Circulation of Tritium in the Pacific Ocean[1]

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ABSTRACT

The input of bomb tritium into the high-latitude Northern Hemisphere waters has demonstrated the spread of a tracer in three dimensions in the North Pacific Ocean. Subsurface tritium maxima in middle and low latitudes clearly show the importance of lateral mixing (along isopycnals) in the upper waters. The tritium pattern as mapped on isopycnal surfaces puts definite time bounds on the exchange between the subtropical anticyclonic gyre of the North Pacific and both the subarctic cyclonic gyre and the system of zonal flows in the equatorial region. The penetration of bomb tritium to depths below 1000 m in the western North Pacific Ocean shows that these waters have been ventilated at least partially in the past 17 years of the post-bomb era. From the tritium pattern the upper waters of the North Pacific can be divided into three regions: a mixed layer that exchanges rapidly with the atmosphere, a laterally ventilated intermediate region (between the mixed layer and at most the winter-outcrop isopycnal) that exchanges on decadal time scales with the atmosphere, and a deeper layer penetrated by vertical diffusion alone, with a longer atmospheric exchange time scale. The greatest percentage of the tritium inventory of the North Pacific is in the intermediate region. This indicates that such lateral ventilations, which take place from all high-latitude regions, are a major source of penetration for atmospheric constituents into the oceans on decadal time scales.

1. Introduction

The nuclear bomb tests of the mid-1950's and early 1960's injected the radioactive isotope tritium (half-life 12.26 years) into the atmosphere. Most of the tritium entered the oceans in the Northern Hemisphere where it is found as HTO. Thus, tritium, which is in a transient state, serves as a chemically conservative tag or a dye injected into the high-latitude northern waters. Studies by Dockins *et al.* (1967), Rooth and Östlund (1972), Dorsey and Peterson (1976) and Broecker and Östlund (1979) have shown tritium's usefulness for examining short-time-scale mixing processes in the oceans.

Before nuclear testing, there was a natural or background inventory of tritium from cosmic production in the oceans and atmosphere. It is estimated that the background tritium in oceanic surface waters was at most 1 TU [TU = 10^{18} (T/H)] (Gilleti *et al.*, 1958), and substantially less below the mixed layer. Prior to the GEOSECS (Geochemical Ocean Sections Study) data (Östlund *et al.*, 1979), there were few Pacific tritium profiles at depth available (cf. Michel and Suess, 1975) and scarcely any from the pre-nuclear era. Early measurements in the Pacific (e.g., Miyake *et al.*, 1975) show that 1957 was probably the first year that tritium measurably exceeding the background was found in surface waters. Consequently, at the time of GEOSECS (1973–74), 17 years after the impact of the first nuclear tests were felt, any samples from below the winter mixed layer and containing more than 0.5 TU clearly must be considered to have mixed with water exposed to the atmosphere in the nuclear era.

Although the series of nuclear tests in the early 1960's increased the global tritium inventory by an order of magnitude over that from the mid-1950's tests, the contribution from the early tests cannot be ignored. The relative importance of the two major pulses (1957 and 1963) has been discussed by Crank (1975), who showed that, at the time of GEOSECS (1974), the first pulse cannot be ignored. Therefore, it will be assumed that water containing bomb

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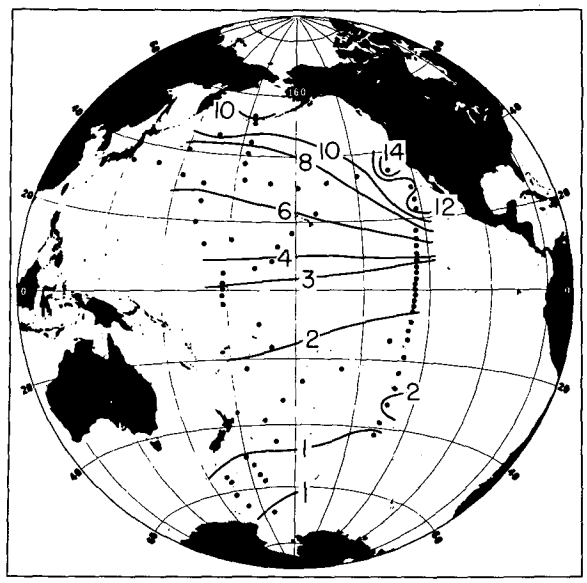


FIG. 1. Tritium (TU) at the sea surface at the time of the Pacific GEOSECS expedition, August 1973–June 1974. Data are from Östlund *et al.* (1979).

tritium is, or has been, in contact with the atmosphere in at most the 17 years prior to GEOSECS. In post-GEOSECS work, the second pulse will probably dominate.

Tritium measured by the GEOSECS expedition in the surface water of the Pacific Ocean is shown in Fig. 1. The pattern is not very different from that shown by Michel and Suess (1975), though it is now better defined and the concentrations are generally lower, in part because of decay. In particular, there were no GEOSECS measurements in the Gulf of Alaska, where Michel and Suess (1975) reported a surface value of 30.6 TU in 1967. The highest GEOSECS value of 14 TU is seen off North America and might extend to the Gulf of Alaska.

The values at the surface increase from south to north, reflecting the greater fallout in the Northern Hemisphere. The history of tritium as a function of time in the surface waters of the Pacific Ocean was represented by Fine and Östlund (1977) primarily as an exponential function of latitude. The values in the Southern Hemisphere are so low that they can yield little direct information about the flow.

Fig. 2a is a tritium section roughly along 180° longitude in the Pacific, prepared from the GEOSECS station data. The values are lower, in part because of decay, than those on the section prepared by Michel and Suess (1975), and they show greater detail. Most of the bomb tritium is still found in the upper waters of the Northern Hemisphere where it entered the ocean. In the region between 6 and 25°N (Fig. 2a) there is a tritium maximum beneath the mixed layer. It is not a single continuous feature in this plane, but is in two parts, north and south of the center of the anticyclonic gyre. As will be seen, these two parts are connected around the eastern part of the gyre.

Folsom (1979) has discussed the fallout of cesium-137 and its subsequent distribution in the upper layers of the North Pacific Ocean. He found, in data from several seasons including spring 1966 to fall 1972, patterns of surface distribution consonant with that of tritium (Fig. 1), although his data give greater detail in the northwest. The data from the Gulf of Alaska show that the area of maximum values found off California (similar to the values of tritium > 12 TU on Fig. 1) do not extend north of 50°N. He accounted for the pattern in terms of highest fallout in the north, and eastward advection from the northwest under continuing fallout. As Michel and Suess (1975) had earlier found for tritium, Folsom found that over most of the southeastern North Pacific the maximum Cs-137 concentration was not at the surface but at depths of 100–150 m or below. He observed that the maxima in some areas lay near

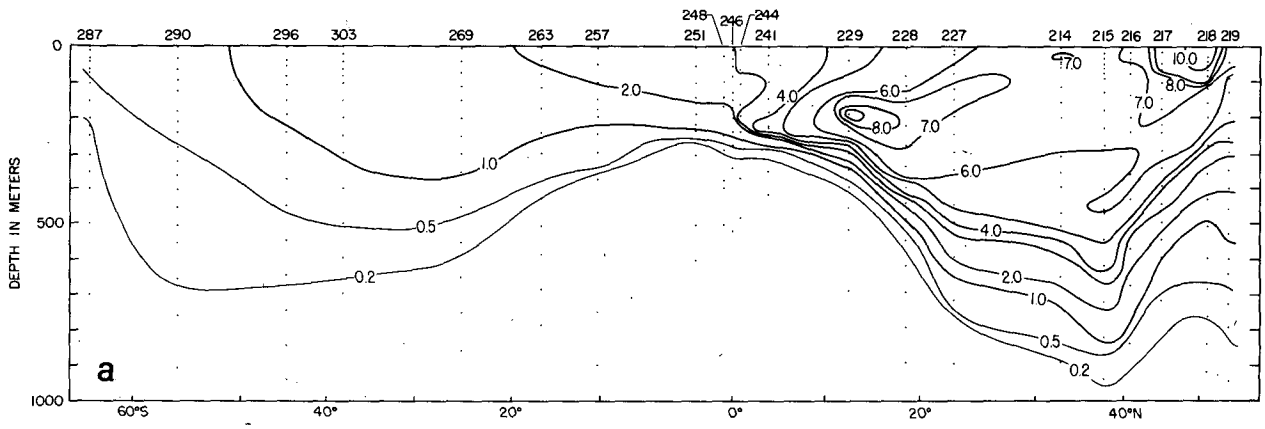


FIG. 2a. North-south vertical section of tritium (TU) along the western GEOSECS track (from the Aleutian Islands to 69°S) between 165°W and 170°E.

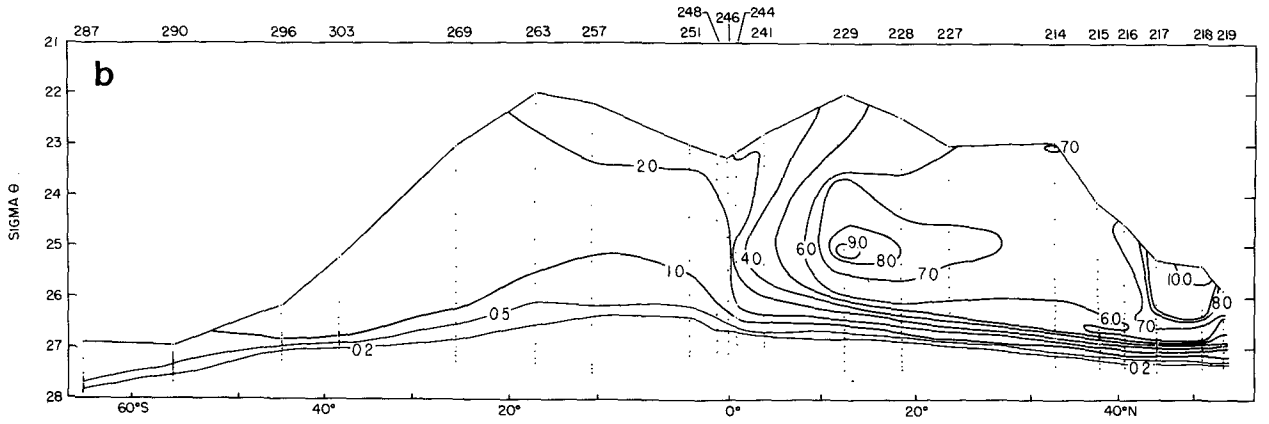


FIG. 2b. As in 2a, but with potential density as the ordinate.

the potential density value of 25.4 and the shallow subsurface salinity minimum.

Tritium has reached its greatest depths near 38°N and 50°S (Fig. 2a), but when tritium data are displayed with potential density as the ordinate (Fig. 2b) the penetrations to the greatest densities are seen to occur at the highest latitudes. The very small supply of bomb tritium in the Antarctic has reached greater densities there than the large supply in the North Pacific, and the possibility of lateral penetrations (along isopycnals) from high latitude sources into lower latitudes is suggested. This may account for the subsurface extrema observed.

2. Subsurface extrema

In a stratified ocean, the large-scale density field is in approximate balance with the geostrophic flow. Isopycnals that lie deep within an anticyclonic gyre may lie shallow or outcrop within an adjacent cyclonic gyre. Characteristics (temperature, salinity, tritium, etc.) maintained in the upper layer in one part of the ocean may extend laterally (along isopycnals) to regions where the corresponding density range places them well beneath the surface. Layers formed from surface waters in different parts of the ocean and spreading through the same region will be arrayed vertically according to their different densities. Thus, the result may be maxima or minima in the vertical profiles of many characteristics.

Some salinity extrema are illustrated in Fig. 3a, on the same north-south section as in the previous figure. The major currents are principally zonal at this mid-ocean longitude and hence normal to the figure, so that the north-south intrusions seen on the figure do not represent flow in this plane alone, but are the result of flow around the two anticyclonic gyres, with the principal flow eastward in higher latitudes, equatorward near the eastern boundary, and westward nearer the equator. A surface maximum in salinity is seen near 30°N, in the subtropical evaporation zone. The potential-density range of 1.024–1.025 g cm^{-3} (or σ_θ of 24–25) outcrops in that zone in winter, and extends southward across the equator below the surface. The high values of salinity from the upper layer in the excess evaporation zone provide a subsurface salinity maximum by extending laterally (within this density range) toward the equator beneath the upper waters of the equatorial zone, which are made low in density by high radiation and rainfall. A cell of high salinity also appears near 15°S (outcropping to the east of this section), and a corresponding salinity maximum extends equatorward beneath the surface and joins that from the north. The field is not symmetric, however. The southern cell is higher in salinity and lies in a slightly greater density range (24.5–25.5 in σ_θ).

At greater depths (Fig. 3a) salinity minima extend toward the equator from the colder, less saline surface layers of high latitudes. The minimum from the north lies near a σ_θ value of 26.8 in midlatitudes, and this isopycnal does not outcrop at the surface in the North Pacific in any season. The low salinities in that density range in the north are achieved, not by convection, but by diffusion downward to beneath the mixed layer in the zone north of 40°N (Reid, 1965). From that zone, lateral extension along this density range provides the subsurface salinity minimum. Fig. 3b, from the same data as Fig. 3a, has σ_θ as the ordinate. In this figure, the lateral extension of salinity features along isopycnal surfaces becomes more obvious.

Characteristics in the upper layer that are derived from or through the atmosphere may thus be found to extend below the mixed layer, both by lateral spreading from other areas where the surface density is higher and by vertical diffusion. Thus, depending on the surface density in the area of the sources of the characteristics, that is, the areas where exchange with the atmosphere provides the highest or lowest concentrations in the mixed layer, the lateral spread-

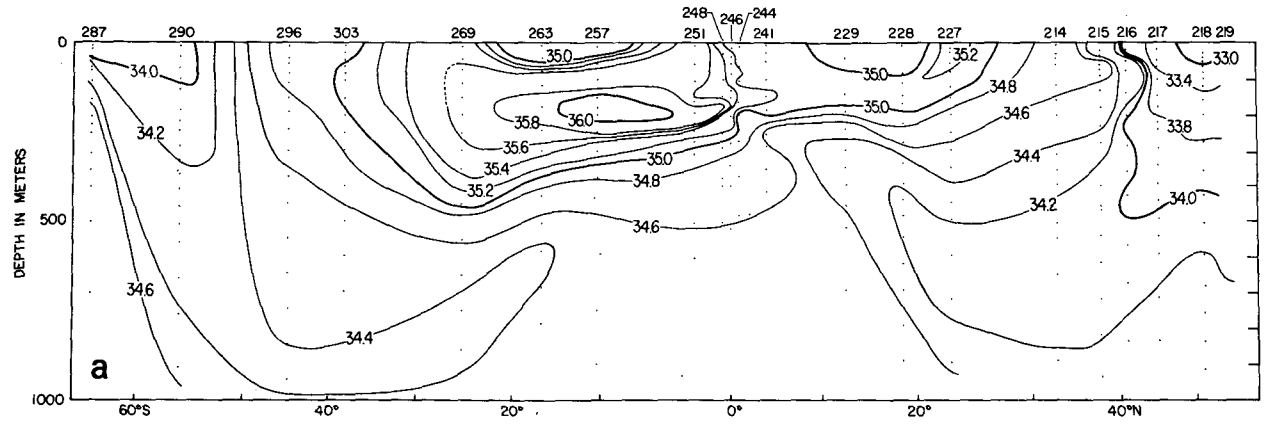


FIG. 3a. North-south vertical section of salinity (‰) along the western GEOSECS track.

ing will take place within various density ranges. Hence, not all subsurface extrema will have the same pattern. Heat, for example, enters primarily in the lower latitudes at relatively low surface densities. It extends to high-latitude subsurface regions by first diffusing downward into deeper water of greater density (as in the case of the deeper of the two salinity minima of the North Pacific) and then spreading laterally from its source area: in both the northern North Pacific and the Antarctic region there exists a subsurface temperature maximum that is derived in this manner. In a parallel manner, tritium, which has a high-latitude source, extends equatorward as subsurface maxima. The distribution of tritium, in terms of the subsurface maxima, must be understood as it is affected by the circulation of the upper layers of the ocean. It is subject to the same processes of advection and vertical and lateral diffusion as the other characteristics (temperature, salinity, etc.), but, having a different source, it will provide different patterns and information.

The maximum tritium value at each station is shown in Fig. 4a. In the North Pacific the maximum value is found at the sea surface only within the zone of maximum fallout north of 40°N and in the northern part of the eastern boundary current; everywhere else it is found beneath the sea surface. The tritium maximum, its depth, and the potential density at that depth are shown in Figs. 4a–4c. The vertical spacing and sparsity of samples at some stations did not always define the maximum very well. The values given for the maximum are those of the highest valued sample: it may be lower than the actual maximum, and the depth and density may be either lower or higher than a more complete sampling would have found.

In some regions the tritium maxima correspond roughly to salinity extrema. The westward flow of the anticyclonic gyre near 10–20°N appears as a subsurface tritium maximum of more than 8 TU. This maximum corresponds closely to the shallow salinity maximum formed by waters leaving the surface in the tropical salinity-maximum cell, as shown in earlier data by Michel and Suess (1975). There is also a subsurface tritium maximum of greater than 10 TU in the eastern Pacific, which is somewhat coincident with the shallow salinity minimum de-

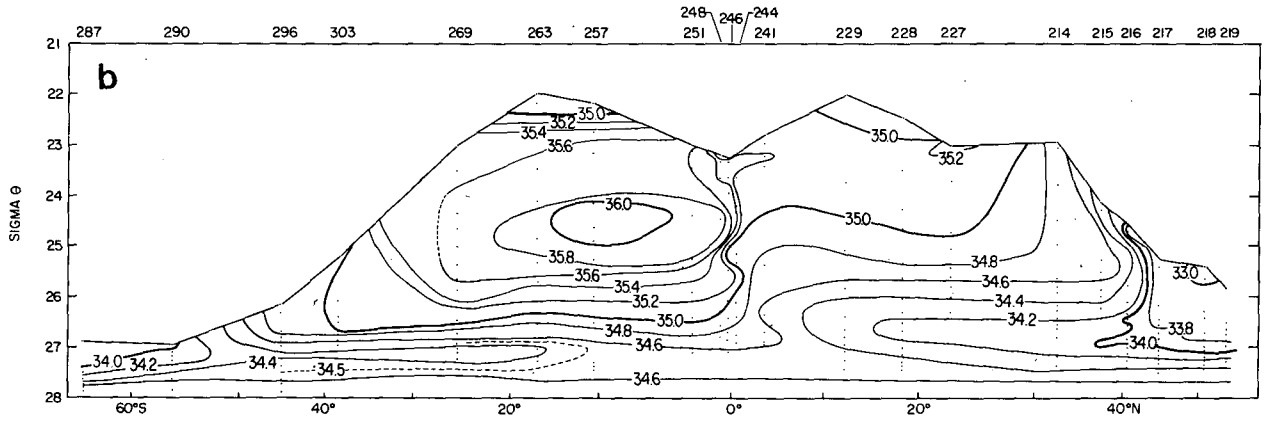


FIG. 3b. As in 3a, but with potential density as the ordinate.

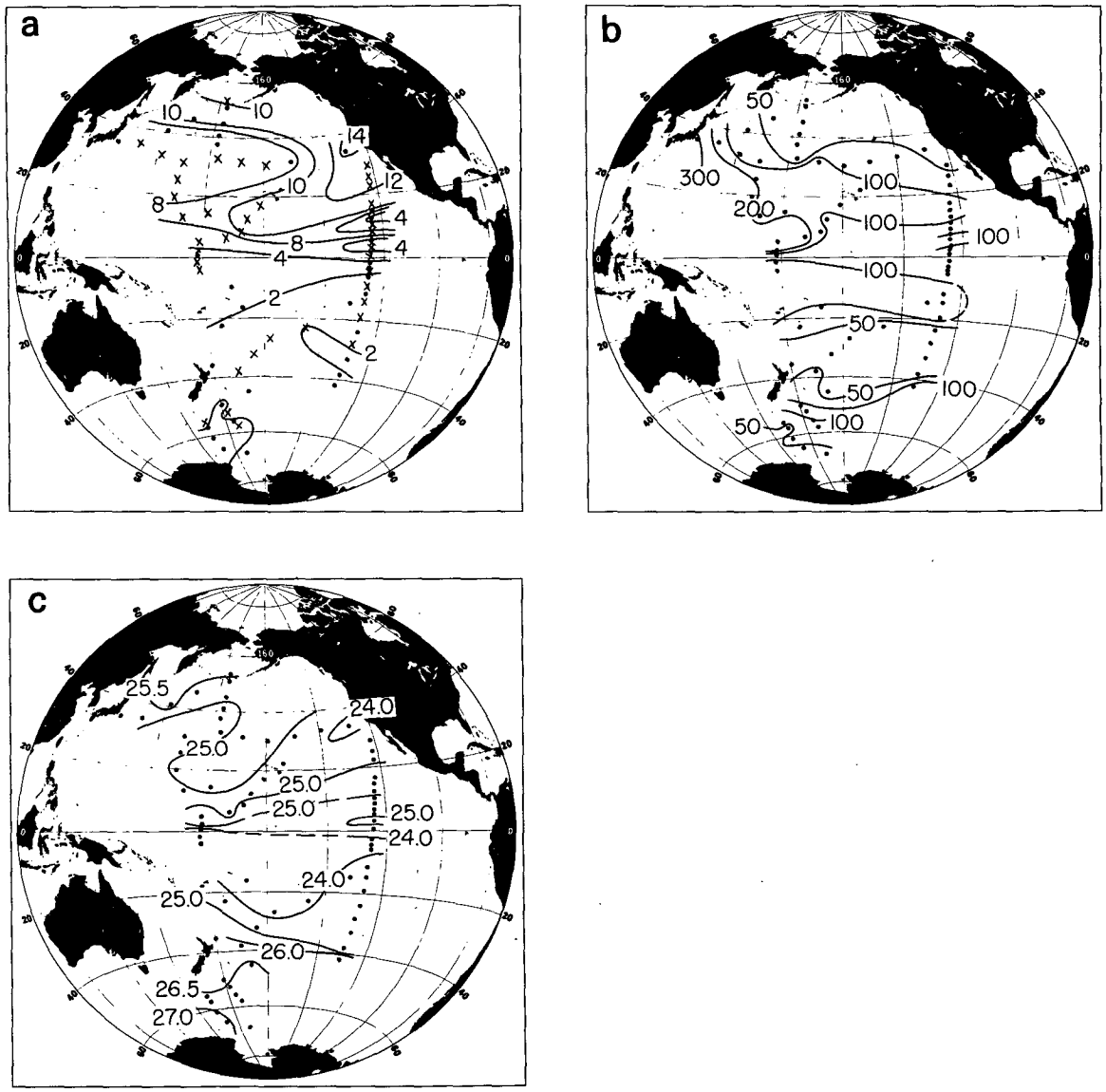


FIG. 4a. Map showing the maximum value of tritium (TU) at each station. Crosses indicate that the maximum was below the surface.

FIG. 4b. Map showing the depth (m) of the maximum tritium value at each station.

FIG. 4c. Potential density (σ_θ) at the depth of the tritium maximum.

scribed by Reid (1973). It represents water from the dense mixed layer of high latitudes that extends southward beneath the less dense, low-latitude waters.

The subsurface tritium maxima that obtain nearly everywhere in the North Pacific beyond the center of the subarctic cyclonic gyre cannot be a consequence of local vertical mixing, and must be accounted for by lateral processes including advection as well as diffusion.

3. General circulation as implied from tritium data

To examine the implications of the tracer for circulation, tritium has been mapped on three surfaces of constant potential density. The tritium values on

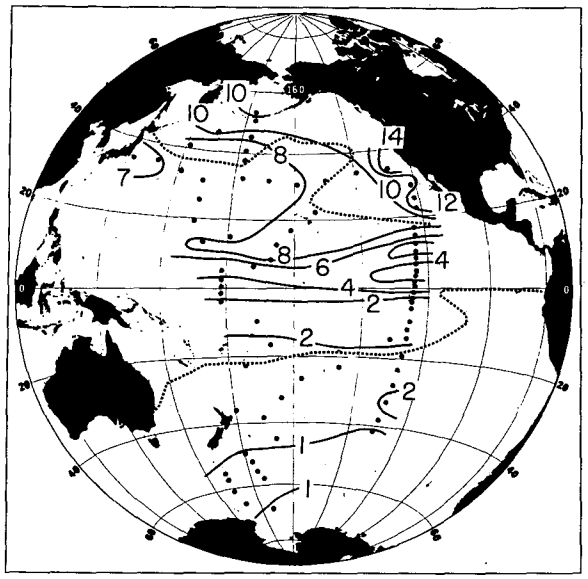


FIG. 5. Tritium (TU) on the isopycnal defined by the potential density (σ_θ) value of 23.90 (δ_θ = 400 cL t^{-1}). Tritium concentrations have been adjusted for decay to correspond to values on 1 January 1972. The dotted line represents the winter outcrop. Poleward of the outcrop the values are at the sea surface.

each surface were obtained by linear vertical interpolation at each station, and the limited vertical resolution at some stations may have led to some roughness in the contours. All of the data were adjusted for decay to correspond to values on 1 January 1972.

Tritium on the shallowest isopycnal (σ_θ = 23.90) is shown in Fig. 5. This isopycnal corresponds approximately to the tropical salinity maximum near 400 cL t^{-1} (Tsuchiya, 1968) that originates from the high salinity cell in the North Pacific (Figs. 3a and 3b). During the northern winter, this isopycnal outcrops at about 23–25°N west of 140°W, 20°N east of 140°W near the zone of highest sea-surface salinity (Reid, 1969). The depth of the isopycnal generally increases from the north equatorward to a little more than 150 m near 5°N, and rises to ~125 m along the equator in the west. Calculations of geostrophic flow at these depths relative to 500 db show the classical near-surface gyre circulation, clockwise around the central North Pacific (Tsuchiya, 1968).

In the region of the North Pacific subtropical gyre tritium on this isopycnal is fairly high, 6.4–9.5 TU, with the highest values extending from the subarctic gyre in a tongue along the eastern boundary, and westward along about 12°N in mid-ocean. Then in the North Equatorial Countercurrent (NECC), tritium abruptly decreases to less than 4 TU. Along about 15°N there is a somewhat systematic decrease in tritium from east to west, which appears to be a result of the width and trajectory of the flow. The salinity and oxygen patterns on this isopycnal, and the geostrophic flow relative to 500 db, indicate that the anticyclonic flow from the north turns westward before reaching 10°N in the east, and approaches closer to the equator farther west (Tsuchiya, 1968). The very low tritium values (less than 4 TU) in the east south of 10°N, further imply that the eastern tropical Pacific either has received little input from the north in the post-nuclear era, or the input has been substantially diluted with pre-bomb water. The area of low tritium corresponds very closely to Tsuchiya's (1968) area of low oxygen.

Tritium on the second density surface (σ_θ = 26.02) is shown in Fig. 6. Michel and Suess (1975) presented a map of their tritium data on almost the same isopycnal (26.00). Their earlier values are higher than the GEOSECS values north of 20°N and in the equatorial zone their later values (from 1970) are roughly the same as the GEOSECS values. With their limited data set they were unable to contour the field, but with due account for decay their pattern is entirely consonant with that shown in Fig. 6. This isopycnal is identical with the 200-cL t^{-1} surface Tsuchiya (1968) illustrated in the zone between 20°N and 20°S, and lies slightly above the σ_θ surface of 26.23 (180 cL t^{-1}) that Reid (1973) used to illustrate the shallow salinity minimum. During the northern winter, this isopycnal outcrops along 40°N, west of 175°W and along 175°W north of 40°N. In summer it outcrops only in a small area near Kamchatka, and in that season the depth of the isopycnal generally varies from the outcrop in the north to 200–400 m near 20°N and 50–200 m near the equator.

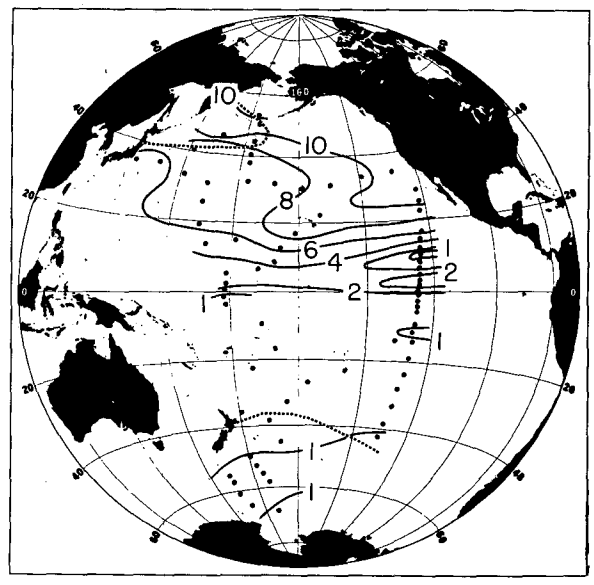


FIG. 6. Tritium on the isopycnal defined by the potential density (σ_θ) value of 26.02 (δ_θ = 200 cL t^{-1}). Tritium concentrations have been adjusted for decay to correspond to values on 1 January 1972. The dotted line represents the winter outcrop. Poleward of the outcrop the values are at the sea surface.

The geostrophic flow relative to 500 db and the salinity and oxygen at this density are very similar to those on the first isopycnal (Tsuchiya, 1968).

Tritium on the second isopycnal has a pattern roughly similar to that on the first isopycnal, yet shows a broader variation. High tritium extends from the subarctic zone (40–50°N) clockwise around the subtropical anticyclonic gyre (which bypasses the eastern tropical zone), but the tongue extending westward in mid-ocean lies farther north than that on the first isopycnal, at about 20°N instead of 12°N. The North Equatorial Countercurrent (NECC) returns some of this water eastward, creating the small maximum seen at 4–8°N near 125°W. A smaller maximum appears at the equator at that longitude on this isopycnal and on the previous isopycnal: they are possibly a consequence of transport in the Equatorial Undercurrent, which Tsuchiya (1968) has shown to contain an oxygen maximum extending from the west on this isopycnal.

A map of salinity (Tsuchiya, 1968) on this density surface (σ_θ = 26.02), shows a sharp gradient in the east at about 15°N where the California Current turns west, and a tongue of low salinity extending westward just south of the Hawaiian Islands. On Fig. 6 there is a corresponding sharp gradient in the tritium showing the penetration of high tritium water into the thermocline of the gyre and flowing westward south of Hawaii. Tritium data in the equatorial zone show little input of this water. South of 12°N in the central Pacific and south of 15°N in the eastern Pacific, tritium is below 4.3 TU. The data still reflect the input of bomb tritium, as they exceed 0.5 TU, yet they also reflect the slowness of the exchange between the equatorial zone and the central gyre. This exchange, which was modeled by Fine and Östlund (1980), corresponds to a horizontal eddy diffusivity of 5×10^7 cm^2 s^{-1}.

The contrast is even more vivid on the densest surface (σ_θ = 26.81, Fig. 7); it corresponds to the deeper salinity minimum of the middle and low latitudes of the North Pacific (Reid, 1965). This isopycnal lies beneath the mixed layer everywhere north of the equator in all seasons. The high tritium in the north, like the low salinity, is derived by diffusion downward in the far northwest where the isopycnal lies immediately below the winter mixed layer, and the concentrations are therefore lower. In accord with the general circulation, this isopycnal lies deepest (~800 m) along 30°N near Japan, shallowest (~150 m) along 50°N, and at ~300 m near the equator. The highest tritium concentrations are confined to the higher latitudes. At these depths the tritium has not yet penetrated the anticyclonic flow as strongly as in the shallower strata. In particular, there is no tongue of high tritium extending around the anticyclonic gyre and westward in mid-ocean. The eastern equatorial zone had received very little tritium from the north and none as yet by return flow in the NECC.

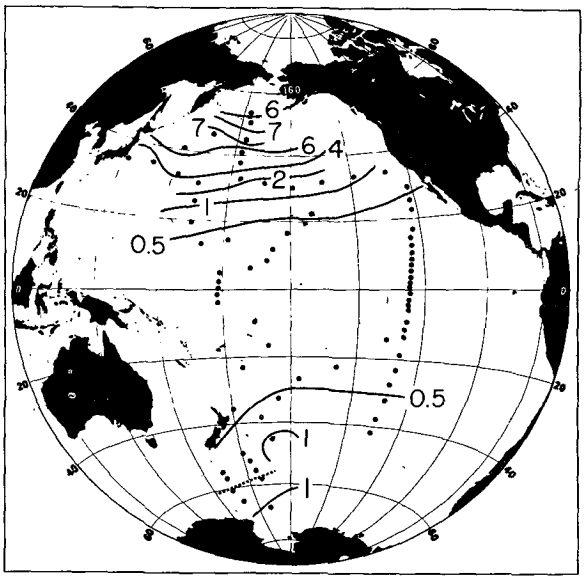


FIG. 7. Tritium on the isopycnal defined by the potential density (σ_θ) value of 26.81 (δ_θ = 125 cL t^{-1}). Tritium concentrations have been adjusted for decay to correspond to values on 1 January 1972. This isopycnal outcrops only in the South Pacific, as shown by the dotted line.

Maps of salinity, oxygen and phosphate on this isopycnal (σ_θ = 26.81) show sharp north–south gradients that lie near 20°N and 20°S in the east and near 10°N and 10°S in the west (Reid, 1965). A similar pattern is seen in the tritium data, but it is even more dramatic because of the time-scale implications. The core of highest tritium (>6 TU) in Fig. 7 lies near 45°N within the subarctic gyre. The high tritium core is evidence that a great portion of this water turns northward and westward around the Gulf of Alaska, remaining within the subarctic gyre instead of flowing southward around the subtropical gyre. The 0.5 TU contour (Fig. 7) across the North Pacific at this density shows that the transit and exchange times with the waters south of 20°N are greater than 17 years. The subsurface maximum in tritium is seen on the meridional section (Fig. 2) near 15°N at a σ_θ-value of about 25 (Fig. 4c). The presence of this subsurface maximum at these lower latitudes indicates an exchange by flow around the subtropical gyre in a time of less than 17 years. But on the deepest isopycnal (Fig. 7) the high values in the north have not yet penetrated south of 20°N. That there has been so little input of bomb tritium south of 20°N shows that the exchange between the northern gyres and the equatorial region is considerably slower at this density than on shallower surfaces.

Of course, there has been previous evidence of the limited exchange of the deeper waters between the equatorial zone and the higher latitudes. The

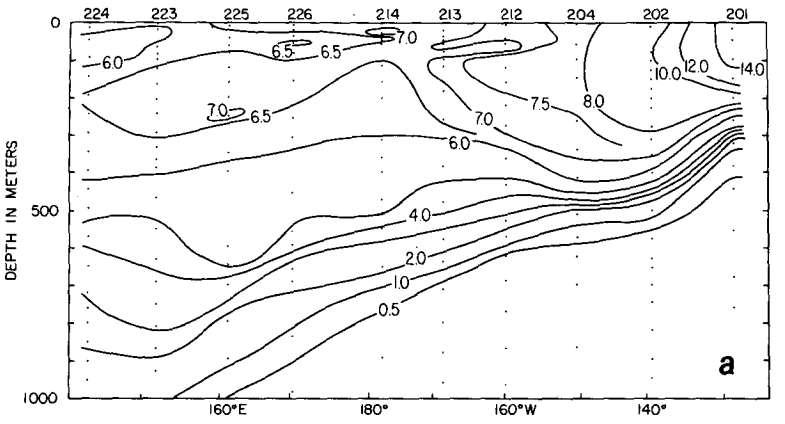


FIG. 8a. East-west vertical section of tritium (TU) from the GEOSECS stations near 35°N, from North America to Japan.

remarkable zonal uniformity of the conservative characteristics in the equatorial domain, between these two zones of sharp gradients, and their differences from the tropical characteristics, were noted by Sverdrup *et al.* (1942). They state (p. 706), "In the equatorial region of the Pacific and below the tropical discontinuity layer, one finds an Equatorial Water mass of a remarkably uniform character which extends over the entire Pacific Ocean from east to west . . . . This Equatorial Water mass has its greatest north-south extension along the American coast, where it is present between latitudes 18°S and 20°N. Towards the west it appears to become narrower . . . ."

The lateral uniformity of tritium and the conservative characteristics within this vertical and horizontal domain, and the extreme differences, particularly in oxygen and nutrients, between this domain and the tropical waters to the north and south in the same density range (Reid, 1965; Tsuchiya, 1968; Barkley, 1968), imply a relatively slow renewal rate of the deeper equatorial waters.

4. Penetration depth of bomb tritium

Generally, the pattern that has emerged from the tritium data is least penetration in the lower latitudes and in the eastern equatorial zone and deepest penetration in the western parts of the subtropical anticyclonic gyres, where the isopycnals lie deepest. As suggested by the map of tritium on the surface where σ_θ is 26.81 (Fig. 7), bomb tritium is found at densities greater than 26.81, even though the maximum outcropping density is less than 26.81.

A tritium section at about 35°N (Fig. 8a) vividly shows the major contrast between the eastern and western Pacific. While the highest concentrations are found in the east, the deepest penetration is found in the west. The reason for this is made clear in Fig. 8b, in which the same tritium data are shown but with density as the ordinate. As the isopleths of tritium at higher densities are nearly parallel to isopycnals, the distributions below about 26.5 in σ_θ are more nearly uniform. Because these isopycnals slope downward from east to west (across the great

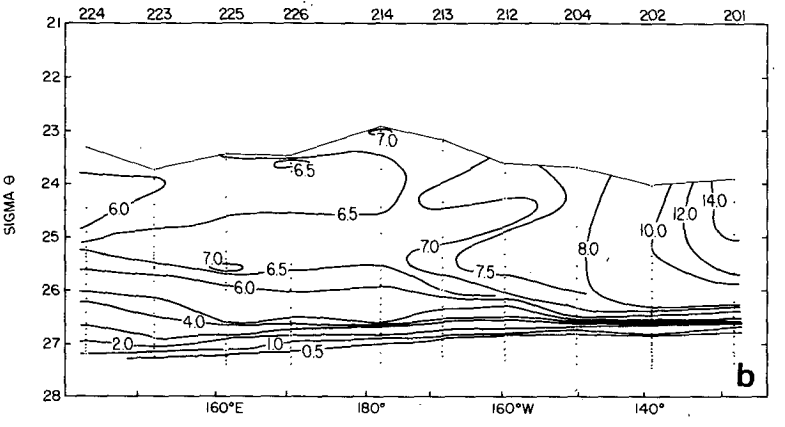


FIG. 8b. As in 8a, but with potential density as the ordinate.

subtropical anticyclonic gyre) the isopleths of tritium also slope in that sense (Fig. 8a), and high values are found at greater depths in the west because of the density field. There is still a difference, however. Tritium has penetrated to slightly higher densities in the west than in the east, as indicated by the isopleths of 1 and 2 TU in Fig. 8b, and this must be a result of continued vertical diffusion as the waters circulate around the anticyclonic gyre.

The profiles of tritium show a sharp decrease with depth at some level, and this decrease may start from quite high values in some areas and from much lower values in others. The break represents the depth to which effective ventilation has occurred in the post-bomb era, though the overlying concentrations will reflect the amount of tritium available as well as the effectiveness of spreading.

The pattern of decreasing tritium with depth from a maximum value is heightened if individual stations are examined. Two typical tritium profiles in the North Pacific at GEOSECS Stations 235 (17°N, 161°W) and 217 (45°N, 177°W) located southwest and northwest of Hawaii are shown in Fig. 9a.

Station 217 is near the center of the subarctic cyclonic gyre and near the zone of maximum fallout. The GEOSECS measurements were in summer and show a very shallow upper layer containing over 9 TU. At this location the greatest winter-mixed-layer depth is ~125 m. Below the mixed layer tritium decreases to about 6 TU at $\sigma_\theta = 26.8$ (250 m). There is no subsurface maximum this far north, and the concentration continues to decrease to 0.1 TU at ~800 m.

At Station 235 the upper layer extends to ~60 m and contains 4.5 TU. At this location the greatest mixed-layer depth during the year is about 90 m. Below the mixed layer, tritium increases to a maximum of 10.5 TU at 160 m. At this latitude, surface tritium has never reached as high as 10.5 TU. In addition, the tritium maximum lies near the tropical salinity maximum, indicating that it was transmitted there mainly by lateral mixing with the more saline waters to the north. Below the maximum, tritium then decreases rapidly to about 350 m where it is 0.6 TU. Below 430 m (the depth where σ_θ is 26.8) tritium is less than 0.1 TU. Fig. 9b shows two Southern Hemisphere stations. There the patterns are similar though not so pronounced.

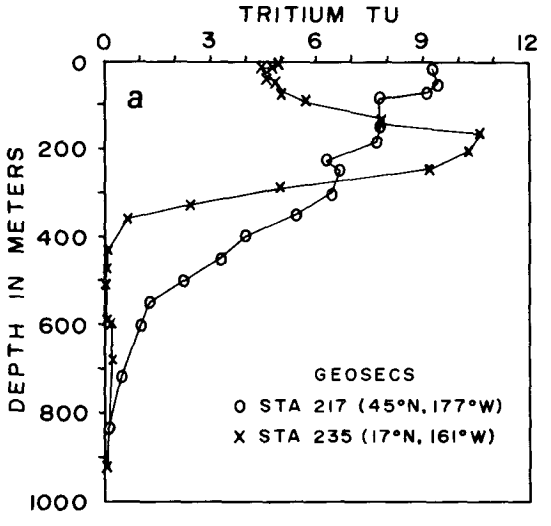


FIG. 9a. Profiles of tritium (TU) at GEOSECS Stations 217 (at 44°40'N, 177°03'W) and 235 (at 16°45'N, 161°23'W).

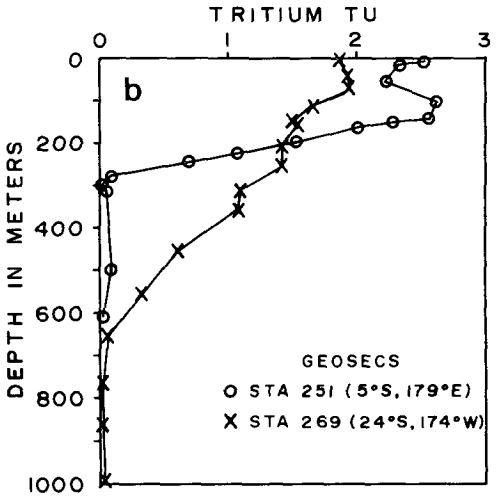
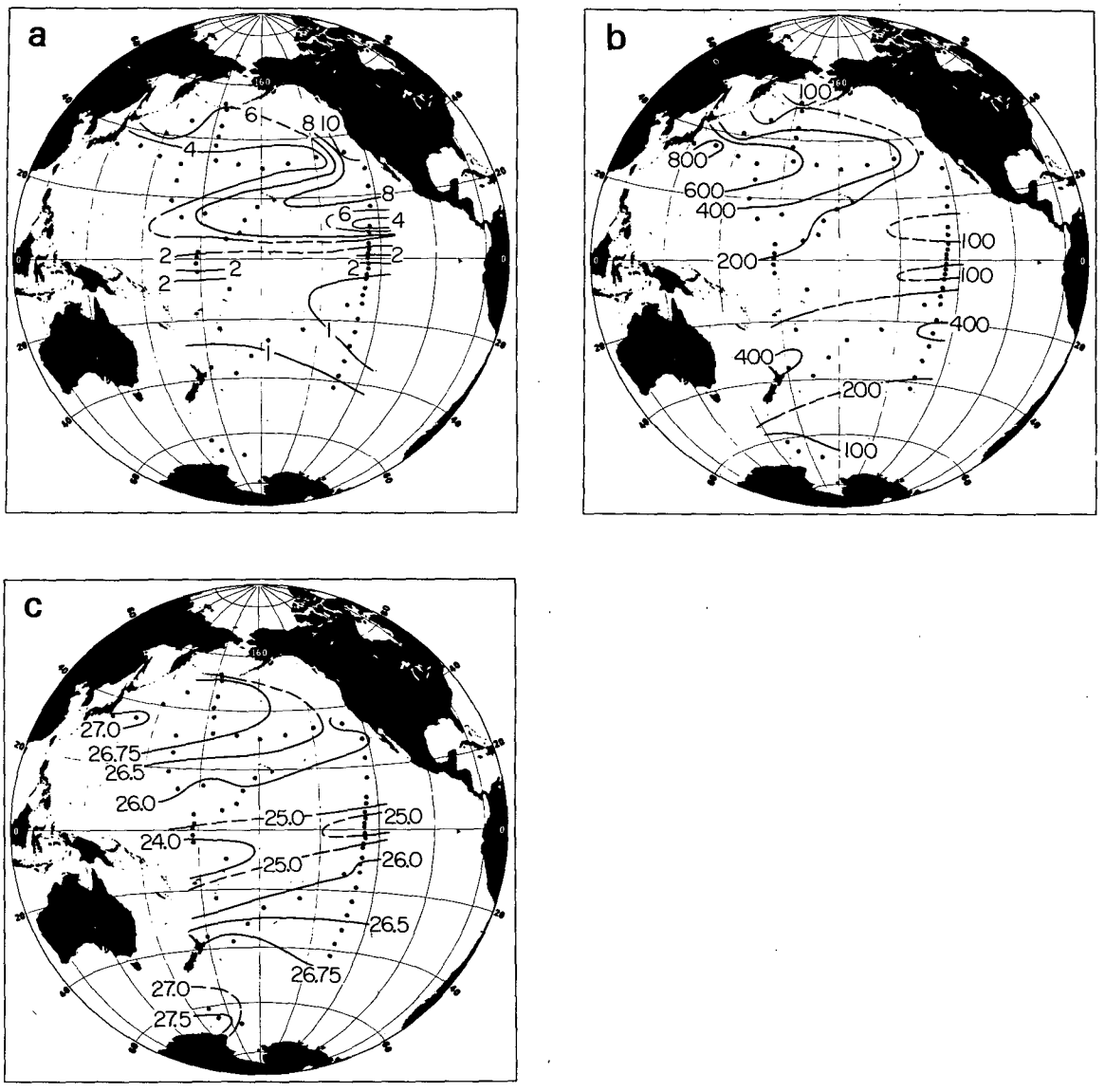


FIG. 9b. Profiles of tritium (TU) at GEOSECS Stations 251 (4°34'S, 178°57'E) and 269 (23°59'S, 174°26'W).

The depth of the maximum vertical gradient of tritium is of some interest. One interpretation is that it may represent roughly the limit of direct ventilation of the column in the post-bomb era. Water above this depth may have received tritium either by convection (as at Station 217) or by lateral extension from an area of convection (Station 235), but the deeper waters have received it only by vertical diffusion from the overlying water. This interpretation is not unique, of course, and in any case the determination of the characteristics of the strongest vertical gradient is limited by the resolution of the data. It seems worthwhile, however, to try to illustrate, if only roughly, the depth below which only vertical diffusion has been effective. The depth shown in Fig. 10b was chosen conservatively as the mid-depth of the two samples defining the strongest gradient. Usually this is defined fairly well, but the tritium and density values of the upper sample may be very different from those of the lower sample: the average values are used, but they may be substantially higher or lower than a finer scale data set would have shown. At several stations, particularly in the far South Pacific, the concentrations were either too low, or the resolution too limited, to define the maximum gradient.



Circulation of Tritium in the Pacific Ocean

FIG. 10a. Tritium (TU) at the depth of the maximum vertical gradient of tritium.

FIG. 10b. Depth (m) of the maximum vertical gradient of tritium.

FIG. 10c. Potential density (σ_θ) at the depth of the maximum vertical gradient of tritium.

The maximum vertical gradient of tritium lies deepest (i.e., substantial direct ventilation has reached farthest down) within the anti-cyclonic gyres, more than 800 m in the North Pacific. The highest values of tritium at the maximum gradient (Fig. 10a) are found in the eastern boundary current of the North Pacific and its westward extension near 20°N, reflecting the strong role of advection. The highest potential density at the maximum gradient of tritium (Fig. 10c) is found near Antarctica, at depths less than 100 m; in the North Pacific it occurs in the western part of the anti-cyclonic gyre. The isopleth of 26.75 in potential density encompasses the northwestern area of the densest outcrop, and some density values in excess of the outcrop density (26.81) occur. This is the area from which the highest tritium values appear to originate (Figs. 4a and 7). Convective overturn there occurred at the highest density of any

part of the North Pacific, and fallout was higher there than in the lower latitudes. The maximum gradient lies shallow, and at lowest densities, in the zone between the tropics, particularly south of the equator where fallout was lower and lateral advection of the ventilated denser waters has not yet penetrated.

The profiles and patterns of tritium in the North Pacific suggest a vertical division of each profile into three layers. The shallowest layer includes the depth range of the deepest winter-mixed layer at each station, that is, the layer that could be ventilated locally in winter. It has received tritium by fallout and has lost some part of lateral transfer to greater depths or by vertical diffusion. We have estimated the depth of this layer from earlier work of Bathen (1972) and Robinson (1976) and unpublished estimates by Reid: of the tritium measured in the North Pacific in the 1973–1974 GEOSECS work, this layer contained ~28%.

The second layer includes the waters that are below the first layer but shallower than the depth of the winter-outcrop isopycnal of maximum value (26.81 in σ_θ). The tritium content of the second layer represents the part that has left the mixed layer, but not yet penetrated to depths below the outcrop density of $\sigma_\theta = 26.8$ (the maximum density encountered in the North Pacific near the top of the pycnocline in winter). It has two sources—diffusion downward from the mixed layer, and lateral extensions of strata that have outcropped farther poleward and received tritium directly from the atmosphere in those outcrop regions. The existence of a subsurface maximum in tritium nearly everywhere equatorward of 40°N indicates that this second source is the more important in lower latitudes. Tritium in the second layer makes up ~58% of the total.

The third layer contains those waters deeper than the outcrop isopycnal. It has received tritium only by vertical diffusion, as it is all denser than any mixed layer in the North Pacific in winter. At Station 235 (17°N), there is very little tritium in this region. Farther north, at Station 217 (45°N) and generally in the region of maximum mixed-layer concentration north of 40°N, especially in the northwest, values of more than 6 TU are found at the depth of the outcrop isopycnal of maximum value, and measurable concentrations are found below 1000 m and at densities greater than $\sigma_\theta = 27.26$. Over the entire North Pacific, the third layer contains ~14% of the total tritium: the part north of 40°N alone contains 11%.

In the South Pacific there were fewer tritium stations (24) than in the North Pacific (40). The major differences between the two oceans result from the lower fallout in the south and the greater density of the mixed-layer waters near Antarctica. Tritium is found at densities greater than $\sigma_\theta = 26.8$ in the southwest Pacific. Surface densities as great as 27.7 in σ_θ are found in the open Pacific near Antarctica in winter, and a correspondingly deeper penetration of high tritium concentrations would have been expected if the fallout had been as great as that in the North Pacific. The South Pacific concentrations are too low to allow an independent interpretation of the flow and mixing processes. The little evidence available suggests a distribution analogous to that in the North Pacific, but operating on lower inputs and at higher densities.

5. Conclusion

The nuclear fallout pattern tagged the high latitude Northern Hemisphere waters with bomb tritium, making it possible to consider the spread of a tracer in three dimensions. Subsurface tritium maxima could not be maintained by diffusion from the mixed layer alone. They are clearly a consequence of lateral spreading from shallower depths in higher latitude (and thus higher tritium) source regions.

The earlier conclusions of Michel and Suess (1975) that the tritium distribution is controlled largely by lateral exchange are confirmed and extended to a broader area of the Pacific and to a greater depth range. The pattern which emerges from mapping tritium on isopycnal surfaces shows definite features of the relative time scales for circulation of the upper waters of the North Pacific. Tritium is fairly well mixed (6–7 TU) on the 26.81 isopycnal in the subarctic cyclonic gyre, in contrast to the large gradient within the anticyclonic gyre to the south. The pattern on this isopycnal shows that the exchange between the two gyres has been slower than along shallower isopycnals. Similarly, the pattern of tritium on the shallower isopycnal surfaces where σ_θ is 23.90 and 26.02 shows slower exchange between the central (anticyclonic) gyre of the North Pacific and the equatorial region, particularly the eastern part.

Observations of bomb tritium at substantial depths in the North Pacific have suggested that, although there are no sources for deep water, the North Pacific has a great capacity to serve as a sink for atmospheric constituents. In the northwest Pacific bomb tritium has been found to depths exceeding 1000 m. Thus, the upper waters of the North Pacific show, in addition to a mixed layer that exchanges rapidly with the atmosphere, an intermediate region that exchanges on decadal time scales.

Although the results presented here are clearly for a chemically nonreactive tracer that follows the water, there are implications for other tracers. The conclusion is that vertical models used at present for air-sea exchange of atmospheric constituents such as CO_2 are not realistic. There is a capacity, even in the North Pacific Ocean, with its low surface density and limited overturn, for a much greater ventilation of subsurface waters than one-dimen-

sional vertical processes alone would achieve. Such lateral ventilation, of course, also would apply in the South Pacific, South Indian and South Atlantic oceans. In the North Atlantic the outcropping isopycnals extend deeper than in the North Pacific, and this sort of penetration by lateral processes can reach greater depths, as the Atlantic GEOSECS tritium data show (Östlund *et al.*, 1976). Such penetrations can add substantially to the ventilation achieved by vertical processes alone, including both the general trans-pycnocline mixing and the deeper convections of the various high-latitude seas. In the North Pacific tritium budget, lateral penetrations are the most effective of the three. The extent of the ventilation in the North Pacific is remarkable. When combined with what may be expected from similar processes in the South Pacific, South Atlantic and South Indian oceans, the dominance of the North Atlantic in exchange of CO_2 may be brought into question.

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