

## TRANSFER OF BOMB $^{14}\text{C}$ TO THE OCEAN SURFACE

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**ABSTRACT.** Additional  $^{14}\text{C}$  data from the atmosphere and ocean have been provided since the ninth  $^{14}\text{C}$  conference in 1976. At the moment, one sampling station in the troposphere in each hemisphere seems to give sufficient accuracy for exchange studies. The  $^{14}\text{C}$  concentration in the troposphere in December 1978 constituted a mean value of  $30 \pm 1$  percent ( $\Delta^{14}\text{C}$ ) above normal level, a concentration that has been reduced to about one half during 12 years.  $^{14}\text{C}$  measurements have been performed with intervals of 1 to 4 months in the surface water of the Atlantic, Pacific, and Indian Oceans. In addition to the  $^{14}\text{C}$  data observed, the salinity and temperature are also measured. Because of earlier objections against storing sea water in steel drums on board ships for months before treatment, the  $\text{CO}_2$  has now been flushed out immediately after collection. The reliability of previous measurements has been confirmed with 10 parallel samples.  $^{14}\text{C}$  concentration in ocean surface on each location shows some seasonal variation due to variable exchange of water with deeper layers.

### INTRODUCTION

The Partial Test Ban Treaty (PTB) of August 1963 was most welcome for the benefit of human health, but gave also a better opportunity to use  $^{14}\text{C}$  as a tracer in studying the exchange of carbon in nature. The PTB was, however, not signed by all nations, and the atmosphere has since been periodically disturbed by minor tests. In addition to underground tests, nuclear reactors and fossil fuel combustion are slightly affecting the  $^{14}\text{C}$  level. All these variable human activities after 1963 have complicated the exchange calculation between various carbon reservoirs in nature. It is especially complicated to predict the future  $^{14}\text{C}$  level, and it is, thus, necessary to perform continuous measurements.

The present paper contains further measurements in the atmosphere and ocean surface (Nydal, Lövseth, and Gulliksen, 1976), a program that was started in the early 1960's (Nydal, 1963; 1968). Sampling in the ocean is at the time regarded as most important, and a revised program has been running for the last three years. This paper contains mainly sampling program, procedure, and data, and further calculation of exchange coefficients has been postponed for more extended studies.

### *$^{14}\text{C}$ production in nuclear activity*

When the Partial Test Ban Treaty was signed, about 500 tests with a total yield of approximately 511 megatons (MT) had been released to the atmosphere. About 2/3 of this yield was released at higher northern latitudes during 1961 and 1962 (fig 1). PTB did not lead to a much lower test frequency by the USA and USSR, but they limited their activity to underground bursts (Zander and Araskog, 1973; SIPRI Yearbook 1975; 1977; 1979). During the period from August 5, 1963 to December 31, 1978, the USA and USSR made 343 and 234 underground tests, respectively. The total yield of all tests is very uncertain, but may constitute about 150 MT. The underground tests were all performed in the northern hemisphere. The USA used mainly the test site in Nevada (ca  $35^\circ\text{N}$ ,  $112^\circ\text{W}$ ), but also one in Amchitka ( $50^\circ\text{N}$ ,  $178^\circ\text{W}$ ) in the north Pacific was used.

The USSR has several test sites, but the main part of the tests were performed at Semipalatinsk ( $49^\circ\text{N}$ ,  $81^\circ\text{E}$ ). A test site at Novaya Zemlya ( $72^\circ\text{N}$ ,  $55^\circ\text{E}$ ) was also somewhat used, mainly for tests with yield in the MT range.

France and China did not sign the PTB and conducted atmospheric tests after August 1963 (figs 1, 3). France got the atomic bomb in 1960, and developed the hydrogen bomb in 1968. Until 1966, only underground tests were performed, in the Sahara. In 1966, France moved to the new test site (CEP) in Tuamotu Islands ( $23^\circ\text{S}$ ,  $147^\circ\text{W}$ ) in the Pacific. The site was inaugurated in 1966. Until December 1974, France performed 41 atmospheric tests, and the total yield was reported to be 8.9 MT. The first thermonuclear explosion of August 24, 1968 was the largest one, with a yield of 2.5 MT. A couple of later bombs had a yield of about 1 MT, the major part was less than 20 kiloton (KT). After 1974, France performed only underground tests.

China got the atomic bomb in 1964 and developed the hydrogen bomb in 1967. A test site at Lop Nor ( $40^\circ\text{N}$ ,  $87^\circ\text{E}$ ) was used for all tests. China performed 21 atmospheric tests at this site in the period October 1964 to December 1978. The total yield of these bombs constituted 19-20 MT. The main part of this energy was released in five bombs with a strength of 3-4 MT each. The last one of 4 MT was released in the atmosphere in November 1976.

Nuclear power reactors represent another  $^{14}\text{C}$  source, where fission neutrons produce  $^{14}\text{C}$  from reactor elements (Wallace, 1977). It has been verified that the  $^{14}\text{C}$  concentration in a reactor area is at a slightly higher level than elsewhere (Levin, Münnich, and Weiss, 1980).  $^{14}\text{C}$  produced in this way has not been regarded as very important, but the present in-

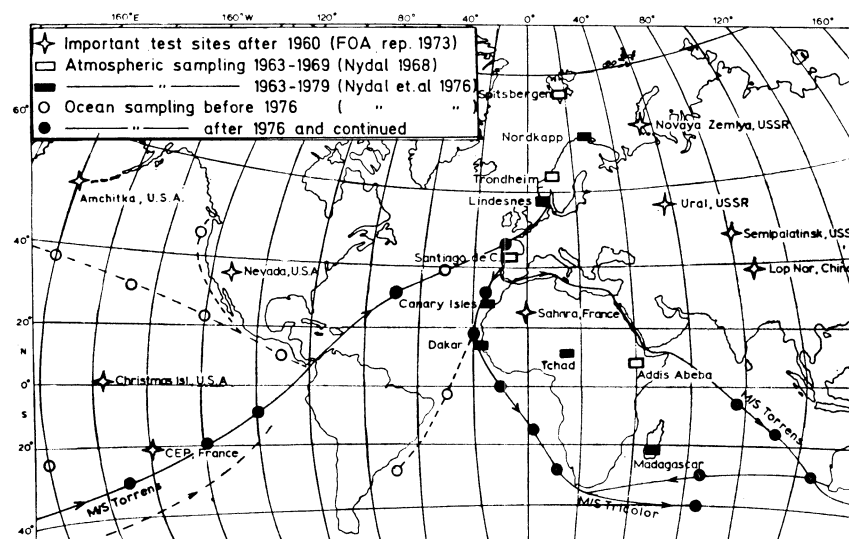


Fig 1. Observation of radiocarbon from nuclear tests.

crease in number of reactors may change this situation. For many countries, especially the underdeveloped, the nuclear power reactors are the cheapest means for producing electric energy. In 1976 173 reactors existed with a total capacity of 73139 MW. The plan for 1984 is a number of 465 with a capacity of 338606 MW (SIPRI, 1979). The importance of the amount of  $^{14}\text{C}$  escaping to the atmosphere in the future depends on the efficiency of the filtering system.

#### *Sampling program and procedure*

$^{14}\text{C}$  sampling in the troposphere has continued at the locations given in figure 1. Only the samples from Nordkapp ( $71^\circ\text{N}$ ,  $24^\circ\text{E}$ ) and Madagascar ( $21^\circ\text{S}$ ,  $47^\circ\text{E}$ ) have been measured regularly during the last few years.

Our former sampling program for the Atlantic and Pacific Oceans came nearly to an end in the summer of 1976, partly because of crises in shipping, which resulted in changes and cancellations of former routes. In developing a new sampling program, we took into account some earlier objections against our sampling and treatment. The most important change was the removal of carbon from the sea water immediately after collection.

The sampling was now performed on the ordinary routes by two ships from Wilh Wilhelmsen Shipping Company in Oslo. One of these, *M/S Tricolor*, sailed on a regular route to New Zealand through the Atlantic and Indian Oceans. The samples were collected from Biscaya, along the western coast of Africa, through the Indian Ocean, and on the return. Another ship, *M/S Torrens*, collected samples on its route

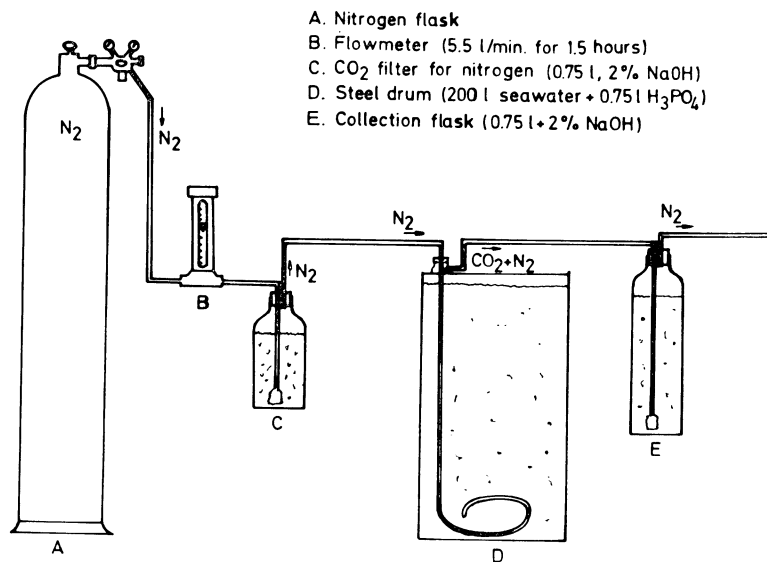


Fig 2. Flushing system for  $\text{CO}_2$  from sea water.

around the world through the Indian Ocean, across the Pacific and Atlantic Oceans.

Each ocean sample consists of 200 liters of sea water, and  $\text{CO}_2$  is flushed out by  $0.6\text{m}^3$  nitrogen, measured by a flowmeter (fig 2). The flushing time is 1.5 hours, and the amount of  $\text{CO}_2$  absorbed varies from 4 to 5 liters, depending on water temperature. This  $\text{CO}_2$  amount is about one-half of the total content. Water samples are collected through the cooling system at a depth of 7m. Ocean temperature and salinity are also measured for each sample at this depth. Several parallel samples of 200 liters of sea water were stored on board for months before flushing, in order to confirm the reliability of a number of previous samples.

TABLE I  
 $^{14}\text{C}$  concentration in the Indian Ocean surface

	Position	Date of collection	$\delta^{14}\text{C}$ (‰)	$\delta^{13}\text{C}$ (‰)	$\Delta^{14}\text{C}$ (‰)	Sal (‰)
TO-1	6° 35' S, 77° 00' E	28/3- 1977	$17.1 \pm 0.6$	-5.8	$12.6 \pm 0.6$	34.180
	6° 35' S, 77° 00' E	20/8- "	$13.9 \pm 0.4$	-7.6	$10.0 \pm 0.4$	34.996
	7° 00' S, 77° 00' E	18/1- 1978	$16.2 \pm 0.9$	-6.1	$11.8 \pm 0.9$	34.188
	7° 00' S, 69° 00' E	24/3- "	$14.4 \pm 0.7$	-6.1	$10.1 \pm 0.7$	34.670
	7° 00' S, 76° 40' E	18/11- "	$13.9 \pm 0.6$	-6.3	$9.6 \pm 0.6$	34.756
	7° 00' S, 78° 00' E	10/3- 1979	$13.8 \pm 0.7$	-8.1	$10.0 \pm 0.7$	34.208
TO-2 a.	18° 10' S, 91° 00' E	23/10-1976	$18.4 \pm 1.4$	-1.8	$12.9 \pm 1.0$	35.020
	b. 18° 10' S, 91° 00' E	23/10-1976	$18.4 \pm 1.4$	-1.8	$12.1 \pm 0.9$	34.992
	18° 00' S, 91° 00' E	31/3- 1977	$19.3 \pm 0.7$	-5.7	$14.7 \pm 0.7$	35.118
	18° 00' S, 91° 00' E	23/8- "	$17.5 \pm 0.9$	-6.0	$13.1 \pm 0.9$	34.918
	18° 00' S, 85° 55' E	2/11- "	$16.1 \pm 0.7$	-5.5	$11.6 \pm 0.7$	34.992
	18° 00' S, 91° 50' E	20/1- 1978	$16.2 \pm 0.8$	-4.0	$11.3 \pm 0.8$	34.886
	18° 40' S, 86° 48' E	20/3- "	$17.6 \pm 0.9$	-6.5	$13.3 \pm 0.9$	35.016
	18° 05' S, 89° 20' E	16/11- "	$15.1 \pm 0.9$	-6.6	$10.9 \pm 0.9$	34.419
	18° 00' S, 93° 47' E	17/2- 1979	$18.0 \pm 0.8$	-7.2	$13.8 \pm 0.7$	34.745
TO-3 a.	30° 00' S, 107° 20' E	25/10-1976	$21.1 \pm 1.2$	-3.4	$15.8 \pm 1.2$	35.437
	b. 30° 00' S, 107° 20' E	25/10- "	$17.3 \pm 1.0$	-10.0	$13.8 \pm 1.2$	35.437
	30° 00' S, 107° 21' E	3/4- 1977	$19.3 \pm 0.9$	-6.6	$14.9 \pm 0.9$	35.752
	30° 00' S, 108° 40' E	26/8- "	$18.2 \pm 0.7$	-6.1	$13.7 \pm 0.7$	35.701
	30° 00' S, 106° 30' E	30/10- "	$12.9 \pm 0.4$	-6.9	$8.8 \pm 0.4$	35.816
	30° 00' S, 108° 17' E	23/1- 1978	$18.8 \pm 0.5$	-6.1	$14.3 \pm 0.5$	35.922
	30° 00' S, 106° 20' E	18/3- "	$20.3 \pm 0.5$			35.969
	30° 18' S, 111° 10' E	13/11- "	$18.8 \pm 0.7$	-6.2	$14.3 \pm 0.7$	35.106
	30° 00' S, 112° 30' E	15/2- 1979	$14.6 \pm 0.6$	-8.6	$10.8 \pm 0.6$	35.650
TR-8	31° 43' S, 65° 30' E	3/3- 1977	$16.4 \pm 0.8$	-10.0	$12.9 \pm 0.8$	35.756
	31° 36' S, 60° 30' E	11/4- "	$17.7 \pm 0.9$	-9.7	$14.1 \pm 0.9$	35.457
	32° 00' S, 65° 00' E	9/7- "	$19.0 \pm 0.9$	-6.6	$14.6 \pm 0.9$	35.410
	30° 00' S, 66° 12' E	13/10- "	$16.8 \pm 0.6$	-7.8	$12.8 \pm 0.6$	35.741
	31° 29' S, 65° 00' E	19/1- 1978	$17.1 \pm 0.5$	-4.4	$12.3 \pm 0.5$	35.670
	31° 59' S, 65° 00' E	24/4- "	$18.8 \pm 0.6$	-5.4	$13.6 \pm 0.6$	35.717
	30° 03' S, 65° 00' E	4/8- "	$20.1 \pm 0.8$	-6.4	$15.6 \pm 0.8$	35.567
TR-7	40° 08' S, 65° 03' E	25/11-1976	$14.0 \pm 0.6$	-10.3	$10.7 \pm 0.6$	35.358
	40° 04' S, 66° 40' E	4/3- 1977	$16.6 \pm 0.8$	-9.1	$12.9 \pm 0.8$	35.319
	40° 00' S, 36° 00' E	30/5- "	$18.5 \pm 0.5$	-7.4	$14.3 \pm 0.5$	35.524
	36° 18' S, 63° 18' E	3/9- "	$12.7 \pm 0.9$	-8.3	$8.9 \pm 0.9$	35.414
	40° 22' S, 68° 00' E	6/12- "	$11.8 \pm 1.0$	-6.2	$7.6 \pm 1.0$	35.362
	37° 02' S, 65° 00' E	16/3- 1978	$17.0 \pm 0.7$	-4.2	$12.1 \pm 0.7$	35.382
	34° 15' S, 65° 00' E	15/6- "	$17.6 \pm 0.4$	-6.3	$13.1 \pm 0.4$	35.532
	36° 51' S, 65° 00' E	3/10- "	$15.1 \pm 0.6$	-7.2	$11.0 \pm 0.6$	35.366
	b. 40° 00' S, 31° 30' E	7/1- 1979	$13.7 \pm 0.8$	-6.5	$9.5 \pm 0.8$	35.390

TABLE 2

	Position	Date of collection	$\delta^{14}\text{C}$ (‰)	$\delta^{13}\text{C}$ (‰)	$\Delta^{14}\text{C}$ (‰)	Sal (‰)
TR-1	a. 46° 00' N, 7° 30' W	27/9- 1976	12.5 ± 1.4	-1.4	7.2 ± 1.4	35.681
	b. 46° 00' N, 7° 30' W	"	12.4 ± 1.0	-10.2	9.0 ± 1.0	35.587
	46° 00' N, 7° 25' W	5/3- 1977	11.1 ± 0.7	-8.3	7.3 ± 0.7	35.524
	46° 00' N, 11° 41' W	29/6- "	14.9 ± 0.8	-7.5	10.8 ± 0.8	35.697
	46° 00' N, 7° 23' W	28/11- "	12.5 ± 0.8	-7.0	8.4 ± 0.8	35.571
	46° 00' N, 7° 25' W	23/12- "	12.6 ± 0.7			
	46° 00' N, 7° 15' W	16/4- 1978	10.7 ± 0.9	-8.8	7.1 ± 0.9	35.548
TR-2	30° 25' N, 14° 15' W	10/11-1976	17.2 ± 0.8	-6.7	12.9 ± 0.8	36.824
	30° 00' N, 14° 05' W	19/1- 1977	14.0 ± 0.6	-10.1	10.7 ± 0.6	36.630
	a. 30° 00' N, 15° 18' W	17/2- "	14.2 ± 0.9	-4.3	10.6 ± 0.9	36.669
	b. 30° 00' N, 15° 18' W	"	16.8 ± 0.7	-4.6	12.0 ± 0.7	36.551
	31° 13' N, 14° 18' W	25/4- 1977	15.2 ± 0.7	-9.6	11.6 ± 0.7	36.547
	a. 30° 00' N, 15° 00' W	19/5- 1977	17.6 ± 0.5	-6.9	13.3 ± 0.5	36.606
	b. " "	"	19.0 ± 0.9	-5.9	3.8 ± 0.9	36.622
	30° 00' N, 15° 00' W	24/7- "	15.8 ± 0.9	-8.5	12.0 ± 0.9	36.574
	a. 30° 40' N, 14° 35' W	18/8- "	15.1 ± 1.1	-7.4	11.1 ± 1.1	36.687
	b. " "	"	14.1 ± 1.1	-1.3	8.7 ± 1.1	36.600
	a. 30° 36' N, 14° 59' W	20/11- "	16.3 ± 1.5	-5.2	11.6 ± 0.5	36.745
	b. " "	"	18.5 ± 1.0	-10.3	10.1 ± 1.0	
	30° 30' N, 14° 35' W	4/2- 1978	16.5 ± 0.5	-6.5	12.2 ± 0.5	36.693
	30° 00' N, 15° 20' W	28/2- "	16.3 ± 0.8	-6.7	12.1 ± 0.8	36.717
	30° 00' N, 15° 10' W	10/5- "	16.2 ± 0.9	-6.4	11.9 ± 0.9	36.661
	30° 00' N, 14° 47' W	30/5- "	13.6 ± 0.9	-5.9	9.2 ± 0.9	36.642
	30° 00' N, 15° 05' W	24/12- "	17.4 ± 0.5	-7.2	13.2 ± 0.5	36.574
TR-3	17° 05' N, 17° 49' W	11/11-1976	11.3 ± 0.6	-5.9	7.1 ± 0.6	35.512
	17° 00' N, 18° 04' W	17/1- 1977	5.0 ± 0.6	-10.7	2.0 ± 0.6	35.725
	a. 15° 28' N, 17° 49' W	19/2- "	8.0 ± 0.8	-9.6	4.7 ± 0.8	35.603
	b. " "	"	8.0 ± 0.9	-5.9	3.8 ± 0.9	35.484
	17° 00' N, 18° 00' W	23/4- "	5.7 ± 0.6	-9.6	2.4 ± 0.6	35.677
	a. 17° 00' N, 18° 04' W	20/5- "	7.2 ± 0.8	-9.3	3.8 ± 0.8	35.780
	b. " "	"	19.1 ± 0.9	-4.3	14.1 ± 0.9	35.946
	17° 00' N, 18° 00' W	23/7- "	7.4 ± 0.8	-4.8	3.1 ± 0.8	35.938
	a. 30° 40' N, 14° 35' W	19/8- "	15.1 ± 1.1	-7.4	11.1 ± 1.1	36.587
	b. " "	"	14.1 ± 1.1	-1.3	8.7 ± 1.1	36.600
	17° 35' N, 17° 42' W	21/11- "	8.2 ± 0.9	-4.4	3.7 ± 0.9	35.914
	17° 06' N, 17° 49' W	2/2- 1978	6.4 ± 0.6	-7.6	2.7 ± 0.6	35.772
	17° 20' N, 17° 50' W	2/3- "	7.7 ± 0.8	-6.0	3.6 ± 0.8	36.021
	17° 00' N, 17° 55' W	8/5- "	7.0 ± 0.5	-5.7	2.9 ± 0.4	35.863
	17° 00' N, 17° 50' W	1/6- "	7.1 ± 0.9	-6.0	3.0 ± 0.9	35.855
	17° 00' N, 18° 00' W	19/8- "	10.5 ± 0.7	-6.6	6.5 ± 0.7	36.203
	17° 15' N, 17° 20' W	20/9- "	11.8 ± 0.9	-4.4	7.2 ± 0.9	35.922
	17° 00' N, 18° 00' W	27/12- "	12.1 ± 1.1	-10.3	8.8 ± 1.1	35.615

In processing the samples on board the ships, the laboratory work is now reduced to the same work as for the atmospheric samples. Only treatment with HCl is necessary for producing  $\text{CO}_2$ , which is stored for one month in order to eliminate the radon gas. Measurements are performed as earlier in  $\text{CO}_2$  proportional counters with effective volume between 1.2 and 1.5 liters.  $\delta^{13}\text{C}$  measurements and corrections to  $\pm 25\%$  are performed for all samples. The  $^{14}\text{C}$  concentration ( $\Delta^{14}\text{C}$ ) is calculated in percent above normal level, according to the formula

$$\Delta^{14}\text{C} = \delta^{14}\text{C} - 2 (\delta^{13}\text{C} + 2.5) \left( 1 + \frac{\delta^{14}\text{C}}{100} \right)$$

$^{14}\text{C}$  concentration in the Atlantic Ocean surface

	Position	Date of collection	$\delta^{14}\text{C}$ (‰)	$\delta^{13}\text{C}$ (‰)	$\Delta^{14}\text{C}$ (‰)	Sal (‰)
TR-4	00° 05' N, 09° 03' W	14/11-1976	11.9 ± 0.9	-8.1	8.1 ± 0.9	35.595
	0° 00' N/S, 09° 34' W	15/1- 1977	11.1 ± 0.7	-9.5	7.7 ± 0.7	35.894
	13° 30' S, 00° 09' W	21/2- "	16.3 ± 0.9	-10.1	12.8 ± 0.9	35.228
	00° 30' S, 10° 00' W	20/4- "	15.6 ± 0.9	-11.7	12.5 ± 0.9	35.843
	00° 00' N/S, 14° 00' W	22/5- "	13.8 ± 0.5	-8.1	9.9 ± 0.5	35.469
	00° 00' N/S, 10° 00' W	20/7- "	10.7 ± 0.5	-6.4	6.6 ± 0.5	35.808
	00° 00' N/S, 08° 51' W	24/8- "	11.0 ± 0.7	-8.1	7.3 ± 0.7	35.701
	00° 00' N/S, 09° 11' W	24/11- "	15.4 ± 0.7	-4.2	10.6 ± 0.7	35.114
	00° 00' N/S, 09° 49' W	30/1- 1978	13.3 ± 0.7	-5.4	8.8 ± 0.7	35.618
	00° 00' N/S, 09° 28' W	4/3- "	14.1 ± 0.5	-4.0	9.3 ± 0.5	35.638
	00° 00' N/S, 09° 20' W	5/5- "	13.9 ± 0.9	-5.7	9.5 ± 0.9	35.441
	00° 00' N/S, 09° 15' W	4/6- "	13.8 ± 0.8	-6.1	9.5 ± 0.8	35.268
	00° 00' N/S, 09° 11' W	16/8- "	11.2 ± 0.5	-7.3	7.2 ± 0.5	35.886
	00° 00' N/S, 09° 12' W	23/9- "	11.3 ± 0.6	-6.2	7.1 ± 0.6	36.437
	00° 00' N/S, 09° 36' W	29/12- "	13.0 ± 0.9	-6.2	8.8 ± 0.9	36.599
TR-5	15° 11' S, 02° 08' E	16/11-1976	10.2 ± 0.7	-6.1	6.0 ± 0.7	36.108
	14° 50' S, 01° 47' E	12/1- 1977	10.0 ± 0.7	-10.4	6.7 ± 0.7	36.365
	15° 00' S, 02° 00' E	23/2- "	12.8 ± 0.7	-9.3	9.2 ± 0.7	36.543
	15° 00' S, 01° 30' E	18/4- "	11.9 ± 1.1	-5.3	7.5 ± 1.1	36.574
	15° 00' S, 01° 00' E	25/5- "	11.2 ± 0.9	-6.7	7.1 ± 0.9	36.377
	15° 00' S, 02° 00' E	18/7- 1977	12.6 ± 0.8	-6.5	8.4 ± 0.8	36.413
	14° 53' S, 01° 57' E	26/8- "	9.8 ± 0.7	-8.9	6.3 ± 0.7	36.195
	14° 58' S, 01° 46' E	26/11- "	14.2 ± 0.9	-5.0	9.7 ± 0.9	36.429
	15° 05' S, 02° 15' E	28/1- 1978	9.8 ± 0.8	-5.9	5.6 ± 0.8	36.433
	15° 00' S, 01° 41' E	7/3- "	9.9 ± 0.8	-4.3	5.4 ± 0.8	36.441
	15° 00' S, 01° 17' E	3/5- "	11.8 ± 0.7	-5.6	7.5 ± 0.7	36.578
	15° 00' S, 02° 10' E	7/6- "	13.4 ± 0.9	-7.6	9.5 ± 0.9	36.512
	15° 00' S, 02° 18' E	13/8- "	12.3 ± 0.8	-7.3	8.3 ± 0.8	36.445
	15° 05' S, 02° 10' E	25/9- "	11.5 ± 0.7			36.452
	15° 00' S, 01° 40' E	1/1- 1979	11.5 ± 0.7	-6.2	6.4 ± 0.9	36.195
TR-6	29° 50' S, 14° 25' E	19/11-1976	14.5 ± 0.8	-8.4	10.7 ± 0.8	35.480
	25° 55' S, 11° 03' E	10/1- 1977	7.4 ± 1.0	-10.4	4.3 ± 1.0	35.189
	29° 57' S, 14° 25' E	26/2- "	13.6 ± 0.9	-9.0	10.0 ± 0.9	35.469
	26° 30' S, 11° 00' E	17/4- "	11.8 ± 0.7	-10.2	8.5 ± 0.7	35.410
	26° 00' S, 10° 33' E	27/5- "	13.5 ± 0.8	-6.1	9.2 ± 0.8	35.476
	26° 00' S, 10° 00' E	16/7- "	16.4 ± 0.9	-6.6	12.1 ± 0.9	35.449
	32° 17' S, 16° 29' E	29/8- "	12.7 ± 0.9	-8.2	8.9 ± 0.9	35.398
	29° 39' S, 14° 05' E	29/11- "	13.5 ± 0.9	-5.4	9.0 ± 0.9	35.437
	26° 25' S, 11° 45' E	26/1- 1978	12.2 ± 0.7	-4.7	8.1 ± 0.7	35.291
	30° 00' S, 14° 05' E	10/3- "	9.6 ± 0.8	-5.1	5.2 ± 0.8	35.347
	30° 00' S, 15° 00' E	1/5- "	11.7 ± 0.8	-5.8	7.4 ± 0.7	35.303
	30° 00' S, 14° 35' E	9/6- "	13.9 ± 0.3	-7.1	9.8 ± 0.3	35.406
	30° 00' S, 14° 42' E	11/8- "	13.7 ± 0.9	-8.1	9.9 ± 0.9	35.429
	30° 00' S, 14° 30' E	27/9- "	14.0 ± 0.9	-6.7	9.9 ± 0.9	35.272
	30° 00' S, 14° 55' E	4/1- 1979	9.7 ± 0.9	-10.1	6.4 ± 0.9	35.256

where  $\delta^{14}\text{C}$  is the uncorrected  $^{14}\text{C}$  excess in percent relative to the NBS standard (oxalic acid), and  $\delta^{13}\text{C}$  represents the deviation in  $^{13}\text{C}/^{12}\text{C}$  ratio relative to the PDB standard (Craig, 1961).

## RESULTS AND DISCUSSION

Most of our  $^{14}\text{C}$  data from the ocean and atmosphere are indicated on figure 3, together with atmospheric tests in the megaton range. No dramatic change in the atmospheric  $^{14}\text{C}$  concentration has occurred after 1963, but the periodic French and Chinese bombs have affected the

rate of decrease. These bombs are released from balloons or towers, respectively, and are, thus, partly surface bursts. Their influence on the  $^{14}\text{C}$  concentration is reflected with peaks during 1968-1972, and also after the 4 MT Chinese bomb in 1976. The earlier experience with a  $^{14}\text{C}$  yield of about  $2 \cdot 10^{26}$   $^{14}\text{C}$  atoms per megaton (Rep UN 1962; 1964) seems to be in fairly good agreement with a change in atmospheric  $^{14}\text{C}$  concentration of 4 to 5 percent during 1968-1972. The mean  $^{14}\text{C}$  concentration in the troposphere for December 1978 is estimated to  $30 \pm 1$  percent above normal level. In spite of minor atmospheric tests, the  $^{14}\text{C}$  curve approaches that of the ocean surface, which shows a much more irregular pattern.

After several breaks in the sampling between 1972 and 1975, continuation was obtained at some locations, both in the Atlantic and Pacific Oceans. It turns out that the mean  $^{14}\text{C}$  level at some locations (fig 4) has been nearly unchanged for 12 years. The oscillation pattern in  $^{14}\text{C}$  concentration is regarded to be real and most probably due to exchange of water with deeper layers. The amplitude in the oscillations is consequently greater in the 1960's than later on, because of smaller differences in  $^{14}\text{C}$  concentration with depth. Other measurements, both in the Atlantic and Pacific Oceans (fig 5) shows a similar oscillating pattern. The great  $^{14}\text{C}$  variation in the period 1967-1972 near the coast of Argentina ( $31^\circ\text{-}33^\circ\text{S}$ ,  $50^\circ\text{-}52^\circ\text{W}$ ) is similar to that at the Canary Islands ( $28^\circ\text{-}30^\circ\text{N}$ ,  $15^\circ\text{-}18^\circ\text{W}$ ), and seems to be a coastal phenomenon where greater exchange with deeper layers is more frequent.

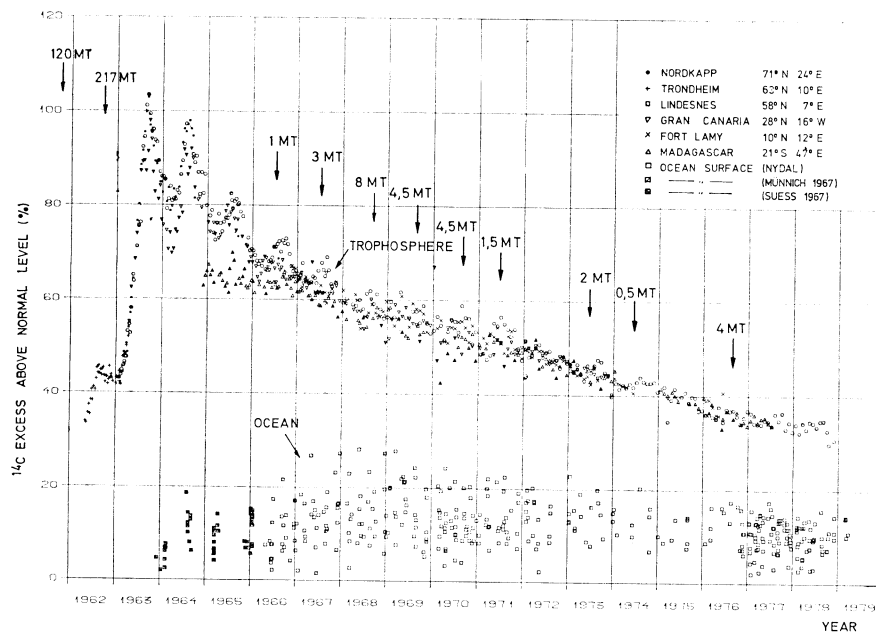


Fig 3.  $^{14}\text{C}$  concentration ( $\Delta^{14}\text{C}$ ) in the atmosphere and ocean surface. The mean yield and moment for nuclear explosions are indicated.

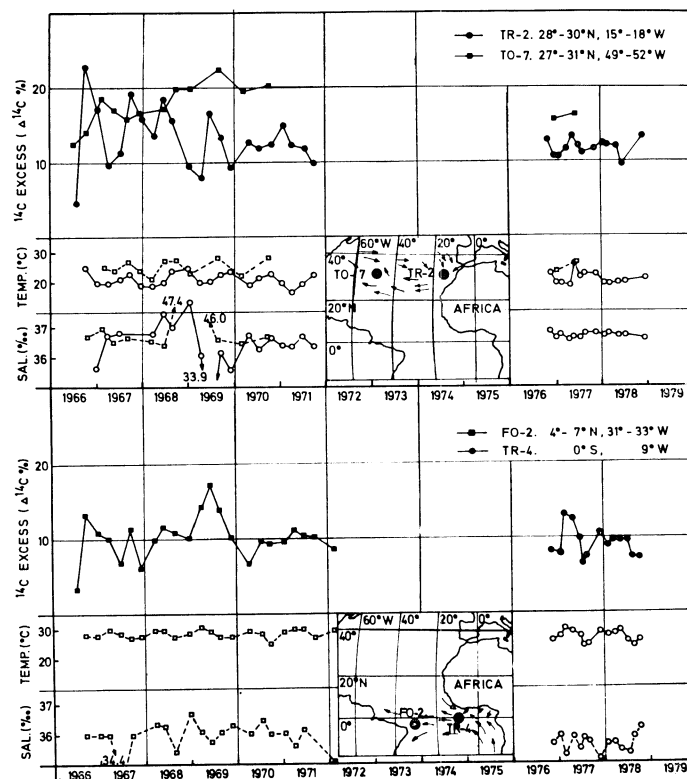
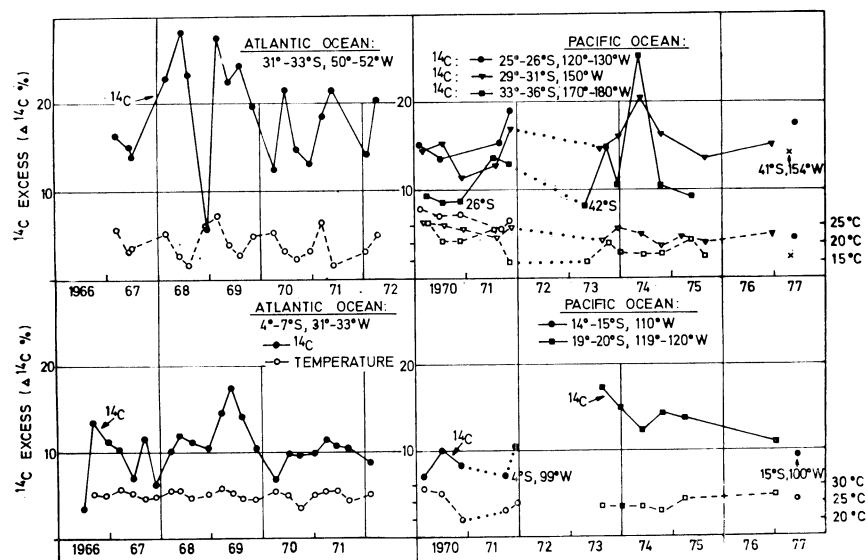
Fig 4.  $^{14}\text{C}$  concentration in the Atlantic Ocean surface.Fig 5.  $^{14}\text{C}$  concentration in the Atlantic and Pacific Ocean surface.



Figure 6 gives a complete view of all measurements for three years with the revised ocean program. The sampling is all done at smaller time intervals than earlier, and at more definite positions. A first important result is the agreement between the parallel samples (a and b), which confirms previous measurements. A main trend in the graphs is that the  $^{14}\text{C}$  variation, to some extent, is in phase with the temperature in the ocean surface. This is especially convincing in the Indian Ocean and in the northern Atlantic Ocean, and is in agreement with exchange of water with deeper layers. This exchange is not clearly reflected in the salinity concentration, which shows a more irregular pattern. The  $^{14}\text{C}$  concentration shows mean values of 10 to 12 percent and 8 to 10 percent in the Indian and Atlantic Oceans, respectively. An exception is obtained at Dakar where the lower  $^{14}\text{C}$  concentration must be due to a more intensive exchange of water with deeper layers.

No serious attempt has been made to calculate new figures for exchange coefficients between various reservoirs. For such purposes, more detailed studies and comparison with results obtained by others have to be performed. We share the opinion expressed by others (Damon and others, 1978) that the controversy in exchange coefficients appearing in literature is not often real, but dependent on the applied models. Up to now, we have used pure box models patented by Craig (1957), but

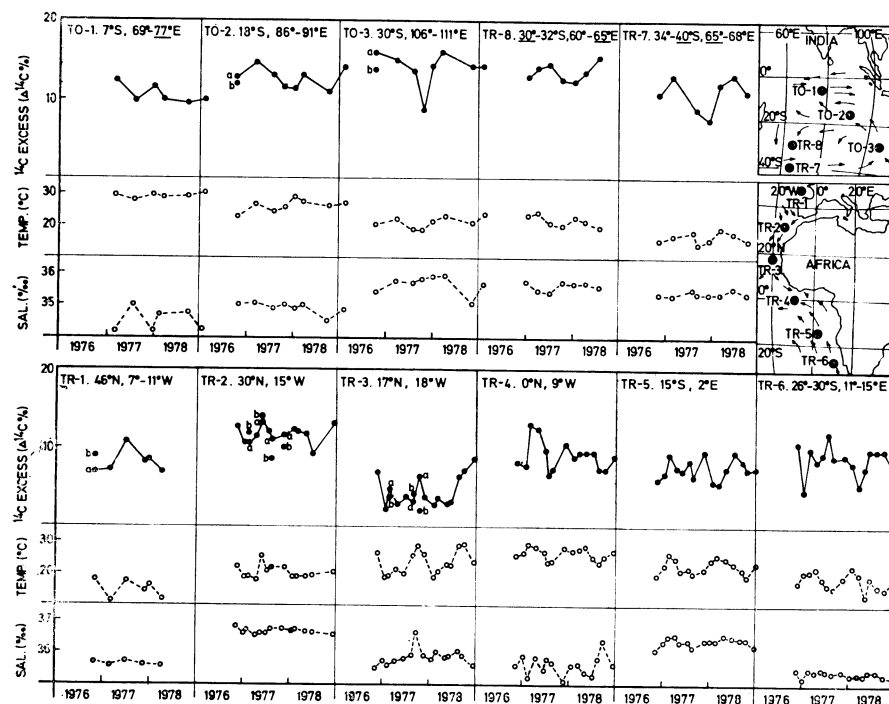


Fig 6.  $^{14}\text{C}$  concentration in the Atlantic and Indian Ocean surface during 1976-1978 (tables 1 and 2).

for further work, the revised box-diffusion model described by Oeschger and others (1975) can be useful.

## ACKNOWLEDGMENTS

The authors are thankful to those who have collected samples during recent years from Nordkapp to Madagascar: Odd Salomonsen, Fruholmen Lighthouse; Ingvar Johansen, Lindesnes Lighthouse; Fernando Molina Herrero, Tenerife; B Diagne, Dakar; Ph Matheu, Tchad; and Arne B Samuelsen, Madagascar.

The ocean sampling program was made possible by the active participation of the Wilh Wilhelmsen Shipping Company. Special thanks go to Inspector K Hornburg, and the chief engineers, M Marthinussen, K Øvrelid, Jens Thorvaldsen, and R Johansen.

This work was supported by The Norwegian Research Council for Science and the Humanities (NAVF), Oslo.

## REFERENCES

- Bien, G and Suess, H, E, 1967, Transfer and exchange of  $^{14}\text{C}$  between the atmosphere and the surface water of the Pacific ocean, *in* Symposium on radioactive dating and methods of low-level counting: Internatl Atomic Energy Agency, Vienna, UN Doc SM-87/55.
- Craig, Harmon, 1957, The natural distribution of radiocarbon and the exchange time of carbon dioxide between atmosphere and sea: *Tellus*, v 9, p 1-17.
- 1961, Mass-spectrometer analyses of radiocarbon standards: *Radiocarbon*, v 3, p 1-3.
- Damon, P E, Lerman, J C, and Long, Austin, 1978, Transporal fluctuations of atmospheric  $^{14}\text{C}$ : Causal factors and implications: *Ann Rev Earth Planetary Sci*, v 6, p 457-494.
- Levin, Ingeborg, Münnich, K O, and Weiss, Wolfgang, 1980, The effect of anthropogenic  $\text{CO}_2$  and  $^{14}\text{C}$  sources on the distribution of  $^{14}\text{C}$  in the atmosphere, *in* Stuiver, Minze and Kra, Renee, eds, Internatl radiocarbon conf, 10th, Proc: *Radiocarbon*, v 22, no. 2, p 379-391.
- Münnich, K O and Roether, Wolfgang, 1967, Transfer of bomb  $^{14}\text{C}$  and tritium from the atmosphere to the ocean. Internal mixing of the ocean and the basis of tritium and  $^{14}\text{C}$  profiles, *in* Symposium on radioactive dating and methods of low-level counting: Internatl Atomic Energy Agency, Vienna, UN Doc SM-87/22.
- Nydal, Reidar 1963, Increase in radiocarbon from the most recent series of thermonuclear tests: *Nature*, v 6, p 212-214.
- 1968, Further investigation on the transfer of radiocarbon in nature: *Jour Geophys Reseach*, v 73, no. 12, p 3617-3635.
- Nydal, Reidar, Lövseth, Knut, and Gulliksen, Steinar, 1979, A survey of radiocarbon variation in nature since the Test Ban Treaty, *in* Berger, Rainer and Suess, H E, eds, Radiocarbon dating, Internatl conf on radiocarbon dating, 9th, Proc: Berkeley/Los Angeles, Univ California Press, p 313-323.
- Oeschger, Hans, Siegenthaler, Ulrich, Schotterer, Ulrich, and Gugelmann, A, 1975, A box diffusion model to study the carbon dioxide exchange in nature: *Tellus*, v 27, no. 2, p 167-191.
- Rept UN, 1962, Report on the United Nations scientific committee on the effects of atomic radiations: Supplement no. 16, A/5216, 442 p.
- 1964, Report on the United Nations scientific committee on the effects of atomic radiations: Supplement no. 14, A/5814, 120 p.
- SIPRI Yearbook, 1975, 1977, and 1979, World armament and disarmaments: Stockholm, Almqvist and Wiksell.
- Wallace, Davis Jr, 1977, Carbon-14 production in nuclear reactors: ORNL/NUREG/TM-12, National Technical Information Service, US Dept Commerce, Springfield, Virginia.
- Zander, I and Araskog, R, 1973, Nuclear explosions 1945-1972, Basic data: Försvarets Forskningsanstalt, Avd 4, Stockholm, FOA 4, rept 4505-A1, 56 p.