 m. Because of a growth hiatus in core C, cores B and C were spliced together to make a continuous record. We sampled core B from the top to 1316-mm depth, whereas core C was sampled from 1104-mm depth to the very bottom. This sampling scheme resulted in an overlap of ~212 mm (13 yr) between core B and core C. This ensured that there was enough repetition between cores B and core C to accurately splice them together, and a clear match point was found in A.D.1926.

High-precision determination of Sr/Ca ratios at 1-mm resolution was undertaken by inductively coupled plasma atomic emission spectrophotometer at Harvard University by use of a method described in detail by Schrag (1999). This record has previously been discussed in Linsley et al. (2000a). The total number of subannual samples analyzed for Sr/Ca was 3698. External precision is better than 0.15% (relative standard deviation,  $1\sigma$ ) on the basis of analysis of replicate samples. These data are available on the Internet at <http://www.ngdc.noaa.gov/paleo/paleo.html>.

$\delta^{18}\text{O}$  analyses were performed by Micromass Optima triple-collecting mass spectrometers at the University at Albany, State University of New York, and at the Harvard University stable isotope facility. The total number of samples analyzed was 2281. The first 864 samples were analyzed every 1 mm, whereas the other downcore samples were analyzed every other

1 mm. At Harvard University, ~1-mg samples are reacted in vacuo in a modified autocarbonate device at 90°C and the purified  $\text{CO}_2$  analyzed. At the University at Albany ~150- $\mu\text{g}$  samples are dissolved in 100%  $\text{H}_3\text{PO}_4$  at 90°C in a Multiprep carbonate inlet system and the resulting  $\text{CO}_2$  gas analyzed. These two different sampling densities (1 mm and every other 1 mm) show equal annual  $\delta^{18}\text{O}$  amplitudes, which suggests that analysis of discrete every other 1-mm samples still captures the full range of the annual cycle. Ten percent of all samples were analyzed in duplicate. External precision at the University at Albany is better than 0.04‰ for  $\delta^{18}\text{O}$  on the basis of analysis of replicate samples. The standard deviation of 468 samples of international NBS-19 analyzed was 0.038‰ for  $\delta^{18}\text{O}$ .

The chronology was developed based on both the density banding observed in X-radiograph-positive prints and annual periodicity of  $\delta^{18}\text{O}$  and Sr/Ca. Both  $\delta^{18}\text{O}$  and Sr/Ca document a total of 271 yr of growth spanning 1997 to 1726. This includes the first 71 yr (1997 to 1926) recorded in core B and the remaining 200 yr (1925 to 1726) recorded in core C. On the basis of our chronology, the top 61 yr were analyzed for both Sr/Ca and  $\delta^{18}\text{O}$  at an average of 15 samples/yr, whereas below 1936, Sr/Ca was analyzed at 15 samples/yr, and  $\delta^{18}\text{O}$  at 7~8 samples/yr. After determining that sampling at 7~8 samples/yr for  $\delta^{18}\text{O}$  did not attenuate the amplitude of the annual cycle, we linearly interpolated both Sr/Ca and  $\delta^{18}\text{O}$  time series to eight points per year for the analysis discussed below (Fig. 4).

### 4. SEPARATING THE CONTRIBUTIONS OF SST AND $\delta^{18}\text{O}_{\text{sw}}$ FROM $\delta^{18}\text{O}$ IN CORALS

#### 4.1. Method

If we assume that coral Sr/Ca is solely a function of SST and that  $\delta^{18}\text{O}$  is a function of both SST and  $\delta^{18}\text{O}_{\text{sw}}$ , the differences between time series of the two tracers measured on the same samples should reflect the effects of  $\delta^{18}\text{O}_{\text{sw}}$  variations. However, quantitatively retrieving the effects of  $\delta^{18}\text{O}_{\text{sw}}$  may not be as straightforward as it appears. Because measured coral  $\delta^{18}\text{O}$  is a multivariable function of SST and  $\delta^{18}\text{O}_{\text{sw}}$  varying at the same time, it may not always be applicable to separate SST and  $\delta^{18}\text{O}_{\text{sw}}$  effects by simply subtracting one from the other through the use of a single-variable equation between  $\delta^{18}\text{O}$  and SST. For a general function of two variables, the effects of them acting at the same time generally are not the simple sum of the effects of two variables acting separately. This is because the effect of one variable is generally influenced by changes of the other. Specifically, at least the value of  $b$  in the  $\delta^{18}\text{O}$ -SST equation ( $\delta^{18}\text{O} = k\text{SST} + b$ ) must be different under different  $\delta^{18}\text{O}_{\text{sw}}$  conditions (even if  $k$  does not change). If this equation is used as the reference to obtain discrepancies of coral  $\delta^{18}\text{O}$  that are due to variations of  $\delta^{18}\text{O}_{\text{sw}}$ , then these discrepancies should represent the variations of coral  $\delta^{18}\text{O}$  due to changes of  $\delta^{18}\text{O}_{\text{sw}}$  relative to the constant level of  $\delta^{18}\text{O}_{\text{sw}}$ , under which the above equation applies. Because  $b$  is different under different levels of  $\delta^{18}\text{O}_{\text{sw}}$ , we have the problem of what  $b$  value we should use. Depending on different values of  $b$  used, the discrepancies or residue obtained will clearly be different. This means that simple subtraction may not give the true contribution of  $\delta^{18}\text{O}_{\text{sw}}$  changes to coral  $\delta^{18}\text{O}$  variations, which should be a unique quantity. For this reason, we use a method in which we look at instantaneous changes of the function caused by

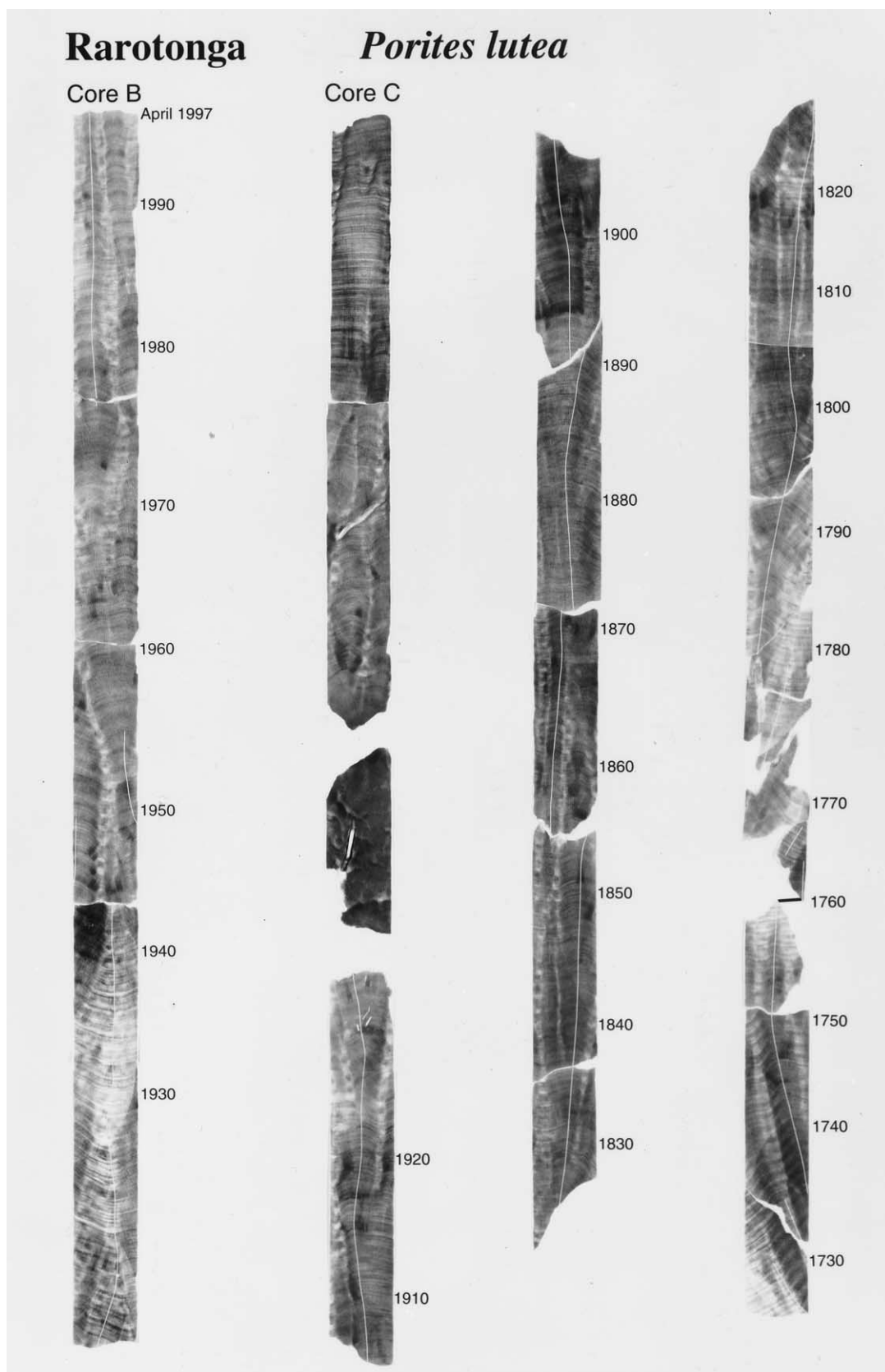


Fig. 3. X-ray-positive collage of two coral cores (cores B and C) used in the study showing the location of millimeter-scale sampling transacts. Note the overall goodness of fit between the individual coral slabs except a growth hiatus in the third section of core C.

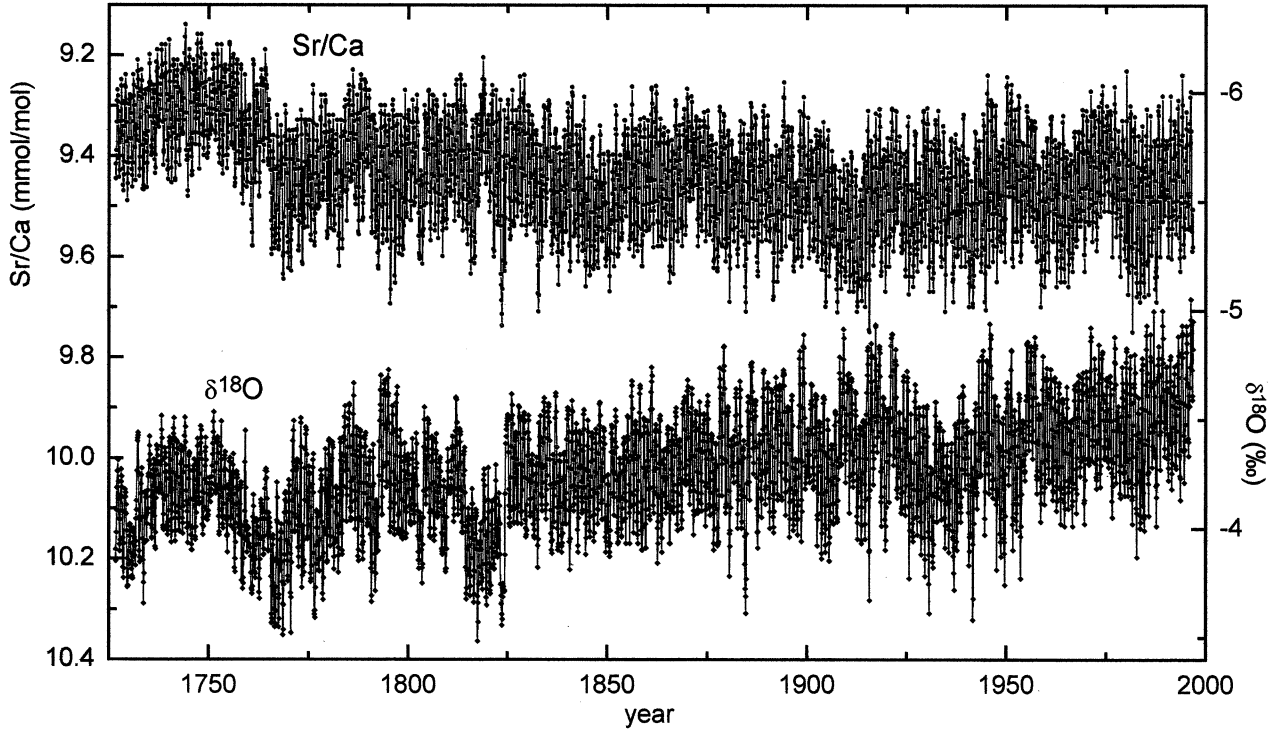


Fig. 4. (Top) Rarotonga subseasonal Sr/Ca ratio for the period 1726 to 1997 (Linsley et al., 2000a). (Bottom) Rarotonga subseasonal  $\delta^{18}\text{O}$  record for the period 1726 to 1997.

instantaneous changes of the variables instead of looking at the absolute values. According to derivative principles, these instantaneous changes of the function can always be thought of as the simple sum of the separate effects brought about by instantaneous changes of its variables. Thus, the instantaneous change of  $\delta^{18}\text{O}$  in corals at a given time can be expressed as the sum of two components: one component represents the contribution brought about by the instantaneous change in SST alone, whereas the other is the contribution brought about by the instantaneous change in  $\delta^{18}\text{O}_{\text{sw}}$ . In mathematical terms,

$$\begin{aligned} \Delta\delta^{18}\text{O}_{(\text{coral})} &= \Delta\delta^{18}\text{O}_{(\text{SST contri})} + \Delta\delta^{18}\text{O}_{(\text{SW contri})} \\ &= (\partial\delta^{18}\text{O}_{(\text{coral})}/\partial\text{SST})\cdot\Delta\text{SST} \\ &\quad + (\partial\delta^{18}\text{O}_{(\text{coral})}/\partial\delta^{18}\text{O}_{\text{sw}})\cdot\Delta\delta^{18}\text{O}_{\text{sw}}, \end{aligned} \quad (1)$$

where  $\partial\delta^{18}\text{O}_{(\text{coral})}/\partial\text{SST}$ , and  $\partial\delta^{18}\text{O}_{(\text{coral})}/\partial\delta^{18}\text{O}_{\text{sw}}$  are the partial derivatives of  $\delta^{18}\text{O}_{(\text{coral})}$  with respect to SST and  $\delta^{18}\text{O}_{\text{sw}}$ , respectively. They represent the rate of change of  $\delta^{18}\text{O}_{(\text{coral})}$  with the change of one variable, whereas the other variable is constant. Given the above linear  $\delta^{18}\text{O}_{(\text{coral})}$ -SST relationship when the seawater  $\delta^{18}\text{O}$  composition does not change (Epstein et al., 1953; Weber and Woodhead, 1972), the first partial derivative is a constant that exactly equals  $k$ , and its generally accepted value in biologic carbonate is  $-0.18$  to  $-0.24\text{‰}/\text{°C}$  (Epstein et al., 1953; Weber and Woodhead, 1972; Fairbanks and Dodge, 1979; McConnaughey, 1989; Shen et al., 1992; Wellington et al., 1996). For this study, the average value of  $-0.21\text{‰}/\text{°C}$  is adopted.

Similarly, the following equation relates changes of Sr/Ca in

corals to changes of SST, assuming Sr/Ca is only a function of SST:

$$\Delta(\text{Sr}/\text{Ca}_{(\text{coral})}) = \{\partial(\text{Sr}/\text{Ca}_{(\text{coral})})/\partial\text{SST}\}\cdot\Delta\text{SST}, \quad (2)$$

where  $\partial(\text{Sr}/\text{Ca}_{(\text{coral})})/\partial\text{SST}$  is the rate of change of Sr/Ca in corals with respect to SST. It is also a constant that has a range of  $-0.054$  to  $-0.070$  mmol/mol/ $\text{°C}$  in biologic carbonates (Smith et al., 1979; Beck et al., 1992; de Villiers et al., 1995; Shen et al., 1996; Gagan et al., 1998). For this study, the average value of  $-0.062$  mmol/mol/ $\text{°C}$  is adopted. Rearranging Eqn. 2, we can then reconstruct instantaneous SST changes from the observed Sr/Ca changes in corals as follows:

$$\Delta\text{SST} = \Delta(\text{Sr}/\text{Ca}_{(\text{coral})})/\{\partial(\text{Sr}/\text{Ca}_{(\text{coral})})/\partial\text{SST}\}. \quad (3)$$

Given the value of  $\partial\delta^{18}\text{O}_{(\text{coral})}/\partial\text{SST}$ , and the above-calculated  $\Delta\text{SST}$ , it is thus easy to find the first term of Eqn. 1 ( $\Delta\delta^{18}\text{O}_{(\text{SST contri})}$ ) for any given interval of time (Fig. 5a). We can also convert the  $\delta^{18}\text{O}$  in corals into instantaneous changes ( $\Delta\delta^{18}\text{O}_{(\text{coral})}$ ) for successive time intervals (Fig. 5b). Then, by use of Eqn. 1, the contribution of  $\delta^{18}\text{O}_{\text{sw}}$  changes to changes of coral  $\delta^{18}\text{O}$  ( $\Delta\delta^{18}\text{O}_{(\text{sw contri})}$ ) (Fig. 5c) can be calculated by subtracting  $\Delta\delta^{18}\text{O}_{(\text{SST contri})}$  from the series of  $\Delta\delta^{18}\text{O}_{(\text{coral})}$ .

Note that the above method only needs the values of  $\partial\delta^{18}\text{O}_{(\text{coral})}/\partial\text{SST}$  and  $\partial(\text{Sr}/\text{Ca}_{(\text{coral})})/\partial\text{SST}$  to do the reconstruction. Because we look at instantaneous changes instead of absolute values, we do not need to worry about the values of  $b$  in the  $\delta^{18}\text{O}_{(\text{coral})}$ -SST and Sr/Ca<sub>(coral)</sub>-SST equations. As noted above, the value of  $b$  in the  $\delta^{18}\text{O}_{(\text{coral})}$ -SST equation may be different under different  $\delta^{18}\text{O}_{\text{sw}}$  conditions. The same may be

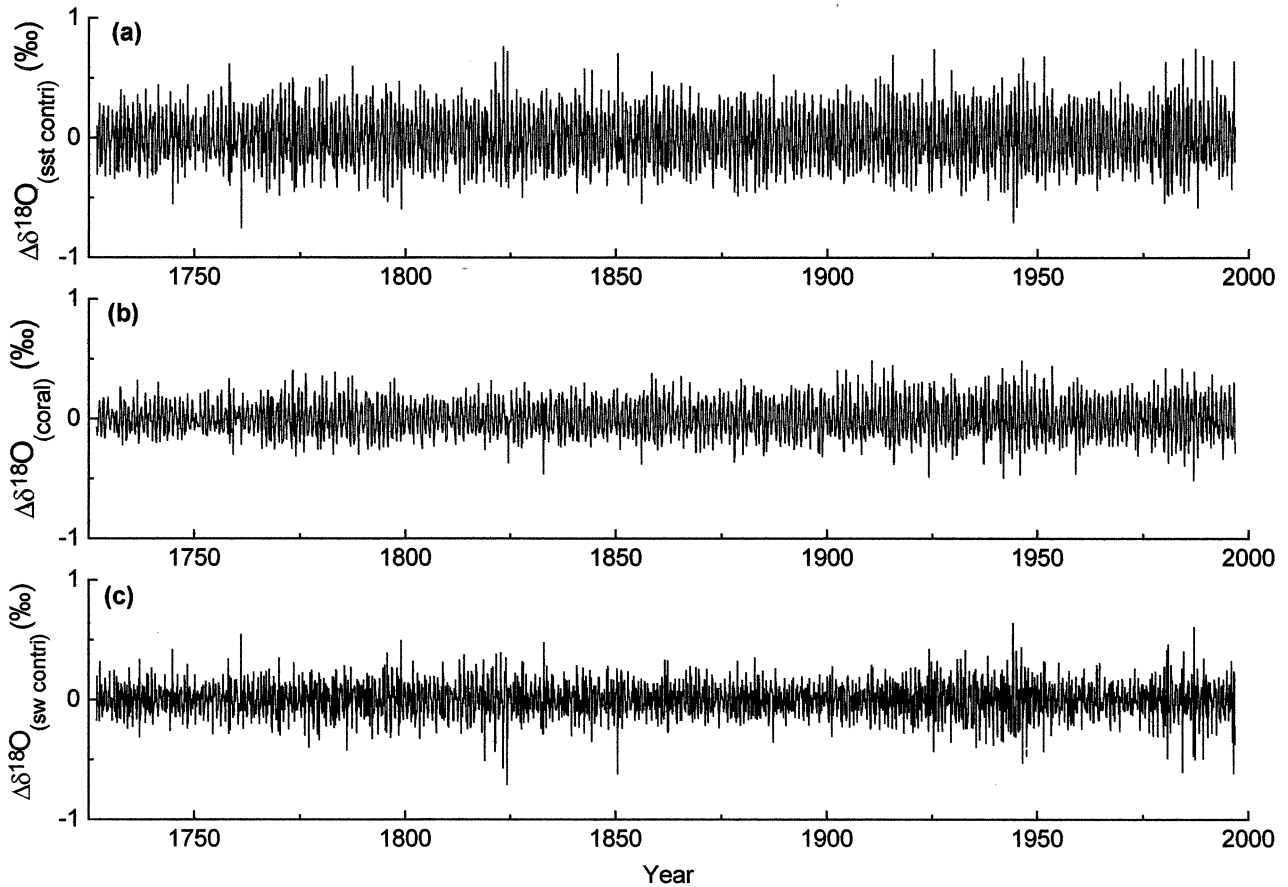


Fig. 5. (a) Instantaneous contribution by SST to the change of  $\delta^{18}\text{O}$  in corals from Sr/Ca change for the period 1726 to 1997. (b) Instantaneous changes of  $\delta^{18}\text{O}$  in corals for the period 1726 to 1997. (c) Instantaneous contribution by  $\delta^{18}\text{O}_{\text{sw}}$  to the change of  $\delta^{18}\text{O}$  in corals for the period 1726 to 1997.

true with  $b$  in the linear Sr/Ca<sub>(coral)</sub>-SST equation. Some authors have pointed out that there are offsets (different  $b$ 's) among the regression lines of Sr/Ca<sub>(coral)</sub>-SST relation amounting to 3.5°C (e.g., fig. 4 in Gagan et al., 2000). These different possible values of  $b$  in both the  $\delta^{18}\text{O}_{\text{(coral)}}$ -SST and Sr/Ca<sub>(coral)</sub>-SST equations will certainly affect the result of the reconstruction of  $\delta^{18}\text{O}_{\text{sw}}$  in the simple subtraction method. But this problem does not exist in the current method because it only involves the values of  $k$  in its calculations.

It should be noted that what are shown in Figures 5a–c only represent instantaneous contributions by SST and  $\delta^{18}\text{O}_{\text{sw}}$  changes to changes of coral  $\delta^{18}\text{O}$ . According to Eqn. 1, if we assume that the partial derivative of  $\delta^{18}\text{O}_{\text{(coral)}}$  with respect to  $\delta^{18}\text{O}_{\text{sw}}$  ( $\partial\delta^{18}\text{O}_{\text{(coral)}}/\partial\delta^{18}\text{O}_{\text{sw}}$ ) is also a constant, we could further estimate the real  $\delta^{18}\text{O}_{\text{sw}}$  changes. However, there are limited data available in the literature on this topic. Because the above assumption appears to be reasonable, we can simply view the shape of  $\Delta\delta^{18}\text{O}_{\text{(sw contri)}}$  curve as also representing the actual variation of  $\delta^{18}\text{O}_{\text{sw}}$  to obtain other useful features—for example, the past variation of salinity, because a factor of a constant will not change the shape of the curve.

The cumulative contributions of  $\delta^{18}\text{O}_{\text{sw}}$  can be obtained by integrating the series in Fig. 5c by adding up all the instantaneous contributions to an arbitrary reference. Although the

choice of the reference would not affect the shape of the curve, it is ideal to select the present  $\delta^{18}\text{O}_{\text{sw}}$  value in this region as the reference. Unfortunately, there is no currently available site-specific  $\delta^{18}\text{O}_{\text{sw}}$  data at Rarotonga. Schmidt (1999) indicates that at present most regional surface water  $\delta^{18}\text{O}$  and salinity relationships tend to converge near  $\delta^{18}\text{O}_{\text{sw}} = 0.8\text{‰}$  when  $S = 36\text{‰}$  and  $\delta^{18}\text{O}_{\text{sw}} = 0\text{‰}$  when  $S = 34.7\text{‰}$  and the  $\delta^{18}\text{O}_{\text{sw}}$  and salinity are roughly linearly related. At Rarotonga, the average salinity is 35.5‰, which would result in  $\delta^{18}\text{O}_{\text{sw}} = 0.57\text{‰}$ . This value is close to a  $\delta^{18}\text{O}_{\text{sw}}$  of 0.52‰ (Beck et al., 1992; J. Recy, unpublished data) measured in New Caledonia, which is west of Rarotonga, but at a similar latitude as Rarotonga. To determine the cumulative seawater contribution, we chose 0.57‰ as the reference for 1997 and summed the instantaneous changes back to 1726 (Fig. 6a). For the period 1726 to 1997, the reconstructed cumulative  $\delta^{18}\text{O}_{\text{(sw contri)}}$  shows clear seasonal, decadal, and secular variations.

#### 4.2. Error Estimate

As noted above, the current method only needs values of  $k$  without involving uncertainties of  $b$ . This will reduce the magnitude of errors. The relative errors incurred in the above calculation of the seawater  $\delta^{18}\text{O}$  composition contribution are

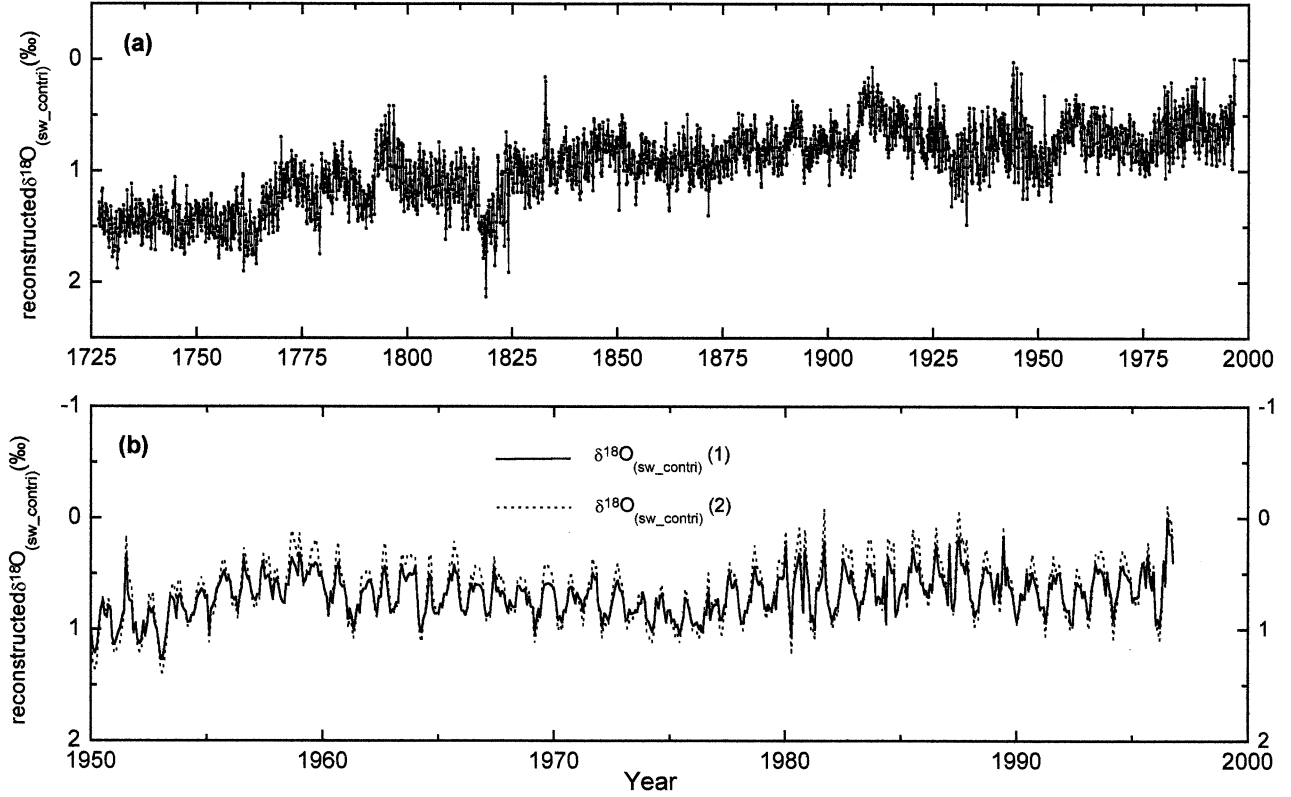


Fig. 6. (a) Reconstructed  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  from  $\delta^{18}\text{O}$  and Sr/Ca ratio in corals for the period 1726 to 1997. (b) Comparison of reconstructed  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  in (a) ( $\delta^{18}\text{O}_{(\text{sw\_contri})}$ , 1 in solid line) with the recalculated  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  ( $\delta^{18}\text{O}_{(\text{sw\_contri})}$ , 2 in dotted line) after adding the relative error of 27% (only shown is the portion 1950 to 1997).

now estimated. Let  $\sigma_1$  be the absolute error of the partial derivative of coral  $\delta^{18}\text{O}$  with respect to SST ( $\pm 0.03$ ),  $\sigma_2$  be the absolute error of the partial derivative of Sr/Ca with respect to

SST ( $\pm 0.008$ ), and  $\sigma$  be the relative error of the calculated instantaneous contribution by  $\delta^{18}\text{O}$  changes. According to Eqns. 1 and 2, we have

$$\begin{aligned} \Delta\delta^{18}\text{O}_{(\text{SST\_contri})} (1 \pm \sigma) &= \{(\partial\delta^{18}\text{O}_{(\text{coral})}/\partial\text{SST} \pm \sigma_1)/(\partial(\text{Sr}/\text{Ca}_{(\text{coral})})/\partial\text{SST} \pm \sigma_2)\} \cdot \Delta(\text{Sr}/\text{Ca}_{(\text{coral})}) \\ &= \{(-0.21 \pm 0.03)/(-0.062 \pm 0.008)\} \cdot \Delta(\text{Sr}/\text{Ca}_{(\text{coral})}). \end{aligned}$$

Because the absolute error of

$$(\partial\delta^{18}\text{O}_{(\text{coral})}/\partial\text{SST} \pm \sigma_1)/(\partial(\text{Sr}/\text{Ca}_{(\text{coral})})/\partial\text{SST} \pm \sigma_2)$$

is

$$(0.062 \cdot 0.03 + 0.21 \cdot 0.008)/0.062^2 = 0.92$$

we have

$$\Delta\delta^{18}\text{O}_{(\text{SST\_contri})} (1 \pm \sigma) = (3.39 \pm 0.92) \cdot \Delta(\text{Sr}/\text{Ca})$$

or

$$\sigma = 0.92/3.39 = 0.27.$$

This means a relative error of up to  $\pm 27\%$  on the reconstructed  $\Delta\delta^{18}\text{O}_{(\text{SST\_contri})}$  due to uncertainties of the values of the two  $k$ 's in the calculations. The effects of this error on the reconstructed  $\Delta\delta^{18}\text{O}_{(\text{sw\_contri})}$  can be tested by tentatively increasing or decreasing the reconstructed  $\Delta\delta^{18}\text{O}_{(\text{SST\_contri})}$  by 27% and

then examining the recalculated  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  (Fig. 6b). From Fig. 6b, it can be seen that although there are some differences in the magnitude of the annual variability in the two curves, the overall interannual and decadal scale patterns are consistent.

## 5. DISCUSSION

### 5.1. Reconstruction of Precipitation and Salinity from $\delta^{18}\text{O}_{\text{sw}}$

We argue that  $\delta^{18}\text{O}_{\text{sw}}$  at Rarotonga generally reflects regional changes in the hydrological budget of the air–sea system because rainfall is depleted in  $^{18}\text{O}$  relative to seawater, whereas evaporation tends to enrich the surface ocean in  $^{18}\text{O}$  (Epstein and Mayeda, 1953; Friedman et al., 1961; Redfield and Feridman, 1965). At Rarotonga, the comparison of  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  with the monthly precipitation data from the Island of Rarotonga does show a general negative correlation for the most of

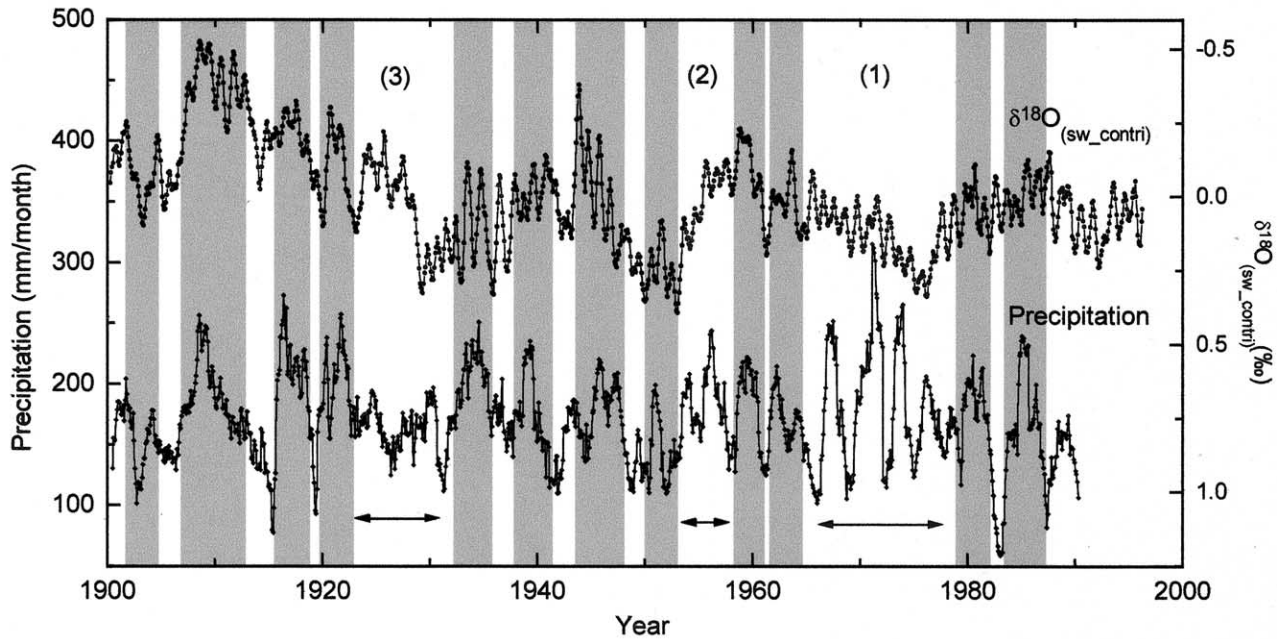


Fig. 7. Comparison of derived  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  and precipitation data (Baker et al 1994) for the period 1900 to 1997. One-year smoothing was applied on the two curves to remove the random noise. The shadows represent their similar variabilities during the same time intervals in  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  and precipitation. The numbers 1 to 3 marked on the figure are the three periods that do not show very apparent similar trends between the two curves.

the period 1900 to 1997, which further supports the validity of this method (Fig. 7). For the same time intervals when precipitation increases,  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  is generally lower, whereas when precipitation decreases,  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  is higher. However, there are some discrepancies between the two curves. For instance, for the three periods marked 1 to 3 in Fig. 7,  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  is also characterized by stronger decadal variability than rainfall, which may be because  $\delta^{18}\text{O}_{(\text{sw})}$  reflects the regional hydrological balance between precipitation and evaporation, rather than only precipitation changes. On interannual time-scales, however, the reconstructed  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  appears to be more related to the past precipitation variation.

Because salinity is also mainly controlled by the precipitation–evaporation balance,  $\delta^{18}\text{O}_{\text{sw}}$  should also reflect the changes of salinity. At Rarotonga, although salinity data (at 20-m depth) are only available after 1980, the comparison of the cumulative  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  with the monthly salinity (NOAA NCEP EMC CMB Pacific monthly salinity) (Ji et al., 1995; Ji and Smith, 1995; Behringer et al., 1998) for 1980 to 1997 does show a positive correlation (Fig. 8). The correlation is better in some years—for example, 1989 and 1996—when salinity exhibits a large decrease, and  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  shows a similar magnitude decrease. Furthermore, they also display similar decadal changes with synchronous shifts in 1988. It should be noticed that there exists a 1- to 2-month offset in several years with salinity leading reconstructed  $\delta^{18}\text{O}_{\text{sw}}$ . The reason for this is not clear. One possibility may be related to the fact that coral growth rates change throughout the year, whereas our age model does not take this into account. Because the salinity data are not in situ data but are model-based data, another possibility may be related to some unknown errors in the salinity data. In addition, a roughly linear positive correlation ( $r = 0.72$ ) be-

tween reconstructed  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  and salinity is identified that agrees with some instrumental data observations and model studies (Craig and Gordon, 1965; Ostlund et al., 1987; Fairbanks et al., 1992; Bauch et al., 1995; Schmidt, 1998, Schmidt, 1999). It suggests that if we extend this correlation to the whole period of the record, this reconstructed  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  technique might be used to evaluate past interannual and decadal salinity changes at Rarotonga back to 1726.

## 5.2. Separate Influences of $\delta^{18}\text{O}_{\text{sw}}$ and SST on $\delta^{18}\text{O}$ in Corals

Comparison of the instantaneous contribution by SST changes (Fig. 5a) with instantaneous changes of coral  $\delta^{18}\text{O}$  (Fig. 5b) indicates that the average annual range in coral  $\delta^{18}\text{O}$  is less than that of the expected contribution on the basis of actual SST variation. Our preferred explanation is that the effect of  $\delta^{18}\text{O}_{\text{sw}}$  must have counteracted that of SST provided that the coral  $\delta^{18}\text{O}$  is mainly a function of  $\delta^{18}\text{O}_{\text{sw}}$  and SST. Detailed comparison of the time series in Fig. 5a with that in Fig. 5c indicates that the contributions from the changes of  $\delta^{18}\text{O}_{\text{sw}}$  and that from the changes of  $\delta^{18}\text{O}_{\text{SST}}$  are generally negatively correlated (Fig. 9). That is, whenever SST increases and causes the decrease of coral  $\delta^{18}\text{O}$ ,  $\delta^{18}\text{O}_{\text{sw}}$  often increases and causes the increase of coral  $\delta^{18}\text{O}$ . Although we only show a 15-yr interval here (1980 to 1995), this relationship is prevalent through the core. The climatology of the Rarotonga region supports this relationship. Rarotonga is located in the trade wind belt ( $18^\circ$  to  $26^\circ$  latitude), which is a region with the highest evaporation and lowest humidity in the summer (Prioto and Kettani, 1973; Levitus, 1982). At Rarotonga, in summer (January–February), when the SST increases, coral



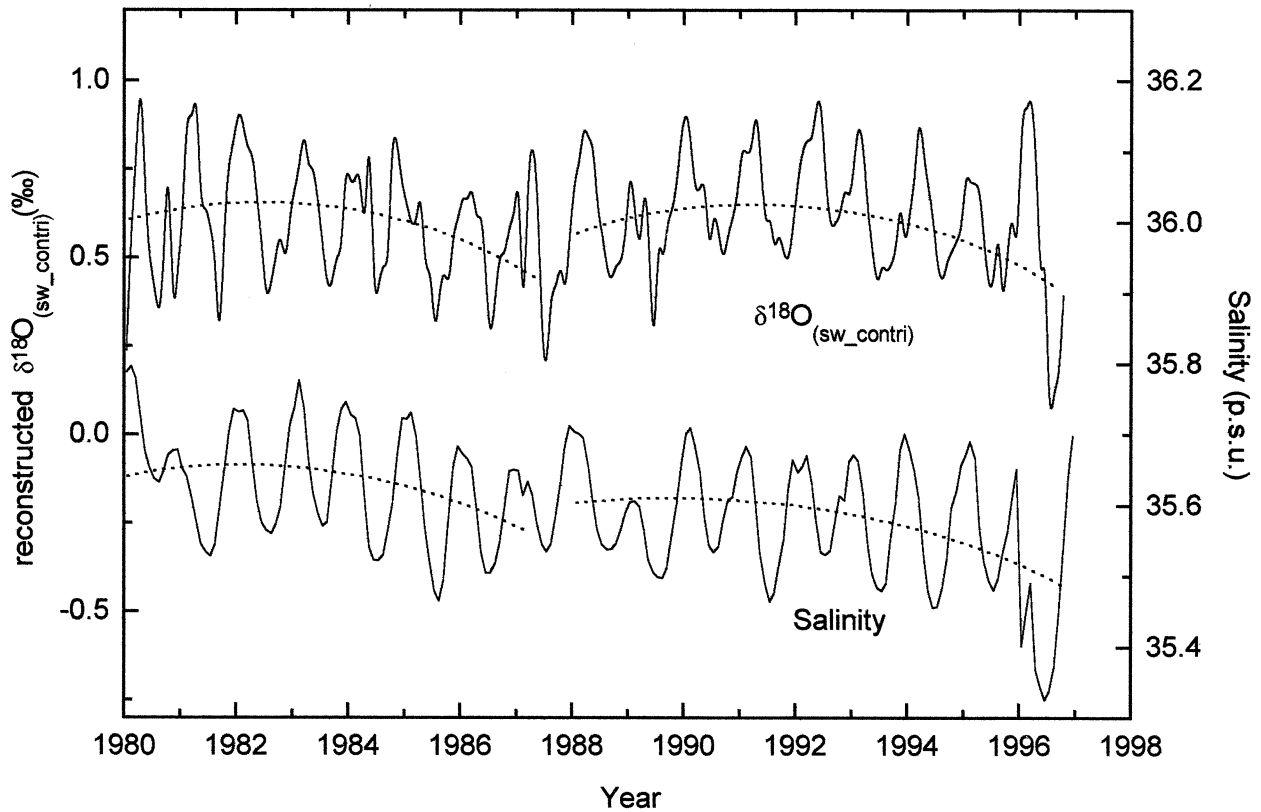


Fig. 8. Comparison between derived  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  and salinity (Ji et al., 1995; Ji and Smith, 1995; Behringer et al., 1998) for the period 1980 to 1997. The dashed lines represent the potential similar trends in  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  and salinity.

$\delta^{18}\text{O}$  decreases. At the same time, higher SST causes an increase in evaporation rate with the help of strong trade winds, and thus the local net atmospheric water balance (precipitation

minus evaporation) decreases and salinity increases (Fig. 2). This causes an increase of  $\delta^{18}\text{O}_{\text{sw}}$ , thus counteracting the effect of SST on coral  $\delta^{18}\text{O}$ . Our derived  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  in the South

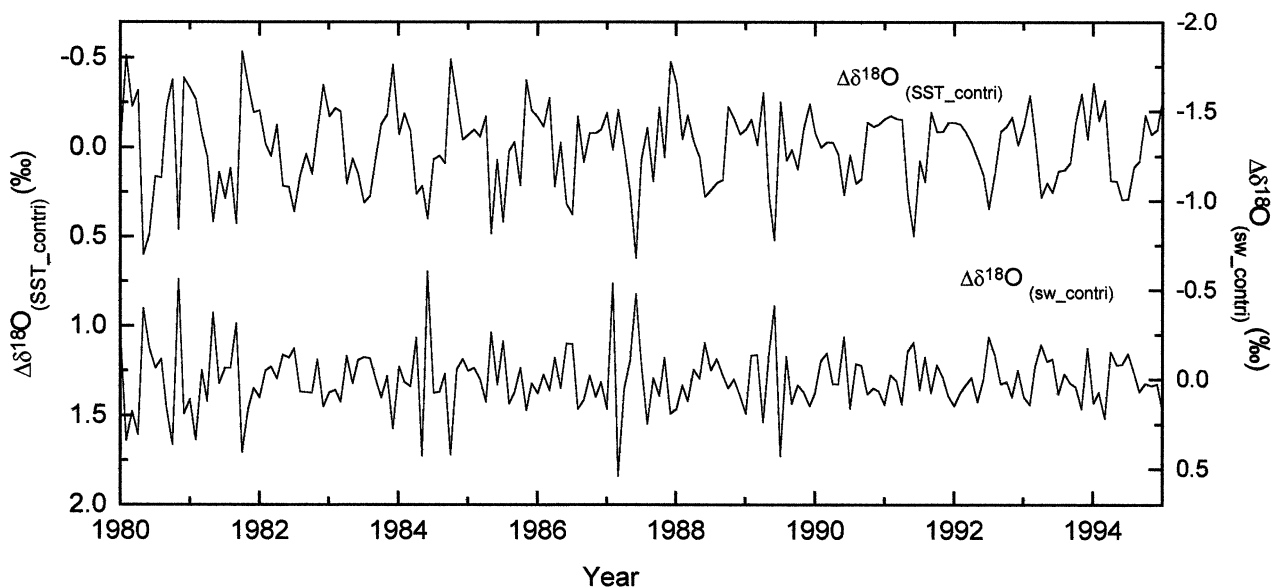


Fig. 9. Comparison of the instantaneous changes of the contribution from SST to the total coral  $\delta^{18}\text{O}$  with that from  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  to the total coral  $\delta^{18}\text{O}$  to show their opposite correlation (only shown is the portion 1980 to 1995).

Pacific gyre region therefore agrees with this regional precipitation and evaporation balance. A similar pattern is also observed along the coast of northwestern Australia at the same latitude as Rarotonga (Gagan et al., 2000). As observed by Gagan et al. (2000), in northwestern Australia,  $\delta^{18}\text{O}_{\text{sw}}$  becomes more positive in summer as evaporation from the ocean surface increases as a result of increasing air temperature and solar radiation.

Given the separate contributions by SST and  $\delta^{18}\text{O}_{\text{sw}}$  to coral  $\delta^{18}\text{O}$ , we can estimate their relative contributions. At Rarotonga, on average, changes in SST account for approximately 61% of the total  $\delta^{18}\text{O}$  coral signal, whereas changes in  $\delta^{18}\text{O}_{\text{sw}}$  account for  $\sim 39\%$ . From this analysis, it is clear that the influence of evaporation in the SPCZ on  $\delta^{18}\text{O}_{\text{sw}}$ , salinity, or both is nonnegligible and plays a large role in the  $\delta^{18}\text{O}$  composition of corals at Rarotonga.

### 5.3. Decadal Variability in Rarotonga Coral $\delta^{18}\text{O}$ and $\delta^{18}\text{O}_{\text{sw}}$

Although decadal–interdecadal variability in the South Pacific remains weakly constrained, decadal variability in the North Pacific has been extensively documented (Graham, 1994; Trenberth and Hurrell, 1994; Mann and Park, 1996; Latif et al., 1997; Nakamura and Yamagata, 1999) and can be represented by the Pacific decadal oscillation (PDO) index that was first defined by Mantua et al. (1997) partly based on the work of Zhang et al. (1997). Mantua et al. (1997) developed the PDO index such that when it is cooler than average in the central North Pacific and warmer than average in the Gulf of Alaska and along the Pacific Coast of North America, the index is positive.

Both coral  $\delta^{18}\text{O}$  and  $\delta^{18}\text{O}_{\text{sw}}$  at Rarotonga show clear decadal-scale variations over the period 1726 to 1997. During some years, the two series are consistent—for example, between 1820 to 1830 and between 1920 to 1940—which implies a common forcing mechanism. To remove the potential interference of any long-term trend, the Rarotonga  $\delta^{18}\text{O}$  and  $\delta^{18}\text{O}_{\text{sw}}$  were detrended of long-term secular variability and compared with a detrended PDO index. For comparison, the three time series are also normalized by their own standard deviations. The comparison of the PDO index with Rarotonga  $\delta^{18}\text{O}$  (Fig. 10a) shows relatively good correlation between decadal-scale variability in coral  $\delta^{18}\text{O}$  and the PDO index ( $r = 0.46$ ). The correlation is reduced as the result of discrepancies in the range of the variations between the two curves during several time intervals (Fig. 10a). In the first (interval 1) and last three time intervals (intervals 5 to 7) the coral  $\delta^{18}\text{O}$  is  $\sim 1$  to 1.5 U lower than the PDO index, whereas in the other three time intervals (intervals 2 to 4), the coral  $\delta^{18}\text{O}$  is  $\sim 1$  to 1.5 U higher than the PDO index. However, almost all these discrepancies between the coral  $\delta^{18}\text{O}$  and the PDO index are correspondingly reflected in the reconstructed  $\delta^{18}\text{O}_{\text{sw}}$ , as shown in Fig. 10b. Although the first (interval 1) and the last three intervals (intervals 5 to 7) are characterized by correspondingly lower  $\delta^{18}\text{O}_{\text{sw}}$ , the other three intervals (intervals 2 to 4) are periods of higher  $\delta^{18}\text{O}_{\text{sw}}$ , showing exactly the opposite to changes of intervals 1 and intervals 5 to 7. This indicates that although coral  $\delta^{18}\text{O}$  cannot be directly correlated with the PDO index (because it reflects both SST and  $\delta^{18}\text{O}_{\text{sw}}$ , whereas the PDO index is based entirely on

SST variations), it can still be combined with the reconstructed  $\delta^{18}\text{O}_{\text{sw}}$  to make inferences about the association of the decadal variability at Rarotonga with the PDO Index. From Figures 10a,b the combined coral  $\delta^{18}\text{O}$  and  $\delta^{18}\text{O}_{\text{sw}}$  appear to be consistent with the PDO index, which supports the observations of Linsley et al. (2000a) that the decadal-scale variability near Rarotonga is related to the processes associated with the PDO. This coral-based result from Rarotonga also agrees with some other studies from instrumental data or model analysis, which suggest that North Pacific interdecadal changes appear to be linked through ocean–atmosphere teleconnections to the Southern Hemisphere and are characterized by global reflection and translation symmetries between the Northern and Southern Hemispheres (e.g., Trenberth and Hurrell, 1994; Garreaud and Battisti, 1999). However, because of the short section of overlap in relationship to the long period of the decadal-scale changes, longer records from the North Pacific would allow a more rigorous evaluation of the extent of coherence of decadal variability in the Pacific.

### 5.4. Long-Term Trend in $\delta^{18}\text{O}_{\text{sw}}$

The long-term trend in  $\delta^{18}\text{O}_{\text{sw}}$  shows a progressive depletion toward the top of the record, implying a gradual trend toward lower salinity in this region (Fig. 6a). The total decrease in  $\delta^{18}\text{O}_{\text{sw}}$  at Rarotonga is 0.75‰ from 1726 to 1997. Urbans et al. (2000) suggest that the trend toward warming and freshening of seawater observed in coral  $\delta^{18}\text{O}$  from Maiana may represent an expansion of western Pacific warm pool over the past 155 yr because Maiana lies at the eastern edge of the existing warm pool. The long-term trend toward freshening in reconstructed  $\delta^{18}\text{O}_{\text{sw}}$  at Rarotonga appears to support their observation as Rarotonga lies at the southeastern edge of the pool.

Unlike  $\delta^{18}\text{O}_{\text{sw}}$ , Sr/Ca at Rarotonga shows a gradual decrease in SST from 1726 to 1900 and a gradual increase after 1900 (Linsley et al., 2000a). The increase in SST since 1900 agrees with several other studies that have demonstrated the existence of Pacific warming in the 20th century (Roemmich and McGowan, 1995; Cane et al., 1997; McGowan et al., 1998; Linsley et al., 2000b). Although there have been no direct measurements of long term variations of  $\delta^{18}\text{O}_{\text{sw}}$  in the South Pacific gyre to demonstrate if the trend in coral  $\delta^{18}\text{O}$  reflects a secular salinity variation, our results suggest that variations of  $\delta^{18}\text{O}_{\text{sw}}$  may contribute more to the long-term trend in coral  $\delta^{18}\text{O}$  than SST at Rarotonga. However, other possible nonclimate contributing factors to this trend includes the potential biologically mediated shift in the vital effect over time, or other unknown coral growth effects. Nonbiologic causes of long-term variability in coral  $\delta^{18}\text{O}$  (such as coral growing at shallower water depth as the coral grows upward) also need to be considered (Glynn and Wellington, 1983; Dunbar et al., 1994; Gagan et al., 2000). To determine the climate significance of this trend, it needs to be replicated by using other corals in the region.

## 6. SUMMARY

(1) Assuming that coral  $\delta^{18}\text{O}$  is a function of SST and  $\delta^{18}\text{O}_{\text{sw}}$ , and that coral Sr/Ca is a function of only SST, the effects of  $\delta^{18}\text{O}_{\text{sw}}$  on coral  $\delta^{18}\text{O}$  can be separated from those of

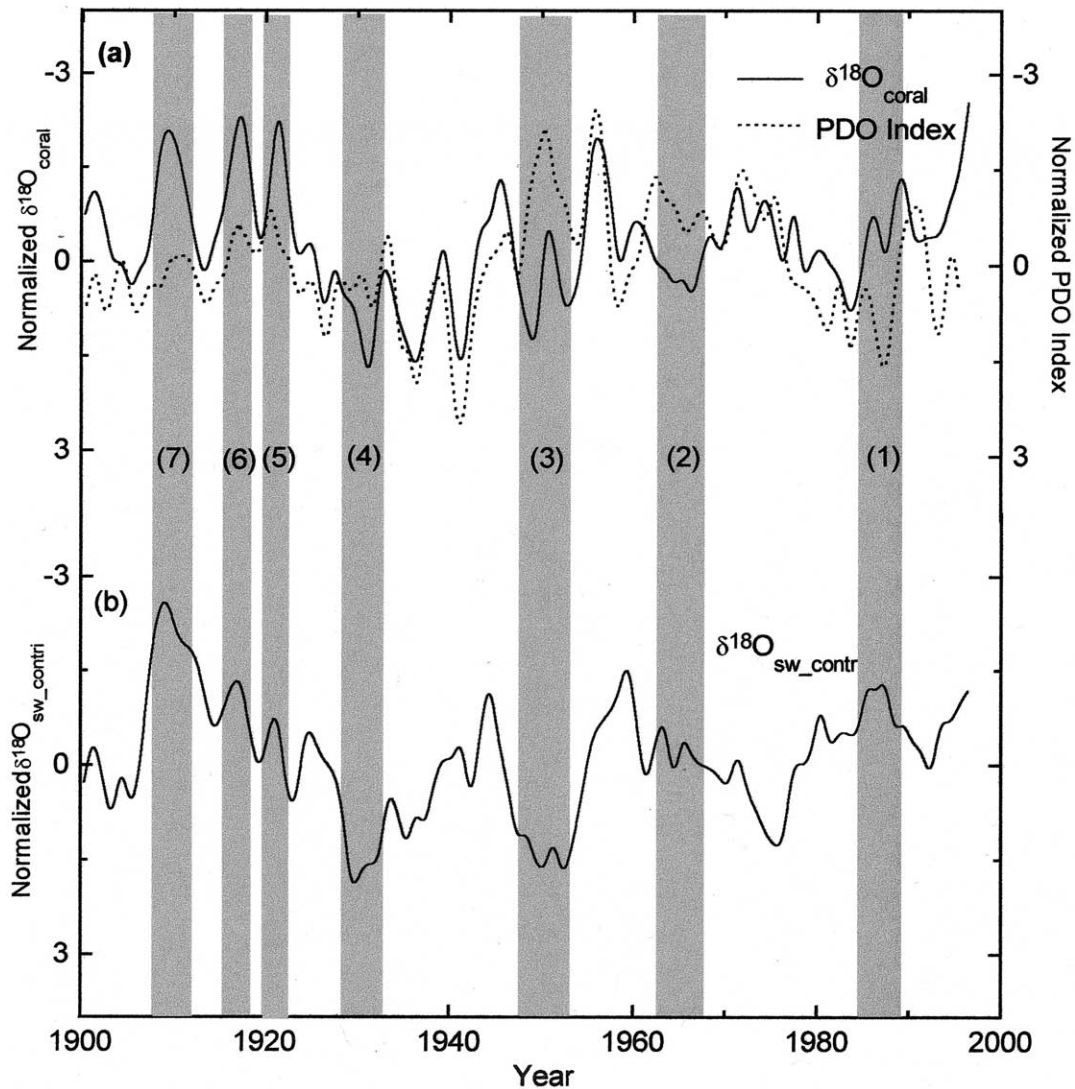


Fig. 10. (a) Comparison between annual average  $\delta^{18}\text{O}$  in Rarotonga corals and annual average PDO Index for the period 1900 to 1997. (b) Reconstructed annual average  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  for the period 1900 to 1997. PDO index, coral  $\delta^{18}\text{O}$  and  $\delta^{18}\text{O}_{(\text{sw\_contri})}$  are all detrended and 5-year smoothed to highlight their decadal variability, and they are all normalized in standard deviation units for comparison. The shaded areas marked by the numbers 1 to 7 in (a) and (b) are the time intervals that have disagreement between normalized  $\delta^{18}\text{O}$  in corals and PDO Index and their corresponding changes in  $\delta^{18}\text{O}_{(\text{sw\_contri})}$ .

SST by breaking the instantaneous changes of coral  $\delta^{18}\text{O}$  into separate contributions by instantaneous SST and  $\delta^{18}\text{O}_{\text{sw}}$  changes, respectively. By finding the contribution of SST from the reconstructed SST by using Sr/Ca, the contribution by  $\delta^{18}\text{O}_{\text{sw}}$  can then be found.

(2) The above method was applied to a coral  $\delta^{18}\text{O}$  record from Rarotonga (21.5°S, 159.5°W) spanning 1726 to 1997. It was found that changes in SST account for approximately 61% of the total coral  $\delta^{18}\text{O}$  variations, whereas changes in  $\delta^{18}\text{O}_{\text{sw}}$  account for ~39%. This suggests that the SPCZ, evaporation rate, or both have a significant effect on  $\delta^{18}\text{O}_{\text{sw}}$  and coral  $\delta^{18}\text{O}$  at this site. The interannual variations of reconstructed  $\delta^{18}\text{O}_{\text{sw}}$  contribution show generally negative correlation with the instrumental precipitation for the most of the period 1900 to 1997. But there also exist some discrepancies between them,

which may be related to the fact that  $\delta^{18}\text{O}_{\text{sw}}$  reflects the regional hydrological balance between precipitation and evaporation, rather than only precipitation. The  $\delta^{18}\text{O}_{\text{sw}}$  also shows a relatively good correlation with salinity for the period 1980 to 1997. The roughly linear correlation between the reconstructed  $\delta^{18}\text{O}_{\text{sw}}$  and salinity ( $r = 0.72$ ) for the period 1980 to 1997 implies that we can use  $\delta^{18}\text{O}_{\text{sw}}$  to estimate the past changes of interannual salinity for the whole period at Rarotonga.

(3) Decadal variability and a long-term trend are observed in the reconstructed  $\delta^{18}\text{O}_{\text{sw}}$ . Comparison with the PDO index suggests that the decadal-scale variability near Rarotonga may be at least partially related to the processes associated with the PDO and may reflect the combined effects of SST and salinity. It agrees with some other studies that suggest that North Pacific interdecadal changes appear to be linked through ocean-atmo-

sphere teleconnections to the Southern Hemisphere. (Cohen et al., 2001; Cole et al; Epstein et al., 1953; Fairbanks et al., 1997; International Atomic Energy Agency 1981; Ji and Smith 1995; Levitus et al., 1994; Linsley et al., 1994; Trenberth 1990; Zhang et al., 1997; Zhang et al., 1998).

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