THE DISTRIBUTION OF RADIOCARBON IN THE GLACIAL OCEAN

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Abstract. Accelerator mass spectrometric radiocarbon measurements on benthic foraminifera shells, picked from samples on which concordant ages were obtained on the shells of two species of planktonic foraminifera, reveal that the age of deep water in the equatorial Atlantic during glacial time was 675±80 years (compared to today's age of 350 years) and that the age of deep water in the South China Sea was 1670±105 years (compared to today's value of 1600 years). These results demonstrate that the 1.3 to 1.5 times higher radiocarbon content of carbon in glacial surface waters of the Caribbean Sea reconstructed by Bard et al. [1990] was primarily the result of a higher global inventory of radiocarbon rather than a decrease in rate of mixing between surface and deep waters of the ocean. The results are also consistent with the conclusion by Boyle and Keigwin [1987] that the flow of North Atlantic Deep Water was considerably weakened during glacial time, allowing deep waters of Antarctic origin to push much further north into the Atlantic than they do today.

INTRODUCTION

During peak glacial time 20,000 to 14,000 years ago, the Earth was a very different place. Not only was it colder and more ice covered, but it was dustier and poorer in greenhouse gases. About 14,000 years ago a change occurred which created conditions more akin to those of today. Broecker and Denton [1989] postulate that this change was brought about by a reorganization of the entire ocean-atmosphere system. If so, then it is important to learn as much as possible about the manner in which the system operated during glacial time. Fortunately, a wealth of information regarding the patterns and rates of large-scale circulation in the ocean is available in deep-sea sediments. To date the most definitive information in this regard comes from cadmium to calcium ratios in shells of benthic foraminifera [Boyle and Keigwin, 1987; Boyle, 1988a]. These results reveal that during glacial time the pattern of circulation was much different than today's. The nutrient constituent maxima which in today's ocean lie at intermediate depth were shifted toward the bottom. The strong contrast between the nutrient content of deep water in the Atlantic and Pacific observed in today's ocean was smaller during glacial time.

Although not a recorder of any specific change in ocean operation, the lower CO2 content of the glacial atmosphere can only be explained through a major change in the interaction between the sea's mixing...
### TABLE 1. Holocene Age Measurement Sets

| Depth, cm | Planktonic Age, Years | Benthic Age, Years | ΔBenth-Plank, Years |
|-----------|-----------------------|--------------------|---------------------|
| 1-3       |                        |                    |                     |
| G sacc    | 2930±120              | 3280±140           | 300±165             |
| G rub     | 3040±130              | 3280±140           |                     |
| Mean      | 2980±90               | 3280±140           | 300±165             |
| Vema 28-122, Caribbean Sea; 11° 56'N, 7° 41'W, 3623 m; Today's Deep Water Age, 300 Years |
| 8-13      |                        |                    |                     |
| G sacc    | 2040±70               | 3970±80            |                     |
| P obl     | 2430±60               |                    |                     |
| Mean      | 2260±190              | 3970±80            | 1710±205            |
| Sonne 50-37KL, South China Sea; 18°54'N, 115°46'E, 2695 m; Today's Deep Water Age, 1600 Years |
| 40-45     |                        |                    |                     |
| G sacc    | 5960±80               | 8270±100           |                     |
| P obl     | 6510±80               |                    |                     |
| Mean      | 6235±275              | 8270±100           | 2035±290            |

*The species names are: Globigerinoides sacculifer, Globigerinoides ruber, Pulleniatina obliquiloculata, and Globorotalia dutertrei.

### TABLE 2. Glacial Age Measurement Sets Yielding Concordant Planktonic Ages

| Depth, cm | Planktonic Age, Years | Benthic Age, Years | ΔBenth-Plank, Years |
|-----------|-----------------------|--------------------|---------------------|
| 25-28     |                        |                    |                     |
| G sacc    | 14150±160             | 14930±200          |                     |
| G rub     | 13870±260             |                    |                     |
| N dut     | 13860±140             |                    |                     |
| Mean      | 13970±100             | 14930±200          | 960±225             |
| Knorr 110-82GGC Equatorial Atlantic Ceara Rise; 4° 20'N, 43° 29'W, 2816 m |
| 30-33     |                        |                    |                     |
| G sacc    | 15100±250             | 16350±280          |                     |
| G sacc    | 15080±120             |                    |                     |
| G rub     | 15450±260             |                    |                     |
| G rub     | 15130±120             |                    |                     |
| N dut     | 15170±260             |                    |                     |
| N dut     | 14820±120             |                    |                     |
| Mean      | 15050±75              | 16350±280          | 1300±290            |
| 35-38     |                        |                    |                     |
| G sacc    | 16090±320             | 16130±240          |                     |
| G rub     | 15870±290             |                    |                     |
| N dut     | 16060±200             |                    |                     |
| Mean      | 16020±145             | 16130±240          | 110±280             |
| 40-43     |                        |                    |                     |
| G sacc    | 16710±250             | 17870±370          |                     |
| G rub     | 17040±250             |                    |                     |
| N dut     | 17610±280             |                    |                     |
| Mean      | 17085±255             | 17870±370          | 785±450             |
| 45-48     |                        |                    |                     |
| G sacc    | 17780±360             | 17900±640          |                     |
| G rub     | 17430±430             |                    |                     |
| N dut     | 17660±260             |                    |                     |
| Mean      | 17650±190             | 17900±640          | 250±665             |
| Knorr 110-66GGC Equatorial Atlantic Ceara Rise; 4° 34'N, 43° 23'W, 3547 m |
| 45-50     |                        |                    |                     |
| G sacc    | 16450±150             | 17030±150          |                     |
| N dut     | 16660±150             |                    |                     |
| Mean      | 16555±105             | 17030±150          | 475±185             |

*The species names are: Globigerinoides sacculifer, Globigerinoides ruber, Pulleniatina obliquiloculata, and Globorotalia dutertrei.*
TABLE 2. (continued)

| Depth, cm | Planktonic Age, Years | Benthic Age, Years | ΔBenth-Plank, Years |
|-----------|-----------------------|--------------------|---------------------|
| **Knorr 110-66GGC, Equatorial Atlantic Ceara Rise; 4° 34'N, 43° 23'W, 3547 m (continued)** |
| 49-53 G sacc | 16800±150 | 17690±150 |
| N dut | 17030±150 |
| Mean | 16945±115 | 17690±150 | 775±190 |
| 53-58 G sacc | 18130±160 | 18630±180 |
| N dut | 18060±180 |
| Mean | 18100±120 | 18630±180 | 535±215 |
| 56-61 G sacc | 18860±190 | 19540±220 |
| N dut | 18980±190 |
| Mean | 18920±135 | 19540±220 | 620±260 |
| **Knorr 110-50GGC, Equatorial Atlantic Ceara Rise; 4° 52'N, 43° 13'W, 3995 m** |
| 20-23 G sacc | 13850±130 | 14760±140 |
| N dut | 14500±200 |
| Mean | 14045±295 | 14760±140 | 715±325 |
| 22-27 G sacc | 16900±170 | 17110±190 |
| N dut | 16740±210 |
| Mean | 16835±130 | 17110±190 | 275±230 |
| 27-32 G sacc | 17350±170 | 18360±200 |
| N dut | 17540±160 |
| Mean | 17450±115 | 18360±200 | 910±230 |
| 31-36 G sacc | 18210±190 | 19110±190 |
| N dut | 18620±200 |
| Mean | 18405±205 | 19110±190 | 705±280 |
| 35-40 G sacc | 19470±180 | 20360±220 |
| N dut | 18980±160 |
| Mean | 19195±245 | 20360±220 | 1165±330 |
| **Vema 28-122, Caribbean Sea; 11° 56'N, 78° 41'W, 3623 m** |
| 115-123 G sacc | 17120±150 | 17300±150 |
| G rub | 16980±140 |
| Mean | 17045±100 | 17300±150 | 255±180 |
| 123-125 G sacc | 17390±160 | 17610±180 |
| G rub | 17680±170 |
| Mean | 17525±145 | 17610±180 | 85±230 |
| 129-139 G sacc | 17910±140 | 18530±120 |
| G rub | 18730±480 |
| Mean | 18245±405 | 18530±420 | 285±585 |
| **Sonne 50-37KL, South China Sea; 18° 54'N, 115° 46'E, 2695 m** |
| 160-165 G sacc | 15140±150 | 17100±200 |
| P obl | 15300±150 |
| Mean | 15220±105 | 17100±200 | 1880±225 |
| 175-180 G sacc | 15910±110 | 17430±140 |
| P obl | 15890±120 |
| Mean | 15900±80 | 17430±140 | 1530±160 |
| 195-200 G sacc | 17460±160 | 18940±160 |
| P obl | 17270±150 |
| Mean | 17360±110 | 18940±160 | 1580±195 |
| 205-210 G sacc | 17660±180 | 19445±190 |
| P obl | 17225±190 |
| Mean | 17455±115 | 19445±190 | 1990±285 |
cycles and biological cycles [Sarmiento and Toggweiler, 1984; Knox and McElroy, 1984; Siegenthaler and Wenk, 1984; Boyle, 1988b; Broecker and Peng, 1989].

A property of importance to the understanding of today's rate of deep-sea ventilation, i.e., the $^{14}C/C$ difference between surface and deep water, can now be reconstructed for glacial time. Radiocarbon measurements by the accelerator mass spectrometric (AMS) method on shells of foraminifera handpicked from deep-sea sediments offer the possibility that this reconstruction can be accomplished for the last 20 thousand years or so [Broecker et al., 1984]. The idea is that the ratio of the $^{14}C/C$ for benthic foraminifera to that for planktonic foraminifera coexisting in deep-sea sediments does not change with time during the glacial period. Hence radiocarbon measurements on coexisting benthic and planktonic foraminifera shells provide a measure of the $^{14}C/C$ difference between surface water and water at the depth from which the core was taken. For convenience this difference is expressed as an age (i.e., the time required for the surface water $^{14}C/C$ ratio to decay to that for deep water). In today's tropical Pacific, this age difference is about 1600 years, while in the tropical Atlantic it is about 350 years.

Using this strategy, Andree et al. [1986] showed that over the course of Holocene time the age difference for waters at 2 km depth in the western Pacific was the same as today's to within the measurement uncertainty (i.e., <200 years). Based on measurements on a core from the Ceara Rise, Broecker et al. [1988a] suggested that the age of deep water in the western tropical Atlantic was roughly twice as great during glacial time than it is today. Shackleton et al. [1988] and Broecker et al. [1988a] obtained results suggesting that the age of deep water in the tropical Pacific was somewhat greater during glacial time (~2000 years) than it is today (~1600 years). These latter results are however far from conclusive. The Shackleton et al. [1988] results come from an area where upwelling currently influences the $^{14}C/C$ ratio in the photic zone. Because of this, the planktonic results do not necessarily reflect conditions typical of the surface ocean. Further, they present only two results from peak stage 2 time (i.e., 20,000 to 14,000 years ago). Both suggest a lower age difference than those before 20,000 years ago. Two of the three cores reported by Broecker et al. [1988a] come from areas of such low accumulation rate that the bioturbation-abundance couple [see Broecker et al., 1984] likely introduces biases in the age difference. The third core analyzed by Broecker et al. [1988a] showed a systematic (and unexplained) discordance between the ages obtained on two planktonic species, G. sacculifera and P. obliquiloculata.

Broecker [1989] pointed out that the smaller surface to deep $^{14}C/C$ ratio difference for the glacial Atlantic could be explained either by a slowdown of the Atlantic's conveyor or by an inversion of the Atlantic's circulation. However, with an inverted glacial circulation he was not able to account for Boyle's [1988a] observation that although the interocean nutrient content difference was smaller during glacial time, waters in the deep Atlantic still had a smaller nutrient content than those in the deep Pacific.

In this paper we present new radiocarbon results which broadly support the conclusions reached in previous papers and which overcome the uncertainties associated with the previous results from the tropical Pacific.

RESULTS

We use as a criterion for validity of each benthic-planktonic age difference measurement that agreement exist (at the 2σ level) between the ages obtained on two separate species of planktonic foraminifera. The logic behind this strategy is that neither the averaging of discordant planktonic results nor the arbitrary selection of one result over the other is likely to produce a reliable estimate of the benthic-planktonic age difference.

To date we have results which meet this criterion from five deep-sea cores, one from the South China Sea (representing 2.1-km depth water in the western tropical Pacific), one from the Caribbean (representing 1.8-km depth water from the western tropical Atlantic) and three from the Ceara Rise (representing 2.8-km to 4.0-km depth water in the western tropical Atlantic). The measurements representing Holocene time are listed in Table 1. Those representing glacial time are listed in Table 2. The age differences obtained for glacial time from those five cores are summarized in Table 3. A complete listing of results from these cores (including abundance data) have been published by Broecker et al. [1988b, 1990a].

For the tropical Pacific we see no discernable change in the surface to deep $^{14}C/C$ difference between glacial and Holocene time. While the mean age differences for the Holocene ocean (1820±165 years) and for the glacial ocean (1670±105 years) are slightly larger than that for today's ocean (1600 years), more benthic-planktonic measurements will have to be obtained before these small differences can be confirmed.

In the case of the Atlantic we think that we now have enough measurements in the 2.8-4.0 km depth range to say with some certainty that the age of North Atlantic Deep Water (NADW) in the western equatorial Atlantic was greater during glacial time than it is today. As shown in Figures 1 to 3 and summarized in Figure 4, the age of Atlantic deep water averaged 675±80 years during peak glacial time as opposed to 350 years today. As shown in Figures 1 to 3, the $^{13}C/C$ ratio for benthic forams was lower (by 0.8±0.2‰) during glacial time than during Holocene time at the sites of these cores.

The core from the Caribbean is representative of water at about 1.8 km depth at about 15°N in the
TABLE 3. Summary of Age Estimates for Glacial Deep Water (i.e., Benthic-Planktonic Age Differences)

| Location | Core    | Latitude | Longitude | Water depth, km | Number of Pairs | Mean Benth-Plank Age, Years | Today's Age, Years |
|----------|---------|----------|-----------|-----------------|-----------------|----------------------------|-------------------|
| Atlantic | V28-122 | 12°N     | 79°W      | 1.8*            | 3               | 195±140                    | 300               |
| Atlantic | K110-82 | 4°N      | 43°W      | 2.8             | 5               | 780±220                    | 350               |
| Atlantic | K110-66 | 5°N      | 43°W      | 3.5             | 4               | 600±105                    | 400               |
| Atlantic | K110-50 | 5°N      | 43°W      | 4.0             | 5               | 705±150                    | 400               |
| Pacific  | S50-37  | 19°N     | 116°E     | 2.1             | 4               | 1670±105                   | 1600              |

*Sill depth of Caribbean.

DISTRIBUTION OF RADIOCARBON IN THE GLACIAL OCEAN

An attempt at reconstructing the distribution of radiocarbon in the glacial ocean is shown in Figure 7. Based on measurements on corals recovered off Barbados by Fairbanks [1989], Bard et al. [1990] show that during peak glacial time a discrepancy of about 3200 years exists between the radiocarbon age and the radiothorium age scale. For example, a coral...
Fig. 2. Carbon and oxygen isotope composition of benthic foraminifera shells as a function of depth in western equatorial Atlantic core KNR110-66GGC [Curry et al., 1988]. Also shown are the levels at which planktonic-benthic age differences were determined. At the left the age of the horizon is given (planktonic mean - 400 years). At the right are the differences between the benthic age and the mean planktonic age.

Fig. 3. Carbon and oxygen isotope composition of benthic foraminifera shells as a function of depth in western equatorial Atlantic core KNR110-82GGC [Curry et al., 1988]. Also shown are the levels at which planktonic-benthic age differences were determined. At the left the age of the horizon is given (planktonic mean - 400 years). At the right are the differences between the benthic age and the mean planktonic age.
Fig. 4. Benthic-planktonic age differences versus horizon age for the three cores from the western basin of the equatorial Atlantic. The mean for these 14 determinations is 675±80 years.

Fig. 5. Carbon and oxygen isotope records for core V28-122 from the Caribbean Sea [Oppo and Fairbanks, 1987]. Also shown are the levels at which benthic-planktonic age differences were determined. At the left are the horizon ages (i.e., mean planktonic age - 400 years). At the right are the age differences.
yielding $^{14}$C ages of 18,700 years yields a $^{230}$Th age of 21,900 years. Bard et al. [1990] make a strong case that this difference reflects a 1.5 times higher Earth $^{14}$C inventory during peak glacial time. The higher $^{14}$C production rate required to maintain this inventory presumably reflects a lower Earth magnetic field. We accept this result and therefore place the atmospheric $^{14}$C/$C$ ratio for peak glacial time at 1.5 times the 1850 A.D. value.

At steady state the atmosphere to surface ocean $^{14}$C/$C$ ratio difference must be of the right magnitude in order that air-sea $CO_2$ exchange carries radiocarbon into the sea as fast as it decays within the sea. The delivery rate depends not only on the air-sea $^{14}$C/$C$ difference but also on the $CO_2$ partial pressure in the atmosphere and the wind velocity over the sea. For glacial time we know from ice core studies [Raynaud et al., 1988; Neftel et al., 1988] that the atmospheric $CO_2$ pressure was about 200 $\mu$atm as opposed to 280 in 1850 A.D. While the mean wind velocity over the ocean may have been different, we have no means to reconstruct even the sign of this difference. Hence we are forced to assume it to be similar to today’s. While temperature influences both the $CO_2$ concentration in seawater and the diffusivity of $CO_2$ in seawater, these factors largely compensate one another with respect to $CO_2$ exchange [see Broecker and Peng, 1982]. Hence, the glacial to interglacial difference in sea surface temperature need not be considered. Hence

\[
\left[1 - \frac{^{14}C/\text{surf}}{^{14}C/\text{atm}}\right]_{\text{glacial}} = \frac{280}{200} \left[1 - \frac{^{14}C/\text{surf}}{^{14}C/\text{atm}}\right]_{1850}
\]

We are also forced to assume that the geographic pattern of $^{14}$C/$C$ ratios in the glacial ocean was similar to today’s. In the 1850 A.D. tropical ocean the $^{14}$C/$C$ ratio for surface water was about 0.95 the atmospheric value [Broecker and Peng, 1982]. Based on the above assumptions the $^{14}$C/$C$ ratio in the glacial tropical surface ocean water is calculated to be 0.93 that in the glacial atmosphere. Note that this value is independent of the absolute $^{14}$C inventory adopted.

We then use the measurements presented in this paper to establish the ratio of the $^{14}$C/$C$ for deep waters to that for surface waters in the tropical Atlantic and in the tropical Pacific. These ratios are used to fix the position of the tropical deep waters in Figure 7.

As concluded by Bard et al. [1990], the change in surface ocean $^{14}$C/$C$ ratio required by their $^{230}$Th/$^{234}$U measurements on corals must be primarily the result of a change in the inventory of radiocarbon in the ocean-atmosphere system rather than a change in the distribution of radiocarbon among the reservoirs. The latter explanation would require that during peak glacial time the age of deep water in the ocean averaged about 3500 years.

**IMPLICATIONS FOR GLACIAL CIRCULATION**

In order to gain some insight as to how the deepwater radiocarbon ages depend on mixing rates, we employ our Pandora "something like the real ocean geochemical model" [Broecker and Peng, 1986, and 1987]. For this exercise we have converted the interbox transfer fluxes used previously into seven circulation loops (see Figure 8). In this way we can alter the magnitude of any one of the loops without having to concern ourselves with conserving water, for in this loop scheme the water fluxes are automatically balanced. In addition to the seven loops shown in Figure 8, an eighth connects the southern thermocline reservoir of the Atlantic (box 3) with the southern thermocline reservoir of the Pacific-Indian (box 7). We envision a rapid mixing between these reservoirs (via circumpolar flow) and therefore maintain a sufficiently high flow via this eighth loop to maintain nearly equal compositions in these two reservoirs. A seemingly curious feature of our loop structure is the branching that occurs in the upper ocean. A fraction, $f$ for the Atlantic and $g$ for the Pacific, traverses the mixed layer, and the remainder, $(1-f)$ for the Atlantic and $(1-g)$ for the Pacific, moves through the thermo-
Fig. 7. Reconstruction of the radiocarbon content of various parts of the ocean-atmosphere system for glacial time. The estimate for tropical surface water is based on the $^{235}$Th-$^{238}$U age comparisons on corals by Bard et al. [1990]. The difference in $^{14}C/C$ ratio for tropical surface water and the overlying atmosphere takes into account the lower CO$_2$ content of the glacial atmosphere. The deep Atlantic value is for the site of the Ceara Rise cores (i.e., equatorial western basin). The deep Pacific value is for the South China Sea. The numbers within the diagram are the ratios of the $^{14}C/C$ in the water of interest to that in the glacial atmosphere.

cline. This scheme proves to be an effective means of reproducing the observed properties of today's surface ocean. In Table 4 we list the fluxes adopted in order to replicate the Holocene ocean and the resulting distribution of properties.

Our first attempt to duplicate the observed glacial distribution of radiocarbon and nutrients involves a slowing down of the three loops (1, 2 and 3), which constitute the flow of NADW (see Figure 9). In order to maintain a nearly uniform $^{14}C/C$ difference between the surface Pacific-Indian box and the deep Pacific-Indian box, decreases in the strength of loop 1 are matched by corresponding increases in the strength of loop 6 (see Table 5). By cutting the strength of the NADW loops we bring about an increase in the surface to deep $^{14}C/C$ difference for the Atlantic Ocean (i.e., an increase in the deepwater age). By contrast, the phosphate content of deep water in the Atlantic does not change significantly with the NADW flux. To understand this, one must recall that the residence time of phosphorus in the ocean is many times longer than the oceanic mixing time. Hence, no significant gain or loss of this nutrient can occur during a single pass through the Atlantic. Since, at least in our model, only NADW is exported, the phosphate content of NADW must be equal to the average in the water entering the Atlantic. As in our model the mix of incoming water is nearly independent of the flux of water through the Atlantic, very little change in the phosphate content of Atlantic deep water occurs as the rate of NADW production changes. Thus, this simple exercise reveals an important truth: radiocarbon and nutrient distributions in the sea are not so tightly tied one to the other as one might expect. Hence, the information gained from radiocarbon measurements on foraminifera is not necessarily redundant to that obtained from cadmium, barium or $^{13}C/^{12}C$ measurements on foraminifera.

A second means of increasing the surface to deep radiocarbon difference in the model's Atlantic and one which should also increase the nutrient content of deep water in the Atlantic is to strengthen loop 4 (equivalent to the input of Antarctic Bottom Water into the Atlantic). However, as listed in Table 6, even a very large increase in this flux (i.e., from 4 to 20 sverdrlups (Sv)) has only a small influence on both the age and nutrient content of deep Atlantic water.

This exercise in modeling has led us to do some thinking about what sets the nutrient content of Atlantic deep waters. As described in a separate paper (W. S. Broecker and T.-H. Peng, Factors controlling the distribution of phosphate in the deep ocean, submitted to Global Biogeochemical Cycles, 1990), while the sense of the deep Atlantic-deep Pacific nutrient difference is set by the existence of the global conveyor, the magnitude of the interocean difference depends on the fraction of the return water which comes via Gordon's [1986] Agulhas retroflection (poor in nutrients) as opposed to the fraction which is supplied by Antarctic surface, intermediate and bottom water (rich in nutrients). Hence, the important factor in determining the interocean nutrient is the pattern of return flow rather than the rate of exchange.

Another way to look at the problem is to consider the deep ocean as a mixture of two end-members, new deep water formed in the northern Atlantic and old deep water in the Pacific. Raymo et al. [1990]
have shown that over the last 3 million years the carbon isotope ratio in the deep western Atlantic has swung back and forth between the compositions of these end-members, giving the impression that the geometry of the zone of mixing has ranged from today's situation where NADW floods most of the deep Atlantic to a situation where Antarctic waters penetrate far up the Atlantic. This situation is not amenable to modeling with fixed geometry boxes. Rather, a scheme involving horizontal advection-diffusion is required. Deep water produced in the Atlantic is advected into a diffusive deep sea. In such an ocean the
TABLE 4. Pandora Holocene Standard Configuration

| Parameter Assignment | Reservoir No. | Reservoir Identity | $pCO_2$, $\mu$atm | $PO_4$, $\mu$mol/kg | $CO_3^{eq}$, $\mu$mol/kg | $\delta^{13}C$, $\%$ | $\Delta^{14}C$, $\%$ | Age, Years |
|----------------------|---------------|--------------------|-------------------|---------------------|------------------------|-----------------|-----------------|------------|
| $f=0.65$             |               |                     | 311               | -                   | -                      | -6.4            | -14             | -           |
| $g=0.65$             | 1             | No. Atl. therm      | 282               | 0.86                | 119                    | 2.2             | -77             | -           |
| L1=6.0 Sv            | 2             | Atl. surface        | 308               | 0.06                | 193                    | 2.8             | -57             | -           |
| L2=13.5 Sv           | 3             | So. Atl. therm      | 338               | 1.40                | 108                    | 2.1             | -104            | -           |
| L3=10.5 Sv           | 4             | Atl. deep           | 327               | 1.20                | 110                    | 1.8             | -111            | 500        |
| L4=4.0 Sv            | 5             | Ant. surface        | 303               | 1.39                | 108                    | 2.2             | -117            | -           |
| L5=3.0 Sv            | 6             | Ant. deep           | 410               | 1.80                | 95                     | 1.3             | -146            | -           |
| L6=15.0 Sv           | 7             | So. Pac.-Ind. therm | 325               | 1.34                | 111                    | 2.1             | -104            | -           |
| L7=20.0 Sv           | 8             | Pac.-Ind. surface   | 309               | 0.03                | 198                    | 2.5             | -54             | -           |
| L8=100 Sv            | 9             | No. Pac. therm      | 369               | 1.92                | 125                    | 1.8             | -169            | -           |
| L9=100 Sv            | 10            | Pac.-Ind. deep      | 376               | 2.58                | 82                     | 0.6             | -185            | 1240       |

$^{13}C$ and $^{14}C$ distributions in the sea would change sympathetically as the advective strength of NADW changed. As shown in Figure 10, a strong concordance exists in the trends for the two isotopes in today's ocean.

Could this same situation have applied in the glacial ocean? In an attempt to answer this question we combine the glacial to Holocene offset in $^{13}C$ measured in benthic forams with the $^{14}C$ results reported here. In order to remove the impact of any change in the $^{14}C$ inventory in the ocean-atmosphere system we reference the $^{14}C$ values for deep water to those for tropical surface water. The results of our reconstruction are shown in Figure 11. As can be seen, the reconstructed points for the Ceara Rise and for the South China Sea suggest that the slope of the $^{13}C$ to $^{14}C$ relationship remained unchanged. The 0.4‰ offset between the glacial and the Holocene trend lines is attributed to a change in the $^{13}C/^{12}C$ ratio for whole ocean carbon during glacial time resulting from lower forest biomass and lower soil humus inventories during glacial time [Shackleton, 1977; Curry et al., 1988]. Hence it is possible that the major difference between the glacial and Holocene oceans is that the strength of NADW was much reduced during glacial times, allowing radiocarbon deficient waters from the Antarctic to penetrate further into the Atlantic.

One further complication must be considered. The $^{18}O/^{16}O$ records for the Greenland ice cores suggest that millennium-long events punctuated the climate of the northern Atlantic region during much of glacial time [Dansgaard et al., 1982]. A likely cause for these oscillations is the turning "on" and "off" of deepwater production in the Atlantic [Broecker et al., 1985, 1990b]. If such alternations were occurring during the time period covered by our measurements (i.e., 13,000 to 19,000 years ago) then because of bioturbation we would obtain the average of the age of Atlantic deep water during the "on" and "off" parts
TABLE 5. Transports in Sverdups Used in Calculations Yielding the Results Summarized in Figure 9

| Water Route | Holocene Standard | NADW x0.8 | NADW x0.6 | NADW x0.4 | NADW x0.2 |
|-------------|-------------------|-----------|-----------|-----------|-----------|
| Loop 1      | 6.0               | 4.8       | 3.6       | 2.4       | 1.2       |
| Loop 2      | 13.5              | 10.8      | 8.1       | 5.4       | 2.7       |
| Loop 3      | 10.5              | 8.4       | 6.3       | 4.2       | 2.1       |
| Σ Loops 1,2,3| 30.0              | 24.0      | 18.0      | 12.0      | 6.0       |
| Loop 4      | 4.0               | 4.0       | 4.0       | 4.0       | 4.0       |
| Loop 5      | 3.0               | 3.0       | 3.0       | 3.0       | 3.0       |
| Loop 6      | 15.0              | 16.2      | 17.4      | 18.6      | 19.8      |
| Loop 7      | 20.0              | 20.0      | 20.0      | 20.0      | 20.0      |
| Loop 8      | 100.0             | 100.0     | 100.0     | 100.0     | 100.0     |

TABLE 6. Sensitivity to Flux of Antarctic Bottom Water (i.e., Loop 4) Into the Deep Atlantic

| Flux Loop 4, Sverdups | Atmospheric pCO2, µatm | PO4 Deep Atlantic, µmol/kg | PO4 Deep Pacific and Indian, µmol/kg | Age Deep Atlantic, Years | Age Deep Pacific and Indian, Years |
|-----------------------|-------------------------|----------------------------|---------------------------------------|--------------------------|-------------------------------------|
| 4                     | 311                     | 1.20                       | 2.58                                  | 500                      | 1240                                |
| 8                     | 311                     | 1.26                       | 2.55                                  | 540                      | 1230                                |
| 12                    | 311                     | 1.31                       | 2.53                                  | 560                      | 1225                                |
| 16                    | 311                     | 1.34                       | 2.52                                  | 580                      | 1225                                |
| NADW = Holocene Standard (i.e., 30 Sv) |
| 4                     | 302                     | 1.23                       | 2.60                                  | 770                      | 1350                                |
| 10                    | 302                     | 1.35                       | 2.56                                  | 820                      | 1340                                |
| 20                    | 301                     | 1.45                       | 2.52                                  | 880                      | 1330                                |
| NADW = 0.6 Holocene Standard (i.e., 18 Sv) |
| 4                     | 296                     | 1.31                       | 2.60                                  | 1030                     | 1420                                |
| 10                    | 295                     | 1.44                       | 2.55                                  | 1080                     | 1420                                |
| 20                    | 295                     | 1.53                       | 2.51                                  | 1120                     | 1410                                |
| NADW = 0.4 Holocene Standard (i.e., 12 Sv) |

of the cycle. For example, if the age during the "on" part of the cycle were 350 years as during Holocene time, then the age during the "off" part of the cycle would have to be considerably greater than 670 years. Indeed, since the time for a half cycle is about 1000 years, it is possible that a steady state of radiocarbon distribution was not achieved.

CONCLUSIONS

The results presented here suggest that the ratio of the radiocarbon age of deep water in the Pacific Ocean to the radiocarbon age of deep water in the Atlantic Ocean was smaller during glacial time than today. Taken together with the nutrient distribution reconstruction for glacial time, this result suggests that the mixing zone between North Atlantic Deep Water and waters in the Antarctic moved well northward from its present position at 30° to 40°S in the Atlantic.

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Fig. 10. Plot of $\Delta^{14}C$ against $\delta^{13}C$ for deep water (> 2 km) from throughout the world ocean. The $\delta^{13}C$ and $\Delta^{14}C$ data for the Indian and Atlantic Oceans are from Ostlund et al. [1987]. Those for the Pacific are from [Kroopnick et al., 1970; Ostlund and Niskin, 1970].

Fig. 11. Attempt to reconstruct the $\Delta^{14}C$ versus $\delta^{13}C$ trend in the glacial deep ocean. The $\delta^{13}C$ offset for the deep Pacific is that observed in benthic foraminifera for the South China Sea [Oppo and Fairbanks, 1987]. That for the deep Atlantic is the 0.8‰ average observed for the three Ceara Rise cores [Curry et al., 1988]. In the case of $\Delta^{14}C$ the tropical surface ocean is used as a reference. This eliminates the influence of changes in the inventory of $^{14}C$ in the ocean-atmosphere system and changes in the air-surface $^{14}C$/$^{12}C$ difference. It is assumed that during glacial time no significant difference existed between the $\Delta^{14}C$ value for tropical surface waters in the Atlantic and those in the Pacific.
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