REGIONAL VARIABILITY OF SURFACE OCEAN RADIOCARBON FROM SOUTHERN GREAT BARRIER REEF CORALS

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ABSTRACT. High-precision $\Delta^{14}C$ and stable isotope ($\delta^{18}O$ and $\delta^{13}C$) records are reported for post-bomb corals from three sites off the eastern Australian coast. We observe that $\Delta^{14}C$ values increased from *ca.* –50‰ in the early 1950s to +130‰ by 1974, then decreased to 110‰ by 1991. There is general agreement between the coral results and $\Delta^{14}C$ of dissolved inorganic carbon (DIC) in seawater measured previously for locations in the South Pacific. $\Delta^{14}C$ values at our southern hemisphere sites increased at a slower rate than those observed previously in the northern hemisphere. Small variations in the $\Delta^{14}C$ records among our three sites are likely due to differences in circulation between the shallow coastal waters and the open ocean influenced by seasonal upwelling. Low $\Delta^{14}C$ is associated with most El Niño/Southern Oscillation (ENSO) events after 1970, indicating input of low ^{14}C waters from the southern-shifted South Equatorial Current. The exception is the severe ENSO event of 1982–1983 when upwelling in the South Equatorial Current could have ceased, causing normal $\Delta^{14}C$ values in the corals during this time.

INTRODUCTION

Corals offer windows into the past, allowing us to study chemical and physical properties of seawater, habitat and climate. Corals accrete an aragonitic skeleton at a rate of 3–25 mm yr^{-1}; this facilitates seasonal sampling in most specimens. The coral's mineral structure is rigid, and not influenced by such processes as bioturbation. It is possible that some coral colonies live for thousands of years. The introduction of uranium-thorium (U-Th) dating by thermal ionization mass spectrometry has enabled corals to be dated with very high accuracy (Edwards, Chen and Wasserburg 1987) back through the last interglacial period and beyond.

Radiocarbon measurement of a banded coral reveals the $^{14}C/^{12}C$ ratio of the dissolved inorganic carbon (DIC) in the seawater that surrounded the coral at the time of accretion. Coral ^{14}C records for the surface Atlantic and Pacific Oceans during the past several hundred years have been reported previously (Druffel and Linick 1978; Druffel 1987; Nozaki *et al.* 1978; Toggweiler, Dixon and Broecker 1991). Alternatively, oxygen isotope records in banded corals ($\delta^{18}O$) are controlled by two factors, water composition (*i.e.*, seawater salinity) and seawater temperature at the time of accretion. Stable carbon isotope ratios ($\delta^{13}C$) are influenced by several factors, including water mass ($\delta^{13}C$ of DIC), reproductive status and metabolic effects.

^{14}C levels in surface seawater vary as a function of two major processes. First, mixing with surrounding surface waters or subsurface waters that contain lower $\Delta^{14}C$ signatures acts to change the surface $\Delta^{14}C$ levels. Second, gas exchange of CO_2 at the air-sea interface allows higher $\Delta^{14}C$ CO_2 from the atmosphere to enter the DIC pool in surface seawater. Hence, if the amount of lateral and vertical mixing and the gas exchange rate between the atmosphere and ocean have remained the same, ^{14}C levels in a given water mass should remain constant over time. This is not the case for the Southwest Pacific over the last 350 yr (Druffel and Griffin 1993).

METHODS

All coral samples used for this project were *Porites australiensis,* an abundant species that grows in the Great Barrier Reef. Corals were collected from a depth of 10–12 m in Abraham Reef (in the Swains Reef complex, 22°S, 153°E), Heron Island (23°S, 152°E) and Lady Musgrave Island (24°S, 153°E). At Abraham Reef, two cores, 10 cm in diameter, were taken from the top of an 8-m-high colony at 10 m water depth; the first core (Abraham-1) was drilled in December 1985, and the sec-

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ond (Abraham-2) in May 1991. At Heron Island, cores were taken in November 1983 from small colonies (1–2 m in diameter) in the region outside the lagoon. At Lady Musgrave Island, a single colony that grew outside of the lagoon was cored in November 1983. Methods used to clean, X-ray and section the corals were reported previously (Griffin and Druffel 1985).

Annual coral bands were taken from all specimens and subjected to ^{14}C analysis. In these corals, high-density bands accrete from October to December of each year. The bands were cut on the leading edge of the high-density bands; hence, the midpoint of each band was approximately March of the year reported (*i.e.*, 19XX.3). There are several samples from the Abraham-1 core that contained 70% of one year and 30% of the band one year younger; thus, the mid-points were 19XX.6 for the years 1961–1970.

We acidified *ca.* 25 g of coral (aragonite) to produce 5 liters of CO_2 gas. The gas samples were converted to acetylene gas *via* a lithium carbide intermediate and purified through charcoal at 0°C. Each sample was counted for 6–7 two-day periods in 1.5-liter quartz, gas proportional β counters according to standard procedures (Druffel and Griffin 1993; Griffin and Druffel 1985).

^{14}C results for the annual coral samples are reported as $\Delta^{14}C$ in Table 1. Uncertainties reported for the $\Delta^{14}C$ measurements include both counting statistics and laboratory reproducibility uncertainties. The average statistical counting uncertainty of each analysis is ± 2.1‰, and includes background and standard (HOxI) measurement uncertainties and the $\delta^{13}C$ correction. The laboratory reproducibility uncertainty was determined from multiple, high-precision analyses of a modern coral standard. The standard deviation of 10 results, each with a statistical uncertainty of 2.1‰ was 3.0‰. Thus, at this precision level, the laboratory uncertainty constitutes *ca.* 40% additional uncertainty. Therefore, to obtain our total uncertainty, we multiply the statistical uncertainty by 1.4. The $\delta^{13}C$ values, measured on the reburned acetylene gas, were used to correct the $\Delta^{14}C$ results according to standard techniques (Stuiver and Polach 1977). All seasonal $\delta^{13}C$ and $\delta^{18}O$ measurements were performed according to standard techniques (Druffel and Griffin 1993). Stable isotope results obtained for this study were performed on a VG Micromass 602E isotope ratio mass spectrometer, with uncertainties of ± 0.1‰ for both measurements.

Results

Figure 1 shows the $\Delta^{14}C$ results for our three Australian corals. Prior to the introduction of bomb-produced ^{14}C to the oceans, coral $\Delta^{14}C$ values averaged −50‰. The average pre-bomb value at Heron Island (−49.8 ± 4.5‰ sd, N=5) was slightly higher, and more variable, than that at Abraham Reef (−53.8 ± 2.0‰ sd, N=5). $\Delta^{14}C$ values increased steadily after 1958 to *ca.* 110‰ by 1970, then rose at a reduced rate through the 1970s. $\Delta^{14}C$ values decreased at Abraham Reef after 1980 from 130‰ to 110‰ by 1991.

Figures 2A and 2B show the seasonal stable isotope data ($\delta^{13}C$ and $\delta^{18}O$) obtained for Heron and Lady Musgrave Islands. The $\delta^{18}O$ values for Heron Island coral average −4.5‰ throughout the 28-yr record. There are poorly defined seasonal patterns that range from 0.3‰ to 0.7‰. The $\delta^{13}C$ values for Heron Island coral average −0.7 ‰, with a significant increase of values observed in the later part of the record. The $\delta^{13}C$ record appears to have a better-defined seasonal signal (with variations that range from 0.4–1.3‰) than the $\delta^{18}O$ record. Unlike the Heron coral, $\delta^{18}O$ values for Lady Musgrave coral show well-defined, annual variations of 0.4‰–0.8‰. The $\delta^{13}C$ values for Lady Musgrave coral show annual variations (0.8–1.3‰) larger than those observed for Heron Island, but no long-term change.

TABLE 1. ^{14}C values for Abraham Reef, Heron Island and Lady Musgrave Corals, 1950–1991. All $\Delta^{14}C$ values are for 1-yr coral bands, except those for 1952.8 and 1968.1 for Heron Island and Abraham 1, respectively, that represent $\Delta^{14}C$ values for 2-yr coral bands.

Year (AD)	Heron Island ($\Delta^{14}C$)	WH-no.	Abraham 1 ($\Delta^{14}C$)	WH-no.	Abraham 2 ($\Delta^{14}C$)	WH-no.	Lady Musgrave ($\Delta^{14}C$)	WH-no.
1950.3	−52.4	360	−52.2	811				
1951.3	−47.5	379	−55.4	1187				
1952.8	−44 9	334						
1953.3			−56.5	1083				
1954.3	−47.7	383	−52.1	1188				
1955.3	−56.3	403	−53.0	1064				
1956.3	−44.8	393					−51.8	751
1957.3	−37.9	401	−51.2					
1958.3	−39.4	398	−44.2	1183			−52.9	724
1959.3	−32.0	404	−43.0	1067				
1960.3	−28.8	403					−25.4	518
1961.3	−21.1	382					−24.4	531
1961.6			−13.7	1178				
1962.3	−29.2	726						
1962.6			−13.7	1344				
1963.3	7.4	333					−6.7	529
1963.6			21.0	900				
1964.3	20.8	719						
1964.6			43.0	824				
1965.3	46.8	397					37.4	527
1966.3	67.6	388						
1967.3	80.2	361			67.8	1367	70.2	523
1968.1			81.7	584				
1968.3	97.7	378			93.3	1375		
1969.3	104.9	391					103.7	519
1970.3	109.4	707			101.5	1370		
1971.3	119.4	399					111.2	526
1972.3	116.7	728			112.5	1357		
1973.3	118.4	332			105.3	1306	113.5	530
1974.3	133.4	380			123.1	1372	123.2	524
1975.3	128.9	749			124.6	1377		
1976.3	145.6	405			136.1	1373		
1977.3	116.0	723			124.0	1376		
1978.3	139.7	395	122.2	1346			144.7	521
1979.3	129.8	718	136.7	1345				
1980.3	156.1	1405	131.7	1343			137.3	528
1981.3	133.3	394					139.9	520
1982.3			125.4	899			125.3	522
1983.3	132.6	331	132.2	1339			121.6	525
1984.3					126.1	1365		
1985.3					128.1	1359		
1986.3					125.8	1374		
1987.3					130.4	1369		
1988.3					119.4	1368		
1989.3					119.2	1371		
1990.3					122.0	1358		
1991.1					109.9	1366		

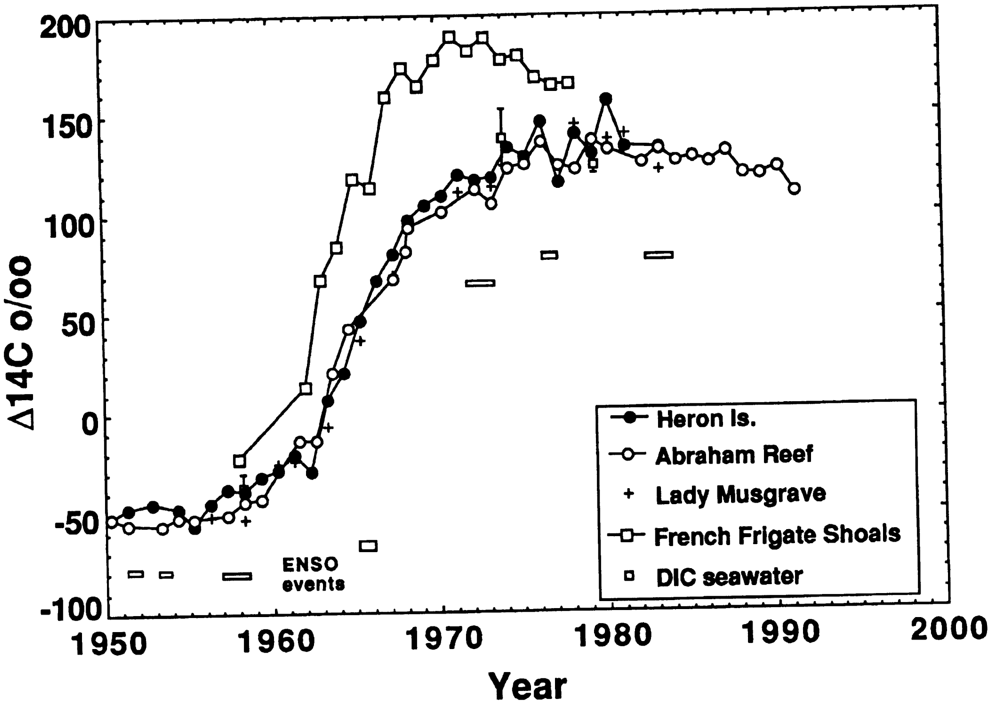

Fig. 1. $\Delta^{14}C$ measurements in annual coral bands from three locations in the Great Barrier Reef, Australia: Heron Island, Abraham Reef and Lady Musgrave Island. The size of the points is approximately equal to 2 σ uncertainty of the $\Delta^{14}C$ measurements. $\Delta^{14}C$ measurements for coral from French Frigate Shoals (23°43′N, 166°06′W) in the North Pacific are included as an example of a northern Pacific coral record (Druffel 1987). For comparison, average $\Delta^{14}C$ results from seawater DIC collected by four groups of investigators are plotted as open squares with vertical bars that include 2-σ uncertainty: 1) GEOSECS—January 1974, Stn 269 [23°57′S, 174°31′W, 124 ± 4‰ at 5 m and 151 ± 4‰ at 10 m] and Stn 263 [16°41′S, 167°03′W, 138 ± 4‰ at 10 m] (Östlund and Stuiver 1980); 2) FGGE Shuttle—April 1979, 23°S, 150°W, 124 ± 4‰ at 8 m (Quay, Stuiver and Broecker 1983); 3) March 1958, 21°S, 173°W, −40 ± 4‰ at 1 m (Rafter 1968); and 4) March 1958, 21°17′S, 177°29′E, −36 ± 6‰ at 0 m; 20°52′S, 175°25′W, −32 ± 9‰ at 0 m; 18°18′S, 172°21′W, −38 ± 5‰ at 0 m (Burling and Garner 1959).

Discussion

Comparison between the coral results and $\Delta^{14}C$ of DIC in seawater from the South Pacific are shown in Figure 1. The $\Delta^{14}C$ values from GEOSECS (Ostlund and Stuiver 1980), the FGGE Shuttle and earlier cruises (Burling and Garner 1959; Rafter 1968) agree within 2 σ of the Australian coral $\Delta^{14}C$ record. This agreement demonstrates that the coral data is representative of an open ocean current that feeds the southern Great Barrier Reef area, namely the East Australian Current.

Significant differences among the three $\Delta^{14}C$ records in Great Barrier Reef corals suggest regional variability. Figure 1 shows that $\Delta^{14}C$ values for Heron Island are generally higher than those for Abraham Reef. Of the 17 yr for which a significant difference (>2 σ) between the two records is noticed, 11 of the Heron Island values are higher. Of the 6 yr when Abraham Reef $\Delta^{14}C$ is higher than the corresponding Heron Island values, 4 yr lie between 1962 and 1965 when the bomb input to the ocean was at its maximum. Of the 12 Lady Musgrave Island $\Delta^{14}C$ values, 11 are either equal to or less than the corresponding Heron Island values. This can be compared to the study of regional $\Delta^{14}C$ in Bermuda corals, where $\Delta^{14}C$ in north Bermuda waters was steadily higher than that in south Bermuda (Druffel 1989).

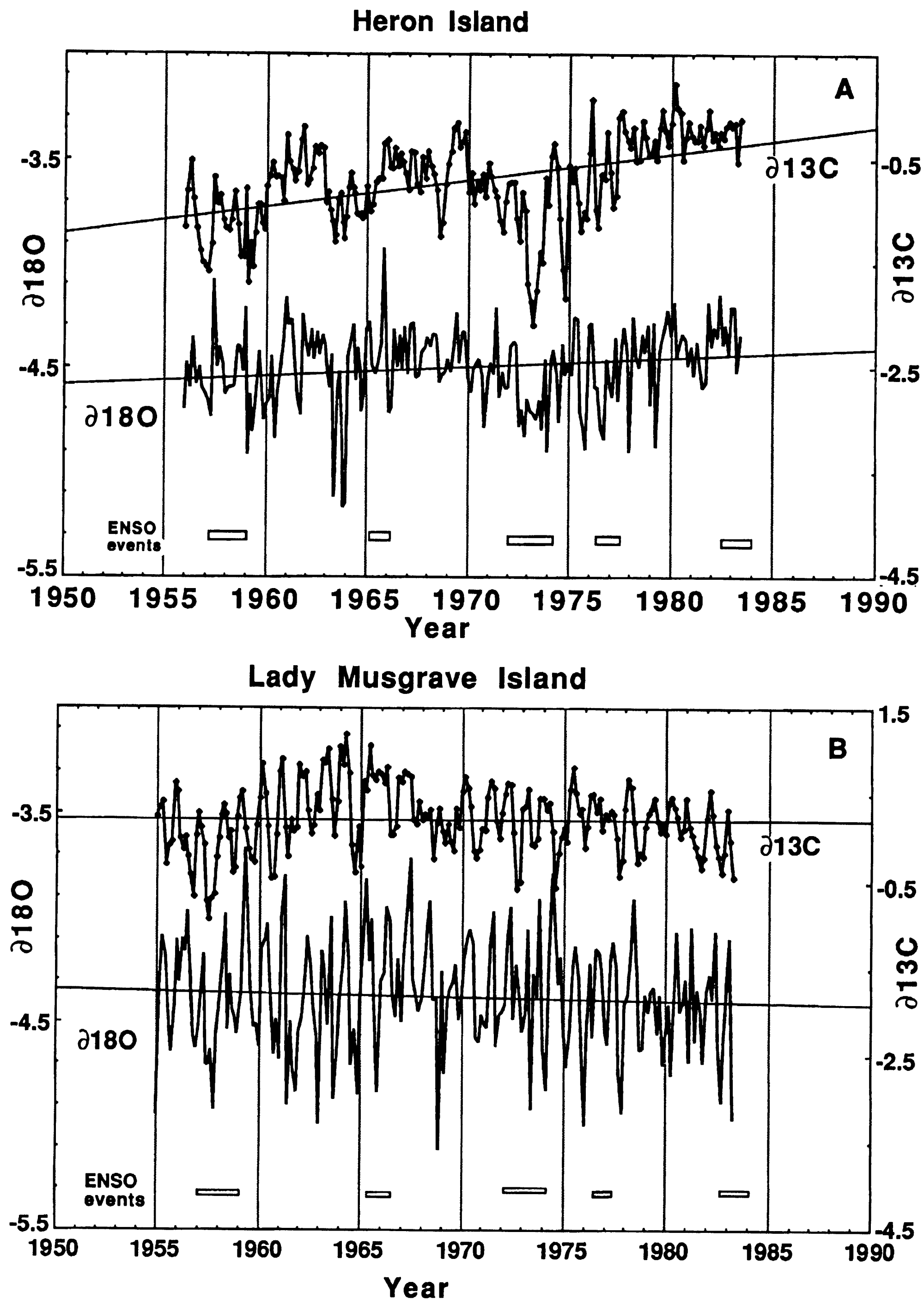

Fig. 2. $\delta^{13}C$ and $\delta^{18}O$ measurements in seasonal coral samples drilled from slabs of coral from (A) Heron Island and (B) Lady Musgrave Island. Samples were roasted in a vacuum for 1 h at 375°C just prior to stable isotope analysis to remove organic matter.

The regional differences of $\Delta^{14}C$ noticed here are most likely related to the general circulation patterns in these areas and their proximity to sources of upwelled (low-$\Delta^{14}C$) water. Figure 3 illustrates the locations of each of our coral sites. Heron is an inner island in the southern Great Barrier Reef, located 40 km from the coast. The predominant flow in this region is from the north-northwest, and contains a relatively larger amount of Coral Sea water than locations to the east. Abraham Reef is located on the southeastern tip of the outer Great Barrier Reef, 200 km offshore of the Queensland coast. It lies close to the shelf break where upwelling has been observed (Andrews and Gentien 1982). The predominant flow in this region is from the westward East Australian Current (EAC). Hence, we assert that Abraham Reef is influenced by lower $\Delta^{14}C$ water from upwelling. Heron Island, in contrast, is laved by non-upwelling waters from the northern coast and Coral Sea. The depth of the water column along most of the coastal traverse is <100 m, which makes it difficult to invoke entrainment of low $\Delta^{14}C$ waters into the surface near Heron Island. Thus, the $\Delta^{14}C$ of these waters is likely to increase slightly in transit by incorporation of high $\Delta^{14}C$ CO_2 from the atmosphere. A model of the carbon isotope balance of this area is the subject of a separate publication (Druffel, ms.).

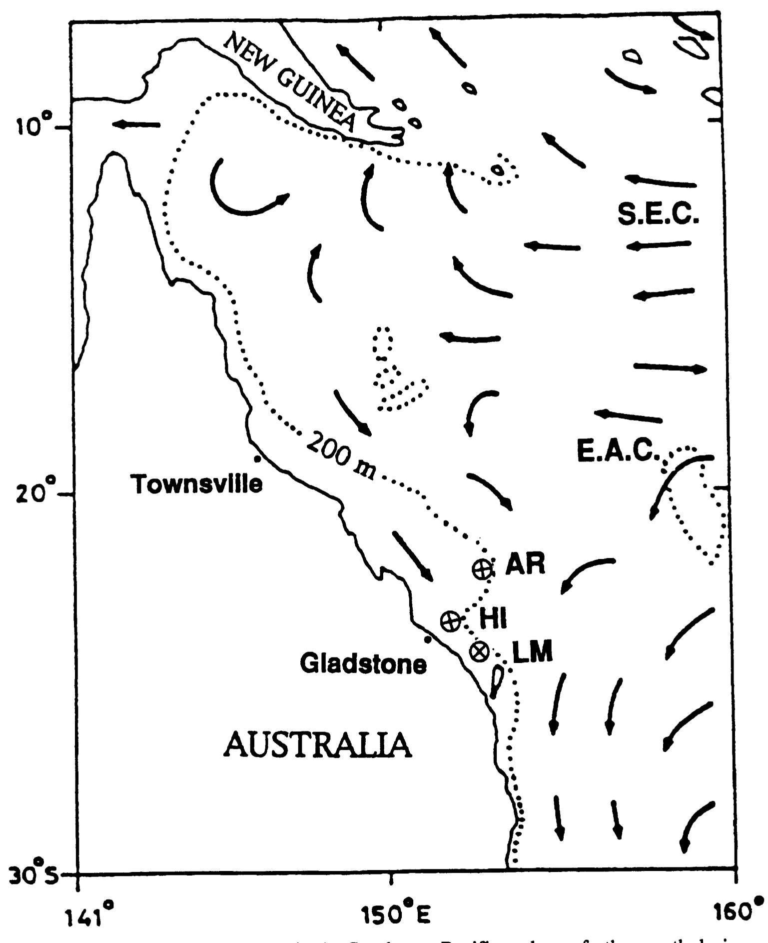

Fig. 3. Map of surface currents in the Southwest Pacific and area farther south during winter [adapted from Pickard *et al.* (1977: Fig. 63)]. Our three coral collection sites are indicated by ⊗ (AR = Abraham Reef; HI = Heron Island; LM = Lady Musgrave).

Compared to coral $\Delta^{14}C$ records from the equatorial and North Pacific, the Great Barrier Reef $\Delta^{14}C$ record is delayed by *ca.* 2 yr during the 1960s and early 1970s (see Fig. 1; Druffel 1987). This agrees with measurements of tropospheric bomb $\Delta^{14}CO_2$ (Levin *et al.* 1985; Nydal and Lovseth 1983) that showed a similar delay between the northern and southern hemisphere owing to the mixing time of the troposphere.

A correlation between low $\Delta^{14}C$ values in Australian coral and El Niño/Southern Oscillation (ENSO) occurrences for the period AD 1635–1957 has been documented (Druffel and Griffin 1993). Most low $\Delta^{14}C$ values for this pre-bomb period coincided with reported ENSO events (Quinn *et al.* 1987) for the eastern tropical Pacific. In our post-bomb data, it is difficult to discern lower $\Delta^{14}C$ values during the 1957–1958 and 1965 ENSO events, as they were likely masked by the large influx of bomb ^{14}C to the surface ocean during this time. Subsequently, the $\Delta^{14}C$ trends at Heron Island and Abraham Reef both decreased during the ENSO events of 1972–1973 and 1976–1977; they did not appear lower during the severe ENSO of 1982–1983.

Druffel and Griffin (1993) hypothesized that lower $\Delta^{14}C$ observed during ENSO was the result of a higher relative input of waters from the South Equatorial Current (SEC) entering the southern Great Barrier Reef region during these events. The westward SEC flowed in the 10–20°S latitude band during the 1982–1983 ENSO, much further south than during normal years (0–10°S) (Meyers and Donguy 1984; Wyrtki 1984). This would bring low $\Delta^{14}C$ equatorial waters from the SEC into the Coral Sea and further south.

Why were the $\Delta^{14}C$ values not lower during the severe ENSO of 1982–1983? It is possible that the ^{14}C levels in the SEC were not low because of the cessation of upwelling for a prolonged period during the 1982–1983 ENSO. This is supported by the fact that none of the severe ENSO events of the past 100 yr (1877–1978, 1891 and 1925–1926) were accompanied by low ^{14}C in the Abraham Reef coral (Druffel and Griffin 1993).

Nonetheless, the general observation of low $\Delta^{14}C$ during most ENSO events is in contrast to the trends previously seen at locations to the east of the Great Barrier Reef. Our location is west of the so-called "shadow zone", where drought and cool sea water occur during ENSO, as opposed to warmer water and higher rainfall found to the east. These coral records provide an interesting antithesis that can be used in larger-scale studies of the timing of ENSO and the heat and water balances that are thrown out of steady state during these events (Druffel, ms.).

Conclusion

Seasonal cycles of stable isotopes in Heron and Lady Musgrave Island corals confirm the annual nature of density bands in *Porites* at these locations. $\Delta^{14}C$ values at our South Pacific sites increased at a slower rate than those observed previously in corals from the northern hemisphere. There is regional variability of the post-bomb $\Delta^{14}C$ signals observed at our three sites in the southern Great Barrier Reef. This variation is due to circulation differences between the coast (Heron Island) and open ocean (Abraham Reef) locales. The correlation between low $\Delta^{14}C$ and ENSO events in post-1970 corals is likely due to the southward shift of the SEC and the increased input of low $\Delta^{14}C$ water to the Coral Sea and Great Barrier Reef region. The exception is during severe ENSOs, such as the 1982–1983 event, when upwelling in the SEC could have ceased, causing normal ^{14}C levels in corals during these times.

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References

Andrews, J. C. and Gentien, P. 1982 Upwelling as a source of nutrients for the Great Barrier Reef Ecosystems: A solution to Darwin's question? *Marine Ecology – Progress Series* 8: 257–269.

Burling, R. W. and Garner, D. M. 1959 A section of ^{14}C activities of sea water between 9S and 66S in the south-west Pacific Ocean. *New Zealand Journal of Geology and Geophysics* 2: 799–824.

Druffel, E. M. and Linick, T. W. 1978 Radiocarbon in annual coral rings from Florida. *Geophysical Research Letters* 5: 913–916.

Druffel, E. R. M. 1987 Bomb radiocarbon in the Pacific: Annual and seasonal timescale variations. *Journal of Marine Chemistry* 45: 667–698.

____1989 Decade time scale variability of ventilation in the North Atlantic determined from high precision measurements of bomb radiocarbon in banded corals. *Journal of Geophysical Research* 94: 3271–3285.

____(ms.) Circulation in the southwestern Pacific as invoked from pre- and post-bomb records of radiocarbon in Australian corals. In preparation.

Druffel, E. R. M. and Griffin, S. 1993 Large variations of surface ocean radiocarbon: Evidence of circulation changes in the southwestern Pacific. *Journal of Geophysical Research* 98: 20249–20259.

Edwards, R. L., Chen, J. H. and Wasserburg, G. J. 1987 ^{238}U-^{234}U-^{230}Th-^{232}Th systematics and the precise measurement of time over the past 500,000 years. *Earth and Planetary Science Letters* 81: 175–192.

Griffin, S. M. and Druffel, E. R. M. 1985 Woods Hole Oceanographic Institution Radiocarbon Laboratory: Sample treatment and gas preparation. *Radiocarbon* 27(1): 43–51.

Levin, I., Kromer, B., Schoch-Fischer, H., Bruns, M., Munnich, M., Berdaun, D., Vogel, J. C. and Munnich, K. O. 1985 25 years of tropospheric ^{14}C observations in Central Europe. *Radiocarbon* 27(1): 1–19.

Meyers, G. and Donguy, J. 1984 South equatorial current during the 1982–83 El Niño. *Tropical Ocean-Atmosphere Newsletter* 27: 10–11.

Nozaki, Y., Rye, D. M., Turekian, K. K. and Dodge, R. E. 1978 ^{13}C and ^{14}C variations in a Bermuda coral. *Geophysical Research Letters* 5: 825–828.

Nydal, R. and Lovseth, K. 1983 Tracing bomb ^{14}C in the atmosphere. *Journal of Geophysical Research* 88: 3621–3646.

Östlund, H. G. and Stuiver, M. 1980 GEOSECS Pacific radiocarbon. *Radiocarbon* 22(1): 25–53.

Pickard, G. L., Donguy, J. R., Henin, C. and Rougerie, F. 1977 *A Review of the Physical Oceanography of the Great Barrier Reef and Western Coral Sea*. Canberra, Australian Government Publishing Service: 135 p.

Quay, P., Stuiver, M. and Broecker, W. 1983 Upwelling rates for the equatorial Pacific Ocean derived from the bomb ^{14}C distribution. *Journal of Marine Research* 41: 769–792.

Quinn, W. H., Neal, V. T. and DeMayolo, S. E. A. 1987 El Niño occurrences over the past four and a half centuries. *Journal of Geophysical Research* 92: 14449–14461.

Rafter, T. A. 1968 ^{14}C variations in nature, Part 3, ^{14}C measurements in the South Pacific and Antarctic Oceans. *New Zealand Journal of Science* 11: 551–588.

Stuiver, M. and Polach, H. A. 1977 Discussion: Reporting of ^{14}C data. *Radiocarbon* 19(3): 355–363.

Toggweiler, J. R., Dixon, K. and Broecker, W. S. 1991 The Peru upwelling and the ventilation of the South Pacific thermocline. *Journal of Geophysical Research* 96: 20467–20497.

Wyrtki, K. 1984 A southward displacement of the subtropical gyre in the South Pacific during the 1982–83 El Niño. *Tropical Ocean-Atmosphere Newsletter* 27: 14–15.