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Journal

Geophysical Research Letters, 8(1)

ISSN

00948276

Author

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Publication Date

1981

DOI

10.1029/GL008i001p00059

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RADIOCARBON IN ANNUAL CORAL RINGS FROM THE EASTERN TROPICAL PACIFIC OCEAN

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Sixty radiocarbon measurements were performed on aragonite from annually banded corals collected from three sites in the Galápagos Islands. Preanthropogenic $\Delta^{14}\text{C}$ values of coral that grew around A.D. 1930 averaged -70‰ . This is substantially lower than average values previously reported (-51‰) for corals from Florida and Belize in the western North Atlantic Ocean. A decrease of 6‰ was noticed in coral that grew from 1930 to 1954. This decrease could be interpreted as a Suess effect in surface ocean water. The 100‰ increase in $\Delta^{14}\text{C}$ for coral that grew from 1954 to 1973 is the result of bomb-produced ^{14}C that was introduced to the surface ocean waters. The ^{14}C levels in corals that grew during El Niño years were considerably higher than those for normal years. These higher values are attributed to the absence of upwelling at the equator during El Niño events.

Introduction

Radiocarbon measurements of dissolved inorganic carbon (DIOC) in ocean waters began in the 1950's (Rubin and Suess, 1954). The values were used to identify water masses and trace their general circulation patterns within the oceans. All of the ^{14}C measurements in surface ocean waters were done after the onset of nuclear weapons testing in the early 1950's. Thus, bomb-produced ^{14}C was present in virtually all of the surface ocean water samples collected for ^{14}C determinations. Corals contain the only known record of pre-bomb radiocarbon concentrations in surface ocean waters.

Radiocarbon concentrations were reported for *Montastrea annularis* from two areas in the Gulf Stream System: the Florida Straits (Druffel and Linick, 1978) and Glover Reef, Belize (Druffel, 1980a). Preanthropogenic $\Delta^{14}\text{C}$ values for these corals averaged -51‰ during the nineteenth century. The input of dead CO_2 to the atmosphere by the burning of fossil fuels decreased the $\Delta^{14}\text{C}$ in these surface waters to -62‰ (Suess effect) by 1954. The uptake of bomb-produced ^{14}C by these Gulf Stream waters increased the $\Delta^{14}\text{C}$ values to 213‰ above normal by 1970. This rise is similar to those seen in Geosecs data for North Atlantic surface waters (Östlund, et al., 1974; Östlund, et al., 1976).

Corals

Hermatypic corals record significant ecological conditions and changes that occur in the area surrounding the reef. Knutson et al. (1972) were first to conclusively demonstrate as annual the periodic variations in bulk density of the accreted aragonite. They found excellent agreement between autoradiographs and x-radiographs taken of thin slabs of Eniwetok coral. The annual bands are primary skeletal characteristics depicted as seasonal variations in bulk density of the secreted skeleton (Buddemeier, et al., 1974; MacIntyre and Smith, 1974).

Most calcium carbonate in hermatypic coral skeletons comes from dissolved inorganic carbon (DIOC) in sea water (Weber, 1974). The remainder, which originates as food (zooplankton) for the coral, contains essentially the same radiocarbon concentrations as the DIOC in the sea water (Druffel, 1980b). The $^{14}\text{C}/^{12}\text{C}$ ratios within coral skeletons do not change with time, as aragonite does not exchange its carbon with other carbonates. Arago-

nite does not dissolve in surface ocean waters to any significant degree. Thus, coral skeletons are permanent records of the radiocarbon levels that were present in the DIOC in the sea water.

Glynn and Wellington (in preparation) studied *Pavona clavus* from the Galápagos Islands and revealed that dense aragonitic bands form during the warm water months of January through March. Thicker, less dense bands form during the cold, upwelling season, which usually is April through December. These workers observed that *Pavona clavus* exhibits increased growth rates during most El Niño years. An El Niño event is the appearance of warm, low salinity water to the surface in the eastern tropical Pacific Ocean (Wyrtki, et al., 1976). Just as stress bands in *Montastrea annularis* from the Florida Straits depict recorded Cold Fronts that occur on the reef (Hudson, et al., 1976; Druffel, 1980b), unusually high rates of coral growth provide markers of growth during known El Niño years.

Samples

A total of four coral heads of *Pavona clavus* were collected by P. Glynn and G. Wellington from three sites in the Galápagos Islands (Figure 1). The Galápagos archipelago lies in the eastern tropical Pacific, about 1000 km west of the coast of Ecuador. Charts of average surface drift (Cromwell and Bennett, 1959) show a prevailing southerly or southeasterly flow through the islands (Figure 1). The water originates from the Perú Current which travels north along the coast of South America. Extensive upwelling of subsurface waters occurs in the area surrounding the Perú Current and the Galápagos Islands.

Two coral heads (HI-6 and HI-7) were collected from 4 m depth in February of 1976 from Gardner Bay, Hood Island (Figure 1). A third coral head (UB-16) came from Urvina Bay, Isabela Island. UB-16 was not collected live, but rather was found above sea level in May 1977. The shoreline was uplifted as a result of volcanic activity in March 1954 (Richards, 1957). Before the uplift, the coral grew at about 3 m depth. A fourth coral head (D-12) was collected off the northeast coast of Duncan Island in May 1977.

Slabs of the above mentioned coral heads (5 mm thick) were x-rayed to depict annual variations in the density of the aragonite. The x-ray positives of three of these slabs are shown in Figure 2. The annual nature of these density band pairs was established by using alizarin staining techniques, field observations (Glynn and Wellington, in prep.) and $^{13}\text{C}/^{12}\text{C}$ and $^{18}\text{O}/^{16}\text{O}$ measurements (Druffel, unpublished data).

The x-rays revealed that HI-6 grew from 1961 to 1976 and HI-7 grew from 1966 to 1976 (Figure 2). Fifteen samples, each of which represented growth during one individual year (midpoint July) were used from HI-6. Eleven samples were taken from HI-7; five of these samples consisted of growth during five individual years. The remaining six samples from HI-7 represented growth during individual six-month periods. This was done in order to detect seasonal fluctuations of the $^{14}\text{C}/^{12}\text{C}$ ratio. The x-ray of UB-16 revealed that this head grew from 1929 to 1954. Twenty-one samples were run from this coral head. In some cases, coral that grew during consecutive years were combined in order to obtain enough material to perform the ^{14}C analyses. The x-ray of D-12 revealed that this coral head grew from 1966 to 1977. Eleven samples were run from this coral head; each represented growth during a single year.

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Figure 1. Map of the eastern tropical Pacific and the Galapagos Islands. Collection sites of *Pavona clavus* are marked by an X.

Radiocarbon Measurements

Each sample was acidified in hydrochloric acid. The evolved carbon dioxide was converted to acetylene gas, via lithium carbide. Gas proportional counting systems were used to analyze all acetylene samples produced in this project. Two quartz counters (2.0- and 2.4-liter volumes) and two stainless steel counters (1.0 and 0.4 liters) were used. Each acetylene sample was counted for two days in each of two counters at 900 mm pressure and 25°C. One-sigma counting errors of about 3.5‰ and 7‰ were obtained for contemporary samples counted in the quartz and stainless steel counters, respectively.

All countings were corrected for isotope fractionation (to a standard value (PDB) of $\delta^{13}\text{C} = -25.0\text{‰}$) and for decay since the time of formation (to A.D. 1950). The standard used was 95% of the net NBS oxalic acid count rate, which was corrected to a $\delta^{13}\text{C} = -19.0\text{‰}$. All results are reported in terms of $\Delta^{14}\text{C}$, which is the per mil (‰) deviation from the activity of nineteenth century wood:

$$\Delta^{14}\text{C} = \delta^{14}\text{C} - 2(\delta^{13}\text{C} + 25.0)(1 + \delta^{14}\text{C}/1000)$$

Figure 2. X-ray positives of the coral slabs of *Pavona clavus* collected from the Galapagos Islands. Dark dense bands represent coral growth during the warm water months of January through March. See text for detail.

Figure 3. Radiocarbon measurements for *Pavona clavus* (UB-16) that grew in Urquina Bay in the Galapagos Islands from 1929 to 1954. The exponential curve fitted through the points could illustrate a Suess effect of -6‰ .

Results

Radiocarbon measurements of *Pavona clavus* from three sites in the Galapagos Islands are shown graphically in Figures 3 and 4 and are listed in Table 1. Radiocarbon results for coral that accreted from 1929 to 1954 (pre-bomb) and from 1961 to 1977 (post-bomb) are discussed separately.

A.D. 1929-1954 As UB-16 grew from 1929 to 1954, all of the $\Delta^{14}\text{C}$ results from this head are representative of the pre-bomb period. The average of twenty-one results is $-72 \pm 5\text{‰}$. A least squares analysis of these points yields a significant slope (Figure 3). A decline of 6‰ is observed from 1929 to 1954. It is unclear whether this decline in $\Delta^{14}\text{C}$ is due to fossil fuel burning or is evidence of long term changes of vertical mixing patterns in the water column. In any case, the Suess effect in water lavng this area is expected to be smaller than that exhibited in temperate

Figure 4. Radiocarbon measurements for *Pavona clavus* (HI-6, HI-7 and D-12) that grew near Hood and Duncan Islands. The values of coral that grew during the El Niño years of 1965, 1969, 1972, 1975, 1976 and 1977 are abnormally high because upwelling in these areas ceases during El Niño events (see text for more detail).

TABLE 1. Coral samples from the Galápagos Islands

LJ #	Coral	Years	$\delta^{13}\text{C}$	$\Delta^{14}\text{C}$
4841	UB-16	1929-31	-2.5	-63 $\pm$ 7
4842	UB-16	1932-33	-2.0	-70 $\pm$ 6
4844	UB-16	1934-35	-2.4	-76 $\pm$ 7
4840	UB-16	1936-37	-2.0	-67 $\pm$ 5
4843	UB-16	1938-39	-1.7	-69 $\pm$ 4
4562	UB-16	1940	-1.2	-67 $\pm$ 7
4641	UB-16	1941	-2.4	-80 $\pm$ 7
4591	UB-16	1942	-3.1	-81 $\pm$ 4
4558	UB-16	1943	-1.4	-66 $\pm$ 5
4552	UB-16	1944-45	-3.0	-69 $\pm$ 5
4589	UB-16	1944	-3.3	-73 $\pm$ 4
4642	UB-16	1945	-2.7	-70 $\pm$ 8
4592	UB-16	1946	-2.7	-72 $\pm$ 4
4556	UB-16	1947	-3.3	-72 $\pm$ 4
4559	UB-16	1948	-2.9	-76 $\pm$ 5
4590	UB-16	1949	-2.8	-78 $\pm$ 4
4555	UB-16	1950	-2.5	-70 $\pm$ 4
4561	UB-16	1951	-2.6	-75 $\pm$ 3
4557	UB-16	1952	-2.1	-69 $\pm$ 3
4560	UB-16	1953	-2.4	-75 $\pm$ 3
4640	UB-16	1954	-2.8	-72 $\pm$ 4
4440	HI-6	1961	-2.5	-59 $\pm$ 9
4435	HI-6	1962	-1.5	-51 $\pm$ 8
4438	HI-6	1963	-2.5	-44 $\pm$ 8
4441	HI-6	1964	-1.9	-24 $\pm$ 6
4349	HI-6	1965	-2.2	-5 $\pm$ 3
4346	HI-6	1966	-3.3	-25 $\pm$ 3
4434	HI-6	1967	-1.9	+1 $\pm$ 3
5018	D-12	1967	-2.8	+16 $\pm$ 5
4437	HI-6	1968	-2.7	+13 $\pm$ 5
4637	HI-7	1968	-3.2	+16 $\pm$ 4
5019	D-12	1968	-2.3	+17 $\pm$ 6
4351	HI-6	1969	-1.7	+31 $\pm$ 4
4598	HI-7	1969a	-2.9	+36 $\pm$ 4
4595	HI-7	1969b	-3.5	+11 $\pm$ 4
5016	D-12	1969	-2.2	+26 $\pm$ 8
4345	HI-6	1970	-2.4	+16 $\pm$ 5
4597	HI-7	1970	-3.7	+18 $\pm$ 4
5017	D-12	1970	-2.2	+16 $\pm$ 4
4347	HI-6	1971	-2.4	+25 $\pm$ 4
4639	HI-7	1971	-2.9	+30 $\pm$ 3
5015	D-12	1971	-2.2	+28 $\pm$ 3
4350	HI-6	1972	-2.2	+48 $\pm$ 3
4638	HI-7	1972a	-2.8	+28 $\pm$ 3
4636	HI-7	1972b	-3.0	+32 $\pm$ 4
5014	D-12	1972	-2.5	+45 $\pm$ 4
4439	HI-6	1973	-2.9	+16 $\pm$ 6
4634	HI-7	1973	-3.3	+17 $\pm$ 5
5008	D-12	1973	-2.4	+13 $\pm$ 5
4436	HI-6	1974	-2.5	+17 $\pm$ 5
4593	HI-7	1974a	-3.2	+17 $\pm$ 4
4596	HI-7	1974b	-3.8	+20 $\pm$ 4
5009	D-12	1974	-2.4	+28 $\pm$ 4
4348	HI-6	1975	-2.6	+39 $\pm$ 4
5007	D-12	1975	-2.4	+38 $\pm$ 4
4594	HI-7	1976	-3.5	+26 $\pm$ 3
5005	D-12	1976	-2.1	+46 $\pm$ 3
5006	D-12	1977	-2.7	+49 $\pm$ 5

Jan-Mar

regions (Druffel, 1980a) where waters have been at the surface for considerably longer.

A.D. 1961-1977 Radiocarbon results obtained from HI-6, HI-7 and D-12 clearly show bomb-produced ^{14}C (Figure 4). Values for the years 1965, 1969, 1972, 1975, 1976, and 1977 are unusually high; this is attributed to El Niño events that occurred during

these years (see below). Values for the non-El Niño years steadily rose from -59‰ in 1961 to $+25\text{‰}$ in 1972. If -75‰ is taken to be the pre-bomb $\Delta^{14}\text{C}$ value (Figure 3), an overall rise of 100‰ is observed by 1972. Atmospheric $^{14}\text{CO}_2$ concentration nearly doubled by 1963 due to the input of bomb-produced ^{14}C . By 1972, the ^{14}C value had decreased to about 500‰ and at present (1980) is about 300‰ . The increase in $\Delta^{14}\text{C}$ due to bomb ^{14}C in the eastern tropical Pacific is much smaller than that observed for North Atlantic corals (214‰ increase) (Figure 5) (Druffel and Linick, 1978; Druffel, 1980a). The smaller rise is attributable to the undefined thermocline in equatorial areas, which allows increased mixing with subsurface waters that contain lower $\Delta^{14}\text{C}$ values than those at the surface.

El Niño The appearance of warm, low salinity waters to the surface in the equatorial Pacific is known as El Niño (Wyrtki, et al., 1976). These waters come from north of the equator and contain higher levels of ^{14}C than the upwelled surface waters normally present in the Galápagos area. El Niño events start in January of certain years and last up to nine months. Results from seasonal samples were used to observe the difference of ^{14}C concentrations between the normal upwelled and El Niño surface waters.

The $\Delta^{14}\text{C}$ value for growth from HI-6 during 1969 was 31‰ (Figure 4). Analyses of the first and second halves of growth from HI-7 during 1969 reveal values of 36‰ and 11‰ , respectively. The average of these two values corresponds to the annual value of 31‰ . The high value for growth during the early part of 1969 reflects the $\Delta^{14}\text{C}$ of the El Niño waters. The El Niño of 1969 was a minor event that lasted only about five months. Upwelling returned during the second half of the year, as indicated by the low value of 11‰ for this period. The $\Delta^{14}\text{C}$ value for growth from HI-6 during 1972 (an El Niño year) was 48‰ , clearly higher than the values for adjacent non-El Niño years. The values for seasonal samples from HI-7, however, were 28‰ and 32‰ for growth during the first and second halves of 1972, respectively. These values do not agree well with that of the annual sample from HI-6. The reason for this is unclear at this time.

Seasonal samples were taken for growth during the non-El Niño year of 1974. The $\Delta^{14}\text{C}$ value for growth from HI-6 during 1974 was 17‰ . Results for growth from HI-7 during the first and second halves of 1974 were 17‰ and 20‰ , respectively. These results corroborate the 1974 value from HI-6. As warm, tropical waters remain north of the equator during non-El Niño years, there should be no noticeable difference between the ^{14}C levels of summer and winter waters in the Galápagos Islands. This was indeed observed for the 1974 coral growth.

Figure 5. Radiocarbon measurements for coral that grew in the Galápagos Islands, Belize and Florida from 1925 to 1978. A considerable difference is apparent between the North Atlantic data (Belize and Florida) and the eastern tropical Pacific data. This is attributed to the source of surface waters for each area.

Interpretation

The $\Delta^{14}\text{C}$ results for coral from the Galápagos Islands and from the North Atlantic Ocean differ considerably (Figure 5). Pre-bomb levels of ^{14}C were about 14‰ lower at the Pacific site than at either the Florida or Belize sites. By 1970, $\Delta^{14}\text{C}$ values in the North Atlantic corals had risen twice as much as those in the Galápagos corals.

The differences between the $\Delta^{14}\text{C}$ records for tropical Pacific coral and North Atlantic coral are due to varying degrees of upwelling for the two sites. The density structure of waters near the Galápagos Islands allows subsurface waters from 60 to 180 m depth to rise to the surface (Eastropac Atlas, 1971, 1972, 1975). Equatorial surface waters have been in contact with the atmosphere for relatively short periods of time. This is characterized by the low oxygen content and the high nutrient concentrations in these waters (Eastropac Atlas, 1971, 1972, 1975). Waters lavaging the Galápagos coral are subsurface most of the time, and as a result, have not received their full share of bomb $^{14}\text{CO}_2$ by exchange with the atmosphere. Waters in the Gulf Stream System exhibit horizontal layers of constant density and contain high oxygen and low nutrient concentrations (Oceano. Atlas of the No. Atlantic Ocean, 1967; Morrison, et al., 1973). These observations illustrate that surface waters in the Gulf Stream System have been in contact with the atmosphere for extended periods of time. The higher $\Delta^{14}\text{C}$ values in corals from Florida and Belize confirm this.

Acknowledgments

I thank Peter Glynn and Gerald Wellington for providing the coral heads used in this project. Thanks go to Sheila Griffin, Carol Hutto, Tim Linick, Don Sullivan and Paul Yeager for their technical services. Discussions with Drs. Bob Michel, Tim Linick, and Prof. Joseph Reid are appreciated. This project was funded by NSF Grant Numbers OCE-7917652 and EAR-78-15183 and constituted part of a doctoral dissertation with Prof. Hans E. Suess as the thesis advisor.

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(Received October 2, 1980;
accepted November 13, 1980.)