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MODERN AND PLEISTOCENE RESERVOIR AGES INFERRED FROM SOUTH PACIFIC CORALS

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ABSTRACT. This paper presents radiocarbon results from modern South Pacific corals from the Marquesas Islands, Vanuatu, Papua New Guinea (PNG), and Easter Island. All of the measurements are from pre-bomb *Porites* corals that lived during the 1940s and 1950s. The data reflect subannual to multiannual surface ocean ^{14}C variability and allow for precise, unambiguous reservoir age determinations. The results are compared with published values from other coral records throughout the South Pacific, with striking consistency. By comparisons with other published values, we identify 3 South Pacific regions with uniform pre-bomb reservoir ages (1945 to 1955). These are 1) the Central Equatorial South Pacific (361.6 ± 8.2 ^{14}C yr, 2 σ); 2) the Western Equatorial South Pacific (322.1 ± 8.6 ^{14}C yr, 2 σ); and 3) the subtropical Pacific (266.8 ± 13.8 ^{14}C yr, 2 σ).

The question of how much, and how fast, South Pacific reservoir ages might have varied in the past is addressed by examining a published record from a Pleistocene coral from Vanuatu that lived over a 700-yr period during the Younger Dryas. The average reservoir age at that time was larger than today, by ~150 yr, and exhibited reservoir age variability on a decadal timescale not seen in modern times. Measured paleo-reservoir ages increase sharply in this record by as many as 300 ^{14}C yr in 3 decades. These increases are punctuated by smaller reservoir age decreases, on the order of 150 yr. This reservoir age variability provides a rare picture of active ocean ventilation and ocean-atmosphere exchange at the close of the Pleistocene.

INTRODUCTION

The marine reservoir effect has long been a topic of interest in radiocarbon research. The first marine reservoir age determination was published by Craig (1954). He measured the ^{14}C content of dissolved inorganic carbon (DIC) from the Atlantic Ocean and Mediterranean Sea, and observed a 5% difference between ocean and atmosphere. From this, he calculated a marine reservoir age of ~400 yr. He attributed this difference to the time required for air-sea exchange and internal oceanic mixing. Craig emphasized that both of these processes are significantly slower than mixing within the atmosphere, and he was able to rule out isotopic fractionation as the cause of the ^{14}C depletion by comparison with ^{13}C data. The next step to understanding the exchange of ^{14}C between the ocean and atmosphere came with the development of carbon cycle box models that considered the exchange in the context of a larger system (Craig 1957; Revelle and Suess 1957). Oeschger et al. (1975) refined this approach, by treating the deep sea as a diffusive medium with constant vertical eddy diffusivity instead of a well-mixed reservoir. Their model became the standard for ^{14}C reservoir age studies (Hughen et al. 2004). Today, ^{14}C continues to be utilized as an indicator of upwelling processes and ocean ventilation, and ^{14}C measurements are a critical component of modeling studies of past and present climate (Guilderson et al. 2000a; Matsumoto et al. 2004; Rodgers et al. 2004; Müller et al. 2006; Meissner 2007; Franke et al. 2008; Singarayer et al. 2008).

Marine reservoir ages alone serve as a qualitative measure of mixing between the surface and deep ocean, with the unlikely units of ^{14}C yr BP. They also make it possible to calculate ^{14}C ages of marine samples. Stuiver et al. (1986) describe 2 means of calibrating reservoir-corrected marine ^{14}C ages: 1) by measuring the marine reservoir age directly (in ^{14}C yr), and subtracting this value from

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the sample for subsequent comparison with the atmospheric calibration curve; or 2) by using a marine calibration curve that incorporates the reservoir correction into it. The latter technique involves the use of a marine model to estimate reservoir ages through time. It has the advantage that it can be applied globally, but depends on knowledge of the reservoir age for a particular locality (Hughen et al. 2004; Reimer and Reimer 2006). The former technique is more direct and unambiguous, but requires that the reservoir correction for a given site be known at the time the sample formed. Corals offer a potential archive that can provide this information.

Corals that form annual bands are well known for their use as proxies of ocean chemistry, ocean circulation, and climate (Druffel 1997). These proxies include ^{14}C, which can be used to directly measure marine reservoir ages by comparison with known atmospheric ^{14}C values. Corals have several advantages over other archives used to determine reservoir ages. For example, they are sessile organisms that produce skeletons from carbon acquired from DIC in seawater. There is no question about the source of carbon or where it was acquired. The calendar age of modern samples (up to 500 yr old) can be established directly by counting annual growth bands, and paleocorals can be accurately dated with U/Th and ^{231}Pa techniques (Edwards et al. 1987; Cutler et al. 2004). Corals are widespread and common throughout the South Pacific, and many live for decades to centuries, so very long records can be constructed, with annual to subannual resolution. The longest modern coral ^{14}C records studied thus far include a ~320-yr record from the Great Barrier Reef (Druffel and Griffin 1993) and a ~370-yr record from the Galapagos (Druffel et al. 2007).

The purpose of this paper is to assess the reservoir age variability in South Pacific coral records. We report 4 new pre-bomb records from the 1940s and 1950s and compare these to existing records published in the literature. We then examine a published South Pacific paleocoral record from the Younger Dryas (Burr et al. 1998) to constrain both the reservoir age at that time, and the rate at which it changed between ~11.8 and 12.3 kyr BP. This paper is restricted to coral results. A recent comprehensive review of South Pacific reservoir ages from a spectrum of natural archives is given by Petchey et al. (2008).

SAMPLING SITES

The ^{14}C content of a coral is a reflection of its physical oceanographic setting, and coral-based ^{14}C time series are often used to examine changes in surface flow and upwelling through time. Specific coral sites give us different information. For example, ^{14}C records from corals in the Galapagos Islands are very sensitive to El Niño events (Druffel 1981; Brown et al. 1993; Guilderson and Schrag 1998) as well as climatic factors (Druffel et al. 2007). ^{14}C records from Fanning Island corals depend on the phase of the Pacific Decadal Oscillation (Grottoli et al. 2004), and $\Delta^{14}C$ coral records from Indonesia are indicative of their source waters (Moore et al. 1997) and monsoonal climatic influences (Fallon and Guilderson 2008). In this study, the aim was to find corals that represent broad regions of the South Pacific for the purpose of constraining marine reservoir ages. With this in mind, live samples of *Porites* were drilled from corals along the coasts of the Marquesas Islands (9°S, 140°W); Espiritu Santo Island, Vanuatu (15°S, 167°E); Rabaul, Papua New Guinea (4°S, 152°E); and Easter Island, Chile (27°S, 109°W) (Figure 1). The first 3 sites are in the tropics, all in the path of the South Equatorial Current (SEC). These were selected to provide a broad east-west profile for the South Pacific. The Easter Island site is a subtropical site in the central portion of the South Pacific Subtropical Gyre, far removed from the direct influence of the SEC. The difference in surface flow regime at Easter Island, as compared with the other sites, is evident in surface velocity time series averaged over the past 15 yr (Figure 2). Surface zonal current velocities at Easter Island are from west to east and relatively weak, as compared to the tropical sites. Zonal currents at the

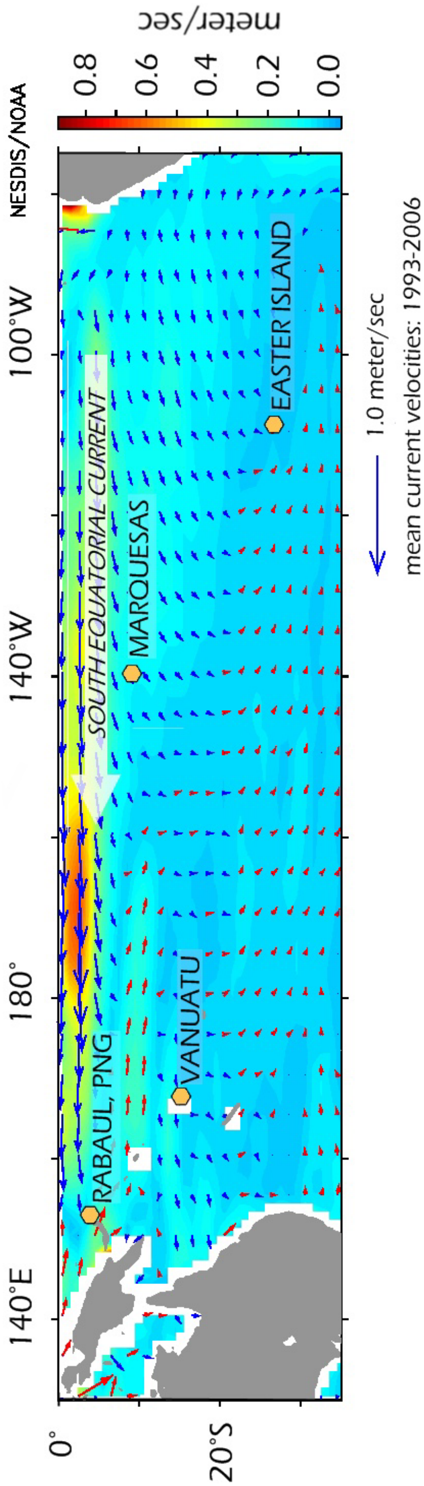

Figure 1 Map showing the locations of corals sampled for this study: a) Marquesas Islands; b) Espiritu Santo Island, Vanuatu; c) Rabaul, Papua New Guinea d) Ovahe, Easter Island.

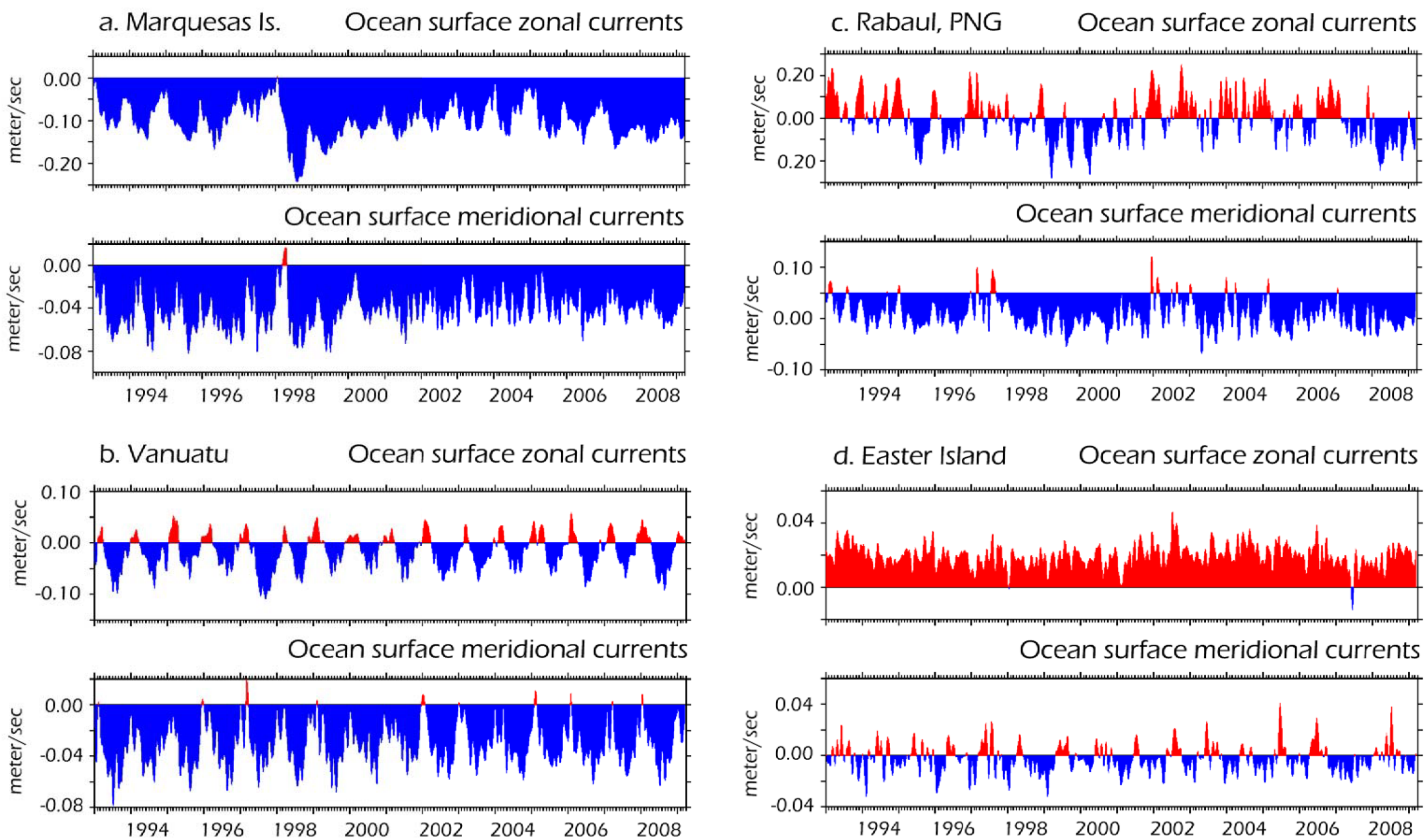

Figure 2 Time series plots for the period 1993–2008, showing inferred regional surface ocean current velocities for the 4 study areas: a) Marquesas Islands (149.5–129.5°W, 14.5–4.5°S); b) Espiritu Santo Island, Vanuatu (160.5–170.5°E, 24.5–4.5°S); c) Rabaul, Papua New Guinea (145.5–160.5°E, 9.5–0.5°N); d) Ovahe, Easter Island (119.5–99.5°W, 35.5–23.5°S). For surface zonal currents, the blue color represents flow from east to west and red represents flow from west to east. Surface ocean currents were derived from satellite altimeter and scatterometer data (Bonjean and Lagerloef 2002) and www.oscar.noaa.gov.

Marquesas Islands travel from east to west year-round. This contrasts with the direction of zonal current flow at Rabaul and Espiritu Santo, where seasonal alternating current directions are observed (Figure 2). Hence, although the 3 tropical sites are all in the path of the SEC, their individual surface ocean current characteristics represent a range of surface flow conditions.

METHODS

Sample Measurement

Samples were obtained using underwater hydraulic drilling equipment. Vertical cores were taken parallel to the growth axes of the corals, from approximately the center of the top surface of each colony. The cores were cut in half along their length with a diamond saw, and 5-mm-thick slabs were made from half of each core. The slabs were X-rayed to identify subannual growth bands. A year of growth corresponds to 1 light and dark band couplet on an X-ray image. Each band was sampled to provide a minimum time resolution on the order of 6 months. In some cases, additional subsamples were taken with a maximum resolution of ~2 months. Each piece of coral was completely dissolved to produce CO_2, which was reduced to graphite for accelerator mass spectrometry (AMS) analysis. In most cases, a split of the CO_2 was taken to determine the $\delta^{13}C$ value of the sample using a conventional mass spectrometer.

Reservoir Age Calculations

The reservoir age of a marine sample is defined as the offset between its ^{14}C age and the ^{14}C age of the contemporaneous atmosphere (Stuiver and Polach 1977; Stuiver et al. 1986; Stuiver and Braziunas 1993):

$$R(t) = {}^{14}\text{C age of marine sample} - {}^{14}\text{C age of atmospheric sample} \quad (1)$$

where a positive R value indicates that the marine sample is relatively older than the atmospheric age (the usual case). Reservoir ages are site-specific and depend principally on the physical oceanographic setting of a particular region. R also varies with time (t), depending on a variety of factors such as surface ocean circulation, atmospheric ^{14}C production, and exchange rates between terrestrial carbon pools.

To quantify a reservoir age using AMS, the first step is to measure fraction modem carbon (F) values, defined as:

$$F = ({}^{14}C/{}^{13}C)_S \,/\, ({}^{14}C/{}^{13}C)_{STD} \quad (2)$$

where $({}^{14}C/{}^{13}C)_S$ is the measured ratio in the sample, normalized to $\delta^{13}C = -25‰$, and $({}^{14}C/{}^{13}C)_{STD}$ is the calculated modern standard ratio at AD 1950, determined from measurements of NBS oxalic acid standards, also normalized to –25‰ (Donahue et al. 1990). The ^{14}C age of a sample is then calculated from F as:

$$^{14}\text{C age} = -8033 \ln F \quad (3)$$

Substituting Equation 3 into Equation 1 for a fixed t, gives a result for the reservoir age in terms of F:

$$R = 8033 \ln\left(\frac{F_{atm}}{F_{mar}}\right) \quad (4)$$

where F_{atm} is a measure of the ^{14}C content of the atmosphere and F_{mar} is a measure of the ^{14}C content of the surface ocean. This equation can be applied to contemporaneous marine and atmospheric samples to calculate reservoir ages directly from F values. A caveat must be kept in mind for samples that formed in AD 1950. The definition of F assigns the value $F = 1.0$ for atmospheric samples in 1950. However, the *measured* atmospheric age for the Southern Hemisphere in 1950 is 164 ± 13 yr, which gives an F value of 0.9798 (McCormac et al. 2004). This discrepancy arises because the activity of the primary standard for AMS (oxalic acid) was chosen to reflect a pre-industrial F value, not the actual 1950 value (Olsson 1970).

Coral ^{14}C results are usually quoted in Δ^{14}C units, using the conventions discussed by Stuiver and Polach (1977). This is the age-corrected proportional difference in the ^{14}C content of a sample, compared to the 1950 atmosphere:

$$\Delta^{14}\mathrm{C} = (Fe^{\lambda(1950-x)} - 1) \times 1000\ ‰ \tag{5}$$

where $\lambda = 1/8267$ is the decay constant for a 5730-yr half-life, and x is the calendar age of the sample BP. The quantities R and Δ^{14}C can both be used to express differences between the ^{14}C content of the ocean and atmosphere. The 2 quantities are subtly and distinctly different, because R compares the contemporary marine ^{14}C value with a contemporary atmospheric ^{14}C value; while Δ^{14}C compares the age-corrected contemporary marine ^{14}C value with the 1950 atmospheric value, as defined by the oxalic acid standard. We can solve Equation 5, for F_{atm} and F_{mar}, and substitute into Equation 4 to get the relationship between R and Δ^{14}C:

$$R = 8033 \ln\left(\frac{\frac{\Delta^{14}\mathrm{C}_{atm}}{1000} + 1}{\frac{\Delta^{14}\mathrm{C}_{mar}}{1000} + 1}\right) \tag{6}$$

where $\Delta^{14}\mathrm{C}_{atm}$ and $\Delta^{14}\mathrm{C}_{mar}$ are contemporary atmospheric and marine values. As is the case for Equation 4, some care must be exercised when applying this equation to samples from 1950. According to the oxalic acid standard, the $\Delta^{14}\mathrm{C}_{atm}$ at 1950 is zero; however, the actual Southern Hemisphere atmospheric value is –20.2 ± 1.6 ‰ (McCormac et al. 2004).

Since most coral papers report their findings as Δ^{14}C values, we include the formula to compute the 1 standard deviation uncertainty (dR) for Equation 6, which is:

$$dR = \left\{\left[\frac{8033}{(\Delta^{14}\mathrm{C}_{atm}/1000) + 1}\right]^2\left(\frac{d\Delta^{14}\mathrm{C}_{atm}}{1000}\right)^2 + \left[\frac{8033}{(\Delta^{14}\mathrm{C}_{mar}/1000) + 1}\right]^2\left(\frac{d\Delta^{14}\mathrm{C}_{mar}}{1000}\right)^2\right\}^{\frac{1}{2}} \tag{7}$$

where $d\Delta^{14}\mathrm{C}_{atm}$ and $d\Delta^{14}\mathrm{C}_{mar}$ are the 1 standard deviation uncertainties in these values. Some of the published data discussed below was reported using Δ^{14}C values that were not age-corrected. This introduces a negligible error when comparing results from 1950. The difference between uncorrected and corrected Δ^{14}C values at 1950 is zero, with a maximum difference of <0.6‰ between 1945 and 1955.

RESULTS

The results for the 4 new coral records are given in Table 1 and shown in Figure 3. Quoted reservoir ages were calculated by subtracting Southern Hemisphere atmospheric values from tree-ring measurements compiled by McCormac et al. (2004) for the period 1940 to 1950. From 1951 to 1955, averaged tree-ring values from Tasmania (Hua et al. 2000) and Armidale, Australia (Hua et al. 2003) were used. Average reservoir values were computed using weighted means that included all of the measurements for each site. The external variance of these values was used to determine the uncertainty for a given site.

Table 1 Fraction modern carbon (F) values, $\Delta^{14}C$ values, reservoir ages, and $\delta^{13}C$ values for modern corals: a. Marquesas Islands; b. Espiritu Santo Island, Vanuatu; c. Rabaul, Papua New Guinea; d. Ovahe, Easter Island. Uncertainties are 1 σ.

Sample ID	Calibrated age	F	^{14}C age BP	$\Delta^{14}C$	Reservoir age (R)[a]	$\delta^{13}C$[b]
a. Marquesas Islands (*n* = 26)						
AA50760	1955.5	0.9451 ± 0.0046	453 ± 38	–55.5 ± 4.9	297 ± 41	–1.8
AA50761	1955.0	0.9300 ± 0.0046	583 ± 39	–70.6 ± 4.9	427 ± 42	–1.1
AA50762	1954.5	0.9318 ± 0.0065	568 ± 55	–68.7 ± 7.0	412 ± 57	–0.6
AA50763	1954.2	0.9363 ± 0.0048	528 ± 41	–64.2 ± 5.1	372 ± 44	–0.6
AA50764	1953.5	0.9447 ± 0.0045	457 ± 38	–55.7 ± 4.8	301 ± 41	–0.8
AA50765	1952.8	0.9280 ± 0.0045	601 ± 38	–72.3 ± 4.9	445 ± 41	–0.8
AA50766	1952.4	0.9375 ± 0.0042	518 ± 35	–62.8 ± 4.5	354 ± 37	–0.6
AA50767	1951.8	0.9370 ± 0.0043	523 ± 36	–63.2 ± 4.6	359 ± 38	–1.0
AA50768	1951.3	0.9330 ± 0.0042	557 ± 35	–67.1 ± 4.5	393 ± 37	–0.9
AA50769	1950.8	0.9375 ± 0.0043	518 ± 36	–62.6 ± 4.6	354 ± 38	–0.9
AA51711	1950.3	0.9302 ± 0.0047	581 ± 39	–69.8 ± 5.1	417 ± 41	0.0
AA51712	1949.8	0.9429 ± 0.0043	472 ± 35	–57.1 ± 4.6	308 ± 37	–0.7
AA51713	1949.3	0.9340 ± 0.0042	548 ± 35	–65.9 ± 4.5	384 ± 37	0.0
AA51714	1948.8	0.9363 ± 0.0041	529 ± 35	–63.6 ± 4.4	365 ± 37	0.0
AA51715	1948.3	0.9466 ± 0.0042	441 ± 35	–53.2 ± 4.4	277 ± 37	–1.0
AA51716	1947.8	0.9284 ± 0.0056	597 ± 47	–71.4 ± 6.0	433 ± 49	–0.6
AA51717	1947.3	0.9389 ± 0.0042	506 ± 35	–60.8 ± 4.5	350 ± 36	–1.0
AA51718	1946.3	0.9414 ± 0.0042	485 ± 35	–58.2 ± 4.5	329 ± 36	–0.9
AA51719	1945.8	0.9291 ± 0.0044	591 ± 37	–70.4 ± 4.7	435 ± 38	–1.2
AA51720	1945.3	0.9379 ± 0.0042	515 ± 35	–61.6 ± 4.5	359 ± 36	–0.9
AA51721	1944.9	0.9388 ± 0.0030	511 ± 37	–60.6 ± 3.2	355 ± 38	–0.8
AA51722	1944.4	0.9403 ± 0.0042	494 ± 35	–59.1 ± 4.5	338 ± 36	–0.9
AA51723	1943.9	0.9429 ± 0.0042	473 ± 35	–56.4 ± 4.5	317 ± 36	–1.0
AA51724	1943.4	0.9461 ± 0.0041	445 ± 34	–53.2 ± 4.3	289 ± 35	–0.6
AA51725	1943.0	0.9370 ± 0.0042	523 ± 35	–62.2 ± 4.5	367 ± 36	–0.5
AA51726	1942.5	0.9401 ± 0.0046	496 ± 38	–59.0 ± 4.9	342 ± 39	–0.7
Average reservoir age = 356.0 ± 9.0						
b. Santo Island, Vanuatu (*n* = 35)						
AA18811	1950.0	0.9301 ± 0.0039	582 ± 34	–69.9 ± 4.2	418 ± 36	–0.4
AA15741	1950.2	0.9457 ± 0.0058	448 ± 49	–54.3 ± 6.1	284 ± 51	–1.0
AA14811	1950.3	0.9401 ± 0.0051	496 ± 44	–59.9 ± 5.4	332 ± 46	(–0.7)
AA18812	1950.6	0.9344 ± 0.0042	545 ± 36	–65.7 ± 4.5	381 ± 38	–0.7
AA14812	1950.9	0.9371 ± 0.0050	522 ± 43	–63.0 ± 5.3	358 ± 45	(–0.7)
AA18809	1951.0	0.9375 ± 0.0038	518 ± 33	–62.6 ± 4.1	354 ± 35	–0.6
AA15739	1951.2	0.9337 ± 0.0052	551 ± 45	–66.4 ± 5.6	387 ± 47	–0.5

Table 1 Fraction modern carbon (F) values, $\Delta^{14}C$ values, reservoir ages, and $\delta^{13}C$ values for modern corals: a. Marquesas Islands; b. Espiritu Santo Island, Vanuatu; c. Rabaul, Papua New Guinea; d. Ovahe, Easter Island. Uncertainties are 1 σ. *(Continued)*

Sample ID	Calibrated age	F	^{14}C age BP	$\Delta^{14}C$	Reservoir age (R)[a]	$\delta^{13}C$[b]
AA14809	1951.3	0.9402 ± 0.0053	495 ± 45	–60.0 ± 5.6	331 ± 47	(–0.6)
AA18810	1951.6	0.9412 ± 0.0038	487 ± 32	–59.0 ± 4.0	323 ± 35	–0.7
AA15742	1951.8	0.9467 ± 0.0070	440 ± 59	–53.5 ± 7.4	276 ± 61	–0.6
AA15740	1951.8	0.9466 ± 0.0056	441 ± 48	–53.6 ± 5.9	277 ± 49	–0.9
AA14810	1951.9	0.9432 ± 0.0052	470 ± 44	–57.0 ± 5.5	306 ± 46	(–0.6)
AA18807	1952.0	0.9377 ± 0.0061	517 ± 52	–62.5 ± 6.5	353 ± 54	–0.6
AA15737	1952.2	0.9469 ± 0.0058	438 ± 49	–53.4 ± 6.1	274 ± 51	–0.7
AA14807	1952.3	0.9414 ± 0.0051	485 ± 44	–58.9 ± 5.4	321 ± 45	(–0.6)
AA18808	1952.6	0.9261 ± 0.0060	617 ± 52	–74.2 ± 6.5	461 ± 54	–0.7
AA15738	1952.8	0.9442 ± 0.0057	461 ± 48	–56.1 ± 6.0	305 ± 51	–0.6
AA18805	1953.0	0.9310 ± 0.0062	574 ± 53	–69.3 ± 6.7	418 ± 56	–0.3
AA15735	1953.2	0.9501 ± 0.0058	411 ± 49	–50.3 ± 6.1	255 ± 52	–0.5
AA14805	1953.3	0.9487 ± 0.0054	423 ± 46	–51.7 ± 5.7	267 ± 48	(–0.4)
AA18806	1953.6	0.9360 ± 0.0063	531 ± 54	–64.4 ± 6.7	375 ± 56	–0.4
AA15736	1953.8	0.9485 ± 0.0062	425 ± 53	–51.9 ± 6.5	269 ± 55	–0.5
AA14806	1953.9	0.9427 ± 0.0051	474 ± 43	–57.7 ± 5.4	318 ± 46	(–0.4)
AA18803	1954.0	0.9362 ± 0.0066	530 ± 57	–64.3 ± 7.1	374 ± 59	–0.3
AA15733	1954.2	0.9440 ± 0.0057	463 ± 49	–56.5 ± 6.0	307 ± 51	–0.7
AA14803	1954.3	0.9521 ± 0.0054	394 ± 46	–48.4 ± 5.7	238 ± 48	(–0.5)
AA18804	1954.6	0.9230 ± 0.0063	644 ± 55	–77.5 ± 6.8	488 ± 57	–0.6
AA15734	1954.8	0.9441 ± 0.0057	462 ± 48	–56.5 ± 6.0	306 ± 51	–0.5
AA14804	1954.9	0.9444 ± 0.0077	460 ± 65	–56.2 ± 8.2	304 ± 67	(–0.5)
AA18801	1955.0	0.9270 ± 0.0066	609 ± 57	–73.6 ± 7.1	453 ± 59	–0.4
AA15731	1955.2	0.9448 ± 0.0055	456 ± 47	–55.8 ± 5.8	300 ± 49	–0.7
AA14801	1955.3	0.9388 ± 0.0054	507 ± 46	–61.8 ± 5.8	351 ± 49	(–0.8)
AA18802	1955.6	0.9397 ± 0.0076	500 ± 65	–60.9 ± 8.1	344 ± 67	–0.8
AA15732	1955.8	0.9481 ± 0.0057	428 ± 48	–52.6 ± 6.0	272 ± 51	–1.2
AA14802	1955.9	0.9596 ± 0.0062	331 ± 52	–41.1 ± 6.5	175 ± 54	(–0.8)
Average reservoir age = 332 ± 10						
c. Rabaul, Papua New Guinea (*n* = 43)						
AA65639	1955.8	0.9495 ± 0.0032	416 ± 27	–51.2 ± 3.4	260 ± 31	–1.5
AA65640	1955.5	0.9476 ± 0.0047	432 ± 40	–53.0 ± 5.0	276 ± 43	–1.8
AA65641	1955.2	0.9516 ± 0.0039	399 ± 33	–49.0 ± 4.1	243 ± 37	–2.2
AA65642	1955.0	0.9467 ± 0.0047	440 ± 40	–53.9 ± 5.0	284 ± 43	–1.7
AA65643	1954.8	0.9440 ± 0.0040	463 ± 34	–56.5 ± 4.2	307 ± 38	–2.1
AA65644	1954.5	0.9381 ± 0.0047	514 ± 40	–62.5 ± 5.0	358 ± 43	(–1.4)
AA65645	1954.2	0.9405 ± 0.0047	493 ± 40	–60.0 ± 5.0	337 ± 43	(–1.4)
AA65646	1954.0	0.9360 ± 0.0047	532 ± 40	–64.5 ± 5.0	376 ± 43	(–1.4)
AA65647	1953.8	0.9451 ± 0.0028	454 ± 24	–55.4 ± 3.0	298 ± 29	(–1.4)
AA65648	1953.5	0.9377 ± 0.0039	517 ± 33	–62.7 ± 4.2	361 ± 37	(–1.4)
AA65649	1953.2	0.9387 ± 0.0043	508 ± 37	–61.7 ± 4.6	352 ± 40	(–1.4)
AA65650	1953.0	0.9453 ± 0.0039	452 ± 33	–55.1 ± 4.1	296 ± 37	(–1.4)
AA65651	1952.8	0.9374 ± 0.0039	520 ± 33	–63.0 ± 4.2	364 ± 37	(–1.4)
AA65652	1952.5	0.9470 ± 0.0040	438 ± 34	–53.3 ± 4.2	274 ± 36	(–1.4)
AA65653	1952.2	0.9434 ± 0.0052	468 ± 44	–56.9 ± 5.5	304 ± 46	(–1.4)

Table 1 Fraction modern carbon (F) values, $\Delta^{14}C$ values, reservoir ages, and $\delta^{13}C$ values for modern corals: a. Marquesas Islands; b. Espiritu Santo Island, Vanuatu; c. Rabaul, Papua New Guinea; d. Ovahe, Easter Island. Uncertainties are 1 σ. *(Continued)*

Sample ID	Calibrated age	F	^{14}C age BP	$\Delta^{14}C$	Reservoir age (R)[a]	$\delta^{13}C$[b]
AA65654	1952.0	0.9315 ± 0.0046	570 ± 40	–68.8 ± 4.9	406 ± 42	(–1.4)
AA65655	1951.8	0.9397 ± 0.0039	500 ± 33	–60.5 ± 4.2	336 ± 36	–0.9
AA65656	1951.5	0.9420 ± 0.0039	480 ± 33	–58.2 ± 4.1	316 ± 36	–2.4
AA65657	1951.2	0.9440 ± 0.0049	463 ± 42	–56.1 ± 5.2	299 ± 44	–0.6
AA65658	1951.0	0.9449 ± 0.0048	455 ± 41	–55.2 ± 5.1	291 ± 43	–0.7
AA65659	1950.8	0.9375 ± 0.0039	518 ± 33	–62.6 ± 4.2	354 ± 36	–1.7
AA65660	1950.5	0.9411 ± 0.0057	488 ± 49	–59.0 ± 6.1	324 ± 50	–1.7
AA65662	1950.0	0.9438 ± 0.0046	465 ± 39	–56.2 ± 4.9	301 ± 41	–2.7
AA65663	1949.8	0.9394 ± 0.0045	502 ± 38	–60.6 ± 4.8	338 ± 41	–2.5
AA65664	1949.5	0.9378 ± 0.0033	516 ± 28	–62.1 ± 3.5	352 ± 31	–1.5
AA65665	1949.2	0.9423 ± 0.0034	477 ± 29	–57.6 ± 3.6	313 ± 32	–1.9
AA65666	1949.0	0.9407 ± 0.0032	491 ± 27	–59.2 ± 3.4	327 ± 30	–2.7
AA65667	1948.8	0.9383 ± 0.0051	512 ± 44	–61.6 ± 5.4	348 ± 46	–1.5
AA65668	1948.5	0.9423 ± 0.0046	477 ± 39	–57.5 ± 4.9	313 ± 41	–1.5
AA65669	1948.2	0.9446 ± 0.0033	458 ± 28	–55.2 ± 3.5	294 ± 31	–2.1
AA65670	1948.0	0.9403 ± 0.0034	494 ± 29	–59.5 ± 3.6	330 ± 32	–2.4
AA65671	1947.8	0.9440 ± 0.0033	463 ± 28	–55.7 ± 3.5	299 ± 31	–1.0
AA65672	1947.5	0.9337 ± 0.0040	551 ± 34	–66.0 ± 4.3	395 ± 35	–1.0
AA65673	1947.2	0.9556 ± 0.0066	365 ± 55	–44.1 ± 6.9	209 ± 56	–2.3
AA65674	1947.0	0.9359 ± 0.0042	532 ± 36	–63.8 ± 4.5	376 ± 37	–0.8
AA65675	1946.8	0.9410 ± 0.0047	489 ± 40	–58.6 ± 5.0	333 ± 41	–0.7
AA65676	1946.5	0.9556 ± 0.0066	365 ± 55	–44.0 ± 6.9	209 ± 56	–1.5
AA65677	1946.2	0.9399 ± 0.0030	498 ± 26	–59.7 ± 3.2	342 ± 27	–0.6
AA65678	1946.0	0.9400 ± 0.0047	497 ± 40	–59.5 ± 5.0	341 ± 41	–0.6
AA65679	1945.8	0.9349 ± 0.0042	541 ± 36	–64.6 ± 4.5	385 ± 37	–0.3
AA65680	1945.5	0.9434 ± 0.0042	468 ± 36	–56.1 ± 4.4	312 ± 37	–0.7
AA65681	1945.2	0.9512 ± 0.0065	402 ± 55	–48.3 ± 6.8	246 ± 55	–0.5
AA65682	1945.0	0.9361 ± 0.0048	530 ± 41	–63.3 ± 5.1	374 ± 42	–0.4
Average reservoir age = 322.5 ± 6.3						
d. Ovahe, Easter Island, Chile (*n* = 9)						
AA40626	1952.2	0.9520 ± 0.0047	395 ± 40	–48.3 ± 4.9	231 ± 42	–2.9
AA40562	1952.6	0.9516 ± 0.0047	399 ± 40	–48.7 ± 4.9	243 ± 43	–3.0
AA42611	1953.1	0.9501 ± 0.0043	411 ± 36	–50.3 ± 4.5	255 ± 40	–2.9
AA42285	1953.6	0.9519 ± 0.0043	396 ± 36	–48.5 ± 4.5	240 ± 40	–2.8
AA42278	1954.2	0.9548 ± 0.0044	372 ± 37	–45.7 ± 4.6	216 ± 40	–2.5
AA42613	1955.0	0.9431 ± 0.0043	471 ± 37	–57.5 ± 4.6	315 ± 40	–2.3
AA42287	1955.4	0.9492 ± 0.0043	419 ± 36	–51.4 ± 4.5	263 ± 40	–2.1
AA41067	1955.7	0.9572 ± 0.0055	351 ± 46	–43.5 ± 5.7	195 ± 49	–2.6
AA42280	1955.8	0.9499 ± 0.0043	413 ± 36	–50.8 ± 4.5	257 ± 40	–2.8
Average reservoir age = 248 ± 11						

[a]Reservoir ages are calculated using data from SHCal data set (McCormac et al. 2004) for 1940 to 1950, and average tree-ring values from Tasmania (Hua et al. 2000) and Armidale, Australia (Hua et al. 2003) for 1951 to 1955.
[b]Values in parentheses are estimated.

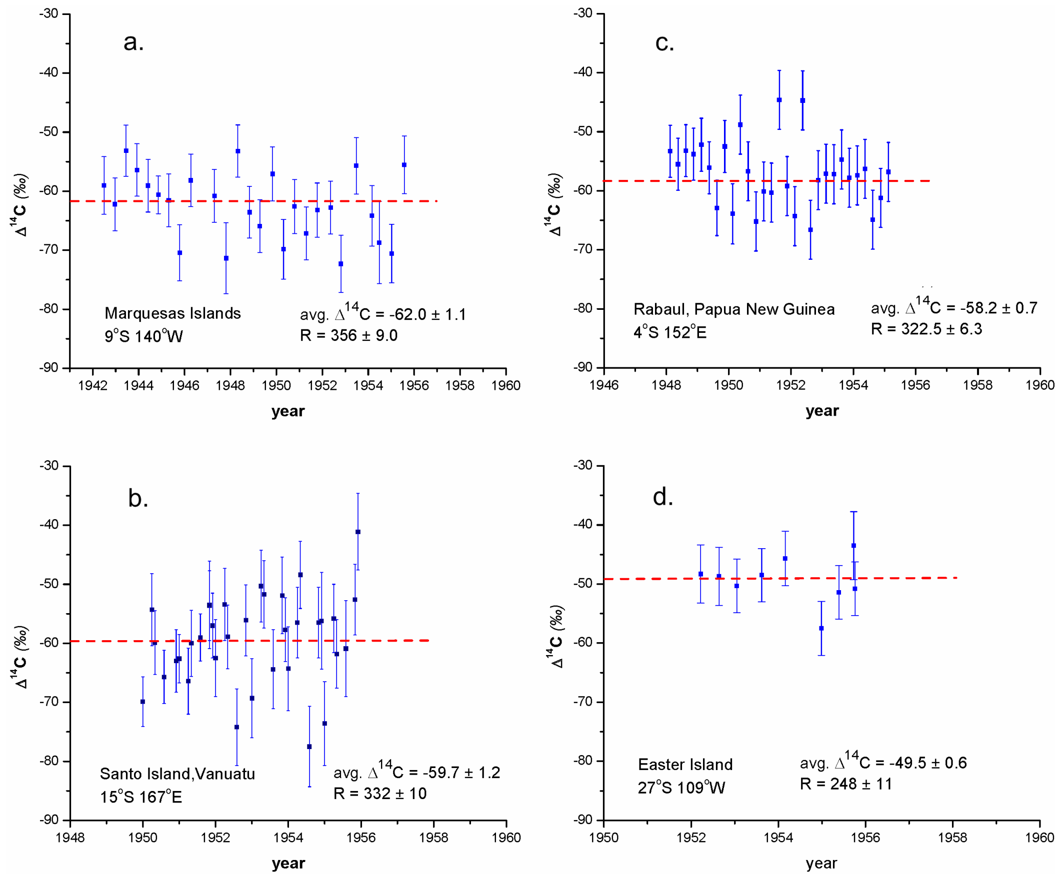

Figure 3 South Pacific coral $\Delta^{14}C$ time series for the 4 sites studied: a) Marquesas Islands; b) Espiritu Santo Island, Vanuatu; c) Rabaul, Papua New Guinea; d) Ovahe, Easter Island. Reservoir ages (*R*) are taken as the weighted average of the measurements. Uncertainties are 1 σ, taken as the external variance from the sample distribution.

All of the reservoir values are plotted together in Figure 3 at the same scale. The Marquesas Islands site has the oldest reservoir age (356.0 ± 9.0 ^{14}C yr). Espiritu Santo (332 ± 10 ^{14}C yr) and Rabaul (322.5 ± 6.3 ^{14}C yr) are slightly younger, and statistically indistinguishable from one another. Seasonal variations in $\Delta^{14}C$ are relatively small at the Marquesas Islands site, with a total range of less than 20‰. They are slightly larger at Rabaul, and substantially larger (~40‰) at Espiritu Santo. This suggests that the seasonal change in surface currents at Vanuatu involves surface waters carrying distinctly different ^{14}C signatures. The data are consistent with progressively younger ages from east to west, parallel to the SEC flow path.

The average reservoir age for Easter Island (248 ± 11 ^{14}C yr) stands apart from the others and reflects its fundamentally different oceanographic setting, in the central portion of the South Pacific Subtropical Gyre. The small amount of data for Easter Island has a very tight range, less than 15‰, consistent with uniform low-velocity surface currents at this site (Figure 3).

DISCUSSION

The coral-based ^{14}C reservoir ages for the 1940s and 1950s reported here show striking consistency with 9 other published studies from the South Pacific (Table 2). The region bound by the Marquesas

Islands, Fiji, and Nauru has a weighted average reservoir age of 361.6 ± 8.2 ^{14}C yr (2 σ). To the south and west, Vanuatu, the Solomon Islands, and Papua New Guinea have a weighted mean average of 322.1 ± 8.6 ^{14}C yr (2 σ). The 2 regions taken together cover about 12 million km^2. The largest reservoir ages are from the East Equatorial Pacific (Druffel 1981), centered around the Galapagos archipelago, at 450 ± 16 ^{14}C yr (2 σ). These data reflect an equatorial zone of reservoir ages that decrease westward, with a gradient that follows the surface currents of the SEC (Figure 4). This trend is a manifestation of the Ekman-driven upwelling of ^{14}C-depleted waters along the coast of Peru (Toggweiler et al. 1991). These ^{14}C-depleted waters propagate westward within the broad SEC system, driven by the easterlies. During westward transport in the SEC, reservoir ages are likely to be reduced in response to continual CO_2 exchange across the air-sea interface. At the same time, upwelling is expected to be attenuated as the thermocline deepens towards the west.

Table 2 Summary of South Pacific reservoir ages. Reservoir ages are calculated in the same manner as the study samples, using published data for South Pacific corals, and 1 sponge record from Vanuatu. Tabulated values were used when available, and interpolated values published in graphic form were used for the remainder. Uncertainties are 1 σ.

Location	Time range	Average reservoir age (^{14}C yr)	Source
a. Tropical sites			
Galapagos Islands (0.5°S, 91.23°W)	1945–1954	450 ± 8	Druffel 1981
Marquesas Islands (9°S, 140°W)	1942–1955	356 ± 9	this study
Fiji (18°S, 179°E)	1945–1955	361 ± 13	Toggweiler et al. 1991
Nauru (0°30′S, 167°E)	1947–1957	369 ± 10	Guilderson et al. 1998
Vanuatu (13.8°S, 167.5°E)	1953–1955	345 ± 21	Fallon et al. 2003 (*sponge record*)
Vanuatu (15°S, 167°E)	1950–1955	332 ± 10	this study
Solomon Islands (9°S, 161°E)	1945–1955	323 ± 11	Schmidt et al. 2004
Solomon Islands (9°S, 159°40′E)	1943–1957	309 ± 8.9	Guilderson et al. 2004
Rabaul, PNG (4°S, 152°E)	1945–1955	322.5 ± 6.3	this study
b. Subtropical sites			
Easter Island, Chile (27°S, 109°W)	1952–1955	248 ± 11	this study
Rarotonga, Cook Islands (21°S, 160°W)	1950–1957	275.0 ± 9.2	Guilderson et al. 2000b
Abraham Reef, Australia *Great Barrier Reef* (22°S, 153°E)	1945–1955	275 ± 9	Druffel and Griffin 1993 Druffel and Griffin 1999
Heron Island, Australia *Great Barrier Reef* (23°S, 152°E)	1950–1955	254 ± 17	Druffel and Griffin 1995

The reservoir age gradient also decreases towards the subtropics because of the influence of the subtropical gyre. This drives strong surface convergence in the mixed layer, depressing the thermocline beyond the reach of wind-driven mixing. Easter Island is located near the latitudinal center of convergence for the subtropics, and is part of a belt that extends westward across the South Pacific. The dynamics of this zone produces a homogeneous reservoir age for all of the sites within it. The weighted average reservoir age for Easter Island, Rarotonga, and the Great Barrier Reef is 266.8 ± 13.8 ^{14}C yr (2 σ). Figure 4 summarizes the marine reservoir picture for the South Pacific between 1945 and 1955 using all available ^{14}C records.

An important corollary to our overview of modern reservoir ages is that composite coral-based reservoir age records can be combined to document and understand temporal reservoir age variability in the past. Paterne et al. (2004) calculated numerous reservoir ages in fossil South Pacific corals from the Marquesas Islands and Tahiti by establishing calendar ages using U/Th dating, and coupling these results with ^{14}C measurements. They estimated a rather uniform marine reservoir age for the central Pacific of ~400 ^{14}C yr up to 9 kyr BP. From 9 to 11 kyr BP, their results showed a reservoir age for the Marquesas Islands of 390 ± 60 ^{14}C yr (2 σ), and 280 ± 50 ^{14}C yr (2 σ) for Tahiti. These are the same as our modern values within errors, and suggest that no significant ocean circulation variability occurred during this time. McGregor et al. (2008) used a similar approach to measure paleo-reservoir ages in Holocene corals from Papua New Guinea. Their data showed a significant change in reservoir age in the Bismarck Sea between 7220 and 5850 BP, when reservoir ages fell to ~180 ^{14}C yr. Between 5850 and 5420, reservoir ages there increased to modern values. These authors suggested that the onset of El Niño activity accompanied a change in surface circulation during this period. The analytical approach of Paterne et al. (2004) and McGregor et al. (2008), combined with the high temporal resolution achieved with dating continuous growth bands, could, in principle, be used to produce high-resolution paleo-reservoir age records for much of the South Pacific—that is, to construct a firmly dated marine calibration curve from banded fossil corals, at least through the Holocene. The longest continuous Holocene coral records available today are a 367-yr record from the Galapagos (Druffel et al. 2007) and a 323-yr record from the Great Barrier Reef (Druffel and Griffin 1993). Fossil corals, collected from uplifted terraces or drilled from the subsurface, could extend these records into the past.

Two examples of such fossil corals are a *Diploastrea heliopora* that lived in Vanuatu between about 11.8 and 12.5 kyr BP (Burr et al. 1998) and a *Goniastrea favulus* that lived in PNG from 13.0 to 13.1 kyr BP (Burr et al. 2004). The *Goniastrea* record lies beyond the limit of the existing ^{14}C tree-ring chronology, but the *Diploastrea* ^{14}C record overlaps the existing tree-ring calibration between 11.8 and 12.4 kyr BP. We use this record to construct the paleo-reservoir time series plot shown in Figure 5. This figure incorporates the ^{14}C data of Burr et al. (1998), and recalculated ^{230}Th ages with updated half-lives (Cheng et al. 2000). Reservoir ages were reconstructed by comparing the coral measurements with tree-ring data for the same period (Friedrich et al. 2004). Each data point shown in Figure 5 is a weighted average of annual ^{14}C coral measurements—using every year for each decade where available.

It is well known that the Younger Dryas was a time of extreme climate change with large fluctuations in deep ocean ventilation (Edwards et al. 1993). Our record indicates substantial reservoir age variability at this time, with a range of about 400 ^{14}C yr (230–650 ^{14}C yr). This range is considerably larger than that observed in modern pre-bomb corals. Such variability is consistent with major ocean ventilation changes linked to North Atlantic freshwater inputs, or possibly changes in ^{14}C produc-

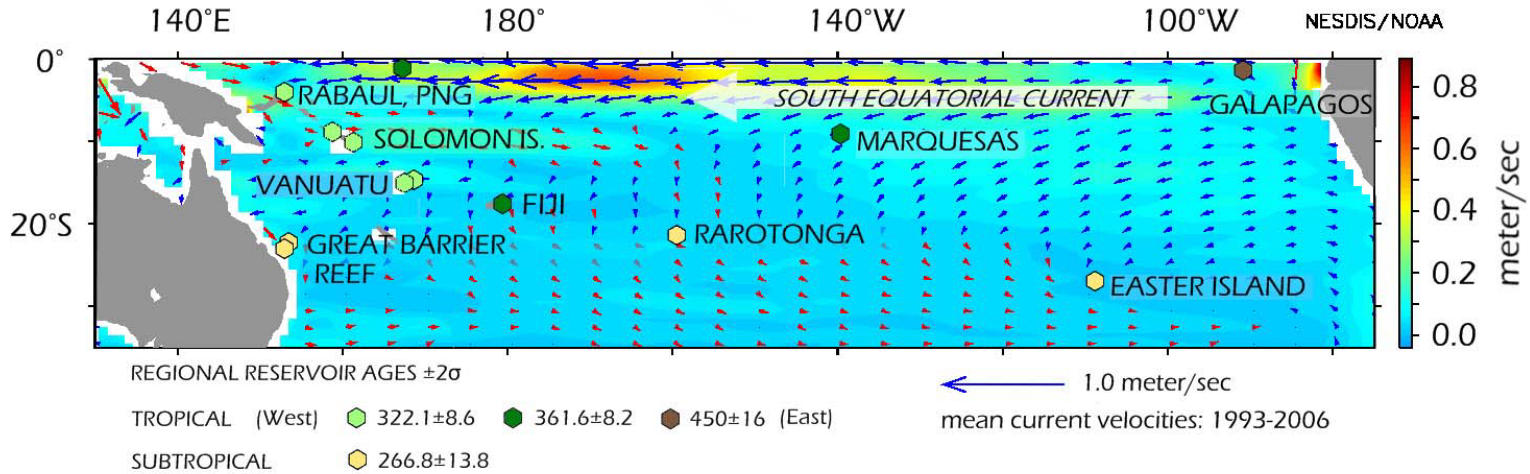

Figure 4 The 1940s–1950s summary plot of sample sites for this study and published studies. Data are given in Table 2. Reservoir ages are computed as described in the text. Each color represents a group of sites that fall within the mean reservoir ages indicated. Uncertainties are taken from the external variance on the weighted means, and are quoted at the 2-σ level.

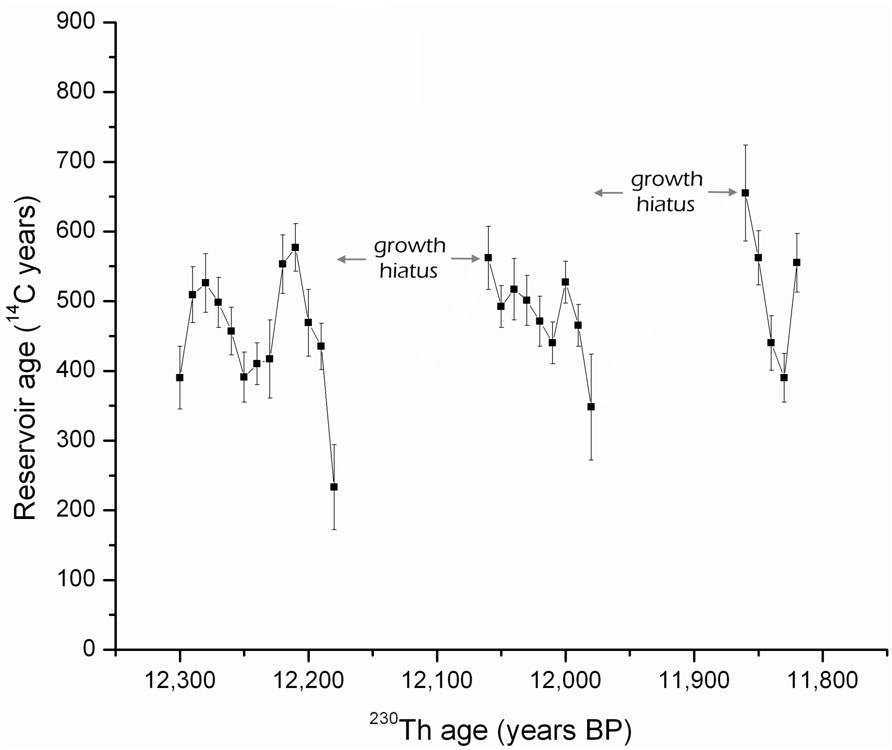

Figure 5 Plot of the surface ocean reservoir age at Vanuatu between 11.9 and 12.3 cal kyr BP. Data compiled from Burr et al. (1998) and Friedrich et al. (2004). The ^{230}Th ages from Burr et al. have been recalculated using the half-life values of Cheng et al. (2000). Uncertainties are 1 σ.

tion rate at that time (Singarayer et al. 2008). An intriguing feature of our record are large reservoir age increases that just precede growth hiatuses, suggesting a concomitant decrease in water temperature (Figure 5). We know from trace element studies of this same coral that the average sea surface temperature (SST) at the time was 4.5 °C cooler than today, and that this was accompanied by substantial SST variability (Corrège et al. 2004). It is also observed that the coral only recovered from the growth hiatus after the reservoir age dropped to lower values.

The maximum continuous single reservoir age increase (~300 ^{14}C yr) is larger than the maximum decrease observed in the record (~150 ^{14}C yr), while the maximum rate of change in reservoir age is about the same in either direction (~100 ^{14}C yr/decade).

Despite these large ^{14}C fluctuations, the weighted average reservoir age for the entire 500-yr period remained rather constant, at 476 ± 26 ^{14}C yr (2 σ). This is not a surprising result because once perturbed the system will seek to restore a steady state, as the ocean and atmosphere are tightly coupled, and *R* values reflect the difference between the contemporary ocean and atmosphere. The paleo-reservoir age for the Younger Dryas is similar to the modern reservoir age value quoted in Burr et al. (1998) of 494 ± 10 ^{14}C yr; however, that value was calculated with a 1950 reservoir age of zero, and should have been reduced by 164 ^{14}C yr, as discussed above. The corrected Younger Dryas average marine reservoir age is ~150 yr older than the reservoir age in modern times and more variable.

The *Diploastrea* record is a good example of the kind of temporal resolution possible with fossil corals. No other coral record from the Younger Dryas is available for comparison; however, Paterne et al. (2004) made similar measurements in 2 fossil corals from Marquesas that showed similar ^{14}C age variability. One of these was U/Th dated to ~12 kyr BP. The authors reported ^{14}C ages in this coral that implied a mean reservoir age of ~750 ^{14}C yr with a reservoir age variability on the order of ±300 yr. A second coral was U/Th dated to ~15 kyr BP and gave similar reservoir age variability. The authors suggested sudden and profound deep ocean ventilation, or possibly diagenetic alteration as the cause of the ^{14}C variability. Our findings from the Vanuatu *Diploastrea* record strongly favor enhanced ocean ventilation.

The picture of reservoir age variability reflected in the *Diploastrea* record is consistent with climate modeling using Younger Dryas $\Delta^{14}C$ values (Singarayer et al. 2008). The Singarayer et al. model study concludes that atmospheric ^{14}C changes during the Younger Dryas were caused primarily by ocean circulation changes. They also found that changes in reservoir effect across the Younger Dryas chronozone were probably substantially different in the South Pacific and North Atlantic. Larger Atlantic basin reservoir effects are likely to have occurred because of their proximity to the center of North Atlantic ocean ventilation changes. Smaller and more homogeneous changes are likely to have occurred in the South Pacific. This is a characteristic that favors using Pacific data when inferring atmospheric ^{14}C values for the purpose of ^{14}C calibration. To conclude, we would like to note that although our findings do not identify the mechanisms that caused the observed South Pacific ^{14}C reservoir age fluctuations, they do place important constraints on the rate and magnitude of these changes.

CONCLUSIONS

Modern reservoir age values are very uniform over vast regions of the South Pacific. We have identified 3 homogeneous regions for the pre-bomb 1940s and 1950s, as follows: 1) Central Equatorial South Pacific (361 ± 8.2 ^{14}C yr, 2 σ); Western Equatorial South Pacific (322.1 ± 8.6 ^{14}C yr, 2 σ); and 3) subtropical South Pacific (266.8 ± 13.8 ^{14}C yr, 2 σ). This uniformity suggests that reconstructions of South Pacific paleo-reservoir ages can be made by combining records from different sites within each region. We find that the average marine reservoir age at Vanuatu was 476 ± 26 ^{14}C yr (2 σ) during the Younger Dryas. This is about 150 yr larger than today. Reservoir age variability during this time featured rapid large increases (up to 300 ^{14}C yr) and smaller decreases (up to 150 ^{14}C yr) over a period of a few decades. Reservoir age variability during the Younger Dryas is consistent with substantial ocean circulation and climatic changes on decadal to century timescales.

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