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RAPID RESPONSE PAPER

Nine-year trajectory of a SOFAR float in the southwestern North Atlantic

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Abstract—A SOFAR float at a depth of approximately 1000 m was tracked intermittently for 9 years, the longest such trajectory ever obtained. This instrument was launched near 24N, 69W in October 1976. Tracking ceased when it was near 22N, 56W in June 1985. The long-term drift was ~1 cm s^{-1} eastward, in agreement with a few other 700 m floats and with geostrophic flow estimates for this region. The kinetic energy level of 20 cm^2 s^{-2} is similar to those observed by current meters in the ocean interior away from western boundary currents, but eddy variability is more concentrated in the mesoscale frequencies. The zonal and meridional variances are roughly the same.

INTRODUCTION

Long-term circulation measurements are difficult to obtain and are, therefore, very rare, despite their usefulness in showing where water goes over long periods of time. Most subsurface ocean trajectories exceeding a year in length have been measured with acoustically tracked (SOFAR) floats which have a nominal lifetime of 2 years (Rossby *et al.*, 1983; Owens, 1984). Several of these have lifetimes in the 4-year range. One particularly long-lived float has been tracked (intermittently) over a 9-year period providing the longest such trajectory ever obtained. This trajectory is described in some detail below.

Float PL-12 was launched in 1976 near 24N, 69W at a nominal depth of 1000 m as part of a geographical exploration of currents in the Northwest Atlantic in preparation for the POLYMODE Experiment (McDowell and Rossby, 1978; Riser and Rossby, 1983). Compared to floats used previously during the MODE experiment (Rossby *et al.*, 1975), these floats had two new features; they had sacrificial ballasting that kept them at constant pressure, preventing them from slowly sinking due to deformation of aluminum hull; and they used a signaling scheme that was more efficient and detectable at larger ranges (Spain *et al.*, 1980).

The battery pack used for PL-12 contained electrical energy for a 2–3 year service. The long life of PL-12 indicates that it operated at only a fraction of full power. Despite this

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low power, its maximum signal range exceeded 3500 km, approximately 50% greater than for floats ballasted for 700 and 2000 m depth and is probably due to the fact that PL-12 is on the axis of the deep sound channel.

Tracking initially was accomplished using both shore-based and moored receiving stations (O'GARA *et al.*, 1982). For 1981–1985 PL-12 was tracked using an array of moored autonomous listening stations (ALS's) that were maintained to track floats launched in the vicinity of the Gulf Stream (RICHARDSON *et al.*, 1981; KENNELLY and MCKEE, 1984; PRICE *et al.*, 1987). Because of the long ranges between the float and moored listening stations and the poor tracking geometry when the float is near the Bahama–Caribbean Island Arc, the absolute accuracy (estimated to be 4–5 km) of the float track is not as high as that obtained during POLYMODE (1–3 km, SPAIN *et al.*, 1980). The float also had an unusually large drift in its internal clock which is estimated in the tracking algorithm (SPAIN *et al.*, 1980). We believe that the 30 km displacement between pieces D and E is a result of differing estimates of clockdrift between the Rhode Island and Woods Hole tracking algorithms. Unfortunately, the earlier clock estimates have not been archived so we were unable to reconcile these differences. Thus, the large-scale movement of the float has an uncertainty of at most 1% while the velocities are accurate to within 1–2 cm s^{-1}.

Float PL-12 and two other floats were launched in an eddy with water properties similar to those of Mediterranean water in the eastern North Atlantic (MCDOWELL and ROSSBY, 1978). The float was ballasted for 900 db, but no pressure data were obtained from it (O'GARA *et al.*, 1982). Temperature measured by the float was about 11°C for the first 40 days, decreasing to 6.5°C and then remaining at approximately 6.0°C for most of the trajectory. The initial high temperature was due to the Mediterranean water in the eddy and the decrease occurred as the float left the eddy. The 6°C isotherm lies near 1000 db in the vicinity of the float trajectory (FUGLISTER, 1960). Sacrificial ballasting and telemetered temperatures suggest that the float remained near 900–1100 m over its lifetime. Only over the last 18 months was there a slow decrease in temperature from 6.2 to 5.8°C, which would correspond to an increase in depth of approximately 100 m.

RESULTS

The trajectory of float PL-12 is broken into seven places, A–G (Fig. 1). Early gaps in the trajectory were caused by difficulties in tracking the float near the Bahama–Caribbean Island Arc. Later gaps occurred due to breaks in the coverage by moored listening stations.

For the first part of the track, pieces A and B, the float trajectory is dominated by anticyclonic looping associated with the eddy. Initially, the eddy drifted southwestward at 7 cm s^{-1}. Temperature data (O'GARA *et al.*, 1982) suggest that the float was separated from the core of the eddy near the end of piece A. The loops and cusps seen in piece B and the beginning of C show that the float was trapped in an anticyclonic eddy moving southeastward along the Bahama–Caribbean Island Arc. It is possible that this eddy is the original eddy that moved northward between pieces A and B, but we cannot be certain. Since there were no other velocity measurements in the vicinity, we cannot differentiate between propagation of the eddy and advection by the large-scale flow. As a result, the mean drifts over the first part of the track may not be representative of flow outside the eddy.

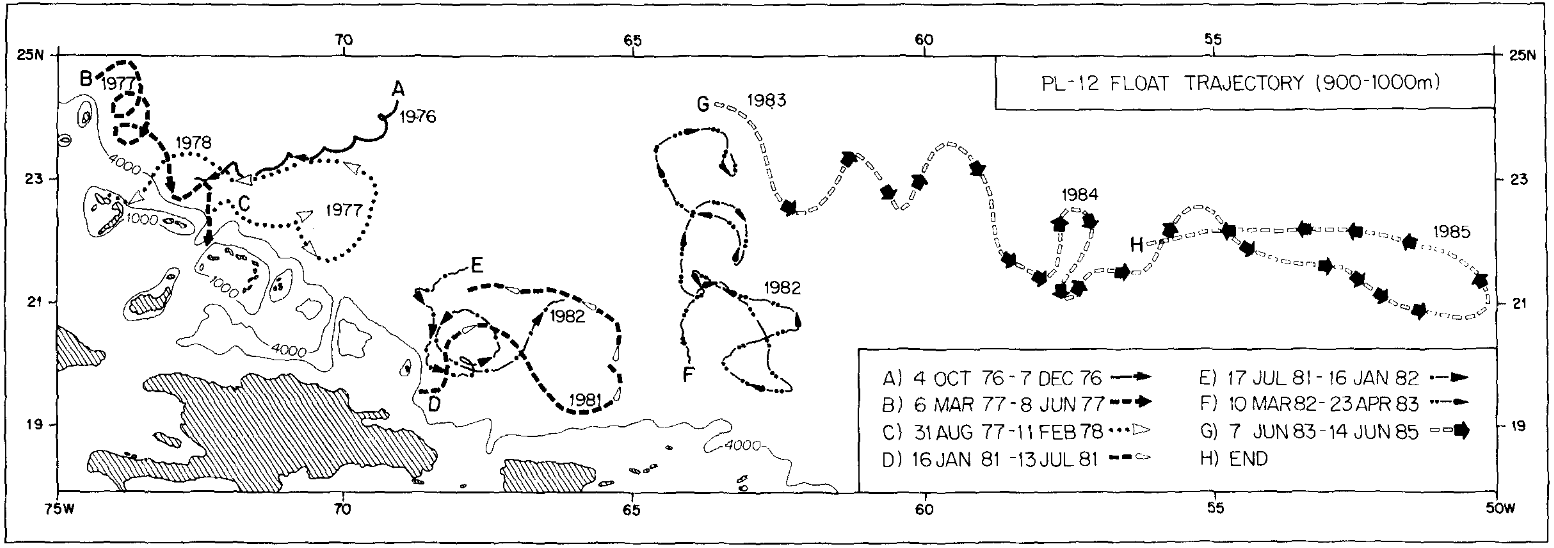

Fig. 1. **Float track for PL-12 between 4 October 1976 and 14 June 1985. Each piece is labeled at its *starting point* with arrows placed along each piece at 30-day intervals.**

It appears that the large gap between pieces C and D occurred because the float passed into the Caribbean Sea at 22°30'N, 74W. If the float had remained in the North Atlantic, it would have been heard by ALS's that were within range of the float at that time. However, no signals were detected at any of the ALS's until those used to calculate the first positions for piece D, 19°30'N, 69W.

During the last 4 1/2 years, pieces D–G, the float moved eastward at a mean velocity of 0.85 cm s^{-1} (Table 1). There appears to be a change in character between the last piece, G, and the previous ones, D–F, in that the eddy variability decreased from approximately 30 to 13 cm^2 s^{-2}. This can also be seen in the time series of velocity (Fig. 2), in which the amplitude of the variations clearly decreased. The mean velocity averaged over pieces D–F is eastward at 0.78 cm s^{-1}. During the first 18 months of the last piece, G, the float moved eastward with a mean velocity of 2.9 cm s^{-1} and then traveled westward during the last 6 months at about the same speed. Thus, although the large-scale drift indicates a mean 1 cm s^{-1} eastward flow there was clearly significant interannual variability of the zonal velocity. This mean eastward flow is consistent with the observed drift of a few other floats in the region near 23N (RISER and ROSSBY, 1983; ROSSBY *et al.*,

Table 1. *Summary of velocity statistics for float* PL-12

	Portion of trajectory		Data	Velocity (cm s^{-1})			Variance (cm^2 s^{-2})		
	Start	End	(days)	$\bar{T}$	$\bar{u}$	$\bar{v}$	$\overline{u'^2}$	$\overline{v'^2}$	EKE
A	4 Oct. 1976	7 Dec. 1976	65	10.4	−6.48	−2.49	28	34	31
B	6 Mar. 1977	8 Jun. 1977	95	6.8	2.41	−3.57	43	53	48
C	31 Aug. 1977	11 Feb. 1978	164	6.7	−1.40	0.20	46	26	36
D	16 Jan. 1981	13 Jul. 1981	178	5.9	0.48	1.14	35	24	30
E	17 Jul. 1981	16 Jan. 1982	182	6.1	1.00	−0.36	37	27	32
F	10 Mar. 1982	23 Apr. 1983	409	6.1	0.23	1.03	25	19	22
G	7 Jun. 1983	14 Jun. 1985	737	5.9	1.24	−0.40	14	12	13
All	4 Oct. 1976	14 Jun. 1985	1830	6.3	0.47	−0.11	28	22	25
D–G	16 Jan. 1981	14 Jun. 1985	1509	6.0	0.85	0.17	23	18	20

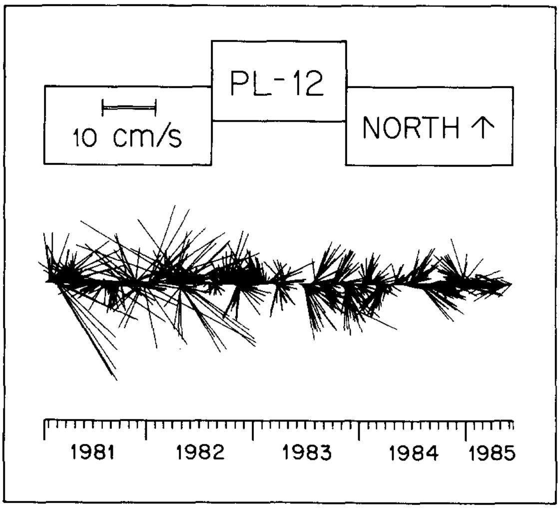

Fig. 2. Time series of daily currents for PL-12. North is up and values are plotted for every other day.

1983). The eddy kinetic energy of 20 cm^2 s^{-2} observed by PL–12 is also similar to that measured by moored current meters in regions far from western boundary currents (Schmitz, 1978; Schmitz *et al.*, 1988).

The eddy kinetic energy spectra (Fig. 3) were computed from the velocity data for pieces D–G using a discrete Fourier transform procedure which assigns energy to each of the basic frequency bands ($\alpha \pm 0.5$) N^{-1}, where N is the number of data days (1500) and $\alpha = 1, \ldots N/2 - 1$. Thus, for example, the lowest resolved frequency band ($\alpha = 1$) represents energy in the band with periods from 3000 to 1000 days. We have summed the kinetic energy over a few frequency bands to estimate the energy in (a) the secular time scale, periods from 3000 to 200 days; (b) the mesoscale, periods from 200 to 30 days; and (c) "high" frequency, periods from 30 to 2 days. This broad frequency range also has been used to describe a number of Eulerian velocity time series (e.g. Schmitz *et al.*, 1988) for regions of comparable eddy kinetic energy levels. The increase in the mesoscale band compared to both the secular and "high" bands is especially pronounced in Fig. 3. In comparison, Eulerian spectra calculated from shorter duration records for regions of comparable overall eddy variability, including the MODE region (28N, 70W), POLY-MODE Array 3B (28N, 41W), and the eastern North Atlantic (32N, 24W) show a "redder" spectral shape with a larger fraction of their variability occurring in

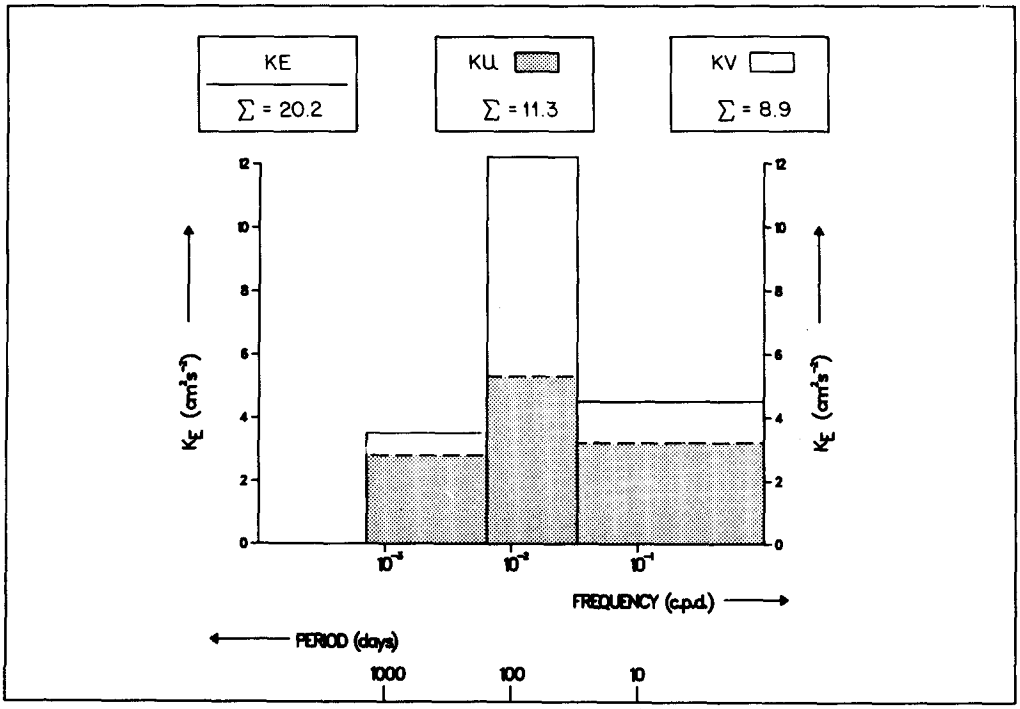

Fig. 3. Frequency distribution of eddy kinetic energy for PL-12. The hatched areas are the zonal kinetic energy, the stippled area the meridional. The total height represents the total kinetic energy.

the secular time scales (SCHMITZ *et al.*, 1988). Interestingly, an Eulerian spectrum computed from a time series of comparable length (7 years) shows a spectral shape with a similar peak as that for PL-12 (ZENK and MÜLLER, 1988). The partition between zonal and meridional components changes dramatically for the different frequency bands (Fig. 3). As one would expect from the trajectory (Fig. 1), the zonal component dominates the secular scale. In the mesoscale band the meridional component is slightly larger while in the "high frequency" band the zonal component dominates.

DISCUSSION

An extremely long-lived SOFAR float has provided us with a glimpse of the long time scale Lagrangian circulation in the southwestern North Atlantic. Although the trajectory is intermittent, the long-term eastward displacement is clearly apparent. This mean eastward velocity is consistent with the displacements of shorter-lived floats in the region (RISER and ROSSBY, 1983; ROSSBY *et al.*, 1983). The dynamic height field for the sea surface relative to both 1000 and 2000 dbar as well as for 1000 dbar relative to 2000 dbar (REID *et al.*, 1977; REID, 1978) also indicate that there should be eastward flow in this region. From the later part of the track of this float, as well as from the tracks of other floats in the region, it appears that this eastward flow near 23N may occur in a rather narrow, swift current. Existence of these narrow, long-lived currents, both as seen here and in other locations, for example in the Canary Basin (KÄSE *et al.*, 1986; PRICE *et al.*, 1986) suggest that the large-scale circulation may have small-scale variations even away from strong western boundary currents, such as the Gulf Stream.

Estimates of the frequency distribution of eddy kinetic energy suggest that the Lagrangian spectra may be more "peaked" in the mesoscale band than is the case for previously reported Eulerian spectra. Although these Eulerian spectra were obtained at other regions in the North Atlantic that had comparable overall eddy energy levels, they were calculated from much shorter records. The only Eulerian time series of comparable duration also shows a more "peaked" spectrum (ZENK and MÜLLER, 1988) suggesting that the previous estimates of a "red" spectral slope were the result of too short time series.

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REFERENCES

FUGLISTER F. C. (1960) Atlantic Ocean Atlas of temperature and salinity profiles and data from the International Geophysical Year of 1957–58. *Woods Hole Oceanographic Institution Atlas Series 1*, 209 pp.

KÄSE R. H., J. F. PRICE, P. L. RICHARDSON and W. ZENK (1986) A quasi-synoptic survey of the thermocline circulation and water mass distribution within the Canary Basin. *Journal of Geophysical Research*, **91**, 9739–9748.

KENNELLY M. A. and T. K. MCKEE (1984) Gulf Stream Recirculation Experiment (GUSREX) and line experiment SOFAR float data 1980–1982. Woods Hole Oceanographic Institution Technical Report WHOI-84-45, 444 pp.

MCDOWELL S. E. and H. T. ROSSBY (1978) Mediterranean water: an intense mesoscale eddy off the Bahamas. *Science*, **202**, 1085–1087.

O'Gara R. M., H. T. Rossby and D. L. Spain (1982) SOFAR float pilot studies in the western North Atlantic 1975–1981. University of Rhode Island Technical Report No. 82-3, 160 pp.

Owens W. B. (1984) A synoptic and statistical description of the Gulf Stream and subtropical gyre using SOFAR floats. *Journal of Physical Oceanography,* **14**, 104–113.

Price J. F., T. K. McKee, P. L. Richardson, J. R. Valdes and L. Armi (1986) SOFAR float Mediterranean Outflow Experiment: Data from the first year, 1984–1985. Woods Hole Oceanographic Institution Technical Report WHOI-86-31, 199 pp.

Price J. F., T. K. McKee, W. B. Owens and J. R. Valdes (1987), Site L SOFAR float experiment, 1982–1985. Woods Hole Oceanographic Institution Technical Report WHOI-87-52, 289 pp.

Reid J. L. Jr (1978) On the mid-depth circulation and salinity field in the North Atlantic Ocean. *Journal of Geophysical Research*, **83**, 5063–5067.

Reid J. L., W. D. Nowlin Jr and W. C. Patzert (1977) On the characteristics and circulation of the southwestern Atlantic Ocean. *Journal of Physical Oceanography*, **7**, 62–91.

Richardson P. L., J. F. Price, W. B. Owens, W. J. Schmitz, H. T. Rossby, A. M. Bradley, J. R. Valdes and D. C. Webb (1981) North Atlantic subtropical gyre: SOFAR floats tracked by moored listening stations. *Science*, **213**, 435–437.

Riser S. C. and H. T. Rossby (1983) Quasi-Lagrangian structure and variability of the subtropical western North Atlantic circulation. *Journal of Marine Research*, **41**, 127–162.

Rossby H. T., S. C. Riser and A. J. Mariano (1983) The western North Atlantic—a Lagrangian viewpoint. In: *Eddies in marine science*, A. R. Robinson, editor, Springer-Verlag, Berlin, pp. 66–91.

Rossby T., A. D. Voorhis and D. Webb (1975) A quasi-Lagrangian study of mid-ocean variability using long range SOFAR floats. *Journal of Marine Research*, **33**, 355–382.

Schmitz W. J. Jr (1978) Observations of the vertical structure of low frequency fluctuations in the western North Atlantic. *Journal of Marine Research*, **36**, 295–310.

Schmitz W. J., J. F. Price and P. L. Richardson (1988) Recent moored current meter and SOFAR float observations in the eastern Atlantic near 32°N. *Journal of Marine Research*, **46**, 301–319.

Spain D. L., R. M. O'Gara and H. T. Rossby (1980) SOFAR float data report of the POLYMODE Local Dynamics Experiment. University of Rhode Island, Graduate School of Oceanography Technical Report, 80-1, 200 pp.

Zenk W. and T. J. Müller (1988) Seven-year current meter record in the eastern North Atlantic. *Deep-Sea Research*, **35**, in press.