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VARIABILITY OF MONTHLY RADIOCARBON DURING THE 1760s IN CORALS FROM THE GALAPAGOS ISLANDS

Ellen R M Druffel[1] • Sheila Griffin • Jeomshik Hwang • Tomoko Komada • Steven R Beaupre • Kevin C Druffel-Rodriguez • Guaciara M Santos • John Southon

Department of Earth System Science, University of California, Irvine, California 92697, USA.

ABSTRACT. Radiocarbon ($\Delta^{14}C$) measurements of monthly samples from a Galapagos surface coral are among the first data sets from the new Keck Carbon Cycle Accelerator Mass Spectrometry laboratory at the University of California, Irvine. An average $\Delta^{14}C$ value of –62‰ is obtained for 144 measurements of samples from monthly coral bands that lived from about AD 1760–1771 (±6 yr). High $\Delta^{14}C$ values were found during January through March, when upwelling was weak or absent at the Galapagos Islands. Low $\Delta^{14}C$ values were obtained mid-year during strong upwelling. The average seasonal variability of $\Delta^{14}C$ was 15–25‰, which is greater than that at other tropical and subtropical locations in the Pacific Ocean because of intense seasonal upwelling at this site. Periods of sustained high $\Delta^{14}C$ values were found during 1762–1763 and 1766. A spectral analysis revealed that the spectral density for the $\Delta^{14}C$ data displays most of its variance at the 5-yr cycle, which is reflective of El Niño periodicity during the 20th century.

INTRODUCTION

Data from banded corals show that the radiocarbon (^{14}C) "age" of pre-bomb, non-polar surface ocean ranges from 620 ^{14}C yr (–72‰) in the eastern tropical Pacific to 340 ^{14}C yr (–40‰) in the mid-gyre regions of the Pacific Ocean (Druffel 1987; Druffel et al. 2001). These non-contemporary reservoir ages of surface dissolved inorganic carbon (DIC) are due mainly to vertical and advective mixing of subsurface water having even "older" ^{14}C ages because of radioactive decay during isolation from the atmosphere. Because ^{14}C has a long turnover time (10 yr) in the atmosphere with respect to the transfer to the sea surface, $\Delta^{14}C$ of DIC in surface seawater is a tracer of circulation patterns and thermocline depth. Records of upper ocean circulation changes during the past are essential for understanding present and future climate changes.

Corals reflect the $\Delta^{14}C$ in surface DIC and provide time histories of $\Delta^{14}C$ on timescales of months to millennia. Records of $\Delta^{14}C$ in the surface ocean reveal past variability of surface-subsurface mixing and horizontal current shifts. We report monthly $\Delta^{14}C$ measurements from a Galapagos coral representing the 11-yr period AD 1760–1771 (±6 yr). We show that $\Delta^{14}C$ is high during the beginning of the year, when trade winds and upwelling were weak, and low $\Delta^{14}C$ values during the rest of the year, when wind-driven upwelling was strong.

OCEANOGRAPHIC SETTING AND SAMPLE COLLECTION

The coral sequence was collected by Drs Rob Dunbar, Mitch Colgan, and Gerard Wellington from a dead, massive head of *Pavona clavus* in Urvina Bay on the west coast of Isabela Island (0°15′S, 91°22′W) in the Galapagos archipelago in 1986 (see Dunbar et al. 1991 for details). The coral site was directly in the path of the cold, nutrient-rich Peru Current and the Equatorial Counter Current (Cromwell Current), which brings subsurface water eastward. The coral and the shoreline of the central coast of Urvina Bay was raised above sea level in March 1954 because of the intrusion and upward movement of magma below the surface (Richards 1957).

[1]Corresponding author. Email: edruffel@uci.edu.

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METHODS

Dunbar et al. (1991) cleaned, X-rayed, and developed an age model for this coral sequence using high-density bands that accrete from about January to April of each year. Based on preliminary ^{230}Th mass spectrometric analyses performed by Bruno Hamelin (LDEO), Dunbar et al. (1991) estimated an uncertainty of ±10 yr for ages at the base of the section (AD 1583), which translates to ±6 yr for our samples during the 1760s (assuming the uncertainty is linear).

We performed Δ^{14}C measurements on coral samples that had been ground off with a diamond-tip dremel tool to a width of 1 mm each from a vertical strip of coral (10 mm wide and 7 mm thick). The sequence was 144 mm long and spanned the time period from late 1760 to mid-1771; the average sampling frequency was 13 samples/yr.

Sub-samples (8 mg each) were converted to CO_2 in evacuated Vacutainers® with 85% phosphoric acid, then to graphite on Co catalyst with H_2 gas as the reducing agent (Vogel et al. 1987). All of the samples were analyzed for ^{14}C/^{12}C using accelerator mass spectrometry (AMS) at the Keck Carbon Cycle AMS Laboratory at UC Irvine. Background subtraction was applied using ^{14}C-free spar calcite. The Δ^{14}C measurements had a total uncertainty (counting statistics and laboratory reproducibility) of ±4–5‰ (1 σ). Radiocarbon measurements are reported as Δ^{14}C values (for geochemical samples with known age) according to Stuiver and Polach (1977). The Δ^{14}C results were corrected using δ^{13}C values measured either by the AMS or on CO_2 splits prior to graphitization.

RESULTS

The average of 144 monthly Δ^{14}C measurements (duplicate analyses and splits of the same CO_2 were averaged to a single point) from the Urvina Bay coral is –62 ± 6 (sd)‰. The range of the individual values is large (33‰), from –80‰ in early 1765 to –47‰ in mid-1770 (Figure 1). A least-squares fit of all monthly Δ^{14}C measurements reveals no significant trend with time.

Seasonal cycles are apparent in the Δ^{14}C data during most years (Figure 1), though these cycles are not well defined. The highest Δ^{14}C values (large grey circles) are at the base of the high-density bands (vertical lines in Figure 1), which are formed when surface waters are warm and upwelling is weak or absent (January through March) (Druffel 1981). The average of these 10 high Δ^{14}C values is –53 ± 3‰. Most of the lowest Δ^{14}C values (large black circles) were from samples in the middle of the bands. The average of the 11 low Δ^{14}C values is –71 ± 5‰. A least-squares fit of the low Δ^{14}C values reveals a 6‰ decrease over the 11-yr time period, that for the high Δ^{14}C values is not significant.

DISCUSSION

There appears to be an interannual fluctuation of the Δ^{14}C values in this record. The Δ^{14}C values for 1765 and 1769 were lower than those for other years. Six to 7 consecutive high Δ^{14}C values were found for 1766 and 1770 (average –54‰ for both). A smoothed line of the monthly data is shown in Figure 1 using a Stineman function and suggests that, based on Δ^{14}C data alone, El Niño events occurred during 1762–1763, 1766, and possibly 1770. During 1762–63, Δ^{14}C values increased during the upwelling season relative to other years, similar to Guilderson and Schrag's (1998) Δ^{14}C increase in Galapagos coral after the climate shift of 1976.

Periodicities within the monthly Δ^{14}C record were investigated by spectral analysis using Spectral software provided by Phil Howell (personal communication, 2000). The spectral density for the Δ^{14}C data displays a small amount of variance at the 1-yr cycle and most of its variance at the 5-yr

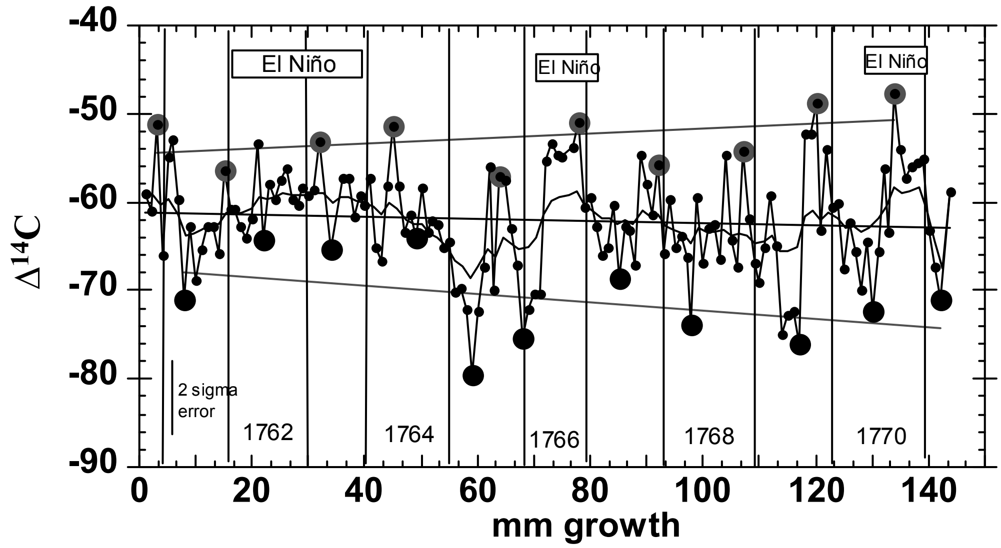

Figure 1 $\Delta^{14}C$ measurements of monthly coral bands from Urvina Bay, Galapagos, during the period 1760 to 1771. The uncertainty of the age assignments in this age range is ±6 yr. Duplicate analyses of separate aliquots from the same coral sample and splits of the same CO_2 were averaged to a single point. Large grey points represent the highest $\Delta^{14}C$ values for each year (lowest upwelling) and large black points represent the lowest $\Delta^{14}C$ values for each year (most intense upwelling). Vertical lines mark the base of the high-density bands, which are generally formed when upwelling is low. Horizontal lines (grey) are the least-squares fits of the high and low ^{14}C values, and that (black) for all of the monthly results. The smoothed line of the monthly data is obtained using a Stineman function, which suggests that El Niño events occurred during 1762–63 and possibly 1766.

cycle (significant to the 95% confidence level). The 5-yr cycle, however, is close to the nyquist frequency of 5.5 yr (11 yr total record/2), so the significance of this result is questionable. Nonetheless, a 5-yr cycle is similar to the frequency of El Niño events during the 20th century, which would suggest that, within the limits of this short data set, El Niño (high $\Delta^{14}C$) events during the 1760s were not different in frequency from those that were observed during recent times.

The average seasonal amplitude of $\Delta^{14}C$ values for the Galapagos coral during the 1760s was 15 to 25‰ (Figure 1), whereas those reported for recent corals from other Pacific sites are significantly lower (3–4‰ for Hawaiian coral, Druffel et al. 2001; 10–15‰ for Raratonga coral, Guilderson et al. 2000; 10–15‰ for Fanning Island coral, Grottoli et al. 2003). Seasonal upwelling at the eastern tropical Pacific is strong during the months of July through September, when the southeast trade winds are strongest. During this period, cold (18–20 °C), nutrient-rich water upwells into the Peru Current and Equatorial Counter Current, both of which lave the Galapagos Islands. The lowest pre-bomb $\Delta^{14}C$ values of any non-polar surface location are found at the Galapagos (Druffel 1981; Toggweiler et al. 1991) because of its proximity to intense equatorial and coastal upwelling.

A comparison of average pre-bomb $\Delta^{14}C$ values for corals from several Pacific locations reveals that the monthly Galapagos record for the 1760s (–62 ± 6‰) and the annual Galapagos record for 1930–1941 (Druffel 1989; –70 ± 6‰) were the lowest. Monthly samples from a Fanning Island coral (4°N, 159°W) have an average $\Delta^{14}C$ value of –55 ± 5‰ (n = 217) between 1922 and 1947 (Grottoli et al. 2003). In the western Pacific, Guilderson et al. (1998) determined the average of monthly $\Delta^{14}C$ values at Nauru (1°S, 166°E) was –58‰ between 1947 and 1956. An average of all Hawaiian bimonthly $\Delta^{14}C$ analyses for the time period 1920.8–1923.0 was –46.4 ± 2.3‰ (Druffel et al. 2001). A coral from the subtropical South Pacific (Rarotonga, 21°S, 160°W) had a pre-bomb, average $\Delta^{14}C$ value of –52‰ for the 1950s (Guilderson et al. 2000). These sites have higher $\Delta^{14}C$ levels because their mixed layers are more stable and there is little or no upwelling compared to the intense upwelling conditions in the eastern equatorial Pacific (Toggweiler et al. 1991).

The physical mechanism that causes temporal variability of climate and $\Delta^{14}C$ on an interannual timescale is El Niño/Southern Oscillation (ENSO). ENSO is caused by interaction of the tropical ocean and atmosphere (Bjerknes 1969). ^{14}C has been shown to increase in Galapagos coral bands that grew during El Niño events of the past 40 yr because upwelled waters no longer reached the sea surface (Druffel 1981; Brown et al. 1993), especially during mid-year (Guilderson and Schrag 1998). These events were generally coincident with warm waters that laved the region. Therefore, in the case of El Niño events, high $\Delta^{14}C$ measurements reflect a cessation of local upwelling, the presence of high ^{14}C surface water advected eastward along the Equator from the western warm pool, and transport of off-equatorial water masses due to the southward migration of the ITCZ during El Niño events. We suggest that these conditions prevailed during 1762–63, 1766, and part of 1770.

CONCLUSIONS

Radiocarbon ($\Delta^{14}C$) measurements of monthly samples from a Galapagos surface coral show an average $\Delta^{14}C$ value of –62‰ for samples that lived during ~1760–1771. Periods of sustained high $\Delta^{14}C$ values were found for the years 1762–63 and possibly 1770. Spectral analysis of the $\Delta^{14}C$ data shows that the spectral density has most of its variance in the 5-yr cycle, reflecting the El Niño cycle; some variance is seen for the annual cycle. The 5-yr cycle is similar to the frequency of El Niño events during the 20th century, which would indicate that El Niño (high $\Delta^{14}C$) events during the 1760s occurred at a frequency similar to that during the last 100 yr. The seasonal variability of $\Delta^{14}C$ during the 1760s, though not well defined, had a higher amplitude range than at other sites in the Pacific because of the strong seasonal upwelling that is unique to the eastern tropical Pacific.

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