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Characteristics of particle dispersion in the North Atlantic: an alternative interpretation of SOFAR float results

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Abstract—An analysis of published results on the dispersion behavior of SOFAR floats indicates a systematic depth dependence of the mixing length in the North Atlantic subtropical gyre. In contrast to the integral time scale, the length scale appears to be independent of eddy intensity in the thermocline (L_x, L_y ~ 80, 45 km) and in the deep ocean ($L_x \approx L_y$: 20 – 30 km). A similar decrease with depth is revealed by particle dispersion in an eddy-resolving circulation model and interpreted as an enhanced effect of wave behavior in the weaker, subthermocline flow. The only weak anisotropy of deep float dispersion suggests an influence of bottom roughness on the structure of eddy variability.

INTRODUCTION

DURING the last years some progress has been made in characterizing the Lagrangian nature of ocean circulation using acoustically tracked, freely drifting floats and satellite-tracked buoys. In particular, the analysis of the dispersion behavior can provide a valuable contribution towards an understanding of lateral mixing processes in the ocean. Lagrangian diffusivities have been derived from the trajectories of various SOFAR float ensembles in the western North Atlantic (FREELAND *et al.*, 1975; RISER and ROSBY, 1983; ROSBY *et al.*, 1983) and eastern North Atlantic (REES and GMITROWICZ, 1987). The dispersion of surface drifters in the North Atlantic was analysed by COLIN DE VERDIERE (1983) and KRAUSS and BÖNING (1987).

In an attempt to rationalize the geographically strongly varying diffusivities, a linear relationship between eddy diffusivity and eddy kinetic energy was proposed (ROSSBY *et al.*, 1983; MCWILLIAMS *et al.*, 1983), implying that the Lagrangian integral time scale is constant, i.e. independent from the eddy intensity. In contrast to this interpretation drawn from the float observations, the surface drifter analysis by KRAUSS and BÖNING (1987) indicated a scaling of eddy diffusivity with r.m.s. velocity, rather than velocity variance; the integral time scale was found to decrease with increasing eddy intensity, whereas the integral length scale remained approximately constant.

The present paper offers a fresh look at the observational results from different perspectives. Specifically, it is intended to draw attention to a previously overlooked aspect of float behavior, i.e. the possibility of a systematic depth dependence. An explanation of the dispersion characteristics is sought by a comparison with particle behavior in an eddy-resolving numerical model (BÖNING and COX, 1988; BÖNING, 1988).

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INTEGRAL TIME AND LENGTH SCALES

Under the assumption of stationary statistics, particle displacements are characterized by the displacement of the center of gravity of an ensemble, and the turbulent dispersion, D, defined by the displacement covariance. The time rate of change of single particle dispersion defines the Lagrangian diffusivity $K = 1/2\ \mathrm{d}/\mathrm{d}t\ D$. While in the general case, K is a function of spreading time and cannot be regarded as a property of the flow field at a given location, a special situation occurs under the additional condition of statistical homogeneity (TAYLOR, 1921; BATCHELOR, 1949). In that case, the dispersion will increase linearly with spreading time for $t \gg T$ (T the integral time scale) and the diffusivity approaches a constant value

$$K = \overline{u'^2}\, T. \tag{1}$$

An alternative form of this relation may be given by introducing the distance L during which particles move during the period T, i.e.

$$L = \overline{u'^2}^{\frac{1}{2}}\, T,$$

characterizing the "mixing length" of the turbulent flow. In terms of this length scale the diffusivity is given by

$$K = \overline{u'^2}^{\frac{1}{2}}\, L. \tag{2}$$

Of course, both forms (1) and (2) are completely equivalent.

It should be emphasized that the validity of these relations critically depend on the existence of a random walk regime with constant diffusivity, i.e. the validity of the homogeneity assumption. Obviously in many regions of the ocean the assumption must be fundamentally wrong, especially in intense current regimes with strong mean shear and large gradients of eddy energy. It seems, however, that the result of float and buoy observations, in more "quiet" regions, support the idea that Taylor's formula does provide at least a good starting ground for analysing mesoscale dispersion in the ocean.

The significance of the homogeneous case lies (a) in the fact that here K can be interpreted in terms of the eddy diffusivity tensor defined in a Eulerian flux-gradient relation, and (b) in the possibility to estimate K via relation (1) or (2), instead of by analysing the dispersion. Since the kinetic energy distribution is certainly the best-known statistic of the oceanic eddy field, it appears important to see whether any rationale behind the integral scales can be found. Lagrangian statistics obtained by SOFAR float observations in the North Atlantic are compiled in Table 1.

In Fig. 1 the variation of the time and length scales is displayed as a function of r.m.s. velocity. The first impression is that, overall, neither the time nor the length scale appear to be constant: T varies between 5 and 18 days, L between 13 and 85 km. Some systematic tendencies are noted, however, if we consider floats in the deep thermocline (~700 m) and below the thermocline (1300–2200 m) separately. In both categories, the time scales tend to decrease with increasing eddy intensity, whereas the length scales appear to be rather constant (except, perhaps, the meridional scale in 700 m). Secondly, the scales revealed by the subthermocline floats are systematically smaller than the scales in the thermocline: L_x is about 80 km in the thermocline, compared with about 28 km in the deep ocean; L_y, with 45 km, is smaller than L_x in the thermocline and becomes similar to L_x in the deep ocean (~20 km).

Table 1. *Statistics from SOFAR floats in the North Atlantic. Underlined values as given in the References, others are derived*

Reference	Area	Depth (m)	$\overline{u'^2}$	$\overline{v'^2}$	K_x	K_y	T_x	T_y	L_x	L_y
			(cm^2 s^{-2})		(10^7 cm^2 s^{-1})		(days)		(km)	
FREELAND *et al.* (1975)	MODE	1500	7.3	8.1	$\underline{0.78}$	$\underline{0.71}$	12.3	10.1	29	25
PRICE (unpublished)	LDE	700	$\underline{120}$	$\underline{85}$	$\underline{8 \pm 2}$	$\underline{5 \pm 2}$	7.7	6.8	73	54
As cited in ROSSBY *et al.* (1983)		1300	$\underline{36}$	$\underline{38}$	$\underline{1.5 \pm 1}$	$\underline{1.5 \pm 0.5}$	4.8	4.6	25	24
RISER and ROSSBY (1983)	POLYMODE									
	"EAST"	700	30	30	$\underline{4.5}$	$\underline{1.8}$	$\underline{18}$	$\underline{7}$	82	33
					(±50%)					
	"NARES"	2000	7.0	4.3	$\underline{0.9}$	$\underline{0.26}$	$\underline{15}$	$\underline{7}$	34	13
	(Near boundary)	700	58	51	$\underline{6.5}$	$\underline{3.5}$	$\underline{13}$	$\underline{8}$	85	49
REES and GMITROWICZ (1987)	Eastern North Atlantic	2200	$\underline{2.8}$	$\underline{3.2}$	$\underline{0.37}$	$\underline{0.21}$	$\underline{17}$	$\underline{10}$	$\underline{25}$	$\underline{15}$

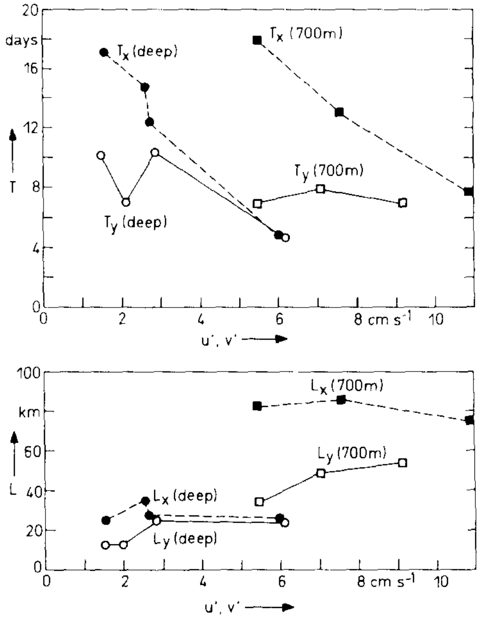

Fig. 1. Integral time and length scales for North Atlantic SOFAR floats: ■, □ results from 700 m floats (zonal, meridional); ●, ○ results from floats in subthermocline levels (1300–2200 m).

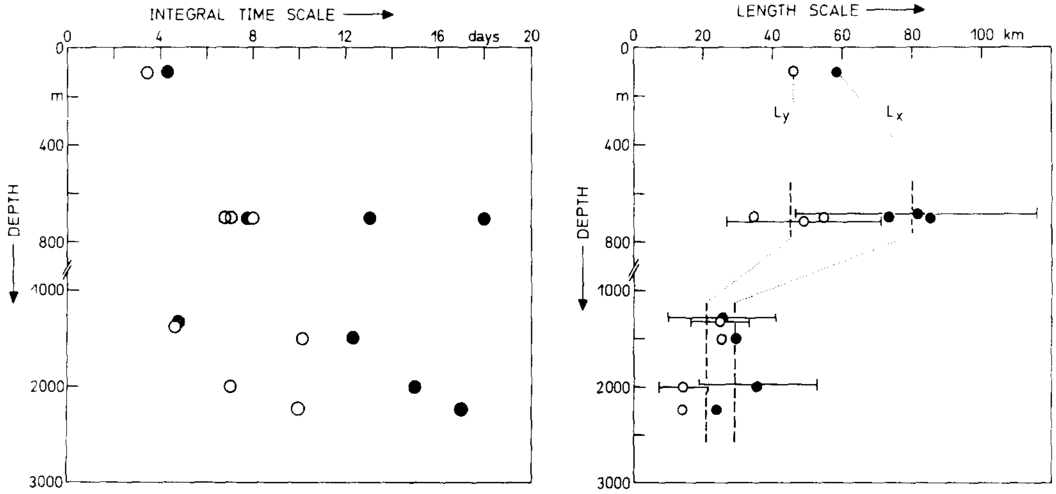

Fig. 2. Vertical dependence of integral time and length scales, derived from SOFAR float and surface drifter trajectories.

Figure 2 puts the mixing scales into another perspective by focusing on the depth dependence. In addition to the float values we have also displayed the integral scales derived in the surface drifter analysis of KRAUSS and BÖNING (1987). While there seems to be no systematic pattern behind the time scale, there is a strong indication of a systematic depth dependence in the length scale: the mixing lengths in the deep ocean are about 20–30 km, rather independent of depth and almost isotropic; the length scales in the thermocline are substantially larger, with an indication of an enhanced anisotropy. This slight anisotropy in particle spreading also is revealed by the surface drifter scales, being somewhat smaller than the mixing lengths in 700 m.

DISCUSSION

The Lagrangian statistics of the deep western North Atlantic have been interpreted previously in terms of an approximately constant integral time scale (ROSSBY *et al.*, 1983; MCWILLIAMS *et al.*, 1983): if the observational results listed in Table 1 are put together regardless of depth, the eddy diffusivity appears to increase linearly with eddy kinetic energy. The present analysis, performed on the same results, suggests another interpretation: overall, neither the integral time nor the length scale can be regarded as constant; however, there is an indication of a systematic depth dependence of the length scale, decreasing from rather uniform values in the thermocline to again rather uniform values in the deeper layers. It should be emphasized that the existing data sets are too limited to clarify this issue. Whether or not, and to what extent, any scale characterizing eddy mixing from the Lagrangian point of view can be considered uniform in the ocean still can not be answered. Rather than giving definite conclusions on this issue, the present analysis at least should caution against the interpretation of float statistics lumped together from different levels.

Constant integral length scales can be expected for energetic eddies of constant horizontal scale (ARMI, 1979). Such a behavior seems to be realized in the more turbulent regime near the surface where wave influences seem relatively small (KRAUSS and BÖNING, 1987). A tendency towards decreasing mixing length scales, by a factor of two from the surface to 1000 m depth, also was found by ARMI and STOMMEL (1983) in their analysis of the β-triangle.

Some hints at the underlying mechanisms can be found in numerical model results. BÖNING and COX (1988) have analysed particle dispersion in the eddy-resolving circulation model of COX (1985). A basin of constant depth and idealized configuration, but wide dimension, representative of the North Atlantic, was used; a sensitivity study (BÖNING, 1988) looked at the effects of a rough bottom topography. In Fig. 3 the length scales characterizing eddy dispersal in the interior of the subtropical model gyre are displayed as a function of depth. The area was found to be fairly homogeneous, with eddy kinetic energy of about 80 $cm^2\ s^{-2}$ at the surface. The depth dependence shows a similar structure as the profiles based on the float results: maximum values are found in the thermocline; below the thermocline both components decrease and eventually become depth independent. An interesting feature of the flat bottom solution is the distinct zonal orientation of particle spreading in the subthermocline levels: this strong anisotropy appears as a main discrepancy when compared with the actual data. In this respect, the deep float behavior seems to be much better characterized by the model which includes a rough bottom floor.

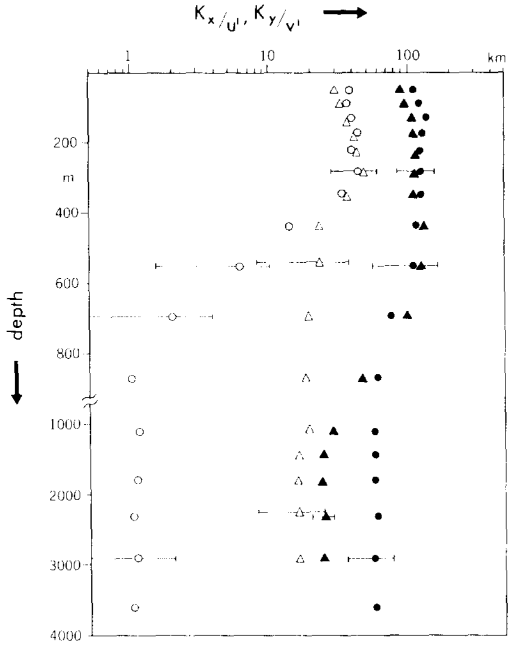

Fig. 3. The vertical dependence of the mixing length in the subtropical gyre of an eddy resolving model: ●, ○ results (L_x, L_y) of the flat bottom case (BÖNING and COX, 1988); ▲, △ results of the rough bottom case (BÖNING, 1988). Each dot represents an average over 1440 particles released in groups of 144, at 10 different times during a 6 year period.

The systematic decrease of the integral length scale, characterizing the particle spreading both in the model and in reality, could be understood as a manifestation of a change in the diffusive character of the fluctuations due to a competition of turbulent behavior with an increasing influence of wave-like, i.e. nondiffusive fluctuations, in weaker flow regimes. In the model, the importance of Rossby wave influences emerged more strongly in areas with smaller r.m.s. velocities, e.g. in the subthermocline layers. As a consequence of the combined action of turbulent eddies and Rossby wave behavior, no simple relationship between diffusivity and velocity variance can exist for an entire oceanic gyre.

A remarkable feature of the float dispersion results is the negligible anisotropy observed in the deeper layers. Theoretical considerations (HOLLOWAY and KRISTMANNSSON, 1984) and numerical experiments based on flat bottom models (D. B. HAIDVOGEL, unpublished data) generally predict a suppression of meridional, and elongation of zonal particle excursions as an effect of the planetary vorticity gradient which becomes dominant in regions of weaker flow intensity. A possible explanation of the observed behavior suggested by model results (BÖNING, 1988) is the influence of bottom roughness on the structure of the eddy variability. More generally, since the corresponding Eulerian signature is hidden in the low-frequency part of the velocity spectrum (which is hardly accessible by observations), it should be emphasized that characteristic features of the float behavior like this can become extremely valuable for testing the validity of eddy-resolving models.

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