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CORAL GROWTH RINGS AND THE TEMPORAL HISTORY OF NUCLEAR $^{14}C/C$ $^{90}Sr/Sr$ IN THE SURFACE OCEAN

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Although progress during the first two years of our DOE support has been slowed by delays in the development of our ^{14}C counting capabilities, we have substantial progress to report. Highlights of our first two years have been: 1) the collection of 129 coral samples from the Atlantic, Pacific, and Indian Oceans, 2) generation of three ^{90}Sr records, one from Bermuda and one each from Oahu in the Hawaiian Islands and Tarawa in the Gilbert Islands, 3) completion and successful routine operation of our benzene synthesis system, 4) the counting of our first coral samples, and 5) the compilation of a great deal of interpretive work leading to the construction and testing of models which have and will be used to reproduce the essential features of the coral ^{90}Sr and ^{14}C time histories. These developments will be detailed below.

Sample Locations

Table 1 lists the sites from which we have collected corals during the first two years of the contract. The Pacific sites are shown in figure 1. We feel that we have a sufficient number of sites sampled in the Pacific to provide a great deal of new information about the fate of bomb tracers in that ocean.

Although the listing in Table 1 shows a number of duplicate samples at many sites, we are likely to have ony one or two corals which have a clear banding record. At several of these sites, the coral with the best banding is unfortunately not the largest or oldest sample. Therefore, some of our records do not extend back to the beginning of the bomb-test era. However, the most useful part of the record oceanographically is the post bomb-test record. Nearly all of our samples are at least this old.

Our sampling site list is notably devoid of samples from the S. Atlantic. This area is extremely important for bomb tracer studies because the area has a very incomplete tracer sampling record for seawater. For most areas the sampling history consists only of GEOSECS data. We plan to undertake a sampling trip to the S. Atlantic sometime next year (1982).

^{90}Sr Records

The results of our ^{90}Sr analyses to date are shown in figures 2-4. Figure 2 shows our Bermuda data. ^{90}Sr activities measured in each band are decay-corrected to the year of growth. These values are then related to ^{90}Sr concentrations in seawater during that year. In fact, the data values plotted in units dpm/100g are more-or-less equivalent to seawater values in the common units dpm/100L because there are ~ .01 moles of Ca^{++} in average seawater and $CaCO_3$ has a molecular weight of 100 g/mole.

Smith _et al_. (1979) showed that coral skeletons are slightly enriched in Sr relative to seawater Sr/Ca ratios. The seawater ratio is close to 0.009. The coral value is about 7% enriched at 25°C and is a function of temperature, showing an 8% inverse variation between 20° and 30°C. In theory, coral ^{90}Sr activities should be about 7% higher than seawater.

Figure 3 shows our Bermuda data plotted along with N. Atlantic seawater values from Bowen _et al._ (1968). While the coral values might be a little high, a difference is not easy to see. Several reasons for this are: 1) counting errors on our ^{90}Sr analyses are about 7%, 2) a percent or so of weighed coral material might not be $CaCO_3$, countering the Sr/Ca fractionation, 3) corals do not grow at the same rate during a banding cycle, and 4) the exact correspondence between a calendar year and the coral year spanning one dense band to the next can only be known plus or minus a few months.

Not much effort has been expended toward interpreting the Bermuda record up to now because our original Bermuda coral was sampled over two-year bands and also because the original coral was collected in 1974. We now have a 1980 coral from which we can take a new suite of samples.

Our interpretive work has been directed mainly toward the Pacific ^{90}Sr records in figure 4 (Toggweiler, 1980). These samples represent latitudes 22°N (Oahu) and 1°N (Tarawa). Our first batch of Fiji results are also plotted in figure 4. These numbers are preliminary and could change but only within the error limits shown.

The contrast of equatorial and N. temperate records is very interesting. The proposal accompanying this report discusses the oceanographic factors producing these time histories at some length. The most interesting aspect concerns the virtually-flat equatorial record after 1965. Our interest in coral time histories originally stemmed from the observation that the equatorial regions of both the Atlantic and Pacific had bomb ^{14}C inventories that were four times lower than adjacent temperate zones. A paper by Broecker _et al._ (1978) attempted to explain the low inventories by calling for upwelling of pre-bomb water at the equator and the subsequent lateral displacement of equatorial water to the north and south. The paper estimated upwelling rates averaging about 25 m/yr throughout the 15°S - 15°N region. Since the top of the thermocline is found at about 150 m depth in this region, this upwelling rate implies a turnover of all the water in six years. Constant replacement of equatorial water with pre-bomb sub-thermocline water would keep bomb ^{14}C invading from the atmosphere from building up.

The Tarawa ^{90}Sr record says that this cannot be true because, if it were, the ^{90}Sr concentrations would be expected to decline at a fairly rapid rate. The original interpretation has been revised and expanded (see Appendix) such that the source of upwelling water is a mixture of bomb and pre-bomb water. This solution can bring ^{90}Sr into the equatorial region to stem the originally anticipated decline but rates of water turnover for the equatorial region must increase dramatically.

A dilemma becomes apparent if one looks at the equatorial dynamics from the perspective of ^{90}Sr and/or ^{3}H. An analysis of literature ^{3}H data for the equatorial region and the major current systems (see attached proposal) shows that ^{3}H and ^{90}Sr are brought into the equatorial region by the North Equatorial Current which feeds the Equatorial Undercurrent and North Equatorial Counter Current (see also Fine and Ostlund, 1980). This analysis does not seem to require rapid turnover of equatorial water or high rates of upwelling of pre-bomb water.

Benzene Synthesis and ^{14}C Counting

Near the end of the first contract year we decided to convert our ^{14}C counting system from CO^2 gas counting to liquid scintillation counting of benzene. Over the long term this changeover will be of great benefit to the geochemistry group at Lamont and the success of this project. The 5ℓ-CO_2 gas-counting chamber we constructed had a large and unreliable background which would have permitted counting errors no better than ±12°/oo. Our initial benzene/LS counting experience has already demonstrated a capability of producing accuracy to 6°/oo and should ultimately permit accuracy to 2°/oo if large enough samples are used. Benzene/LS counting will also permit our radiocarbon facility to keep pace with the state-of-the-art as far as decay counting of ^{14}C is concerned. Due to Lamont's physical location on top of a diabase sill, an underground ^{14}C gas-counting system is out of the question. Nearly all state-of-the-art ^{14}C laboratories have gone this route in order to lower backgrounds and improve counting errors.

LS counting affords one the opportunity to circumvent the background problem by increasing sample size without increasing the volume of exposure to background radiation. Liquid scintillation counters are also inherently more stable and require less attention to achieve good results. Our initial experience in the last month has shown that we can achieve counting errors which are limited primarily by count rate and count time and not by unexplained and uncorrectable replication problems.

In April of 1980 we completed design and construction of a benzene synthesis vacuum line to process our ^{14}C samples. The technique uses three reactions to produce the benzene products. First, CO_2 is reacted with lithium metal at 700°C to produce lithium carbide (Li_2C_2). This product is then reacted with water at room temperature to form acetylene (C_2H_2). The acetylene is cleaned and then reacted on a catalyst to form benzene (C_6H_6).

The catalyst is the main limiting step for high yields. We have found the greatest part of yield loss to be due to formation of substituted aromatic compounds of higher molecular weight and lower volatility than benzene. Figure 5 shows a gas chromatograph of the residue left in our system after the sample benzene has been frozen into a sample vial. Benzene indistinguishable from the carbon disulfide solvent and appears on the far left. The peak at 5.55 cm we believe to be napthalene ($C_{10}H_8$), which is an aromatic compound consisting of two benzene rings combined together. We have found it is possible to maximize sample yields by running the catalyst reaction at slow rates and low temperatures. In this way the benzene formation reaction is more favored than competing reactions.

We routinely achieve yields of between 92 and 97% for the complete synthesis on real samples. While competing reactions and incomplete product formation open the door to isotope fractionation, high yields prevent fractionation effects from having a substantial effect on the final sample. This improves prospects for a high degree of sample replication.

In May of the present contract year (1980) our engineering group completed designs for our liquid scintillation counting system which was to be built by a local engineering firm. After holding the contract until late September, the contractor informed us that the instrument and its specifications were beyond his abilities. After plunging into the LSC market once again, we ordered an instrument in December from Beckman and made plans for its modification to suit our needs. In the interim we have begun using an older but nearly identical Beckman owned by our Marine Biology group. Although its background is higher than we would like (~ 7 cpm for a 7-ml glass vial), we find that unexplained variance on background counts, that is, error in excess of counting statistics, is almost totally accounted for by a correlation with atmospheric pressure changes (Pearson, 1979). Thus we are able to define background to ± .05 cpm which makes total sample errors of $6^{o}/oo$ possible on three day counts of a benzene volume equivalent in carbon content to 30g of coral.

Our new machine will provide manual control over most functions and will dump data to an Apple computer. The high voltage on the phototubes will be lowered to decrease background. Counting windows will be set manually for maximum efficiency.

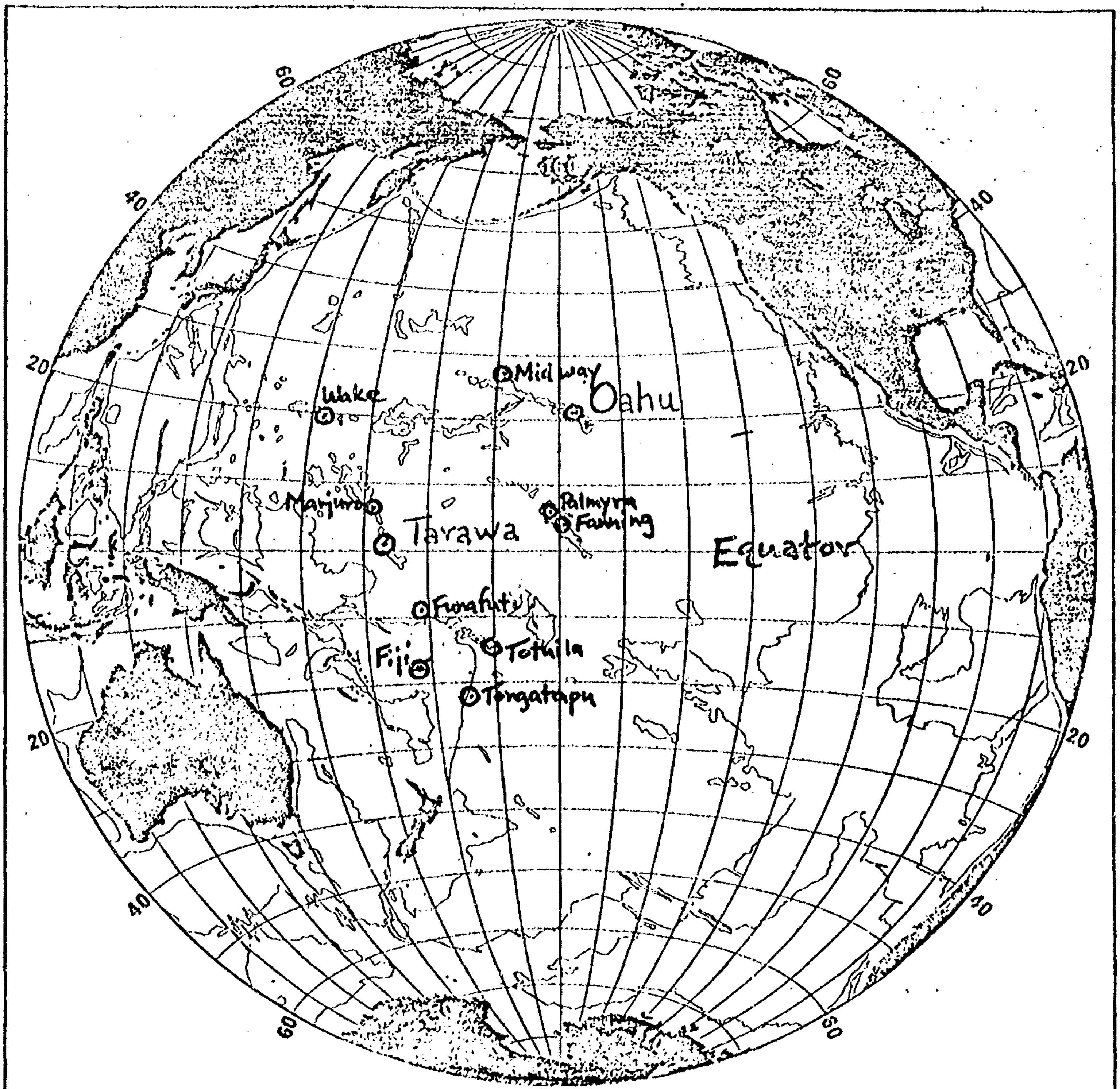

FIGURE 1. CORAL SAMPLE LOCATIONS

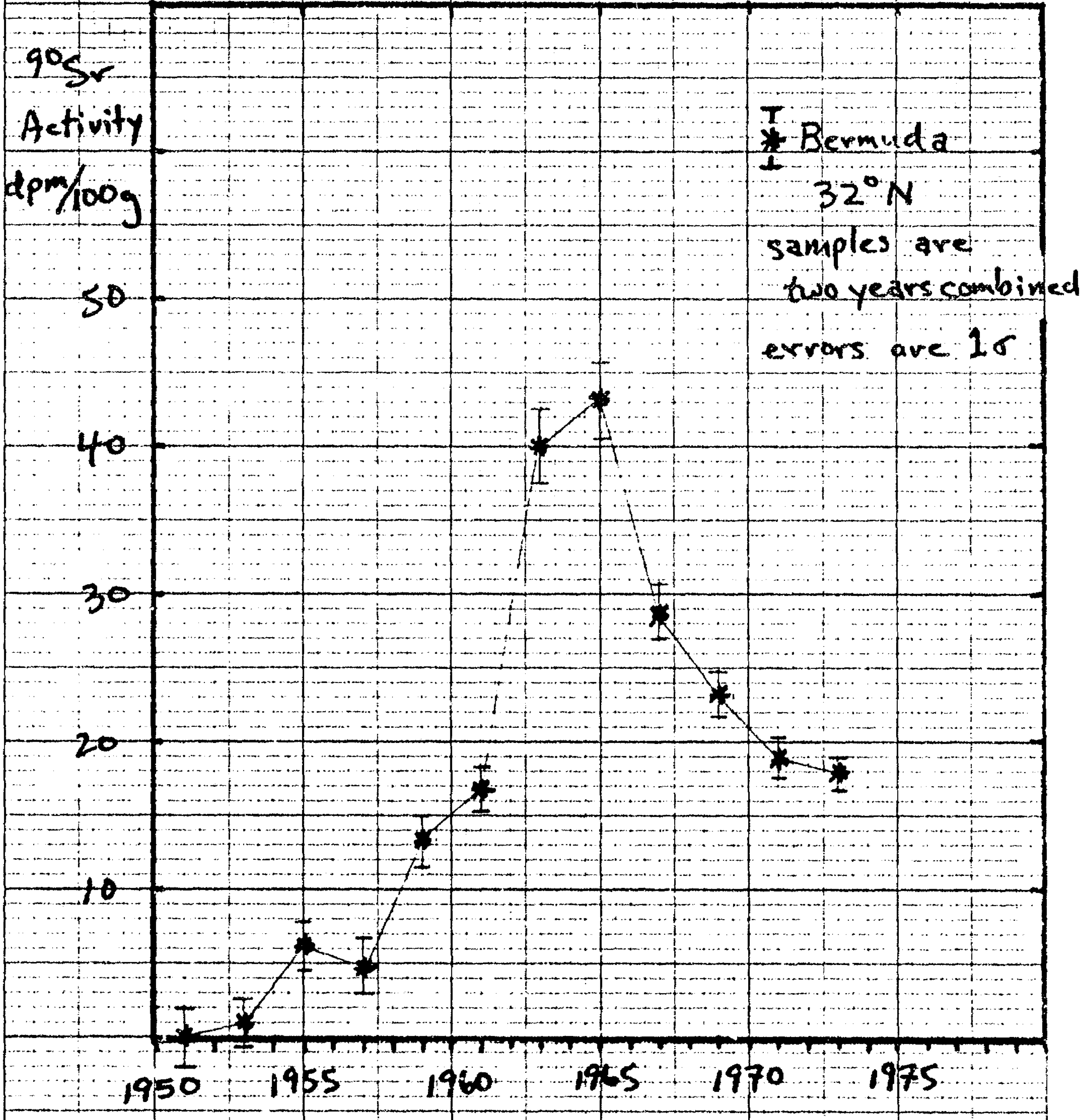

FIGURE 2. ^{90}Sr record from Bermuda Units are equivalent to ^{90}Sr in seawater at dpm/100L. Counting data are decay corrected to year of growth.

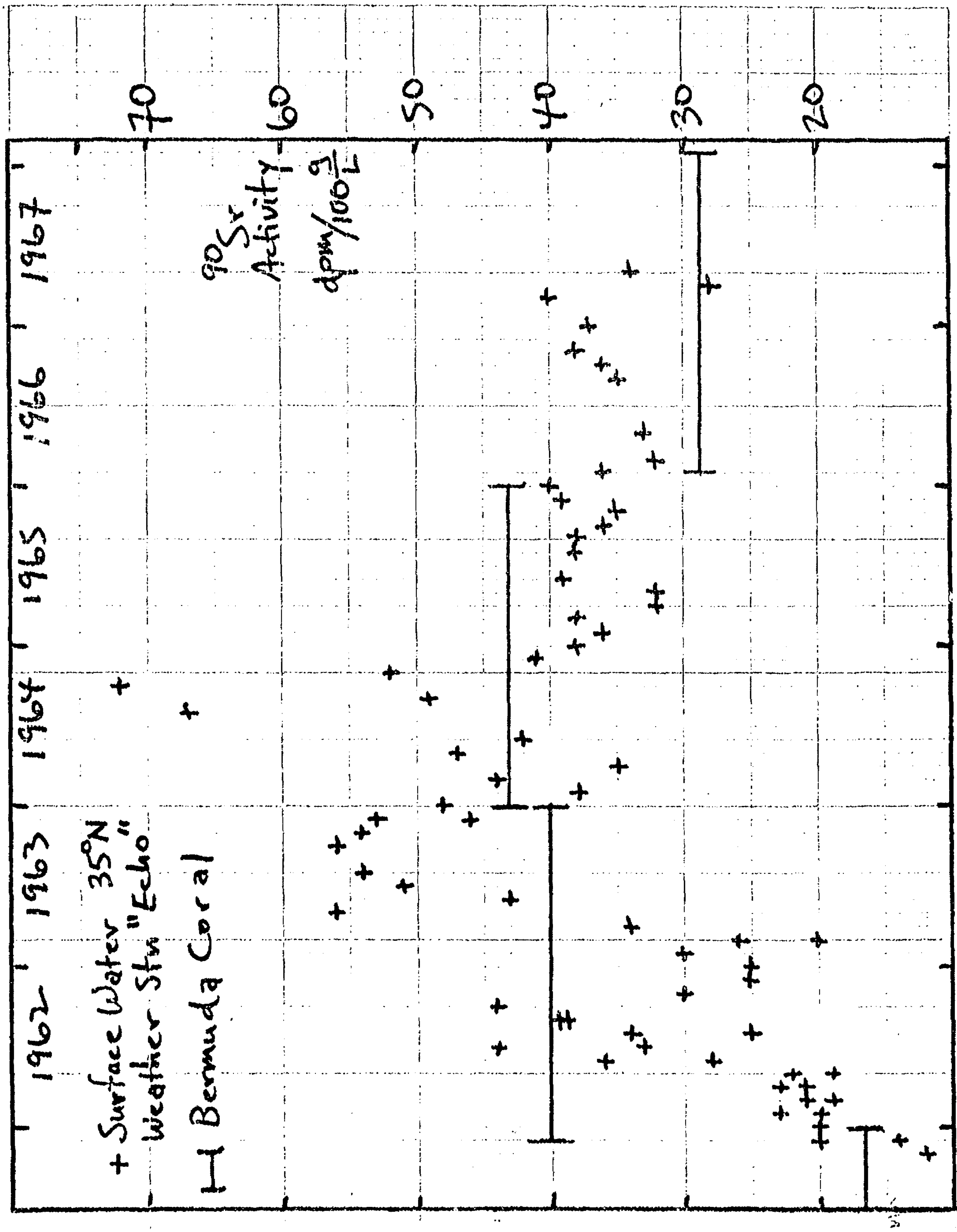

FIGURE 3. ^{90}Sr data from Bermuda (horizontal bars) compared to ^{90}Sr seawater data (dpm/100L) from Bowen *et al.*, 1968.

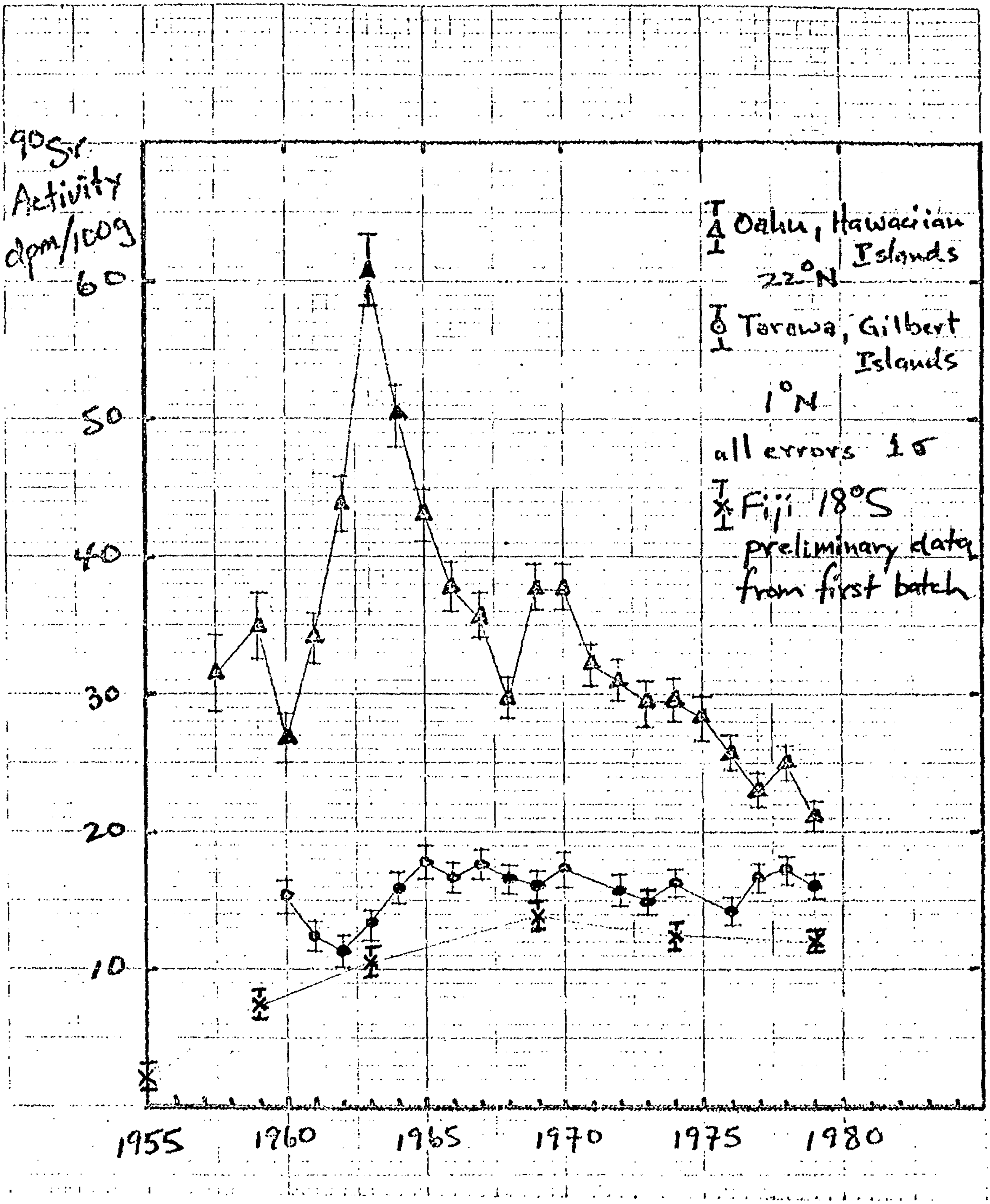

FIGURE 4. ^{90}Sr records from three Pacific sites. Counting data are decay corrected to year of growth. Units are equivalen to ^{90}Sr in seawater in units dpm/100L.

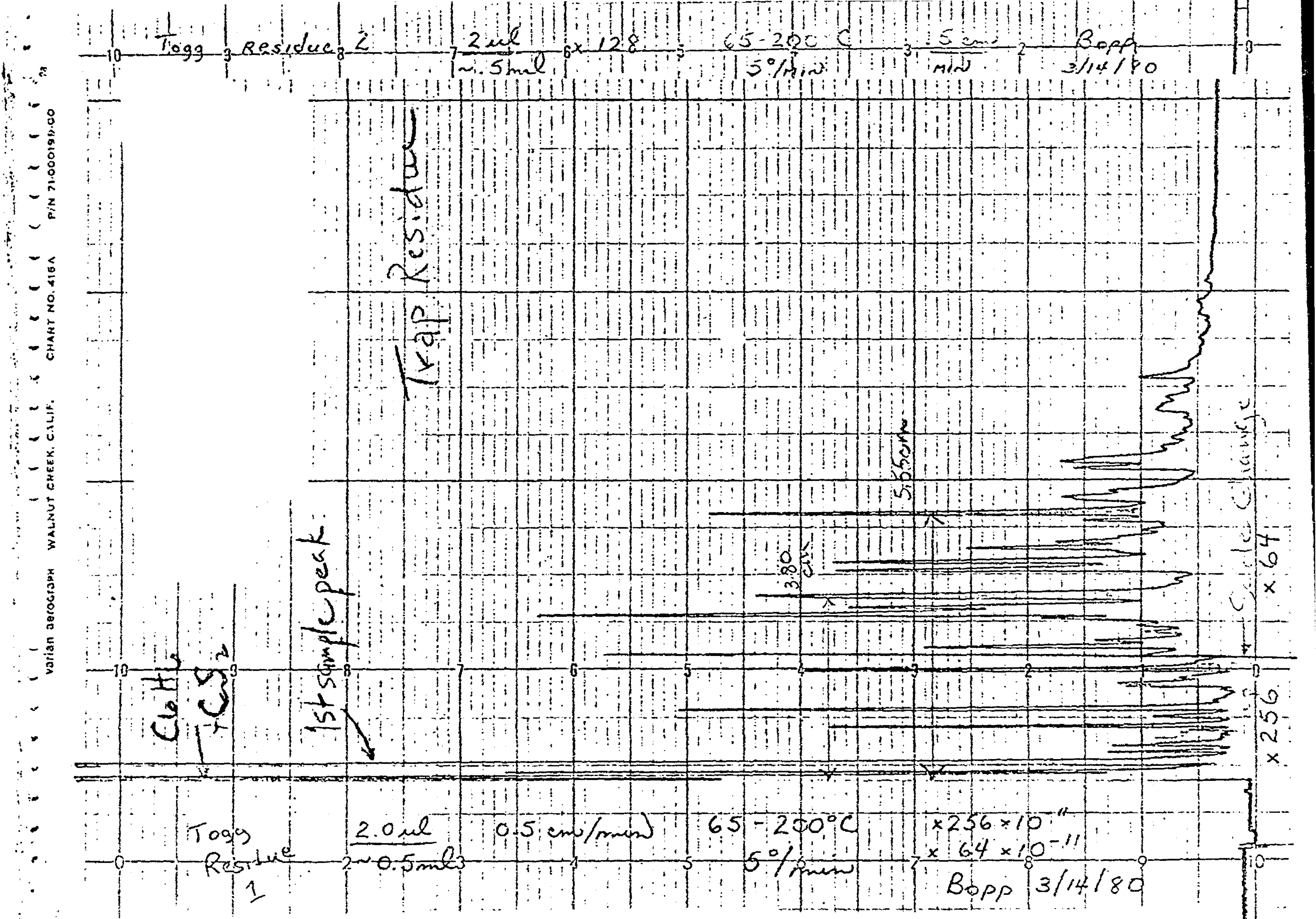

FIGURE 5. Gas chromatograph of non-benzene residue remaining after sample removed.

Table 1. Coral Collection Sites

Site	Latitude	# Samples LDGO Collection	Date of Collection
Atlantic			
Barbados	13°N	20	Nov.78 and Jan.79
Bermuda	32°N	3	1974 and July 1980
Haiti	18°N	6	April 1980
Pacific			
Fanning (Line Islands)	4°N	4	May 1979
Viti Levu (Fiji)	18°S	13	March 78 & April 79
Funafuti (Ellice Islands)	9°S	13	April 1979
Midway (Hawaiian Islands)	28°N	1	May 1979
Marjuro (Marshall Islands)	7°N	9	April 1979
Oahu (Hawaiian Islands)	21°N	4	May 1979
Palmyra (Line Islands)	6°N	5	May 1979
Tarawa (Gilbert Islands)	1°N	11	April 1979
Tongatapu (Tonga)	22°S	9	May 11979
Totuila (Samoa)	15°S	7	May 1979
Wake Island	19°N	2	May 1979
Indian			
Cocos Island	12°S	5	April 1978
Mauritius	20°S	8	June 1978
Sri Lanka	6°N	9	May 1978

References

Bowen, V.T., V.E. Noshkin, H.L. Volchok and T.T. Sugihara, 1968, Fallout ^{90}Sr in Atlantic Ocean Surface Water, HASL-197, U.S. Atomic Energy Comm. Health and Safety Laboratory Quarterly Report, NY, p. 2-65.

Broecker, W.S., T.-H. Peng and M. Stuiver, 1978, An estimate of the upwelling rate in the Equatorial Atlantic based on the distribution of bomb radiocarbon, JGR (83) p. 6179-6186.

Fine, R.A. and H.G. Ostlund, 1980, Exchange times in the Pacific equatorial current system, EPSL (49) p. 447-452.

Pearson, G.W., 1979, Precise ^{14}C measurement by liquid scintillation counting, Radiocarbon (21) p. 1-21.

Smith, S.V., R.W. Buddemeier, R.C. Redalie and J.E. Houck, 1979, Strontium-Calcium Thermometry in Coral Skeletons, Science (204) p. 404-407.

Toggweiler, J.R., 1980, Time history of Sr-90 in Pacific Ocean surface water as recorded by head-forming corals, (Abs.) EOS (61) p. 984.

APPENDIX

Geochemical Tracers and Thermocline Dynamics

Wallace S. Broecker

INTRODUCTION

The distributions of chemical and radiochemical species within the sea have much to tell us about large-scale oceanic mixing and transport processes. This potential remains largely untapped. The availability of the GEOSECS global data set provides the base upon which such studies can be built. In this paper I have drawn together the key tracer information for the main oceanic thermocline. Especially interesting in this regard are the distributions of the transient tracers bomb ^{14}C and ^{3}H. My approach is to compare the situation for the three oceans; the Indian Ocean being particularly interesting in this regard as it lacks the strong northern source for tritium found in the Atlantic and Pacific Oceans.

The approach will be as follows. The equatorial and temperate thermoclines are separated by strong fronts located about 15 degrees north and south of the equator. In the first section these boundaries are described. Next the distributions of ^{3}H and ^{14}C within each of the five temperate and three equatorial zones at the time of the GEOSECS surveys are described (The Indian Ocean lacks a true north temperate zone). The time histories of these inventories are examined. The evolution of these distributions in space and time has much to tell us about the ventilation of these zones. Finally a simplified model which accounts for much of what is seen is presented.

BOUNDARIES BETWEEN THE EQUATORIAL AND TEMPERATE ZONES

In a publication discussing the tritium results obtained during the GEOSECS Atlantic expedition (Broecker and Ostlund, 1979) the importance of the thermocline front at about 15°N was discussed. The contrast in potential temperature, oxygen, silica and tritium concentration across this front attests to the fact that the rate of horizontal mixing is far more rapid within the temperate zone north of the front and within the equatorial zone to the south of the front than across the frontal zone itself. The fact that the temperature contrast along any given isopycnal horizon between the north temperate and equatorial zone is much larger than that between the south temperate and equatorial zone requires either that the equatorial waters in the Atlantic come from the south or that they are generated by vertical mixing within the equatorial zone. In either case contribution of water from north of the front must be quite small (<20%).

The equatorial-temperate thermocline front which stands out so clearly in the North Atlantic is also found in the South Atlantic Ocean, in the South Indian Ocean, and on both sides of the equatorial zone in the Pacific Ocean. These fronts can be seen in the latitude trend of the depth of any given isopycnal horizon within the thermocline (figure 1), in the potential temperature along these same isopycnals (figure 2), in the distributions of dissolved oxygen along these isopycnals (figure 3), in the distribution of dissolved silica along these isopycnals (figure 4), and in the distribution of tritium along these isopycnals (figure 5). The front in the North Atlantic shows up for all five properties. In the South Atlantic the potential temperature, dissolved silica concentration and tritium concentration to the north and south of this front are almost identical and the front shows up only for depth and dissolved oxygen. The front in the South Indian Ocean stands out for all five properties. Only one station in the Indian Ocean north of 15°N was occupied during the GEOSECS expedition. Its properties do not give any indication of a 15°N front in this ocean. In the South Pacific the front shows up in depth, in dissolved oxygen concentration, and in dissolved silica concentration but not in temperature or tritium concentration. In the North Pacific the front shows up in depth, potential temperature, dissolved oxygen concentration and tritium concentration but not in dissolved silica concentration. For the Pacific significant gradients in these properties exist within the equatorial and temperate zones. Because of these gradients the fronts are not as pronounced as in the North Atlantic and South Indian Oceans.

Hints of the nature of the north-south transport can be seen from vertical profiles of salinity, tritium and radiocarbon for stations in the transition zone between the temperate and equatorial zones. In the Atlantic and Pacific Oceans vertical profiles of these properties in the latitude range 12° to 18°N all show evicence for northward penetration of equatorial surface water (see figure 6). In the Atlantic neither a salinity nor radiocarbon maximum is found between 100 and 150 meters depth at stations in the southern transition zone (see figure 7). Because of the absence of a significant tritium gradient between the equatorial and south temperate zones of the Atlantic and Pacific Oceans, a similar feature would not be expected in tritium profiles from 12° to 18°S. Both a salinity and radiocarbon maximum are present in the eastern South Pacific temperate-eqquatorial transition zone. In the western South Pacific a subsurface salinity maximum but no radiocarbon maximum is seen. Thus, in qualitative terms, more of the water upwelled in the equatorial zone appears to go to the north than to the south. In the Atlantic the situation is less clear for the Pacific Ocean. Conversely, it could be stated that these profiles indicate the penetration of temperate thermocline water into the equatorial zone.

DISTRIBUTION OF TRITIUM AT THE TIME OF THE GEOSECS SURVEYS

Surface water concentrations and water column inventories of tritium based on measurements made during the GEOSECS program are given in figure 8 and 9, respectively. As can be seen from these figures and the averages given in table 1, the tritium produced during bomb testing resides mainly north of the 14° fronts in the Atlantic and Pacific Oceans. This is because the bomb tests which produced the tritium occurred largely in the northern hemisphere. The tritium generated by these tests was largely injected into the stratosphere and subsequently returned to the troposphere through the gap in the tropopause located at about 45° N. Once in the troposphere the tritium was rapidly (in a few weeks) removed to the earth's surface by vapor exchange and by rainfall. As shown by Weiss et al. (1979) vapor exchange dominated this removal. Hence most of the tritium was deposited in the temperate and polar Atlantic and Pacific Oceans. A reconstruction of the global pattern and time history of tritium fallout is given by Weiss and Roether (1980). Because of its geography the Indian Ocean received far less tritium than the Atlantic and Pacific Oceans. Even north of 14°N the water column inventory of tritium in the Indian Ocean is no greater than that in the equatorial and south temperate zones. The decay-corrected water column inventory for tritium is larger in the south temperate Indian Ocean than in the south temperate zones of the Atlantic and Pacific Oceans (see table 1).

As shown in table 2, the mean penetration depth of tritium is largest in the north temperate oceans, intermediate in the south temperate oceans and smallest in the equatorial oceans.

Figure 10 shows the temporal record of tritium input to the north temperate zone. As can be seen the input is more or less symmetrically distributed about the peak in 1963. Most of the tritium now in the sea arrived prior to 1967. The concentrations in north temperate surface waters peaked in 1964 or 1965 and then over the next few years dropped rapidly to about one-half this maximum value (see Dreisigacker and Roether, 1978, for a summary of the Atlantic surface water record, and Bainbridge et al., 1967, for Pacific surface water record). This initial drop presumably represents vertical mixing through the upper several hundred meters of the temperate region. Once accomplished, the rate of change in surface water concentration (corrected for radioactive decay) became much smaller. In this paper I will disregard this early more complex history of the tritium and concentrate on the past 1968 record.

Information with regard to the post-1968 history of tritium at any given place in the ocean is rather sparse. A summary (up to 1973) of the data for North Atlantic surface waters has been published by Dreisigacker and Roether (1978). New data from region IV of these authors (North American continent to 35°W and 20° to 40°N) has been obtained by Jenkins et al. (1979). As shown in figure 11, after correction for the radioactive decay of tritium, the rate of decrease is quite small (~ 3%/yr) over the period 1966 to 1977. The decay corrected tritium inventory in this area appears to have remained nearly constant over this time interval (see table 3 and figure 12). There has been a small increase in the mean penetration depth (see table 3). As shown in figure 13, while the decay-corrected tritium content of the well mixed region above 350 meters has been decreasing with time, in the thermocline beneath 350 meters the tritium content has been increasing. In order to make sure that these increases reflect increases along given isopycnal horizons, the results for the thermocline region are replotted against potential temperature in figure 14. Again the increase with time at any given temperature horizon is evident. As shown in table 3, the decay-corrected water column inventory increased slightly over this time interval.

Information regarding the temporal evolution of tritium in the equatorial zone of the Atlantic is sparse. As shown in figure 15, the decay-corrected tritium concentration in surface waters of the Atlantic equatorial zone decreased by about a factor of two between 1967 and 1973. As shown in table 3, the decay-corrected water column inventory in equatorial Atlantic appears to have increased over this period (i.e., the decrease in surface water concentration was compensated by an increase in the mean penetration depth). Unfortunately the shape of this trend is not constrained by points between 1967 and 1972-3.

The situation for Pacific surface waters is summarized in table 4 and in figure 16. Over the period 1968 to 1974 the decay-corrected concentrations appear to have been decreasing in the temperate ocean and increasing in the equatorial Pacific. As seen from table 5 and figure 17 in the low salinity surface waters along the northern and eastern boundaries of the temperate North Pacific the decay corrected water column inventories for tritium decreased at the rate of about 8%/yr in the early 1970's. As for the Atlantic the decay corrected tritium inventory for the north temperate Pacific shows no change with time while that in the equatorial zone appears to be increasing.

No information regarding the temporal trends of tritium is available for the south Atlantic, South Pacific or Indian Ocean.

DISTRIBUTION OF RADIOCARBON

The distribution of $^{14}C/^{12}C$ ratios in surface ocean water at the time of the GEOSECS surveys is shown in figure 18. The distribution of bomb ^{14}C inventories as measured during the GEOSECS program is shown in figure 19. As pointed out by Stuiver (1980), the equatorial zone of the Atlantic Ocean shows both lower surface water $\Delta^{14}C$ value and lower water column inventories than do the adjacent temperate zones. The same situation is found in the Pcific and Indian Oceans (except that the one GEOSECS station in the north temperate Indian Ocean has a surface water $\Delta^{14}C$ and water column bomb ^{14}C inventory similar to those in the equatorial zone. Low values, surface water $\Delta^{14}C$ values and water column-bomb ^{14}C inventories are also found in upwelling areas along the eastern boundaries of the Atlantic and Pacific Oceans.

As pointed out by Stuiver (1980), both the water column inventories of bomb-produced radiocarbon and the surface water bomb $^{14}C/C$ excesses are lower in the equatorial zones of the Atlantic Ocean than in the adjacent temperate zones. This is also true for the Pacific and Indian Oceans (see figures 18 and 19 and also table 5). The inventory of bomb ^{14}C in the equatorial Pacific and Indian Oceans is similar to that found in the equatorial Atlantic.

Unfortunately we have only sparse information with regard to the time trend of bomb-produced radiocarbon in the ocean. Our main source of data concerns the time history of radiocarbon concentration in surface water. These data show considerable variability (see figures 20 to 22). This noise appears to have three modes of origin.

1) As much of the data was obtained through the use of ships of opportunity there is always the possibility of contamination during the collection and either storage or shipboard extraction of the dissolved inorganic carbon.

2) At many places in the sea there must be a seasonal cycle in the surface water $^{14}C/C$ ratio. Broecker (in press) has shown that this occurs in the temperate ocean due to the accumulation of ^{14}C in the thin summer mixed layer followed by dilution in the winter months when the thermocline undergoes considerable thickening. A similar process very likely occurs in the polar regions. The data of Nydal et al., 1980 show clear evidence for changes in $^{14}C/C$ ratios in areas of seasonal upwelling. The $\delta^{14}C$ values are lower during the upwelling episodes than during the periods between them. Although yet to be shown it is likely that seasonal shifts in surface current strength and direction could also bring about a seasonality in $^{14}C/C$ ratio.

3) In any given region of the ocean there are geographical gradients in the $^{14}C/C$ ratio. Since much of the data is from expeditions following different tracks the establishment of temporal trends involves the use of data from rather large geographical areas.

In figure 20 I show the surface water time trends for four of the five temperate ocean regions (~ 23°S to 36°N). The data used in these figures is listed in tables 6 to 8. The scatter is large. There is a lack of data for the period over which the increase place (1964-1968). It is hard to say whether there is any significant trend in the data from 1970 to 1978.

As shown in figure 21, the situation in the equatorial ocean is somewhat better. Little change occurred during the interval 1968 to 1978. The data plotted in this figure are summarized in tables 9 and 10.

As shown in figure 22 the temporal history of the $^{14}C/C$ ratio in the low salinity (i.e., < 34 $^{o}/oo$) surface water associated with the California current is not well constrained by the available data. The SE data are listed in table 11.

As shown so dramatically by Druffel and Linick (1978) and Druffel (1980) the answer to the surface water time history problem lies in measurements on ring dated corals. As can be seen from their results in figure 23, the problem of continuity of record and noise are conquered at least at sites where corals grow. Corals eliminate the problem of seasonality by integrating over the whole year. Of course it is possible that all corals will not produce as smooth a record as those from the Gulf of Honduras and the Florida Straits. One can think of a number of reasons why there could be noise in the year to year trend. Indeed the one record from Bermuda obtained by Nozaki et al. (1978) shows a reversal in the trend of increasing bomb ^{14}C. In any case this promising approach must be exploited. As the large coral heads needed for this research are rarely found poleward of about 22° the reconstruction will only be possible for the equatorial and southern temperate zones.

It should be mentioned at this point that while corals do not carry paleotritium records they do contain paleoradiostrontium (^{90}Sr) records (Toggweiler, 1980). As the fallout patterns of ^{90}Sr and ^{3}H are very similar, the measurements of Sr^{90} in ring dated corals will allow an improvement of our knowledge of the time histories of tritium in various regions of the surface ocean.

MAINTENANCE OF THE BOMB TRITIUM AND RADIOCARBON INVENTORIES.

The information regarding the inventories of bomb tritium in the three equatorial zones and five temperate zones is summarized in table 12. The important point to be made is that where information is available, the decay-corrected inventory of tritium has remained nearly constant since 1968. This could be taken as evidence that the exchange of water between the equatorial and north temperate zones is sufficiently slow so as not to have a measurable impact on the distribution of these isotopes on the time scale over which we have information.

As pointed out by Broecker et al.(1978) this explanation does not hold for bomb radiocarbon. The combination of low surface water $\Delta^{14}C$ values and low water column inventories for the equatorial zones is not to be explained unless a rapid flushing of water from the equatorial to adjacent temperate zones is involved. This transfer must be include the input of water low in bomb ^{14}C content (i.e., via upwelling of water from depths not yet contaminated with the products of bomb testing).

The crux of this argument concerns a major difference between the geochemistries of bomb tritium and bomb radiocarbon. The first difference is that the tritium produced during nuclear testing resided in the atmosphere only a few years. As of 1968 it had been transferred entirely to the land surface and sea. The small amount of tritium added to the sea after this time came from nuclear tests performed by France and China and from continental runoff and evaporation of continental waters. By contrast the ^{14}C produced during bomb tests has a much longer atmospheric residence time. As of 1980 roughly 25% of that produced still remained in the atmosphere. Thus during the period subsequent to 1968 relatively little bomb tritium has reached the surface of the equatorial ocean from the atmosphere, sizable amounts of bomb ^{14}C have been entering.

The second difference is that the flux of tritium produced by bomb testing to the planetary surface was concentrated in the region north of 15°N latitude. Hence the lower inventories in the equatorial zone relative to the north temperate zone can simply be explained by smaller deliveries from the atmosphere. By contrast bomb ^{14}C spread throughout the atmosphere far more rapidly than it was removed to the sea. Its delivery to the sea, therefore, should have been nearly uniform over the world ocean. That this is the case is seen in the similarity between the bomb ^{14}C inventories for the north and south temperate zones. As will be documented below, were there no significant transfer of water between the equatorial and temperate zones on a decade timescale, then the equatorial zones should have bomb ^{14}C inventories more similar to those seen in the temperate zones.

If the explanation for the low equatorial bomb ^{14}C inventory owe its explanation to the large scale mixing dynamics of the sea, one obvious possibility can be immediately eliminated. Horizontal mixing and/or mixing along isopycnal surfaces between the temperate zones would lead to an increase in the equatorial bomb ^{14}C inventory. This is because along all horizontal surfaces (including the sea surface) and isopycnal surfaces the bomb ^{14}C content of equatorial waters is lower than that of the adjacent temperate waters. Were the low equatorial bomb ^{14}C inventories to have their origin in lateral mixing, then at some level or on some isopycnal the equatorial waters would have to have excess ^{14}C. As such an excess is not observed, lateral mixing aggrevates rather than alleviates the problem! It is for this reason that the influx of upwelled water must be called upon.

The diagrams in figure 24 is designed to demonstrate why this is the case. In the first of these diagrams the time history of the $\Delta^{14}C$ in the atmospheric CO_2 over the north temperate ocean and the time history of ΔC^{14} in surface ocean carbon from the north temperate zone are shown. The second gives the same information for the equatorial atmosphere and ocean. If little transfer of water has occurred between the equatorial and temperate zones, and if the CO_2 invasion rate (averaged over a year) has remained nearly constant from year to year, then the information given in these diagrams defines the shapes of both the time history of water column inventory and the time history of mean penetration depth of bomb C^{14} (see dashed lines in the figure). These curves can be made absolute by assigning a CO_2 invasion rate to each zone. The important point is as follows: if the mean annual CO_2 invasion rate is similar in the temperate and the equatorial zones, in the absence of water transport between the zones, the water column inventories and mean penetration depths at any given time would have to be very nearly the same in the two zones. As shown in table 1 the north temperate zones of the Pacific and Atlantic had at the times of the GEOSECS surveys respectively, 3.3 and 4.0 times higher water column inventories of bomb ^{14}C than the corresponding equatorial zones. (The penetration depth for H^3 is 5.0 times higher in the north temperate than equatorial Atlantic and 3.5 times higher in the north temperate than equatorial Pacific). Hence either the mean annual CO_2 invasion rate must be about 4 times lower for the equatorial ocean than for the temperate ocean <u>or</u> much of the ^{14}C which has entered the equatorial ocean by invasion has been pushed aside into the adjacent temperate zones by waters upwelling into the equatorial zone.

Before proceeding, it must be made clear that the bomb ^{14}C in the equatorial zone has been sufficiently homogenized to obscure the path of entry of this upwelled water. It need not be entirely along the equator;

a substantial contribution may well come from the coastal upwelling zones which, through transport along the surface, feed the equatorial zone. Such upwelling zones are located along the eaten boundaries of the Atlantic and Pacific Oceans and along the western boundary of the Indian Ocean.

Broecker et al. (1978) opted for the upwelling explanation. The arguments against such a large CO_2 invasion rate difference between temperate and equatorial waters are as follows:

1) the radon evasion rates as measured during the GEOSECS program were on the average only 15% lower in equatorial zones than the temperate zones of the Atlantic and Pacific Oceans (Peng et al., 1979). Based on 40 radon profiles in the 15° to 40° latitude zone an average piston velocity of 2.9 m/day was obtained. Based on 24 radon profiles at latitudes less than 15° a average piston velocity of 2.5 m/day was obtained.
2) The mean wind velocity in the equatorial zones is 7.5m/sec and in the temperate zone 8.0m/sec. Using either the gas exchange versus wind velocity curve found in the wind tunnel H.C. Broecker et al., 1978 or the relationship between wind velocity and gas exchange rate observed in the ocean (see figure 25) a difference of only about 15% would be predicted for the gas exchange rates in the equatorial and temperate zones.

Thus while the CO_2 invasion rate averages perhaps 10 to 20% lower in the equatorial ocean than in the temperate ocean this difference is far too small to explain the fourfold difference in the bomb C^{14} inventories for these zones.

It might be argued that since the GEOSECS radon measurements in temperate regions mainly were made during the summer months, the influence of winter storms was missed. It also might be argued that the comparison of average scalar wind speeds could be misleading. Since wind tunnel measurements show gas exchange rates to vary roughtly as the ratio of the square of the wind speed, the mean gas exchange rate in the temperate region when the range of wind speeds is greater than that in the equatorial zone were the range is much smaller could be even larger than the simple means given above.

Several arguments can be given which suggest that while perhaps qualitatively correct, these arguments cannot lead to a fourfold difference in CO_2 invasion rate between the temperate and equatorial zones.

1) The CO_2 invasion rate calculated from the equatorial zone radon results would lead to the invasion of an amount of bomb radiocarbon about three times the observed inventory.

2) Radon measurements made to date at sea fail to confirm a strong wind speed dependence on gas exxhange rate. Specifically, the large radon efficiences expected after major wind events have not been observed. The suggestion is that because of large waves at sea, the wind velocity dependences observed in the wind tunnel may not be applicable. If the non-linear dependence of gas exchange on wind velocity were to be the explanation for the low equatorial bomb ^{14}C budgets, then an even greater than square power dependence would be needed.

If these arguments about the gas exchange rate are accepted then one is driven to accept the conclusion that significant transfers the bomb produced tracers C^{14} and H^3 have occurred between the equatorial and temperate zones. As pointed out by Broecker et al., 1978 this presents a problem in conjunction with the tritium inventories of the equatorial zones. The rates of upwelling necessary to push at the proper amount of bomb ^{14}C from the equatorial zone to the adjacent temperate zones would in a decade remove a major fraction of the tritium which entered this zone through rainfall and vapor exchange prior to 1967. Instead of a dramatic decrease, there has been, as shown above, a slight increase.

UPWELLING MODEL CONSISTENT WITH BOTH THE TEMPORAL HISTORIES OF BOMB C^{14} AND H^{3}

In order to find whether a self-consistent explanation for both the inventories of ^{14}C and ^{3}H in the equatorial zone can be achieved, I have constructed a model of equatorial zone flushing which involves inputs from the adjacent temperate thermoclines as well as from below. In order to keep the number of unknowns sufficiently small so as to be uniquely determined by the data, I have made one major simplifying assumption. It is that waters in the temperate thermoclines are linear mixtures of surface water and of sub-thermocline water free of bomb-produced ^{3}H and ^{14}C (i.e., the bomb tritium to bomb radiocarbon ratio throughout the thermocline is the same as that measured in temperate surface water at the surface of the temperate ocean). This assumption reduces the end member water types to three (north temperate surface water, south temperate surface water, and equatorial zone upwelling water). The extent to which this assumption holds is best seen in a plot of $\Delta^{14}C$ versus tritium for waters in the north temperate and equatorial zone. Such plots are given for the Atlantic and Pacific in figure 26. In both oceans surface water samples fall along a different trend than upper thermocline waters. The upper thermocline waters give the appearance of mixtures of suface water from the northeastern part of the ocean with subthermocline equatorial waters (free of tritium). By contrast the surface waters follow a bowed trend such that for any given ^{3}H content the sample has a higher bomb ^{14}C content. These systematics are consistent with the model adopted here.

The ^{14}C content of this upwelling equatorial zone water is defined by the potential temperature at which the equatorial zone θ-^{3}H trend reaches zero (see figures 27A and 27B). As summarized in table 13, this procedure gives -80°/oo, -95°/oo, and -90°/00, respectively, for the Atlantic, Indian and Pacific Ocean equatorial zones. As shown in table 13 the actual $^{14}C/C$ ratios for tritium free water at the base of the temperate thermoclines are reasonably similar to the equatorial zone value except for the North Pacific, where a much lower value is obtained.

The tritium inventory in the equatorial zone is assumed to have been nearly constant at the time of the GEOSECS survey (an assumption sufficiently consistent with observation to justify its use in the rough calculations done here). As the upwelling water is assumed to carry no tritium and as delivery of new tritium from the atmosphere can be taken as negligible at the time of the GEOSECS surveys, the tritium balance is given by

$$n\ FC_N + s\ FC_S = FC_E$$

where F is the total flushing rate of the equatorial zone, n is the fraction of this water originating at the surface of the north temperate zone, s is the fraction of this water originating at the surface of the south temperate zone, and C_N, C_S, and C_E are, respectively, the concentrations of tritium in north temperate surface water, south temperate surface water, and equatorial zone surface water. This equation defines the relationship between the inputs of northern surface waters and southern surface waters to the equatorial zone. It can be rewritten as follows:

$$n = \frac{C_E - sC_S}{C_N}$$

As for tritium, the rate of change of the radiocarbon inventory at the time of the GEOSECS survey is taken to be small, i.e., steady state is assumed. The radiocarbon mass balance for the equatorial zone must take into account the input of ^{14}C from the atmosphere as well as from the temperate waters. The equation governing this balance is as follows:

$$\begin{aligned} & n\ F\ [\Sigma CO_2]_N\ {}^{14}C/C)_N + s\ F\ [\Sigma CO_2]_S\ {}^{14}C/C)_S \\ & + (1-n-s)\ F\ [\Sigma CO_2]_D\ {}^{14}C/C)_D + I\ {}^{14}C/C)_A = (n\ F\ [\Sigma CO_2]_N \\ & + s\ F\ [\Sigma CO_2]_S + (1-n-s)\ [\Sigma CO_2]_D + I)\ {}^{14}C/C)_E \end{aligned}$$

where F, n, and s are as defined above, $[\Sigma CO_2]_N$, $[\Sigma CO_2]_S$ and $[\Sigma CO_2]_D$ are the total dissolved inorganic carbon contents of the three input waters, I is the invasion rate of atmospheric CO_2, and

$^{14}C/C)_A$, $^{14}C/C)_N$, $^{14}C/C)_S$, $^{14}C/C)_E$ and $^{14}C/C)_D$

are respectively the radiocarbon to carbon ratios in atmospheric CO_2, north temperate surface water carbon, south temperate surface water carbon, equatorial surface water carbon and carbon in the upwelling deep water. This equation can be greatly simplified if the ΣCO_2 concentrations for the three water types are the same. While this is not the case (the upwelling deep water has from 5% to 10% more dissolved carbon than does temperate surface water), the error introduced by this assumption is small compared to the other uncertainties inherent in this simplified approach. Thus the assumption is made that all the waters have ΣCO_2 contents of 2 moles/m^3. A further simplification is achieved if the $^{14}C/C$ ratios are all expressed in the following form:

$$R_N = \frac{{}^{14}C/C)_N}{{}^{14}C/C)_A^*}$$

where ${}^{14}C/C)_A{}^*$ is the ${}^{14}C/C$ ratio for atmospheric carbon in the absence of bomb ${}^{14}C$ (i.e., .95 the ${}^{14}C/C$ ratio in the NBS oxalic acid standard). The simplified form of the ${}^{14}C$ balance equation is thus

$$n\ R_N\ F + s\ R_S\ F + (1-n-s)\ R_D\ F + R_A\ I/2 = (F + I/2)\ C_A$$

Eliminating n by simultaneous solution of the tritium balance and radiocarbon balance equations, the following relationship for s is obtained:

$$s = \frac{F\ [(R_E-R_D) - C_E/C_N(R_N-R_D)] - I/2(R_A-R_E)}{F\ [(R_S-R_D) - C_S/C_N(R_N-R_D)]}$$

The input data for the model are summarized in table 14. The reasoning behind the choice of $\Delta^{14}C$ values for upwelling equatorial waters is given above. The ambient $\Delta^{14}C$ and ${}^3H$ values observed during the GEOSECS program are used for the temperate surface water values. The extent to which the choices for the northern temperate zone approximate the waters in these regions is shown in figure 24.

The fractional contributions of the three source waters as a function of the total flushing rate calculated from these equations are shown for the Atlantic and Pacific Oceans in table 15. If the flux from the south temperate to equatorial zone is required to be positive, the F or the Pacific F must be greater than 50 m/yr. For the Atlantic the lower limit on F is 45 m/yr. No upper limits can be given.

Because the Indian Ocean has no equivalent of the north temperate zone in the Atlantic or Pacific Ocean, I have taken n to be zero for this ocean. The tritium budget then fixes the ratio of the deep water to south temperate surface water flux at 1 to 4. The $\Delta^{14}C$ value for this mixture (i.e., $80^{o}/oo$) is very close to the mean $\Delta^{14}C$ value for equatorial surface water (i.e., $\sim 90^{o}/oo$). This does not leave much room for the contribution of bomb ^{14}C invading from the atmosphere (i.e., U >> I/2 or U >> 8 m/yr). Unless F is greater than 150 m/yr, the model calculated $\Delta^{14}C$ value for equatorial surface water will be significantly greater than the observed value.

Thus, if the model outlined here has any validity, the mean upwelling rate of water in all three oceans must exceed 45 m/yr. This limit is greater than the upwelling estimate of 27 m/yr obtained by Broecker *et al.* (1978). As these previous calculations disregarded the contribution of temperate surface water, a lower upwelling rate was obtained. As temperate surface waters carry a higher $^{14}C/C$ ratio than do equatorial surface waters, their inclusion in the model *raises* the deep water flux necessary to balance the radiocarbon budget. Not only must the upwelling deep waters flush out the bomb ^{14}C entering from the atmosphere, they must also dilute the excess bomb ^{14}C in the temperate surface water reaching the equatorial zone.

This conclusion finds support in the CO_2 budget for the equatorial Pacific which requires an upwelling rate of deep water of about 65 m/yr (Broecker *et al.*, in press).

TEMPERATE ZONE TRITIUM INVENTORY

In order to assess the influence of the fluxes required to maintain the equatorial zone tritium inventory on the temperate zone inventory of this isotope, it is necessary to know the fate of the water which flushes the equatorial zone. While it is generally accepted that this water is carried away from the zone along the surface. it is not clear what fraction of this flow goes to the north temperate and what fraction to the south temperate zone. In the Atlantic and Pacific Oceans vertical profiles of salinity, of tritium and of radiocarbon in the latitude range 12° to 18°N all show evidence for northward penetration of equatorial surface water (see figure 6). Because of the absence of a significant tritium gradient between the equatorial and south temperate zones of the Atlantic and Pacific Oceans, a similar feature would not be expected in tritium profiles from 12° to 18°S. In the Atlantic neither a salinity nor radiocarbon maximum is found between 100 and 150 meters depth in stations from the southern transition zone (see figure 7). Both a salinity and radiocarbon maximum are present in the eastern South Pacific temperate-equatorial transition zone. In the western South Pacific a subsurface salinity maximum but no radiocarbon maximum is seen. Thus, in qualitative terms, more of the water upwelled in the equatorial zone appears to go to the north than to the south in both the Atlantic and in the Pacific Ocean.

As an extreme case the effect on the temperate bomb isotopes inventories in the Atlantic can be calculated assuming that all the upwelling water flows northward. (This is extremely unlikely, for the net northward flux of water would then exceed the flux of water to the south beneath the thermocline). In this case any tritium added to the equatorial zone from the north temperate zone would be returned from whence it came. That entering the equatorial zone from the south temperate zone would be transferred to the north temperate zone. If an upwelling flux of 150 m/yr is adopted (i.e., a total flux of 3×10^{15} m^3/yr or about 100 Sverdrups for the Atlantic equatorial zone), then the flux of water from the south temperate zone to the north temperate zone would be 1×10^{15} m^3/yr. Taking the average tritium content of this water to be 2 T.U. (i.e., 1.3×10^{11} atoms/m^3), the amount of tritium transferred between 1967 and 1973 would be about 8×10^{26} atoms. As summarized in table 16, this would cause the decay-corrected tritium inventory of the south temperate zone to drop by almost a factor of two but would increase the north temperate zone tritium inventory by only 8%. The latter is consistent with observation. Unfortunately the time history of the tritium inventory in the south temperate Atlantic is not known.

Table 1. Inventories of bomb-produced radiocarbon and tritium in the central portion of the equatorial and temperate zones of the three oceans

OCEAN	N. TEMP. 35°N to 25°N	EQUAT. 10°N to 10°S	S. TEMP. 25°S to 35°S
	BOMB RADIOCARBON WATER COLUMN INVENTORY 10^9 ATOMS/CM^2		
ATLANTIC (1973)	15.9	4.0	11.2
INDIAN (1978)	-	4.2	16
PACIFIC (1974)	17.2	5.2	10.5
	BOMB TRITIUM WATER COLUMN INVENTORY 10^9 ATOMS/CM^2 (Decay cor. to 1/73)		
ATLANTIC (1973)	33	3	5
INDIAN (1978)	-	4	10
PACIFIC (1974)	30	5	5

Table 2. Mean penetration depth of tritium as observed during the GEOSECS surveys*

OCEAN (YEAR)	N. TEMP. 35°N to 25°N	EQUAT. 10°N to 10°S	S. TEMP. 25°S to 35°S
	BOMB TRITIUM MEAN PENETRATION DEPTH METERS		
ATLANTIC (1973)	680 (5)	135 (8)	345 (3)
INDIAN (1978)	--	180 (12)	390 (4)
PACIFIC (1974)	565 (11)	195 (18)	330 (7)

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* The mean penetration depth is obtained by dividing the water column inventory by the surface concentration. The numbers in parentheses are the number of stations included to obtain the average. The tritium results are given by Ostlund _et al._ (1976), Ostlund _et al._ (1979), and Ostlund (1980).

Table 3A. Time trends in the water column tritium inventories* and mean penetration depths for various places in the Atlantic Ocean

STN	COL. DATE	LAT.	LONG.	$\bar{h}$ METER	WCI* 10^9 atoms/cm^2	REF**
			SARGASSO SEA			
P6808-2	Sept 1968	31.0	64.9	550	28	1)
BRMD-72	May 1972	32.3	65.5	600	28	1)
GEOSECS 30	Sept 1972	31.8	50.8	750	33	2)
S74546	Nov 1974	30.5	67.5	750	34	3)
S75625	Mar 1975	30.5	58.5	700	34	3)
PAN001	Mar 1977	30.2	64.5	740	34	3)
PAN002	May 1977	"	"	770	33	3)
PAN003	June 1977	"	"	770	32	3)
			EQUATORIAL ZONE			
P6706- 48	Sept 1967	0.0°	4.0°W	45	1.1	1)
P6707B-12	Nov 1967	0.0°	18.2°W	60	1.3	1)
NAGS -8	Sept 1973	5.0°S	11.1°W	105	1.3	4)
NAGS -3B	Sept 1973	0.2°S	10.0°W	120	1.7	4)

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* Water column inventories decay corrected to Jan. 1, 1973.

**1) Ostlund Miami Tritium Laboratory Data Reports
2) Ostlund *et al.* (1976)
3) Jenkins *et al.* (1979)
4) Ostlund *et al.* (1977)

Table 3B. Change in the decay corrected mean tritium content of the 300-meter thick winter mixed layer near Bermuda.

STATION	LAT. °N	LONG. °W	COLL. DATE	H^3* T.V.	REF.
P6808-2	31.0	64.9	9/68	7.34 (12)	Ostlund
BRMD-72	32.3	65.5	5/72	6.90 (8)	Ostlund
GEOSECS 30	31.8	50.8	9/72	6.66 (4)	Jenkins 1979
S74546	30.5	67.5	11/74	6.96 (11)	Jenkins 1979
S75625	30.5	58.5	3/75	7.29 (11)	Jenkins 1979
PAN 001	30.2	64.5	3/77	6.56 (9)	Jenkins 1979
PAN 002	30.2	64.5	5/77	6.32 (10)	Jenkins 1979
PAN 003	30.2	64.5	6/77	6.04 (8)	Jenkins 1979

* mean 0-300 meters decay corrected to 1/1/1973. The number in parentheses is the number of measurements averaged to obtain the mean.

Table 4. Trends in the Tritium Content of Surface Water in the Pacific Ocean

EXPEDITION	STN NO.	LAT.	LONG.	DATE	H3 T.U.	H3* T.U.	SLOPE %/yr
SEVEN-TOW	5	51°N	172°W	7/70	17.7	15.4	-10
GEOSECS	218	50°N	177°W	10/73	10.5	11.0	
SEVEN-TOW	4	45°N	167°W	7/70	15.9	13.9	-11
GEOSECS	217	45°N	177°W	10/73	9.3	9.7	
SEVEN-TOW	3	40°N	165°W	7/70	11.5	10.0	
SEVEN-TOW	S.W.	41°N	166°W	7/70	13.3	11.6	-11
GEOSECS	216	41°N	177°W	9/73	7.3	7.6	
SEVEN-TOW	S.W.	36°N	161°W	7/70	11.3	9/9	
SEVEN-TOW	S.W.	38°N	163°W	7/70	11.7	10.2	-11
GEOSECS	215	37°N	177°W	9/73	6.8	7.1	
SEVEN-TOW	1	28°N	156°W	3/70	11.5	9.8	
SEVEN-TOW	2	30°N	156°W	7/70	11.3	9.9	
SEVEN-TOW	S.W.	32°N	158°W	7/70	10.5	9.2	-6
GEOSECS	204	31°N	150°W	9/73	7.9	8.2	
GEOSECS	212	30°N	160°W	9/73	7.3	7.6	
GEOSECS	I	28°N	122°W	9/69	24.3	20.2	
GOGO	I	28°N	122°W	10/71	16.8	15.7	-8
GEOSECS	347	28°N	122°W	6/74	12.5	13.6	
SEVEN-TOW	11	23°N	157°W	7/70	8/6	7.5	-3
GEOSECS	206	22°N	154°W	9/73	6/5	6.8	
SEVEN-TOW	10	18°N	169°W	6/70	7.3	6.3	
GEOSECS	228	19°N	169°E	11/73	4.7	4.9	-5
GEOSECS	235	17°N	161°W	12/73	5.2	5.5	
SCAN	4	15°N	170°W	8/69	7.4	6.2	
SEVEN-TOW	12	14°N	167°W	3/70	7.4	6.3	-5
GEOSECS	231	14°N	179°W	11/73	4.7	5.0	
GEOSECS	237	13°N	165°W	11/73	4.9	5.2	
STYX	4	12°N	161°W	8/68	6.0	4.7*	
SEVEN-TOW	9	13°N	166°W	6/70	6.9	6.0	-4
GEOSECS	237	13°N	165°W	11/73	4.9	5.2	
SOUTH-TOW	1	10°N	123°W	1/72	4.9	4.6	
GEOSECS	340	10°N	124°W	6/74	3.3	3.6	-10
STYX	3	7°N	163°W	8/68	3.7	2.9	
GEOSECS	238	8°N	167°W	11/73	3.4	3.6	+4

Table 4 (Continued)

EXPEDITION	STN NO.	LAT.	LONG.	DATE	H3 T.U.	H3* T.U.	SLOPE %/yr
SOUTH-TOW	2	5°N	124°W	1/72	3.7	3.5	
GEOSECS	337	5°N	124°W	5/74	3.0	3.2	-4
SEVEN-TOW	7	3°N	165°W	6/70	3.7	3.2	
GEOSECS	244	1°N	179°E	11/73	3.2	3.4	+2
GEOSECS	241	5°N	179°E	11/73	3.2	3.4	
STYX	2	0°	166°W	8/68	3.0	2.4	
GEOSECS	246	0°	179°E	11/73	3.0	3.2	+5
SOUTH-TOW	3	0°	126°W	1/72	3.6	3.4	
GEOSECS	334	0°	125°W	6/74	3.1	3.4	0
STYX	1	5°S	167°W	8/68	2.8	2.2	
GEOSECS	251	5°S	179°E	11/73	2.4	2.5	+2
SOUTH-TOW	4	5°S	126°W	1/72	2.8	2.6	
GEOSECS	331	5°S	125°W	5/74	2.1	2.3	-5
SOUTH-TOW	6	9°S	169°W	2/72	2.9	2.8	
GEOSECS	257	10°S	170°W	1/74	2.2	2.3	-10
SOUTH-TOW	5	10°S	127°W	1/72	2.3	2.2	
GEOSECS	238	9°S	126°W	5/74	1.5	1.6	-13
SOUTH-TOW	10	13°S	126°W	9/72	2.1	2.0	
GEOSECS	327	12°S	126°W	5/74	1.8	1.9	-8
GEOSECS	326	14°S	126°W	5/74	1.6	1.7	
SOUTH-TOW	6	30°S	145°W	2/72	2.4	2.3	
GEOSECS	319	29°S	128°W	4/74	1.9	2.0	-5
GEOSECS	320	33°S	128°W	4/74	2.0	2.1	
SOUTH-TOW	7	40°S	138°W	2/72	1.9	1.8	
GEOSECS	321	39°S	129°W	4/74	1.6	1.7	-3
ARIES	2	60°S	166°E	1/71	1.4	1.2	
GEOSECS	285	61°S	170°E	2/74	0.8	0.9	-9
GEOSECS	282	58°S	170°E	2/74	0.9	1.0	
GEOSECS	290	58°S	174°E	2/74	0.8	0.9	
ARIES	1	63°S	151°E	1/71	1.2	1.1	
GEOSECS	285	61°S	170°E	2/74	0.8	0.9	-8
GEOSECS	286	66°S	174°E	2/74	0.7	0.8	

*Decay corrected to 1/1/1973

Table 5. Time trends in water column tritium inventories and mean penetration depths for various places in the Pacific Ocean

Expedition	Stn.	Col. Date	Lat.	Long.	$\bar{\pi}$ m	WCI* $\frac{10^9 \text{ atoms}}{\text{cm}^2}$	REF**
NORTHERN PACIFIC							
SEVEN-TOW	5	July 1970	50.9°N	161.1°W	190	19	5)
GEOSECS	218	Oct 1973	50.4°N	176.6°W	280	19	6)
NORTHERN PACIFIC							
SEVEN-TOW	4	July 1970	45.0°N	167.1°W	320	30	5)
GEOSECS	217	Oct 1973	44.7°N	177.0°W	380	24	6)
GEOSECS	221	Oct 1973	45.1°N	169.4°E	320	22	6)
TEMP. NO. PACIFIC							
NOVEMBER	STN	SEPT 1971	30.0°N	140.0°W	370	30	5)
"		Feb 1972	"	"	380	34	5)
"		Mar 1972	"	"	390	35	5)
"		June 1972	"	"	420	31	5)
"		Sept 1972	"	"	400	32	5)
"		May 1972	"	"	380	36	5)
:		Nov 1973			380	32	5)
EASTERN NO. PACIFIC							
GEOSECS	I	Sept 1969	28.5°N	121.5°W	210	29	7)
GOGO	I	Nov 1971	"	"	210	24	8)
GEOSECS	347	June 1974	"	"	210	19	6)
TEMP. NO. PACIFIC							
SCAN	4	July 1969	15.4°N	169.5°W	+	16	5)
GEOSECS	235	Dec 1973	16.7°N	161.4°W	+	16	6)

Table 5. (Cont.)

Expedition	Stn.	Col. Date	Lat.	Long.	h m	WCI* $\frac{10^9 \text{ atom}}{\text{cm}^2}$	REF**
			EQUATORIAL PACIFIC				
STYX	3	Aug 1968	7.0°N	163.0°W	+	6.3	5)
GEOSECS	239	Dec 1973	5.9°N	172.0°W	+	6.8	6)
			EQUATORIAL PACIFIC				
STYX	2	Aug 1968	0.0°	165.7°W	200	3.1	5)
GEOSECS	246	Dec 1973	0.0°	179.0°W	200	4.0	6)
			EQUATORIAL PACIFIC				
STYX	1	Aug 1968	5.0°S	167.1°W	160	2.4	5)
GEOSECS	251	Dec 1973	4.6°S	179.0°W	210	4.0	6)

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* Water column inventories decay corrected to Jan. 1, 1973.

**5) Michel and Suess (1975)
6) Ostlund *et al.* (1977)
7) Roether *et al.* (1970)
8) Roether (1974)

\+ Profile has subsurface maximum.

Table 6. Radiocarbon measurements on surface waters from the north temperate Pacific (excluding those from the California Current)

COLLECTION DATE	LAT.	LONG.	T °C	S °/oo	ΔC^{14} °/oo
SWAN SONG EXPEDITION (Linick, 1978)					
Aug.20, 1961	27.5°N	150.6°W	25.0	35.3	- 4±30
LUSIAD EXPEDITION (Linick, 1978)					
May 20, 1962	35.0°N	140.1°W	16.5	34.3	+40±8
" 24 "	35.0°N	160.0°W	18.1	34.5	+52±9
" 26 "	35.8°N	170.2°W	17.5	34.69	+37±15
" 28 "	35.1°N	180.0°	17.8	34.80	+42±15
" 31 "	35.0°N	170.0°W	-	-	+37±16
June 2 "	34.8°N	160.3°E	20.4	34.78	+ 7±15
" 4 "	30.3°N	147.8°E	-	-	+40±15
" 6 "	27.2°N	140.0°E	25.0	35.00	+45±15
URSA MAJOR EXPEDITION (Linick, 1978)					
Aug.11, 1964	35.0°N	155.0°W	24.3	34.72	+148±16
Sept.10 "	31.5°N	155.0°W	-	-	+137±12
" 12 "	27.4°N	155.0°W	-	-	+137±12
USS RADFORD CRUISE (Linick, 1978)					
Sept.14,1968	32.1°N	157.8°W	25.9	35.29	+120±34
" 14 "	30.0°N	157.8°W	26.9	35.19	+165±18
" 14 "	28.2°N	157.8°W	26.5	35.23	+152±20
" 15 "	26.2°N	157.8°W	26.5	34.88	+131±24
" 15 "	24.0°N	157.8°W	27.3	34.71	+137±18
SCAN EXPEDITION (Linick, 1978)					
Apr.14, 1969	28.3°N	139.9°W	19.5	35.21	+169±11
" 16 "	23.8°N	139.8°W	21.5	34.71	+158±12
DRAGON EXPEDITION (Linick, 1978)					
June 11,1969	23.0°N	118.0°W	20.5	34.27	+188±20
" 12 "	23.2°N	118.3°W	19.0	33.98	+193±9
CLIMAX II EXPEDITION (Linick, 1978)					
Sept.7, 1969	28.4°N	155.3°W	24.3	35.15	+169±20
" 10 "	26.5°N	155.7°W	25.3	35.11	+221±15
" 10 "	24.5°N	155.4°W	-	35.04	+141±14

(Cont.)

Table 6. (Cont.)

COLLECTION DATE	LAT.	LONG.	T °C	S °/oo	ΔC^{14} °/oo
HUDSON TO EXPEDITION (LINICK, 1978)					
May 28, 1970	25.0°N	150.0°W	23.3	35.19	+194±8
" 29 "	28.8°N	150.0°W	22.8	35.52	+190±7
" 31 "	35.9°N	150.0°W	18.2	34.22	+144±6
USCGC ACUSHNET (Linick, 1978)					
June 29,1970	30.0°N	165.0°W	25.5	34.99	+169±8
" 30 "	31.0°N	164.5°W	23.7	34.72	+111±11
July 1 "	34.0°N	162.8°W	23.0	34.50	+145±29
SEVEN-TOW EXPEDITION (Linick, 1978)					
July 4,1970	23.9°N	156.8°W	25.0	34.98	+150±18
" 5 "	26.5°N	155.8°W	24.8	35.28	+192±11
" 5 "	28.0°N	155.2°W	24.6	35.30	+188±9
" 7 "	30.1°N	156.2°W	23.6	35.07	+157±9
" 12 "	34.0°N	155.2°W	23.5	35.02	+158±12
" 13 "	35.9°N	161.1°W	23.0	34.38	+114±8
GEOSECS PACIFIC (Ostlund and Stuiver 1980)					
Aug. 30,1973	33.1°N	139.6°W	21.6	34.65	+205±4
Sept. 5 "	31.4°N	150.0°W	23.5	34.88	+178±4
" 22 "	31.0°N	168.5°W	23.2	-	+187±4
" 25 "	32.0°N	177.0°W	25.8	-	+145±4
Oct. 20 "	35.0°N	151.8°E	22.6	-	+163±4
" 24 "	34.3°N	142.0°E	23.8	-	+132±4
Nov. 6 "	32.6°N	161.9°E	22.1	-	+150±4
" 9 "	30.6°N	170.6°E	24.7	-	+160±4
" 12 "	25.0°N	170.1°E	27.0	-	+185±4

Table 7. Radiocarbon measurements on surface ocean water from the south temperate Indian Ocean

COLLECTION DATE	LAT.	LONG.	T °C	S $^0/oo$	ΔC^{14}
MONSOON EXPEDITION (Linick, 1978)					
Dec.13, 1960	23.0°S	64.1°E	-	-	-25±13
" 15 "	23.9°S	73.9°E	23.9	35.5	-16±8
" 18 "	33.3°S	72.7°E	18.3	35.5	-51±14
" 29 "	36.3°S	98.7°E	15.4	35.2	-26±14
Jan. 1 1961	33.2°S	108.7°E	18.3	35.5	- 5±9
LUSIAD EXPEDITION (Linick, 1978)					
Nov. 2, 1962	26.0°S	58.2°E	21.8	35.6	+ 3±12
" 4 "	30.5°S	61.9°E	18.7	35.6	- 5±11
" 22 "	33.8°S	96.0°E	14.9	35.4	-32±15
" 25 "	34.1°S	105.8°E	16.6	35.7	+ 5±16
NORWEGIAN STATION TO 3 (Nydal *et al*., 1980)					
Nov.25, 1976	30.0°S	107.3°E	-	35.4	+158±12
" 25 "	30.0°S	107.3°E	-	35.4	+138±12
Apr. 3 1977	30.0°S	107.3°E	-	35.8	+149±9
Aug.26 "	30.0°S	108.7°E	-	35.7	+137±7
Nov.30 "	30.0°S	108.5°E	-	35.8	+88±4
Jan.23 1978	30.0°S	108.3°E	-	35.9	+143±5
Mar.18 "	30.0°S	106.3°E	-	36.0	+159±20
Nov.13 "	30.3°S	110.2°E	-	35.1	+144±20
Feb.15 1979	30.0°S	112.5°E	-	35.7	+108±6
NORWEGIAN STATION TR 8 (Nydal *et al*., 1980)					
Mar. 3, 1977	31.7°S	65.5°E	-	35.8	+129±8
Apr.11 "	31.6°S	60.6°E	-	35.5	+141±9
July 9 "	32.0°S	65.5°E	-	35.4	+146±9
Nov.13 "	30.0°S	66.2°E	-	35.7	+128±5
Jan.19 1978	31.5°S	65.0°E	-	35.7	+123±5
Apr.24 "	32.0°S	65.0°E	-	35.7	+136±5
Aug. 4 "	30.1°S	65.0°E	-	35.6	+156±5
NORWEGIAN STATION TR 7					
June 15,1978	34.3°S	65.0°E	-	35.5	+131±4
GEOSECS INDIAN (Ostlund, 1980)					
Jan.30, 1978	27.1°S	57.0°E	-	-	+130±4

Table 8. Radiocarbon measurements on surface water samples from the south temperate Pacific

COLLECTION DATE	LAT.	LONG.	T °C	S °/oo	ΔC^{14} °/oo
DOWNWIND EXPEDITION (Linick, 1978)					
Nov.28, 1957	34.8°S	135.9°E	17.7	35.1	+ 6±10
MONSOON EXPEDITION (Linick, 1978)					
Mar. 7, 1961	34.1°S	161.9°W	21.4	35.1	-26±16
" 9 "	30.4°S	160.5°W	-	34.8	- 3±7
" 11 "	26.5°S	160.5°W	27.2	35.6	-37±7
" 12 "	24.7°S	155.3°W	-	34.9	-22±6
PIQUERO EXPEDITION (Linick, 1978)					
Dec.25, 1968	25.1°S	91.0°W	-	35.3	+143±7
Mar. 3 1969	30.0°S	81.0°W	-	34.8	+158±7
CLIMAX II EXPEDITION (Linick, 1978)					
Oct. 3, 1969	24.1°S	155.0°W	-	-	+133±10
HUDSON 70 EXPEDITION (Linick, 1978)					
May 5, 1970	35.0°S	150.0°W	18.2	35.4	+132±11
" 6 "	30.0°S	150.0°W	21.6	35.5	+137±6
" 8 "	25.0°S	150.0°W	24.2	35.7	+143±9
ARIES EXPEDITION (Linick, 1978)					
Mar. 4, 1971	34.8°S	169.4°W	19.6	35.3	+131±10
" 6 "	30.9°S	160.9°W	23.6	35.7	+129±8
" 7 "	28.8°S	156.7°W	25.0	35.5	+146±7
" 13 "	25.8°S	254.3°W	25.4	35.6	+131±12
SOUTH-TOW EXPEDITION (Linick, 1978)					
Jan.30, 1972	24.2°S	129.5°W	26.8	35.8	+176±9
Feb.17 "	25.3°S	148.4°W	27.3	35.5	+169±10

(Cont.)

Table 8. (Cont.)

COLLECTION DATE	LAT.	LONG.	T °C	S °/oo	ΔC¹⁴ °/oo
		GEOSECS PACIFIC (Ostlund and Stuiver 1980)			
Jan.14, 1974	24.0°S	174.4°W	27.3	-	+124±4
Mar.27 "	32.8°S	163.6°W	22.0	-	+139±4
Apr. 3 "	27.0°S	157.1°W	23.8	-	+159±4
" 20 "	23.6°S	127.2°W	24.3	-	+141±4
" 25 "	33.3°S	128.6°W	24.6	-	+171±4
May 7 "	23.0°S	146.1°W	23.6	-	+155±4
		NORWEGIAN GLOBAL SURVEY (Nydal *et al.*, 1980)			
Sept. 1974	30°S	150°W	19.5	-	+160±10
July 1975	30°S	150°W	20.5	-	+135±10
Dec. 1976	30°S	150°W	22.5	-	150±10

Table 9. Summary of radiocarbon results on surface water from the equatorial Indian Ocean

EXPEDITION	COLLECTION DATE	LAT.	LONG.	ΔC^{14} °/oo
MONSOON*	Oct. 1960	10°S	106°E	-38±13
LUSIAD*	Oct. 1962	8°S	71°E	- 9±23
"	" "	5°S	75°E	-31±23
"	" "	6°S	64°E	-35±36
"	" "	10°S	56°E	0±16
DODO*	Aug. 1964	1°S	42°E	- 7±20
"	" "	2°S	49°E	+15±21
"	" "	2°N	46°E	-27±20
"	" "	5°N	51°E	-11±20
"	" "	10°N	53°E	+22±21
"	" "	2°N	55°E	+31±10
"	Sept. 1964	6°S	55°E	+29±11
GEOSECS**	Jan. 1978	6°N	64°E	+75±4
"	" "	4°N	57°E	+95±4
"	" "	0°	51°E	+93±4
"	" "	6°S	51°E	+95±4
NORWAY***	Mar. 1977	7°S	77°E	+126±6
"	Aug. "	7°S	77°E	+100±4
"	Jan. "	7°S	77°E	+118±9
"	Mar. "	7°S	69°E	101±7
"	Nov. "	7°S	77°E	96±15
"	Mar. 1979	7°S	78°E	100±7

* Linick (1978)
** Ostlund and Stuiver (1980)
*** Nydal *et al.* (1980)

Table 10. Summary of radiocarbon results on surface water samples from the equatorial Pacific Ocean*

EXPEDITION	COLLECTION DATE	LAT.	LONG.	ΔC^{14} $^{o}/oo$
DORADO	July 1959	6°N	-	-75±8
TETHYS	July 1960	7°N	159°W	-45±13
"	" "	8°N	157°W	-26±13
AMPHITRITE	Feb. 1964	10°N	134°W	+25±8
"	" "	5°N	134°W	+17±10
"	" "	0°	139°W	+ 7±8
STYX	Aug. 1968	0°	166°W	+54±16
"	" "	2°S	166°W	+43±15
"	" "	4°S	168°W	+67±19
"	" "	8°S	167°W	+68±22
"	" "	10°S	168°W	+76±13
PIQUERO	Dec. 1968	8°N	113°W	+95±17
"	" "	4°N	112°W	+86±8
"	" "	0°	111°W	+43±13
"	" "	4°S	110°W	+21±7
"	" "	8°S	108°W	+26±15
SCAN	Apr. 1969	10°N	140°W	+83±6
"	" "	8°N	140°W	+100±9
"	" "	5°N	140°W	+62±7
CLIMAX II	Sept. 1969	8°N	155°W	+49±20
"	" "	6°N	155°W	+54±16
"	" "	2°N	155°W	+57±9
"	" "	1°S	155°W	+47±8
"	" "	3°S	155°W	+45±10
"	" "	6°S	155°W	+48±8
"	" "	7°S	155°W	+48±8
"	" "	9°S	155°W	+54±8
HUDSON 70	May 1970	10°N	150°W	+90±6
"	" "	5°N	150°W	+65±6
"	" "	3°N	150°W	+71±10
"	" "	2°N	150°W	+65±8
"	" "	0°	150°W	+43±16
"	" "	2°S	150°W	+62±10
"	" "	3°S	150°W	+51±9
"	" "	5°S	150°W	+58±6
"	" "	20°S	150°W	+90±8

(Cont.)

Table 10. (Cont.)

EXPEDITION	COLLECTION DATE		LAT.	LONG.	ΔC^{14} $^{0}/oo$
SEVEN-TOW	Apr.	1970	10°N	171°W	+128 ±8
"	"	"	8°N	174°W	+113 ±8
"	"	"	6°N	175°W	+85 ±8
"	"	"	2°N	175°W	+56 ±7
"	"	"	0°N	174°W	+42 ±11
"	"	"	2°S	170°W	+57 ±7
"	"	"	4°S	170°W	+60 ±7
"	"	"	6°S	171°W	+94 ±19
"	"	"	8°S	171°W	+87 ±10
"	June	1970	8°S	169°W	+94 ±8
"	"	"	6°S	168°W	+82 ±10
"	"	"	4°S	167°W	+54 ±9
"	"	"	2°S	167°W	+66 ±9
"	"	"	0°	166°W	+81 ±14
"	"	"	2°N	165°W	+45 ±16
"	"	"	4°N	164°W	+75 ±9
"	"	"	6°N	161°W	+68 ±9
"	"	"	8°N	159°W	+24 ±12
"	"	"	10°N	155°W	+86 ±7
ARIES	Apr.	1971	2°N	152°W	+33 ±11
"	"	"	5°S	156°W	+50 ±14
"	"	"	9°S	154°W	+85 ±8
SOUTH TOW	Jan.	1972	8°N	124°W	+79 ±8
"	"	"	0°	126°W	+39 ±6
"	"	"	2°S	126°W	+28 ±10
"	"	"	6°S	127°W	+25 ±6
"	"	"	8°S	127°W	+25 ±6
"	"	"	10°S	127°W	+31 ±8
GEOSECS	Dec.	1973	6°N	172°W	+84 ±4
"	"	"	4.5°N	179°E	+87 ±4
"	"	"	0°	179°E	+72 ±4
"	"	"	4.5°S	170°E	+86 ±4
"	Jan.	1974	10°S	170°W	+102 ±4
"	May	1974	5°N	124°W	+61 ±4
"	"	"	0°	125°W	+73 ±4
"	"	"	5°S	125°W	+41 ±4

(Cont.)

Table 10. (Cont.)

EXPEDITION	COLLECTION DATE		LAT.	LONG.	ΔC^{14} ‰
FGCE	Apr.	1979	10°N	158°W	+115 ±4
"	"	"	8°N	158°W	+115 ±4
"	"	"	8°N	158°W	+110 ±4
"	"	"	4°N	150°W	+95 ±4
"	"	"	2°N	150°W	+95 ±4
"	"	"	1°N	150°W	+100 ±4
"	"	"	0°	150°W	+100 ±4
"	"	"	1°S	150°W	+90 ±4
"	"	"	2°S	150°W	+85 ±4
"	"	"	5°S	150°W	+95 ±4
"	"	"	9°S	150°W	+90 ±4

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* Except for the GEOSECS and FGGE data, these results are all from Linick (1975 and 1978). The GEOSECS results were obtained in part by Stuiver of the University of Washington and in part by Ostlund of the University of Miami, Ostlund and Stuiver (1980). The FGGE results were obtained by Stuiver and Quay of the University of Washington.

Table 11. Radiocarbon measurements on samples from the California Current (i.e., salinity < 34.0°/oo)

COLLECTION DATE	LAT.	LONG.	T °C	S °/o	ΔC^{14} °/oo
HORIZON CRUISE 5910H (Linick, 1968)					
Oct. 14, 1959	30.5°N	117.8°W	19.3	33.5	-9±5
AMPHITRITE EXPEDITION (Linick, 1968)					
Feb. 27, 1964	25.0°N	123.0°W	-	-	+87±11
LA PARED EXPEDITION (Linick 1968)					
Apr. 29, 1965	27.7°N	118.2°W	-	-	+100±8
DRAGON EXPEDITION (Linick, 1978)					
June 12, 1969	23.2°N	118.3°W	19.0	34.0	+193±9
GEOSECS I TEST CRUISE (Ostlund and Niskin, 1970)					
Sept.25, 1969	28.5°N	121.5°W	19.5	33.7	+246±5
GOGO TEST CRUISE (Roether, 1974)					
Nov. 18, 1971	28.5°N	121.7°W	17.4	33.4	+212±5
SOUTH-TOW EXPEDITION (Linick, 1978)					
Jan. 8, 1972	23.8°N	119.8°W	17.0	33.6	+202±6
GEOSECS PACIFIC EXPEDITION (Ostlund and Stuiver 1980)					
Aug. 25, 1973	34.2°N	127.9°W	17.6	33.1	+189±4
June 8, 1974	28.5°N	121.5°W	17.1	33.6	+195±4

Table 12. Summary of information regarding the time trends of tritium and radiocarbon distributions at various places in the ocean after 1967.

	TRITIUM (Decay corrected to 1/1/73)			RADIOCARBON		
	Conc Surf Ocean	Mean Pen Depth	Water Col Inven	Conc Surf Ocean	Mean Pen Depth	Water Col Inven
NORTH TEMPERATE ZONE						
ATL.	-3%	+4%/yr	~Const	~Const	-	-
IND.	-	-	-	-	-	-
PAC.	-7%/yr	-	~Const	~Const	-	-
EQUATORIAL ZONE						
ATL.	-8%/yr	Inc	Inc	~Const	-	-
IND.	-	-	-	-	-	-
W. PAC.	+3%/yr	Inc	Inc	~Const	-	-
SOUTH TEMPERATE ZONE						
ATL.	-	-	-	-	-	-
IND.	-	-	-	-	-	-
PAC.	-7%/yr	-	-	-	-	-
BOUNDARY CURRENTS						
CALIF.	-8%	~Const	-9%/yr	~Const	-	-
ALEUT.	-11%/yr	Inc	-7%/yr	~Const(?)	-	-

Table 13. Properties of water at the base of the tritium-contaminated zone

		ATL.	IND.	PAC.
NORTH TEMPERATE	$\Delta^{14}C$ °/oo	-70	-	-190
	θ °C	9.3	-	3.7
	σ_θ °/oo	27.3	-	27.3
EQUATORIAL	$\Delta^{14}C$ °/oo	-80	-95	-90
	θ °C	8.0	9.6	10.0
	σ_θ °/oo	27.1	27.2	26.8
SOUTH TEMPERATE	$\Delta^{14}C$ °/oo	-80	-60	-70
	θ °C	6.0	7.4	8.0
	σ_θ °/oo	27.1	27.1	26.9

Table 14. Model input data

	ATL. 1972	IND. 1978	PAC. 1973
$\Delta^{14}C_A$ °/oo	500	400	480
$\Delta^{14}C_N$ °/oo	150	-	150
$\Delta^{14}C_S$ °/oo	150	125	150
$\Delta^{14}C_E$ °/oo	75	90	75
$\Delta^{14}C_D$ °/oo	-80	-95	-90
C_N (T.U.)	6.6	-	6.6
C_S (T.U.)	2.2	3.0	1.9
C_E (T.U.)	2.3	2.4	2.8
C_U (T.U.)	0.0	0.0	0.0

Table 15. Model results

	ATLANTIC				
F(m/yr)*	45	70	100	150	200
FxA (SVERDRUPS)**					
n	.35	.29	.22	.24	.22
s	.00	.18	.27	.34	.38
(1-n-s)	.65	.53	.51	.42	.40
	PACIFIC				
F(m/Yr)*	51	70	100	150	200
FxA(SVERDRUPS)**					
n	.42	.39	.37	.35	.34
s	.00	.10	.18	.24	.27
(1-n-s)	.58	.51	.45	.41	.39

*averaged over the entire equatorial zone

** the area of the equatorial zone is taken as that between 10°N and 10°S

Table 16. Effect of equatorial flushing on the ^{3}H inventory of the Atlantic temperate zones

	TRITIUM INVENTORY (10^{26} Atoms)+	
	1967	1973
NO. TEMPERATE ($3 \times 10^{13} m^2$)	91***	99*
EQUATORIAL ($2 \times 10^{13} m^2$)	6**	6*
SO. TEMPERATE ($2 \times 10^{13} m^2$)	18***	10*
TOTAL	115 ++	115*

\+ Decay corrected to Jan. 1, 1973.
* Measured.
** Observed to remain nearly constant with time.
*** Computed using F=150 m/yr and C_S=2 T.U. (all upwelled water flows north).
++ Conservation of ^{3}H atoms.

Figure Captions

Figure 1. Depth of the 26.5^{o}/oo isopycnal horizon as a function of latitude along the GEOSECS tracks in the western Atlantic, western Indian and western Pacific.

Figure 2. Potential temperature as a function of latitude along the 26.5^{o}/oo isopycnal horizon on the GEOSECS tracks in the western Atlantic, in the eastern and central Indian and in the western Pacific Oceans.

Figure 3. Dissolved oxygen concentration as a function of latitude along the 26.5^{o}/oo isopycnal horizon on the GEOSECS tracks in the Atlantic, Indian and Pacific.

Figure 4. Dissolved silica concentration as a function of latitude along the 26.5^{o}/oo isopycnal horizon on the GEOSECS tracks in the Atlantic, eastern and central Indian and western Pacific.

Figure 5. Tritium concentration as a function of latitude along the 26.5^{o}/oo isopycnal horizon on the GEOSECS tracks in the Atlantic, Indian and Pacific (data from Ostlund *et al.*, 1976; Ostlund *et al.*, 1979; and Ostlund, 1980a).

Figure 6. Salinity, tritium and radiocarbon as a function of depth at GEOSECS stations in the transition zone between equatorial and north temperate zone in the western Atlantic and western Pacific Oceans (for station 34 in the Atlantic no ^{14}C samples

Figure 6. (Cont.) were taken). (The tritium measurements were made by Ostlund of the University of Miami. The radiocarbon measurements were made by Ostlund of the University of Miami and Stuiver of the University of Washington.)

Figure 7. Salinity and radiocarbon as a function of depth for GEOSECS stations in the transition zone between the south temperate and equatorial zones of the Atlantic and Pacific Oceans. (The tritium measurements were made by Ostlund of the University of Miami. The radiocarbon measurements were made by Ostlund of the University of Miami and Stuiver of the University of Washington.)

Figure 8. Tritium concentration in surface water along the GEOSECS tracks Atlantic, Indian and Pacific Oceans (data from Ostlund et al., 1976; Ostlund et al., 1979; and Ostlund, 1980a). Included in the Atlantic are the results from several NAGS expedition stations (data from Ostlund et al., 1977).

Figure 9. Water column inventories of tritium along the GEOSECS tracks in the Atlantic (1972-1973), Indian (1977-1978) and Pacific (1973-1974) (*not* decay-corrected) (data from Ostlund *et al.*, 1976; Ostlund *et al.*, 1979; and Ostlund, 1980a). Included in the Atlantic are the results of some of the NAGS expedition stations (data from Ostlund *et al.*, 1977).

Figure 10. Tritium input to the ocean as a function of time as reconstructed by Dreisigacker and Roether (1978).

Figure 11. Decay-corrected tritium content of surface water for the Sargasso Sea. The open circles are averages given by Dreisigacker and Roether (1978). The solid circles are the the results of Jenkins *et al.*, from the Bermuda area.

Figure 12. Decay-corrected (to Jan. 1973) water column inventories for tritium in the Sargasso Sea. The solid circles are the results of Ostlund *et al.* (19). The open circles are based on lbs results of Jenkins *et al.*, (1979).

Figure 13. Plots of decay-corrected tritium concentration versus water depth in the Bermuda area over the period 1968 to 1977. The 1968 to 1972 points were measured by Ostlund *et al.*, (19) and the 1977 points by Jenkins *et al.*, (1979).

Figure 14. Plot of decay-corrected tritium concentration as a function of potential temperature for water below about 300 meters in the Sargasso Sea near Bermuda. The 1968-1972 data are from Ostlund et al and the 1977 data is from Jenkins *et al.*, (1979).

Figure 15. Decay-corrected tritium concentration in surface water along the equator in the Atlantic Ocean. The data are from Ostlund *et al.*, ( ).

Figure 16. Rates of change (%/yr) of decay-corrected tritium concentration in surface waters in the Pacific Ocean for the period 1968 to 1973 based on the data in table . Temperate waters show decreases varying from 3 to 11%/yr. Western equatorial waters (10°N to 10°S) show increases from 2 to 5%. Eastern equatorial water show a decrease.

Figure 17. Tritium inventory (decay-corrected to Jan. 1, 1973) as a function of time for the California Current (open circles) and for the Aluetian Current (closed circles). Table 5 gives the data sources.

Figure 18. Water column inventories of bomb radiocarbon along the GEOSECS tracks in the Atlantic (1972-1973), Indian (1977-1978) and Pacific (1973-1974) Oceans (data from Ostlund et al., 1976; Ostlund *et al.*, 1979; and Ostlund, 1980).

Figure 19. ^{14}C for surface waters along the GEOSECS tracks in the Atlantic (1972-1973), Indian (1977-1978) and Pacific (1973-1974) Oceans. The Atlantic and Pacific results were obtained in part by Ostlund's University of Miami ^{14}C lab and in part by Stuiver's University of Washington lab.

Fig. 20. Time trends in the ^{14}C/C ratio in surface ocean water carbon in the temperate zones of the world ocean based on the analyses of water samples. The GEOSECS results are from Stuiver and Ostlund (1980). The La Jolla results are from Linick 1978 and the Norwegian results are from Nydal et al. (1979 and 1980).

Fig. 21. Time trends in the ^{14}C/C ratio in surface ocean water carbon from the equatorial zones of the ocean. The data sources are the same as those in figure 18.

Fig. 22 Time trends in the ^{14}C/C ratio in surface ocean water in the Aleutian Current and California Current. The data sources are the same as those in figure 18 except for the Seattle points which were obtained by Stuiver and Quay as part of the FGGE program.

Fig. 23 Radiocarbon measurements on growth ring dated corals from the Florida Straits (DFruffel and Linick 1978) and from Glover Reef Belize (Druffel 1980).

Fig. 24 Temporal record of the Δ^{14}C for atmospheric CO_2 and for the Δ^{14}C for surface ocean water in the north temperate (upper panel) and equatorial ocean (lower panel). Assuming that the CO_2 invasion rate in each zone remained nearly constant over the time interval shown and that no transfer of water occurred between the equatorial and temperate zones the temporal evolution of both the water column inventory of bomb ^{14}C and the mean penetration depth of bomb ^{14}C can be calculated (see dashes). These are given in arbitrary units in order to avoid assigning absolute CO_2 invasion rates to each zone. The arbitrary units are the same for both panels. Thus if the CO_2

Figure 24. (Cont.) invasion rate were the same in both zones the water column inventories would be nearly the same (2.6 for the equatorial zone and 2.7 for the north temperate zone at the time of the Atlantic GEOSECS survey). The mean penetration depths would also be about the same (3.1 for the equatorial zone and 3.0 for the north temperate zone).

Figure 25. Plots of apparent stagnant film thickness (inversely proportional to flux) against wind velocity for wind tunnel experiements (by the Hamburg group Broecker et al., 1978) and for the ocean. The circles are estimates based on radon data for discreet areas of the ocean and for the whole ocean, the sequence is based on the distribution of natural radiocarbon between the ocean and atmosphere and the triangle on the uptake of bomb radiocarbon by the Atlantic Ocean (see Peng et al., 1978 for a summary of these results). The wind velocity scale for the tunnel experiments has been adjected to a height of 10 meters to make it comparable with ocean wind data.

Figure 26. Plots of $\Delta^{14}C$ versus ^{3}H for samples from the north temperate and equatorial zones in the Atlantic (upper panel) and Pacific (lower panel) Oceans. The large squares represent the values chosen for the model calculations. The surface water tritium values are high in the northeastern part of each ocean and decrease as the equatorial zone is approached. All the results are from the GEOSECS program. (The ^{14}C data are published by Ostlund and Stuiver (1980) and Stuiver and Ostlund (1980); the tritium results are from reports published by the Miami Laboratory of Ostlund.)

Figure 27. Tritium and radiocarbon results from the GEOSECS program versus potential temperature for the equatorial zones of the western Atlantic, the western Indian, and the eastern and western Pacific. The $\Delta^{14}C$ for water with the potential temperature of the zero tritium intercept is taken to be that of upwelling deep water. (The tritium measurements were made by Ostlund of the University of Miami. The radiocarbon measurements were made by Ostlund of the University of Miami and Stuiver of the University of Washington.)

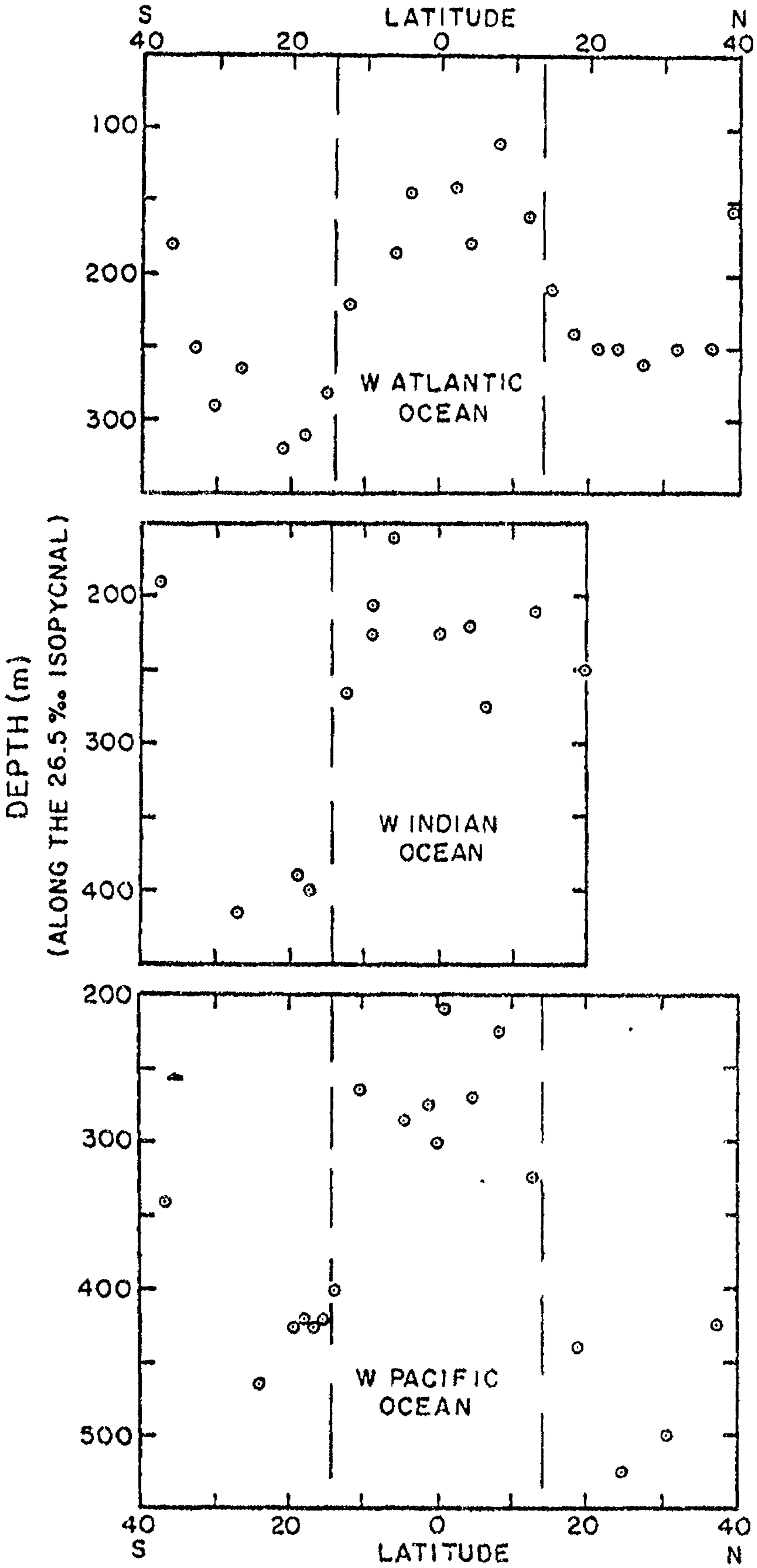
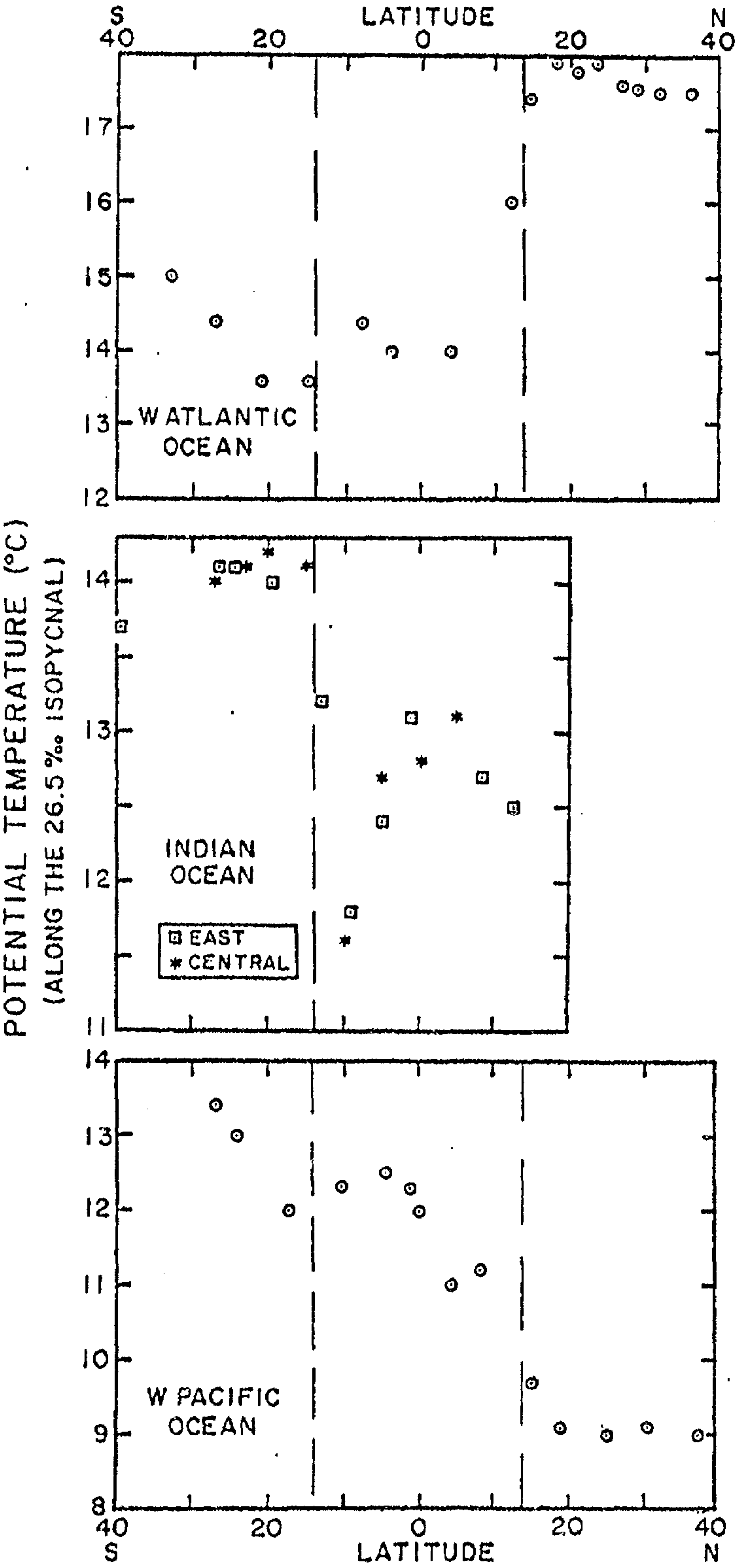

S
LATITUDE
N
40
20
0
20
40
100
200
300
W ATLANTIC
OCEAN
DEPTH (m)
(ALONG THE 26.5 ‰ ISOPYCNAL)
200
300
400
W INDIAN
OCEAN
200
300
400
500
W PACIFIC
OCEAN
40
20
0
20
40
S
LATITUDE
N

Fig. 1



S
N
LATITUDE
40
20
0
20
40
POTENTIAL TEMPERATURE (°C)
(ALONG THE 26.5 ‰ ISOPYCNAL)
17
16
15
14
13
12
W ATLANTIC
OCEAN
14
13
12
11
INDIAN
OCEAN
⊡ EAST
✱ CENTRAL
14
13
12
11
10
9
8
W PACIFIC
OCEAN
40
S
20
0
20
40
N
LATITUDE

Fig. 2

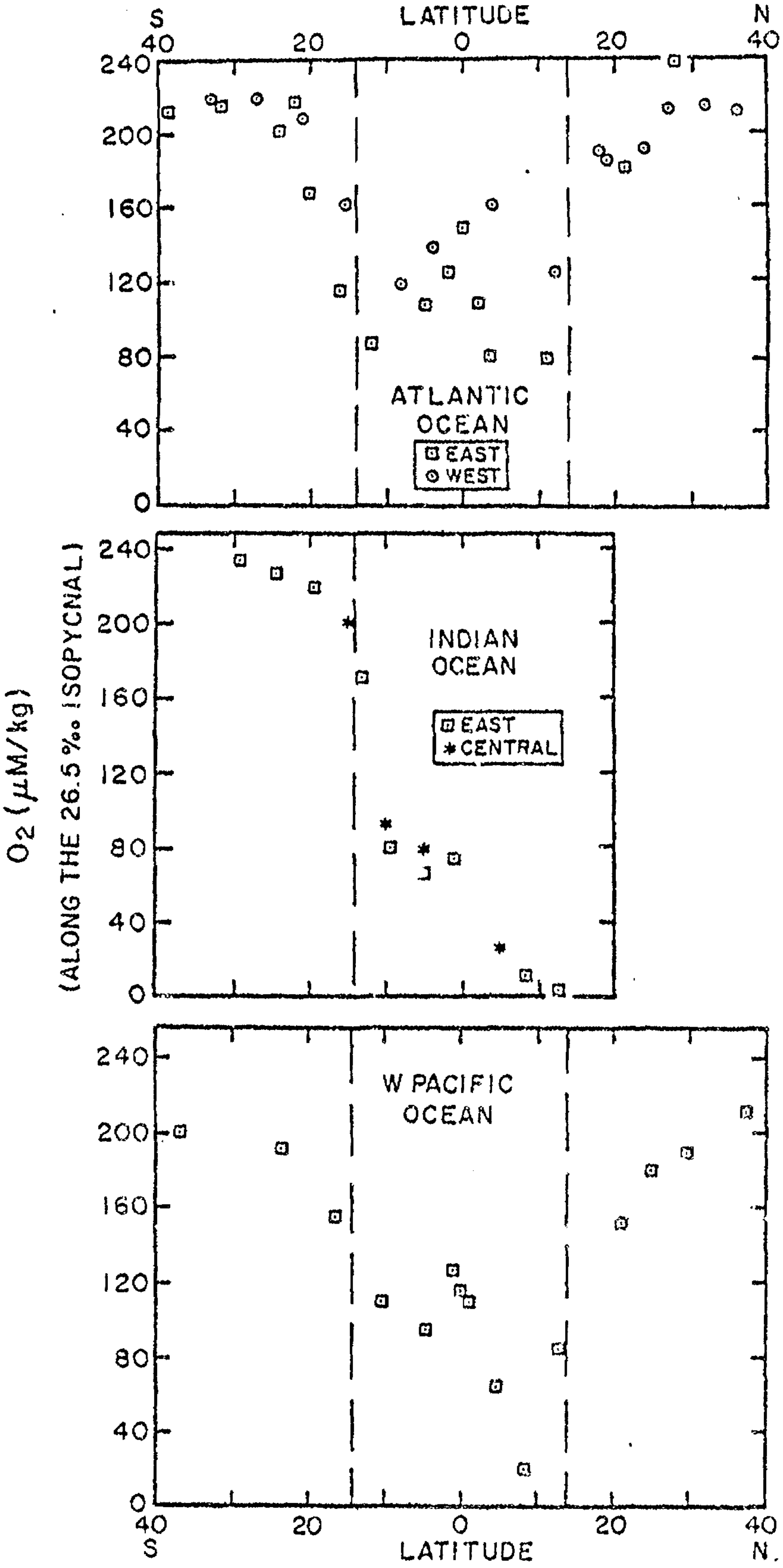

LATITUDE
S
N
40
20
0
20
40
240
200
160
120
80
40
0
ATLANTIC OCEAN
⊡ EAST
⊙ WEST
INDIAN OCEAN
⊡ EAST
* CENTRAL
W PACIFIC OCEAN
O_2 (μM/kg)
(ALONG THE 26.5‰ ISOPYCNAL)
LATITUDE

Fig. 3

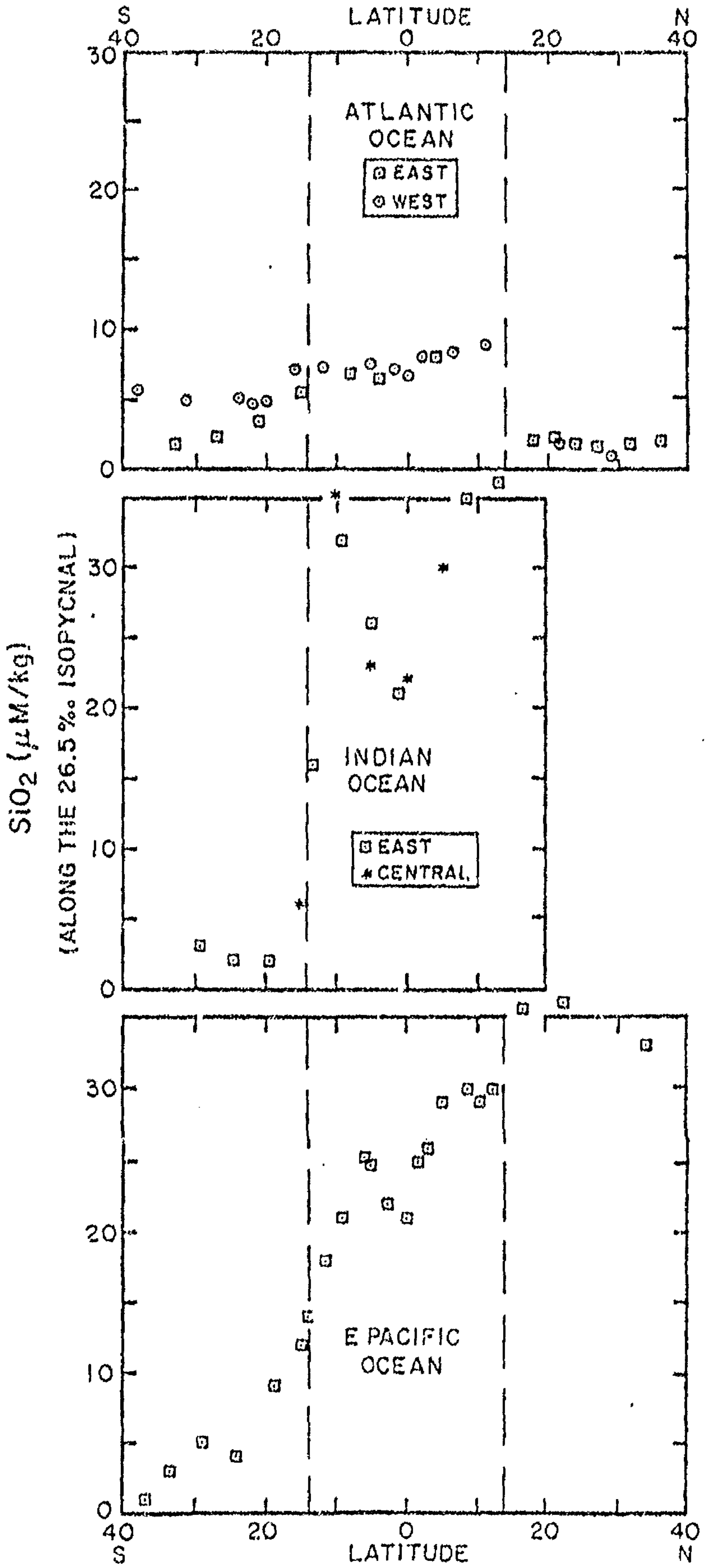

S
LATITUDE
N
40
20
0
20
40
30
20
10
0
ATLANTIC OCEAN
EAST
WEST
SiO2 (μM/kg)
(ALONG THE 26.5‰ ISOPYCNAL)
30
20
10
0
INDIAN OCEAN
EAST
CENTRAL
30
20
10
0
E PACIFIC OCEAN
40
20
0
20
40
S
LATITUDE
N

Fig. 4

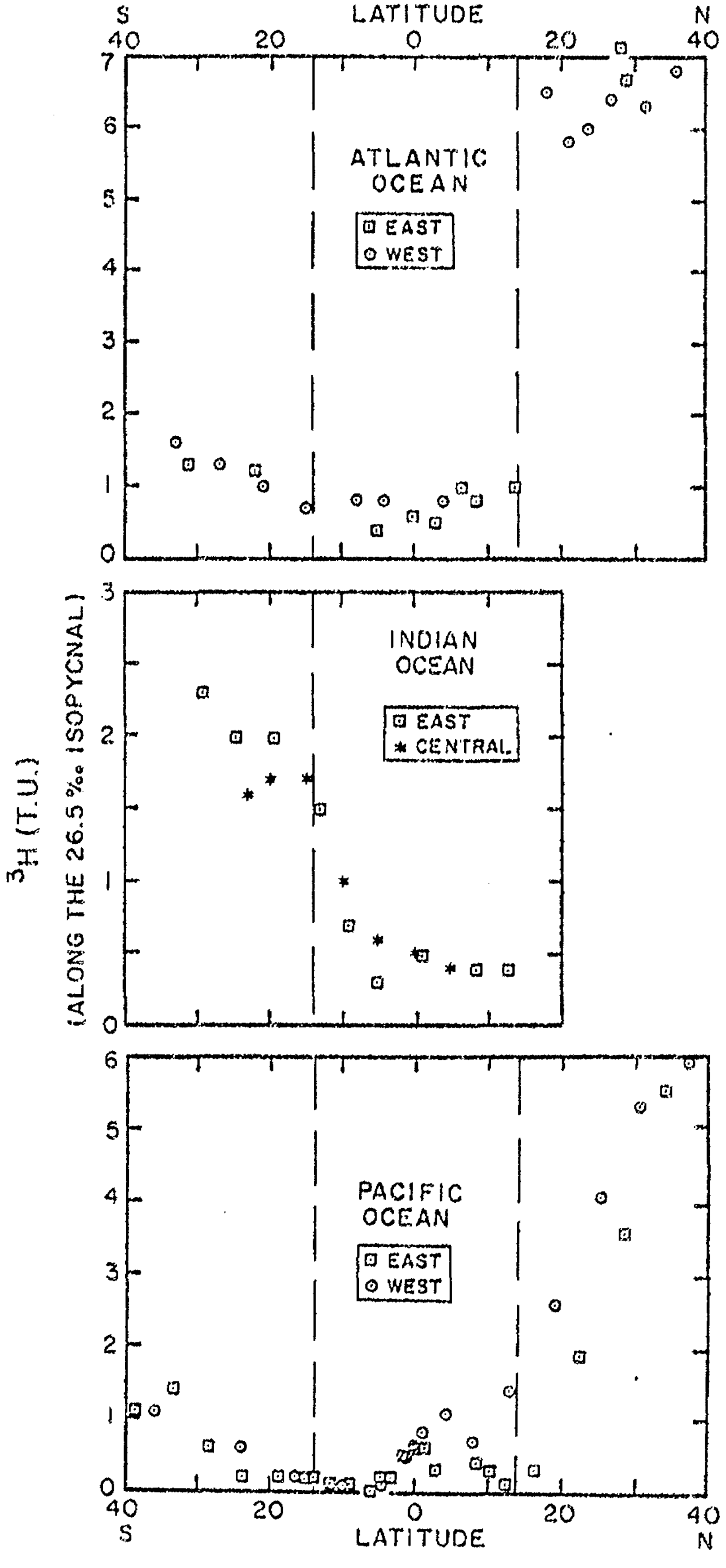

S
LATITUDE
N
40
20
0
20
40
7
6
5
4
3
2
1
0
ATLANTIC OCEAN
□ EAST
○ WEST
3
2
1
0
INDIAN OCEAN
□ EAST
* CENTRAL
^3H (T.U.)
(ALONG THE 26.5 ‰ ISOPYCNAL)
6
5
4
3
2
1
0
PACIFIC OCEAN
□ EAST
○ WEST
40
S
20
0
20
40
N
LATITUDE

Fig. 5

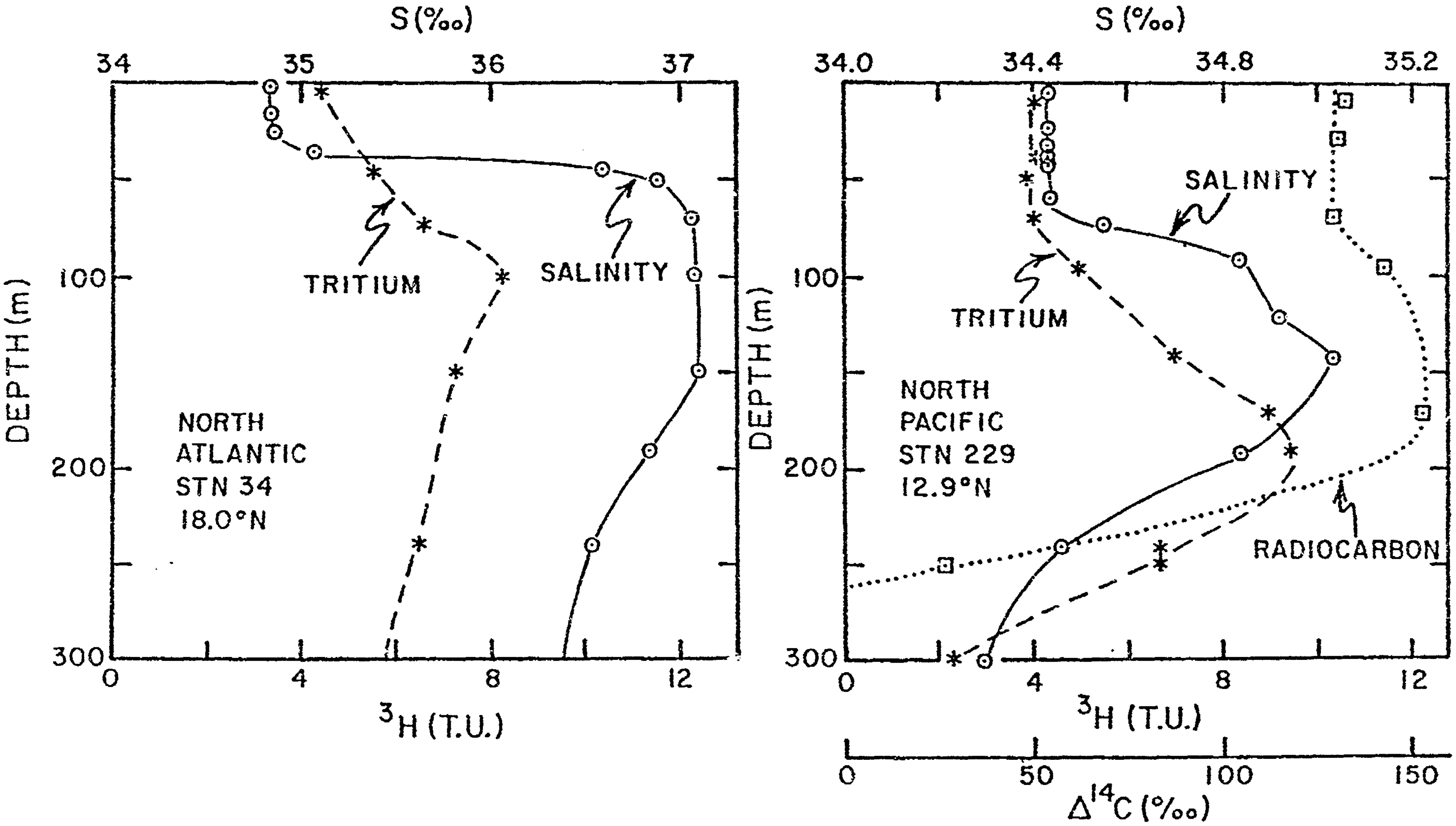

S (‰)
34
35
36
37
DEPTH (m)
100
200
300
0
4
8
12
³H (T.U.)
TRITIUM
SALINITY
NORTH
ATLANTIC
STN 34
18.0°N
S (‰)
34.0
34.4
34.8
35.2
DEPTH (m)
100
200
300
0
4
8
12
³H (T.U.)
0
50
100
150
Δ¹⁴C (‰)
SALINITY
TRITIUM
RADIOCARBON
NORTH
PACIFIC
STN 229
12.9°N

Fig. 6

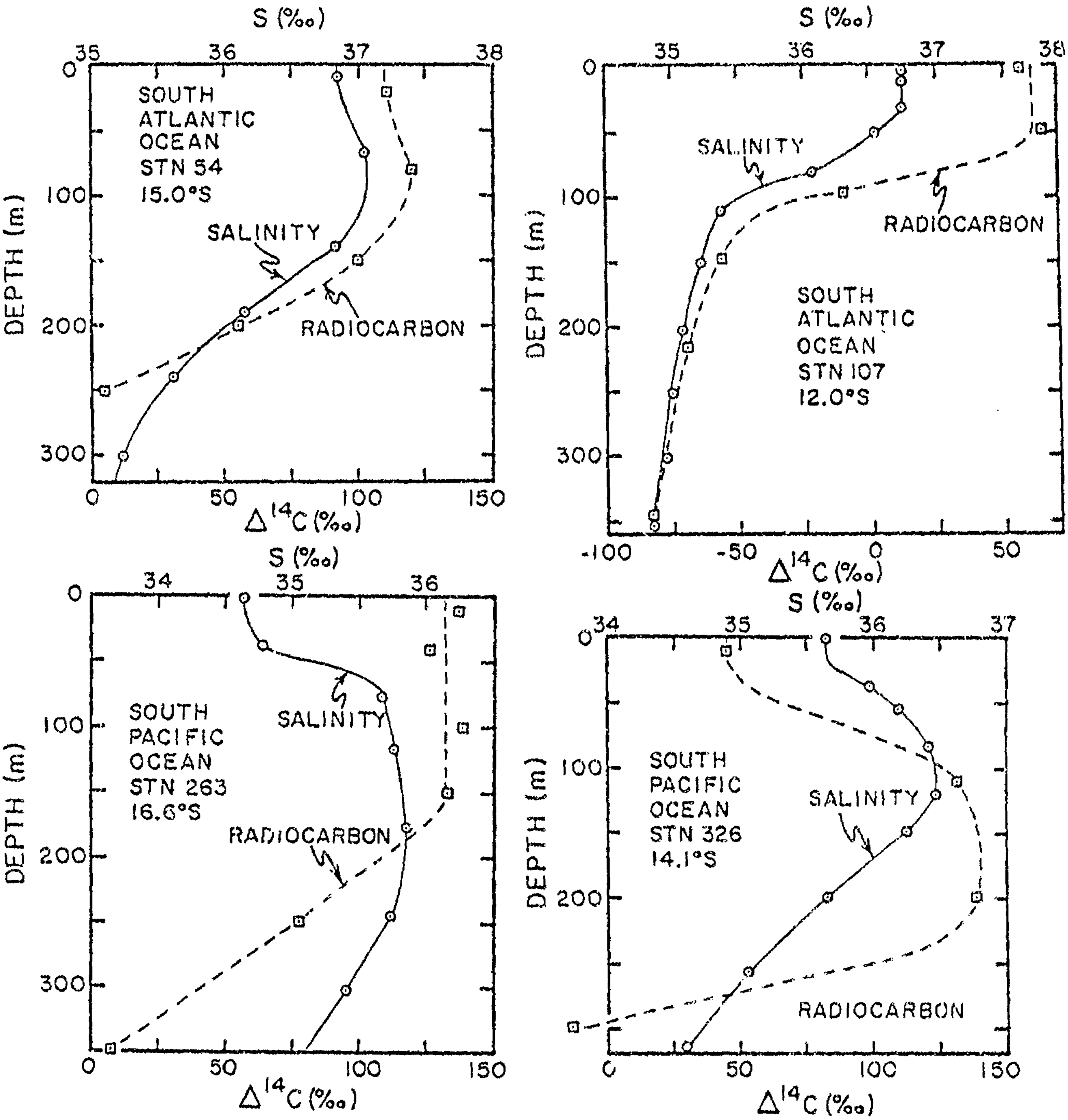

S (‰)
35
36
37
38
0
100
200
300
DEPTH (m)
SOUTH
ATLANTIC
OCEAN
STN 54
15.0°S
SALINITY
RADIOCARBON
0
50
100
150
Δ14C (‰)
S (‰)
35
36
37
38
0
100
200
300
DEPTH (m)
SALINITY
RADIOCARBON
SOUTH
ATLANTIC
OCEAN
STN 107
12.0°S
-100
-50
0
50
Δ14C (‰)
S (‰)
34
35
36
0
100
200
300
DEPTH (m)
SOUTH
PACIFIC
OCEAN
STN 263
16.6°S
SALINITY
RADIOCARBON
0
50
100
150
Δ14C (‰)
S (‰)
34
35
36
37
0
100
200
DEPTH (m)
SOUTH
PACIFIC
OCEAN
STN 326
14.1°S
SALINITY
RADIOCARBON
0
50
100
150
Δ14C (‰)

Fig. 7

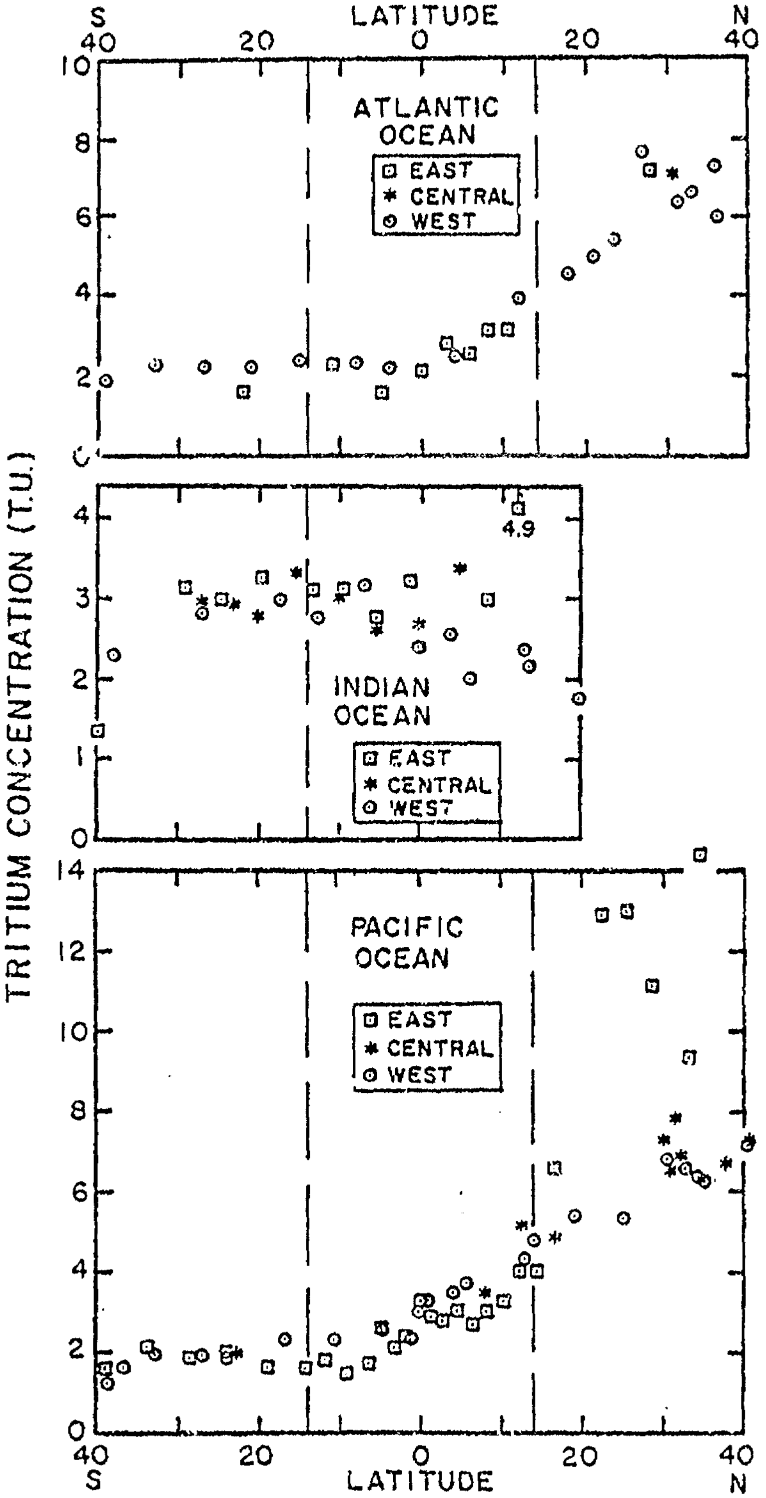

LATITUDE
S
N
40
20
0
20
40
ATLANTIC OCEAN
EAST
CENTRAL
WEST
INDIAN OCEAN
4.9
PACIFIC OCEAN
TRITIUM CONCENTRATION (T.U.)
0
2
4
6
8
10
12
14
1
3

Fig. 8

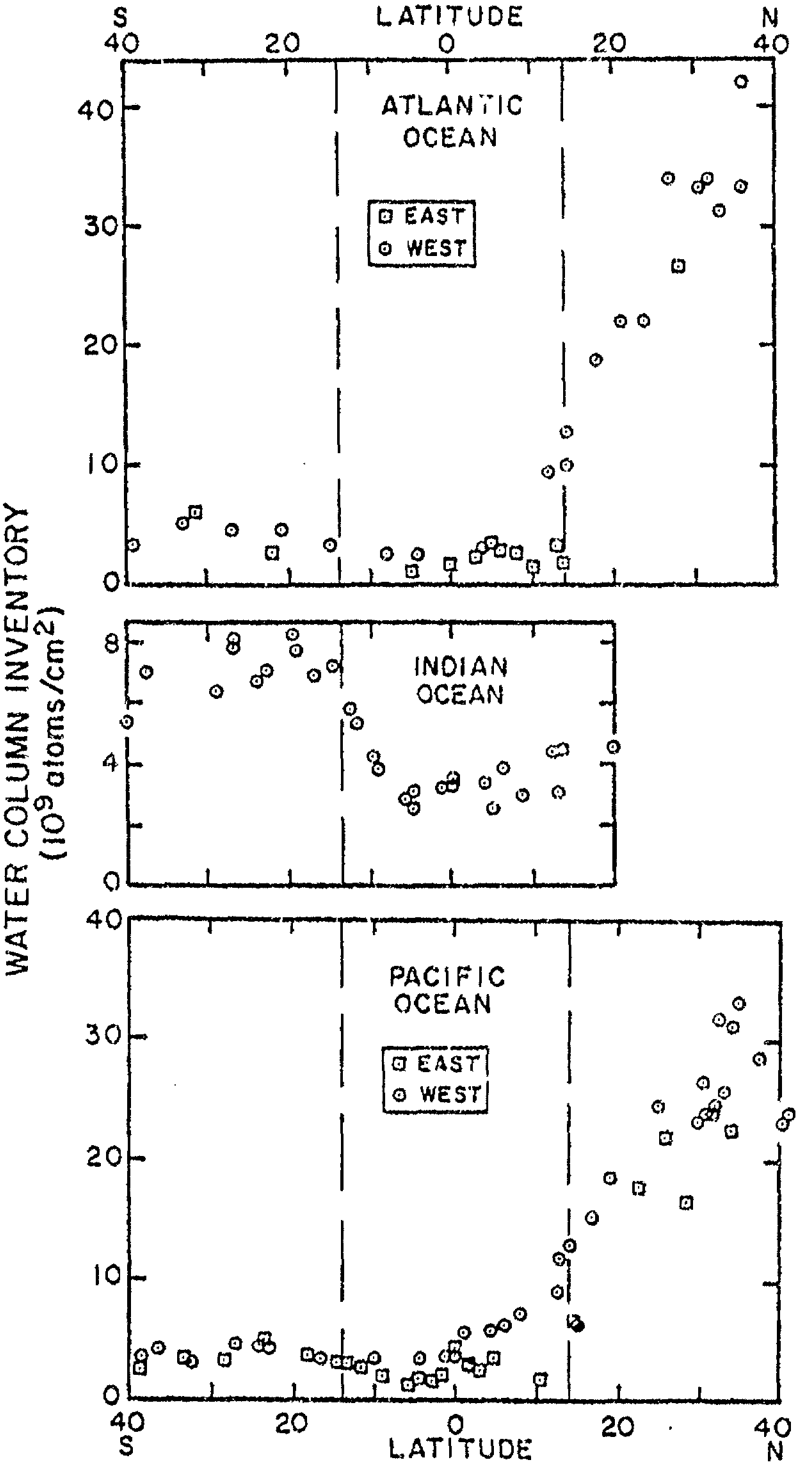

LATITUDE
S
N
40
20
0
20
40
ATLANTIC OCEAN
EAST
WEST
INDIAN OCEAN
PACIFIC OCEAN
EAST
WEST
WATER COLUMN INVENTORY (10^9 atoms/cm^2)
0
10
20
30
40
0
4
8
0
10
20
30
40
40
S
20
0
20
40
N
LATITUDE

Fig. 9

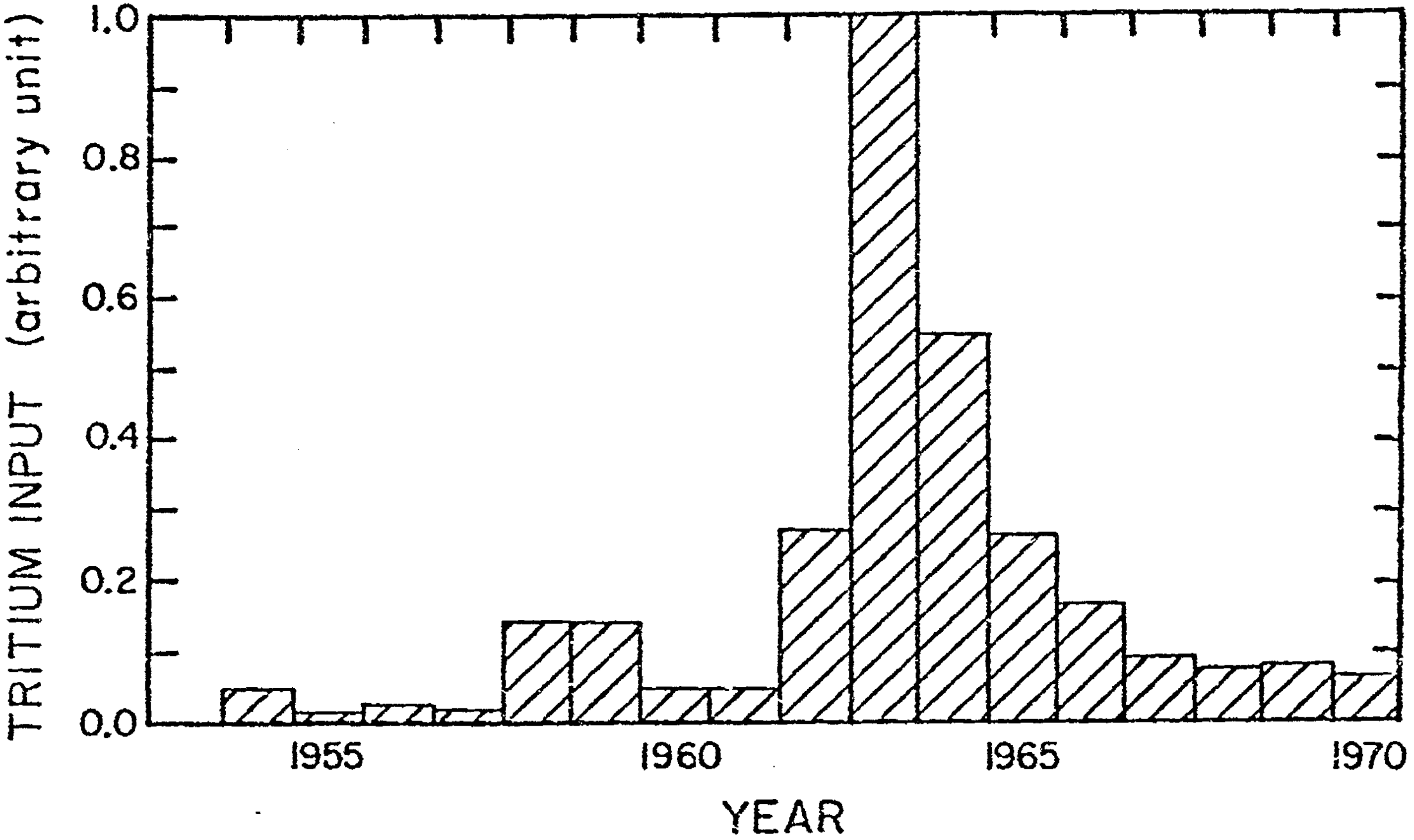

TRITIUM INPUT (arbitrary unit)
0.0
0.2
0.4
0.6
0.8
1.0
1955
1960
1965
1970
YEAR

Fig. 10

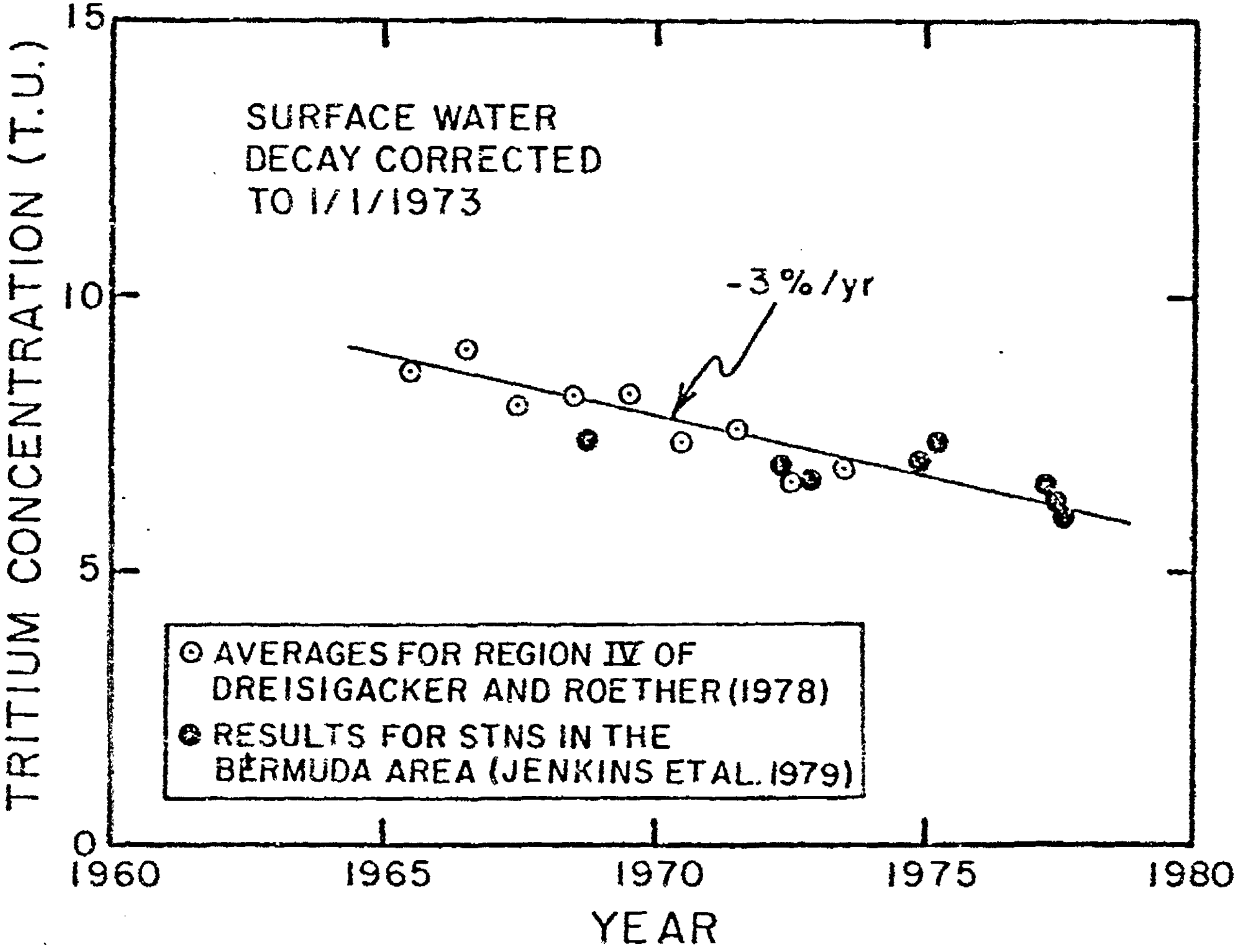

15
10
5
0
TRITIUM CONCENTRATION (T.U.)
1960
1965
1970
1975
1980
YEAR
SURFACE WATER
DECAY CORRECTED
TO 1/1/1973
-3%/yr
⊙ AVERAGES FOR REGION IV OF
DREISIGACKER AND ROETHER (1978)
● RESULTS FOR STNS IN THE
BERMUDA AREA (JENKINS ET AL. 1979)

Fig. 11

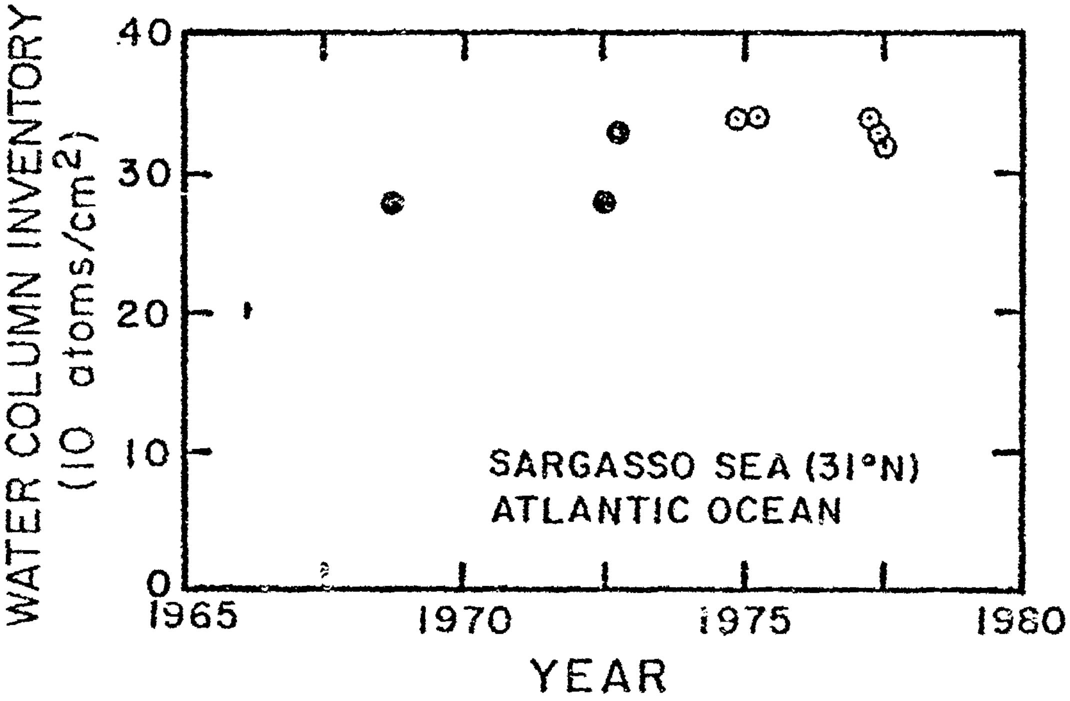

WATER COLUMN INVENTORY
(10 atoms/cm^2)
40
30
20
10
0
1965
1970
1975
1980
YEAR
SARGASSO SEA (31°N)
ATLANTIC OCEAN

Fig. 12

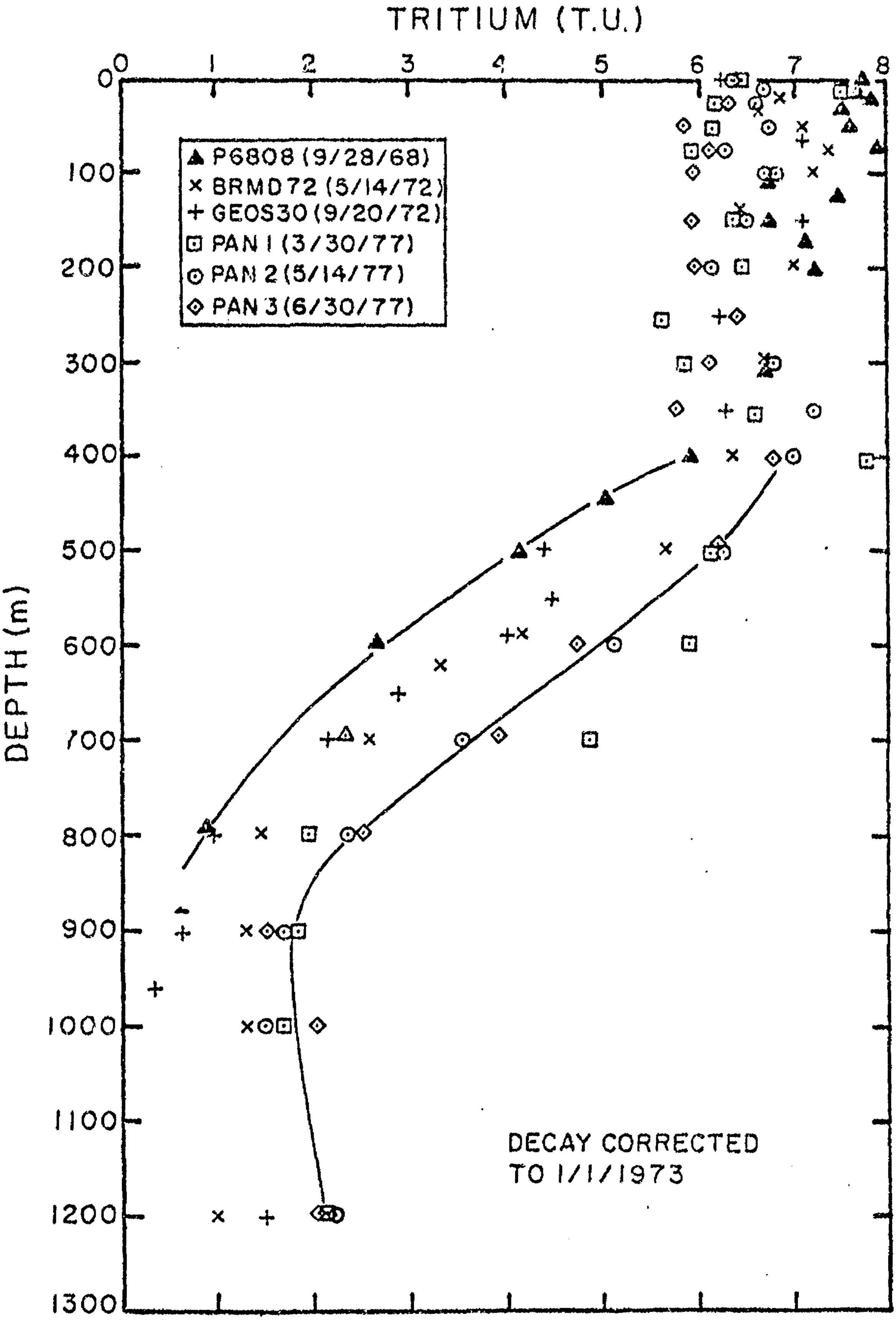

TRITIUM (T.U.)
0
1
2
3
4
5
6
7
8
DEPTH (m)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
▲ P6808 (9/28/68)
× BRMD72 (5/14/72)
+ GEOS30 (9/20/72)
⊡ PAN 1 (3/30/77)
⊙ PAN 2 (5/14/77)
◇ PAN 3 (6/30/77)
DECAY CORRECTED
TO 1/1/1973

Fig. 13

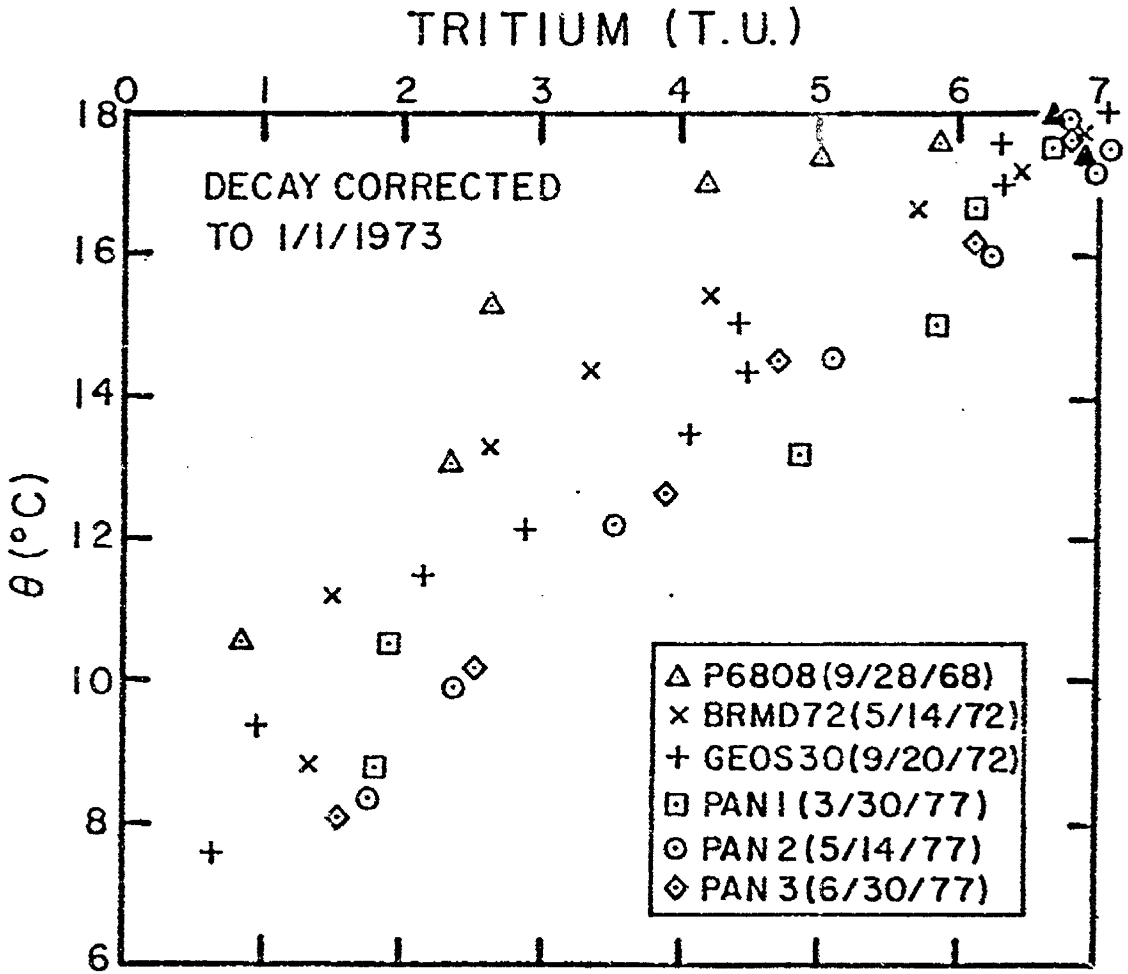

TRITIUM (T.U.)
0
1
2
3
4
5
6
7
18
16
14
12
10
8
6
θ (°C)
DECAY CORRECTED
TO 1/1/1973
△ P6808(9/28/68)
× BRMD72(5/14/72)
+ GEOS30(9/20/72)
⊡ PAN1(3/30/77)
⊙ PAN2(5/14/77)
◇ PAN3(6/30/77)

Fig. 14

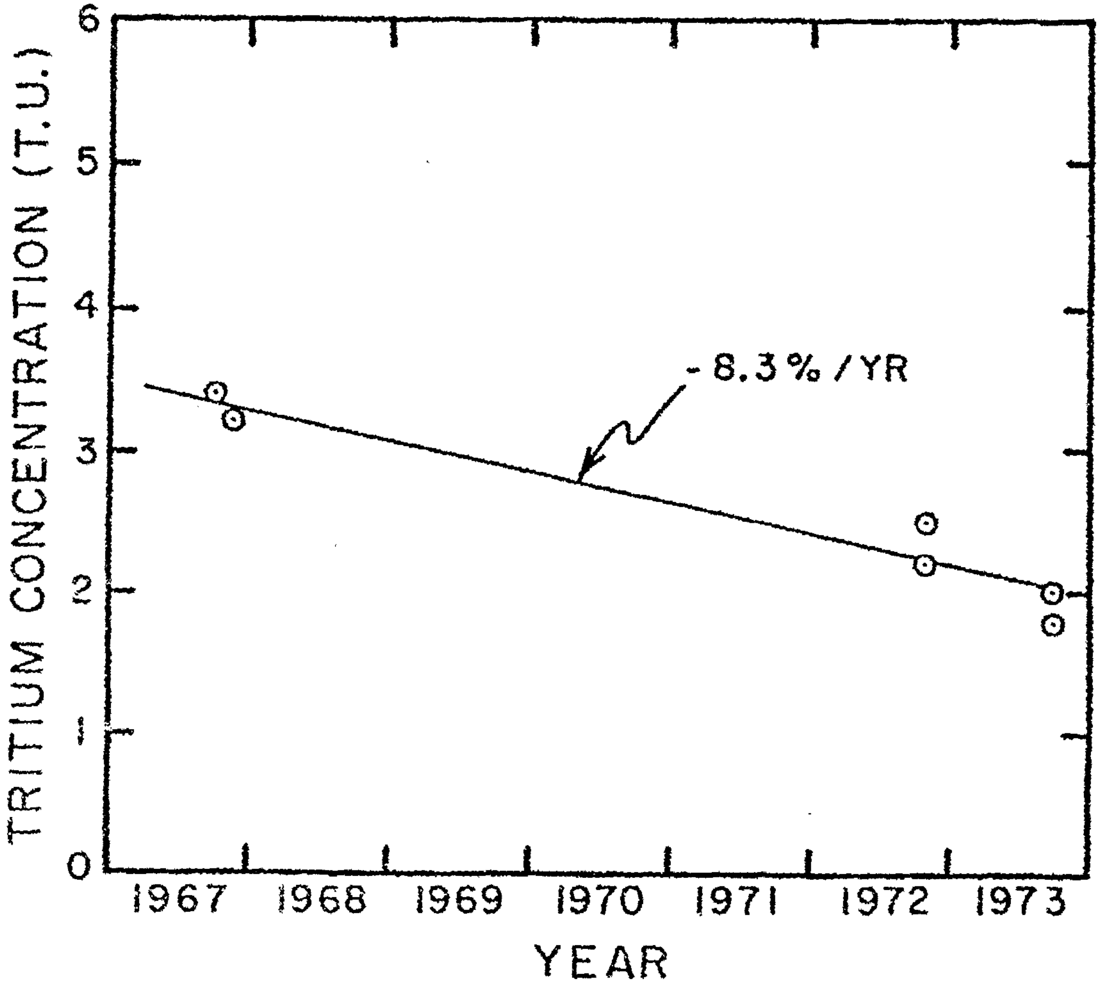

TRITIUM CONCENTRATION (T.U.)
0
1
2
3
4
5
6
1967
1968
1969
1970
1971
1972
1973
YEAR
-8.3% / YR

Fig. 15

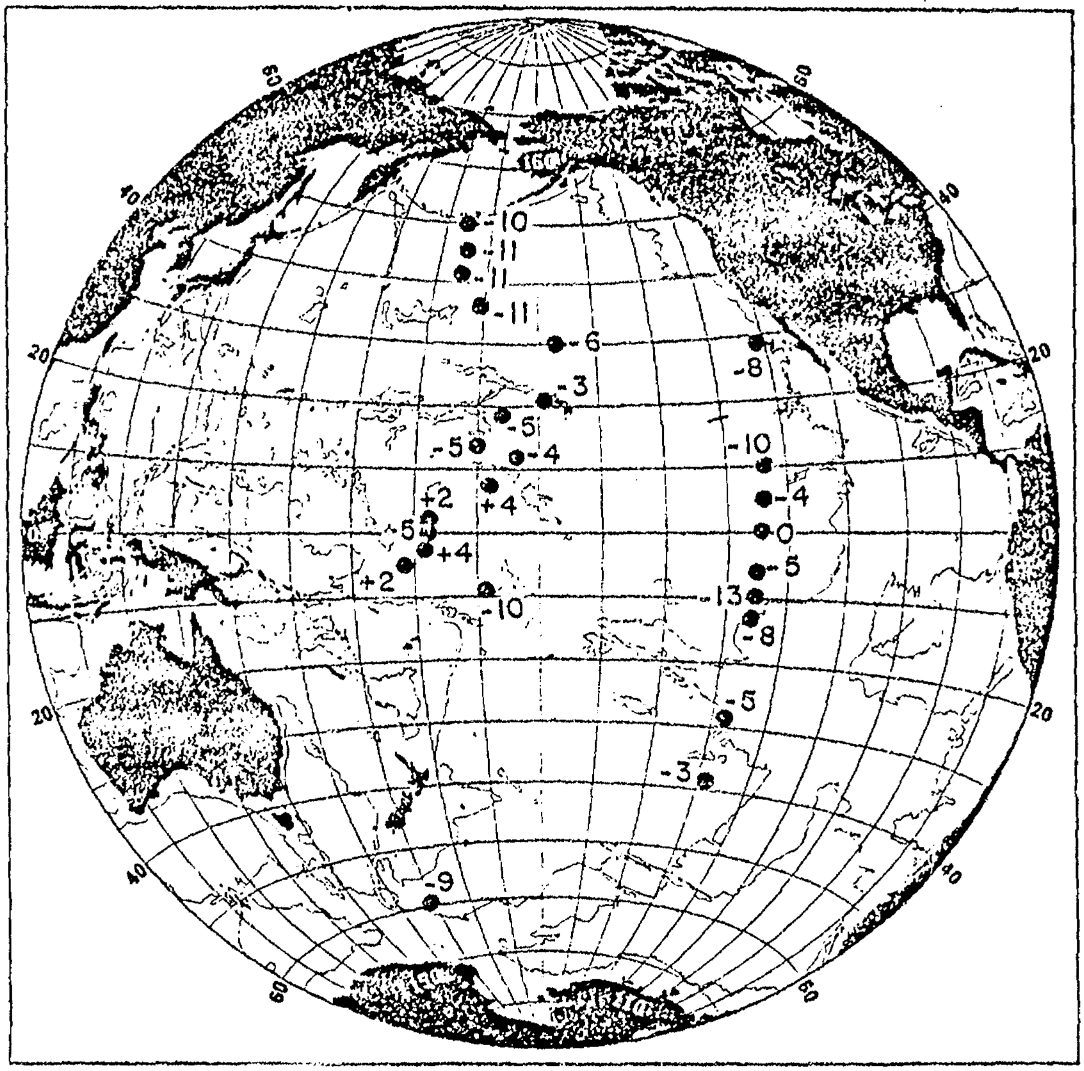
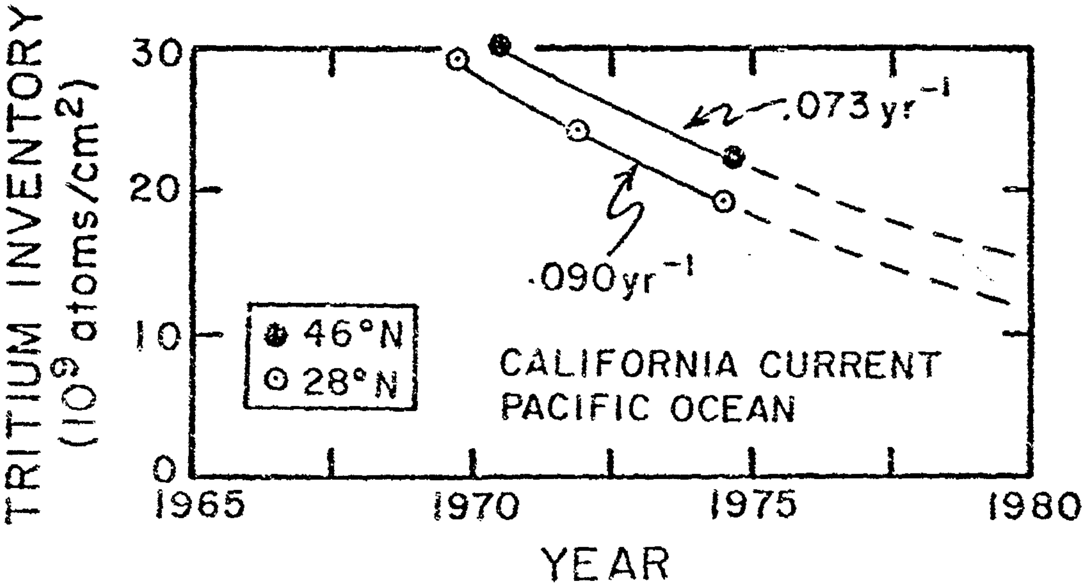

60
60
160
40
40
-10
-11
-11
-11
20
-6
-8
20
-3
-5
-10
-5
-4
+2
-4
+4
-5
0
+4
+2
-5
-10
-13
-8
20
-5
20
-3
40
-9
40
60
60

Fig. 16



TRITIUM INVENTORY
(10^9 atoms/cm^2)
30
20
10
0
1965
1970
1975
1980
YEAR
.073 yr^{-1}
.090 yr^{-1}
● 46°N
⊙ 28°N
CALIFORNIA CURRENT
PACIFIC OCEAN

Fig. 17

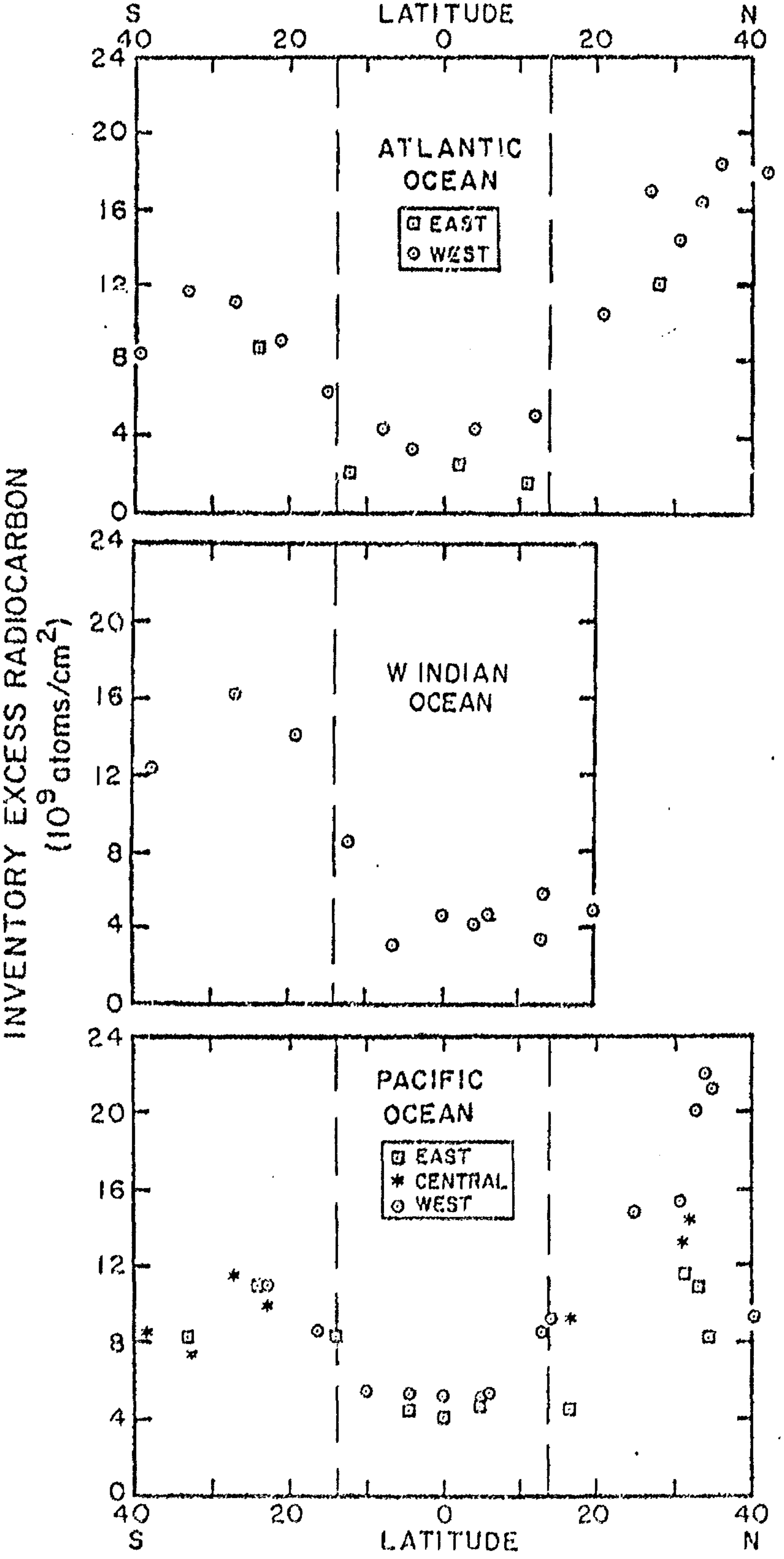
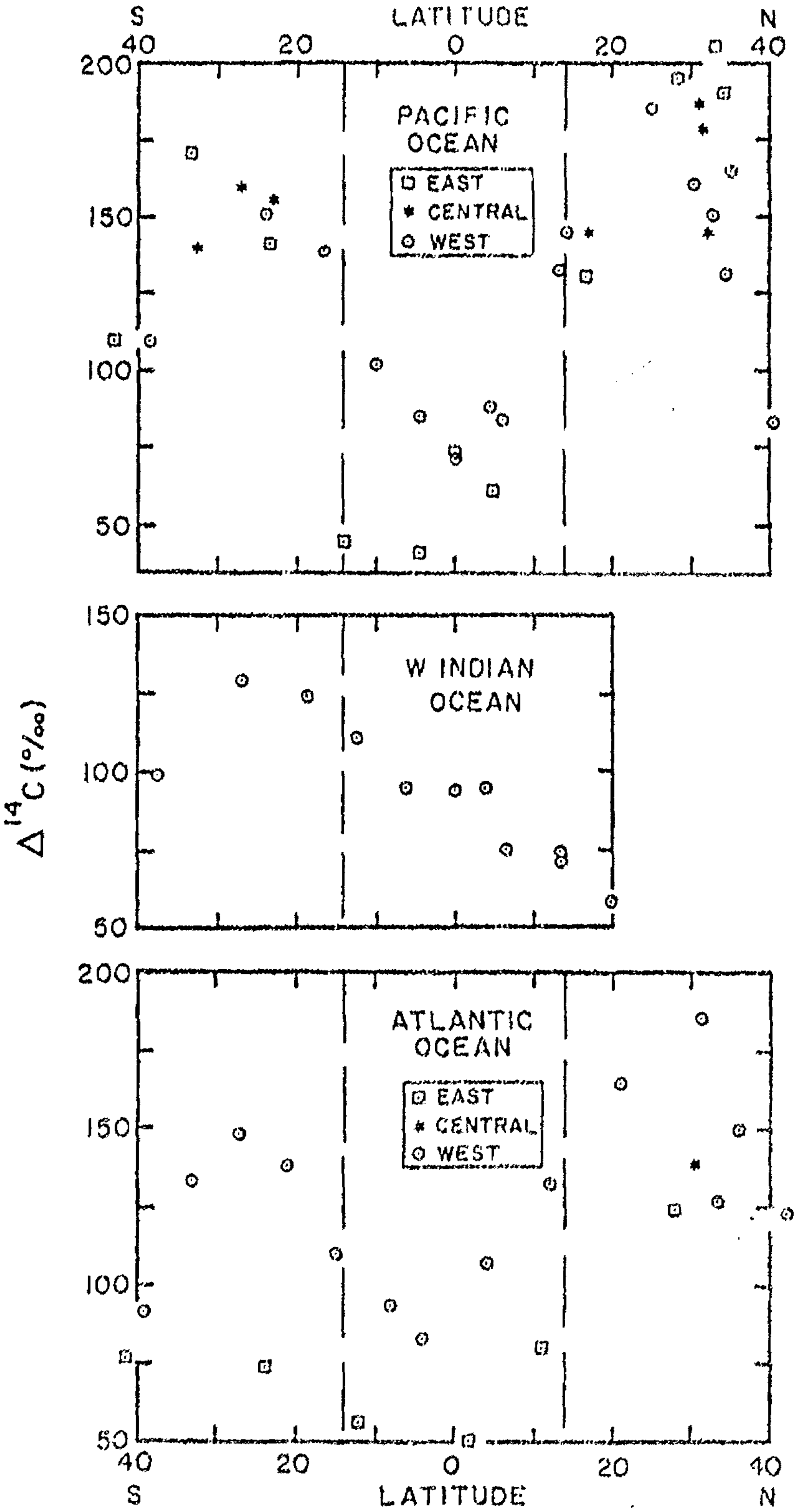

S
LATITUDE
N
40
20
0
20
40
24
20
16
12
8
4
0
ATLANTIC OCEAN
☐ EAST
○ WEST
W INDIAN OCEAN
PACIFIC OCEAN
☐ EAST
* CENTRAL
○ WEST
INVENTORY EXCESS RADIOCARBON
(10^9 atoms/cm^2)

Fig. 18



S
LATITUDE
N
40
20
0
20
40
200
150
100
50
PACIFIC OCEAN
EAST
CENTRAL
WEST
150
100
50
W INDIAN OCEAN
$\Delta^{14}C$ (°/oo)
200
150
100
50
ATLANTIC OCEAN
EAST
CENTRAL
WEST
40
20
0
20
40
S
LATITUDE
N

Fig. 19

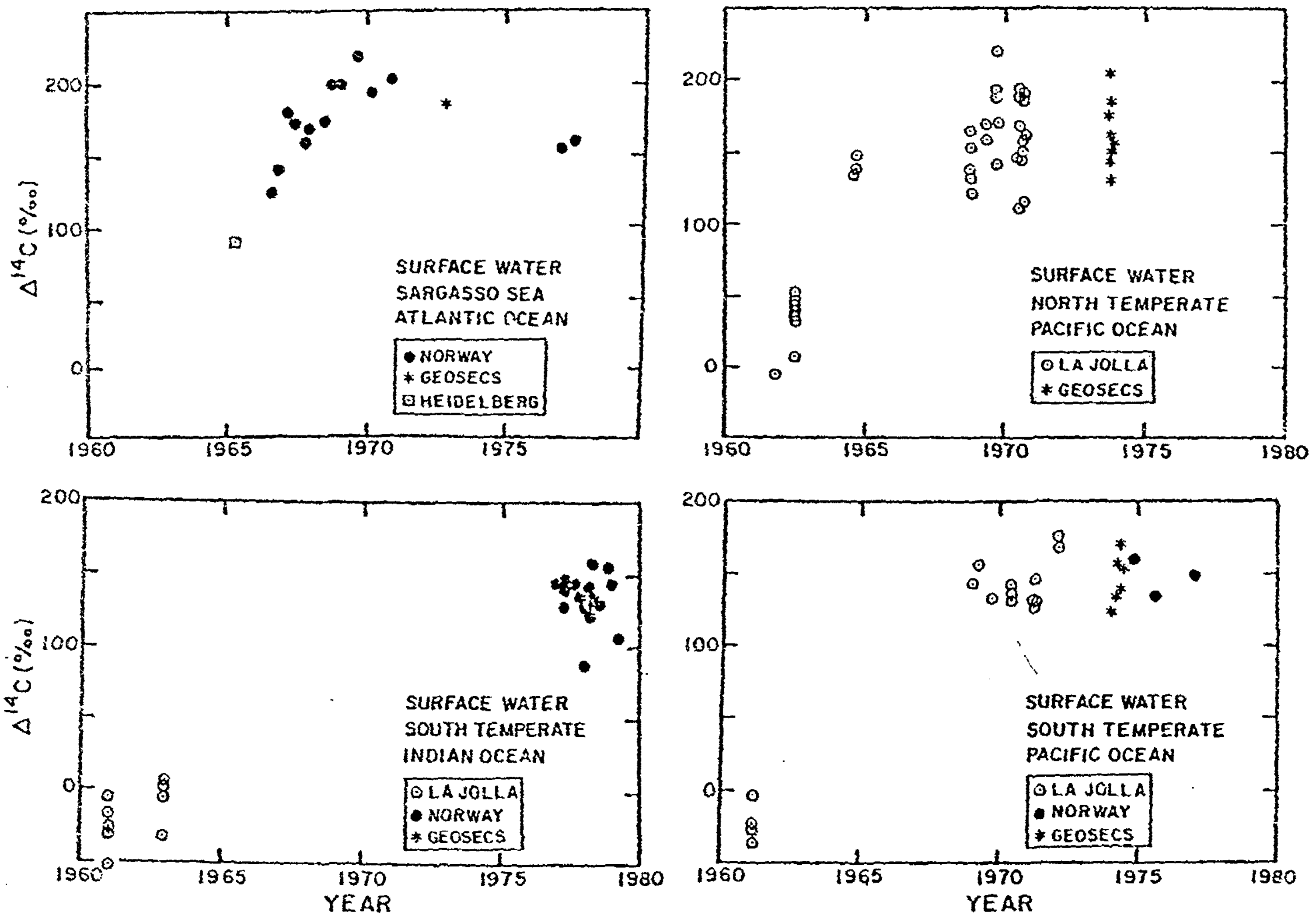
SURFACE WATER
SARGASSO SEA
ATLANTIC OCEAN
● NORWAY
* GEOSECS
⊡ HEIDELBERG
SURFACE WATER
NORTH TEMPERATE
PACIFIC OCEAN
⊙ LA JOLLA
* GEOSECS
SURFACE WATER
SOUTH TEMPERATE
INDIAN OCEAN
⊙ LA JOLLA
● NORWAY
* GEOSECS
SURFACE WATER
SOUTH TEMPERATE
PACIFIC OCEAN
⊙ LA JOLLA
● NORWAY
* GEOSECS
Δ14C (‰)
200
100
0
1960
1965
1970
1975
1980
YEAR

Fig. 20

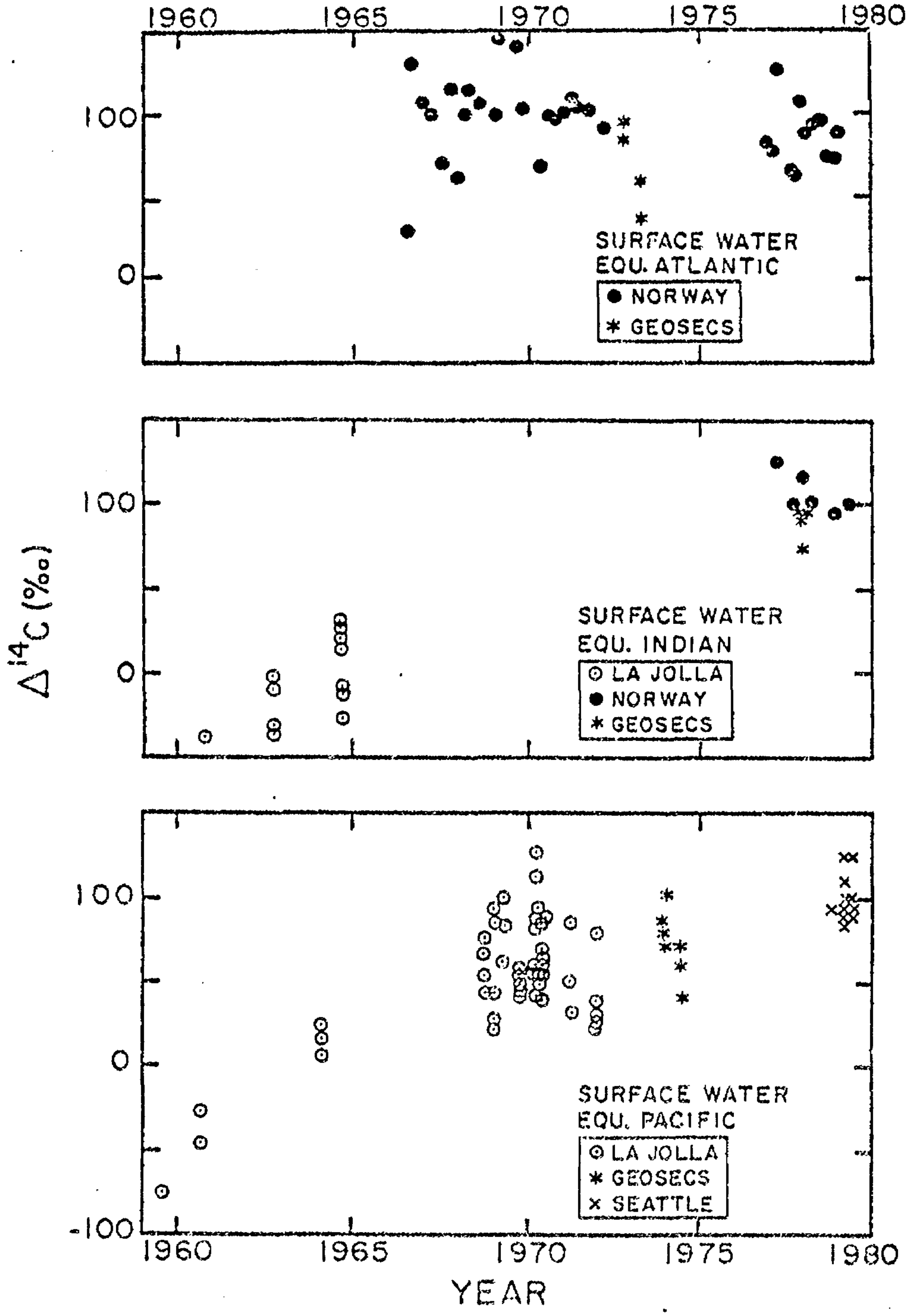

1960
1965
1970
1975
1980
100
0
SURFACE WATER
EQU. ATLANTIC
● NORWAY
* GEOSECS
Δ14C (‰)
SURFACE WATER
EQU. INDIAN
⊙ LA JOLLA
● NORWAY
* GEOSECS
-100
SURFACE WATER
EQU. PACIFIC
⊙ LA JOLLA
* GEOSECS
× SEATTLE
YEAR

Fig. 21

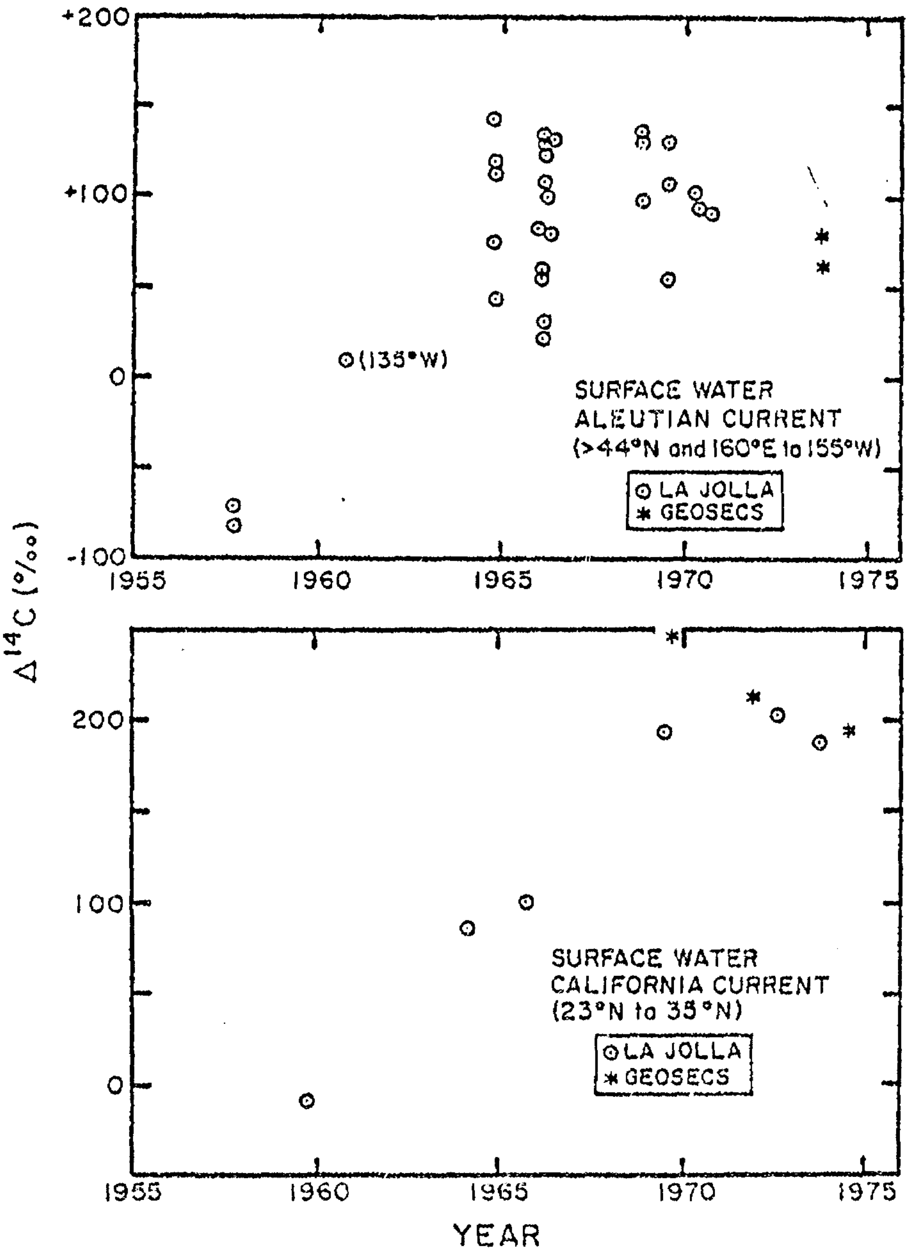

+200
+100
0
-100
1955
1960
1965
1970
1975
Δ¹⁴C (‰)
(135°W)
SURFACE WATER
ALEUTIAN CURRENT
(>44°N and 160°E to 155°W)
LA JOLLA
GEOSECS
200
100
0
1955
1960
1965
1970
1975
YEAR
SURFACE WATER
CALIFORNIA CURRENT
(23°N to 35°N)
LA JOLLA
GEOSECS

Fig. 22

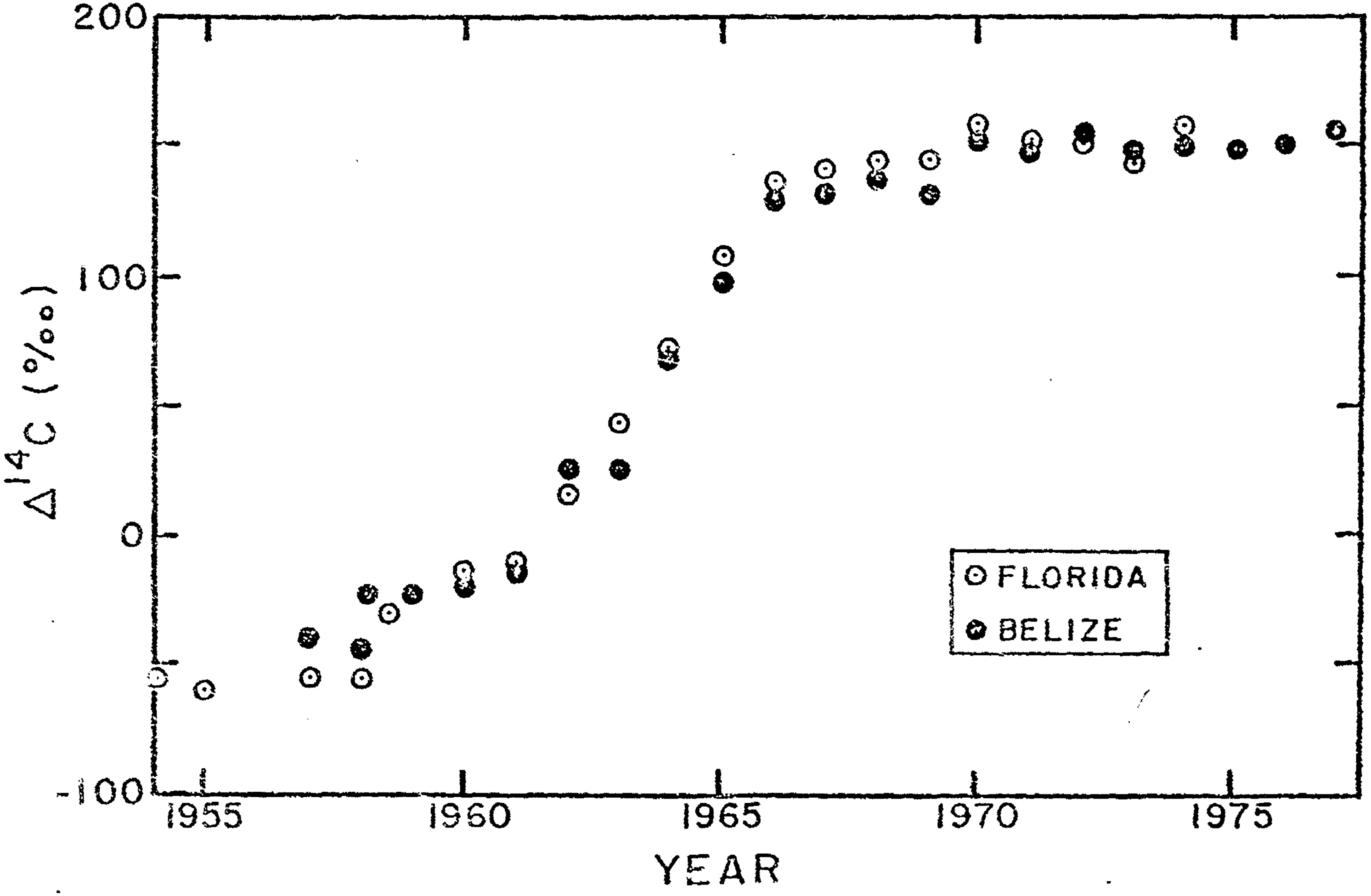

200
100
0
-100
Δ^{14}C (°/oo)
1955
1960
1965
1970
1975
YEAR
○ FLORIDA
● BELIZE

Fig. 23

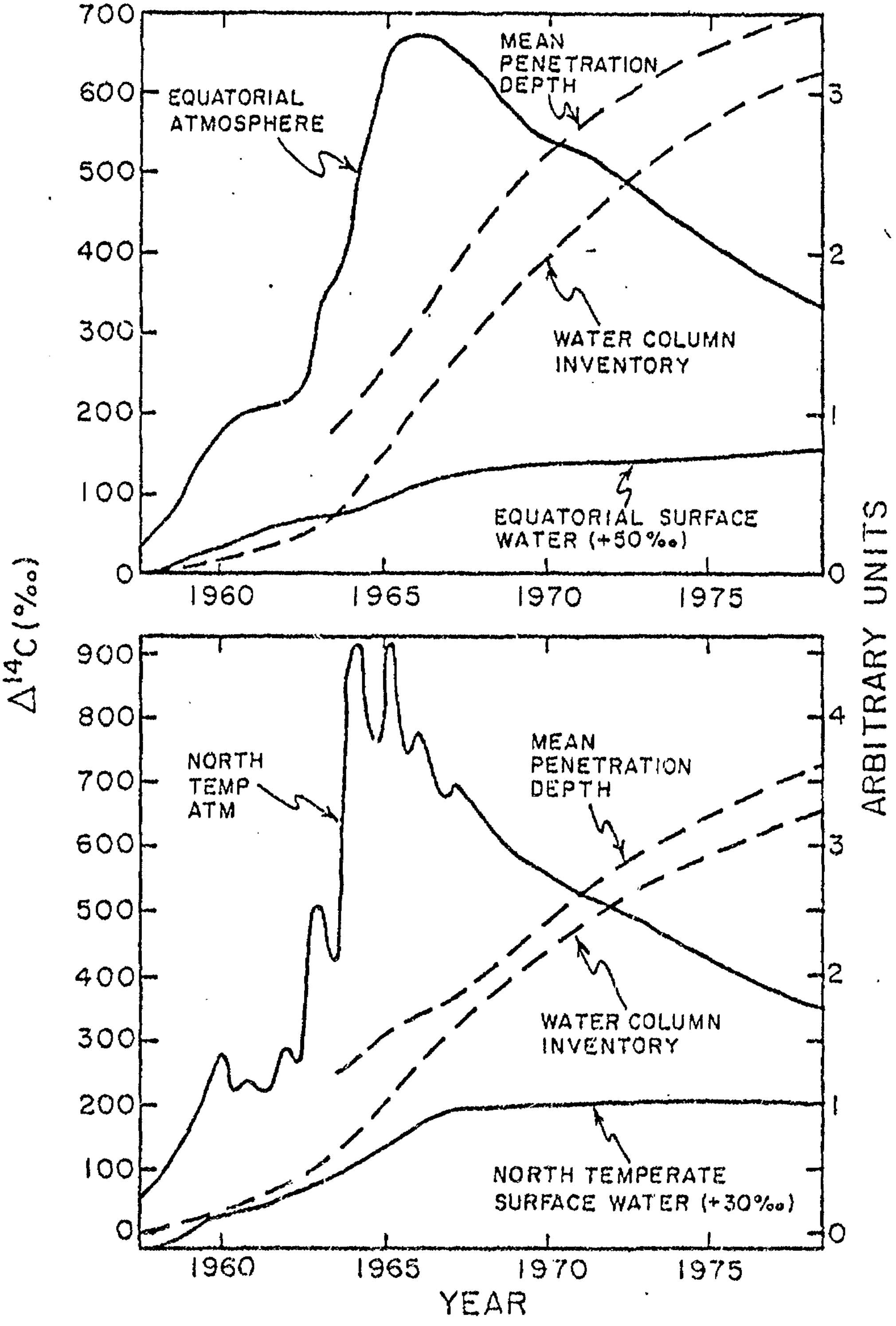
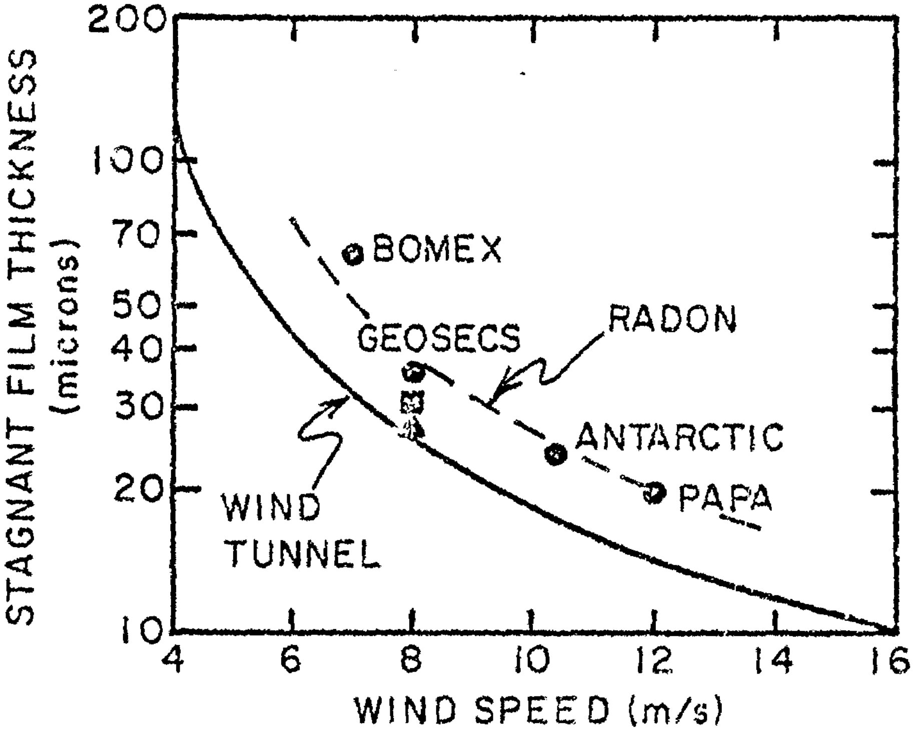

700
600
500
400
300
200
100
0
EQUATORIAL ATMOSPHERE
MEAN PENETRATION DEPTH
WATER COLUMN INVENTORY
EQUATORIAL SURFACE WATER (+50‰)
3
2
1
0
1960
1965
1970
1975
900
800
700
600
500
400
300
200
100
0
NORTH TEMP ATM
MEAN PENETRATION DEPTH
WATER COLUMN INVENTORY
NORTH TEMPERATE SURFACE WATER (+30‰)
4
3
2
1
0
1960
1965
1970
1975
YEAR
Δ¹⁴C (‰)
ARBITRARY UNITS

Fig. 24



STAGNANT FILM THICKNESS (microns)
200
100
70
50
40
30
20
10
4
6
8
10
12
14
16
WIND SPEED (m/s)
BOMEX
GEOSECS
RADON
ANTARCTIC
PAPA
WIND TUNNEL

Fig. 25

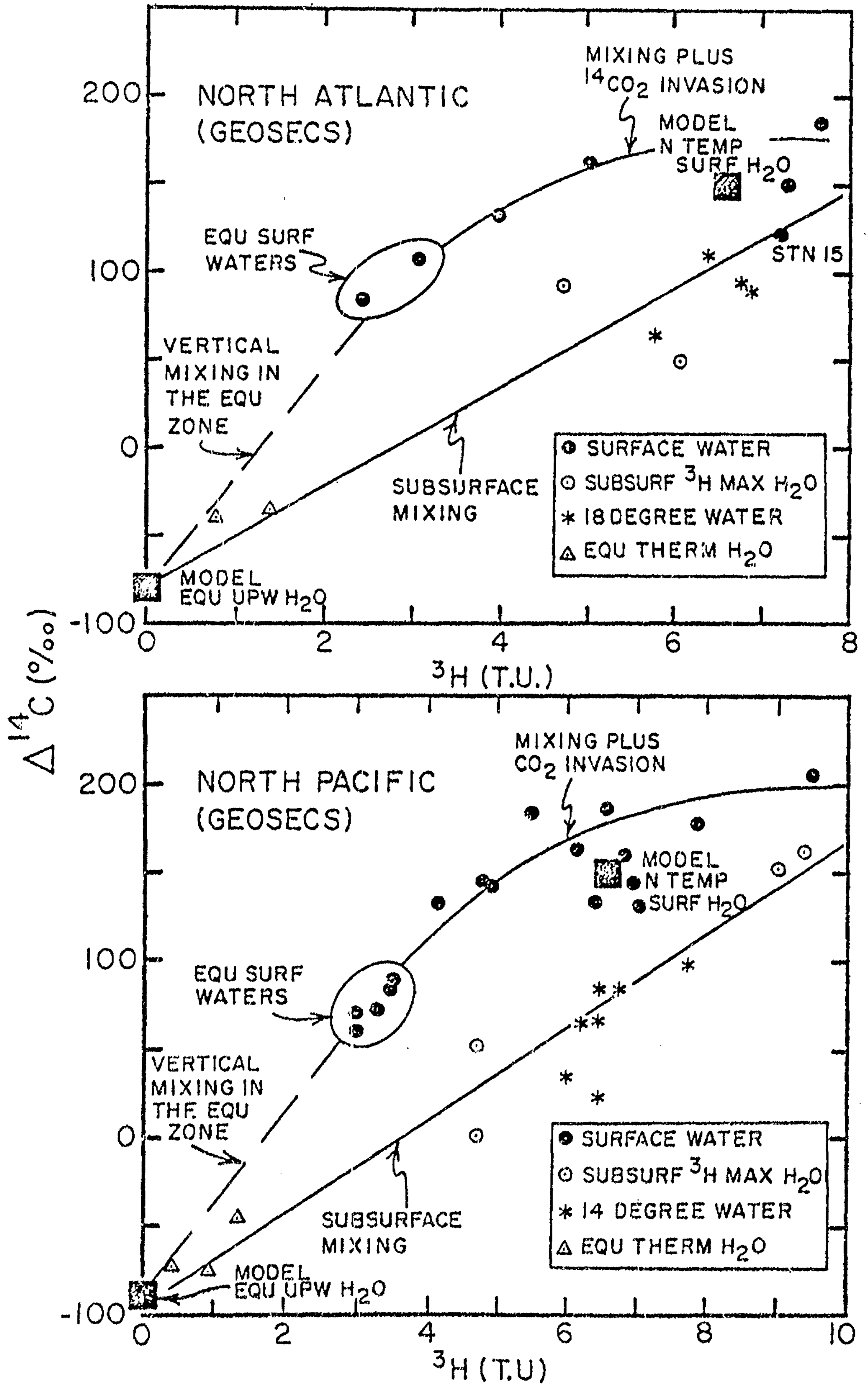

NORTH ATLANTIC
(GEOSECS)
MIXING PLUS
$^{14}CO_2$ INVASION
MODEL
N TEMP
SURF H_2O
STN 15
EQU SURF
WATERS
VERTICAL
MIXING IN
THE EQU
ZONE
SUBSURFACE
MIXING
MODEL
EQU UPW H_2O
● SURFACE WATER
○ SUBSURF ^3H MAX H_2O
* 18 DEGREE WATER
△ EQU THERM H_2O
200
100
0
-100
0
2
4
6
8
^3H (T.U.)
$\Delta^{14}C$ (‰)
NORTH PACIFIC
(GEOSECS)
MIXING PLUS
CO_2 INVASION
MODEL
N TEMP
SURF H_2O
EQU SURF
WATERS
VERTICAL
MIXING IN
THE EQU
ZONE
SUBSURFACE
MIXING
MODEL
EQU UPW H_2O
● SURFACE WATER
○ SUBSURF ^3H MAX H_2O
* 14 DEGREE WATER
△ EQU THERM H_2O
200
100
0
-100
0
2
4
6
8
10
^3H (T.U)

Fig. 26

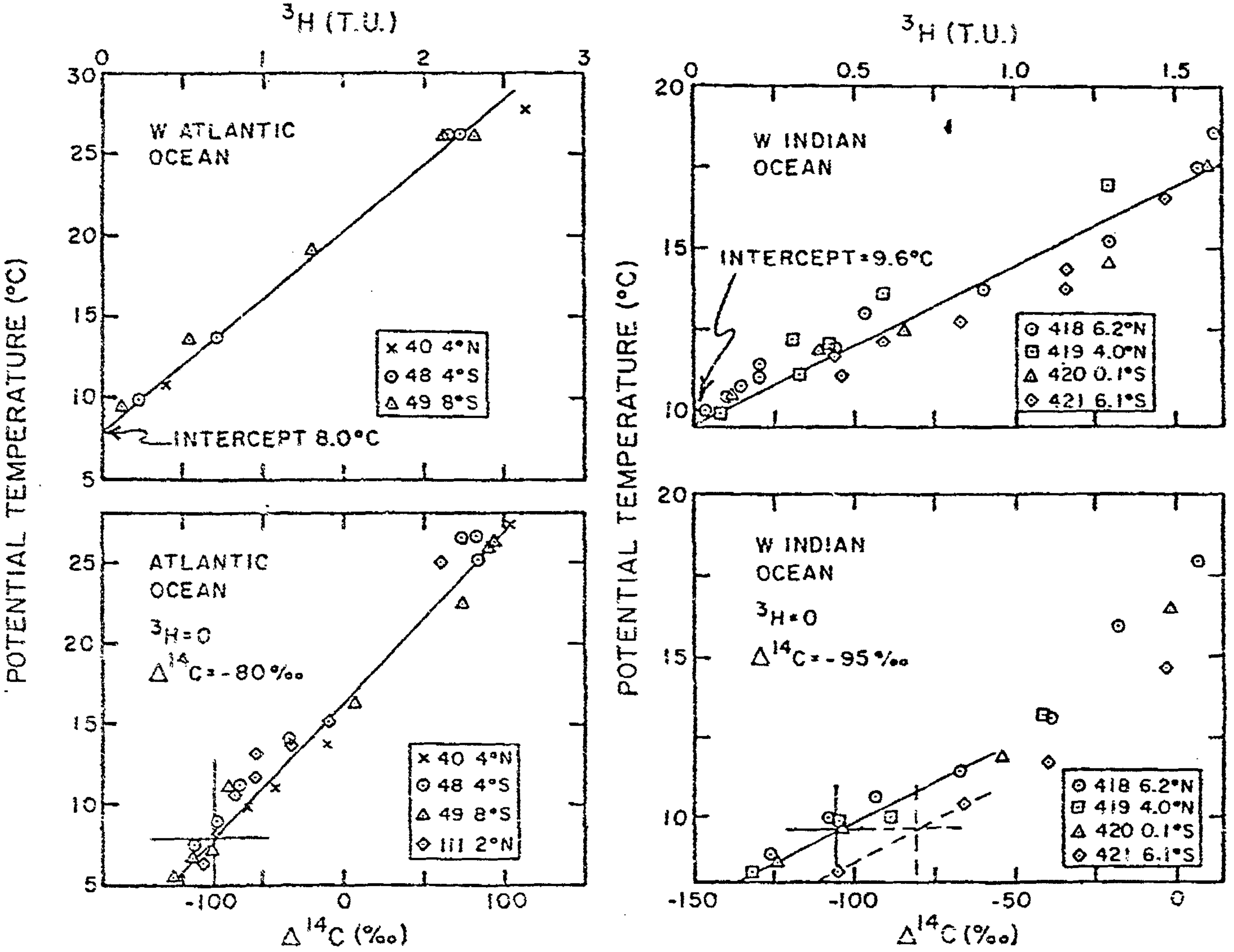
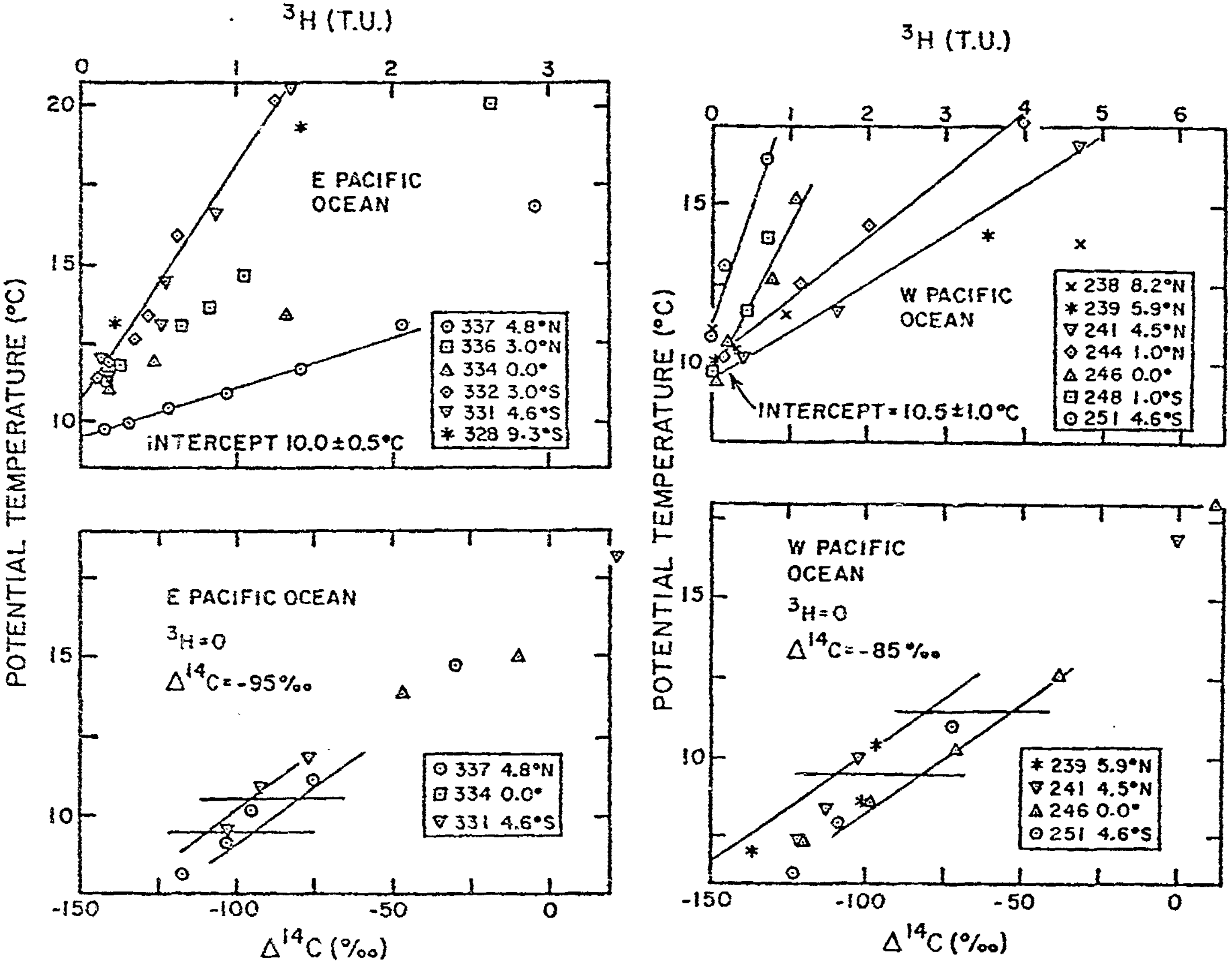

^3H (T.U.)
0
1
2
3
30
25
20
15
10
5
W ATLANTIC OCEAN
× 40 4°N
⊙ 48 4°S
△ 49 8°S
INTERCEPT 8.0°C
POTENTIAL TEMPERATURE (°C)
ATLANTIC OCEAN
^3H=0
$\Delta^{14}C$=-80‰
× 40 4°N
⊙ 48 4°S
△ 49 8°S
◇ 111 2°N
-100
0
100
$\Delta^{14}C$ (‰)
^3H (T.U.)
0
0.5
1.0
1.5
20
15
10
W INDIAN OCEAN
INTERCEPT=9.6°C
⊙ 418 6.2°N
⊡ 419 4.0°N
△ 420 0.1°S
◇ 421 6.1°S
POTENTIAL TEMPERATURE (°C)
W INDIAN OCEAN
^3H=0
$\Delta^{14}C$=-95‰
⊙ 418 6.2°N
⊡ 419 4.0°N
△ 420 0.1°S
◇ 421 6.1°S
-150
-100
-50
0
$\Delta^{14}C$ (‰)

Fig. 27A



³H (T.U.)
E PACIFIC OCEAN
INTERCEPT 10.0±0.5°C
337 4.8°N
336 3.0°N
334 0.0°
332 3.0°S
331 4.6°S
328 9.3°S
POTENTIAL TEMPERATURE (°C)
E PACIFIC OCEAN
³H=0
Δ¹⁴C=-95‰
337 4.8°N
334 0.0°
331 4.6°S
Δ¹⁴C (‰)
³H (T.U.)
W PACIFIC OCEAN
INTERCEPT=10.5±1.0°C
238 8.2°N
239 5.9°N
241 4.5°N
244 1.0°N
246 0.0°
248 1.0°S
251 4.6°S
POTENTIAL TEMPERATURE (°C)
W PACIFIC OCEAN
³H=0
Δ¹⁴C=-85‰
239 5.9°N
241 4.5°N
246 0.0°
251 4.6°S
Δ¹⁴C (‰)

Fig. 27B

REFERENCES

BROECKER, W.S., T.-H. PENG, M. STUIVER (1978) An Estimate of the Upwelling Rate in the Equatorial Atlantic Based on the Distribution of Bomb Radiocarbon. J. Geophys. Res. 83, 6179-6186.

Broecker, W.S. and H.G. Ostlund (1979) Property Distributions along the $\sigma_\theta = 26.8^o$/oo Isopycnal Surface in the Atlantic Ocean. J. Geophys. Res. 84, 1145-1154.

Druffel, E.M. (1980) Rediocarbon in annual coral rings of the Pacific and Atlantic Oceans. Ph.D. thesis, Univ. of California, San Diego.

Druffel, E.M. and T.W. Linick (1978) Radiocarbon in annual coral rings of Florida, Geophys. Res. Lett. (5), p. 913-916.

Jenkins, W.J., M.V. Collentro and R.D. Boudreau (1979) Woods Hole Oceanographic Institution Helium Isotope Laboratory Data Release #1, WHOI-79-60.

Linick, T.W. (1975) Uptake of Bomb-Produced Radiocarbon in the Surface Water of the Pacific Ocean. Ph.D. dissertation, University of California, San Diego, 255pp.

Linick, T.W., (1978) La Jolla Measurements of Radiocarbon in the Oceans. Radiocarbon 20, 333-359.

Ostlund, H.G., H.G. Dorsey and R. Brescher (1976) Miami Tritium Laboratory Data Report #5. GEOSECS Atlantic Radiocarbon and Tritium Results.

Ostlund, H.G., Dorsey, H.G., Brescher and Peterson, W.H. (1977) Miami Tritium Laboratory Data Report #6. Ocean Tritium Profile NAGS Cruises, 1972-1973.

Ostlund, H.G., R. Brescher, R. Oleson and M.J. Ferguson (1979) Miami Tritium Laboratory Data Report #8. GEOSECS Pacific Radiocarbon and Tritium Results.

Ostlund, H.G. (1980a) GEOSECS Indian Ocean Final Tritium Results.

Ostlund, H.G. (1980b) GEOSECS Indian Ocean Final Radiocarbon Results, Miami.

Peng, T.-H. and W.S. Broecker (in press) A Model for the Uptake of Bomb ^{14}C, ^{3}H and Fossil Fuel CO_2 by the Main Oceanic Thermocline.

Roether, W., K-O Munnich and H.G. Ostlund (1969) Tritium Profile at the North Pacific GEOSECS Intercalibration Station. J. Geophys. Res. 75, 7672-7675.

Roether, W. (1974) The tritium and carbon-14 profiles at the GEOSECS I (1969) and GOGO I (1971) North Pacific stations. Earth and Planet. Sci. Lett. 23, 108-115.

Stuiver, M. (1980) ^{14}C Distribution in the Atlantic Ocean. J. Geophys. Res. 85, 2711-2718.

Toggweiler, J.R. (1980) Time history of Sr-90 in Pacific surface water as recorded by head-forming corals, abs., EOS (61) p. 984.