Title
Radiocarbon in annual coral rings of Florida

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Abstract. Radiocarbon measurements on a 175-year (A.D. 1800 to 1974) growth of the coral Montastrea annularis from the Florida Keys reveal the rate of local uptake of fossil fuel CO\textsubscript{2} and bomb 14C by surface ocean waters of the Gulf Stream. In the nineteenth century, the pre-bomb, pre-industrial Δ14C value of surface ocean waters as seen in these corals of the Gulf Stream in the Florida Straits was −51 ± 2‰. By 1955, uptake of industrial CO\textsubscript{2} by these waters had lowered the Δ14C values to about −61‰. The results can be used to make predictions regarding anthropogenic CO\textsubscript{2} that can be expected to enter the oceans in future decades. Bomb-produced 14C is found to be present in the corals in comparable concentrations to that found in the dissolved inorganic carbon (DIOC) of the North Pacific and North Atlantic Oceans.

Introduction

Radiocarbon measurements of dissolved inorganic carbon (DIOC) in ocean waters began in the mid-1950's (Bien. et al., 1960; Broecker. et al.. in press). They were used to identify water masses and to trace their general circulation patterns within the world's oceans. With the introduction of bomb-produced 14C to the ocean waters, 14C measurements of DIOC circulation patterns within the world's oceans, with the introduction of bomb-produced 14C to the ocean waters, 14C measurements of DIOC circulation patterns within the world's oceans. Pre-industrial Δ14C values for bomb-produced 14C to the ocean waters, 14C measurements of DIOC of the North Pacific and North Atlantic Oceans.

The Pre-Anthropogenic Δ14C Values

Table 1 (on microfiche) lists the results of radiocarbon measurements for Montastrea annularis growth from A.D. 1800 to 1974. The Δ14C values are reported in per mille (‰) based on a 0.95 NBS oxalic acid standard. All Δ14C values are normalized to a δ13C of −25‰ and for 14C decay from the time of ring formation to A.D. 1950. The table is available on microfiche. Order from American Geophysical Union, 1909 K Street, N. W., Washington, D. C. 20006. Document L78-004; $1.00. Payment must accompany order.
The Suess effect, which results from the burning of fossil fuels, has decreased the atmospheric concentration of carbon-14 by 11% since 1950. The Suess effect can also be observed in tree rings. The decrease in atmospheric carbon-14 has lowered the carbon-14 concentration in surface ocean waters, with an observed value of 0% in Gulf Stream surface waters. The decrease is exponential since its onset in the late 1800s (Revelle and Suess, 1957; Brannon, et al., 1957). In this way, an 11% decrease in DIOC radiocarbon from 1900 to 1955 is apparent.

## Bomb 14C

The testing of thermonuclear devices during the late 1950s and early 1960s released large amounts of neutrons, which reacted with nitrogen to form carbon-14. This increase in carbon-14 concentration in the atmosphere is known as the Suess effect. The Suess effect can be observed in tree rings, with a decrease of 11% in DIOC radiocarbon from 1900 to 1955.

### Fossil Fuel CO2

The combustion of fossil fuel since the late nineteenth century has increased the CO2 content of the atmosphere by 6% (Revelle and Suess, 1957). Carbon dioxide originating from the burning of fossil fuels contains no measurable carbon-14. As a result, this "dead" gas has diluted the existing atmospheric CO2 and has lowered the atmospheric carbon-14 concentration. This decrease (the Suess effect) was first observed in tree rings. It was found to be 33 ± 10% by 1955 in the northern hemisphere (Revelle and Suess, 1957; Münich and Vogel, 1958; Brannon, et al., 1957; Houtemans, et al., 1967). The Suess effect can also be expected to decrease surface ocean carbon-14 levels. Indeed, Figure 4 shows a decrease of 14C in coral from 1900 to 1955. Note that the four points for 1938, 1943, 1948 and 1953 are averages of five 14C measurements each, and error bars are standard deviations of those five points.

An exponential curve, fitted through the experimental values from 1900 to 1955, is shown in Figure 4 as a solid line. This type of fit is used because the input of fossil fuel CO2 to the atmosphere has been nearly exponential since its onset in the late 1800s (Revelle and Suess, 1957; Brannon, et al., 1957). In this way, an 11% decrease in DIOC radiocarbon from 1900 to 1955 is apparent.

### Bomb 14C

The testing of thermonuclear devices during the late 1950s and early 1960s released large amounts of neutrons, which reacted with nitrogen to form carbon-14. After rapid oxidation of the carbon-14 atoms to carbon dioxide, the concentration of tropospheric carbon dioxide in the northern hemisphere temporarily reached values a factor of two above normal (Figure 3). This carbon-14 "bomb spike" decreased during the following years, primarily by isotope exchange with the ocean's DIOC. The coral data reported here (Figure 4) show that, as early as 1959, bomb carbon-14 was present in observable amounts in Gulf Stream surface waters. Its maximum carbon-14 value of 152%o was reached around 1969. This time delay between the atmospheric and oceanic carbon-14 maxima shows that several years are required for the atmosphere and the surface ocean to approach a steady state. Similar carbon-14 values were obtained by GESECS in 1972-73 for DIOC in the surface waters of the Atlantic Ocean; in the mid-North Atlantic carbon-14 values of about 150 to 185%o prevailed during that time (Ostlund, et al., 1974; Ostlund, et al., 1976). In the northern mid-Pacific, carbon-14 values for DIOC in surface waters (Linick, 1975) were similar to those for the corals shown in Figures 3 and 4.
4. Bomb $^{14}C$ was first detected there in the late 1950's. Its maximum of 160‰ was reached around 1970. Bomb $^{14}C$ in equatorial surface waters is considerably diluted due to the upwelling of subsurface waters having diminished $^{14}C$ concentrations.

The origin of Gulf Stream waters in the Florida Straits is mainly the southwestern Sargasso Sea and the North Equatorial Current (Iselin, 1936; Stommel, 1965). Less than one-third of the water originates in the South Atlantic. Therefore, as we might expect, Gulf Stream waters responded to atmospheric bomb $^{14}C$ somewhat like the North Pacific and North Atlantic mid-oceanic gyre surface waters, but dissimilar to equatorial surface waters where significant upwelling occurs.

Conclusions

The coral data presented here give the first accurate information on pre-fossil fuel concentrations of $^{14}C$ in surface water DIOC. $^{14}C$ values of $-5 \pm 2\%_o$ prevailed with no significant variation during the time period from A.D. 1800 to 1900.

The presence of both fossil fuel CO$_2$ and bomb $^{14}C$ in annual coral rings from the Gulf Stream near the Florida coast can be recognized. The bomb $^{14}C$ observed by us for the Gulf Stream is in some ways similar to that of mid-gyre surface waters in the oceans of the world. If one applies a simple three-box model to the situation where the three boxes are the troposphere, the surface ocean (to about 100m depth where total inorganic carbon of the troposphere equals that of the surface ocean) and the deep ocean, then one can make the following statement. Using known atmospheric $^{14}C$ values (Nydal, in press), a close fit of the bomb $^{14}C$ measurements in coral growth from 1959 to 1974 requires apparent residence times for carbon dioxide in the atmosphere (with respect to transfer to the surface ocean) and in the surface ocean (with respect to transfer to the deep ocean) of 14 and 8.5 years, respectively. Using these values, the predicted drop by 1955 in the radiocarbon of Gulf Stream surface waters due to the input of fossil fuel CO$_2$ is 12‰. This agrees with the experimentally determined decrease of 11‰ found in this work.

Extrapolation of the exponential curve fitted to the experimental $^{14}C$ values between 1900 and 1955 predicts future uptake of excess CO$_2$ from fossil fuel combustion (dashed line, Figure 4). If the input of fossil fuel CO$_2$ to the atmosphere continues to grow exponentially, then an additional $^{14}C$ decrease of 12‰ can be expected by the year A.D. 2000 (from 1955) for the DIOC of Gulf Stream waters.

$^{14}C$ concentrations in the DIOC of the surface layers of the northern Pacific and Atlantic Oceans are slightly higher than that of the corals in the Florida Straits. This may be a result of some North Equatorial Current water (subject to upwelling) entering the Gulf Stream System.

It must be pointed out that this one set of $^{14}C$ measurements is by no means sufficient for the purpose of examining the uptake of industrial CO$_2$ and bomb $^{14}C$ by the surface waters of the world's oceans. Many more coral series from varying localities must be analyzed in order to obtain a firm handle on this problem.
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