A Tritium Box Model of the North Atlantic Thermocline

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ABSTRACT

A box model of 1972 tritium observations on isopycnal surfaces in the main thermocline of the North Atlantic subtropical gyre is used to estimate the time scales and volume of exchange of the thermocline with respect to surface waters. The flux of water between the surface and the thermocline implied by this model ($\sim 40 \times 10^6$ m^3 s^{-1}) greatly exceeds the downward Ekman pumping ($\sim 8 \times 10^6$ m^3 s^{-1}). This suggests that mixing and convective overturning are the dominant mechanisms for exchange between surface waters and the interior geostrophic flow. The flux rate is approximately the same size as conventional estimates of the Sverdrup transport. This suggests that ventilation of the thermocline may occur by recirculation combined with a very efficient exchange across the poleward boundary of the gyre.

1. Introduction

The exchange between the surface mixed layer and thermocline waters of the subtropical gyres plays a major role in tracer uptake and the oceanic heat budget. Observations of bomb-produced tritium in the North Atlantic show that in 1972 more than two-thirds of the tritium, which entered the oceans primarily between 1962 and 1964, was found above 1000 m in the subtropical gyre. Other ocean basins such as the North Pacific have even higher proportions of their tritium in the thermocline because of the absence of significant deep-water formation regions such as exist in the North Atlantic.

Tracer observations provide an important tool for understanding the mechanisms and time scales of mixed layer–thermocline exchange. Jenkins (1980), for example, was able to show that observations in the North Atlantic main thermocline of bomb-produced tritium and its daughter, helium-3, are inconsistent with significant cross-isopycnal exchange. In the same paper he used the tritium and helium-3 data to arrive at estimates of the time scales of exchange of interior thermocline waters with surface waters along isopycnal surfaces.

In the present study the time scales of exchange of thermocline and surface waters along isopycnal surfaces are recalculated using a larger data set representative of the entire subtropical gyre. The interior volumes of reservoirs bounded by surfaces of constant potential density and the areas of their outcrops are computed using the hydrographic data of Levitus and Oort (1977). The combined results make it possible to use the time scales to estimate the apparent *volume* of exchange or replacement rate of interior waters with respect to the mixed layer.

Stommel (1979) discussed the role of the downward pumping of water due to convergent Ekman flow in the mixed layer (Ekman pumping) in the exchange between the mixed layer and the interior geostrophic flow. The exchange rates computed in the present study far exceed the estimated Ekman pumping. Thus it is evident that other processes, such as isopycnal eddy mixing and wintertime convection, dominate the exchange of tracer between the surface mixed layer and the geostrophic flow below. The estimated exchange rates match conventional estimates of the wind driven Sverdrup transport in the subtropical gyre fairly closely and are thus suggestive of ventilation of the isopycnal surfaces by recirculation combined with a very efficient exchange across the poleward boundary of the gyre.

2. Model and results

Observations of tritium on isopycnal surfaces have been discussed by Broecker and Östlund (1979) and Sarmiento *et al.* (1982a). The data used in the present study are illustrated for two density surfaces in Fig. 1 (taken from Sarmiento *et al.*, 1982a). The maps in Fig. 1 show that very little tritium has managed to penetrate south of a broad line at ~15°N. The shallower surface has a nearly uniform distribution whereas the deeper surface has a large scale structure reflecting primarily the entry of tritium from the northwest.

The model used in this study is depicted schematically in Fig. 2. The upper thermocline of the North Atlantic is divided into a series of reservoirs (*interior* boxes), separated by surfaces of constant density. The shallow reservoirs outcrop in the subtropical gyre and

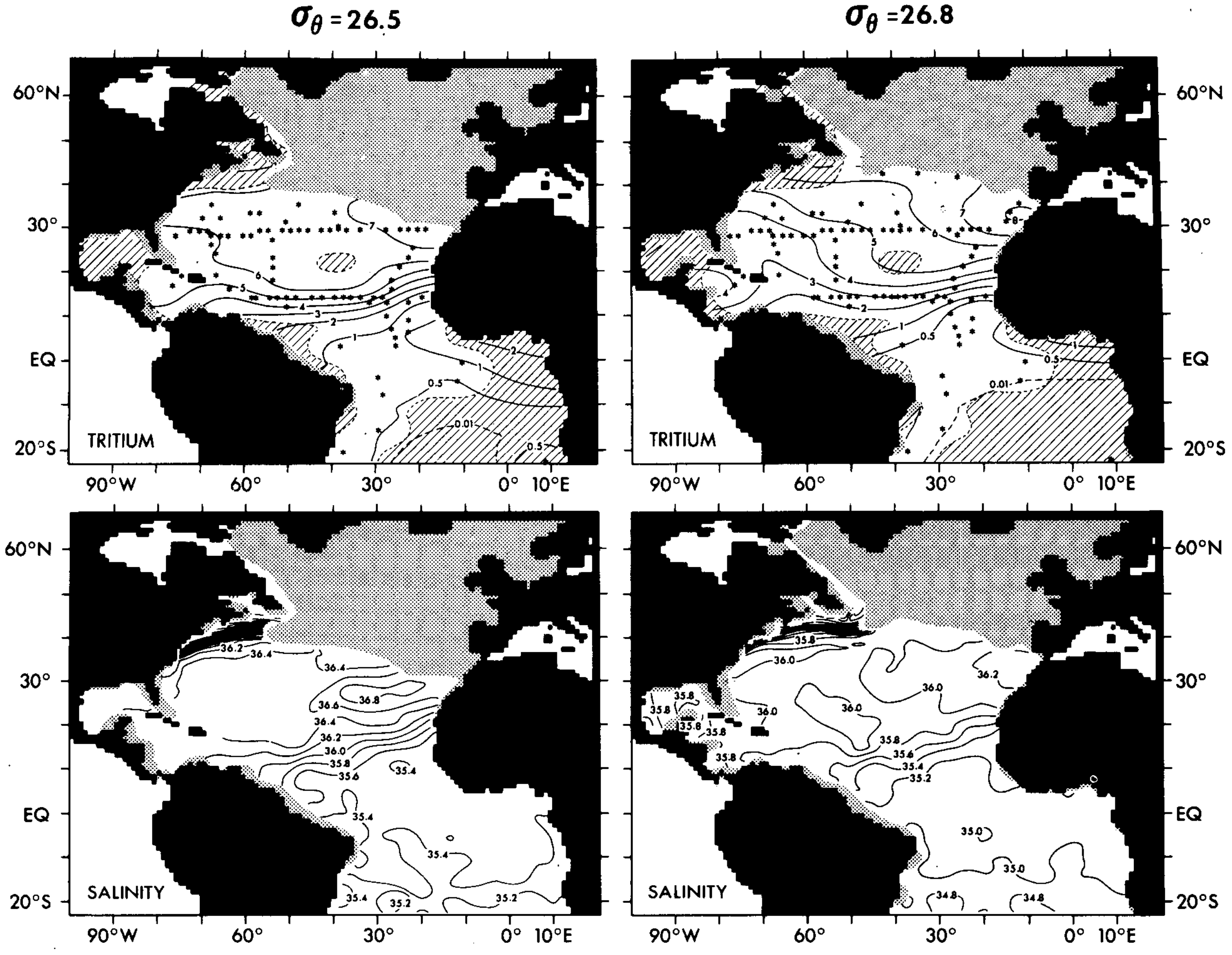

FIG. 1. Maps of salinity and of tritium in 1972 on σ_θ = 26.5 and σ_θ = 26.8 from Sarmiento *et al.* (1982a). The stars indicate the locations of stations used in mapping. Tritium is essentially well mixed on the 26.5 surface within the subtropical gyre. Very little penetration occurs south of the boundary of the gyre in the North Equatorial Current at ~15°N. The distribution of salinity is quite similar to the tritium distribution. The salinity on σ_θ = 26.8 is also well mixed, but the tritium exhibits a large scale structure reflecting entry of tracer from the northwest corner of the gyre. The circulation time scale on this surface is presumably of the same order as the time between the bomb tests and 1972 (~10 years).

deeper reservoirs outcrop in the subarctic gyre (Fig. 3).

The total tracer in a given reservoir is governed by the following equation:

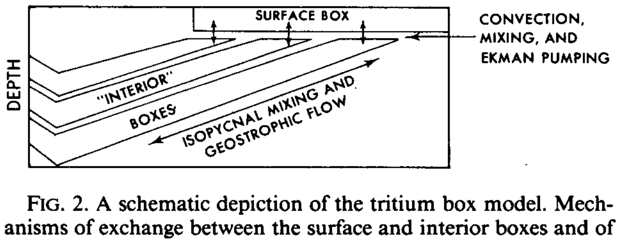

FIG. 2. A schematic depiction of the tritium box model. Mechanisms of exchange between the surface and interior boxes and of spreading on interior boxes are suggested. See further discussion in text.

$$\int\left(\frac{\partial C}{\partial t}+\lambda C\right)dV=-\int \mathbf{n}\cdot(\mathbf{u}C-K\nabla C)dS, \qquad (1)$$

where C is tracer concentration, λ is the decay constant of tritium ($1.79 \times 10^{-9}\ \mathrm{s}^{-1}$), V is volume, $\mathbf{n}$ a unit vector normal to the boundaries of the interior box, $\mathbf{u}$ is velocity, K diffusivity, and S is surface area.

It is assumed that exchange of tracer between an interior box and the rest of the ocean occurs only at the surface outcrop of the box. Any exchange south of 15°N and between interior boxes is ignored. It is further assumed that mass is conserved and that the water entering the interior boxes has a concentration C_s and that the water leaving them has a concentration C_I. Note that it is *not* assumed that the concentration of the interior box is uniform, but rather that the water *leaving* the box has the mean concentration

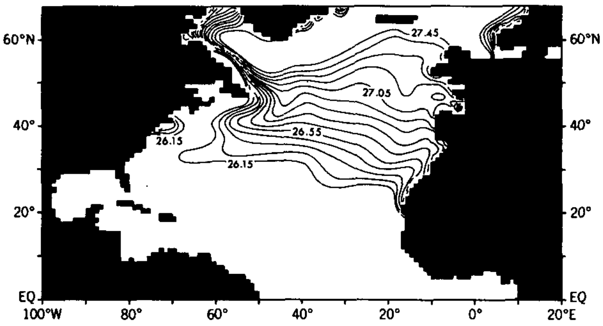

FIG. 3. A map showing the wintertime outcrop of σ_θ's discussed in the paper. Data are from Levitus and Oort (1977) and are averages for the months of February, March, and April.

of the interior C_I. The impact of this assumption on the final results is carefully examined below. The final box model equation is

$$\frac{\partial C_I}{\partial t} = \frac{1}{\tau}(C_s - C_I) - \lambda C_I, \tag{2}$$

where

$$\frac{1}{\tau} = \frac{A_s}{V}\left(u_{av} + \frac{K}{L}\right). \tag{3}$$

In (3) A_s is the area of the surface outcrop; V is now the volume contained in each interior box; u_{av} is the total transport in at the outcrop divided by A_s which is equal to the transport out because of mass conservation; and L is an unspecified length scale that depends on the tracer distribution.

The hydrographic data of Levitus and Oort (1977) have been used to calculate A_s and V for each interior box. The interior boxes cover intervals of $\Delta\sigma_\theta = 0.1$ centered on values of σ_θ between 26.2 and 27.4. The boxes span the thermocline from a mean depth of 140 to 700 m (Table 1). The outcrops used for the interior boxes are those for winter. The tritium observations discussed by Sarmiento *et al.* (1982a) are consistent with the selection of winter waters for the ventilation of interior thermocline waters, and Stommel (1979) has discussed how this selection process might occur. The wintertime outcrops of the interior boxes span a latitude range of approximately 20 to 60°N (Fig. 3), which takes them well up into the subpolar gyre.

The yearly average surface concentration of tritium (C_s) is given as a function of time between 1952 and 1972 by Dreisigacker and Roether (1978). Dreisigacker and Roether discuss evidence suggesting the C_s has been nearly constant at a given time within the entire latitude range we are dealing with here. The C_I is calculated for each box for 1972 from 1971–74 tritium observations as mapped in three dimensions using an objective analysis technique (Sarmiento *et al.*, 1982b). These values will be referred to below as C_I('72).

Eq. (2) is solved by finite difference methods for various values of τ until the correct result for C_I('72) is obtained. The τ which is obtained is a mean value for the period 1952–72 which tends to be weighted towards periods of high $(C_s - C_I)$. In a recent paper, Jenkins (1982) has shown evidence of large interannual variations in ventilation time scales at the Panulirius station in the Sargasso Sea (32.5°N, 64.5°W). His estimates show a minimum in τ at approximately the time of peak C_s. To the extent that the Panulirius station represents the entire subtropical gyre, Jenkins' results thus suggest that the values for τ calculated here may be lower than the climatic average.

One can also calculate an equivalent exchange flux from the volume of water contained in each $\Delta\sigma_\theta$ =

TABLE 1. Data and model results.

					Ekman pumping*							
	Mean depth (m)	C_I('72) (TU)	τ (year)	f ($\times 10^6$ m^3 s^{-1})	Up	Down (10^6 m^3 year^{-1})	Net	V ($\times 10^{15}$ m^3)	A_s (10^{12} m^2)	Mean thickness (m)	Ekman/A_s down (m year^{-1})	f/A_s (m year^{-1})
26.2	140	6.50	7.2	1.6	−0.23	1.65	1.41	0.36	0.88	23	59	57
0.3	150	6.49	7.3	2.1	−0.22	1.39	1.17	0.48	1.04	29	42	63
0.4	180	6.40	7.5	2.7	−0.22	0.79	0.57	0.64	0.83	36	30	100
0.5	210	6.17	8.2	3.8	−0.22	0.73	0.51	0.98	0.82	53	28	150
0.6	250	5.83	9.3	4.1	−0.23	0.71	0.47	1.2	0.86	62	26	150
0.7	300	5.45	11	3.4	−0.25	0.66	0.42	1.1	0.95	56	22	110
0.8	340	5.05	12	3.1	−0.16	0.61	0.45	1.2	0.93	56	21	100
0.9	380	4.77	14	3.1	−0.18	0.44	0.27	1.3	0.91	60	15	110
27.0	430	4.60	15	3.5	−0.14	0.36	0.22	1.6	0.86	69	13	130
0.1	480	4.28	16	3.7	−0.26	0.34	0.08	1.9	1.17	77	9.1	100
0.2	540	3.78	19	3.7	−0.54	0.10	−0.44	2.2	0.92	89	3.4	130
0.3	610	2.78	29	2.6	−0.92	0.06	−0.86	2.4	0.75	92	2.5	110
0.4	700	2.21	39	2.1	−0.75	0.11	−0.64	2.6	0.49	98	7.1	140
Total:				39.5	−4.3	8.0	3.6	18.0	11.41	800	Average: 22	110

* Annual winds, February–March–April outcrops.

0.1 interval:

$$f = \frac{V}{\tau} = A_s\left(u_{av} + \frac{K}{L}\right), \quad (4)$$

and a number which has the units of velocity by dividing f by the area of the outcrop.

$$\frac{f}{A_s} = u_{av} + \frac{K}{L}. \quad (5)$$

The results of the calculations of τ, f and f/A_s are shown in Table 1 and Figs. 4 and 5.

An attempt was made to estimate the sensitivity of f to errors in $C_s(t)$, which is based on a somewhat limited data base (Dreisigacker and Roether, 1978). For a 10% increase in $C_s(t)$, the total f drops from 39.5×10^6 to 33.3×10^6 m^3 s^{-1}, a change of 16%. A 10% decrease in $C_s(t)$ leads to a 24% increase in the total f to 49.1×10^6 m^3 s^{-1}. Similar error ranges are obtained for a 10% decrease of C_I('72) and a 10% increase of C_I('72), respectively. The value of C_I('72) is based on a reasonably solid data base (Sarmiento *et al.*, 1982b) and is not likely to be in error by more than a few percent. The value of $C_s(t)$, however, may be somewhat underestimated in that Dreisigacker and Roether (1978) assume that it is constant everywhere, whereas, there are some indications that $C_s(t)$ may increase at higher latitudes (Sarmiento *et al.*, 1982a). A more realistic estimate of total f may thus be closer to 30×10^6 m^3 s^{-1}. This does not substantially affect the discussion below.

Another possible source of error in the model is in the assumption that the water leaving the box has a concentration equal to the average C_I. If the water leaving the box has a lower concentration, the values of f given in Table 1 would be too high. A calculation was thus done in which the water leaving the box was assumed to have a concentration of zero. The total f thus obtained was 25×10^6 m^3 s^{-1}. Again, this value is high enough that the discussion below is not substantially affected.

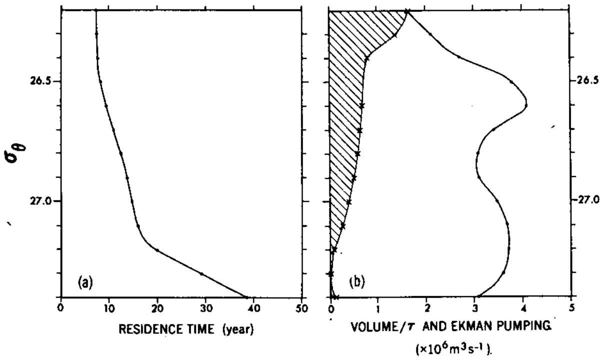

FIG. 4 (a) The residence times calculated from the model. (b) The exchange rate calculated from the model and the Ekman pumping calculated from the wind stress (cross-hatched).

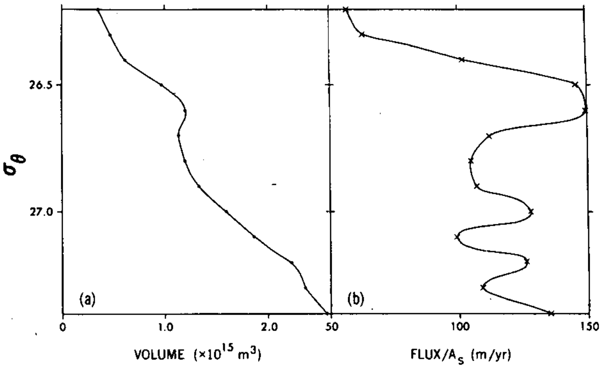

FIG. 5 (a) The volume of $\Delta\sigma_\theta$ intervals of 0.1 from $\sigma_\theta = 26.15$ to 27.45, and (b) the f/A_s's calculated from the model for these density intervals.

Jenkins (1980) has done a calculation of τ equivalent to the one done here using data from a single location: the Panulirius station at 32.5°N, 64.5°W. He also had measurements of He-3, the tritium daughter product. Jenkins obtains much faster ventilation time scales (<1 year) for $\sigma_\theta < 26.5$ because his data are quite near the wintertime outcrop regions of these density surfaces and are not representative of the mean concentrations on the isopycnals. For $\sigma_\theta > 26.8$, his ventilation time scales are as much as twice those calculated here because, as one can see in Fig. 1, these surfaces are not homogeneous in tritium and the concentrations at Panulirius under-represent the mean values. Between $\sigma_\theta = 26.5$ and 26.8 his values agree with those given here.

3. Discussion

The 1972 North Atlantic tritium observations require that the subtropical gyre main thermocline between 140 and 700 m exchange with surface waters at a rate that is equivalent to a flux of the order of (30–40) $\times 10^6$ m^3 s^{-1} (Table 1). This coincides with the volume of the wind-driven Sverdrup transport in the region (Leetmaa and Bunker, 1978); and suggests that the recirculation within the gyre, coupled with a very efficient exchange across the poleward boundary of the gyre, plays the major role in ventilating the main thermocline.

The recent papers by Luyten, Pedlosky and Stommel (1983a,b) are helpful in understanding the redistribution processes on isopycnal surfaces. They depict three regions within the subtropical gyre that are best characterized in terms of the structure of potential vorticity. The region they focus most attention on is the "ventilated thermocline." The potential vorticity contours in this region outcrop directly at the surface, and it can thus receive water directly from the mixed layer by Ekman pumping. The water columns that flow through the wintertime outcrop regions of the isopycnals are not completely volumetrically renewed with water pumped down from the mixed layer by Ekman convergence. Their tracer properties may, however, be completely renewed by convective overturning.

In the northwestern quadrant of the subtropical gyre is the "pool" region within which the potential vorticity contours close on themselves. This region may correspond to the gyre as depicted by Rhines and Young (1982). The third region is the "shadow" zone, which lies to the southeast and south of the ventilated region. Potential vorticity contours within this region intersect the sides of the basin.

The potential vorticity structure depicted by Luyten *et al.* (1983a) is supported by observations as discussed by Sarmiento *et al.* (1982a) and McDowell *et al.* (1982). The implication of the potential vorticity structure in the pool and shadow regions is that they can only exchange with the surface or the ventilated region by mixing. Luyten *et al.* (1983b) give estimates from Armi and Stommel (1983) showing that the time scales of diffusive exchange between the surface and the shadow zone (~300 years) is an order of magnitude longer than the time scale of exchange between the surface and the ventilated region (~30 years). They do not discuss exchange between the unventilated pool in the northwest and the ventilated region and/or the surface.

Observations of tritium on isopycnal surfaces as discussed by Broecker and Ostlund (1979) and Sarmiento *et al.* (1982a) are consistent with the existence of a shadow zone to the south of the subtropical gyre. The tritium maps in Fig. 1 show that very little tritium has managed to penetrate south of a broad line at ~15°N. However, the pool region in the northeastern quadrant of the gyre is evidently receiving tritium at a rate which is just as rapid as that of the ventilated thermocline. The tritium distribution on the density levels shown in Fig. 1, as well as below them, show no evidence of low tritium values in the pool region. Jenkins (1980) and Sarmiento *et al.* (1982a) have provided arguments suggesting that entry of tritium into the northeastern portion of the subtropical gyre is probably by eddy exchange with higher latitude waters in the region of the Gulf Stream front. Gordon (1981) has discussed the importance of the poleward overshoot of the western boundary poleward current in contributing to the thermocline ventilation in this region.

The volume of downward Ekman pumping as calculated from the annual mean wind stresses of Hellerman (1967) acting on the wintertime outcrop regions of the isopycnals is $\sim 8 \times 10^6$ m^3 s^{-1} (Table 1). The Ekman flux is represented by the $A_s u_{av}$ term in Eq. (4). If the Ekman pumping is equivalent to 8×10^6 m^3 s^{-1}, the $A_s K/L$ term, which represents processes other than pumping, is clearly dominant at a magnitude of the order of $(20\text{–}30) \times 10^6$ m^3 s^{-1}. Fig. 4b shows that the Ekman pumping flux is important only in the shallowest part of the main thermocline.

Also shown in Table 1 and Fig. 5b are f/A_s values for each potential density interval. The top two isopycnal surfaces have f/A_s values of the order of 60 m year^{-1}, approximately half that of most other isopycnal surfaces. It is possible that at these shallower surfaces there is some loss of tritium across the 15°N front. In such a case, the f calculated here would be a lower limit. At $\sigma_\theta = 26.5$ and 26.6, f/A_s reaches a peak value of 150 m year^{-1}, probably related to the fact that these isopycnals are those on which the Eighteen Degree Water is found (Worthington, 1959). The effect of the Eighteen Degree Water on the volume contained in each density interval can be readily discerned in Fig. 5a. Below these densities, f/A_s fluctuates around ~115 m year^{-1}, which can be compared with an Ekman pumping of the order of 20 m year^{-1}.

Table 1 shows the upward as well as downward Ekman pumping. The upward pumping occurs primarily along the western edge of the subtropical gyre and in the subpolar gyre. The imbalance between the total upwelling and downwelling (3.6×10^6 m^3 s^{-1}, downwelling) is not negligible and must be balanced by flow across the other boundaries of the boxes. However, this net flow is small enough not to affect the conclusions of this paper. The deeper density surfaces have a substantial net upwelling. The author has made no attempt here to look at the various isopycnal surfaces independently of each other, but clearly these Ekman pumping calculations deserve more detailed attention. The tritium and other data indicate a transition at $\sigma_\theta \sim 27.3$ and below to waters that are ventilated at a slower rate (Jenkins, 1980; Sarmiento *et al.*, 1982a; Luyten *et al.*, 1983b) then above. A likely explanation is that these density surfaces outcrop within the subpolar gyre where upwelling is dominant. Any tracer entering from the subpolar gyre must cross the boundary between the subpolar and subtropical gyres in order to enter the subtropical gyre.

The application of the present model to problems such as the uptake by the oceans of fossil fuel CO$_2$ is straightforward and should prove instructive when compared with the one dimensional diffusion models usually used in such studies. The direct exchange of surface with interior waters has been used to model deep ocean processes (e.g., Craig, 1958; Broecker *et al.*, 1971; Björkström, 1979; Hoffert *et al.*, 1981) but only recently has there been an attempt to use such an approach in the thermocline as well (Jenkins, 1980; MacDonald *et al.*, 1980). The new set of tritium and other tracer measurements being obtained at the present time by the Transient Tracers in the Oceans project will make it possible to place even tighter constraints on calculations such as those given here.

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REFERENCES

Armi, L., and H. Stommel, 1983: Four views of the North Atlantic subtropical gyre. *J. Phys. Oceanogr.*, **13,** 828–857.

Björkström, A. A., 1979: A model of CO_2 interaction between atmosphere, oceans and land biosphere. *SCOPE 13, The Global Carbon Cycle,* B. Bolin *et al.*, Eds., Wiley, 403–475.

Broecker, W. S., and H. G. Östlund, 1979: Property distribution along the $\sigma_\theta = 26.8$ isopycnal in the Atlantic Ocean. *J. Geophys. Res.*, **84,** 1145–1154.

——, Y.-H. Li and T.-H. Peng, 1971: Carbon dioxide—Man's unseen artifact. *Impingement of Man on the Oceans,* D. W. Hood, Ed., Wiley, 287–324.

Craig, H. A., 1958: A critical evaluation of mixing rates in the oceans and atmosphere by use of radiocarbon techniques. *Proc. Second Int. Conf. Peaceful Uses of Atomic Energy,* Vol. 18, United Nations, Geneva, 358–363.

Dreisigacker, E., and W. Roether, 1978: Tritium and ^{90}Sr in North Atlantic surface water. *Earth Planet. Sci. Lett.*, **38,** 301–312.

Gordon, A. L., 1981: South Atlantic thermocline ventilation. *Deep Sea Res.*, **28A,** 1239–1264.

Hellerman, S., 1967: An updated estimate of the wind stress on the World Ocean. *Mon. Wea. Rev.*, **95,** 607–626. [Corrigendum (1968), **96,** 63–74.]

Hoffert, M. I., A. J. Callegari and C.-T. Hsieh, 1981: A box-diffusion carbon cycle model with upwelling, polar bottom water formation and a marine biosphere. *SCOPE 16, Carbon Cycle Modelling,* B. Bolin, Ed., Wiley, 287–306.

Jenkins, W. J., 1980: Tritium and ^{3}He in the Sargasso Sea. *J. Mar. Res.*, **38,** 533–569.

——, 1982: On the climate of a subtropical ocean gyre: Decade timescale variations in watermass renewal in the Sargasso Sea. *J. Mar. Res.*, **40**(Suppl.), 265–290.

Leetmaa, A., and A. F. Bunker, 1978: Updated charts of the mean annual wind stress, convergences in the Ekman layers and Sverdrup transports in the North Atlantic. *J. Mar. Res.*, **36,** 311–322.

Levitus, S., and A. H. Oort, 1977: Global analysis of oceanographic data. *Bull. Amer. Meteor. Soc.*, **58,** 1270–1284.

Luyten, J. L., J. Pedlosky and H. Stommel, 1983a: The ventilated thermocline. *J. Phys. Oceanogr.*, (in press).

——, —— and ——, 1983b: The climatic inferences from the ventilated thermocline. *Climatic Change* (in press).

MacDonald, G., H. Abarbanel, J. Chamberlain, F. Dyson, H. Foley, N. Fortson, W. Happer, W. Munk, W. Nierenberg, O. Rothaus, M. Ruderman, S. Treiman, J. Vesecky and F. Zachariasen, 1980: The long term impacts of increasing atmospheric carbon dioxide levels. Tech. Rep. JSR-79-04, SRI International, Arlington, VA, 111–141.

McDowell, S. E., P. B. Rhines and T. Keffer, 1982: North Atlantic potential vorticity and its relation to the general circulation. *J. Phys. Oceanogr.*, **12,** 1417–1436.

Rhines, P. B., and W. R. Young, 1982: A theory of the wind-driven circulation. I: Mid-ocean gyres. *J. Mar. Res.*, **40**(Suppl.), 559–596.

Sarmiento, J. L., C. G. H. Rooth and W. Roether, 1982a: The North Atlantic tritium distribution in 1972. *J. Geophys. Res.*, **87,** 8047–8056.

——, J. Willebrand and S. Hellerman, 1982b: Objective analysis of tritium observations in the Atlantic Ocean during 1971–1974. Tech. Rep. 1, Ocean Tracers Lab., Dept. of Geol. and Geophys. Sci., Princeton University, 19 pp.

Stommel, H., 1979: Determination of water mass properties of water pumped down from the Ekman layer to the geostrophic flow below. *Proc. Nat. Acad. Sci. U.S.A.*, **76,** 3051–3055.

Worthington, L. V., 1959: The 18° water in the Sargasso Sea. *Deep Sea Res.*, **5,** 297–305.