IV. OCEANOGRAPHY

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LONG-TERM VARIABILITY OF TEMPERATURE AND ^{14}C IN THE GULF STREAM: OCEANOGRAPHIC IMPLICATIONS

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ABSTRACT. Variability in temperature and ^{14}C levels are recorded in coralline aragonite that grew in the Gulf Stream during the past four centuries. In particular, $^{18}O/^{16}O$ ratios reflect a decrease of ca 1°C in surface water temperature during the latter part of the Little Ice age. ^{14}C levels also rose in the surface waters of the Gulf Stream and in atmospheric CO_2 during the Maunder minimum. These observations indicate that ocean circulation may have been significantly different in the North Atlantic around the beginning of the 18th century.

INTRODUCTION

^{14}C levels were especially high during 3 distinct periods of the 2nd millenium AD (Stuiver and Quay, 1981). These intervals are known as the Wolf minimum (AD 1300), Sporer minimum (AD 1500) and Maunder minimum (AD 1700), when solar activity was especially low (Waldmeier, 1961; Eddy, 1976). The galactic cosmic ray flux responsible for ^{14}C production is modulated by changes in solar wind magnetic fields. When the intensity of the solar wind decreases, as in a time of low sun spot numbers, more galactic cosmic rays are admitted to the earth's atmosphere, causing increased ^{14}C production. The three periods of unusually high ^{14}C production were coincident, though not directly correlated (Stuiver, 1980), with recorded intervals of especially severe winters in Europe (Suess, 1980), a period known as the Little Ice age. Whether the Little Ice age was a direct result of low solar activity or a coincidence has not yet been resolved.

One possibility not yet investigated is that which could involve the oceans as the cause of the increase in atmospheric ^{14}C levels. It is conceivable that decreased vertical mixing in the upper few hundred meters of the water column could have induced this rise in ^{14}C. In order to eliminate this possibility, however, it is necessary to acquire ^{14}C and temperature records for this period in the oceans. Banded, hermatypic corals are useful for recovering valuable information on past surface ocean water character (Druffel and Linick, 1978; Nozaki *et al*, 1978; Druffel, 1982). Coral records can be correlated with atmospheric ^{14}C records to determine the causal relationship and timing of ^{14}C variations observed in these two reservoirs during the past, and they can also yield important information about changes in ocean circulation during the Little Ice age.

Within the aragonitic skeleton, corals record the $^{14}C/^{12}C$ ratio of the dissolved inorganic carbon (DIC) in sea water at the time of formation (Druffel and Linick, 1978). Temperature records can also be reconstructed for waters at the time of formation using the $^{18}O/^{16}O$ ratio of calcium carbonate in corals (Fairbanks and Dodge, 1979). As the world's surface oceans are saturated with respect to aragonite, hermatypic coral skeletons do not dissolve with time. Nor does aragonite exchange with any other source of carbon. Coralline aragonite is a permanent, unaltered record of the $^{14}C/^{12}C$ and $^{18}O/^{16}O$ ratios that existed in past surface sea waters.

A morphologic characteristic that make reef-building corals so useful as geochemical probes is the annual density variation of the accreted aragonite. These 'bands' are primary skeletal features exhibited as seasonal variations in the bulk density of the secreted skeleton (Buddemeier, Maragos, and Knutson, 1974). The growth bands are discernible by X-ray (some by the naked eye) of a thin slab of coral skeleton (4 to 10mm thick). Many authors have confirmed the annual nature of coral banding by using various techniques such as in situ alizarin staining, densiometry, autoradiography, and direct field observations (Knutson, Buddemeier and Smith, 1972; MacIntyre and Smith, 1974; Hudson et al, 1976). Various radioisotopes, such as bomb-produced ^{14}C, ^{90}Sr, and ^{228}Ra have also corroborated the annual nature of growth bands in corals (Druffel, 1980; Toggweiler, 1980; Moore and Krishnaswami, 1974).

PROCEDURE

The coral cores used in this project were collected from "The Rocks" reef off the Florida Keys. They were laved by waters flowing through the Florida Straits, a part of the Gulf Stream System, which originates in the Caribbean Sea. Hudson et al (1976) used corals of the same species (Montastrea annularis) from the Florida Straits to illustrate a second type of high density banding, stress bands, that occur during periods of extreme cold on the reef. These workers observed an excellent correlation between Cold Fronts recorded in southern Florida and the appearance of unusually high density bands in the coral record spanning the past 50 years.

Examination of the stress banding in two cores reveals an excellent correlation with Cold Fronts recorded as far back as 1856. This indicates that Montastrea annularis do not eliminate growth bands, nor do they accrete extra bands.

The coral cores were X-rayed (fig 1) and sectioned in the manner described elsewhere (Druffel, 1982). ^{14}C measurements were made on samples representing one to ten years' growth. Gas proportional counting techniques were used with acetylene as the counting gas. ^{14}C values are

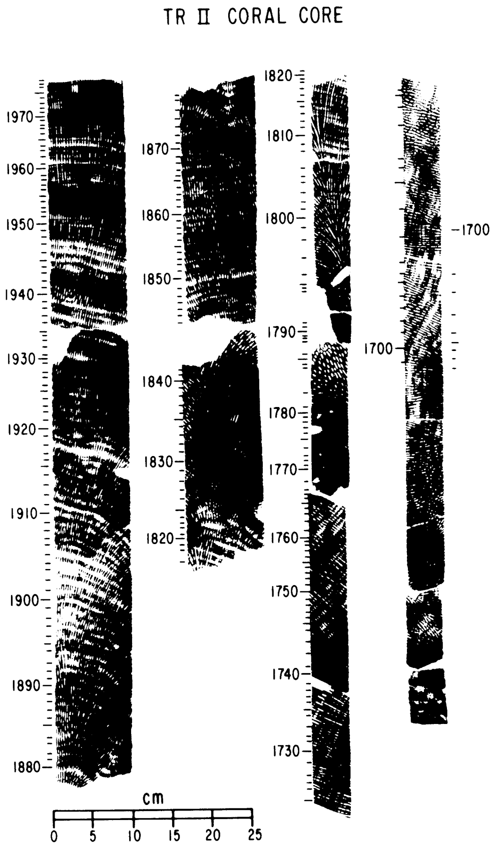

Fig 1. X-radiographs of the coral slabs from the core of Montastrea annularis (TRII) collected in July, 1978. A core collected in June 1975 (TRI) was also used in this project. Dark, dense bands represent growth during warm water months (July through September). Thus, TRII represents coral growth from AD 1694 to 1978.

reported in the standard Δ notation (Broecker and Olson, 1961) and were corrected for decay from the time of formation to AD 1950. Precision of these measurements ranged from 3^{o}/oo to 6^{o}/oo. ^{18}O/^{16}O ratios were performed by W G Mook at the University of Groningen on samples of one year's growth (Druffel, 1982). Results are reported in the standard δ (^{o}/oo) notation relative to the PDB-1 standard. Precision for isotopic measurements was ±0.05^{o}/oo.

RESULTS

^{14}C measurements were made on two Florida coral cores (TRII shown in Figure 2) for the period AD 1642-1952. Several trends are apparent in this time series. First, the baseline $\Delta^{14}C$ value is ca -48^{o}/oo. A deviation from this trend

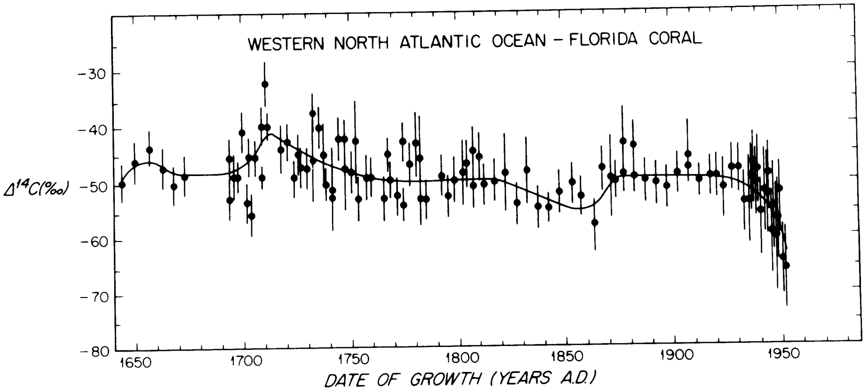

Fig 2. $\Delta^{14}C$ measurements of Florida coral cores (1642-1952). Three long-term trends are apparent: 1) 1710-1750: Little Ice age effect seen as a 7^{o}/oo rise in $\Delta^{14}C$ and subsequent decrease. This is probably the result of increased ^{14}C levels in the atmosphere during this time; 2) 1820-1870: 4^{o}/oo to 5^{o}/oo decrease in $\Delta^{14}C$, which may be the result of decreased ^{14}C levels in the atmosphere during the 19th century; 3) 1900-1952: Suess effect is ca -12^{o}/oo in the Gulf Stream surface ocean waters (Druffel and Linick, 1978).

occurred ca AD 1710, when values rose sharply by 7^{o}/oo in about ten years and then slowly decayed back to -50^{o}/oo by 1750. Second, $\Delta^{14}C$ values decreased slowly during the early to mid-1800's by $4-5^{o}$/oo, and then returned to the ambient level (-50^{o}/oo) rather quickly. Third, a decrease of 11^{o}/oo is noticed from AD 1900-1952, and is attributed to the dilution of existing ^{14}C levels by the input of fossil fuel CO_2 to the oceans (Druffel and Linick, 1978; Nozaki et al, 1978). Estimates for the Suess effect in the atmosphere range from -18^{o}/oo to -25^{o}/oo.

To interpret this oceanic ^{14}C record, it must be correlated with the ^{14}C record in the atmosphere obtained from tree rings (Stuiver and Quay, 1981). Line drawings representing both of these ^{14}C records appear in Figure 3. As CO_2 is exchanged between atmosphere and ocean, a rise in the atmospheric $^{14}CO_2$ concentration would also be

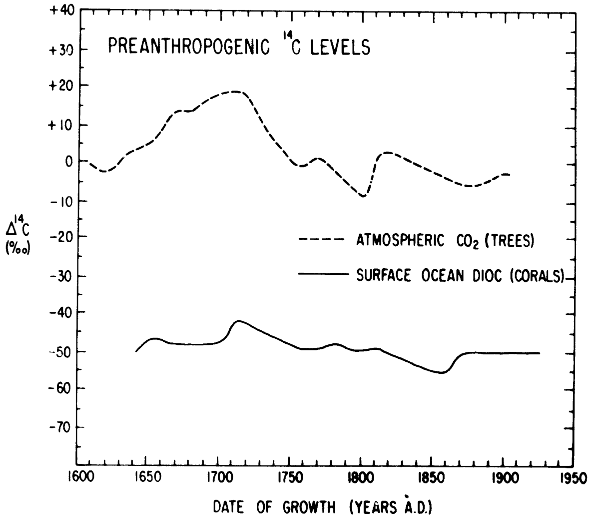

Fig 3. Average pre-anthropogenic ^{14}C levels in tree rings and coral rings that grew from AD 1600-1900. The Δ^{14}C trend for trees is based on data from numerous areas in North America (Stuiver and Quay, 1980; Tans, de Jong and Mook, 1979). The Δ^{14}C trend for corals is a spline curve fitted to data from Montastrea annularis collected from the Florida Straits (Druffel, 1982).

expected in the DIC of the surface ocean. Such is the case with the ^{14}C peak ca 1700. There is a lag time of 3 to 4 decades between the onset of the rise in the atmosphere and in the ocean. Part of this delay can be attributed to the long residence time of 10-15 years for $^{14}CO_2$ in the atmosphere (Druffel and Suess, in press). The rise probably originates in the atmosphere due to solar modulation of the cosmic-ray flux. The overall ^{14}C rise in the atmosphere was ca 20^{o}/oo, whereas that in the oceans was only 7^{o}/oo. The signal was attenuated in the oceans due to vertical exchange of older subsurface waters (which contain less ^{14}C due to in situ decay) with surface waters.

During the 19th century, ^{14}C levels in both the atmosphere and ocean decreased substantially. Again, the amount of decrease in the ocean (4-5^{o}/oo) was attenuated in comparison to that in the atmosphere (9^{o}/oo). This change in the ^{14}C level is also believed to have been caused by variation in solar activity; the decrease in ^{14}C originated in the atmosphere and then filtered into the surface ocean by gas exchange.

An alternative explanation for the rise in ^{14}C ca AD 1700 involves the role of the oceans during this period. A decrease in the rate of vertical mixing in the upper few hundred meters of the water column could conceivably have caused a rise in ^{14}C levels in both the surface ocean and atmosphere. This scenario would also be accompanied by higher surface water temperatures, a phenomenon not expected during a small ice age.

Stable isotopic measurements of yearly samples from the Florida cores, however, indicate that the water temperature in the Gulf Stream was slightly lower during the early 1700's and increased ca 1°C by 1800 (fig 4). Superimposed on this trend toward lighter (warmer) $\delta^{18}O$ values with time, is a fine structure that illustrates variations on a decade time scale. Cooler surface water temperatures during the early 1700's implies that there was an increase in vertical mixing between surface and subsurface waters, not a decrease as would have been the case had changes in ocean circulation been the cause of the ^{14}C rise in the atmosphere during this period.

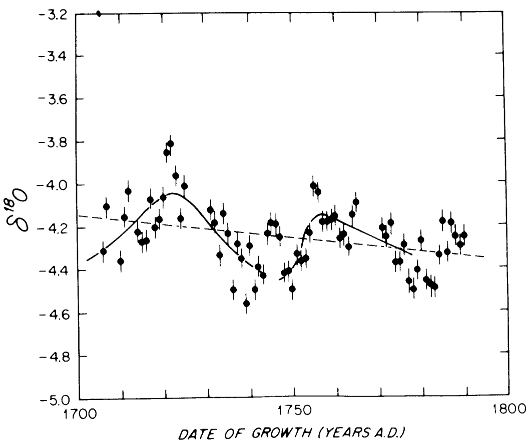

Fig 4. $\delta^{18}O$ measurements (made by W G Mook) for annual coral samples from the TRI core, relative to the Chicago PDB standard. A least squares fit of the individual measurements (dashed line) reveals a 0.2°/oo decrease from AD 1700-1790. Using the calibration curve of Dunbar and Wellington (1981) this decrease represents an overall rise in seawater temperature of ca 1°C from 1700-1790. There also appears to be two maxima in $\delta^{18}O$ ca 1720 and 1760, representing periods of lower seawater temperature.

OCEANOGRAPHIC IMPLICATIONS

The Gulf Stream originates in the Sargasso Sea, an anti-cyclonic, subtropical gyre in the North Atlantic (fig 5).

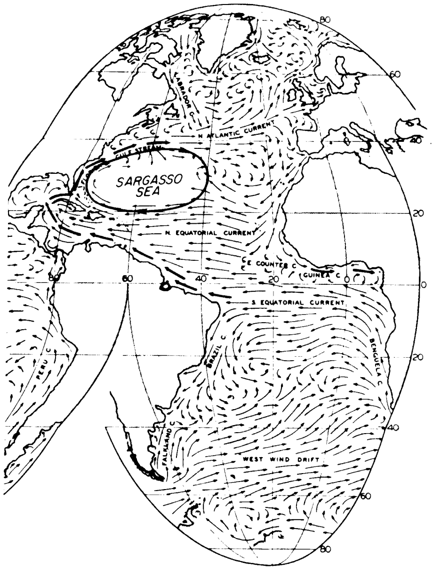

Fig 5. Surface currents of the Atlantic Ocean. The Sargasso Sea, a subtropical gyre in the northwestern Atlantic, circulates in an anticyclonic (clockwise) direction and is the main source of water for the Gulf Stream.

The circulation in the surface mixed layer is wind-driven (Ekman transport) and that in the deep water is powered by geostrophic forces. Ekman transport is convergent in a subtropical gyre, which forces water downward from the mixed layer (fig 6). There is a complex process at work that selects only late winter water for actual net downward pumping, called Ekman pumping, into the geostrophic regime below (Stommel, 1979). As the surface waters in the Gulf Stream were 1°C cooler during the early 1700's, the Sargasso Sea surface waters were probably also cooler during this period as well. It is likely that cooler surface water temperatures during the latter part of the Little Ice age promoted enhanced downward penetration of waters in the Sargasso Sea during the late winter, and perhaps induced prolonged convection that extended from early winter to

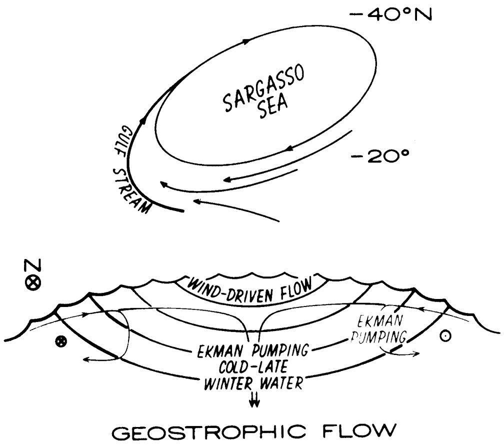

Fig 6. Areal view of the circulation of the Sargasso Sea (upper portion). Schematic representation of isopycnals and circulation within the gyre along 30°N (lower portion). Water is carried downward by Ekman transport (downwelling) and is incorporated into the deeper geostrophic flow only during late winter, when water is cold and dense.

spring.

Variations in temperature on decade time scales in Gulf Stream surface waters (fig 4) also have important implications for our understanding of ocean circulation. Jenkins (1982) calculated a factor of two variation in the shallow water mass renewal rates from 1954-1980 based on oxygen, salinity, and ^3H-^3He data from the Sargasso Sea. The data presented here also imply that long-term variations in circulation have occurred in the ocean and cannot be ignored when modeling geochemical quantities such as Lagrangian tracers.

CONCLUSIONS

The ^{14}C rise in surface waters of the Florida Straits and in atmospheric CO_2 during the Little Ice age was probably the result of reduced solar activity during the Maunder minimum. Stable isotopic analyses ($\delta^{18}O$) of these corals show that slightly cooler surface water temperatures (by 1°C) were present in the Gulf Stream during the latter part of the Little Ice age. This cooling suggests that ocean mixing patterns may have been different in the Gulf Stream during this period. A likely scenario may have included enhanced convection in the Sargasso Sea that consisted not only of late winter water (Stommel, 1979) but also the downward penetration of cooler spring and early winter water into the geostrophic regime below.

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