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Meddy trajectories in the Canary Basin measured during the SEMAPHORE experiment, 1993–1995

Philip L. Richardson

Physical Oceanography Department, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

Aude Tychensky

Centre Militaire d'Océanographie, Service Hydrographique et Océanographique de la Marine, Toulouse, France

Abstract. As part of the Structures des Echanges Mer–Atmosphere, Proprietes des Heterogeneites Oceaniques: Recherche Experimentale (SEMAPHORE) experiment, four Mediterranean water eddies (Meddies) were identified in the Canary Basin and tracked with freely drifting RAFOS floats. One large and energetic Meddy, discovered 1700 km west of Cape Saint Vincent, Portugal, set a distance and speed record as it translated another 1700 km southwestward at 3.9 cm/s during 1.5 years. This Meddy traveled 57% of the distance from Cape Saint Vincent toward the spot *McDowell and Rossby* [1978] found a possible Meddy north of the Dominican Republic. Two Meddies were observed to interact with the Azores Current as they passed underneath or through it. Three Meddies collided with tall seamounts, which seemed to disrupt the normal swirl velocity, perhaps fatally in two cases. One Meddy appeared to bifurcate when it collided with seamounts.

1. Introduction

Although Mediterranean water eddies (Meddies) transport a significant amount of heat and salt from the Mediterranean into the North Atlantic, very little information is available concerning the life histories of these eddies after they reach the Canary Basin. Three Meddies tracked earlier (1984–1987) in the Canary Basin with SOFAR floats [*Armi et al.*, 1989; *Richardson et al.*, 1989] seemed to behave very differently; one collided with seamounts after 8 months and was destroyed, another drifted southward and decayed slowly over 2 years [*Armi et al.*, 1989], and the third drifted rather slowly southwestward for 1.5 years and probably also slowly decayed. Although these measurements provided a first look at Meddy life histories and paths, many questions were raised, such as how long do Meddies typically survive and what is the typical cause of death. The two observed Meddy deaths, one a rather slow (~2 year) decay caused by mixing [*Armi et al.*, 1989; *Schultz Tokos and Rossby*, 1991; *Hebert et al.*, 1990] and the other a fast (few weeks) catastrophic death by collision with seamounts, were very different. Can Meddies survive long enough to cross into the western Atlantic as suggested by *McDowell and Rossby* [1978]? The estimated lifetime of Meddies obtained by backtracking the three, which were continuously tracked with SOFAR floats to the probable origin near Cape Saint Vincent, is ~4–7 years, which seems to be in conflict with the much more rapid observed e-folding decay rate of about 1 year of the longest tracked Meddy. The detailed information we do have of the three continuously tracked Meddies indicates some types of behavior that are possible, but the sparse number of case histories has prevented us from putting together a coherent picture of Meddy behavior or accurately assessing the importance of Meddies in maintaining the Mediterranean salt tongue in the Atlantic.

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The Structures des Echanges Mer–Atmosphere, Proprietes des Heterogeneites Oceaniques: Recherche Experimentale (SEMAPHORE) experiment, which occurred in the Canary Basin during 1993–1994, provided an opportunity to identify and seed Meddies with floats with the goal of obtaining a few more case histories. SEMAPHORE observations were concentrated in the region roughly bounded by 31.5°–36.0°N, 20.5°–26.0°W (Figure 1). The measurements were obtained by conductivity-temperature-depth, expendable bathythermograph, acoustic Doppler current profiler (CTD, XBT, ADCP) surveys of the region (Table 1), RAFOS floats, surface drifters, moored current meters, meteorological moorings, and remote sensing by satellite. As part of this experiment, air–sea fluxes and the mesoscale ocean circulation were observed in the vicinity of the Azores Current. The objectives were to describe and dynamically assess mesoscale variability, to validate numerical models, to validate satellite observations and analysis methods, and to evaluate assimilation techniques.

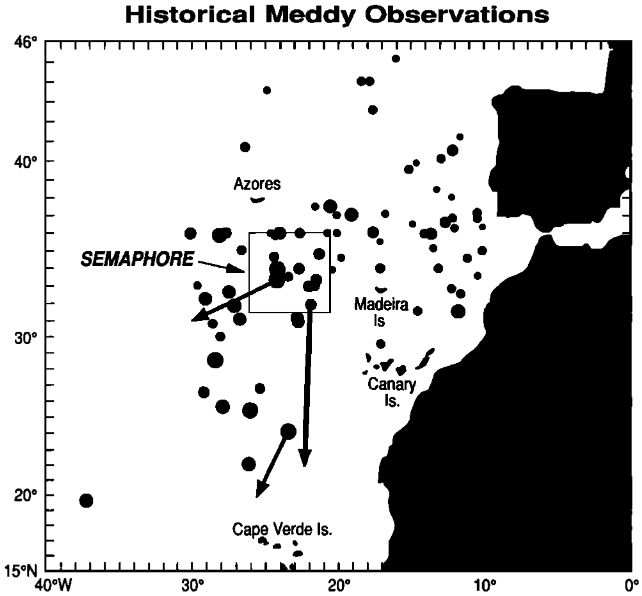

Figure 1 Positions of Mediterranean water eddy (Meddy) observations listed by *Richardson et al.* [1991] and *Shapiro and Meschanov* [1996] and the mean displacement vectors of three Meddies tracked with SOFAR floats during 1984–1987 as shown by *Richardson et al.* [1989]. The diameter of dots indicates the magnitude of the salinity anomaly which ranges from 0.4 to 1.1 practical salinity units (psu). The SEMAPHORE study area is located in prime Meddy territory. The Azores Current flows eastward through the SEMAPHORE box near 34°N, and the line of Great Meteor Seamounts lies just to the west of the box near 28°W.

A description of the main SEMAPHORE field program and some early results have been given by *Eymard et al.* [1996] and by *Hernandez and LeTraon* [1995]. This report is a first description of the float trajectories in the four Meddies discovered on the SEMAPHORE cruises. One of the interesting results described in this paper and amplified in some of the accompanying papers [*Tychensky and Carton*, this issue; *Tychensky et al.*, this issue] is the intense interactions between Meddies and the Azores Current. A second interesting result is the collision of three of the Meddies with seamounts in which two of the Meddies were apparently destroyed, thus adding evidence that this may be a common phenomenon.

2. Methods

The Meddies were tracked with freely drifting RAFOS floats purchased from Seascan Corporation in Falmouth, Massachusetts, and assembled, calibrated, and ballasted at the Woods Hole Oceanographic Institution (WHOI) (Table 2). The floats recorded temperature, pressure, and times of arrival from moored sound sources. At the end of their 1.5 year mission each float dropped a weight, rose to the surface, and transmitted the data to the laboratory via the Argos satellite system. Three sound sources were deployed as part of SEMAPHORE near 30°N, 24°W; 36°N, 27°W; and 37°N, 21°W. Although they transmitted three times per day, only two of these transmissions were recorded by the floats because of memory constraints and the relatively long float mission. The third time of arrival from each source was linearly interpolated from the recorded ones in order to obtain an evenly spaced time series. Meddies 2–4 remained in the vicinity of the SEMAPHORE sound source array, and the floats were tracked without any difficulties. Meddy 1 drifted far to the west of the sound source array and west of numerous seamounts. The acoustic transmissions were intermittently blocked by seamounts, which caused gaps in the records. In order to supplement the tracking of this Meddy, recorded times of arrival were used from an additional source launched near 43°N, 36°W by H.T. Rossby [*Anderson-Fontana et al.*, 1996]. Tracking errors in position within the SEMAPHORE box were estimated to be around 4 km based on a comparison of float launch locations

Table 1. SEMAPHORE XBT–CTD Surveys

Phase	Ship	Dates	Meddies[a]	Floats Launched
1	*Alcyon*	July 5–30, 1993	Meddy 1 (Hyperion), Meddy 2 (Ceres)	171, 172, 174, 175, 176, 177
2	*Laperouse*	September 4–13, 1993[b]	Meddy 2 (Ceres), Meddy 3 (Encelade)[c]	...
3	*Ailette, Alcyon, D'Entrecasteaux, Suroît, Pr. Stockman*	October 12 to November 20, 1993	Meddy 2 (Ceres), Meddy 3(Encelade)[c]	168, 173
4	*D'Entrecasteaux*	August 23 to September 5, 1994	Meddy 4 (Zoe)	101, 133

CTD is conductivity–temperature–depth.
[a]The Meddies' French names used in some of the SEMAPHORE papers are given here so that the interested reader can match up the Meddies.
[b]Expendable bathythermographs (XBTs) only.
[c]In addition to these Meddies was a small salty blob interpreted to be a piece of Meddy 3 located southwest of Meddy 3.

Table 2. SEMAPHORE Meddy Floats

		Launch			Surface			Initial	Initial	
	Float	Date	Latitude, °N	Longitude, °W	Date	Latitude, °N	Longitude, °W	Temperature, °C	Depth, m	Comments
Meddy 1	171	July 24, 1993	35.92	28.00	Jan. 15, 1995	27.07	42.68	12.9	875	sank 170 m
Meddy 1	175	July 24, 1993	35.92	28.00	Jan. 15, 1995	26.00	40.71	12.3	1240	
Meddy 1	176	July 24, 1993	35.90	27.77	Jan. 15, 1995	...	...	...	(1000)	never heard from
Meddy 1	177	July 24, 1993	35.92	28.00	Jan. 15, 1995	26.90	43.16	12.1	1015	
Meddy 2	172	July 28, 1993	35.77	24.26	Jan. 19, 1995	35.17	30.06	11.8	1015	
Meddy 2	174	July 28, 1993	35.89	24.25	Jan. 19, 1995	31.08	28.27	11.8	1060	
Meddy 3	168	Nov. 15, 1993	32.94	21.90	May 9, 1995	33.63	29.86	12.8	1040	sank 200 m
Meddy 3	173	Nov. 12, 1993	32.84	21.68	May 6, 1995	29.44	27.90	12.5	1070	
Meddy 4	101[a]	Sept. 9, 1994	35.99	23.89	Sept. 4, 1995	33.37	32.18	11.2	760	
Meddy 4	133[a]	Sept. 9, 1994	36.00	23.60	Sept. 4, 1995	...	...	...	(1200)	never heard from

[a] Floats 101 and 133 had solid drop weights. The glass hulls of these floats were broken during original shipping. The floats were returned to Woods Hole Oceanographic Institution (WHOI), repaired, and reshipped.

and first tracked positions. West of the seamounts, the errors in tracking floats in Meddy 1 could be much larger than this (~40 km) because of poor tracking geometry, blocking by seamounts, and interpolation.

In order to help resolve the looping trajectories of the floats in Meddy 1 (south of 33°N) gaps in the times of arrival series were interpolated using an objective analysis technique called krieging [*Hansen and Herman*, 1989]. It was necessary to specify the float looping frequency, which was obtained from the series before and after each gap or from another series. Problems with the technique were encountered when the looping frequency varied over a gap and when the data were noisy (e.g., low signal to noise ratio), which made it difficult to eliminate erroneous data. Some bad data caused erroneous phase shifts of the interpolated series. The floats in Meddy 1 were tracked using the krieged times of arrivals. Some portions of the trajectories looked incorrect in comparison to good Meddy trajectories and were discarded. These and a few gaps where two or more times of arrival series were not available were interpolated subjectively (~23% of the time series for float 177) using continuity, looping frequency, and diameter as observed in the available times of arrival series. The overall trajectory of float 177 shown for Meddy 1 is judged to be qualitatively correct; the details of the loops south of 33°N should be viewed with caution.

A cubic spline function was passed through the three daily float positions to calculate velocity. The positions and velocities were smoothed to reduce noise and high-frequency tidal and inertial oscillations using a Gaussian-shaped filter ($\sigma = 1$ day).

Ten floats were launched in the four SEMAPHORE Meddies (Table 2). Two floats either did not surface or did not transmit. One of these (133) had been handled very roughly during shipping as demonstrated by its broken glass pressure hull. The glass hull was replaced and a clock timing problem adjusted before launch. One float (168) recorded acoustic transmissions for only the first 100 days. This float sank around 200 m over its life, which suggests that a slow leak could have caused the acoustic receiver to fail. Another float (173) in the same Meddy (Meddy 3) recorded poor quality data during the first 60 days. Combining the two float trajectories gave a complete series for this Meddy.

We used hollow aluminum drop weights with the first eight floats and sealed the glass tubes with an aluminum end plate and silicone sealant. These floats tended to sink at a rate around 50 ± 33 m over the 1.5 years, which implies that either the hollow weights or float hulls leaked. Most of the mean sink rate was caused by two floats which sank 170 m (float 171) and 200 m (float 168). On the basis of early results in the A Mediterranean Undercurrent Seeding Experiment (AMUSE) [*Bower et al.*, 1997] we switched to solid drop weights and a better sealing technique for the last two floats. For these the end plate was sealed to the glass hull with butyl tape and a shrink-wrapped sleeve over the connection. A partial internal vacuum (~1/2 atm) was created to hold the end plate tightly against the hull during air shipment and as a test for leaks.

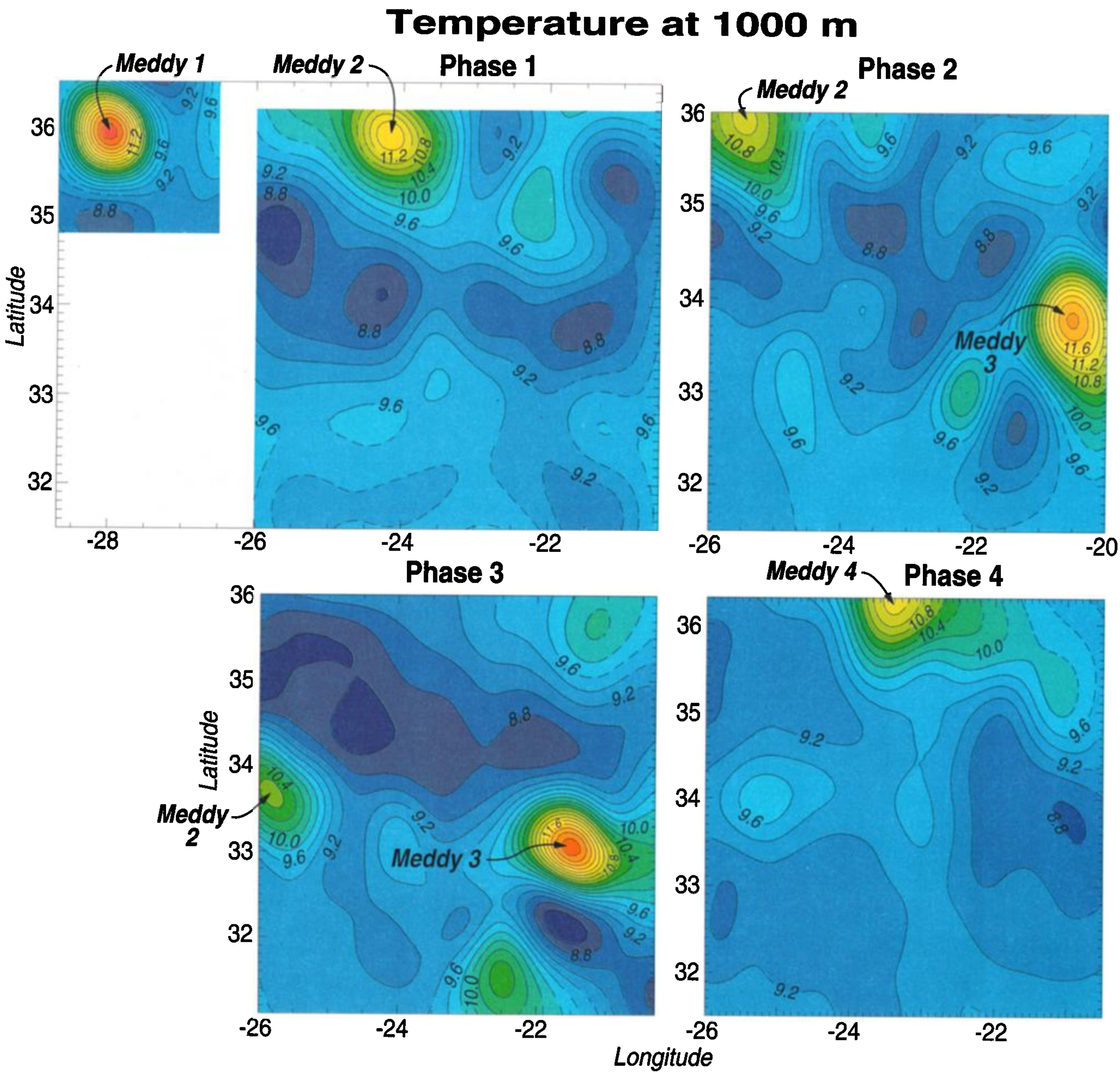

Plate 1 Horizontal maps of temperature at 1000 m in the SEMAPHORE region based on a space–time objective analysis of the conductivity–temperature–depth and expendable bathythermograph (CTD and XBT) shipboard surveys (Table 1). The central times of the four maps are July 20, 1993; September 7, 1993; October 26, 1993; and August 29, 1994. The temporal and spatial correlation radii of the objective analysis were 20 days, 160 km in the zonal direction and 200 km in the meridional direction. Each Meddy was sampled by two XBT (1800 m depth) sections with stations spaced every 12 km and one CTD section with stations spaced at approximately 10 km. Sixty-two stations were used to contour Meddy 1, 32 for Meddy 2, 47 for Meddy 3, and 15 for Meddy 4. For more details see Tychensky *et al.* [this issue].

3. Results

Four energetic Meddies were discovered on the SEMAPHORE surveys (Figure 2). Meddy 1 was located 200 km west of the SEMAPHORE box; the centers of the other three Meddies were all within the box. Meddy 2 was measured on three surveys, and Meddy 3 was measured on two surveys. Temperature maps in the SEMAPHORE box revealed the Meddies' anomalously warm cores near a depth of 1000 m (Plate 1). Temperatures at 200 m show the strong temperature gradient associated with the location of the Azores Current (Plate 2). Meddies 2 and 3 passed through or under the Azores Current during SEMAPHORE (Figure 2). The temperature and salinity structure of the Meddies extended over most of the upper 2000 m and out to a diameter of around 100 km (Plate 3 and Figure 3). *Tychensky and Carton* [this issue] and *Tychensky et al.*

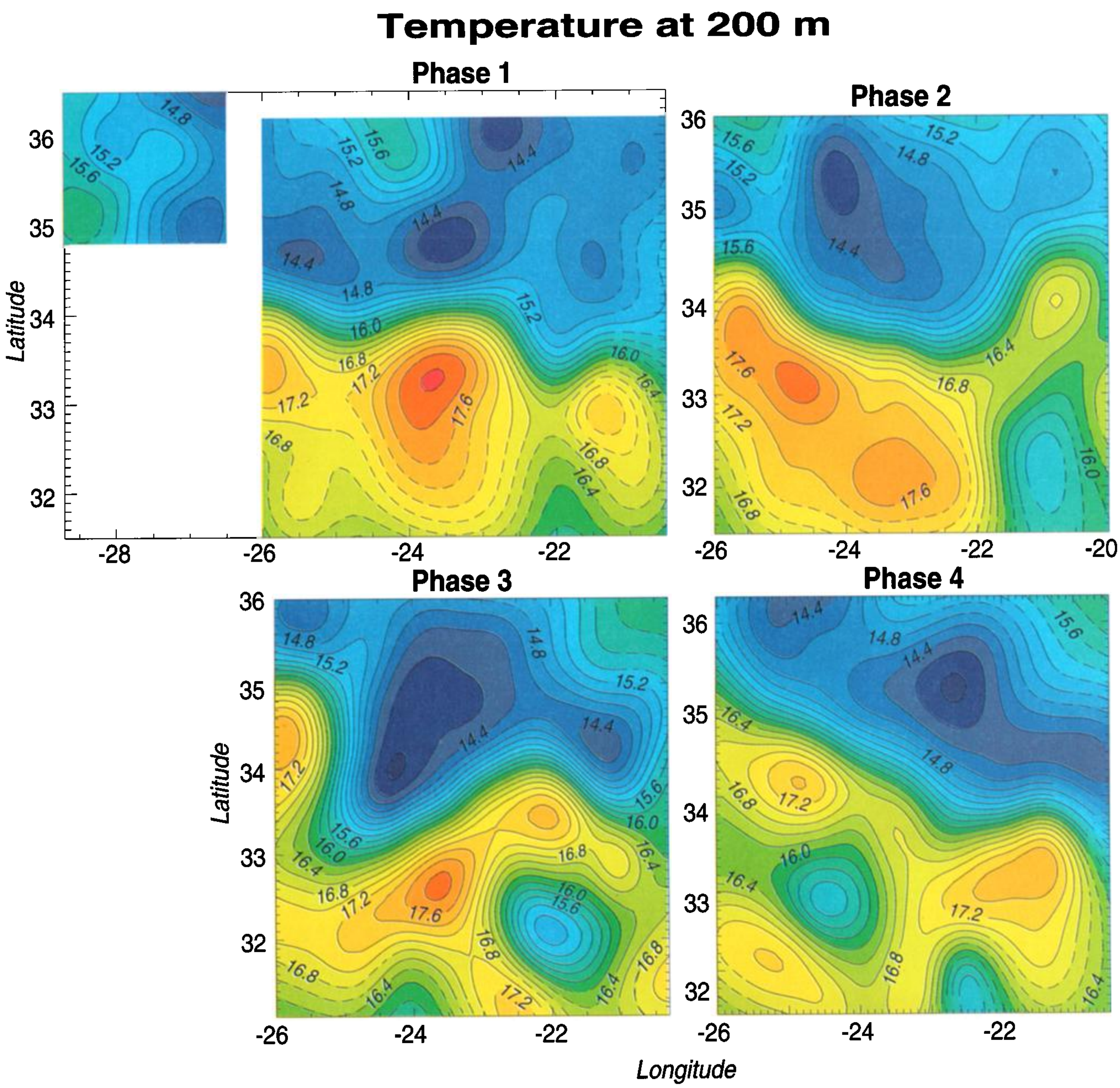

Plate 2 Horizontal maps of temperature at 200 m depth obtained with the same space-time objective analysis used in Plate 1 showing the strong gradient in the frontal region which is indicative of the Azores Current. The frontal region is shown schematically in Figure 2.

[this issue] discuss the detailed hydrographic properties of the Meddies and Azores Current. Below we describe the float trajectories in each Meddy with some reference to hydrographic characteristics.

4. Meddy 1

Meddy 1 was discovered and well measured during the phase 1 XBT–CTD survey July 5–30, 1993 (Table 1, Plate 1). Meddy 1 was large and energetic and contained double maxima in both temperature and salinity (Plate 3, Figure 3, and Table 3). Values reached 36.5 practical salinity units (psu) at 1250 m and 13.2°C at 880 m, and anomalies were 1.1 psu and 4.1°C, largest of the four Meddies.

Three floats launched near Meddy 1's center revealed its long-term 1.5 year trajectory (Figure 4). Two floats (171, 177) remained looping for the full 1.5 years. The third float (175) stopped looping after around 1.2 years. This float was deeper ~1230 m than the other two, which were at 1040 and 1125 m, which suggests that the bottom of the Meddy core may have eroded by the end of the tracking. The core rotation period was 4.4 days at the beginning and 6.2 days at the end (Table 4).

Meddy 1 was found roughly 1700 km west of the presumed Meddy formation region near Cape Saint Vincent, and it translated another 1700 km southwestward over the 1.5 years (Figure 5). This Meddy sets records for the farthest a Meddy has been continu-

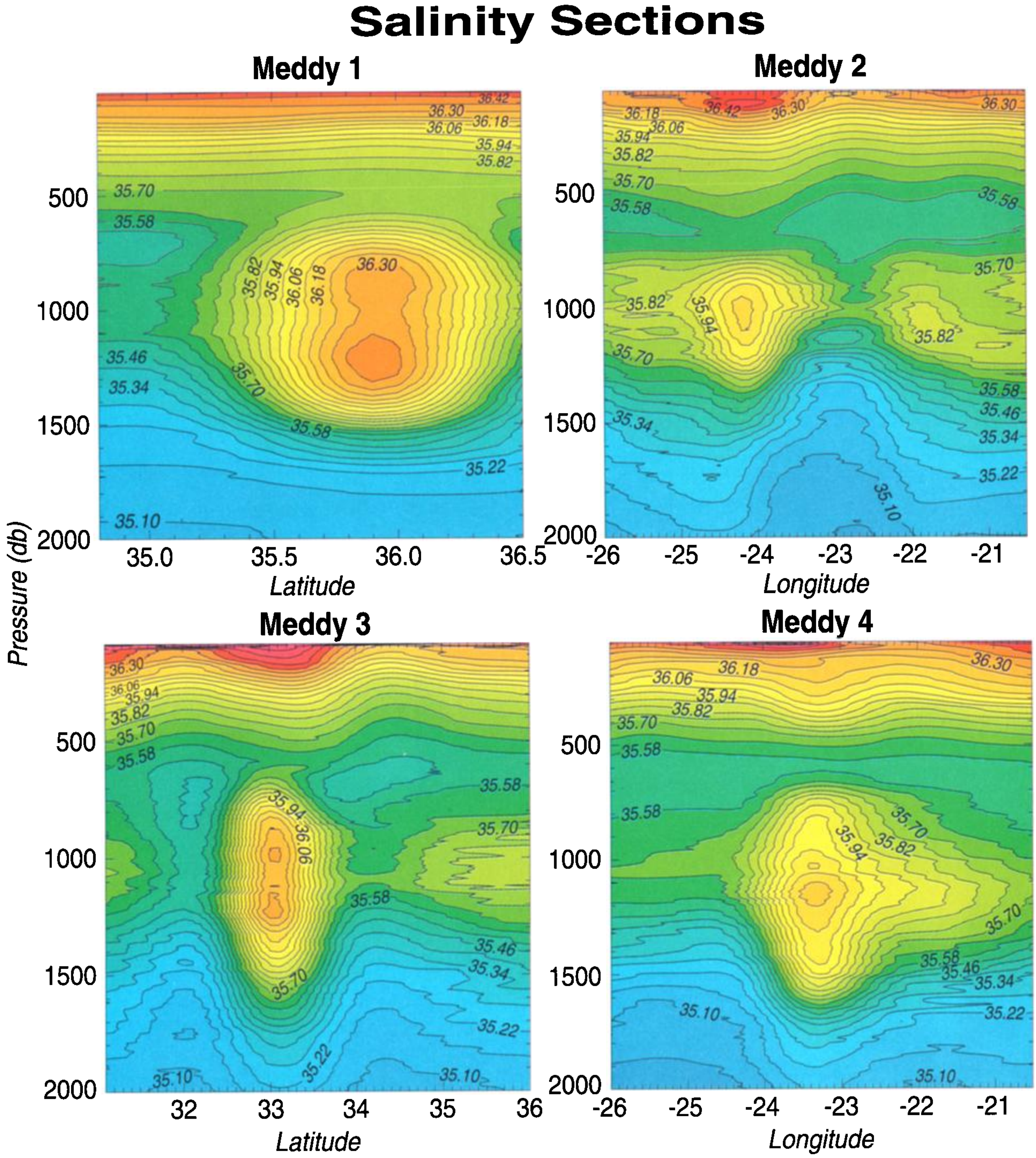

Plate 3 Vertical sections of salinity through each Meddy based on the objective analysis. The section through Meddy 1 is located at 28.0°W, Meddy 2 at 35.9°N, Meddy 3 at 21.5°W, and Meddy 4 at 36.5°N. The typical diameter of the Meddies is around 100 km, although Meddy 3 seems to be closer to 150 km. The overall diameter is difficult to estimate because the background temperature and salinity field varies significantly. Therefore the overall diameters could be larger than the nominal 100 km. The four Meddies appear to extend downward in the water column to at least 2000 m as seen by a depression of isohalines. Above Meddies 2–4 is a depression of isohalines (and isotherms) suggesting the presence of warm and salty structures which may have been influenced by the Meddies. Anticyclonic motion in the near-surface layer of Meddies 1–3 was observed by looping surface drifters.

ously tracked and the fastest mean velocity of a tracked Meddy 3.9 cm/s toward 235°. Although Meddy 1 had traveled almost one half of the way across the Atlantic, it had not yet crossed the Mid-Atlantic Ridge. During the last two months, Meddy 1 translated westward at roughly 4 cm/s; at this rate it would have crossed the Ridge in about another month.

In October 1993, Meddy 1 crossed over or around

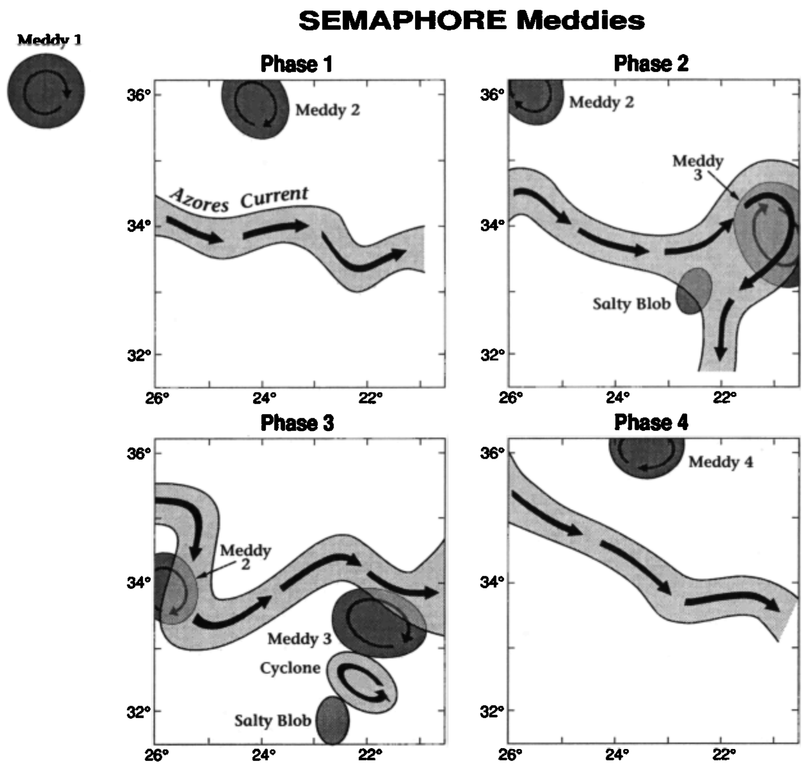

Figure 2 Schematic diagram showing the location of observed Meddies and the Azores Current within the SEMAPHORE box based on an interpretation of Plates 1 and 2. Meddy 2 passed underneath or through the Azores Current during phase 3. Meddy 3 passed underneath or through the Azores Current during phases 2 and 3. A small salty blob, which we think is a piece of Meddy 3, was observed southwest of it on phases 2 and 3. A cyclonic eddy pinched off from the Azores Current was observed adjacent to Meddy 3 on phase 3.

Plato seamount, which rises to within 476 m of the ocean surface [*Hunter et al.*, 1983]. At this time the loops of float 177 increased in diameter from about 15 to 60 km, implying a disruption of the normal Meddy circulation. Floats 171 and 175 revealed simultaneous increases in loop diameter.

No hydrographic measurements of this Meddy are available after the initial survey. On the basis of float 171, which remained closest to the center, ~15 km radius, and which measured a temperature of 11.0°C at 1040 m just before surfacing, we estimate from historical temperature data [*Fuglister*, 1960] that the temperature anomaly in the core was around 4°C. Float 177, which was around 30 km from the center, measured a temperature of 7.8°C at 1120 m before surfacing, which amounts to a temperature anomaly of 1.2°C. Although the temperature of the core had decreased by a degree, the temperature anomaly remained almost as large as it had been at the float launch because the Meddy translated into cooler and fresher water. On the basis of the temperature, salinity, and anomalies at the start and the temperature at the end we infer that Meddy 1 had a core salinity of around 36.1 psu and a salinity anomaly of 0.9 psu near 1040 m when float 177 surfaced. Therefore Meddy 1 still contained significant anomalies in temperature and salinity at the end of the tracking.

One last bit of information about Meddy 1 was obtained when the floats surfaced. As they drifted at the surface, each float made half of an anticyclonic loop about a common center, implying that the Meddy's swirl velocity extended to the sea surface. Float 171, which had been closest to the Meddy center, was also closest to the center of the surface loop. Typical surface swirl speeds were around 8 cm/s. After 3 weeks and what we infer to be a gradually increasing loop diameter up to around 100 km the two floats left the surface expression of the Meddy.

5. Meddy 2

Meddy 2 was found near the northern edge of the SEMAPHORE box during phase 1 and was well measured (Plate 1). It appeared to be the smallest of the four Meddies, and its temperature and salinity anomalies were also the smallest (Table 3). Two floats (172 and 174) were launched near its center near the same depth (1015 and 1060 m). They both initially looped with a period of 5.6 days at diameters of 20–30 km (Figure 6). The trajectory of float 174 is shown in Figures 4 and 6 because it looped longer than float 172.

Meddy 2 remained near the edge of the SEMAPHORE box during all three phases and was observed three

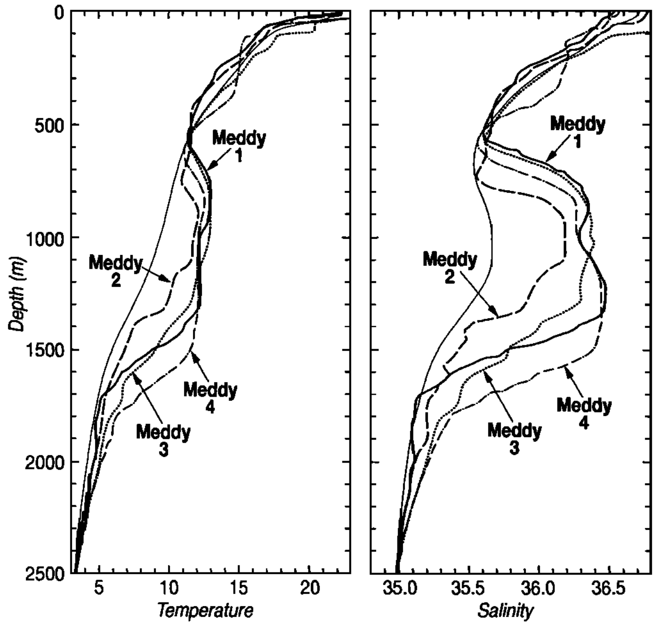

Figure 3 Temperature and salinity profiles through the central core region of each of the four SEMAPHORE Meddies. A mean profile from all SEMAPHORE CTD profiles is added as a reference. The profiles in Meddy 1 and Meddy 4 have double maxima in both temperature and salinity similar to the upper and lower cores of the Mediterranean outflow water near Cape Saint Vincent, Portugal [see *Zenk and Armi*, 1990; *Käse and Zenk*, 1996; *Bower et al.*, 1997].

times by the CTD–XBT surveys (Plate 1). For the first 2 months, while it was north of the Azores Current, Meddy 2 translated westward at 2 cm/s. At the end of September (phase 2) it turned and translated 300 km southward for 2 months with speeds up to 10 cm/s in October (phase 3). Because the translation rate was almost as fast as the swirl velocity, the loops appear as cusps (Figure 6). Both floats remained close to each other and looped during this period, providing evidence that the Meddy core (<30 km diameter) remained intact. Meddy 2 appeared to be advected southward by the Azores Current and to cross underneath or through it (Figure 2). In November, Meddy 2 turned more westward again. It translated westward 150 km and at the end of the year stopped abruptly near Cruiser Seamount, which has two peaks each < 800 m deep according to *Hunter et al.* [1983]. In January, Meddy 2 turned southward and translated over or around Cruiser Seamount. Both floats stopped looping in February, implying that the normal Meddy circulation had been disrupted by the seamounts.

6. Meddy 3

Meddy 3 is one of the largest Meddies ever observed. It had high values of temperature (13.1°C), and salinity (36.45 psu), and large anomalies (0.9 psu 4.0°C), compared to background values (Table 3, Plate 3, and Figure 3). Meddy 3 was well sampled during both phase 2 and phase 3 as it translated southwestward and interacted with the Azores Current (Figure 2). In phase 2 a main branch of the Azores Current meandered over the top of Meddy 3, forming a surface intensified anticyclonic eddy (Plate 2). By phase 3, Meddy 3 had passed under or through the Azores Current, which had pinched off a cyclonic eddy located adjacent to and south of Meddy 3. Another, but much smaller, warm and salty blob or lens was observed southwest of Meddy 3 on both phase 2 and phase 3. The evidence suggests that this could have been a piece of Meddy 3 shed during its interaction with the Azores Current.

Two floats (168 and 173) launched during phase 3 gave Meddy 3's trajectory (Figure 7a). Both floats looped initially with a 3.6 day period near a depth of 1050 m and within a diameter of around 15 km. This sets a record as the fastest rotation rate of the seven Meddies tracked in the Canary Basin. From November 1993 to May 1994, Meddy 3 translated westward with a mean velocity of 3.4 cm/s. Meddy 3 passed entirely through the SEMAPHORE box in 6 months, entering

Table 3. Maximum Temperature and Salinity in Each Meddy

Meddy	Depth, m	Maximum Temperature, °C	Maximum Salinity, psu	Temperature Anomaly,[a] °C	Salinity Anomaly,[a] psu	Overall Diameter,[b] km
1 (Hyperion)[c]	850	13.2	36.37	3.0	0.8	120
	1250	12.3	36.50	4.1	1.1	···
2 (Ceres)	950	12.2	36.25	1.2	0.4	100
3 (Encelade)	950	13.1	36.45	4.0	0.9	150
4 (Zoe)[c]	900	12.4	36.28	2.4	0.6	100
	1150	12.0	36.45	3.8	0.9	···

Practical salinity units are psu.
[a]The anomalies were estimated by comparing core profiles to profiles near the periphery of the Meddies.
[b]The nominal diameter is crudely estimated from the various data sets. Fluctuations in the background temperature and salinity fields due to the Azores Current, its cutoff rings, and other eddies make it difficult to estimate the overall size of Meddies (see Plates 1 and 3).
[c]Double maxima were observed in both temperature and salinity profiles of Meddy 1 and Meddy 4 (Plate 3 and Figure 3).

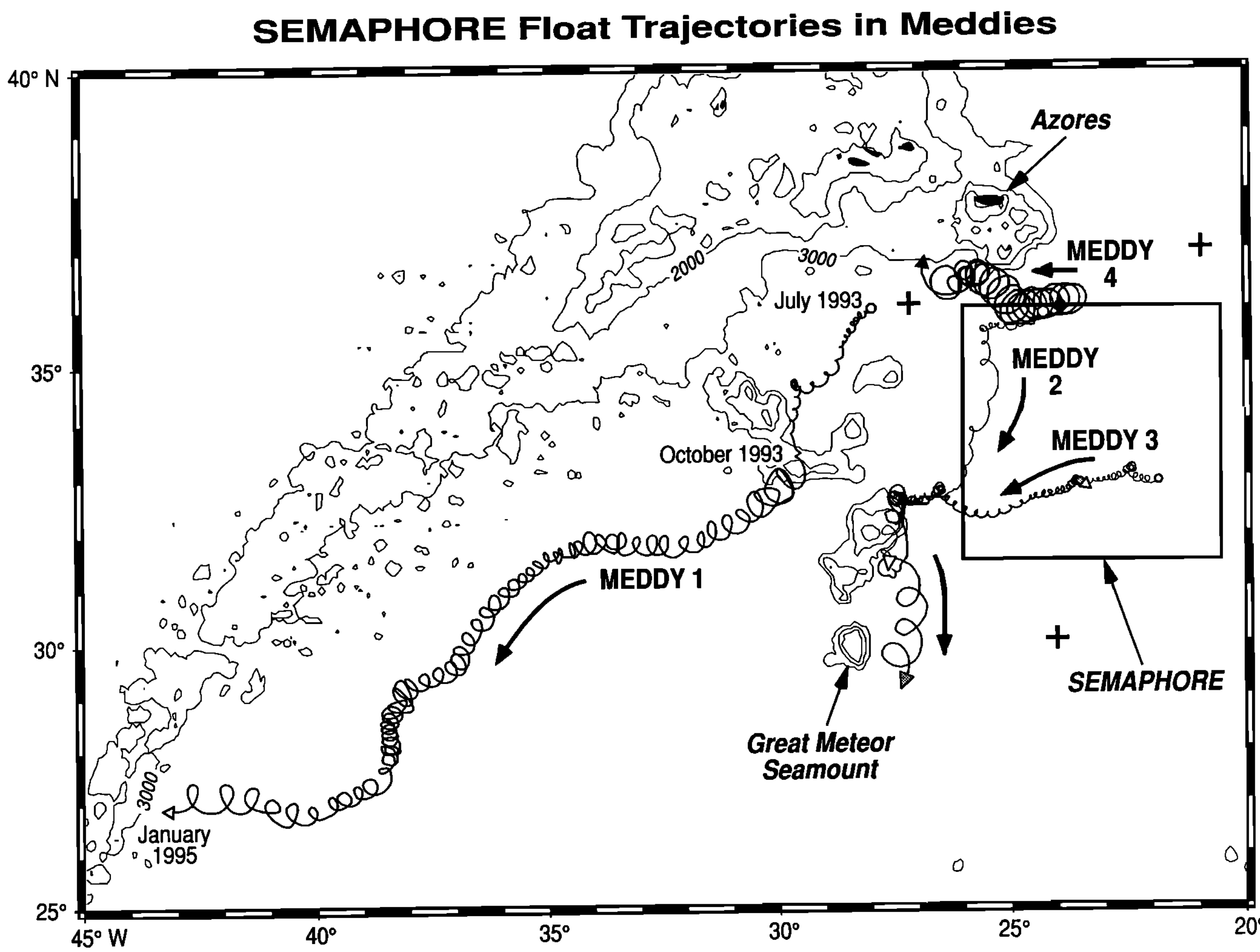

Figure 4 Translation of four Meddies as given by the looping trajectories of RAFOS floats, 1993–1995. The SEMAPHORE box is shown. The trajectory of float 177 in Meddy 1 stopped where the float surfaced after its 1.5 year mission. The trajectory of float 101 in Meddy 4 stopped when the sound sources were retrieved. The floats in Meddies 2 (float 174) and 3 (float 173) stopped looping after their collision with the line of Great Meteor Seamounts. The nonlooping portions of float trajectories were omitted for clarity. Depth contours are from the Earth Topography 5-arc-min grid (ETOPO5) bathymetry data.

in September 1993 and exiting in March 1994. In early June, Meddy 3 abruptly stopped in front of Cruiser Seamount, almost exactly where Meddy 2 had stopped 5 months before. Meddy 3 then turned and translated southward (as Meddy 2 did) at 3.9 cm/s over or around Cruiser Seamount and then east of Hyeres and Great Meteor Seamounts from mid-June to mid-October 1994, when float 173 stopped looping. As Meddy 3 translated southward, the loops of float 173 increased in diameter to around 60 km, and the period of loops increased to around 25 days.

In April 1994, as Meddy 3 approached the seamounts, float 172 (which had been ejected from Meddy 2 2 months previously) was entrained into Meddy 3's circulation and began to loop with a diameter, which began at 120 km and eventually decreased to around 50 km (Figure 7b). In June at the time of Meddy 3's collision with Cruiser Seamount float 172's loops diverged from float 173's loops, implying that the Meddy was somehow cleaved by the seamounts into two roughly equal-sized smaller Meddies, which then separated (Figure 7c). Another possibility, but one we think less likely, is that float 172 was diverted from Meddy 3 into another already existing Meddy located west of Irving Seamount. Float 173 looped and translated southward, and float 172 looped and translated northwestward (Figure 7b). Both floats stopped looping in their respective Meddies at almost the same time in mid-October.

7. Meddy 4

Meddy 4 was discovered near the northern edge of the SEMAPHORE box in September 1994 during phase 4. The Meddy core contained double maxima in the temperature and salinity profiles (Plate 3 and Figure 3)

Table 4. Meddy Float Summary

	Float	Days in Meddy	Number of Loops	Average Period of Rotation, days	Rotation Period of Core,[a] days	$\bar{T}$, °C	$\bar{p}$, dbar	$\bar{u}$,[b] cm/s	$\bar{v}$,[b] cm/s	Speed, cm/s	Direction
Meddy 1	177	533	78[c]	6.8	4.4	10.5	1060	-2.9	-2.1	3.6	234
Meddy 2	174	200	29	6.9	5.6	11.6	1051	-1.8	-2.8	3.3	213
Meddy 3	168, 173[d]	333	63	5.3	3.6	11.5	1078	-1.7	-1.4	2.2	231
Meddy 4	101[e]	167	20	8.4	6.0	11.3	756	-1.8	0.7	1.9	291

T is temperature, p is pressure, and u and v are velocities in the east and north directions, respectively.

[a]Values are the rotation period of small <20 km diameter loops in the Meddy core, except for float 101 in Meddy 4, whose smallest loop was around 30 km in diameter. Float 101 was located shallower than the maximum in temperature and salinity, which implies that the core of Meddy 4 could have rotated with a smaller period than given here. The core rotation period of Meddy 1 at the end of tracking was around 6.2 days based on float 171, which was near a diameter of 30 km and depth of 1040 m. The cores of two earlier Meddies in this region were in solid body rotation out to a diameter of around 40 km [(*Richardson et al.*, 1989; *Schultz Tokos and Rossby*, 1991], which suggests that the 30 km values are probably representative of the core region. The core rotation periods of the three earlier Meddies were 4 days (Meddy 2), 5 days (Meddy 3), and 6 days (Meddy 1, the one tracked for 2 years).

[b]The mean velocity of the four Meddies, assuming each one gave an independent sample of velocity is $\bar{u} = -2.0\pm$ 0.3 cm/s, $\bar{v} = -1.4\pm$ 0.8 or 2.5 cm/s toward 236°. This is somewhat faster than the mean velocity of three earlier Meddies 1.5 cm/s toward 199°, especially the most southern (20°–24°N) slow (1.1 cm/s) Meddy.

[c]Float 171 in Meddy 1 completed an estimated 102 loops during the same time interval at an average period of rotation of 5.2 days. Float 177 is summarized here because it provided the best tracking data.

[d]Float 168 tracked Meddy 3 for the first 62 days, float 173 afterward. These two floats were at similar depths, 1070 and 1080 m.

[e]Float 101 looped an additional six times over 80 days as inferred from the times of arrival from a single sound source after the SEMPAHORE sources were retrieved in February 1995.

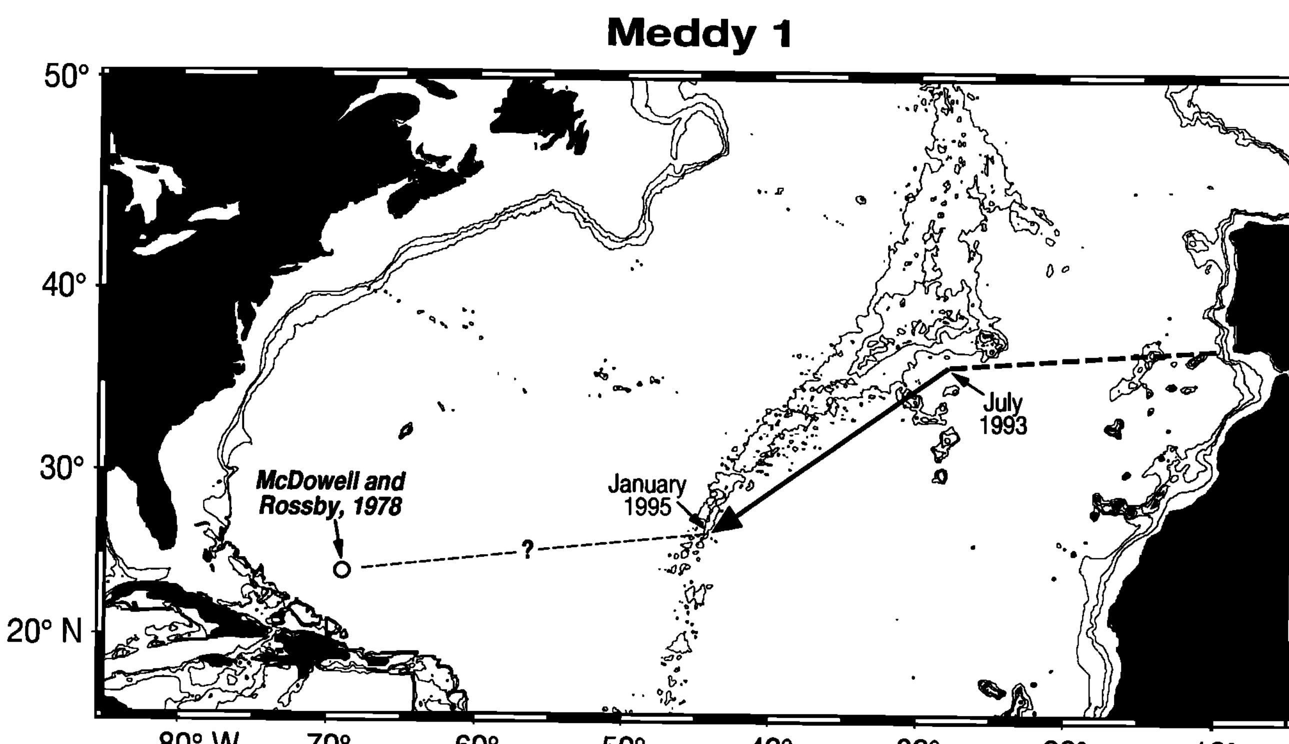

Figure 5 The solid line shows the displacement vector of Meddy 1, as it translated 1700 km southwestward from July 24, 1993, to January 15, 1995. The dark dashed line shows the displacement of Meddy 1 from its presumed formation near Cape Saint Vincent [*Bower et al.*, 1997] to the beginning of continuous tracking. The 100 km diameter dot north of the Dominican Republic shows the location and size of the eddy (possibly a Meddy) found by *McDowell and Rossby* [1978]. Meddy 1 traveled 3400 km or 57% of the distance from Cape Saint Vincent to this spot. At its mean translation speed, Meddy 1 would have reached the McDowell and Rossby eddy spot in an additional 2.1 years.

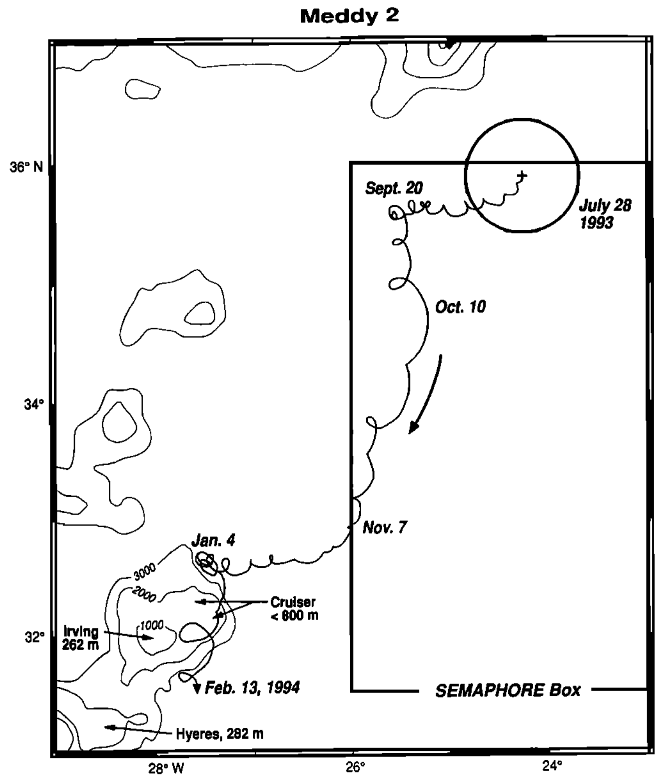

Figure 6 Trajectory of float 174 in Meddy 2 from July 28, 1993, to February 13, 1994. A 100 km diameter circle indicates the Meddy's characteristic size. Meddy 2 translated westward then southward just inside the SEMAPHORE box and was observed during the first three phases of the experiment. In December 1993, Meddy 2 collided with Cruiser Seamount located near 28°W, and in February 1994, float 174 stopped looping. Depth contours are at 1000, 2000, and 3000 m from ETOPO5 bathymetric data which show the general characteristics of the seamounts. A chart by *Hunter et al.* [1983] shows Cruiser Seamount to have two peaks rising above 800 m, one near 32.28°N, 27.55°W, the other near 32.39°N, 27.65°W. Nearby is Irving Seamount, which peaks at 260 m below the sea surface.

with peak values of 12.4°C (900 m) and 36.45 psu (1150 m). The period of rotation of its core (760 m) was around 6.0 days significantly longer than that for Meddies 1 and 3. It is possible that the deeper core could have rotated faster than that where the float was located. Float 101 looped 20 times at a characteristic diameter of 60 km with swirl speeds up to 30 cm/s as Meddy 4 translated westward at 1.8 cm/s (Figure 8). During January 1995, as it meandered northward, its center passed within around 70 km of Santa Maria Island in the Azores. Southwest of Santa Maria where the Meddy circulation impinged on the southern flank of the Azores Plateau, the loops briefly decreased to around 30 km diameter and then increased again to 60 km.

The SEMAPHORE sound sources were retrieved in February, which stopped the tracking, but float 101 continued to receive acoustic signals from a source farther east launched by Amy Bower [*Bower et al.*, 1997]. The times of arrival imply that float 101 looped six more times from February 23 to May 15, 1995, at an average period of 13 days. The diameter of the last loop increased to around 90 km, which suggests that the overall diameter of Meddy 4 was at least 100 km. No further hydrographic measurements are available for this Meddy.

8. Discussion and Summary

8.1. The Lifetime and Fate of Meddies

The trajectory of Meddy 1 sets records for both long length, 1700 km, and fast mean velocity, 3.9 cm/s averaged over 1.5 years. Meddy 1 illustrates that a Meddy starting near the Azores can thread its way through the seamount chain and travel a long distance southwestward along the eastern flank of the Mid-Atlantic Ridge. Backtracking Meddy 1 to Cape Saint Vincent (Table 5) suggests that Meddy 1 was around 2.8 years old when tracking stopped. At that point, Meddy 1 appeared to be still going strong despite an earlier disruptive encounter with tall seamounts. At its mean translation rate, Meddy 1 could have crossed the Mid-Atlantic Ridge and traveled as far as the *McDowell and Rossby* [1978] possible Meddy sighting in the western Atlantic in an additional 2.1 years. The McDowell and Rossby Meddy was ~100 km in diameter, had a 9 day rotation period, and translated southwestward at 6 cm/s. At this rate, Meddy 1 would have required an additional 1.4 years to arrive there. It seems possible that Meddy 1 could have survived another 1.4–2.1 years, but the total lifetime would depend on the size and strength of Meddy 1 at the end of tracking and on how disruptive the crossing of the Mid-Atlantic Ridge would have been. All we know is that the core (<30 km diameter) rotation period at the end was around 6.2 days, the overall Meddy size was larger than float 177's 60 km diameter loops, and the estimated temperature and salinity anomalies near a depth of 1040 m were large, around 4°C and 0.9 psu. When tracking stopped, Meddy 1 was located close to the axis of the Mediterranean salt tongue which extends westward across the Atlantic [*Lozier et al.*, 1995].

The early *McDowell and Rossby* [1978] Meddy sighting in the western Atlantic created a lot of interest in these eddies and led to studies of their population and life histories in the eastern Atlantic. In a curious turn of events, however, recent hydrographic and float data [*Anderson–Fontana et al.*, 1996] have now led Rossby and Prater (H. T. Rossby, personal communication, 1997) to conclude that eddies with temperature–salinity properties similar to the McDowell and Rossby eddy form near the northwestern corner of the Gulf Stream–North Atlantic Current system located east of Newfoundland and that these eddies could be advected south and west by Gulf Stream recirculations to end up near the McDowell and Rossby eddy site. Rossby and Prater think that the northwestern corner is the most probable formation site of the McDowell and Rossby eddy and argue that it was not a Meddy. The new long

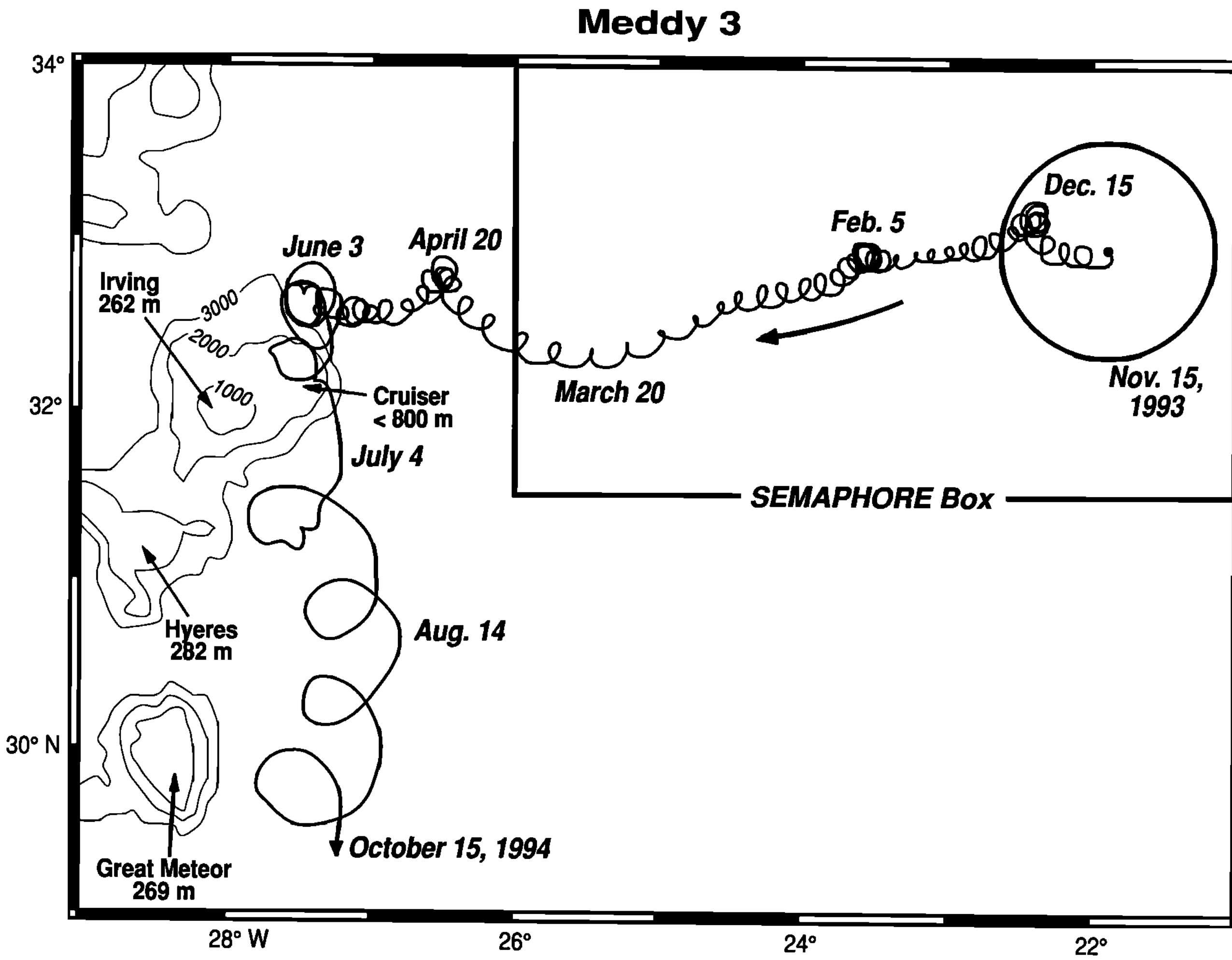

Figure 7a Trajectories of floats 168 and 173 joined to provide a continuous record of Meddy 3 from November 15, 1993, to October 15, 1994. A 150 km diameter circle was added to indicate Meddy 3's characteristic size. During SEMAPHORE Meddy 3 translated westward all the way through the SEMAPHORE box and collided with Cruiser Seamount 5 months after Meddy 2 collided with it. At that point the Meddy appeared to bifurcate as shown by floats 172 and 173 (see Figure 7c). Meddy 3 then turned and translated southward over or around Cruiser Seamount. Float 173 stopped looping where the trajectory terminates east of Great Meteor Seamount.

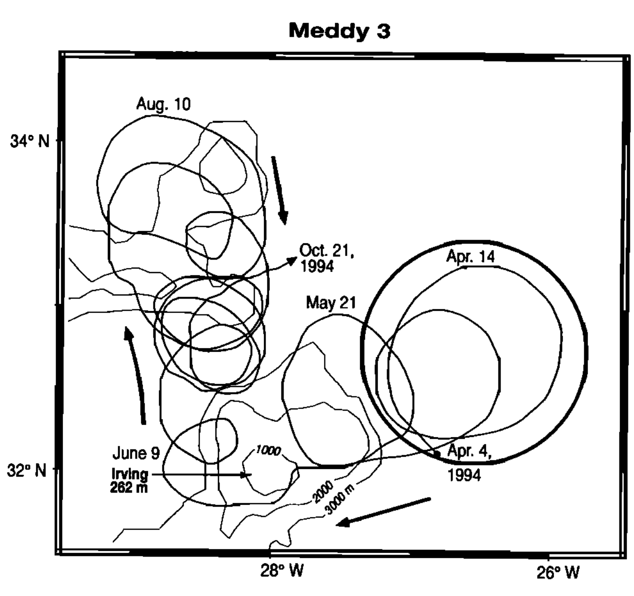

Figure 7b Trajectory of float 172 from April 4 to October 21, 1994, after it was entrained into Meddy 3, which appeared to bifurcate in early June. A 150 km diameter circle was added to show the overall size of Meddy 3 before bifurcation. Float 172 continued to loop for another 4.5 months as the bifurcated piece of Meddy 3 translated first northward then southward in the vicinity of several seamounts. After October 21, float 172 drifted in a large arc to the north and west.

trajectory of Meddy 1, however, adds further support for the original Meddy conclusion. Further research on eddies is required to clearly sort out their formation sites and pathways and to settle the issue of the origin of the McDowell and Rossby eddy.

Meddy 4 was tracked for too short a time to determine its long-term fate. Backtracking Meddy 4 suggests

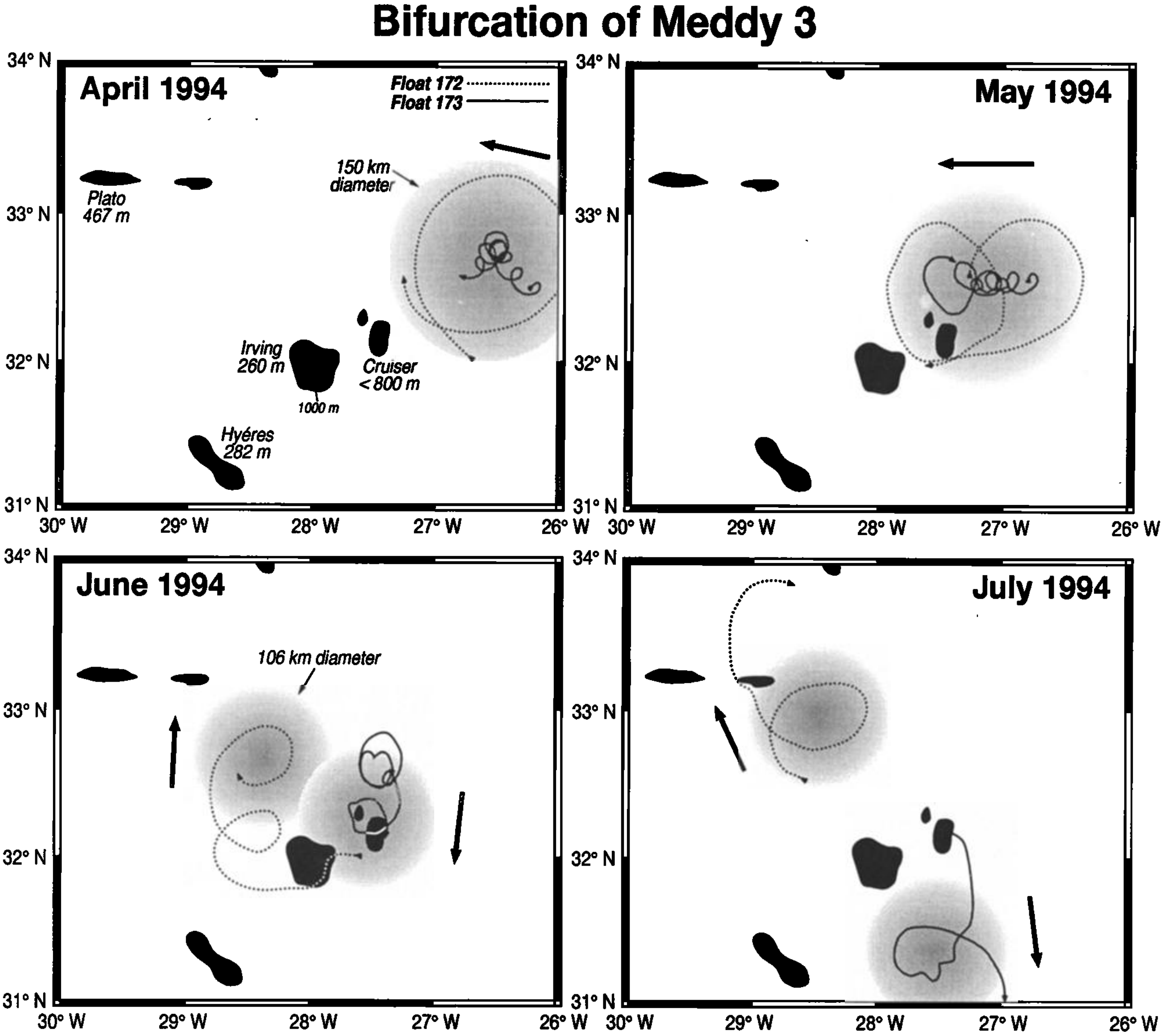

Figure 7c Bifurcation of Meddy 3 as shown by floats 172 and 173, which diverged in early June 1994 when the Meddy collided with the seamounts. Float 172, which was looping with a diameter around 100 km, was diverted south of Irving Seamount and began looping with a diameter around 50 km west of Irving. During June, float 172 continued to loop northeast of Irving. The overall diameter of Meddy 3 was around 150 km as seen in the largest loops of float 172 and shown by shading. Assuming conservation of Meddy area, the diameters of the bifurcated pieces would be around 106 km, which is consistent with the float trajectories. The dark shading shows depths < 1000 m based on a chart by *Hunter et al.* [1983].

that it was 2.5 years old when the tracking stopped. At that point, Meddy 4 was 150 km from and heading toward the spot where Meddy 1 was found, implying that Meddy 4 could have followed a similar long-term trajectory.

Both Meddies 2 and 3 were observed to interact with the Azores Current as they crossed it [*Tychensky and Carton*, this issue; *Tychensky et al.*, this issue]. A southward Azores Current meander apparently caused the 300 km southward jog in Meddy 2's path (Plate 2). Meddy 3 seemed to have triggered some meanders in the Azores Current, including the formation of a cyclonic eddy (Plate 2). After crossing the Azores Current both Meddies translated westward and collided with Cruiser Seamount 5 months apart. At the time of impact both Meddies came to a complete stop then turned and translated southward over or around Cruiser Seamount. Evidence from two floats suggests that Meddy 3 split into two smaller Meddies at the time of collision. Within a few months after impact, all five of the floats in these Meddies had stopped looping. The implication is that around twice a year, Meddies collide with these

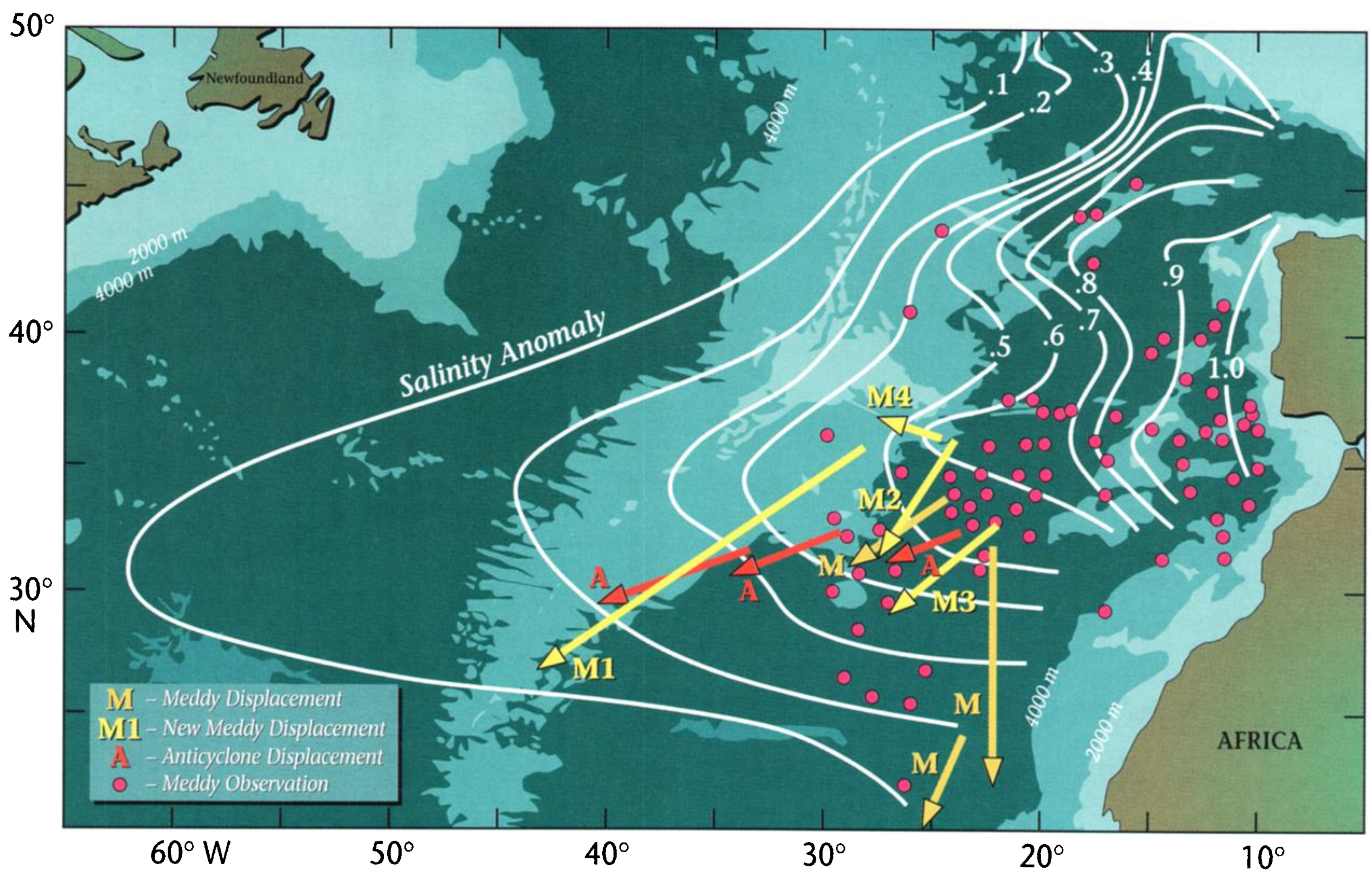

Plate 4 Summary of historical Meddy observations (see Figure 1) and Meddy displacement vectors of the seven Meddies continuously tracked by floats. SEMAPHORE Meddies are labeled with numbers M1 to M4. The displacement vectors of three anticyclones which are similar to but weaker than Meddies are also shown [see *Richardson*, 1993]. Contours of the salinity anomaly relative to 35.01 psu near 1100 dbar are based on a figure by *Needler and Heath* [1975] and shown by *Joyce* [1981]. This figure is an update of one shown earlier by *Richardson* [1993].

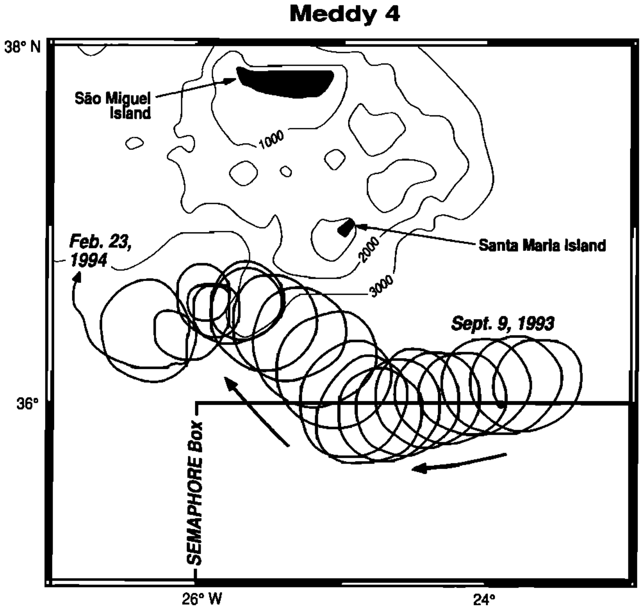

Figure 8 Trajectory of float 101 looping in Meddy 4 from September 9, 1994, to February 23, 1995. Meddy 4 translated westward along the northern edge of the SEMAPHORE box, meandered northward, and impinged on the seafloor topography southwest of Santa Maria Island in the Azores as inferred from variations in the diameter of the float loops there. Tracking ceased when the SEMAPHORE sound source array was retrieved in February 1995, but the float continued to loop for another 80 days as shown by times of arrival from a single source located farther east.

seamounts, which causes a major, if not fatal, disruption of the normal swirl circulation of the Meddies. One earlier Meddy tracked with SOFAR floats collided with nearby Hyeres Seamount and was destroyed (Plate 4). These three new case histories plus some hydrographic measurements of a Meddy which collided nonfatally with these seamounts [*Shapiro et al.*, 1995; *Dykhno et al.*, 1991] suggest that Meddies often collide with the seamounts but not always fatally. Backtracking Meddies 2 and 3 suggests that they were 1.8 and 2.8 years old when the floats stopped looping.

Floats in the core region of Meddies which do not hit seamounts tend to loop with a very regular pattern consisting of nearly constant diameter, period of rotation, and temperature for long periods of time (years). Examples are given in this study and in an earlier one [*Richardson et al.*, 1989]. Floats in the core region of Meddies which hit seamounts exhibit behavior that implies a major disruption of the normal Meddy circulation. Examples are (1) a possible Meddy bifurcation (floats 172 and 173 in Meddy 3), (2) rapid radial movements after collision with seamounts plus a rapid decrease in temperature anomaly (floats 171, 175, and 177 in Meddy 1, floats 172 and 174 in Meddy 2, and float 173 in Meddy 3), and (3) a cessation of looping altogether (floats 172 and 174 in Meddy 2, and floats 172 and 173 in Meddy 3). The decrease in float temperature anomaly following a collision with seamounts is often accomplished by large (~1°C) and very rapid (few days) temperature fluctuations. We interpret the increase in diameter, the cessation of looping, and the

Table 5. Estimated Lifetimes of Meddies

	Mean Velocity, cm/s	Continuously Tracked, years	Backtracked to 37°N, 10°W,[a] years	Total Life,[b] years
		SEMAPHORE		
Meddy 1	3.9	1.5	1.3	2.8
Meddy 2	3.3	0.5	1.2	1.8
Meddy 3	2.2	0.9	1.6	2.6
Meddy 4	1.9	0.5	2.0	2.5
		Three Earlier Meddies (1984–1987)[c]		
Meddy 1	1.8	2.1	2.2	4.3 (3.7)[d]
Meddy 2	2.3	0.7	1.8	2.5 (2.3)
Meddy 3	1.1	1.5	5.4	6.9 (4.5)

[a]Meddies were backtracked using their mean velocity from their first observed position to 37°N, 10°W, their presumed origin near Cape Saint Vincent, Portugal. Recent float trajectories suggest that Meddies form near Cape Saint Vincent near 37°N and also farther north near the Tejo Plateau near 39°N [*Bower et al.*, 1995, 1997; *Käse and Zenk*, 1996; *Pingree*, 1995; *Zenk et al.*, 1992].

[b]Meddies 1 and 4 were still vigorous at the end of the tracking, which suggests the possibility of a significantly longer lifetime than given here. Meddy 4 looped at least another 0.2 years as inferred by times of arrival from a single sound source. Meddies 2 and 3 were severely and possibly fatally disrupted by collision with seamounts.

[c]From Table 3, given by *Richardson et al.* [1989].

[d]The values in parentheses were estimated by using a linear increase of mean southwestard velocity versus latitude observed by the three earlier Meddies, which implies that the mean velocity of Meddies near Cape Saint Vincent is around 2.7 cm/s.

decrease in temperature anomaly to mean that pieces of the core regions of the Meddies were mixed with background water, which diluted the originally large temperature and salinity anomalies in the Meddy cores and caused a much more rapid decay than is usual for Meddies which remain clear of seamounts. A clue to how this was accomplished is given by float 173 (in Meddy 3), which exhibited smaller-scale anticyclonic loops (~10 km diameter and ~4 day rotation period) embedded in larger loops (~60 km diameter and ~25 day period). This smaller-scale eddy could have been generated either directly by the seamounts or indirectly by the seamounts initiating the breakup of the original Meddy core into smaller pieces. The float temperature in the small loops was 10.3°C, 2.2°C below the float temperature in the Meddy core (12.5°C) before the collision with seamounts. This decrease is around half of the core temperature anomaly before impact. The generation of small eddies and their subsequent mixing of Meddy water with background water could be responsible for the faster than usual Meddy decay.

The total lifetimes of Meddies which hit seamounts would appear to be roughly 2–3 years, although it is possible for a remnant Meddy to have continued after the floats ceased looping. The lifetimes of Meddies which did not fatally collide with seamounts could be significantly longer than 3 years, perhaps as long as the 4 (or more) years estimated from earlier Meddies which translated southward into the Canary Basin and decayed there.

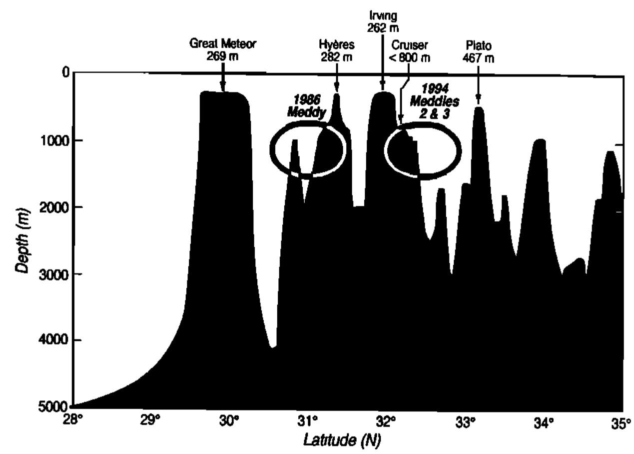

Figure 9 A north–south section showing the projected sea floor depth profile along the Great Meteor Seamounts from a chart by *Hunter et al.* [1983]). These are the seamounts faced by a Meddy translating westward between 28°and 35°N. Two Meddies are shown schematically, each one 100 km in diameter and 800 m thick; the southern Meddy collided with Hyeres Seamount in 1986 and was destroyed [*Richardson et al.*, 1989]; the northern Meddy shows where Meddies 2 and 3 translated westward between 32°and 33°N and collided with Cruiser Seamount in 1994. Also shown is Plato Seamount, which was hit by Meddy 1 as it translated southward in October 1993. Another tall seamount, Atlantis, located near 34.4°N, 30.0°W rises up to within around 400 m of the sea surface. Most of this seamount is off the edge of the *Hunter et al.* [1983] chart, and therefore the seamount is not plotted here.

8.2. Meddy Paths

Combining the SEMAPHORE Meddy trajectories with the three earlier ones suggests three general paths (Plate 4). First, some Meddies translate southward into the southern Canary Basin near 24°N, 24°W, where they decay (earlier Meddies 1 and 3). Second, some Meddies translate westward into the area just south of the Azores (Meddies 1, 2, and 4). When they are not interacting with the Azores Current, these Meddies tend to translate westward counter to the mean Azores Current (Meddies 2, 3, and 4). Some of these can continue through the seamounts far westward to at least 43°W (Meddy 1), possibly across the Mid-Atlantic Ridge. Third, Meddies often translate westward between 29°N and 35°N near 28°W and collide with the Great Meteor Seamounts (Meddies 2, 3, and earlier Meddy 2). These Meddies can be severely disrupted, sometimes fatally, by the collision. The seamounts appear to be a major obstacle preventing Meddies from freely translating westward between 29°N and 35°N (Figure 9). By blocking the Meddies and causing their early death, seamounts could have an important local influence on the transport of heat and salt and the structure of the Mediterranean salt tongue.

8.3 Meddy Translation Velocity

The mean translation rate of the SEMAPHORE Meddies ranged from 1.9 cm/s for Meddy 4 up to 3.6 cm/s for Meddy 1 (Table 4). Meddy 1 seems a little faster than the others, but the mean velocity of Meddies 2 and 3 before they hit seamounts was 3.9 and 3.4 cm/s, respectively, which suggests that Meddy 1 was not anomalous. The velocity obtained by averaging the four Meddy velocities is 2.5 ± 0.5 cm/s toward 236°. SEMAPHORE Meddies were swifter than the three earlier ones especially the slow one located near 24°N, 24°W, which translated at only 1.1 cm/s during 1.5 years.

8.4. Meddy Population

Before SEMAPHORE began, we estimated from earlier studies that we would find 4–6 Meddies in the SEMAPHORE region. We actually found four major Meddies, including one west of the SEMAPHORE box, and one smaller piece of a Meddy. One Meddy was found in the box in phases 1 and 4, and two Meddies (plus a piece) were found in phases 2 and 3. By assuming an overall diameter of 100 km and estimating the fraction of each Meddy in the SEMAPHORE box (excluding the piece) we estimate that an average of 4% of the box contained Meddies. This is in agreement with earlier studies [*Armi and Zenk*, 1984; *Richardson et al.*, 1991; *Käse and Zenk*, 1996], which suggested that Meddies comprise 4–8% of the region. Therefore the population of Meddies observed during SEMAPHORE appears to be rather typical.

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P. L. Richardson, Mail Stop #29, Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, MA 02543-1541, (prichardson@whoi.edu)

A. Tychensky, CMO/SHOM, 18 Avenue Edouard Belin, 31055 Toulouse Cedex, France, (Aude.Tychensky@cnes.fr)

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