Tracking Three Meddies with SOFAR Floats‡

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ABSTRACT

Three Meddies were tracked for up to two years in the Canary Basin using neutrally buoyant SOFAR floats. These Meddies have cores of warm, salty Mediterranean Water and are approximately 100 km in diameter, 800 m thick, and are centered at a depth of 1100 m. Meddy 1 was tracked for two years (1984–86) with five floats as it drifted 1090 km southward with a mean velocity of 1.8 cm s^{-1}. Four shipboard surveys made during these two years revealed the nearly total decay of Meddy 1 by gradual mixing processes. Meddy 2 drifted 530 km southwestward over 8.5 months with a mean velocity of 2.3 cm s^{-1} until it collided with Hyères Seamount near 31°N, 29°W. The floats trapped in this Meddy then stopped looping abruptly, implying a major disruption of this Meddy. Meddy 3 drifted 500 km southwestward for a year and a half with a mean translation velocity of 1.1 cm s^{-1}. A comparison of the velocity of Meddies to the velocity of nearby floats at 1100 m depth outside of the Meddies shows clearly that all three Meddies moved southwestward through the surrounding water at a speed of about 1.3 cm s^{-1}.

The floats inside the Meddies looped anticyclonically in a nearby solid-body rotation with a period of 6 days for Meddy 1, 4 days for Meddy 2, and 5 days for Meddy 3. The rotation period of Meddy 1 appeared to remain constant over nearly two years despite a large decrease in the Meddy's thickness and diameter due to mixing. Rotation velocities in the Meddies were as great as 34 cm s^{-1} (Meddy 2), much faster than speeds of nearby floats outside of the Meddies.

1. Introduction

The Mediterranean salt tongue is one of the most prominent hydrographic features of the main thermocline of the North Atlantic (Fig. 1). The physical processes that maintain the apparent westward salt flux in the tongue are poorly known; we do not know roles of the mean flow, mesoscale fluctuations (jets and eddies), or the very salty lenses known as Meddies. In 1984 a study of the velocity field of the Mediterranean outflow in the Canary Basin was initiated using SOFAR floats (Price et al. 1986). Floats were released in a cluster with 25 km spacing (14 foats), while others were released individually at farther separations (10 floats) and in three different Meddies (8 floats). This report uses the float data to describe the movement and histories of the three Meddies; the history of one of these Meddies (our Meddy 1) has been described previously by Armi et al. (1988, 1989), Hebert (1988a,b, 1989), and Ruddick and Hebert (1988).

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How and where Meddies form is not known, but their large salinity and temperature anomalies, 0.8 psu and 2.5°C, compared to North Atlantic Central Water (Armi and Zenk 1984), suggest a source close to Cape St. Vincent, Portugal. When observed in the Madeira Abyssal Plain, Meddies typically have a diameter of approximately 100 km, a thickness of about 800 m, and are centered at the depth of the Mediterranean Water, 1100 m. They all rotate anticyclonically.

Until this present series of studies with SOFAR floats, the long-term motion and fate of the Meddies was also poorly known. An observation of a subsurface salty lens off the Bahamas (McDowell and Rossby 1978) suggested that Meddies might be able to travel long distances and last many years. However, a comparison of Meddies in the Canary Basin (Fig. 1) with this first Meddy suggests that it might have had a different origin (Rossby, personal communication). The purpose of the work described here was to track a few Meddies in order to observe where they go, how long they last, how they decay, and to then form an estimate of how important they are in transporting salt and heat.

2. Methods

The Meddies were tracked with freely drifting SOFAR floats. These floats transmitted acoustic signals

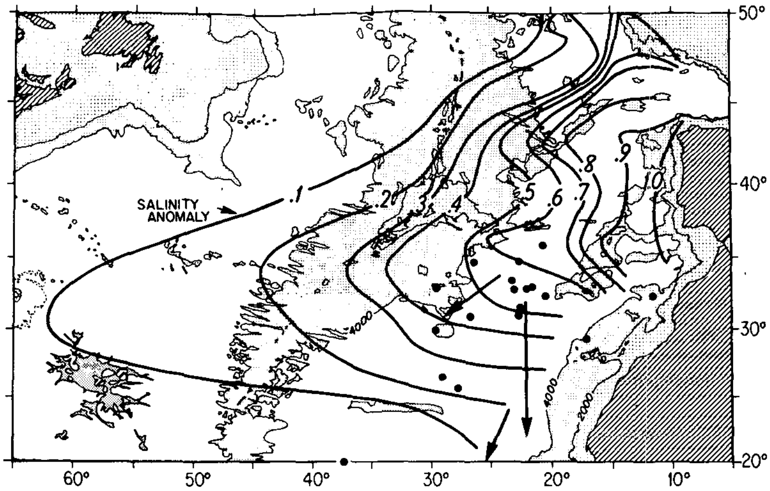

FIG. 1. Mediterranean Water tongue in the North Atlantic and the area of Meddy study. The salinity anomaly is relative to 35.01 psu on the potential density surface 27.7, which lies near 1100 m [based on a figure by Needler and Heath (1975) and shown by Joyce (1981)]. The displacement vectors of the three Meddies are shown by arrows. Individual Meddy observations are shown by dots (Piip 1969; Armi and Stommel 1983; Armi and Zenk 1984; Williams et al. 1986; Käse and Zenk 1987; Yegorikhin et al. 1987; and Stalcup et al. 1988).

twice each day which were detected and recorded by an array of moored listening stations. The floats were built by Webb Research Corporation, and four listening stations were built and deployed by the SOFAR float operations group of Woods Hole Oceanographic Institution. Data from additional listening stations deployed by the SOFAR float group at Centre Oceanologique de Bretagne were used to track the floats that drifted west of about 29°W. Listening stations were deployed from October 1984 to June 1988.

Floats were ballasted for pressures of either 1100 or 1000 db but tended to settle deeper by an average of about 100 db. Active ballasting then made them rise to their target pressures at a rate of about 0.6 m day^{-1}. Without the active ballasting, floats tend to sink slowly (0.5 m day^{-1}) due to compressional creep of the aluminum pressure housing. Temperature and pressure measured by the float were transmitted every other day. A defective component in the telemetry circuit (discovered after launch) caused some failures in temperature and pressure measurements and a shorter than average life of some floats.

Floats were tracked at W.H.O.I. using the acoustic signals received at the four listening stations. Obvious erroneous values of position, temperature and pressure were discarded, and short gaps (less than 10 days) were linearly interpolated. The quality of float data in this experiment was very high, and there were very few such erroneous values or gaps. Reports that describe data from the first two years are by Price et al. (1986), Schmitz et al. (1988), and Zemanovic et al. (1988).

A cubic spline function was passed through the twice daily positions to calculate the velocity of the floats. Several of the float trajectories, and all of those known to be released in Meddies, showed an anticyclonic looping with a period of about 7 days. In order to separate this Meddy-induced rotation from the bulk translation of the Meddy, the float trajectories were

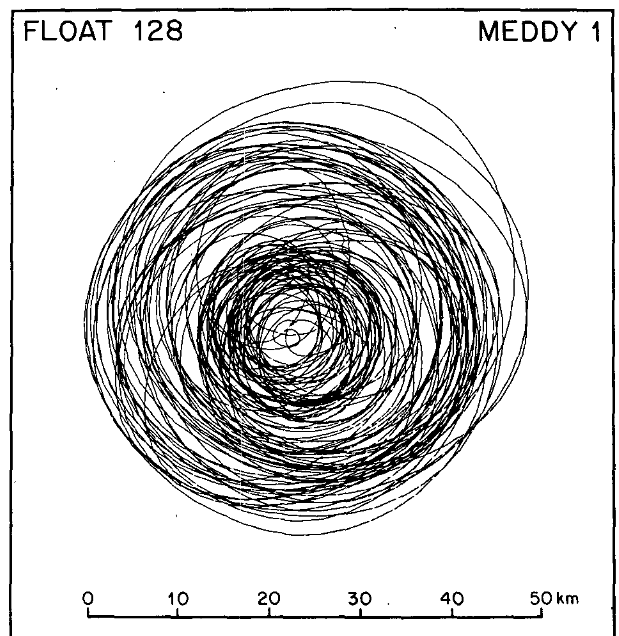

FIG. 2. Movement of float 128 around the center of Meddy 1 from October 1984 to October 1986. This trajectory was obtained by subtracting the Meddy translation from the original trajectory of float 128. The average period of rotation is 7 days.

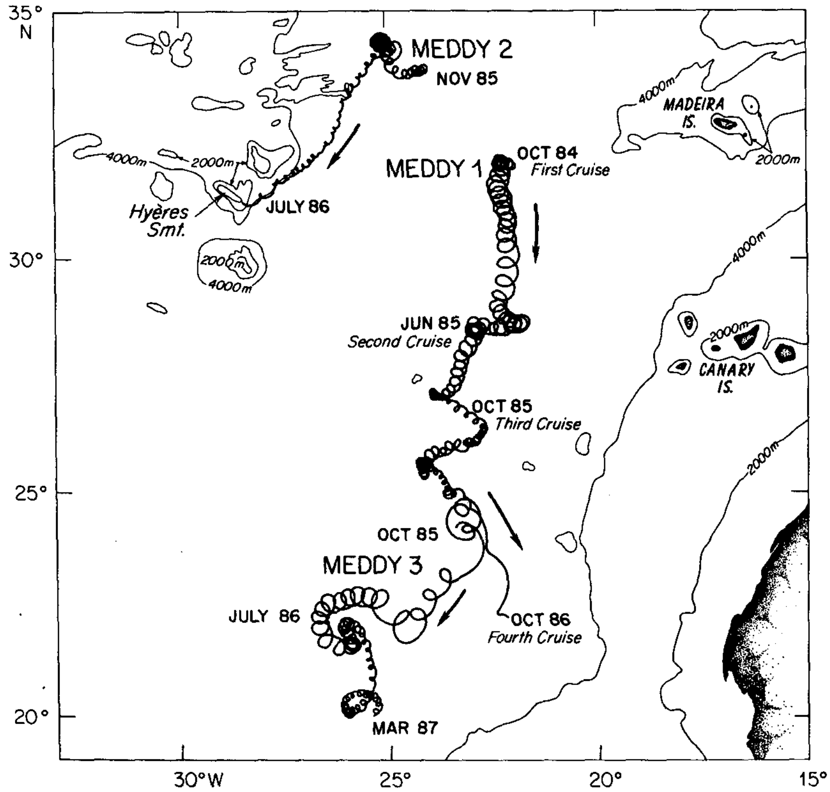

FIG. 3. The translation of three Meddies as given by the trajectories of SOFAR foats. Float 128 came out of Meddy 1 in October 1986, float 149 stopped looping in Meddy 2 when this Meddy collided with a seamount in July–August 1986, and float 145 in Meddy 3 stopped transmitting in March 1987.

smoothed with a Gaussian tapered filter whose length was about three–four times the typical rotation period. These smoothed trajectories were subtracted from the original trajectories to give positions and velocities of the float relative to the Meddy center. These were then decomposed into radius, rotation velocity, and radial

TABLE 1. Floats in Meddies.

		Launched								
Meddy	Float	Date	Lat (°N)	Long (°W)	Days tracked in meddy	Number of loops	Period of loops (days)	$\bar{u}$ (cm s^{-1})	$\bar{v}$ (cm s^{-1})	EKE[c] (cm^2 s^{-2})
1	128[a]	9-29-84	31.89	21.82	720	100	7.2	−0.2	−1.8	128
1	140[a]	9-29-84	31.97	21.92	118	20	5.9	0.1	−2.2	40
1	141[a]	9-17-84	31.93	21.86	240	41	5.8	−0.4	−1.6	41
1	143[a]	9-29-84	31.94	21.88	335	51	6.6	−0.7	−1.9	57
1	150[b]	10-29-85	26.96	23.72	151	8	18.9	−0.5	−1.3	20
2	148	11-11-85	33.33	24.11	247	57	4.3	−1.9	−1.4	189
2	149[b]	11-11-85	33.34	24.13	252	62	4.1	−2.0	−1.2	130
3	145	9-17-85	24.06	23.40	552	56	9.9	−0.4	−1.0	76
All floats outside of Meddies[d]								−0.5	−0.1	7

[a] Floats 128, 140, 141, 143 were tracked beginning mid-October 1984, when the listening stations were moored.

[b] Floats 149 and 150 were actively ballasted for 1000 db, the others for 1100 db.

[c] Eddy kinetic energy (EKE) is the average of variances about the mean in the east and north directions. EKE = $\frac{1}{2}(\overline{u'^2} + \overline{v'^2})$, where $u' = u - \bar{u}$, u is the velocity in eastward direction, $\bar{u}$ the average velocity, u' the departure from the average velocity, and $\overline{u'^2}$ the variance; similarly for v in the northward direction.

[d] The mean velocity of all floats exclusive of Meddy floats differs slightly from the average of floats outside but near Meddies ($u = -0.3$ and $v = -0.2$ cm s^{-1}) mainly because the table includes several cluster floats located in a narrow ~100 km westward jet, which gives a higher westward velocity component.

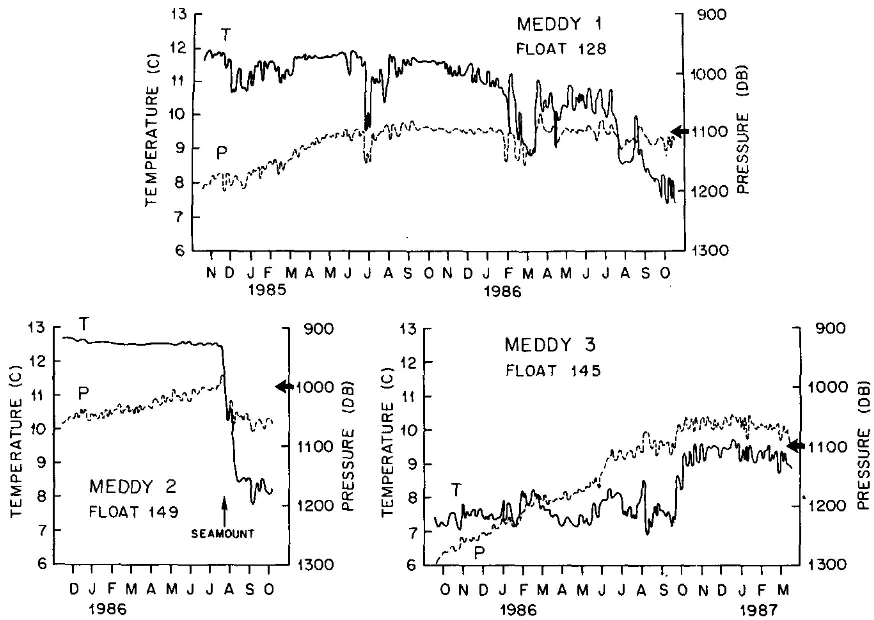

FIG. 4. Temperature and pressure series from a float in each Meddy. All three floats initially settled deep and gradually rose toward the target pressure (shown by dark arrows). The large drop in temperature measured by float 149 coincides with Meddy 2's collision with Hyères Seamount and the float encountering cooler, fresher water. The downward spikes in temperature and pressure of float 128 in July 1985 and spring 1986 are inferred to be a result of the float encountering patches or layers of fresher cooler water. The sudden rise in September 1986 of float 145 is due to its encountering the warmer, saltier Meddy core.

velocity. Figure 2 shows the residual trajectory of float 128 after the translation of Meddy 1 had been removed. During the two years, float 128 slowly varied its radius of looping and maintained a very nearly circular path about the center of Meddy 1. The slight variation from circular motion that does exist is probably due to the method of subtracting the translation in the presence of accelerations and decelerations of the Meddy center.

To be sure that the main results we describe below are not an artifact of the analysis method, we also used a second decomposition method, dividing each trajectory into overlapping segments and fitting a least-squares model of a linear drift plus circular looping,

$$x(t) = ut + R\sin(at + b)$$

$$y(t) = vt + R\cos(at + b),$$

where (u, v) is the Meddy translation, and R is the radius of the float's loop in motion. Because the looping motion is nearly circular, this method gave qualitatively similar results for rotation period, etc. Since the first method seemed somewhat more versatile, it was used throughout and results were checked by the second method.

3. Meddy 1

The first Meddy was found in September 1984 by L. Armi and T. Rossby during a dedicated Meddy survey. They carefully mapped its hydrographic properties, measured some velocity profiles, and tagged the Meddy with four SOFAR floats whose trajectories we describe here. Later surveys of this Meddy were carried out in

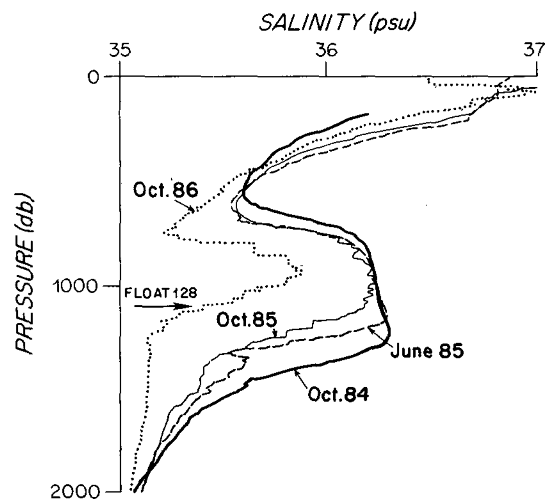

FIG. 5. Salinity profiles through the central region of Meddy 1, showing the gradual decrease with time of its salty core. Float 128 was near 1100 db, near the lower boundary of Meddy 1, during the last cruise in October 1986. This figure is similar to one shown by Armi et al. (1988, 1989).

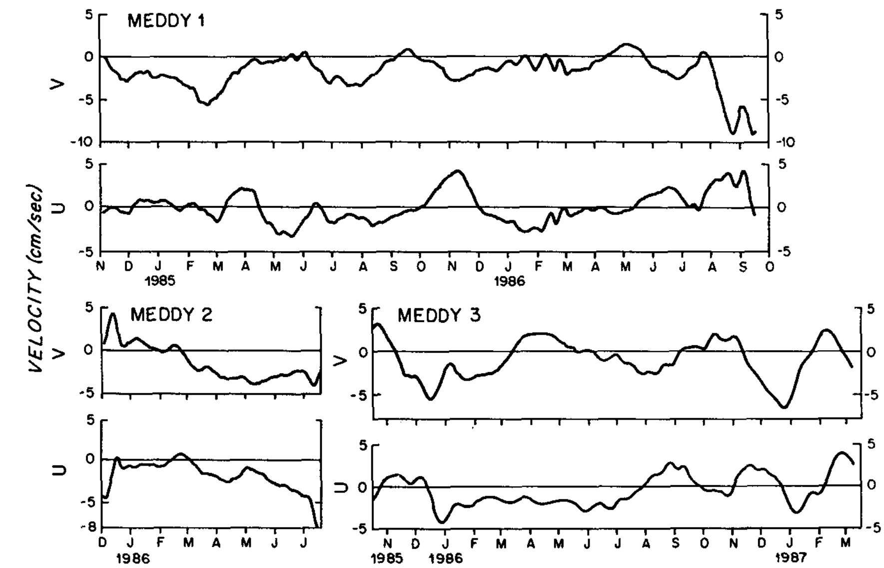

FIG. 6. Time series of Meddy translation velocity calculated from the smoothed trajectories of floats 128, 149 and 145.

June 1985 by D. Hebert, N. Oakey and B. Ruddick, again in October 1985 by L. Armi and A. Bower, and again in October 1986 by J. Price and P. Richardson (see Armi et al. 1988, 1989). To our knowledge, these observations of Meddy 1 comprise the longest available history of any specific ocean eddy.

The movement of Meddy 1 is shown by the trajectory of float 128, which stayed in the Meddy for a full two years (Fig. 3). Over most of its two year drift float 128 remained well within the core of Meddy 1; only during the last few months did 128 appear to be leaving the Meddy. Float 128 looped about 100 times with a radius of 10 km to 20 km (Fig. 2, Table 1). The float trajectory changed character near the end as the Meddy translation accelerated and the period of looping increased. At this time the float was located near the lower boundary of the Meddy. Initially float 128 settled at a pressure of 1200 db; gradually over the next six months it rose and stabilized at 1100 db for the remaining 18 months (Fig. 4). The Meddy was eroded from the sides as it drifted southward (see Armi et al. 1989), so that its lower boundary was at about 1100 db at the end of the second year (Fig. 5). During the last few months, the float temperature dropped from 10.5° to 7.8°C, an indication that the float was leaving the warm core of the Meddy. By this time the Meddy had decayed significantly, retaining only a small remnant of its original properties (Armi et al. 1988, 1989).

TABLE 2. Translation velocity of Meddies.

	Absolute velocity (cm s^{-1})[a]			Velocity relative to nearby floats			Rossby number[b]	Rotation velocity[c]
	$\bar{u}$	$\bar{v}$	N	$\bar{u}$	$\bar{v}$	N	v/fl	Advection velocity
Meddy 1	0.0 ± 0.5[d]	−1.8 ± 0.5	655	0.0 ± 0.3	−1.4 ± 0.3	4246	.18	12
Meddy 2	−1.7 ± 0.7	−1.5 ± 0.9	223	−1.5 ± 0.6	−0.9 ± 0.6	916	.23	15
Meddy 3	−0.5 ± 0.3	−1.0 ± 0.7	506	−0.7 ± 0.6	−1.2 ± 0.7	762	.27	15
3 Meddies	−0.5 ± 0.4	−1.5 ± 0.4	1384	−0.3 ± 0.3	−1.3 ± 0.2	5924		

[a] The absolute velocity of the Meddies was obtained from the smoothed float trajectories (Float 128 for Meddy 1, 149 for Meddy 2, 145 for Meddy 3). The velocity of Meddies relative to nearby floats was determined from floats that passed within about 350 km of each Meddy. Average values were calculated within a box 10° in latitude and longitude, centered at the Meddy. N is the number of daily velocity observations.

[b] Rossby Number, v/fl, was estimated from the solid body rotation rate v/r in Fig. 9 and f from the mean latitude of each Meddy. Another estimate of the Rossby Number is given by the ratio of the relative vorticity to the Coriolis parameter (ζ/f) which will give values twice as large as those listed here.

[c] Rotation velocity (cm s^{-1}) is the maximum observed in Fig. 9.

[d] Standard errors which follow velocity values were estimated using $\sigma(2\tau/N)^{1/2}$, where σ is the standard deviation of velocity values about the mean velocity, N is the number of daily velocity observations, and τ is the integral time scale of the autocorrelation function, which was estimated to be 23 days for $\bar{u}$ and 19 days for $\bar{v}$ from the two-year trajectory of Meddy 1.

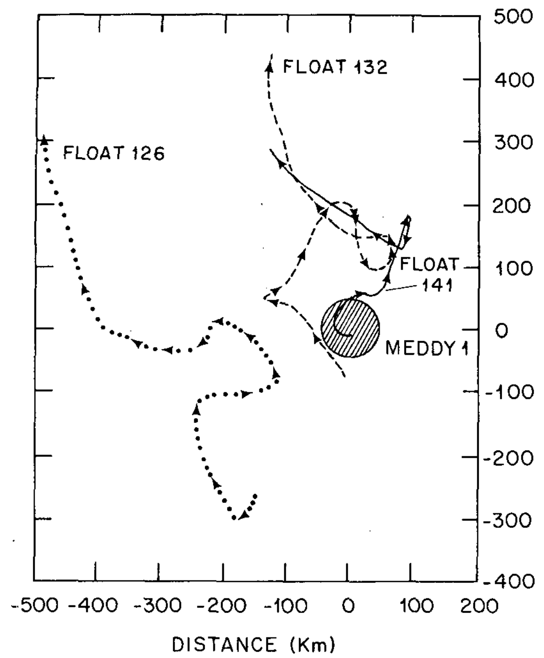

FIG. 7. Trajectories of three floats that passed close to Meddy 1. Trajectories are relative to the Meddy center and were obtained by subtracting the Meddy trajectory from each float trajectory. The apparent northward movement of floats on this figure is due to the southward translation of the Meddy. Float 141 was launched in Meddy 1 and remained there looping for about eight months before coming out and being left behind as the Meddy translated southward.

a. Translation

The net translation of Meddy 1 was 1090 km southward at a mean velocity of 1.8 ± 0.5 cm s^{-1} (Figs. 3, 6, Table 2). This southward translation is qualitatively different from the flow of the surrounding water at 1100 db as seen in trajectories of nearby floats plotted relative to Meddy 1 (Fig. 7). The mean velocity of floats at 1100 m *outside* of Meddies was very small (Table 1), about 0.3 cm s^{-1}, in agreement with the results of a 7-year long current meter record at 1000 m near 33°N, 22°W which measured a mean velocity of $u = -0.14 \pm 0.79$ cm s^{-1}, $v = 0.15 \pm 0.61$ cm s^{-1} (Zenk and Muller 1988). The mean southward velocity of Meddy 1 relative to all nearby floats was 1.4 ± 0.3 cm s^{-1}, or very similar to its absolute translation velocity (Table 2). Thus it appears that Meddy 1, and as we see later the other two Meddies as well, moved southward through the surrounding water at 1100 m depth.

b. Rotation

Time series of the rotation frequency, radius, and rotation velocity of float 128 (Meddy 1) are given in Fig. 8. Note that radius and rotation velocity are very similar, except over the last several months of the record. Thus the rotation velocity is a nearly linear function of radius (Fig. 9) which suggests that the core of Meddy 1 was in solid body rotation with a rotation period of about six days. Other investigators have reached a similar conclusion regarding the rotation velocity at the core of Meddies (Armi et al. 1988, 1989 and references therein). Velocities peaked near 22 cm s^{-1} at a radius of 20–25 km.

The only velocity measurements made at a greater radius were from float 141, which left the Meddy in July 1985. The rotation velocity of this float (Fig. 10) shows an exponential-like decrease of speed at radii greater than about 10 km with an *e*-folding scale of around 30–40 km. A comparison of Figs. 9 and 10 shows that 141 had lower rotation velocities than other floats between a radius of 10–20 km. Because temperature and pressure measurements from this float were unreliable, we do not know its depth. We suspect that this float left the Meddy by sinking gradually due to creep of the pressure housing, and that the decrease in velocity with radius (outside of 10 km) is due to both horizontal and vertical shear within the Meddy. For this reason, the data taken outside a radius of 10 km was excluded from Fig. 9.

Meddies are very energetic compared to the background flow field of the Canary Basin. The root-mean-

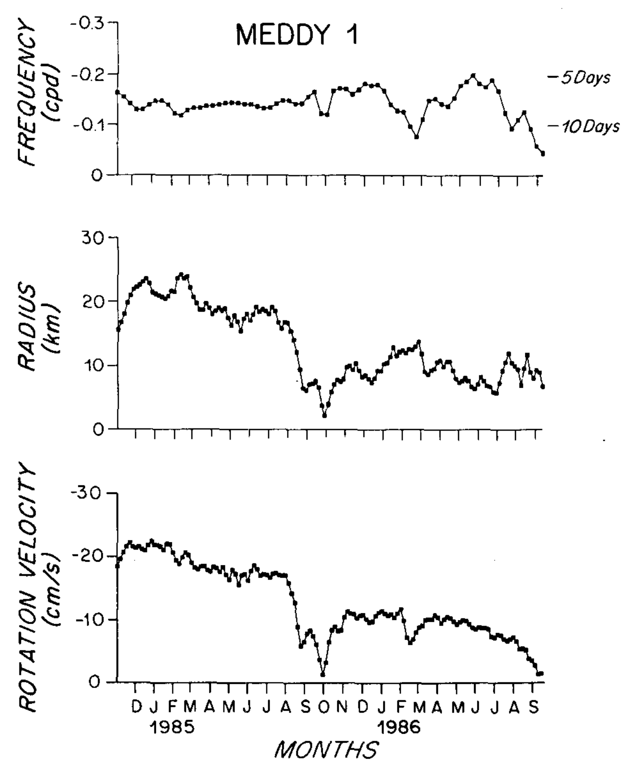

FIG. 8. Time series of rotation frequency (inverse period), radius, and rotation velocity of float 128 in Meddy 1. Float 128 remained within the core of Meddy 1 its whole life, gradually moving inward. The rotation rate remained remarkably constant over its two year life. Only during the last months (August–September 1986) did the rotation frequency decrease when the float was near the lower edge of Meddy 2.

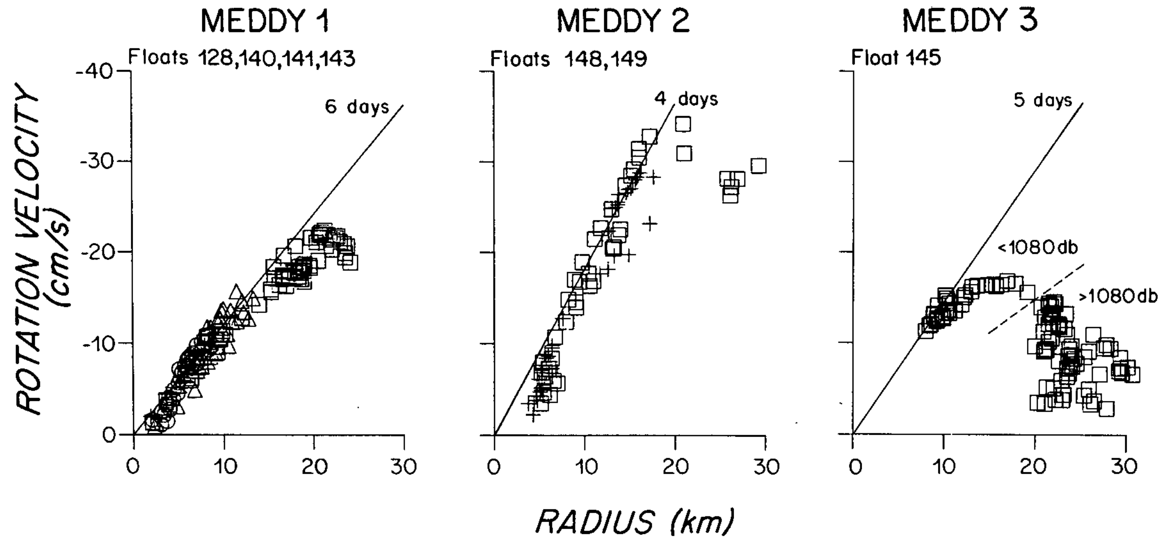

FIG. 9. Rotation velocity versus radius for the three Meddies. Values from different floats are shown by different symbols. Negative values indicate anticyclonic rotation. The interior 10–20 km appear to be in nearly solid-body rotation. The float in Meddy 3 rose from a depth of 1300 to 1050 db into a faster rotating regime (the fastest points on the curve near 10 km). The light lines which connect the origin to the fastest rotating part of each Meddy are equivalent to solid body rotation periods of 6 days for Meddy 1, 4 days for Meddy 2, and 5 days for Meddy 3.

square (rms) velocity about the mean for float 128 was 16 cm s^{-1} and its eddy kinetic energy (EKE) was 128 $cm^2 s^{-2}$ (Table 1). These are much larger than the values of rms velocity (3.7 cm s^{-1}) and EKE (7 cm^2 s^{-2}) of floats outside of Meddies. The increase of Meddy energy over background levels is due to the high rotation velocities; the translation velocities are similar to background velocities as noted above.

c. Decay

The decay of Meddy 1 was determined from four cruises to the Meddy and is discussed by Armi et al. (1988, 1989); only the gross physical changes are noted here. Over the two year study of Meddy 1, the vertical extent of the Meddy decreased by half from around 800 to 400 m (Fig. 5), and the diameter decreased by two-thirds from around 100 to 35 km. Thus the October 1986 volume of the Meddy was only abut 6% of its October 1984 volume. The salinity anomaly of the core also decreased over the two years. This decay is thought to have occurred mainly through mixing by thermohaline intrusions at the sides of the Meddy, though salt fingers at the bottom and thermohaline convection at the top may also have contributed (Armi et al. 1988a,b).

A crude estimate of the total lifetime of Meddy 1 can be made by backtracking to its probable source near Cape St. Vincent (Table 3, see Fig. 1). Backtracking Meddy 1 with its average speed gives an age in October 1986 of about four years. Since this Meddy was nearly erased by mixing at that time, this is also the likely total lifetime of Meddies away from topographic features.

4. Meddy 2

Meddy 2 was found, mapped hydrographically, and seeded with floats 148 and 149 in November 1985 by L. Armi and A. Bower. The vertical extent of Meddy 2 was about 1000 db (Fig. 11), the radius of the core region (stations 9–12) was about 10 km and the radius of the outer regions riddled with intrusions was at least 50 km. The very large maximum salinity of 36.56 psu and the double salinity maxima centered at 800 and 1300 db are characteristic of Mediterranean Water near

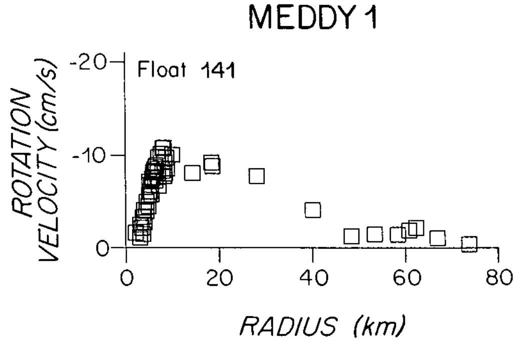

FIG. 10. Radial variation of rotation velocity as float 141 came out of Meddy 1 and was left behind. The decrease in velocity with radius (>10 km) is thought to be due both to horizontal and vertical shear within the Meddy.

TABLE 3. Estimated lifetime of Meddies.

	Mean velocity (cm s^{-1})	Continuously tracked (years)	Backtracked to 37°N, 10°W (years)	Total life (years)
	Using mean Meddy velocity[a]			
Meddy 1	1.8	2.1	2.2	4.3
Meddy 2	2.3	0.7	1.8	2.5
Meddy 3	1.1	1.5	5.4	6.9
	Using increase of Meddy velocity with latitude[b]			
Meddy 1	2.5	2.1	1.6	3.7
Meddy 2	2.6	2.7	1.6	2.3
Meddy 3	2.0	1.5	3.0	4.5

[a] Meddies were backtracked using their mean velocity from their first observed position northwestward to 37°N, also 10°W, the origin of the Mediterranean salt tongue off Cape St. Vincent, Portugal.

[b] Meddies were backtracked using the nearly linear increase of southwestward mean velocity with latitude observed by the three Meddies which implies that the mean velocity of Meddies near Cape St. Vincent is around 2.7 cm s^{-1}.

Cape St. Vincent (Ambar et al. 1976) which we therefore believe is the likely formation site for Meddy 2. Density profiles 1 and 11 show a significant horizontal density gradient centered near 700 and 1400 db corresponding to geostrophic shear above and below the core. Within a 300 db thick layer near 1000 db the density profiles overlay, indicating an absence of vertical shear in the geostrophic current.

Meddy 2 was the most energetic of the three Meddies: its rotation velocity reached 34 cm s^{-1}, and its rotation period was about four days for the portion in nearly solid body rotation within a radius of 20 km (Fig. 9). The EKE measured by float 148 while it was in Meddy 2 was 189 cm^2 s^{-2}, or almost 30 times the EKE of nearby floats that were not in Meddies (Table 1).

The movement of Meddy 2 is inferred from the track of float 149, which looped about 60 times (Figs. 3, 6; Table 1). Meddy 2 first drifted northwestward for a month, then stalled near 34°N 25°W for two months, and finally drifted southwestward for five months until it collided with seamounts near 31°N, 29°W. The overall translation of Meddy 2 was 530 km toward 230° with a mean velocity of 2.3 cm s^{-1}. This is close to its mean velocity relative to the few nearby floats, 1.8 cm s^{-1} toward 238° (Table 2), which shows that this Meddy was also translating southwestward through the water at 1100 m.

a. Collision with Hyères Seamount

Until mid-July the trajectories of floats 148 and 149 looked similar as they looped in Meddy 2 and translated southwestward (Fig. 12). During mid-July the Meddy approached Hyères Seamount, which extends to within 282 m of the sea surface, and the looping became less regular. At the end of July both floats passed between Hyères Seamount on the north and a smaller apparently unnamed seamount 40 km to the south (reaching

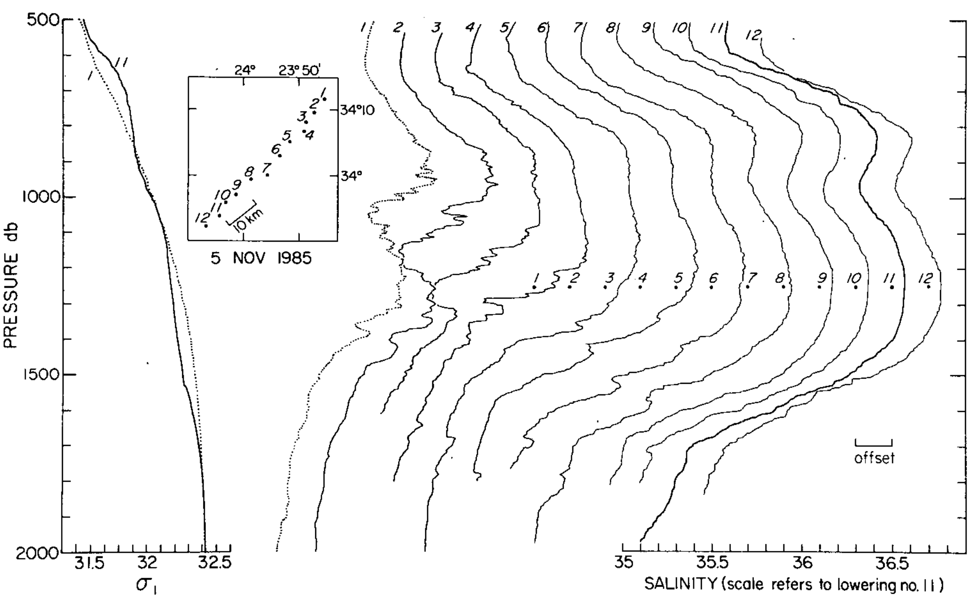

FIG. 11. Profiles of salinity (psu) from CTD lowerings through Meddy 2 on 5 November 1985. Station 11 is located near the Meddy center and station 1 is near the Meddy edge. Successive salinity profiles are offset from each other by a constant amount. For each lowering a dot is placed at 1250 db and 36.5 psu for ease of comparison. Station positions are shown on the inset chart, and density profiles from the Meddy center and Meddy edge are superimposed on the left.

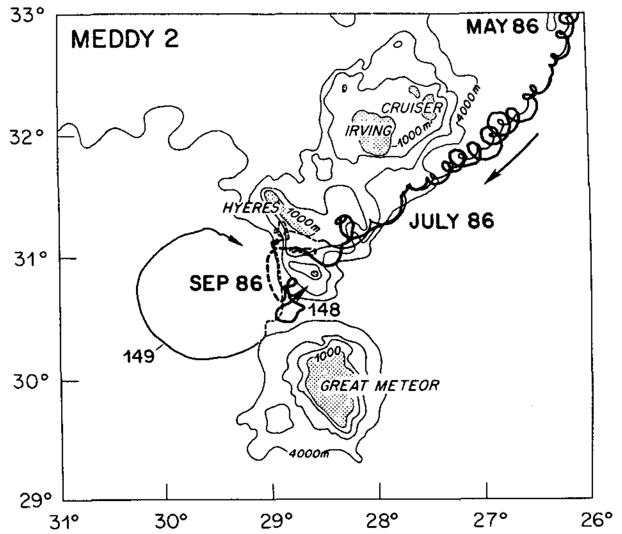

FIG. 12. Expanded scale plot of the trajectories of floats 148 and 149 as Meddy 2 collided with Hyères Seamount. Just after they passed between Hyères and a smaller seamount 40 km south of Hyères at the end of July 1988, the floats' temperature dropped about 4°C and they stopped looping. Dashed trajectories indicate the portions of decreasing temperature (see Fig. 4).

above 1000 m). Between 18 July and 8 August, float 149 measured a 4°C decrease in temperature, from 12.5° to 8.5°C, and a 50 m drop in depth, from 1000 to 1050 db (Fig. 4). Float 148 repeated this pattern starting on 1 August and descended from 1100 to 1200 db over a three-week period. After the temperature decrease, neither float looped in a manner characteristic of a Meddy. This suggests that in July 1986 Meddy 2 collided catastrophically with Hyères Seamount.

Given the bottom topographic profile (Fig. 13) and the size of Meddy 2 in November 1985, it is difficult to see how it could pass through the seamounts without a severe disruption. The small seamount (between Hyères and Great Meteor) must have acted like a huge stirring rod reaching into the Meddy core. The dominant disruption apparently occurred over five weeks, when the floats descended from Meddy core water into fresher, colder surrounding water. It would appear almost impossible for Meddies as large as these to pass through the line of seamounts stretching from 30° to 35°N.

In early October, two months after the collision, J. Price and P. Richardson aboard the R/V *Endeavor* searched for this Meddy in the vicinity of floats 148 and 149 which were located acoustically from the ship (Fig. 14). Thirty-five deep (1750 m) XBT profiles were made along with nine CTD profiles. The survey showed conclusively that the floats were no longer in the Meddy and found no identifiable remnant of the Meddy. It is possible that the Meddy shed the two floats near the seamounts and kept on going perhaps as a smaller, weaker remnant. An extrapolation of Meddy 2's means path suggests that at the time of the shipboard search in early October, Meddy 2 could have moved southwestward to lie near 30.3°N, 30.0°W, outside the area searched. A farther extrapolation of Meddy 2's path to match a two-year hypothetical lifetime (from November 1985 to November 1987) suggests that Meddy 2 could have traveled a total of 1500 km southwestward to around 26°N, 36°W, still well to the east of the mid-Atlantic Ridge. Based on this example it is difficult to see how a Meddy of the size discussed here could cross over the mid-Atlantic Ridge into the western Atlantic.

b. Float depth changes

Why did the floats descend and indicate colder temperature as they came out of the Meddy? Imagine

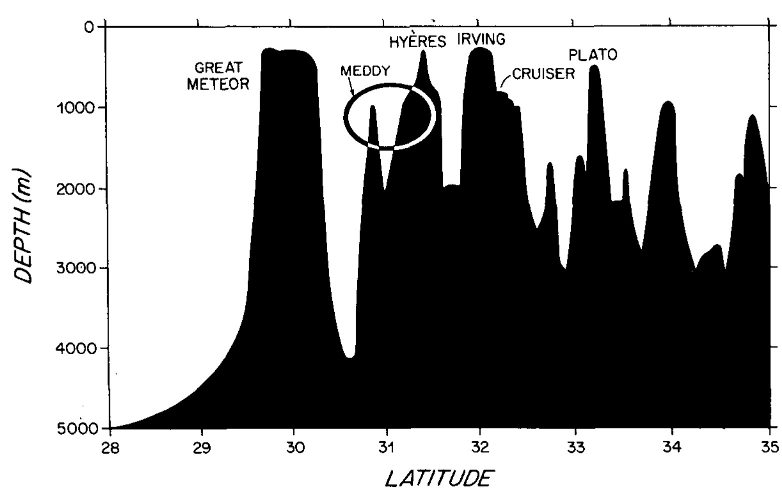

FIG. 13. A north–south section showing the projected depth profile along the Great Meteor Seamounts from a chart given by Hunter et al. (1983). Meddy 2 is shown schematically centered where its two floats 148 and 149 passed through the line of seamounts.

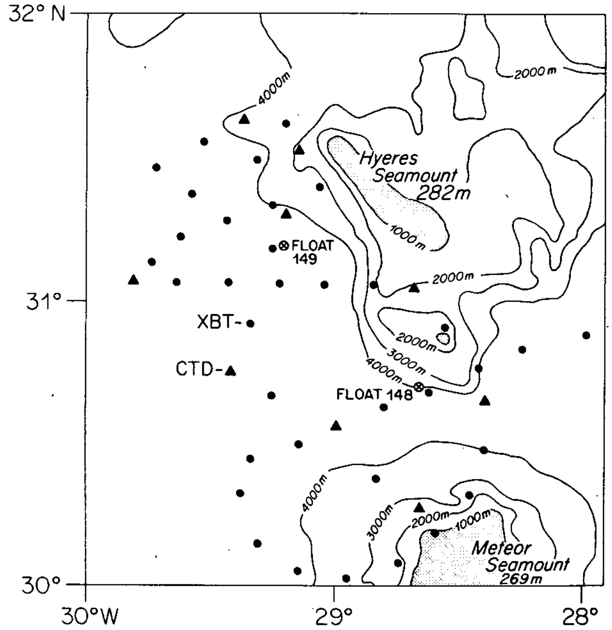

FIG. 14. Search for Meddy 2 during October 5–8, 1986 (*Endeavor* 149). Floats 148 and 149 were located with shipboard listening equipment, and a survey was made in their vicinity with deep XBTs and CTDs. No indication of a Meddy was found.

moving a float that had equilibrated in the core of a Meddy to the same depth outside of the Meddy. The outside water has the same density but is several degrees colder and fresher. The float would quickly become colder and denser due to thermal contraction and sink until it reached a new equilibrium depth based on its thermal expansion and compressibility and the in situ water characteristics. A calculation using values appropriate for SOFAR floats and Meddies shows that a float typically will drop 100 m in depth and several degrees in temperature when it leaves a Meddy (Fig. 15), very much as happened to floats 148 and 149. This also suggests that a float located just above the base of a Meddy and gradually sinking could rapidly drop out altogether when it begins to reach cooler water (as seems to have occurred to some floats in Meddy 1). Conversely a float gradually rising from just below the base of a Meddy could rapidly jump up into the core (as perhaps occurred to float 145 in Meddy 3).

5. Meddy 3

Meddy 3 was discovered and tracked when float 145 was launched in it by chance in September 1985. Its initial location was close to the later track of Meddy 1. Float 145 was one of eleven floats launched at wide spacings in the Canary Basin to measure characteristics of the regional flow field. It is not surprising we hit a Meddy with one of these floats-at-large, as the probability of encountering a Meddy hydrographically is reported to be 5%–8% based on CTD surveys (Käse and Zenk 1987; Armi and Zenk 1984) and 4% based on a study of historical data (Armi and Zenk 1984). The identification of Meddy 3 is based on the looping motion of float 145 which is characteristic of the other Meddies, the temperature and pressure telemetry from the float, and a chance CTD cast made very near the float in November 1986 by the group from the Institut für Meereskunde, Kiel, aboard *Meteor* (Fig. 16). The CTD profile reveals a salinity anomaly from 700 to 1400 db of about 0.8 psu and a temperature anomaly of about 3°C, both of which are typical of fairly strong Meddies. This profile is somewhat unusual in having very thick steps, up to 100 m thick, including within its upper levels where salt fingering would not be expected to occur. It also has a marked double maxima in anomalies, with a minimum in the range 900–1000 db. The double maxima in salinity could be a result of lateral mixing by intrusions during the Meddy's life. It is also possible, but we think less likely, that the double maxima is a signature of the double maxima found near the origin of the Mediterranean outflow near Cape St. Vincent as seen in Meddy 2 (Fig. 11).

Float 145 initially settled to 1300 db, near the bottom of Meddy 3, and gradually rose over the next 10 months toward the target pressure of 1100 db (Fig. 4). At the end of September 1986 the float suddenly rose about 50 m above its target pressure and temperature increased nearly 2° to be above 9°C. We think the 50 m jump is diagnostic of the float encountering the warm salty Meddy core and rising into it due to the thermal expansion of the float. A maximum temperature of 9.8°C was reached in mid-December 1986 (at a pressure of 1050 db). These values are quite close to the CTD cast value of 10.0°C at 1050 db measured on 12 November 1986.

The rotation velocity of float 145 gradually increased from small values, ~7 cm s^{-1} when the float was deep up to ~14 cm s^{-1} after the float had risen into the

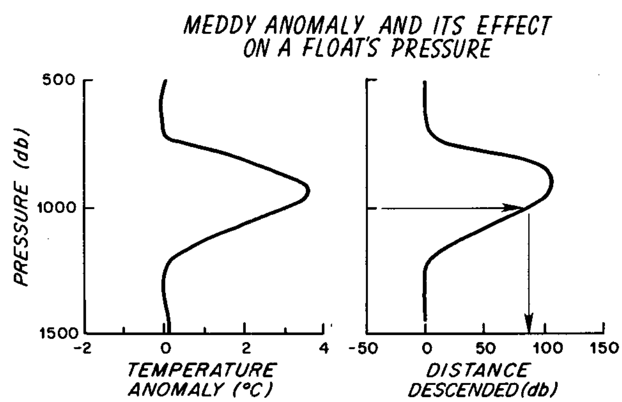

FIG. 15. Temperature anomaly (°C) profile in the center of Meddy 1 in October 1986, and the calculated descent (m) of a float moved laterally from an equilibrium position inside the Meddy to a position outside. Temperature and salinity anomalies nearly compensate for each other in density so that density profiles inside and outside a Meddy are similar.

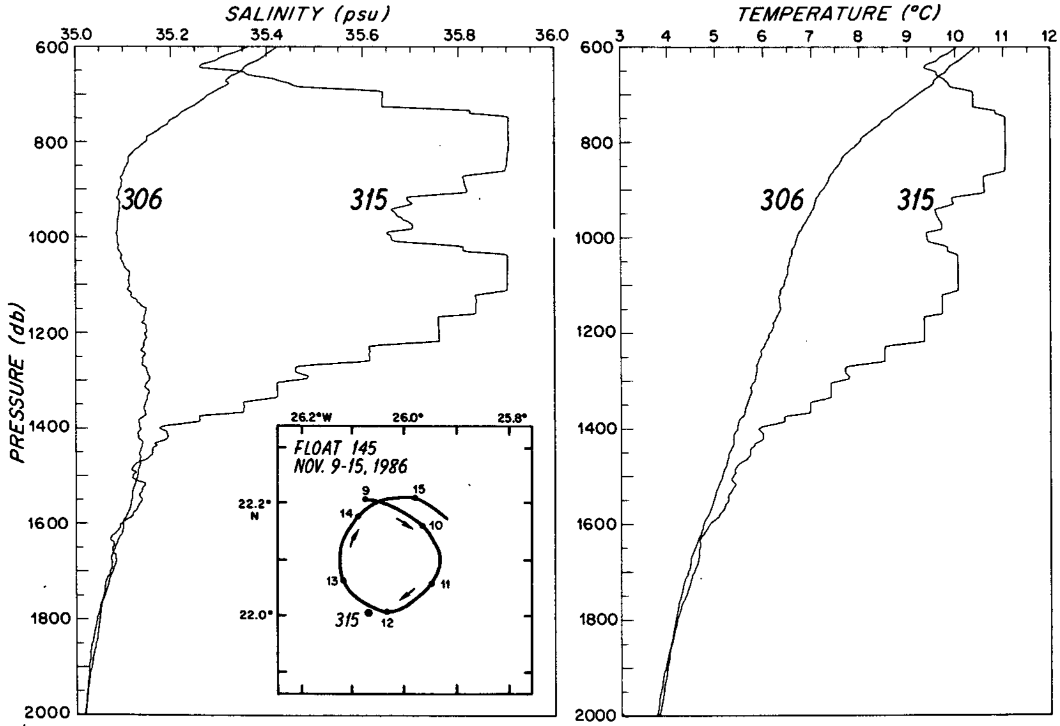

FIG. 16. Salinity and temperature profiles measured on 12 November 1986 at 22.00°N, 26.07°W (*Meteor* station 315) very near the location of float 145 and clearly in a Meddy. A typical profile from the region but not in a Meddy (*Meteor* station 306 at 22.33°N 22.39°W) has been superimposed. Note the pronounced steps in the Meddy profile and the double maxima in the anomalies of salinity and temperature. The trajectory of float 145 from 9–15 November 1986, and location of Meteor 315 are shown in the inset.

rapidly rotating core region above 1100 db (Fig. 17). Thus much of the scatter of points in Fig. 9 for Meddy 3 is a result of vertical shear in the rotation velocity. Assuming that the swiftest values at the shallowest depths (<1080 db) are representative of the core, then the inferred solid body rotation period of Meddy 3 is around 5 days.

Meddy 3 moved southwestward 500 km with a mean velocity of 1.1 cm s^{-1}, slightly slower than the other two Meddies (Table 2). It clearly survived for 18 months and was still quite strong based upon the large temperature and salinity anomalies in November 1986 and upon the fast rotation velocity just before float 145 stopped transmitting. It was then in the same general area where Meddy 1 was found to be almost totally decayed. This shows, not surprisingly, that Meddies can follow quite different life histories. We do not know why Meddy 3 was stronger than Meddy 1, but note that such a difference could arise from a different formation region or mechanism, from a reduced decay rate, or from a faster southward translation velocity prior to tagging with the SOFAR float.

Backtracking Meddy 3 with its mean velocity to Cape St. Vincent requires an extrapolation of 5.4 years and suggests a total lifetime of 6.9 years up to March 1987 (Table 3). This inferred total lifetime seems long compared to the measured decay of Meddy 1, which has an *e*-folding time of about one year. A shorter total lifetime of 4.5 years is obtained when the increase of mean southwestward velocity with latitude measured by the three Meddies is used to backtrack Meddy 3 (Table 3).

6. Meddy translation and salt flux

The mean translation velocities of the three Meddies ranged in direction from south to southwest and in speed from 1.1 to 2.3 cm s^{-1}. The mean velocity of all three Meddies grouped together was 1.50 cm s^{-1} toward 199°; their mean velocity relative to nearby floats was 1.35 cm s^{-1} toward 193°. We think that a likely explanation for the south-southwestward translation of the Meddies is that they are advected by the large-scale flow field above 800 db. In the upper layers the mean flow field is generally southwestward increasing in speed toward the surface (Saunders 1982; Stramma 1984). The hydrographic signature and rotation velocity of Meddies extends up into this southwestward flow, and the influence of the Meddy can be seen in the isopycnal displacements at depths as shallow as 300 db below the sea surface (Armi et al. 1989). Käse and Zenk (1987) have suggested that the anticyclonic circulation in Meddies extends up to the sea surface as evidenced by the anticyclonic looping of two surface drifters over

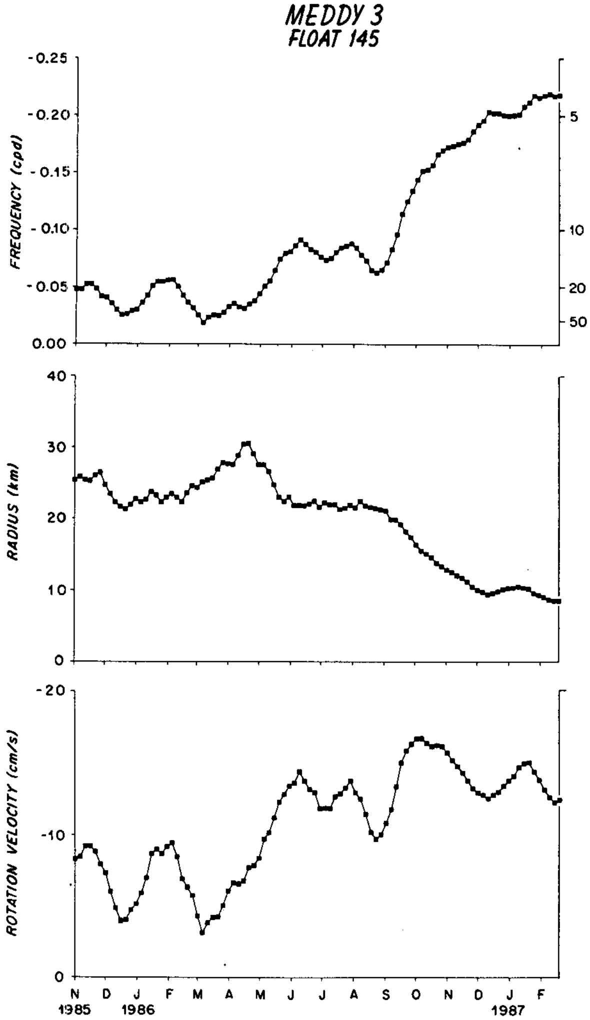

FIG. 17. Time series of rotation frequency, radius and rotation velocity for float 145 in Meddy 3. During the year float 145 rose from about 1300 to 1050 db into the core of the Meddy (Fig. 4), rotation velocity doubled, and the period of rotation decreased to around 5 days.

two different Meddies. Thus it seems probable to us that the large-scale flow field above the Meddy center will advect Meddies in this region to the southwest.

How important to the salt flux of the Mediterranean outflow are Meddies? Combining a 5% estimate of the number of Meddy observations in the Canary Basin (Armi and Zenk 1984; Käse and Zenk 1986) and that an area bounded by 20°–36°N, 15°–30°W is populated by Meddies, each 100 km in diameter, yields a population of ~24 Meddies at any one time with a spacing between their centers of ~400 km. Of course, Meddies in the south are more decayed and smaller than those in the north. If Meddies survive 2–3 years on average, then 8–12 must form yearly to maintain a steady population. Coupling this obviously crude estimate with the integrated salt anomaly of Meddy, 1, 2×10^{12} kg (Armi et al. 1989), yields an annual salt flux due to Meddies of 20×10^{12} kg yr^{-1}. This is about one fourth of the salt anomaly flux out of the Mediterranean, 80×10^{12} kg yr^{-1}, estimated from the outflow volume transport ~ 10^6 m^3 s^{-1} (Lacombe and Richez 1982) with a salinity anomaly ~ 2.5 psu. This suggests that Meddies are an important but probably not the principal carrier of the salt flux of Mediterranean outflow, especially in the Canary Basin (see also Hebert 1988b; Armi and Zenk 1984; McWilliams 1985). Meddies act like a distributed source—they advect salt and heat southwestward while mixing into the surrounding water (Armi and Stommel 1983). By transporting salt into fresher water, they must be important in determining the location and shape of the salt tongue.

7. Summary and discussion

For the first time, the long-term trajectories of Meddies (Mediterranean Water eddies) have been obtained in the Canary Basin. These data give first estimates of how long Meddies last and the first evidence of Meddy decay and destruction. Two Meddies were surveyed by ship and seeded intentionally with floats; another, Meddy 3, was found when a float was launched in it by chance. The three Meddies show some similarities in behavior—a core region that rotates as a solid body with a period of rotation of about 5 days, south to southwestward translation with mean speeds of 1–2 cm s^{-1}, and some differences—the inferred destruction of Meddy 2 as it crashed against some seamounts versus the slower decay of Meddies 1 and 3 by mixing.

Meddy 1 was continuously tracked for two years, and hydrographic surveys show that it was almost completely decayed at the end. Its total lifetime was estimated to be around four years based on backtracking to a possible formation site near Cape St. Vincent.

Meddy 2 apparently died catastrophically in a collision with seamounts after 8.5 months of a mean southwestward drift. At the time of the collision two floats that had been in its core came out, indicating a severe disruption of the normal circulation and water properties. If this Meddy had lasted another 1.3 years to equal the lifetime of Meddy 1, it would have traveled around 900 km more, but probably would not have crossed the mid-Atlantic Ridge. The implication from this Meddy is that Meddies are blocked by seamounts from moving freely west of 29°W, at least between 30° and 35°N. Backtracking Meddy 2 gives a total lifetime of 2.5 years.

Meddy 3 was continuously tracked for 1.5 years as it drifted southwestward. A chance CTD plus the similarity of float trajectories in all three Meddies confirm that it was a Meddy. Backtracking gives a total lifetime of 4–7 years. The long inferred lifetime of Meddies that do not hit seamounts seems to be in conflict with the *e*-folding time scale of decay of Meddy 1 which was about one year. To reconcile this requires further work on the formation and early history of Meddies.

The mean velocity of Meddies based on the total of 4.2 years of continuous tracking is 1.5 cm s^{-1} south-southwestward (toward 199°). This is not statistically different from the mean velocity of Meddies relative to nearby floats, indicating that Meddies move through their surrounding water at a depth of 1100 db. We speculate that Meddies move southwestward because their upper portion lies within the generally southwestward return flow of the subtropical gyre and that this large scale flow advects the whole Meddy southwestward. Because the Meddies move through the surrounding water at 1100 db, the salt anomaly mixed from a Meddy into the surrounding water should be left behind in the Meddy's wake. To refine our knowledge of Meddies and learn their role in salt and heat flux, we need further studies of their formation, numbers, geographical distribution, movement, and decay. The results presented here are only a first step in that direction.

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