A STUDY OF A MULTI-CENTURY CORAL STABLE ISOTOPE RECORD FROM RAROTONGA, SOUTHWEST SUBTROPICAL PACIFIC, FOR THE PERIOD 1726-1997

by

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ABSTRACT

This study presents a 271-year (1726-1997) subseasonal oxygen and carbon isotopes ($\delta^{18}O$ and $\delta^{13}C$) records from a coral colony of *porites lobata* at Rarotonga (21.5°S, 159.5°W) in the southwest subtropical Pacific. A new method is introduced whereby the effects of sea surface temperature (SST) can be separated from those of seawater $\delta^{18}O$ composition ($\delta^{18}O_{sw}$) on coral $\delta^{18}O$ by using the coupled coral Sr/Ca and $\delta^{18}O$. Different from the previous methods that treat coral $\delta^{18}O$ as the sum of two separate single-variable functions ($\delta^{18}O$ vs. SST; and $\delta^{18}O$ vs. $\delta^{18}O_{sw}$), this method separates the effects of $\delta^{18}O_{sw}$ from SST by breaking the instantaneous changes of coral $\delta^{18}O$ into separate contributions by instantaneous SST and $\delta^{18}O_{sw}$ changes, respectively. It was found that reconstructed $\delta^{18}O_{sw}$ contributes significantly to the annual changes of coral $\delta^{18}O$ at Rarotonga for the period 1726-1997. Changes of $\delta^{18}O_{sw}$ account for ~39% of the total coral $\delta^{18}O$ variation, while changes of SST account for ~61%. The reconstructed $\delta^{18}O_{sw}$ also shows a positive linear correlation with a satellite-based estimated salinity for the period 1980-1997 (r=0.72). This linear correlation between reconstructed $\delta^{18}O_{sw}$ and salinity makes it possible to use the reconstructed $\delta^{18}O_{sw}$ to estimate the past interannual and decadal salinity changes in this region.

Applying a similar method to coral $\delta^{13}C$, the effects of kinetic and metabolic activity on coral $\delta^{13}C$ were also quantitatively estimated. The results show that the variation of coral $\delta^{13}C$ appears to be mainly caused by variation of metabolic activity rather than that of kinetic activity in both tropical and subtropical regions. For the tropical regions, changes of metabolic activity account for ~90% of the total $\delta^{13}C$ variation in corals, while for

subtropical regions, metabolic activity still accounts for approximately 70-75% of the total variation of coral $\delta^{13}C$ despite a larger range of SST changes in the subtropics. One implication of this study is that kinetic effects may be negligible especially in the tropical regions and thus future work should be concentrated on the processes of metabolic fractionation in order to gain a better understanding of the relationships between $\delta^{13}C$ and various climatic variables and to utilize coral $\delta^{13}C$ for reconstructing the paleoclimate variations.

This study also examined the interannual and interdecadal variability in coral $\delta^{18}O$ at Rarotonga for the period 1726-1997. The results suggest that although Rarotonga is located outside of the center of action of ENSO, it is generally sensitive to ENSO variability in this region. The decadal-scale variability (~12 yr) was further differentiated from the interdecadal-scale variability (~32 yr) for the period 1726-1997 at Rarotonga. Based on the analysis of both tropical and subtropical coral data and comparisons with the instrumental data (Nino3.4 SST index and PDO index), it was hypothesized that the decadal and interdecadal-scale variability might result from separate forcing mechanisms. The decadal variability appears to be primarily a response to the tropical Pacific forcings while the interdecadal variability is more related to a mid-latitude oscillation. As the ocean is simultaneously affected by many climate forcings, multiple forcings may contribute to the change of the oceans in differing amounts.

The reliability of both coral $\delta^{18}O$ and $\delta^{13}C$ records from Rarotonga was also examined in this study. It is revealed that coral $\delta^{18}O$ is a good indicator of environmental variables such as SST and precipitation while coral $\delta^{13}C$ fails to document common characteristics of interannual and interdecadal signals at Rarotonga.

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CHAPTER 1

PROBLEMS AND OBJECTIVES

1.1 Introduction

The tropical ocean-atmosphere is an active component of the Earth's climate system and it exerts a strong influence on climate variability worldwide (Troup, 1965; Bjerknes, 1966, 1972; Rasmusson and Carpenter, 1982; Cane, 1986; Glantz, 1996 to cite a few). Over interannual to decadal periods, tropical climate variability has global consequences, as seen in extratropical manifestations of El Niño Southern Oscillation (ENSO) and the Asian Monsoon. In addition to ENSO events, recently there has been considerable interest in documenting climate variations on decadal and longer time scales, motivated in part by a need to distinguish natural modes in the ocean-atmosphere system from those caused by anthropogenic impacts on global climate. However, because high quality instrumental records from low latitudes are generally limited to the past several decades and to isolated sites, our current understanding of natural variability in tropical climate does not yet provide the necessary baseline data required for detection of anthropogenic change. Nor does it provide insight into the potential role of tropical heat and moisture pumps as feedbacks on past or future climate change. As a result, the development of proxy records of past climate variability in these under-sampled regions is highly desirable, as it will enable the instrumental climate record to be extended and thus improve our understanding of climate variability over a wide spectrum of timescales.

Long-lived hermatypic corals are uniquely suited for high resolution studies of sea surface conditions. Corals can live for centuries, extending at rates of millimeters to centimeters per year, with most species producing annual growth bands. The high growth rate of hermatypic corals enables subannual sampling of skeletal aragonite, with a demonstrated resolution on the order of weeks to months. Many studies have shown that chemical tracers within coral skeletal aragonite can accurately record seasonal and interannual changes in environmental parameters, such as sea surface temperature (SST), salinity, rainfall, etc. (Swart, 1983; McConnaughey, 1989; Cole et al., 1993; Beck et al., 1992; Linsley et al., 1994; Dunbar et al., 1994; and many others). Among the present array of available tracers, oxygen isotopes ($\delta^{18}O$) and Sr/Ca have become mainstays in coral-based climate reconstruction. In the past decade, the oxygen isotopic signature in coral skeletons has been widely used to reconstruct SST and salinity in the oceans. In regions where the oxygen isotopic composition of seawater is relatively constant, coral skeletal $\delta^{18}O$ may be converted into an estimate of past SST variability (Dunbar et al., 1994; Wellington and Dunbar, 1995). Alternatively, in some other regions where there is little variation in SST, the skeletal $\delta^{18}O$ may be used to estimate changes in seawater oxygen isotope composition through time due to variations in the input of isotopically light precipitation or river discharge (Cole and Fairbanks, 1990; Cole et al., 1993; Linsley et al., 1994). The carbon isotopic composition ($\delta^{13}C$) of coral skeleton is another important isotopic signature which has more potential forcing variables than $\delta^{18}O$ and its interpretation is currently a source of controversy (Land et al., 1975; Fairbanks and Dodge, 1979; McConnaughey, 1989a). As opposed to $\delta^{18}O$, coral $\delta^{13}C$ is affected by both kinetic and metabolic fractionation (McConnaughey, 1989a). Therefore, physiological processes, such as photosynthesis (a light driven metabolic reaction), respiration, and heterotrophy, can also affect the skeletal carbon isotopic composition in addition to SST and $\delta^{13}C$ of dissolved inorganic carbon (DIC) in seawater. It is generally believed that as the rate of photosynthesis in zooxanthellae increases with increasing solar radiation, the carbon pool becomes relatively depleted in ^{12}C relative to ^{13}C, resulting in an increase in skeletal $\delta^{13}C$ (Swart, 1983; McConnaughey, 1989). In certain environments coral $\delta^{13}C$ highly correlates to climatic variables, such as solar radiation or ocean productivity. Current interpretations of coral $\delta^{13}C$ variability are driven by observed correlations to specific processes or conditions, rather than by a thorough understanding of all relevant processes. It is clear that only when the processes controlling carbon isotope fractionation in the coral skeleton are better understood, can the utility of $\delta^{13}C$ be extended.

During the past 10 years, interest in the use of corals for examining past oceanographic variability has rapidly increased, especially at interannual timescales. On interannual timescales, the ENSO phenomenon generates much of the variability observed in global climate. Therefore, reconstructing past variations of ENSO is essential for documenting and understanding the past behavior of the tropical climate system, assessing future changes, and also providing a more accurate baseline for current climatic models (Cane, 1986; Enfield, 1989; Glantz, 1996). ENSO induces temperature and precipitation anomalies throughout the tropical Pacific and Indian Oceans. Past ENSO events have been identified using $\delta^{18}O$ composition of coral skeletons located in ENSO sensitive settings (Druffel et al., 1990; Cole and Fairbanks, 1990; Cole et al., 1993; Charles et al., 1997). In many cases the $\delta^{18}O$ composition of coral skeletons has been shown to be a good indicator of seasonal and interannual changes in SST and/or precipitation which are both associated with changes in ENSO (Dunbar and Wellington, 1981; Swart, 1983; Wellington et al., 1996; and others). Records of this type can be used to examine past variations in frequency or pacing of the ENSO system.

In addition to ENSO events, there is increasing interest in climatic variability that occurs on decadal to century time-scales. In the Pacific, a persistent decadal/interdecadal oscillation has been termed the Pacific Decadal Oscillation (PDO) in the North Pacific (Mantua et al., 1997; Zhang et al., 1997) and Interdecadal Pacific Oscillation (IPO) over the entire Pacific (Power et al., 1999; Salinger et al., in press). Based on instrumental data, the PDO and IPO appear to be a robust, recurring pattern of ocean-atmosphere climate variability on decadal-scales. Some studies suggest that the decadal-scale variability may originate in the subtropics of the North and/or South Pacific Ocean through unstable ocean-atmosphere interactions (Ghil and Vautard, 1991; Latif and Barnett, 1994; Gu and Philander, 1997), while others argue that tropical ENSO forcing plays a key role (Jacobs et al., 1994; Trenberth and Hurrell, 1994; Zhang et al., 1997; Garreaud and Battisti, 1999). White et al. (1997) and White and Cayan (1998) examined the historical upper ocean temperature record for the period 1900-1990 from 40°S to 60°N in the Pacific and revealed two dominant sub-ENSO cycles: decadal (9-13 years) and interdecadal (18-23 years). They suggested that evolution of decadal signals is different from that of interdecadal signals. The evolution of the interdecadal signal appears to be dominated by equatorward propagation of SST anomalies from the extratropics to tropics, while the decadal signal seems to involve the advection of SST anomalies by Rossby waves physics which is also responsible for ENSO frequencies near 15°-30° latitude in both hemispheres. Lau and Weng (1995) and Mann and Park (1996) have also isolated the decadal from the interdecadal variance in near-century long SST and Sea Level Pressure (SLP) data.

In order to evaluate decadal/interdecadal climate variability over time, climate records have to be long enough to capture multiple decadal periods. Since corals may grow for several hundred years, they are uniquely suited for providing some information related to correct interpretation on decadal/ interdecadal variability.

1.2 Main Problems

Although it is now recognized that coral $\delta^{18}O$ can be used to reconstruct past environmental variables such as SST and salinity, and that this tracer has greatly improved our understanding of the past behavior of the oceans, there are still some important questions regarding the use of corals in reconstructing climate. Some of the main problems are outlined as follows:

(1) Because coral skeletal $\delta^{18}O$ reflects a combination of local SST and the $\delta^{18}O$ of ambient sea water, it is often difficult to clearly distinguish their separate effects based on coral $\delta^{18}O$ alone. Several studies have attempted to use paired Sr/Ca and $\delta^{18}O$ in corals to separate the effects of SST and $\delta^{18}O_{sw}$ variations since the skeletal Sr/Ca ratio appears to be mainly influenced by SST (Smith et al., 1979; Beck et al., 1992). McCulloch et al. (1994) made the first attempt to quantitatively separate the effects of SST from those of $\delta^{18}O_{sw}$ on skeletal $\delta^{18}O$ by using paired coral $\delta^{18}O$ and Sr/Ca analysis on the same samples. Gagan et al. (1998; 2000) used a similar method by which the effects of SST (estimated from Sr/Ca) are directly subtracted from the observed skeletal coral $\delta^{18}O$ to obtain the residual effects of $\delta^{18}O_{sw}$. To do so, these authors first convert the $\delta^{18}O$ data into units of temperature ($T_{\delta 18O}$) by using an empirical SST-$\delta^{18}O$ equation and then subtract this from the Sr/Ca-reconstructed SST ($T_{Sr/Ca}$). The residual $\delta^{18}O$ is then interpreted as reflecting the effects of the seawater $\delta^{18}O$ composition. However, the empirical equation they used to convert coral $\delta^{18}O$ into SST is obtained by linear

regression of the $\delta^{18}O$ data against SST in their study area. This equation can be used only if the other variable that affects $\delta^{18}O$, i.e. $\delta^{18}O_{sw}$ is assumed to be a constant. It is clear that this assumption is not valid for the regions where the $\delta^{18}O_{sw}$ has a significant influence on coral $\delta^{18}O$ each year. Also it may not be justified to assume that a variable is constant while at the same time attempting to reconstruct its variations. To better separate the effects of $\delta^{18}O_{sw}$ from SST, other methods should be sought.

(2) The $\delta^{13}C$ signal in corals is complicated by the interaction with physiological processes that involve strong isotopic fractionation. It is often difficult to decipher the different processes in environmental terms. At present, there is not a consensus about the relative importance of physiological vs. environmental factors on the variation of coral $\delta^{13}C$. Some authors believe that coral $\delta^{13}C$ is predominantly influenced by metabolic (photosynthesis) fractionation (Muscatine et al., 1989; Grottoli and Wellington, 1999). They observe that skeletal $\delta^{13}C$ varies seasonally in accordance with light levels and decrease with water depth (Fairbanks and Dodge, 1979; Land et al., 1975; Leder et al., 1991; Shen et al., 1992b). However, some other authors argue that kinetic fractionation can be more important than metabolic fractionation and kinetic depletion of ^{13}C can sometimes overpower the metabolic ^{13}C increase (McConnaughey, 1989a, b). Observed correlations to factors such as insolation and ocean productivity suggest that coral $\delta^{13}C$ may also provide paleo-environmental information. However, the separate effects of different climatic variables have never been quantified. It is clear that only when these fundamental questions are solved, can $\delta^{13}C$ be possibly used in reconstructing basic environmental parameters.

(3) The possible influence of biological processes such as the growth rate on the skeletal $\delta^{18}O$ and $\delta^{13}C$ composition is not clear. Aragonite deposited by scleractinian corals is usually depleted in ^{13}C and ^{18}O, relative to equilibrium with ambient seawater (McConnaughey, 1989a). The usefulness of corals as recorders of environmental variables depends on the assumption that this departure from equilibrium remains constant. However, there are several reports of a relationship between skeletal growth rate and isotopic values (Land et al., 1975; Allison et al., 1996; Cohen and Hart, 1997). Allison et al. (1996) observed that skeletal growth rate and $\delta^{18}O$ are inversely related in several *Porites lutea* coral skeleton from Phuket, South Thailand. McConnaughey (1989a) also reported an inverse relationship between linear extension and $\delta^{13}C$ and $\delta^{18}O$ in *Pavona clavus* heads from Galapagos, but that only occurred in those parts of the coral growing at less than 5mm/yr. For more rapidly growing parts of the coral, calcification rate did not appear to have a significant effect. At present, whether isotopic signatures have any potential dependence on coral growth processes still remains poorly constrained. Clearly, such questions must be answered satisfactorily before we can reliably use coral $\delta^{18}O$ and $\delta^{13}C$ for the reconstruction of past environmental variables.

(4) Other related questions concern developing $\delta^{13}C$ and $\delta^{18}O$ in corals to document patterns of interannual and interdecadal climatic variability in selected areas of the subtropical Pacific. While many studies have documented past variability of the ENSO system in the equatorial regions (e.g. Dunbar and Cole, 1993), the spatial and temporal evolution of ENSO events across the subtropical south Pacific is not well established. Based on their studies in New Caledonia (166°E, 22.5°S), Quinn et al. (1998) suggest that the subtropical regions may not correlate strongly with ENSO indices. But

studies from Moorea lagoon (149.5°W, 17.3°S) (Boiseau et al., 1998) indicate that climatic variability is strongly affected by ENSO events in the subtropical Pacific. In order to ascertain the relatively subtle interannual variability in the subtropical Pacific, it is necessary to have more records of key climatic variables such as SST and precipitation around these areas.

(5) Although interdecadal scale variability has been commonly recognized in most long coral $\delta^{18}O$ records, interpretations about this variability are diverse (Druffel and Griffin, 1993; Charles et al., 1997; Lough and Barnes, 1997; Cole et al., 2000; Linsley et al., 2000b; Urbans et al., 2000). In addition, the spatial pattern of the decadal/interdecadal variability is poorly constrained. Quinn et al. (1998) report the correlation between the PDO variation and the decadal/interdecadal variability observed in coral $\delta^{18}O$, and they imply that it may relate to the processes influencing the PDO. Cole et al. (2000) propose that the tropical Pacific is probably more important in amplifying and propagating the decadal signal due to the lack of the coherency between $\delta^{18}O$ records and the PDO in the western Indian Ocean. At present, due to the paucity of meteorologic and oceanographic data which generally extend back only about 50 years, the decadal/interdecadal variability in surface ocean properties in the Pacific gyres remains poorly understood.

1.3 Present Objectives

In view of the above problems, this study involved two major parts. The first part is concerned with evaluating the paleoclimate utility of $\delta^{18}O$ and $\delta^{13}C$ in corals based on comparison of coral and instrumental records in order to improve the precision of reconstructions of paleo-climate from proxy coral data. For this purpose, a long coral record spanning 271 years from Rarotonga in the subtropical South Pacific is used for analysis and comparison with available instrumental records.

The island of Rarotonga is located at 21.5°S, 159.5°W in the Cook Islands of the western subtropical South Pacific (WSSP). It has been recognized that WSSP is a dominant source region for water transport to the equatorial thermocline (Wyrtki and Kilonsky, 1984; Tsuchiya et al., 1989). In addition, this region is also recognized as an important source region for interannual SST anomalies propagating into higher latitudes of the Southern Hemisphere and the Antarctic Circumpolar Current (White and Peterson, 1996; Peterson and White, 1998).

Specifically, this part of the study is concerned with the following major objectives:

1. Developing a new method to separate the effects of SST from those of $\delta^{18}O_{sw}$ on coral $\delta^{18}O$ (Ren et al., in review). Based on the paired analysis of $\delta^{18}O$ and Sr/Ca in corals, a revised method of separating the effects of $\delta^{18}O_{sw}$ from that of SST is developed, and then a multi-century reconstruction of the paleo-temperature and paleo-salinity is retrieved for this region.

2. Quantitatively separating the effects of kinetic and metabolic fractionation on coral $\delta^{13}C$ in order to evaluate the effects of their corresponding environmental factors such as SST and radiation on coral $\delta^{13}C$. The similar method developed for coral $\delta^{18}O$ (Ren et al., in review) is used to separate the effects of kinetic and metabolic fractionation. This method is also applied to several other published coral $\delta^{13}C$ time-

series in order to obtain a better understanding of the role of the separate effects of kinetic and metabolic fractionation.

3. In order to test the reliability of $\delta^{18}O$ and $\delta^{13}C$ as environmental tracers, this study also involves a detailed examination of the reproducibility of skeletal $\delta^{18}O$ and $\delta^{13}C$ at Rarotonga. Another coral core collected from Rarotonga is used to examine the potential growth rate effect on both $\delta^{18}O$ and $\delta^{13}C$.

The second part of the study involves the reconstruction of the interannual (ENSO) and decadal/interdecadal variability at Rarotonga based on the analysis of $\delta^{18}O$ for the whole period of 1726-1997. For this part of the study, questions addressed include: (1) how is the record of ENSO different in this off-equatorial axis region compared to other coral-climate record of ENSO, and (2) Is decadal-interdecal scale variability at Rarotonga in the southwest Pacific correlated with North Pacific or tropical Pacific?

1.4 Chapter Overview

Chapter 2 describes a revised method for the separation of the effects of variation of $\delta^{18}O_{sw}$ from that of SST using the paired coral $\delta^{18}O$ and Sr/Ca for the period 1726-1997, and attempts to use this method to retrieve the paleo-salinity at Rarotonga. A paper describing this method is also in review at *Geochimica et Cosmochimica Acta*.

Chapter 3 describes a quantitative method similar to that used on coral $\delta^{18}O$ to separate the effects of kinetic from metabolic fractionation on $\delta^{13}C$ in corals. This method is also applied to several other areas in order to obtain a better understanding of the role of these two separate effects on coral $\delta^{13}C$.

Chapter 4 presents the general characteristics of coral $\delta^{18}O$ at Rarotonga for the total period of 1726-1997 and focuses on reconstructing the interannual and decadal/ interdecadal variability from $\delta^{18}O$ in corals in this region in order to examine the differences between the response of subtropical and tropical areas in interannual and decadal/interdecadal time scales.

Chapter 5 discusses the colony reproducibility of coral $\delta^{13}C$ and $\delta^{18}O$ by using another core collected at Rarotonga.

Chapter 6 is the conclusions and problems for future work.

CHAPTER 2

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

Abstract. To reconstruct oceanographic variations in the subtropical South Pacific, 271-year long subseasonal time series of Sr/Ca and $\delta^{18}O$ 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) (Linsley et al., 2000a) and coral $\delta^{18}O$ is a function of both sea surface temperature (SST) and sea water $\delta^{18}O$ composition ($\delta^{18}O_{sw}$). Here I focus on extracting the $\delta^{18}O_{sw}$ signal from these proxy records. A method is presented assuming that coral Sr/Ca is solely a function of SST and that coral $\delta^{18}O$ is a function of both SST and $\delta^{18}O_{sw}$. This method separates the effects of $\delta^{18}O_{sw}$ from SST by breaking the instantaneous changes of coral $\delta^{18}O$ into separate contributions by instantaneous SST and $\delta^{18}O_{sw}$ changes respectively. The results show that on average $\delta^{18}O_{sw}$ at Rarotonga explains ~39% of the variance in $\delta^{18}O$ and that variations in SST explains the remaining ~61% of $\delta^{18}O$ variance. Reconstructed $\delta^{18}O_{sw}$ shows systematic increases in summer months (Dec-Feb) consistent with the regional pattern of variations in precipitation and evaporation. The $\delta^{18}O_{sw}$ also shows a positive linear correlation with satellite-derived estimated salinity for the period 1980-1997 (r=0.72). This linear correlation between reconstructed $\delta^{18}O_{sw}$ and salinity makes it possible to use the reconstructed $\delta^{18}O_{sw}$ to estimate the past interannual and decadal salinity changes in this region. Comparisons of coral $\delta^{18}O$ and $\delta^{18}O_{sw}$ at Rarotonga with the Pacific Decadal Oscillation (PDO) 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.

2.1 Introduction

It has now been recognized that the western subtropical South Pacific (WSSP) is a dominant source region for water transport to the equatorial thermocline in part due to its relatively high salinity (Tsuchiya, 1968; Wyrtki and Kilonsky, 1984; Tsuchiya, 1989; Knuass, 1996). In addition, this region is also identified as an important source region for interannual 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 ($\delta^{18}O_{sw}$) 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 I focus on utilizing coral records from Rarotonga (21.5°S, 159.5°W) in the WSSP.

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 sea surface temperature (SST) variations. Besides SST, $\delta^{18}O$ of seawater ($\delta^{18}O_{sw}$) is another important parameter that can potentially be reconstructed using corals. $\delta^{18}O_{sw}$ 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, since the $\delta^{18}O$ composition of coral skeletons is at least a function of both SST and $\delta^{18}O_{sw}$ (Weber and Woodhead, 1972), it is generally difficult to separate the effects of SST and $\delta^{18}O_{sw}$ using coral $\delta^{18}O$ alone. One great advantage of corals for paleoclimatic studies is that they possess a remarkable array of chemical tracers which contain information on past environmental variations. While coral $\delta^{18}O$ reflects the effects of both SST and $\delta^{18}O_{sw}$, 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). Using both $\delta^{18}O$ and Sr/Ca it is therefore potentially possible to separate the different effects of $\delta^{18}O_{sw}$ and SST in a coral $\delta^{18}O$ time series (McCulloch et al., 1994; Gagan et al., 1998; 2000).

McCulloch et al. (1994) made the first attempt to quantitatively separate the effects of SST from those of $\delta^{18}O_{sw}$ on skeletal $\delta^{18}O$ by using paired coral $\delta^{18}O$ 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 $\delta^{18}O$ to obtain the residual effects of $\delta^{18}O_{sw}$. To do so, they first converted coral $\delta^{18}O$ into units of temperature ($T_{\delta^{18}O}$) by using an empirical SST-$\delta^{18}O$ equation 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 both McCulloch et al.'s and Gagan et al.'s methods is to use a linear $\delta^{18}O$-SST equation (i.e. $\delta^{18}O = k*SST + b$) as the reference to obtain the discrepancies of coral $\delta^{18}O$ due to 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 (1989a) and Gagan et al. (1994), respectively. The equation obtained in this way *may* not represent the true $\delta^{18}O$-SST relationship in areas with significant effects of $\delta^{18}O_{sw}$, 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 chapter I present a revised method of retrieving $\delta^{18}O_{sw}$ using instantaneous changes in paired measurements of $\delta^{18}O$ and Sr/Ca in corals. I apply this technique to the Rarotonga coral Sr/Ca and $\delta^{18}O$ records spanning 1726-1997. The derived $\delta^{18}O_{sw}$ time-series is then examined and discussed in terms of how paleo-salinity and rainfall varied in this region during the past three centuries.

2.2 Study Area

The island of Rarotonga is located at 21.5°S and 159.5°W in the Cook Islands of the WSSP (Fig. 2.1). 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°C to 27°C with an average annual variation of ~4°C (Fig. 2.2). 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 ~27°C (NOAA NCDC GCPS monthly station precipitation) (Baker et al., 1994).

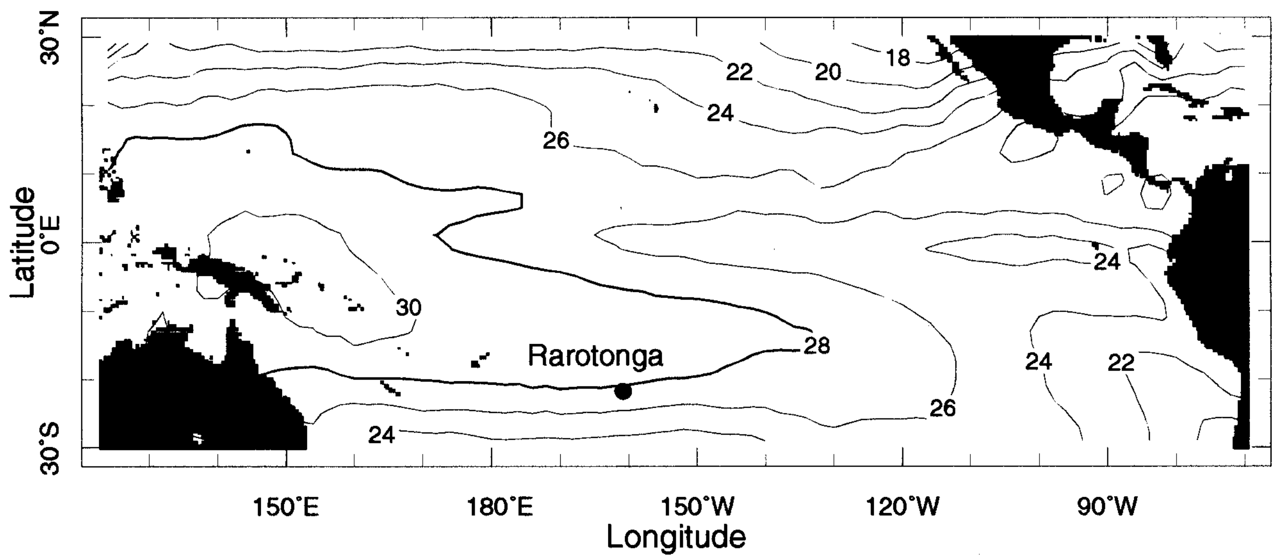

Fig. 2.1 The geographic location of Rarotonga. The contours shown are monthly averaged sea surface temperature (SST) in the Pacific. SST data is from IGOSS SST (Reynolds and Smith, 1994). The warm pool is indicated by the 28°C isotherm.

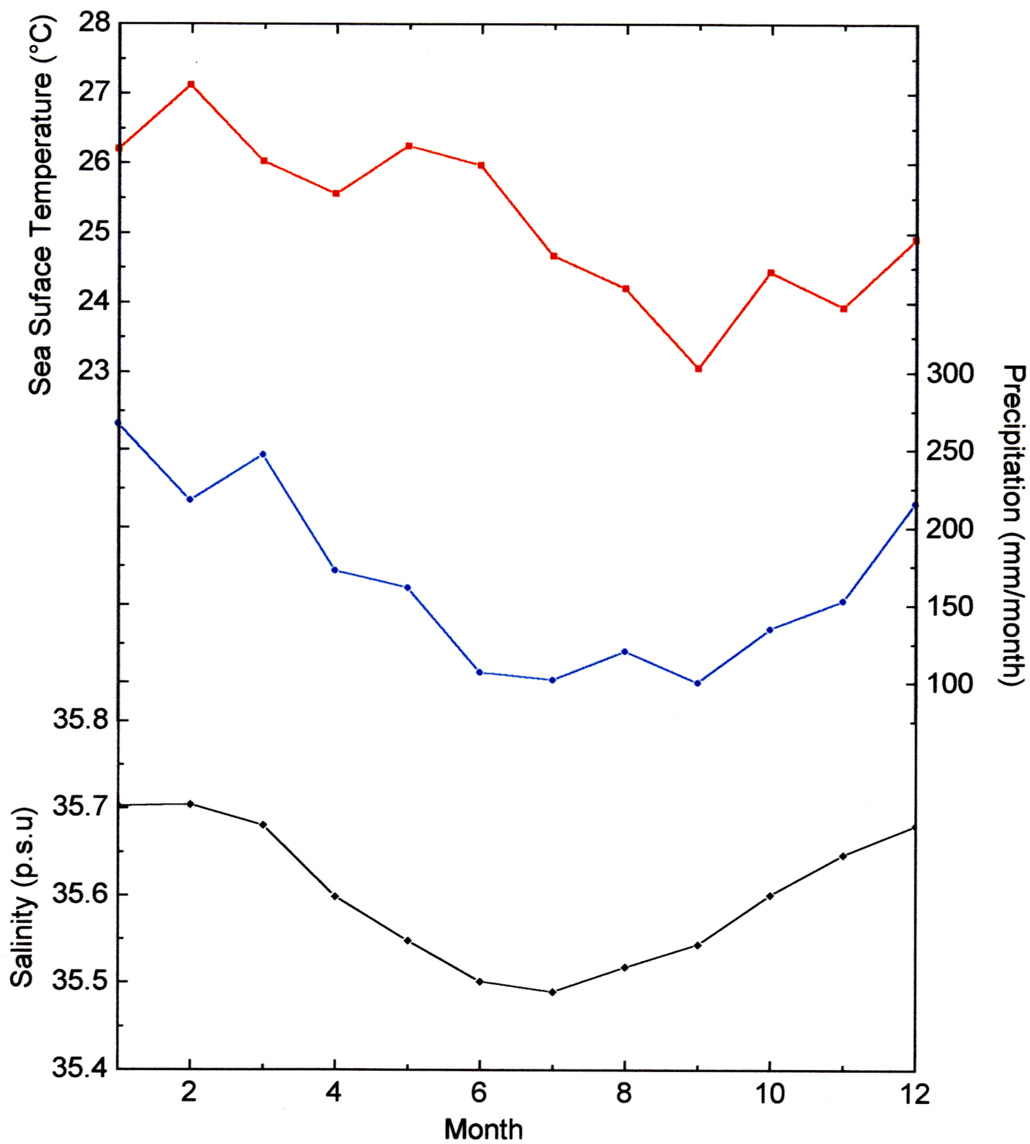

Fig. 2.2 Composite annual curves calculated by averaging monthly sea surface temperature (SST) (in red), rainfall (in blue), and salinity (at 20m depth) (in black) in the vicinity of Rarotonga for the period 1981-1997. The SST data is from IGOSS SST (Reynolds and Smith, 1994), while rainfall and salinity data are from NOAA NCDC GCPS monthly precipitation(Baker et al., 1994) and NOAA NCEP EMC CMB Pacific monthly salinity (Behringer et al., 1998; Ji et al., 1995; Ji and Smith, 1995), respectively.

In this region, instrumental salinity measurements are very limited and a satellite-derived salinity record is available only after 1980 (NOAA NCEP EMC CMB Pacific monthly salinity) (Behringer et al., 1998; Ji et al., 1995; Ji and Smith, 1995). 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 0.5-1.5p.s.u. (Ji et al., 1995). The annual salinity maxima (at 20m 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).

2.3 Methods and Results

In April 1997 several coral cores were collected from a large colony of *Porites lutea* in 18.3m (60 feet) of water on the southwest side of the Island of Rarotonga. This coral colony was not influenced by shading or other micro-environmental factors. Slabs of coral (7mm 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 1mm intervals using a low-speed micro-drill along tracks parallel to corallite traces as identified in x-ray positives (Fig. 2.3). Splits from the same sample powder were used for both $\delta^{18}O$ and Sr/Ca analyses. The total usable length of core B is 1.4m, while core C is 3.6m. Because of a growth hiatus in core C, cores B and C were spliced together to make a continuous record. I sampled core B from the top to 1316mm depth, while core C was sampled from 1104mm depth to the very bottom. This sampling scheme resulted in an overlap of about 212mm (13 years) 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 1926 A.D.

High precision determination of Sr/Ca ratios at 1mm resolution was undertaken by inductively coupled plasma atomic emission spectrophotometer (ICP-AES) at Harvard University using 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 3817. External precision is better than 0.15% (relative standard deviation, 1σ) based on analysis of replicate samples. These data are available at www.ngdc.noaa.gov/paleo/paleo.html.

$\delta^{18}O$ 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 2358. The first 889 samples were analyzed every 1 mm, while the other down-core samples were analyzed every other 1 mm. At Harvard University ~1mg samples are reacted in vacuo in a modified autocarbonate device at 90°C and the purified CO_2 analyzed. At the University at Albany ~150µg samples are dissolved in 100% H_3PO_4 at

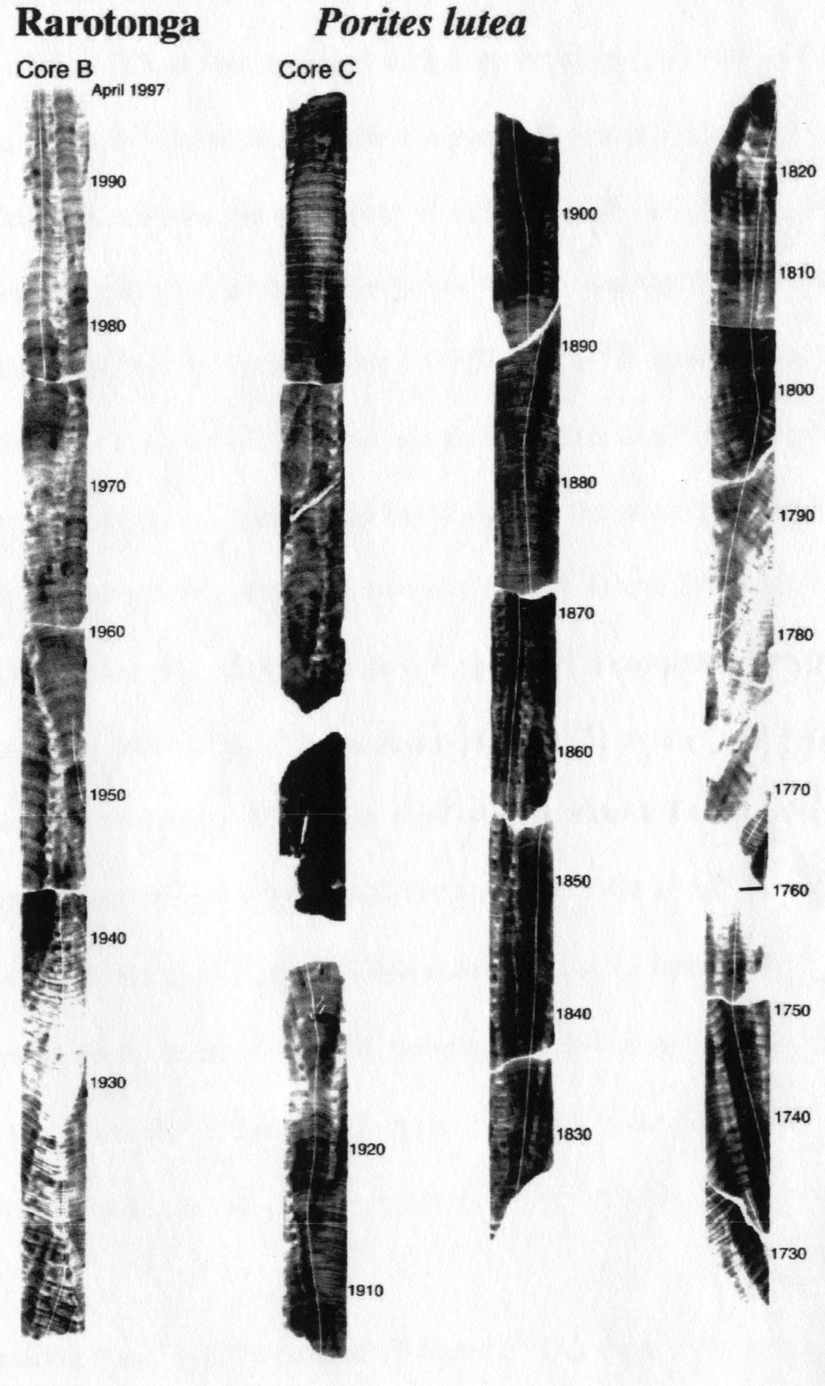

Fig. 2.3 X-ray positive collage of two coral cores (cores B and C) used in the study showing the location of mm-scale sampling transacts. Note the overall goodness of fit between the individual coral slabs except for a growth hiatus in the third section of core C.

90°C in a Multiprep carbonate inlet system and the resulting CO_2 gas analyzed. These two different sampling densities (1mm and every other 1 mm) show equal annual $\delta^{18}O$ amplitudes which suggests that analysis of discrete every other 1 mm samples still captures the full range of the annual cycle. 10% of all samples were analyzed in duplicate. External precision at the University at Albany is better than 0.04‰ for $\delta^{18}O$ based on analysis of replicate samples. The standard deviation of 468 samples of international NBS-19 analyzed was 0.038‰ for $\delta^{18}O$.

The chronology was developed based on both the density banding observed in X-radiograph positive prints and annual periodicity of $\delta^{18}O$ and Sr/Ca and it is the same as published in Linsley et al. (2000a). Both $\delta^{18}O$ and Sr/Ca document a total of 271 years of growth spanning 1997-1726. This includes the first 71 years (1997-1926) recorded in core B and the remaining 200 years (1925-1726) recorded in core C. Based on the chronology, the top 61 years were analyzed for both Sr/Ca and $\delta^{18}O$ at an average of 15 samples/year, while below 1936, Sr/Ca was analyzed at 15 samples/year and $\delta^{18}O$ at 7~8 samples/year. After determining that sampling at 7~8 samples/year for $\delta^{18}O$ did not attenuate the amplitude of the annual cycle, I linearly interpolated both Sr/Ca and $\delta^{18}O$ time series to 8 points per year for the analysis discussed below (Fig. 2.4).

2.4 Separating the Contributions of SST and $\delta^{18}O_{sw}$ from $\delta^{18}O$ in Corals

2.4.1 Method

If we assume that coral Sr/Ca is solely a function of SST and that $\delta^{18}O$ is a function of both SST and $\delta^{18}O_{sw}$, the differences between time series of the two tracers measured on the same samples should reflect the effects of $\delta^{18}O_{sw}$ variations. However,

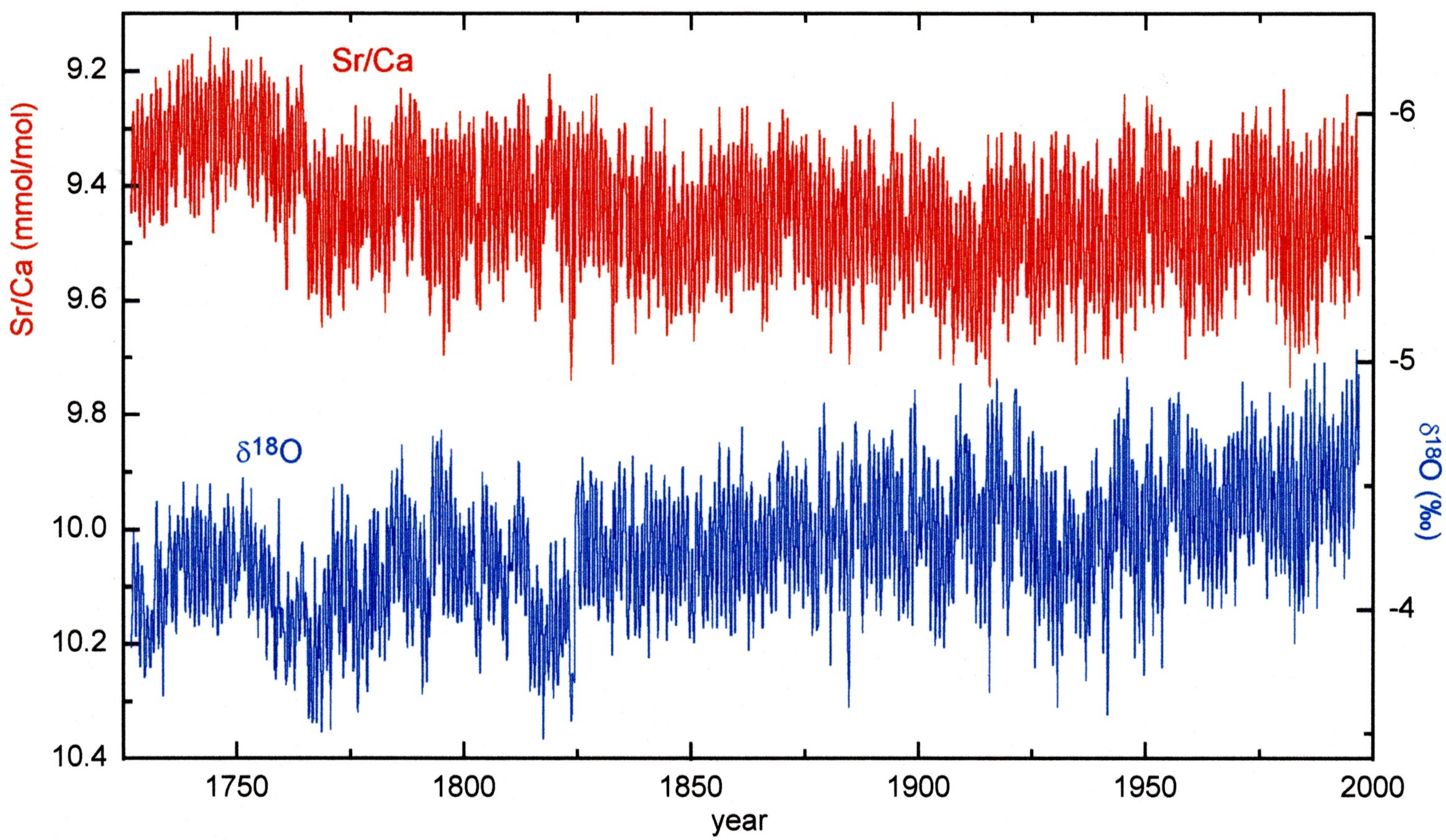

Fig. 2.4 Top curve in red: Rarotonga subseasonal Sr/Ca ratio for the period 1726-1997 (Linsley, et al., 2000a). Bottom curve in blue: Rarotonga subseasonal $\delta^{18}O$ record for the period 1726-1997.

quantitatively retrieving the effects of $\delta^{18}O_{sw}$ may not be as straightforward as it appears. Since measured coral $\delta^{18}O$ is a *multivariable*-function of SST and $\delta^{18}O_{sw}$ varying at the same time, it may not always be applicable to separate SST and $\delta^{18}O_{sw}$ effects by simply subtracting one from the other through the use of a *single-variable* equation between $\delta^{18}O$ and SST. For the coral $\delta^{18}O$-SST relationship the value of b in the $\delta^{18}O$-SST equation ($\delta^{18}O = k\text{SST} + b$) must be different under different $\delta^{18}O_{sw}$ conditions (even if k does not change). If this equation is used as the reference to obtain the component of coral $\delta^{18}O$ that is due to variations of $\delta^{18}O_{sw}$, then this component should represent the variations of coral $\delta^{18}O$ due to changes of $\delta^{18}O_{sw}$ relative to the constant level of $\delta^{18}O_{sw}$ under which the above equation applies. Since b is different under different levels of $\delta^{18}O_{sw}$, 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 $\delta^{18}O_{sw}$ changes to coral $\delta^{18}O$ variations, which should be a unique quantity. For this reason, I use a method in which I look at *instantaneous* changes of the function caused by *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 $\delta^{18}O$ 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, while the other is the contribution brought about by the instantaneous change in $\delta^{18}O_{sw}$. In mathematical terms:

$$\Delta\delta^{18}O_{(coral)} = \Delta\delta^{18}O_{(SST\ contri)} + \Delta\delta^{18}O_{(sw\ contri)}$$

$$= (\partial\delta^{18}O_{(coral)}/\partial SST)*\Delta SST + (\partial\delta^{18}O_{(coral)}/\partial\delta^{18}O_{sw})*\Delta\delta^{18}O_{sw} \quad (1)$$

where $\partial\delta^{18}O_{(coral)}/\partial SST$, and $\partial\delta^{18}O_{(coral)}/\partial\delta^{18}O_{sw}$ are the partial derivatives of $\delta^{18}O_{(coral)}$ with respect to SST and $\delta^{18}O_{sw}$, respectively. They represent the rate of change of $\delta^{18}O_{(coral)}$ with the change of one variable while the other variable is constant. Given the above linear $\delta^{18}O_{(coral)}$-SST relationship when the seawater $\delta^{18}O$ 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 biological carbonate is -0.18 to -0.24‰/°C (Epstein et al., 1953; Weber and Woodhead, 1972; Fairbanks and Dodge, 1979; McConnaughey, 1989a; Shen et al., 1992b; Wellington et al., 1996). For this study the average value of -0.21‰/°C is adopted.

Similarly, we have the following equation that relates *changes* of Sr/Ca in corals to *changes* of SST assuming Sr/Ca is only a function of SST:

$$\Delta(Sr/Ca_{(coral)})=\{\ \partial(Sr/Ca_{(coral)})/\partial SST)\ \}*\Delta SST \quad (2)$$

where $\partial(Sr/Ca_{(coral)})/\ \partial SST$ is the rate of change of Sr/Ca in corals with respect to SST. It is also a constant which has a range of -0.054 to -0.070mmol/mol/°C in biological 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 -0.062mmol/mol/°C is adopted. Rearranging (2) we can then reconstruct instantaneous SST changes from the observed Sr/Ca changes in corals as follows,

$$\Delta SST = \Delta(Sr/Ca_{(coral)}) / \{ \partial(Sr/Ca_{(coral)})/\partial SST \} \qquad (3)$$

Given the value of $\partial\delta^{18}O_{(coral)}/\partial SST$, and the above-calculated ΔSST, it is thus easy to find the first term of equation (1) ($\Delta\delta^{18}O_{(SST\ contri)}$) for any given interval of time (Fig. 2.5a). We can also convert the $\delta^{18}O$ in corals into instantaneous changes ($\Delta\delta^{18}O_{(coral)}$) for successive time intervals (Fig. 2.5b). Then using equation (1) the contribution of $\delta^{18}O_{sw}$ changes to changes of coral $\delta^{18}O$ ($\Delta\delta^{18}O_{(sw\ contri)}$) (Fig. 2.5c) can be calculated by subtracting $\Delta\delta^{18}O_{(SST\ contri)}$ from the series of $\Delta\delta^{18}O_{(coral)}$.

Note that the above method only needs the values of $\partial\delta^{18}O_{(coral)}/\partial SST$ and $\partial(Sr/Ca_{(coral)})/\partial SST$ to do the reconstruction. Since we utilize instantaneous changes instead of absolute values, we do not need to worry about the values of *b* in the $\delta^{18}O_{(coral)}$-SST and $Sr/Ca_{(coral)}$-SST equations. As noted above, the value of *b* in the $\delta^{18}O_{(coral)}$-SST equation may be different under different $\delta^{18}O_{sw}$ conditions. The same may be true with *b* in the linear $Sr/Ca_{(coral)}$-SST equation. Some authors have pointed out that there are offsets (different *b*'s) among the regression lines of $Sr/Ca_{(coral)}$-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 $\delta^{18}O_{(coral)}$-SST and $Sr/Ca_{(coral)}$-SST equations will certainly affect the result of the reconstruction of $\delta^{18}O_{sw}$ in the subtraction method. But this problem does not exist in the current method since it only involves the values of *k* in its calculations.

It should be noted that what are shown in Figs. 2.5a-c only represent instantaneous contribution*s* by SST and $\delta^{18}O_{sw}$ *changes* to *changes* of coral $\delta^{18}O$.

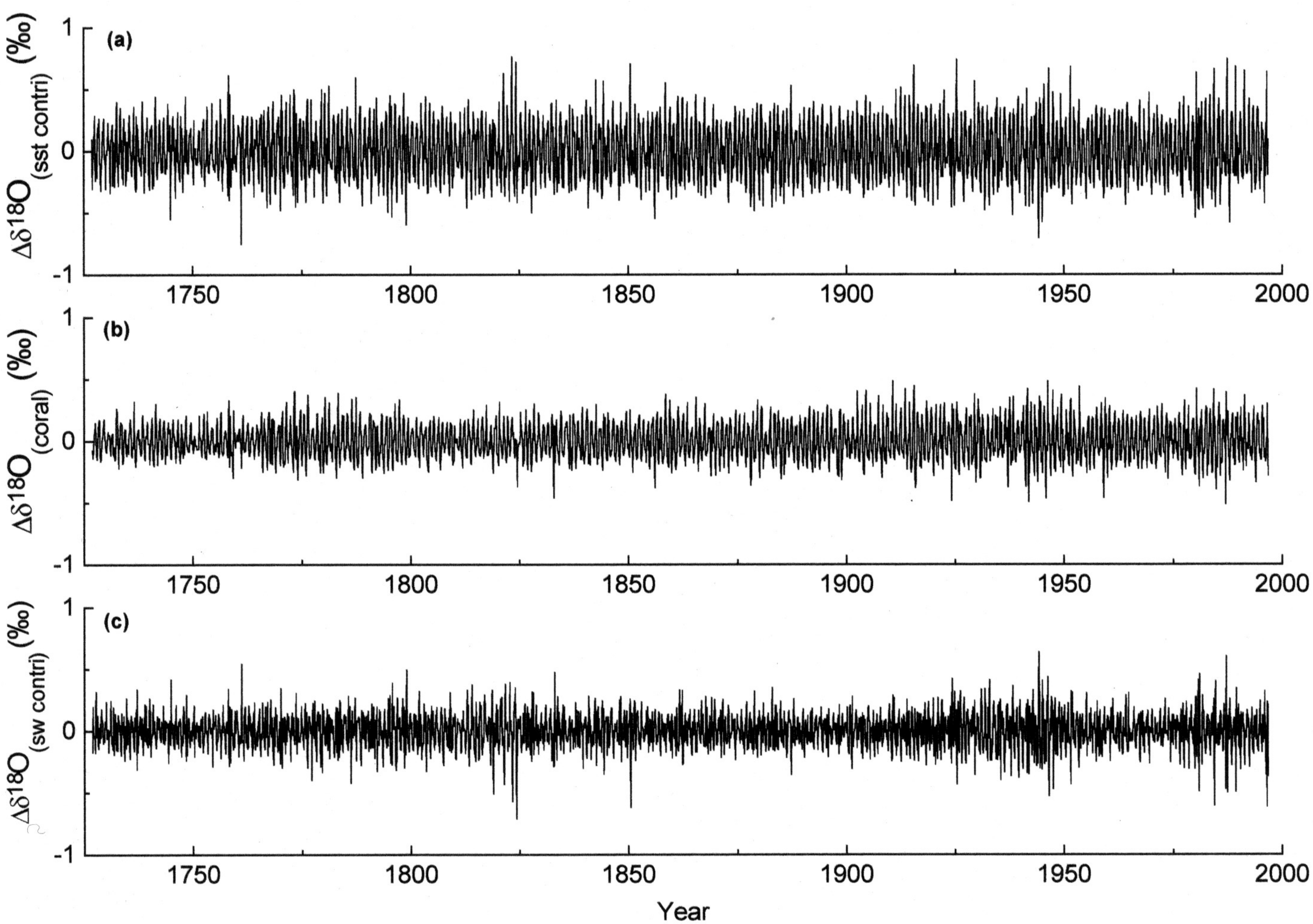

Fig. 2.5 (a) The instantaneous contribution by SST to the change of $\delta^{18}O$ in corals from Sr/Ca change for the period 1726-1997 **(b)** The instantaneous changes of $\delta^{18}O$ in corals for the period 1726-1997. **(c)** The instantaneous contribution by $\delta^{18}O_{sw}$ to the change of $\delta^{18}O$ in corals for the period 1726-1997.

According to equation (1) if we assume that the partial derivative of $\delta^{18}O_{(coral)}$ with respect to $\delta^{18}O_{sw}$ ($\partial\delta^{18}O_{(coral)}/\partial\delta^{18}O_{sw}$) is also a constant, we could further estimate the real $\delta^{18}O_{sw}$ changes. However, there is very limited data available in the literature on this topic. Since the above assumption appears to be reasonable, we can simply view the shape of $\Delta\delta^{18}O_{(sw\ contri)}$ curve as also representing the actual variation of $\delta^{18}O_{sw}$ 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 $\delta^{18}O_{sw}$ can be obtained by integrating the series in Fig. 2.5c 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 $\delta^{18}O_{sw}$ value in this region as the reference. Unfortunately, there is no currently available site-specific $\delta^{18}O_{sw}$ data at Rarotonga. Schmidt (1999) indicates that at present most regional surface water $\delta^{18}O$ and salinity relationships tend to converge near $\delta^{18}O_{sw}$=0.8‰ when S=36‰ and $\delta^{18}O_{sw}$=0‰ when S=34.7‰ and the $\delta^{18}O_{sw}$ and salinity are roughly linearly related. At Rarotonga the average salinity is 35.5‰ which would result in $\delta^{18}O_{sw}$=0.57‰. This value is close to a $\delta^{18}O_{sw}$ of 0.52‰ (Beck et al., 1992; J. Recy, unpublished data, 1995) measured in New Caledonia which is west of Rarotonga, but at a similar latitude as Rarotonga. To determine the cumulative seawater contribution I choose 0.57‰ as the reference for 1997 and summed the instantaneous changes back to 1726 (Fig. 2.6a). For the period 1726-1997 the reconstructed cumulative $\delta^{18}O_{(sw\ contri)}$ shows clear seasonal, decadal, and secular variations.

2.4.2 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 $\delta^{18}O$ composition contribution are now estimated. Let σ_1 be the absolute error of the partial derivative of coral $\delta^{18}O$ with respect to SST (±0.03), σ_2 be the absolute error of the partial derivative of Sr/Ca with respect to SST (±0.008), and σ be the relative error of the calculated instantaneous contribution by $\delta^{18}O$ changes. According to equation (1) and (2) we have:

$$\Delta\delta^{18}O_{(SST\ contri)}\ (1\pm\sigma) = \{(\partial\delta^{18}O_{(coral)}/\partial SST \pm \sigma_1)/(\partial(Sr/Ca_{(coral)})/\partial SST \pm \sigma_2)\} * \Delta(Sr/Ca_{(coral)})$$

$$= \{ (-0.21\pm 0.03)/(-0.062 \pm 0.008) \} * \Delta(Sr/Ca_{(coral)})$$

Since the absolute error of $(\partial\delta^{18}O_{(coral)}/\partial SST\pm\sigma_1)/(\partial(Sr/Ca_{(coral)})/\partial SST\pm \sigma_2)$ is $(0.062*0.03 + 0.21*0.008)/0.062^2 = 0.92$, we have,

$$\Delta\delta^{18}O_{(SST\ contri)}\ (1\pm \sigma) = (3.39\pm 0.92) * \Delta(Sr/Ca)$$

or

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

This means a relative error of up to ±27% on the reconstructed $\Delta\delta^{18}O_{(SST\ contri)}$ due to uncertainties of the values of the two *k*'s in the calculations. The effects of this error on the reconstructed $\Delta\delta^{18}O_{(sw\ contri)}$ can be tested by tentatively increasing or decreasing the reconstructed $\Delta\delta^{18}O_{(SST\ contri)}$ by 27% and then examining the recalculated $\delta^{18}O_{(sw\ contri)}$ (Fig. 2.6b). From Fig. 2.6b it can be seen that although there are some differences in

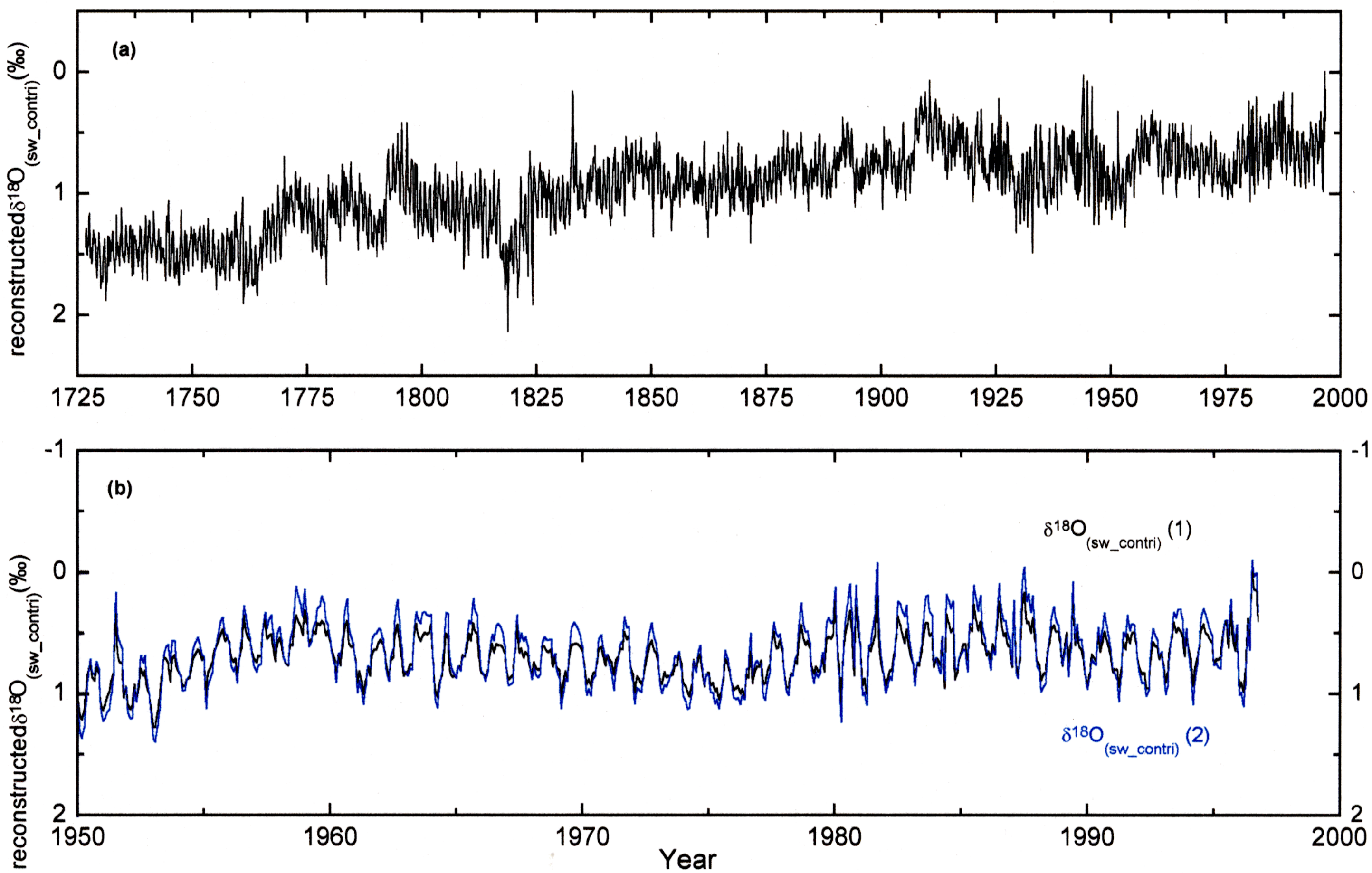

Fig. 2.6 (a) Reconstructed $\delta^{18}O_{(sw\_contri)}$ from $\delta^{18}O$ and Sr/Ca ratio in corals for the period 1726-1997. **(b)** Comparison of reconstructed $\delta^{18}O_{(sw\_contri)}$ in (a) ($\delta^{18}O_{(sw\_contri)}$ (1) in black) with the recalculated $\delta^{18}O_{(sw\_contri)}$ ($\delta^{18}O_{(sw\_contri)}$ (2) in blue) after adding the relative error of 27% (only show the portion of 1950-1997) (see text for discussion of error estimate).

the magnitude of the annual variability in the two curves, the overall interannual and decadal scale patterns are consistent.

2.5 Discussion

2.5.1 The Reconstruction of Precipitation and Salinity from $\delta^{18}O_{sw}$

I argue that $\delta^{18}O_{sw}$ at Rarotonga generally reflects regional changes in the hydrological budget of the air-sea system since rainfall is depleted in ^{18}O relative to seawater, while evaporation tends to enrich the surface ocean in ^{18}O (Epstein and Mayeda, 1953; Friedman et al., 1961; Redfield and Feridman, 1965). At Rarotonga the comparison of $\delta^{18}O_{(sw\ contri)}$ with the monthly precipitation data from the Island of Rarotonga does show a general negative correlation for the most of the period 1900-1997, which further supports the validity of this method (Fig. 2.7). For the same time intervals when precipitation increases, $\delta^{18}O_{(sw\ contri)}$ is generally lower, while when precipitation decreases, $\delta^{18}O_{(sw\ contri)}$ is higher. However, there are some discrepancies between the two curves, for instance, for the three periods marked (1) to (3) in Fig. 2.7. $\delta^{18}O_{(sw\ contri)}$ is also characterized by stronger decadal variability than rainfall which may be due to the fact that $\delta^{18}O_{sw}$ reflects the regional hydrological balance between precipitation and evaporation, rather than only precipitation changes. On interannual time scales, however, the reconstructed $\delta^{18}O_{(sw\ contri)}$ appears to be more related to the past precipitation variation.

As salinity is also mainly controlled by the precipitation-evaporation balance, $\delta^{18}O_{sw}$ should also reflect the changes of salinity. At Rarotonga, although salinity data (at 20m depth) are only available after 1980, the comparison of the cumulative $\delta^{18}O_{(sw\ contri)}$

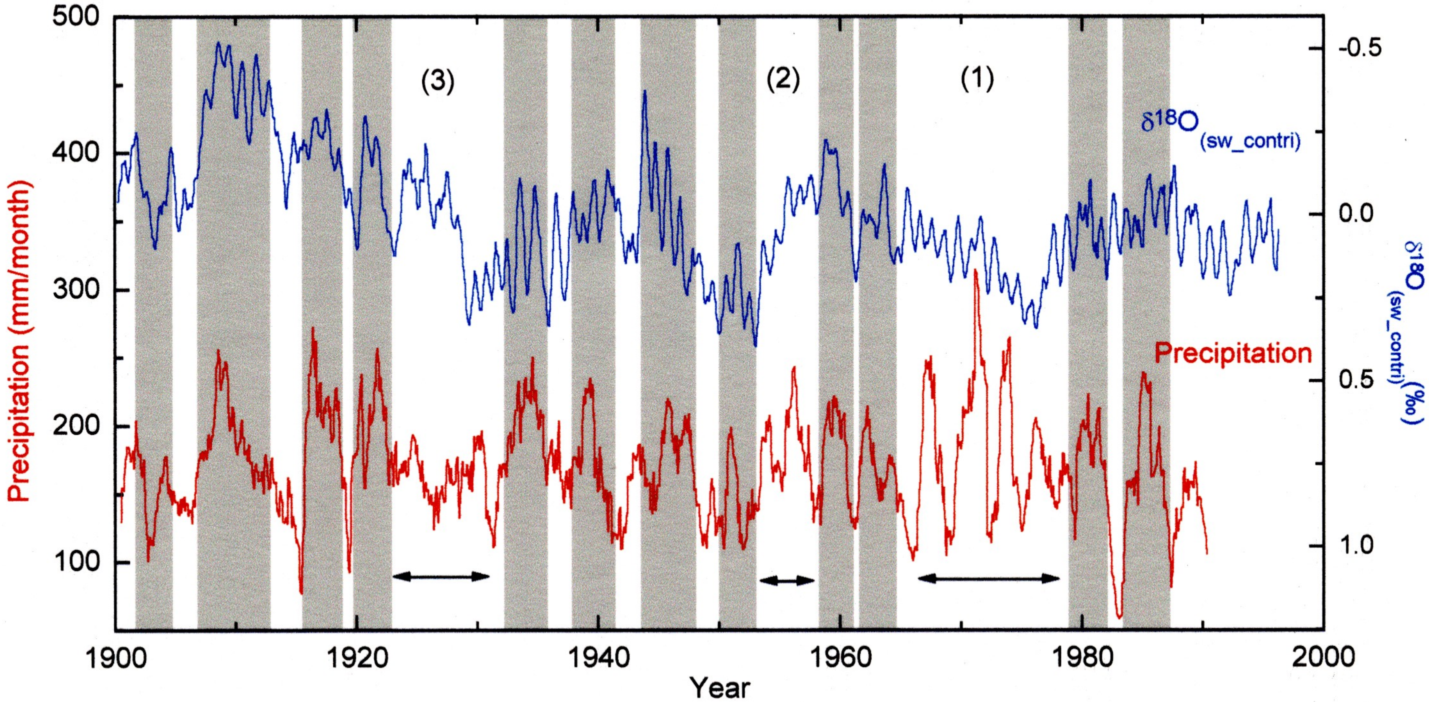

Fig. 2.7 Comparison of derived $\delta^{18}O_{(sw\_contri)}$ (in blue) and precipitation data (in red) (Baker et al., 1994) for the period 1900-1997. 1-year smooting applied on the two curves to remove the random noise. The shadows represent their similar variabilities during the same time intervals in $\delta^{18}O_{(sw\_contri)}$ and precipitation. The numbers (1)-(3) marked in the figure are the three periods that do not show very apparent similar trend between the two curves.

with the monthly salinity (NOAA NCEP EMC CMB Pacific monthly salinity) (Behringer et al., 1998; Ji et al., 1995; Ji and Smith, 1995) for 1980-1997 does show a positive correlation (Fig. 2.8). The correlation is better in some years, for example 1989 and 1996, when salinity exhibits a large decrease, and $\delta^{18}O_{(sw\ contri)}$ 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 1-2 month offset in several years with salinity leading reconstructed $\delta^{18}O_{sw}$. The reason for this is not clear. One possibility may be related to the fact that coral growth rates change throughout the year while our age model does not take this into account. As the salinity data is not in situ data, but is 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) between reconstructed $\delta^{18}O_{(sw\ contri)}$ and salinity is identified which 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 $\delta^{18}O_{(sw\ contri)}$ technique might be used to evaluate past interannual and decadal salinity changes at Rarotonga back to 1726.

2.5.2 The Separate Influences of $\delta^{18}O_{sw}$ and SST on $\delta^{18}O$ in Corals

Comparison of the instantaneous contribution by SST changes (see Fig. 2.5a) with instantaneous changes of coral $\delta^{18}O$ (see Fig. 2.5b) indicates that the average annual range in coral $\delta^{18}O$ is less than that of the expected contribution based on actual SST variation. Our preferred explanation is that the effect of $\delta^{18}O_{sw}$ must have counteracted

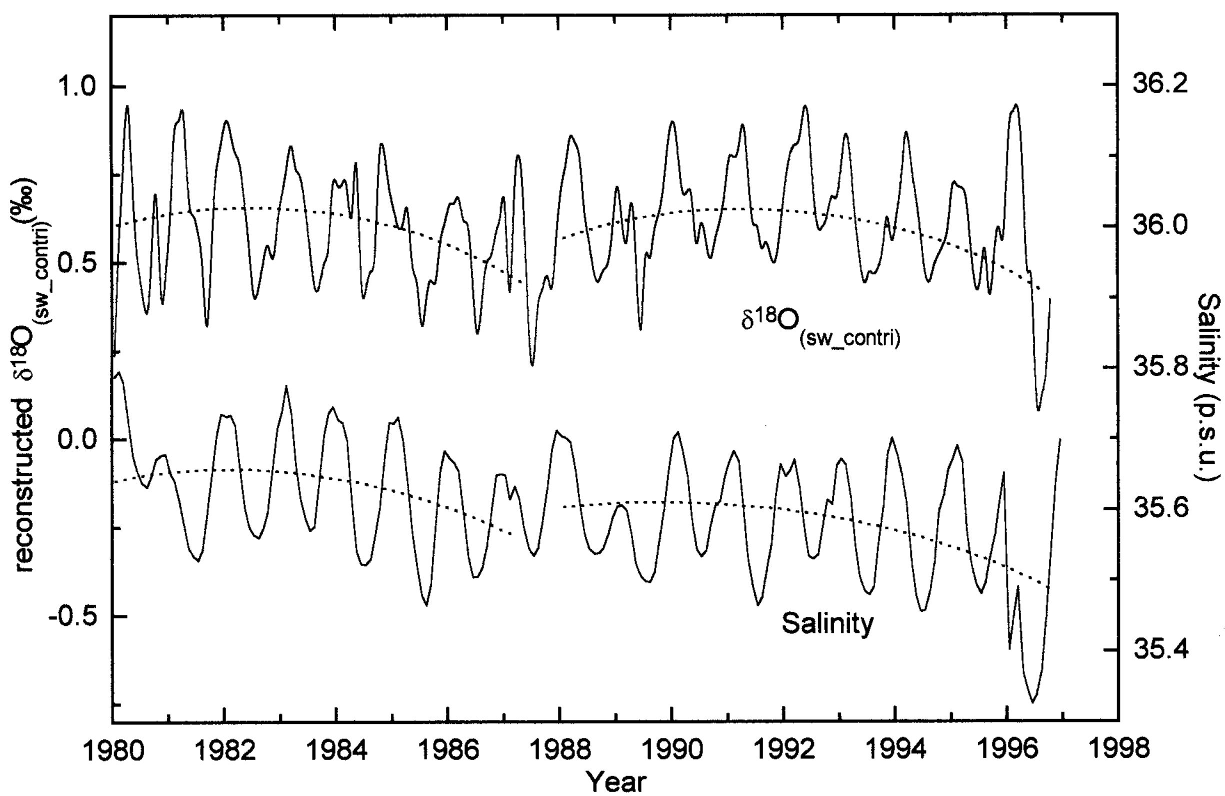

Fig. 2.8 Comparison between derived $\delta^{18}O_{(sw\_contri)}$ and salinity (Behringer, et al., 1998; Ji et al., 1995; Ji and Smith, 1995) for the period 1980-1997. The dash lines represent the potential similar trends in $\delta^{18}O_{(sw\_contri)}$ and salinity.

that of SST provided that the coral $\delta^{18}O$ is mainly a function of $\delta^{18}O_{sw}$ and SST. Detailed comparison of the time series in Fig. 2.5a with that in Fig. 2.5c indicates that the contributions from the changes of $\delta^{18}O_{sw}$ and that from the changes of $\delta^{18}O_{SST}$ are generally negatively correlated (Fig. 2.9). That is, whenever SST increases and causes the decrease of coral $\delta^{18}O$, $\delta^{18}O_{sw}$ often decreases and causes the increase of coral $\delta^{18}O$. Although I only show a 15-year interval here (1980-1995), 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°-26° latitude) which is a region with the highest evaporation and lowest humidity in the summer (Prixoto and Kettani, 1973; Levitus, 1982). At Rarotonga, in summer (January-February) when the SST increases, coral $\delta^{18}O$ 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 (see Fig. 2.2). This causes an increase of $\delta^{18}O_{sw}$ thus counter-acting the effect of SST on coral $\delta^{18}O$. My derived $\delta^{18}O_{(sw\ contri)}$ in the South 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 $\delta^{18}O_{sw}$ becomes more positive in summer as evaporation from the ocean surface increases due to increasing air temperature and solar radiation.

Given the separate contributions by SST and $\delta^{18}O_{sw}$ to coral $\delta^{18}O$ we can estimate their relative contributions. At Rarotonga on average, changes in SST account for approximately 61% of the total $\delta^{18}O$ coral signal while changes in $\delta^{18}O_{sw}$ account for

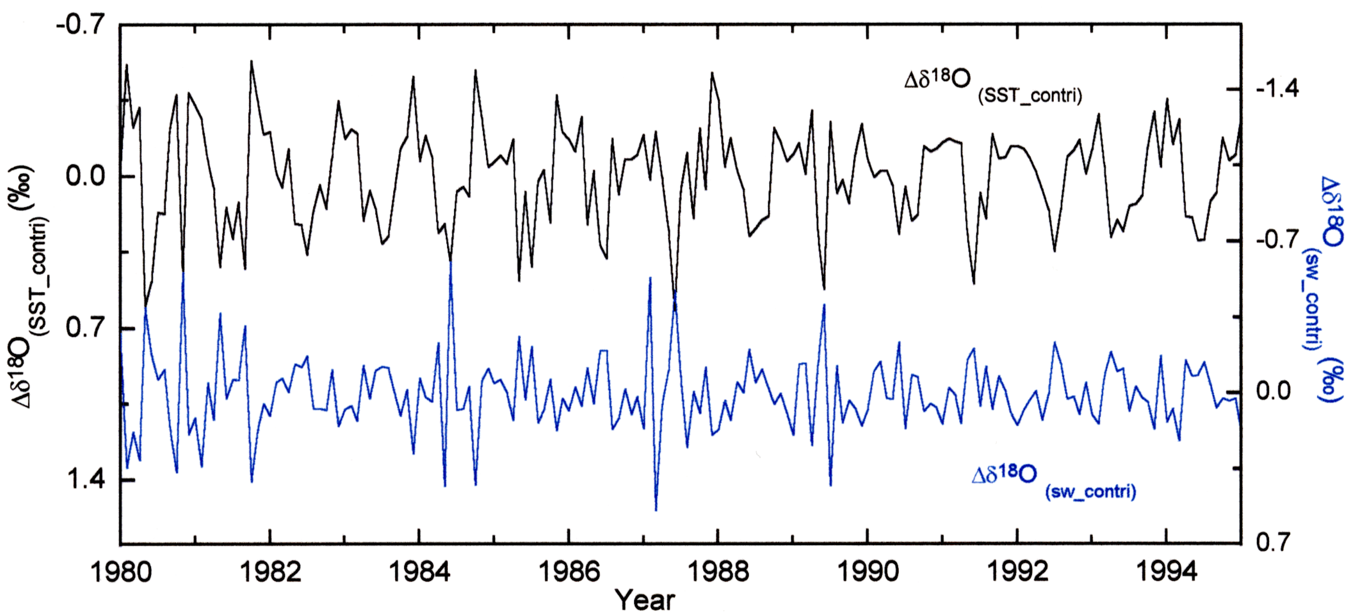

Fig. 2.9 Comparison of the instantaneous changes of the contribution from SST (in black) to the total coral $\delta^{18}O$ with that from $\delta^{18}O_{(sw\_contri)}$ (in blue) to the total coral $\delta^{18}O$ to show their opposite correlation (only shows the portion of 1980-1995).

about 39%. From this analysis it is clear that the influence of evaporation in the SPCZ on $\delta^{18}O_{sw}$ and/or salinity is non-negligible and plays a large role in the $\delta^{18}O$ composition of corals at Rarotonga.

2.5.3 The Decadal Variability in Rarotonga Coral $\delta^{18}O$ and $\delta^{18}O_{sw}$

Although decadal-interdecadal variability in the South Pacific remains weakly constrained, decadal variability in the North Pacific has been extensively documented in recent years (Trenberth and Hurrell, 1994; Graham, 1994; Mann and Park, 1996; Latif et al., 1997; Nakamura and Yamagata, 1999) and can be represented by the Pacific Decadal Oscillation (PDO) index which 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 $\delta^{18}O$ and $\delta^{18}O_{sw}$ at Rarotonga show clear decadal-scale variations over the period 1726-1997. During some years the two series are consistent, for example between 1820-30 and between 1920-40, which implies a common forcing mechanism. To remove the potential interference of any long-term trend, the Rarotonga $\delta^{18}O$ and $\delta^{18}O_{sw}$ records were detrended of long-term secular variability and compared to 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 $\delta^{18}O$ (Fig. 2.10a) shows relatively good correlation between decadal-scale variability in coral $\delta^{18}O$ and the PDO Index. The correlation is reduced due to discrepancies in the range of the variations between the two curves during several time intervals (see Fig. 2.10a). In the first (#1) and

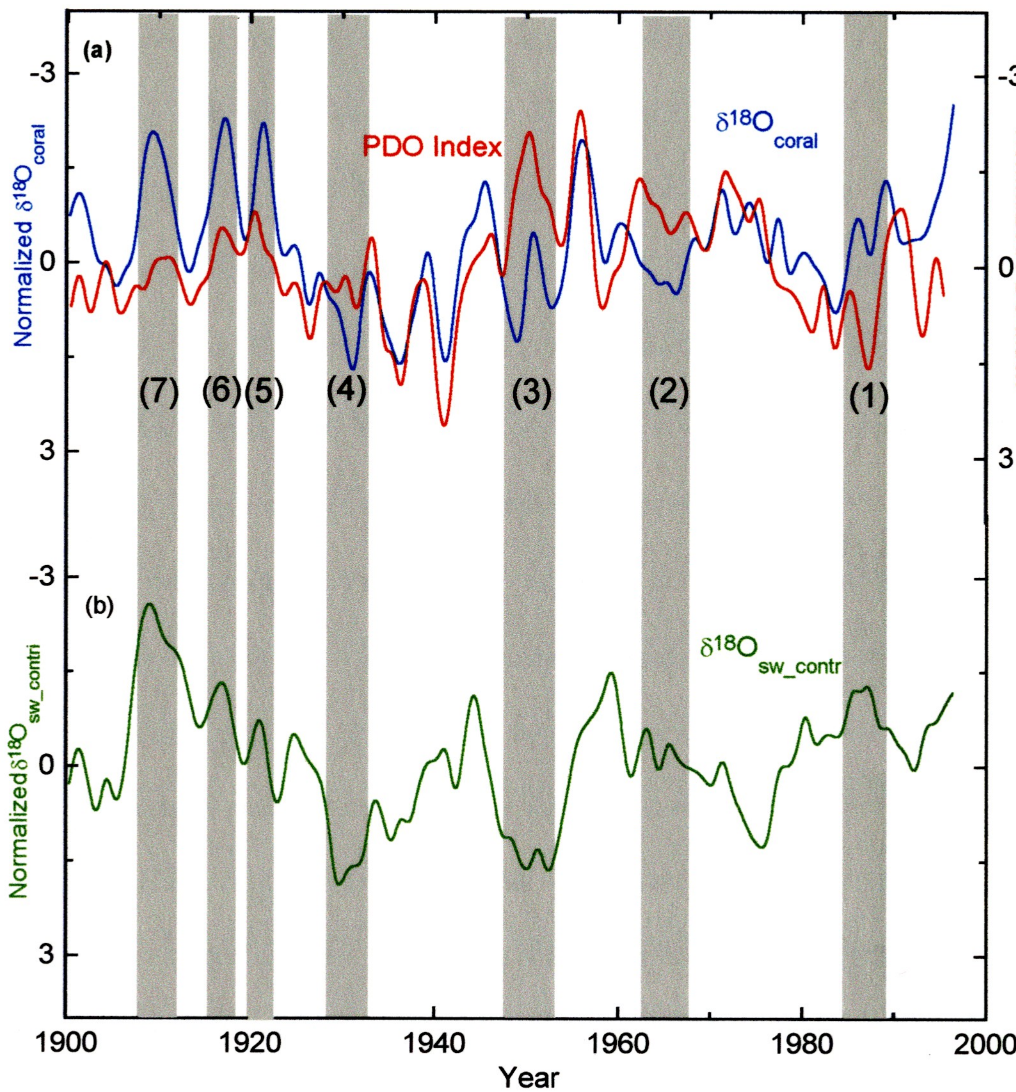

Fig. 2.10 (a) Comparison between annual average $\delta^{18}O$ (in blue) in Rarotonga corals and annual average PDO Index (in red) for the period 1900-1997. **(b)** The reconstructed annual average $\delta^{18}O_{(sw\_contri)}$ for the period 1900-1997. PDO Index, coral $\delta^{18}O$ and $\delta^{18}O_{(sw\_contri)}$ are all detrended and 5-year smoothing to highlight their decadal variability and they are all normalized in standard deviation units for comparison. The shadows marked by (1)-(7) in (a) and (b) are the time intervals that have disagreement between normalized $\delta^{18}O$ in corals and PDO Index and their corresponding changes in $\delta^{18}O_{(sw\_contri)}$.

last three time intervals (#5-7) the coral $\delta^{18}O$ is ~1-1.5 units lower than the PDO index, while in the other three time intervals (#2-4) the coral $\delta^{18}O$ is ~1-1.5 units higher than the PDO index. However, almost all these discrepancies between the coral $\delta^{18}O$ and the PDO index are correspondingly reflected in the reconstructed $\delta^{18}O_{sw}$ as shown in Fig. 2.10b. While the first (#1) and the last three intervals (#5-7) are characterized by correspondingly lower $\delta^{18}O_{sw}$, the other three intervals (#2-4) are periods of higher $\delta^{18}O_{sw}$, showing exactly the opposite to changes of #1 and #5-7 intervals. This indicates that although coral $\delta^{18}O$ cannot be directly correlated with the PDO index (due to the fact that it reflects both SST and $\delta^{18}O_{sw}$ while the PDO index is based entirely on SST variations), it can still be combined with the reconstructed $\delta^{18}O_{sw}$ to make inferences about the association of the decadal variability at Rarotonga with the Pacific Decadal Oscillation. From Figs 2.10a-2.10b the combined coral $\delta^{18}O$ and $\delta^{18}O_{sw}$ 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 hemisphere (e.g., Trenberth and Hurrel, 1994; Garreaud and Battisti, 1999). However, due to the short section of overlap in relationship to the long period of the decadal-scale changes, longer records from both the North and South Pacific would allow a more rigorous evaluation of the extent of coherence of decadal variability in the Pacific.

2.5.4 The Long-term Trend in $\delta^{18}O_{sw}$

The long-term trend in $\delta^{18}O_{sw}$ shows a progressive depletion towards the top of the record, implying a gradual trend towards lower salinity in this region (see Fig. 2.6a). The total decrease in $\delta^{18}O_{sw}$ at Rarotonga is 0.75‰ from 1726-1997. Urban et al. (2000) suggest that the trend towards warming and freshening of seawater observed in coral $\delta^{18}O$ from Maiana (1°N, 173°E) may represent an expansion of western Pacific warm pool over the past 155 years, since Maiana lies at the eastern edge of the existing warm pool. The long-term trend towards freshening in reconstructed $\delta^{18}O_{sw}$ at Rarotonga appears to support this observation as Rarotonga lies at the southeastern edge of the pool (see Fig. 2.1).

Unlike $\delta^{18}O_{sw}$, 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 which have demonstrated the existence of Pacific warming in the 20th century (Roemmich and McGowan, 1995; McGowan et al., 1998; Cane et al., 1997, Linsley et al., 2000b). Although there have been no direct measurements of long term variations of $\delta^{18}O_{sw}$ in the South Pacific gyre to demonstrate if the trend in coral $\delta^{18}O$ reflects a secular salinity variation, my results suggest that variations of $\delta^{18}O_{sw}$ may contribute more to the long-term trend in coral $\delta^{18}O$ 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. Non-biological causes of long-term variability in coral $\delta^{18}O$ (such as coral growing at shallower water depth as the coral grows upwards) 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 using other corals in the region.

2.6 Summary

(1) Assuming that coral $\delta^{18}O$ is a function of SST and $\delta^{18}O_{sw}$, and that Sr/Ca is a function of only SST, the effects of $\delta^{18}O_{sw}$ on coral $\delta^{18}O$ can be separated from those of SST by breaking the instantaneous changes of coral $\delta^{18}O$ into separate contributions by instantaneous SST and $\delta^{18}O_{sw}$ changes, respectively. By finding the contribution of SST from the reconstructed SST using Sr/Ca, the contribution by $\delta^{18}O_{sw}$ can then be found.

(2) The above method was applied to a coral $\delta^{18}O$ record from Rarotonga (21.5°S, 159.5°W) spanning 1726-1997. It was found that changes in SST account for approximately 61% of the total coral $\delta^{18}O$ variations while changes in $\delta^{18}O_{sw}$ account for about 39%. This suggests that the SPCZ and/or evaporation rate have a significant effect on $\delta^{18}O_{sw}$ and coral $\delta^{18}O$ at this site. The interannual variations of reconstructed $\delta^{18}O_{sw}$ contribution show generally negative correlation with instrumental precipitation for the most of the period 1900-1997. But there also exist some discrepancies between them, which may be related to the fact that $\delta^{18}O_{sw}$ reflects the regional hydrological balance between precipitation and evaporation, rather than only precipitation. The $\delta^{18}O_{sw}$ also shows a relatively good correlation with satellite derived salinity for the period 1980-1997. The roughly linear correlation between the reconstructed $\delta^{18}O_{sw}$ and salinity (r=0.72) for the period 1981-1997 implies that we

can use $\delta^{18}O_{sw}$ 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 $\delta^{18}O_{sw}$. 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 reflect the combined effects of SST and salinity. It agrees with some other studies which suggest that North Pacific interdecadal changes appear to be linked through ocean-atmosphere teleconnections to the southern hemisphere.

CHAPTER 3

SEPARATING THE EFFECTS OF KINETIC AND METABOLIC FRACTIONATION ON CORAL $\delta^{13}C$

Abstract. This chapter presents a 271-year (1726-1997) subseasonal carbon isotope ($\delta^{13}C$) record from a Rarotonga coral (*Porites lutea*) in the southwest subtropical Pacific. A quantitative method similar to that used for separating the effects of SST from those of $\delta^{18}O_{sw}$ on coral $\delta^{18}O$ (see chapter 2) is applied to part of this $\delta^{13}C$ record in order to separate the effects of kinetic and metabolic fractionation on $\delta^{13}C$ over the period from 1983-1991. Assuming that $\delta^{13}C$ in Dissolved Inorganic Carbon (DIC) was constant for the period 1983-1991, the instantaneous changes of $\delta^{13}C$ in corals can be expressed as the sum of two separate instantaneous contributions brought about by instantaneous changes of kinetic and metabolic fractionation, respectively. Based on experimental data, the relative proportions of these two effects are estimated. The results show that $\delta^{13}C$ at Rarotonga appears to be mainly affected by metabolic activity (72%) rather than kinetic activity (28%). The method is also applied to several $\delta^{13}C$ records from other areas (Nauru, Kiritimati, Clipperton, and New Caledonia) from both the tropical and subtropical Pacific. The results show that for tropical areas, $\delta^{13}C$ variation in corals is predominantly influenced by changes of metabolic activity. The contributions by changes of metabolic fractionation are almost identical to the total coral $\delta^{13}C$ changes, while those attributed to kinetic fractionation are very small. For subtropical areas, despite the apparent strong effects of kinetic activity due to larger annual range of SST, coral $\delta^{13}C$ is also primarily controlled by metabolic activity rather than kinetic activity.

3.1 Introduction

Studies during the past several decades have demonstrated the utility of a diverse array of chemical and physical tracers in corals as climate proxies. While the stable oxygen isotopic signature ($\delta^{18}O$) in reef corals has proven to be a reliable recorder of sea surface temperature (SST) and salinity, the application of the carbon isotope ($\delta^{13}C$) record is still problematic because of the complicated interactions of physiological processes that involve strong isotopic fractionation. Unlike $\delta^{18}O$, $\delta^{13}C$ in corals is affected by both kinetic and metabolic fractionation. Kinetic fractionation results from discrimination against the heavy isotopes of both C and O during the hydration and hydroxylation of CO_2 (McConnaughey 1989a, b). Slow exchange of oxygen and carbon isotopes between dissolved CO_3^{2-} and seawater relative to the fast rate of calcification appears to be the main effect preventing $\delta^{18}O$ and $\delta^{13}C$ equilibrium during $CaCO_3$ precipitation (Land et al., 1975; McConnaughey, 1989a, 1997). Although some authors report an inverse correlation between skeletal growth rate and coral $\delta^{18}O$ and $\delta^{13}C$ (Land, et al., 1975; Allison et al., 1996; Cohen and Hart, 1997), many researchers suggest that the departure from the equilibrium appears to remain constant above linear extension rates of 5mm/yr (e.g. McConnaughey, 1989a). Therefore, it is generally assumed that along the axis of maximum growth in massive hermatypic corals the effects of growth rate on coral isotopes are constant, and the kinetic fractionation mainly varies with the change of SST. With an increase of SST, kinetic fractionation will become stronger which causes coral $\delta^{13}C$ to be more depleted (Grossman and Ku, 1986; Bemis et al., 2000).

Metabolic fractionation produces additional changes in skeletal $\delta^{13}C$, apparently arising from changes in the $\delta^{13}C$ of the dissolved inorganic carbon (DIC) reservoir from which the skeleton precipitates (McConnaughey, 1989a; McConnaughey et al., 1997). There are two main sources and two processes that may potentially alter the carbon reservoir. The two main sources of carbon for corals are DIC in the surrounding sea water, which has a mean $\delta^{13}C_{PDB}$ value of 0‰, and zooplankton with $\delta^{13}C_{PDB}$ values ranging from –14 to –25‰ and lower (Rau et al., 1989, 1990). The two processes that may change the internal carbon pool are autotrophy (photosynthesis and respiration) and heterotrophy. It is generally believed that as the rate of photosynthesis in zooxanthellae increases, the carbon pool becomes relatively depleted in ^{12}C relative to ^{13}C. This results in an enrichment in skeletal ^{13}C. On the contrary, respiration lowers the $\delta^{13}C$ of the DIC reservoir. Several studies have suggested that the respiratory effect is apparently small in corals (Land et al., 1975; McConnaughey, 1989a). The intensity of photosynthesis depends on several environmental factors such as radiation (solar irradiance levels), cloud cover, water transparency, upwelling events, as well as SST (Land et al., 1975; Fairbanks and Dodge, 1979; Jacques et al., 1983; McConnaughty, 1989a; Leder et al., 1991). As radiation levels increase and/or cloud cover decreases, photosynthesis will generally increase. Increased water transparency and decreased upwelling will also increase light levels, thus increasing photosynthesis (Lelekin and Zvalinsky, 1981). Experiments also show that the rate of photosynthesis increases at higher temperatures in corals (Coles and Jokiel, 1977; Jacques et al., 1983). Although rising temperature increases both the rates of photosynthesis and respiration, generally corals show a growth optimum around 24°-

28°C which coincides with the maximum rate of photosynthesis rather than that of respiration (Swart, 1983).

In addition to processes of photosynthesis and respiration, the process of heterotrophy can also alter the carbon pool available to corals (Rau et al., 1989; 1990). The role of heterotrophic nutrition has been investigated by several authors, e.g. Porter (1976), Edmunds and Davies (1986), Sorokin (1993), and Grottoli and Wellington (1999), and the prevalent conclusion drawn from these studies is that the majority of hermatypic coral species are largely autotrophic.

Therefore, the main processes that affect the skeletal $\delta^{13}C$ in corals include kinetic and metabolic fractionation (Weber and Woodhead, 1970; McConnaughey, 1989a). While the former is mainly controlled by SST, the latter is a complex function of several climatic variables including solar radiation and SST. At present there are mainly two different opinions about the relative importance of the effects of these two processes on temporal variations of coral $\delta^{13}C$. Some authors believe that coral $\delta^{13}C$ is predominantly influenced by metabolic fractionation (Fairbanks and Dodge, 1979; Land et al., 1975; Leder et al., 1991; Shen et al., 1992b). Because photosynthesis is a light driven metabolic reaction, these studies observed that: (1) skeletal $\delta^{13}C$ varies seasonally in accordance with light levels (Fairbanks and Dodge, 1979; Shen et al., 1992; Gagan et al., 1994; Wellington and Dunbar, 1995), and that (2) skeletal $\delta^{13}C$ levels decrease with water depth (Land et al., 1975; Fairbanks and Dodge, 1979; Leder et al., 1991). Fairbanks and Dodge (1979) also observed that individuals from shallower depths have higher $\delta^{13}C$ and those from deeper depths have a lower $\delta^{13}C$ as a consequence of the exponential reduction of light with depth. Thus they suggested that $\delta^{13}C$ in corals can be used to retrieve past variations of solar radiation and/or cloud cover. However, other authors argue that kinetic fractionation can be more important than metabolic fractionation (McConnaughey, 1989a). They observed that the kinetic depletion of ^{13}C sometimes overpowers the photosynthetic ^{13}C increase (McConnaughey, 1989a; Muscatine et al., 1989; McConnaughey et al., 1997).

Current interpretations of coral $\delta^{13}C$ variability are generally driven by observed correlations to specific processes or conditions, rather than by a thorough understanding of all relevant processes. Although some studies have shown that in certain environments coral $\delta^{13}C$ shows a strong correlation with specific climatic variables such as solar radiation (e.g. Fairbanks and Dodge, 1979), the separate effects of kinetic and metabolic fractionation have never been quantified. In this chapter I propose a method for quantitatively separating the effects of kinetic and metabolic fractionation similar to the method I used for separating SST from $\delta^{18}O_{sw}$ in coral $\delta^{18}O$ at Rarotonga (see chapter 2). I also apply this method to several other published coral $\delta^{13}C$ records in order to obtain a better understanding of the role of kinetic and metabolic fractionation on coral $\delta^{13}C$. After the separation of these two effects, the questions as to whether $\delta^{13}C$ is mainly affected by kinetic or metabolic fractionation or both and to what extent $\delta^{13}C$ is related to them is examined.

3.2 Study Area

In April 1997 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 in the western subtropical South Pacific. Over the last two decades in the region of Rarotonga, SST in the grid measuring 2° by 2° (CAC SST) and 1° by 1° (IGOSS SST) (Reynolds and Smith, 1994) has ranged between 23° to 27° with an average annual variation of ~4°C (Fig. 3.1). Highest SST occurs in February-March and lowest in August-September of the year. Radiation data was obtained from the ISCCP MONTHLY solar radiation database for the period of 1983-1991 which is a monthly averaged result of the shortwave Surface Radiation Budget (SRB) and Atmospheric Radiation Budget (ARB) (the shortwave radiative fluxes absorbed at the surface and in the atmosphere) (Bishop and Rossow, 1991). The data are given on a 2° × 2° latitude/longitude grid (Fig. 3.1). The average annual solar radiation is about 230w/m^2 with the maximum of 320w/m^2 in December-January and the minimum of 130w/m^2 in June. The monthly averaged solar radiation near Rarotonga is relatively uniform during 1983-1991 with an exception in 1988-89 when anomously low radiation levels were recorded. It is interesting to note that in this region minimum and maximum radiation precede those of SST by 2-3 months each year.

The processes of sample preparation and mass spectrometer analysis of $\delta^{13}C$ are the same as those of $\delta^{18}O$ and are described in chapter 2. The standard deviation of 468 samples of international NBS-19 analyzed was 0.016‰ for $\delta^{13}C$.

3.3 General Characteristics of Coral $\delta^{13}C$

The coral record of $\delta^{13}C$ for Rarotonga for the period 1726-1997 is shown in Fig. 3.2. Clear seasonal and interannual variations are apparent, as well as a long-term secular trend. Coral $\delta^{13}C$ has decreased by about 1.25‰ over the period 1726-1997. It is interesting to note that most of this decrease occurred after 1900 (about 1‰) while from 1726-1900, the total depletion of $\delta^{13}C$ is only about 0.25‰. Similar patterns of long-term

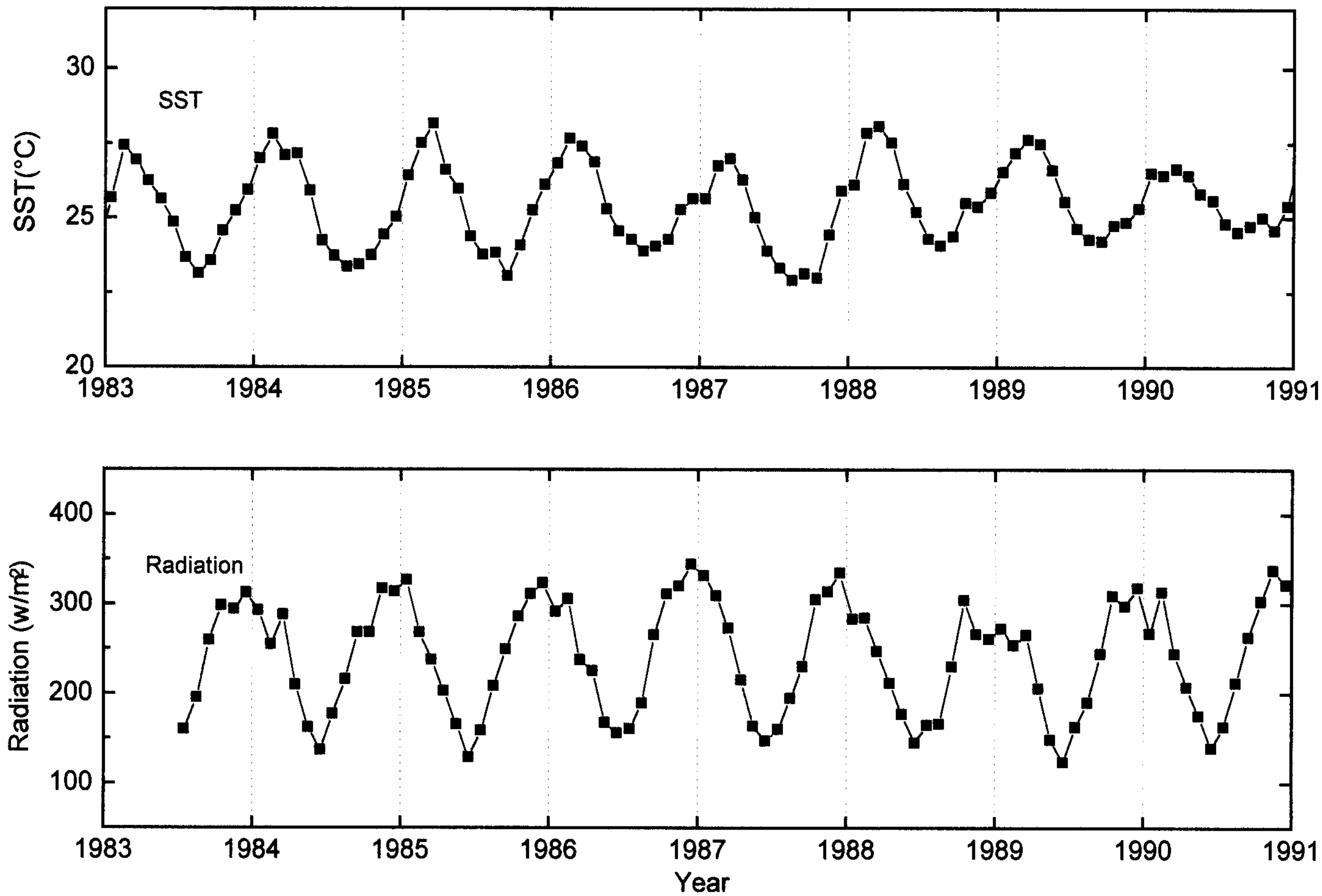

Fig. 3.1 Monthly sea surface temperature (SST), and radiation in the vicinity of Rarotonga for the period 1983-1991. The SST data is from the IGOSS data archive for the 1x1 degree latitude-longitude block (Reynolds and Smith, 1994) while radiation data is from ISCCP for 2x2 degree latitude-longitude grid surrounding Rarotonga.

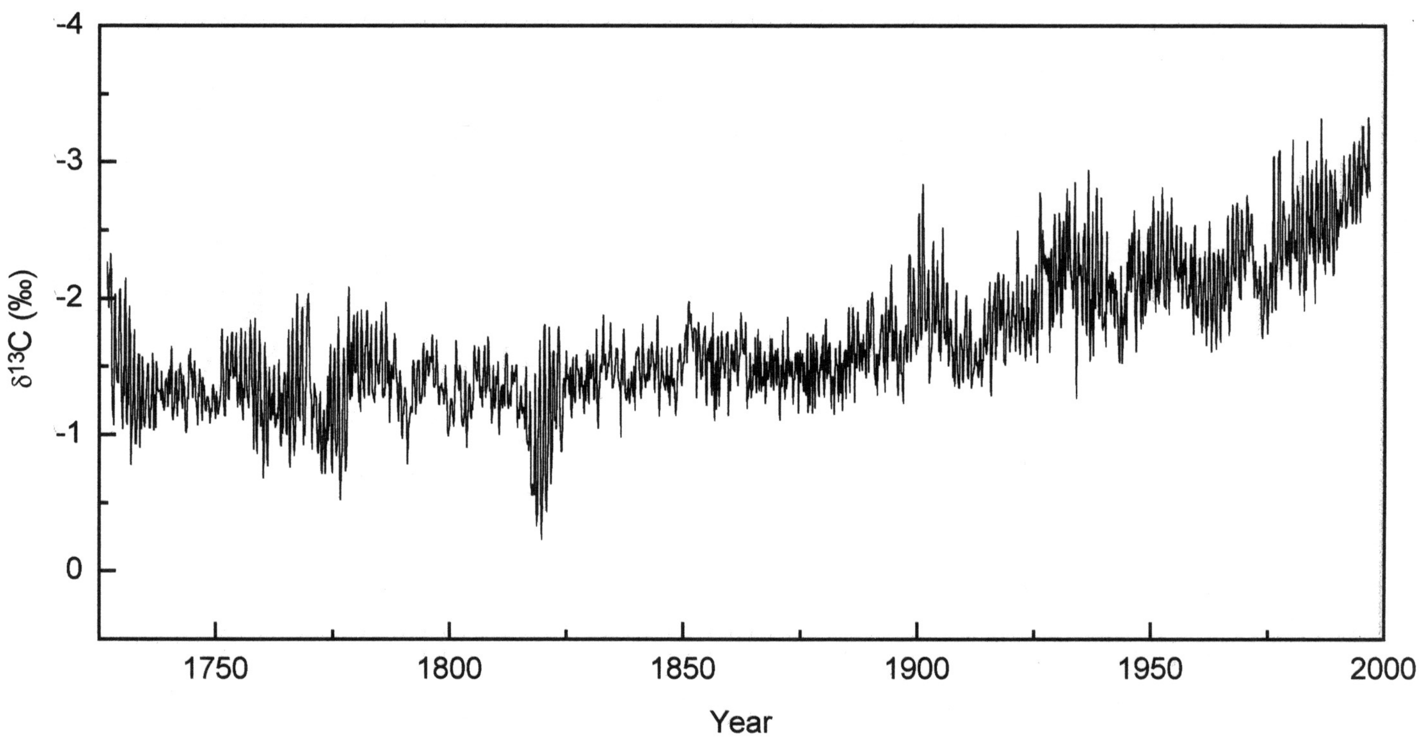

Fig. 3.2 Subseasonal $\delta^{13}C$ (relative to Peedee belemnite (PDB)) spanning 1726-1997 at Rarotonga.

variation have also been observed in corals from Clipperton Atoll (Linsley et al., 2000b) and New Caledonia (Quinn et al. 1998). Based on direct measurements made during three National Oceanographic and Atmospheric Administration (NOAA) research cruises in the period of 1970-1990, Quay et al. (1992) estimated that the average $\delta^{13}C$ value of DIC in the surface waters of the Pacific decreased by about 0.9‰ between 1900-1990 which appears close to the change of coral $\delta^{13}C$ at Rarotonga for the same period. This suggests that the long-term depletion of coral $\delta^{13}C$ may reflect the anthropogenic perturbation of the ^{13}C reservoir. However, other factors such as long-term salinity effects on coral $\delta^{13}C$ (Moberg et al., 1997), and growth rate effect may complicate the interpretation of the long-term trend of coral $\delta^{13}C$ record.

In addition to the pronounced long-term trend, coral $\delta^{13}C$ at Rarotonga also shows significant fluctuations on the interannual and interdecadal time scales (see Fig. 3.2). Three distinct stages of variation can be recognized. Before 1825, fluctuations mainly occurred on decadal time scales while between 1825-1900, they are mainly shown on interannual time scales. After 1900, there is a shift back to decadal variation again. The 20th century portion of the coral $\delta^{13}C$ record contains three minor pronounced decadal transitions between 1924-25, 1946-47 and 1976-77, respectively. As will be discussed in chapter 5, over the interval 1926-1997 these 20th century decadal transitions do not replicate in a second coral $\delta^{13}C$ record from Rarotonga. Another abrupt enrichment in $\delta^{13}C$ occurs over the period of 1815-25 which is also observed in the $\delta^{18}O$ and Sr/Ca record from Rarotonga (see chapter 2) and it is interpreted as due to the influence of the volcanic eruption in Tambora, Indonesia in 1815 (Linsley et al., 2000a).

The $\delta^{13}C$ record also shows clear seasonal variations. Although solar radiation data is only available after 1983, the comparison of coral $\delta^{13}C$ with instrumental SST and radiation at Rarotonga for the period 1983-1991 shows that coral $\delta^{13}C$ varies consistently with the variation of radiation while it has a consistent ~3 month offset with SST (Fig. 3.3). This offset is real because coral $\delta^{18}O$ measured on the same sample is used to set the chronology based on assumed correlation with the annual SST cycle. To show their relationship more clearly, the monthly data of $\delta^{13}C$, SST and radiation is averaged for the period 1983-1991 and replotted in Fig. 3.4. From Jan to Dec, it clearly shows that $\delta^{13}C$ changes in phase with radiation while there is about a ~3 month offset between $\delta^{13}C$ and SST. If we assume that $\delta^{13}C$ of DIC in the seawater for the period 1983-1991 was relatively constant and photosynthesis is the main driving force to metabolic fractionation, this offset suggests that variations of $\delta^{13}C$ are more related to the variation of radiation than SST at Rarotonga.

3.4 Method

Since the $\delta^{13}C$ composition of coral skeleton is a function of several different variables including SST, radiation, heterotrophy activity, and the $\delta^{13}C$ of DIC in the ambient seawater, it is generally difficult to separate their effects by simply comparing the $\delta^{13}C$ record with the instrumental SST and radiation records, respectively. In order to examine in more detail of their separate effects on $\delta^{13}C$, a quantitative method is used on $\delta^{13}C$ at Rarotonga which is similar to the method I used on coral $\delta^{18}O$ (see chapter 2). If we assume that the $\delta^{13}C$ of DIC in the ambient seawater was relatively constant for the

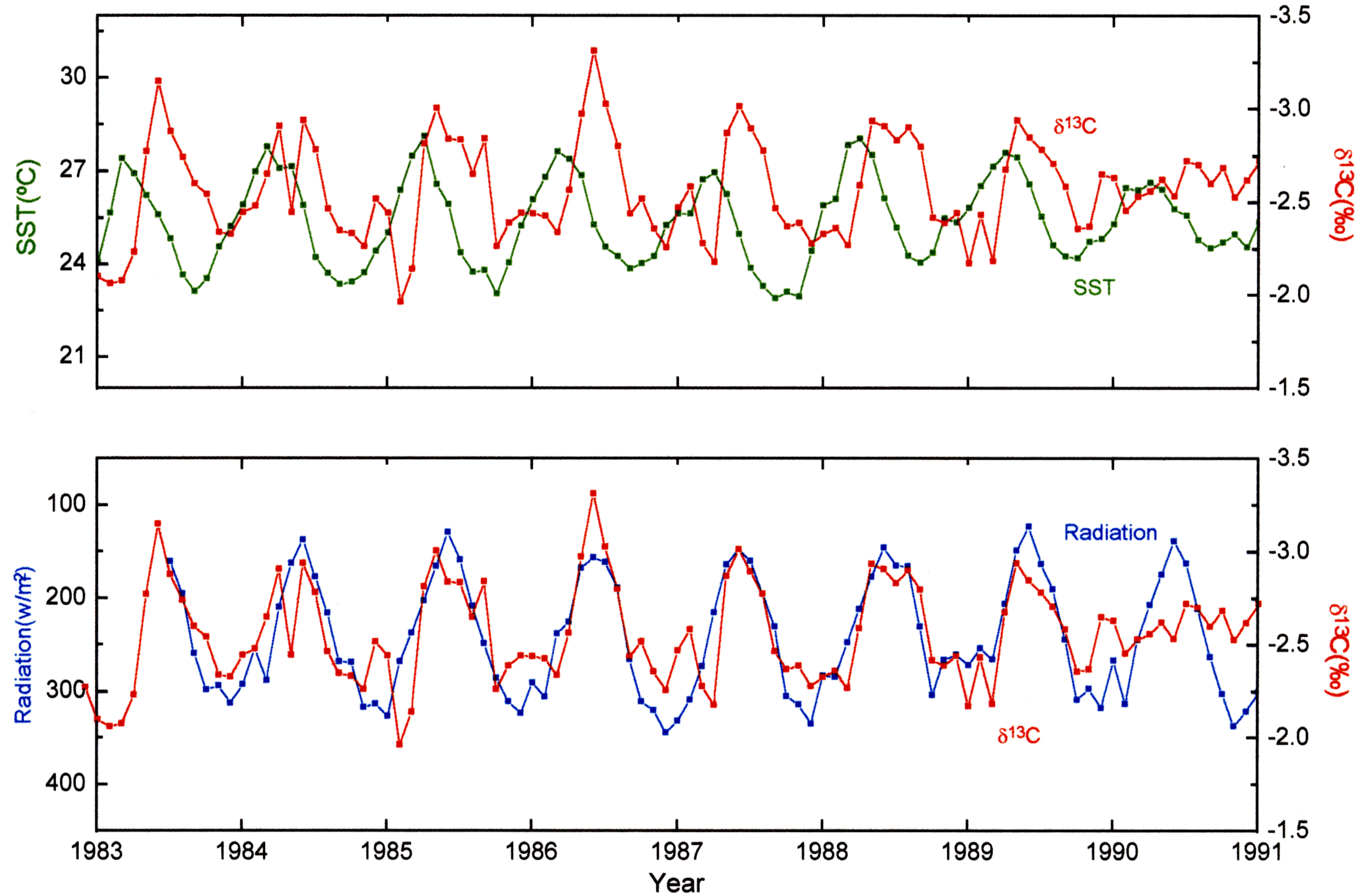

Fig. 3.3 Comparison of $\delta^{13}C$ (in red) in corals with monthly SST (in green) and radiation (in blue) data for the period 1983-1991 at Rarotonga.

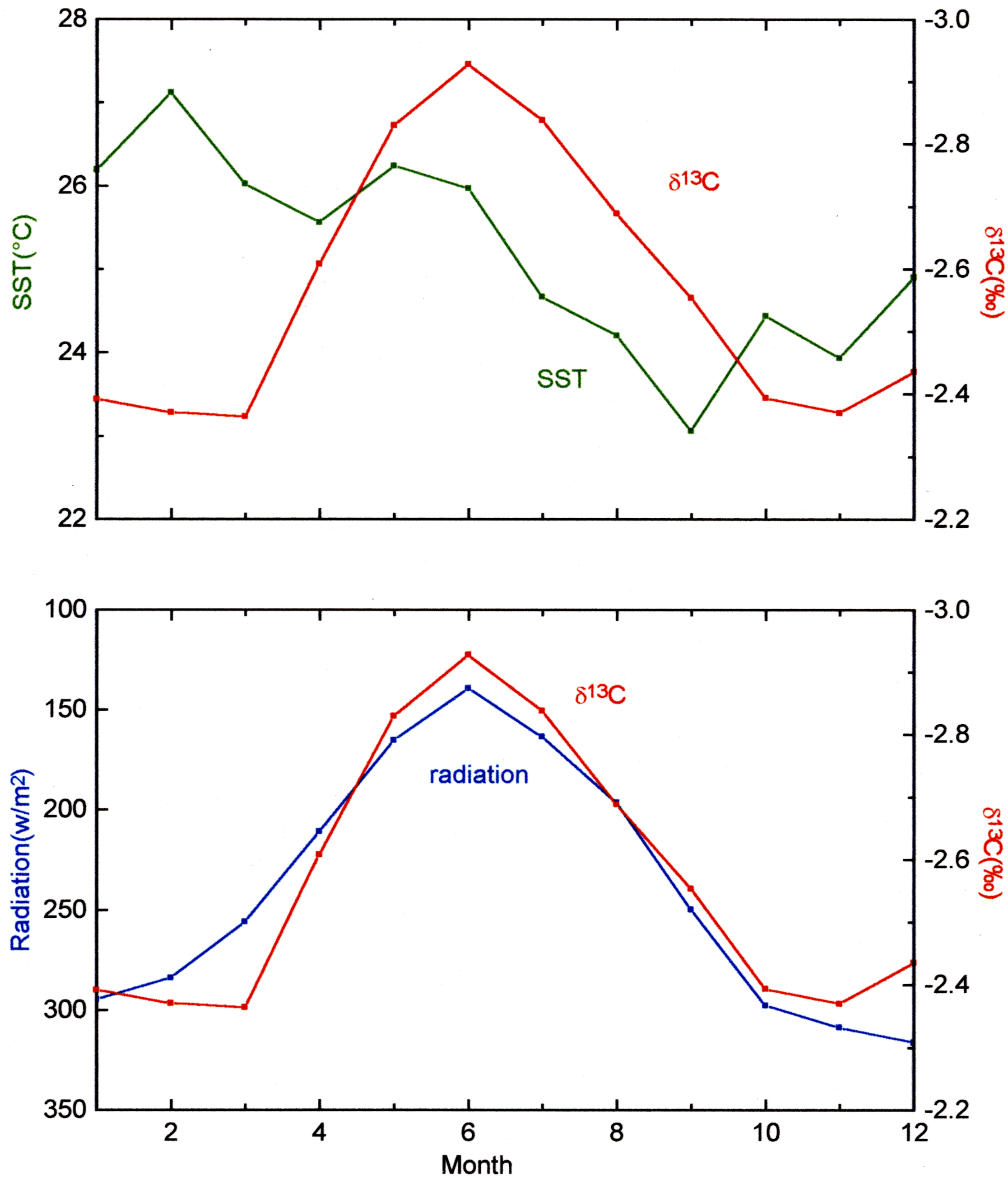

Fig. 3.4 Plots of average monthly SST (in green), solar radiation (in blue), as well as $\delta^{13}C$ in corals (in red) for Rarotonga. The SST data is from IGOSS data while solar radiation is from ISCCP and both cover the period 1983-1991. The average monthly coral $\delta^{13}C$ also covers the same period.

period 1983-1991, we can think of coral $\delta^{13}C$ as a complex function of two variables K and M that represent the intensities of the kinetic and metabolic processes, respectively. These in turn are also functions of the climatic variables SST and/or radiation. With these assumptions and according to derivative principles, the instantaneous changes of $\delta^{13}C$ can be expressed as the sum of two separate instantaneous contributions brought by instantaneous changes of kinetic (K) and metabolic (M) activity, respectively:

$$\Delta\delta^{13}C_{(coral)} = \Delta\delta^{13}C_{(kinetic\_contri)} + \Delta\delta^{13}C_{(metabolic\_contri)} \qquad (1)$$

where $\Delta\delta^{13}C_{(kinetic\_contri)}$ is the part of the total instantaneous change in $\delta^{13}C$ caused by instantaneous change of kinetic activity, and $\Delta\delta^{13}C_{(metabolic\_contri)}$ is the part of the instantaneous change in $\delta^{13}C$ caused by instantaneous change of metabolic activity. Since the kinetic intensity can be regarded as a simple function of SST, we have:

$$\begin{aligned}\Delta\delta^{13}C_{(kinetic\_contri)} &= (\partial\delta^{13}C_{(coral)}/\partial K)\Delta K \\ &= (\partial\delta^{13}C_{(coral)}/\partial K)(\partial K/\partial SST)*\Delta SST \\ &= (\partial\delta^{13}C_{(coral)}/\partial SST)*\Delta SST \qquad (2)\end{aligned}$$

where $\partial\delta^{13}C_{(coral)}/\partial K$ is the partial derivative of $\delta^{13}C_{(coral)}$ with respect to the kinetic factor, $\partial K/\partial SST$ is the partial derivative of the kinetic intensity with respect to SST, and $\partial\delta^{13}C_{(coral)}/\partial SST$ is the partial derivative of $\delta^{13}C_{(coral)}$ with respect to SST. Note that the partial derivative $\partial\delta^{13}C_{(coral)}/\partial SST$ represents the rate of change of $\delta^{13}C$ per degree C change of SST when the metabolic intensity is constant.

So the instantaneous contribution by kinetic activity ($\Delta\delta^{13}C_{(kinetic\_contri)}$) can be found by multiplying the partial derivative of $\delta^{13}C$ with respect to SST ($\partial\delta^{13}C_{(coral)}/\partial SST$) by the instantaneous change of SST (ΔSST). While ΔSST can be directly found from instrumental SST data, the partial derivative $\partial\delta^{13}C_{(coral)}/\partial SST$ is a parameter that can only be constrained by experimental data. According to experimental studies of Grossman and Ku (1986), and Bemis et al. (2000), the rate of change of $\delta^{13}C$ with SST is a constant that does not change with SST when metabolic activity is absent. Based on experiments with the benthic deep-sea foraminifera *Hoeglundina elegans* and symbiont-free molluscs, Grossman and Ku (1986) obtained the following linear equations for $\delta^{13}C_{(coral)}$–SST relationship:

$$\delta^{13}C - \delta^{13}C_{(DIC)} = 2.40 - 0.108 \times SST\ (°C)$$

$$\delta^{13}C - \delta^{13}C_{(DIC)} = 2.66 - 0.131 \times SST\ (°C)$$

As shown in the above equations, the rate of change of $\delta^{13}C$ with SST ranges between –0.108‰/°C ~ –0.131‰/°C. Bemis et al. (2000) also examined the effects of temperature on calcitic shell $\delta^{13}C$ values based on laboratory experiments with planktonic foraminifera *Globigerina bulloides* (nonsymbiotic) in which no photosynthetic activity was involved. They showed that *G. bulloides* shells have lower $\delta^{13}C$ values at higher temperatures with a slope of –0.10 ~ –0.13‰/°C.

$$\delta^{13}C - \delta^{13}C_{(DIC)} = -0.47(\pm 0.15) - 0.13(\pm 0.01) \times SST\ (°C) \quad \text{11-chambered shell}$$

$$\delta^{13}C - \delta^{13}C_{(DIC)} = -0.77(\pm 0.08) - 0.11(\pm 0.00) \times SST\ (°C) \quad \text{12-chambered shell}$$

$$\delta^{13}C - \delta^{13}C_{(DIC)} = -0.78(\pm 0.22) - 0.10(\pm 0.01) \times SST\ (°C) \quad \text{13-chambered shell}$$

From these data, an average value of –0.11‰/°C is therefore adopted as the $\partial\delta^{13}C_{(coral)}/\partial SST$ factor in the calculations of equation (2), where ΔSST for each time interval is directly calculated from the instrumental SST. The instantaneous contribution by changes of kinetic fractionation for any given time for the Rarotonga coral is shown in Fig. 3.5a. Next I convert the coral $\delta^{13}C$ into instantaneous changes of $\delta^{13}C$ for any given interval of time (Fig. 3.5b). Knowing the total changes of $\delta^{13}C$ ($\Delta\delta^{13}C_{(coral)}$) and the kinetic contributions ($\Delta\delta^{13}C_{(kinetic\_contri)}$), the instantaneous contributions due to changes of metabolic fractionation ($\Delta\delta^{13}C_{(metabolic\_contri)}$) can then be calculated by subtracting $\Delta\delta^{13}C_{(kinetic\_contri)}$ of Fig. 3.5a from $\Delta\delta^{13}C_{(coral)}$ of Fig. 3.5b as follows (Fig. 3.5c):

$$\Delta\delta^{13}C_{(metabolic\_contri)} = \Delta\delta^{13}C_{(coral)} - \Delta\delta^{13}C_{(kinetic\_contri)} \qquad (3)$$

Thus, the separate contributions to instantaneous $\delta^{13}C$ changes by kinetic and metabolic processes are obtained for the period 1983-1991 for the study area. The positive values shown in Fig. 3.5a and 3.5c represent positive contributions, which enrich

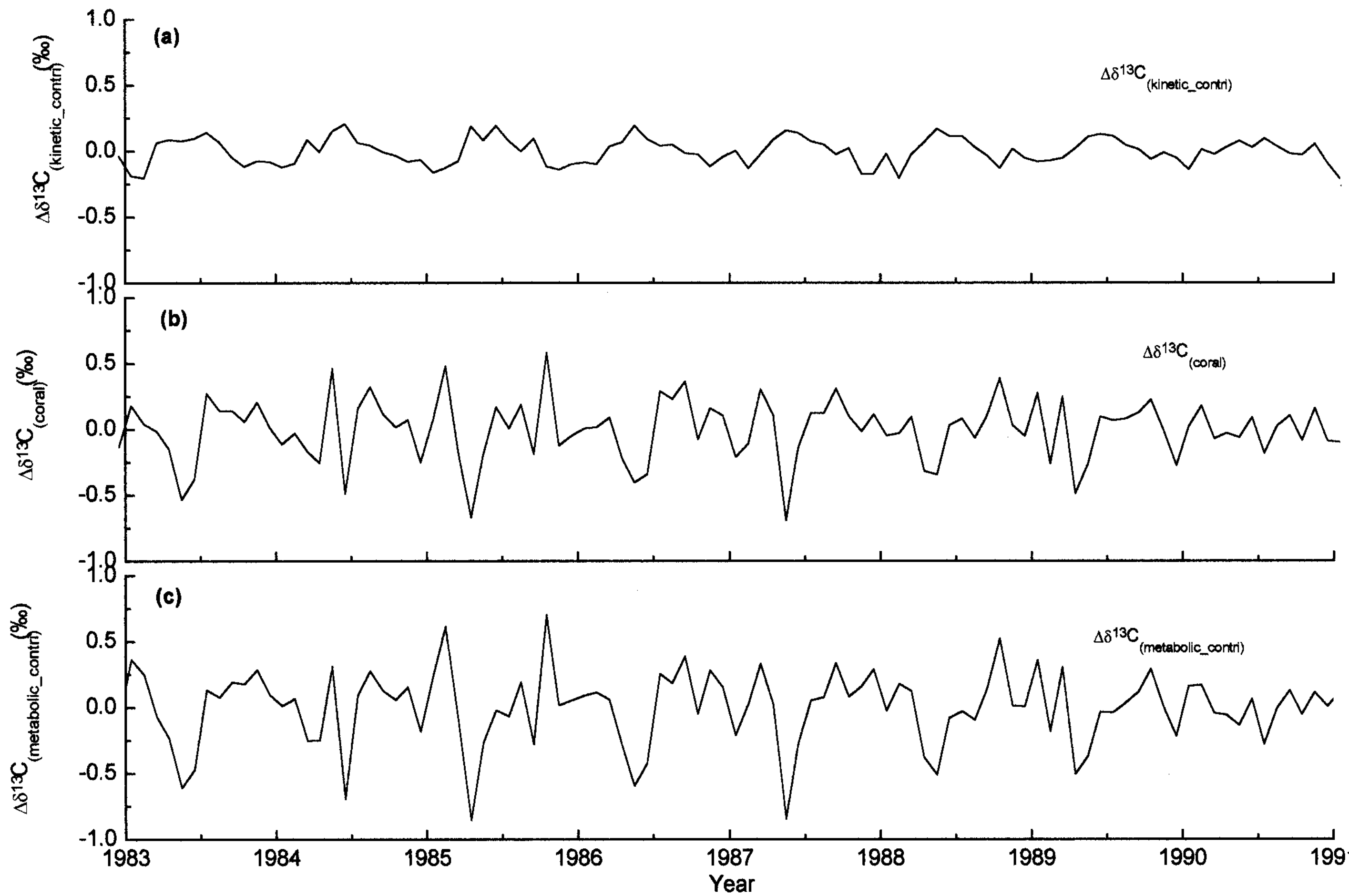

Fig. 3.5 (a) The instantaneous contribution by changes of kinetic activity to the total changes of $\delta^{13}C$ in corals for the period 1983-1991. **(b)** The instantaneous changes of $\delta^{13}C$ in corals for the period 1983-1991. **(c)** The instantaneous contribution by changes of metabolic activity to the total changes of $\delta^{13}C$ in corals for the period 1983-1991.

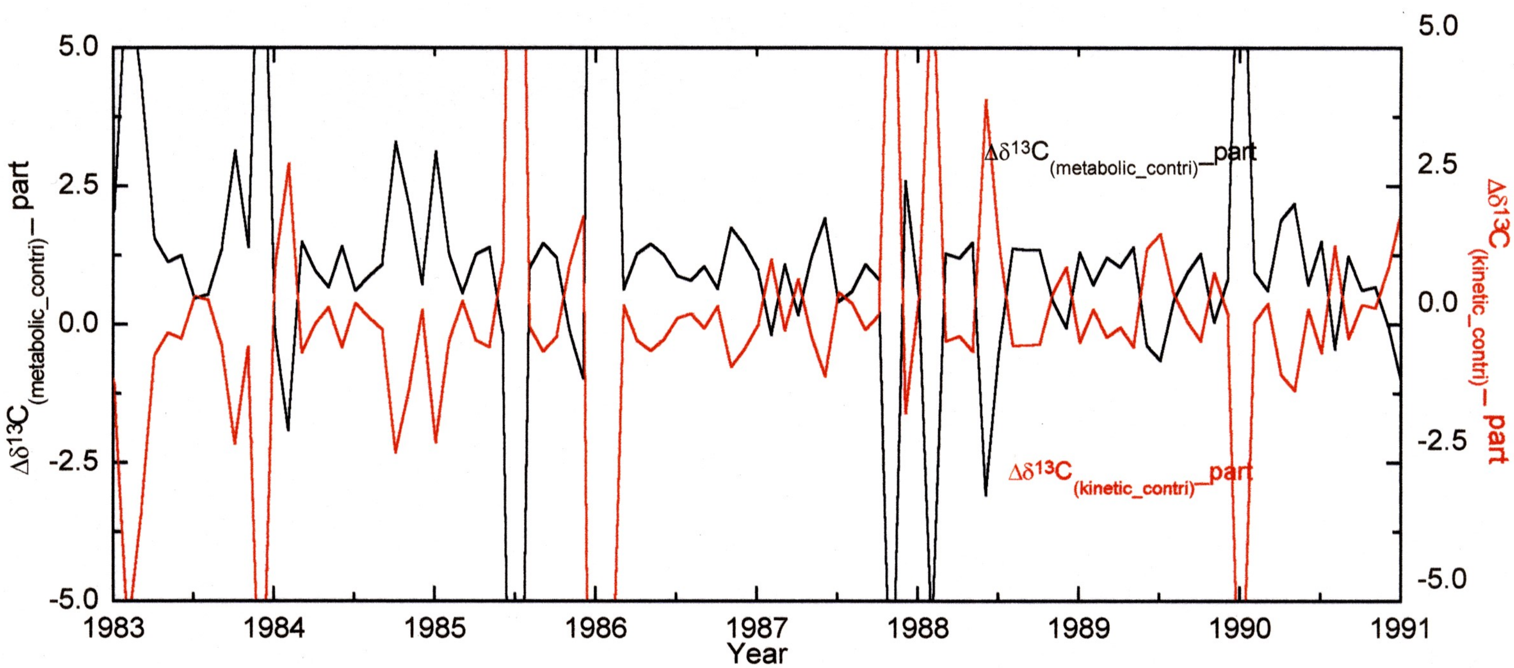

Fig. 3.6 Normalization of the two instantaneous contributions by changes of kinetic (in red) and metabolic (in black) activity to the total coral $\delta^{13}C$ changes for the period 1983-1991 to show their actual correlation with coral $\delta^{13}C$.

the coral skeleton in ^{13}C, while negative values represent negative contributions, whose effect is to deplete coral in ^{13}C. It clearly shows that the instantaneous contributions of changes of metabolic activity (see Fig. 3.5c) to the total coral $\delta^{13}C$ are larger than those of kinetic activity changes (see Fig. 3.5a) for the period 1983-1991. To show how the two contributions are correlated with the actual $\delta^{13}C$ changes, both are normalized by the corresponding $\delta^{13}C$ changes and replotted in Fig. 3.6. Note that the positive values now indicate that the instantaneous contributions are positively correlated with $\delta^{13}C$ changes while negative values represent a negative correlation. Since the sum of the two is equal to 1, both curves show a mirror symmetry. It can be seen that for the Rarotonga region the instantaneous contribution by metabolic effect is almost always positively correlated with $\delta^{13}C$ except for brief intervals, and it fluctuates around a magnitude of about 1. On the other hand, the instantaneous contribution of kinetic effects is often negatively correlated with $\delta^{13}C$ and fluctuates around a magnitude of about 0. It suggests that the variation of $\delta^{13}C$ in corals at Rarotonga is mainly caused by metabolic fractionation rather than kinetic fractionation.

The accumulative effects of kinetic and metabolic activity can be obtained by integrating the two series in Fig. a and c by adding up all the instantaneous contributions to an arbitrary reference, respectively (Fig. 3.7). We can see that the $\delta^{13}C$ and accumulative metabolic contribution are almost identical in shape at Rarotonga. But the derived kinetic contribution does not show similar characteristics with coral $\delta^{13}C$ and the magnitude of its contribution is small compared to that of accumulative metabolic contribution. This is further illustrated in Fig. 3.8 where $\delta^{13}C$ is plotted against the

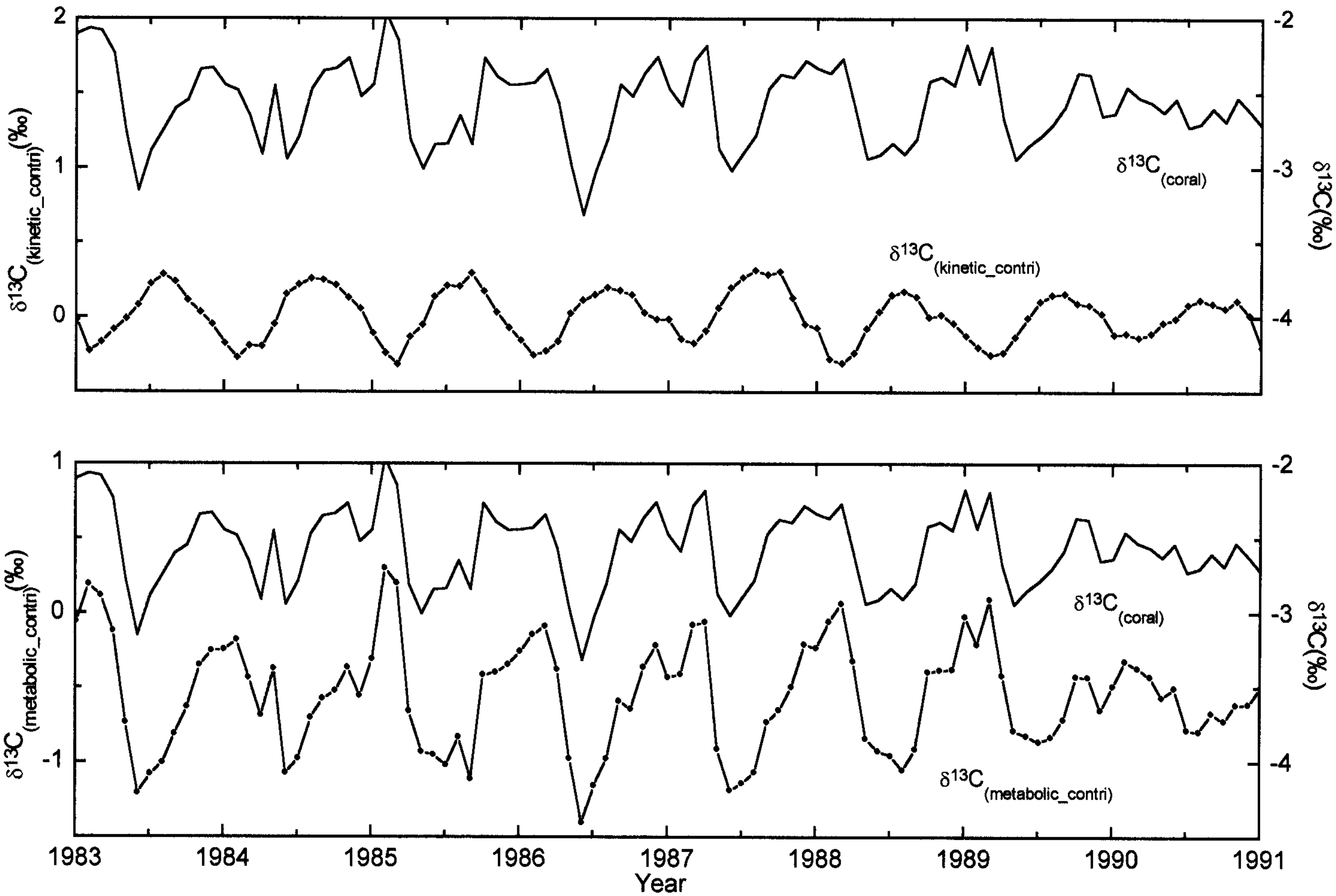

Fig. 3.7 Comparison of the accumulative contribution by changes of kinetic and metabolic activity with those of coral $\delta^{13}C$, respectively for the period 1983-1991.

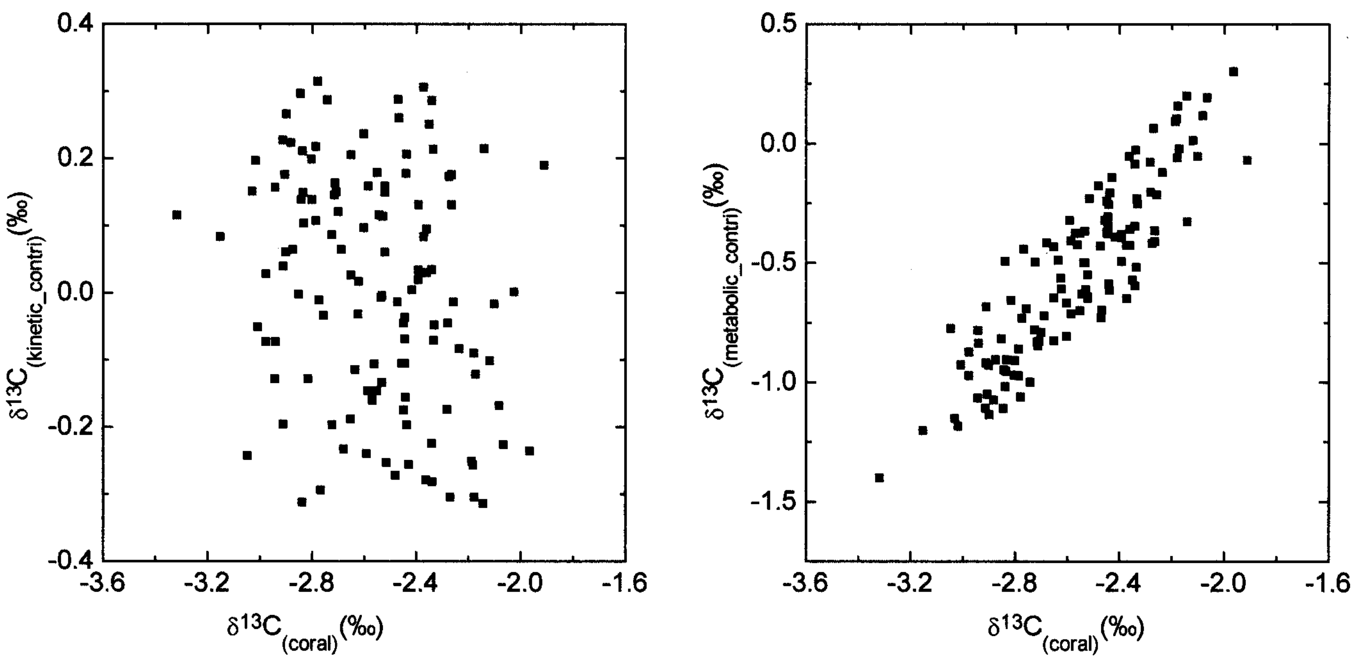

Fig. 3.8 Plots of coral $\delta^{13}C$ vs. reconstructed accumulative contributions by changes of kinetic and metabolic fractionation, respectively for the period 1983-1991.

accumulative kinetic contribution and the accumulative metabolic contribution, respectively for the period 1983-1991. It can be seen that the variation of coral $\delta^{13}C$ is more related to that of metabolic effect than that of kinetic effect. There is no apparent correlation between derived kinetic contribution and coral $\delta^{13}C$ in this region for the period 1983-1991.

3.5 Application to Other Coral $\delta^{13}C$ Records

One of the important questions regarding the above analysis on coral $\delta^{13}C$ at Rarotonga, is whether this relationship between kinetic and metabolic contributions to coral $\delta^{13}C$ are applicable to coral $\delta^{13}C$ in other regions. To answer this question, the above method is applied to several other published coral $\delta^{13}C$ records. These records are from different regions of the Pacific showing various relationships between coral $\delta^{13}C$ and instrumental radiation and SST. Some of the corals in the available database (www.ngdc. noaa.gov/paleo/paleo.html) either only have $\delta^{18}O$ data or did not grow in an open environment, so they are not chosen for this study. Coral $\delta^{13}C$ data from four other sites in the western and eastern Pacific were selected for analysis (Table 3.1) and for comparison to my results from Rarotonga. Two are from the western Pacific (Nauru; Guilderson and Schrag, 1999; and New Caledonia; Quinn et al., 1998), one is from the central Pacific (Kiritimati, Evans et al., 1998), and one from the eastern Pacific (Clipperton; Linsley, et al., 2000b). Of the five sites analyzed, Nauru (166°E, 0.5°S), Kiritimati (157°W, 2°N), and Clipperton (109°W, 10°N) are in the tropical Pacific while Rarotonga (159°W, 21°S), New Caledonia (166°E, 22°S) are in the subtropical Pacific.

Site	*Location*	**Time period**	*Species*	*Annual SST*	*Reference*
Nauru	166°E, 0.5°S	1952-1995	Porites australiensis	~0.5-1°C	Guilderson & Schrag (1999)
Kiritimati	157°W, 2°N	1938-1993	Porites sp.	~1°C	Evans et al. (1998)
Clipperton	109°W, 10°N	1893-1994	Porites lobata	~1.5-2°C	Linsley et al. (2000b)
Rarotonga	159°W, 21°S	1726-1997	Porites lutea	~4°C	This study
New Caledonia	166°E, 22°S	1952-1992	Porites lutea	~4°C	Quinn et al. (1998)

Table 3.1 Coral $\delta^{13}C$ records used in this work.

These five areas show different average annual ranges of SST (from about 0.5° up to 4°C). More importantly, the sites display a range of phasing relationship between coral $\delta^{13}C$ and instrumental radiation and SST. As previously discussed, at Rarotonga coral $\delta^{13}C$ varies in phase with variation of radiation but shows a 2-3 month offset with that of SST (see Fig. 3.3). At New Caledonia, coral $\delta^{13}C$ does not show a clear correlation with either SST or radiation (Fig. 3.9). At Clipperton, coral $\delta^{13}C$ changes in phase with annual variations of SST but shows 2-3 month offset with seasonal changes in radiation (Fig. 3.10). Coral $\delta^{13}C$ and radiation, and $\delta^{13}C$ and SST both show similar trends for the period 1983-1991 at Nauru (Fig. 3.11). Guilderson and Schrag (1999) have suggested that coral $\delta^{18}O$ mainly reflects the variation of SST at Nauru. The similarity between $\delta^{13}C$ and $\delta^{18}O$ at this site provides a good opportunity to test whether $\delta^{13}C$ can be mainly affected by SST. Finally at Kiritimati, the instrumental radiation and SST show a very similar trend while $\delta^{13}C$ is different from both radiation and SST for the period 1983-1991 (Fig. 3.12).

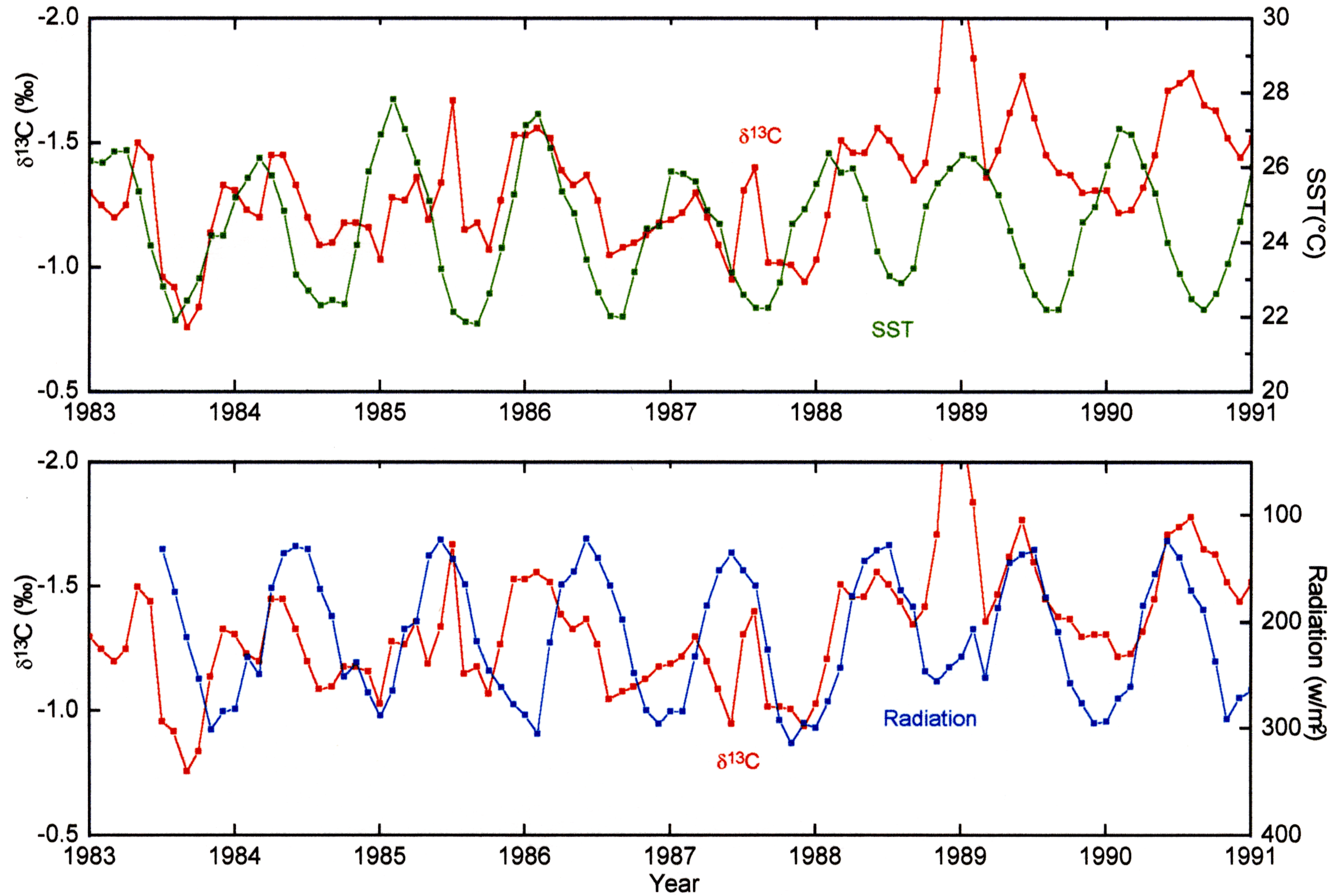

Fig. 3.9 Comparison of $\delta^{13}C$ in corals (in red) with monthly SST (in green) and solar radiation (in blue) data for the period 1983-1991 at New Caledonia. The SST data is from CAC for 2x2 degree latitude-longitude grid surrounding New Caledonia while the solar radiation data is from ISCCP for 2x2 degree latitude-longitude grid surrounding New Caledonia.

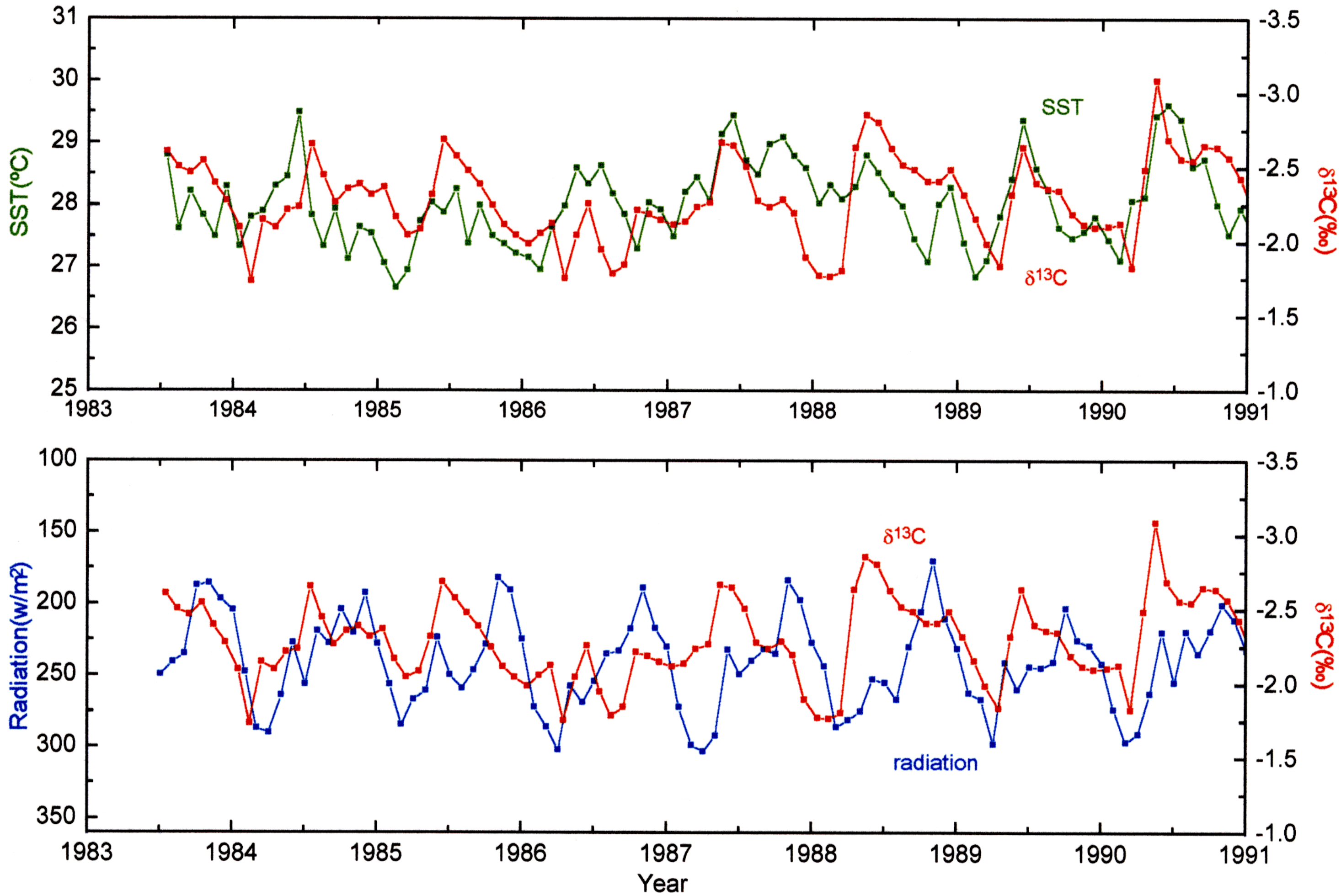

Fig. 3.10 Comparison of $\delta^{13}C$ in corals (in red) with monthly SST (in green) and solar radiation (in blue) data for the period 1983-1991 at Clipperton. The SST data is from CAC for 2x2 degree latitude-longitude grid surrounding Clipperton while the solar radiation data is from ISCCP for 2x2 degree latitude-longitude grid surrounding Clipperton.

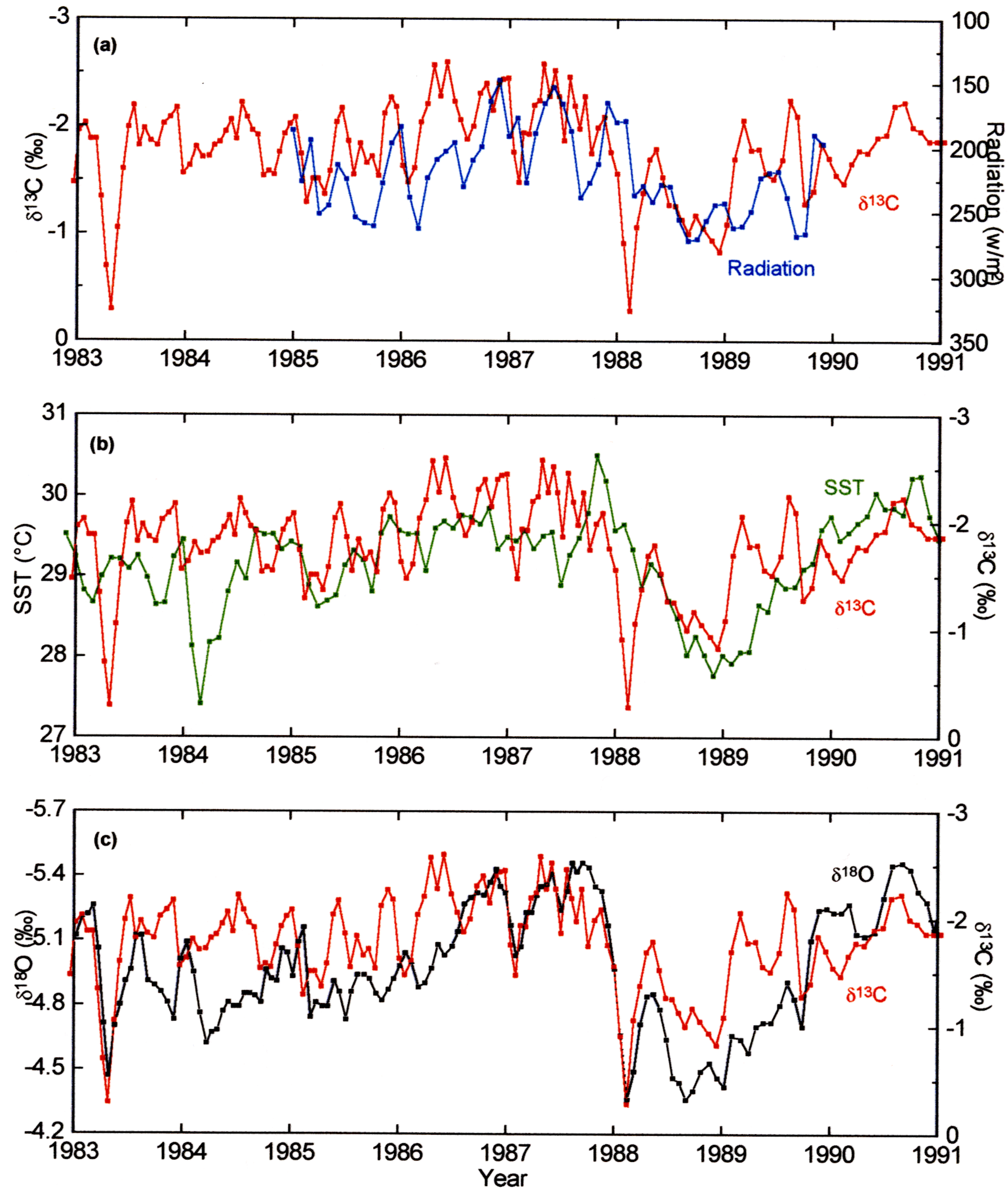

Fig. 3.11 (a) Comparison of $\delta^{13}C$ in corals (in red) with monthly solar radiation data (in blue) for the period 1983-1991 at Nauru. **(b)** Comparison of $\delta^{13}C$ in corals (in red) with monthly SST data (in green) for the period 1983-1991 at Nauru. **(c)** Comparison of $\delta^{13}C$ in corals (in red) with $\delta^{18}O$ in corals (in black) for the period 1983-1991 at Nauru. The SST data is from CAC for 2x2 degree latitude-longitude grid surrounding Nauru while the solar radiation data is from ISCCP for 2x2 degree latitude-longitude grid surrounding Nauru.

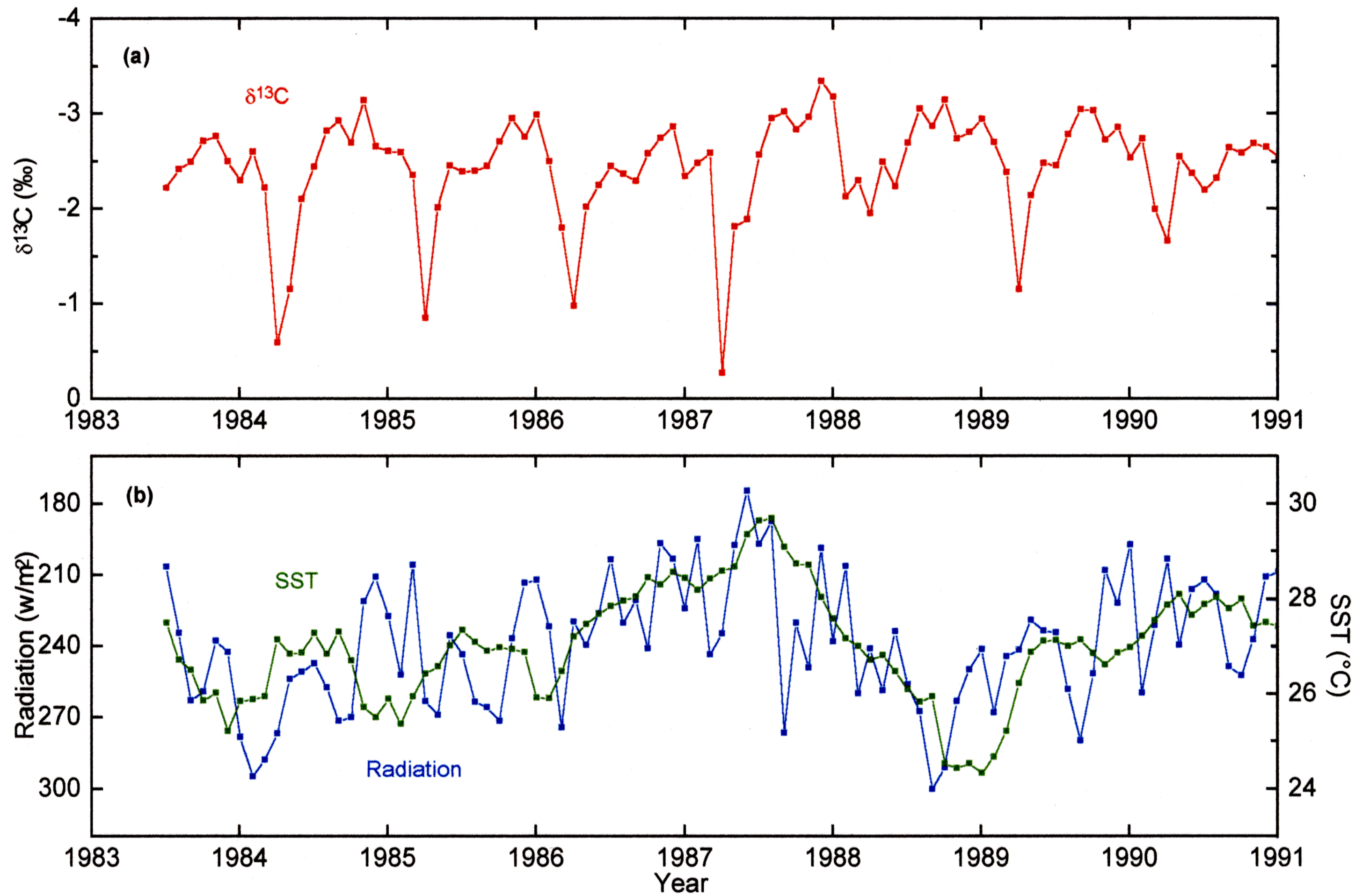

Fig. 3.12 (a) The $\delta^{13}C$ in corals (in red) for the period 1983-1991 at Kiritimati. **(b)** Comparison of monthly SST data (in green) with monthly solar radiation data (in blue) for the period 1983-1991 at Kiritimati. The SST data is from CAC for 2x2 degree latitude-longitude grid surrounding Kiritimati while the solar radiation data is from ISCCP for 2x2 degree latitude-longitude grid surrounding Kiritimati.

The same analytical steps used for Rarotonga coral $\delta^{13}C$ were applied to coral $\delta^{13}C$ from all the other four sites. First, the separate instantaneous contributions by kinetic and metabolic fractionation to the total coral $\delta^{13}C$ changes are obtained in all the four regions (Fig. 3.13) (Rarotonga is also shown in Fig. 3.13 for comparison). Again positive values represent contributions that cause enrichment in ^{13}C, while negative values represent depletion in ^{13}C. At all sites instantaneous contributions of changes in metabolic activity to the total instantaneous changes of coral $\delta^{13}C$ are larger than those of changes of kinetic activity for the period 1983-1991. The dominance of metabolic activity is more pronounced for tropical regions (Nauru and Kiritimati) where the contributions caused by variations of metabolic activity are predominantly larger than those of kinetic activity. At subtropical regions (Rarotonga and New Caledonia), although the effect of kinetic fractionation is larger than that at tropical regions due to the larger range of annual SST, the contributions by changes of the metabolic effect are still larger than those of kinetic effect. To show how the signs of the separate contributions of kinetic and metabolic activity are correlated with the actual coral $\delta^{13}C$ changes, each was normalized by the corresponding $\delta^{13}C$ changes and replotted in Fig. 3.14 for all five regions. It can be seen that the contributions by changes of metabolic fractionation are almost always positively correlated with $\delta^{13}C$, while those of kinetic fractionation are often negatively correlated with $\delta^{13}C$ for all the five regions. This analysis suggests that regardless of the phasing between the original $\delta^{13}C$ and the instrumental radiation and SST, and regardless of whether the corals grew under tropical or subtropical conditions, the variation of coral $\delta^{13}C$ appears to be mainly caused by the variation of metabolic activity rather than by variations of kinetic fractionation

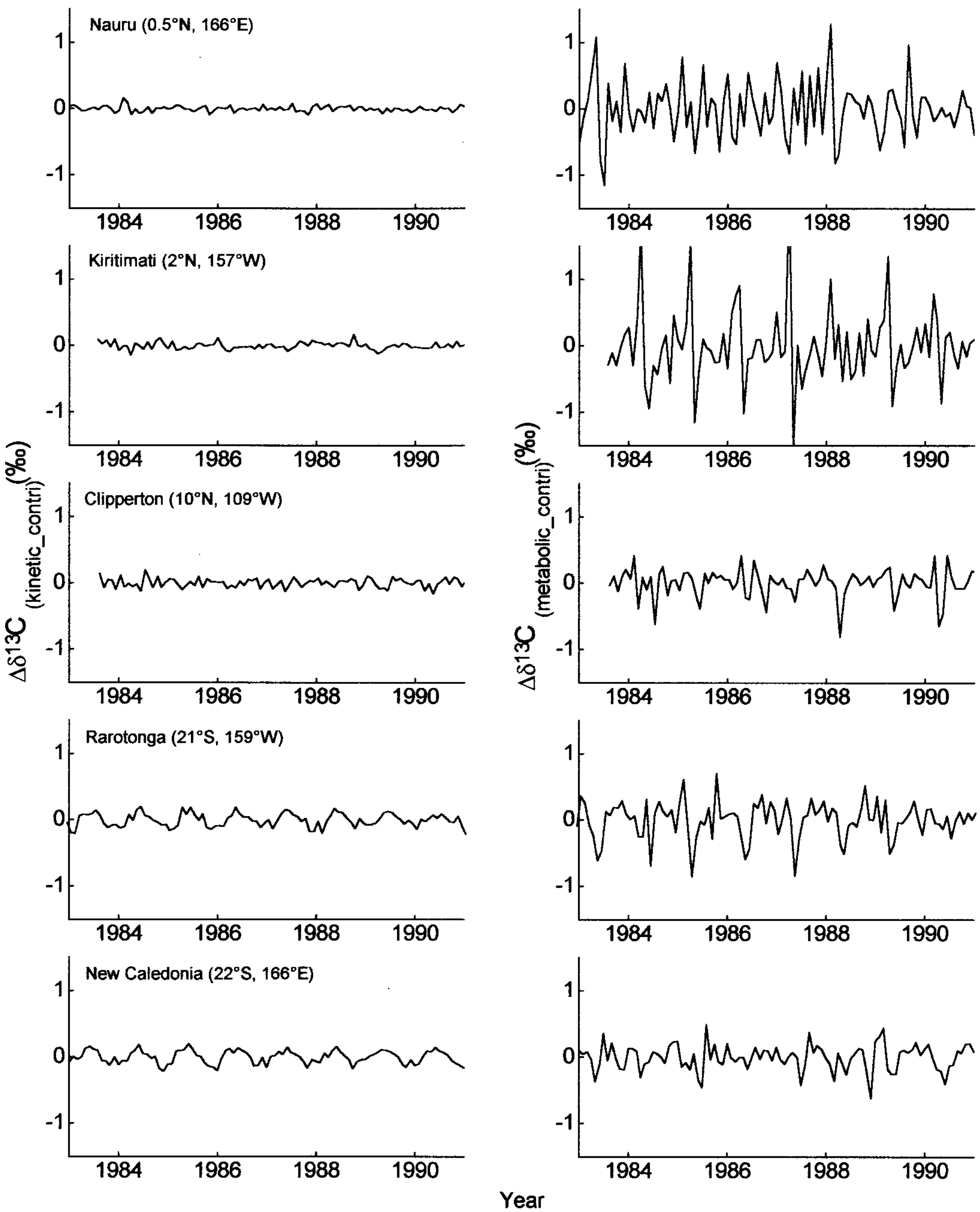

Fig. 3.13 The instantaneous contributions by changes of kinetic (left) and metabolic (right) activity to the total changes of coral $\delta^{13}C$ at Nauru, Kiritimati, Clipperton, Rarotonga, and New Caledonia, respectively for the period 1983-1991.

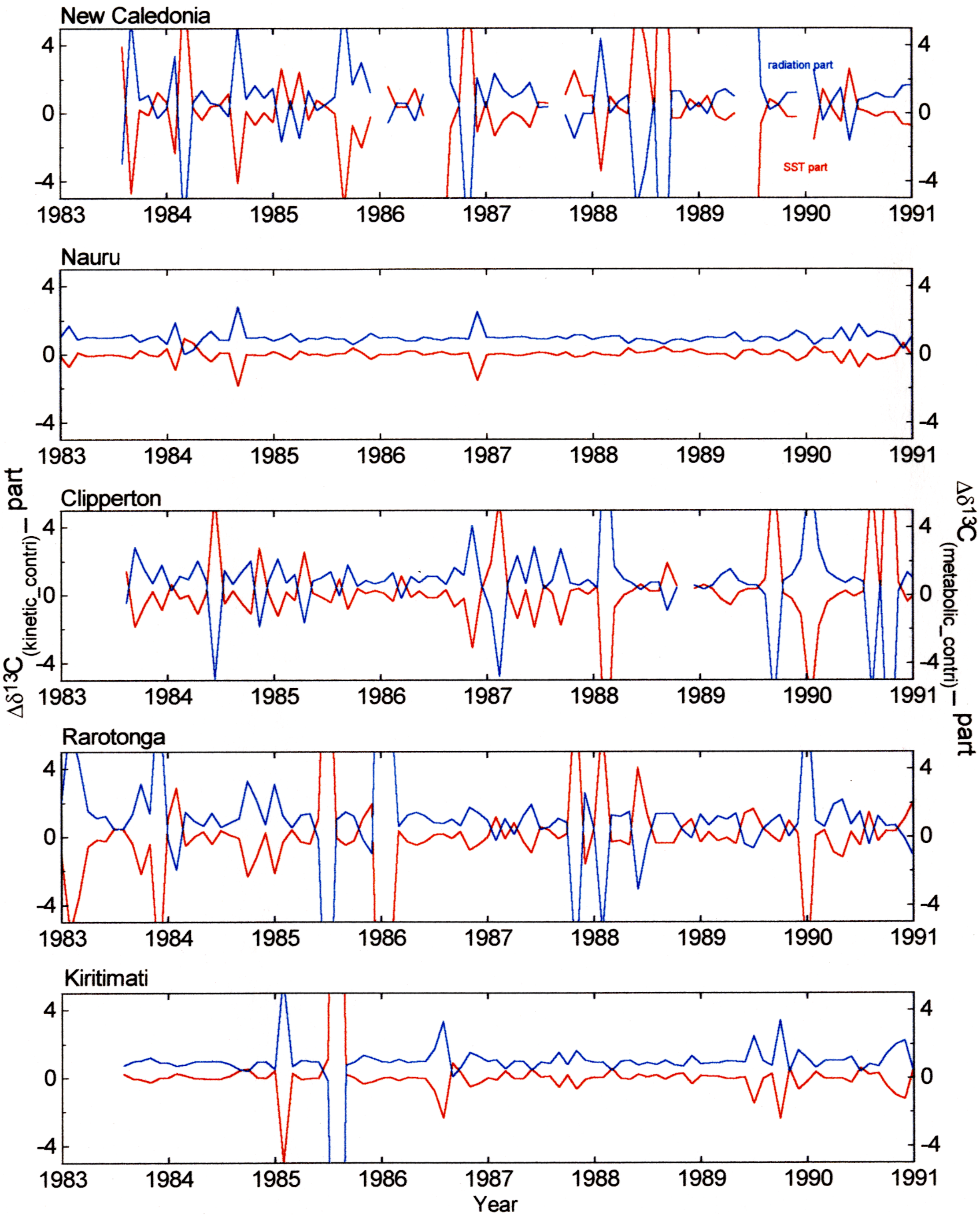

Fig. 3.14 Normalization of the two instantaneous contributions by changes of kinetic (in red) and metabolic (in blue) activity to the total coral $\delta^{13}C$ changes at Nauru, Kiritimati, Clipperton, Rarotonga, and New Caledonia, respectively for the period 1983-1991.

To summarize the results I have calculated the relative contributions of metabolic and kinetic effects after the separation of the instantaneous contributions by metabolic and kinetic activity on $\delta^{13}C$ for each these five sites (Table 3.2). At equatorial sites (Nauru and Kiritimati), the effect of kinetic activity is very small which is about 5-10% of the total changes of $\delta^{13}C$. At the higher latitude sites (Rarotonga and Clipperton), the effect of kinetic fractionation accounts for 20-30% (Rarotonga and Clipperton) and 40% (New Caledonia) of total $\delta^{13}C$ signals.

Site	***Annual SST range (°C)***	***$\Delta\delta^{13}C_{(metabolic\_contri)}$ (%)***	***$\Delta\delta^{13}C_{(kinetic\_contri)}$ (%)***
Nauru	~0.5-1	91	9
Kiritimati	~1-2	95	5
Clipperton	~2	77	23
Rarotonga	~4	72	28
New Caledonia	~4	59	41

Table 3.2 Quantitative analysis of the contributions of metabolic and kinetic effects on coral $\delta^{13}C$ from the selected areas. The % represents the percentage of the contributions of the effects of metabolic and kinetic fractionation to the total changes of coral $\delta^{13}C$, respectively.

The accumulative effects of changes in kinetic and metabolic fractionation can be obtained by adding up all the instantaneous contributions to an arbitrary reference. The results for these five sites are shown in Fig 3.15. In the tropical regions (Nauru and Kiritimati) $\delta^{13}C$ and the accumulative metabolic contribution are almost identical for the period 1983-1991 while the accumulative kinetic contribution is very small. For subtropical regions, the cumulative contributions of changing metabolic activity is also more related to the total $\delta^{13}C$ than kinetic activity. The only exception is New Caledonia, where the magnitude of the contribution of metabolic activity appears to be

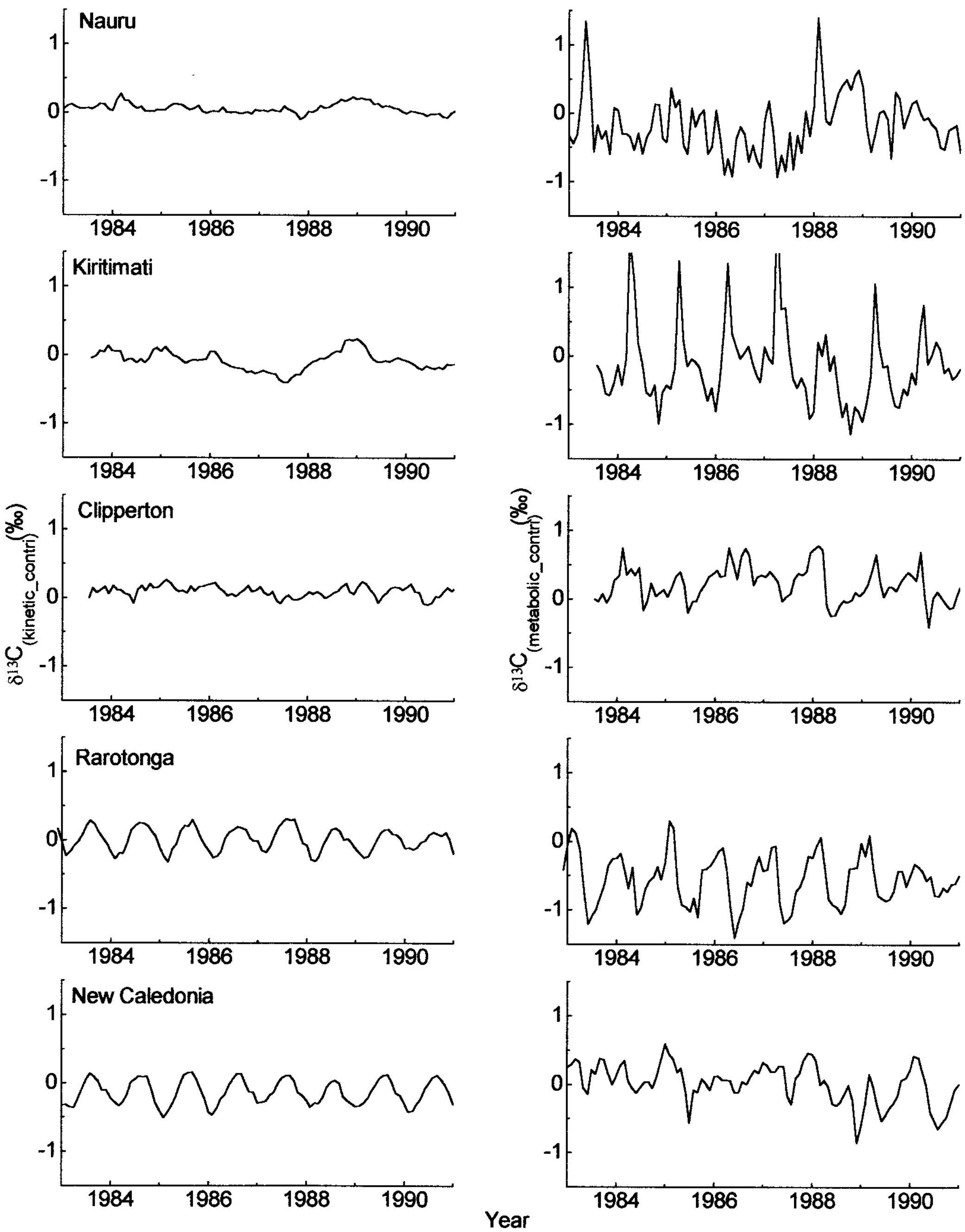

Fig. 3.15 The reconstructed accumulative contribution by changes of kinetic (left) and metabolic (right) activity to the total changes of coral $\delta^{13}C$ at Nauru, Kiritimati, Clipperton, Rarotonga, and New Caledonia, respectively for the period 1983-1991.

approximately equal to that of kinetic activity. Therefore, statistically, variations of metabolic activity appear to dominant coral $\delta^{13}C$ variation rather than kinetic activity.

3.6 Discussion

The above analysis has yielded results suggesting that metabolic activity plays a more important role in causing variations in $\delta^{13}C$ in corals than kinetic fractionation. The validity of this conclusion is largely determined by the validity of the method developed. Therefore it is necessary to discuss any underlying problems in this new method. As shown in equation (2), the magnitude of the instantaneous contribution by changes of kinetic activity is determined by two factors: the partial derivative of coral $\delta^{13}C$ with respect to SST and the annual range of SST variation. While ΔSST is what is actually observed in a particular region, the partial derivative is a parameter that has to be chosen somewhat arbitrarily from experimental data.

Although it has been suggested that the partial derivative $\partial\delta^{13}C_{(coral)}/\partial SST$ is a constant that does not change with SST, it is still possible that it may vary with the metabolic activity, when it is fixed at a different level. This is indeed shown in some experiments (Grossman, 1984; Bemis et al., 2000) which found slightly different $\delta^{13}C$-temperature relationships with different radiation levels. Bemis et al. (2000) explained that the small positive coefficients of change of $\delta^{13}C$ with SST are probably due to the simultaneous influence of symbiont photosynthesis on $\delta^{13}C$. Since the symbiont photosynthetic rate increases at higher temperature, this effect may counteract the kinetic related temperature influence on $\delta^{13}C$. However, it must be pointed out that these rates of change of $\delta^{13}C$ with respect to SST (which are different from those I used in the previous two sections) do not represent the partial derivative that we need. Note that $\partial\delta^{13}C_{(coral)}/\partial SST$ is the rate of change of $\delta^{13}C$ with respect to SST when the metabolic activity (rather than radiation) is constant. This hypothetical situation is difficult to realize in experiments. When SST varies, it will also affect metabolic processes. Although we could adjust the other environmental factor (such as radiation) to keep the metabolic intensity constant, this would be very difficult to do in actual experiments. Instead, experiments are relatively easy to design by keeping radiation at a constant level. Under this situation, metabolic activity will generally increase when SST increases, counteracting the kinetic effect, and causing $\delta^{13}C$ to decrease slowly with SST or even slightly increase with SST. This appears to explain why Bemis et al. (2000) found small negative or even positive values of $\partial\delta^{13}C_{(coral)}/\partial SST$ when radiation was constant in their experiments. So whether $\partial\delta^{13}C_{(coral)}/\partial SST$ does vary with metabolic activity is a question difficult to answer using experimental studies. However, considering that kinetic fractionation is a process that has apparently little to do with photosynthesis and respiration rate (McConnaughey, 1989a), we can reasonably assume that $\partial\delta^{13}C_{(coral)}/\partial SST$ does not vary with metabolic activity as long as the latter is hypothetically kept at a fixed level. In this case, the average value of –0.11‰/°C which Grossman and Ku (1986) and Bemis et al. (2000) obtained when no metabolic activity was present has been used in my calculations.

In order to evaluate the potential influence of the use of different partial derivatives on the final results, I also reran the analysis of Rarotonga coral $\delta^{13}C$ using 0.05‰/°C as proposed by Bemis et al. (2000). The results are shown in Fig. 3.16. It can be seen that in this case the instantaneous contributions of changes in metabolic activity

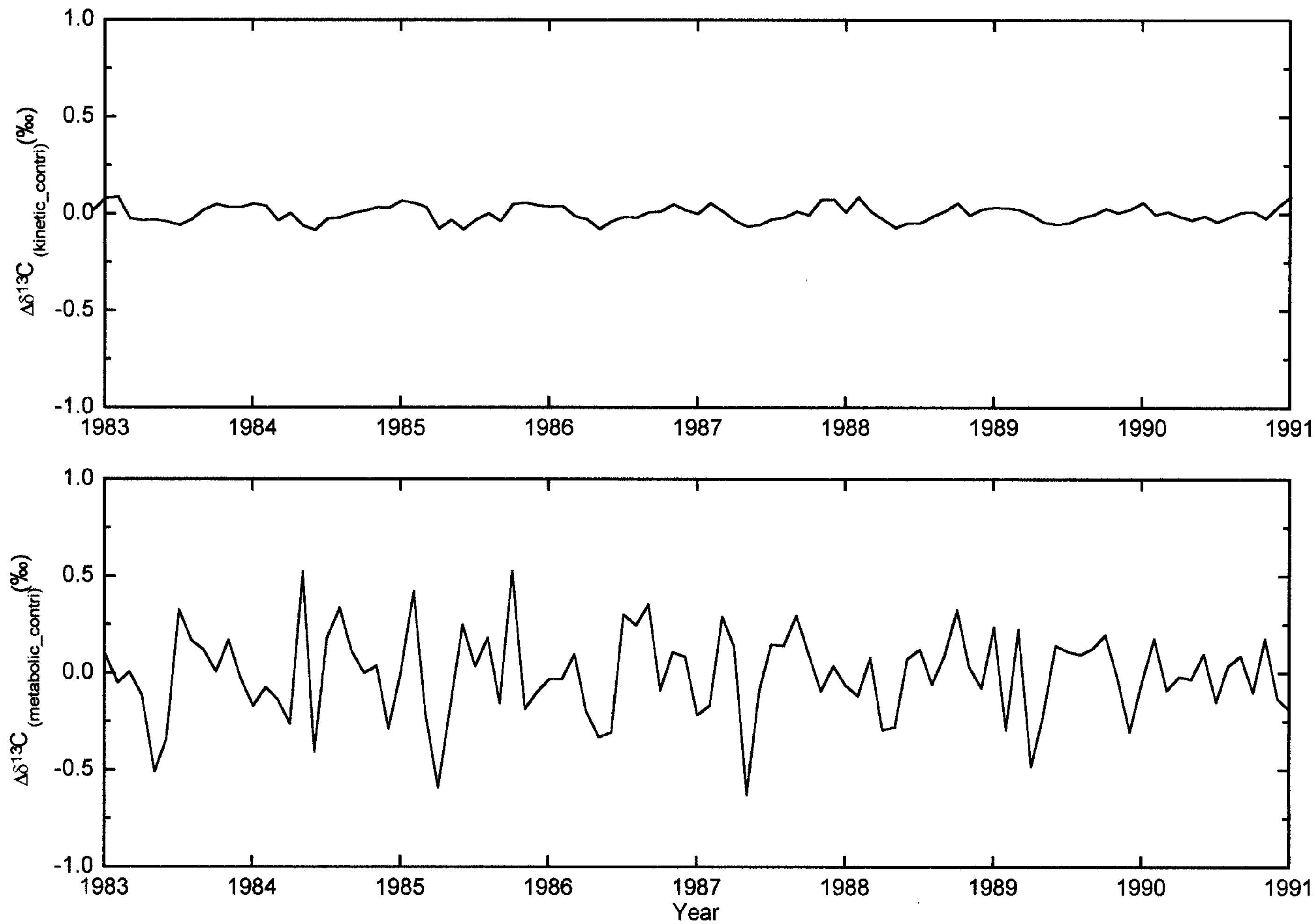

Fig. 3.16 The instantaneous contributions by changes of kinetic and metabolic activity to the total changes of $\delta^{13}C$ in corals at Rarotonga for the period 1983-1991. The partial derivative chosen for calculating the contribution of kinetic activity is 0.05‰/°C.

on coral $\delta^{13}C$ are also larger than those of kinetic activity at Rarotonga. In this analysis kinetic fractionation accounts for about 19% of the total $\delta^{13}C$ coral signal, compared to 81% from metabolic fractionation. When the value of –0.11‰/°C was used previously, the instantaneous contribution by kinetic activity accounted for about 28%. Thus, even if the $\partial\delta^{13}C_{(coral)}/\partial SST$ may vary with different levels of metabolic activity, the contribution by changes of metabolic fractionation still appears to be larger than that of kinetic fractionation. Small variations of $\partial\delta^{13}C_{(coral)}/\partial SST$ with metabolic fractionation may not cause much change in the final analysis.

3.7 Concluding Remarks

To my knowledge, although some experiments have been made to quantify the effect of metabolic fractionation on coral $\delta^{13}C$ (e.g. Juillet-Leclerc, 1997), this is the first attempt to quantitatively separate the effects of kinetic and metabolic fractionation on $\delta^{13}C$ in corals. The results of this study support the opinion that metabolic fractionation plays a dominant role in producing variations in coral $\delta^{13}C$. Several authors have previously arrived at the same conclusions (e.g. Fairbanks and Dodge, 1979; Grottoli and Wellington, 1999). But the new method proposed here gives actual estimates of different magnitudes of contributions by the two competing processes. One implication of this study is that kinetic effects may be negligible especially in the tropical regions and thus understanding the metabolic fractionation in terms of the various environmental factors remains to be a challenging part of our studies. A better understanding of the process of metabolic fractionation will be the key to understanding the relationships between $\delta^{13}C$

and the various climatic variables and utilizing coral $\delta^{13}C$ for reconstructing the paleoclimate variations.

CHAPTER 4

INTERANNUAL TO INTERDECADAL VARIABILITY IN THE SUBTROPICAL PACIFIC: A RECONSTRUCTION FROM THE MULTI-CENTURY OXYGEN ISOTOPE RECORD FROM A RAROTONGA CORAL

Abstract. In this chapter I have concentrated on a 271 year (1726-1997) subseasonal oxygen isotope ($\delta^{18}O$) record from a coral colony of *Porites lobata* at Rarotonga (21.5°S, 159.5°W) in the southwest subtropical Pacific. Coral $\delta^{18}O$ in this region appears to be influenced by the effects of both sea surface temperature (SST) and precipitation-evaporation balance. Nearly all strong and very strong ENSO events listed in Quinn et al. (1987) and Quinn (1992) can be identified in the Rarotonga $\delta^{18}O$ record. Interannual ENSO-band $\delta^{18}O$ variability in the coral is also inversely correlated to the tropical Niño3.4 region. It suggests that although Rarotonga is located outside of the center of action of ENSO, there is a consistent response in this South Pacific region to ENSO forcing and $\delta^{18}O$ in corals faithfully records past El Niño events in this region. Interdecadal variability (~30yr) accounts for about 5% of the variance in the $\delta^{18}O$ record and appears to be related to processes associated with the Interdecadal Pacific Oscillation (IPO) and the Pacific Decadal Oscillation (PDO). Using band-pass filtering I have separated decadal coral $\delta^{18}O$ variability (~12yr period) from interdecadal variability (~30yr period). Comparison of the Rarotonga $\delta^{18}O$ record with other coral data from both the tropical and subtropical Pacific (New Caledonia (20.7°S, 166.2°E), Nauru (0.5°S, 166°E), and Maiana (1°N, 173°E)) with the Niño3.4 and PDO index suggests that the decadal and interdecadal variability may have separate forcing mechanisms. The decadal variability appears primarily a response to the tropical Pacific while the interdecadal variability is more related to the midlatitude oscillation which is in agreement with studies that have examined the instrumental SST record.

4.1 Introduction

It is well known that the climate exhibits significant variability on interannual time scales due to the effects of El Niño-Southern Oscillation (ENSO). El Niño events are associated with anomalous patterns of SST in the tropical Pacific Ocean including the eastward shift of the warm pool coupled with dramatic changes in global climate and ocean circulation. However, while many coral-based paleoclimatic studies have documented past variability of the ENSO system in the tropics before the instrumental record (e.g. Cole et al., 1993; Urban et al., 2000), the spatial and temporal evolution of ENSO events across the subtropical south Pacific is not well established. Based on their studies in New Caledonia (166°E, 22.5°S), Quinn et al. (1998) conclude that the western subtropical South Pacific may not correlate strongly with ENSO indices. But a study from Moorea lagoon (149.5°W, 17.3°S) (Boiseau et al., 1998) indicates that climatic variability is strongly affected by ENSO events in the central gyre region of the subtropical South Pacific. In the tropics, some studies suggest that El Niño events appear to have become more severe and more frequent in recent decades, possibly due to human-induced greenhouse forcing (Hughen et al., 1999). In order to ascertain the relatively subtle interannual variability in the subtropical Pacific, it is necessary to develop additional records of sufficient length to allow accurate characterization of key climatic variables such as SST and precipitation in this region.

On decadal time-scales, recent studies have demonstrated the existence of a persistent decadal/interdecadal oscillation in the Pacific, commonly referred to as the PDO (Pacific Decadal Oscillation) in the North Pacific (Trenberth and Hurrel, 1994; Mantua et al., 1997; Zhang et al., 1997) and IPO (Interdecadal Pacific Oscillation) over the entire Pacific (Power et al., 1999; Salinger et al., in press). Based on instrumental data, the IPO and PDO appear to be robust, recurring patterns of Pacific-wide ocean-atmosphere climate variability (Mantua et al., 1997; Zhang et al., 1997; Salinger et al., in press) which is spatially similar to ENSO, but which is weaker in amplitude and lasts for a much longer period of time. Although there is a paucity of meteorologic and oceanographic data in the South Pacific before 1950, similar SST variations have been documented in a coral Sr/Ca record from Rarotonga (Linsley, et al., 2000a). This coral-based result agrees with other studies which have suggested that the North and South Pacific gyres may respond to similar forcing mechanisms (Mantua et al., 1997; Zhang et al., 1997; White and Cayan, 1998).

Despite the identification of the decadal mode in the Pacific, the origin of this decadal-interdecadal scale oscillation remains poorly understood. Some authors suggest that unstable atmosphere-ocean interactions over the mid-latitude North Pacific coupled with changes in the large-scale ocean circulation might force the decadal/interdecadal climate variability (Ghil and Vautard, 1991; Latif and Barnett, 1994; Gu and Philander, 1997), while others argue that tropical forcing is a stronger influence (that is, ENSO may contribute to the decadal-scale variability) (Jacobs et al., 1994; Trenberth and Hurrell, 1994; Zhang et al., 1997). White et al. (1997) and White and Cayan (1998) examined the historical upper ocean temperature record for the period 1900-1990 from 40°S to 60°N in the Pacific and revealed two dominant sub-ENSO cycles: decadal (9 to 13 year) and interdecadal (18 to 23 year). They suggested that the origin of decadal signals is different from that of interdecadal signals. The evolution of the interdecadal signal appears to be dominated by equatorward propagation of SST anomalies from the extratropics to tropics, while the decadal signal seems to involve the advection of SST anomalies by Rossby waves physics which is also responsible for ENSO frequencies near 15°-30° latitude in both hemispheres. This idea was supported by Lau and Weng (1995) and Mann and Park (1996) who also isolated the decadal and interdecadal signals from one to another by analyzing the surface temperature record from 1854 to 1993, and near-century long SST and sea level pressure (SLP) data.

Since massive scleractinian hermatypic corals can live up to several hundred years, they are potentially an ideal source of information on interannual and interdecadal variations in surface ocean conditions over the past several centuries. Geochemical time series derived from coral skeletons has been recognized as promising monitors of past climate change in the oceans (for review see Dunbar and Cole, 1993). In this chapter I discuss a coral-based subseasonal oxygen isotopic ($\delta^{18}O$) record (which was also used in Chapter 2) spanning the period 1726-1997 (271 years) from Rarotonga (159°W, 21°S) in the southwest subtropical Pacific. This $\delta^{18}O$ record provides new evidence of interannual to interdecadal Pacific climate variability over the last three centuries. In addition to developing a multi-century reconstruction of environmental history in this region, in this chapter I compare the Rarotonga record with other Pacific Ocean coral $\delta^{18}O$ and instrumental records to examine the temporal features and spatial patterns of interannual and decadal/ interdecadal variability in the southwest Pacific gyre.

4.2 Study Area and Coral Cores

The island of Rarotonga is located at 159.5°W and 21.5°S in the Cook Islands of the western subtropical South Pacific (WSSP) (Fig. 4.1). It has been recognized that the

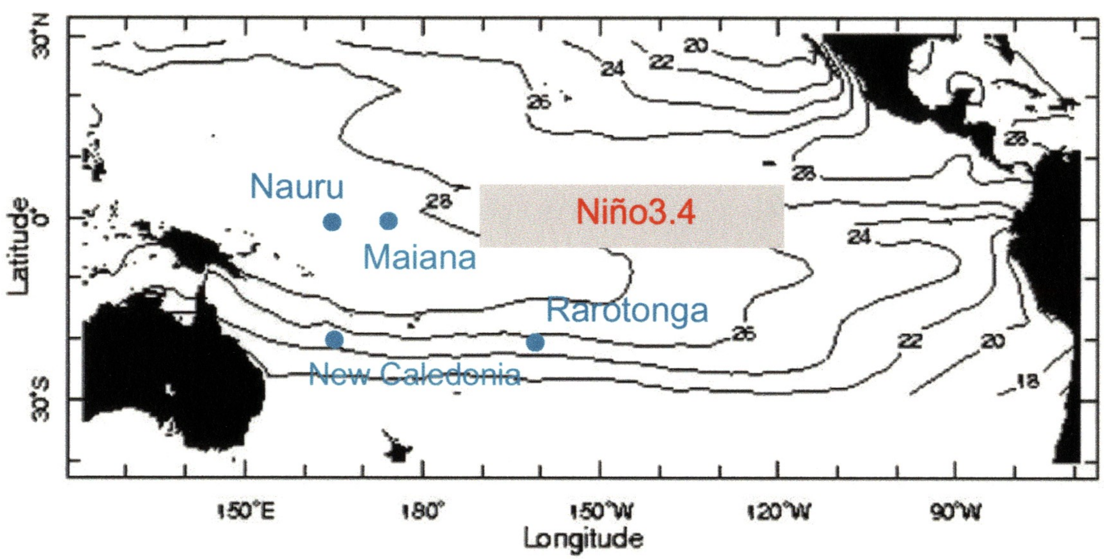

Fig. 4.1 The geographic location of Rarotonga. Also shown in the figure are the locations of New Caledonia, Nauru, and Maiana Atoll. The contours shown are sea surface temperature (SST) in the tropical Pacific in June, 2000. Also shown are the regions used to define large-scale ENSO indices: the Niño3.4 SST region is outlined by a box.

WSSP is a dominant source region for water transport to the equatorial thermocline (Johnson and McPhaden, 1999). In addition, the WSSP is also 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). Since Rarotonga is one of the southern-most islands in the tropical south Pacific, with no islands directly between Rarotonga and the Antarctic, it may provide us a unique opportunity for reconstructing the past climate change in the southwest subtropical Pacific.

In April 1997 coral cores were collected from a colony of *Porites lutea* in 18.3m (60 feet) of water on the southwest side of the island of Rarotonga in open-ocean conditions. Cores B and C were collected in the same colony within 0.5 meters from each other. The total usable length of core B is 1.3m while core C is 3.5m (Fig. 4.2).

Over the last two decades SST for both the 2°x2° (CAC SST) and 1°x1° area (IGOSS SST) (Reynolds and Smith, 1994) surrounding Rarotonga has ranged from 24° to 27° with an average annual variation of ~4°C. The highest SST occurs in February and the lowest in July-August of each year. Precipitation is also generally highest in February-March when the South Pacific Convergence Zone (SPCZ) is in its most southern position (Baker et al., 1994).

4.3 Methods

4.3.1 Sample Preparation

~7mm thick slabs of coral cut from cores drilled along the major axis of growth were cleaned with deionized water to remove saw-cuttings and were oven dried at 40°C.

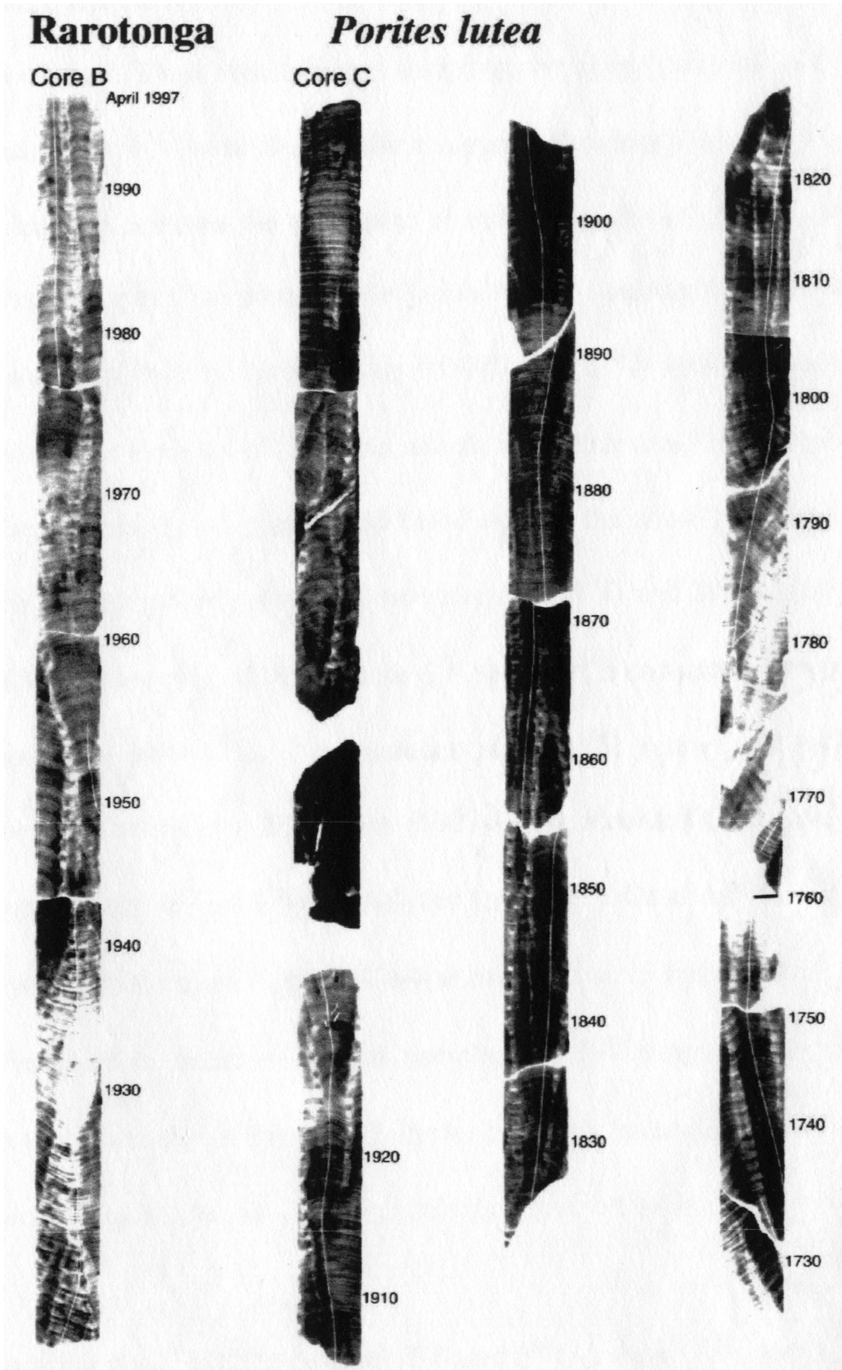

Fig. 4.2 X-ray positive collage of two coral cores (cores B and C) used in the study showing the location of mm-scale sampling transacts. Note the overall goodness of fit between the individual coral slabs except for a growth hiatus in the third section of core C.

Samples were continuously drilled at 1mm intervals using a low-speed micro-drill along tracks parallel to corallite traces as identified in X-ray positives. Because of a growth hiatus in core C, cores B and C were spliced together to make a continuous record (see Fig. 4.2). Core B was sampled from the top to 1316mm depth, while core C was sampled from 1104mm depth to the very bottom. This sampling scheme resulted in an overlap of about 212mm (~13 years) between core B and core C. This ensured that there was some repetition between core B and core C. A clear match point in coral Sr/Ca and $\delta^{18}O$ was found at 1926 A.D. and the data from two cores was spliced at this point.

4.3.2 Mass Spectrometer Analysis

Oxygen isotope 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 2596. The first 668 samples were analyzed every 1mm at Harvard University while all other samples were analyzed every other mm at the University at Albany. At Harvard University ~1mg samples are reacted in vacuo in a modified autocarbonate device at 90°C and the purified CO_2 analyzed. At the University at Albany ~150µg samples were dissolved in 100% H_3PO_4 at 90°C in a Multiprep carbonate inlet system and the resulting CO_2 gas analyzed. These two different sampling densities show equal annual $\delta^{18}O$ amplitudes, which indicates that analysis of every other mm samples still captures the full range of the annual cycle. This result agrees with Boiseau et al. (1998) and Quinn et al. (1998) who concluded that with a relatively small annual SST range the bimonthly sampling captures the full range of the annual cycle. External precision at the University at Albany is better than 0.04‰ for $\delta^{18}O$ based on analysis of replicate samples. The standard deviation of 468 samples of the international NBS-19 standard analyzed was 0.038‰ for $\delta^{18}O$. At Harvard University the analytical uncertainty and reproducibility of ±0.05‰ is documented by analysis of an in-house homogenized coral standard. 10% of all samples were analyzed in duplicate. The average difference between duplicate analyses was 0.025‰.

4.3.3 Chronology

The chronology was developed based on the annual periodicity of $\delta^{18}O$ and Sr/Ca and is the same as published in Linsley, et al. (2000a). The total record spans from 1726-1997 and includes the 71 years (1997-1926) recorded in core B and the remaining 200 years (1925-1726) recorded in core C (an overlap of about 13 years was discarded from core B). This places large positive $\delta^{18}O$ anomalies in the record during the intervals 1782-84, 1791-94, 1876-78, 1940-41, and 1982-83 when there were noted very strong El Niño events and colder SST anomalies in the eastern equatorial Pacific (Quinn et al., 1987; Quinn, 1992). Based on our chronology, the top 61 years was analyzed for $\delta^{18}O$ at an average of 15 samples/year, while below 1935, $\delta^{18}O$ was analyzed at 7~8 samples/year. In order to compare with the monthly instrumental data the subannual age estimates were then linearly interpolated into 12 points/year for $\delta^{18}O$. Since $\delta^{18}O$ analyzed at 7~8 samples/year did not attenuate the amplitude of the annual cycle, this method does not appear to bias the data in any way. The final result of subseasonal $\delta^{18}O$ at 12 samples/year for the period 1726-1997 from Rarotonga is shown in Fig. 4.3.

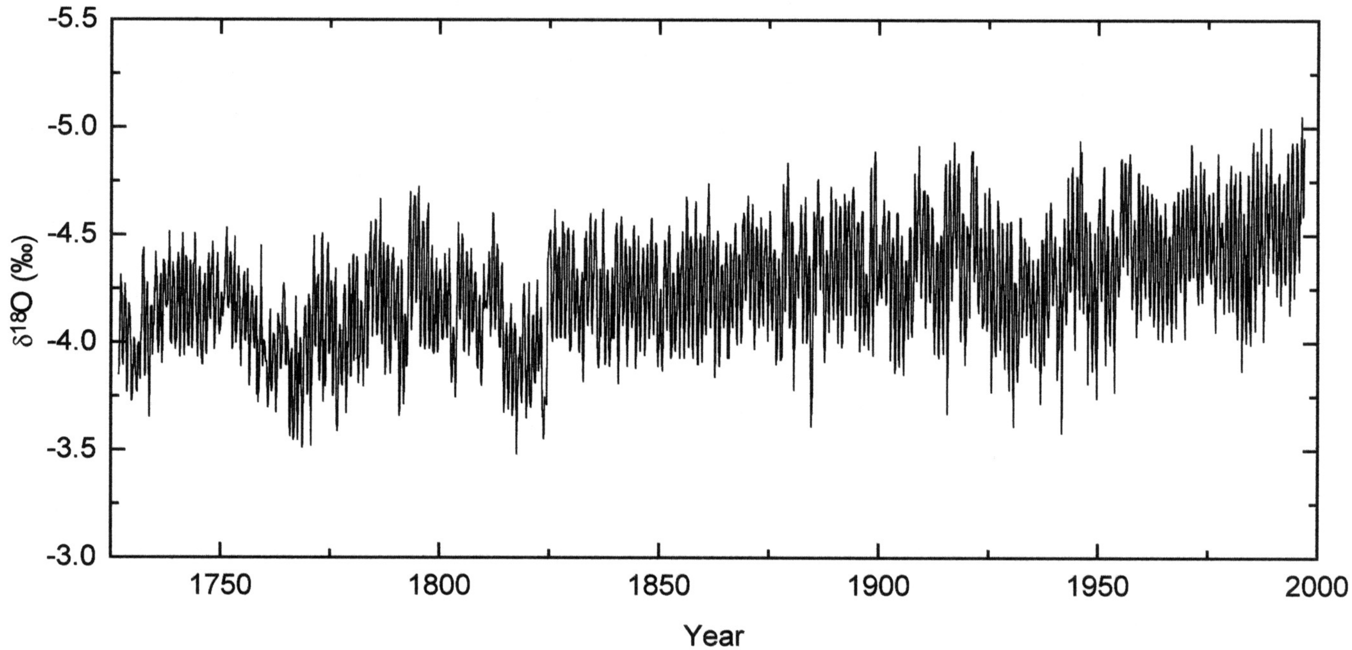

Fig. 4.3 Rarotonga subseasonal coral $\delta^{18}O$ (relative to Peedee belemnite (PDB)) spanning 1726-1997.

4.3.4 Time Series Analysis

A Singular Spectrum Analysis (SSA) software program written by E. Cook (Lamont-Doherty Earth Observatory) was used in the analysis of the coral and climate time series discussed below. Briefly, SSA is a fully nonparametric analysis technique based on principal component analysis of delay coordinates in vector space for a time series. It uses M-lagged copies of a centered time series to calculate eigenvalues and eigenvectors of their covariance matrix. Reconstructed components (RC's) are then calculated which allow a unique expansion of the signal into a sum of the different frequency components. A detailed description of this technique and its paleoclimate application is given by Vautard and Ghil (1989) and Vautard et al (1992). SSA analysis of the $\delta^{18}O$ data was run multiple times with different window lengths (M). When set between M=80 months to M=160 months, there was little difference in the results. In table 4.1 I show SSA results for M set equal to 125 months.

Eigenvector	***Variance (%)***	***Cumulative Variance (%)***	***Mean Period (year)***
1	30.42	30.42	Trend
2, 3	38.04	68.46	1
4	4.67	73.14	10.42
5-8	9.47	82.61	3-7
9, 10	2.76	85.37	2.98

Table 4.1. Singular Spectrum Analysis for Rarotonga: Unfiltered $\delta^{18}O$ Series 1726-1997. Window length M=125 months.

4.4 Results and Discussion

4.4.1 General Characters and Frequency Analysis of Coral $\delta^{18}O$

The annual mean $\delta^{18}O$ value of this Rarotonga coral has decreased by about 0.45‰ over the period 1726-1997 (see Fig. 4.3). This trend is not uniform and occurs in three stages. Before 1825 the trend is superimposed on large decadal fluctuations, while between 1825 and 1925 the trend is relatively stable showing a constant rate of decreasing $\delta^{18}O$. After 1900, $\delta^{18}O$ shows abrupt decadal shifts to about 1950, then is more constant to the top of the core. This result is contrary to that found at Mariana Atoll in the equatorial western Pacific (Urban et al., 2000). They observed higher amplitude decadal variations and weaker interannual variations in coral $\delta^{18}O$ in the 19th century. The abrupt shift between 1925-1940 which has been observed in several other coral $\delta^{18}O$ records (for example, New Caledonia; Quinn et al., 1998), also occurs at Rarotonga, while another inferred climate shift between 1840-60 which is observed in Galápagos (Dunbar et al., 1994) and the Great Barrier Reef (Druffel and Griffin, 1993) coral $\delta^{18}O$ records is not recognized in our record. Finally, consistent with previous work on ENSO behavior (Trenberth and Shea, 1987; Cole et al., 1993; Linsley et al., 2000b), interannual $\delta^{18}O$ variance is attenuated between 1920-1940.

The record of $\delta^{18}O$ shows clear seasonal variations (Fig. 4.4). Although the $\delta^{18}O$ data shows good negative correlation with monthly SST in the period 1970-1997 (r=0.8), the slope of the SST-$\delta^{18}O$ calibration is –0.135‰/°C which is much higher than the value derived from empirical and laboratory observations for biogenic aragonite (–0.21‰/°C ~ –0.23‰/°C) (Epstein et al., 1953; Tarutani et al., 1969; Grossman and Ku, 1986). If we

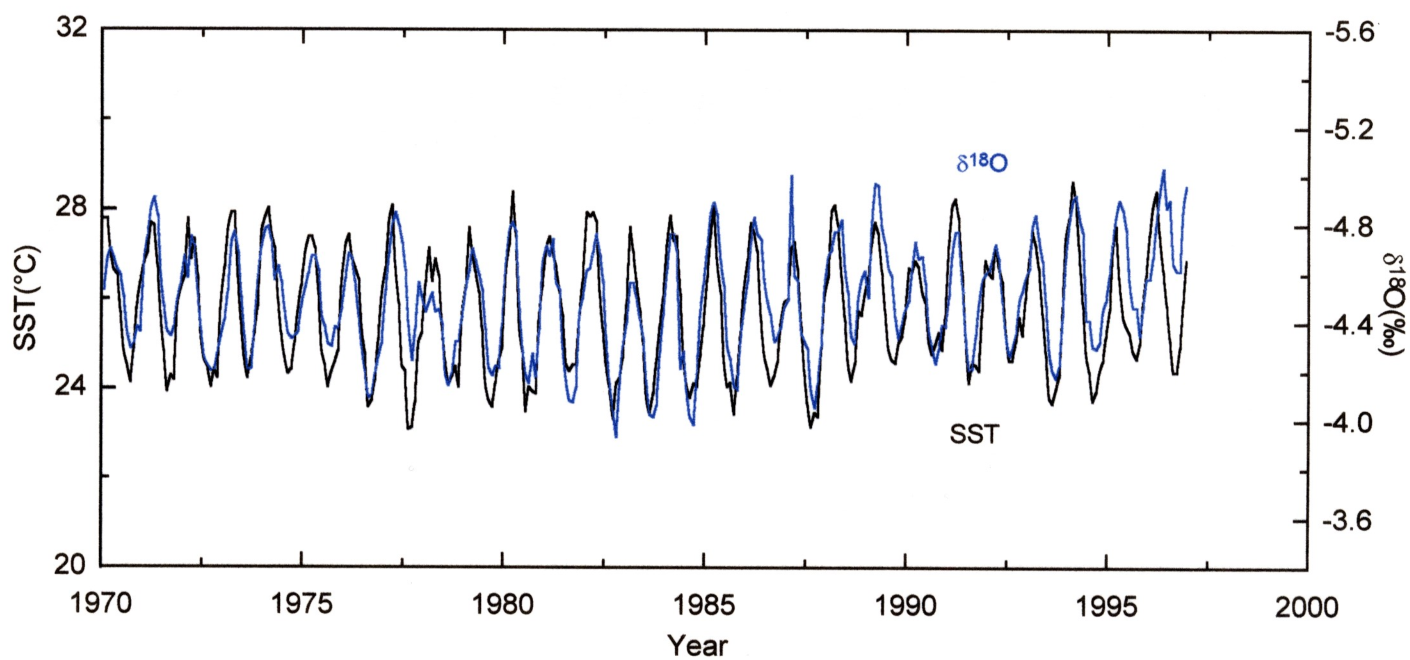

Fig. 4.4 Comparison of $\delta^{18}O$ in corals (in blue) with monthly instrumental SST data (in black) for the period 1970-1997. SST data is from CAC-NMC data archive for the 2x2 degree latitude-longitude block surrounding Rarotonga.

assume that the variation in coral $\delta^{18}O$ is a function of variability of both $\delta^{18}O_{sw}$ and SST this deviation in slope should reflect the variation of $\delta^{18}O_{sw}$ (The separate effects of SST and $\delta^{18}O_{sw}$ on coral $\delta^{18}O$ was discussed in Chapter 2).

SSA was used to more precisely identify and assess the pacing and amplitude of the interannual, interdecadal and long-term $\delta^{18}O$ components in this $\delta^{18}O$ record. For the original unfiltered data, the 10 most significant eigenvectors and their associated variance and periods are listed in Table 4.1. The most significant component is the annual cycle which accounts for ~38% of the total variance. The long-term trend counts for about ~30% of the total variance. SSA also indicates a significant non-oscillatory decadal mode and several interannual modes. As discussed below the interannual components (3.0 to 7.6 years) appear to be related to ENSO.

4.4.2 Interannual Variance

During ENSO "warm mode" events the SPCZ moves to the northeast joining the ITCZ in the central-western Pacific (Trenberth, 1991) which leads to cooler and drier than average conditions in the region of Rarotonga. During ENSO "cool mode" events, the situation reverses; SST rises and the SPCZ intensifies near Rarotonga. Monthly SST data for Rarotonga spanning the period 1971-1997 indicate ~1°C anomalies during most El Niño events (1976-77, 1982-83, and 1992-93) (Reynolds and Smith, 1994). To examine whether the interannual (3~7 year) $\delta^{18}O$ variance at Rarotonga is associated with tropical ENSO variability, I compared the Rarotonga coral $\delta^{18}O$ record with Quinn et al's (1987) and Quinn's (1992) ENSO reconstruction and the Niño 3.4 SST Index (Fig. 4.5). The coral $\delta^{18}O$ data was detrended by removing a linear trend and a 1-year smoothing

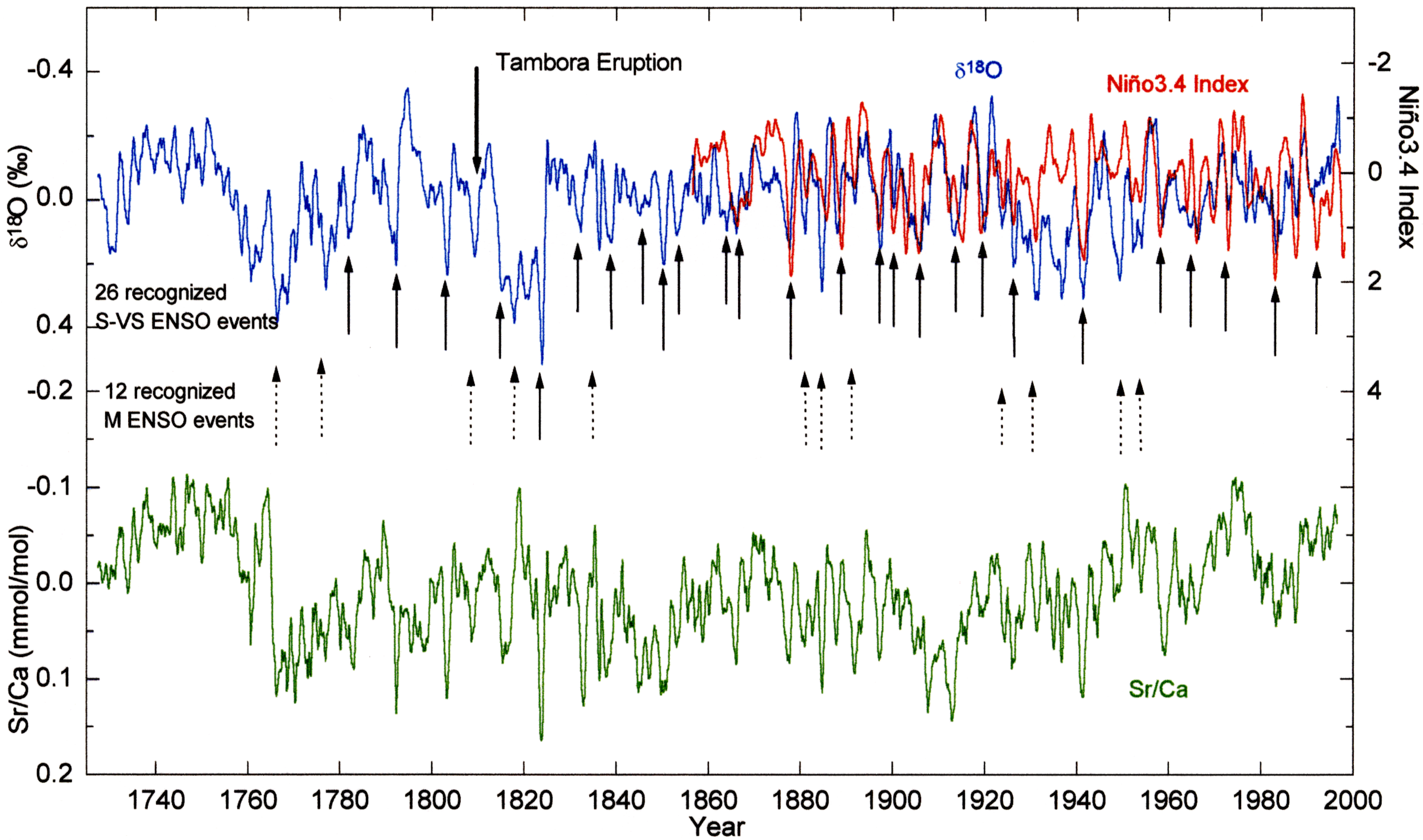

Fig. 4.5 Comparison of annual averaged record of coral $\delta^{18}O$ (in blue) from Rarotonga with annual averaged Niño3.4 Index (in red) for the period 1726-1997. The black arrows represent the strong and very strong ENSO events reconstructed by Quinn (1987; 1992) while the dotted black arrows represent the moderate ENSO events reconstructed by Quinn (1987; 1992). The annual averaged record of coral Sr/Ca (in green) is also shown. All curves are detrended and 1-year smoothing to emphasize the interannual variability.

filter was applied to highlight the interannual variability. Nearly all the strong and very strong ENSO events listed in Quinn (1992) can be identified in the Rarotonga $\delta^{18}O$ record for the period 1760-1997. Of the 28 strong to very strong ENSO events presented by Quinn (1992), 26 are reflected in our $\delta^{18}O$ ENSO reconstruction. The only two exceptions are the 1827-28 and 1911-12 ENSO events. 12 of the moderate ENSO events identified by Quinn (1992) are also recognized in our $\delta^{18}O$ record which include 1768-69, 1776-78, 1806-07, 1817, 1835-36, 1880-81, 1884-85, 1891, 1923, 1932, 1951-52, and 1953. However, it should be noticed that the strength of tropical ENSO events and the amplitude of the subtropical isotopic excursion are not directly correlated. The most apparent example is the moderate ENSO event of 1884-85 identified by Quinn et al. which is shown by a very large anomaly in our $\delta^{18}O$ record (~0.25‰ enrichment in coral $\delta^{18}O$ which is equal to ~1.2°C in SST if it is assumed that all the enrichment is due to the effect of SST (Epstein et al., 1951), ~0.65‰ in salinity if all is assumed as due to the effect of salinity (Schmidt, 1999), or some combination thereof) and even larger than most of the stronger ENSO events. Moreover, a few events for example in 1936-37 revealed in my ENSO reconstruction are not referenced by Quinn (1992).

Overall the strong correlation between coral $\delta^{18}O$ at Rarotonga and ENSO events in the tropics is consistent with the coral-based $\delta^{18}O$ record from Moore-lagoon in the central subtropical Pacific (149.5°W, 17.3°S) (Boiseau et al., 1998) but disagrees with another coral-based $\delta^{18}O$ record from New Caledonia in the South subtropical Pacific (166°E, 22°S) (Quinn et al., 1998).

The coral $\delta^{18}O$ interannual variability at New Caledonia is not correlated strongly with ENSO indices in contrast to the results of Rarotonga and Moore-lagoon. Quinn et al.

(1998) suggest that some of the coral $\delta^{18}O$ variability at New Caledonia may have been caused by volcanic eruptions near New Caledonia as first demonstrated by Crowley et al. (1997). However, this appears to be a minor factor in the Rarotonga region with the exception of the period 1815-1828 when coral $\delta^{18}O$ at Rarotonga exhibits an abnormal enrichment. This period roughly coincides with the time that the Mount Tambora eruption (April, 1815) occurred which has been identified as the largest and deadliest volcanic eruption in recorded history (Rampino and Self, 1982; Stothers, 1984). Large amounts of fine ash and volatiles were dispersed into the upper atmosphere by Tambora eruptions, and Rampino and Self (1982) demonstrated that they could have led to long-term climate cooling. A similar abrupt shifting in Sr/Ca which occurred in 1815 appears to support this observation (Linsley et al., 2000a). However, since the coral $\delta^{18}O$ shift lasted for more than 10 years, the possibility cannot be excluded that there was also decadal oceanographic variability influencing coral $\delta^{18}O$ over this same period.

The strong correlation between coral $\delta^{18}O$ and ENSO events at Rarotonga is further demonstrated when compared to the Niño3.4 SST Index for the period 1856-1997 (Trenberth and Hoar, 1996; Niño3.4 Index from Kaplain et al., 1998). Interannual variations of $\delta^{18}O$ is highly coherent with Niño3.4 Index in both time and frequency domains (see Fig. 4.5). The strong ENSO events in 1876-78, 1899-90, 1913-15, 1918-20, 1940-41, 1957-58, 1972-73 and 1982-83 are all synchronously represented in the Rarotonga $\delta^{18}O$ record. This both confirms the chronology and suggests that this coral $\delta^{18}O$ record can be used to assess the response of the South Pacific gyre to ENSO forcing over the last 271 years. At Rarotonga, although stronger decadal variability for some periods (such as 1930-40) causes the visual offset between coral $\delta^{18}O$ and Niño3.4 Index (see Fig. 4.5), the interannual changes are consistent with Niño3.4 over the total period of 1850-1997. This disagrees with the result from Druffel and Griffin (1999) who analyzed coral $\Delta^{14}C$ and $\delta^{18}O$ from Abraham Reef in the southwestern Pacific (153°E, 22°S). Although they also observed decreases in coral $\delta^{18}O$ during the ENSO events, they indicated that the correlation between ENSO events and $\delta^{18}O$ is not as good between 1870 and 1920 as the other time intervals. At Rarotonga, the interannual changes show consistent correlation with the Niño3.4 region SST for the period 1850-1997.

Finally, since the Niño3.4 SST Index only extends back to 1856, to display the spatial pattern of interannual variation around Rarotonga over the whole period of 1726-1997, the interannual variability of $\delta^{18}O$ is compared with that of Rarotonga coral Sr/Ca which is also shown in Fig. 4.5. In general, $\delta^{18}O$ and Sr/Ca show consistent interannual variations over most of the record. For the period before 1850, when there is no Niño3.4 record, Sr/Ca and $\delta^{18}O$ show generally consistent correlation which is most pronounced for the period 1726-1765. There also exist discrepancies between coral Sr/Ca and $\delta^{18}O$ in some periods of time, for example 1815-1820 and 1808-1813, which may be due to the fact that coral Sr/Ca is mainly a function of SST (Linsley et al., 2000a) while $\delta^{18}O$ is a function of both SST and $\delta^{18}O_{sw}$. But overall for the El Niño event years, the anomalous enrichment of $\delta^{18}O$ (decreased SST and/or decreased precipitation) corresponds to an anomalous enrichment of Sr/Ca (decreased SST). During the La Niña event years, anomalous depletion of $\delta^{18}O$ corresponds to an anomalous depletion of Sr/Ca.

From the above analysis I suggest that although Rarotonga is outside of the center of El Niño activity, it is sensitive to oceanographic variability during ENSO events. There is a consistent response in this South Pacific region to ENSO forcing with El Niño events which extends at least over the past 271 years. There is no strong evidence showing that ENSO events are intensifying in recent decades in this area which disagrees with the observation by Trenberth and Hoar (1996, 1997) and Hughen et al., (1999). However, it should be pointed out that since the subtropics is not in the center of action for ENSO variability, the possibility cannot be excluded that if other external factors are influencing coral $\delta^{18}O$ at Rarotonga, they could obscure the influences of SST and SSS and result in indistinct characteristics of ENSO at this site.

4.4.3 Decadal/Interdecadal Variance

Characteristics of Decadal/Interdecadal Variance

Another interesting aspect of the Rarotonga $\delta^{18}O$ record is the large magnitude of decadal-scale variability. I compare the Rarotonga $\delta^{18}O$ record with the PDO index for the period of 1900-1997 and find notable similarities in time and frequency domains (Fig. 4.6). The two major decadal-scale phases in the PDO index (which are consistent with IPO index) are clearly shown in the Rarotonga $\delta^{18}O$ record: A relatively warm/wet phase at Rarotonga prevailed between 1900-1924 and between 1947-1976, while a cool/dry phase dominated between 1925-1946 and from 1977 through the mid-1990's (see Fig. 4.6) (Latif and Barnett, 1994; Mantua et al., 1997). In addition, shifts of shorter duration in the Rarotonga $\delta^{18}O$ data (such as an abrupt warming and/or salinity reduction beginning in 1940-41, a sudden cooling and/or salinity increase in 1958, and a warming and/or salinity reduction again after 1988) are also coherent with those in the PDO index. The correlation between $\delta^{18}O$ and the PDO index is best for the period 1925-46 (r=0.72) compared with other periods and it is this period when Pacific-wide interannual ENSO

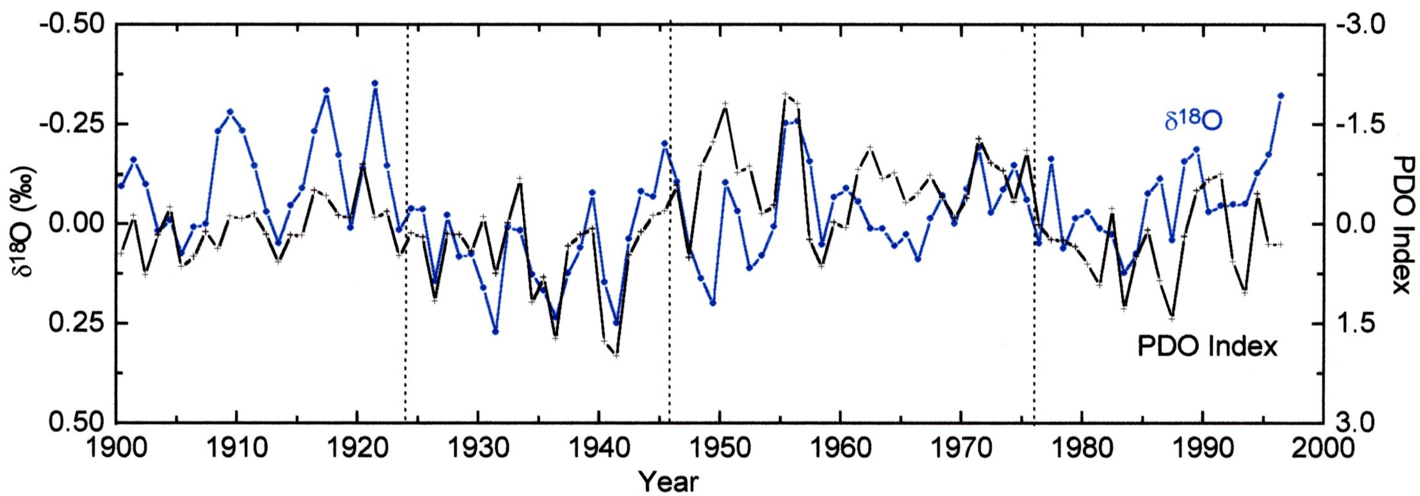

Fig. 4.6 Comparison of annually average Rarotonga coral $\delta^{18}O$ and annually averaged PDO Index for the period of 1900-1997. The dashed black lines represent the stages of decadal variability recognized in the PDO (Mantua et al., 1997).

variability was relatively weak (e.g., Trenberth and Shea, 1987). Based on the analysis of corals from Maiana Atoll, Urban et al. (2000) suggest that in general decadal variability should be strongest, and interannual variability weakest when environmental conditions are relatively cooler and drier in the Pacific. Our results seem to support their observation although this coupling occurred in a different period at Rarotonga (1925-46) from that at Maiana Atoll (mid to late nineteenth century).

Thus the decadal/interdecadal SST and/or SSS variability in $\delta^{18}O$ may be related to the process underlying the PDO and IPO. This agrees with some authors (e.g., Trenberth, 1990; Trenberth and Hurrel, 1994) who propose 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 hemisphere. Salinger et al. (in press) suggest that the decadal changes induced by the IPO in the South West Pacific regions originate as changes in atmospheric mass between the western and eastern parts of the region. White and Cayan (1998) and Johnson and McPhaden (1999) further document that the South Pacific dominates the Pacific interdecadal signal as the largest magnitude interdecadal upper ocean temperature anomalies occur at the depth of the main pycnocline in the South Pacific and the southern Hemisphere interior pycnocline flow in the Pacific carries about three times more subtropical water towards the equator than does the northern interior route.

Potential Mechanisms of Decadal/Interdecadal Variance

The mechanism driving decadal-scale climate variability is still poorly constrained. In order to examine the spatial patterns of decadal-scale variability preserved in corals in the Pacific, western Pacific coral $\delta^{18}O$ records from both subtropical and tropical regions are compared with the Niño3.4 SST index and the PDO index. In the western subtropical Pacific, a seasonal resolution $\delta^{18}O$ record from New Caledonia (20.7°S, 166.2°E; 1660-1991) (Quinn et al., 1998) is compared to our data from Rarotonga. To evaluate the tropical signal, two $\delta^{18}O$ series from the western tropical Pacific: a bimonthly $\delta^{18}O$ record from Maiana (1°N, 173°E; 1840-1994) (Urban et al., 2000) and a seasonal $\delta^{18}O$ record from Nauru (0.5°S, 166°E; 1891-1995) (Guilderson and Schrag, 1999) are examined. All time series were low-pass filtered at 7 years then analyzed with SSA. Results are shown in Table 4.2. This analysis differentiates the interdecadal from decadal variations. The PDO index only shows interdecadal variance while Nino3.4 index only shows decadal variability. The subtropical records (Rarotonga and New Caledonia) show both decadal and interdecadal variability while the tropical

	Location	*Decadal Variance (yr)*	*Interdecadal Variance (yr)*
PDO index	Used as North Pacific Decadal index	--	~30
Niño3.4 index	Used as El Niño index	~12-16	--
Rarotonga	South subtropics (21°S, 159°W)	~12-15	~31
New Caledonia	South subtropics (20°S, 166°E)	~11-15	~30
Maiana	Tropics (1°N, 173°E)	~13	--
Nauru	Tropics (0.5°N, 166°E)	~13	--

Table 4.2. Singular Spectrum Analysis for PDO index, Niño3.4 SST index, and four regions including Rarotonga, New Caledonia, Maiana and Nauru: Low passed filtered at period=7yr for all series.

records (Maiana and Nauru) only show decadal variability. These results support the suggestion that the climatic fingerprints of interdecadal variability are most visible in the subtropical sector (Mantua et al., 1997; Evans et al., 2000).

Decadal variability is preserved at all four coral sites (Fig. 4.7) and comparisons with Niño3.4 index show that the decadal variability changes in phase with no lag and covaries in amplitude with Niño3.4 in most of the overlapping sections in all four regions. There is no distinct difference of the spatial pattern between tropical regions and subtropical regions although the magnitude of the decadal variability at tropical regions (Nauru and Maiana) is generally larger than that at subtropical regions (Rarotonga and New Caledonia). The correlation is highest in 1910, 1940, and 1977 for the four regions, which also happen to be strong El Niño years (Quinn et al., 1987; 1992).

Interdecadal variability is only preserved in the subtropical records of New Caledonia and Rarotonga. The interdecadal components of both New Caledonia and Rarotonga show a similar pattern to that of PDO index throughout most of the 20th century (Fig. 4.8). Several of the most pronounced interdecadal changes in the PDO index are evident in the Rarotonga and New Caledonia $\delta^{18}O$ records (for example at 1976-77 and 1945-46). However, disagreements also exist between the coral interdecadal components and the PDO index in some intervals (for example over 1915-25 and 1960-70). It is possible that these intervals represent the fact that $\delta^{18}O$ is affected by both $\delta^{18}O_{sw}$ and SST while the PDO index is derived from only SST in the North Pacific. Thus, the lack of correlation in these intervals may be due to variations of $\delta^{18}O_{sw}$. Another possible explanation for these disagreements may be related to the fact that we are comparing coral $\delta^{18}O$ series from two specific points in the South Pacific with a

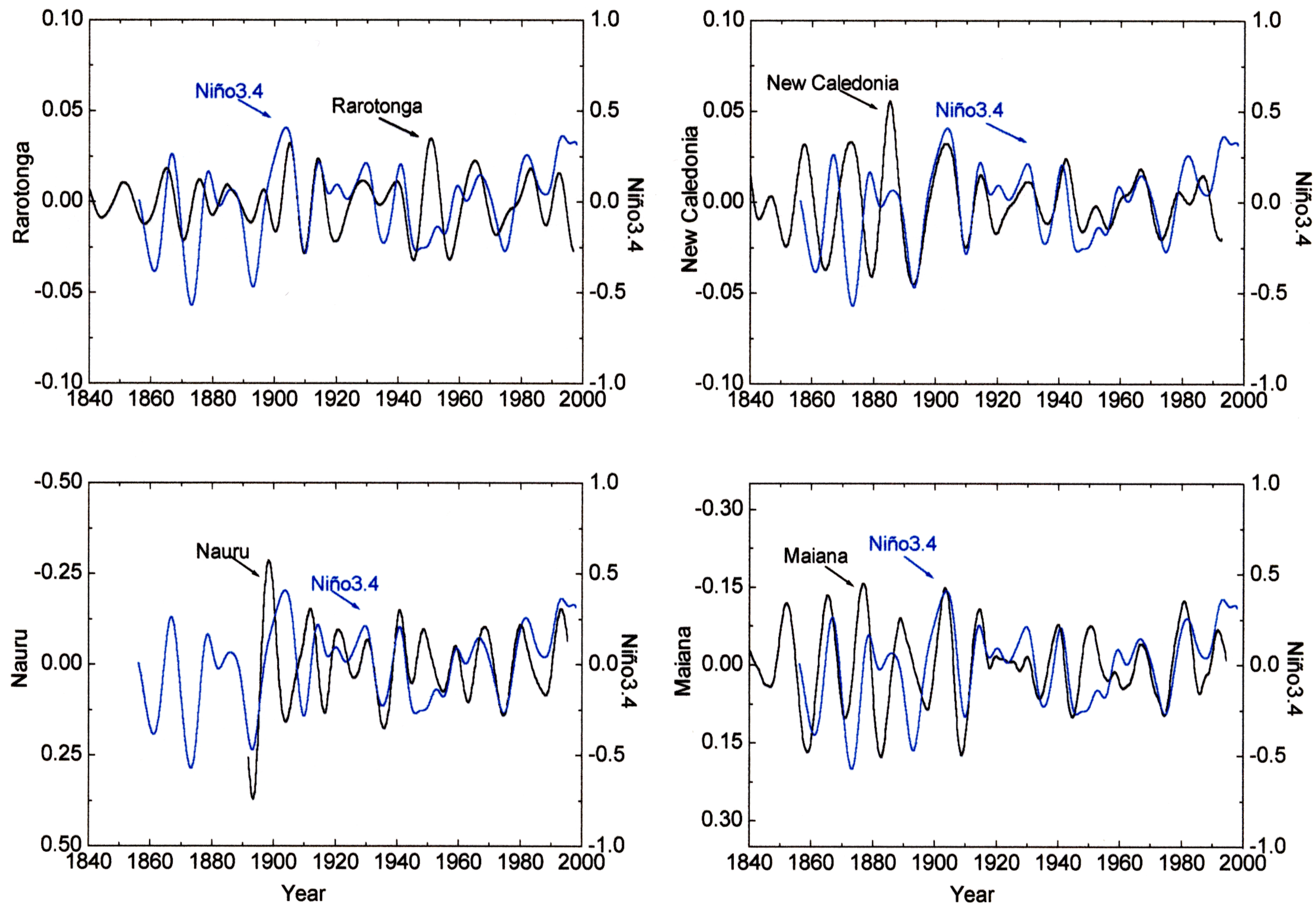

Fig. 4.7 Comparison of singular spectrum analysis (SSA) extracted decadal band RCs from Rarotonga, New Caledonia, Nauru and Maiana Atoll (in black) with that of Niño3.4 Index (in blue) for the period 1840-1997. Note that the scales of Niño3.4 Index are the same for the four regions while the scales of decadal band of coral $\delta^{18}O$ are different.

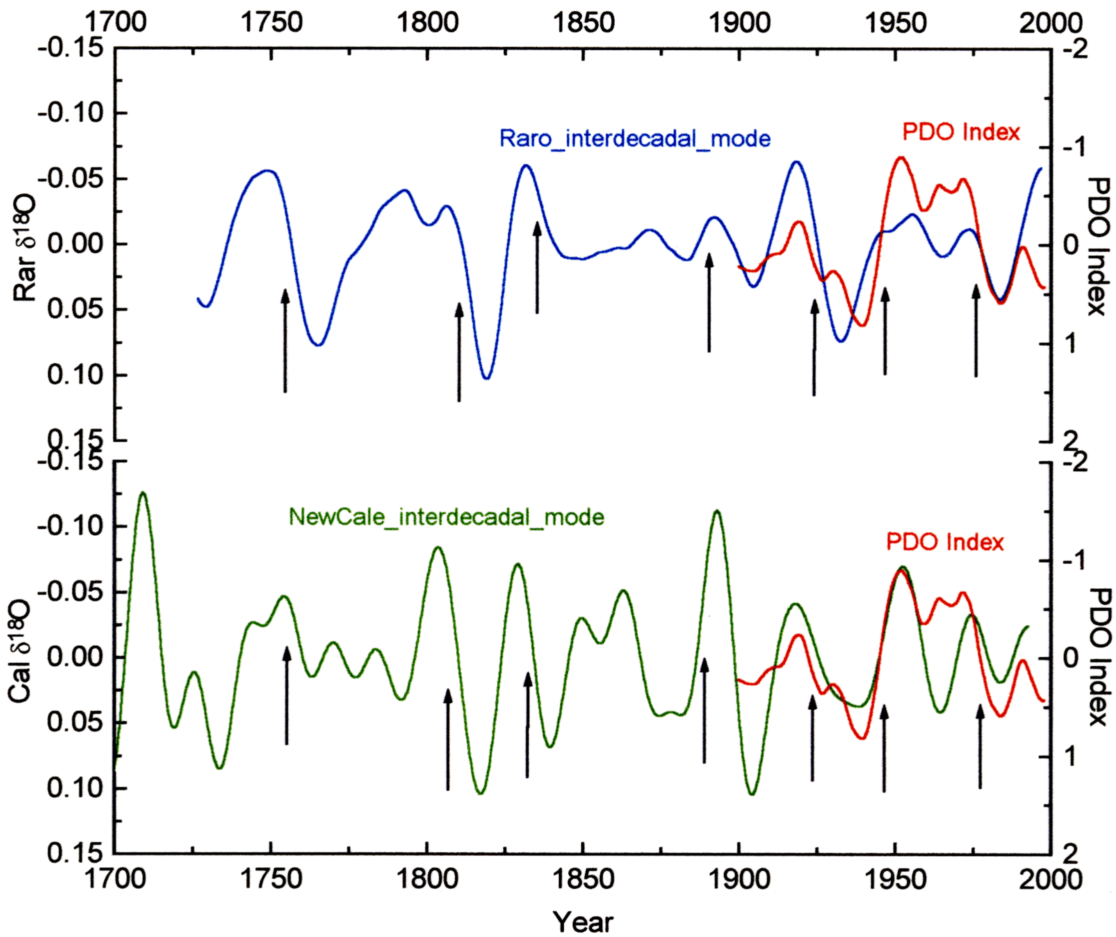

Fig. 4.8 Comparison of singular spectrum anlaysis (SSA) extracted interdecadal band RCs of $\delta^{18}O$ from Rarotonga (in blue), and New Caledonia (in green) with that of PDO Index (in red) for the period 1900-1997. Comparison of SSA extracted interdecadal bands RCs of $\delta^{18}O$ from Rarotonga and New Caledonia in the period 1700-1997. The black arrows represent the correlation observed between $\delta^{18}O$ in Rarotonga and that in New Caledonia.

North Pacific-wide index as indicated in Linsley et al. (2000a). The similar interdecadal trends between Rarotonga and New Caledonia in 1915-25 and 1960-70 seems to favor the later explanation (see Fig. 4.8).

The above analysis indicates that in the subtropical South Pacific, coral $\delta^{18}O$ decadal variability appears to be more related to tropical variations while the interdecadal variability appears to be more closely related to mid-latitude variations. Decadal variation is absent in the PDO while interdecadal variation is absent in the Niño3.4 and equatorial coral $\delta^{18}O$ records. The decadal variability in the subtropics shows consistent temporal patterns at Rarotonga and New Caledonia but with a smaller amplitude than in the tropics at Nauru and Maiana. Interdecadal variability is only preserved in the subtropics. Therefore, I speculate that these two types of variability may represent separate SST and/or SSS spatial structures with different sources as suggested by White et al. (1997), White and Cayan (1998) and Mann and Park (1996). It leads me to hypothesize that there might exist separate modes of decadal and interdecadal variability in the Pacific. Decadal variability appears to be primarily a response to the tropical Pacific while interdecadal variability appears to be more related to the mid-latitudes of the South Pacific. The results from a western Indian coral Ocean further supports our hypothesis (Cole et al., 2000). Cole et al. (2000) also observed decadal time-scale variability of coral $\delta^{18}O$ from Kenya in the western Indian Ocean. Since there is not a PDO signature in the Indian Ocean SST and SLP fields (Mantua et al., 1997), they suggested that the tropical Pacific is the strong candidate for forcing of decadal climate variability in the Indian Ocean.

Since the PDO index only extends back to 1900, to obtain temporal and spatial patterns of interdecadal variation in the subtropical southwest Pacific over a longer time scale the interdecadal component of the Rarotonga record can also be compared with that of New Caledonia (see Fig. 4.8) back to the early 1700's. A similar interdecadal pattern over the whole period is observed although they display different amplitudes over part of the period. It appears that the interdecadal variability at New Caledonia was stronger during the 19th century but weaker during the 18th century while at Rarotonga it was weaker during the 19th century but stronger during the 18th and 20th centuries. In general, it is evident that the interdecadal variability has persisted for the last three hundred years in the Pacific.

Trenberth (1990) pointed out that since the ocean is simultaneously affected by many climate forcings, it may be very difficult to clearly separate different causes for any observed phenomenon and there may be multiple forcings contributing to any observed change in differing amounts. Therefore, further research on multi-century coral cores from broader areas is required to gain a better understanding of the longer-term changes.

4.5 Summary

(1) A 271-year $\delta^{18}O$ coral record (1726-1997) has been developed from Rarotonga using a specimen of *Porites lobata*. The $\delta^{18}O$ data shows clear seasonal variation with inverse correlation with SST. However, a $\delta^{18}O$-SST relationship of –0.135‰/°C indicates that salinity may also play a significant role in $\delta^{18}O$ changes due to the influence of SPCZ rainfall.

(2) Comparisons with historical ENSO activities reconstructed by Quinn et al. (1987; 1992) and Niño3.4 Index suggest that although Rarotonga is located outside of the center of action of ENSO, the $\delta^{18}O$ record is generally sensitive to ENSO variability

in this region. Its in-phase variation with the Niño3.4 suggests a consistent response in the region of the south Pacific to ENSO forcing. The comparison of coral $\delta^{18}O$ with Sr/Ca further suggests that climate variability at this site is strongly affected by ENSO events which can extend back to 271 years.

(3) There is a large percentage of variance in $\delta^{18}O$ at decadal/interdecadal scales at Rarotonga. Comparison with the PDO index shows that the interdecadal variability in Rarotonga may be related to the processes associated with the North Pacific Oscillation. It supports the suggestion by some studies that North Pacific changes appears to be linked through air-ocean teleconnections to the southern hemisphere interactions.

(4) The decadal-scale variability (11 to 16 year) is differentiated from the interdecadal-scale variability (~30 year) for the period of 1726-1997 at Rarotonga. Comparisons of the decadal component of $\delta^{18}O$ of both tropical and subtropical regions with that of Niño3.4 Index appear to suggest that the decadal-scale variability is different from interdecadal variability in periodicity and spatial structures. This observation implies that in the South Pacific gyre, decadal and interdecadal oceanographic variability might result from separate mechanisms.

CHAPTER 5

EXAMINATION OF THE REPRODUCIBILITY OF $\delta^{18}O$ AND $\delta^{13}C$ IN CORALS

Abstract. Stable oxygen isotope ($\delta^{18}O$) analysis of two separate coral cores (1726-1997; 1926-2000) from *Porites Lutea* colonies growing on the opposite sides of the island of Rarotonga (21.5°S, 159.5°W) suggests that coral $\delta^{18}O$ is mainly affected by environmental variables such as SST and precipitation, while the effect of growth rate is minimal. Coral $\delta^{18}O$ at Rarotonga not only faithfully records seasonal variability, but also interannual variability and a long-term trend. Coral $\delta^{18}O$ at this site can therefore be reliably used to reconstruct past variation of SST and precipitation in this region. However, stable carbon isotope ($\delta^{13}C$) from the same corals fails to document common features in interannual to decadal signals at Rarotonga. Its interpretation therefore remains enigmatic. As the carbon in corals is derived from some combination of sources, development of robust paleoclimatic interpretations from coral $\delta^{13}C$ records requires an improved understanding of both endogenous and exogenous factors that control $\delta^{13}C$ fractionation in coral skeletons. Any environmental interpretation of $\delta^{13}C$ record in corals should be made with caution.

5.1 Introduction

It is known that coral $\delta^{18}O$ is several permil more depleted than expected from carbonate accreted in isotopic equilibrium with the ambient seawater (McConnaughey, 1989a). Weber and Woodland (1972) demonstrated that although hermatypic corals deposit their aragonite skeleton in disequilibrium with seawater, the slope of the curve showing the relationship between $\delta^{18}O$ and ambient temperature is constant and the same as that given by the equation of Epstein et al. (1953). It is this assumption, that the departure from equilibrium remains constant, that makes coral $\delta^{18}O$ useful as a recorder of SST and $\delta^{18}O_{sw}$. Therefore, at present it is generally believed that as long as a consistent, maximum growth axis is sampled within a coral colony (Weber and Woodhead, 1972; McConnaughey, 1989a; Shen et al., 1992b; Gagan et al., 1994; Wellington et al., 1996; Linsley et al., 2000b), $\delta^{18}O$ in corals can be used to reconstruct environmental factors. However, several studies question this assumption and show that the rate of skeletal accretion may also be an important factor that influences coral $\delta^{18}O$ (e.g. Land et al., 1975; Barnes and Lough, 1993; Allison et al., 1996; Cohen and Hart, 1997). Land et al. (1975) observed greater depletion in skeletal ^{18}O in the faster growing areas of single coral colonies and also in the faster growing skeletal elements from the same calice. Cohen and Hart (1997) also reported significant $\delta^{18}O$ differences along sample tracks only 2 cm apart in two sections. They attributed the $\delta^{18}O$ offset to different calcification rates on the irregular surface of this colony.

Therefore, one particular problem with the use of coral isotopic records in climatic studies is the reproducibility of the $\delta^{18}O$ analysis, which is directly related to the validity and accuracy of the interpretation of the variation of skeletal $\delta^{18}O$. At present there are several studies on the reproducibility of coral stable oxygen isotopic time series and there is some disagreement on the degree of reproducibility (Tudhope et al., 1995; Azzolina, 1997; Guilderson and Schrag, 1999; Linsley et al., 2000b). Azzolina (1997) examined $\delta^{18}O$ in four coral cores collected from northern Red Sea and found no exact agreement among them and he attributed this disagreement as due to variations in the effect of the growth rate and the environmental stress during the winter months on the slower growing corals. Alternatively, Guilderson and Schrag (1999) observed a consistency of two coral $\delta^{18}O$ records from Nauru in the western Pacific and confirmed that coral $\delta^{18}O$ is a robust recorder of environmental variables. Tudhope et al. (1995) and Linsley et al. (2000b) arrived at similar conclusions based on reproducibility studies of $\delta^{18}O$ at New Guinea and Clipperton, respectively. In this chapter, the reproducibility of temporal variations in coral $\delta^{18}O$ record from Rarotonga (159°W, 21°S) is examined based on comparisons of the two coral records (cores 2B+2C, used in previous chapters 2-4; and core 3R) collected from Rarotonga in 1997 and 2000, respectively. The potential growth rate effect on $\delta^{18}O$ is also discussed.

Unlike $\delta^{18}O$, the $\delta^{13}C$ signal in coral skeletons is often difficult to decipher due to its complicated interactions with physiological processes. Although at certain sites coral $\delta^{13}C$ shows strong correlation with changes in some environmental variables such as light levels (e.g. Fairbanks and Dodge, 1979; Leder et al., 1991), several studies on the reproducibility of $\delta^{13}C$ at adjacent corals all indicate little similarity in their $\delta^{13}C$ signatures (Guilderson and Schrag, 1999; Linsley et al., 2000b). In this chapter, the reproducibility of $\delta^{13}C$ of the same two coral records (2B+2C; 3R) from Rarotonga is also examined and the complexity of $\delta^{13}C$ signature is discussed.

5.2 Sample Preparation and Chronology of Core 3R

Coral colonies of *Porites lutea* were collected at Rarotonga in 1997 and 2000. Two cores (2B+2C) were collected in April 1997 from the same colony on the southwest side of the island at a water depth of 18m (60 feet) (see chapters 2-4). In May 2000, another coral core (3R) was collected from a colony of *Porites lutea* at a water depth of 9m (30 feet) on the north side of the Rarotonga island. Average wave amplitude at this location is weaker than on the southwest side and a small river is 0.5km from the coral site. The sample preparation and mass spectrometer analysis are the same as those for core 2B and 2C presented in the previous chapters. The total usable length of core 3R is 2.1m, of which 1025mm has been analyzed presently. Similar to cores 2B and 2C, the first 400mm of core 3R was sampled every 1 mm while the interval from 400 to 1025mm was sampled every other 1 mm. These two different sampling densities result in equal annual $\delta^{18}O$ amplitudes, similar to the results for cores 2B and 2C. The standard deviation of 106 analyses of the international NBS-19 standard was 0.033‰ for $\delta^{18}O$ and 0.016‰ for $\delta^{13}C$.

The chronology of core 3R was developed based on both the dense banding observed in X radiograph positive prints and annual periodicity of $\delta^{18}O$ obtained from stable isotope profiles. Both methods documented a total of 74 years over the analyzed section of 3R. As this core was collected live from Rarotonga in June 2000, the first year is assigned to April 2000 (to account for the tissue layer) and the last year is counted down to 1926. The final result of subseasonal $\delta^{18}O$ and $\delta^{13}C$ for the period 1926-2000 of core 3R is shown in Fig. 5.1.

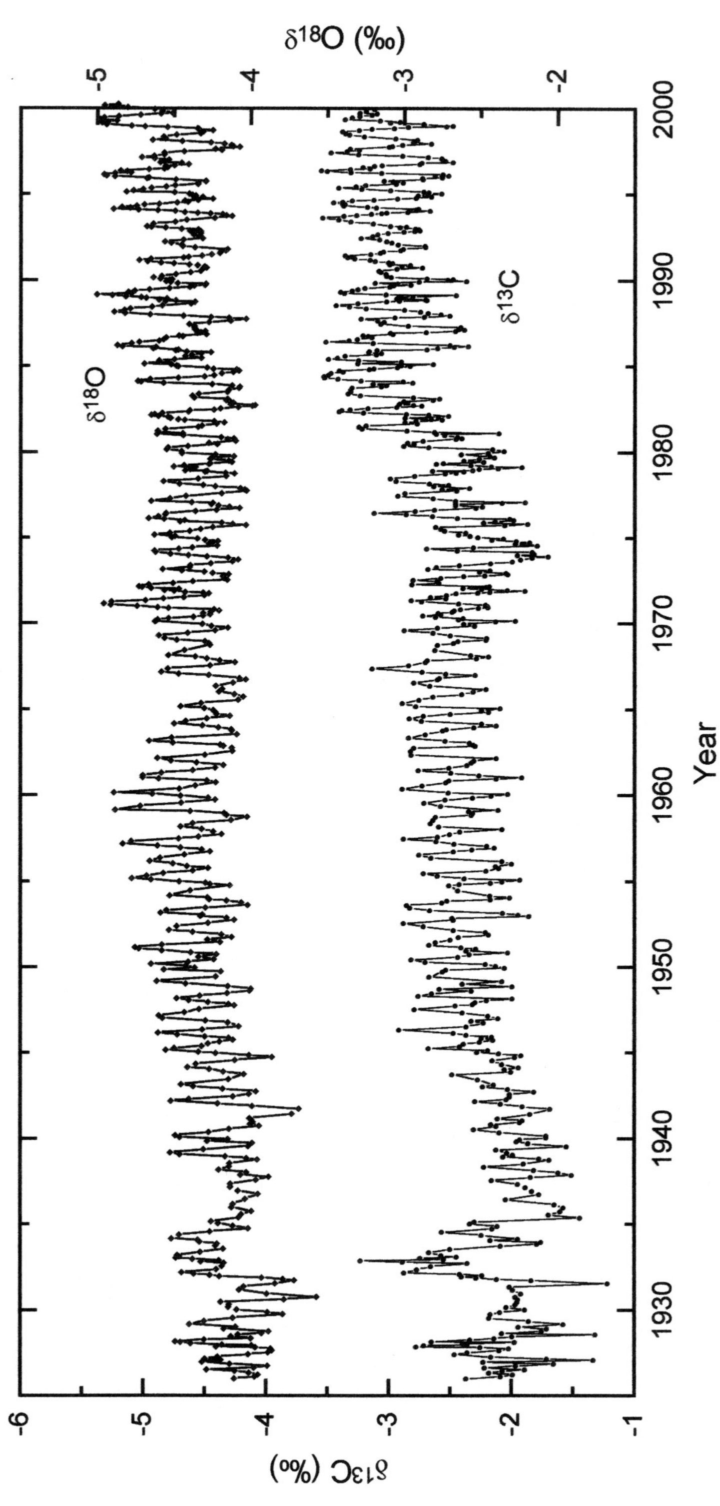

Fig. 5.1 Rarotonga subseasonal $\delta^{18}O$ and $\delta^{13}C$ of core 3R spanning the period 1926-2000.

5.3 Oxygen Isotopes

Subseasonal oxygen isotope results are highly consistent along the length of the two records for the period 1926-1997 (r=0.8) (Fig. 5.2a and 5.2b). The average amplitude of the $\delta^{18}O$ seasonal cycles in the two records is similar, with an annual range of variation of ~0.6‰ in both. In some years, for example, in 1931, 1951, 1959, 1971, and 1988, when 3R displays abnormal depletion or enrichment in $\delta^{18}O$, 2B+2C also shows similar $\delta^{18}O$ amplitudes. The only exception occurs between 1935 and 1940 in which the annual amplitude of variation of $\delta^{18}O$ in core 2B+2C is twice as large as that in core 3R. Examination of the 1 year moving correlation window shows that $\delta^{18}O$ records of 3R and 2B+2C are strongly correlated with each other, sharing an average of 83% variance (Fig. 5.2c). Closer inspection indicates that before 1950, the shared variance is ~74%, while after 1950 it reaches ~87%.

The consistency of these two records also generally occurs on interannual time scales. Both show interannual variation with ~0.2-0.3‰ amplitude. In order to highlight the interannual variability the $\delta^{18}O$ data in both records are smoothed using a 12-month running average (Fig. 5.3). The interannual variance of the two $\delta^{18}O$ series shows common anomalies during ENSO event years and displays a strong correlation with R=0.84. For the period of 1926-1997, all the strong and very strong ENSO events identified in Quinn et al. (1987) and Quinn (1992) can be identified on both $\delta^{18}O$ records (for example in 1940-41, 1957-58, 1965-66, 1972-73, and 1982-83). As discussed in chapter 4 core 2B+2C $\delta^{18}O$ is sensitive to ENSO variability (see Chapter 4). The strong correlation between coral $\delta^{18}O$ in core 2B+2C and 3R provides strong evidence that supports this observation although core 3R only extends back to 1926. However, I also

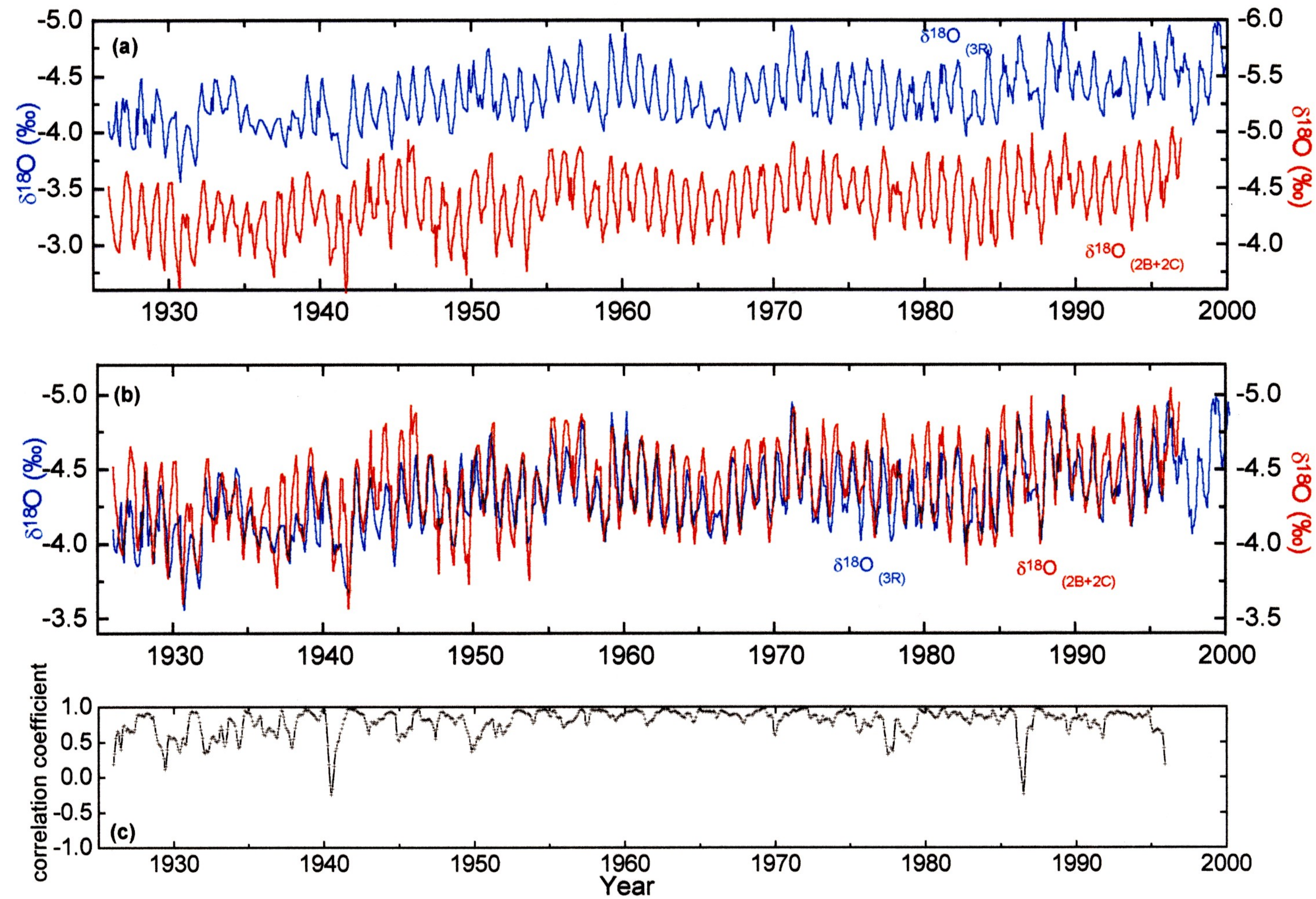

Fig. 5.2 (a) & (b) Comparison of $\delta^{18}O$ of core 2B+2C (in red) with that of core 3R (in blue) for the period 1926-1997 at Rarotonga. **(c)** Moving correlation coefficient (1-year window) showing the correlation between 2B+2C and 3R $\delta^{18}O$.

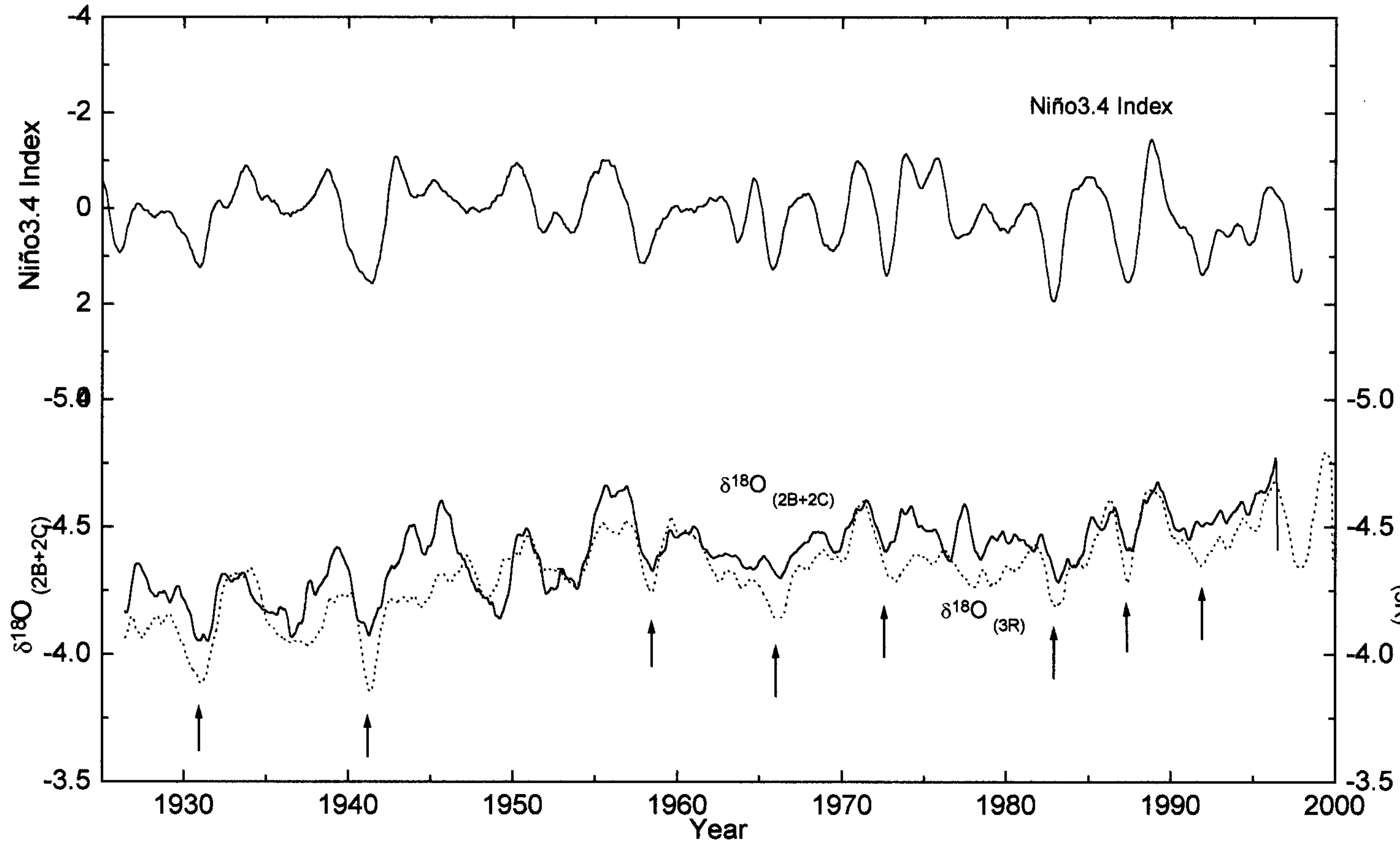

Fig. 5.3 Comparison of 12-month running average record of 2B+2C coral $\delta^{18}O$ (in solid line) with 3R coral $\delta^{18}O$ (in dotted line) from Rarotonga for the period 1926-1997. The black arrows represent the strong and very strong ENSO events reconstructed by Quinn (1987; 1992). The 12-month running average record of Niño3.4 SST Index is also shown.

note that there are a few discrepancies on interannual time-scales between the two curves, for example in 1942-47 and 1955-57, which can be as large as ~0.2‰ [equal to ~1°C in SST (Epstein et al., 1953), or ~0.5‰ in salinity (Schmidt, 1999), or some combination thereof]. These differences may be related to the fact that 3R is more affected by salinity due to a small local river which is 0.5km from it.

A long-term trend of –0.4‰ in $\delta^{18}O$ is observed in both records, showing a progressive shift toward more negative values over the interval 1926 to 1997. There is no offset in absolute values between the two $\delta^{18}O$ records for the period 1926-1997. The differences in $\delta^{18}O$ between the cores 2B+2C and 3R ($\delta^{18}O_{2B+2C} - \delta^{18}O_{3R}$) for the period 1926-1997 are relatively small, and vary around zero with no trend, which suggests that the relative disequilibrium between the two records is constant (Fig. 5.4).

It is generally believed that the factors that cause the long-term trend may include the secular change in SST due to global warming (Quay, 1992), a salinity change due to the secular change of the ocean circulation (Gagan et al., 1998) and/or some unknown coral growth effect (Land et al., 1975). At Rarotonga the average monthly temperature data (NOAA NODC WOA 98 monthly temperature) (Conkright et al., 1998) shows essentially the same variations at 10m and 20m although the data in several months is not available (Fig. 5.5a). The average monthly salinity data (NOAA NCEP EMC CMB Pacific monthly salinity) (Ji et al., 1995) shows identical variation at 10m and 20m water depth (Fig. 5.5b). Thus, we can assume that the variations of SST and salinity would have approximately the same effects on these two corals collected from different depths. The similar magnitude of the secular trend (–0.4‰) shown in the two records therefore implies that the effect of the growth rate of these two corals should also be approximately

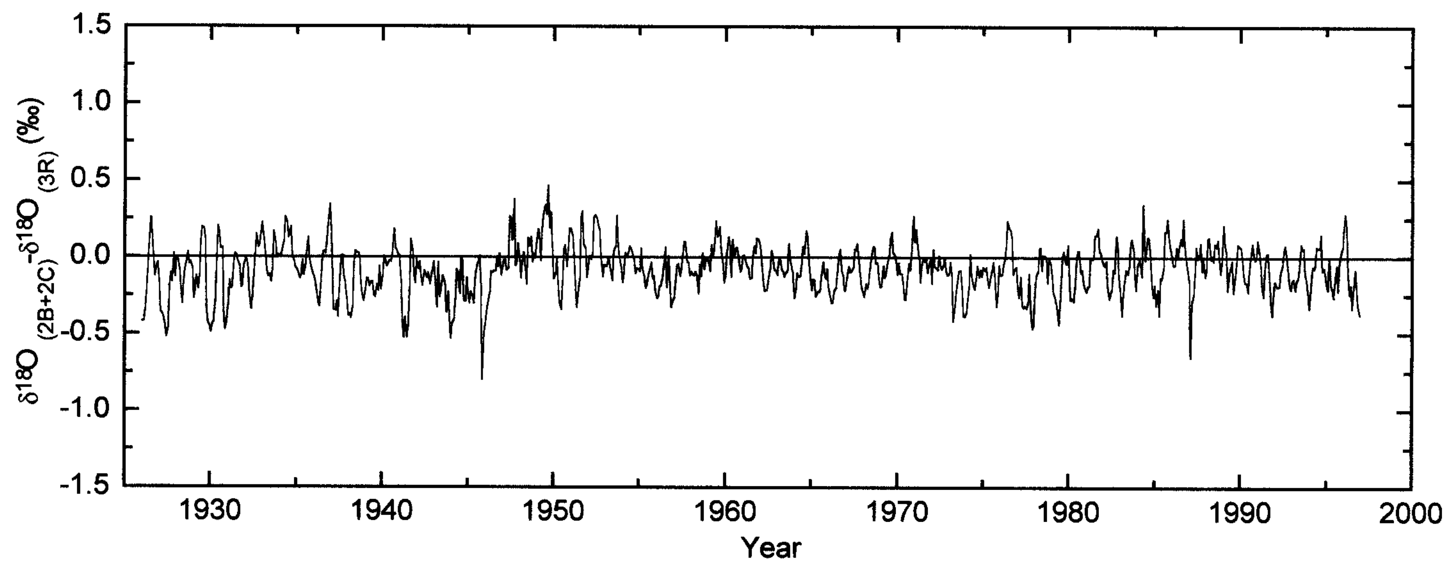

Fig. 5.4 The differences in $\delta^{18}O$ between the record 2B+2C and 3R ($\delta^{18}O_{2B+2C}$ - $\delta^{18}O_{3R}$) for the period 1926-1997 at Rarotonga.

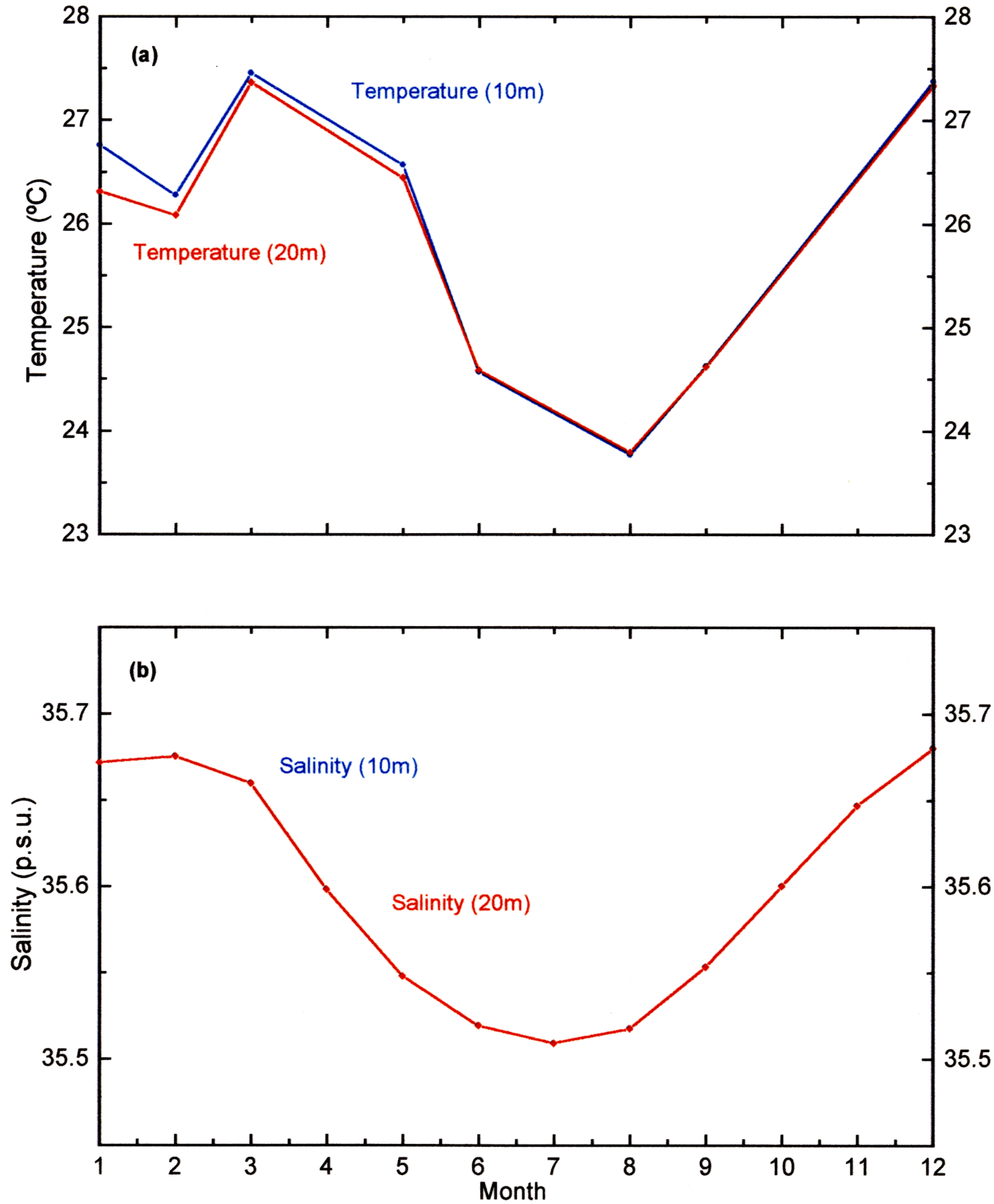

Fig. 5.5 (a) Monthly average seawater temperature at 10m (in blue) and 20m (in red) at Rarotonga (NOAA NODC WOA 98 monthly temperature) (Conkright et al., 1998). **(b)** Monthly average salinity at 10m (in blue) and 20m (in red) at Rarotonga (NOAA NCEP EMC CMB Pacific monthly salinity) (Ji et al., 1995).

the same. However, the examination of their linear extension rates shows that the characteristics of the two extension rate records are different (Fig. 5.6).

Skeletal growth parameters can be separated into components of extension, density, and calcification. Linear extension can be estimated directly from x-radiographs by measuring the width of each annual density couplet. Consequently, this aspect of skeletal growth is the most commonly reported (Lough and Barnes, 1997), and growth-rate related isotopic variations in coral skeleton are most often reportedly linked to variations in linear extension rather than calcification (Land et al., 1975; Aharon, 1991; de Villiers et al., 1995; Allison et al., 1996). Thus, if the linear extension rate is used as an albeit imprecise proxy for calcification rate, over the same period of 1926-1997, the linear extension rate of core 2B+2C was faster and increased from 14.8mm/yr to 16.5mm/yr (totally 1.7mm increase of extension rate) while core 3R was slower and remained constant at about 13mm/yr. The differences of the extension rates between the two cores range from 1.8mm to 3.5mm over the 71 years. Changes in linear extension in the two cores do not correspond to the long-term trend in the $\delta^{18}O$ profiles, which may suggest that extension rate is not responsible for the long-term secular changes in $\delta^{18}O$ in the two records. Closer examination of Fig. 5.4 shows that before 1946 the difference between the two $\delta^{18}O$ records was larger than after 1946. It is around this period that an important decadal shift occurred in the North Pacific, (Mantua et al., 1997; Zhang et al., 1997). This change in the difference between the two coral $\delta^{18}O$ records is therefore not likely attributable to the extension rate, but probably related to a major shift in environmental parameters (Latif and Barnett, 1994; Trenberth and Hurrell, 1994). In addition, as the two colonies are of different total age, the same 0.4‰ $\delta^{18}O$ trend in the

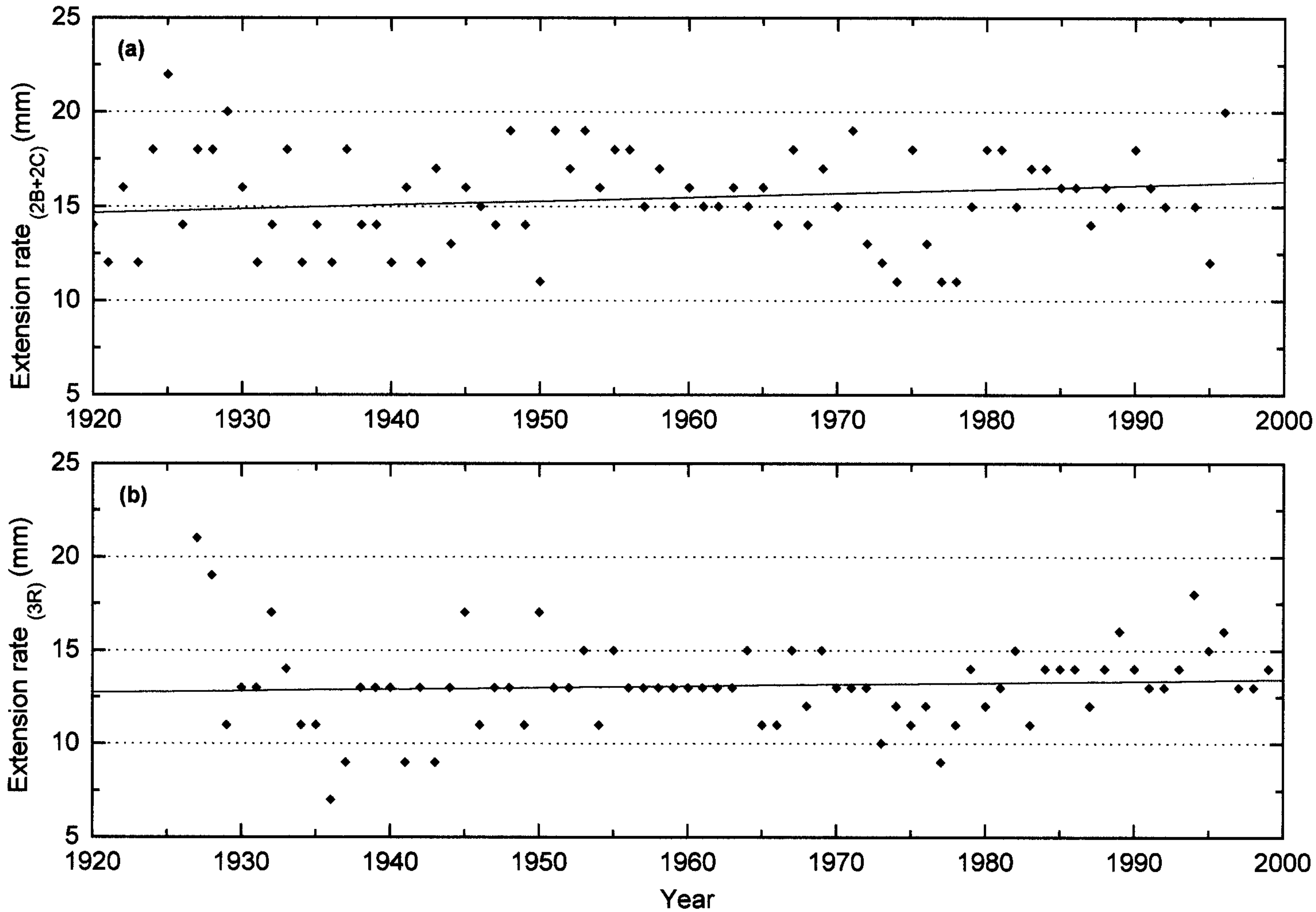

Fig. 5.6 The extension rates of **(a)** core 2B+2C and **(b)** 3R for the period 1926-2000, respectively at Rarotonga. The line in each figure represents the trend of each extension rate.

two cores with different ages supports the above analysis that the long-term trend in $\delta^{18}O$ may not be biological mediated but rather may be due to external environmental changes.

My results agree with the observations of Guilderson and Schrag (1999). From the analysis of two separate coral records from Nauru, the authors also interpret the secular trend in coral $\delta^{18}O$ to be the result of environmental changes rather than a change in calcification-rate-driven disequilibria. In addition, from the analysis of three different coral records at Clipperton Atoll, Linsley et al. (2000b) also suggested that the long-term trend is not likely a result of biological growth effect. Therefore, these new results support the argument that if a consistent, maximum growth axis is sampled within a coral colony, $\delta^{18}O$ in corals may be reliably used to reconstruct the past variations of SST and $\delta^{18}O_{sw}$.

5.4 Carbon Isotopes

5.4.1 Reproducibility of Carbon Isotope in Corals

While the oxygen isotope results show mostly common features between the two records, the carbon isotope results are disparate (Fig. 5.7). Although in general, the seasonal cycles of the two records show a similar annual ranges of ~0.7‰, examination of the 1 year moving correlation window shows that the correlation between 3R and 2B+2C $\delta^{13}C$ records are much lower than that of $\delta^{18}O$, sharing only ~42% variance. Especially before 1950, the average of the variance is near ~0%, with negative correlation in some time intervals. The difference between the two records ($\delta^{13}C_{2B+2C} - \delta^{13}C_{3R}$) highlights this varying discrepancy which are much larger than those between $\delta^{18}O$ records (Fig. 5.8 and see Fig. 5.4). There is also a big change in $\delta^{13}C$ difference around

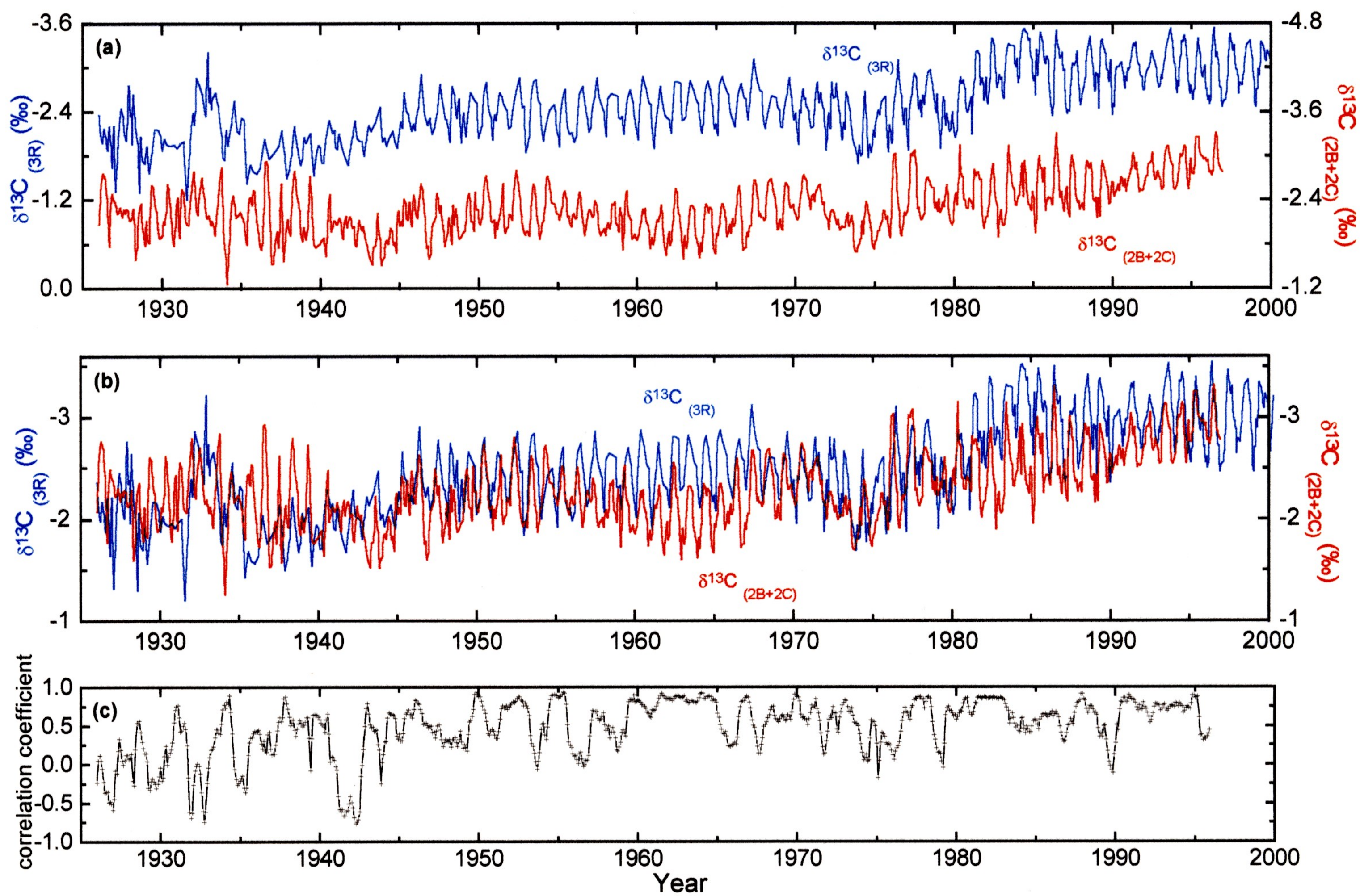

Fig. 5.7 (a) & (b) Comparison of $\delta^{13}C$ of core 2B+2C (in red) with core 3R $\delta^{13}C$ (in blue) for the period 1926-1997 at Rarotonga. **(c)** Moving correlation coefficient (1-year window) showing the correlation between 2B+2C $\delta^{13}C$ and 3R $\delta^{13}C$.

1946, which is similar to that found in $\delta^{18}O$. Before 1946 the difference between the two $\delta^{13}C$ records is larger and more negative than after 1946. The interannual and interdecadal modes of the two $\delta^{13}C$ records are also very different (Fig. 5.9). For example, between 1950-1970, $\delta^{13}C$ in core 3R shows relatively little variation while in core 2B+2C it shows strong decadal-scale variability. Alternatively, between 1980-1997, $\delta^{13}C$ in core 2B+2C shows relatively little low frequent variation while in core 3R it shows relatively strong decadal-scale variability. However, there is one exception around 1975-76 when the two $\delta^{13}C$ time series show similar amplitudes of anomalous enrichment. It is in this period that a significant decadal climatic shift in the northern Hemisphere has been recognized (Trenberth, 1990; Mantua et al., 1997). In the long-term trend, although both show a secular trend towards more negative values for the period 1926-1997, $\delta^{13}C$ in 2B+2C displays a shift from –2.2 to –3.0‰ while 3R displays a $\delta^{13}C$ shift from –2.0 to –3.0‰ from 1926-1997 (See Fig. 5.9).

In summary, the $\delta^{13}C$ records from cores 2B+2C and 3R fail to display consistently common characteristics of interannal and interdecadal variability at Rarotonga which agrees with analysis of corals from other areas (Guilderson and Schrag, 1999; Linsley et al., 1999; Linsley et al., 2000b). The variation of coral $\delta^{13}C$ still remains enigmatic.

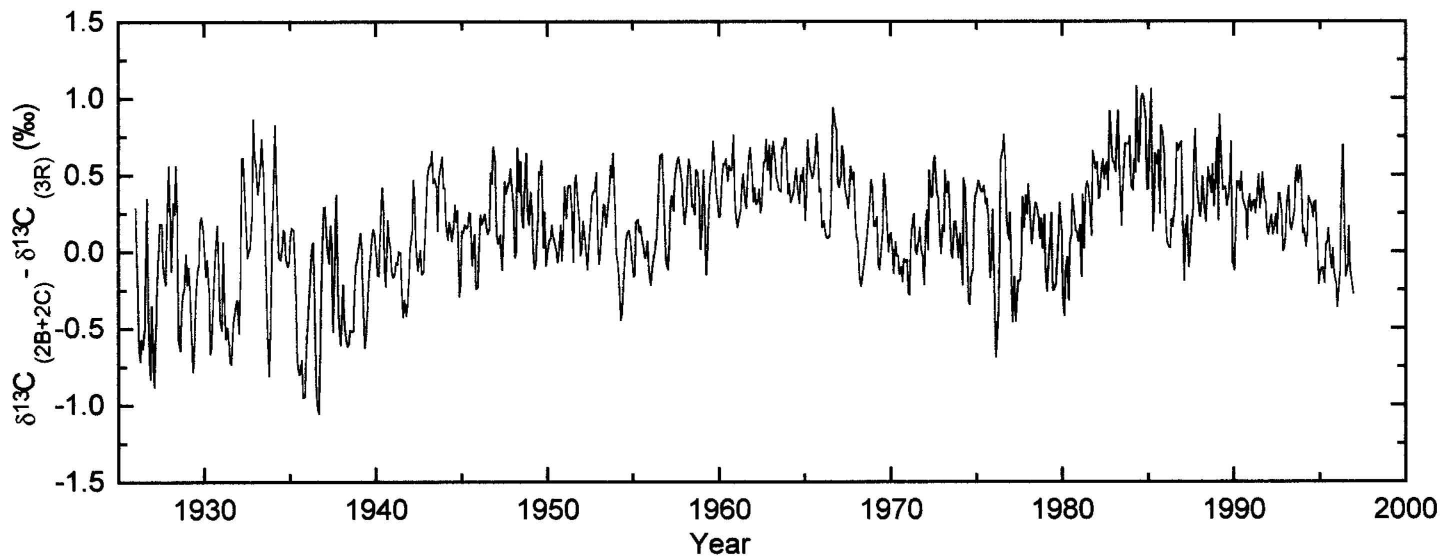

Fig. 5.8 The differences in $\delta^{13}C$ between the record 2B+2C and 3R ($\delta^{13}C_{2B+2C} - \delta^{13}C_{3R}$) for the period 1926-1997 at Rarotonga.

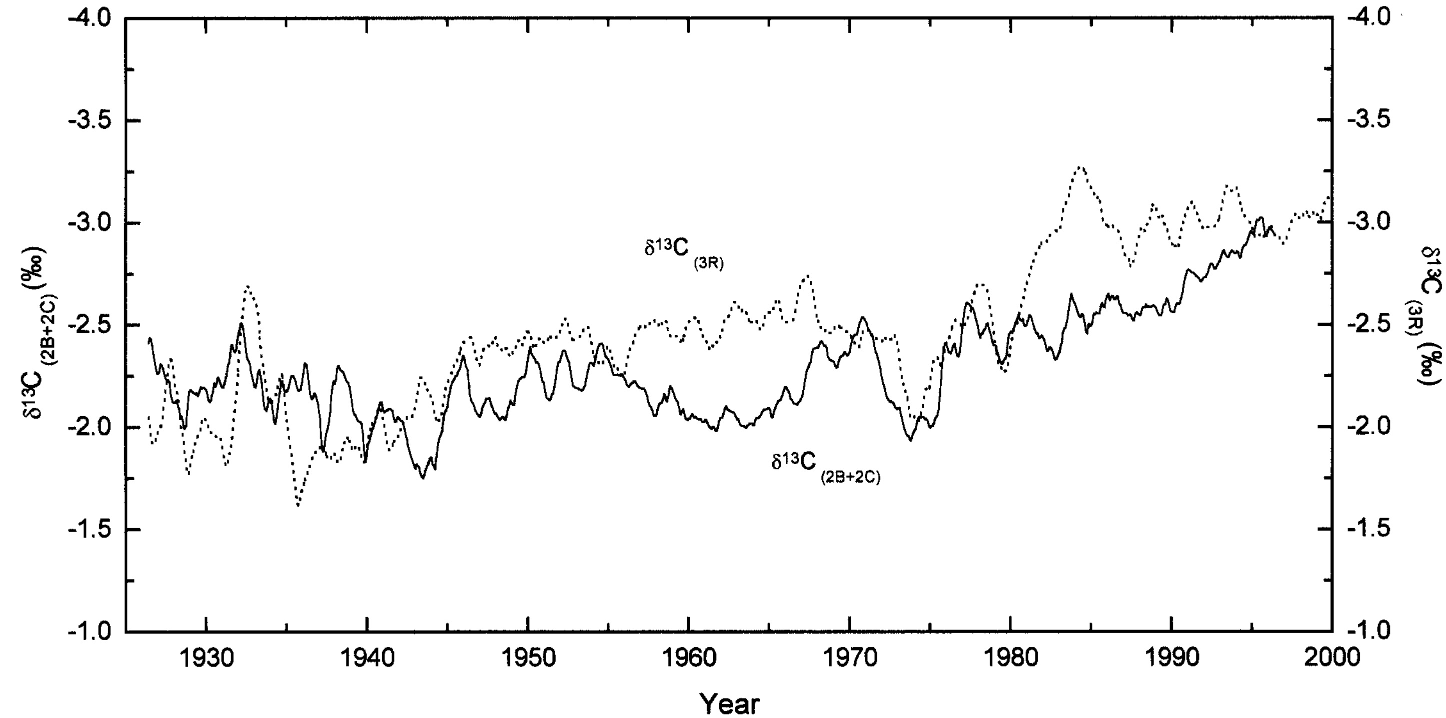

Fig. 5.9 Comparison of 12-month running average coral record of 2B+2C $\delta^{13}C$ (in solid line) with 3R $\delta^{13}C$ (in dotted line) from Rarotonga for the period 1926-1997.

5.4.2 Complexity of Effects of Various Factors on Coral $\delta^{13}C$

When comparing the two coral $\delta^{13}C$ records, I found that although they grew at different depths, there is no offset in absolute values between the two time series and they show a similar depletion departure from disequilibrium over the period 1926-1997 (See Fig. 5.7). As discussed in the previous section, the effect of SST variation can be regarded as essentially the same at the two depths. Then, according to $\delta^{13}C$-depth relationship (Fairbanks and Dodge, 1979; McCloskey and Muscatine, 1984; Leder et al., 1991; Juillet-Leclerc et al., 1997), $\delta^{13}C$ in 2B+2C (at 18m) should be more depleted than $\delta^{13}C$ in 3R (at 9m), provided that photosynthesis is the main process for the metabolic fractionation while heterotrophy is negligible (Porter, 1976; Sorokin, 1993). The similar $\delta^{13}C$ depletion of the two cores appears to contradict with the hypothesis that $\delta^{13}C$ composition in corals is strongly depth-dependent upon light intensity. One explanation could be that the effect of heterotrophy cannot be negligible and the levels of heterotrophy at 3R and 2B+2C were different, which have counteracted the discrepancies due to the effects of different light levels at the two different depths. Some experiments by McCloskey and Muscatine (1984) and Grottoli and Wellington (1999) appear to support this opinion. They observed that deeper corals have an obligate requirement for heterotrophically obtained carbon, while by contrast, shallower corals appear to be phototrophic with respect to carbon. However, since zooplankton and particulate organic material in seawater have lower carbon isotopic values (Rau et al., 1989; 1990), high levels of heterotrophic feeding in corals should be accompanied by a decrease in the $\delta^{13}C$ values. As a result, coral $\delta^{13}C$ in 2B+2C, which grew at deeper water depth, should be even more depleted than, rather than closer to, $\delta^{13}C$ of 3R. Therefore, besides the effects of radiation, SST, as well as heterotrophy on metabolic fractionation, some other factors must also be responsible for complicating the deviation of $\delta^{13}C$ of the two corals. Some experiments with hermatypic corals reveal that although photosynthetic intensity decreases with increasing depth, photosynthetic efficiency increases and energy expenditure decreases when water depth increases (McCloskey and Muscatine, 1984). The reason given by McCloskey and Muscatine (1984) for this effect is because although at deeper water depths zooxanthellae density in corals is lower than that at shallower depth, the chlorophylla *a* per algal cell is increased at deeper depth which may result in an increase in coral $\delta^{13}C$. In addition, Juillet-Leclerc et al. (1997) hypothesized other internal and/or external factors that may also induce different physiological activity and isotopic carbon fractionation. Their experiments revealed that even for colonies growing in identical environmental conditions at the same depths, a large variability of both metabolic and isotopic $\delta^{13}C$ data is still observed. They therefore concluded that high $\delta^{13}C$ may simply indicate that corals grew in more favorable conditions, rather than high solar radiation. Furthermore, colony-specific effects may also have influence on the $\delta^{13}C$ composition of the skeleton (Guilderson and Schrag, 1999; Linsley et al., 2000b).

Therefore, as the carbon in corals is derived from some combination of sources, the balance between autotrophic and heterotrophic carbon supply to the calcification site, the ability of corals to modulate algal photosynthesis by controlling pigment or zooxanthellar concentrations, as well as some unknown internal and/or external factors may all combine to make the interpretation of $\delta^{13}C$ extremely difficult. Some authors suggest that $\delta^{13}C$ record in coral skeletons represents a promising cloud-cover and/or solar radiation proxy (e.g. Fairbanks and Dodge, 1979), however as discussed above, these new results from Rarotonga support other studies and suggest that any environmental interpretation of $\delta^{13}C$ records in corals should be made with more caution.

CHAPTER 6

CONCLUSIONS AND PROBLEMS FOR FUTURE WORK

This study has attempted an evaluation of the paleoclimate utility of both $\delta^{18}O$ and $\delta^{13}C$ in corals in terms of quantitatively separating the effects of the different climatic factors and/or processes on coral $\delta^{18}O$ and $\delta^{13}C$ from the island of Rarotonga. It has also examined the interannual and interdecadal variability from the analysis of a coral $\delta^{18}O$ record from Rarotonga for the period 1726-1997. This concluding chapter summaries the main results obtained in this study and also comments on possible further work.

6.1 Summary

One of the most important results of this study is the development of a revised method of separating the effects of SST and $\delta^{18}O_{sw}$ on coral $\delta^{18}O$ by using coupled coral Sr/Ca and $\delta^{18}O$ analyses. Different from the previous methods (McCulloch, 1994; Gagan et al., 1998; 2000) that treat coral $\delta^{18}O$ as the sum of two separate single-variable functions ($\delta^{18}O$ vs. SST; and $\delta^{18}O$ vs. $\delta^{18}O_{sw}$), this method separates the effects of $\delta^{18}O_{sw}$ from SST by breaking the instantaneous changes of coral $\delta^{18}O$ into separate contributions by instantaneous SST and $\delta^{18}O_{sw}$ changes, respectively. This method was applied to the $\delta^{18}O$ record from Rarotonga for the period 1726-1997. It was found that the reconstructed $\delta^{18}O_{sw}$ contributes significantly to the annual changes of $\delta^{18}O$ in corals. Changes in SST account for 61% of the total coral $\delta^{18}O$ variation, while changes in $\delta^{18}O_{sw}$ account for 39%. The variation of the reconstructed $\delta^{18}O_{sw}$ agrees with the local seasonal pattern of variation in the precipitation and evaporation balance in this area. In addition, the reconstructed $\delta^{18}O_{sw}$ also shows a roughly linear correlation with instrumental salinity in this region although the salinity data is only available after 1980. Therefore, the reconstructed $\delta^{18}O_{sw}$ not only provides us with significant information on the past variation of salinity, precipitation and evaporation in the study region, but the method may also be of potential use for estimating past changes of salinity in other regions.

Applying the similar principles to coral $\delta^{13}C$, the effects of kinetic and metabolic activity on coral $\delta^{13}C$ were also quantitatively separated. If we assume that the coral $\delta^{13}C$ in DIC was relatively constant over the period 1983-1991, the instantaneous changes of $\delta^{13}C$ can be expressed as the sum of two separate instantaneous contributions brought by instantaneous changes of kinetic and metabolic activity, respectively. When this method was applied to coral $\delta^{13}C$ from both tropical and subtropical regions in the Pacific for the period 1983-1991, it was found that the variation of coral $\delta^{13}C$ appears to be mainly caused by the variation of metabolic activity rather than by that of kinetic activity. Although the same views have been proposed by several other authors (e.g. Fairbanks and Dodge, 1979; Grottoli and Wellington, 1999), the analysis of this study is the first attempt to quantitatively separate the effects of kinetic and metabolic fractionation on $\delta^{13}C$ in corals and it gives actual estimates of different magnitudes of contributions by the two processes. It shows that in the tropical regions over 90% of the variation of coral $\delta^{13}C$ is due to the effects of metabolic activity, while in the subtropical regions, despite their larger annual ranges of SST variation, there is still approximately 70% of the total variation of coral $\delta^{13}C$ that is caused by effects of metabolic activity. One implication of these results is that in order to better understand the relationships between $\delta^{13}C$ and the various climatic variables and to utilize coral $\delta^{13}C$ for reconstructing the paleoclimate variations, more work should be concentrated on a better understanding of the processes of metabolic fractionation.

In addition to the above results, another important result of this study involved the development of a coral $\delta^{18}O$ record at Rarotonga for the period 1726-1997 and the examination of the interannual and decadal/ interdecadal variability in coral $\delta^{18}O$ in this region. Firstly, it demonstrated that although Rarotonga is located outside of the center of action of ENSO, it is generally sensitive to ENSO variability in this region and coral $\delta^{18}O$ faithfully records the past El Niño events. There is a consistent response in this south Pacific region to ENSO forcing which extends at least to the past 270 years. Secondly, the comparison of the interdecadal mode of the coral $\delta^{18}O$ with the PDO index suggests that the interdecadal variability in Rarotonga may be related to the processes associated with North Pacific Oscillation. In addition, the decadal-scale variability (~12 years) was further differentiated from the interdecadal-scale variability (~32 years) for the period 1726-1997 at Rarotonga. Based on the analysis of both subtropical and tropical coral data and comparison with the instrumental data (Niño3.4 SST index and PDO index), it was hypothesized that the decadal and interdecadal variability might result from separate forcing mechanisms. The decadal variability appears to be primarily a response to the tropical pacific while the interdecadal variability is more related to a midlatitude oscillation. As the ocean is simultaneously affected by many climate forcings, multiple forcings may contribute to the changes of the oceans in differing amounts.

Finally, the reliability of both coral $\delta^{18}O$ and $\delta^{13}C$ records from Rarotonga was also examined in this study. Based on the comparison with another coral isotopic record from Rarotonga, coral $\delta^{18}O$ appears to be a robust indicator of environmental variables such as SST and precipitation, while the potential effects of growth rate on $\delta^{18}O$ are minimal. This implies that $\delta^{18}O$ could be used for reconstructing the environmental variables in the oceans, while the effects of growth rate could be neglected. On the other hand, however, the coral $\delta^{13}C$ fails to document common characteristics of interannual and decadal signals at Rarotonga. The lack of the reliable coherent $\delta^{13}C$ from the two separate coral records implies that when using $\delta^{13}C$ to interpret the variation of environmental variables such as cloud cover as suggested by some authors, more caution should be exercised.

6.2 Future Research

Although the relative importance of the effects of different climatic factors and/or processes on $\delta^{18}O$ and $\delta^{13}C$ has been evaluated in this study, and the interannual and interdecadal variability on $\delta^{18}O$ examined at Rarotonga, many questions remain to be answered in further work. Some of these are outlined as follows.

--- Although the method of separating effects of SST from $\delta^{18}O$ in corals developed in this study has been successfully used for reconstructing $\delta^{18}O_{sw}$ from coupled Sr/Ca and $\delta^{18}O$ records from Rarotonga, it is not known whether it is generally applicable to other regions. Further evaluation of this method is therefore needed, which includes applying this method to other coral records from both tropical and subtropical areas.

--- The fundamental problem with the method involves some assumptions that remain to be verified. One such underlying assumption is that the partial derivative of $\delta^{18}O$ with respect to $\delta^{18}O_{sw}$ ($\partial\delta^{18}O_{(coral)}/\partial\delta^{18}O_{sw}$) is a constant, so that the shape of the reconstructed contribution by $\delta^{18}O_{sw}$ could be used to represent the actual variation of $\delta^{18}O_{sw}$. However, this assumption needs to be justified. In order to better reconstruct the past variation of $\delta^{18}O_{sw}$, the salinity as well as the precipitation, future studies and experiments should be carried out to quantify the $\delta^{18}O_{coral}$-$\delta^{18}O_{sw}$ relationships under controlled conditions. This kind of study is also helpful for us to better examine the relative importance of the effects of SST and $\delta^{18}O_{sw}$ on coral $\delta^{18}O$.

--- Another problem involves the partial derivative of $\delta^{13}C$ with respect to SST ($\partial\delta^{13}C_{(coral)}/\partial SST$) in the coral $\delta^{13}C$ system. Note that $\partial\delta^{13}C_{(coral)}/\partial SST$ in equation 2 (see chapter 3) is the rate of change of $\delta^{13}C$ with respect to SST when the metabolic activity rather than radiation is constant. It is a parameter whose accurate value is difficult to find from available experimental data. Present experiments (e.g. Bemis et al., 2000) are usually designed to fix SST or radiation rather than metabolic or kinetic activity. Since when SST varies, it must also affect the metabolic process, the experiments thus have to be designed to adjust the other environmental factor, such as radiation to keep the metabolic intensity constant. This kind of experiment is of particular importance for improving our understanding of the relative significance of the roles of kinetic and metabolic activity and how to utilize $\delta^{13}C$ for reconstructing environmental variables such as cloud cover.

--- Another kind of experiment is also needed for evaluating the effects of different factors on coral $\delta^{13}C$ under different controlled conditions. At present, more experiments are concentrated on attempting to examine the effects of light level and/or zooplankton on coral $\delta^{13}C$, while few experiments quantify the effect of SST on $\delta^{13}C$. As a matter of fact, SST not only determines the magnitude of the kinetic activity, but it also affects the metabolic process. Closer monitoring on the variation of coral $\delta^{13}C$ with SST is thus crucial on fully determining the different effects of individual factors on coral $\delta^{13}C$.

--- Another interesting aspect for future investigation is related to the establishment of the network of the coral records so far we have. At present, there are over 30 coral records available worldwide. Development of spatially comprehensive reconstruction of annual to century scale variability in tropical and subtropical ocean-atmosphere systems (e.g. ENSO, interdecadal variability), based on coral proxy data is therefore possible. In this study I have only attempted to analyze and compare the coral data at Rarotonga with some of those from tropical and subtropical areas. The ultimate goal should be to establish a systematic reconstruction of SST and other environmental variables from proxy coral data for the past 300-1000 years.

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APPENDIX I

CORAL $\delta^{18}O$ AND $\delta^{13}C$ IN CORES B AND C FROM RAROTONGA FOR THE PERIOD 1726-1997

Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
1996.96	1	-2.74	-4.97	1993.85	51	-2.47	-4.40
1996.92	2	-2.79	-4.95	1993.79	52	-2.93	-4.23
1996.89	3	-2.85	-4.90	1993.73	53	-2.85	-4.23
1996.85	4	-2.84	-4.89	1993.67	54	-2.91	-4.13
1996.81	5	-2.75	-4.69	1993.60	55	-2.99	-4.23
1996.78	6	-2.91	-4.61	1993.52	56	-3.12	-4.29
1996.74	7	-2.83	-4.61	1993.45	57	-3.16	-4.48
1996.70	8	-2.77	-4.62	1993.38	58	-3.13	-4.65
1996.67	9	-2.90	-4.59	1993.31	59	-3.05	-4.72
1996.62	10	-3.25	-4.64	1993.24	60	-2.89	-4.81
1996.57	11	-3.27	-4.77	1993.17	61	-2.57	-4.88
1996.53	12	-3.27	-4.92	1993.10	62	-2.52	-4.79
1996.48	13	-3.37	-4.88	1993.04	63	-2.67	-4.63
1996.44	14	-3.26	-4.88	1992.97	64	-2.69	-4.59
1996.39	15	-3.06	-5.02	1992.91	65	-2.73	-4.58
1996.34	16	-2.80	-5.06	1992.84	66	-2.80	-4.52
1996.30	17	-2.91	-4.93	1992.78	67	-2.73	-4.50
1996.25	18	-2.73	-4.96	1992.71	68	-2.69	-4.36
1996.17	19	-2.80	-4.74	1992.65	69	-2.68	-4.33
1996.08	20	-2.78	-4.64	1992.58	70	-2.74	-4.27
1996.00	21	-2.96	-4.56	1992.52	71	-3.06	-4.27
1995.92	22	-2.93	-4.61	1992.45	72	-3.04	-4.35
1995.83	23	-2.98	-4.38	1992.38	73	-2.80	-4.46
1995.75	24	-2.96	-4.33	1992.32	74	-2.96	-4.59
1995.67	25	-2.99	-4.56	1992.25	75	-2.90	-4.75
1995.58	26	-3.00	-4.40	1992.17	76	-2.74	-4.71
1995.50	27	-3.06	-4.68	1992.08	77	-2.73	-4.65
1995.42	28	-3.26	-4.85	1992.00	78	-2.62	-4.60
1995.33	29	-3.26	-4.89	1991.92	79	-2.55	-4.61
1995.25	30	-3.26	-4.93	1991.83	80	-2.53	-4.56
1995.19	31	-2.90	-4.83	1991.75	81	-2.55	-4.46
1995.12	32	-2.78	-4.75	1991.67	82	-2.52	-4.30
1995.06	33	-2.75	-4.64	1991.58	83	-2.73	-4.17
1994.99	34	-2.78	-4.55	1991.54	84	-2.78	-4.20
1994.93	35	-3.01	-4.48	1991.49	85	-2.96	-4.27
1994.86	36	-2.73	-4.46	1991.44	86	-2.88	-4.36
1994.80	37	-2.60	-4.31	1991.39	87	-2.76	-4.43
1994.73	38	-2.54	-4.39	1991.35	88	-2.92	-4.64
1994.67	39	-2.83	-4.21	1991.30	89	-3.13	-4.78
1994.60	40	-3.11	-4.34	1991.25	90	-3.04	-4.79
1994.52	41	-3.17	-4.43	1991.20	91	-2.87	-4.78
1994.45	42	-3.09	-4.42	1991.14	92	-2.80	-4.77
1994.38	43	-2.96	-4.78	1991.09	93	-2.77	-4.63
1994.31	44	-3.03	-4.79	1991.04	94	-2.70	-4.54
1994.24	45	-3.03	-4.92	1990.99	95	-2.73	-4.38
1994.17	46	-2.79	-4.93	1990.93	96	-2.68	-4.40
1994.10	47	-2.66	-4.90	1990.88	97	-2.38	-4.43
1994.04	48	-2.64	-4.83	1990.83	98	-2.55	-4.33
1993.98	49	-2.57	-4.79	1990.77	99	-2.73	-4.29
1993.92	50	-2.55	-4.58	1990.72	100	-2.60	-4.25

Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
1990.67	101	-2.60	-4.22	1987.43	151	-3.00	-4.32
1990.61	102	-2.70	-4.32	1987.37	152	-3.10	-4.35
1990.56	103	-2.70	-4.32	1987.31	153	-2.69	-4.56
1990.51	104	-2.73	-4.42	1987.25	154	-2.15	-4.61
1990.46	105	-2.68	-4.54	1987.18	155	-2.24	-4.60
1990.41	106	-2.50	-4.67	1987.10	156	-2.57	-5.12
1990.35	107	-2.49	-4.69	1987.03	157	-2.64	-4.47
1990.30	108	-2.99	-4.63	1986.96	158	-2.20	-4.48
1990.25	109	-2.53	-4.75	1986.89	159	-2.30	-4.42
1990.17	110	-2.53	-4.74	1986.81	160	-2.39	-4.33
1990.08	111	-2.45	-4.55	1986.74	161	-2.55	-4.39
1990.00	112	-2.64	-4.46	1986.67	162	-2.44	-4.28
1989.92	113	-2.65	-4.46	1986.61	163	-2.76	-4.46
1989.83	114	-2.35	-4.36	1986.56	164	-2.85	-4.50
1989.75	115	-2.36	-4.33	1986.50	165	-3.04	-4.47
1989.69	116	-2.50	-4.44	1986.44	166	-3.30	-4.59
1989.63	117	-2.75	-4.58	1986.39	167	-3.34	-4.74
1989.56	118	-2.68	-4.67	1986.33	168	-2.93	-4.77
1989.50	119	-2.79	-4.58	1986.28	169	-2.62	-4.77
1989.44	120	-2.82	-4.76	1986.22	170	-2.50	-4.81
1989.38	121	-2.91	-4.76	1986.17	171	-2.34	-4.89
1989.31	122	-2.96	-4.94	1986.10	172	-2.41	-4.70
1989.25	123	-2.66	-5.00	1986.03	173	-2.50	-4.57
1989.19	124	-2.18	-4.97	1985.96	174	-2.34	-4.47
1989.13	125	-2.20	-4.85	1985.89	175	-2.52	-4.42
1989.08	126	-2.47	-4.77	1985.82	176	-2.35	-4.21
1989.02	127	-2.08	-4.44	1985.75	177	-2.26	-4.05
1988.96	128	-2.41	-4.63	1985.69	178	-2.81	-4.17
1988.90	129	-2.46	-4.56	1985.64	179	-2.89	-4.26
1988.84	130	-2.39	-4.61	1985.58	180	-2.62	-4.25
1988.78	131	-2.39	-4.52	1985.53	181	-2.68	-4.31
1988.73	132	-2.44	-4.38	1985.47	182	-3.03	-4.53
1988.67	133	-2.80	-4.27	1985.42	183	-2.84	-4.61
1988.61	134	-2.83	-4.36	1985.36	184	-2.97	-4.66
1988.55	135	-3.02	-4.54	1985.31	185	-3.05	-4.77
1988.49	136	-2.78	-4.51	1985.25	186	-2.80	-4.94
1988.43	137	-2.86	-4.68	1985.18	187	-2.18	-4.89
1988.37	138	-3.16	-4.84	1985.10	188	-1.88	-4.85
1988.31	139	-2.76	-4.73	1985.03	189	-2.32	-4.71
1988.25	140	-2.58	-4.84	1984.96	190	-2.64	-4.58
1988.17	141	-2.27	-4.75	1984.89	191	-2.43	-4.52
1988.08	142	-2.37	-4.69	1984.81	192	-2.18	-4.32
1988.00	143	-2.33	-4.68	1984.74	193	-2.37	-4.00
1987.92	144	-2.28	-4.49	1984.67	194	-2.35	-3.99
1987.83	145	-2.40	-4.18	1984.61	195	-2.28	-4.02
1987.75	146	-2.37	-4.14	1984.56	196	-2.68	-4.08
1987.67	147	-2.47	-4.01	1984.50	197	-2.79	-4.17
1987.61	148	-2.75	-4.14	1984.44	198	-2.96	-4.31
1987.55	149	-2.82	-4.28	1984.39	199	-2.91	-4.31
1987.49	150	-2.92	-4.35	1984.33	200	-2.39	-4.08

Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
1984.28	201	-2.93	-4.74	1981.32	251	-2.76	-4.59
1984.22	202	-2.88	-4.77	1981.27	252	-2.90	-4.56
1984.17	203	-2.65	-4.78	1981.22	253	-2.67	-4.73
1984.12	204	-2.48	-4.78	1981.17	254	-2.28	-4.79
1984.07	205	-2.48	-4.70	1981.10	255	-2.35	-4.65
1984.02	206	-2.46	-4.60	1981.04	256	-2.40	-4.72
1983.97	207	-2.42	-4.46	1980.97	257	-2.40	-4.75
1983.92	208	-2.33	-4.41	1980.91	258	-2.43	-4.47
1983.87	209	-2.08	-4.30	1980.84	259	-2.30	-4.33
1983.82	210	-2.47	-4.19	1980.78	260	-2.25	-4.17
1983.77	211	-2.58	-4.02	1980.71	261	-2.38	-4.31
1983.72	212	-2.47	-4.04	1980.65	262	-2.41	-4.16
1983.67	213	-2.60	-4.00	1980.58	263	-2.42	-4.15
1983.60	214	-2.71	-4.04	1980.54	264	-2.63	-4.18
1983.54	215	-2.85	-4.13	1980.49	265	-2.75	-4.22
1983.48	216	-2.90	-4.27	1980.44	266	-2.73	-4.31
1983.42	217	-3.15	-4.40	1980.39	267	-2.81	-4.31
1983.35	218	-2.83	-4.42	1980.35	268	-3.22	-4.57
1983.29	219	-2.57	-4.51	1980.30	269	-2.99	-4.76
1983.23	220	-2.02	-4.54	1980.25	270	-2.68	-4.83
1983.17	221	-2.08	-4.60	1980.19	271	-2.37	-4.82
1983.10	222	-2.08	-4.56	1980.13	272	-2.28	-4.80
1983.03	223	-1.99	-4.40	1980.06	273	-2.64	-4.74
1982.96	224	-2.28	-4.32	1980.00	274	-2.42	-4.58
1982.89	225	-2.27	-4.23	1979.94	275	-2.13	-4.36
1982.82	226	-2.10	-4.02	1979.88	276	-2.06	-4.20
1982.75	227	-1.90	-3.86	1979.81	277	-2.08	-4.30
1982.69	228	-2.26	-4.07	1979.75	278	-2.10	-4.14
1982.63	229	-2.50	-4.14	1979.68	279	-2.16	-4.21
1982.56	230	-2.40	-4.24	1979.60	280	-2.46	-4.22
1982.50	231	-2.73	-4.44	1979.53	281	-2.61	-4.39
1982.44	232	-2.96	-4.59	1979.46	282	-2.62	-4.53
1982.38	233	-2.78	-4.66	1979.39	283	-2.39	-4.58
1982.31	234	-2.74	-4.75	1979.31	284	-2.28	-4.66
1982.25	235	-2.50	-4.80	1979.24	285	-2.39	-4.67
1982.19	236	-2.37	-4.68	1979.17	286	-2.29	-4.74
1982.12	237	-2.26	-4.63	1979.11	287	-2.25	-4.61
1982.06	238	-2.12	-4.66	1979.06	288	-2.23	-4.59
1981.99	239	-2.19	-4.56	1979.00	289	-2.43	-4.51
1981.93	240	-2.14	-4.48	1978.94	290	-2.20	-4.42
1981.86	241	-1.99	-4.45	1978.89	291	-2.33	-4.36
1981.80	242	-2.08	-4.14	1978.83	292	-2.38	-4.28
1981.73	243	-2.24	-4.15	1978.78	293	-2.33	-4.33
1981.67	244	-2.69	-4.02	1978.72	294	-2.26	-4.24
1981.62	245	-2.56	-4.08	1978.67	295	-2.57	-4.14
1981.57	246	-2.74	-4.16	1978.54	296	-2.58	-4.17
1981.52	247	-2.83	-4.17	1978.42	297	-2.66	-4.47
1981.47	248	-2.70	-4.22	1978.29	298	-2.74	-4.44
1981.42	249	-2.78	-4.41	1978.17	299	-2.64	-4.56
1981.37	250	-2.70	-4.54	1978.07	300	-2.14	-4.43

Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
1977.97	301	-2.19	-4.49	1974.17	351	-2.12	-4.81
1977.87	302	-2.09	-4.58	1974.08	352	-1.87	-4.80
1977.77	303	-2.31	-4.36	1974.00	353	-1.81	-4.78
1977.67	304	-2.29	-4.21	1973.92	354	-1.78	-4.69
1977.56	305	-3.06	-4.59	1973.83	355	-1.70	-4.54
1977.46	306	-3.10	-4.72	1973.75	356	-1.71	-4.28
1977.35	307	-3.00	-4.82	1973.67	357	-1.77	-4.19
1977.25	308	-3.03	-4.88	1973.61	358	-2.02	-4.21
1977.18	309	-2.67	-4.78	1973.55	359	-2.19	-4.32
1977.10	310	-2.36	-4.67	1973.49	360	-2.19	-4.44
1977.03	311	-2.29	-4.53	1973.43	361	-2.13	-4.55
1976.96	312	-2.20	-4.32	1973.37	362	-2.00	-4.69
1976.89	313	-2.20	-4.29	1973.31	363	-2.10	-4.72
1976.81	314	-2.26	-4.21	1973.25	364	-2.24	-4.85
1976.74	315	-2.04	-4.19	1973.08	365	-2.03	-4.46
1976.67	316	-1.92	-4.05	1972.92	366	-2.05	-4.32
1976.58	317	-1.96	-4.13	1972.75	367	-2.00	-4.18
1976.50	318	-2.28	-4.26	1972.68	368	-2.15	-4.22
1976.42	319	-2.44	-4.32	1972.60	369	-2.07	-4.23
1976.33	320	-2.80	-4.51	1972.53	370	-2.10	-4.26
1976.25	321	-3.05	-4.62	1972.46	371	-2.18	-4.36
1976.17	322	-3.02	-4.70	1972.39	372	-2.27	-4.44
1976.10	323	-2.79	-4.69	1972.31	373	-2.27	-4.70
1976.04	324	-2.37	-4.60	1972.24	374	-2.27	-4.74
1975.98	325	-2.02	-4.52	1972.17	375	-2.24	-4.78
1975.92	326	-1.90	-4.40	1972.11	376	-1.96	-4.57
1975.85	327	-2.01	-4.38	1972.06	377	-2.06	-4.71
1975.79	328	-2.17	-4.40	1972.00	378	-2.14	-4.64
1975.73	329	-2.19	-4.35	1971.94	379	-2.16	-4.55
1975.67	330	-2.15	-4.28	1971.89	380	-2.18	-4.52
1975.62	331	-2.12	-4.32	1971.83	381	-2.21	-4.46
1975.57	332	-2.33	-4.30	1971.78	382	-2.32	-4.38
1975.53	333	-2.33	-4.40	1971.72	383	-2.46	-4.38
1975.48	334	-2.20	-4.42	1971.67	384	-2.35	-4.31
1975.44	335	-2.15	-4.43	1971.61	385	-2.49	-4.38
1975.39	336	-2.08	-4.60	1971.55	386	-2.58	-4.45
1975.34	337	-2.08	-4.65	1971.49	387	-2.63	-4.52
1975.30	338	-1.99	-4.68	1971.43	388	-2.60	-4.61
1975.25	339	-1.99	-4.69	1971.37	389	-2.63	-4.83
1975.17	340	-1.99	-4.68	1971.31	390	-2.49	-4.92
1975.08	341	-1.86	-4.57	1971.25	391	-2.52	-4.92
1975.00	342	-1.84	-4.54	1971.21	392	-2.38	-4.89
1974.92	343	-1.74	-4.45	1971.17	393	-2.39	-4.86
1974.83	344	-1.80	-4.32	1971.13	394	-2.48	-4.78
1974.75	345	-2.00	-4.37	1971.10	395	-2.50	-4.73
1974.67	346	-2.10	-4.32	1971.06	396	-2.47	-4.71
1974.57	347	-2.23	-4.39	1971.02	397	-2.48	-4.67
1974.47	348	-2.39	-4.55	1970.98	398	-2.44	-4.52
1974.37	349	-2.39	-4.64	1970.94	399	-2.30	-4.32
1974.27	350	-1.91	-4.57	1970.90	400	-2.25	-4.30

Year A.D.	Depth (mm)	δ^{13}C (‰)	δ^{18}O (‰)	Year A.D.	Depth (mm)	δ^{13}C (‰)	δ^{18}O (‰)
1970.87	401	-2.61	-4.40	1967.61	451	-2.35	-4.12
1970.83	402	-2.38	-4.31	1967.55	452	-2.56	-4.28
1970.79	403	-2.40	-4.33	1967.49	453	-2.63	-4.27
1970.75	404	-2.51	-4.29	1967.44	454	-2.69	-4.48
1970.65	405	-2.71	-4.30	1967.38	455	-2.66	-4.56
1970.56	406	-2.69	-4.48	1967.32	456	-2.69	-4.66
1970.46	407	-2.80	-4.60	1967.27	457	-2.33	-4.65
1970.36	408	-2.57	-4.62	1967.21	458	-2.22	-4.68
1970.26	409	-2.37	-4.69	1967.14	459	-1.94	-4.61
1970.17	410	-2.18	-4.72	1967.07	460	-2.10	-4.58
1970.10	411	-2.15	-4.65	1967.01	461	-1.90	-4.51
1970.04	412	-2.09	-4.55	1966.94	462	-2.01	-4.46
1969.98	413	-2.29	-4.45	1966.87	463	-1.86	-4.27
1969.92	414	-2.24	-4.32	1966.80	464	-1.66	-4.14
1969.85	415	-2.36	-4.25	1966.73	465	-1.81	-4.12
1969.79	416	-2.32	-4.13	1966.67	466	-1.73	-4.01
1969.73	417	-2.33	-4.13	1966.59	467	-2.10	-4.10
1969.67	418	-2.30	-4.02	1966.51	468	-2.49	-4.22
1969.60	419	-2.29	-4.07	1966.44	469	-2.61	-4.37
1969.54	420	-2.56	-4.28	1966.36	470	-2.58	-4.43
1969.47	421	-2.61	-4.37	1966.28	471	-2.44	-4.48
1969.40	422	-2.64	-4.54	1966.21	472	-2.17	-4.52
1969.34	423	-2.65	-4.66	1966.14	473	-2.04	-4.46
1969.27	424	-2.56	-4.71	1966.07	474	-2.06	-4.45
1969.21	425	-2.26	-4.73	1966.01	475	-2.18	-4.41
1969.16	426	-1.93	-4.59	1965.94	476	-1.92	-4.20
1969.11	427	-1.98	-4.70	1965.87	477	-2.07	-4.25
1969.06	428	-2.10	-4.68	1965.80	478	-2.09	-4.20
1969.01	429	-2.15	-4.60	1965.73	479	-1.93	-4.15
1968.96	430	-2.13	-4.50	1965.67	480	-1.91	-4.09
1968.91	431	-2.00	-4.42	1965.60	481	-2.11	-4.17
1968.86	432	-1.90	-4.30	1965.54	482	-2.23	-4.26
1968.81	433	-2.13	-4.32	1965.47	483	-2.30	-4.42
1968.77	434	-2.30	-4.31	1965.40	484	-2.38	-4.48
1968.72	435	-2.31	-4.30	1965.34	485	-2.36	-4.55
1968.67	436	-2.43	-4.24	1965.27	486	-2.24	-4.63
1968.55	437	-2.57	-4.30	1965.21	487	-2.21	-4.70
1968.44	438	-2.70	-4.48	1965.16	488	-2.02	-4.57
1968.32	439	-2.68	-4.66	1965.11	489	-1.90	-4.50
1968.21	440	-2.63	-4.73	1965.06	490	-1.96	-4.49
1968.15	441	-2.47	-4.69	1965.01	491	-1.98	-4.50
1968.10	442	-2.17	-4.69	1964.96	492	-1.80	-4.42
1968.05	443	-2.15	-4.62	1964.91	493	-1.65	-4.33
1967.99	444	-2.13	-4.53	1964.86	494	-1.59	-4.23
1967.94	445	-2.18	-4.49	1964.81	495	-1.92	-4.21
1967.88	446	-2.15	-4.42	1964.77	496	-1.81	-4.09
1967.83	447	-2.17	-4.31	1964.72	497	-2.24	-4.09
1967.78	448	-2.24	-4.19	1964.67	498	-2.28	-4.01
1967.72	449	-2.20	-4.12	1964.58	499	-2.31	-4.13
1967.67	450	-2.19	-4.07	1964.48	500	-2.22	-4.17

Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
1964.39	501	-2.36	-4.45	1961.09	551	-1.87	-4.69
1964.30	502	-2.35	-4.55	1961.03	552	-1.74	-4.64
1964.21	503	-2.09	-4.60	1960.97	553	-1.88	-4.65
1964.14	504	-1.86	-4.59	1960.91	554	-1.90	-4.58
1964.07	505	-1.67	-4.58	1960.85	555	-1.73	-4.42
1964.01	506	-1.85	-4.55	1960.79	556	-1.81	-4.23
1963.94	507	-1.59	-4.31	1960.73	557	-2.10	-4.22
1963.87	508	-1.72	-4.22	1960.67	558	-2.07	-4.21
1963.80	509	-1.86	-4.15	1960.60	559	-2.09	-4.25
1963.73	510	-1.89	-4.13	1960.54	560	-2.23	-4.37
1963.67	511	-1.93	-4.02	1960.47	561	-2.35	-4.39
1963.61	512	-2.21	-4.15	1960.40	562	-2.17	-4.28
1963.55	513	-2.38	-4.23	1960.34	563	-2.29	-4.63
1963.49	514	-2.31	-4.30	1960.27	564	-2.14	-4.54
1963.44	515	-2.26	-4.44	1960.21	565	-2.06	-4.78
1963.38	516	-2.48	-4.59	1960.14	566	-2.03	-4.70
1963.32	517	-2.27	-4.63	1960.07	567	-1.91	-4.69
1963.27	518	-2.11	-4.66	1960.01	568	-1.86	-4.68
1963.21	519	-2.03	-4.69	1959.94	569	-1.90	-4.65
1963.15	520	-1.74	-4.63	1959.87	570	-1.86	-4.38
1963.09	521	-1.75	-4.59	1959.80	571	-2.04	-4.25
1963.03	522	-1.96	-4.52	1959.73	572	-1.83	-4.16
1962.97	523	-1.87	-4.42	1959.67	573	-1.88	-4.11
1962.91	524	-1.56	-4.25	1959.60	574	-2.12	-4.22
1962.85	525	-1.78	-4.29	1959.54	575	-2.19	-4.36
1962.79	526	-1.83	-4.13	1959.47	576	-2.19	-4.39
1962.73	527	-2.10	-4.12	1959.40	577	-2.27	-4.39
1962.67	528	-2.21	-4.08	1959.34	578	-2.53	-4.68
1962.59	529	-2.22	-4.19	1959.27	579	-2.59	-4.79
1962.51	530	-2.50	-4.30	1959.21	580	-2.21	-4.79
1962.44	531	-2.61	-4.43	1959.15	581	-1.83	-4.79
1962.36	532	-2.42	-4.49	1959.09	582	-1.71	-4.65
1962.28	533	-2.20	-4.65	1959.03	583	-2.17	-4.43
1962.21	534	-2.00	-4.71	1958.97	584	-2.20	-4.15
1962.14	535	-1.74	-4.68	1958.91	585	-2.32	-4.20
1962.07	536	-1.82	-4.51	1958.85	586	-1.99	-4.18
1962.01	537	-1.99	-4.43	1958.79	587	-1.93	-4.11
1961.94	538	-1.88	-4.33	1958.73	588	-2.15	-4.12
1961.87	539	-1.66	-4.17	1958.67	589	-2.09	-4.03
1961.80	540	-1.65	-4.18	1958.62	590	-2.29	-4.14
1961.73	541	-1.77	-4.16	1958.57	591	-2.44	-4.27
1961.67	542	-1.93	-4.13	1958.51	592	-2.33	-4.20
1961.60	543	-2.18	-4.18	1958.46	593	-2.39	-4.43
1961.54	544	-2.41	-4.36	1958.41	594	-2.35	-4.55
1961.47	545	-2.28	-4.54	1958.36	595	-2.23	-4.53
1961.40	546	-2.17	-4.56	1958.31	596	-1.95	-4.47
1961.34	547	-2.11	-4.60	1958.26	597	-2.01	-4.50
1961.27	548	-2.16	-4.66	1958.21	598	-2.08	-4.58
1961.21	549	-2.09	-4.75	1958.12	599	-2.12	-4.56
1961.15	550	-2.03	-4.72	1958.03	600	-1.89	-4.40

Year A.D.	Depth (mm)	δ13C (‰)	δ18O (‰)	Year A.D.	Depth (mm)	δ13C (‰)	δ18O (‰)
1957.94	601	-2.03	-4.42	1955.05	651	-2.20	-4.61
1957.85	602	-1.99	-4.27	1954.99	652	-2.22	-4.58
1957.76	603	-1.97	-4.23	1954.94	653	-2.20	-4.39
1957.67	604	-1.93	-4.16	1954.88	654	-2.27	-4.42
1957.61	605	-1.94	-4.20	1954.83	655	-2.31	-4.33
1957.55	606	-2.13	-4.31	1954.78	656	-2.35	-4.27
1957.49	607	-2.25	-4.42	1954.72	657	-2.36	-4.26
1957.44	608	-2.32	-4.56	1954.67	658	-2.36	-4.22
1957.38	609	-2.39	-4.69	1954.58	659	-2.37	-4.26
1957.32	610	-2.41	-4.88	1954.48	660	-2.56	-4.30
1957.27	611	-2.20	-4.82	1954.39	661	-2.68	-4.36
1957.21	612	-2.19	-4.89	1954.30	662	-2.77	-4.45
1957.15	613	-2.17	-4.87	1954.21	663	-2.64	-4.51
1957.09	614	-2.24	-4.83	1954.16	664	-2.27	-4.49
1957.03	615	-2.30	-4.82	1954.11	665	-2.20	-4.45
1956.97	616	-2.26	-4.76	1954.06	666	-2.05	-4.47
1956.91	617	-2.25	-4.70	1954.01	667	-2.10	-4.46
1956.85	618	-2.19	-4.67	1953.96	668	-2.11	-4.31
1956.79	619	-2.06	-4.56	1953.91	669	-1.95	-4.31
1956.73	620	-1.97	-4.38	1953.86	670	-1.89	-4.21
1956.67	621	-1.93	-4.32	1953.81	671	-1.87	-4.10
1956.62	622	-2.12	-4.33	1953.77	672	-2.09	-4.05
1956.57	623	-2.04	-4.73	1953.72	673	-2.03	-3.93
1956.51	624	-2.24	-4.38	1953.67	674	-2.14	-3.77
1956.46	625	-2.39	-4.53	1953.62	675	-2.15	-3.88
1956.41	626	-2.46	-4.57	1953.58	676	-2.52	-3.98
1956.36	627	-2.50	-4.67	1953.53	677	-2.51	-4.06
1956.31	628	-2.54	-4.75	1953.48	678	-2.66	-4.23
1956.26	629	-2.37	-4.80	1953.44	679	-2.65	-4.41
1956.21	630	-2.29	-4.87	1953.39	680	-2.60	-4.62
1956.14	631	-2.06	-4.81	1953.35	681	-2.41	-4.60
1956.07	632	-2.18	-4.84	1953.30	682	-2.39	-4.60
1956.01	633	-2.22	-4.77	1953.25	683	-2.13	-4.62
1955.94	634	-2.27	-4.72	1953.21	684	-1.92	-4.63
1955.87	635	-2.04	-4.51	1953.13	685	-1.93	-4.54
1955.80	636	-2.06	-4.48	1953.05	686	-2.02	-4.39
1955.73	637	-2.12	-4.41	1952.98	687	-1.96	-4.37
1955.67	638	-2.19	-4.36	1952.90	688	-1.93	-4.32
1955.62	639	-2.19	-4.42	1952.82	689	-1.97	-4.27
1955.58	640	-2.18	-4.48	1952.74	690	-2.09	-4.08
1955.53	641	-2.38	-4.59	1952.67	691	-2.22	-3.99
1955.48	642	-2.48	-4.63	1952.61	692	-2.39	-4.04
1955.44	643	-2.54	-4.75	1952.55	693	-2.48	-4.03
1955.39	644	-2.52	-4.79	1952.49	694	-2.67	-4.08
1955.35	645	-2.52	-4.86	1952.44	695	-2.71	-4.13
1955.30	646	-2.44	-4.84	1952.38	696	-2.76	-4.15
1955.25	647	-2.31	-4.84	1952.32	697	-2.83	-4.26
1955.21	648	-2.28	-4.88	1952.27	698	-2.60	-4.46
1955.15	649	-2.17	-4.83	1952.21	699	-2.64	-4.55
1955.10	650	-2.12	-4.61	1952.16	700	-2.35	-4.54

Year A.D.	Depth (mm)	δ^{13}C (‰)	δ^{18}O (‰)	Year A.D.	Depth (mm)	δ^{13}C (‰)	δ^{18}O (‰)
1952.11	701	-2.18	-4.48	1948.76	751	-1.87	-4.06
1952.06	702	-2.10	-4.41	1948.67	752	-1.99	-3.87
1952.01	703	-2.17	-4.42	1948.63	753	-1.93	-4.05
1951.96	704	-2.29	-4.48	1948.60	754	-1.96	-3.91
1951.91	705	-2.20	-4.35	1948.57	755	-2.45	-3.97
1951.86	706	-2.02	-4.16	1948.54	756	-2.25	-4.14
1951.81	707	-2.08	-4.06	1948.50	757	-2.30	-3.96
1951.77	708	-1.97	-4.06	1948.47	758	-2.28	-4.03
1951.72	709	-2.16	-4.03	1948.44	759	-2.20	-4.42
1951.67	710	-1.96	-3.90	1948.40	760	-1.96	-4.31
1951.62	711	-1.90	-3.97	1948.37	761	-2.01	-4.40
1951.57	712	-2.12	-4.04	1948.34	762	-2.37	-4.38
1951.51	713	-2.67	-4.40	1948.31	763	-2.09	-4.39
1951.46	714	-2.42	-4.18	1948.27	764	-1.97	-4.57
1951.41	715	-2.31	-4.60	1948.24	765	-1.69	-4.18
1951.36	716	-2.25	-4.80	1948.21	766	-2.03	-4.58
1951.31	717	-2.21	-4.84	1948.15	767	-2.07	-4.45
1951.26	718	-2.18	-4.81	1948.09	768	-2.18	-4.57
1951.21	719	-1.91	-4.83	1948.03	769	-1.97	-4.43
1951.14	720	-2.09	-4.65	1947.97	770	-1.96	-4.30
1951.07	721	-2.11	-4.58	1947.91	771	-1.85	-4.12
1951.01	722	-1.87	-4.48	1947.85	772	-1.77	-4.21
1950.94	723	-2.19	-4.39	1947.79	773	-1.81	-4.08
1950.87	724	-2.01	-4.23	1947.73	774	-2.09	-4.22
1950.80	725	-2.21	-4.42	1947.67	775	-2.14	-3.81
1950.73	726	-2.08	-4.25	1947.59	776	-2.34	-4.18
1950.67	727	-2.39	-4.20	1947.51	777	-2.23	-4.12
1950.55	728	-2.58	-4.32	1947.44	778	-2.37	-4.01
1950.44	729	-2.77	-4.60	1947.36	779	-2.61	-4.50
1950.32	730	-2.60	-4.68	1947.28	780	-2.24	-4.56
1950.21	731	-2.20	-4.66	1947.21	781	-2.08	-4.66
1950.15	732	-2.15	-4.63	1947.15	782	-2.17	-4.58
1950.09	733	-2.08	-4.60	1947.09	783	-2.09	-4.60
1950.03	734	-1.99	-4.62	1947.03	784	-2.10	-4.64
1949.97	735	-2.25	-4.43	1946.97	785	-1.83	-4.56
1949.91	736	-2.28	-4.34	1946.91	786	-1.64	-4.48
1949.85	737	-2.28	-4.31	1946.85	787	-1.55	-4.22
1949.79	738	-2.26	-4.04	1946.79	788	-1.82	-4.25
1949.73	739	-2.69	-4.07	1946.73	789	-1.77	-4.21
1949.67	740	-1.99	-3.74	1946.67	790	-1.76	-4.14
1949.59	741	-2.11	-3.94	1946.59	791	-2.18	-4.18
1949.51	742	-2.10	-3.88	1946.51	792	-2.35	-4.21
1949.44	743	-2.38	-3.92	1946.44	793	-2.50	-4.31
1949.36	744	-2.51	-4.06	1946.36	794	-2.70	-4.40
1949.28	745	-2.49	-4.47	1946.28	795	-2.49	-4.51
1949.21	746	-2.21	-4.57	1946.21	796	-2.44	-4.98
1949.12	747	-2.00	-4.37	1946.15	797	-2.26	-4.84
1949.03	748	-1.98	-4.27	1946.10	798	-2.17	-4.88
1948.94	749	-1.94	-4.28	1946.05	799	-2.13	-4.84
1948.85	750	-1.91	-4.09	1945.99	800	-2.25	-4.82

Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
1945.94	801	-2.35	-4.79	1942.10	851	-2.06	-4.48
1945.88	802	-2.52	-4.66	1941.99	852	-2.03	-4.17
1945.83	803	-2.47	-4.98	1941.88	853	-2.21	-4.26
1945.78	804	-2.05	-4.40	1941.78	854	-2.15	-3.71
1945.72	805	-2.05	-4.17	1941.67	855	-2.04	-3.58
1945.67	806	-2.17	-4.16	1941.55	856	-2.26	-4.08
1945.60	807	-2.38	-4.23	1941.44	857	-1.87	-4.29
1945.54	808	-2.39	-4.32	1941.32	858	-1.96	-4.22
1945.47	809	-1.91	-4.37	1941.21	859	-2.20	-4.58
1945.40	810	-2.25	-4.48	1941.03	860	-2.07	-3.98
1945.34	811	-2.36	-4.70	1940.85	861	-2.14	-3.97
1945.27	812	-2.56	-4.75	1940.67	862	-1.98	-3.83
1945.21	813	-2.09	-4.79	1940.55	863	-2.71	-4.18
1945.13	814	-2.03	-4.75	1940.44	864	-1.95	-4.23
1945.05	815	-2.20	-4.67	1940.32	865	-1.60	-4.34
1944.98	816	-1.99	-4.46	1940.21	866	-1.91	-4.51
1944.90	817	-2.35	-4.25	1939.94	867	-1.82	-4.41
1944.82	818	-2.18	-4.30	1939.67	868	-1.77	-4.18
1944.74	819	-1.60	-4.14	1939.55	869	-1.82	-4.31
1944.67	820	-1.84	-3.97	1939.44	870	-2.39	-4.34
1944.59	821	-1.80	-4.03	1939.32	871	-2.79	-4.51
1944.51	822	-1.97	-4.40	1939.21	872	-2.08	-4.67
1944.44	823	-2.05	-4.36	1939.07	873	-1.85	-4.61
1944.36	824	-1.97	-4.40	1938.94	874	-2.08	-4.45
1944.28	825	-1.77	-4.54	1938.80	875	-1.77	-4.21
1944.21	826	-1.88	-4.86	1938.67	876	-2.27	-4.03
1944.13	827	-1.85	-4.77	1938.51	877	-2.46	-4.11
1944.05	828	-1.81	-4.77	1938.36	878	-2.86	-4.09
1943.98	829	-1.55	-4.80	1938.21	879	-2.49	-4.66
1943.90	830	-1.62	-4.57	1938.07	880	-1.85	-4.46
1943.82	831	-1.50	-4.31	1937.94	881	-2.17	-4.37
1943.74	832	-1.96	-4.44	1937.80	882	-1.99	-4.10
1943.67	833	-1.94	-4.25	1937.67	883	-1.58	-3.90
1943.62	834	-1.89	-4.26	1937.59	884	-2.10	-3.93
1943.60	835	-2.27	-4.03	1937.51	885	-2.69	-4.18
1943.59	836	-2.19	-4.17	1937.44	886	-2.08	-4.47
1943.57	837	-2.45	-4.59	1937.36	887	-1.67	-4.43
1943.51	838	-1.91	-4.23	1937.28	888	-2.01	-4.40
1943.46	839	-1.73	-4.34	1937.21	889	-1.95	-4.61
1943.41	840	-1.80	-4.40	1936.94	890	-1.43	-3.70
1943.36	841	-1.81	-4.49	1936.67	891	-2.89	-3.95
1943.31	842	-1.73	-4.56	1936.51	892	-2.98	-3.97
1943.26	843	-1.53	-4.31	1936.36	893	-1.86	-4.39
1943.21	844	-1.54	-4.87	1936.21	894	-1.68	-4.39
1943.03	845	-1.68	-4.41	1936.07	895	-2.01	-4.26
1942.67	846	-2.05	-4.09	1935.94	896	-2.15	-4.23
1942.55	847	-1.98	-4.18	1935.80	897	-2.66	-4.09
1942.44	848	-2.17	-4.20	1935.67	898	-2.34	-3.89
1942.32	849	-1.97	-4.57	1935.55	899	-2.50	-4.04
1942.21	850	-1.66	-4.58	1935.44	901	-2.35	-4.21

Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
1935.32	903	-1.72	-4.10	1928.82	1003	-2.04	-4.10
1935.21	905	-2.08	-4.41	1928.74	1005	-2.02	-3.93
1934.94	907	-2.25	-4.24	1928.67	1007	-2.36	-3.88
1934.67	909	-2.17	-3.91	1928.51	1009	-2.21	-4.17
1934.51	911	-2.48	-4.18	1928.36	1011	-1.47	-4.30
1934.36	913	-2.36	-4.16	1928.21	1013	-2.35	-4.61
1934.21	915	-1.68	-4.48	1928.07	1015	-2.15	-4.42
1934.10	917	-1.21	-4.39	1927.94	1017	-2.11	-4.13
1933.99	919	-1.70	-4.32	1927.80	1019	-2.32	-4.10
1933.88	921	-1.90	-4.27	1927.67	1021	-2.23	-3.97
1933.78	923	-2.89	-4.16	1927.58	1023	-2.28	-4.06
1933.67	925	-2.72	-4.04	1927.48	1025	-2.15	-4.43
1933.55	927	-2.47	-4.37	1927.39	1027	-2.30	-4.54
1933.44	929	-2.15	-4.37	1927.30	1029	-2.32	-4.56
1933.32	931	-1.89	-4.48	1927.21	1031	-2.17	-4.69
1933.21	933	-2.15	-4.49	1927.10	1033	-2.32	-4.61
1933.07	935	-2.06	-4.34	1926.99	1035	-2.39	-4.39
1932.94	937	-2.21	-4.14	1926.88	1037	-2.44	-4.25
1932.80	939	-2.14	-4.20	1926.78	1039	-2.57	-4.08
1932.67	941	-2.43	-4.03	1926.67	1041	-1.78	-3.94
1932.51	943	-2.72	-4.29	1926.44	1043	-2.69	-4.00
1932.36	945	-2.50	-4.58	1926.21	1045	-2.79	-4.25
1932.21	947	-2.09	-4.58	1926.00	1047	-2.07	-4.53
1932.03	949	-2.84	-4.30	1925.89	1049	-1.83	-4.23
1931.85	951	-2.56	-4.05	1925.78	1051	-1.71	-4.06
1931.67	953	-2.07	-3.82	1925.67	1053	-1.53	-3.77
1931.51	955	-2.09	-3.87	1925.60	1055	-1.91	-4.27
1931.36	957	-2.49	-4.00	1925.54	1057	-1.83	-4.14
1931.21	959	-2.59	-4.35	1925.47	1059	-2.19	-4.06
1931.10	961	-1.81	-4.15	1925.41	1061	-2.25	-4.40
1930.99	963	-2.53	-4.26	1925.34	1063	-2.03	-4.63
1930.88	965	-2.27	-4.29	1925.28	1065	-2.04	-4.67
1930.78	967	-1.76	-4.07	1925.21	1067	-1.95	-4.73
1930.67	969	-1.88	-3.61	1925.10	1069	-2.09	-4.70
1930.51	971	-2.31	-3.87	1924.99	1071	-1.78	-4.47
1930.36	973	-2.73	-4.06	1924.89	1073	-1.74	-4.27
1930.21	975	-2.05	-4.57	1924.78	1075	-1.70	-4.12
1930.10	977	-2.15	-4.55	1924.67	1077	-2.03	-4.06
1929.99	979	-1.90	-4.56	1924.55	1079	-2.19	-4.37
1929.88	981	-1.90	-4.31	1924.44	1081	-1.99	-4.43
1929.78	983	-1.87	-4.26	1924.32	1083	-1.52	-4.46
1929.67	985	-2.25	-3.78	1924.21	1085	-1.69	-4.85
1929.55	987	-2.32	-3.89	1924.07	1087	-1.73	-4.24
1929.44	989	-2.57	-4.05	1923.94	1089	-1.62	-4.10
1929.32	991	-2.62	-4.49	1923.80	1091	-2.02	-4.10
1929.21	993	-2.11	-4.60	1923.67	1093	-1.77	-4.07
1929.13	995	-1.55	-4.43	1923.52	1095	-2.22	-4.23
1929.05	997	-2.13	-4.48	1923.36	1097	-1.72	-4.44
1928.98	999	-2.12	-4.32	1923.21	1099	-1.51	-4.57
1928.90	1001	-1.68	-4.19	1922.94	1101	-1.75	-4.29

Year A.D.	Depth (mm)	δ^{13}C (‰)	δ^{18}O (‰)	Year A.D.	Depth (mm)	δ^{13}C (‰)	δ^{18}O (‰)
1922.67	1103	-1.93	-4.14	1915.80	1203	-1.21	-4.03
1922.58	1105	-1.83	-4.18	1915.67	1205	-1.70	-3.67
1922.49	1107	-2.15	-4.40	1915.52	1207	-2.14	-4.07
1922.39	1109	-2.11	-4.69	1915.36	1209	-1.91	-4.73
1922.30	1111	-1.92	-4.79	1915.21	1211	-1.90	-4.87
1922.21	1113	-1.81	-4.85	1915.07	1213	-1.73	-4.68
1922.07	1115	-1.64	-4.56	1914.94	1215	-1.62	-4.57
1921.94	1117	-1.55	-4.30	1914.80	1217	-1.58	-4.23
1921.80	1119	-1.85	-4.50	1914.67	1219	-1.70	-3.95
1921.67	1121	-2.15	-4.29	1914.55	1221	-1.63	-4.05
1921.44	1123	-2.56	-4.89	1914.44	1223	-2.03	-4.41
1921.21	1125	-1.78	-4.89	1914.32	1225	-1.82	-4.48
1921.07	1127	-1.59	-4.83	1914.21	1227	-1.54	-4.50
1920.94	1129	-1.87	-4.57	1914.03	1229	-1.55	-4.48
1920.80	1131	-1.87	-4.46	1913.85	1231	-1.34	-4.11
1920.67	1133	-1.87	-4.12	1913.67	1233	-1.55	-3.93
1920.52	1135	-2.05	-4.51	1913.55	1235	-1.68	-3.95
1920.36	1137	-2.00	-4.47	1913.44	1237	-1.73	-4.46
1920.21	1139	-1.70	-4.56	1913.32	1239	-1.54	-4.45
1920.07	1141	-1.80	-4.50	1913.21	1241	-1.42	-4.48
1919.94	1143	-1.70	-4.12	1913.03	1243	-1.43	-4.25
1919.80	1145	-1.58	-3.97	1912.85	1245	-1.53	-4.11
1919.67	1147	-1.83	-3.90	1912.67	1247	-1.51	-3.95
1919.52	1149	-2.14	-4.15	1912.55	1249	-1.69	-4.10
1919.36	1151	-1.93	-4.54	1912.44	1251	-1.65	-4.38
1919.21	1153	-1.88	-4.62	1912.32	1253	-1.50	-4.54
1919.03	1155	-1.75	-4.54	1912.21	1255	-1.49	-4.67
1918.85	1157	-1.51	-4.30	1911.94	1257	-1.44	-4.39
1918.67	1159	-1.55	-4.01	1911.67	1259	-1.34	-4.19
1918.55	1161	-1.53	-4.17	1911.55	1261	-1.66	-4.23
1918.44	1163	-2.20	-4.38	1911.44	1263	-1.88	-4.28
1918.32	1165	-2.02	-4.75	1911.32	1265	-1.92	-4.62
1918.21	1167	-1.86	-4.84	1911.21	1267	-1.80	-4.71
1918.07	1169	-1.80	-4.82	1911.07	1269	-1.48	-4.63
1917.94	1171	-2.03	-4.68	1910.94	1271	-1.40	-4.43
1917.80	1173	-1.70	-4.46	1910.80	1273	-1.50	-4.33
1917.67	1175	-1.89	-4.35	1910.67	1275	-1.63	-4.07
1917.52	1177	-2.12	-4.47	1910.52	1277	-2.03	-4.72
1917.36	1179	-2.20	-4.67	1910.36	1279	-1.92	-4.62
1917.21	1181	-2.12	-5.03	1910.21	1281	-1.74	-4.74
1917.12	1183	-1.83	-4.81	1910.07	1283	-1.63	-4.61
1917.03	1185	-1.61	-4.73	1909.94	1285	-1.46	-4.44
1916.94	1187	-1.75	-4.55	1909.80	1287	-1.36	-4.37
1916.85	1189	-1.54	-4.39	1909.67	1289	-1.63	-4.21
1916.76	1191	-1.64	-4.33	1909.52	1291	-1.63	-4.45
1916.67	1193	-2.11	-4.20	1909.36	1293	-1.73	-4.61
1916.44	1195	-1.99	-4.41	1909.21	1295	-1.74	-4.98
1916.21	1197	-1.90	-4.88	1909.03	1297	-1.34	-4.68
1916.07	1199	-1.66	-4.77	1908.85	1299	-1.35	-4.58
1915.94	1201	-1.50	-4.58	1908.67	1301	-1.51	-4.29

Year A.D.	Depth (mm)	δ13C (‰)	δ18O (‰)
1908.55	1303	-1.51	-4.30
1908.44	1305	-1.83	-4.40
1908.32	1307	-2.09	-4.73
1908.21	1309	-1.52	-4.82
1908.03	1311	-1.31	-4.34
1907.85	1313	-1.62	-4.24
1907.67	1315	-1.42	-4.03
1907.54	1317	-1.63	-4.05
1907.41	1319	-1.66	-4.05
1907.28	1321	-1.79	-4.51
1907.21	1323	-1.90	-4.54
1907.07	1325	-1.71	-4.53
1906.94	1327	-1.83	-4.42
1906.80	1329	-1.45	-4.17
1906.67	1331	-1.61	-4.02
1906.52	1333	-1.99	-4.18
1906.36	1335	-2.18	-4.36
1906.21	1337	-1.63	-4.39
1906.07	1339	-1.75	-4.36
1905.94	1341	-1.73	-4.08
1905.80	1343	-1.70	-4.02
1905.67	1345	-2.15	-3.85
1905.55	1347	-2.53	-3.97
1905.44	1349	-2.49	-4.29
1905.32	1351	-2.01	-4.48
1905.21	1353	-1.87	-4.51
1905.03	1355	-1.49	-4.25
1904.85	1357	-1.85	-4.12
1904.67	1359	-1.61	-3.89
1904.52	1361	-1.92	-3.95
1904.36	1363	-2.33	-4.59
1904.21	1365	-1.98	-4.61
1904.07	1367	-1.79	-4.57
1903.94	1369	-1.98	-4.20
1903.80	1371	-1.67	-3.90
1903.67	1373	-1.92	-3.86
1903.52	1375	-2.42	-4.24
1903.36	1377	-2.36	-4.43
1903.21	1379	-1.67	-4.50
1903.03	1381	-1.63	-4.45
1902.85	1383	-1.48	-4.18
1902.67	1385	-1.38	-3.92
1902.55	1387	-1.95	-4.12
1902.44	1389	-2.23	-4.61
1902.32	1391	-2.09	-4.59
1902.21	1393	-1.89	-4.63
1902.07	1395	-1.78	-4.55
1901.80	1397	-1.76	-4.20
1901.67	1399	-1.91	-4.18
1901.52	1401	-2.19	-4.25

Year A.D.	Depth (mm)	δ13C (‰)	δ18O (‰)
1901.36	1403	-2.71	-4.54
1901.21	1405	-2.88	-4.70
1901.07	1407	-1.76	-4.57
1900.94	1409	-1.72	-4.57
1900.80	1411	-1.69	-4.41
1900.67	1413	-2.15	-4.21
1900.58	1415	-2.24	-4.24
1900.49	1417	-2.37	-4.24
1900.39	1419	-2.72	-4.25
1900.30	1421	-2.39	-4.43
1900.21	1423	-1.64	-4.48
1900.03	1425	-1.70	-4.27
1899.85	1427	-1.58	-4.24
1899.67	1429	-1.74	-4.18
1899.44	1431	-2.03	-4.47
1899.21	1433	-2.26	-4.91
1899.10	1435	-1.71	-4.85
1898.99	1437	-1.79	-4.72
1898.89	1439	-1.75	-4.48
1898.78	1441	-1.59	-4.12
1898.67	1443	-1.54	-3.94
1898.52	1445	-2.30	-4.28
1898.36	1447	-2.33	-4.62
1898.21	1449	-2.26	-4.89
1898.10	1451	-1.60	-4.58
1897.99	1453	-1.67	-4.45
1897.89	1455	-1.53	-4.14
1897.78	1457	-1.54	-4.07
1897.67	1459	-1.80	-3.97
1897.21	1461	-1.66	-4.34
1897.07	1463	-1.17	-4.26
1896.94	1465	-1.40	-4.18
1896.80	1467	-1.45	-4.03
1896.67	1469	-1.45	-3.99
1896.52	1471	-1.76	-4.24
1896.36	1473	-1.74	-4.61
1896.21	1475	-1.46	-4.61
1896.07	1477	-1.45	-4.53
1895.94	1479	-1.24	-4.20
1895.80	1481	-1.61	-4.09
1895.67	1483	-1.55	-3.96
1895.44	1485	-1.98	-4.55
1895.21	1487	-1.56	-4.56
1895.10	1489	-1.57	-4.55
1894.99	1491	-1.54	-4.42
1894.89	1493	-1.86	-4.24
1894.78	1495	-1.47	-4.20
1894.67	1497	-1.77	-4.06
1894.52	1499	-2.26	-4.36
1894.36	1501	-2.08	-4.64

Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
1894.21	1503	-1.72	-4.73	1886.94	1603	-1.54	-4.55
1893.94	1505	-1.95	-4.69	1886.80	1605	-1.61	-4.48
1893.67	1507	-1.41	-4.13	1886.67	1607	-1.24	-4.25
1893.55	1509	-1.82	-4.15	1886.52	1609	-1.75	-4.34
1893.44	1511	-1.64	-4.41	1886.36	1611	-1.93	-4.60
1893.32	1513	-2.06	-4.51	1886.21	1613	-1.92	-4.77
1893.21	1515	-1.19	-4.67	1886.10	1615	-1.51	-4.74
1893.07	1517	-1.62	-4.63	1885.99	1617	-1.69	-4.75
1892.94	1519	-1.46	-4.54	1885.89	1619	-1.67	-4.53
1892.80	1521	-1.70	-4.48	1885.78	1621	-1.48	-4.53
1892.67	1523	-1.80	-4.13	1885.67	1623	-1.31	-4.13
1892.58	1525	-1.87	-4.16	1885.55	1625	-1.58	-4.25
1892.49	1527	-1.88	-4.53	1885.44	1627	-1.96	-4.44
1892.39	1529	-1.86	-4.64	1885.32	1629	-1.77	-4.60
1892.30	1531	-1.69	-4.64	1885.21	1631	-1.45	-4.61
1892.21	1533	-1.83	-4.74	1885.03	1633	-1.68	-4.28
1892.07	1535	-1.61	-4.42	1884.85	1635	-1.24	-3.78
1891.94	1537	-1.50	-4.24	1884.67	1637	-1.62	-3.61
1891.80	1539	-1.59	-4.02	1884.44	1639	-1.58	-3.92
1891.67	1541	-1.58	-3.98	1884.21	1641	-1.37	-4.42
1891.52	1543	-1.25	-4.11	1884.10	1643	-1.14	-4.37
1891.36	1545	-1.63	-4.53	1883.99	1645	-1.47	-4.36
1891.21	1547	-1.35	-4.66	1883.89	1647	-1.54	-4.30
1890.99	1549	-1.43	-4.52	1883.78	1649	-1.32	-4.04
1890.78	1551	-1.60	-4.10	1883.67	1651	-1.31	-4.00
1890.67	1553	-1.86	-4.00	1883.55	1653	-1.78	-4.22
1890.44	1555	-2.05	-4.38	1883.44	1655	-1.56	-4.43
1890.21	1557	-1.96	-4.71	1883.32	1657	-1.52	-4.67
1890.07	1559	-1.62	-4.56	1883.21	1659	-1.14	-4.68
1889.94	1561	-1.65	-4.31	1883.07	1661	-1.50	-4.40
1889.80	1563	-1.77	-4.24	1882.94	1663	-1.51	-4.21
1889.67	1565	-1.46	-4.11	1882.80	1665	-1.51	-4.10
1889.52	1567	-1.99	-4.23	1882.67	1667	-1.63	-4.00
1889.36	1569	-1.90	-4.42	1882.55	1669	-1.63	-4.31
1889.21	1571	-1.70	-4.73	1882.44	1671	-1.40	-4.50
1889.07	1573	-1.38	-4.71	1882.32	1673	-1.11	-4.64
1888.94	1575	-1.62	-4.50	1882.21	1675	-1.38	-4.64
1888.80	1577	-1.60	-4.18	1882.03	1677	-1.42	-4.46
1888.67	1579	-1.57	-4.05	1881.85	1679	-1.42	-4.40
1888.52	1581	-1.76	-4.21	1881.67	1681	-1.19	-4.21
1888.36	1583	-1.47	-4.27	1881.52	1683	-1.53	-4.27
1888.21	1585	-1.50	-4.45	1881.36	1685	-1.68	-4.37
1888.03	1587	-1.68	-4.36	1881.21	1687	-1.62	-4.42
1887.85	1589	-1.61	-4.07	1881.10	1689	-1.42	-4.39
1887.67	1591	-1.47	-3.91	1880.99	1691	-1.67	-4.27
1887.55	1593	-1.73	-4.01	1880.89	1693	-1.51	-4.02
1887.44	1595	-1.79	-4.20	1880.78	1695	-1.36	-3.96
1887.32	1597	-1.91	-4.40	1880.67	1697	-1.57	-3.78
1887.21	1599	-1.49	-4.59	1880.52	1699	-1.88	-4.13
1887.07	1601	-1.49	-4.58	1880.36	1701	-1.55	-4.53

Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
1880.21	1703	-1.25	-4.57	1873.21	1803	-1.54	-4.61
1880.07	1705	-1.35	-4.51	1873.10	1805	-1.42	-4.53
1879.94	1707	-1.74	-4.11	1872.99	1807	-1.47	-4.45
1879.80	1709	-1.64	-4.11	1872.89	1809	-1.49	-4.17
1879.67	1711	-1.48	-4.07	1872.78	1811	-1.57	-4.09
1879.52	1713	-1.60	-4.51	1872.67	1813	-1.43	-4.07
1879.36	1715	-1.47	-4.72	1872.52	1815	-1.60	-4.24
1879.21	1717	-1.50	-4.88	1872.36	1817	-1.94	-4.43
1879.10	1719	-1.28	-4.74	1872.21	1819	-1.40	-4.56
1878.99	1721	-1.30	-4.60	1872.09	1821	-1.33	-4.49
1878.89	1723	-1.45	-4.50	1871.97	1823	-1.63	-4.43
1878.78	1725	-1.43	-4.34	1871.85	1825	-1.28	-4.19
1878.67	1727	-1.53	-4.15	1871.73	1827	-1.26	-4.03
1878.52	1729	-1.69	-4.47	1871.67	1829	-1.45	-3.97
1878.36	1731	-1.54	-4.67	1871.52	1831	-1.37	-4.17
1878.21	1733	-1.06	-4.76	1871.36	1833	-1.80	-4.43
1878.07	1735	-1.62	-4.37	1871.21	1835	-1.55	-4.69
1877.94	1737	-1.59	-3.94	1871.10	1837	-1.33	-4.56
1877.80	1739	-1.78	-3.93	1870.99	1839	-1.53	-4.52
1877.67	1741	-1.16	-3.92	1870.89	1841	-1.33	-4.25
1877.44	1743	-1.58	-4.15	1870.78	1843	-1.36	-4.19
1877.21	1745	-1.74	-4.44	1870.67	1845	-1.11	-4.11
1877.10	1747	-1.20	-4.30	1870.44	1847	-1.49	-4.39
1876.99	1749	-1.38	-4.26	1870.21	1849	-1.66	-4.71
1876.89	1751	-1.51	-4.04	1870.10	1851	-1.46	-4.63
1876.78	1753	-0.98	-3.94	1869.99	1853	-1.35	-4.63
1876.67	1755	-1.74	-3.90	1869.89	1855	-1.44	-4.32
1876.52	1757	-1.73	-4.20	1869.78	1857	-1.62	-4.26
1876.36	1759	-1.28	-4.39	1869.67	1859	-1.59	-4.20
1876.21	1761	-1.36	-4.44	1869.52	1861	-1.57	-4.24
1876.07	1763	-1.30	-4.41	1869.36	1863	-1.32	-4.58
1875.94	1765	-1.56	-4.28	1869.21	1865	-1.36	-4.61
1875.80	1767	-1.32	-4.12	1869.07	1867	-1.61	-4.51
1875.67	1769	-1.32	-4.06	1868.94	1869	-1.78	-4.63
1875.52	1771	-1.60	-4.15	1868.80	1871	-1.20	-4.06
1875.36	1773	-1.51	-4.48	1868.67	1873	-1.70	-4.00
1875.21	1775	-1.59	-4.62	1868.44	1875	-1.49	-4.21
1875.10	1777	-1.35	-4.59	1868.21	1877	-1.41	-4.41
1874.99	1779	-1.65	-4.37	1868.07	1879	-1.41	-4.40
1874.89	1781	-1.49	-4.30	1867.94	1881	-1.53	-4.29
1874.78	1783	-1.42	-4.11	1867.80	1883	-1.53	-4.17
1874.67	1785	-1.16	-4.01	1867.67	1885	-1.28	-3.99
1874.52	1787	-1.62	-4.34	1867.55	1887	-1.21	-4.03
1874.36	1789	-1.42	-4.49	1867.44	1889	-1.64	-4.35
1874.21	1791	-1.59	-4.54	1867.32	1891	-1.43	-4.54
1874.03	1793	-1.60	-4.45	1867.21	1893	-1.34	-4.56
1873.85	1795	-1.41	-4.37	1867.03	1895	-1.43	-4.44
1873.67	1797	-1.40	-4.08	1866.85	1897	-1.39	-4.35
1873.52	1799	-1.19	-4.14	1866.67	1899	-1.32	-4.07
1873.36	1801	-1.52	-4.32	1866.52	1901	-1.69	-4.12

Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
1866.36	1903	-1.58	-4.20	1859.32	2003	-1.75	-4.50
1866.21	1905	-1.22	-4.49	1859.21	2005	-1.73	-4.51
1866.03	1907	-1.82	-4.33	1859.03	2007	-1.46	-4.17
1865.85	1909	-1.48	-3.93	1858.85	2009	-1.41	-3.90
1865.67	1911	-1.31	-3.93	1858.67	2011	-1.52	-3.90
1865.55	1913	-1.31	-3.93	1858.52	2013	-1.51	-4.06
1865.44	1915	-1.76	-4.34	1858.36	2015	-1.71	-4.64
1865.32	1917	-1.46	-4.41	1858.21	2017	-1.77	-4.66
1865.21	1919	-1.43	-4.48	1858.03	2019	-1.51	-4.47
1865.03	1921	-1.54	-4.41	1857.85	2021	-1.36	-4.24
1864.85	1923	-1.34	-4.12	1857.67	2023	-1.21	-3.93
1864.67	1925	-1.33	-4.07	1857.52	2025	-1.71	-4.00
1864.52	1927	-1.23	-4.21	1857.36	2027	-1.72	-4.28
1864.36	1929	-1.65	-4.31	1857.21	2029	-1.44	-4.52
1864.21	1931	-1.31	-4.38	1857.10	2031	-1.13	-4.44
1864.07	1933	-1.42	-4.28	1856.99	2033	-1.59	-4.48
1863.94	1935	-1.28	-4.19	1856.89	2035	-1.46	-4.34
1863.80	1937	-1.30	-3.99	1856.78	2037	-1.08	-4.15
1863.67	1939	-1.19	-3.89	1856.67	2039	-1.18	-3.98
1863.52	1941	-1.53	-4.01	1856.52	2041	-1.36	-4.29
1863.36	1943	-1.87	-4.49	1856.36	2043	-1.97	-4.52
1863.21	1945	-1.54	-4.53	1856.21	2045	-1.45	-4.71
1863.07	1947	-1.72	-4.43	1856.07	2047	-1.27	-4.59
1862.94	1949	-1.58	-4.17	1855.94	2049	-1.75	-4.09
1862.80	1951	-1.68	-3.98	1855.80	2051	-1.46	-4.19
1862.67	1953	-1.63	-3.84	1855.67	2053	-1.68	-3.93
1862.52	1955	-1.75	-4.13	1855.52	2055	-1.54	-4.18
1862.36	1957	-1.94	-4.36	1855.36	2057	-1.55	-4.38
1862.21	1959	-1.61	-4.49	1855.21	2059	-1.66	-4.56
1862.03	1961	-1.57	-4.42	1855.03	2061	-1.19	-4.36
1861.85	1963	-1.48	-4.28	1854.85	2063	-1.35	-4.35
1861.67	1965	-1.36	-4.07	1854.67	2065	-1.79	-3.93
1861.55	1967	-1.52	-4.12	1854.44	2067	-1.72	-4.25
1861.44	1969	-1.70	-4.28	1854.21	2069	-1.67	-4.43
1861.32	1971	-1.76	-4.59	1854.07	2071	-1.40	-4.38
1861.21	1973	-1.77	-4.77	1853.94	2073	-1.52	-4.15
1861.07	1975	-1.49	-4.66	1853.80	2075	-1.37	-4.07
1860.94	1977	-1.44	-4.59	1853.67	2077	-1.54	-3.96
1860.80	1979	-1.67	-4.27	1853.52	2079	-1.64	-3.97
1860.67	1981	-1.48	-4.04	1853.36	2081	-1.79	-4.24
1860.52	1983	-1.53	-4.07	1853.21	2083	-1.83	-4.32
1860.36	1985	-1.66	-4.24	1853.07	2085	-1.54	-4.32
1860.21	1987	-1.65	-4.51	1852.94	2087	-1.39	-4.16
1860.10	1989	-1.31	-4.46	1852.80	2089	-1.23	-3.94
1859.99	1991	-1.42	-4.29	1852.67	2091	-1.76	-3.93
1859.89	1993	-1.38	-4.25	1852.52	2093	-1.77	-4.02
1859.78	1995	-1.30	-3.91	1852.36	2095	-1.78	-4.34
1859.67	1997	-1.14	-3.91	1852.21	2097	-1.72	-4.55
1859.55	1999	-1.82	-4.07	1852.10	2099	-1.60	-4.53
1859.44	2001	-1.65	-4.46	1851.99	2101	-1.71	-4.38

Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
1851.89	2103	-1.77	-4.33	1844.21	2203	-1.46	-4.55
1851.78	2105	-1.75	-4.17	1844.07	2205	-1.52	-4.52
1851.67	2107	-1.88	-4.06	1843.94	2207	-1.29	-4.20
1851.44	2109	-1.80	-4.34	1843.80	2209	-1.42	-4.09
1851.21	2111	-2.00	-4.49	1843.67	2211	-1.52	-4.07
1851.03	2113	-1.87	-4.41	1843.21	2213	-1.69	-4.47
1850.85	2115	-1.51	-4.00	1843.10	2215	-1.50	-4.40
1850.67	2117	-1.80	-3.87	1842.99	2217	-1.51	-4.26
1850.55	2119	-1.75	-3.90	1842.89	2219	-1.47	-4.16
1850.44	2121	-1.74	-3.94	1842.78	2221	-1.40	-3.93
1850.32	2123	-1.63	-4.24	1842.67	2223	-1.41	-3.89
1850.21	2125	-1.54	-4.25	1842.58	2225	-1.64	-4.00
1850.03	2127	-1.52	-4.04	1842.49	2227	-1.53	-4.40
1849.85	2129	-1.46	-3.99	1842.39	2229	-1.44	-4.40
1849.67	2131	-1.36	-3.89	1842.30	2231	-1.36	-4.47
1849.52	2133	-1.51	-4.01	1842.21	2233	-1.46	-4.49
1849.36	2135	-1.66	-4.37	1841.94	2235	-1.34	-4.18
1849.21	2137	-1.66	-4.48	1841.67	2237	-1.44	-4.08
1849.07	2139	-1.52	-4.41	1841.52	2239	-1.56	-4.29
1848.94	2141	-1.56	-4.32	1841.36	2241	-1.86	-4.52
1848.80	2143	-1.45	-4.18	1841.21	2243	-1.51	-4.61
1848.67	2145	-1.32	-4.04	1841.03	2245	-1.26	-4.30
1848.44	2147	-1.13	-4.25	1840.85	2247	-1.30	-4.12
1848.21	2149	-1.27	-4.58	1840.67	2249	-1.45	-3.81
1848.07	2151	-1.41	-4.57	1840.52	2251	-1.61	-4.04
1847.94	2153	-1.41	-4.38	1840.36	2253	-1.65	-4.42
1847.80	2155	-1.34	-4.12	1840.21	2255	-1.57	-4.56
1847.67	2157	-1.38	-4.02	1840.03	2257	-1.62	-4.53
1847.52	2159	-1.66	-4.14	1839.85	2259	-1.52	-4.33
1847.36	2161	-1.38	-4.32	1839.67	2261	-1.18	-4.02
1847.21	2163	-1.41	-4.48	1839.55	2263	-1.50	-4.18
1847.10	2165	-1.18	-4.41	1839.44	2265	-1.49	-3.97
1846.99	2167	-1.46	-4.24	1839.32	2267	-1.25	-4.28
1846.89	2169	-1.32	-4.13	1839.21	2269	-1.32	-4.39
1846.78	2171	-1.30	-3.99	1838.94	2271	-1.47	-4.03
1846.67	2173	-1.35	-3.94	1838.67	2273	-1.29	-3.89
1846.52	2175	-1.66	-4.15	1838.52	2275	-1.21	-3.94
1846.36	2177	-1.47	-4.41	1838.36	2277	-1.41	-4.19
1846.21	2179	-1.32	-4.45	1838.21	2279	-1.37	-4.35
1845.94	2181	-1.37	-4.26	1838.03	2281	-1.28	-4.29
1845.67	2183	-1.46	-3.96	1837.85	2283	-1.25	-3.93
1845.55	2185	-1.44	-4.00	1837.67	2285	-1.27	-3.90
1845.44	2187	-1.68	-4.18	1837.44	2287	-1.59	-4.17
1845.32	2189	-1.38	-4.28	1837.21	2289	-1.81	-4.62
1845.21	2191	-1.41	-4.55	1837.10	2291	-1.34	-4.62
1845.03	2193	-1.31	-4.30	1836.99	2293	-1.54	-4.49
1844.85	2195	-1.10	-4.04	1836.89	2295	-1.55	-4.22
1844.67	2197	-1.58	-3.88	1836.78	2297	-1.54	-4.19
1844.52	2199	-1.89	-4.13	1836.67	2299	-0.98	-4.03
1844.36	2201	-1.67	-4.22	1836.56	2301	-1.42	-4.23

Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
1836.45	2303	-1.30	-4.44	1827.78	2403	-1.33	-4.35
1836.40	2305	-1.37	-4.05	1827.63	2405	-1.46	-4.02
1836.15	2307	-1.40	-3.87	1827.47	2407	-1.48	-4.03
1835.91	2309	-1.63	-3.98	1827.32	2409	-1.48	-4.22
1835.66	2311	-1.63	-4.33	1827.17	2411	-1.58	-4.44
1835.41	2313	-1.45	-4.58	1827.03	2413	-1.43	-4.42
1835.17	2315	-1.41	-4.51	1826.90	2415	-1.21	-4.40
1834.98	2317	-1.34	-4.29	1826.77	2417	-1.26	-4.10
1834.80	2319	-1.34	-4.15	1826.63	2419	-1.31	-3.99
1834.62	2321	-1.61	-4.00	1826.50	2421	-1.44	-4.10
1834.44	2323	-1.84	-4.44	1826.37	2423	-1.64	-4.46
1834.26	2325	-1.62	-4.60	1826.23	2425	-1.11	-4.53
1834.10	2327	-1.50	-4.56	1826.08	2427	-1.14	-4.62
1833.95	2329	-1.53	-4.30	1825.89	2429	-1.55	-4.33
1833.81	2331	-1.46	-4.19	1825.71	2431	-1.27	-4.00
1833.67	2333	-1.45	-4.08	1825.53	2433	-1.39	-4.03
1833.52	2335	-1.38	-4.13	1825.35	2435	-1.44	-4.15
1833.38	2337	-1.59	-4.36	1825.17	2437	-1.41	-4.52
1833.24	2339	-1.57	-4.53	1824.97	2439	-1.65	-4.50
1833.08	2341	-1.51	-4.28	1824.77	2441	-1.26	-4.46
1832.89	2343	-1.94	-4.52	1824.57	2443	-1.42	-4.38
1832.71	2345	-1.59	-3.77	1824.37	2445	-1.37	-3.71
1832.53	2347	-1.45	-3.99	1824.08	2447	-0.87	-3.72
1832.35	2349	-1.52	-4.33	1823.89	2449	-0.88	-3.75
1832.17	2351	-1.41	-4.25	1823.71	2451	-1.06	-3.53
1831.98	2353	-1.26	-4.16	1823.53	2453	-1.66	-3.64
1831.80	2355	-0.99	-3.95	1823.35	2455	-1.80	-3.72
1831.62	2357	-1.26	-3.97	1823.17	2457	-1.65	-4.02
1831.44	2359	-1.81	-4.23	1823.02	2459	-1.21	-4.17
1831.26	2361	-1.42	-4.34	1822.88	2461	-1.00	-4.08
1831.09	2363	-1.34	-4.29	1822.74	2463	-1.14	-3.93
1830.94	2365	-1.21	-4.15	1822.60	2465	-1.07	-3.92
1830.78	2367	-1.60	-4.03	1822.45	2467	-1.42	-3.84
1830.63	2369	-1.51	-4.17	1822.31	2469	-1.64	-4.04
1830.47	2371	-1.45	-4.34	1822.17	2471	-1.56	-4.29
1830.32	2373	-1.41	-4.54	1822.02	2473	-0.88	-4.16
1830.17	2375	-1.51	-4.44	1821.88	2475	-0.82	-3.93
1830.00	2377	-1.58	-4.22	1821.74	2477	-0.62	-3.80
1829.83	2379	-1.21	-3.98	1821.60	2479	-1.47	-3.83
1829.67	2381	-1.31	-3.96	1821.45	2481	-1.67	-3.88
1829.50	2383	-1.62	-4.04	1821.31	2483	-1.81	-4.13
1829.33	2385	-1.45	-4.45	1821.17	2485	-0.94	-4.12
1829.17	2387	-1.25	-4.53	1820.98	2487	-0.71	-3.88
1828.98	2389	-1.41	-4.50	1820.80	2489	-0.36	-3.70
1828.80	2391	-1.09	-4.23	1820.62	2491	-0.76	-3.70
1828.62	2393	-1.36	-4.02	1820.44	2493	-1.80	-3.78
1828.44	2395	-1.34	-4.02	1820.26	2495	-1.80	-4.29
1828.26	2397	-1.49	-4.50	1820.08	2497	-0.66	-3.97
1828.09	2399	-1.48	-4.51	1819.89	2499	-0.45	-3.77
1827.94	2401	-1.26	-4.59	1819.71	2501	-0.16	-3.61

Year A.D.	Depth (mm)	δ¹³C (‰)	δ¹⁸O (‰)	Year A.D.	Depth (mm)	δ¹³C (‰)	δ¹⁸O (‰)
1819.53	2503	-1.12	-3.94	1809.62	2603	-1.19	-3.82
1819.35	2505	-1.73	-4.11	1809.44	2605	-1.54	-3.79
1819.17	2507	-1.13	-4.27	1809.26	2607	-1.21	-3.99
1819.00	2509	-0.98	-4.22	1809.07	2609	-1.07	-4.24
1818.83	2511	-0.39	-3.82	1808.87	2611	-1.33	-4.09
1818.67	2513	-0.33	-3.72	1808.67	2613	-1.32	-3.88
1818.50	2515	-0.98	-3.79	1808.47	2615	-1.54	-3.91
1818.33	2517	-1.46	-4.03	1808.27	2617	-1.75	-4.18
1818.17	2519	-0.56	-3.94	1808.08	2619	-1.34	-4.33
1817.94	2521	-0.64	-3.92	1807.92	2621	-1.34	-4.30
1817.72	2523	-0.54	-3.71	1807.75	2623	-1.27	-4.16
1817.50	2525	-0.63	-3.48	1807.58	2625	-1.66	-4.07
1817.28	2527	-1.37	-4.05	1807.42	2627	-1.57	-4.05
1817.06	2529	-0.86	-4.09	1807.25	2629	-1.43	-4.28
1816.83	2531	-0.95	-3.90	1807.08	2631	-1.19	-4.44
1816.61	2533	-0.92	-3.62	1806.92	2633	-1.25	-4.34
1816.39	2535	-1.58	-4.00	1806.75	2635	-1.35	-3.99
1816.17	2537	-1.04	-4.18	1806.58	2637	-1.27	-3.94
1815.97	2539	-1.19	-4.01	1806.42	2639	-1.60	-4.21
1815.77	2541	-1.20	-3.79	1806.25	2641	-1.64	-4.41
1815.57	2543	-1.15	-3.68	1806.08	2643	-1.46	-4.42
1815.37	2545	-1.37	-4.00	1805.89	2645	-1.38	-4.28
1815.17	2547	-1.25	-4.09	1805.71	2647	-1.45	-4.02
1814.97	2549	-1.09	-3.96	1805.53	2649	-1.55	-3.93
1814.77	2551	-1.19	-3.73	1805.35	2651	-1.67	-4.16
1814.57	2553	-1.04	-3.67	1805.17	2653	-1.33	-4.48
1814.37	2555	-1.51	-4.12	1805.01	2655	-1.18	-4.51
1814.17	2557	-1.48	-4.37	1804.86	2657	-1.23	-4.34
1813.97	2559	-1.37	-4.33	1804.71	2659	-1.10	-4.21
1813.77	2561	-1.46	-3.98	1804.55	2661	-1.17	-4.08
1813.57	2563	-1.36	-3.98	1804.40	2663	-1.37	-4.30
1813.37	2565	-1.55	-4.12	1804.24	2665	-1.36	-4.45
1813.17	2567	-1.21	-4.43	1804.08	2667	-1.17	-4.56
1812.97	2569	-1.32	-4.46	1803.92	2669	-1.16	-4.17
1812.77	2571	-1.23	-4.20	1803.75	2671	-0.90	-3.92
1812.57	2573	-1.19	-4.05	1803.58	2673	-1.08	-3.74
1812.37	2575	-1.58	-4.34	1803.42	2675	-1.46	-3.90
1812.17	2577	-1.59	-4.59	1803.25	2677	-1.16	-4.03
1812.00	2579	-1.52	-4.60	1803.04	2679	-1.06	-4.08
1811.83	2581	-1.20	-4.27	1802.79	2681	-1.06	-3.80
1811.67	2583	-1.31	-4.09	1802.54	2683	-1.21	-3.91
1811.50	2585	-1.36	-4.03	1802.29	2685	-1.54	-4.26
1811.33	2587	-1.19	-4.34	1802.10	2687	-1.33	-4.46
1811.17	2589	-1.35	-4.42	1801.97	2689	-1.32	-4.21
1810.92	2591	-1.27	-4.26	1801.83	2691	-1.47	-4.24
1810.67	2593	-1.00	-4.16	1801.70	2693	-1.36	-4.01
1810.42	2595	-1.53	-4.19	1801.57	2695	-1.66	-4.07
1810.17	2597	-1.37	-4.16	1801.43	2697	-1.70	-4.09
1809.98	2599	-1.43	-4.39	1801.30	2699	-1.48	-4.31
1809.80	2601	-1.20	-4.13	1801.17	2701	-1.23	-4.41

Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
1800.94	2703	-1.05	-4.15	1792.55	2803	-1.42	-3.90
1800.72	2705	-1.19	-4.01	1792.40	2805	-1.54	-3.89
1800.50	2707	-1.26	-4.03	1792.24	2807	-1.54	-4.10
1800.28	2709	-1.26	-4.23	1792.07	2809	-1.14	-4.13
1800.08	2711	-1.06	-4.34	1791.87	2811	-1.21	-3.68
1799.89	2713	-1.03	-4.30	1791.67	2813	-1.16	-3.88
1799.71	2715	-0.98	-4.12	1791.47	2815	-1.11	-4.13
1799.53	2717	-1.23	-3.91	1791.27	2817	-1.03	-4.42
1799.35	2719	-1.32	-4.21	1791.07	2819	-0.76	-3.96
1799.17	2721	-1.50	-4.39	1790.87	2821	-1.22	-3.60
1799.00	2723	-1.30	-4.26	1790.67	2823	-1.27	-3.97
1798.83	2725	-1.22	-3.97	1790.47	2825	-1.35	-4.37
1798.67	2727	-1.33	-3.95	1790.27	2827	-1.15	-4.30
1798.50	2729	-1.32	-3.96	1790.08	2829	-1.15	-4.19
1798.33	2731	-1.37	-4.32	1789.89	2831	-0.94	-3.99
1798.17	2733	-1.34	-4.45	1789.71	2833	-1.32	-4.06
1797.98	2735	-1.35	-4.31	1789.53	2835	-1.47	-4.27
1797.80	2737	-1.19	-4.01	1789.35	2837	-1.44	-4.44
1797.62	2739	-1.32	-3.96	1789.17	2839	-1.10	-4.41
1797.44	2741	-1.49	-4.11	1788.98	2841	-1.21	-4.32
1797.26	2743	-1.70	-4.65	1788.80	2843	-1.41	-3.84
1797.09	2745	-1.37	-4.58	1788.62	2845	-1.43	-3.91
1796.94	2747	-1.37	-4.36	1788.44	2847	-1.69	-3.99
1796.78	2749	-1.34	-4.15	1788.26	2849	-1.75	-4.37
1796.63	2751	-1.37	-3.94	1788.10	2851	-1.41	-4.45
1796.47	2753	-1.63	-4.05	1787.95	2853	-1.41	-4.44
1796.32	2755	-1.74	-4.49	1787.81	2855	-1.46	-4.15
1796.17	2757	-1.53	-4.56	1787.67	2857	-1.50	-3.90
1795.98	2759	-1.56	-4.56	1787.52	2859	-1.23	-3.81
1795.80	2761	-1.57	-4.18	1787.38	2861	-1.55	-4.31
1795.62	2763	-1.42	-3.94	1787.24	2863	-1.04	-4.36
1795.44	2765	-1.49	-4.17	1787.10	2865	-1.55	-4.49
1795.26	2767	-1.61	-4.47	1786.95	2867	-1.39	-4.18
1795.10	2769	-1.59	-4.73	1786.81	2869	-1.38	-3.95
1794.98	2771	-1.49	-4.68	1786.67	2871	-1.68	-4.17
1794.85	2773	-1.41	-4.52	1786.52	2873	-1.91	-4.28
1794.73	2775	-1.25	-4.25	1786.38	2875	-1.99	-4.74
1794.60	2777	-1.43	-4.17	1786.24	2877	-1.27	-4.50
1794.48	2779	-1.72	-4.32	1786.09	2879	-1.30	-4.34
1794.35	2781	-1.57	-4.61	1785.94	2881	-1.35	-4.13
1794.23	2783	-1.30	-4.69	1785.78	2883	-1.23	-4.05
1794.08	2785	-1.26	-4.66	1785.63	2885	-1.72	-4.03
1793.89	2787	-1.23	-4.60	1785.47	2887	-1.94	-4.26
1793.71	2789	-1.23	-4.18	1785.32	2889	-1.55	-4.60
1793.53	2791	-1.54	-4.01	1785.17	2891	-1.54	-4.53
1793.35	2793	-1.54	-4.35	1785.00	2893	-1.38	-4.47
1793.17	2795	-1.50	-4.70	1784.83	2895	-1.37	-4.26
1793.01	2797	-1.36	-4.57	1784.67	2897	-1.51	-4.03
1792.86	2799	-1.12	-4.44	1784.50	2899	-1.51	-4.34
1792.71	2801	-1.31	-4.16	1784.33	2901	-1.84	-4.26

Year A.D.	Depth (mm)	δ13C (‰)	δ18O (‰)	Year A.D.	Depth (mm)	δ13C (‰)	δ18O (‰)
1784.17	2903	-1.37	-4.56	1776.94	3003	-0.82	-3.86
1784.02	2905	-1.23	-4.47	1776.72	3005	-0.47	-3.58
1783.88	2907	-1.27	-4.40	1776.50	3007	-1.07	-3.62
1783.74	2909	-1.29	-4.17	1776.28	3009	-2.02	-4.35
1783.60	2911	-1.31	-3.90	1776.10	3011	-0.93	-4.29
1783.45	2913	-1.46	-3.87	1775.97	3013	-0.91	-4.17
1783.31	2915	-1.88	-4.36	1775.83	3015	-0.84	-3.81
1783.17	2917	-1.49	-4.31	1775.70	3017	-0.98	-3.74
1783.02	2919	-1.65	-4.46	1775.57	3019	-1.20	-3.80
1782.88	2921	-1.29	-4.03	1775.50	3021	-1.62	-4.11
1782.74	2923	-1.29	-3.97	1775.37	3023	-1.63	-4.24
1782.60	2925	-1.57	-3.78	1775.23	3025	-1.19	-4.29
1782.45	2927	-1.91	-3.98	1775.10	3027	-1.01	-4.19
1782.31	2929	-1.89	-4.08	1774.98	3029	-0.65	-3.97
1782.17	2931	-1.65	-4.18	1774.85	3031	-0.84	-3.95
1782.00	2933	-1.64	-4.19	1774.73	3033	-1.19	-3.95
1781.83	2935	-1.25	-3.94	1774.60	3035	-1.67	-4.32
1781.67	2937	-1.37	-3.93	1774.48	3037	-1.55	-4.48
1781.50	2939	-1.40	-3.81	1774.35	3039	-1.04	-4.44
1781.33	2941	-1.77	-3.93	1774.23	3041	-1.23	-4.34
1781.17	2943	-1.91	-4.37	1774.11	3043	-0.83	-4.21
1781.04	2945	-1.12	-4.41	1774.00	3045	-1.44	-3.82
1780.92	2947	-1.28	-4.32	1773.89	3047	-1.19	-3.79
1780.79	2949	-1.40	-4.30	1773.78	3049	-0.93	-3.92
1780.67	2951	-1.24	-4.10	1773.67	3051	-0.95	-4.01
1780.54	2953	-1.28	-3.88	1773.56	3053	-0.79	-3.89
1780.42	2955	-1.74	-4.00	1773.44	3055	-0.63	-3.66
1780.29	2957	-1.98	-4.41	1773.33	3057	-1.08	-4.03
1780.17	2959	-1.56	-4.40	1773.22	3059	-1.19	-4.52
1780.05	2961	-1.42	-4.31	1773.08	3061	-1.15	-4.48
1779.93	2963	-1.51	-4.09	1772.92	3063	-0.89	-4.10
1779.81	2965	-1.44	-3.78	1772.75	3065	-0.71	-3.91
1779.70	2967	-1.57	-3.90	1772.58	3067	-0.88	-3.82
1779.58	2969	-1.89	-4.17	1772.42	3069	-1.31	-4.01
1779.46	2971	-1.85	-4.22	1772.25	3071	-1.17	-4.32
1779.34	2973	-1.44	-4.37	1772.08	3073	-0.94	-4.28
1779.17	2975	-1.28	-3.98	1771.89	3075	-0.85	-4.26
1779.01	2977	-1.69	-4.01	1771.71	3077	-1.02	-3.98
1778.86	2979	-1.27	-3.80	1771.53	3079	-1.27	-3.99
1778.71	2981	-1.25	-3.62	1771.35	3081	-1.29	-4.50
1778.55	2983	-2.07	-3.94	1771.17	3083	-1.37	-4.40
1778.40	2985	-2.08	-4.22	1771.00	3085	-1.12	-4.12
1778.24	2987	-1.38	-4.27	1770.83	3087	-1.20	-3.83
1778.09	2989	-0.92	-4.17	1770.67	3089	-0.89	-3.52
1777.94	2991	-0.77	-3.97	1770.50	3091	-1.26	-3.89
1777.78	2993	-0.71	-3.80	1770.33	3093	-1.33	-4.17
1777.63	2995	-1.13	-3.81	1770.17	3095	-1.42	-4.22
1777.47	2997	-1.65	-3.97	1769.88	3097	-2.05	-3.71
1777.32	2999	-1.59	-4.06	1769.60	3099	-1.94	-4.02
1777.17	3001	-0.88	-4.08	1769.31	3101	-1.29	-4.18

Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
1769.10	3103	-0.99	-4.10	1760.54	3203	-1.73	-3.91
1768.97	3105	-1.06	-3.80	1760.29	3205	-0.58	-3.91
1768.83	3107	-0.92	-3.64	1760.10	3207	-1.10	-4.00
1768.70	3109	-1.17	-3.46	1759.95	3209	-1.12	-4.00
1768.57	3111	-2.01	-3.68	1759.81	3211	-1.28	-4.01
1768.43	3113	-1.84	-3.83	1759.67	3213	-1.06	-3.89
1768.30	3115	-1.62	-4.04	1759.52	3215	-1.64	-3.98
1768.17	3117	-1.40	-3.98	1759.38	3217	-1.80	-4.05
1768.03	3119	-0.90	-3.69	1759.24	3219	-1.36	-4.49
1767.97	3121	-1.53	-4.01	1759.08	3221	-1.28	-4.06
1767.83	3123	-1.20	-3.83	1758.92	3223	-0.86	-3.95
1767.70	3125	-1.09	-3.60	1758.75	3225	-1.00	-3.77
1767.57	3127	-1.77	-3.54	1758.58	3227	-1.49	-3.72
1767.43	3129	-2.06	-3.83	1758.42	3229	-1.85	-4.01
1767.30	3131	-1.65	-4.10	1758.33	3231	-1.54	-3.74
1767.17	3133	-1.24	-4.21	1758.17	3233	-0.89	-4.21
1766.98	3135	-0.91	-3.81	1757.98	3235	-1.33	-4.18
1766.80	3137	-0.83	-3.57	1757.80	3237	-1.33	-3.97
1766.62	3139	-1.46	-3.54	1757.62	3239	-1.65	-3.98
1766.44	3141	-1.94	-3.68	1757.44	3241	-1.89	-4.10
1766.26	3143	-1.13	-3.97	1757.26	3243	-1.41	-4.23
1766.09	3145	-1.12	-3.93	1757.08	3245	-1.19	-4.26
1765.94	3147	-0.73	-3.59	1756.89	3247	-1.27	-4.08
1765.78	3149	-0.99	-3.55	1756.71	3249	-1.32	-3.89
1765.63	3151	-1.89	-3.86	1756.53	3251	-1.46	-3.76
1765.47	3153	-1.42	-3.99	1756.35	3253	-1.79	-4.14
1765.32	3155	-0.98	-4.03	1756.17	3255	-1.27	-4.34
1765.17	3157	-1.03	-4.07	1756.02	3257	-1.38	-4.25
1764.97	3159	-1.37	-3.86	1755.88	3259	-1.00	-4.06
1764.77	3161	-1.46	-4.02	1755.74	3261	-1.36	-4.04
1764.57	3163	-1.36	-4.25	1755.60	3263	-1.33	-3.98
1764.37	3165	-0.95	-4.28	1755.45	3265	-1.96	-4.33
1764.17	3167	-1.30	-4.18	1755.31	3267	-1.08	-4.30
1763.97	3169	-0.84	-3.92	1755.17	3269	-1.43	-4.20
1763.77	3171	-1.28	-3.86	1754.92	3271	-1.31	-4.13
1763.57	3173	-1.57	-4.06	1754.67	3273	-1.20	-3.89
1763.37	3175	-1.11	-4.09	1754.42	3275	-1.74	-4.11
1763.17	3177	-1.15	-4.13	1754.17	3277	-1.43	-4.35
1762.94	3179	-1.07	-3.88	1753.97	3279	-1.50	-4.31
1762.72	3181	-1.05	-3.64	1753.77	3281	-1.38	-4.12
1762.50	3183	-1.51	-3.93	1753.57	3283	-1.78	-3.99
1762.28	3185	-1.12	-4.03	1753.37	3285	-1.68	-4.07
1762.08	3187	-1.30	-4.04	1753.17	3287	-1.43	-4.49
1761.89	3189	-1.10	-3.90	1753.01	3289	-1.48	-4.27
1761.71	3191	-1.12	-3.76	1752.86	3291	-1.25	-4.11
1761.53	3193	-1.53	-3.82	1752.71	3293	-1.29	-3.93
1761.35	3195	-1.24	-4.16	1752.55	3295	-1.77	-4.09
1761.17	3197	-0.77	-4.05	1752.40	3297	-1.59	-4.38
1761.04	3199	-0.79	-3.74	1752.24	3299	-1.41	-4.42
1760.79	3201	-1.42	-3.69	1752.08	3301	-1.13	-4.39

Year A.D.	Depth (mm)	δ13C (‰)	δ18O (‰)	Year A.D.	Depth (mm)	δ13C (‰)	δ18O (‰)
1751.89	3303	-1.15	-4.16	1742.92	3403	-1.19	-4.20
1751.71	3305	-1.28	-4.16	1742.75	3405	-1.25	-3.98
1751.53	3307	-1.57	-4.21	1742.58	3407	-1.45	-3.99
1751.35	3309	-1.80	-4.54	1742.42	3409	-1.52	-4.10
1751.17	3311	-1.36	-4.44	1742.25	3411	-1.44	-4.37
1750.83	3313	-1.21	-4.23	1742.10	3413	-1.25	-4.41
1750.50	3315	-1.15	-4.12	1741.95	3415	-1.29	-4.30
1750.17	3317	-1.31	-4.23	1741.81	3417	-1.10	-4.02
1749.98	3319	-1.09	-4.06	1741.67	3419	-1.33	-3.94
1749.80	3321	-1.26	-4.06	1741.52	3421	-1.47	-4.13
1749.62	3323	-1.32	-4.03	1741.38	3423	-1.39	-4.53
1749.44	3325	-1.38	-4.30	1741.24	3425	-1.28	-4.45
1749.26	3327	-1.17	-4.42	1741.09	3427	-1.20	-4.41
1749.04	3329	-1.19	-4.25	1740.94	3429	-1.12	-4.14
1748.79	3331	-1.06	-4.06	1740.78	3431	-1.10	-3.90
1748.54	3333	-1.24	-3.95	1740.63	3433	-1.62	-4.09
1748.29	3335	-1.28	-4.40	1740.47	3435	-1.65	-4.37
1748.10	3337	-1.25	-4.48	1740.32	3437	-1.33	-4.42
1747.95	3339	-1.17	-4.34	1740.17	3439	-1.30	-4.37
1747.81	3341	-1.19	-4.34	1739.98	3441	-1.49	-4.04
1747.67	3343	-1.24	-4.11	1739.80	3443	-1.16	-4.00
1747.52	3345	-1.36	-4.13	1739.62	3445	-1.33	-3.96
1747.38	3347	-1.32	-4.22	1739.44	3447	-1.41	-4.25
1747.24	3349	-1.42	-4.43	1739.26	3449	-1.37	-4.32
1747.10	3351	-1.07	-4.32	1739.08	3451	-1.20	-4.37
1746.97	3353	-1.38	-4.11	1738.92	3453	-1.18	-4.13
1746.83	3355	-1.39	-4.00	1738.75	3455	-1.31	-3.99
1746.70	3357	-1.43	-3.91	1738.58	3457	-1.22	-4.01
1746.57	3359	-1.48	-4.13	1738.42	3459	-1.46	-4.31
1746.43	3361	-1.28	-4.32	1738.25	3461	-1.25	-4.52
1746.30	3363	-1.30	-4.27	1738.08	3463	-1.32	-4.37
1746.17	3365	-1.07	-4.26	1737.89	3465	-1.32	-4.17
1745.94	3367	-1.23	-3.90	1737.71	3467	-1.31	-4.19
1745.72	3369	-1.25	-3.90	1737.53	3469	-1.34	-4.15
1745.50	3371	-1.54	-4.01	1737.35	3471	-1.57	-4.30
1745.28	3373	-1.36	-4.35	1737.17	3473	-1.05	-4.36
1745.08	3375	-1.27	-4.33	1737.01	3475	-1.29	-4.39
1744.92	3377	-1.48	-4.11	1736.86	3477	-1.17	-4.18
1744.75	3379	-1.42	-3.93	1736.71	3479	-0.98	-3.90
1744.58	3381	-1.63	-4.08	1736.55	3481	-1.68	-3.92
1744.42	3383	-1.48	-4.17	1736.40	3483	-1.40	-4.35
1744.25	3385	-1.58	-4.40	1736.24	3485	-1.18	-4.26
1744.10	3387	-1.26	-4.52	1736.08	3487	-1.19	-4.19
1743.95	3389	-1.27	-4.37	1735.89	3489	-1.02	-3.96
1743.81	3391	-1.00	-4.36	1735.71	3491	-1.12	-3.95
1743.67	3393	-1.04	-4.10	1735.53	3493	-1.53	-4.23
1743.52	3395	-1.01	-3.96	1735.35	3495	-1.43	-4.33
1743.38	3397	-1.35	-4.08	1735.17	3497	-1.35	-4.42
1743.24	3399	-1.34	-4.33	1735.03	3499	-1.21	-4.23
1743.08	3401	-1.43	-4.38	1734.90	3501	-1.12	-4.25

Year A.D.	Depth (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
1734.77	3503	-1.05	-4.09
1734.63	3505	-1.09	-4.06
1734.50	3507	-1.20	-3.94
1734.37	3509	-1.63	-4.13
1734.23	3511	-1.35	-4.17
1734.08	3513	-1.03	-4.16
1733.92	3515	-1.27	-3.93
1733.75	3517	-0.90	-3.65
1733.58	3519	-1.61	-3.86
1733.42	3521	-1.56	-4.05
1733.25	3523	-1.19	-4.28
1733.10	3525	-1.05	-4.21
1732.97	3527	-0.93	-4.14
1732.83	3529	-0.93	-3.85
1732.70	3531	-1.12	-3.84
1732.57	3533	-1.86	-4.08
1732.43	3535	-1.36	-4.44
1732.30	3537	-1.21	-4.42
1732.17	3539	-1.16	-4.40
1732.00	3541	-0.97	-4.12
1731.83	3543	-0.77	-4.04
1731.67	3545	-1.74	-3.83
1731.50	3547	-1.94	-3.92
1731.33	3549	-1.19	-4.00
1731.17	3551	-1.37	-3.98
1731.01	3553	-1.07	-3.77
1730.86	3555	-1.17	-3.77
1730.71	3557	-2.18	-3.83
1730.55	3559	-2.03	-3.90
1730.40	3561	-1.17	-4.00
1730.24	3563	-1.52	-4.02
1730.07	3565	-0.99	-3.88
1729.87	3567	-1.27	-3.74
1729.67	3569	-1.74	-3.73
1729.47	3571	-2.13	-4.04
1729.27	3573	-1.80	-4.14
1729.09	3575	-1.38	-4.18
1728.94	3577	-1.39	-4.11
1728.78	3579	-1.41	-3.83
1728.63	3581	-1.53	-3.75
1728.47	3583	-2.16	-4.01
1728.32	3585	-1.74	-4.21
1728.17	3587	-1.07	-4.27
1728.01	3589	-1.15	-4.16
1727.86	3591	-1.27	-3.96
1727.71	3593	-1.56	-3.87
1727.55	3595	-2.41	-4.09
1727.40	3597	-2.12	-4.23
1727.24	3599	-2.22	-4.32
1727.09	3601	-1.93	-4.19
1726.94	3603	-2.00	-4.00
1726.78	3605	-2.26	-3.85

APPENDIX II

CORAL $\delta^{18}O$ AND $\delta^{13}C$ IN CORE 3R FROM RAROTONGA FOR THE PERIOD 1926-2000

Year A.D.	depth (mm)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)	Year A.D.	depth (mm)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)
2000.28	1	-4.863	-3.211	1996.52	52	-4.562	-3.152
2000.17	2	-4.948	-2.938	1996.46	53	-4.661	-3.315
2000.07	3	-4.802	-2.669	1996.40	54	-4.845	-3.549
1999.96	4	-4.624	-3.117	1996.34	55	-4.806	-3.498
1999.86	5	-4.574	-3.184	1996.29	56	-4.780	-3.308
1999.75	6	-4.507	-3.233	1996.23	57	-4.883	-3.057
1999.69	7	-4.583	-3.096	1996.17	58	-4.954	-2.558
1999.62	8	-4.716	-3.134	1996.11	59	-4.938	-2.513
1999.56	9	-4.860	-3.234	1996.05	60	-4.882	-2.622
1999.49	10	-4.955	-3.297	1995.99	61	-4.661	-2.565
1999.36	12	-4.978	-3.356	1995.93	62	-4.674	-2.724
1999.30	13	-4.871	-3.068	1995.87	63	-4.488	-2.717
1999.23	14	-4.931	-2.904	1995.81	64	-4.290	-3.037
1999.17	15	-4.967	-2.984	1995.75	65	-4.292	-2.964
1999.12	16	-4.943	-2.716	1995.68	66	-4.340	-2.878
1999.07	17	-4.938	-2.708	1995.61	67	-4.343	-2.936
1999.01	18	-4.776	-2.472	1995.53	68	-4.490	-3.189
1998.96	19	-4.688	-2.528	1995.46	69	-4.552	-3.268
1998.91	20	-4.542	-2.837	1995.39	70	-4.644	-3.405
1998.86	21	-4.346	-2.952	1995.32	71	-4.701	-3.218
1998.80	22	-4.336	-3.133	1995.24	72	-4.761	-2.985
1998.75	23	-4.245	-3.237	1995.17	73	-4.810	-2.715
1998.65	24	-4.310	-3.375	1995.11	74	-4.497	-2.670
1998.56	25	-4.324	-3.347	1995.05	75	-4.399	-2.566
1998.46	26	-4.485	-3.320	1994.99	76	-4.381	-2.684
1998.36	27	-4.566	-3.198	1994.93	77	-4.360	-2.759
1998.27	28	-4.556	-2.942	1994.87	78	-4.314	-2.651
1998.17	29	-4.638	-2.766	1994.81	79	-4.365	-2.775
1998.10	30	-4.444	-2.789	1994.75	80	-4.244	-2.927
1998.03	31	-4.259	-2.797	1994.69	81	-4.340	-3.118
1997.96	32	-4.170	-2.653	1994.63	82	-4.428	-3.295
1997.89	33	-4.125	-2.888	1994.58	83	-4.409	-3.377
1997.82	34	-4.112	-2.968	1994.52	84	-4.481	-3.448
1997.75	35	-4.071	-2.997	1994.46	85	-4.596	-3.374
1997.67	36	-4.229	-3.312	1994.40	86	-4.691	-3.352
1997.58	37	-4.186	-3.237	1994.34	87	-4.741	-3.365
1997.50	38	-4.434	-3.340	1994.29	88	-4.839	-3.174
1997.42	39	-4.563	-3.470	1994.23	89	-4.783	-3.099
1997.34	40	-4.562	-3.245	1994.17	90	-4.890	-2.753
1997.25	41	-4.629	-2.884	1994.12	91	-4.729	-2.776
1997.17	42	-4.707	-2.675	1994.08	92	-4.604	-2.823
1997.10	43	-4.626	-2.567	1994.03	93	-4.494	-2.660
1997.03	44	-4.535	-2.557	1993.98	94	-4.429	-2.846
1996.96	45	-4.566	-2.539	1993.94	95	-4.345	-3.014
1996.89	46	-4.586	-2.475	1993.89	96	-4.264	-3.056
1996.82	47	-4.451	-2.728	1993.84	97	-4.185	-3.139
1996.75	48	-4.404	-2.744	1993.80	98	-4.160	-3.263
1996.69	49	-4.497	-3.052	1993.75	99	-4.122	-3.365
1996.63	50	-4.555	-3.112	1993.63	100	-4.232	-3.537
1996.58	51	-4.541	-3.210	1993.52	101	-4.416	-3.404

Year A.D.	depth (mm)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)	Year A.D.	depth (mm)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)
1993.40	102	-4.490	-3.308	1989.75	152	-4.297	-2.817
1993.29	103	-4.635	-3.125	1989.68	153	-4.368	-2.961
1993.17	104	-4.673	-2.982	1989.61	154	-4.394	-2.988
1993.12	105	-4.645	-2.856	1989.53	155	-4.530	-3.193
1993.07	106	-4.556	-2.908	1989.46	156	-4.659	-3.250
1993.01	107	-4.451	-2.783	1989.39	157	-4.755	-3.295
1992.96	108	-4.343	-2.756	1989.32	158	-4.794	-3.389
1992.91	109	-4.398	-2.743	1989.24	159	-4.773	-3.360
1992.86	110	-4.323	-2.787	1989.17	160	-5.000	-3.023
1992.80	111	-4.384	-2.875	1989.12	161	-4.901	-2.450
1992.75	112	-4.324	-3.005	1989.08	162	-4.813	-2.800
1992.65	113	-4.370	-3.088	1989.03	163	-4.713	-2.919
1992.56	114	-4.339	-3.132	1988.98	164	-4.679	-2.891
1992.46	115	-4.311	-3.225	1988.94	165	-4.544	-2.933
1992.36	116	-4.439	-3.074	1988.89	166	-4.596	-2.699
1992.27	117	-4.558	-3.014	1988.84	167	-4.488	-2.686
1992.17	118	-4.515	-2.973	1988.80	168	-4.555	-2.912
1992.09	119	-4.452	-2.922	1988.75	169	-4.365	-3.018
1992.00	120	-4.441	-2.704	1988.65	170	-4.389	-3.251
1991.92	121	-4.361	-2.699	1988.56	171	-4.575	-3.426
1991.83	122	-4.148	-2.878	1988.46	172	-4.642	-3.319
1991.75	123	-4.164	-2.900	1988.36	173	-4.782	-3.181
1991.68	124	-4.194	-3.041	1988.27	174	-4.821	-2.871
1991.61	125	-4.200	-3.068	1988.17	175	-4.889	-2.741
1991.53	126	-4.256	-3.147	1988.10	176	-4.818	-2.676
1991.46	127	-4.316	-3.353	1988.03	177	-4.654	-2.576
1991.39	128	-4.404	-3.298	1987.96	178	-4.436	-2.498
1991.32	129	-4.439	-3.335	1987.89	179	-4.257	-2.706
1991.24	130	-4.652	-3.277	1987.82	180	-4.143	-2.950
1991.17	131	-4.725	-3.149	1987.75	181	-4.031	-3.226
1991.11	132	-4.669	-3.107	1987.65	182	-4.131	-3.088
1991.05	133	-4.582	-3.001	1987.56	183	-4.271	-3.034
1990.99	134	-4.498	-2.970	1987.46	184	-4.399	-3.063
1990.93	135	-4.401	-2.991	1987.36	185	-4.368	-2.840
1990.87	136	-4.344	-2.825	1987.27	186	-4.367	-2.412
1990.81	137	-4.299	-2.889	1987.17	187	-4.364	-2.426
1990.75	138	-4.289	-2.723	1987.11	188	-4.354	-2.381
1990.65	139	-4.313	-2.931	1987.05	189	-4.295	-2.453
1990.56	140	-4.323	-3.077	1986.99	190	-4.327	-2.693
1990.46	141	-4.392	-3.063	1986.93	191	-4.348	-2.982
1990.36	142	-4.488	-3.021	1986.87	192	-4.288	-2.962
1990.27	143	-4.579	-3.015	1986.81	193	-4.466	-3.209
1990.17	144	-4.632	-2.981	1986.75	194	-4.443	-3.167
1990.12	145	-4.588	-2.689	1986.67	195	-4.551	-3.137
1990.07	146	-4.514	-2.474	1986.58	196	-4.565	-3.255
1990.01	147	-4.529	-2.515	1986.50	197	-4.597	-3.322
1989.96	148	-4.551	-2.366	1986.42	198	-4.727	-3.508
1989.91	149	-4.520	-2.750	1986.34	199	-4.777	-3.124
1989.86	150	-4.475	-3.111	1986.25	200	-4.865	-2.500
1989.80	151	-4.293	-2.929	1986.17	201	-4.834	-2.350

Year A.D.	depth (mm)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)	Year A.D.	depth (mm)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)
1986.11	202	-4.616	-2.465	1982.36	252	-4.405	-3.403
1986.05	203	-4.633	-2.601	1982.30	253	-4.576	-3.204
1985.99	204	-4.471	-2.687	1982.23	254	-4.624	-2.853
1985.93	205	-4.487	-3.096	1982.17	255	-4.646	-2.671
1985.87	206	-4.416	-3.154	1982.11	256	-4.600	-2.510
1985.81	207	-4.259	-3.161	1982.05	257	-4.539	-2.595
1985.75	208	-4.320	-3.058	1981.99	258	-4.519	-2.867
1985.67	209	-4.385	-3.100	1981.93	259	-4.470	-2.654
1985.58	210	-4.424	-3.353	1981.87	260	-4.430	-2.560
1985.50	211	-4.320	-3.419	1981.81	261	-4.236	-2.778
1985.42	212	-4.496	-3.487	1981.75	262	-4.170	-2.864
1985.34	213	-4.595	-3.245	1981.65	263	-4.221	-2.766
1985.25	214	-4.542	-2.894	1981.56	264	-4.318	-3.181
1985.17	215	-4.693	-3.249	1981.46	265	-4.342	-3.239
1985.11	216	-4.515	-2.634	1981.36	266	-4.553	-3.216
1985.05	217	-4.485	-2.896	1981.27	267	-4.603	-2.847
1984.99	218	-4.472	-2.825	1981.17	268	-4.601	-2.623
1984.93	219	-4.284	-2.925	1981.11	269	-4.441	-2.101
1984.87	220	-4.242	-3.119	1981.05	270	-4.610	-2.608
1984.81	221	-4.091	-3.156	1980.99	271	-4.439	-2.544
1984.75	222	-4.074	-3.400	1980.87	273	-4.193	-2.435
1984.67	223	-4.113	-3.372	1980.81	274	-4.110	-2.399
1984.58	224	-4.188	-3.470	1980.75	275	-4.148	-2.448
1984.50	225	-4.236	-3.490	1980.65	276	-4.096	-2.717
1984.42	226	-4.300	-3.528	1980.56	277	-4.269	-2.842
1984.34	227	-4.472	-3.520	1980.46	278	-4.215	-2.792
1984.25	228	-4.654	-3.410	1980.36	279	-4.407	-2.875
1984.17	229	-4.735	-3.226	1980.27	280	-4.538	-2.671
1984.10	230	-4.714	-2.881	1980.17	281	-4.547	-2.150
1984.03	231	-4.565	-2.804	1980.07	282	-4.452	-2.056
1983.96	232	-4.251	-3.125	1979.96	283	-4.445	-2.190
1983.89	233	-4.119	-3.017	1979.86	284	-4.228	-2.405
1983.82	234	-4.072	-3.056	1979.75	285	-4.110	-2.171
1983.75	235	-4.074	-3.295	1979.69	286	-4.250	-2.138
1983.63	236	-4.143	-3.308	1979.62	287	-4.263	-2.258
1983.52	237	-4.149	-3.308	1979.49	289	-4.142	-2.384
1983.40	238	-4.338	-3.326	1979.43	290	-4.120	-2.224
1983.29	239	-4.379	-3.227	1979.36	291	-4.261	-2.552
1983.17	240	-4.368	-2.797	1979.30	292	-4.270	-2.609
1983.10	241	-4.150	-2.583	1979.23	293	-4.432	-2.327
1983.03	242	-4.160	-2.634	1979.17	294	-4.499	-2.161
1982.96	243	-4.135	-2.874	1979.12	295	-4.358	-1.912
1982.89	244	-4.113	-2.844	1979.07	296	-4.378	-2.105
1982.82	245	-4.131	-2.910	1979.01	297	-4.390	-2.260
1982.75	246	-3.970	-2.797	1978.96	298	-4.426	-2.310
1982.69	247	-3.988	-2.730	1978.91	299	-4.283	-2.642
1982.62	248	-4.080	-2.934	1978.86	300	-4.294	-2.387
1982.56	249	-4.196	-3.169	1978.80	301	-4.164	-2.448
1982.49	250	-4.236	-3.314	1978.75	302	-4.106	-2.537
1982.43	251	-4.395	-3.378	1978.61	303	-4.159	-2.787

Year A.D.	depth (mm)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)	Year A.D.	depth (mm)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)
1978.46	304	-4.343	-2.983	1973.83	354	-4.146	-1.826
1978.32	305	-4.566	-2.940	1973.75	355	-4.081	-1.921
1978.17	306	-4.462	-2.668	1973.63	356	-4.117	-1.992
1978.09	307	-4.309	-2.508	1973.52	357	-4.257	-2.166
1978.00	308	-4.228	-2.630	1973.40	358	-4.391	-2.423
1977.92	309	-4.067	-2.339	1973.29	359	-4.394	-2.608
1977.83	310	-4.036	-2.562	1973.17	360	-4.569	-2.676
1977.75	311	-4.027	-2.443	1973.10	361	-4.444	-2.170
1977.61	312	-4.186	-2.866	1973.03	362	-4.302	-2.257
1977.46	313	-4.419	-2.923	1972.96	363	-4.247	-2.044
1977.32	314	-4.523	-2.638	1972.89	364	-4.140	-2.026
1977.17	315	-4.647	-2.451	1972.82	365	-4.176	-2.213
1977.10	316	-4.384	-1.884	1972.75	366	-4.181	-2.386
1977.03	317	-4.246	-2.074	1972.65	367	-4.170	-2.571
1976.96	318	-4.255	-2.454	1972.56	368	-4.149	-2.795
1976.89	319	-4.208	-2.455	1972.46	369	-4.377	-2.606
1976.82	320	-4.137	-2.232	1972.36	370	-4.506	-2.591
1976.75	321	-4.071	-2.289	1972.27	371	-4.665	-2.810
1976.65	322	-4.222	-2.624	1972.17	372	-4.724	-2.178
1976.56	323	-4.357	-2.781	1972.12	373	-4.705	-2.205
1976.46	324	-4.552	-3.112	1972.07	374	-4.646	-2.390
1976.36	325	-4.555	-2.852	1972.01	375	-4.465	-2.240
1976.27	326	-4.600	-2.643	1971.96	376	-4.557	-2.030
1976.17	327	-4.662	-2.440	1971.91	377	-4.497	-1.888
1976.10	328	-4.562	-2.011	1971.86	378	-4.427	-2.171
1976.03	329	-4.430	-1.980	1971.80	379	-4.307	-2.270
1975.96	330	-4.457	-2.132	1971.75	380	-4.271	-2.447
1975.89	331	-4.187	-2.223	1971.65	381	-4.302	-2.527
1975.82	332	-4.117	-1.863	1971.56	382	-4.434	-2.658
1975.75	333	-4.030	-2.054	1971.46	383	-4.568	-2.532
1975.63	334	-4.247	-2.614	1971.36	384	-4.682	-2.812
1975.52	335	-4.327	-2.574	1971.27	385	-4.906	-2.730
1975.40	336	-4.396	-2.542	1971.17	386	-4.953	-2.429
1975.29	337	-4.527	-2.370	1971.10	387	-4.908	-2.209
1975.17	338	-4.625	-2.426	1971.03	388	-4.736	-2.193
1975.10	339	-4.492	-2.334	1970.96	389	-4.603	-2.188
1975.03	340	-4.511	-2.273	1970.89	390	-4.533	-2.266
1974.96	341	-4.348	-2.063	1970.82	391	-4.237	-2.412
1974.89	342	-4.295	-2.158	1970.75	392	-4.203	-2.463
1974.82	343	-4.213	-1.956	1970.68	393	-4.258	-2.477
1974.75	344	-4.246	-1.851	1970.61	394	-4.310	-2.593
1974.65	345	-4.269	-1.964	1970.53	395	-4.263	-2.572
1974.56	346	-4.218	-1.784	1970.46	396	-4.308	-2.718
1974.46	347	-4.381	-2.309	1970.39	397	-4.371	-2.617
1974.36	348	-4.467	-2.687	1970.32	398	-4.535	-2.393
1974.27	349	-4.627	-2.436	1970.24	399	-4.606	-2.429
1974.17	350	-4.615	-1.829	1970.17	400	-4.612	-1.966
1974.09	351	-4.521	-1.810	1970.11	401	-4.619	-2.123
1974.00	352	-4.403	-1.949	1969.99	403	-4.311	-2.387
1973.92	353	-4.283	-1.700	1969.87	405	-4.255	-2.297

Year A.D.	depth (mm)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)	Year A.D.	depth (mm)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)
1969.75	407	-4.144	-2.601	1962.56	509	-4.118	-2.816
1969.61	409	-4.229	-2.868	1962.36	511	-4.296	-2.814
1969.46	411	-4.409	-2.638	1962.17	513	-4.605	-2.119
1969.32	413	-4.596	-2.494	1962.03	515	-4.515	-2.301
1969.17	415	-4.558	-2.196	1961.89	517	-4.349	-2.321
1969.07	417	-4.478	-2.205	1961.75	519	-4.173	-2.358
1968.96	419	-4.295	-2.432	1961.61	521	-4.230	-2.505
1968.86	421	-4.272	-2.467	1961.46	523	-4.374	-2.757
1968.75	423	-4.264	-2.601	1961.32	525	-4.580	-2.489
1968.46	425	-4.431	-2.619	1961.17	527	-4.702	-2.260
1968.17	427	-4.533	-2.328	1961.07	529	-4.699	-1.910
1968.07	429	-4.357	-2.182	1960.96	531	-4.595	-2.121
1967.96	431	-4.285	-2.282	1960.86	533	-4.284	-2.506
1967.86	433	-4.200	-2.683	1960.75	535	-4.224	-2.532
1967.75	435	-4.101	-2.696	1960.56	537	-4.359	-2.722
1967.56	437	-4.261	-2.835	1960.36	539	-4.462	-2.883
1967.36	439	-4.536	-3.128	1960.17	541	-4.888	-2.513
1967.17	441	-4.581	-2.724	1960.07	543	-4.638	-2.024
1967.09	443	-4.465	-2.531	1959.96	545	-4.456	-2.163
1967.00	445	-4.271	-2.294	1959.86	547	-4.276	-2.313
1966.83	449	-4.069	-2.582	1959.75	549	-4.229	-2.539
1966.75	451	-4.028	-2.601	1959.56	551	-4.449	-2.707
1966.56	453	-4.113	-2.791	1959.36	553	-4.719	-2.574
1966.36	455	-4.225	-2.662	1959.17	555	-4.880	-2.104
1966.17	457	-4.184	-2.203	1959.07	557	-4.391	-2.342
1966.03	459	-4.204	-2.305	1958.96	559	-4.170	-2.315
1965.89	461	-4.104	-2.399	1958.86	561	-4.156	-2.325
1965.75	463	-4.045	-2.637	1958.75	563	-4.019	-2.615
1965.56	465	-4.081	-2.749	1958.56	565	-4.126	-2.638
1965.36	467	-4.320	-2.883	1958.36	567	-4.375	-2.654
1965.17	469	-4.456	-2.777	1958.17	569	-4.456	-2.589
1965.07	471	-4.300	-2.088	1958.03	571	-4.318	-2.075
1964.96	473	-4.243	-2.241	1957.89	573	-4.242	-2.415
1964.86	475	-4.228	-2.182	1957.75	575	-4.186	-2.498
1964.75	477	-4.222	-2.493	1957.61	577	-4.338	-2.597
1964.61	479	-4.134	-2.711	1957.46	579	-4.467	-2.874
1964.46	481	-4.282	-2.826	1957.32	581	-4.774	-2.608
1964.32	483	-4.420	-2.729	1957.17	583	-4.828	-2.465
1964.17	485	-4.497	-2.239	1957.07	585	-4.604	-2.196
1964.07	487	-4.313	-2.119	1956.96	587	-4.453	-2.133
1963.96	489	-4.207	-2.300	1956.86	589	-4.318	-2.318
1963.86	491	-4.125	-2.524	1956.75	591	-4.263	-2.467
1963.75	493	-4.119	-2.558	1956.56	593	-4.431	-2.752
1963.56	495	-4.088	-2.700	1956.36	595	-4.586	-2.652
1963.36	497	-4.512	-2.831	1956.17	597	-4.653	-2.071
1963.17	499	-4.659	-2.535	1956.03	599	-4.505	-1.994
1963.07	501	-4.505	-2.336	1955.89	601	-4.412	-2.123
1962.96	503	-4.195	-2.308	1955.75	603	-4.275	-2.099
1962.86	505	-4.173	-2.291	1955.61	605	-4.373	-2.204
1962.75	507	-4.122	-2.794	1955.46	607	-4.565	-2.715

Year A.D.	depth (mm)	δ^{18}O (‰)	δ^{13}C (‰)	Year A.D.	depth (mm)	δ^{18}O (‰)	δ^{13}C (‰)
1955.32	609	-4.676	-2.601	1948.32	709	-4.329	-2.753
1955.17	611	-4.772	-2.381	1948.17	711	-4.478	-1.991
1955.09	613	-4.647	-1.930	1948.07	713	-4.401	-2.196
1955.00	615	-4.464	-2.075	1947.96	715	-4.274	-2.293
1954.92	617	-4.293	-2.168	1947.86	717	-4.140	-2.311
1954.83	619	-4.261	-2.421	1947.75	719	-4.103	-2.454
1954.75	621	-4.134	-2.506	1947.56	721	-4.335	-2.787
1954.46	623	-4.392	-2.433	1947.36	723	-4.428	-2.396
1954.17	625	-4.526	-2.171	1947.17	725	-4.594	-2.186
1954.07	627	-4.278	-2.009	1947.03	727	-4.570	-2.103
1953.96	629	-4.265	-2.167	1946.89	729	-4.291	-2.323
1953.86	631	-4.156	-2.521	1946.75	731	-4.146	-2.226
1953.75	633	-4.057	-2.564	1946.56	733	-4.075	-2.362
1953.61	635	-4.017	-2.847	1946.36	735	-4.312	-2.914
1953.46	637	-4.290	-2.825	1946.17	737	-4.599	-2.471
1953.32	639	-4.546	-2.662	1946.07	739	-4.473	-2.364
1953.17	641	-4.583	-2.066	1945.96	741	-4.296	-2.158
1953.07	643	-4.312	-1.945	1945.86	743	-4.141	-2.239
1952.96	645	-4.324	-1.853	1945.75	745	-4.113	-2.148
1952.86	647	-4.154	-2.479	1945.63	747	-4.199	-2.257
1952.75	649	-4.106	-2.469	1945.52	749	-4.273	-2.383
1952.56	651	-4.277	-2.873	1945.40	751	-4.316	-2.418
1952.36	653	-4.478	-2.712	1945.29	753	-4.494	-2.672
1952.17	655	-4.530	-2.471	1945.17	755	-4.548	-2.187
1952.03	657	-4.375	-2.209	1945.07	757	-4.338	-2.276
1951.89	659	-4.186	-2.184	1944.96	759	-4.225	-2.099
1951.75	661	-4.122	-2.426	1944.86	761	-4.007	-1.919
1951.61	663	-4.279	-2.495	1944.75	763	-3.857	-1.970
1951.46	665	-4.194	-2.613	1944.56	765	-4.100	-2.151
1951.32	667	-4.575	-2.669	1944.36	767	-4.355	-2.072
1951.17	669	-4.750	-2.405	1944.17	769	-4.410	-1.938
1951.07	671	-4.725	-2.285	1944.03	771	-4.268	-2.054
1950.96	673	-4.576	-2.363	1943.89	773	-4.177	-2.002
1950.86	675	-4.389	-2.026	1943.75	775	-4.040	-2.478
1950.75	677	-4.219	-2.339	1943.46	777	-4.140	-2.273
1950.61	679	-4.337	-2.433	1943.17	779	-4.449	-2.142
1950.46	681	-4.239	-2.810	1943.03	781	-4.372	-2.228
1950.32	683	-4.406	-2.696	1942.89	783	-4.180	-2.027
1950.17	685	-4.647	-2.209	1942.75	785	-3.961	-1.811
1950.07	687	-4.419	-2.123	1942.61	787	-4.010	-2.011
1949.96	689	-4.362	-2.052	1942.46	789	-4.113	-2.012
1949.86	691	-4.563	-2.531	1942.32	791	-4.398	-2.037
1949.75	693	-4.193	-2.556	1942.17	793	-4.518	-2.292
1949.46	695	-4.227	-2.669	1942.03	795	-4.212	-2.082
1949.17	697	-4.610	-2.075	1941.89	797	-3.989	-1.908
1949.03	699	-4.422	-2.398	1941.75	799	-3.684	-1.683
1948.89	701	-4.146	-1.987	1941.46	801	-3.728	-1.846
1948.75	703	-3.995	-2.585	1941.17	803	-4.004	-2.110
1948.61	705	-4.003	-2.322	1941.07	805	-3.993	-1.904
1948.46	707	-4.151	-2.646	1940.96	807	-3.983	-1.927

Year A.D.	depth (mm)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)	Year A.D.	depth (mm)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)
1940.86	809	-4.000	-2.159	1932.89	909	-4.206	-3.222
1940.75	811	-3.941	-2.120	1932.82	911	-4.319	-2.882
1940.56	813	-4.139	-2.300	1932.75	913	-4.170	-2.354
1940.36	815	-4.269	-2.096	1932.56	915	-4.184	-2.649
1940.17	817	-4.488	-1.715	1932.36	917	-4.221	-2.767
1940.07	819	-4.458	-1.716	1932.17	919	-4.447	-2.870
1939.96	821	-4.145	-1.927	1932.10	921	-4.365	-2.418
1939.86	823	-4.279	-1.952	1932.03	923	-4.261	-2.232
1939.75	825	-3.989	-1.860	1931.96	925	-4.198	-2.399
1939.56	827	-4.011	-1.547	1931.89	927	-3.927	-2.279
1939.36	829	-4.306	-2.118	1931.82	929	-3.787	-2.116
1939.17	831	-4.520	-2.029	1931.75	931	-3.711	-1.831
1939.07	833	-4.457	-1.986	1931.56	933	-3.839	-1.216
1938.96	835	-4.164	-2.063	1931.36	935	-4.042	-2.010
1938.86	837	-4.024	-1.771	1931.17	937	-4.072	-1.982
1938.75	839	-3.953	-1.685	1930.96	939	-3.891	-1.917
1938.56	841	-4.134	-1.895	1930.75	941	-3.567	-1.963
1938.36	843	-4.136	-2.219	1930.61	943	-3.781	-1.944
1938.17	845	-4.206	-1.813	1930.46	945	-4.194	-1.947
1938.03	847	-4.025	-1.612	1930.32	947	-4.136	-1.964
1937.89	849	-4.062	-1.504	1930.17	949	-4.140	-2.038
1937.75	851	-3.878	-1.840	1930.03	951	-4.087	-1.886
1937.56	853	-3.963	-2.155	1929.89	953	-3.888	-2.090
1937.36	855	-4.129	-1.944	1929.75	955	-3.787	-2.165
1937.17	857	-4.130	-1.880	1929.56	957	-4.111	-2.175
1936.96	859	-4.078	-1.828	1929.36	959	-4.299	-1.852
1936.75	861	-3.950	-1.770	1929.17	961	-4.396	-1.572
1936.46	863	-4.033	-2.043	1929.03	963	-4.095	-1.936
1936.17	865	-4.113	-1.645	1928.89	965	-4.171	-1.706
1935.96	867	-4.119	-1.571	1928.75	967	-3.880	-1.750
1935.75	869	-3.990	-1.598	1928.65	969	-3.924	-2.073
1935.56	871	-4.057	-1.693	1928.56	971	-4.079	-1.310
1935.36	873	-4.077	-1.436	1928.46	973	-4.124	-1.990
1935.17	875	-4.253	-2.295	1928.36	975	-3.997	-2.135
1935.03	877	-4.209	-2.331	1928.27	977	-4.302	-2.335
1934.89	879	-4.113	-2.110	1928.17	979	-4.489	-2.645
1934.75	881	-4.011	-2.149	1928.11	981	-4.453	-1.967
1934.56	883	-4.263	-2.562	1928.05	983	-4.386	-2.392
1934.36	885	-4.463	-2.240	1927.99	985	-4.184	-2.354
1934.17	887	-4.513	-1.944	1927.93	987	-3.990	-2.707
1934.07	889	-4.342	-2.167	1927.87	989	-4.219	-2.769
1933.96	891	-4.330	-1.755	1927.81	991	-3.967	-2.252
1933.86	893	-4.215	-1.786	1927.75	993	-3.868	-2.015
1933.75	895	-4.225	-2.084	1927.63	995	-3.858	-2.096
1933.56	897	-4.176	-2.493	1927.52	997	-3.884	-2.355
1933.36	899	-4.326	-2.667	1927.40	999	-4.014	-2.460
1933.17	901	-4.474	-2.570	1927.29	1001	-4.214	-2.162
1933.10	903	-4.464	-2.441	1927.17	1003	-4.296	-1.708
1933.03	905	-4.483	-2.741	1927.07	1005	-4.192	-1.327
1932.96	907	-4.373	-2.545	1926.96	1007	-4.312	-2.222

Year A.D.	depth (mm)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)
1926.86	1009	-4.133	-1.649
1926.75	1011	-3.886	-1.960
1926.65	1013	-3.974	-2.213
1926.54	1015	-4.283	-1.887
1926.44	1017	-4.098	-2.067
1926.33	1019	-4.008	-2.179
1926.23	1021	-3.952	-1.985
1926.12	1023	-3.970	-2.084
1926.02	1025	-4.103	-2.366