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Oceanic climate and circulation changes during the past four centuries from radiocarbon in corals

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[1] We analyzed radiocarbon in annual coral bands from the Galápagos Islands in the tropical east Pacific to understand natural variability of past ocean circulation associated with climate change. Variability was observed on El Niño timescales (3–7 years) as well as at decadal and multi-decadal periods. Low radiocarbon levels persisted for ten years during the early 1600s and for sixteen years during the early 1800s, both coincident with periods of high volcanic aerosol loading in the atmosphere from massive eruptions. Intensification of tropical circulation at this time may be linked to climatically-controlled changes in the structure of the tropical thermocline that is responsible for delivering cool, upwelled waters to the tropical east Pacific. **Citation:** Druffel, E. R. M., S. Griffin, S. R. Beaupré, and R. B. Dunbar (2007), Oceanic climate and circulation changes during the past four centuries from radiocarbon in corals, *Geophys. Res. Lett.*, 34, L09601, doi:10.1029/2006GL028681.

1. Introduction

[2] Radiocarbon (^{14}C) in dissolved inorganic carbon of surface seawater is a tracer of the mixing rate between high ^{14}C surface and lower ^{14}C subsurface waters, and indicates changes in climate. During El Niño events, upwelling is suppressed in the central and eastern tropical Pacific and coral $\Delta^{14}\text{C}$ (per mil deviation from the $^{14}\text{C}/^{12}\text{C}$ ratio in nineteenth century wood) values are higher than normal [Brown *et al.*, 1993; Druffel, 1981; Guilderson and Schrag, 1998]. Since corals form annual bands that record the $\Delta^{14}\text{C}$ value of dissolved inorganic carbon in seawater at the time of skeletal formation [Druffel, 1987; Nozaki *et al.*, 1978], a $\Delta^{14}\text{C}$ record from this tropical region provides a record of past El Niño activity. Decadal shifts of climate linked to the Pacific Decadal Oscillation (PDO) [Mantua *et al.*, 1997] are also recorded in corals. The PDO shift of 1976/77 included a warming of tropical waters [Gu and Philander, 1995] that was marked by an abrupt increase in the wintertime $\Delta^{14}\text{C}$ of a Galápagos coral [Guilderson and Schrag, 1998]. This shift in $\Delta^{14}\text{C}$ was attributed to a decreased contribution of high-latitude water (Subantarctic Mode Water or SAMW) entrained into the Equatorial Undercurrent (EUC) during 1976/77 [Rodgers *et al.*, 2004]. Thus, the dynamical framework exists for interpreting $\Delta^{14}\text{C}$ as a proxy of thermocline

shifts and ultimately of climate change recorded in corals that grew centuries ago.

2. Methods

[3] We report a pre-nuclear, annual $\Delta^{14}\text{C}$ record from a Galápagos coral (Figure 1) that grew from AD 1587 to 1954. The coral sequence (UR-86) was collected from an uplifted colony of *Pavona clavus* in Urvina Bay on the west coast of Isabella Island ($0^{\circ}15'S$, $91^{\circ}22'W$) in 1986 [Dunbar *et al.*, 1994]. This site is well-flushed by cold, nutrient-rich waters of both the westward Peru Current and the eastward EUC (Figure 1).

[4] The coral analyzed was age-dated by band counting and verified by U/Th dating at two levels within the 1800s [Dunbar *et al.*, 1994]. The relative age error for growth bands at 1800 is ± 2 years and for the oldest part of the coral core ± 5 years. Our $\Delta^{14}\text{C}$ measurements were performed on annual samples that had been cut with a band saw and crushed, or ground off with a Dremel tool. Samples were converted to graphite and analyzed using accelerator mass spectrometry (AMS) [Southon *et al.*, 2004] with a total uncertainty of $\pm 2.6\%$ (one sigma). There are periods with no data (1701, 1757–1759, 1883–1888, 1906–1938) due to insufficient sample remaining in the core.

3. Results and Discussion

[5] The annual $\Delta^{14}\text{C}$ values range from -47.3% (in 1698 and 1722) to -76.1% (in 1946) (Figure 2a), reflecting significant variability in surface ocean $\Delta^{14}\text{C}$ during the past four centuries. Decadal variability is apparent during most of the record. The average $\Delta^{14}\text{C}$ value from 1610 through the mid-1700s is $\geq -60\%$, whereas before 1610 and after 1790 it is $< -60\%$. The annual $\delta^{18}\text{O}$ record from this coral sequence was reported by Dunbar *et al.* [1994] (shown in Figure 2a for comparison), which can be used to interpret regional changes in sea surface temperature [Wellington *et al.*, 1996]. The $\Delta^{14}\text{C}$ and $\delta^{18}\text{O}$ values are inversely correlated during the early to mid-1600s, the 1800s and 1938–1951. Weak or no apparent correlation is present between 1670 and 1800.

[6] Wavelet analysis [Torrence and Compo, 1998] of the $\Delta^{14}\text{C}$ record (Figure 2b) reveals variance concentrated at periods typical of El Niño/Southern Oscillation (ENSO) variability (3–7 years) during the 1600s, similar to results reported for $\delta^{18}\text{O}$ in fossil corals from the mid-Pacific [Cobb *et al.*, 2003]. Both $\Delta^{14}\text{C}$ and $\delta^{18}\text{O}$ variances are enhanced at decadal periods after 1710 and 1750, respectively (Figures 2b and 2c). Additionally, there is high $\Delta^{14}\text{C}$ variance at a period of ~ 30 yrs between 1650 and 1750 and high $\delta^{18}\text{O}$ variance at a similar period between 1750 and

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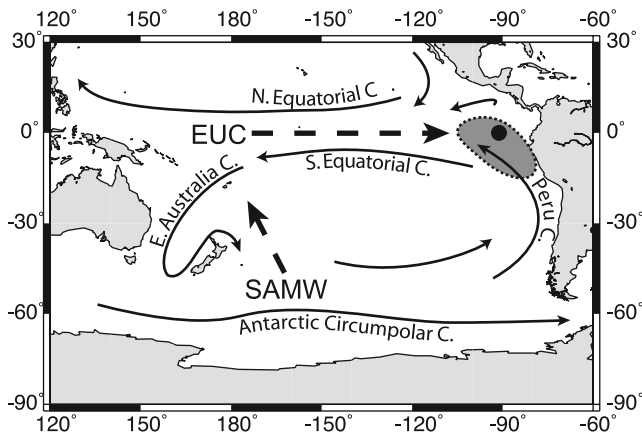


Figure 1. Map of the tropical and South Pacific showing the Galápagos Islands (filled circle), the surrounding upwelling region of the tropical east Pacific (shaded region), and a conceptual rendering of some major surface currents. The subsurface flows of the Equatorial Undercurrent (EUC) and Subantarctic Mode Water (SAMW) are indicated by dashed arrows.

1880. Iterative cross spectral analyses (P. J. Howell, Arand Crospec Software, 1997) reveal significant coherency between the $\Delta^{14}\text{C}$ and $\delta^{18}\text{O}$ [Dunbar *et al.*, 1994] records for the 5-year period (95% CL) from 1610–1680 and the 3-year period (95% CL) from 1780–1840 (Figure 2a). Coherency between these time series is also present for the 11-year period (95% CL) between 1720–1860 and for the \sim 18-year period (80% CL) between 1660–1730.

[7] Most notable is the span of extended, low $\Delta^{14}\text{C}$ values from 1808–1823 (average $-69.2 \pm 1.8\text{‰}$ $n = 16$) in the coral. Even the maximum $\Delta^{14}\text{C}$ values during this time are lower than the minimum values during nearly all other times in the record. This low $\Delta^{14}\text{C}$ period occurred too long after (20–30 years) the low $\Delta^{14}\text{C}$ period in the tree ring record (Figure 3a) for this to have been caused by air-sea gas exchange. Thus, the low $\Delta^{14}\text{C}$ values in the coral during the early 1800s indicate that the surface ocean was responding to a forcing independent from atmospheric ^{14}C levels.

[8] The atmospheric $\Delta^{14}\text{C}$ record from annual tree rings [Stuiver and Quay, 1981] (Figure 3a) shows a steady rise from 1600–1700, during the Maunder Minimum in sunspot activity, a period of increased production of radiocarbon in the stratosphere. Had the surface ocean simply responded to increased atmospheric $\Delta^{14}\text{C}$ levels by CO_2 exchange, the coral values would have increased by one-third to one-half as much as that in the atmosphere during the 1600s [Druffel, 1981; Oeschger *et al.*, 1975], as indicated by the model-calculated $\Delta^{14}\text{C}$ values for the mixed layer shown in Figure 3a [Stuiver *et al.*, 1986]. The long-term coral trend neither agreed with the model mixed layer trend in the early part of the record, nor during the early 1800s. A plot of residual $\Delta\Delta^{14}\text{C}$ (coral $\Delta^{14}\text{C}$ minus model $\Delta^{14}\text{C}$) (Figure 3b) shows negative anomalies of $\geq -18\text{‰}$ during these two time periods. Additionally, the coral $\Delta^{14}\text{C}$ values varied on much shorter timescales than the tree ring $\Delta^{14}\text{C}$

values, indicating that the surface ocean was responding to an internal forcing such as climate change.

3.1. Radiocarbon and Climate Change

[9] Natural causes of climate change include variability in solar irradiance and volcanism, both deemed important causes of pre-1850 surface temperature variability on Earth during the past 1000 years [Crowley, 2000]. Injections of volcanic sulfate aerosols into the stratosphere increase backscatter of solar radiation and cause cooling on interannual timescales [Bradley, 1988]. The early 1800s were marked by the most intense volcanic activity during the past 400 years, namely Tambora in 1815 and an unnamed Indonesian eruption in 1809 (Figure 3c). The two periods of lowest $\Delta^{14}\text{C}$ values (1811–1814, averaged $-70.7 \pm 1.1\text{‰}$ sd; and 1823, -72.5‰) in the Galápagos coral occurred several years after the two highest peaks in volcanic aerosol optical depth at the equator (1809–1810 and 1815–1816) [Robertson *et al.*, 2001] (Figure 3c). The uncertainty in the coral chronology makes precise assessment of the lag time questionable. Nonetheless, the period of highest volcanic aerosol injection to the atmosphere coincides with the period of lowest overall surface ocean $\Delta^{14}\text{C}$. A causal relationship, however, cannot be definitively proven.

[10] Studies of $\delta^{18}\text{O}$ in corals have shown a correlation between volcanic eruptions and cooling of surface ocean waters in the southwest Pacific [Crowley *et al.*, 1997] and the tropical east Pacific [Dunbar *et al.*, 1994] (Figure 2a). Cooling is detected in the early 1800s at these locations, but for a considerably shorter time than the 16-year period of low $\Delta^{14}\text{C}$ we observed at Galápagos.

3.2. Radiocarbon and Circulation Changes

[11] Low $\Delta^{14}\text{C}$ ($\leq -72\text{‰}$) surface water in the tropical east Pacific originates in the subantarctic region as SAMW [Toggweiler *et al.*, 1991] (Figure 1), and is entrained from below the base of the directly ventilated thermocline up into the EUC [Rodgers *et al.*, 2004] whose $\Delta^{14}\text{C}$ value is higher. The low annual $\Delta^{14}\text{C}$ values we observe during the early 1600s (-65‰ to -70‰) and early 1800s (-67‰ to -72‰) likely reflect increased entrainment of SAMW into the EUC for extended periods. Wintertime low $\Delta^{14}\text{C}$ values in this Galápagos coral during the 1760s [Druffel *et al.*, 2004] and early 1800s (E. Druffel and S. Griffin, unpublished data, 2006) ranged from -65‰ to -82‰ , suggesting that the contribution of SAMW varied significantly over time.

[12] The mechanism responsible for the variable SAMW entrainment likely involves zonal processes. As southeast trade wind intensity increases in the tropical Pacific, the tilt of the thermocline along the equator increases, resulting in greater upwelling, increased cooling and low $\Delta^{14}\text{C}$ in the tropical east Pacific. A positive feedback between strong trade winds and an increasing zonal sea surface temperature gradient could prolong this period of increased upwelling for several years [Bjerknes, 1969]. Our observation of low $\Delta^{14}\text{C}$ values in the early 1800s contrasts with the climate model results showing tropical volcanic eruptions increase the probability of El Niño events occurring in the winter following an eruption [Adams *et al.*, 2003]. This remains an interesting issue that needs further study.

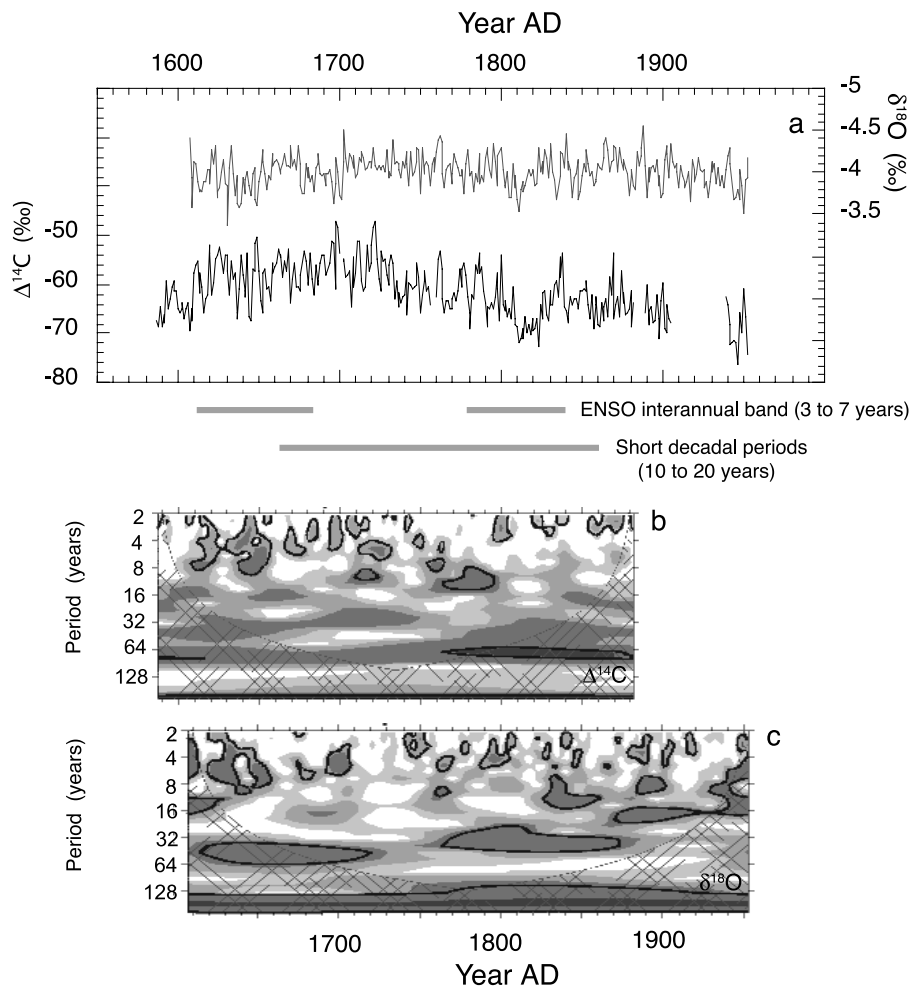


Figure 2. (a) Records of $\Delta^{14}\text{C}$ (this study, thin black line) and $\delta^{18}\text{O}$ [Dunbar *et al.*, 1994] (thin grey line) values for annual Galápagos coral bands from the UR-86 coral sequence from Urvina Bay. Grey bars show time periods of significant coherency between the $\Delta^{14}\text{C}$ and $\delta^{18}\text{O}$ records as revealed by iterative cross spectral analyses (see text for detail). Wavelet spectral density of the (b) $\Delta^{14}\text{C}$ and (c) $\delta^{18}\text{O}$ records from annual coral bands. The greyness scale shows that 75%, 50%, 25% and 5% of the wavelet power is above each level (white, grey, dark grey, darkest grey), respectively. The black lines show the 20% significance level using a red-noise (autoregressive lab 1) background spectrum. The cross-hatched region is the cone of influence where boundary effects are significant [Torrence and Compo, 1998].

[13] The production rate of SAMW in the South Pacific may also be an important mechanism for controlling entrainment of low $\Delta^{14}\text{C}$ water into the EUC. Production of SAMW is correlated with changes in wind stress [Rintoul and England, 2002], and the position and intensity of the southern hemisphere westerlies. The mean position of the mid-latitude westerlies has shifted poleward over the last 40 years as the climate has warmed [Hurrell and van Loon, 1994; Shindell and Schmidt, 2004] and is projected to shift even further poleward by the end of the 21st century [Yin, 2005]. This is in contrast to the last glacial period and Little Ice Age, when the position of the westerlies in the southern hemisphere was significantly closer to the equator than it is now [Lamy *et al.*, 2001; Lamy *et al.*, 2002]. Thus, it is feasible that the sustained, low $\Delta^{14}\text{C}$ values during the early 1800s may have been caused by an equatorward shift of the westerlies associated with climate change. Though the transit time of SAMW from subduction in the South Pacific

(Figure 1) to its arrival in the mid-tropical Pacific is estimated to be on the order of decades [Rodgers *et al.*, 2003], immediate changes in the rate of SAMW delivery to the surface of the tropical east Pacific could be controlled directly by changes in southeast trade wind intensity.

[14] Whether the period of low $\Delta^{14}\text{C}$ values during the early 1600s and early 1800s was caused by regional processes associated with changes in the tilt of the thermocline along the equator, or remote processes associated with SAMW production in the South Pacific, or both, is not yet known. Monthly $\Delta^{14}\text{C}$ measurements and simulations of ocean models designed to test the sensitivity of zonal wind speed and other parameters to change in the entrainment of SAMW into the EUC are needed. Whether intense volcanic activity initiated the low $\Delta^{14}\text{C}$ period, or was simply a coincidence, is also not yet resolved. Notwithstanding, a direct connection between short term climate change and transport of subpolar waters to the tropics would have

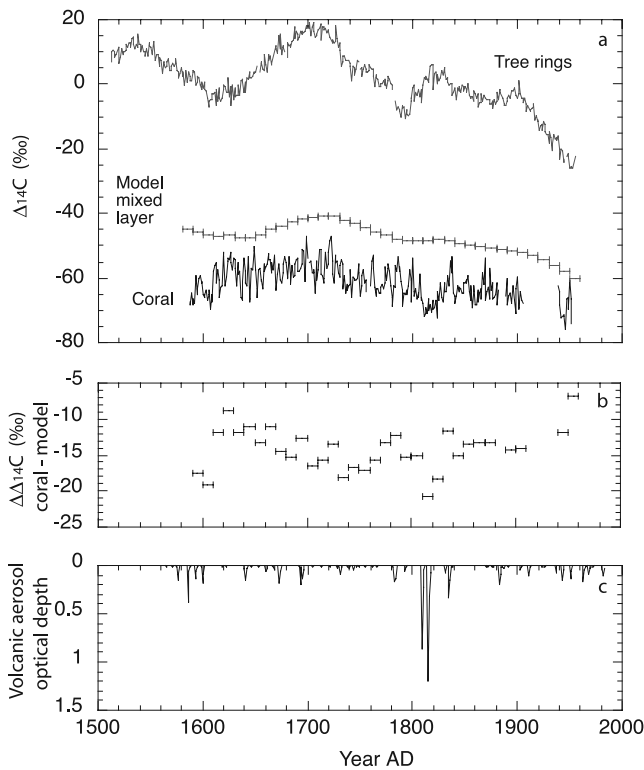


Figure 3. (a) $\Delta^{14}\text{C}$ measurements in annual tree rings [Stuiver and Quay, 1981] (grey line) and annual coral bands from Urvin Bay, Galápagos (this study, black line). Also shown are model-calculated $\Delta^{14}\text{C}$ values of the mixed layer (hatched grey line), using decadal atmospheric $\Delta^{14}\text{C}$ values and a box-diffusion model of the oceans (values reported by Stuiver et al. [1986]); (b) residual $\Delta\Delta^{14}\text{C}$ (decadally-averaged coral $\Delta^{14}\text{C}$ value minus decadal model $\Delta^{14}\text{C}$ value); and (c) volcanic aerosol optical depth at the equator [Robertson et al., 2001].

implications for CO_2 transfer between air and sea, and ultimately for the storage capacity of the oceans for excess CO_2 .

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