

CARBON-14 IN THE SOUTHERN INDIAN OCEAN

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ABSTRACT. ^{14}C measurements were carried out on sea water samples collected in 1973, in the Indian ocean. The results obtained for 9 vertical profiles between 27°S and 48°S are presented. In surface water, the bomb ^{14}C content is maximum at middle latitudes. A time lag relative to the north hemisphere bomb ^{14}C delivery is apparent. In the more southern latitudes, ^{14}C content remains very low.

INTRODUCTION

The distribution of bomb ^{14}C in the oceans has been studied by numerous authors, either to determine the residence time of carbon in the different oceanic reservoirs or to measure the velocity of displacement of water masses. Most work has been done in the Atlantic Ocean (Broecker and others, 1960; Broecker and Olson, 1961; Broecker, Peng, and Stuiver, 1978; Fairhall, Young and Bradford, 1972; Fonselius and Östlund, 1959; Östlund, Dorsey, and Rooth, 1974; Ribbat, Roether, and Munnich, 1976; Stuiver, 1976; 1978; Vogel, 1972) and in the Pacific ocean (Bien, Rakestraw, and Suess, 1963; 1965; Rafter and O'Brien, 1972; Fairhall, Young, and Bradford, 1972).

Very few data are presently available for the Indian Ocean. The only ^{14}C measurements known for that part of the ocean are given by Bien, Rakestraw, and Suess (1963; 1965). They have, very interestingly, demonstrated that when bomb ^{14}C entered the surface waters of the southern hemisphere, natural ^{14}C concentration was still preserved in the deep waters.

The present work shows the distribution of ^{14}C in the western part of the Southern Indian Ocean in 1973. Sea water samples were collected at the end of the austral summer, during the 1973 OSIRIS I hydrological expedition, on board the *R/V Marion Dufresne*. Figure 1 shows the position of the ^{14}C stations.

EXPERIMENTAL METHOD

Water samples were collected with 30-liter Niskin bottles. Because of the limited number of bottles and of time available for the ^{14}C program, the volume of collected water was only 60L down to 1000m depth and 90L for the deeper levels. At each depth, a reversing thermometer gave temperature measurements and some water was collected for salinity and ΣCO_2 . At each step of the sampling procedure as well as during the extraction, special attention was paid to eliminate all risk of contamination.

Inorganic carbon was extracted on board the ship in the usual manner. Immediately after sampling, the water from the bottle was transferred by pumping into a 100L metallic tank that was previously filled with nitrogen. The water was then acidified and warmed with an immersion heater to help the outgassing process. The released CO_2 was then trapped in a purified 6N NaOH solution that was prepared previously in the laboratory under an inert atmosphere and sealed in flasks. The transfer

of CO₂ was accomplished by circulating nitrogen through the system in a closed loop using a pump.

The duration of one operation was about 4 hours for a 60L sample and 6 hours for a 90L sample. Upon return to the laboratory, the alkaline solution was placed under vacuum and quickly acidified with H₂SO₄. The CO₂ removed, after drying and purification, was counted for ¹⁴C activity. Although shipboard operations were carried out very carefully, extraction of CO₂ was not always complete, partly because of lack of time during the stations. The volume of CO₂ available for ¹⁴C measurements thus varied from 2 to 3.5L. Two different 1.2L proportional counters, having 1.06 and 1.27 cpm, respectively, as backgrounds, were used for counting. Corrections for isotopic fractionation and calculations of the usual Δ¹⁴C values were effected using δ¹³C measurements made on the CO₂ filling the proportional counters, after the ¹⁴C measurements. The average of the measured δ¹³C, +0.02‰, was adopted for correction, in some cases, when δ¹³C measurements were missing. The experimental dispersion around this average value was then included in the calculation of the errors on Δ¹⁴C

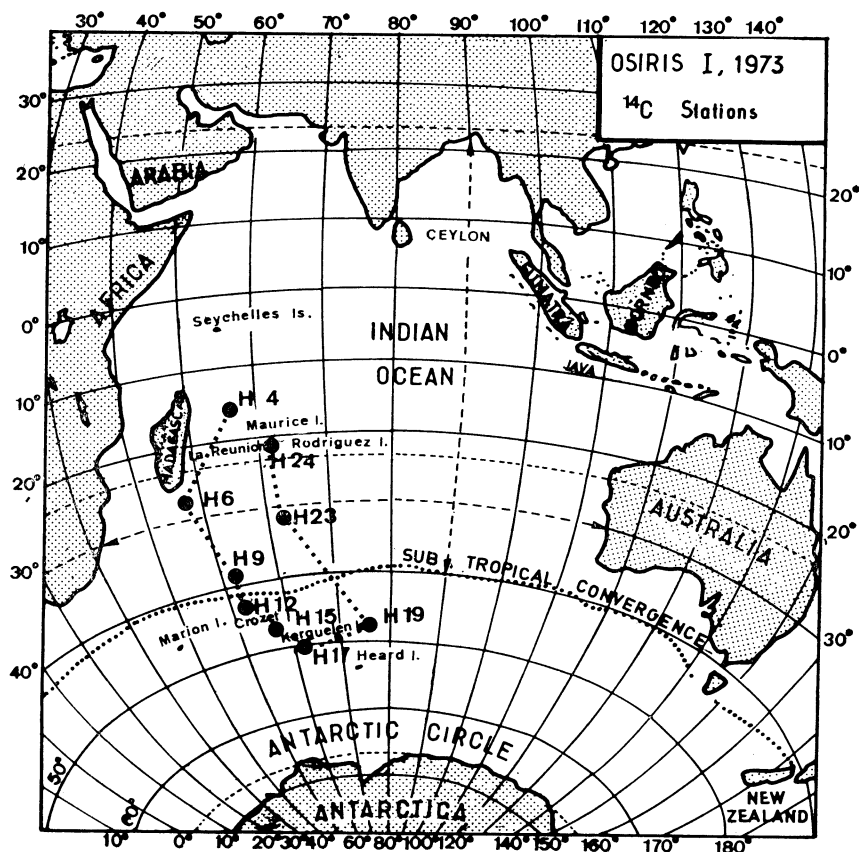


Fig. 1. Map showing the track of the ship, with the location of ¹⁴C stations.

($\pm 4\text{‰}$ added). Accuracy obtained for $\Delta^{14}\text{C}$ measurements is $\pm 6\text{‰}$, in most cases, but it is very variable (from $\pm 4\text{‰}$ to $\pm 10\text{‰}$) mainly because of the varying amount of carbon available for measurement and the missing $\delta^{13}\text{C}$ measurements.

The value of modern carbon used as reference was the NBS oxalic activity $\times 0.95$, corrected for decay from 1950 to 1973, the year of the water sampling.

RESULTS

All ^{14}C data and $\delta^{13}\text{C}$ measurements are shown in table 1 with the location of the stations arranged from north to south. Salinity and ΣCO_2 data (Le Floch and Tanguy, 1973) given in the same table were obtained from water collected in a separate bottle at the same time as the ^{14}C samples. Variations in $\Delta^{14}\text{C}$ values obtained in 1973 with depth and latitude of the sampling in the Southern Indian Ocean are of interest. Although evidence of bomb ^{14}C is present in most samples from upper levels of the water column, this is often not the case for deep levels. Consequently, it will often be necessary to refer to the available pre-atomic values.

Surface waters

Pre-nuclear bomb ^{14}C levels in the Indian ocean

The natural ^{14}C level of ocean surface water in the Indian Ocean is not well known. To obtain precise values, we measured the activity of two shells collected alive on a specific date that were carefully preserved in a collection:

— *Cyprata mauritania*, living in 1914, at Maurice Island ($13^\circ 25' \text{ S}$, $48^\circ 30' \text{ E}$). The apparent age found is 399 ± 35 years, corresponding to a $\Delta^{14}\text{C}$ of $-47.2 \pm 4\text{‰}$ (Gif-4064).

— *C. carneala*, living in 1853, at Nossibe, Madagascar ($20^\circ 15' \text{ S}$, $57^\circ 30' \text{ E}$). The apparent age is 350 ± 35 years, corresponding to a $\Delta^{14}\text{C}$ of $-41.5 \pm 4\text{‰}$ (Gif-4065).

These values are corrected for radioactive decay and isotopic fractionation. Some values obtained at the very beginning of the ^{14}C bomb advent for surface water, south of the Antarctic convergence, are reported:

— $57^\circ 07' \text{ S}$, $07^\circ 05' \text{ W}$, ($\theta = +1^\circ\text{C}$), in 1958: $\Delta^{14}\text{C} = -120 \pm 5\text{‰}$ (Broecker and others, 1960)

— $55^\circ 27' \text{ S}$, $57^\circ 10' \text{ W}$, ($\theta = +3^\circ\text{C}$), in 1958: $\Delta^{14}\text{C} = -111 \pm 7\text{‰}$ (Broecker and others, 1960)

— $64^\circ 11' \text{ S}$, $168^\circ 58' \text{ W}$, ($\theta = +1.7^\circ\text{C}$), in 1961: $\Delta^{14}\text{C} = -120 \pm 20\text{‰}$ (L.J-410) (Bien, Rakestraw, and Suess, 1965).

Although obtained in the South Atlantic and South Pacific Oceans, these values are important for comparison with our present data, if Antarctic surface water is considered to be well mixed in the circumpolar region. We can also use the $\Delta^{14}\text{C}$ value of $-149 \pm 7\text{‰}$ (L-570) given for the flesh of a seal killed in 1959 (Broecker and others, 1960) at Mac Murdo, (77° S , 164° E). These very low surface water values are due to the presence of uplifted, deep, old water, which do not remain at the surface long enough to reach equilibrium with the atmosphere.

TABLE 1

Sampling date	Station	Latitude	Longitude	Depth (m)	Salinity ‰	Temperature (°C)	CO ₂ m mole/l	δ ¹³ C ‰	δ ¹³ C* ‰	Δ ¹³ C ² ‰	Sample no.
5/6/73	H4	15°05'S	55°31'E	0	34.80	28	2.084	+158	+1.27	+ 97 ± 7	Gif-3113
				50	34.85	27.5	2.042	+152	(+0.02)	(+ 94 ±11)	Gif-3160
				100	35.10	21.55	2.147	+166	-1.35	+111 ± 7	Gif-3163
				1000	34.70	5.54	2.325	- 69	-1.05	-113 ± 7	Gif-3125
				1500	34.68	3.65	2.384	-114	+0.41	-164 ± 6	Gif-3126
6/2/73	H24	20°30'S	61°58'E	0	34.88	25.9	2.090	+138	+0.43	+ 80 ± 6	Gif-3106
				50	35.15	25.5	2.072	+183	-2.81	+130 ± 9	Gif-3158
				100	35.36	21.6	2.146	+172	+1.13	+111 ± 5	Gif-3157
				200	35.56	18.7	2.220	+152	+1.49	+ 91 ± 6	Gif-3156
				300	35.42	14.7	2.239	+141	(+0.02)	(+ 84 ±10)	Gif-3155
				700			2.251	+ 36	+0.13	- 16 ± 6	Gif-3153
				1000	34.68	6.18	2.291	- 92	+0.91	-139.5 ± 5	Gif-3144
				1500	34.79	3.29	2.365	- 83	(+0.02)	(-129 ±12)	Gif-3143
				2000	34.72	2.86	2.347	- 93	-4.3	-130.5 ± 6	Gif-3142
5/9/73	H6	26°48'S	48°39'E	0	35.01	24.1	2.09	+175	+0.76	+114 ± 5	Gif-3100
				100	35.43	19.14	2.146	+217	+1.27	+153 ±10	Gif-3107
				500	35.12	11.99	2.216	+ 82	+1.27	+ 47 ±10	Gif-3108
				700	34.78	9.41	2.251	+ 26	+2.16	- 30 ± 6	Gif-3109
				1500	34.57	3.22	2.365	- 81	-0.80	-128 ± 6	Gif-3110
				2000	34.72	2.44	2.347	- 99	+1.27	-128 ± 6	Gif-3111
				3000	34.74	1.84	2.347	-134	-0.11	-177 ± 5	Gif-3112
				5/28/73	H23	31°00'S	61°51'E	0	35.52	19.31	2.090
50	35.51	19.15	2.072					+205	+0.71	+143 ± 6	Gif-3115
100	35.49	17.17	2.146					+186	+0.94	+124 ± 6	Gif-3116
200	35.37	14.41	2.220					+123	+1.17	+ 64 ± 6	Gif-3117
300	35.29	13.40	2.239					+134	+1.17	+ 75 ± 6	Gif-3118
500	35.14	12.16	2.216					+ 87	+1.27	+ 29 ±10	Gif-3119
700	35.04	11.32	2.251					+ 70	+1.01	+ 14 ± 5	Gif-3120
1000	34.52	6.95	2.291					- 39	-1.09	- 85 ±10	Gif-3121
1500	34.52	3.19	2.365					- 52	+1.27	-102 ±10	Gif-3122
2000	34.68	2.48	2.347					- 97	+0.86	-143 ± 6	Gif-3123
3000	34.75	1.79	2.347					- 89	+1.27	-146 ± 5	Gif-3124
5/14/73	H9	38°42'S	50°37'E	0	35.50	16.97	2.146	+150	+1.02	+ 90 ± 6	Gif-3101
				100	35.55	16.99	2.145	+178.5	-0.08	+120 ± 8	Gif-3136
				600	35.21	12.96	2.193	+ 64	-1.93	+ 15 ±10	Gif-3137
				1000	34.81	8.15	2.258	+ 13	+1.53	- 48 ± 6	Gif-3138
				1500	34.46	3.58	2.348	- 45	(+0.02)	(- 93 ±15)	Gif-3139
				2000	34.65	2.79	2.321	-103	-0.63	-146 ± 6	Gif-3140
5/16/73	H12	43°48'S	51°17'E	50	33.79	7.42	2.200	+ 95	-1.64	+ 44 ± 8	Gif-3161
				100	33.86	4.87	2.200	- 11	+0.85	- 62 ± 6	Gif-3165
				200	33.96	3.07	2.260	- 5.5	-2.41	- 50 ± 9	Gif-3166
				300	34.13	3.08	2.287	- 7	-1.39	- 54 ± 5	Gif-3167
				500	34.30	2.33	2.319	- 8.5	-2.56	- 52 ± 4	Gif-3168
				700	34.51	2.31		- 37	-2.18	- 90 ± 6	Gif-3169
				1500	34.61	2.36	2.342	- 75	-1.44	-102 ± 8	Gif-3170
5/18/73	H15	46°54'S	58°11'E	0	34.02	8.50	2.190	+111	+1.13	+ 41 ± 7	Gif-3102
				1000	34.51	2.44		- 77	-1.59	-120 ± 6	Gif-3171
				1500	34.71	2.28	2.353	- 75	+2.76	-126 ± 6	Gif-3130
				3000			2.330	- 68	-2.37	-111 ± 6	Gif-3132
5/23/73	H19	47°05'S	75°47'E	0	33.74	7.82	2.188	+105	+2.76	+ 44 ± 6	Gif-3104
				50	33.70	6.49	2.174	+ 80	+1.68	+ 22 ± 8	Gif-3162
				100	33.70	6.81	2.171	+ 98	-0.45	+ 44 ± 5	Gif-3172
				200	34.25	6.18	2.185	+ 57	-0.07	+ 42 ± 5	Gif-3173
				300	34.25	4.58	2.234	+ 57	-2.22	+ 4 ± 5	Gif-3174
				500	34.30	3.51	2.271	- 6	-0.80	- 53 ± 5	Gif-3175
				700			2.327	+ 22	-0.84	- 27 ± 5	Gif-3176
				1000	34.52	2.41	2.329	- 85	(+0.02)	(-130 ± 9)	Gif-3133
				1500	34.71	2.37	2.353	- 76	(+0.02)	(-122 ± 9)	Gif-3134
2000	34.71	2.08	2.376	- 74	(+0.02)	(-120 ±10)	Gif-3135				
5/19/73	H17	48°60'S	60°13'E	0	33.77	4.97	2.227	+ 41	+2.81	- 17 ± 5	Gif-3103
				100	33.78	4.68	2.228	+ 89	+1.04	+ 34 ± 6	Gif-3151
				300	34.18	2.39	2.342	- 17	+0.85	- 65 ± 6	Gif-3150
				700	34.50	2.26	2.346	- 66	+0.22	-113 ± 5	Gif-3148
				1000	34.69	2.34	2.369	- 93	+2.46	-114 ± 5	Gif-3147
				1500	34.77	1.98	2.371	- 80	(+0.02)	(-126 ±10)	Gif-3146
2000	34.76	1.95	2.330	- 66	+2.31	-117 ± 6	Gif-3145				
12/12/74		55°41'S	143°56'E	0		3.3		+ 17	+1.0	- 36 ± 6	Gif-3177
2/16/75		66°40'S	140°00'E	0		-1		- 90.2	-1.83	-132 ± 6	Gif-3178

* δ¹³C values between brackets does not correspond to individual measures but to an average value of the φ¹³C given in the table. The Δ¹³C values between brackets are calculated from this mean value (+0.02).

$\Delta^{14}\text{C}$ in surface waters collected at 0m depth in 1973

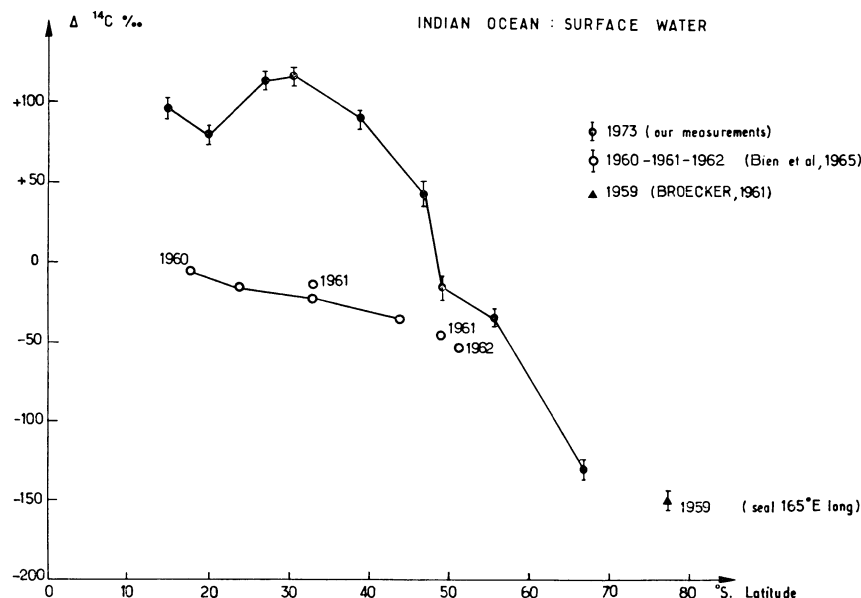
$\Delta^{14}\text{C}$ values obtained for surface water, in the western part of the southern Indian Ocean in 1973 are plotted versus latitude in figure 2. The most striking feature of the observed variation is a monotonous decrease from north to south, down to some very low $\Delta^{14}\text{C}$ values for the most southern latitudes. It may be observed that,

— from 15° to 40°S , in the subtropical zone, $\Delta^{14}\text{C}$ values are fairly high, from $+80\text{‰}$ to $+120\text{‰}$. An activity maximum is situated around 30°S where $\Delta^{14}\text{C}$ reaches values of $+114 \pm 5\text{‰}$ at H6 station ($26^\circ 48' \text{S}$) and $+117 \pm 6\text{‰}$ at H23 station (31°S);

— south of 40°S , $\Delta^{14}\text{C}$ decreases rapidly as do water surface temperatures; when the Antarctic Convergence is reached at station H17 ($48^\circ 59' \text{S}$), $\Delta^{14}\text{C}$ becomes negative: -17‰ , the temperature being $4^\circ 97\text{C}$.

Compared to the 1962 values (Bien, Rakestraw, and Suess, 1965) $-56 \pm 9\text{‰}$ at $51^\circ 07' \text{S}$, $65^\circ 51' \text{E}$, and $-45 \pm 10\text{‰}$ at $49^\circ 29' \text{S}$, $132^\circ 17' \text{E}$, the 1973 value, nevertheless, shows appreciably increased activity due to bomb ^{14}C .

Further south, but to the east, we obtained two water surface samples in 1975, one taken from the *RV Thaladan* ($55^\circ 41' \text{S}$) and another at the foot of the Astrolabe glacier in Terre Adélie, Antarctica. For these two samples, CO_2 extraction was performed in the laboratory. Results obtained are included in figure 2. $\Delta^{14}\text{C}$ shows a very negative value, -132‰ at $66^\circ 40' \text{S}$, 140°E ($\theta = -1^\circ\text{C}$), which may be due partly to the melting of old glacier water. However, it is close to the -128‰ value found in 1958, at $66^\circ 29' \text{S}$, $170^\circ 55' \text{E}$ (Rafter and O'Brien, 1972).



Vertical distribution

The vertical distribution of $\Delta^{14}\text{C}$ for the 9 stations studied is given in figure 3. A similar trend is apparent for all the profiles. The influence of bomb ^{14}C appears clearly in the upper few hundred meters, in which $\Delta^{14}\text{C}$ shows great variability. Below 1000m depth, $\Delta^{14}\text{C}$ decreases rapidly, becoming very negative and almost constant for all the deepest levels. There are some noticeable differences between the profiles, however, depending on their latitudes.

Most of the profiles are of the subtropical region, where $\Delta^{14}\text{C}$ values are particularly high, often greater than $+100\text{‰}$ for the first 200 to 300m. Penetration of bomb ^{14}C from the surface is evident and is maximum at stations H23 and H9 (31° S and $38^\circ\ 42'\ \text{S}$, respectively) where 1000m depth is reached.

In order to estimate the inventory of uptake of bomb ^{14}C during the CO_2 exchange in the upper 1000m, the difference between the 1973 and the 1960 $\Delta^{14}\text{C}$ values is integrated with depth (Broecker, 1978). It is done for the stations close to well-documented stations where profiles were made in 1960 for natural concentrations.

The water column inventories of bomb ^{14}C , for a latitude band from 24° to $39^\circ\ \text{S}$, lead to a mean value of $2.4 \cdot 10^{-8}\ \mu\ \text{mole of }^{14}\text{C}/\text{cm}^2$, with a range of 1.96 to $2.72 \cdot 10^{-8}\ \mu\ \text{mole}/\text{cm}^2$. This yields to an overall estimate of $26\ \text{moles}/\text{m}^2/\text{yr}$ for the CO_2 exchange rate.

This is a little too high, but not significant, if compared to the rate of $22\ \text{moles}/\text{m}^2/\text{yr}$ (corresponding to $2.0 \cdot 10^{-8}\ \mu\ \text{M}/\text{cm}^2$ of ^{14}C), calculated for the temperate and equatorial latitudes in the Atlantic Ocean (Broecker, 1978); but it is higher than the average of $1.7 \cdot 10^{-8}\ \mu\ \text{M}/\text{cm}^2$ of ^{14}C obtained on the GEOSECS samples for the South Pacific Ocean (Broecker, 1978).

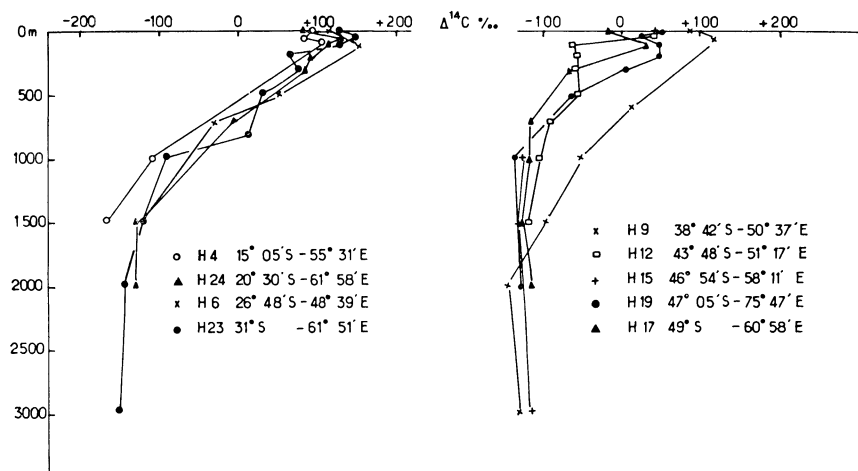


Fig 3. Vertical profiles giving the variation of ^{14}C concentration versus latitude, in the Indian Ocean, in 1973.

The transfer to the deeper water of the bomb ^{14}C introduced at the sea-air interface, and the resemblance of the profiles can be explained by the high rate of mixing prevailing in the first 1000m of water at these latitudes rather than by an appreciable difference in the CO_2 exchange rate.

The three southernmost profiles, H12, H15, and H19, are in the sub-antarctic area. The influence of bomb ^{14}C is weaker and is only evident in the first 300 to 500m. The low $\Delta^{14}\text{C}$ value of $-53 \pm 5\text{‰}$, at 500m depth at stations H19 and H12, does not allow for definitive data on the presence of bomb ^{14}C at this depth.

At station H17 ($48^\circ 59' \text{S}$) a sharp drop of surface temperature ($\theta = 4^\circ 97\text{C}$) indicates the proximity of the Antarctic Convergence. The vertical temperature gradient, already less important in the sub-antarctic region, becomes very weak in this profile. The same thing is found for the $\Delta^{14}\text{C}$ gradient. Bomb ^{14}C is evident only above 100 to 200m while at 700m depth $\Delta^{14}\text{C}$, it is very low, $-113 \pm 5\text{‰}$, and so it becomes difficult to decide if these values are, or are not, natural concentrations.

DISCUSSION

Two different phenomena combine to make of the middle latitudes in the South Indian Ocean (around 30°S) a favored zone for the introduction of the atmospheric bomb ^{14}C into the upper part of the ocean,

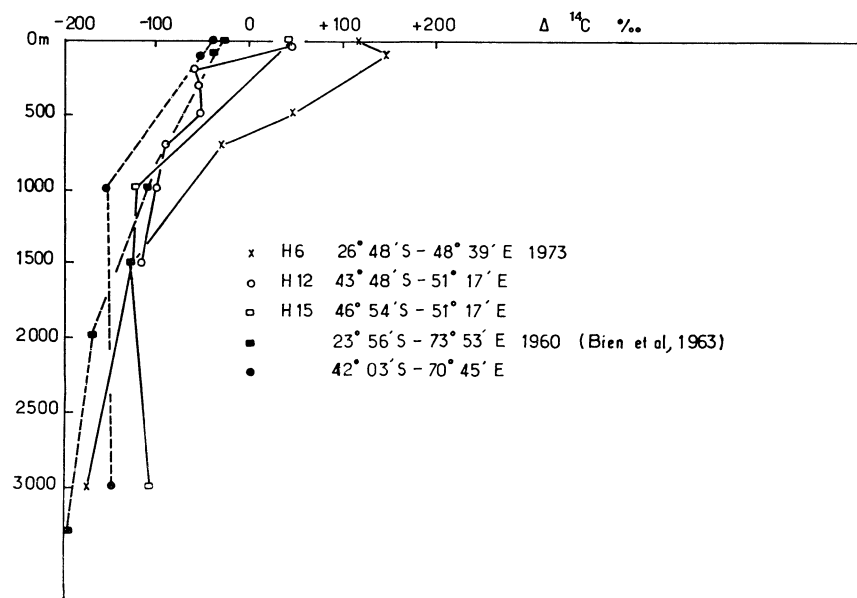


Fig 4. Comparison of $\Delta^{14}\text{C}$ vertical profiles obtained in 1973 (this study) and in 1960 (Bien, Rakestraw, and Suess, 1963).

— intensity of the exchange of CO₂ with the atmosphere, due to agitation of the sea surface,

— high mixing rate which affects the first 1000m and carries down atmospheric CO₂ dissolved at the surface.

The important feature of the penetration of bomb ¹⁴C into surface waters at these latitudes is evidenced by comparison with the earlier data of Bien, Rakestraw, and Suess (1965), plotted in figure 2. Two profiles studied in 1960 (fig 4) show some significant differences in the very nearly vertical profiles obtained in 1973 in the upper levels of the Indian Ocean. However, the highest $\Delta^{14}\text{C}$ value recorded at the surface in this study is $+117 \pm 6\text{‰}$ when the average value, between 45° N and 35° S, in 1972 in surface water of the Atlantic Ocean was $+127\text{‰}$ (Stuiver, 1978). Thus, it seems that ¹⁴C delivery to surface water, even in this particular part of the South Indian Ocean, still displayed some time lag in 1973. This was due to the fact that nuclear explosions essentially took place in the northern hemisphere and that bomb ¹⁴C gradually penetrated into the southern hemisphere by exchange across the equator. Indeed, it is only since 1968-1969 that the troposphere has been completely mixed; in 1973, $\Delta^{14}\text{C}$ in both hemispheres was around +50 percent (our measurements).

Despite rather high $\Delta^{14}\text{C}$ values found down to 1000m at station H9 (-48‰), the presence of bomb ¹⁴C around 1000 to 1500m depth is questionable. The average $\Delta^{14}\text{C}$ values for all the stations studied in 1973, is -121‰ with an important variability, from -139‰ to -85‰ . For the same depths and similar latitude, the value was around -110‰ in 1960, also with an important dispersion, from -120‰ to -90‰ . Consequently, it can be said that,

— these levels, on the whole, were not yet reached by bomb ¹⁴C in 1973, the two average values being similar.

— the great variability in the $\Delta^{14}\text{C}$ values already existed in 1960 when the presence of bomb ¹⁴C was strictly impossible at these depths.

The hydrologic study of salinity and temperature (Le Floch and Tanguy, 1973) allowed us to identify Antarctic Intermediate Water at these depths. This water mass derives from Surface Antarctic Water, near the Convergence. It is cold heavy water (salinity $\cong 34\text{‰}$, $\theta \cong 3^\circ\text{C}$) which sinks and attains density equilibrium at depth, then moves northwards, slowly mixing with waters above and below. It can be identified by a minimum in vertical salinity profiles at 34-34.5‰.

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