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# On the Radio-carbon Age of the Ocean Waters*

by

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## Abstract

The radioactive decay rate of radio-carbon in the ocean ($1.5\times10^{-11}$ g/m$^2$, y) is much smaller than the rate of biological uptake and regeneration of inorganic radio-carbon from organic matters ($1\times10^{-10}$ g/m$^2$, y) and the exchange rate at the air-sea interface ($2\times10^{-10}$ g/m$^2$, y). Therefore, the radio-carbon age of sea water is controlled not only by the radioactive decay but also by the other factors mentioned above. This is the reason for the higher age of the surface water in polar areas.

The radio-carbon age of sea water in the deep layers of the oceans is determined by radioactive decay, the exchange of inorganic carbon between the surface and the deep layers and regeneration of the inorganic carbon through biological decomposition. Owing to the smaller concentration of the inorganic carbon at the surface layer than that in the deep layer, the specific activity of radio-carbon in the deep layer tends to decrease through mixing with surface water, which gives a higher radio-carbon age to the deep waters. Results of calculation show that when the residence time of the deep waters is 200 to 300 years and that of the surface water is 5 to 7 years, the apparent age is estimated to be about 1,300 years, which is in good accordance with the observation.

## 1. The change in the radio-carbon content in the ocean

The change with time in the content of the inorganic radio-carbon in the ocean can be expressed by the following equation:

$$\frac{\partial C^*}{\partial t}=-\lambda C^*+(e-s)-(p-b) \tag{1}$$

where $C^*$ is the amount of C–14 in the forms of $CO_2$ (or $H_2CO_3$), $HCO_3^-$ and $CO_3^{2-}$ in the ocean water, g/m$^2$; $\lambda$ is the radioactive decay constant of C–14; $e$ is a rate of entry of C–14 from the atmosphere, g/m$^2$,y; $s$ is a rate of escape of C–14 from the ocean to the atmosphere, g/m$^2$,y; $p$ is a rate of incorporation of C–14 into organic matters through the primary organic production, g/m$^2$, y; and $b$ is a rate of regeneration of the inorganic radio-carbon from organic matters, g/m$^2$, y. In the above equation, the dynamical motion of waters is not considered.

In the whole oceans, the annual rate of primary production is regarded to be

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80 g C/m$^2$,y on an average. In the steady state, the rate of primary production is equal to the decomposition rate of organic matters. As the atomic ratio of the radio-carbon to the normal carbon is $1.24\times10^{-12}$, $p$ and $b$ will be equal to $1\times10^{-10}$ g/m$^2$, y. The total amount of inorganic carbon in the oceans is estimated to be about 112,000 g/m$^2$ (2.3 mg atom C/$l$) in which the amount of radio-carbon is $1.2\times10^{-7}$ g/m$^2$ (or $3\times10^{-14}$ g/$l$), assuming that the depth of the ocean is 4,000 m and the mean specific activity of radio-carbon in sea water is 15% less than that in the air. The decay constant of C–14 is $1.26\times10^{-4}$/y. Therefore, the rate of radioactive decay ($\lambda C^*$) will be $1.46\times10^{-11}$ g/m$^2$, y.

The amount of carbon dioxide in the atmosphere is $4.7\times10^3$ g/m$^2$, in which $1.28\times10^3$ g/m$^2$ of carbon is contained. Assuming that the residence time of carbon dioxide in the atmosphere is 7 years, 180 g of carbon enters the oceans through the sea-air boundary per square meter annually. In a steady state, the same amount of inorganic carbon returns annually to the air from the sea. 180 g of carbon in the air contains $2.2\times10^{-14}$ g of C–14.

As stated above, in a steady state, the rate of photosynthesis of C–14 ($p$) is equal to that of regeneration of the inorganic C–14 from the organic matters ($b$). Therefore, the difference between rates of entry ($e$) and escape ($s$) of C–14 must be equal to the rate of radioactive decay of radio-carbon $\lambda C^*$ in the oceans. Thus, the rate of escape of radio-carbon from the sea will be $2.05\times10^{-10}$ g/m$^2$, y.

It is important to note that the rate of radioactive decay $\lambda C^*$ ($1.5\times10^{-11}$ g/m$^2$, y) is much smaller than the average rate of biological intake ($p$) or regeneration ($b$) ($1\times10^{-10}$ g/m$^2$, y). $\lambda C^*$ is also smaller than the rate of exchange of C–14 through the air-sea interface (2.2 and $2.05\times10^{-10}$ g/m$^2$, y).

This suggests that in a non-steady state, the content of inorganic C–14 in sea water is determined not only by the radioactive decay but also by the rates of biological production and decomposition, and also by the exchange rate of C–14 through the air-sea interface. When the biological production rate exceeds that of regeneration, the content of the inorganic C–14 in sea water decreases, which will give an older radio-carbon age to the sea water. Such conditions may occur in areas with lower water temperature but with sufficient solar radiation to allow photosynthesis. In the polar seas, the primary production rate often reaches as high as 400 g/m$^2$, y, while the decomposition rate is much smaller owing to the extremely low water temperature.

On the other hand, when the difference between the entry and escape ($e-s$) is smaller than $\lambda C^*$, the radio-carbon age will also be older and *vice versa*. The condition of $(e-s)<\lambda C^*$ may occur when the partial pressure of $CO_2$ in sea water exceeds that in the air above the sea surface. In the Antarctic Ocean, pH of surface sea water as low as 7.6 is often observed (Torii *et al.*, 1959), which accelerates the escape of $CO_2$ from the sea (Miyake and Matsuo, 1963). The astonishingly older age of the surface sea water found in the Antarctic Ocean and its surrounding areas may arise as a result of combination of the conditions of $p>b$ and $(e-s)<\lambda C^*$.

## 2. Radio-carbon age of sea water in deep layers of the oceans

It is well known that the radio-carbon age of sea water often exceeds 1,000 years in the deeper layer of the oceans. By extensive studies of the distribution of radio-carbon in different oceans, BROECKER (1963) gave the values of 800 years and 500 years respectively to the Indo-Pacific and the Atlantic deep waters as the minimum residence time of water in the deep layers in both oceans. The residence time of water in a layer of the ocean is the average length of time during which water molecules remain in the same layer.

For the sake of simplicity, we divide the ocean into two layers, *i.e.*, the surface or the mixed layer and the deep layer. When the mass conservation of water is considered, the following relation holds with respect to the transfer of water between the surface and the deep layer.

$$K'W' = KW \tag{2}$$

where, $W'$ and $W$ are the amounts of water respectively in the surface and deep layers, $K'$ and $K$ are mean velocity constants of transfer of water from the surface to the deep and from the deep to the surface respectively. The mean residence time of water in the surface water ($\tau'$) and that in the deep water ($\tau$) are equal respectively to $1/K'$ and $1/K$.

The residence time of water in the surface layer of 100 m thick is considered to be 5 to 10 years. From the above equation (2), the residence time of deep water with the mean thickness of 3,900 m must lie in the range between 195 and 390 years. Unless the residence time in the surface exceeds 13 years, that of the deep water can not be longer than 500 years.

MIYAKE *et al.* (1962), BOWEN (1960, 1962, 1963), NAGAYA (1965), BELYAEV *et al.* (1964) and HIGANO (1966) showed the rapid rate of transfer of the fallout radio-nuclides, Sr-90, Cs-137 *etc.* from the surface into the deep layer. The rapid penetration of radioactive materials into the deeper layer suggests the shorter residence time of water in the deep layer.

On the other hand, in the study of phosphate and silicate concentrations in sea water, MIYAKE (1966) gave about 250 and 120 years as the mean residence time of water in the deep layers in the Indo-Pacific and the Atlantic respectively.

The change with time in the radio-carbon content in the surface and deep layers of the oceans can be expressed respectively as follows:

$$\frac{\partial(\beta C')}{\partial t} = \alpha KWc - \beta K'W'c' + E - \beta S - \sigma P + \sigma\beta B' - \lambda\beta C' \tag{3}$$

$$\frac{\partial(\alpha C)}{\partial t} = \beta K'W'c' - \alpha KWc + \sigma\beta B - \lambda\alpha C \tag{4}$$

In the above equation, $C'$ and $C$ are the total amounts of inorganic carbon in the surface and deep layers (g/m$^2$), $\alpha$ and $\beta$ are the relative, specific activities of the radio-carbon respectively in the deep and surface waters assuming that the specific activity in the air is one. $\sigma$ is the isotopic separation factor of the radio-carbon in the marine organisms ($\sigma=1.05$). $c'$ and $c$ are the concentrations of inorganic carbon in the surface and deep waters. $P$ is the rate of the primary production of inorganic carbon into organic carbon. $B'$ and $B$ are the rates of regeneration of organic carbon to inorganic carbon respectively in the surface and deep layers. $\lambda$ is the radioactive decay constant of the radio-carbon ($1.26\times10^{-4}$/y), $E$ and $S$ are respectively the rate of entry of inorganic carbon from the air to the sea and the rate of escape from the sea. $E$ and $S$ are 180 g C/m², y when the residence time of carbon dioxide in the air is 7 years.

By referring to the equation (2), $K'W'c'$ or $K'C'$ can be rewritten as follows:

$$K'C'=rKWc=rKC \tag{5}$$

where $r$ is the ratio of $c'$ to $c$. Since the surface concentration of the total carbonic acid is about 2 mg atom C/$l$ (or 24 mg/$l$) and that of deep water is 2.3—2.4 mg atom C/$l$, $r$ is in the range of 0.83—0.87.

In a steady state, the equations (3) and (4) can be rewritten as follows:

$$\gamma=\frac{KC+\lambda C}{rKC+\sigma B} \tag{6}$$

$$\alpha=\frac{E}{\gamma(rKC+S+\sigma P-\sigma B'-\lambda\beta C')-KC} \tag{7}$$

where $\gamma$ is the ratio of the specific activities, $\beta$ to $\alpha$ ($\gamma>1$). The relative specific activity of the inorganic radio-carbon in deep waters, $\alpha$ is smaller than one, and from $\delta=1-\alpha$, we can calculate the apparent radio-carbon age of water as follows:

$$t=\frac{\delta}{\lambda}=\tau_c-\tau_c\frac{E}{(rKC+S+\sigma P-\sigma B')-KC}$$

where $\tau_c$ is the mean life of radio-carbon (7,936 years).

Observations of the radio-carbon in the oceans show that, on the weighted average, the relative, specific activity at the surface, $\beta$ is 0.94, and in the deep, $\alpha$ is 0.84 (or $\gamma$ is 1.12) which corresponds to the apparent age of water of 1,280 years.

The average primary production rate in the oceans $P$ is 80 g C/m², y in which it is assumed that a half of it is regenerated in the surface layer and the rest is transported to the deep layer followed by decomposition ($B'=B=40$ g C/m², y). By putting some numerical values for $r$, $\tau$, $C$ *etc.* into the equations (6) and (7), $\gamma$ and $\tau'$ can be calculated. The results are given in Table 1.

As shown in Table 1, the calculated ratio of $\gamma$ falls in the range from 1.08 to 1.12 which is in good agreement with the observation. $\tau'$, the residence time of water in the surface, is from 5.2 to 7.7 years, which is also in good accordance with the estimation given by previous studies.

In the case of $r=0.83$, $\gamma=1.11$ and $\tau=300$ years, the apparent age $t$ of the deep layer is obtained by the equation (7). The result of calculation shows the apparent age of water to be 1,380 years, which coincides well with the observation. In the

Table 1. Calculated values of $\gamma$ and $\tau'$.

| $r$ | $\tau$ (years) | $KC$ ($g/m^2$, y) | $\gamma$ (calculated) | $\tau'$ (years) (calculated) |
|---|---|---|---|---|
| 0.85 | 200 | 548 | 1.11 | 5.2 |
| | 300 | 365 | 1.08 | 7.7 |
| 0.83 | 200 | 560 | 1.12 | 5.2 |
| | 300 | 374 | 1.10 | 7.7 |

same way, by assuming that the apparent age $t$ is 1,100 years, $\tau$=200 years and $r$=0.83, the calculation of $E$ and $S$ can be done. The result of calculation shows that $E$ or $S$ is 220 $g/m^2$, y which corresponds to the residence time of the carbon dioxide in the atmosphere of about 5.7 years.

From the above discussions, we may conclude that the residence time of water in the deep and surface layers are respectively 200–300 years and 5 to 7 years on the average. It is also concluded that the residence time of the carbon dioxide in the air is about 6 to 7 years and the mean apparent radio-carbon age of the deep water is about 1,300 years.

The discrepancy between the comparatively short residence time of deep water (200–300 years) and the longer apparent carbon age (1,300 years) is caused by the unbalanced exchange of inorganic carbon through the interface of the surface and the deep layers, which brings about the decrease in the specific activity of the radio-carbon in the deep waters. This is due to the smaller concentration of the inorganic carbon in the surface layer or the condition of $r<1$ as shown in the equation (6). This tendency is partly compensated for by the transfer of organic debris from the surface to the deep layer, but this is not enough to reduce the ratio $\gamma$ to the original value.

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# 海洋水の放射性炭素年令について

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海水の放射性炭素の含有量から，深海水の平均寿命（一度深海に没してから，ふたたび表層に出るまでの平均時間）が求められているが，著者らは炭素の循環に着目し，海水の平均寿命といわゆる放射性炭素年令との間の関係を明らかにした。

海水中の放射性炭素は放射能壊変にのみ支配されるものではなく，生物による摂取，大気―海洋間の交換，表層―深層間の交換，有機物の分解による無機炭素の再生産を考慮しなければならない。

計算の結果は，平均寿命として表面水については 5～7 年，深層水については 200～300 年という値が得られた。これらは従来考えられている深海水の 1000 年をこえる値にくらべると，かなり小さい。