

TRITIUM AND HELIUM 3 IN THE NORTHEASTERN ATLANTIC OCEAN DURING THE 1983 TOPOGULF CRUISE

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Abstract. This study is part of the TOPOGULF program, in which tracer measurements were closely associated with the hydrological data. The sampled area was located near the Azores Islands on the both sides of the Mid-Atlantic Ridge. The tritium content of the surface waters reveals a strong front along the Azores current. The ^3He distributions are used to identify some areas where ventilation processes are active. At depth, the spatial distribution of tritium is studied along isopycnals. In the thermocline it is essentially the anticyclonic gyre which is responsible for the northeast-southwest gradient in tritium concentrations. The respective influences of the Labrador Sea Water and the Mediterranean Water are noticeable through the tritium data. The Mediterranean Water seems to be an end member responsible for a decrease of the tritium contents in the north and for an increase in the south, by mixing. A quantitative approach using a mixing model is used to check the validity of the ^3He - ^3H "age." The model leads to two extreme values of the time scales for the middepth circulation in the studied area: 35 years for the ventilation time of the Labrador Sea Water and around 200 years for the residence time of the oldest waters in the southeastern area.

Introduction

Previous studies of the chemical and transient tracer distributions in thermoclinal and middepth North Atlantic waters have shown that transport into the subtropical anticyclonic gyre is essentially governed by isopycnal processes [Sarmiento et al., 1982; Jenkins, 1982; Kawase and Sarmiento, 1985, 1986]. The simultaneous use of tritium and its radioactive daughter ^3He is particularly suited to the study of the water mass transport and the ventilation processes and to deduction of interior ocean travel times [Jenkins, 1980, 1987; Thiele et al., 1986; Fuchs, 1987].

This study is based on measurements carried out on samples taken during the TOPOGULF cruise in July-August 1983. In the first section of this paper we briefly describe the experimental procedures. We report in the second section the ^3He and tritium distributions using isopycnal charts and diagrams of tracers versus hydrological data in order to examine the importance of ventilation processes and to identify the contributions of different water masses. In the third section we discuss the validity of the tritium input functions for the surface waters of the North Atlantic [Dreisigacker and Roether, 1978;

Broecker et al., 1986] compared to the whole data set available from 1965 to 1985. We use an "observed" tritium distribution versus time for the northeast Atlantic surface waters in order to run a simple mixing model, and we discuss our ^3He -tritium data compared with the output of the model. The tritium- ^3He "age" is compared with our computed values of ventilation times of some water masses.

Field Work and Experimental Procedure

One of the aims of the TOPOGULF program was to evaluate the zonal transport between the western and eastern basins of the North Atlantic above the Mid-Atlantic Ridge (MAR) at mid-latitudes and to add an important set of hydrological and tracer data for the central Atlantic [Institut für Meereskunde (IFM), 1986]. In this context, 240 samples have been collected for ^3He and tritium measurements.

Figure 1 shows the stations sampled during the TOPOGULF cruise. They are located in the area 24°N - 40°N , 23°W - 50°W near the Azores Islands, along the eastern and western flanks of the Mid-Atlantic Ridge and perpendicular to it.

The shaded areas on Figure 1 correspond to the water outcropping locations of the 25.6, 26.5, and 26.8 σ_θ levels determined from historical wintertime temperature data from Sarmiento et al. [1982]. In the TOPOGULF area these outcrops are identical to those redetermined by Thiele et al. [1986].

Helium 3 data were obtained by mass-spectrometric measurements as well as tritium concentrations which are determined by the ^3He regrowth technique. The experimental procedure and accuracy of measurements are reported elsewhere [Andrié, 1987; Jean-Baptiste et al., 1988] and are basically those described by Clarke et al. [1976] and Jenkins [1981].

The ^3He data are reported in $\delta^3\text{He} \%$ (Figures 2 and 3), i.e. the deviation of the isotopic ratio of the sample $^3\text{He}/^4\text{He}$ from the standard isotopic ratio of the atmosphere ($R_a = 1.384 \times 10^{-6}$), expressed in percentage:

$$\delta \text{ \%} = \left[\frac{(^3\text{He} / ^4\text{He})_{\text{sample}}}{(^3\text{He} / ^4\text{He})_{\text{air}}} - 1 \right] \times 100$$

The tritiumgenic ^3He concentrations $^3\text{He}_{\text{tri}}$, expressed in $\text{cm}^3\text{STP/g}$ of seawater, are obtained by subtracting the ^3He value corresponding to the isotopic equilibrium value in seawater from the total amount of ^3He in the sample [Weiss, 1971; Benson and Krause, 1980].

Tritium concentrations (Figures 2 and 3) are expressed in tritium units, or TU (1 TU represents 1 tritium atom for 10^{18} hydrogen atoms) or

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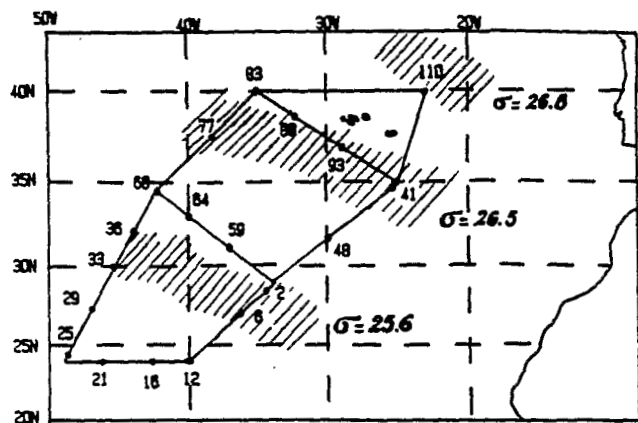


Fig. 1. Map of the TOPOGULF cruise. Numbers show position of stations. The shaded areas correspond to the water outcropping locations of the 25.6, 26.5 and 26.8 σ_t levels.

in TU 81N (Figure 3) (i.e. tritium contents normalized to January 1, 1981 [Ostlund, 1984]).

Typically, when these analyses were done, the data accuracy was $\pm 0.25\%$ for $\delta^3\text{He}$ and ± 0.2 TU for tritium [Andrié, 1987]; since then, some changes in our analytical procedure have been carried out (ion counting system for ^3He , lower blank, automation), and so the accuracy of our data has been improved.

We shall discuss in the following the validity

of the tritium- ^3He "age" (called A) for the study of the middepth water circulation. The reported age values A have been computed from

$$A = \lambda^{-1} \ln \left(1 + \frac{^3\text{He}}{^3\text{H}} \right)$$

where λ is the decay constant for tritium (0.0557 y^{-1}) and ^3He and ^3H are the respective ^3He and tritium contents of the sample (expressed in numbers of atoms).

Water samples were drawn from Niskin bottles into copper tubes ($\sim 40 \text{ cm}^3$). Usually, 12 samples were collected for each station at 10, 40, 70, 100, 200, 350, 500, 650, 800, 1000, 1500 and 2000 m depth. In the next section, as the North Atlantic distribution of tritium is controlled largely by winter outcropping and isopycnal advection processes, we shall study the distributions of tritium and ^3He along six isopycnal levels previously used by Sarmiento et al. [1982]: surface, 25.6, 26.5, 26.8, 27.1, and 27.4 relative to the thermocline and middepth Atlantic waters.

For each isopycnal we calculate the corresponding $\delta^3\text{He}$ and tritium contents using linear interpolations between sampled levels. In addition, we use for each isopycnal the hydrological data (temperature, salinity and oxygen) available from IFM [1986] and the vorticity values computed by M. Arhan (personal communication, 1987). Figure 4 shows the correspondence between depth

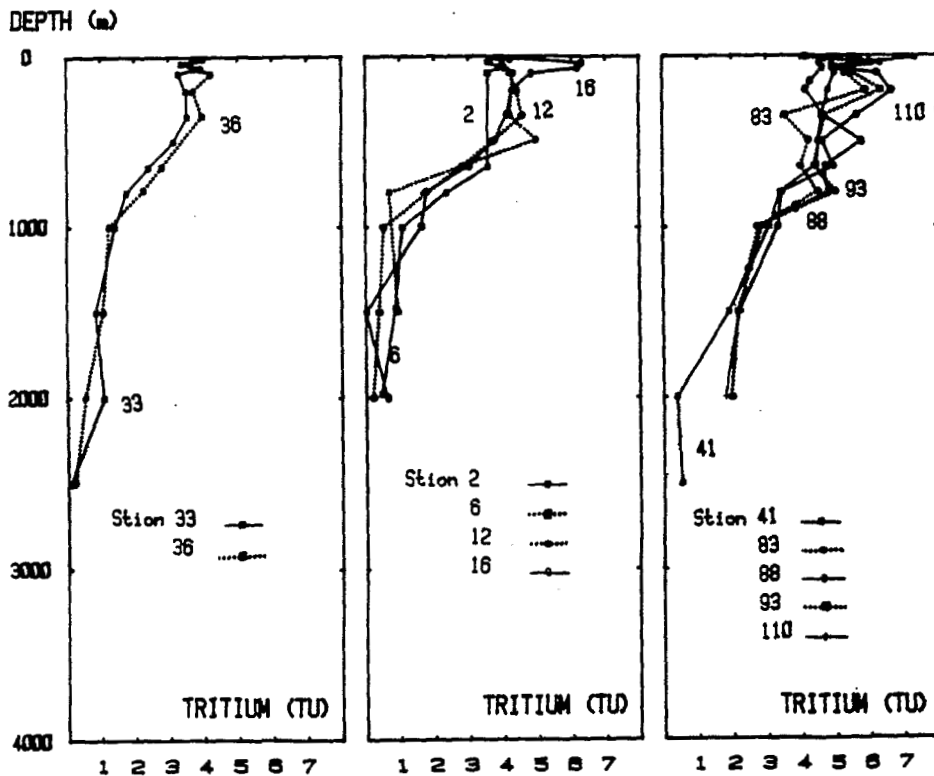


Fig. 2a

Fig. 2. Profiles of (a) tritium versus depth and (b) ^3He versus depth for the southwestern (33 and 36), southeastern (2, 6, 12, and 16), and northern (41, 83, 88, 93, and 110) stations.

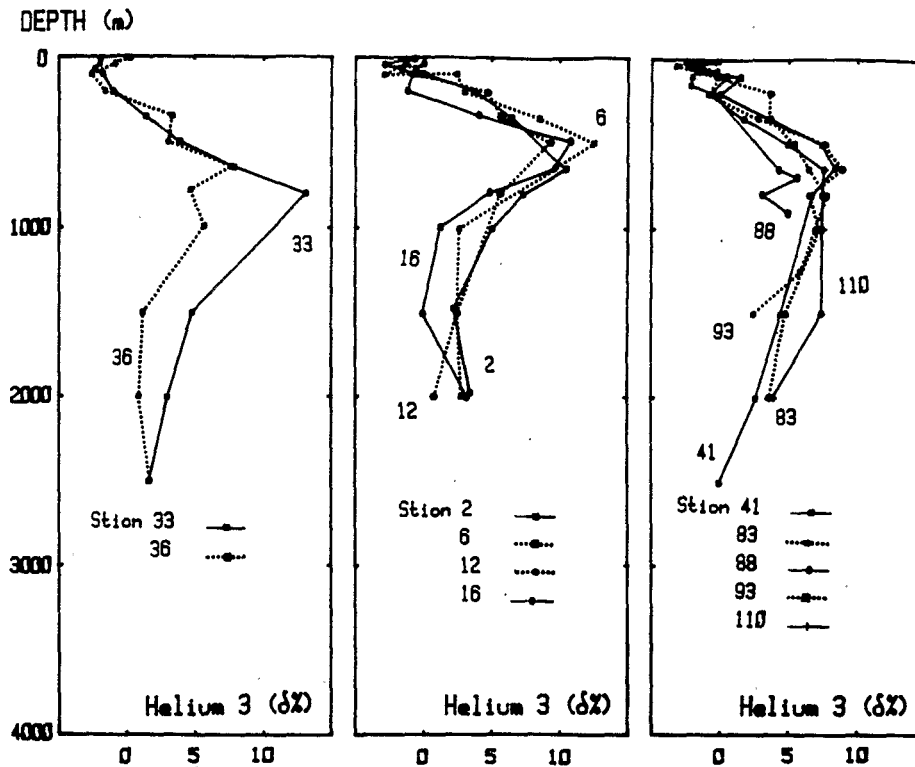


Fig.2b

and σ_θ levels for the eastern track of the cruise [from IFM, 1986].

Results and Discussion

The data are reported in Table 1. In Figure 2, profiles of tritium and ^3He versus depth are presented for TOPOGULF stations. They have been split into three groups on the basis of their geographic location (southwest, southeast and north). These profiles reflect the opposite boundary conditions for tritium and ^3He at the atmosphere-ocean interface. The ^3He maximum observed in the 600-700 m range, located just under the tritium maximum, results from the trade-off between the ^3He evasion through ventilation or convection processes and the tritium penetration which generates ^3He with time.

Figure 3 gives the ^3He ($\delta^3\text{He}$) and tritium (TU81N) distributions along the six isopycnal levels within the TOPOGULF area. The four first levels outcrop during winter within the subtropical anticyclonic gyre; the last one outcrops in the subarctic gyre [Sarmiento et al., 1982]. In the following, we successively discuss the $\delta^3\text{He}$ and tritium distributions along these isopycnal levels using hydrological data such as salinity, vorticity, and oxygen in order to identify the water masses and to determine the importance of ventilation processes and "aging."

Surface and 25.6 isopycnal levels. For the surface and for the first 25.6 isopycnal level the mean $\delta^3\text{He}$ values obtained for the samples over the whole TOPOGULF area are -1.21% and -1.44%, respectively (Figure 3). These values are somewhat higher than the solubility equilibrium

value of -1.7% from Benson and Krause [1980]. Our observed excess ^3He in the ocean surface layer agrees with the reported values of Fuchs et al. [1987] and are essentially due to the summer erosion of the surface layer. Everywhere in the TOPOGULF area, the 25.6 isopycnal level is within the mixed layer.

We observe a very homogeneous tritium content of the surface waters in the area located south of 34°N with a mean measured value of 4.5 TU81N (standard deviation ± 0.15 TU). In contrast, northern stations show a higher and less homogeneous tritium concentration. This difference in the surface tritium content between southern and northern stations reflects the existence of the subtropical front (the Azores front) near 35°N [Worthington, 1962; Käse et al., 1986; Krauss, 1986]. The front is well defined during the TOPOGULF cruise (Figure 4) by the sharp gradient in the density field near station 41 [IFM, 1986]. Such a general trend of increasing surface tritium concentration with latitude in the 20°N - 50°N range has been previously reported [Weiss and Roether, 1980; Jenkins, 1982; Broecker et al., 1986; Thiele et al., 1986]. Nevertheless, the exact reason for the specially high tritium value at station 41 is not clear. Similar features were observed during the Geochemical Ocean Sections Study (GEOSECS) (station 3 [from Ostlund, 1984]) and Transient Tracers in the Ocean (TTO) (stations 224, 225 [from Ostlund and Grall, 1987]) cruises. The higher tritium variability in the northern stations is probably linked to the mesoscale eddies created by the Azores front north of 35°N [Käse and Siedler, 1982; Kielmann and Käse, 1987].

In the subsurface (25.6 isopycnal level) we

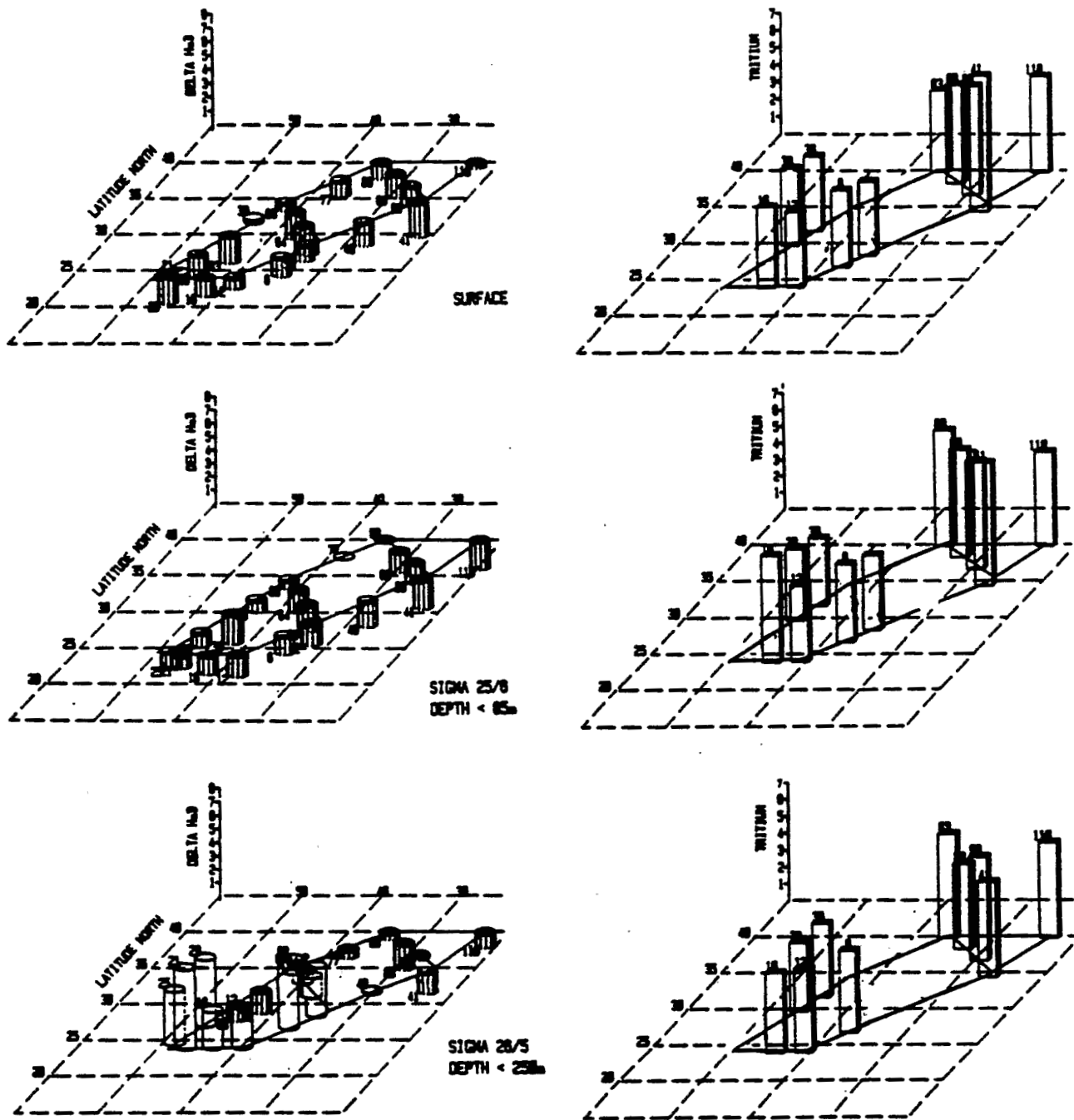


Fig. 3a

Fig. 3. Helium 3 and tritium distributions (hatched columns are used for negative $\delta^3\text{He}$ values) for (a) the surface and the 25.6 and 26.5 isopycnal levels and (b) the 26.8, 27.1, and 27.4 isopycnal levels. Numbers identify the sampled stations (see Figure 1).

observe a puzzling layer of enriched tritium in station 16. This enrichment cannot be an artifact because it encompasses four data points (Figure 2). Such an anomaly has been recently reported by Nies [1988] in a different area (47.5°N , 20°W) with a tritium concentration increasing from 3.8 TU at the surface to 7.5 TU at 300 m and correlated with a ^{90}Sr anomaly. In both cases, the origin of this anomaly cannot be clearly determined.

The 26.5 isopycnal level. The 26.5 isopycnal level is the first one for which positive $\delta^3\text{He}$ values appear in the south (Figure 3). Nevertheless, we observe negative $\delta^3\text{He}$ values for stations 33 and 36 in the southwest (equal to -1.0% and -1.5% , respectively). In addition, the $\delta^3\text{He}$ -vorticity and $\delta^3\text{He}$ -oxygen diagrams in Figure 5 show that these negative values are correlated with low vorticity and high oxygen values. These features identify the 18°C Mode Water [Mc

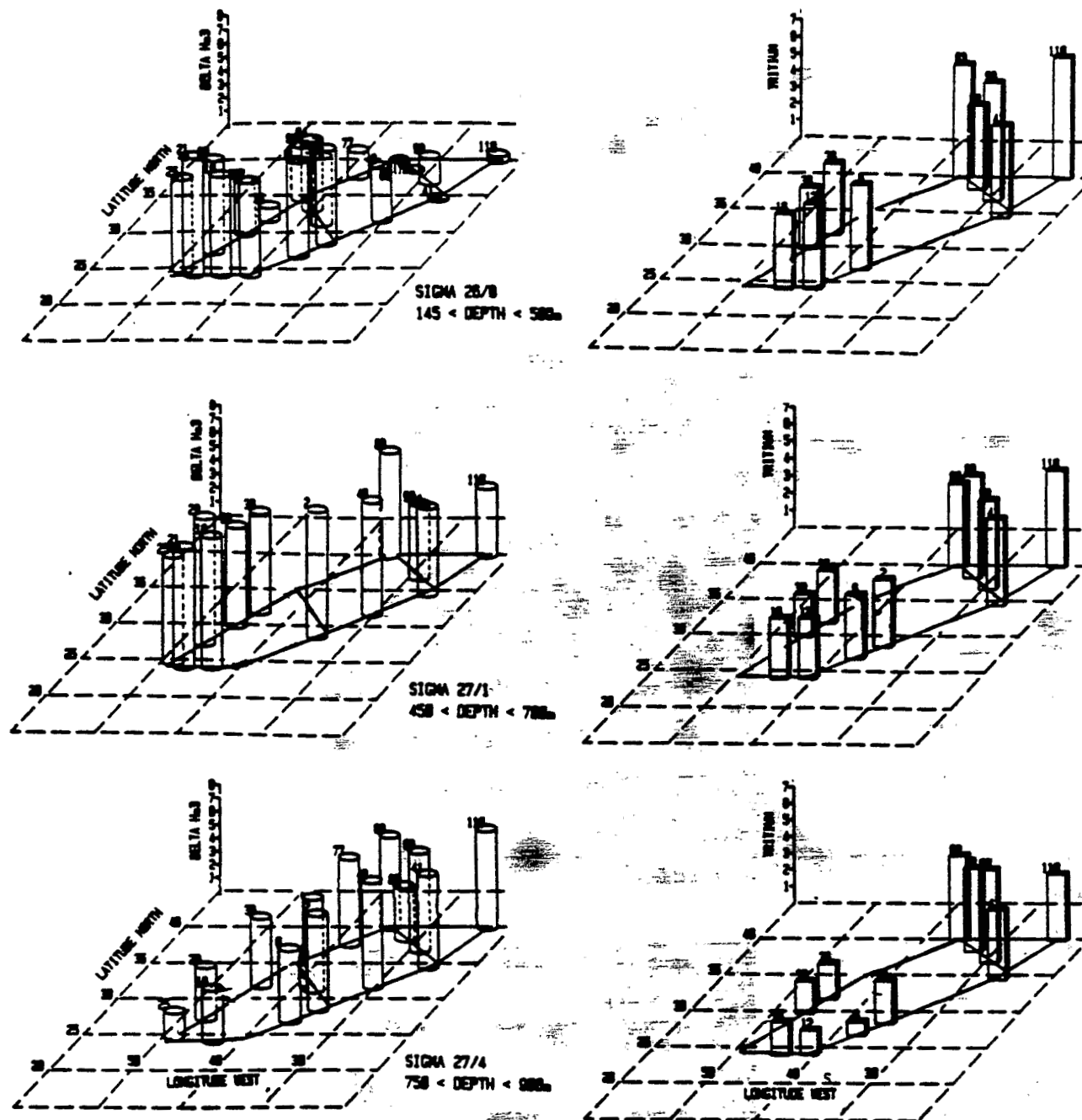


Fig. 3b

Cartney, 1982] in this area. Helium 3 is a powerful tool for this identification, as this tracer is sensitive to the age of the mode water when vorticity or oxygen stay nearly constant during the displacement of the water mass. The observed $\delta^3\text{He}$ values for stations 33 and 36 ($\sim -1.4\%$) are close to the atmospheric equilibrium value, and we can conclude that the 18°C Mode Water here comes from recent convection.

For the tritium distribution in the south, we observe higher tritium contents than in the surface layer (stations 6, 12, and 16). We note in Figure 1 that the 26.5 isopycnal level outcrops north of the Azores front during winter, in a tritium enriched area. This subsurface maximum

most likely results from the southwestward isopycnal transport of these tritium enriched waters. As we shall see for the next isopycnal level, the west-east asymmetry in the south is due to the effect of the anticyclonic gyre on the water circulation. On the 26.5 isopycnal level, vertical mixing with surface waters in stations 33 and 36 (18°C Mode Water formation) can also be responsible for lower tritium content in the west than in the east.

The 26.8 isopycnal level. The tritium distribution on the 26.8 isopycnal level (Figure 3) shows a tritium increase for the northern stations 83, 93, and 110. These subsurface maxima are well defined in the tritium-depth profiles in

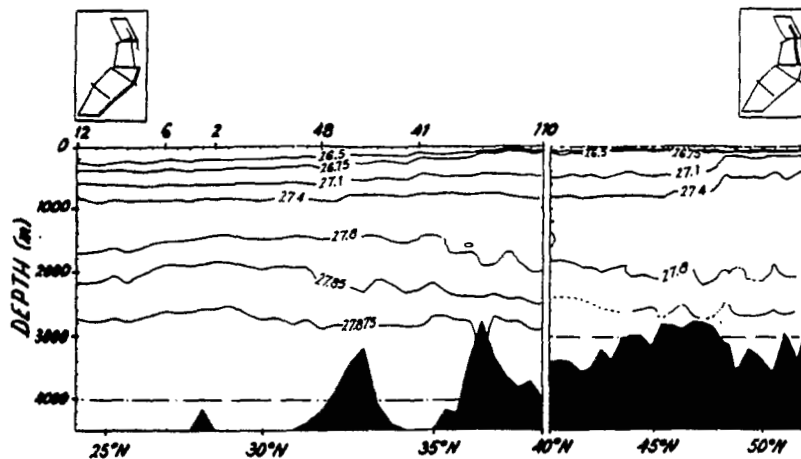


Fig. 4. Distribution of σ_0 versus depth along the eastern track of the cruise (the northern track, not sampled for tritium and ^3He , is given for the continuity of the hydrological situation).

Figure 2a ($100 < z < 200$ m). The 26.8 isopycnal is the first one for which the wintertime outcrop is located north of the sampled area, near 50°N . As was mentioned by Broecker and Ostlund [1979], the tritium distribution on the 26.8 isopycnal level is consistent with the location of its wintertime outcrop and an advective flow along this horizon in the thermocline. In the south, we observe the same west-east asymmetry as for the 26.5 level, principally due to the water traveling around the gyre.

The 27.1 isopycnal level. The 27.1 isopycnal level corresponds to the Basal Thermocline Water where the water masses are very homogeneous ($T = 12.5^\circ\text{C}$, $S = 35.64\%$) and are principally composed of Subpolar Mode Water or Subarctic Water [Harvey, 1982; McCartney and Talley, 1982]. Figure 3 clearly indicates the northeast-southwest asymmetry of the tritium distribution which suggests that gyre scale circulation has dominated the transient tracer redistribution process. From such a pattern, we can roughly evaluate the advection rate of the flow from northeast to southwest. The tritium content of 4.6 and 3 TU for stations 110 and 12, respectively, leads to a transit time of around 7.5 years (i.e., an advection rate of 1 cm s^{-1} assuming a purely isopycnal advection process).

The 27.4 isopycnal level. The 27.4 isopycnal level does not outcrop during winter into the subtropical gyre [McCartney and Talley, 1982]. The tritium-oxygen diagram (Figure 6a) indicates that the tritium-enriched stations 83, 88, and 93 have a Labrador Sea Water component characterized by a high oxygen content [Talley and McCartney, 1982]. Such a tritium enrichment associated with the Labrador Sea Water has been previously reported by Jenkins and Clarke [1976] and is noticeable in TPO data for the Labrador Sea [Ostlund and Grall, 1987]. On the other hand, the tritium-salinity diagram (Figure 6b) shows a Mediterranean input for stations 110 and 41 with higher salinities and lower tritium content. Tritium data from the 1981 PHYCEMED cruise [Andrié and Merlivat, 1988] are available in the Mediterranean Sea near Gibraltar (Alboran Sea). Using the assumption of Roether and Weiss [1975]

for a 2/3, 1/3 mixing of Deep Occidental Water and Levantine Intermediate Water to make the Mediterranean outflow, we estimate a tritium content in Gibraltar equal to 2.2 TU81N. Such a Mediterranean input in the east has been reported in the β triangle tritium data [Jenkins, 1987].

TABLE 1. Tritium and ^3He Data of the TOPOGULF Samples

Depth, m	Density, ‰	Tritium, TU	^3He , ‰
<u>Station 2</u>			
40	25.4177	n.d.	-0.01
70	26.0003	3.84	-0.61
97	26.1721	3.53	-0.47
100	26.1648	3.56	-0.04
198	26.5182	n.d.	3.71
348	26.7462	n.d.	6.46
649	27.1928	3.56	10.46
798	27.3717	2.36	7.31
1002	27.5990	1.07	5.04
1472	27.8118	0.86	2.18
1977	27.8583	0.47	3.43
<u>Station 6</u>			
40	25.4710	3.97	-1.35
100	26.1387	4.28	-0.09
204	26.5304	n.d.	4.66
344	26.7217	4.19	5.65
491	26.9389	4.96	9.26
644	27.1613	2.80	n.d.
798	27.3673	0.70	5.61
1497	27.8038	0.94	2.46
1999	27.8606	n.d.	2.75
<u>Station 12</u>			
10	25.0951	3.87	-0.71
35	25.1032	3.56	n.d.
99	26.0539	4.18	2.40
203	26.4949	4.39	2.94
350	26.7623	4.56	8.49
500	27.0018	3.71	12.52
1003	27.5300	0.53	2.61
1499	27.7556	0.39	2.44
2001	27.8434	0.21	0.76

TABLE 1. (continued)

Depth, m	Density, ‰	Tritium, TU	$\delta^3\text{He}$, ‰
<u>Station 16</u>			
10	25.0288	4.19	-1.24
40	25.0285	6.28	-2.90
70	25.4635	6.17	-1.60
100	25.7353	4.81	-0.82
200	26.3219	4.24	-1.21
342	26.6103	4.11	4.08
489	26.8914	3.78	10.80
642	27.1315	3.01	9.62
791	27.3257	1.78	4.86
995	27.5007	1.62	1.20
1502	27.7455	0.01	-0.10
2002	27.8282	0.63	3.18
<u>Station 33</u>			
10	23.9533	3.99	-1.94
40	25.1887	3.65	-2.00
70	25.9998	3.73	-2.36
99	26.2267	3.28	-1.75
201	26.4423	3.51	-0.97
349	26.5984	3.54	1.44
499	26.7918	3.13	3.90
649	27.0322	2.39	7.87
799	27.3111	1.74	13.13
997	27.5756	1.42	n.d.
1498	27.8146	0.85	4.79
2000	27.8543	1.08	2.96
2500	27.8700	0.07	1.61
<u>Station 36</u>			
10	24.1967	3.87	0.27
40	25.4477	3.37	-0.82
70	26.1839	3.93	n.d.
100	26.4018	4.20	-1.60
199	26.5304	3.71	-1.59
347	26.6712	3.97	3.34
499	26.8935	n.d.	3.04
645	27.0895	2.78	7.66
781	27.2862	2.25	4.69
995	27.5616	1.25	5.68
1497	27.7963	1.06	1.19
1995	27.8429	0.53	0.88
2497	27.8623	0.20	1.68
<u>Station 41</u>			
10	25.2098	7.33	-2.50
40	25.7427	6.06	n.d.
70	26.2914	5.04	-1.41
100	26.4574	4.99	-1.51
201	26.7524	4.81	0.05
351	26.9686	4.61	3.62
503	27.1332	4.52	7.42
638	27.2616	4.46	8.37
801	27.4455	3.40	6.69
999	27.6528	3.08	n.d.
1500	27.8067	1.90	4.47
2002	27.8331	0.39	2.65
2504	27.8647	0.52	-0.02
<u>Station 83</u>			
10	24.7016	4.15	-1.04
40	25.2622	6.34	-3.20
70	26.3795	5.41	n.d.
101	26.6548	5.30	-0.10
202	26.8213	5.93	-0.83
349	26.9520	n.d.	2.78
500	27.0869	4.23	7.61

TABLE 1. (continued)

Depth, m	Density, ‰	Tritium, TU	$\delta^3\text{He}$, ‰
<u>Station 83 (continued)</u>			
648	27.2380	4.00	8.90
797	27.4365	4.48	6.53
999	27.6280	2.88	7.26
1499	27.7669	2.17	4.78
1999	27.7924	1.96	3.64
<u>Station 88</u>			
10	24.8796	5.01	-1.62
40	25.4832	4.54	-2.25
70	26.1621	4.64	-1.69
102	26.5674	n.d.	-2.00
152	26.7034	4.28	-2.15
200	26.7485	4.15	-0.46
350	26.8862	4.66	n.d.
500	27.0248	5.80	n.d.
648	27.1615	4.73	4.28
697	27.2099	4.66	5.65
799	27.3261	4.84	3.14
899	27.4463	3.85	4.97
<u>Station 93</u>			
10	25.1278	5.52	-1.35
40	25.7845	5.70	-1.55
70	26.2548	4.94	-0.23
101	26.6192	5.55	-0.13
200	26.8614	6.37	3.64
350	27.0163	4.71	3.61
499	27.1277	4.54	5.41
647	27.2598	4.40	6.46
799	27.4457	5.03	7.80
998	27.6263	2.76	6.94
1248	27.7435	2.46	5.89
1497	27.7815	n.d.	2.50
<u>Station 110</u>			
10	25.2423	4.88	-0.25
40	25.6551	4.93	-2.06
70	26.6295	4.93	-0.84
101	26.7877	6.25	0.52
202	26.9176	6.67	-0.77
349	27.0190	5.65	1.73
500	27.1276	4.63	4.94
648	27.2207	4.96	7.57
798	27.3551	3.45	7.49
998	27.5390	3.34	7.44
1494	27.7775	2.20	7.44
1998	27.8102	1.83	3.90

Tritium and ^3He data are relative to the date of sampling; n.d. stands for "not determined."

It can be responsible for the tritium-salinity correlation observed in Figure 6b (relative tritium enrichment in station 2 compared with station 12).

The low tritium concentrations observed for stations 6, 12, and 16 correspond to the Antarctic Intermediate Water component [Broecker and Takahashi, 1981] characterized by a low salinity (Figure 6b) as well as a high silica content [IFM, 1986].

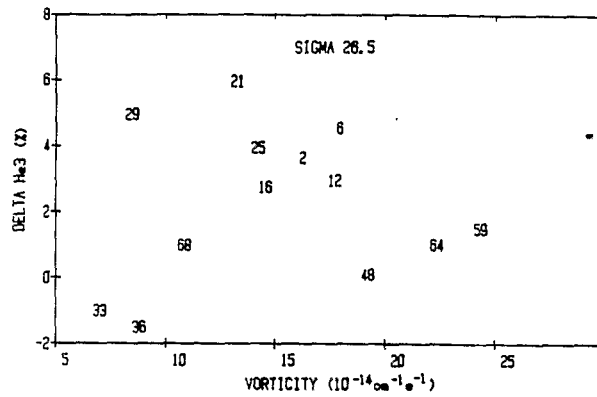


Fig. 5a

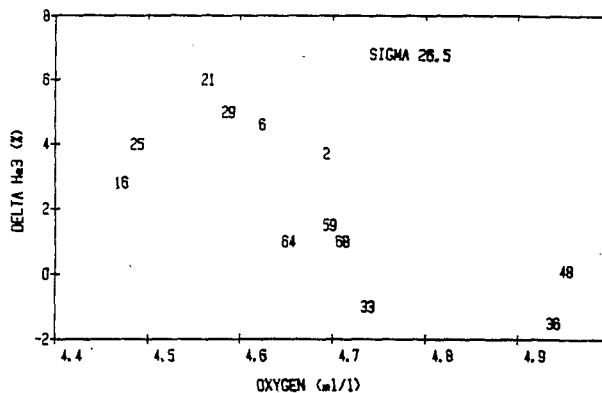


Fig. 5b

Fig. 5. Diagrams of (a) $\delta^3\text{He}$ versus vorticity and (b) $\delta^3\text{He}$ versus oxygen for the 26.5 isopycnal level. Numbers identify the sampled stations (see Figure 1).

Tritium and Helium 3 in the Ventilated Thermocline: A Quantitative Approach

Several kinds of models have been used to compute the transport of chemical or transient tracers in the North Atlantic [Jenkins, 1980, 1987; Sarmiento, 1983; Cox and Bryan, 1984; Thiele et al., 1986; Fuchs, 1987] using essentially the tritium input function of Dreisigacker and Roether [1978]. In a more quantitative study of the TOPOGULF data, three questions arise :

1. Are the previously reported tritium distributions versus time for the surface waters of the north Atlantic suitable for the 1983 samples?

2. Can we apply a mixing model without any hypothesis relative to mixing and transport processes of the water within the subtropical gyre in order to define the time scales for transport and ventilation?

3. Can we consider the $^3\text{He}/^3\text{H}$ "age" of the water samples as a useful tool for the evaluation of time scales for transport or ventilation?

Evolution With time of the Tritium Surface Concentrations

Figure 7 shows the tritium distribution versus time of the North Atlantic surface waters in the 20°N-50°N band given by Dreisigacker and Roether [1978] and referred to in the following discussion as DRF and the distributions proposed by Broecker et al. [1986] (referred to as BPOF1 and

BPOF2 for the 20°N-40°N band and for latitudes greater than 40°N, respectively). Also plotted are all the reported tritium data for the area 25°N-60°N from 1965 to 1985 [Rooth and Ostlund, 1972; Bowen and Roether, 1973; Ostlund et al., 1974; Dreisigacker and Roether, 1978; Jenkins et al., 1979, 1985; Ostlund, 1984; Thiele et al., 1986; Ostlund and Grall, 1987]. Crosses show data from the 25°N-40°N area; circles show data from the 40°N-60°N area. The first observation that we make from such a pattern is the great scatter of the data. Because this variability it appears difficult to refer to any one of the three input functions DRF, BPOF1, or BPOF2 in a modeling approach of our TOPOGULF data.

The shaded area in Figure 7 includes nearly the whole data set of the temperate zone (25°N-40°N) and we shall consider as the "observed" tritium distribution (OTF) the two lower and upper boundaries OTF1 and OTF2, respectively, which constitute the envelope of this data set. The DRF nearly coincides with the lower limit OTF1. The BPOF1 (20°N-40°N) has been clearly under the lower limit OTF1 since 1972. Tritium data in precipitation from 1973 to 1978 do not show any decrease over Valentia Island, Ireland [International Atomic Energy Agency, 1981]. This feature, in addition to the observed sea surface tritium data, suggests a possible underestimation of the BPOF1 after 1972. The upper limit OTF2 of the envelope has been very close to the BPOF2

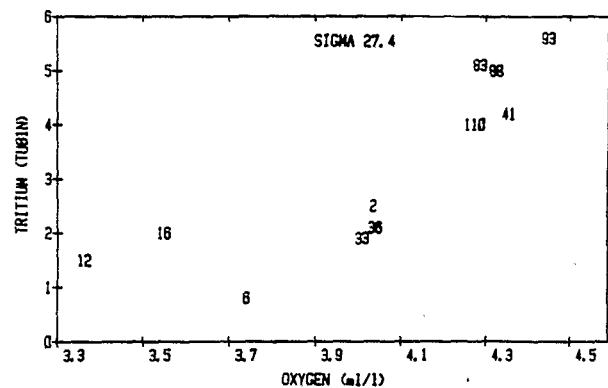


Fig. 6a

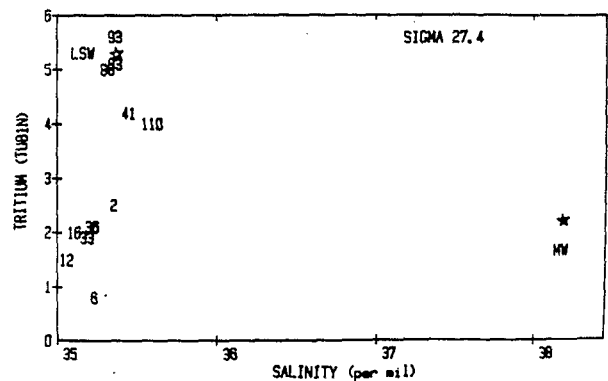


Fig. 6b

Fig. 6. Diagrams of (a) tritium versus oxygen and (b) tritium versus salinity for the 27.4 isopycnal level. The Mediterranean outflow component MW is plotted for reference. Numbers identify the stations (see Figure 1).

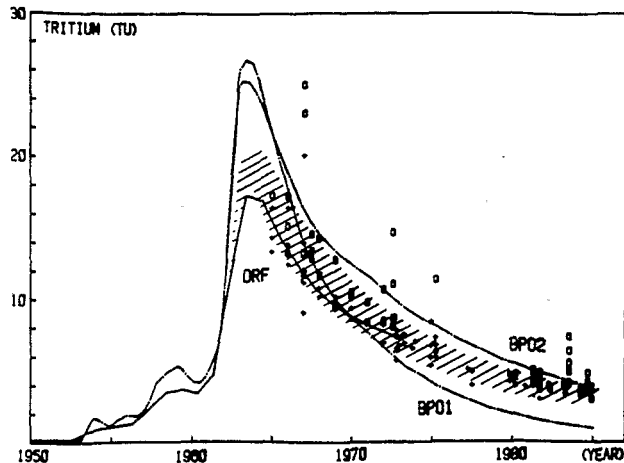


Fig. 7. Distributions of tritium versus time for surface waters of the North Atlantic Ocean. DRF refers to Dreisigacker and Roether [1978]; BPOF1 and BPOF2 refer to the 20°N - 40°N and $>40^{\circ}\text{N}$ latitudinal bands, respectively, from Broecker et al. [1986]. Also shown are the data available from 1965 to 1985 (see text for references) for the 25°N - 40°N latitude range (crosses), and for the 40°N - 60°N latitude range (circles). The shaded area is the envelope of the data set for the temperate zone (25°N - 40°N). Its lower and upper limits are called OTF1 and OTF2, respectively, in the text ("observed" tritium versus time distributions for surface waters).

(> 40°N) since 1965. Our OTF is very approximative before 1965 because of the almost complete lack of data. Nevertheless, the influence of the size and shape of the tritium distribution at this remote period of the tritium input history is low in our calculation, and it leads to uncertainties within the experimental error.

The Model

Our calculation is derived from the transport model used by Jenkins [1980]. It is a simple mixing model where one considers that the evolution of the tritium concentration at any depth is driven by the exchange of water coming from the surface. As we know that the penetration of tritium in the North Atlantic waters is governed mainly by winter outcropping processes and water injection by Ekman pumping [Stommel, 1979], this scheme seems realistic. The difference with the Jenkins model is that we do not suppose that the surface water is being instantaneously transported into the ocean. The surface water is allowed to travel during a certain "transit" time τ before reaching the depth of interest. The time τ integrates all the physical processes occurring between the surface and a given depth (Ekman pumping, mixing, advection, diffusion, etc.) and so cannot be considered as a real transit time. Nevertheless, we consider that during this time, tritium and ^3He concentrations of the surface water evolve owing to radioactive decay of tritium and to subsequent production of ^3He . At any given depth, changes in tritium and ^3He concentrations with time are given by writing the mass balance for both elements (^3H and ^3He , respectively)

$$^3\text{H}(t+\Delta t) = ^3\text{H}(t) \left(1 - \frac{\Delta Q}{Q} \right) e^{-\lambda \Delta t} + \frac{\Delta Q}{Q} ^3\text{H}_s(t+\Delta t - \tau) e^{-\lambda \tau} \quad (1)$$

$$^3\text{He}(t+\Delta t) = (^3\text{He}(t) + ^3\text{H}(t)) \left(1 - \frac{\Delta Q}{Q} \right) - \frac{\Delta Q}{Q} ^3\text{H}_s(t+\Delta t - \tau) - ^3\text{H}(t+\Delta t) \quad (2)$$

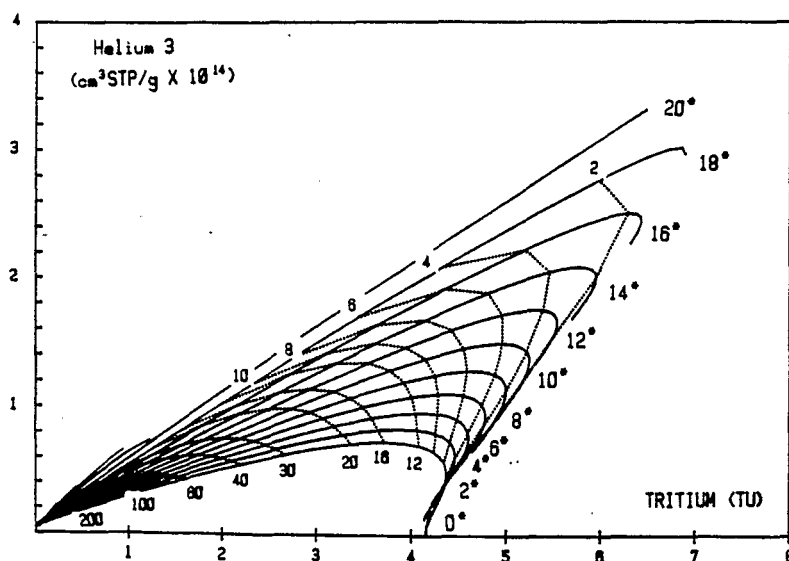


Fig. 8. Response curves of the model (described in the text) run with OTF2 (solid line). These outputs are computed for ventilation times T ranging from 1 to 1000 years and different "transit" times τ (from 0 to 20 years; numbers are reported on the right side of the curves with asterisks). Also drawn are several "isoventilation time" curves from 2 to 200 years (dotted lines, identified by small numbers above and below the curves).

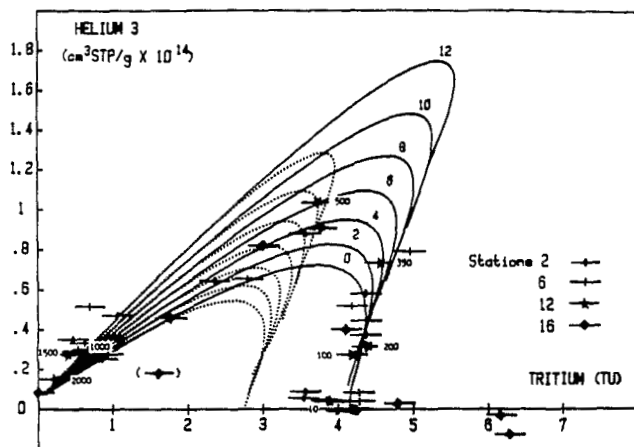


Fig. 9a

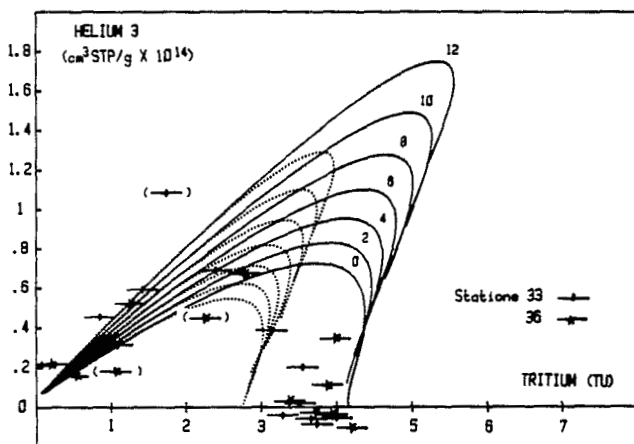


Fig. 9b

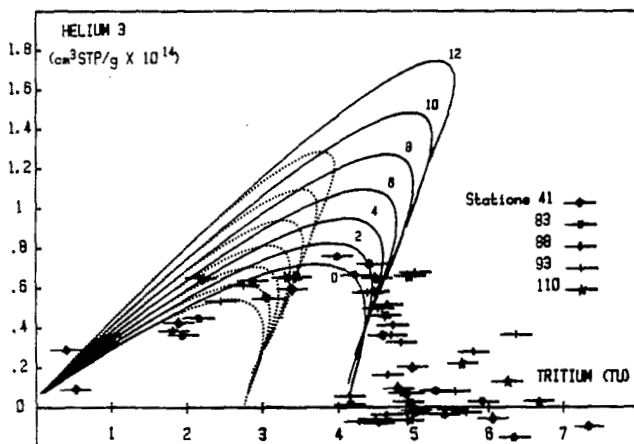


Fig. 9c

Fig. 9. Comparison between TOPOGULF data and the outputs of the model run either with the OTF2 (solid lines) or the OTF1 (dotted lines) tritium distributions. The computation is done using several "transit" times (from 0 to 12 years, reported at the top of each OTF2 curve). (a) Southeastern stations (2, 6, 12, and 16). The depths of the helium-tritium data pairs for station 12 are reported. (b) Southwestern stations (33, and 36). (c) Northern stations (41, 83, 88, 93, 110). Parentheses are used to identify particular samples, discussed in the text.

where Δt is the time step (1 year), τ is the "transit" time of the surface water, H_s is the surface water tritium concentration, λ is the radioactive decay constant for tritium, and $\Delta Q/Q$ is the ventilation rate, i.e., the percentage of water replaced by water coming from the surface by step of time Δt . Instead of $\Delta Q/Q$ we can introduce the ventilation time T by the transformation $\Delta Q/Q = \Delta t/T$.

The right-hand side terms include the in situ radioactive decay of tritium (or regrowth for ^3He) during the time step Δt , the tritium contribution from the surface associated with the renewal rate $\Delta Q/Q$ and affected by the "transit" time τ , and the tracer outgoing with respect to the mass balance.

The initial conditions are fixed considering the system to be in steady state in the year 1950, with a tritium concentration at the surface equal to 0.2 TU [Jenkins, 1980]. Figure 8 is the response of the model run between 1950 and 1983, considering OTF2 as the tritium distribution versus time for the surface waters, i.e., the relationship between ^3H and ^3He for different ventilation times T and transit times τ (0 to 20 years). Also reported are several "isoventilation time" curves from 2 to 200 years.

For each TOPOGULF station, from the surface to 2000 m depth, we have compared the response of the model (run with either OTF1 or OTF2) with each tritium- ^3He data pair of our samples (Figures 9a, 9b, and 9c for southeastern (2, 6, 12, and 16), southwestern (33, and 36), and northern (41, 83, 88, 93, and 110) stations, respectively). From each data pair we can determine a single T - τ pair. We observe great differences among the ^3H - ^3He pair distributions in the southeastern, southwestern, and northern areas.

Southeastern area. For the southeastern area, data are in good agreement with the model using the OTF2 input function (Figure 9a). A puzzling feature is the remarkable subsurface tritium maximum in the mixed layer for station 16, previously mentioned. One datum for station 16 falls in the interior of the response model curve (shown in parentheses in Figure 9a, for 1000 m depth or $\sigma_\theta \sim 27.5$), probably owing to the influence of the Antarctic Intermediate Water component. For depths greater than 100 m the data fit the model using transit times ranging from 0 to 6 years. This feature corroborates our previously mentioned southward isopycnal transport of the water masses from wintertime outcropping surfaces. At middepth ($\sigma_\theta \sim 27.1$), the highest transit time is obtained for station 12, equal to 6 ± 1 years: this value is close to the 7.5-year travel time between stations 110 and 12, evaluated using a completely different approach (see discussion of the 27.1 isopycnal level).

The ^3H - ^3He pairs for the southwestern stations 33 and 36 are plotted with the response curves of the model using either OTF1 or OTF2 (Figure 9b). From the surface to 600 m depth, the ^3H - ^3He dots are located between the two OTF1 and OTF2 model response curves. This results from the fact that in this depth range (from the surface down to $\sigma_\theta = 27.0$), the waters are coming either from isopycnal transport from northern areas or from convection processes occurring close to the sampled area (18°C Mode Water). The combination of these two processes, described by the OTF2 and

TABLE 2. Tritium- ^3He Age A and Ventilation Time T for Station 12

Depth, m	T, years	A, years
10	n.d.*	0.8
100	4.25	3.2
200	4.75	3.5
350	5.50	6.9
500	14.00	10.6
1000	90 ± 10	18.2
1500	70 ± 30	21.5
2000	200 ± 100	23.0

* Undetermined value not described by the model.

OTF1 tritium distributions, respectively, explains the location of our measured ^3H - ^3He pairs in Figure 9b. This feature was not noticeable for the southeastern stations (Figure 9a) where local convection does not exist down to 600 m.

Below 600 m, it is difficult to distinguish whether the OTF1 or OTF2 model response curve (Figure 9b) best fits the data.

We notice a particular data pair corresponding to a ^3He -enriched sample for station 33 (in parentheses in Figure 9b), probably of hydrothermal origin. The $\delta^3\text{He}$ anomaly is observed at 800 m for station 33 (Table 1). The ^3He content at the same depth for station 6, located on the other side of the Mid-Atlantic Ridge, is considerably lower (Figure 2b). The respective $\delta^3\text{He}$ values are 13.1‰ for station 33 and 5.6‰ for station 6. In this area, the ridge is relatively high, referred to the bottom depth for station 88 (~ 1000 m), or the data of Miyashiro et al. [1971] (the crest of the MAR at 30°N 42°W is located at 1460 m depth), or the bathymetric map of Litvin et al. [1972]. A likely origin for the ^3He anomaly in station 33 is the input of hydrothermal activity from the MAR [Rona et al., 1984]. Such an ^3He excess has been described by Jenkins et al. [1980] near the MAR at 26°N. The ^3He anomaly suggests that the middepth circulation is westward in this area.

For station 36 the data fall into the interior of the model response curves at 800 m and 1500 m (in parentheses in Figure 9b), probably as a result of mixing with an Antarctic Intermediate Water component. In contrast, station 33 does not show such an "anomaly," perhaps because of remainders of hydrothermal activity which mask the influence of Antarctic Intermediate Water [Broecker and Takahashi, 1981].

Northern area. The ^3He - ^3H pairs for the northern stations 41, 83, 88, 93, and 110 are plotted with the response curves of the model (Figure 9c). All the data from the surface to 600 m depth are shifted from the model response to greater tritium values. This deviation was expected, as we have not considered the TOPOGULF data in the determination of the OTF2 tritium distribution. Figure 7 shows a positive shift between the TOPOGULF data in the northern band 40°N-60°N (reported by circles for 1983) and other reported values relative to tritium concentrations at the sea surface. The deviation observed between the response of the model run with

OTF2 and our surface and subsurface tritium data is the result of this shift.

Below 600 m the measured ^3He - ^3H pairs fall near the response model curves corresponding to short transit times ($0 < \tau < 4$ years).

Estimates of Some Ventilation Times

The ^3He - ^3H age (called A in the following discussion) has often been considered as a powerful tool for oceanographic studies on time scales of less than 1 decade [Jenkins and Clarke, 1976; Jenkins, 1980, 1987; Fuchs, 1987]. On the other hand, we must take the greatest care when using it for time scales greater than 10 years because of its non linearity in regard to mixing. This observation has to be kept in mind when using the ^3He and tritium tracers in order to evaluate the ventilation ages of water masses or, by this way, the oxygen utilisation rates.

Table 2 gives the respective ventilation time T values and the age A values computed from tritium and ^3He data for station 12. As was mentioned by Jenkins [1980], for depth ranging from the surface to 500 m, the calculated A values are in relatively good agreement with the ventilation times computed from the model. In contrast, for depths greater than 500 m, there is a great discrepancy between A and T values, as expected, due to the mixing effects. We notice that the computation is very approximate for tritium contents lower than 1 TU, owing to the experimental errors and to the shape of the different curves of the model response for large values of the ventilation time (Figure 9a). An important feature is the high ventilation time for the deep waters ($T = 200 \pm 100$ years at 2000 m). By contrast, on the same isopycnal level for station 110 (equal to 35 years at 1500 m). For this layer, the tritium-oxygen diagram in Figure 10 identifies the "young" waters of Labrador Sea origin (high tritium and oxygen contents) in the northern stations 41, 83, 93 and 110. The southern stations 2, 6, 12, and 16 with poor tritium and oxygen contents are close to the so-called "shadow" region of more stagnant waters [Luyten et al., 1983; Kawase and Sarmiento, 1985]. These observations explain the two extreme values obtained for the ventilation time at station 12 (200 ± 100 years) and at station 110 (35 ± 5 years) on the 27.8 isopycnal level.

Lazier [1973] and Talley and McCartney [1982] have mentioned the variability of the ventilation time of the Labrador Sea Water due to decadal changes in renewal rate and properties. Their volumetric calculation leads to a ventilation time of 9 years, while the Worthington's [1976] evaluation is about 36 years. The ventilation time of 35 ± 5 years evaluated by the model for station 110, mainly consisting of Labrador Sea Water (Figure 10), is in good agreement with the latter value and must be considered as a mean evaluation over at least 2 decades owing to the transient injection of tritium.

It has to be pointed out that the highest value obtained over the whole TOPOGULF area for the ventilation time ($T = 200 \pm 100$ years at station 12 at 2000 m) can be compared with the previously reported residence time values for the

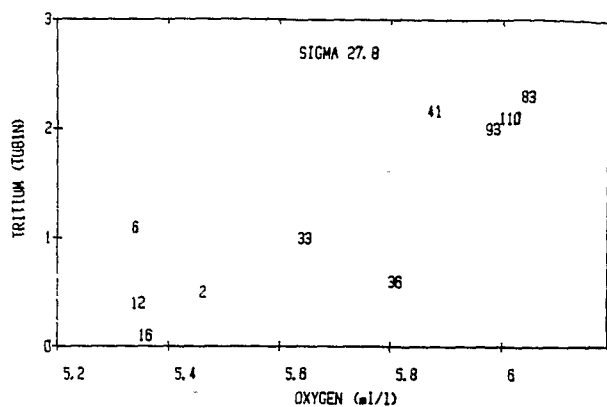


Fig. 10. Tritium-oxygen diagram for the 27.8 isopycnal level. Numbers identify the sampled stations (see Figure 1).

North Atlantic deep waters (230 years from Stuiver [1976]; ~ 100 years from Broecker [1979]).

Summary and Conclusions

We summarize the principal features inferred from the study of the helium 3 and tritium distributions in the TOPOGULF area:

1. An important frontal tritium distribution for the surface waters is revealed, associated with the Azores current.

2. The ^3He distribution in the subsurface level identifies the convection efficiency in the north and a formation zone for the 18°C Mode Water in the southwest.

3. All over the sampled area, the tritium distribution of the middepth waters is essentially governed by the injection of the tracer along isopycnal levels during their wintertime outcropping at the sea surface. The northeast-southwest asymmetry of the distributions is due to the circulation along the subtropical anticyclonic gyre. On the 27.1 isopycnal level, we evaluate the transit time of the waters from the northern to the southern areas as about 7 years, which suggests an advection rate close to 1 cm s^{-1} assuming a purely isopycnal process.

4. At depth, the respective influences of the Labrador Sea Water and the Mediterranean Water are noticeable through the tritium data. The Mediterranean outflow seems to be an end member responsible either for a decrease of the tritium contents in the north or for an increase in the south.

5. A ^3He excess, probably from a hydrothermal input, has been noticed near 30°N on the western side of the MAR.

A more quantitative approach, using a mixing model, corroborates these results. The model, run without any hypothesis for the circulation of the middepth waters, has shown that the $^3\text{He}/^3\text{H}$ "age" was not adequate for the study of the circulation time scales in this area owing to the simultaneous influences of ventilation rate, transit rate, and mixing. We evaluate two extreme values: a ventilation time for the Labrador Sea Water equal to 35 years and a residence time of the waters within the "shadow" area around 200 years.

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References

- Andrié, C., Utilisation des traceurs hélium-3 et tritium en océanographie, *Thèse de Doctorat ès Sciences Physiques*, 340 pp., Univ. Pierre et Marie Curie, Paris, 1987.
- Andrié, C., and L. Merlivat, Tritium in the western Mediterranean Sea during 1981 Phycemed cruise, *Deep Sea Res., Part A*, **35** (2), 247-267, 1988.
- Benson, B. B., and D. Krause Jr., Isotopic fractionation of helium during solution: A probe for the liquid state, *J. Solution Chem.*, **9**(12), 895-909, 1980.
- Bowen, V. T., and W. Roether, Vertical distributions of strontium 90, cesium 137 and tritium near 45°North in the Atlantic, *J. Geophys. Res.*, **78**(27), 6277-6285, 1973.
- Broecker, W. S., A revised estimate for the radiocarbon age of the North Atlantic deep water, *J. Geophys. Res.*, **84**(C6), 3218-3226, 1979.
- Broecker, W. S., and H. G. Ostlund, Property distributions along the $\sigma_\theta=26.8$ isopycnal in the Atlantic Ocean, *J. Geophys. Res.*, **84**(C3), 1145-1154, 1979.
- Broecker, W. S., and T. Takahashi, Hydrography of the central Atlantic, IV, Intermediate waters of antarctic origin, *Deep Sea Res., Part A*, **28**(3), 177-193, 1981.
- Broecker, W. S., T. H. Peng, and H. G. Ostlund, The distribution of bomb tritium in the ocean, *J. Geophys. Res.*, **91**(C12), 14,331-14,344, 1986.
- Clarke, W. B., W. J. Jenkins and Z. Top, Determination of tritium by mass spectrometric measurement of ^3He , *Int. J. Appl. Radiat. Isot.*, **27**, 515-522, 1976.
- Cox, M. D., and K. Bryan, A numerical model of the ventilated thermocline, *J. Phys. Oceanogr.*, **14**, 674-687, 1984.
- Dreisigacker, E., and W. Roether, Tritium and ^{90}Sr in the North Atlantic surface water, *Earth Planet. Sci. Lett.*, **38**, 301-312, 1978.
- Füchs, G., Ventilation of the warmwater sphere of the northeast Atlantic derived by the ^3He -and-tritium distributions, Inaugural dissertation zur Erlangung der Doktorwürde der Naturwissenschaftlich-Mathematischen Gesamtfakultät, 322 pp., Ruprecht-Karls-Universität, Heidelberg, Federal Republic of Germany, 1987.
- Füchs, G., W. Roether, and P. Schlosser, Excess ^3He in the ocean surface layer, *J. Geophys. Res.*, **92** (C6), 6559-6568, 1987.

- Harvey, J., θ -S relationships and water masses in the eastern North Atlantic, Deep Sea Res., Part A, **29**, 1021-1033, 1982.
- Institut für Meereskunde (IFM), TOPOGULF: A joint programme initiated by IFREMER, Brest (France) and IFM, Kiel (W. Germany), data report, vol.1, 183 pp., Kiel, Federal Republic of Germany, 1986.
- International Atomic Energy Agency, Statistical treatment of environmental isotope data in precipitation, Tech. Rep. 206, 256 pp., Vienna, 1981.
- Jean-Baptiste, P., C. Andrié, and M. Lelu, Mesure du couple tritium-hélium océanique par spectrométrie de masse, in Proceedings of the International Symposium on radioactivity and oceanography, Radionuclides: A Tool for Oceanography, Elsevier, Amsterdam, in press, 1988.
- Jenkins, W. J., Tritium and ^3He in the Sargasso Sea, J. Mar. Res., **38**(3), 533-569, 1980.
- Jenkins, W. J., Mass spectrometric measurements of tritium and ^3He , paper presented at the Meeting on Low-Level Tritium Measurements, Int. Atom. Energy Agency, Vienna, 1981.
- Jenkins, W. J., On the climate of a subtropical ocean gyre: Decade timescale variations in water mass renewal in the Sargasso Sea, J. Mar. Res., **40**, suppl., 265-289, 1982.
- Jenkins, W. J., ^3H and ^3He in the beta-triangle: Observations of gyre ventilation and oxygen utilization rates, J. Phys. Oceanogr., **17**(6), 763-783, 1987.
- Jenkins, W. J., and W. B. Clarke, The distribution of ^3He in the western Atlantic Ocean, Deep Sea Res., **23**, 481-494, 1976.
- Jenkins, W. J., W. V. Collentro and R. D. Boudreau, Data Release 1, 28 pp., Helium Isotope Lab., Woods Hole Oceanogr. Inst., Woods Hole, Mass., 1979.
- Jenkins, W. J., P. A. Rona and J. M. Edmond, Excess ^3He in the deep water over the Mid-Atlantic Ridge at 26°N: Evidence of hydrothermal activity, Earth Planet. Sci. Lett., **49**, 39-44, 1980.
- Jenkins, W. J., D. E. Lott, M. W. Davis, and R. D. Boudreau, Tritium and ^3He data from the beta-triangle, Helium Isotope Data Rep. 2, 32 pp., Helium Isotope Lab., Woods Hole Oceanogr. Inst., Woods Hole, Mass., 1985.
- Käse, R. H., and G. Siedler, Meandering of the subtropical front south-east of the Azores, Nature, **300**, 245-246, 1982.
- Käse, R. H., J. F. Price, P. L. Richardson and W. Zenk, A quasi-synoptic survey of the thermocline circulation and water mass distribution within the canary basin, J. Geophys. Res., **91**(C8), 9739-9748, 1986.
- Kawase, M., and J. L. Sarmiento, Nutrients in the Atlantic thermocline, J. Geophys. Res., **90**(C5), 8961-8979, 1985.
- Kawase, M., and J. L. Sarmiento, Circulation and nutrients in middepth Atlantic waters, J. Geophys. Res., **91**(C8), 9749-9770, 1986.
- Kielmann, J., and R. H. Käse, Numerical modeling of meander and eddy formation in the Azores current frontal zone, J. Phys. Oceanogr., **17**, 529-541, 1987.
- Krauss, W., The North Atlantic current, J. Geophys. Res., **91**(C4), 5061-5074, 1986.
- Lazier, J. R. N., The renewal of Labrador Sea Water, Deep Sea Res., **20**, 341-353, 1973.
- Litvin, V. M., N. A. Marova, M. V. Rudenko and G. B. Udintsev, Morphostructure of the Atlantic rift zone in the area of the Kurchatov fault and Atlantis canyon, Oceanology, Engl. Transl., **12**, 527-534, 1972.
- Luyten, J. R., J. Pedlosky and H. Stommel, The ventilated thermocline, J. Phys. Oceanogr., **13**, 292-309, 1983.
- McCartney, M. S., The subtropical recirculation of mode waters, J. Mar. Res., **40**, suppl., 427-464, 1982.
- McCartney, M. S., and L. D. Talley, The Subpolar Mode Water of the North Atlantic Ocean, J. Phys. Oceanogr., **12**, 1169-1188, 1982.
- Miyashiro, A., F. Shido, and M. Ewing, Metamorphism in the Mid-Atlantic Ridge near 24°N and 30°N, Philos. Trans. R. Soc. London Ser. A, **268**, 589-603, 1971.
- Nies, H., Artificial radioactivity in the northeast Atlantic, in Proceedings of the International Symposium on Radioactivity and Oceanography, Radionuclides: A Tool for Oceanography, Elsevier, in press, 1988.
- Ostlund, H. G., NAGS tritium, Data Rep. 13, Tritium Lab. 324 pp., Univ. of Miami, Miami, Fla., 1984.
- Ostlund, H. G., and C. Grall, North and tropical Atlantic tritium and radiocarbon, Data Rep. 16, Tritium Lab. 277 pp., Univ. of Miami, Miami, Fla., 1987.
- Ostlund, H. G., H. G. Dorsey, and C. G. Rooth, GEOSECS North Atlantic radiocarbon and tritium results, Earth Planet. Sci. Lett., **23**, 69-86, 1974.
- Roether, W., and W. Weiss, On the formation of the outflow through the Strait of Gibraltar, Geophys. Res. Lett., **2**(7), 301-304, 1975.
- Rona, P. A., G. Thompson, M. J. Mottl, J. A. Karson, W. J. Jenkins, D. Graham, M. Mallette, K. Von Damm and J. M. Edmond, Hydrothermal activity at the trans-Atlantic geotraverse hydrothermal field, Mid-Atlantic Ridge crest at 26°N, J. Geophys. Res., **89**(B13), 11,365-11,377, 1984.
- Rooth, C. G., and H. G. Ostlund, Penetration of tritium into the Atlantic thermocline, Deep Sea Res., **19**, 481-492, 1972.
- Sarmiento, J. L., A tritium box model of the North Atlantic thermocline, J. Phys. Oceanogr., **13**, 1269-1274, 1983.
- Sarmiento, J. L., C. G. H. Rooth, and W. Roether, The North Atlantic tritium distribution in 1972, J. Geophys. Res., **87**(C10), 8047-8056, 1982.
- Stommel, H., Determination of water mass properties of water pumped down from the Ekman layer to the geostrophic flow below, Proc. Natl. Acad. Sci. USA, **76**(7), 3051-3055, 1979.
- Stuiver, M., The ^{14}C distribution in west Atlantic abyssal waters, Earth Planet. Sci. Lett., **32**, 322-330, 1976.
- Talley, L. D., and M. S. McCartney, Distribution and circulation of Labrador Sea Water, J. Phys. Oceanogr., **12**, 1189-1205, 1982.
- Thiele, G., W. Roether, P. Schlosser, R. Kuntz, G. Siedler and L. Stramma, Baroclinic flow and transient-tracer fields in the Canary-Cape Verde basin, J. Phys. Oceanogr., **16**, 814-826, 1986.
- Weiss, R. F., Solubility of helium and neon in

- water and seawater, J. Chem. Eng. Data, 16, 235-241, 1971.
- Weiss, W., and W. Roether, The rates of tritium input to the world oceans, Earth Planet. Sci. Lett., 49, 435-446, 1980.
- Worthington, L. V., Evidence for a two gyre circulation system in the North Atlantic, Deep Sea Res., 9, 51-67, 1962.
- Worthington, L. V., On the North Atlantic circulation, The Johns Hopkins Univ. Stud. Oceanogr., 6, 110 pp., 1976.

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