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Water Mass Transport and Ventilation in the Northeast Atlantic Derived from Tracer Data [and Discussion]

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Water mass transport and ventilation in the Northeast Atlantic derived from tracer data

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A large ^{3}He and tritium data base collected in the Northeast Atlantic since 1977 allows construction of extensive tracer distributions on isopycnal surfaces in the main thermocline. A distinct southward increase in tritium–^{3}He age is observed that depicts the outcrop boundaries and allows one to quantify the interior transport. This transport is directed towards the south.

1. Introduction

This paper assesses the water mass transport of upper waters in the Northeast Atlantic from the viewpoint of observed ^{3}He and tritium distributions. The underlying method was developed by Jenkins & Clarke (1976) and Jenkins (1980, 1987).

In the North Atlantic, an excess of ^{3}He relative to a solubility equilibrium with atmospheric He is present below the surface layer. This excess results from the radioactive decay of tritium (half life 12.43 years) that has been introduced into the environment by nuclear-weapon testing in the early 1960s. Because of gas exchange with the atmosphere, the oceanic surface layer attains a near equilibrium with the atmosphere (Fuchs *et al.* 1987), whereas in the interior ^{3}He increases while tritium decays. This means that the so-called tritium–^{3}He age, τ, also increases, and according to the decay law is

$$\tau = (T_{\frac{1}{2}}/\ln 2)\ \ln([^3\mathrm{He}^*]/[\mathrm{T}]+1),$$

$T_{\frac{1}{2}}$ being the half life, [^{3}He*] the radiogenic ^{3}He component (excess over the solubility-equilibrium value), and [T] the tritium concentration. One can interpret τ as a formal water age, i.e. the time since the water parcel left the surface layer.

Clearly, the process of ventilation of the oceanic main thermocline, by which is meant its exchange with the surface layer, must be reflected in the distribution of τ. Neglecting mixing processes and assuming that the velocity direction is oriented orthogonally to the isolines of τ and that the distribution of τ is stationary, the velocity $\boldsymbol{v}$ is given by

$$|\boldsymbol{v}| = 1/|\nabla\tau|, \tag{1}$$

where $|\nabla\tau|$ is the magnitude of gradient τ. If mixing is present, the transport direction is no longer necessarily orthogonal to the τ-isolines, and the correct relation becomes (Jenkins 1987)

$$\boldsymbol{v}_{\mathrm{I}}\cdot\nabla_{\mathrm{I}}\tau + w\frac{\partial\tau}{\partial z} = 1 - \frac{\partial\tau}{\partial t} + K_{\mathrm{I}}\nabla_{\mathrm{I}}^2\tau + K_z\frac{\partial^2\tau}{\partial z^2} + K_{\mathrm{I}}\nabla_{\mathrm{I}}\ln([\mathrm{T_S}][\mathrm{T}])\,\nabla_{\mathrm{I}}\tau + K_z\frac{\partial}{\partial z}\ln([\mathrm{T_S}][\mathrm{T}])\,\frac{\partial\tau}{\partial t}. \tag{2}$$

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In (2) the velocity $\boldsymbol{v}$ is split up into components $\boldsymbol{v}_I$ along the isopycnal surface and w orthogonal to it (i.e. essentially vertical). The two-dimensional gradient operator on the isopycnal surface is ∇_I and z is the orthogonal direction. K_I and K_Z are the isopycnal and diapycnal diffusivities. Here, T is the tritium concentration and $[T_S]$ is 'stable tritium', i.e. the sum of the radiogenic ^{3}He and tritium concentrations (Jenkins 1987; Fuchs 1987).

In this paper, the tritium–^{3}He age distribution observed in a certain area of the Northeast Atlantic is described (§2). In §3 a scale analysis is performed to find out which terms in (2) are relevant. The age distribution is then converted into a velocity distribution. Section 4 gives a brief discussion of the results.

2. Tracer data

Samples were collected on ten research cruises between 1977 and 1984. Table 1 summarizes these cruises, giving also the number of samples taken. Station positions are shown in figure 1. Sections along 38° W and the so-called β-triangle (Jenkins *et al.* 1985; Jenkins 1987) have been included. For the Heidelberg data (see table 1), the measuring precision for tritium is between 0.1 and 0.2 TR and for ^{3}He between 0.03 and 0.06 TR (1 TR = 1 tritium atom/10^{18} H-atoms or 1 ^{3}He atom/10^{18} H atoms); hence the precision of τ is usually between a few months and one year (Fuchs *et al.* 1987; Jenkins *et al.* 1985).

Table 1. Relevant cruises

cruise	cruise period	number of samples analysed: ^{3}H	number of samples analysed: T
Knorr-66/2[a]	Jun. 1977	60	91
Oceanus-52[a]	Oct. 1978	178	282
Meteor-56/6	Apl 1981	395	639
Meteor-64	Apl 1983	84	18
Walther-Herwig-57	Mar. 1983	57	36
Poseidon-104	Nov. 1983	49	—
Valdivia-19	Mar. 1984	173	77
Poseidon-111	Jly 1984	126	29
Meteor-69/2	Aug. 1984	166	87
Meteor-69/6	Nov. 1984	111	37
Atlantic II-107[b]	Oct. 1979	467	505
Oceanus-78[b]	Mar. 1980		

[a] Unpublished data from Woods Hole–Heidelberg cooperation (with W. J. Jenkins and W. Weiss).
[b] Data from Jenkins *et al.* (1985).
For data from all the other cruises see Fuchs (1987).

Figure 2 shows the age distribution on three isopycnal surfaces (σ_θ = 27.0, 27.3, 27.6; the depth range covered by these densities is roughly 500–1000 m over much of the area). The rationale for isopycnal mapping is that, in a first approximation, transport is generally regarded as being adiabatic (Sarmiento *et al.* 1982; Kawase & Sarmiento 1985). To obtain the distributions, individual station profiles were interpolated to the densities in question, the maps being constructed from the interpolated values (Fuchs 1987). In figure 2, the age increases with density as well as southward, the rate of increase becoming larger towards the south. There is also a tendency towards increasing ages towards the African coast. The influence of younger water of Mediterranean origin can be seen on the σ_θ = 27.6 surface. Winter outcropping of the

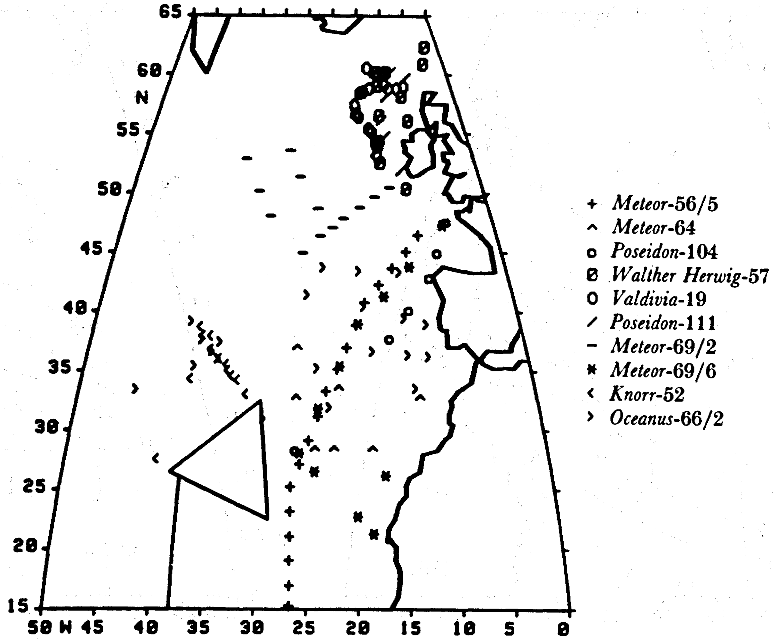

FIGURE 1. Station map including data on the 38° section and β-triangle from Jenkins *et al.* (1985).

surfaces in question occurs far to the north of the area covered in figure 2 so that the age contours are uninfluenced by seasonal effects.

3. Scale analysis and velocity distribution

To derive a velocity distribution from the data given in figure 2, a scale analysis on the basis of (2) was made (Fuchs 1987). The diffusivities were taken to be $K_I = 400\ \mathrm{m^2\,s^{-1}}$ and $K_Z = 10^{-5}\ \mathrm{m^2\,s^{-1}}$ (Armi & Stommel 1983; Olbers *et al.* 1985). It was found that north of a certain latitude the diffusion terms contribute no more than about 10%; this is the region where τ gradients are fairly smooth. The diapycnal advection term $w \cdot \partial\tau/\partial z$, with values for w as reported by Olbers *et al.* (1985), was found not to exceed about 5%. Stationarity was checked by comparing profiles at stations close to each other taken a few years apart. The indication was that $\partial\tau/\partial t < 0.15$. It is to be expected that under a stationary velocity field only mixing could make the age distribution vary in time. It is therefore concluded that over much of the area sampled, (2) reduces to

$$\boldsymbol{v}_I \cdot \nabla\tau \approx 1. \tag{3}$$

Assuming the velocity to be orthogonal to the isolines of τ leads back to (1).

Velocities calculated on the basis of (1) are shown in figure 3. Values are given only for positions where the neglected terms contribute no more than 30%. Within this limit, the assumption that the velocity is orthogonal to the age isolines should be valid. It is found in figure 3 that on the $\sigma_\theta = 27.0$ and 27.3 horizons the velocity is directed to the south, with a magnitude around $1\ \mathrm{cm\,s^{-1}}$. Velocities decrease with increasing density. On the $\sigma_\theta = 27.6$ level a southeastward flow is obtained.

This velocity distribution points to ventilation of the layers in question directly from the winter outcrop regions to the north (Luyten *et al.* 1983; Kawase & Sarmiento 1985; Jenkins

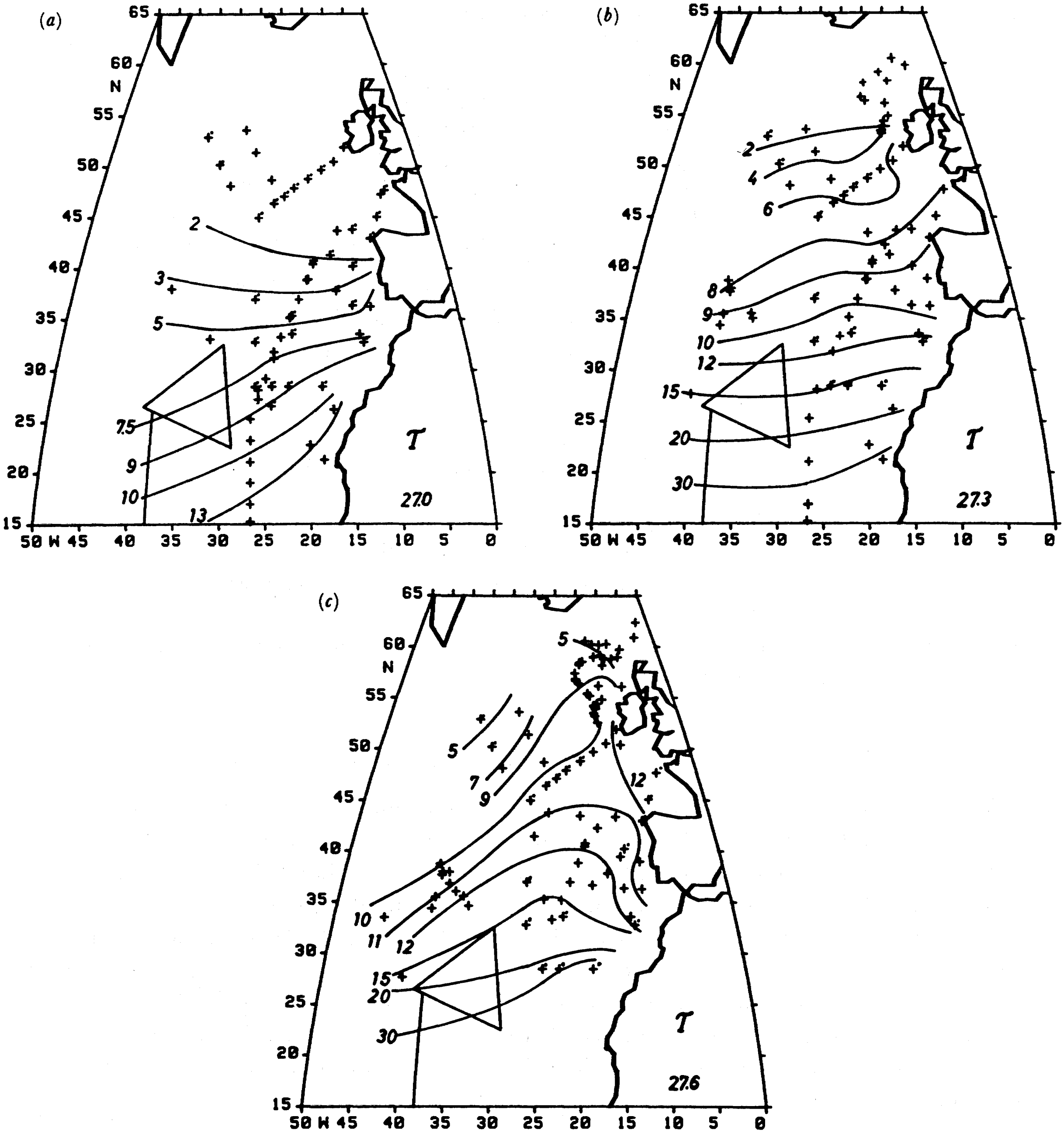

FIGURE 2. Tritium–^{3}He age distribution (units in years) on density surfaces $\sigma_\theta = 27.0$ (*a*), 27.3 (*b*) and 27.6 (*c*).

1987). The total velocities give a southward flow across 45° N of about 5×10^6 m^3 s^{-1} for the layer bounded by $\sigma_\theta = 27.0$ and 27.6 between 10° and 30° W. This is in agreement with an estimate by Krauss (1986). The conclusion that these layers of the Northeast Atlantic are ventilated by advection from the subpolar region is supported by the age distribution in figure 2. An extrapolation of the τ isolines on the isopycnals to zero age leads to boundaries of wintertime ventilation for these isopycnals that are fully consistent with boundaries derived from

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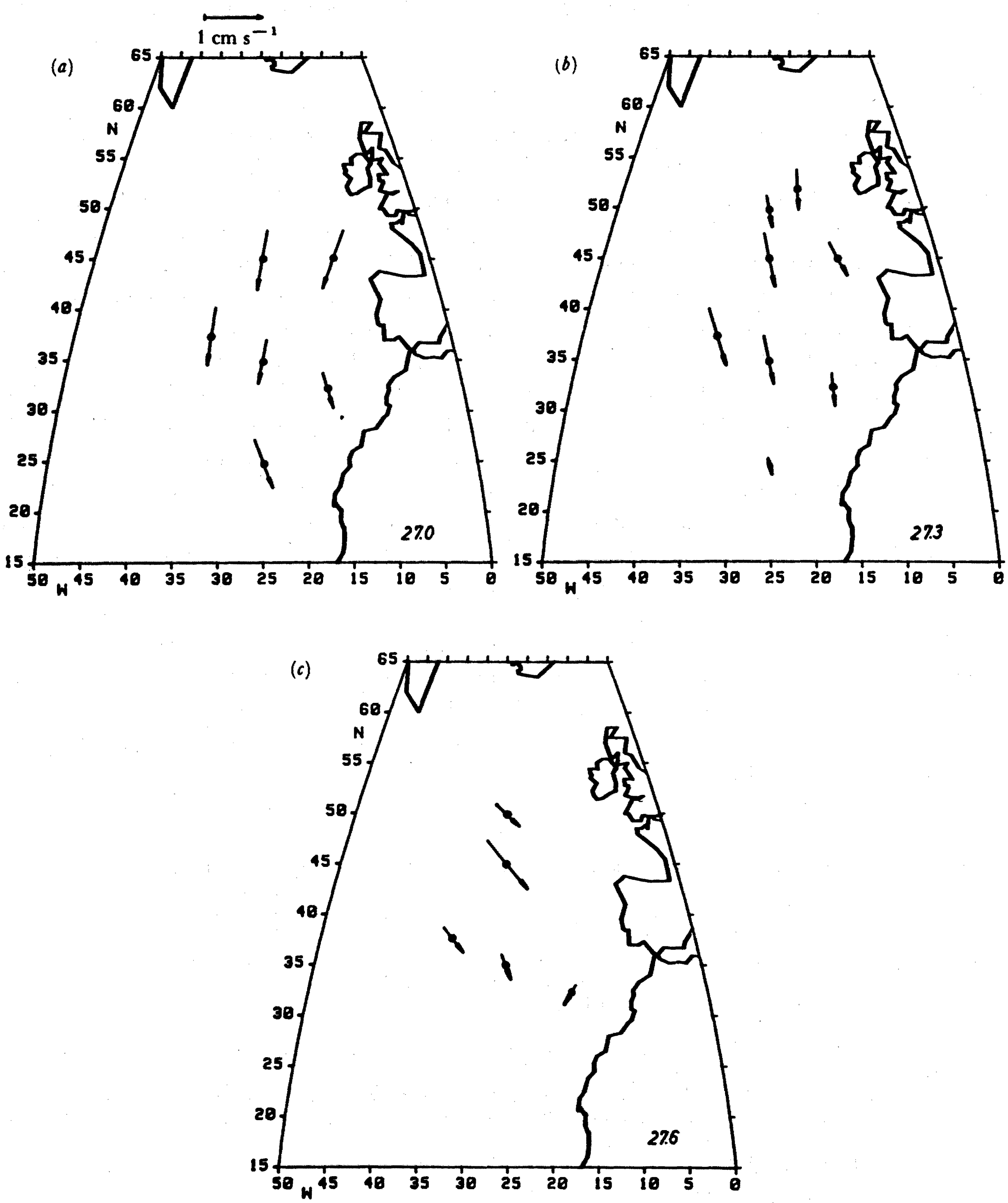

FIGURE 3. Velocity at selected points (centre of the arrows) in the Northeast Atlantic at the density horizons $\sigma_0 = 27.0$ (*a*), 27.3 (*b*) and 27.6 (*c*).

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hydrographic observations (Sarmiento *et al.* 1982; see also the assessment by Jenkins (1987) for shallower layers).

4. Discussion

Our result of basically southward flow is at variance with geostrophic (Saunders 1982) and β-spiral (Olbers *et al.* 1985) calculations, which, in the depth range in question, derive north to northeastward flow, at least in the region north of 40° N. We might be wrong if our assumed diffusivities were too small or if the tracer concentrations at some intermediate latitude in the area considered were determined not by advective or diffusive meridional exchange but rather by strong zonal inflow from the west that might then, together with some meridional mixing, produce the observed meridional age gradient. A simple calculation with a northward flow velocity, such as that derived by Olbers *et al.* (1985), being balanced by isopycnal mixing shows, however, that an isopycnal diffusivity of at least about $5 \times 10^4\ m^2\ s^{-1}$ would be required to explain the observed meridional age gradients. Such a value is quite unrealistically large. It is further believed that diapycnal processes should contribute rather less than the isopycnal ones. As for an interfering zonal flow, one would expect it to lead to observable east–west gradients in age that are not apparent in our data, although there is a data gap towards the west at about 40°–45° N (see figure 2). The discrepancy between velocities deduced from tracer distribution and from geostrophic circulation therefore remains unresolved.

We are grateful for the assistance of the masters, crews and chief scientists of the various cruises from which our data originate. We thank especially W. J. Jenkins, P. Schlosser and W. Weiss for allowing us to use their unpublished data. G. Zimmek and G. Bader carried out the helium and tritium measurements at Heidelberg. This study was supported by the Deutsche Forschungsgemeinschaft.

References

Armi, L. & Stommel, H. 1983 Four views of a portion of the North Atlantic subtropical gyre. *J. phys. Oceanogr.* **13**, 828–857.

Fuchs, G. 1987 Ventilation der Warmwassersphäre des Nordostatlantiks abgeleitet aus ^{3}Helium- und Tritium-Verteilungen. Doctoral dissertation, Institut für Umweltphysik, University of Heidelberg.

Fuchs, G., Roether, W. & Schlosser, P. 1987 Excess ^{3}He in the ocean surface layer. *J. geophys. Res.* **92**, 6559–6568.

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

Jenkins, W. J. 1987 ^{3}H and ^{3}He in the beta triangle: observations of gyre ventilation and oxygen utilization rates. *J. phys. Oceanogr.* **17**, 763–783.

Jenkins, W. J. & Clarke, W. B. 1976 The distribution of ^{3}He in the Western Atlantic Ocean. *Deep Sea Res.* **23**, 481–494.

Jenkins, W. J., Lott, D. E., Davis, M. W. & Boudreau, R. D. 1985 W.H.O.I. Helium Isotope Laboratory Data Report no. 2, Tritium and ^{3}He data from the Beta Triangle (AII – 107, Oct. 1979 and OC-78, March 1980) Woods Hole Oceanographic Institution.

Kawase, M. & Sarmiento, J. L. 1985 Nutrients in the Atlantic thermocline. *J. geophys. Res.* **90**, 8961–8979.

Krauss, W. 1986 The North Atlantic Current. *J. geophys. Res.* **91**, 5061–5074.

Luyten, J. R., Pedlosky, J. & Stommel, H. 1983 The ventilated thermocline. *J. phys. Oceanogr.* **13**, 292–309.

Olbers, D. J., Wenzel, M. & Willebrand, J. 1985 The interference of North Atlantic circulation patterns from climatological hydrographic data. *Rev. Geophys.* **23** (4), 313–356.

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

Saunders, P. M. 1982 Circulation in the eastern North Atlantic. *J. mar. Res.* **40** (suppl.), 641–657.

Discussion

W. J. Jenkins (*Woods Hole Oceanographic Institution, Woods Hole, U.S.A.*). I am uncomfortable with the comparison of model or climatologically averaged data that are presented at constant depth with 'isopycnal' velocities. Could part of the discrepancy that Professor Roether reports between the tracer-derived velocities and such flow fields be explained by the northward shoaling of the density surface coupled with vertical shears in the flow field?

Would it not be more appropriate to compare Professor Roether's tracer-derived velocities to geostrophic estimates with the hydrographic data obtained from his cruises?

Further, Professor Roether's comment that one would require substantially larger isopycnic or diapycnic diffusivities (than he has used) to explain the differences is intriguing. Has he done the 'inverse' calculation of estimating how large such diffusivities must be to bring the two flow fields into agreement?

W. Roether. It is true that geostrophic analysis deals with level surfaces in contrast with our isopycnal interpretation and that non-synoptic data may be a problem. Still, these differences in my view do not open a straightforward escape route from our apparent discrepancy, and more work is certainly needed. The isopycnic diffusivity required to override advection is $5 \times 10^4\ m^2\ s^{-1}$. This value has been substantiated also by an inverse-model evaluation of the isopycnal age fields.

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