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Input of tritium to intermediate depth water in the South Pacific

by J. R. Harries and G. E. Calf

ABSTRACT

Tritium concentrations have been determined for seawater samples collected near the western boundary of the South Pacific. The deepest penetration of tritium, in terms of either depth or isopycnal surface, occurs between latitudes 14 and 30S and the penetration is greater than that observed in the mid-South Pacific during the Geochemical Ocean Sections Study (GEOSECS) cruise. The tritium distribution in the South Pacific was obtained by combining the tritium concentrations for the Tasman and Coral seas with earlier results. The tritium distribution on the \( \sigma_t = 27.0 \) surface shows sources of tritium where the isopycnal surface reaches the surface of the ocean in the circumpolar current and also in the vicinity of the East Australian Current. The source of tritium in the Tasman Sea is explained by the enhanced vertical mixing caused by the East Australian Current. The large area of essentially tritium-free water on the \( \sigma_t = 27.0 \) surface in the mid-ocean shows that mixing and advection on this surface is slow compared to the half-life of tritium.

1. Introduction

The distribution of transient tracers in the ocean provides information about the direction and timescale of mixing and advection processes. Tritium, the heaviest isotope of hydrogen, is an ideal tracer for ocean water movement because it is radioactive, decaying to helium-3 with a half-life of 12.43 years, and because it moves with ordinary water and is not affected by chemical or biological processes.

Tritium is produced naturally by the interaction of cosmic rays with nitrogen nuclei high in the atmosphere. In the period 1958 to 1962, a series of high yield thermonuclear (hydrogen) bombs released many hundreds of kilograms of tritium into the atmosphere (Miskel, 1973) and completely overshadowed the 3 kg inventory of naturally produced tritium on Earth. Most of the tritium released in the atmosphere reacts with water vapor to produce tritiated water which is ultimately transferred into the ocean by precipitation, molecular exchange and river runoff. All of these processes add the tritium into the surface mixed layer of the ocean, from whence it is mixed and advected to greater depths.

1. Australian Atomic Energy Commission Research Establishment, Private Mail Bag, Sutherland, New South Wales 2232, Australia.
The inventory of tritium in all the oceans in 1970-72 was estimated to be about 200 kg (Michel, 1976; Östlund and Fine, 1979). Because most of the bomb tests were carried out in the northern hemisphere, the input of tritium into the southern hemisphere oceans was much less than that for northern hemisphere oceans; consequently the inventory of tritium in the southern oceans is only about 20% of the total ocean inventory (Östlund and Fine, 1979; Weiss and Roether, 1980).
The exchange of surface ocean water between the northern and southern hemispheres is too slow to be a significant source of tritium to the South Pacific.

This paper is concerned with the southern hemisphere tritium distributions. Tritium concentrations have been determined for seawater samples collected from the Tasman and Coral seas. These results are combined with other published data to obtain the overall South Pacific tritium distribution.

2. Method

Seawater samples were collected off the east coast of Australia during seven cruises of the CSIRO research vessel *Sprightly* between October 1978 and February 1981. Stations for each cruise are shown in Figure 1. The samples were collected in 6 L Niskin bottles at the same location as standard Nansen casts. Usually four samples were collected at each station, at depths of 15, 175, 400 and 800 m, with the two deepest bottles on the same wire as the Nansen bottles. A 2.25 L sample from each Niskin bottle was transported to the laboratory at Lucas Heights in a glass flagon. At each station a duplicate sample was taken from one of the Niskin bottles to check on the reproducibility of the analytical procedure.

Briefly the method of tritium determination, discussed in more detail elsewhere (Harries and Calf, 1980), was to distil 2 kg seawater samples and enrich the tritium by electrolysis. The initial sample was reduced to 16 g, which enriched the tritium 95-fold, and the enriched sample counted in a liquid scintillation spectrometer. The tritium concentrations are expressed in tritium units (TU) which denote the number of tritium atoms in $10^{18}$ atoms of hydrogen. The standard deviation in the tritium determination from counting statistics and enrichment errors was estimated to be 0.1 TU for most samples. For the last three cruises, the salinity of the sample was determined in the laboratory and checked against the salinity profile obtained for the Nansen samples.

A tritium versus depth profile was drawn for each station assuming that the tritium concentration was constant in the mixed layer. Profiles for the stations south of 30S are shown in Harries and Calf (1980).

3. Results

The station locations shown in Figure 1 provided a good coverage of the western margin of the South Pacific Ocean between longitudes 145E and 155E. The vertical distributions of tritium concentrations along this section are shown in Figure 2 where the distribution for each station is plotted against latitude regardless of longitude. The surface tritium concentrations exceed 2 TU between 18 and 30S, but decrease both to the south and to the north of these latitudes. Figure 2 also shows the depths of the two isopycnal (constant density) surfaces, $\sigma_t = 26.0$ and 27.0, where $\sigma_t$, the density anomaly, $= (\rho - 1000)$ kg m$^{-3}$. 

The East Australian Current and its associated eddy field produce the large fluctuations in both $\sigma_t$ and tritium concentration between 30 and 36S. Even though some of the samples came from inside the eddies and others from the outside, the tritium concentrations in samples collected from the Tasman Sea between 30 and 40S were constant on isopycnal surfaces (Harries and Calf, 1980). However, for $\sigma_t$ values of about 26.8, the tritium concentration in the Tasman Sea between 30 and 40S was about 60% of the concentration in the Southern Ocean between 45 and 50S.

The abrupt change at 30S in both tritium concentration and isopycnal surfaces, which is evident in Figure 2, is caused by the presence of the East Australian Current. The stations between 25 and 30S were all to the northeast of the Current, which tends to leave the coast somewhere near 33S and flow east (Boland and Church, 1981). Figure 2 shows that although the tritium concentrations tend to follow the isopycnal surfaces, there is a greater penetration of the 0.5 TU tritium contour through the $\sigma_t = 27.0$ surface between latitudes 18 and 30S.

4. Discussion

a. Buildup of tritium in the southern hemisphere. The maximum annual release of tritium from the stratosphere in the southern hemisphere occurred in 1965 and, by 1969, the release rate had decreased to almost half the 1965 value (Schell et al., 1974). Since then, the tritium concentrations in rainfall have been halving every four to five years. When the radioactive decay of the tritium is taken into account, the cumulative amount of tritium precipitated in the southern hemisphere would have increased from 3 kg in 1964 to 11 kg in 1966 and 19 kg in 1970. By that
time the radioactive decay was comparable to the input and the total only increased to 22 kg in 1974, after which it decreased to 20 kg in 1978 and 18 kg in 1982. Hence the tritium inventory has been relatively constant between 1970 and 1981 when most of the tritium measurements in the South Pacific were carried out.

b. Previous measurements of tritium in the South Pacific. Michel and Suess (1975) measured tritium concentrations in samples of surface water collected bimonthly from American Samoa (14° 16' S, 170° 43' W) between 1960 and 1973, and Canton Island (2° 50' S, 171° 40' W) between 1960 and 1968. Although the data show considerable variation in the earlier years, possibly due to the different water masses flowing past the islands, there was a gradual buildup in the surface tritium concentrations between 1962 and 1966; there was, however, no indication of the peak in the tritium concentrations that occurred in the North Pacific in 1964/65. The surface tritium concentration still appeared to be increasing in 1973 but at a much slower rate than in 1962 to 1966. The observed buildup of tritium was consistent with the buildup of the tritium inventory discussed above.

Miyake et al. (1975) reported tritium concentrations for water samples collected in 1968/69 from four stations along a north-south section at 170W. Samples were collected from four to five depths down to about 500 m. The surface tritium concentrations decreased, with increasing distance from the equator, from 1.6 TU at 6°S to 0.8 TU at 20°S and 0.4 TU at 53°S. Miyake et al. (1975) also reported the tritium concentrations for samples collected between longitudes 87W and 150W in December 1971 and January 1972. The surface concentrations were significantly higher than those observed on the earlier cruise, probably due to the buildup of tritium in the three years between the two cruises.

The South Tow cruise took place at about the same time as the second cruise reported by Miyake et al. (1975) and tritium analysis was carried out for six stations occupied in the South Pacific from January to March 1972 (Michel and Suess, 1975). The tritium concentrations of Michel and Suess had a similar relative distribution to those of Miyake et al. but were mostly at least double those of Miyake et al. for stations in the same general location. The description of the analytical method used by Miyake et al. shows that their counting system had a high background countrate, varying between 11 and 19 counts min⁻¹, and a counting efficiency of 18-20%. In view of the large background countrate correction in these results, and because the Michel and Suess data are consistent with the Geochemical Ocean Sections Study (GEOSECS) cruise data, we believe that the Michel and Suess results were probably a better representation of the tritium concentrations in the South Pacific in early 1972.

The largest set of tritium data for the South Pacific is that obtained for 35 stations occupied during the GEOSECS cruise between December 1973 and May 1974 (Östlund et al., 1979; Fine et al., 1981) which covered the South Pacific be-
between 180 and 120W. Between 8 and 16 samples were collected from the top 1000 m at each station which provided good resolution tritium profiles.

The GEOSECS results show that the surface tritium concentrations decreased from greater than 2.0 TU at the equator down to about 1.0 TU at latitudes 40 to 50S, but there was also an east-west asymmetry with the tritium concentrations on any latitude decreasing toward the east (Fine et al., 1981). Apart from one station at 33S 120W where the surface tritium concentration was 2.09 TU, surface tritium concentrations greater than 2.0 TU were only found north of a line running from 3S at 130W to 20S at 170W.

c. Tasman and Coral seas. The present results for the Tasman and Coral seas were for samples collected between 1978 and 1981; i.e., five to seven years after the GEOSECS cruise. Although, as discussed earlier, the total South Pacific inventory will not have changed greatly over this time, mixing and advection could have significantly changed the distribution of the tritium. The measurements being reported in this paper were made in a different part of the ocean from those of any of the earlier cruises, so there is some ambiguity in separating possible spatial differences from temporal changes.

The surface tritium concentrations in the Tasman and Coral seas are greater than 2.0 TU for all stations north of 30S except for two stations near the Torres Strait (Fig. 1). This is consistent with an extension into the Tasman Sea of the line mentioned above which separated the less than 2.0 TU from the greater than 2.0 TU surface tritium concentrations measured for the GEOSECS cruise. Although the surface tritium in the eastern Pacific could have changed, it is likely that the anticlockwise circulation of the subtropical gyre would carry the tritium farther south in the Tasman Sea than in the eastern South Pacific. Hence the greater southward penetration observed in the Coral and Tasman seas is probably a real effect.

d. Tritium distribution on isopycnal surfaces. The dominant transport processes in the mid ocean below the surface mixed layer are lateral mixing and advection on isopycnal surfaces. In a study of the tritium and helium-3 in the Sargasso Sea, Jenkins (1980) showed that vertical mixing contributed less than 10% to the mass balance in the thermocline. Figures 3 and 4 show, respectively, the distribution of tritium on the $\sigma_t = 27.0$ and the $\sigma_t = 26.0$ surfaces in the South Pacific. These figures combine the present results for the Tasman and Coral seas with those from GEOSECS (Östlund et al., 1979) and Michel and Suess (1975). Contours have been drawn for the whole figure, but the two sets of results might not be strictly comparable because of the five to seven year time interval between the collection of samples in the two regions.

The tritium concentration on the $\sigma_t = 27.0$ isopycnal surface (Fig. 3) is high in the circumpolar current and along the coast of Australia. The high concentration
Figure 3. Tritium concentrations on the $\sigma_t = 27.0$ isopycnal surface. The dotted contours show the depth of the isopycnal surface. Station locations are shown for the AAEC data (solid circles), GEOSECS (triangles) and Michel and Suess (1975) (open circles).

Figure 4. Same as Figure 3 but showing results for the $\sigma_t = 26.0$ isopycnal surface.
near 60S occurs where the $\sigma_t = 27.0$ surface reaches the surface of the ocean, thus allowing tritium to be added directly from the atmosphere. This tritium will be transported on the isopycnal surface with the Antarctic Intermediate Water which originates at the Polar Front and flows toward the equator in the mid South Pacific (Reid, 1965). The core layer of the Antarctic Intermediate Water is identified by the salinity minimum which is found at $\sigma_t = 27.1$ or 27.2 in the South Pacific. The decrease in tritium concentration to the north is due to a combination of radioactive decay in transit, the time which has elapsed since the bomb tritium was released, and horizontal mixing with low tritium concentration water. The comparatively steep gradient in the tritium concentration, which reduces from 0.6 TU at 50S to 0.2 TU at 40S across most of the South Pacific, shows that the timescale for penetration of Antarctic Intermediate Water to 40S on the $\sigma_t = 27.0$ surface by either mixing or advection is comparable to the 12 year half-life of tritium and the nine years that elapsed between the peak bomb tritium input and the GEOSECS cruise.

The tritium concentrations on the $\sigma_t = 27$ surface in the Tasman and Coral seas are much higher than the tritium concentrations at similar latitudes farther east in the mid-ocean. This is likely to be a real effect, even allowing for the fact that the Tasman and Coral sea data were taken five to seven years after the GEOSECS data. The additional time would allow the tritium to spread somewhat farther north in the mid Pacific, but even if the northward penetration doubled in the intervening years, there would still be no significant tritium beyond 30S in the mid-Pacific.

The high concentration near the western boundary indicates an additional source of tritium to the $\sigma_t = 27.0$ isopycnal surface near latitude 25S, off the coast of Australia. The Antarctic Intermediate Water enters the Tasman Sea from two directions (Wyrtki, 1962; Rochford, 1960a, b), but neither flow can supply the tritium; the flow from the south between Tasmania and New Zealand is poorly developed and extends only as far north as 34S, and the flow from the east between Fiji and New Zealand, which extends into the Coral Sea, had a very low tritium concentration when it was measured during the GEOSECS cruise to the north of New Zealand (Fig. 3). The high concentrations of tritium must be produced by vertical eddy-diffusion from either the overlying water or from the surface. Enhanced vertical mixing will occur in the turbulent boundary layer where the East Australian Current flows along the continental shelf. Possibly tritium could be transported into the Tasman Sea with the high oxygen water that has a $\sigma_t$ of about 26.7 and is found at a depth of about 400 m in the Tasman Sea south of 34S (Wyrtki, 1962). However, the tritium measurements in the Tasman Sea showed that the tritium concentration in this water mass was no higher than in the overlying water (Harries and Calf, 1980).

The high tritium concentration water in the Tasman Sea would be expected to
flow toward the north with the Antarctic Intermediate Water, (Wyrtki, 1962; Rougerie and Donguy, 1975). There is no significant flow of the $\sigma_t = 27.0$ water to the east. Even the overlying $\sigma_t = 26.4$ water which does flow to the east from the coast of Australia does not travel much beyond 150W before returning to the coast of Australia north of 20S (Tsuchiya, 1981). This $\sigma_t = 26.4$ water then bifurcates, flowing to the north and to the south to complete the gyre. Hence it is not surprising that on the $\sigma_t = 27.0$ surface the high tritium concentration water, which was formed in the Tasman Sea, should be restricted to the Tasman and Coral seas.

On the $\sigma_t = 26.0$ surface there is a minimum tritium concentration at 10S and the tritium concentration increases to the south, Figure 4. There is some evidence of a maximum in the tritium concentration in the Tasman Sea, but the concentrations are not significantly higher than at some other locations on the same latitude in the South Pacific.

In some areas of the South Pacific, particularly to the east of New Zealand, the surface water as far north as 30S can be cooled in winter to a density of $\sigma_t = 26.0$ (Reid, 1969). The resulting mixed layer forms a direct path for transfer of tritium from the surface to depths of 200 m. The decrease in the tritium concentration from 30 to 10S is due to a combination of decay during advection in the subtropical gyre and mixing with lower tritium water from nearer the equator. The water south of about 22S on the $\sigma_t = 26.0$ surface is advected to the east in the subtropical gyre before turning anticyclonically and returning to the west. The 1.2 TU isoline to the east of New Zealand, Figure 4, roughly follows the boundary between the eastward flow and westward flow on the $\sigma_t = 26.0$ surface.

The fact that all the water on the $\sigma_t = 26.0$ surface has a tritium concentration greater than 0.4 TU allows the elapsed time since the water was in the surface mixed layer to be estimated. If the principal transport process is advection, the tritium concentration of 0.4 TU would have resulted from radioactive decay in the elapsed time. The surface concentrations where the $\sigma_t = 26.0$ water outcrops is now about 1.2 to 1.6 TU, but before the bomb-input it would have been less than 1 TU (Craig and Lal, 1961). Hence the age must be less than about twenty years. If, on the other hand, mixing is assumed to be the predominant process, the timescale can be estimated by considering a box model for mixing. As there is no water of concentration less than 0.4 TU on the $\sigma_t = 26.0$ surface, the decay of tritium from the 0.4 TU surface must be balanced by mixing with water originally from the surface where the tritium concentration was, say, 1.0 TU. A two-box model of mixing shows that 3.8% of the 0.4 TU water must be exchanged with surface water every year, giving a mixing time of 26 years. The mixing time would be less if the surface water originally had a lower tritium concentration. Hence, both mixing and advection give a similar upper limit of about 20 years for the age of the 0.4 TU water. This would be the maximum age for any water on the $\sigma_t = 26.0$ surface.
5. Conclusion

The general characteristics of the tritium distribution in the South Pacific can be understood on the basis of the known ocean circulations. Most of the distribution can be explained by horizontal mixing and advection on isopycnal surfaces. Only in the vicinity of the East Australian Current is there evidence of significant transport of tritium across isopycnal surfaces by vertical mixing.

The timescale for mixing and advection varies with depth, being more rapid on the \( \sigma_t = 26.0 \) surface than on the \( \sigma_t = 27.0 \) surface. The estimation of the timescale is complicated by the difficulty of distinguishing the contribution of the pulse of bomb tritium from the naturally produced tritium. Future measurements of the tritium distribution as the bomb tritium decays will clarify the two effects and provide better estimates of the timescale of mixing and advection processes.

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