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# Changing atmospheric $\Delta^{14}C$ and the record of deep water paleoventilation ages

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**Abstract.** We propose a new calculation method to better estimate the deep water ventilation age from benthic-planktonic foraminifera $^{14}C$ ages. Our study is motivated by the fact that changes in atmospheric $\Delta^{14}C$ through time can cause contemporary benthic and planktonic foraminifera to have different initial $\Delta^{14}C$ values. This effect can cause spurious ventilation age changes to be interpreted from the geologic data. Using a new calculation method, $^{14}C$ projection ages, we recalculate the data from the Pacific Ocean. Contrary to previous results, we find that the Pacific intermediate and deep waters were about 600 years older than today at the last glacial maximum. In addition, there are possible signals of ventilation age change prior to ice sheet melting and at the Younger Dryas. However, the data are still too sparse to constrain these ventilation transients.

## Introduction

Studies of the past oceanic nutrient distributions have provided insight into changing patterns of paleo-ocean circulation [*Boyle and Keigwin*, 1982; *Oppo and Fairbanks*, 1987; *Duplessy et al.*, 1988; *Boyle*, 1992; *Sarnthein et al.*, 1995]. However, these data do not provide direct information on the rate of circulation. As the ocean is presumed to play a large part in the Earth's heat transport, circulation rate information is of prime importance for the study of past climates. Accelerator mass spectrometry (AMS) studies of the radiocarbon content of contemporary benthic and planktonic foraminifera have provided our only direct information on these rates [*Broecker et al.*, 1988; *Shackleton et al.*, 1988; *Duplessy et al.*, 1989; *Broecker et al.*, 1990a, b; *Duplessy et al.*, 1991; *Kennett and Ingram*, 1995]. In these studies, it is assumed that the age difference between benthic foraminifera and planktonic foraminifera from the same depth in a sediment core is equal to the radiocarbon age difference between the waters in which they grew. By comparing benthic and planktonic pairs from different depths in the core, the radiocarbon age history of deep water at one site is then reconstructed.

The most comprehensive of these studies [*Broecker et al.*, 1990b] compared glacial time slices from several cores to their corresponding core top and modern water ventilation ages. These authors found that the glacial Pacific was slightly older than today and that the glacial intermediate Atlantic was about half as old as it is today. The Atlantic results are consistent with the nutrient tracer data that show, relative to today, an invasion of nutrient-rich southern-source bottom waters farther north in the glacial deep Atlantic. Other studies have attempted to measure benthic-planktonic ventilation ages (B-P ages) through time at a single site [*Andree et al.*, 1986; *Duplessy et al.*, 1989]. In this paper, we examine how B-P ages can be biased by changes in the atmospheric radiocarbon inventory since the last glacial maximum. We propose a new scheme for calculating past ventilation ages in a changing atmospheric environment called $^{14}C$ projection ages. By using the B-P data and the record of atmospheric $\Delta^{14}C$ variations, we compare the B-P ages with our new $^{14}C$ age projections. After developing the recalculation scheme, we summarize the $^{14}C$ projection ages of the deglacial Pacific.

## Effect of Changing Atmospheric $\Delta^{14}C$ on Ventilation Ages

There are at least two processes that can alter benthic-planktonic ages from the true deep water ventilation age. B-P ages assume that the initial $^{14}C/^{12}C$ ratio of the planktonic foraminifera represents the $^{14}C/^{12}C$ ratio that a water mass had when it left the surface. However, it has been shown that surface waters in high-latitude deep water formation sites have $^{14}C$ ages up to 900 years older than tropical and subtropical surface waters [*Broecker*, 1963; *Bard*, 1988; *Berkman and Forman*, 1996]. This age difference between surface water at a core site and surface water in deep water formation sites means that true water ventilation ages are not identical to deep-surface ages. Second, the atmospheric $\Delta^{14}C$, and therefore the surface [$^{14}C$], has been shown to change over the past 20,000 years [*Bard et al.*, 1990; *Bard et al.*, 1993; *Edwards et al.*, 1993; *Kromer and Becker*, 1993; *Pearson et al.*, 1993; *Stuiver and Becker*, 1993]. Water masses that left deep water recharge zones at some point before the benthic foraminifera grew did not necessarily equilibrate with the same atmospheric $\Delta^{14}C$ as their coexisting planktonic counterparts. This latter process is the starting point for this study.

In order to illustrate how benthic-planktonic ages can be biased by changing atmospheric $\Delta^{14}C$, we have modeled three simple atmospheric $\Delta^{14}C$ scenarios. In Figures 1a-1c, the atmospheric $\Delta^{14}C$ time histories (solid gray lines) are prescribed for (a) a constant value of $\Delta^{14}C$, (b) a sloping value of $\Delta^{14}C$, and

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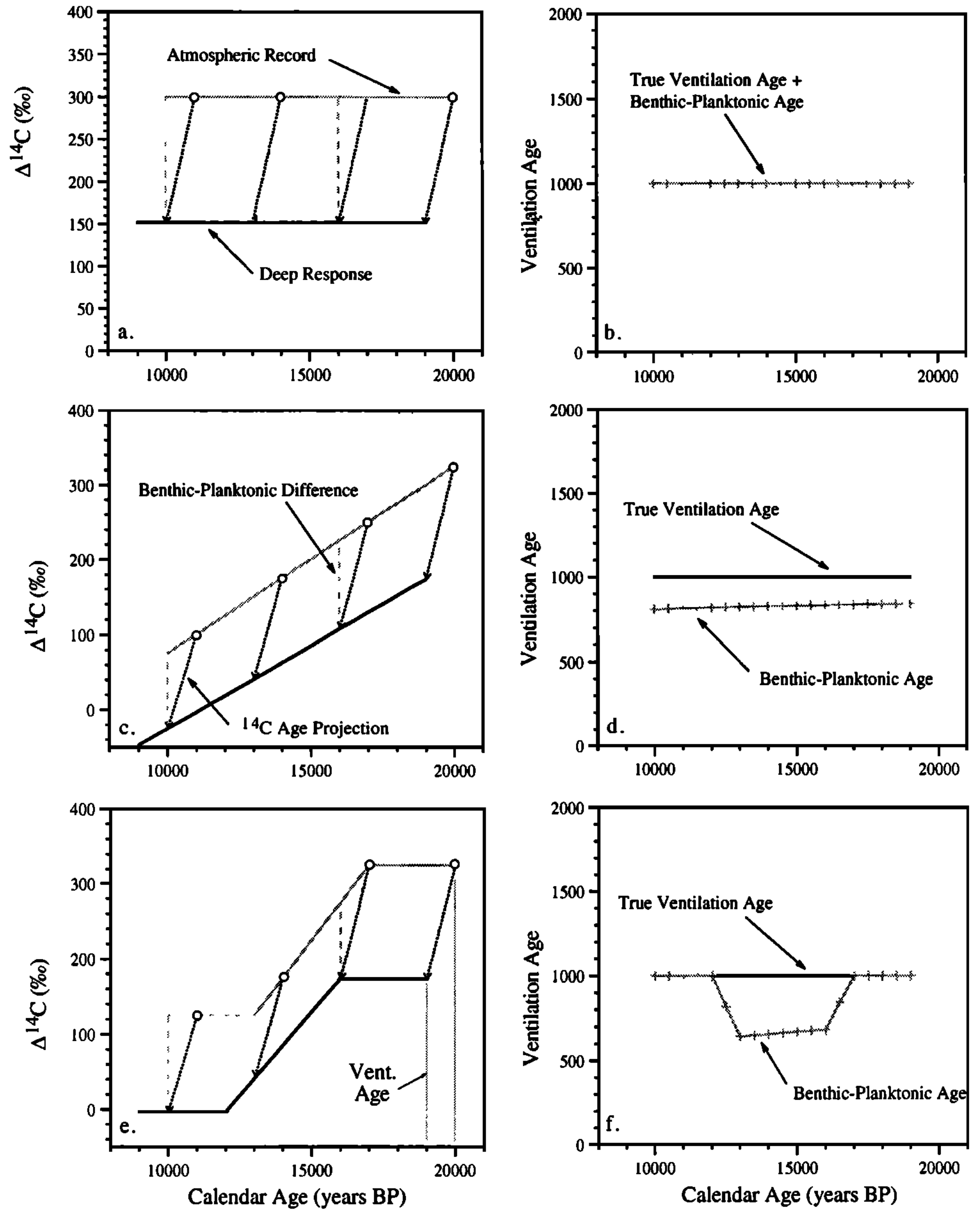


**Figure 1.** Three theoretical atmospheric $\Delta^{14}C$ scenarios with their deep water responses. Figures 1a, 1c and 1e prescribe an atmospheric $\Delta^{14}C$ (gray lines) and then calculate the deep response for a 1000-year ventilation age. Benthic-planktonic ages (B-P ages) are calculated by subtracting the deep $\Delta^{14}C$ from the contemporary surface value, while the true ventilation age is prescribed to be 1000 years in all cases. Figures 1b, 1d and 1f compare the B-P ages with the true ventilation age for the three corresponding atmospheric $\Delta^{14}C$ histories. Changes in atmospheric $\Delta^{14}C$ are recorded in the deep as phase lags that can lead to spurious B-P ventilation ages.

(c) a changing value of $\Delta^{14}C$. Deep water responses (solid black lines) to these atmospheric scenarios are then generated from a given atmospheric value by calculating the $\Delta^{14}C$ after 1000 years of decay. For example, in Figure 1a the atmosphere has a $\Delta^{14}C$ of 300‰ at 20 ka. After 1000 years of decay the $\Delta^{14}C$ is 152‰. This value is then assigned to the deep waters at 19 ka. In order to generate the deep response line, this process is repeated for the entire atmospheric record. Because the ventilation age is held constant for all scenarios, the deep response is just a phase-lagged version of the atmosphere. This procedure simulates a deep water mass that has (a) a single source region at the surface (i.e., no mixing between deep waters of different ages), (b) a 1000-year ventilation age and (c) no reservoir age for the surface waters in the source region.

The three idealized atmospheric $\Delta^{14}C$ records of Figures 1a, 1c and 1e are used to generate B-P ventilation ages. These ages are calculated from the $\Delta^{14}C$ difference between the surface and deep records at a given time in the past (dashed gray lines in Figures 1a-1c). This $\Delta^{14}C$ is then converted into time using the true radiocarbon mean life. The deep response, however, follows different trajectories than the dotted gray lines indicating B-P ages. In this model, once the surface water leaves contact with the atmosphere, it follows a closed system $^{14}C$ decay path (dotted black lines). This 1000-year decay time causes the deep response to mimic the shape of the atmospheric curve but with a 1000 year time lag. Because the ventilation age was prescribed to be 1000 years, all dotted black lines have nearly the same length.

Figures 1b, 1d and 1f compare the B-P age calculation method to the prescribed ages for the three separate scenarios. When the atmosphere has a constant $\Delta^{14}C$ (Figure 1a), there is no difference between the B-P age and the true age (Figure 1b). An atmosphere with a constant but nonzero slope in $\Delta^{14}C$ (Figure 1c) generates a constant offset between the B-P age and the prescribed 1000 years (Figure 1d). The B-P ages are always too low because they assume a smaller initial $^{14}C/^{12}C$ ratio for the deep water than was actually the case. For example, the deep water in Figure 1b at 16 ka left the surface with a $\Delta^{14}C$ value of 250‰. However, the B-P age calculation only "sees" a value of 225‰ and therefore underestimates the ventilation age. Finally, when the atmospheric $\Delta^{14}C$ record changes slope, the phase-lagged nature of the deep response produces false ventilation age changes (Figure 1f). Whenever the surface and deep records parallel one another, the B-P ventilation age offset will be constant. However, there can be situations (Figure 1e) where the deep $\Delta^{14}C$ record is constant while the surface record is changing (16-15 ka) or vice versa (13-12 ka). This type of situation creates false ventilation age changes in B-P data and can lead to misinterpretation of past climate systems.

## Recalculation Method

We propose a new calculation scheme, the $^{14}C$ projection method, that is essentially the inverse of the deep response calculation described above. Instead of starting from the atmosphere and decaying for a known time, we use the measured deep water $\Delta^{14}C$ and project backward in time to its intersection with the surface. We use the atmosphere as the reference point for this calculation and then correct for surface reservoir ages afterward. Therefore the $^{14}C$ projection method requires a calendar age estimate for the sediment sample, a deep $\Delta^{14}C$, and a record of atmospheric $\Delta^{14}C$ in order to calculate a ventilation age. Calendar ages for a benthic and planktonic foraminiferal pair can be calculated from the planktonic radiocarbon age and the tree ring/coral calibration curves. This calculation requires knowing the reservoir age of the planktonic foraminifera's growth environment and may introduce a small source of error into the ventilation age. Given the calendar (cal) age, the deep $\Delta^{14}C$ value can be calculated in the following manner. First, the benthic foraminifera's $^{14}C$ age is converted to a measured (meas) $^{14}C/^{12}C$ ratio:

$$\left(\frac{^{14}C}{^{12}C}\right)_{meas} = \left(\frac{^{14}C}{^{12}C}\right)_{PIPN} e^{-^{14}C\ age/8033}$$

PIPN is the preindustrial prenuclear atmosphere [*Stuiver and Polach*, 1977], and 8033 is the Libby mean life for radiocarbon. The measured isotopic ratio is a function of the $^{14}C/^{12}C$ of the deep water mass in which the foraminifera grew and the time since the foraminifera died:

$$\left(\frac{^{14}C}{^{12}C}\right)_{meas} = \left(\frac{^{14}C}{^{12}C}\right)_{deep\ water} e^{-cal\ age/8266}$$

Here 8266 is the true $^{14}C$ mean life in years. So, equating the two expressions for $(^{14}C/^{12}C)_{meas}$

$$\left(\frac{^{14}C}{^{12}C}\right)_{deep\ water} = \frac{\left(\frac{^{14}C}{^{12}C}\right)_{PIPN} e^{-^{14}C\ age/8033}}{e^{-cal\ age/8266}}$$

and using the definition of $\Delta^{14}C$:

$$\Delta^{14}C_{deep\ water} = \left(\frac{\left(\frac{^{14}C}{^{12}C}\right)_{deep\ water} - \left(\frac{^{14}C}{^{12}C}\right)_{PIPN}}{\left(\frac{^{14}C}{^{12}C}\right)_{PIPN}}\right) \times 1000$$

The expression for the deep water isotope ratio can be substituted into the above expression to generate the deep water $\Delta^{14}C$ value:

$$\Delta^{14}C_{deep\ water} = \left(\frac{e^{-^{14}C\ age/8033}}{e^{-cal\ age/8266}} - 1\right) \times 1000$$

This expression does not depend on knowing the PIPN atomic ratio, the measured fraction modern [*Donahue et al.*, 1990], or the $\delta^{13}C$ of the samples [*Stuiver and Polach*, 1977]. These values are already incorporated into the reported $^{14}C$ ages.

Using the equation above, previously published benthic/planktonic pairs can be converted to deep water $\Delta^{14}C$ values. The problem is how to relate this deep $\Delta^{14}C$ to a true water ventilation age. The deep water $\Delta^{14}C$ is a function of the source zone's reservoir age, the ventilation age, and the atmospheric $\Delta^{14}C$. Deciding which past atmospheric $\Delta^{14}C$ value to correct to is, in turn, dependent on the ventilation age itself. By back calculating the $^{14}C$ history the deep water parcel would have had if it followed closed system decay, we propose to account for the effect of changing atmospheric $\Delta^{14}C$ on the deep $\Delta^{14}C$ concentration. Though there are several assumptions involved with the new method (discussed below), the $^{14}C$ projection calculation provides a consistent and independent way to choose the best initial atmospheric $\Delta^{14}C$ value for the deep water mass.

An example of this calculation is shown in Figure 2 using the intermediate western North Pacific data of *Duplessy et al.* [1989] (CH 84-14, 41°44'N, 142°33'E, 978 m depth). The atmospheric $\Delta^{14}C$ record from tree rings and corals is shown in gray, and the converted benthic foraminifera values are shown in black. Error bars for the benthic data are large because of uncertainties in the radiocarbon to calendar age conversion and plateaus in the radiocarbon timescale. Black lines that begin at the benthic data and extend back toward the atmospheric record are the $^{14}C$ age projections. This is the path, in $\Delta^{14}C$ space, that deep water with the measured calendar age and $\Delta^{14}C$ would have followed if it behaved as a closed system for radiocarbon decay. If there was no mixing between deep waters of different source regions, then the intersection of these projections with the atmospheric record is the estimated time the deep water parcels left the surface. Therefore the calendar age difference between the intersection point and the benthic data point is the ventilation age relative to the atmosphere (see the area labeled vent. age in Figure 2 for the graphical calculation).

However, this ventilation age still needs to be corrected for two factors: the reservoir age of the deep water source region

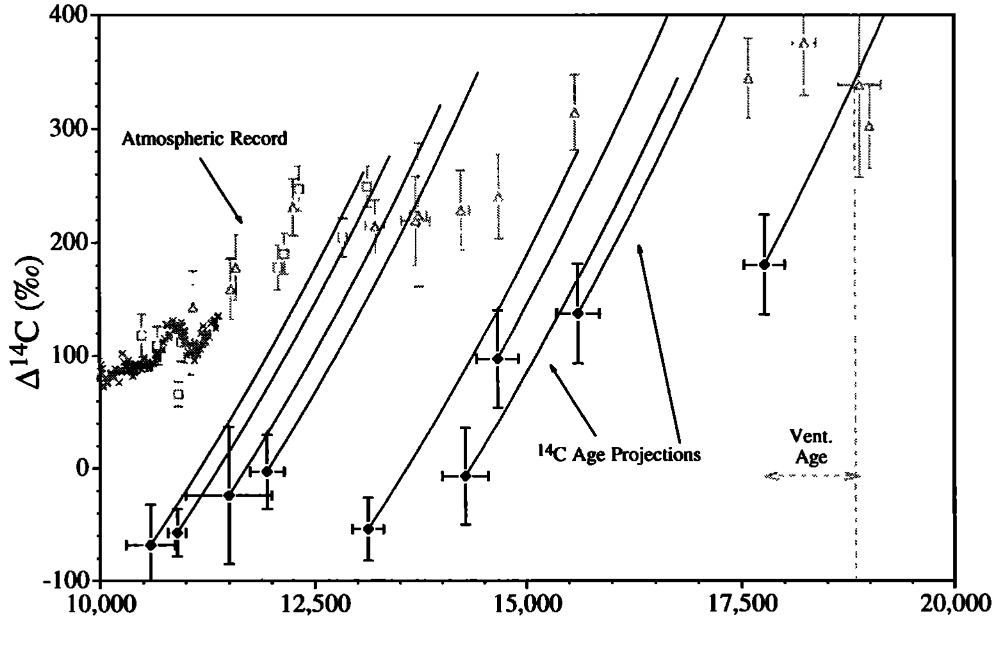


**Figure 2.** Data from *Duplessy et al.* [1989] transformed into deep $\Delta^{14}C$ values (solid diamonds). The atmospheric records of $\Delta^{14}C$ from tree rings and corals are in gray: German oak and pine record (crosses), *Bard et al.* [1993] data (open triangles) and *Edwards et al.* [1993] data (open squares). Error bars are $2\sigma$. The $^{14}C$ age projections are the $\Delta^{14}C$ values the Duplessy et al. data would have had if they followed closed system radiocarbon decay. The intersection of the age projections and the atmospheric record indicate the time in the past the deep water left the surface. The difference between the deep age and the intersection age is the ventilation age relative to the atmosphere.

and, as mentioned above, mixing between waters of two source regions. If the deep water is from a single source region that has a constant offset from the atmosphere, the region's reservoir age can be subtracted and the calculation is straightforward. Exactly how constant the reservoir ages of deep water source regions are through time is the subject of current research [*Bard et al.*, 1994; *Austin et al.*, 1995; *Goslar et al.*, 1995]. From the comparison between the tree ring and coral records over the past 11.5 kyr, we know that the tropical reservoir age in both the Atlantic and Pacific has remained roughly 400 years [*Bard et al.*, 1990; *Bard et al.*, 1993; *Edwards et al.*, 1993]. When this reservoir age is subtracted from the coral record, it agrees precisely with the record of atmospheric $\Delta^{14}C$ as measured in tree rings. Only three of the nineteen coral points that overlap with the tree ring record lie outside $2\sigma$ errors. On the other hand, recent work on terrestrial and marine carbon that is coeval with the Vedde Ash has shown that the high-latitude surface North Atlantic may have been 300 years older than today during the Younger Dryas [*Bard et al.*, 1994; *Austin et al.*, 1995; *Gronvold et al.*, 1995; *Birks et al.*, 1996]. In any event, the B-P and the $^{14}C$ projection calculations both will contain the same errors due to possible reservoir age differences at the deep water source zones.

If the deep water is a mixture of southern and northern source waters, calculating the exact reservoir age is more complicated [*Broecker*, 1979; *Broecker et al.*, 1991]. In certain "two source" deep waters, like the modern deep Atlantic, the $^{14}C$ projection ages can overstate the ventilation age. The error arises from choosing the incorrect reservoir age to subtract from the $^{14}C$ projection ages. When waters with old reservoir ages from the Southern Ocean mix with northern source waters with younger reservoir ages, the resulting "initial" value for the deep water mass is older than the usual planktonic correction of 400 years. This means that the $^{14}C$ projection age will not fully account for the reservoir age and will predict a ventilation age that is too high. We have examined this effect in some detail and concluded that it is a secondary effect that requires more detailed treatment elsewhere.

There is another possible complication to the $^{14}C$ projection method based on how the atmospheric $\Delta^{14}C$ changes are caused in the first place: through production rate variations or changes in the carbon pool exchange rates. While it is possible that changes in ocean circulation themselves can cause changes in atmospheric $\Delta^{14}C$, analysis of the paleogeomagnetic field [*Tric et al.*, 1992] and the radiocarbon timescale [*Mazaud et al.*, 1991] have shown that nearly all of the long-term radiocarbon inventory changes can be explained by production rate variations. However, several recent studies [*Goslar et al.*, 1995; *Bjork et al.*, 1996; *Stocker and Wright*, 1996] have argued that there was an increase in atmospheric $\Delta^{14}C$ at the beginning of the Younger Dryas that could be caused by a decrease in North Atlantic Deep Water (NADW) formation. This circulation change causes the atmosphere $\Delta^{14}C$ to rise sharply, thus making $^{14}C$ projection ages and B-P ages look older than reality. Though there are situations where the ventilation age can be overstated by systematically and

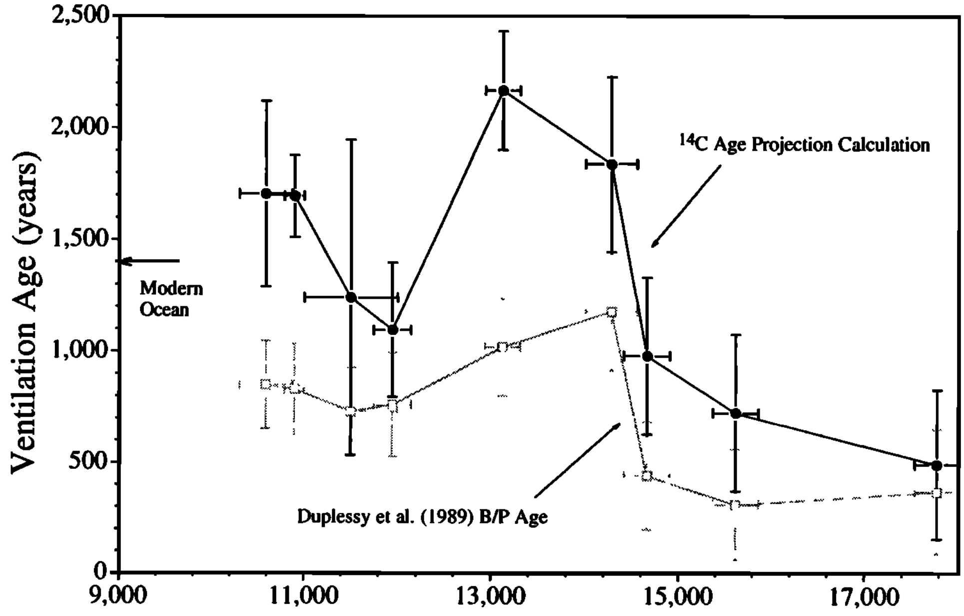


**Figure 3.** Ventilation ages predicted by the data in Figure 2 compared with the B-P ages reported by *Duplessy et al.* [989] The black arrow labeled modern ocean indicates the age of modern bottom waters at this site. A 560-year reservoir age has been subtracted from the $^{14}C$ projection ages.

independently removing the effect of atmospheric $\Delta^{14}C$ variations, the $^{14}C$ projection ages can provide a better estimate of circulation rate.

## Implications of New Method

The *Duplessy at al.* [1989] data in Figure 2 are from the western North Pacific core CH 84-14 (41°44'N, 142°33'E, 978 m depth). This area probably fits the criterion of a single source for the deep waters. We therefore disregard the secondary effects on ventilation ages due to mixing. Once the Duplessy et al. benthic results are converted to deep water $\Delta^{14}C$ values, we can use Figure 2 to graphically calculate the $^{14}C$ projection ages for this data set and compare them with the B-P ages (Figure 3, Table 1). We have subtracted a 560-year reservoir age from all $^{14}C$ projection ages in order to be consistent with Duplessy et al.'s age calculations. As shown in Figure 3, all of the $^{14}C$ projection ages are higher than the B-P ages. This result is due to the fact that the long-term trend in atmospheric $\Delta^{14}C$ from 20 to 10 ka is a decrease from about 300‰ to 100‰. As was shown in the model calculations (Figures 1c and 1d), this trend will lead to B-P ages that underestimate the true ventilation age. In addition, the point where the two methods are in the best agreement (17.7 ka) occurs where the atmospheric record is relatively constant.

The biggest difference in the structure of the two curves is seen for the four most recent points. Here the B-P ages predict, within error, a constant ventilation age. The $^{14}C$ projection ages, on the other hand, rise toward the modern value. Examination of the atmospheric record shows that the planktonic foraminifera record a $\Delta^{14}C$ decrease in surface waters, yet the deep waters left the surface when the $\Delta^{14}C$ was nearly flat. In this case, planktonic foraminifera were recording a changing atmosphere that the benthic water masses never "saw." This type of artifact in B-P ages occurs at $^{14}C$ age plateaus. Because they are caused by the rate of atmospheric $^{14}C$ decrease being equal to the natural rate of $^{14}C$ decay, plateaus are times when the $^{14}C$ projections will parallel the atmospheric record. Carbon 14 projections will therefore predict a much different starting atmospheric value of $\Delta^{14}C$ for the benthic foraminifera than recorded by the planktonic foraminifera. In such situations, the atmospheric correction to ventilation ages is very important.

Recent work, as was discussed above, has argued for a rapid rise in atmospheric $\Delta^{14}C$, due to a reduction in NADW formation, during the period spanned by these last four points in Figure 3. Because the $^{14}C$ projection method is sensitive to atmospheric $\Delta^{14}C$ changes, the corrected data in Figure 3 may be overstated. However, during this period, the atmosphere clearly changes from an average value of about 200‰ to about 100‰ (Figure 2). So while the situation is more complicated than a passive ocean responding to an atmospheric $\Delta^{14}C$ change, there is some component of changing $\Delta^{14}C$ missing in the B-P ages during the $^{14}C$ age plateau. The effect of the most recent $^{14}C$ age plateau on modern ventilation age estimates has been previously addressed [*Broecker et al.*, 1991]. These authors found that the plateau from 1600 to 1950 A.D., shown to be due to production rate changes modulated by the Sun, had at most a 10-15% effect on the modern Atlantic ventilation ages. However, as pointed out by the authors, the full effect of the plateau has not been seen because the Atlantic contains southern component waters which are buffered against the atmospheric changes of the last millennium.

In an effort to synthesize the Pacific ventilation age results, we have reanalyzed the available data. We concentrate here on three cores: CH 84-14 from the northwestern intermediate Pacific

**Table 1.** Recalculated Foraminiferal Ventilation Ages from the Pacific

| Depth cm | Calendar Age | | Benthic $^{14}C$ | | $[^{14}C]$ | | Intersection | | Ventilation Age | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Years | Error | Years | Error | ‰ | Error | Age, years | Error | Years | Error |
| | | | | *Core CH 84-14 (41°44'N 142°33'E, 978 m)*[a] | | | | | | |
| 230 | 10,585 | 285 | 10,850 | 140 | -68 | 36 | 12,850 | 300 | 1,705 | 414 |
| 280 | 10,895 | 105 | 11,060 | 150 | -57 | 21 | 13,150 | 150 | 1,695 | 183 |
| 310 | 11,500 | 500 | 11,370 | 130 | -24 | 61 | 13,300 | 500 | 1,240 | 707 |
| 340 | 11,944 | 200 | 11,630 | 180 | -3 | 33 | 13,600 | 225 | 1,096 | 301 |
| 400 | 13,122 | 186 | 13,200 | 150 | -54 | 28 | 15,850 | 190 | 2,168 | 266 |
| 430 | 14,362 | 211 | 13,010 | 170 | 125 | 37 | | age reversal in core | | |
| 480 | 14,276 | 273 | 13,930 | 220 | -7 | 43 | 16,675 | 280 | 1,839 | 391 |
| 510 | 14,660 | 248 | 13,500 | 200 | 97 | 43 | 16,200 | 250 | 980 | 352 |
| 550 | 15,615 | 248 | 14,140 | 200 | 137 | 44 | 16,900 | 250 | 725 | 352 |
| 690 | 17,772 | 236 | 15,940 | 190 | 180 | 44 | 18,825 | 240 | 493 | 337 |
| | | | | *Core Sonne 50-37KL (18°54'N 115°46'E, 2695 m)*[b] | | | | | | |
| 60-65 | 9,070 | 110 | 10,030 | 120 | -140 | 17 | 11,550 | 250 | 2,080 | 273 |
| 80-85 | 11,500 | 500 | 11,890 | 110 | -85 | 57 | 13,900 | 500 | 2,400 | 707 |
| 160-165 | 17,537 | 132 | 17,100 | 220 | -7 | 31 | 20,350 | 150 | 2,400 | 200 |
| 175-180 | 18,380 | 101 | 17,430 | 140 | 55 | 22 | 20,850 | 125 | 2,070 | 161 |
| 195-200 | 20,197 | 136 | 18,940 | 160 | 89 | 28 | 22,500 | 140 | 1,903 | 195 |
| 205-210 | 20,311 | 162 | 19,445 | 190 | 37 | 32 | 23,100 | 170 | 2,390 | 235 |
| | | | | *Core TR 163-31B (3°37'S 83°58'W, 3210 m)*[c] | | | | | | |
| 85 | 16,755 | 248 | 15,660 | 270 | 81 | 49 | 18,600 | 250 | 1,270 | 350 |
| 103 | 18,286 | 285 | 16,850 | 230 | 121 | 50 | 20,100 | 285 | 1,245 | 403 |
| 114 | 19,149 | 322 | 19,510 | 330 | -106 | 51 | | age reversal in benthics [d] | | |
| 121 | 19,796 | 298 | 17,400 | 240 | 257 | 59 | 20,850 | 330 | 475 | 445 |
| 153 | 23,174 | 322 | 22,140 | 310 | 49 | 58 | 26,100 | 350 | 2,345 | 475 |
| 166 | 25,795[d] | 347 | 23,420 | 310 | 228 | 70 | 27,640 | 350 | 1,280 | 493 |
| 176 | 25,758 | 310 | 24,530 | 470 | 64 | 74 | 28,700 | 320 | 2,380 | 445 |

[a]From *Duplessy et al.* [1989]. 560-year reservoir age correction.
[b]From *Broecker et al.* [1990a]. 400-year reservoir age correction. Only used data with replicated planktonic ages.
[c]From *Shackleton et al.* [1988]. 580-year reservoir age correction. All data from depths with benthics.
[d]The Shackleton et al. data have two points where $^{14}C$ ages show reversals, one planktonic and one benthic. Following their ideas, we interpret the benthic record as less susceptible to atmospheric fluctuations in $^{14}C$ inventory and throw out the benthic age reversal. The planktonic reversal leads to the two different ventilation ages at 26 ka in Figure 4. This discrepancy may be due to rapid variations in the atmospheric $\Delta^{14}C$ that do not propagate down to the depth of the core location. See the text. The data table shows all the data used to compile the Pacific ventilation age history in Figure 4. The depths and benthic $^{14}C$ ages are taken directly from the data tables in the original papers. Calendar ages are calculated from the reported planktonic $^{14}C$ ages and the tree ring/coral calibration data. Benthic $\Delta^{14}C$ was calculated from the calendar age, and the $^{14}C$ age for the benthic foraminifera was calculated according to the equations in the Recalculation Method section of the present paper. Intersection and ventilation ages were calculated graphically as described in the text and Figure 2.

(41°44'N, 142°33'E, 978 m) [*Duplessy et al.*, 1989]; Sonne 50-37KL from the South China Sea with a sill depth of about 2500 m (18°54'N, 115°46'E, 2695 m) [*Broecker et al.*, 1990a, b] and TR 163-31B from the eastern Pacific in the Panama Basin (3°37.2'S, 83°58'W, 3210 m) [*Shackleton et al.*, 1988]. The results are shown in Figure 4 and listed in Table 1. When available, we only used points where all planktonic species from the same depth had the same radiocarbon age within $2\sigma$ errors. Modern ventilation ages for the three sites, calculated from the Geochemical Ocean Sections Study (GEOSECS) data, are also pictured. Errors from the calendar ages are propagated in the deep $\Delta^{14}C$ calculations and can lead to large uncertainties. The points at 11.5 ka are particularly affected by the calendar age errors because they derive from a $^{14}C$ age plateau and therefore provide little constraint on the ventilation age. A reinterpreted record of the meltwater record in corals is also pictured in Figure 4. We have fitted a polynomial through the combined sea level data of *Bard et al.* [1993] and *Edwards et al.* [1993] and calculated the fit's first derivative. No corrections were made for possible variations in a particular coral species depth of growth.

Ventilation ages of both the intermediate and deep Pacific waters were about 600 years older than today's values during the last glacial. This is older than *Broecker et al.*'s [1990b] previous result but is in rough agreement with the analysis of *Shackleton et al.* [1988] Broecker et al. attribute this difference to upwelling at the site of TR 163-31B. However, this analysis shows that different atmospheric histories of $\Delta^{14}C$ for the Sonne data, 20-15 ka, as opposed to the Trident data, before 20 ka, can also contribute to the different results. Though poorly constrained by the coral data, there is more of a decrease in atmospheric $\Delta^{14}C$ during 20-15 ka than before 20 ka. This difference in atmospheric $\Delta^{14}C$ slope can lead to offsets between B-P ages from the two different times.

The data also show a decrease in ventilation age before the onset of rapid melting in the North Atlantic. However, this result requires patching together cores. No one record preserves the

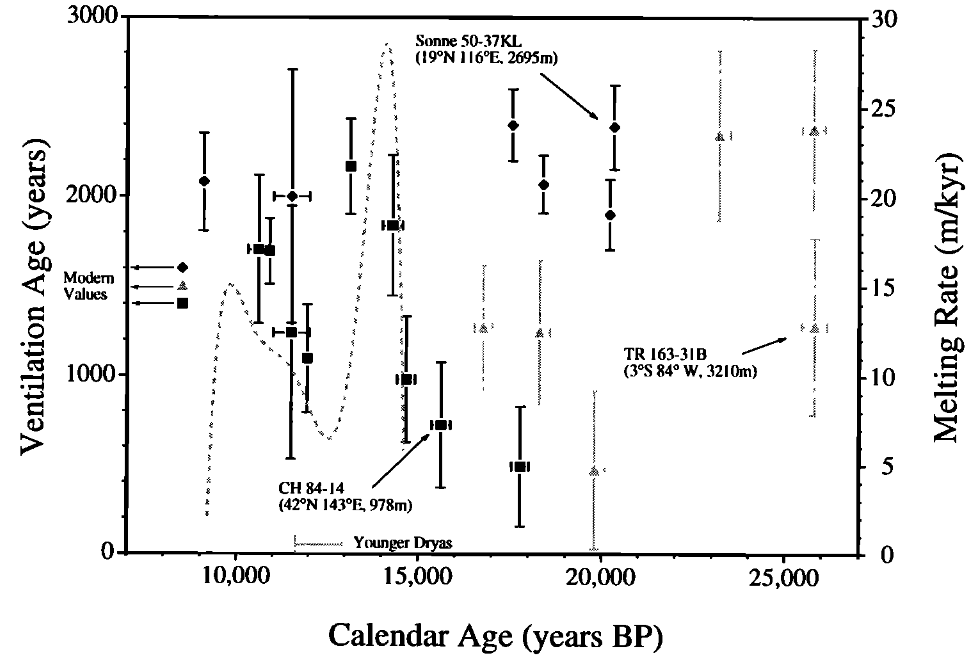


**Figure 4.** Summary of Pacific deep ventilation age data. The data from three cores CH 84-14 (solid squares) from the South China Sea (41°44'N, 142°33'E, 978 m depth), Sonne 50-37KL (solid diamonds) from the western tropical Pacific (18°54'N, 115°46'E, 2695 m) and TR163-31B (gray triangles) from the eastern Pacific (3°37.2'S, 83°58'W, 3210 m) in the Panama Basin have been recalculated using $^{14}C$ age projections. The meltwater history predicted by the sea level data of *Bard et al.* [1993] and *Edwards et al.* [1993] is plotted as a dashed line. Modern values for the bottom waters at the three core sites are shown at the left. The age of the Younger Dryas cold interval as found in the GISP2 ice core [*Alley et al.*, 1993] is shown at the bottom.

entire transition, and the best constrained record, Sonne 50-37KL, alone shows no transient in ventilation age. While this result is intriguing, we require further data before the exact timing of ventilation age changes and ice sheet decay can be established. In the data of *Duplessy et al.* [1989], there is also an indication of a speedup of intermediate circulation during the Younger Dryas that is partially supported by the South China Sea core. Recalculated data from the Santa Barbara basin also indicate a decrease in Pacific intermediate ventilation age at the beginning of the Younger Dryas [*Ingram and Kennett,* 1995; *Kennett and Ingram,* 1995]. Pacific deep water values are still several hundred years older than modern values at the beginning of the Holocene. This feature was seen in earlier data from the South China Sea [*Andree et al.*, 1986], but different species of planktonic foraminifera from the same depths rarely gave the same radiocarbon age in these cores and so were determined to be biased by dissolution artifacts. Until better dated records of ventilation age changes are obtained, the conclusion that ocean circulation changes preceded ice sheet decay is preliminary at best.

## Conclusions

The traditional calculation method for benthic-planktonic ventilation ages can be biased by changes in the atmosphere's radiocarbon inventory. These biases have different effects depending on the temporal history of the atmospheric record, but under plausible circumstances this effect can show false ventilation age changes when ocean circulation was in an unchanging state. Using the new calculation scheme of $^{14}C$ projection ages, the primary effect of the changing atmospheric record can be removed. A key assumption of this new method is that atmospheric $\Delta^{14}C$ is driven chiefly by production rate effects and not by exchanges between carbon reservoirs. However, both the B-P ages and the $^{14}C$ projection ages are affected by changes in surface reservoir ages, so both calculation schemes are estimates rather than true values. In addition, the $^{14}C$ projection method can underestimate the ventilation ages for deep waters that are a mixture of waters from two different source regions.

Our reanalysis of the existing data shows that Pacific intermediate and deep waters were both about 600 years older than their modern values at the last glacial maximum. At the beginning of the Holocene, the deep waters were still several hundred years older than core top and modern water data, indicating that there have been circulation changes during the past 10,000 years. In addition to the steady circulations, two transients in ventilation age are also apparent in the recalculated data. The first is a minimum in ventilation age at the time of glacial melting. The circulation change appears to precede the meltwater pulse, but the exact date of the ventilation age switch is not well constrained. There is also the hint of better ventilated intermediate waters during the Younger Dryas on both sides of the Pacific basin, but the data are too sparse to draw firm conclusions. A faster ocean circulation prior to ice sheet melting may indicate that increased ocean heat transports initiated glacial decay. This ventilation signal could be better constrained by records from deep-sea corals and more B-P data from high sedimentation rate cores.

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