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CHANGES IN OCEAN VENTILATION RATES OVER THE LAST 7000 YEARS BASED ON ^{14}C VARIATIONS IN THE ATMOSPHERE AND OCEANS

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ABSTRACT. Changes in the ocean ventilation rate may be one of the causes for a net decrease of 100‰ $\Delta^{14}C$ in atmospheric CO_2 over the last 8000 years. Ocean ventilation rates of the past can be derived from the ^{14}C record preserved in planktonic and benthic foraminifera in deep-sea sediments. Results of ^{14}C dating using accelerator mass spectrometry on deep sea sediments from the South China Sea show that the age differences between planktonic (*G sacculifer)* and benthic foraminifera increase from 1350 yr ca 7000 yr ago to 1590 yr at present. An 11-box geochemical model of global ocean circulation was used for this study. Both tree-ring-determined atmospheric ^{14}C values and foraminifera ^{14}C age differences are used as constraints to place limits on patterns of changes in ocean ventilation rates and in atmospheric ^{14}C production rates. Results indicate: 1) ^{14}C production rates in the atmosphere may have decreased by as much as 30% between 7000 and 3000 yr ago, and may have increased again by ca 15% in the past 2000 yr, and 2) the global ocean ventilation rate may not have been at steady state over the last 7000 yr, but may have slowed by as much as 35%.

INTRODUCTION

The study of variations in the cadmium-to-calcium ratio of the North Atlantic Deep Water (NADW), as recorded in the benthic foraminifera (Boyle & Keigwin, 1982), indicates that the intensity of glacial NADW flow is reduced relative to the flux of Antarctic water sources. Results of benthic foraminifera faunal studies in deep-sea cores raised from the Mid-Atlantic Ridge (Streeter & Shackleton, 1979) also suggest that the present production of large volumes of NADW is typical of only a limited period during the past 150,000 years. Streeter and Shackleton (1979) concluded that, for most of this time, little or no deep or bottom water formed in the North Atlantic. Hence, the ocean ventilation rate must have been very different from that found in present oceans. Evidence from isotope studies of deep-sea sediments (Duplessy, Chenouard & Vila, 1975; Shackleton, 1977; Broecker, 1982; Shackleton, Imbrie & Hall, 1983) also suggests that the production of deep water in the northern Atlantic was reduced greatly during the peak of glacial time. Broecker, Peteet and Rind (1985) proposed two very different modes of ocean circulation (with opposite direction of main ocean flow) corresponding to the warm and cold intervals seen in ice core records. Therefore, we can expect that the ocean is subject to changes in ventilation rates with time.

Changes in ocean ventilation rates cause changes in the atmospheric $^{14}C/^{12}C$ ratio. Variations of ^{14}C levels in the atmosphere as recorded in tree rings over the last 8000 years have been measured by several radiocarbon laboratories (eg, Arizona, Pennsylvania, La Jolla, Groningen, Seattle, Pretoria and Heidelberg). A composite ^{14}C data set compiled by Klein *et al* (1980) is shown in Figure 1. These data indicate that $\Delta^{14}C$ of atmospheric CO_2 was 85‰ ca 7000 yr ago and decreased slowly to -15‰ ca 1500 yr ago.

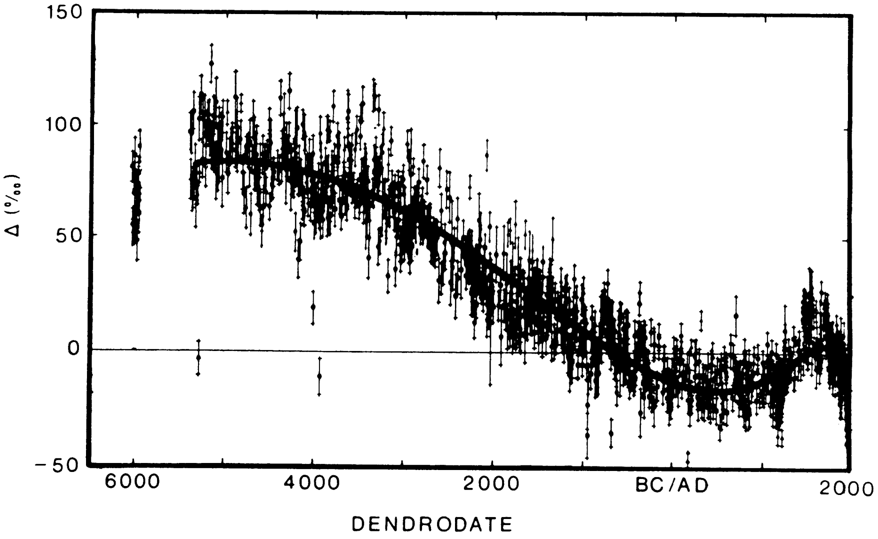

Fig 1. Composite ${}^{14}C$ data for atmospheric CO_2 (Klein *et al,* 1980). ${}^{14}C$ values are reconstructed from measurements on samples of known age (dendrochronologically dated), principally bristlecone pine and giant sequoia.

It then increased to a prebomb value of 0‰. Variations in atmospheric ${}^{14}C$ content with time have been interpreted as resulting mainly from varying ${}^{14}C$ production rates caused by the fluctuating magnetic field of the earth (Damon, Lerman & Long, 1978; Suess, 1980; Neftel, Oeschger & Suess, 1981). This conclusion is based on the assumption that the ocean is at steady state with a constant ventilation rate.

Distribution of ${}^{14}C$ in the ocean is controlled mainly by ocean ventilation rates. The difference in the ${}^{14}C/{}^{12}C$ ratio in sea water between surface and bottom layers is small when the ventilation rate is high. This difference increases as the ventilation rate decreases. Assuming that the ${}^{14}C/{}^{12}C$ ratio of the surface water is recorded in fossil planktonic foraminifera shells and that of deep water is recorded in benthic foraminifera shells, the time history of variation in ocean ventilation rates could be derived from ${}^{14}C$ measurements of single species of foraminifera in the deep-sea sediments. Andrée *et al* (1984, 1985, 1986) measured ${}^{14}C$ ages of foraminifera from the South China Sea by accelerator mass spectrometry (AMS), where the sediment accumulation rate is on the order of 10–15cm/ky. Also, comparison of ${}^{14}C$ measurements for sea water in the South China Sea and in the adjacent Philippine Sea indicates that deep water in the South China Sea is rapidly flushed with deep waters in the open Pacific. Hence, the ${}^{14}C$ age difference between surface and deep waters in this study area is a good approximation for that in the open Pacific Ocean.

Results of ${}^{14}C$ dating of foraminifera by Andrée *et al* (1986) indicate that the age difference between the mixed benthics and planktonic species *(G sacculifer)* changes with time. Linear regression of these measurements, as shown in Figure 2, shows that the age differences increase from 1300 yr

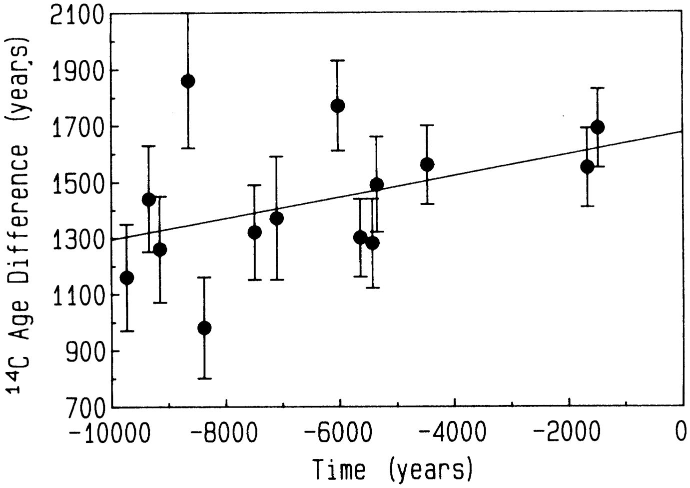

Fig 2. Linear regression of ^{14}C age differences between mixed benthic foraminifera and *G sacculifer* as a function of the ^{14}C age of the sedimentary horizon (data from Andrée *et al,* 1986).

10,000 yr ago to 1650 yr at present. Assuming that other factors stay constant, the increasing ^{14}C age difference implies that the ocean ventilation rate may have decreased in the past 10,000 yr. If so, the ^{14}C of the atmospheric CO_2 would also have increased with time because 1) the ocean would not take up ^{14}C fast enough under a slower ventilation condition, and 2) the ^{14}C production in the atmosphere maintains a constant rate. On the other hand, if we assume a constant ventilation rate and adopt the generally accepted scenario that the ^{14}C production rate in the atmosphere has decreased >50% in the past 8000 yr, we expect that the foraminiferal age difference would decrease with time because the surface water would contain less ^{14}C (*ie,* older) due to the reduced atmospheric source.

OCEAN MODEL

The detailed structure of the 11-box geochemical model of the global oceans (PANDORA) has been reported by Broecker and Peng (1986). As shown in Figure 3a, the ocean is vertically divided into a warm surface layer, an intermediate (*ie,* thermocline) layer and a deep layer. The Antarctic Ocean, linking world oceans together, is divided into cold surface and deep layers only. The northern Atlantic Ocean is separated as one vertical box for simulating its specific function of the production of NADW. For simplicity, the Indian and Pacific Oceans are combined as one water column. Figure 3b shows the fractions of the ocean's volume constituted by each reservoir and the fractions of the ocean's surface area occupied by those boxes interfacing with the atmosphere. The water flow pattern and the magnitude of the water fluxes in sverdrups (sv = 10^6 m^3/s) between boxes are shown in Figure 4. These water fluxes are required to match the present distribution of ^{14}C in the oceans. The fluxes in the model of the

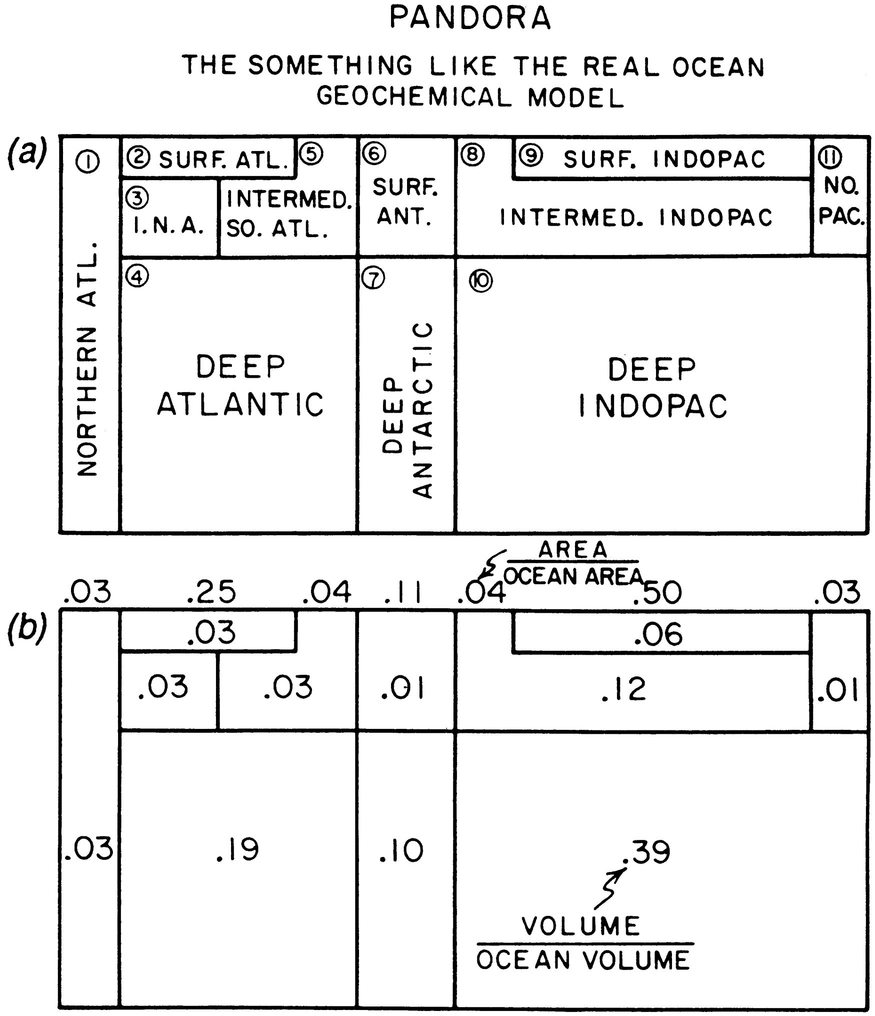

Fig 3. Basic structure of the 11-box geochemical model (PANDORA) of the global ocean. (a) 11 reservoirs of the model ocean. (b) Fraction of the ocean's volume constituted by each reservoir and fraction of the ocean's surface area occupied by boxes inferfacing with the atmosphere.

NADW (20 Sv) and the Antarctic circumpolar current (10 Sv) are quite consistent with values accepted by current oceanographic knowledge.

Since this model was developed to evaluate the impacts of possible differences between the operation of the glacial and interglacial ocean-atmosphere system on the CO_2 content of the atmosphere, proper chemistry of carbon, alkalinity and nutrients (mainly PO_4) needs to be incorporated in the model. As shown in Figure 4, the biologic pumping of the carbon and the limiting nutrients from the surface boxes to the underlying boxes is simulated by assigning mean residence times to nutrients in the surface

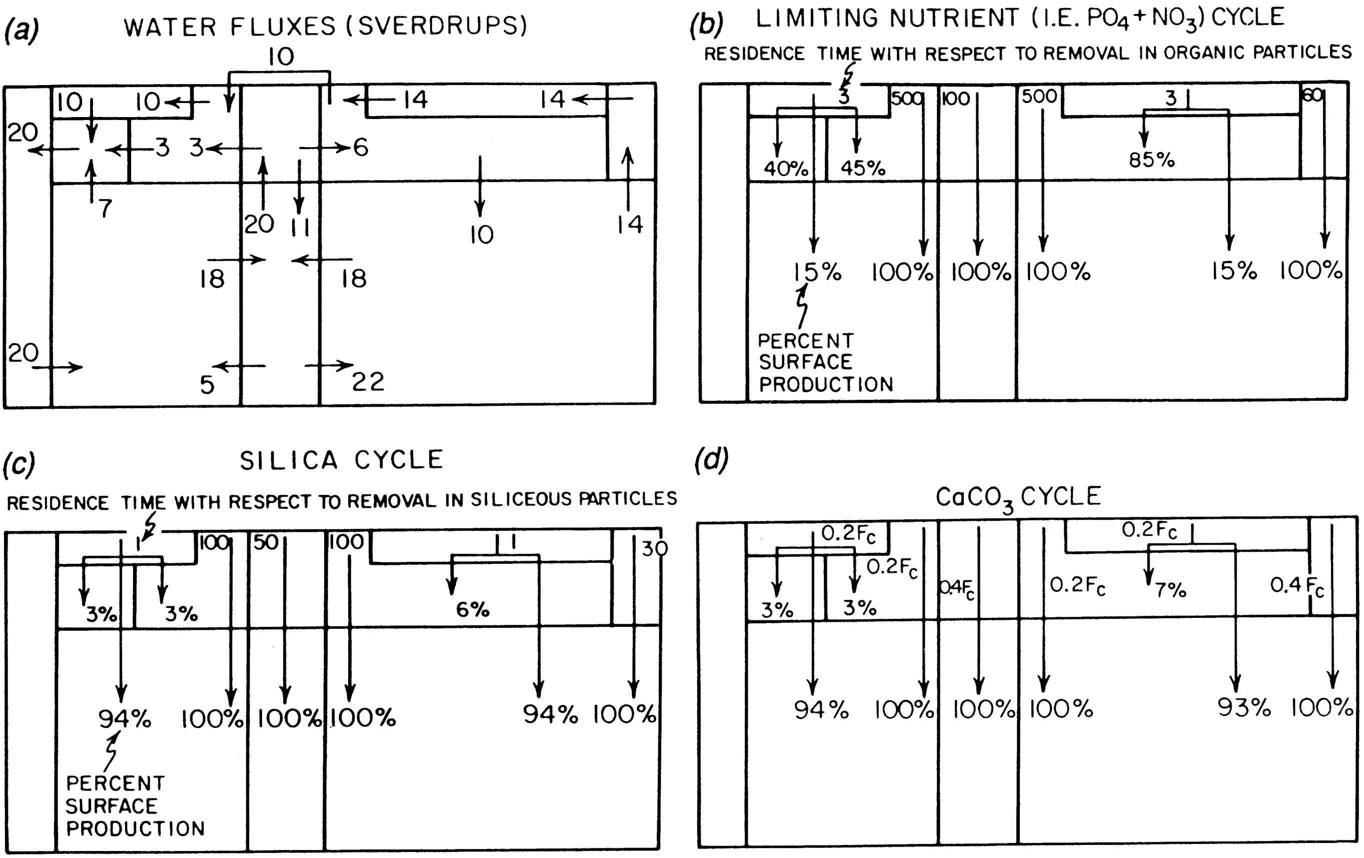

Fig 4. Global ocean water fluxes and biological cycling in the PANDORA model. (a) Water fluxes (in sverdrups) between the boxes required to match the present ^{14}C distribution. (b) Limiting nutrient cycle. The nutrient is assigned residence times (in yr) with respect to removal from the reservoir in organic debris. The percentages indicate the fate of this falling debris. All the debris is recycled. (c) Rules for opal formation and destruction set up as for limiting nutrients. (d) $CaCO_3$ cycle. The production of $CaCO_3$ is taken to be a fixed fraction of the organic production flux (shown as Fc). The destruction percentages are also shown.

boxes. The organic debris falling from the surface box is assumed to be completely recycled in the deeper boxes. The values of biologic residence time in the surface boxes and of the destruction percentage of organic debris in the deeper boxes are chosen to match the observed nutrient (mainly PO_4) distribution. The production of $CaCO_3$ is tied directly to the production of organic matter. In the warm surface (Atlantic and Indo-Pacific) reservoirs and intermediate reservoirs with atmospheric outcrops, 1 mol of falling $CaCO_3$ for each 5 mol of falling organic debris is allowed. In the cold surface (Antarctic and North Pacific) reservoirs, 2 mol of falling $CaCO_3$ for each 5 mol of falling organic debris is allowed. A far greater percentage of the $CaCO_3$ is dissolved in the deep boxes than in the intermediate boxes. These rules are designed to reproduce the observed salinity-normalized calcium distribution in the ocean (as determined from the nitrate-corrected and salinity-normalized alkalinity distribution). The silica cycle is handled in the same manner as the limiting nutrient cycle. However, a different set of biologic residence times and destruction percentages is required to reproduce the observed silica distribution.

After the model is calibrated with the observed data, the ^{14}C production rate in the atmosphere is raised so that atmospheric $\Delta^{14}C$ reaches 85‰, which represents the mean atmospheric ^{14}C activity 7000 yr ago (as recorded in tree rings). Since the atmospheric ^{14}C level before this time is unknown, it is assumed that the ocean-atmosphere system was at steady state. The subsequent changes in the atmospheric ^{14}C production and ocean mixing rates are needed to match the observed ^{14}C data in the atmosphere and ocean. Although it is very likely that the ocean-atmosphere system was in a transitional state 7000 yr ago because of continuous climate changes from the last glacial to the current interglacial period, we do not have data to calibrate the model accordingly.

RESULTS

In the comparison of model ^{14}C results with ^{14}C dating of foraminifera shells taken from the South China Sea, only the Indo-Pacific warm surface and deep reservoirs in the model are considered. Figure 5c shows ^{14}C age differences between planktonic and benthic forams plotted as a function of time both for model results and for observed data. The model began with ^{14}C age difference of 1385 yr 7000 yr ago, and increased to 1600 yr at present. The model ^{14}C age difference at present is consistent with ^{14}C measurements of present-day sea water in the Pacific Ocean. It shows that the model predictions of ^{14}C age differences are quite consistent with the observations of the whole period. The conditions necessary for such model ocean predictions are shown in Figure 5a. The water fluxes of the whole ocean are required to decrease by 15% from 7000 to 2000 yr ago and to remain constant at that level to the present. In this case, the atmospheric ^{14}C production rate is assumed to be constant with time. Although the model can predict oceanic ^{14}C distribution reasonably well, the model atmospheric ^{14}C variations under these conditions are completely inconsistent with the observed atmospheric ^{14}C variations shown in Figure 5b. The atmospheric data are represented by a best-fit curve (solid curve) that is calculated from

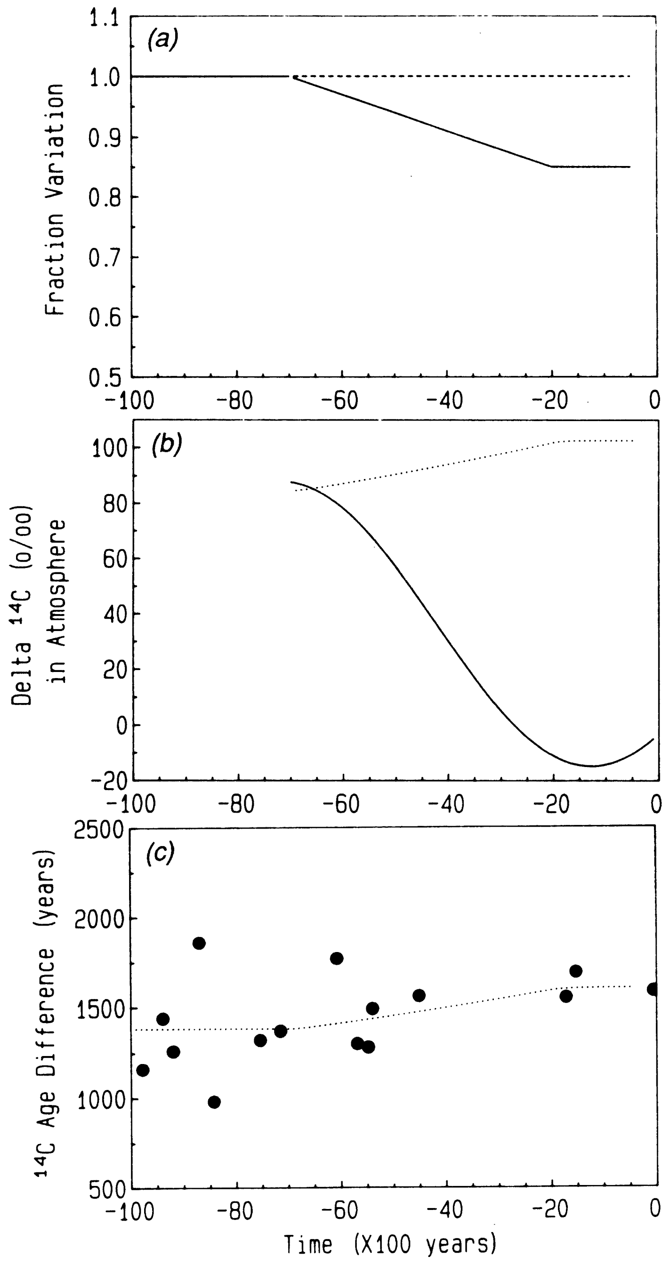

Fig 5. Model results under constant ^{14}C production rates. (a) Dashed line = change in the ^{14}C production rate. Solid line = change in the ocean ventilation rate. Both rates are assumed to be constant before 7000 yr ago. (b) Model atmospheric ^{14}C activity (dotted curve) is compared with the observations (solid curve). (c) Model ^{14}C age difference in the Indo-Pacific Ocean (dotted curve) is compared with measurements made in the South China Sea by Andrée *et al* (1986). A steady-state model ^{14}C age difference of 1385 yr is assumed for the ocean 7000 yr ago.

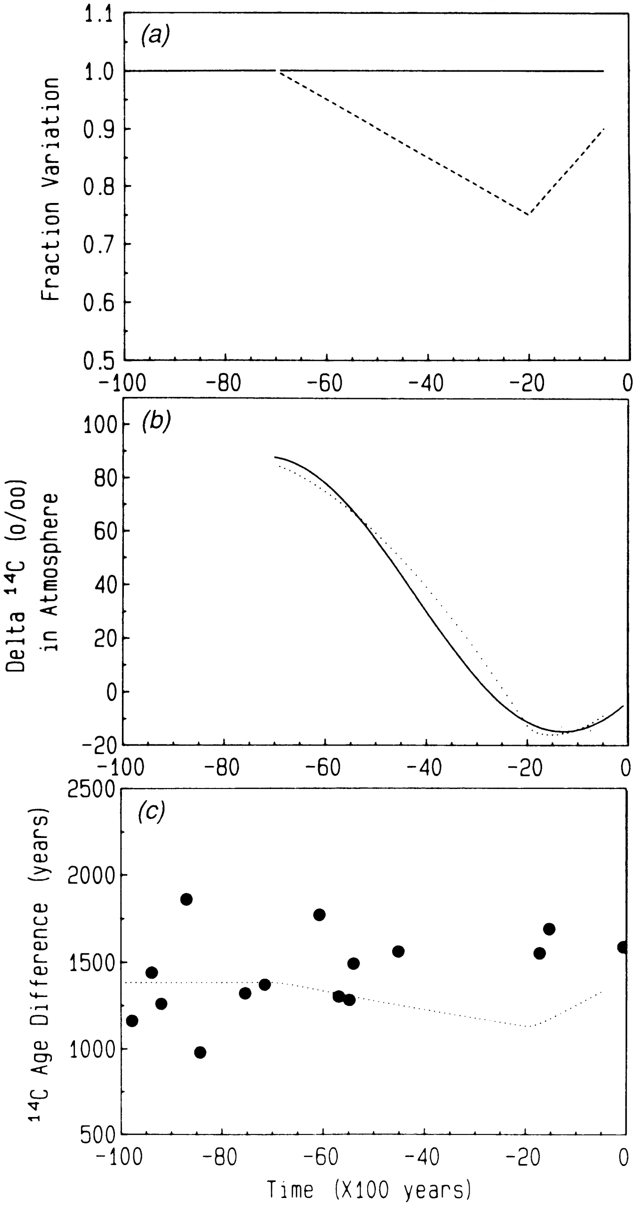

Fig 6. Model results under constant ocean ventilation rates. (a) Dashed line = change in the ^{14}C production rate. Solid line = change in the ocean ventilation rate. Both rates are assumed to be constant before 7000 yr ago. (b) Model atmospheric ^{14}C activity (dotted curve) is compared with the observations (solid curve). (c) Model ^{14}C age difference in the Indo-Pacific Ocean (dotted curve) is compared with measurements made in the South China Sea by Andrée *et al* (1986). A steady-state model ^{14}C age difference of 1385 yr is assumed for the ocean 7000 yr ago.

an equation given by Neftel, Oeschger and Suess (1981). Obviously, we can conclude from this comparison that the atmospheric ^{14}C production rate has not remained constant for the last 7000 yr.

If we assume that the ventilation rate of the ocean has remained constant over the last 7000 yr, the atmospheric ^{14}C production rate must have changed in order to produce the observed trend of atmospheric ^{14}C variations. To reproduce such a trend in the model (Fig 6b, dotted curve), the atmospheric ^{14}C production must decrease by 25% from 7000 to 2000 yr ago and then increase by 15% from 2000 yr ago to the present (Fig 6a). However, the model ^{14}C distribution in the ocean (Fig 6c) is inconsistent with the foraminifera ^{14}C measurements. This indicates that the ocean ventilation rate has not been constant over the last 7000 yr.

Based on these model calculations, we would expect that both atmospheric ^{14}C production rates and the ocean ventilation rates change with time simultaneously to produce the observed ^{14}C distribution both in the atmosphere and ocean. When the ocean ventilation rate slows down, the ^{14}C age difference between surface water and deep water increases because less ^{14}C is transported to the deep ocean. The atmospheric ^{14}C activity also increases because less ^{14}C is taken up by the ocean with the slower ocean mixing rate. When the atmospheric ^{14}C production rate decreases, the atmospheric ^{14}C concentration decreases because of less ^{14}C supply. The oceanic ^{14}C age difference between surface water and deep water also decreases because the surface water becomes older when less atmospheric ^{14}C is available for transfer into the surface ocean. When these features are combined appropriately, the model should reproduce both the time history of atmospheric ^{14}C variations and the variations with time in the oceanic ^{14}C age differences between surface water and deep water. Figure 7 shows the results of such simulation. Both atmospheric ^{14}C production rates and ocean ventilation rates are required to decrease with time simultaneously until 2000 yr ago and to increase with time to the present (Fig 7a). To make a better match of the variations of the atmospheric ^{14}C trend between model results and the observations (Fig 7b), the ^{14}C production rates have to be constant 3000–2000 yr ago. The lowest ^{14}C production rate during this period is 30% less than that of 7000 yr ago. However, the ocean ventilation rate decreased continuously by 35% until 2000 yr ago and has increased relatively rapidly by ca 25% to the present. The model oceanic ^{14}C age differences (Fig 7c) remain almost constant until ca 3000 yr ago and increase sharply to the present observed age difference of 1600 yr ca 1000 yr ago. Since we do not have foraminifera ^{14}C data for 4000–2000 yr ago, the sharp changes in age differences in this period cannot be confirmed. During these model experiments, we have learned that a constant ^{14}C age difference with time does not necessarily mean that the ocean ventilation rates also remain constant. In fact, a constant ^{14}C age difference in the ocean requires simultaneously the same trend of variations in both atmospheric ^{14}C production rates and oceanic ventilation rates.

^{14}C measurements of various species of foraminifera in the deep-sea sediments provide useful constraints not only on the ocean ventilation rate changes but also on the atmospheric ^{14}C production rate changes. Unfortunately, there are very limited ^{14}C measurements of foraminifera from very few selected geographic locations. More measurements are needed in the

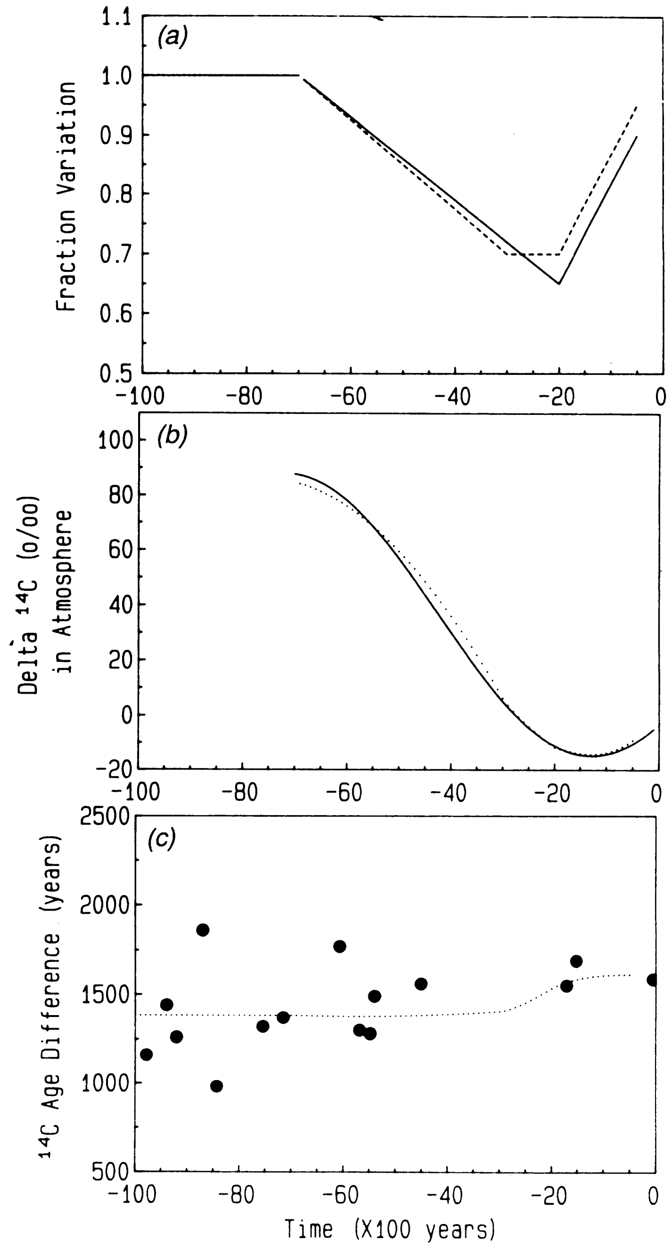

Fig 7. Model results under changing ^{14}C production rates and changing ocean ventilation rates. (a) Dashed line = change in the ^{14}C production rate. Solid line = change in the ocean ventilation rate. Both rates are assumed to be constant before 7000 yr ago. (b) Model atmospheric ^{14}C activity (dotted curve) is compared with the observations (solid curve). (c) Model ^{14}C age difference in the Indo-Pacific Ocean (dotted curve) is compared with measurements made in the South China Sea by Andrée *et al* (1986). A steady-state model ^{14}C age difference of 1385 yr is assumed for the ocean 7000 yr ago.

future to provide a stronger data base for studying variations of rates of ocean ventilation.

The choice of *G sacculifer* as a representative recorder of the $^{14}C/^{12}C$ ratio in the surface water is certainly a subject of debate. As reported by Andrée *et al* (1986), another planktonic species, *P obliquiloculata,* picked in the same core at the same depth, appears to be on the average ca 400 yr older than *G sacculifer*. It was postulated that *P obliquiloculata* might live below the surface mixed layer and hence represent a slightly lower $^{14}C/^{12}C$ ratio. The point here is that we do not really understand why the ratios are different, and we are only beginning our quest into paleoceanic ^{14}C distribution. Reliable determination of the $^{14}C/^{12}C$ ratio of sea water in the paleocean is still in its infancy.

There are recent concerns whether ^{14}C activity measured in benthic foraminifera is a true proxy for bottom water ^{14}C concentration. Zahn, Winn and Sarnthein (1986) showed that the $\delta^{13}C$ values of the benthic foraminifera *Uvigerina peregrina* group from deep sea cores are not a true recorder of $^{13}C/^{12}C$ ratios in sea water. They demonstrate that the $\delta^{13}C$ values of *U peregrina* group correlate largely with the accumulation rates of organic carbon, suggesting a local "habitat effect" because these organisms live within sediment that may have isotope concentrations different from those in the bottom water. McCorkle, Emerson and Quay (1985) showed that the carbon isotope ratio in the sediment pore waters is affected by oxidation of organic matter. These findings imply that benthic foraminifera may also not be a valid recorder of the $^{14}C/^{12}C$ ratio of the deep water. This would add an extra problem to the deconvolution of past ocean ventilation rates using ^{14}C data. It is not certain whether the scatter of foraminifera ^{14}C data reflects uncertainty due to this "habitat effect". Because of this effect and the scarcity of foraminifera ^{14}C data, it is quite possible that results obtained from this study may be modified as more data become available and a better understanding of the mechanisms affecting carbon isotope composition in the deep-sea sediments is obtained.

CONCLUSION

AMS ^{14}C dating of handpicked planktonic and benthic foraminifera in deep-sea sediments offers a new possibility for reconstructing past variations in ocean ventilation rates. With the help of atmospheric ^{14}C data recorded in tree rings, ocean model experiments show that ocean ventilation rates have not remained constant over the last 7000 yr. In fact, ventilation rates may have decreased as much as 35% during the past 7000 yr. However, due to the scarcity of foraminifera ^{14}C data and the uncertainty of carbon isotope proxies for sea water, this conclusion may be modified as future studies are conducted.

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