

# Radiocarbon variability in the western equatorial Pacific inferred from a high-resolution coral record from Nauru Island

Thomas P. Guilderson<sup>1</sup> and Daniel P. Schrag

Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts

Michaele Kashgarian and John Southon

Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, Livermore, California

**Abstract.** We have generated a high resolution coral  $\Delta^{14}\text{C}$  record spanning the last 50 years to document the seasonal and interannual redistribution of surface waters in the western tropical Pacific. Prebomb (1947-1956)  $\Delta^{14}\text{C}$  values average  $-63\text{‰}$  and have a total range of  $30\text{‰}$ . Values begin to increase in 1957, reaching a maximum of  $137\text{‰}$  in mid-1983. Large interannual variability of up to  $80\text{‰}$  closely follows the El Niño-Southern Oscillation (ENSO). During each ENSO warm phase,  $\Delta^{14}\text{C}$  values begin to increase, reflecting the reduction of low- $^{14}\text{C}$  water upwelling in the east and the invasion of subtropical water into the western equatorial tropical Pacific. Maximum  $\Delta^{14}\text{C}$  values are in phase or lag the corresponding sea surface temperature maxima in the eastern tropical Pacific, whereas the rapid return to more negative  $\Delta^{14}\text{C}$  is in phase with eastern Pacific ENSO indices. The highest-amplitude excursions occur during the 1965/1966 and 1972/1973 events, when the  $^{14}\text{C}$  contrast is highest between the eastern Pacific and subtropics. The 1982/1983 El Niño, although a larger ENSO event, has a lower  $\Delta^{14}\text{C}$  amplitude, reflecting the penetration of bomb radiocarbon into the equatorial undercurrent and the reduced contrast in  $\Delta^{14}\text{C}$  between thermocline and subtropical surface waters at that time. This coral record demonstrates the potential for using similar radiocarbon time series for documenting variability in Pacific shallow circulation over interannual and decadal timescales.

## 1. Introduction

The western tropical Pacific plays an important role in the localization of deep atmospheric convective activity and in the development of El Niño - Southern Oscillation (ENSO) events [e.g., *Philander*, 1990; *Peixoto and Oort*, 1992]. On interannual and longer time-scales, coupled air-sea interactions in the tropical Pacific surface waters have a large impact globally through atmospheric teleconnections. The mean southeasterly trade winds combined with surface heating results in a buildup of warm surface water in the western tropical Pacific, the Pacific "warm pool." In the east, the trade winds induce shoaling of the thermocline and outcropping of colder isotherms, primarily of the Equatorial Undercurrent (EUC). The water feeding this upwelling originates as subtropical surface water which, during winter months, becomes more dense and sinks to intermediate depths [*Bryden and Brady*, 1985; *Tsuchiya et al.*, 1989]. Potential temperature and salinity measurements indicate that the southern hemisphere contributes at least 50% of tropical thermocline water [*Knauss*, 1966; *Tsuchiya*, 1968; *Tsuchiya et al.*, 1989; *Wyrtki and Kilonsky*, 1984]. During its eastward

transit, the EUC entrains some amount of deeper thermocline water, although the exact amount has not been well constrained. Transient tracer data presented by *Quay et al.* [1983], *Toggweiler et al.* [1991], and, more recently, *Fine and Maillet* [1996], suggest that a significant amount of deeper thermocline water ( $26.5$  to  $27.3 \sigma_t$ ) is entrained through diapycnal processes. The deeper component, derived from middle latitudes, is less well ventilated than the water at shallower levels. Tracer data indicate that the tropical thermocline is ventilated on a 10-20 year timescale [*Fine et al.*, 1994 among others]. The bulk of the upwelled water is then advected westward at the surface within the South Equatorial Current.

On both the seasonal and interannual timescale, the redistribution of tropical Pacific surface waters has a large impact globally via atmospheric teleconnections initiated through the transfer of sensible and latent heat. These variations, both the depth of the thermocline and the redistribution of surface waters, are a response to the large scale wind field. Unfortunately, direct oceanographic observations of currents and properties (temperature, salinity, nutrients) are, in general, limited to the last 25 years and contain spatial and temporal biases [e.g., *Philander*, 1990].

Surface current studies have relied predominantly upon ship drift data [e.g., *Richardson and McKee*, 1989]. Increased interest in the genesis of El Niño - Southern Oscillation since the 1980s resulted in the deployment of the Tropical Ocean-Global Atmosphere (TOGA) network which has increased the number of direct observations of tropical Pacific ocean

<sup>1</sup>Also at Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, Livermore, California.

circulation [e.g., *Goriou and Toole*, 1993]. *Reverdin et al.* [1994] provided a synthesis of the seasonal variability in the surface currents of the equatorial Pacific between 1987 and 1992 using combined current meter and drifter data. In these and other studies, it is shown that there is a zonal and meridional redistribution of surface waters on a spectrum of timescales. Direct oceanographic observations provide discrete realizations of the circulation that can be combined to document the mean state and seasonal structure. However, without long-term observations, it is difficult to assess the true amount of interannual variability or even address decadal scale variability.

The analysis of transient anthropogenic tracers (chlorofluorocarbons,  $^{14}\text{C}$ , and tritium) has augmented direct current observations. CFC studies have provided important information on deep thermohaline circulation [e.g., *Rhein et al.* 1995] as well as ventilation of subthermocline waters [e.g., *Reverdin et al.*, 1993; *Fine et al.*, 1994; *Jenkins*, 1996]. Tracer studies such as these reflect the integration of seasonal and interannual variability, yielding information on the mean flow field.

Atmospheric nuclear testing in the 1950s and early 1960s resulted in an excess of  $^{14}\text{C}$  which has augmented the natural dissolved inorganic carbon (DIC)  $^{14}\text{C}$  gradient between surface and subsurface waters [e.g., *Broecker et al.*, 1985]. In the early 1970s, the Geochemical Ocean Sections Study (GEOSECS) provided a snapshot of the  $^{14}\text{C}/^{12}\text{C}$  distribution in the ocean [*Östlund and Suiver*, 1980]. The GEOSECS data identified an increase in radiocarbon content of the surface ocean from the equator toward the temperate latitudes, with a range of  $\Delta^{14}\text{C}$  values between 50 and 100 per mil (‰). *Broecker and Peng* [1982] interpreted this distribution as representing upwelling of low radiocarbon water from the lower thermocline in equatorial regions, with migration of the  $^{14}\text{C}$  rich surface water toward higher latitudes.

Radiocarbon measurements of coral skeletal material which accurately records  $\Delta^{14}\text{C}$  of  $\Sigma\text{CO}_2$  [e.g., *Druffel*, 1981; *Toggweiler et al.*, 1991] have added important information to water sampling programs like GEOSECS and the World Ocean Circulation Experiment (WOCE). Through the analysis of hermatypic corals, it has been possible to reconstruct the mean annual prebomb and preindustrial radiocarbon content of the surface waters [e.g., *Nozaki et al.*, 1978; *Druffel*, 1981; *Druffel and Suess*, 1983; *Konishi et al.*, 1982]. By measuring the radiocarbon content of massive corals at higher resolution, seasonal and interannual variability in surface ocean radiocarbon can be recovered. *Druffel* [1987] compared approximately seasonal radiocarbon records from Canton Island (3°S, 172°W) and Fanning Island (4°N, 159°W). These results were then used to study the exchange of surface waters across the equator. *Brown et al.* [1993] produced a 4 year record with 3 month resolution from a coral from the Galapagos Islands, observing 35 to 50‰ seasonal variability. More recently, *Moore et al.*, [1997] generated a 15 year long (1970-1985) bimonthly coral  $\Delta^{14}\text{C}$  record from the Makassar Straits (Lankai, 5°03'S, 119°07'E) in the Indonesian Seaway which exhibited 50‰ seasonal variability. They showed that this variability was derived from similar variability in the North Equatorial Current, as illustrated by a coral  $\Delta^{14}\text{C}$  record from Guam (13°21'N, 144°39'E).

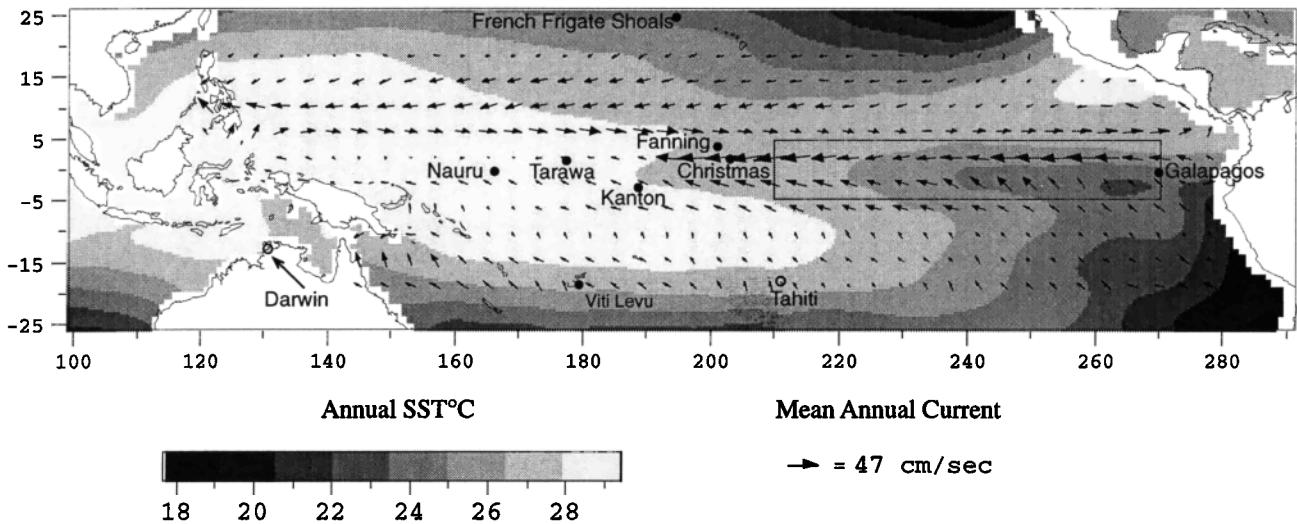
The objective of this study is to examine how  $\Delta^{14}\text{C}$

variability in Pacific surface waters responds to changes in the wind-driven surface currents. The largest interannual variability in surface winds occurs within the El Niño - Southern Oscillation cycle [e.g., *Philander*, 1990]. During "normal" years, radiocarbon-depleted water upwells in the east and is advected westward within the equatorial waveguide, primarily within the equatorward branch of the South Equatorial Current (SEC) mixing into the western Pacific warm pool. During warm ENSO events (El Niño), the equatorial trade winds relax and/or reverse. This results in a deepening of the thermocline in the eastern equatorial Pacific and oftentimes an eastward propagation of surface waters from the west [e.g., *Philander*, 1990; *Trenberth*, 1991]. Waters of direct subtropical origin, which have a higher concentration of radiocarbon, then infiltrate into the western Pacific warm pool. The rate of biological processes on  $\Delta^{14}\text{C}$  DIC are negligible relative to surface water dynamics and, as such,  $\Delta^{14}\text{C}$  in surface water is a quasi-conservative, passive advective tracer.

We have generated a high-resolution coral  $\Delta^{14}\text{C}$  record spanning the last 50 years to document the seasonal and interannual redistribution of surface waters in the western tropical Pacific. These new results exhibit a previously undocumented dynamic  $\Delta^{14}\text{C}$  range in the western tropical Pacific. Nauru Island (Figure 1) is in a position to monitor the seasonal and interannual redistribution of surface waters in the warm pool of the western tropical Pacific where the mixing of radiocarbon-depleted water advected in from the east with that of the subtropics occurs.

## 2. Methods

A large *Porites spp.* coral head at 14 m bottom depth located offshore of the north side of Nauru Island (166°30'S) was drilled in August 1995. The cores (7.6 cm diameter) were cut into ~1 cm slabs, cleaned in distilled water, and air dried. No regions were infiltrated with boring filamentous algae or other organisms. After identifying the major vertical growth axis, the coral was sequentially sampled at 2 mm increments with a low-speed drill. Splits (~1 mg) were reacted in vacuo in a modified autocarbonate device at 90°C and the purified  $\text{CO}_2$  analyzed on a gas source stable isotope ratio mass spectrometer. Stable isotope data are presented in standard per mil notation relative to Vienna Pee Dee Belemnite [Copen, 1993]. Analytical precision based on an in-house standard is better than  $\pm 0.05\%$  ( $1\sigma$ ) for both oxygen and carbon. The remaining sample splits (nominally 10 mg) were placed in individual reaction chambers, evacuated, heated, and then acidified with orthophosphoric acid at 90°C. The evolved  $\text{CO}_2$  was purified, trapped, and converted to graphite in the presence of cobalt catalyst in individual reactors [*Vogel et al.*, 1987]. Graphite targets were measured at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory [*Davis et al.*, 1990]. Radiocarbon results are reported as  $\Delta^{14}\text{C}$  (‰) as defined by *Suiver and Polach* [1977] and include the  $\delta^{13}\text{C}$  correction obtained from the stable isotope results. Analytical precision and accuracy of the radiocarbon measurements is  $\pm 4\%$  ( $1\sigma$ ). Data have not been corrected for the known age correction to afford direct comparison with previous and on going studies.



**Figure 1.** Tropical Pacific mean annual sea surface temperatures [Levitus and Boyer, 1994] and current vectors [Reverdin et al., 1994]. Locations discussed in the text are demarked in addition to Tahiti and Darwin, the locations which define the Southern Oscillation Index. The Niño 3 region is boxed.

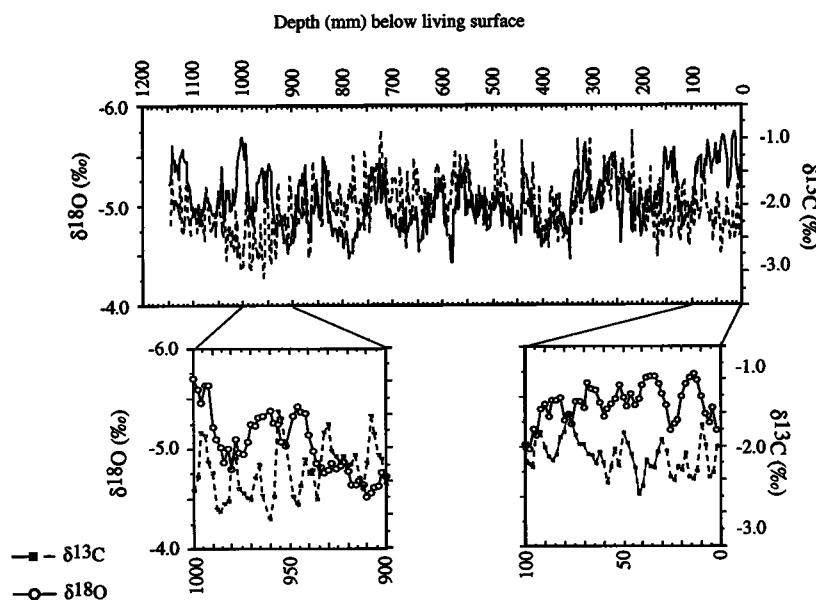
### 3. Results

#### 3.1 Nauru Coral Age Model

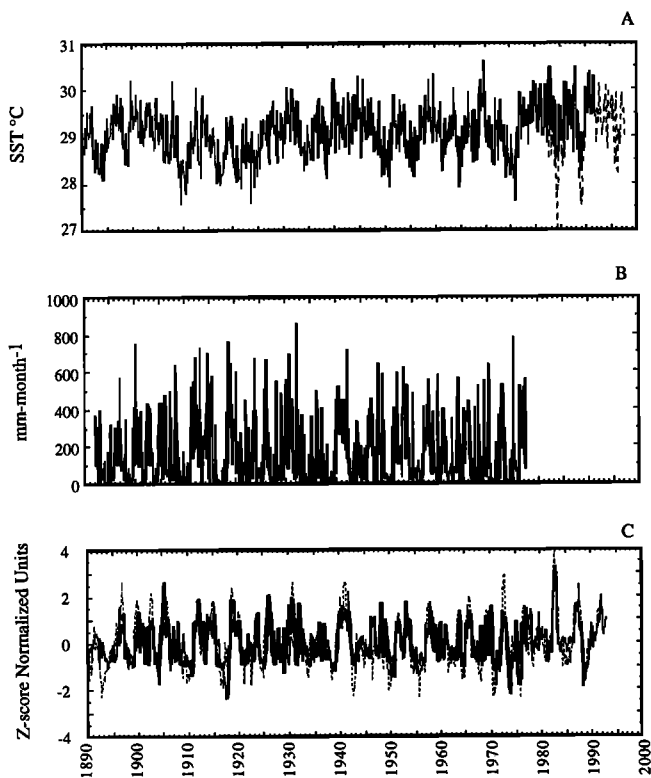
Coral chronology usually relies upon the presence of annual high- and low-density band couplets [e.g., Knutson et al., 1972; Buddemeier, 1974; Dodge and Vaisnys, 1980] or the seasonal variability in coral  $\delta^{13}\text{C}$  which reflects surface irradiance [e.g., Fairbanks and Dodge, 1979; Cole and Fairbanks, 1990; Shen et al., 1992]. Independent chronologies based on these two methods on the same coral specimen tend to agree within a few months [e.g., Shen et al., 1992]. Nauru, located within  $0.5^\circ$  of the equator, experiences a double maximum in surface radiation. We created a

preliminary age model based upon the seasonal structure within the  $\delta^{13}\text{C}$  record (Figure 2). In order to obtain the best timescale and because we are not interested in the coral  $\delta^{18}\text{O}$  as an independent measure of precipitation or temperature [e.g., Cole and Fairbanks, 1990], we have refined our age model by correcting the preliminary age model through coral  $\delta^{18}\text{O}$  comparisons with instrumental records.

Coral  $\delta^{18}\text{O}$  reflects the effects of temperature and the oxygen isotope composition of seawater  $\delta_w$  [e.g., Fairbanks and Dodge, 1979]. Nauru, located within the warm pool of the western tropical Pacific, experiences minimal fluctuations in sea surface temperature, seasonally and interannually (Figure 3a). It does, however, experience large changes in precipitation in concert with variations of the Indonesian Low



**Figure 2.** Stable isotope results from the Nauru coral as a function of depth below the living surface. Windowed sections are representative of the variability in both  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ .



**Figure 3.** (a) Sea surface temperature for the grid box containing Nauru for 1890-1992 (solid curve) from the reconstructed sea surface temperature records of *Kaplan et al.* [1998], and for 1982-1997; (dashed curve) from the Integrated Global Ocean Station System blended data set [*Reynolds and Smith*, 1994]. (b) Monthly mean precipitation at Nauru from the National Oceanic and Atmospheric Administration monthly station archive [*Baker et al.*, 1995]. (c) Comparison of the Niño 3 region SST anomaly derived from *Kaplan et al.*, [1996] (dashed curve), the Southern Oscillation Index (thin solid curve, Tahiti - Darwin sea level pressure anomaly, Climate Diagnostic Center digital database), and the Nauru precipitation anomaly (thick solid curve). Anomalies were calculated by subtracting the monthly climatological means from the records and then converted to Z score normalized units by dividing by their respective standard deviations. To facilitate comparison, the Southern Oscillation Index (SOI) was multiplied by -1 so that it is in the same sense as the Niño 3 (positive = warm), and Nauru (positive = wet) anomalies.

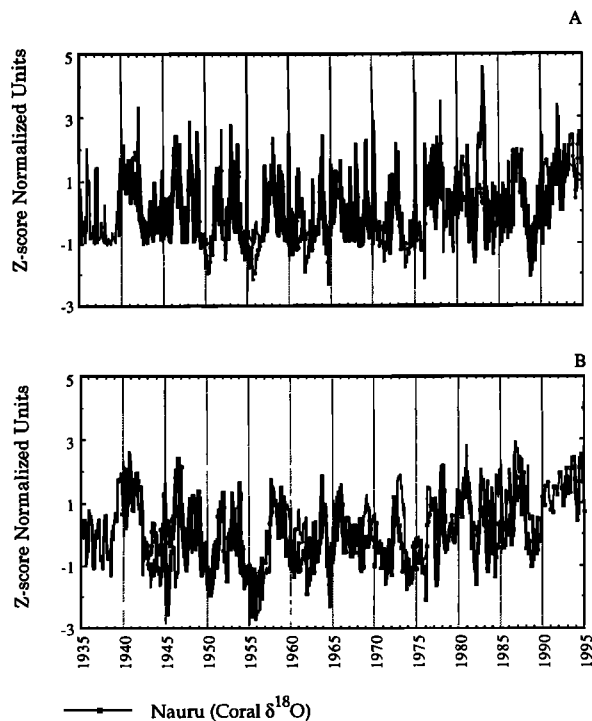
during ENSO events. The local Nauru monthly precipitation record is continuous from 1892 through 1977 (*Baker et al.*, 1995, Figure 3b), and it matches nearly peak to peak with the Southern Oscillation Index and the Niño 3 SST anomaly (Figure 3c). After splicing the SOI index onto the precipitation anomaly to extend the record through 1995, we linearly mapped the Z score normalized coral  $\delta^{18}\text{O}$  record to it [*Martinson*, 1982; *Paillard et al.*, 1996] achieving a correlation coefficient (R value) of 0.71 (Figure 4a).

The resulting chronology and coral  $\delta^{18}\text{O}$  matches quite well the coral  $\delta^{18}\text{O}$  record from nearby Tarawa (Figure 4b) [*Cole and Fairbanks*, 1990]. Like the Tarawa record [*Cole and Fairbanks*, 1990], the 1982-1983 El Niño event is noticeably absent whereas in the SOI record it is one of the largest documented (Figure 4a). During this El Niño event the precipitation anomaly was observed at the easternmost

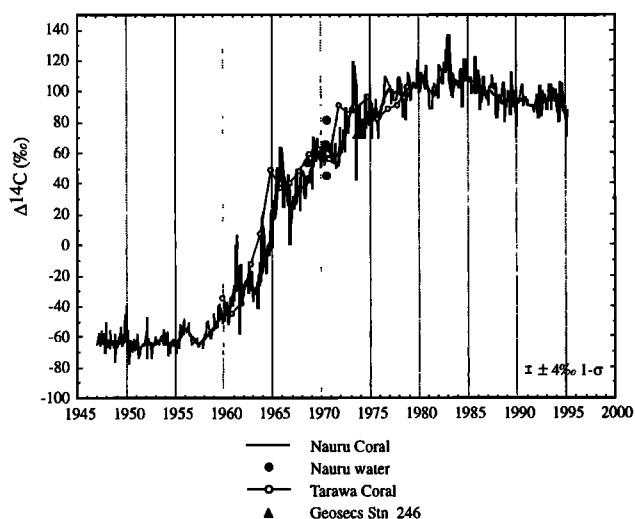
location of Kiritmati (157°W, 2°N (*M. N. Evans et al.*, manuscript in preparation, 1998), missing both Nauru and Tarawa. The final age model extends back through 1940 and indicates an average linear extension rate of 21 mm/yr. Our best estimate of the error associated with this age model is  $\pm 2$ -3 months. The corresponding  $\Delta^{14}\text{C}$  record begins in 1947 and is nearly continuous until July 1995, with an average resolution of 1.5 months.

### 3.2 Radiocarbon Time Series

Between 1947 and 1995,  $\Delta^{14}\text{C}$  at Nauru has a dynamic range of 215‰, from a low of -78‰ (1950.32) to a high of 137‰ (1983.13; see Figure 5). The prebomb interval analyzed in this study (1947-1956) averages -63‰ (-58‰ age corrected), consistent with previous annual mean prebomb measurements from the western Pacific [*Druffel*, 1987], but individual (approximately monthly) measurements have a total range of nearly 30‰. Beginning in 1957, annual  $\Delta^{14}\text{C}$  begins to rise with the increase in atmospheric nuclear weapons testing. Between 1957 and 1961, annual  $\Delta^{14}\text{C}$  increased  $\sim 10$ ‰ per year and then remained nearly constant through 1963. Increases of 20‰ and  $\sim 45$ ‰ occurred in 1964 and 1965 respectively. After a  $\sim 15$ ‰ reduction in 1966,  $\Delta^{14}\text{C}$  rose nearly continuously until it reached its peak annual values in 1982 (115‰) and 1983 (117‰). A general decrease in annual  $\Delta^{14}\text{C}$  occurred between 1983 (117‰) and 1988 (93‰). From



**Figure 4.** Coral  $\delta^{18}\text{O}$  reflects the effects of temperature and the oxygen isotope composition of seawater ( $\delta^{18}\text{O}_w$ ). Nauru, located in the warm pool of the western equatorial Pacific, has minimal SST fluctuations but large variations in precipitation that impact seawater  $\delta^{18}\text{O}_w$ . We refined our preliminary  $\delta^{13}\text{C}$  age model by linear mapping the coral  $\delta^{18}\text{O}$  to the Nauru precipitation / SOI anomalies. (a) Corresponding age model with a correlation coefficient of 0.71. (b) Comparison of coral  $\delta^{18}\text{O}$  from Nauru and nearby Tarawa [*Cole and Fairbanks*, 1990].



**Figure 5.** Nauru  $\Delta^{14}\text{C}$  (‰) as a function of time. Bold line is a 13-point smoothed record equivalent to annual averaging. For comparison, we have added the mean annual coral  $\Delta^{14}\text{C}$  from nearby Tarawa [Toggweiler *et al.*, 1991], and discrete water sample measurements: GEOSECS station 246 (179°E, 0°N [Östlund and Stuiver, 1980]) and assorted La Jolla stations [Linick, 1978].

1988 to 1995, annual mean  $\Delta^{14}\text{C}$  remained within 5‰ of 93‰.

Superimposed over the long-term increase in  $\Delta^{14}\text{C}$ , which reflects oceanic uptake and subsequent dilution of bomb-derived radiocarbon, are higher amplitude variations. In particular, there are large positive excursions (>20‰) in 1949/1950, 1951/1952, 1955/1956, 1961/1962, 1963/1964, 1965/1966, 1972/1973, 1976 and 1982/1983. In general, these positive  $\Delta^{14}\text{C}$  excursions have a characteristic termination with a rapid return to more negative  $\Delta^{14}\text{C}$  values and they correspond with El Niño events. The largest of these excursions occurs in 1972/1973, with a total amplitude of 80‰. The 1961/1962 and 1965/1966 events are both 60‰ but because of its broad interval, the 1965/1966 event is more striking. The 1982/1983 excursion has a total amplitude of 40‰. The brief prebomb interval that our sampling has spanned exhibits 30‰ variability in 1949/1950 and 1951/1952 and 25‰ variability in 1955/1956.

## 4. Discussion

### 4.1 Comparison with Western Pacific Radiocarbon Data

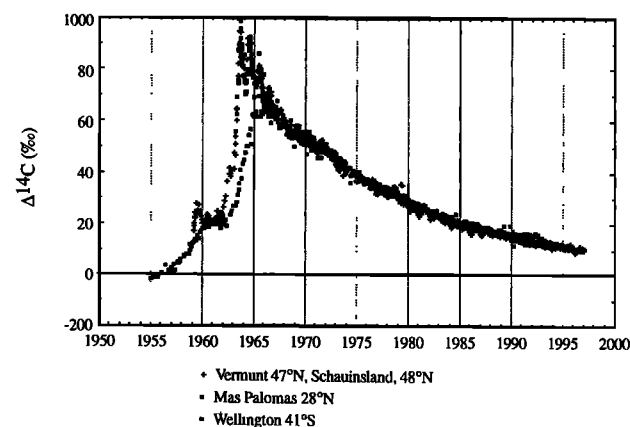
Previously published  $\Delta^{14}\text{C}$  from other nearby sites in the western tropical Pacific such as Tarawa (1°N, 172°E) [Toggweiler *et al.*, 1991] and Kanton, more towards the central tropical Pacific (2.8°S, 171.72°W) [Druffel, 1987], agree with annual mean values of the Nauru record (Figure 5). It is difficult to directly compare with ocean water measurements from GEOSECS taken during 1973 and 1974 [Östlund and Stuiver, 1980] because this is the time when the Nauru coral has a large amount of interannual variability. The intrinsic temporal biasing in discrete water samples is illustrated in attempting to compare the GEOSECS results and the Nauru coral record, illuminating the problems associated with taking

snapshots of a dynamic system. This is especially true because the interval of Pacific GEOSECS sampling occurred during the conclusion of an El Niño event when the longitudinal  $\Delta^{14}\text{C}$  gradient was minimized.

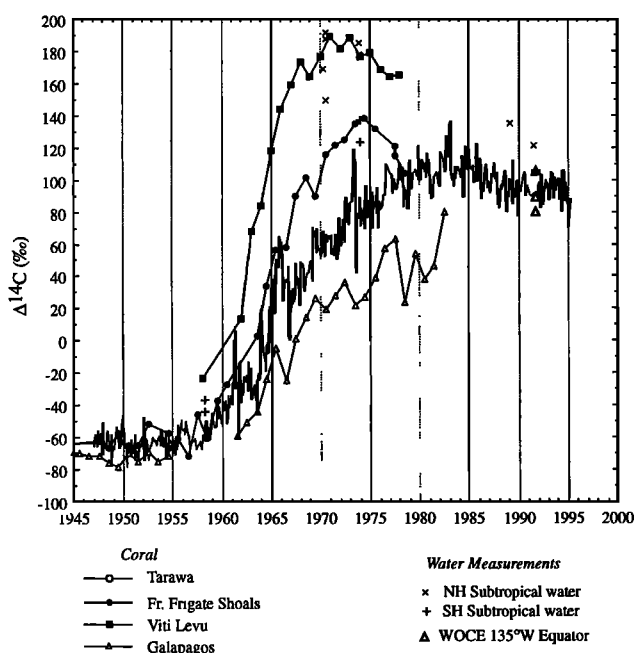
Detailed comparisons between the coral records are complicated by uncertainties in their respective age models, particularly for those sampled at annual resolution. In addition, sampling the coral at an annual interval can bias the  $^{14}\text{C}$  values if the extension rate is not constant over the seasonal cycle. This is of particular importance with regard to the record from Tarawa [Toggweiler *et al.*, 1991] which shows an apparent lead of nearly a year compared with that of Nauru during the early 1960s, although it is less than 800 km away. The apparent offset is most likely due to a combination of sampling bias (loss of sample where it was cut with a saw) and age model deviations.

### 4.2 Uptake of Bomb-Derived Radiocarbon

The long-term Nauru  $\Delta^{14}\text{C}$  record reflects the uptake of bomb-derived radiocarbon and subsequent dilution as surface waters mix into and with the deeper ocean reservoirs. Atmospheric testing (1944 until the moratorium in 1964, with higher yield tests starting in the mid-1950s) raised tropospheric  $\Delta^{14}\text{C}$  values in the northern hemisphere to 900–1000‰ in 1964–1965 (Figure 6) [Nydal, 1983, 1996; Levin *et al.*, 1985, 1994; Levin and Kromer, 1997] and to ~700‰ in the southern hemisphere in 1965–1966 [Manning and Melhuish, 1994]. Tropospheric values have subsequently been decreasing in an exponential fashion (~100‰ in 1996 [Levin and Kromer, 1997]) as bomb-derived radiocarbon is mixed into the various reservoirs, primarily oceanic dissolved inorganic carbon [e.g., Broecker and Peng, 1982; Sundquist, 1985]. The initial rise in  $\Delta^{14}\text{C}$  in 1957–1958 in the Nauru record is consistent with previous studies documenting the influx of bomb radiocarbon into the tropical Pacific (Fanning Island [Druffel, 1987]), and subtropical South Pacific (Fiji; [Toggweiler *et al.*, 1991]). The 2 years of largest  $\Delta^{14}\text{C}$  increase in the Nauru record (1964, 1965) correspond to the years when the ocean-atmosphere gradient was ~900‰ [Nydal,



**Figure 6.** Atmospheric  $\Delta^{14}\text{C}$  variations measured at 47–48°N (Vermunt and Schauenisland [Levin *et al.*, 1985, 1994; Levin and Kromer, 1997]), 28°N (Mas Palomas [Nydal and Loveseth, 1996]); and at 41°S (Wellington [Manning and Melhuish, 1994]).



**Figure 7.** Pacific coral based  $\Delta^{14}\text{C}$  time series from Nauru (this study), Tarawa [Toggweiler *et al.*, 1991], French Frigate Shoals [Druffel, 1987], Viti Levu [Toggweiler *et al.*, 1991], and the Galapagos Archipelago [Druffel, 1981, 1987; Brown *et al.*, 1993]. Discrete water samples from respective locations [Burling and Garner, 1959; Rafter, 1968; Linick, 1978; Östlund *et al.*, 1987; Takahashi *et al.*, 1991] and the World Ocean Circulation Experiment (WOCE) stations straddling the equator at 135°W [Key *et al.*, 1996]. The  $\Delta^{14}\text{C}$  variability at Nauru reflects mixing varying proportions of subtropical water (French Frigate Shoals, Viti Levu) with that derived from upwelling in the eastern equatorial Pacific (Galapagos).

1983, 1996; Levin *et al.*, 1985, 1994]. However, this increase is not simply due to the invasion of atmospheric  $^{14}\text{C}$  into the tropical ocean but also reflects the changes in oceanic circulation during the El Niño of 1965 discussed herein.

The  $\Delta^{14}\text{C}$  maximum in surface waters in general is delayed relative to the maximum of the troposphere because of the time required for isotopic equilibration and complicated by ocean mixing [e.g., Druffel and Suess, 1983; Druffel, 1987]. In the stable waters of the subtropical gyres this delay is shortest. The  $\Delta^{14}\text{C}$  coral record from French Frigate Shoals [Druffel, 1987] (Figure 7) shows a postbomb maximum of 189‰ in 1971 and a similar value in 1973 (188‰) relative to the northern hemisphere (NH) troposphere maximum in 1964–1965. The southern hemisphere subtropical  $\Delta^{14}\text{C}$  record from Viti Levu shows similar behavior, reaching peak values in 1973–1974 (134–138‰). The postbomb mean annual maximum at Nauru does not occur until 1982–1983 (115‰, 117‰). Thus the occurrence of the post-bomb  $\Delta^{14}\text{C}$  maximum is time transgressive, and a single location is not representative of the ocean as a whole in modeling the uptake and distribution of bomb radiocarbon.

Atmospheric  $\Delta^{14}\text{C}$  between 1971 and 1974 ranged from 500‰ to 400‰ and was  $\sim$ 250‰ during 1982/1983. Hence the atmosphere to surface ocean gradient was at least 300‰ during the subtropical  $\Delta^{14}\text{C}$  maximum (1971–1974) and  $\sim$ 130‰ in the early 1980s. That  $\Delta^{14}\text{C}$  at both French Frigate Shoals and

Viti Levu decreased until the end of the respective records (1978) in the presence of a positive air-sea gradient indicates a source of low  $^{14}\text{C}$  water competing with air-sea equilibration. Exchange of surface waters between the tropics and subtropical gyre is a plausible source of the low  $^{14}\text{C}$  necessary to decrease subtropical  $\Delta^{14}\text{C}$  values [Quay *et al.*, 1983]. Along the equator, the invasion of bomb  $^{14}\text{C}$  competes with low  $^{14}\text{C}$  undercurrent water upwelled in the eastern Pacific. At Nauru it is the westward advection of this newly upwelled water that dampens the rate of  $\Delta^{14}\text{C}$  increase and causes the delay of the post-bomb maximum.

The eastern Pacific records [Druffel, 1981, 1987; Brown *et al.*, 1993] give some indication of the eastern contribution of low  $^{14}\text{C}$  water versus invasion of atmospheric or bomb-derived  $^{14}\text{C}$ . These records range until early 1983 and do not appear to reach a postbomb maximum. The temporal variation in the  $\Delta^{14}\text{C}$  content of upwelled surface waters in the eastern equatorial Pacific and its subsequent westward transport determines not only the delay in the postbomb  $\Delta^{14}\text{C}$  maximum at Nauru but also the seasonal and interannual variability.

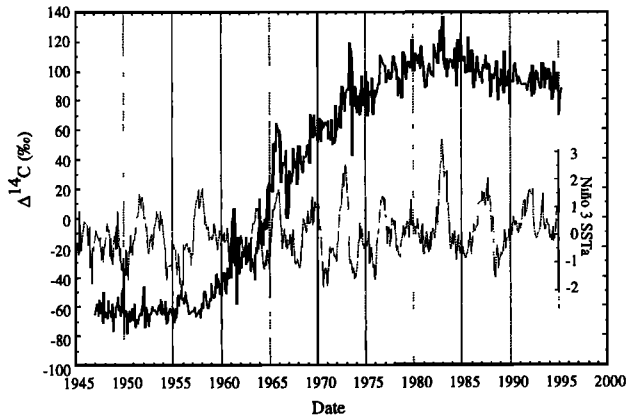
### 4.3 Seasonality

The Nauru  $\Delta^{14}\text{C}$  record does not exhibit a consistent seasonal cycle. In only 10 of the postbomb years (1961, 1967, 1968, 1969, 1971, 1981, 1987, 1988, 1990, 1994) is there a cleanly defined  $\Delta^{14}\text{C}$  seasonal cycle (20‰). This agrees with nearby current meter data that document variable zonal currents which only when averaged over several years, present a consistent seasonal cycle [cf. Reverdin *et al.*, 1994]. The explanation for this low seasonality is that interseasonal variability dominates the surface currents in this area. This is consistent with the model calculations of Rodgers *et al.* [1997] who showed low  $^{14}\text{C}$  seasonality in an ocean circulation model when forced with climatological winds.

### 4.4 Interannual Variability

The interannual redistribution of Pacific surface waters is reflected in the Nauru  $\Delta^{14}\text{C}$  record because of the large gradient in  $\Delta^{14}\text{C}$  between subtropical surface waters and the waters upwelling in the eastern Pacific. A conceptual model of this process can be described in terms of ENSO variability. The physical manifestations of the warm ENSO phase (El Niño) are decreased upwelling (less low  $^{14}\text{C}$  water) and weaker easterly trade winds (longer transport time and more air-sea equilibration), which are combined and reinforce a positive  $\Delta^{14}\text{C}$  anomaly. The cold ENSO phase (La Niña) is the antithesis of El Niño; stronger than average trade winds cause increased upwelling from perhaps a deeper source and a rapid transequatorial transport (east to west transport within the equatorial waveguide and primarily within the SEC [cf. Druffel, 1987, and references therein]), minimizing the influence of air-sea equilibration. These effects reinforce a negative  $\Delta^{14}\text{C}$  excursion.

The  $\Delta^{14}\text{C}$  interannual variability at Nauru, in general, occurs in concert with the warm and cold phases of the ENSO cycle as depicted in the Niño 3 SST index in the eastern Pacific (Figure 8a; 90°W–150°W,  $\pm$ 5° latitude) and concomitant changes in the intensity of the trade winds. During 1961–1962,  $\Delta^{14}\text{C}$  rises rapidly from  $-52$ ‰ to a maximum of 6‰ (1961.37) and then returns to a low of  $-58$ ‰ by 1961.61



**Figure 8a.** Nauru  $\Delta^{14}\text{C}$  (solid curve) and the Niño 3 SST anomaly (stippled curve) (degrees Celsius) derived from data in Kaplan *et al.*, [1998].

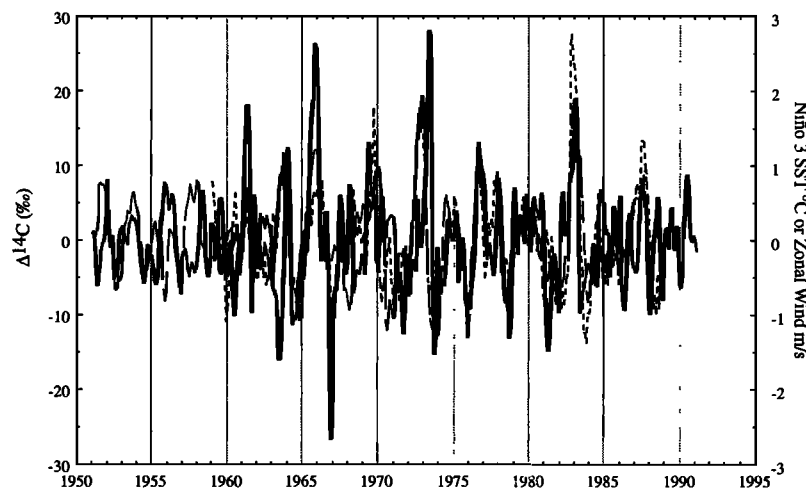
before plateauing near  $-25\text{‰}$  for the remainder of 1961 and through 1962. Although atmospheric testing was occurring during this time (Figure 6), the rapid rise in  $\Delta^{14}\text{C}$  followed by an overshoot toward more negative values seems to indicate that this was an oceanic manifestation of an El Niño event or, at the very least an increase in the upwelling intensity in the eastern equatorial Pacific during the latter half of 1961 and into 1962.

During the 1963/1964 El Niño the Nauru record experiences a  $45\text{‰}$  oscillation. Rising atmospheric  $\Delta^{14}\text{C}$  concentrations as a consequence of the increased atmospheric testing just prior to the moratorium reinforced the oceanic circulation component of the Nauru  $\Delta^{14}\text{C}$  record. The large ( $>900\text{‰}$ ) air-sea  $\Delta^{14}\text{C}$  gradient masks the ocean circulation driven  $\Delta^{14}\text{C}$  changes in the following years. In 1964 there was a strong and pronounced cold phase or La Niña. During a La Niña the trade winds tend to be more intense than normal, resulting in increased upwelling in the eastern tropical Pacific and stronger

than average equatorial currents [e.g., Philander, 1990; Wyrtki, 1974]. Thus, in the absence of air-sea transfer of bomb-derived radiocarbon, the Nauru  $\Delta^{14}\text{C}$  record should have decreased relative to the preceding year, not increased by  $20\text{‰}$ .

The 1965/1966 El Niño in the Nauru  $\Delta^{14}\text{C}$  record is particularly striking because of the length of this event. As discussed previously, part of the  $\Delta^{14}\text{C}$  character during this interval is due to air-sea exchange of  $^{14}\text{C}$  creating the rise in  $\Delta^{14}\text{C}$  in 1964 which continues through the 1965/1966 El Niño. The total amplitude of this event is nearly  $65\text{‰}$ , reflecting the influx of subtropical waters with high radiocarbon content and air-sea exchange. That the Nauru  $\Delta^{14}\text{C}$  record decreases during the La Niña of 1966 is remarkable, given that the air-sea gradient was near  $900\text{‰}$ . The decrease in  $\Delta^{14}\text{C}$  at Nauru during this La Niña is a reflection of the rapid transport of recently upwelled water from the eastern Pacific.

The manifestation of the 1972/1973 El Niño in the Nauru  $\Delta^{14}\text{C}$  record is nearly  $80\text{‰}$  from  $60\text{‰}$  (1972.10), reaching a maximum of  $119\text{‰}$  (1973.33) and returning to  $42\text{‰}$  (1973.64) during the cold event in the latter half of 1973. In the Nauru coral the  $80\text{‰}$  swing occurs in 8 mm or less than 4 months. The 1982/1983 El Niño was the largest documented this century, but in terms of  $\Delta^{14}\text{C}$  at Nauru its amplitude was only half that of the 1972/1973 event. The  $\Delta^{14}\text{C}$  values at the beginning of 1982 were  $95\text{‰}$ , peaked at  $137\text{‰}$  (1983.13) and by the middle of 1983, reached a minimum of  $96\text{‰}$  (1983.48). During the evolution of the 1982/1983 ENSO event the rise is more of a stepfunction ( $20\text{‰}$  in less than 1 month) which leads the SST expression in the east. This is consistent with the genesis of the 1982/1983 El Niño being "abnormal" with respect to a canonical (composite) El Niño. The 1982/1983 anomaly began in the western Pacific as a relaxation of the trade winds which then penetrated eastward [e.g., Philander, 1990] whereas the canonical ENSO begins as an amplification of the seasonal cycle in the east where warm SSTs persist



**Figure 8b.** Interannual variability in the Nauru  $\Delta^{14}\text{C}$  coral record (solid curve), COADS monthly zonal wind (dotted curve) for the region  $140^{\circ}\text{-}180^{\circ}\text{W } \pm 3^{\circ}$  latitude [Slutz *et al.*, 1985], and the Niño 3 SST anomaly (dashed curve). After linearly interpolating to monthly resolution, the Nauru record was passed through a 50 weight cosine taper filter with a half-amplitude period of 4 years. Similar filtering was performed on the instrumental data sets. The filter minimizes amplitude attenuation relative to the unfiltered SST and zonal wind anomalies and captures the interannual variability of the western Pacific  $\Delta^{14}\text{C}$  record.

longer than usual. This is in contrast to the slow increase in  $\Delta^{14}\text{C}$  during 1972, culminating in 1973, which is more similar to a composite El Niño.

To more clearly define the interannual nature of the Nauru  $\Delta^{14}\text{C}$  record, we have high-pass filtered the record (Figure 8b). Prior to filtering, the record was linearly interpolated to monthly resolution. The interpolated record was then passed through a cosine (Tukey) 50-weight taper filter with a half-amplitude frequency of  $0.25 \text{ year}^{-1}$ . The tails of the record have been clipped (at half bandwidth) after filtering to alleviate aliasing. A similar procedure was applied to the Niño 3 SST and zonal wind anomalies, with minimal amplitude attenuation relative to the unfiltered records (not shown). Pertinent to this discussion is the postbomb interval when the  $\Delta^{14}\text{C}$  gradient between the subtropics and outcropped undercurrent water is analytically resolvable (see Figure 7). Maximum  $\Delta^{14}\text{C}$  lags the corresponding eastern Pacific SST maxima during the 1963/1964 and 1972/1973 events by 3-4 months but is nearly in phase during the 1965/1966, 1976/1977 and 1982/1983 El Niños. The return to more negative  $\Delta^{14}\text{C}$  is in phase and reflects the rapid transport of  $^{14}\text{C}$  depleted water across the expanses of the tropical Pacific, with minimal air-sea exchange. The rapid return to more negative  $\Delta^{14}\text{C}$  indicates a relative transequatorial transit time of as little as 2-3 months (as few as two samples). Refinement of the age model through the measurement of additional environmental proxies (e.g., [Sr/Ca], a temperature proxy) may solidify the age model so that finer scale features can be directly compared.

The interannual  $\Delta^{14}\text{C}$  variability at Nauru does match our conceptual model of a "canonical" or composite  $\Delta^{14}\text{C}$  El Niño in a general "sawtooth" pattern, namely, slow rises and sharp terminations. Rising  $\Delta^{14}\text{C}$  values occur in concert with the relaxation of the trade winds allowing more water of subtropical origin to infiltrate the western Pacific warm pool [cf. Moore *et al.*, 1997]. The  $\Delta^{14}\text{C}$  values continue to rise and may peak just after the SST maximum in the east. The  $\Delta^{14}\text{C}$  expression is rapidly terminated by a large negative excursion which indicates rapid and relatively undiluted transport of radiocarbon-depleted waters from the east.

The  $\Delta^{14}\text{C}$  amplitude of these events is not strictly a function of the amplitude of the ENSO anomaly. As discussed earlier, the 1972/1973  $\Delta^{14}\text{C}$  amplitude was twice that of the 1982/1983 event whereas the El Niño of 1982/1983 was the largest documented in this century prior to the more recent 1997/1998 event. Modulation of the  $\Delta^{14}\text{C}$  expression of these events is determined by the evolution of the  $\Delta^{14}\text{C}$  content of the undercurrent water feeding eastern equatorial Pacific upwelling, coupled with the  $\Delta^{14}\text{C}$  history of the subtropical waters. The 1972/1973  $\Delta^{14}\text{C}$  event at Nauru was so large because of the  $\sim 160\%$  spatial gradient in  $\Delta^{14}\text{C}$  between the upwelled water in the eastern equatorial Pacific ( $\sim 20\%$ ) and the subtropics ( $\sim 180\%$ ). The currently available coral records do not document the continued evolution of these two end-member water masses, but the trends suggested by the coral-based data and the more recent WOCE water-sampling program [Key *et al.*, 1996] imply that the gradient has continued to decrease.

Additional radiocarbon records from within the equatorial waveguide will allow us to better constrain the time dependent history of the bomb transient as it penetrates into the surface waters and the undercurrent. Furthermore, additional records

will allow us to document the decadal  $\Delta^{14}\text{C}$  variability, of which we now only have a hint. The large dynamic range in  $\Delta^{14}\text{C}$  between subtropical and equatorial surface waters in concert with high resolution ocean modeling [e.g., Rodgers *et al.*, 1997] will afford us the opportunity to test directly the current hypotheses regarding the source of decadal climate variability [e.g., Latif and Barnett, 1996; Gu and Philander, 1997].

#### 4.5 Comparison With Ocean Modeling

Radiocarbon has been used as a tracer in ocean circulation models to study thermocline ventilation [e.g., Toggweiler *et al.*, 1991] and the decadal variability associated with ocean uptake of the bomb transient [e.g., Duffy and Caldeira, 1995; Jain *et al.*, 1995]. However, the resolution of these models has not been adequate enough to accurately reflect the currents responsible for ventilating the thermocline. Using a model with much higher vertical and meridional resolution ( $1/3^\circ$  near the equator), and in a sensitivity test with idealized boundary conditions, Rodgers *et al.* [1997] found that the western equatorial Pacific showed large variability in  $\Delta^{14}\text{C}$  when forced with observed winds during the 1982/1983 event. This same study, when the model was forced with climatological winds, produced approximately 30% seasonal extremes in prebomb  $\Delta^{14}\text{C}$ , an amplitude similar to the variability we observe in the prebomb section of our coral record. These results demonstrate that ocean models can simulate the dynamic behavior of radiocarbon in surface waters of the tropical Pacific. With future efforts, more detailed comparisons of model simulations with coral radiocarbon time series may improve the skill of the models, enabling a more detailed description of interannual and decadal variability in the shallow tropical Pacific circulation.

## 5. Conclusions

We have generated the first of a series of high-resolution  $\Delta^{14}\text{C}$  coral-based records spanning the postbomb era to study how the shallow circulation of the tropical Pacific varies over seasonal and interannual timescales. The results presented here, a 50 year  $\Delta^{14}\text{C}$  time series from Nauru Island in the western equatorial Pacific, document previously unrecognized high-amplitude (up to 80%)  $\Delta^{14}\text{C}$  variability in the western Pacific. This variability is the result of mixing between waters of subtropical origin (higher  $\Delta^{14}\text{C}$ ) and water upwelled in the eastern equatorial Pacific (lower  $\Delta^{14}\text{C}$ ). Prebomb (1947-1952) values average  $-63\%$  ( $\pm 6\%$  population; number of samples  $N=60$ ), similar to previously published mean annual  $\Delta^{14}\text{C}$  coral measurements from the western tropical Pacific [Toggweiler, *et al.*, 1991] but have a total range of seasonal extremes of nearly 30%, well in excess of the  $\pm 4\%$  measurement error. The postbomb maximum occurred in mid-1983, approximately 10 years after the maximum is reached in the subtropics [Druffel and Suess, 1983; Druffel, 1987; Toggweiler *et al.*, 1991] and 20 years after the atmosphere maximum. The delay is a consequence of low- $^{14}\text{C}$  water in the eastern equatorial Pacific advected zonally by equatorial currents. The low- $^{14}\text{C}$  water in the east is in itself a consequence of outcropping of the EUC which has entrained deeper thermocline water in conjunction with a subsurface ventilation pathway.



The  $\Delta^{14}\text{C}$  time series is dominated by interannual variability in concert with the oceanic manifestation of ENSO. During the warm phase of ENSO (El Niño), the western equatorial Pacific has higher  $\Delta^{14}\text{C}$ , indicative of a larger component of subtropical origin water. During the cold phase of ENSO (La Niña), stronger than average trade winds increase the upwelling in the eastern equatorial Pacific and decrease the time that it takes to advect the newly upwelled water across the Pacific, resulting in low  $\Delta^{14}\text{C}$  in the western equatorial Pacific. Maximum  $\Delta^{14}\text{C}$  during El Niño events tends to lag the corresponding SST anomaly in the eastern equatorial Pacific by 3-4 months, whereas the return to more negative  $\Delta^{14}\text{C}$  is in phase. This implies that during the termination of El Niño events there is rapid transport of water across the equatorial Pacific in as little as 2 months.

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T. P. Guilderson and D. P. Schrag, Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138 (e-mail: guilderson@eps.harvard.edu)

M. Kashgarian, and J. Southon, Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, L-397, 7000 East Avenue, Livermore, CA 94551.

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