Lagrangian Observations of Meddy Formation during A Mediterranean Undercurrent Seeding Experiment*

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ABSTRACT

Mediterranean eddies (meddies) play an important role in maintaining the temperature and salinity distributions in the North Atlantic, but relatively little is known about their early life histories, including where, how often, and by what mechanism they form. A major field program, called A Mediterranean Undercurrent Seeding Experiment, has been carried out to directly observe meddy formation and the spreading pathways of Mediterranean Water into the North Atlantic. Between May 1993 and March 1994, 49 RAFOS floats were deployed sequentially in the Mediterranean Undercurrent south of Portugal and tracked acoustically for up to 11 months. The float deployments were accompanied by high-resolution XBT sections across the undercurrent.

Nine meddy formation events were observed in the float trajectories, six near Cape St. Vincent, at the southwestern corner of the Iberian Peninsula, and three near the Estremadura Promontory, along the western Portuguese continental slope. Meddy formation thus occurs where the continental slope turns sharply to the right (when facing in the downstream direction of the undercurrent). After conditionally sampling the float dataset to identify floats that were well seeded in the undercurrent, the authors have estimated a meddy formation rate of 15–20 meddies per year. The timescale for meddy formation at Cape St. Vincent was found to be 3–7 days, shorter than previous estimates based on the volume of larger meddies. Meddies were observed to form most frequently when the speed of the Mediterranean Undercurrent was relatively fast.

The meddy formation process at Cape St. Vincent resembles the conceptual model of E. A. D'Asaro, whereby anticyclonically rotating eddies are formed by separation of a frictional boundary layer (with negative relative vorticity) at a sharp corner. Comparison of the relative vorticity in the anticyclonic shear zone of the undercurrent and that of the newly formed meddies shows that much of the anticyclonic relative vorticity in meddies can be accounted for by the horizontal shear in the undercurrent. This confirms earlier work suggesting that the classical mechanism for the generation of submesoscale coherent vortices, by collapse and geostrophic adjustment of a weakly stratified fluid injected into a stratified ocean, may not be the principle mechanism at work in the formation of meddies at Cape St. Vincent.

1. Introduction

Some of the intermediate and all of the deep water masses of the world's oceans are produced as the result of intense air–sea exchange in marginal seas (Warren 1981). The water mass formed in the marginal sea typically enters the open ocean as a dense outflow through a restricted channel or strait. One of the most well-known outflows is that from the Mediterranean Sea, which enters the North Atlantic through the Strait of Gibraltar in the lower layer of a two-way exchange flow. Due to its high density, the Mediterranean Water (MW) flows down the continental slope in the Gulf of Cadiz as a narrow gravity current, entraining less dense North Atlantic Central Water. Due to Coriolis acceleration, the outflow current is deflected to the right as it leaves the strait and follows the northern rim of the Gulf of Cadiz in an upper and lower core. Near 8°W, the outflow becomes gravitationally stable and continues westward in a wall-bounded flow known as the Mediterranean Undercurrent (e.g., Heezen and Johnson 1969; Madelain 1970; Ambar and Howe 1979a, b; Bar-

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inger and Price 1997). After rounding Cape St. Vincent, at the southwestern corner of the Iberian Peninsula, the outflow water begins to spread into the eastern North Atlantic to form a warm and salty tongue that extends from Portugal westward across the eastern Atlantic (see, e.g., Worthington 1976; Lozier et al. 1995). This tongue is one of the most prominent features of the North Atlantic at intermediate depths, and its high-salinity water has been implicated in the preconditioning of North Atlantic Deep Water (Reid 1978).

Traditionally, tongues of various water properties such as this one have been interpreted to be the result of advection and/or eddy diffusion of the property from its source (e.g., Worthington 1976; Needler and Heath 1975; Richardson and Mooney 1975; Armi and Haidvogel 1982). These views of how the Mediterranean salt tongue is maintained have been challenged by the discovery of coherent vortices containing cores of warm and salty MW. One of the earliest observations of such an eddy was that of McDowell and Rossby (1978) in the western North Atlantic using floats and hydrographic data. They found a 100-km diameter, anticyclonically rotating lens of water with anomalously high salinity and temperature centered at about 1100 m. Based on the *T–S* characteristics of the lens, McDowell and Rossby suggested that it formed from MW in the eastern North Atlantic, and coined the term ''meddy,'' for Mediterranean eddy, to describe the feature.

This discovery prompted a search for meddies closer to their proposed source, and in the past two decades, many meddies have been found in the eastern North Atlantic (see e.g., Armi and Zenk 1984; Armi et al. 1989; Richardson et al. 1991; Zenk et al. 1992; Pingree and Le Cann 1993; Prater and Sanford 1994; Shapiro et al. 1995). The hydrographic properties of meddies have been surveyed in detail, and the velocity structure inferred using the dynamic method and current meters (e.g., Armi and Zenk 1984) and observed directly using floats and velocity profilers (e.g., Armi et al. 1989; Richardson et al. 1989; Schultz Tokos and Rossby 1991; Zenk et al. 1992; Prater and Sanford 1994). From these studies we have learned that meddies are lenslike features, containing a core of MW 200–1000 m thick centered at about 1000 m, that are less stratified than the surrounding fluid. This density structure supports an energetic anticyclonic rotation with peak azimuthal velocities of about 30 cm s^{-1} and rotation periods of 2–7 days. Meddies are typically 20–100 km in diameter and have temperature and salinity anomalies of about 2°C and 1 psu. They have been observed to live for several years, advecting MW thousands of kilometers from its source region. Some meddies die slowly, distributing MW gradually along their path (Armi et al. 1989; Hebert et al. 1990), while others are destroyed catastrophically when they crash into seamounts (Richardson et al. 1989; Shapiro et al. 1995).

It has become increasingly apparent that meddies are not just curiosities, but that they play a fundamental role in maintaining the large-scale salt tongue. For example, during the early exploration of meddies, Armi and Stommel (1983) measured the salt flux divergence in an area of the large-scale salt tongue and noted that it could be balanced by decay of just three meddies per year. Richardson et al. (1989) estimated that 8–12 meddies form each year based on estimates of the number of coexisting meddies and their average lifetime (2–3 yr), and that they may transport about 25% of the salinity anomaly flux that comes through the Strait of Gibraltar. More recently, Arhan et al. (1994) suggested that meddies may be responsible for more than 50% of the zonal salinity flux at the level of the MW based on the simultaneous observation of three meddies along a hydrographic section at 15°W and previous work showing that some meddies drift westward at a speed five times the background flow. Mazé et al. (1997) observed weak *eastward* volume transport at the MW level across 12°30′W, and through a scaling analysis of the advective/diffusive equation for salt, concluded that meddies and other eddies are responsible for virtually all of the westward salt flux across that section.

In spite of the growing body of knowledge about the structure and dynamics of meddies, and their potentially important role in maintaining active and passive tracer distributions in the North Atlantic, some fundamental questions about their early life histories have remained unanswered. Without direct observations of meddy formation, we have only been able to speculate on where, how often, and by what mechanism meddies are generated. Several meddy formation sites have been suggested in the literature. Käse and Zenk (1987) demonstrated how meddies could form in the Canary Basin from interactions between the Azores Current and the large-scale salt tongue. The *T–S* characteristics of some meddies have pointed to formation sites along the continental slope of Portugal (e.g., Armi et al. 1989; Pingree and Le Cann 1993; Arhan et al. 1994; Prater and Sanford 1994). Some meddy cores have two salinity maxima, corresponding to the upper and lower cores of MW in the Mediterranean Undercurrent. These cores are vertically aligned around Cape St. Vincent, implicating the cape as a probable meddy formation site. Some young meddies have been observed close to and against the slope (Zenk et al. 1992; Pingree and Le Cann 1993; Prater and Sanford 1994), but there have been no direct observations of meddies forming. Several authors have speculated on how frequently meddies are formed. As mentioned above, Richardson et al. (1989) indirectly estimated a meddy formation rate of 8–12 meddies per year based on a crude estimate of the number of coexisting meddies. Armi and Zenk (1984) estimated that it could take 10–20 days to form a meddy of the size observed in the eastern North Atlantic from the volume transport of the undercurrent.

The study of meddy formation *mechanisms* has also been hampered by the lack of direct observations. One of the mechanisms proposed for the generation of anticyclonic submesoscale coherent vortices (SCVs) like meddies is by collapse and geostrophic adjustment of a mixed patch of fluid (with no initial relative vorticity) injected into a stratified ocean (McWilliams 1985), which has been demonstrated theoretically and in laboratory models by several investigators (e.g., McWilliams 1988; Hedstrom and Armi 1988). In a review of this and five other suggested formation mechanisms, Prater (1992) pointed out that the classical adjustment process was probably not the principle mechanism at work in the formation of the Cadiz Meddy, a small young meddy near Cape St. Vincent (Prater and Sanford 1994), and that the source water for the core of the meddy must have had some initial anticyclonic relative vorticity. D'Asaro (1988) proposed that negative relative vorticity, produced by viscous shear stress in the boundary layer of a coastally trapped jet, could generate SCVs at a sharp corner due to separation of the boundary layer. Prater considered this as a possible formation mechanism for the Cadiz Meddy, but lacked sufficiently high-resolution velocity observations in the undercurrent to measure its relative vorticity. He concluded that the D'Asaro mechanism, and instability of a buoyancy-driven coastal current (e.g., Griffiths and Linden 1981), were the most consistent with his observations.

To better understand the meddy formation process and the role of meddies in the North Atlantic, direct observations of meddy formation were needed. A major field program, called A Mediterranean Undercurrent Seeding Experiment (AMUSE), has been carried out to directly observe meddy formation and the spreading of MW away from the Iberian Peninsula via meddies and other processes. Since the Mediterranean Undercurrent and meddy formation are time-dependent phenomena, a Lagrangian approach was taken, and 49 subsurface RAFOS floats were deployed sequentially in the Mediterranean Undercurrent south of Portugal (see Fig. 1) over a 10-month period in 1993–94, and tracked acoustically for up to 11 months. The float deployments were accompanied by high-resolution (3 km) XBT sections across the undercurrent. In this paper, we present an overview of the Lagrangian results from AMUSE with a focus on meddy formation. Detailed analyses of the XBT observations and large-scale MW spreading patterns will be the subject of future papers. In the following section, the float deployment strategy and data collection procedures for AMUSE are described. An overview of the float observations is presented in section 3, and the primary results regarding meddy formation follow in section 4. In section 5, a number of other meddy observations made during AMUSE are described. These results are discussed in section 6, including estimation of a meddy formation rate and evaluation of some meddy formation mechanisms that have been suggested in the literature. The results are summarized in section 7.

2. Data collection and processing

a. Float/XBT deployment site selection

Our objective in choosing a suitable launch site for the RAFOS floats and XBTs during AMUSE was to identify a location in the Mediterranean Undercurrent that was 1) downstream of the region where the MW is sinking from the sill depth in the Strait of Gibraltar (~300 m) to its level of neutral buoyancy (600–1300 m), 2) upstream of all proposed meddy formation sites, and 3) within one or two days steaming of a port that could support the operations of a chartered research vessel. A site was selected based on previous observations (Ambar and Howe 1979a,b) and a detailed conductivity–temperature–depth (CTD) survey of the undercurrent and western Gulf of Cadiz carried out in May 1993 aboard the R/V *Oceanus.* Figure 2 shows the distribution of salinity during this survey on the 32.25 σ_1 density surface, corresponding to the density of the lower core of the undercurrent, at a pressure of about 1100–1200 dbars. The highest salinities (and warmest temperatures, not shown), indicating the purest MW, were found close to the slope and extending offshore in Portimão Canyon. Examination of the individual CTD profiles revealed that east of Portimão Canyon, the MW was being transported by a bottom boundary current flowing around complex topography (see also Baringer and Price 1997) not suitable for the deployment of isobaric floats. We therefore chose a float seeding location between the 1000 and 2000 m isobaths near the head of Portimão Canyon at 36.5°N, 8.5°W. Figure 3 shows vertical distributions of salinity and temperature along the CTD section that crossed over the chosen seeding site (see Fig. 2 for location). The warmest and saltiest MW was against the slope between about 600 and 1500 dbar, concentrated in two cores at about 750 and 1200–1300 dbars. The upper core was warmer and less saline than the lower core, with maximum values of 13.2°C/36.62 psu and 12.0°C/36.68 psu, respectively. At the level of the lower core, the MW extends farther southward than at shallower depths indicating that the offshore protrusion of purer MW in Portimão Canyon seen in Fig. 2 is limited to the level of the lower core.

b. Deployment strategy

We deployed a total of 49 RAFOS floats in the undercurrent, two from R/V *Oceanus* on the preliminary CTD cruise in May 1993 and 47 on 22 of 24 cruises on a chartered research vessel, *Kialoa II,* between July 1993 and March 1994. RAFOS floats are acoustically tracked, subsurface drifters that collect tracking, temperature, and pressure data during a preprogrammed underwater mission, then return to the surface to transmit the data to the ARGOS satellites (for more details, see Rossby et al.

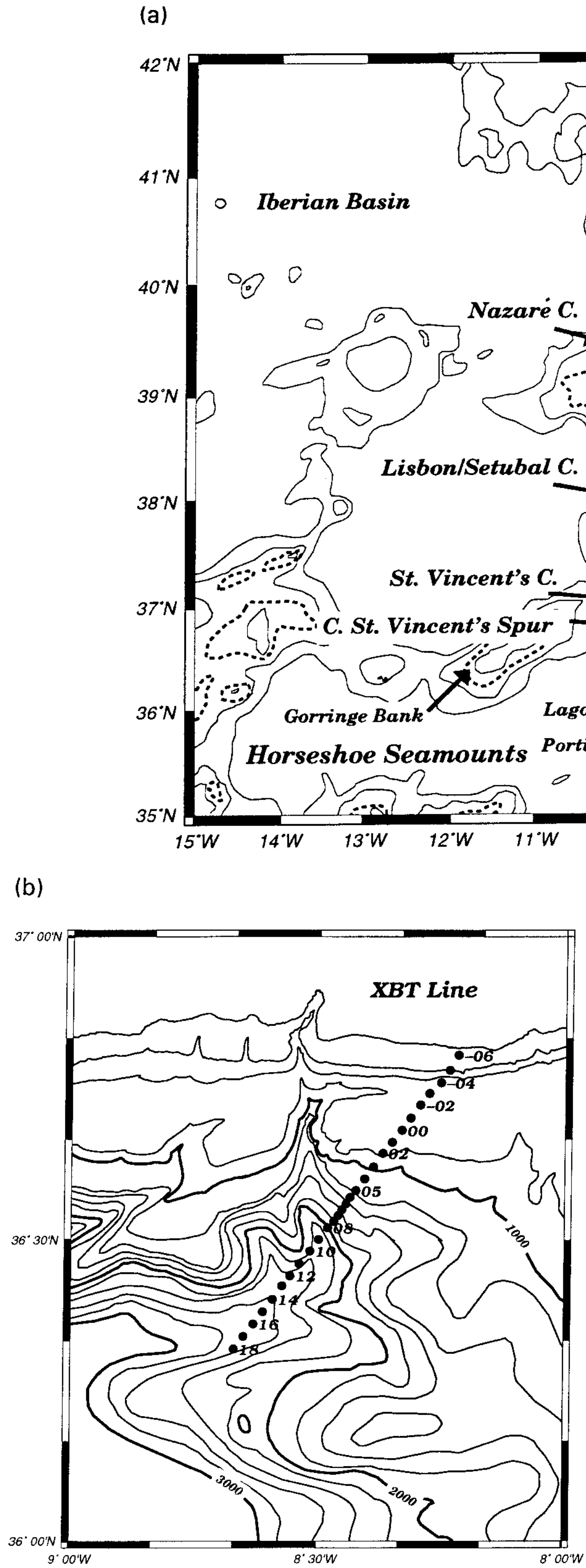

FIG. 1. (a) Chart of the AMUSE study area in the eastern North Atlantic showing major topographic features and the float/XBT deployment line. Bathymetric contours are indicated every 1000 m and the 2000-m contour is dotted for reference. The shaded area south of Portugal is expanded in (b) to show the detailed bathymetry in the vicinity of the float/XBT deployments. Contours in (b) are plotted at 200-m intervals, highlighted every 1000 m. The dots indicate the XBT stations, from −06 to 18. RAFOS floats were deployed between stations 05 and 08, where XBT station spacing was halved to resolve the detailed horizontal structure of the undercurrent.

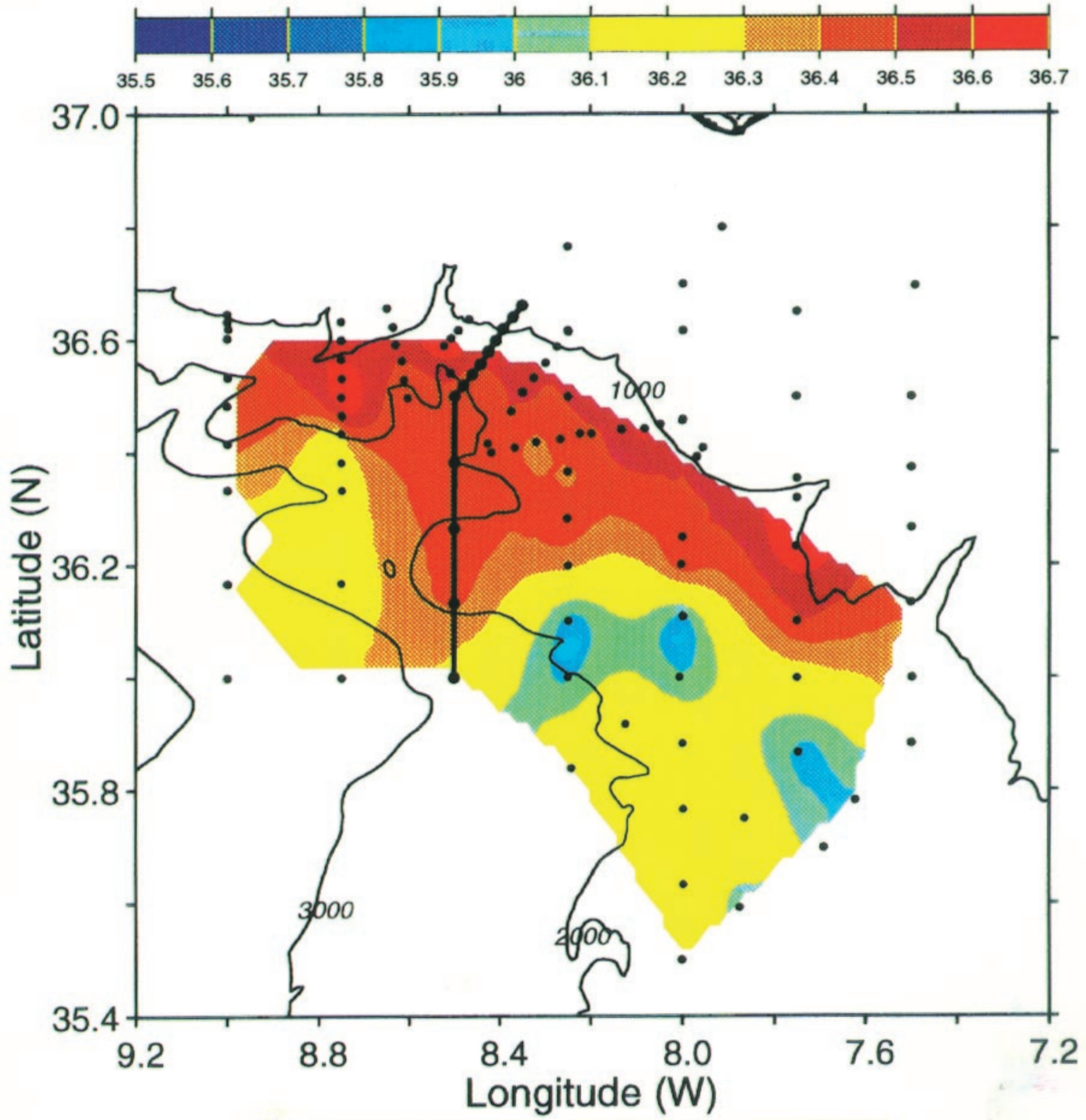

FIG. 2. Salinity on the 32.25 σ_1 density surface in the western Gulf of Cadiz during the preliminary CTD survey conducted in May 1993 aboard R/V *Oceanus.* The shading interval is 0.1. Station positions are indicated by dots. Section shown in Fig. 3 is indicated by bent line. Thin underlining contours indicate water depth in 1000-m intervals.

1986). Each float deployment from *Kialoa II* was accompanied by a high-resolution XBT section across the undercurrent, using 1800-m T-5 XBTs. During each cruise, one float was launched as close to the slope as possible and a second several kilometers offshore to observe any differences in the pathways of the inner and outer parts of the undercurrent. Such close spacing was justified based on previous studies of the undercurrent (Ambar and Howe 1979a,b) and the preliminary CTD survey, which showed the baroclinic structure of the undercurrent to be only about 10–15 km wide.

A time line showing the dates of each cruise, floats launched, and length of each float mission is given in Fig. 4 and listed in Table 1. Thirty-eight floats were programmed for the full-length, 333-day mission, 10 for a shorter 30-day mission, and one for a 119-day mission. Note that seven floats (those marked with a or b in Fig. 4) were recovered at sea, refurbished, and redeployed for a second mission. Also note that on cruises K20, K23, and K24, three, rather than two, floats were launched.

At the beginning of the experiment, the RAFOS floats were ballasted for 1100 dbars, the average pressure of the middepth salinity maximum in the deep North Atlantic. Later, the target pressure was changed to 1200

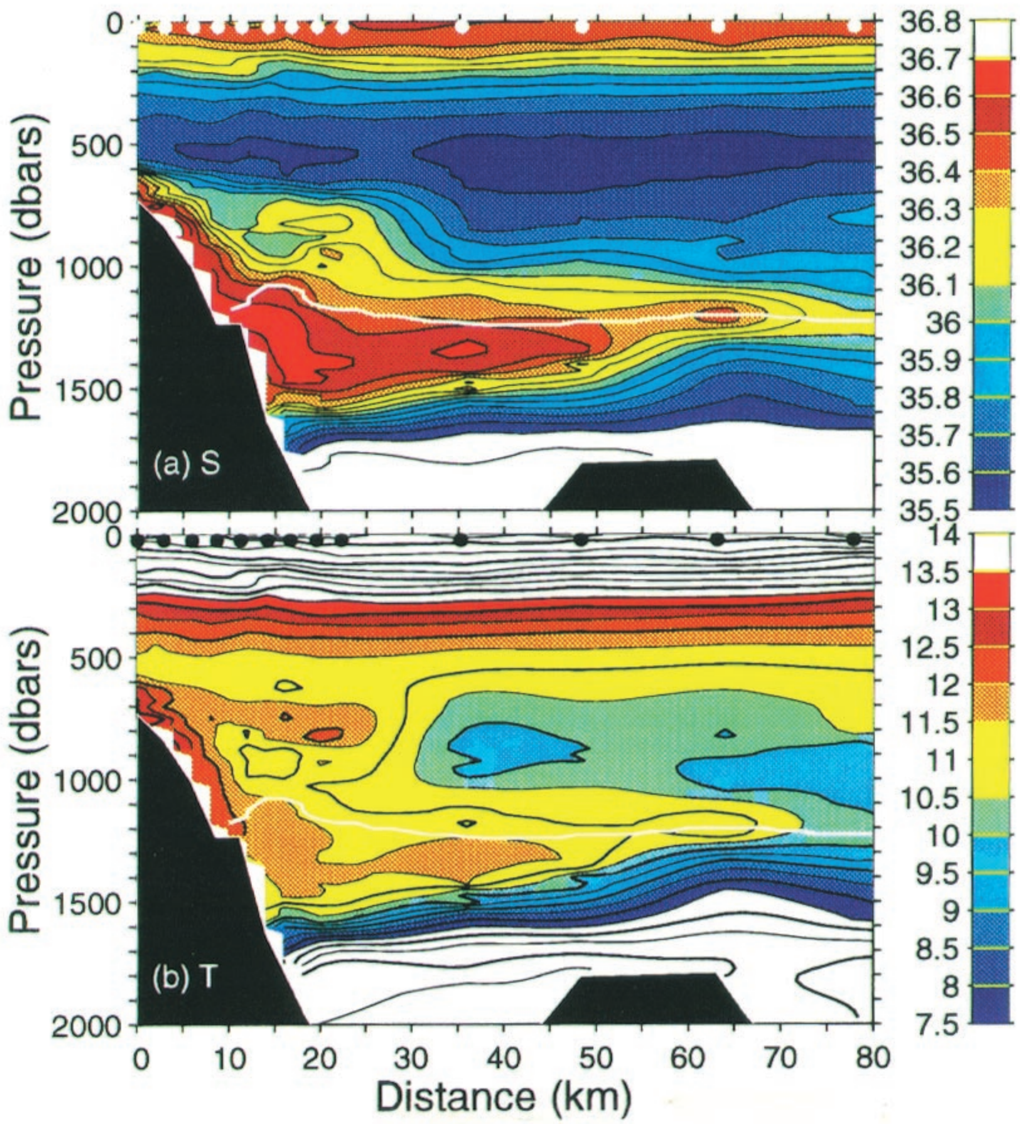

FIG. 3. Vertical distributions of (a) salinity (contour interval = 0.1) and (b) temperature (contour interval = 0.5°C) along section indicated in Fig. 2. Northern end of the section is to the left. The station locations are plotted as dots along the top axis. The heavier white line shows the depth of the $32.25\sigma_1$ density surface along the section.

dbars, closer to the pressure of the temperature and salinity maxima associated with the lower core, Fig. 3.

Two mechanical failure modes impacted the deployment schedule and the amount of data returned. First, some floats sank rapidly when water leaked into the glass housing or the hollow drop weight. These floats (and their data) were not lost however since all floats were programmed to return to the surface immediately and transmit the data they had collected up to that point if they sank below 1400 dbars. Some seeding cruises were delayed during the first half of the experiment while this problem was being corrected. Second, many of the longer-mission floats lost their ballast weights prematurely, resulting in shorter than expected missions. The cause of this problem has not been determined, although fishbite of the drop weight lanyard and corrosion are the most likely candidates. Mostly as a result of this second problem, the average percent of mission accomplished by the floats was 73%. Also, seven floats were mistakenly ballasted for pressures around 800 dbars, which fortuitously put them near the level of the upper core of the undercurrent. Overall, 48 of the 49 floats launched returned to the surface, and 44 returned some useful data. A total of more than 20 float-years of data were obtained.

An expanded view of the float/XBT deployment region, with nominal station positions, is shown in Fig. 1b. Up to 28 XBT stations were occupied on each cruise,

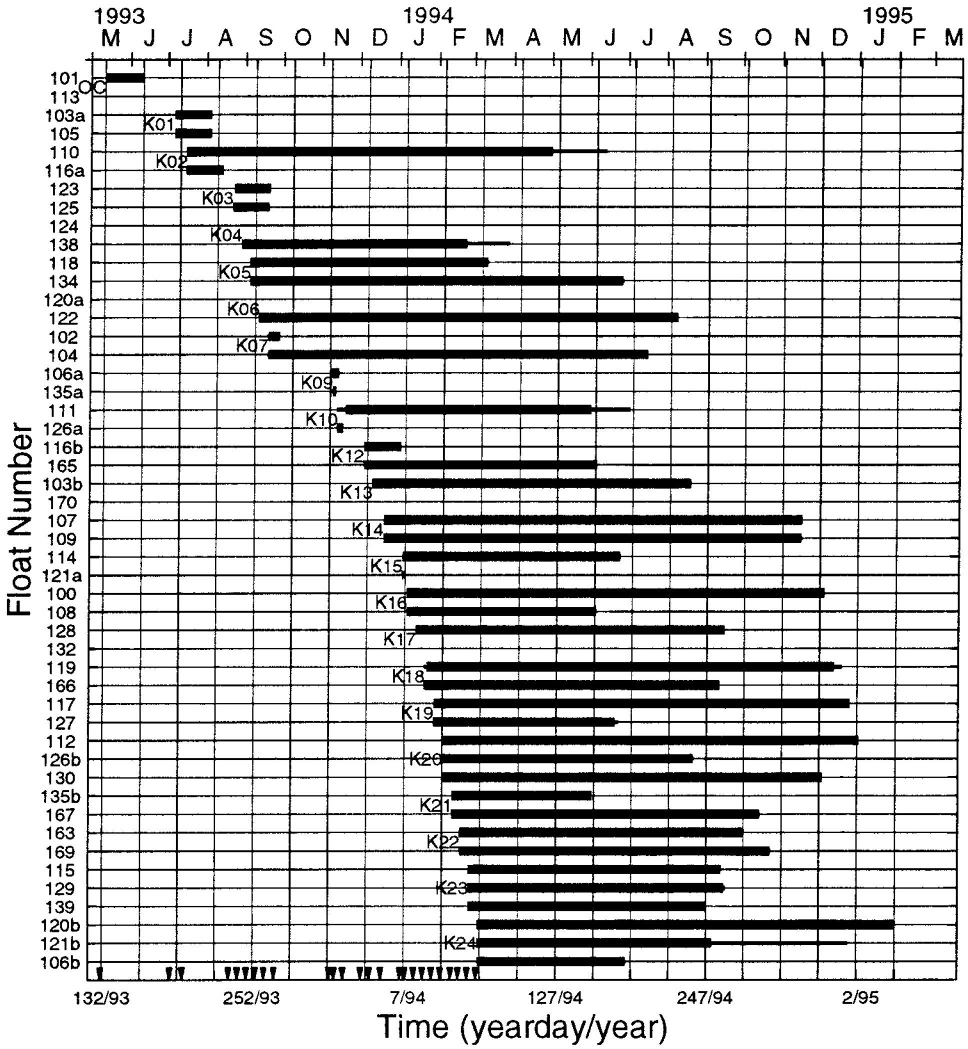

FIG. 4. Time line of R/V *Oceanus* and *Kialoa II* cruises and float launchings during AMUSE. Time is indicated in yearday and year (94 ≡ 1994) along the bottom axis and by month and year along the top axis. The inverted triangles along the bottom axis show the times of the one R/V *Oceanus* cruise and 24 *Kialoa II* cruises. The heavy horizontal lines indicate the duration of each float mission (line is slightly thinner when only temperature and pressure data were obtained), and the labels (e.g., K01) refer to the cruise on which each set of floats was deployed.

separated by approximately 2.8 km [positions determined to within 0.18 km using the Global Positioning System (GPS)]. In the center of the lower core, between stations 06 and 08, three stations were added to increase the resolution of the undercurrent's structure. The floats were not launched at the same sites on each cruise; rather, the XBT profiles were used to find the stations with the warmest temperatures at the level of the lower core between XBT stations 05 and 08, and two (or three) floats were launched at these sites.

c. Tracking and data processing

The AMUSE floats were tracked using an array of ten sound sources moored in the eastern North Atlantic, three deployed as part of AMUSE and the others by French and German scientists [see aknowledgments and Bower et al. (1996) for details]. The floats collected acoustic tracking data from these sources, and temperature and pressure observations three times daily. Velocity was estimated along the tracks by fitting cubic splines to latitude and longitude time series. Toward the end of the experiment, only two sources were still available, making it difficult to track some floats. The details of data processing and tracking are provided by Bower et al. (1996).

d. Major bathymetric features

Before describing the major results of the float seeding, we note the complex bathymetry along the conti-

TABLE 1. Float/XBT deployment summary.

Cruise	Date (yymmdd) (yearday/yr)	Number of XBTs	Float launched	XBT site	Mission (days)	Mean *T* (°C)	Mean *P* (dbar)	Min *P* (dbar)	Max *P* (dbar)
OC258	930511	NA	101	ctd110	30	11.8	1274	1218	1334
	131/93		113	ctd111	1		no useful data obtained		
K01	930705	17	103a	K0106	30	12.3	1141	1101	1173
	186/93		105	K0107	30	11.6	1071	1043	1100
K02	930715	21	116a	K0205	30	11.8	1064	1038	1103
	196/93		110	K0207A	333	11.9	1237	1100	1366
K03	930821	24	123	K0306	30	11.6	825	773	850
	233/93		125	K0307	30	12.6	757	718	780
K04	930828	24	124	K0405A	0		no data obtained		
	240/93		138	K0407	216	11.5	1073	1031	1108
K05	930904	24	118	K0506	204	11.9	1005	960	1036
	247/93		134	K0507	297	11.6	726	455	917
K06	930911	24	120a	K0606A	3		no useful data obtained		
	254/93		122	K0607A	333	11.5	569	372	794
K07	930918	24	102	K0706	10	11.4	1338	1212	1394
	261/94		104	K0707A	333	11.1	1207	1160	1265
K08	930926	24	none						
	269/93								
K09	931109	0	106a	K0906	6	12.3	1202	1163	1379
	313/93		135a	K0907A	5	11.4	1173	1154	1231
K10	931113	27	111	K1006	235	9.3	1319	1200	1407
	317/93		126a	K1007	5	11.3	1240	1206	1379
K11	931120	24	none						
	324/93								
K12	931204	27	116b	K1205A	30	11.7	1154	1130	1179
	338/93		165	K1208	185	11.6	1112	1015	1204
K13	931211	26	103b	K1306	254	11.4	1133	1093	1174
	345/93		170	K1307A	269		no useful data obtained		
K14	931220	28	107	K1406	333	11.4	806	624	923
	354/93		109	K1407A	333	11.2	724	496	907
K15	940104	28	114	K1505A	174	12.3	814	497	873
	4/94		121a	K1506A	3	12.5	1359	1319	1391
K16	940108	28	100	K1606	333	10.6	1090	1038	1142
	8/94		108	K1608	151	11.3	1100	1030	1146
K17	940115	28	128	K1705A	246	11.0	1117	1078	1152
	15/94		132	K1706A	134		no tracking data obtained		
K18	940122	28	119	K1806A	333	11.0	1104	1016	1165
	22/94		166	K1807A	245	11.2	1184	1159	1223
K19	940129	28	117	K1905A	333	10.7	1094	1053	1147
	29/94		127	K1907A	148	11.7	1179	1077	1230
K20	940205	28	112	K2005A	333	10.9	1151	1083	1223
	36/94		126b	K2006A	201	11.1	1176	1140	1211
			130	K2007A	303	11.3	1070	1010	1147
K21	940213	28	135b	K2105A	112	11.3	1201	1141	1239
	44/94		167	K2106A	247	11.9	1066	992	1172
K22	940219	28	164	K2205A	226	10.7	1143	1102	1188
	50/94		169	K2207	249	10.7	1118	1075	1171
K23	940226	28	115	K2305A	203	11.0	1088	1003	1158
	57/94		139	K2307	190	11.2	1125	1101	1159
			129	K2307A	206	12.1	1170	1139	1200
K24	940305	28	120b	K2406	333	10.7	1085	1025	1136
	64/94		121b	K2406A	297	10.2	1129	980	1180
			106b	K2407	119	11.6	1164	1140	1196

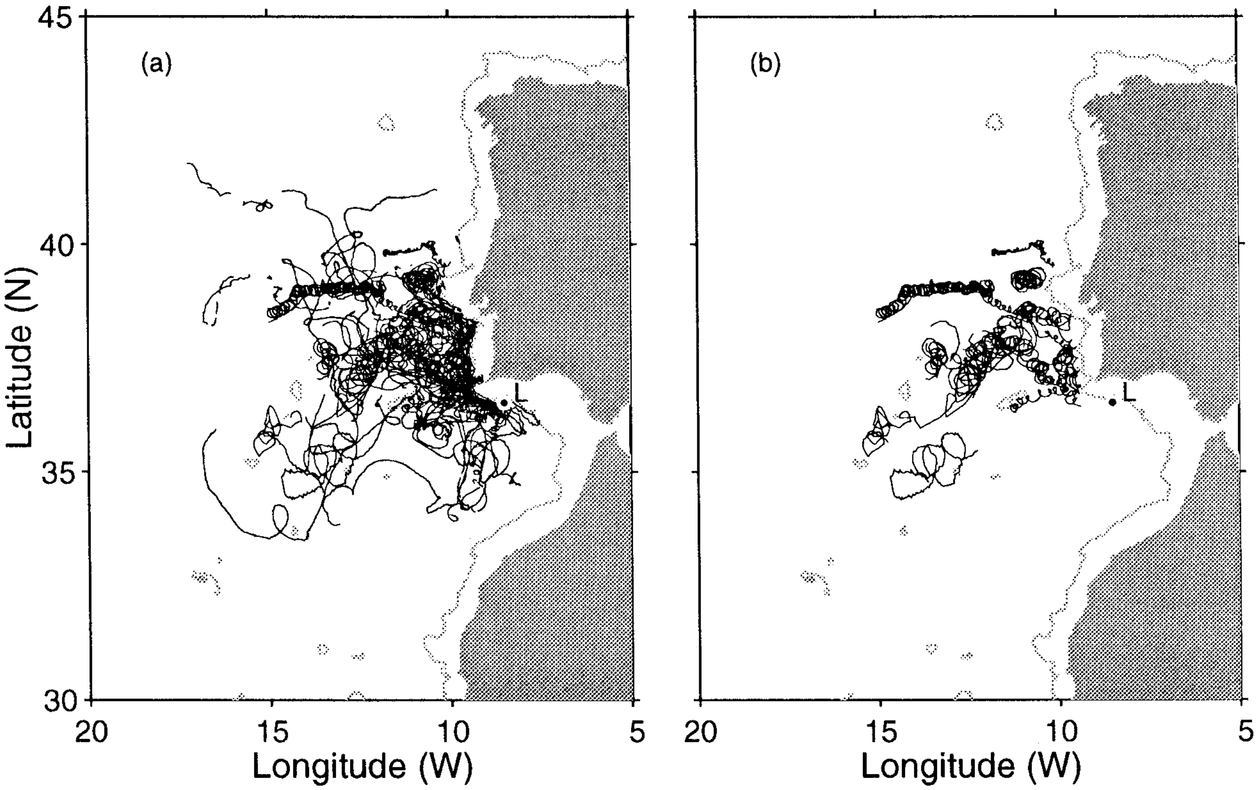

FIG. 5. (a) Spaghetti diagram of all 44 floats that returned useful data during AMUSE; (b) tracks of 14 floats that observed meddies. The 1000-m isobath is indicated by a gray line, and the float launch site is labeled with an "L."

nental slope of Portugal and immediately offshore, Fig. 1a. The slope varies in steepness and is deeply indented by several submarine canyons. The isobaths converge sharply in the region of Portimão Canyon and the float launch site, and the slope is quite steep between the launch site and Cape St. Vincent (5%–7%). It is interrupted along this path by the somewhat smaller Lagos Canyon. In the vicinity of Cape St. Vincent, the continental slope protrudes somewhat in a feature we call the Cape St. Vincent Spur, which forms the southern wall of the wide St. Vincent's Canyon. The slope is rather irregular and relatively broad north of St. Vincent's Canyon as far as about 38°N, where Lisbon and Setubal Canyons extend far into the slope. The slope then turns northwestward and steepens along the southern flank of Estremadura Promontory (also referred to, in previous works, as the Tejo or Tagus Plateau). The isobaths fan out at the western end of the promontory, then converge on the northern flank. Another deep canyon, Nazaré Canyon, is found north of the promontory.

Just offshore of the continental slope, there are a number of tall seamounts known as the Horseshoe Seamounts. In particular, Gorringe Bank, southwest of Cape St. Vincent, rises to within 25 m of the surface. Farther to the southwest, there are several peaks shallower than 1000 m.

3. Overview of float observations

To illustrate the scope of the float observations collected during AMUSE, the trajectories of all 44 floats that returned useful position data are shown in a spaghetti diagram, Fig. 5a. These observations span a 21-month period from May 1993 to March 1995. The length of each of the tracks varies from 2 to 333 days, with an average of 180 days. The spaghetti diagram is most representative of fluid particle pathways between 1000 and 1200 dbars, where 73% of the observations were made. About 18% of the measurements were made at pressures between 300 and 1000 dbars, and 9% between 1200 and 1400 dbars.

The floats were all launched within 10 km of 36.5°N, 8.5°W, and they dispersed over the region between 33° and 42°N, 7° and 17°W. The concentration of trajectories along the continental slope south of Portugal indicates that the majority of floats were initially advected westward from the launch site toward Cape St. Vincent. About 60% of the floats turned the corner at the cape within 30 days of being launched (many of them in much less time), and some continued drifting northward along the western continental slope of Portugal. Floats apparently left the western slope at various locations such that no floats were located along the boundary north of 40°N at the end of their missions. In addition

TABLE 2. Meddy float statistics.

Float	Dates in meddy (yearday/yr)	Meddy start location	Days in meddy (total days)	Mean P in meddy (dbars)	Mean T in meddy (°C)	Looping radius (km)	Looping period (days)
am103a	190–216/93	36.62°N 9.43°W	26 (30)	1144	12.3	9	3.0
am103b	51–116/94	37.51°N 11.61°W	65 (254)	1149	11.5	28	10.0
am104	1–23/94	38.37°N 9.97°W	22 (333)	1245	11.1	10–15	8.0
am110	201/93–164/94	36.68°N 9.34°W	328 (333)	1239	11.9	11	3.5
am114	57–121/94	39.05°N 10.51°W	64 (174)	849	12.3	20	7.0
am115	177–257/94	35.75°N 12.50°W	80 (203)	1075	10.8	40	21.0
am116a	200–211/93	36.71°N 9.43°W	11 (30)	1060	12.1	10	4.5
am118	312/93–70/94	39.55°N 10.15°W	126 (204)	1006	11.9	3	3.0
am120b	287/94–32/95	36.86°N 9.36°W	109 (333)	1067	11.9	13	4.0
am126b (same as 114)	77–127/94	39.26°N 10.73°W	50 (200)	1194	11.3	18	9.0
am126b (same as 129)	145–227/94	38.06°N 10.68°W	82 (200)	1166	10.9	∼35	24.0
am129	62–261/94	36.47°N 9.27°W	199 (206)	1171	12.1	14	4.5
am134	313/93–143/94	37.67°N 11.49°W	195 (297)	718*	11.6	27	11.0
am138	323–343/93	37.50°N 9.85°W	20 (216)	1082	11.9	19	6.5
am138*	57–87/94	38.80°N 10.30°W	30 (216)	1070	11.5	8	3.5
am166	27–38/94	36.85°N 9.48°W	11 (236)	1202	12.3	14	4.5

* Looping observed in TOA record only.

to the preferred pathway along the slope, another grouping of trajectories extends northwestward from Cape St. Vincent, suggesting that this is also a dominant pathway by which MW spreads into deeper water. Note also that some floats initially drifted away from the launch site toward the south and circulated in the Gulf of Cadiz.

The presence of both coherent and incoherent eddy structures is revealed in the tangle of trajectories west of the Iberian Peninsula. Fourteen floats exhibited the rapid and/or persistent anticyclonic looping characteristic of meddies. They are listed in Table 2 and plotted in Fig. 5b just for the period when they were looping. Ten of these floats were caught in nine separate meddy formation events, and one in a possible formation event. In addition, five of the floats were entrained into the periphery of preexisting meddies. Some floats were trapped in meddies for only a few cycles (e.g., am116a and am166, Table 2), while others traced out the path of a meddy for many months, like am110, which stayed with the same feature for 328 days.

Looping periods of the floats were less than 10 days except for am103b, am134, am115, and am126b (second meddy). The looping periods for these floats were significantly longer than the period of rotation associated with meddy cores (3–5 days), indicating that these floats were probably circulating near the edges of meddies. Note that two of the meddy floats, am114 and am134, were near the level of the undercurrent's upper core, with mean pressures of 814 and 726 dbars, respectively. In the next section, these trajectories are examined in more detail to illustrate where and under what circumstances meddies form.

4. Observations of meddy formation

a. Meddy formation sites

The identification of meddy formation events in the float data was generally straightforward. In previous experiments, where floats were launched directly into meddies, the floats exhibited a distinctive epicycloidal motion resulting from the rapid anticyclonic circulation of the meddies (azimuthal speeds ∼20–30 cm s^{-1} with looping periods of 3–10 days, depending on radius) su-

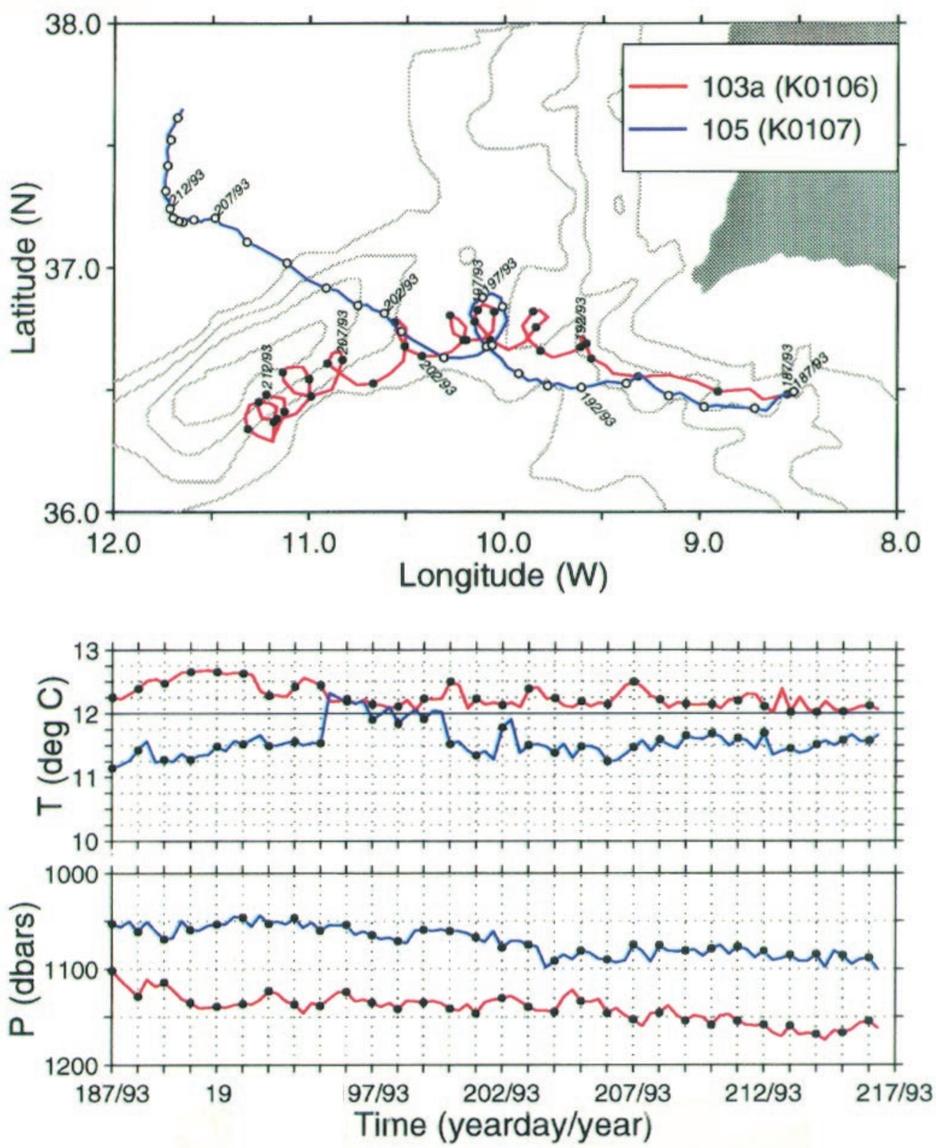

FIG. 6. Event 1: Trajectories of am103a (K0106, red) and am105 (K0107, blue) launched on 5 July 1993, yearday 186/93. All 8-h float positions are connected by line segments, and 24-h positions are indicated by circles along the track. Filled circles indicate where $T > 12.0°C$. Positions are labeled at regular intervals with the date in yearday/year. Gray lines show bathymetry contours every 1000 m from 1000 to 4000 m. Temperature and pressure along float tracks are shown in lower panels. Dots correspond to circles on float tracks.

perimposed on a relatively slow translation speed (~2 cm s^{-1}). These floats also observed the warm and uniform temperatures typical of the core fluid in meddies (Armi et al. 1989; Richardson et al. 1989). Using these results as a model, we identify meddy formation in the AMUSE data when the character of a float track changes abruptly from a straight or boundary-following flow, indicative of the Mediterranean Undercurrent, to the anticyclonic epicycloidal path characteristic of floats in the core fluid of meddies, accompanied by the warm temperatures characteristic of MW in the undercurrent (e.g., 12°C near the float launch site, Fig. 3). Figure 6 shows a typical example of meddy formation in the track of float am103a. We observed meddies to form most frequently near Cape St. Vincent, where six meddies originated. Three more meddies were observed to form near Estremadura Promontory. In the following, the common features of meddy formation at each of these sites are described and illustrated with specific examples. The objective here is to identify where meddies

TABLE 3. Floats in Cape St. Vincent meddies.

Event	Cruise	Date of float launch	Float number	Launch site	Mean T (°C) (3-day)	Mean P (dbars) (3-day)	Mean U (cm s^{-1}) (3-day)	Mean V (cm s^{-1}) (3-day)
1	K01	186/93	103a (M)	06	12.5	1120	−34.1	6.3
		(930705)	105	07	11.3	1060	−21.8	−0.5
2 and 3	K02	196/93	116a (M)	05	12.1	1050	−28.7	6.1
		(930715)	110 (M)	07A	10.8	1105	−22.8	2.1
4	K18	22/94	119	06A	11.8	1120	−35.6	6.5
		(940122)	166 (M)	07A	12.3	1175	−23.7	2.6
5	K23	57/94	115	05A	11.7	1110	−25.3	0.3
		(940226)	139	07	11.5	1110	−21.9	−1.7
			129 (M)	07A	11.7	1145	−13.8	−0.4
6*	K24	282/94	120b (M)	06	10.5	1045	−19.8	3.2
		(941009)						

* Meddy formed seven months after float was launched, when passed over launch site for second time.

form and to document the formation process, thus providing insight into the mechanism of meddy formation. Resolving the detailed dynamics of meddy formation is not possible using these float tracks and is not the focus of this work.

1) MEDDY FORMATION AT CAPE ST. VINCENT

The float tracks that document the six definite meddy formation events at Cape St. Vincent are shown in the top panels of Figs. 6–10, and the relevant float information for each event is listed in Tables 2 and 3. Time series of temperature and pressure data along the tracks are shown in the lower panels of each figure. For the first 30 days after deployment, daily positions are marked along the colored float tracks with symbols that are keyed to temperature (filled circles indicate T ≥ 12°C). Along the track, positions are marked with the date in yeardays followed by the year (e.g., 94 is 1994). The time series show only the first 30 days of temperature and pressure data, except in Fig. 10 where 60 days of data are plotted. As noted earlier, the warmest whole degree at the level of the lower core at the float launch site is 12°C (Fig. 3), so we have chosen this as a reference temperature in the following discussion. Cruise and station numbers are given after float numbers to provide easier cross-reference. For example, am103a is equivalent to K0106 for *Kialoa II* cruise 01 and station 06.

The first five meddy formation events at Cape St. Vincent (Figs. 6–9) were observed in the tracks of floats deployed on *Kialoa II* cruises K01, K02, K18, and K23, spanning the time frame July 1993 to February 1994. In these five events, meddy formation was observed less than 10 days after the floats were launched. On the other hand, event 6 (Fig. 10) was observed in the track of am120b seven months after it was launched, when the float made its *second* passage along the continental slope south of Portugal. After its first transit from the launch site to Cape St. Vincent, it was deflected southward within the Gulf of Cadiz. It circulated slowly around the gulf and eventually returned to Portimão Canyon, where it passed almost directly over the launch site, accelerated rapidly downstream in the undercurrent, and revealed the formation of a new meddy just northwest of Cape St. Vincent.

The six formation events have several characteristics in common. First, the floats that ended up in meddies (referred to henceforth as meddy floats) were advected rapidly westward from the launch site along the continental slope south of Portugal and started looping just after they passed the Cape St. Vincent Spur. Zonal speeds averaged over the first three days after launch ranged from 34 cm s^{-1} [event 1, am103a (K0106)] to 13 cm s^{-1} [event 5, am129 (K2307A)] (Table 3). Even faster downstream speeds, on the order of 50 cm s^{-1}, were briefly measured by some floats along this path. In events 1 and 5 (Figs. 6 and 9), the looping started southwest of the spur, while in events 2, 3, 4, and 6 (Figs. 7, 8, and 10), the meddy floats followed the slope around the spur and began their epicycloidal motion northwest of that feature.

A second common characteristic of all six events is that the meddy floats measured temperatures greater than or equal to 12°C when they were looping. This contrasts with floats that did not end up in meddies, which observed gradually decreasing temperature as they drifted away from the Portuguese continental slope. Interestingly, three meddy floats observed temperatures *below* 12°C *before* they started to loop, that is, am110 (K0207A, Fig. 7), am129 (K2307A, Fig. 9), and am120b (K2406, Fig. 10). The most dramatic example is am110 (Fig. 7), which was launched at 1100 dbars and measured an initial temperature of 10.6°C. The XBT section from K02 (not shown) indicates that am110 was launched in a temperature minimum layer between two warm cores of MW. Am110 was advected rapidly westward with a mean zonal speed over the first three days of about 23 cm s^{-1}. At the spur, this float curved anticyclonically and entered St. Vincent's Canyon. Tem-

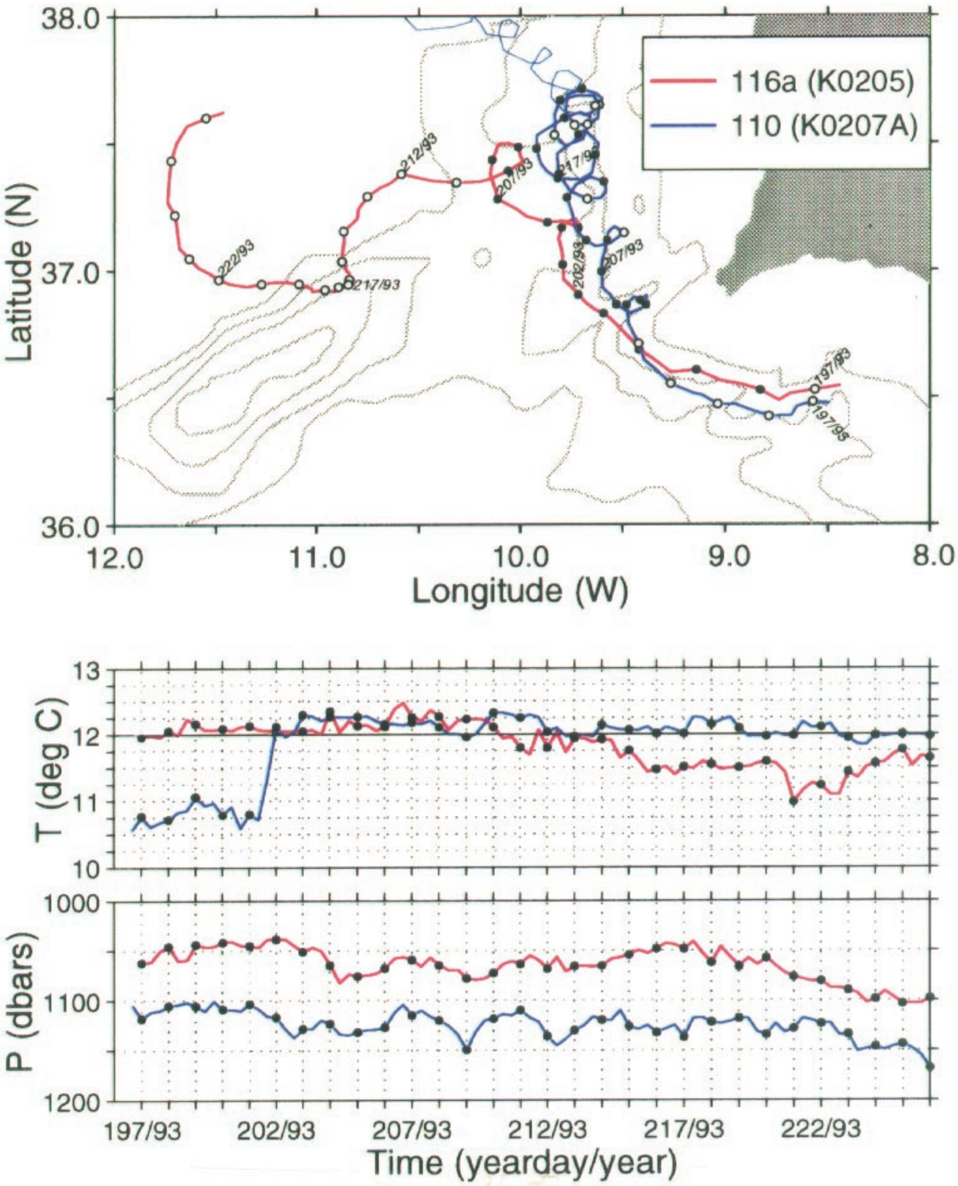

FIG. 7. Events 2 and 3: Same as in Fig. 6 but for am116a (K0205, red) and am110 (K0207A, blue) launched on 15 July 1993, yearday 196/93. Only the first 30 days of temperature and pressure data for am110, corresponding to highlighted part of the track in the upper panel, are shown.

perature increased sharply from 10.7° to 12.1°C over a 16-h interval on yearday 201/93, just as am110 turned into the canyon. The float made two small loops in the canyon, then looped northward along the slope with a rotation period of about 3.5 days, trapped in a newly formed meddy.

The rapid rise in temperature observed by this float as it entered St. Vincent's Canyon suggests that either the cool layer or filament within which am110 was embedded mixed quickly with warmer MW as the float entered the canyon, or vertical motion brought warmer water to the level of the float, which maintains constant pressure.

In two of the six formation events, the meddy floats looped for only a few cycles, am116a (K0205, Fig. 7) and am166 (K1807A, Fig. 8). These floats measured temperatures above 12°C starting at the launch site and continuing during repeated looping motion, suggesting that they were initially in the core fluid of new meddies. Just before the floats stopped looping, temperature fluctuated markedly by as much as 0.5°C, then decreased slowly to background levels (around 11°–11.5°C) after

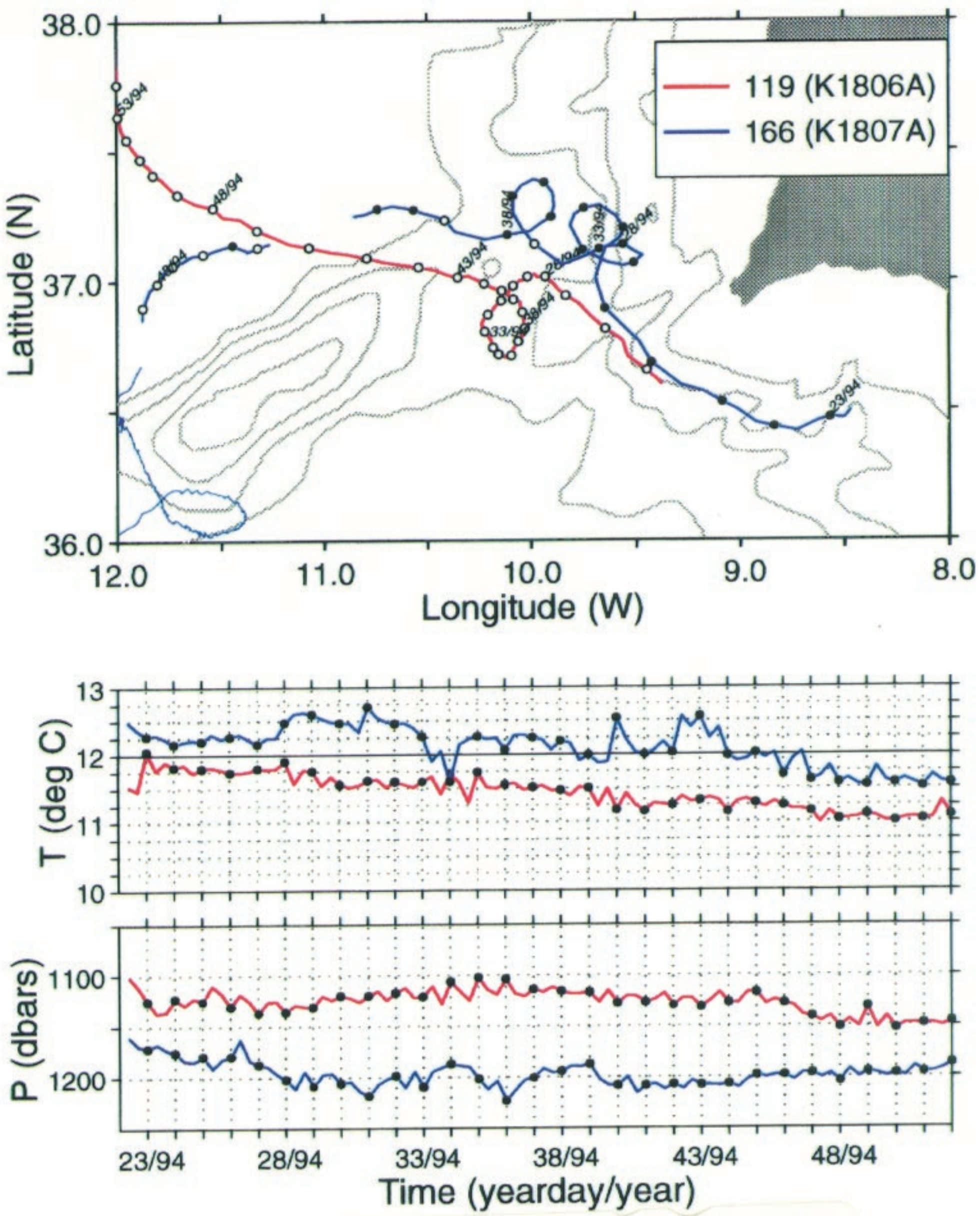

FIG. 8. Event 4: As in Fig. 6 but for am119 (K1806A, red) and am166 (K1807A, blue) launched on 22 January 1994, yearday 22/94. Note that the first few days of am119's trajectory are missing due to poor acoustics.

looping stopped. Since the floats stopped looping, the long-term fate of these meddies is not known. They may have been destroyed by interaction with other meddies, other eddies, the undercurrent, or topography.

A third feature of these six meddy formation events is that there is no obvious correlation between launch position (or offshore distance at launch) of the floats and the likelihood of ending up in a meddy. Floats that ended up in meddies were deployed at different stations between 05, the farthest inshore float launch station, and 07A, the second most offshore station. Furthermore, in three of the first five formation events, of the two or three floats deployed on the cruise, it was the float launched at the offshore position that ended up in a newly formed meddy (events 3, 4, and 5: Figs. 7, 8, and 9). In the other two formation events, the float launched at the inshore position (events 1 and 2: Figs. 6 and 7) revealed the meddy formation (see also Table 3).

Although the details of the undercurrent's velocity structure at the time the floats were launched are not known, in the three former cases the mean zonal speed during the first three days after launch (listed in Table

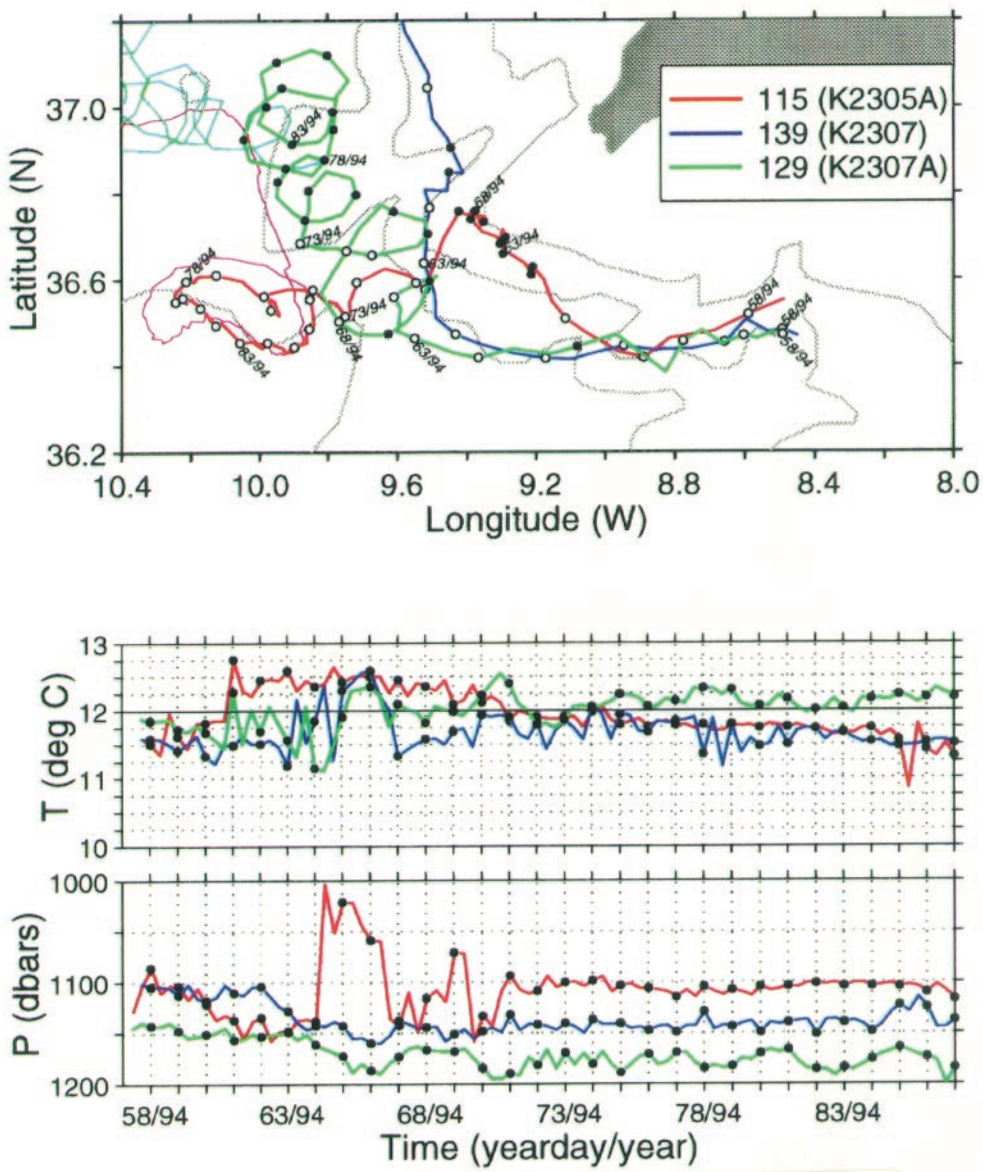

FIG. 9. Event 5: As in Fig. 6 but for am115 (K2305A, red), am139 (K2307, blue), and am129 (K2307A, green) launched on 26 February 1994, yearday 57/94. Note change in scales in upper panel compared to previous figures.

3) was less for the offshore floats, suggesting that they were on the cyclonic side of the undercurrent [am110 (K0207A), am166 (K1807A), am129 (K2307A)]. A notable example is am129, which ended up in meddy formation event 5. This and two other floats were launched along the XBT section, but only am129, launched farthest offshore and advected downstream more slowly than the inshore floats, ended up in a meddy near the cape (Fig. 9). Figure 11 shows a time sequence of four-day track segments of these three floats. Dots along the tracks indicate where the floats observed temperatures greater than or equal to 12°C. Floats am115 (red), am139 (blue), and am129 (green) were deployed at stations 05A, 07, and 07A, respectively, spanning a total distance of about 6 km. All three floats were initially between 1100 and 1150 dbars (Fig. 9, pressure time series), and all observed temperatures less than 12°C for the first several days of their missions (Fig. 9, temperature time series). As am115 crossed the entrance to Lagos Canyon, Fig. 11a, it curved northwestward and onshore. Its temperature increased to over 12.0°C after it crossed the 2000-m isobath. It stalled near the 1000-m contour at the spur on about yearday 63/94, Fig. 11b, and its pressure record shows an abrupt shoaling of more than 100

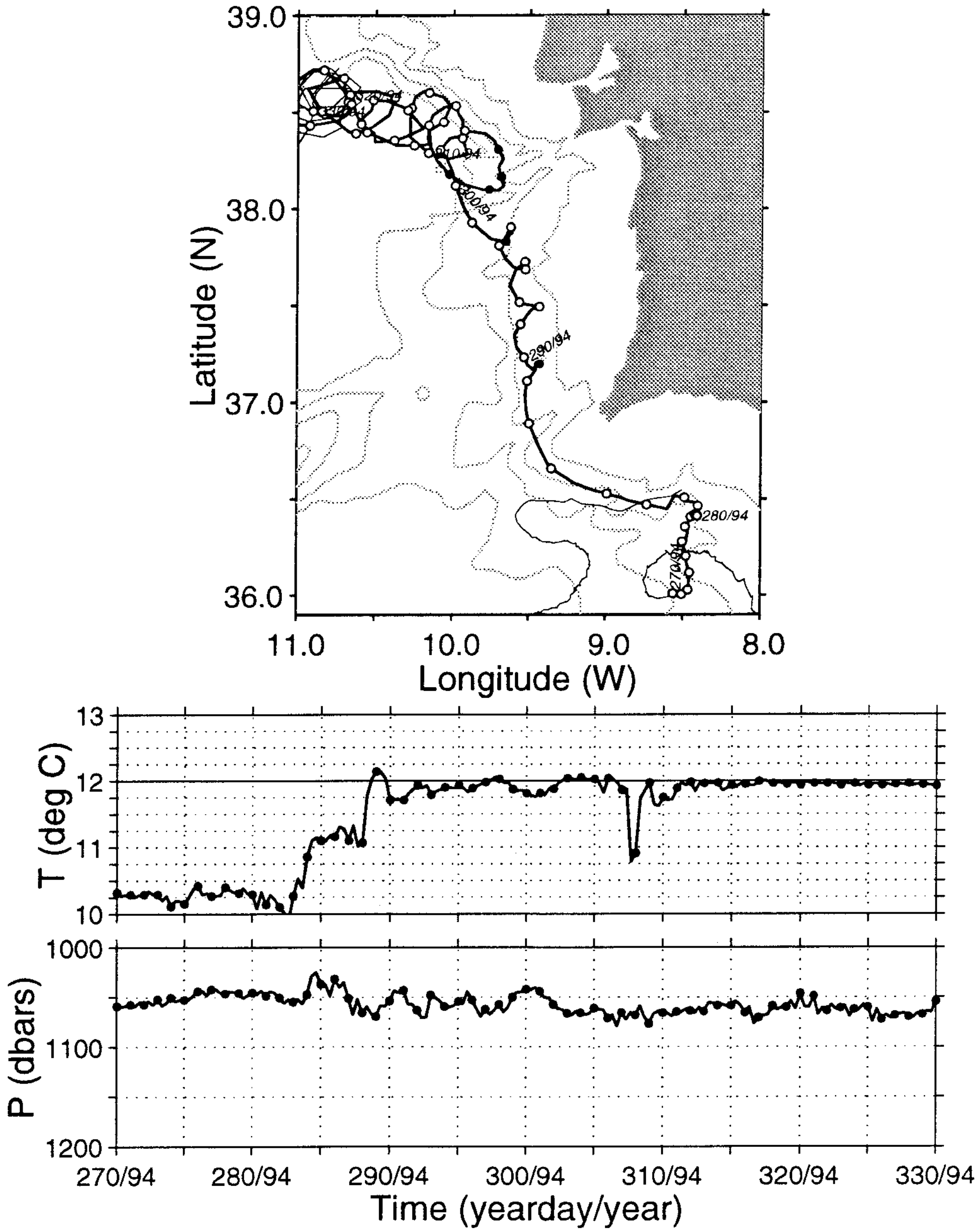

FIG. 10. Event 6: As in Fig. 6 but for am120b (K2406) launched on 5 March 1994, yearday 64/94. Highlighted track and temperature and pressure shown for 60 days starting on yearday 270/94.

dbars, Fig. 9, suggesting that the float may have come in contact with the seafloor.

Meanwhile, am139 and am129 were advected more toward the west-southwest, and am129 started to occasionally observe temperatures greater than 12°C on yearday 61/94. At about 9.3°W, am139 veered anticyclonically toward the north and crossed the entrance to St. Vincent's Canyon between yeardays 63 and 66/94 (Figs. 11b,c). Its temperature increased to greater than 12°C while it was in the vicinity of the canyon. Float am129 did not follow am139 but started looping anticyclonically on yearday 63/94, Fig. 11b. Its temperature continued to fluctuate above and below 12°C until yearday 74/94, when the float started its third loop and temperature stabilized above 12°C. While am129 was making the second loop, am115 was swept off the slope in a series of cyclonic cusps, its temperature dropping below 12°C once it left the slope, Fig. 11d. Float am129 continued to loop in a newly formed meddy as it drifted first northwestward, then southwestward.

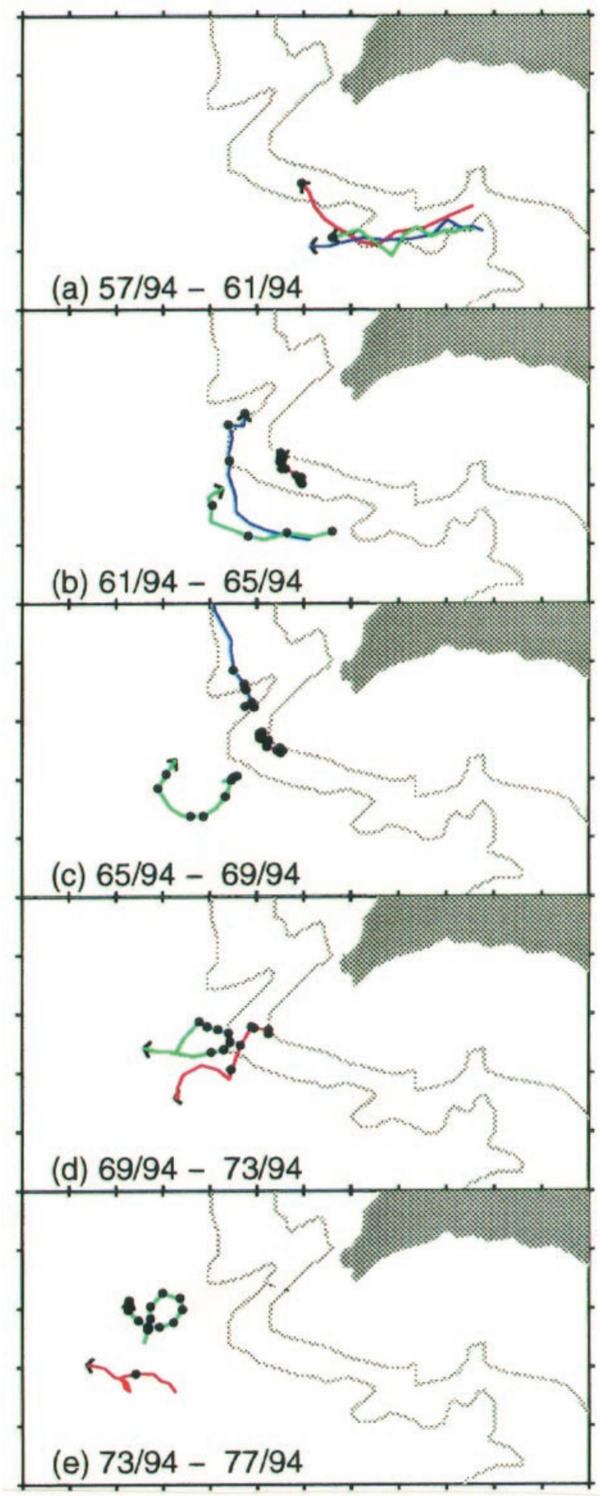

FIG. 11. Time sequence of four-day track segments for the three floats deployed on K23, showing meddy formation near Cape St. Vincent. Floats shown are am115 (K2305A, red), am139 (K2307, blue), and am129 (K2307A, green). Am129 ended up in the core of meddy whereas the other two did not. Area shown is the same as in Fig. 9. Sequence starts on yearday 57/94 and continues for 20 days. Dots along the tracks indicate where the floats observed T $\geq$ 12.0°C. The 1000-m and 2000-m isobaths are indicated by gray lines.

The above example also illustrates a fourth characteristic that was common to some degree in all the formation events, which is a minimum in float speed just before the onset of anticyclonic looping. Figure 12 shows float speed as a function of time for the first 20 days for each of the six meddy floats. The heavy vertical line indicates approximately when each float started looping (the exact time of formation cannot be determined from these single float tracks). The deceleration is particularly evident in the tracks of am103a between yeardays 189 and 191/93 (Fig. 12a) and am110 between yeardays 201 and 203/93 (Fig. 12c), and am129 between yeardays 62 and 66/94 (Fig. 12d) (refer also to Figs. 6–10). In these examples, float speed dropped from about 20 cm s^{-1} or greater to 10 cm s^{-1} or less just before, or as, looping began. Less dramatic decelerations were observed in the other formation events, particularly that involving am166. Some of these floats looped around the meddies at speeds comparable to their advection rate in the undercurrent (e.g., am110), whereas others had looping speeds that were somewhat less than their speed in the undercurrent (e.g., am103a).

Finally, one of the most surprising features of the formation events observed at Cape St. Vincent was how quickly the newly formed meddies were advected away from the formation site, thus terminating the formation process. The lack of synoptic observations during the formation events makes it difficult to determine exactly the limits of the formation process, but the float tracks give some information on approximately how long it took the meddies to form. For example, the meddy floats passed from boundary-following flow to anticyclonic looping, indicating that formation was underway, in about 3–7 days (measured as the time for the float to make the first loop). Furthermore, during or after the float made its first loop, the meddies were advected away from the formation site, indicating the termination of the formation process. This was particularly evident in the case of events 1 and 6 (Figs. 6 and 10) and less evident in event 5 (Fig. 9).

Supporting evidence for a formation timescale on the order of several days comes from the fact that for all six formation events, only one float was caught in each meddy, and none of the floats launched on the previous or following cruises ended up in the same meddy. This puts an upper bound on the formation time of about one week, the nominal deployment period. It also seems clear that the formation process does not involve the whole undercurrent since there was not a single case where more than one of the two or three floats launched on the same cruise ended up in the same meddy even though they all passed the vicinity of the cape within a few days of the formation event.

We can summarize the characteristics of these six meddy formation events as follows: 1) meddies were observed to form just southwest or northwest of the Cape St. Vincent Spur in the tracks of floats that were advected rapidly westward from the launch site toward

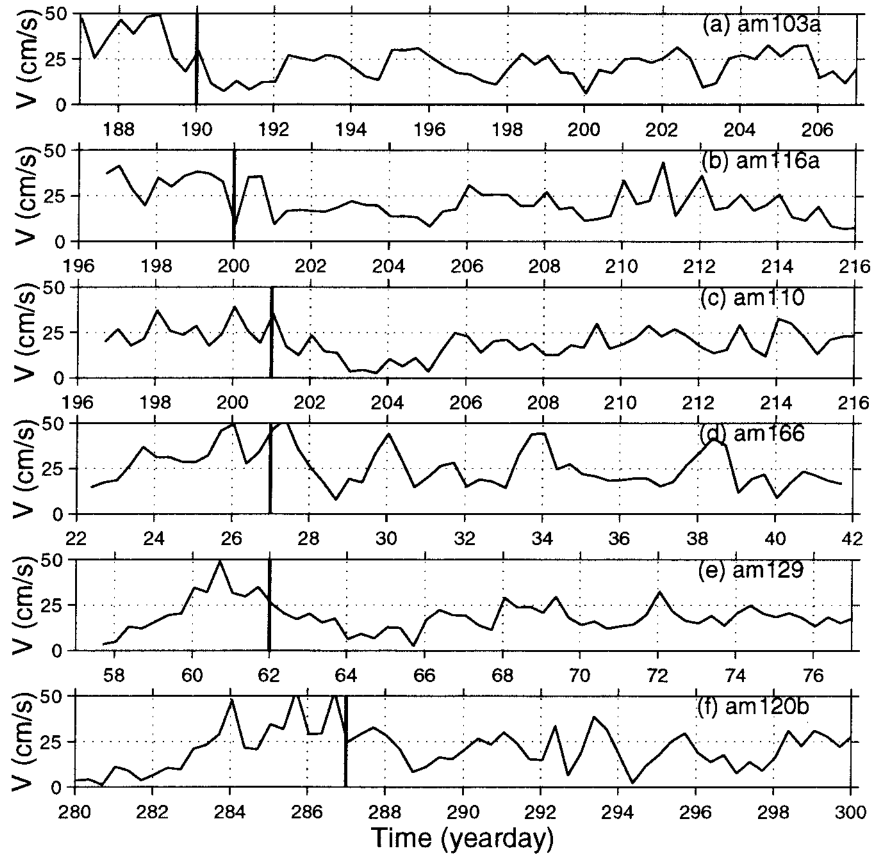

FIG. 12. Time series of float speed for six meddy floats during the first 20 days of each track. Heavy vertical lines indicate approximately when anticyclonic looping began.

the cape; 2) temperatures measured by the meddy floats while they were looping were greater than or equal to 12°C, although some observed significantly cooler temperatures before looping began; 3) there was no apparent correlation between launch position and the probability of a float ending up in a meddy, and about half of the meddy floats were launched at the more offshore deployment site on their respective cruise, apparently in the cyclonic shear zone of the undercurrent; 4) to some degree, the meddy floats appeared to slow down before the onset of anticyclonic looping; and 5) the timescale for meddy formation at Cape St. Vincent was on the order of several days to one week, possibly constrained by the drift of the meddy away from the formation site.

2) MEDDY FORMATION AT ESTREMADURA PROMONTORY

Some of the floats launched in the Mediterranean Undercurrent south of Portugal rounded Cape St. Vincent and drifted northward along the western Portuguese slope. Four of these floats revealed the formation of three meddies in the vicinity of the Estremadura Promontory, a major westward protrusion of the continental slope centered at about 39°N (see Fig. 1a). The three formation events occurred between November 1993 and February 1994. Figures 13–15 show the tracks of the floats that revealed these formation events along with their temperature and pressure time series. The tracks are of varying length, and temperature is not indicated along the tracks. Positions are marked with a dot every five days rather than every day as in the previous figures.

These float tracks are similar to those shown earlier in that they illustrate the transition from a boundary-following flow to anticyclonic looping with periods characteristic of meddies, but they differ in several ways. First, the temperatures measured by the floats while they were looping were consistently less than those observed in the meddies formed at Cape St. Vincent. This is not surprising since the properties of the undercurrent are modified by mixing along its path, making it cooler and less saline. Second, one meddy observed near the promontory did not drift away from the formation site, but stayed near the slope for at least several months, blocking the northward progression of MW along the slope. Since the formation events at the promontory are few in number and quite different from

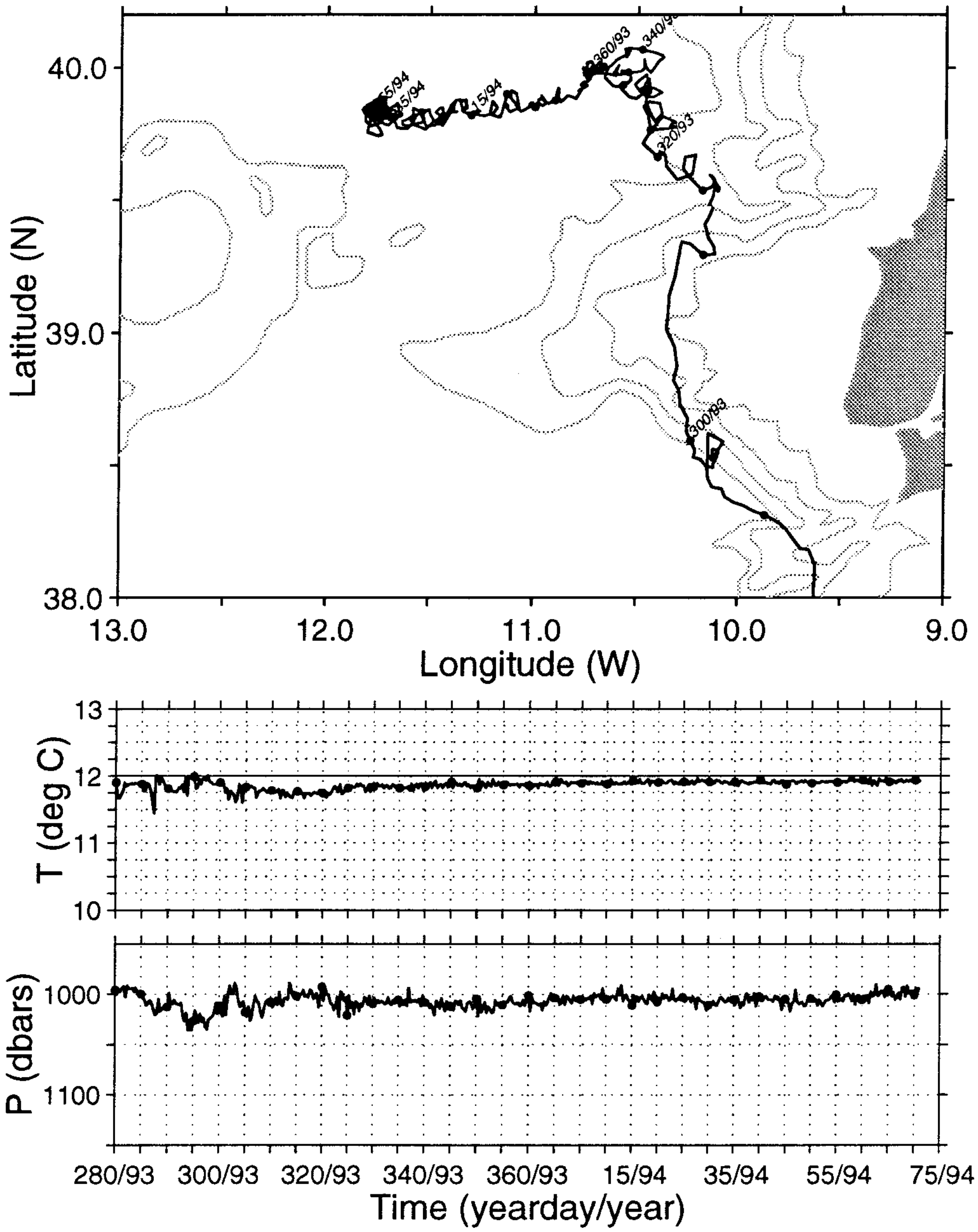

FIG. 13. Portion of trajectory of am118 (k0506) launched on 4 September 1993 yearday 247/93. Dots indicate position (but not temperature) at 5-day intervals and the 1000–4000-m isobaths are also plotted. Temperature and pressure records along the float track are shown in lower panels.

one another, these features are illustrated through a brief description of each event.

The first event was revealed in the trajectory of am118, Fig. 13, which was launched on yearday 247/93 at about 990 dbars. After yearday 280/93, am118 was being advected rapidly northward, then around the western side of Estremadura Promontory, reaching a maximum speed of about 30 cm s^{-1} on yearday 303/93. Where the slope turns sharply eastward, forming the northern flank of the promontory and the southern wall of Nazaré Canyon, the float decelerated and exhibited first irregular motion, then anticyclonic looping as it drifted slowly northward across the entrance of Nazaré Canyon. The irregular shape of the loops is due to the fact that their radius is of the same order as the tracking accuracy, 2–3 km. The period of looping was about three days, consistent with what would be expected for a meddy core.

The temperature record along this float track (Fig. 13) shows more variability while the float was south of the

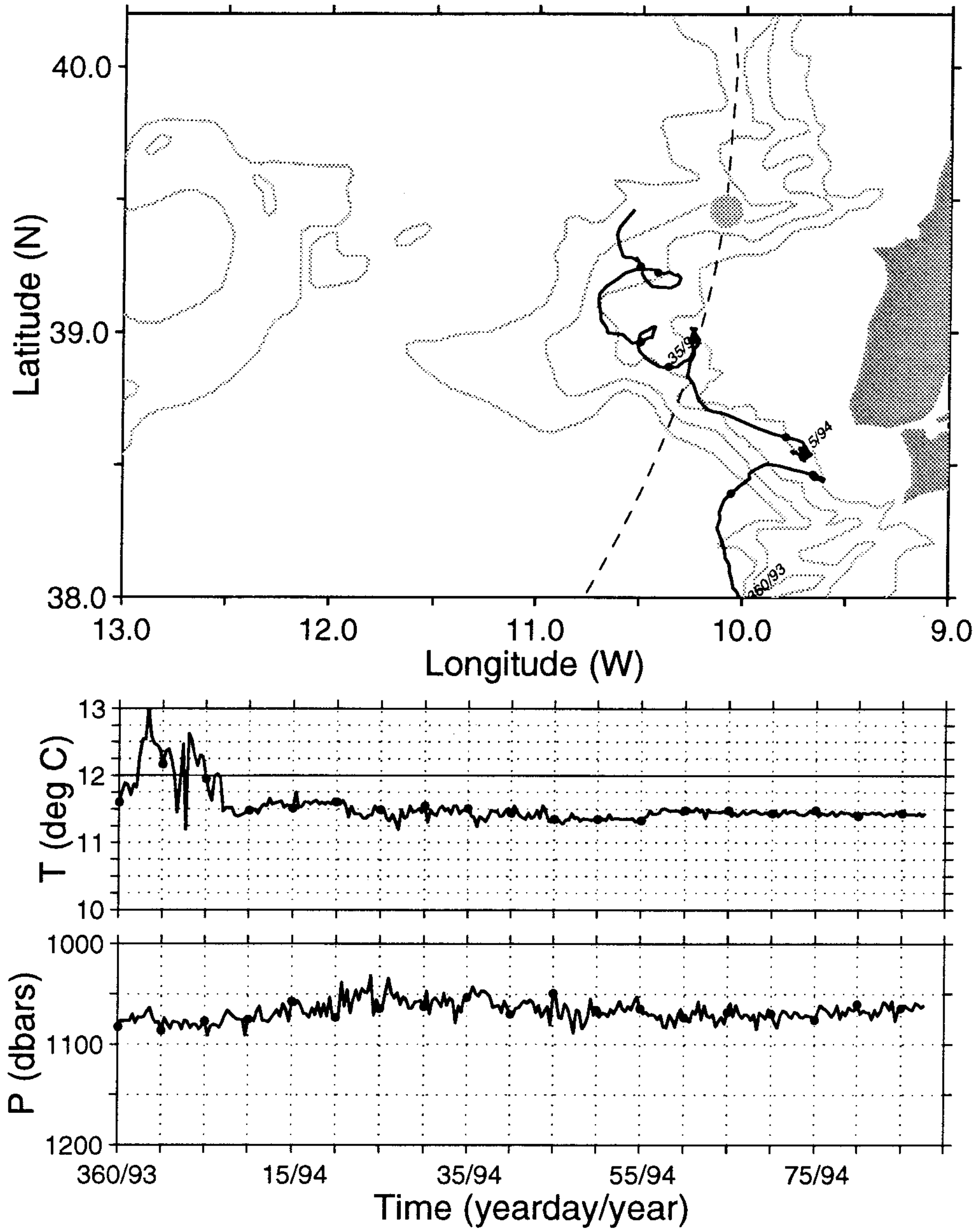

FIG. 14. As in Fig. 13 except for am138 (K0407) launched on 28 September 1993, yearday 240/93. Dashed curve shows range from sound source as described in the text. Shaded circle indicates hypothetical meddy position on yearday 57/94.

promontory, fluctuating between 11.5° and 12.0°C. At about the time that the float started to loop, around yearday 310/93, high-frequency temperature variability decreased and temperature slowly increased to about 11.9°C.

The next float to reach Estremadura Promontory was am138, Fig. 14, launched at 1060 dbars. This float rounded Cape St. Vincent, then circulated back and forth along the western Portuguese slope for several months before reaching the promontory. On yearday 25/94, it was drifting rapidly along the southern flank of the promontory at maximum speed ~30 cm s^{-1}. As it passed the southwestern corner of the promontory, it curved sharply northward and made three anticyclonic loops as it traveled along the western edge of the promontory. On yearday 54/94, acoustic signals from all but one sound source were lost when the float moved to the northern flank of the promontory. The TOA (time of arrival) record from the one audible sound source (located at 40°N, 15°W), Fig. 16, shows that after the last

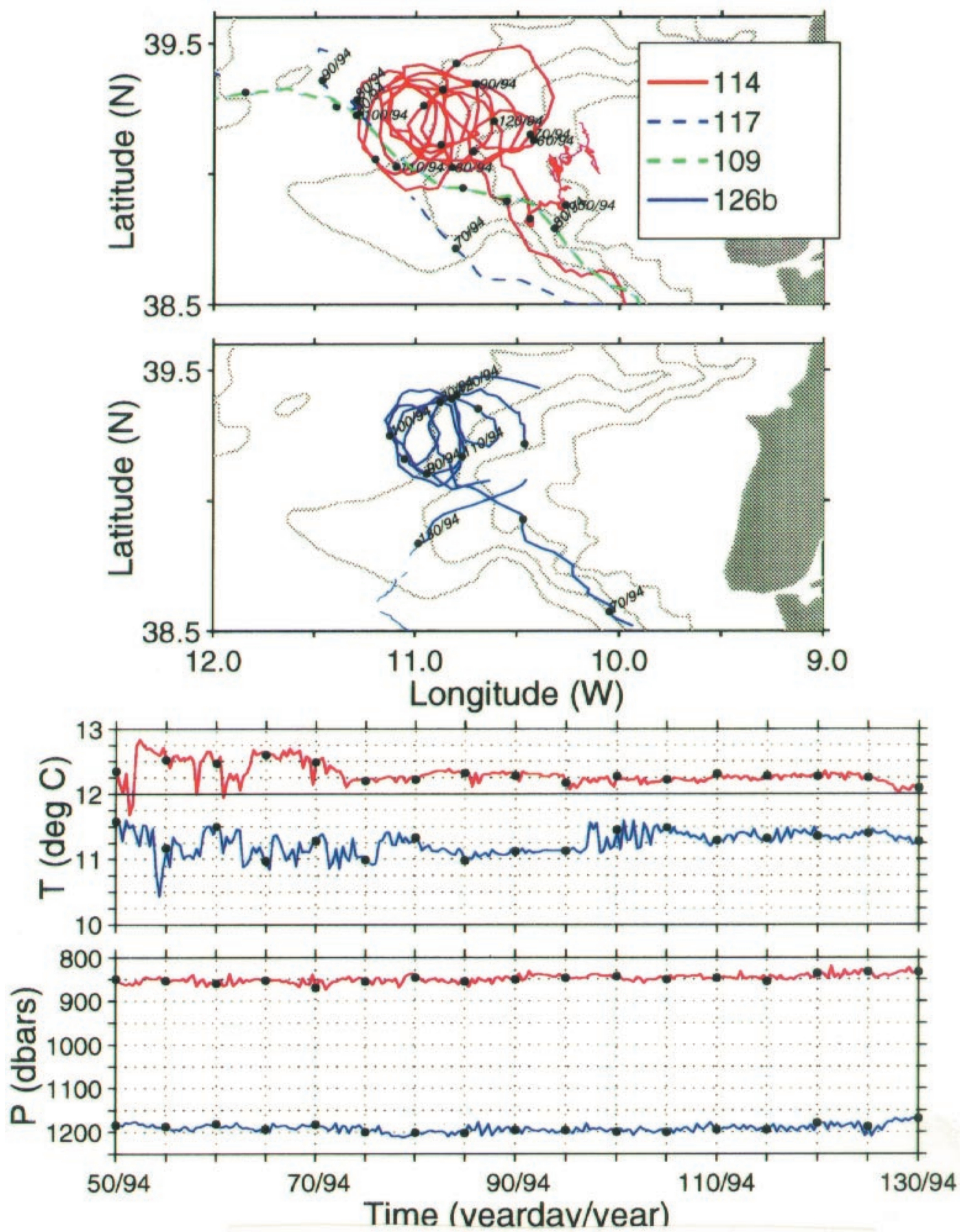

FIG. 15. Trajectories of am114 (K1505A, red), am117 (K1905A, dashed blue), and am109 (K1407A, dashed green) are shown in the upper panel, highlighted during time period 50/94 through 130/94. Dots are plotted every 5 days along tracks. Am126b (K2006A, blue) is shown in second panel during same time period. Temperature and pressure along float tracks am114 (red) and am126b (solid blue) only are shown in lower panels.

position was obtained on yearday 54/94 (indicated by solid vertical line), am138 moved rapidly away from the source (generally eastward), drifting about 52 km in 2.6 days (~23 cm s^{-1}). On yearday 57/94, this movement away from the source stopped and the float started oscillating toward and away from the source with a period of about 3.3 days and a peak-to-peak amplitude of 15 km. These characteristics are consistent with what would be expected if the float were looping in a meddy.

Float am138's temperature fluctuated from 11.2°C to 13°C before it reached the promontory. On yearday 55/94, just before looping began, temperature increased stepwise by about 0.2°C to 11.5°C, providing further evidence that this float ended up in a meddy near Nazaré

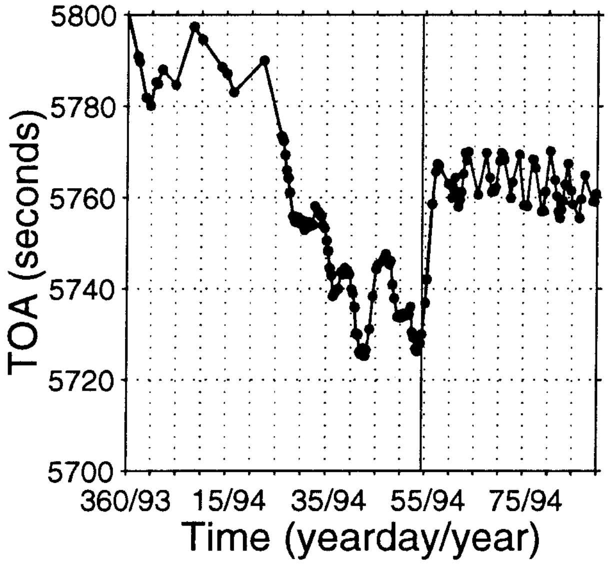

FIG. 16. Time series of time of arrival (TOA) from sound source located at 40°N, 15°W as observed by am138. Dots indicate actual observations. Vertical line at yearday 54/94 indicates time of last position (see text). TOA is measured in elapsed seconds from 0000 UTC.

Canyon. A hypothetical position for this meddy, with diameter 15 km, has been plotted in Fig. 14 along the appropriate range circle from the sound source at its point of closest approach to the last known position of am138.

The third formation event at the promontory, revealed most clearly in the track of am114, Fig. 15 (red track), was unusual in that it involved a meddy that remained adjacent to the slope for at least several months. Float am114, ballasted for 850 dbars, drifted rapidly northward along the western Portuguese slope at speeds as high as 40 cm s^{-1}. Just after the float passed the western protrusion of Estremadura Promontory, it started looping anticyclonically with a period of about seven days. Temperature fluctuated over 1°C along the slope south of the promontory and during the first few loops, then leveled out at about 12.3°C on yearday 75/94, after the third loop (note that maximum upper core temperatures are generally warmer than for the lower core, see Fig. 3).

At about that same time, a second float approaching the promontory from the south, am126b, started looping anticyclonically in the same location with a period of about nine days (blue track in second panel of Fig. 15). This is noteworthy because am126b was at a pressure of about 1200 dbars, 350 dbars deeper than am114. This indicates that this meddy spanned the depths of both the upper and lower cores of the undercurrent. Like am114, am126b observed relatively uniform temperature while it was looping, although considerably cooler, at about 11.1°C.

Just after am126b started looping, the meddy apparently drifted slightly westward for about one month, then back toward the slope. Around yearday 125/94, after circulating within the meddy for more than two months, am114 stopped looping and stalled near the 1000-m isobath at the western edge of the promontory, Fig. 15, upper panel. Three or four days later, am126b also stopped looping. In both cases, temperature slowly decreased by several tenths of a degree after the floats stopped looping.

Both of these floats made the transition from boundary-following flow to anticyclonic looping at different pressures (850 and 1200 dbars). Their periods of rotation were relatively long, particularly in the case of the deeper float, am126b. This combined with the cool temperatures observed by am126b suggest that at least the deeper float was probably entrained into the periphery of an existing meddy revealed by am114. The fate of this meddy is not completely clear, but both floats stopped looping when the meddy was close to the slope, suggesting topographic or undercurrent interaction.

The presence of this meddy against the slope may have important implications for the continuity of the undercurrent around Estremadura Promontory. Several floats that approached the promontory from the south while the meddy was next to the slope were deflected away from the slope into deeper water. Two of them, am117 (dashed blue) and am109 (dashed green), are shown in the upper panel of Fig. 15.

b. Conditions for meddy formation

In this subsection, we focus on the well-sampled meddy formation site near Cape St. Vincent to examine the conditions under which meddies are most likely to form. Figure 17 shows the first three days of all the floats, arranged by cruise number, OC and K01–K24. Line styles indicate the level of the float: in the lower core ($P > 1000$ dbars, solid line) or above the lower core ($P < 1000$ dbars, dashed). The five floats that ended up in a meddy formation event at Cape St. Vincent on their first pass are designated with an ''M.'' Keep in mind that the deployment cruises were not all evenly spaced in time.

One of the most striking features in this figure is the low-frequency variability in both initial pathways and speed of the floats over the course of the experiment. For example, the first two deployments on K01 and K02 (July 1993) showed rapid westward flow speeds (faster than 20 cm s^{-1}) at the lower core level compared to the six-month period that followed (K03–K16; August 1993 to January 1994). Although the sampling in the lower core was not very consistent during this six-month period, the floats that were deployed at that level (on K04, K09, K12, K13, and K16) all indicated weaker westward flow than that observed during K01 and K02. The most anomalous pathways in the lower core were observed on K16, when am100 drifted due south during the first three days of its mission, and am108 made a cyclonic loop in Portimão Canyon. Variability was also observed at the level of the upper core. Weak *eastward* flow was observed shallower than 1000 dbars by am123 and am125, launched on K03, while on K05 and K14, relatively rapid downstream speed was observed above 1000 dbars.

The anomalous pathways observed in the lower core on K16 were followed in the next two weeks by rapid downstream flow, revealed in the tracks of am128 (K17), am119, and am166 (K18). The westward advection of floats moderated somewhat over the next two weeks (K19 and K20), then am167 indicated a return to faster speeds, and the remaining floats observed downstream advection similar to what was observed during K01 and K02.

These tracks seem to indicate that meddies form at Cape St. Vincent when the undercurrent is flowing strongly westward. To examine this tendency more quantitatively, the mean east velocity component, averaged over the first three days of each float track, and mean temperature and pressure, are plotted as a function of time in Fig. 18. Data points with open circles denote floats launched in the lower core (mean pressure greater than 1000 dbars), and those marked with an x indicate the floats that ended up in meddies at Cape St. Vincent.

The time series of mean eastward velocity, Fig. 18a, shows quantitatively the low-frequency variations in zonal speed of the undercurrent off southern Portugal during AMUSE. The floats deployed on K01 and K02 measured westward speeds greater than 20 cm s^{-1}, which was not observed again at the level of the lower core until K17. Zonal speed decreased to less than 20 cm s^{-1} on K19 and K20, then increased again for the rest of the experiment. The first four meddy floats (launched on K01, K02, and K18) all had three-day mean westward speeds greater than 20 cm s^{-1}. Float am129 (K23), which revealed the fifth formation event, measured a mean zonal speed of only 13 cm s^{-1}, but the two other floats launched on the same cruise showed westward speeds in excess of 20 cm s^{-1}. Based on these results, a downstream speed greater than about 12 cm s^{-1} in the undercurrent south of Portugal appears to be a necessary condition for meddy formation at Cape St. Vincent. We note that it is not a sufficient condition, however, since not all the floats that observed rapid downstream speeds in the undercurrent were trapped in meddies. In at least one such case, involving the floats launched on K24, this may have been because all three floats were deflected southward at the cape due to the presence of the meddy that formed just a week earlier (am129, K23; see also Fig. 17).

The time series of mean temperature, Fig. 18b, shows again that two of the meddy floats measured mean temperatures below 12°C before they ended up in meddies, even though temperature observed in the meddies was above 12°C. This figure also reveals that there were about 10 floats that measured mean temperatures greater than 12°C for the first three days of their mission that did not end up in meddies at the cape.

Figure 18d shows the launch position of each float measured in kilometers from the northernmost float launch station, 05. Comparing this figure to Fig. 18a, it seems apparent that there is no obvious correlation between mean float speed and launch site, and a plot of mean zonal velocity as a function of along-section distance (not shown) bears that out. There is considerable scatter in mean zonal velocity at each launch site and no visible trend, indicating that the observed variability in the float speeds is primarily due to temporal variability in the undercurrent and not to differing launch positions.

This panel also shows the lack of correlation between float launch site and the chance of a float ending up in a meddy, as mentioned previously. Furthermore, there does not appear to be a strong relationship between distance offshore *downstream* of the launch site and meddy formation, as illustrated in Fig. 19. Here we show a superposition of the first 30 days of the 32 floats that were near the level of the lower core ($P > 1000$ dbars). The tracks of the five floats that ended up in meddies at Cape St. Vincent are highlighted. In three of these cases, the floats followed the slope quite closely westward from the launch site (+s) and around Cape St. Vincent's Spur. But there were a number of other floats that also followed this path that did not end up in meddies. Also, in two cases, floats that ended up in meddies followed a more offshore path as they were advected westward toward Cape St. Vincent's Spur. Thus, proximity to the slope does not appear to be a necessary condition for a float to end up in a meddy.

5. Other meddy observations

Five other meddies were observed during AMUSE when floats were entrained into their peripheral regions, and the float tracks that best reveal these features are shown in Fig. 20 and listed in Table 2. These observations are differentiated from the meddy formation events because the floats did not observe the persistently warm and uniform temperatures that are characteristic of meddy cores while they were looping, and in most cases, the period of looping was relatively long (≥10 days; see Table 2). The time for which the float was circulating around the meddy is indicated in Fig. 20 by the thicker track line. In two cases (Figs. 20a and 20d), looping began in the region just north of Gorringe Bank, and the tagged meddy drifted southwestward toward (am103b) and even through (am134) the gap west of the bank. Tracking of am134 was not very good through the gap, and it is possible that this float left one meddy and was entrained into a different one. Am138 (Fig. 20b) made a few loops around a meddy along the slope north of Cape St. Vincent, and observed fluctuating temperature as it did so, suggesting that it was not in the core fluid of the meddy. Am104 also made a few loops

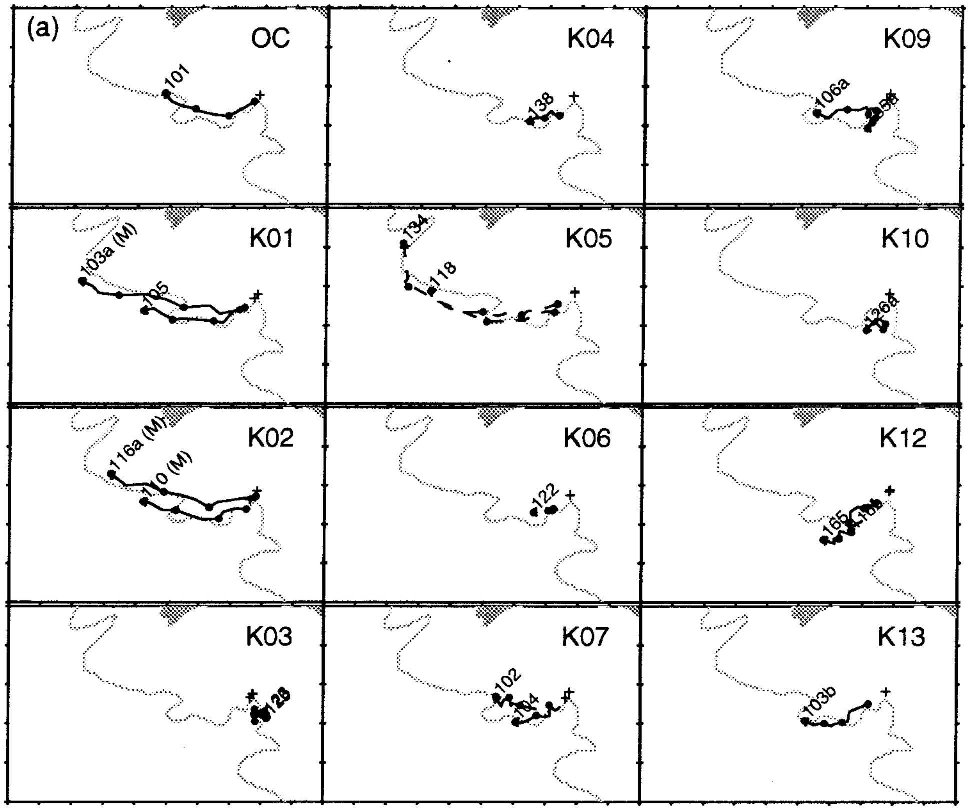

FIG. 17. First three days of each float trajectory for floats launched on one *Oceanus* and 22 *Kialoa II* cruises. Dashed lines indicate floats shallower than 1000 dbars, and dots on float tracks indicate daily positions. The +s show launch positions of floats. The 2000-m isobath is shown for reference. Area plotted is 36°–37.2°N, 8°–10°W.

starting along the southern flank of Estremadura Promontory. Coincidentally, this meddy was also surveyed hydrographically and tracked with deeply drogued surface drifters (Pingree 1995). Another meddy may be present northwest of the promontory at the end of am104's track. Finally, am115 circulated very slowly anticyclonically around a meddy in the vicinity of the Horseshoe Seamounts. From these and the previously described observations of meddies, it appears that floats ended up in the cores of meddies only along the continental slope, and not in deep water away from the slope.

6. Discussion

a. Frequency of meddy formation

The sequential float seeding in AMUSE was designed to directly measure the rate at which meddies form. The irregular sampling caused by the technical problems with the floats has made this calculation more uncertain, but some new results have nonetheless emerged. For the purposes of estimating a formation rate, we conditionally sampled the dataset and considered only the 32 floats that were deployed at the level of the lower core ($P \geq 1000$ dbars) that remained submerged for at least 30 days (see Table 1). Of these 32 floats, 5 ended up in the cores of meddles near Cape St. Vincent (am103a, am116a, am110, am166, and am129). We do not include the sixth formation event, involving am120b, because it took place many months after am120b was launched, representing a different sample. Based on these numbers, there is about a 15% probability that a float in the seeded portion of the undercurrent will end up in a meddy near Cape St. Vincent. Three additional floats ended up in meddies near Estremadura Promontory, indicating about a 10% probability that a float in the undercurrent south of Portugal will end up in a meddy near the promontory. Since floats were deployed more or less throughout the year, these percentages represent annual averages.

To convert the percentages to formation rates, an estimate of the time between independent samples is needed. In section 4, it was shown that the timescale of meddy formation is on the order of 3–7 days. From this we estimate that the time between independent sampling periods is about 5 days. Since there was no occasion on which more than one float ended up in the same meddy, we consider all the floats to be independent samples, which leads us to an estimate of the meddy formation rate at

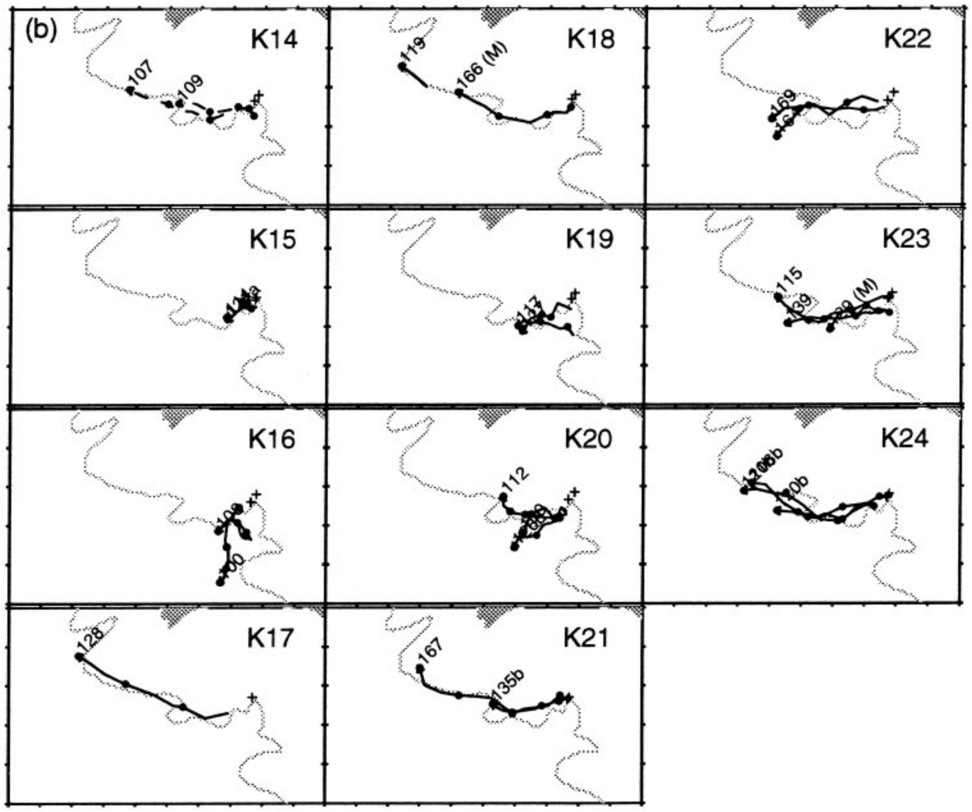

FIG. 17. (*Continued*)

Cape St. Vincent of about 10 meddies per year. Similarly, at Estremadura Promontory, we estimate a formation rate of about seven meddies per year.

This direct estimate of the annual meddy formation rate, totaling about 15–20 meddies per year, is larger than the 8–12 estimate of Richardson et al. (1989), which was based on an estimate of about 24 coexisting meddies in the area bounded by 20°–36°N, 15°–30°W with lifetimes of 2–3 years.

Another feature of meddy formation that emerges from the AMUSE results is the variability in the time between formation events, most strikingly at Cape St. Vincent. In Fig. 18d, one can see that three meddies formed in rapid succession starting on yearday 190/93 [revealed by am103a (K01), and am116a and am110 (K02)], with an average time between events of about eight days. On the other hand, only two meddies were observed to form during the second half of the deployment period [revealed by am166 (K18) and am129 (K23)], separated by about 35 days, at a time when the sampling was regular. Some of this variability is probably caused by variability in the speed of the undercurrent, as discussed in section 4. Also, the time between formation events may be influenced by how quickly a newly formed meddy moves away from the formation region, thus allowing another meddy to form. As discussed previously, one meddy remained adjacent to Estremadura Promontory for several months (see Fig. 15), deflecting the undercurrent offshore, and perhaps preventing subsequent formation events. Also, the fifth formation event at Cape St. Vincent, revealed by am129, resulted in the southward deflection of all three floats deployed a week later on K24 when they reached the cape (see Fig. 17).

b. Meddy formation mechanisms

The float data collected during AMUSE have revealed some basic features of the meddy formation process. Meddy formation occurs where the continental slope curves away to the right (facing downstream), causing at least some part of the undercurrent to separate from the boundary. Near Cape St. Vincent, the slope turns through more than 90° at the Cape St. Vincent Spur due to the presence of the deep and wide St. Vincent's Canyon to the north. Near Estremadura Promontory, a preferred meddy formation site seems to be located at the northwestern corner of the promontory, which is also sharpened by the presence of Nazaré Canyon. It is not clear if the canyons themselves, or headlands and promontories, are critical to the formation process. In events 1 and 5 at Cape St. Vincent (Figs. 6 and 9), meddy formation took place southwest of the spur, apparently not influenced by St. Vincent's Canyon. On the

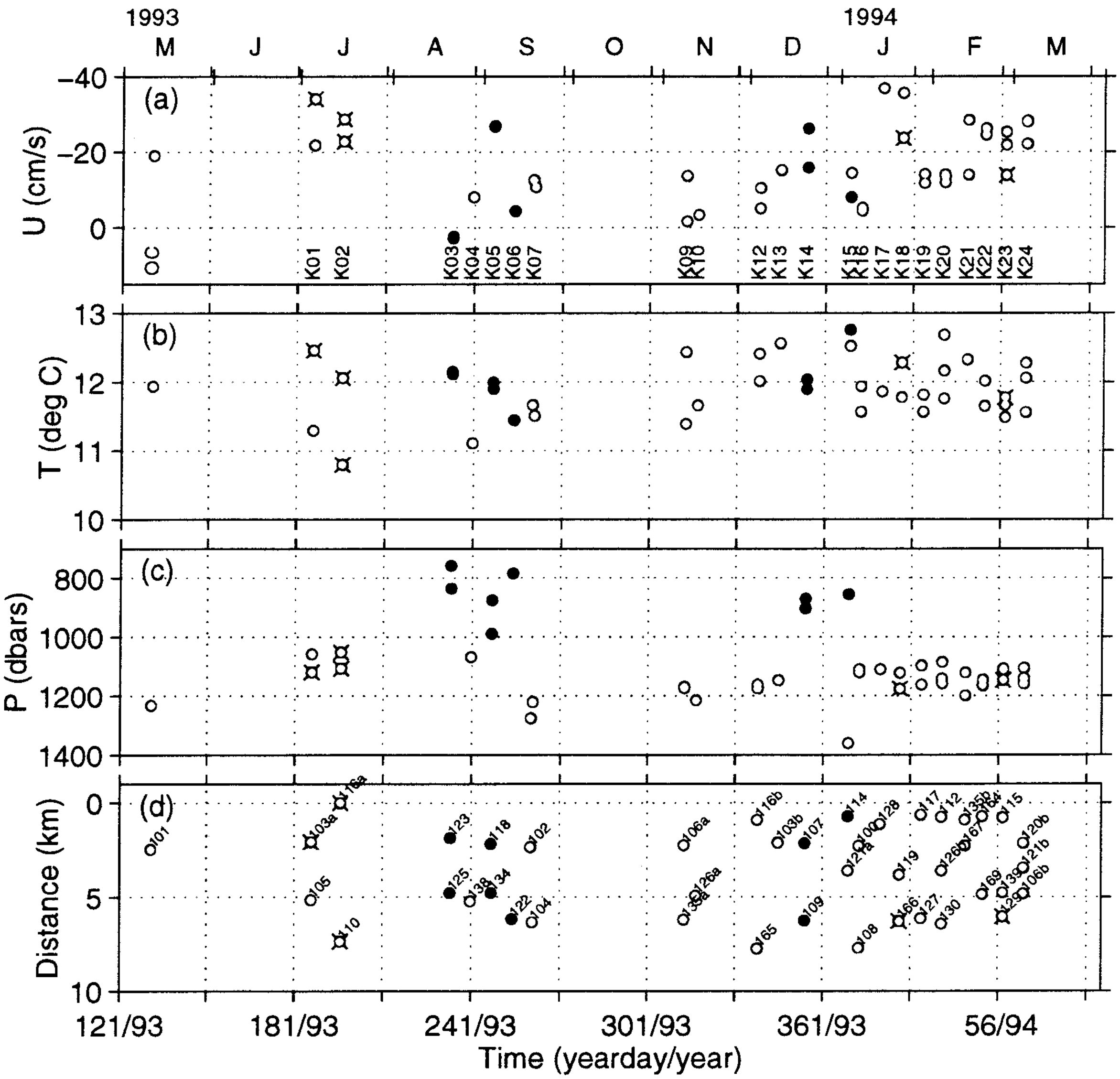

FIG. 18. (a) Time series of average zonal velocity measured by each float during first three days after launch as a function of time. Unfilled circles indicate floats near the level of the lower core (P > 1000 dbars) and x's mark the five floats that ended up in meddies; (b) 3-day mean temperature; (c) 3-day mean pressure; and (d) launch position measured as distance from northernmost float launch site, 05. Float numbers are also indicated. The +'s along the top axis of (a) indicate month boundaries.

other hand, in event 3 (Fig. 7) am110 rounded the spur and circulated anticyclonically in St. Vincent's Canyon for several days before looping northward in a new meddy.

The separation of the undercurrent and subsequent meddy formation observed in the float data are at least qualitatively consistent with D'Asaro's (1988) conceptual model of the formation of submesoscale coherent vortices (SCVs) in which the generation of anticyclonic vorticity in the frictional boundary layer of a coastally trapped jet leads to the formation of anticyclonic eddies downstream of a sufficiently sharp corner. This is fundamentally different from the formation mechanism that relies on vertical mixing (McWilliams 1985), rather than frictional torque, to generate the low potential vorticity source water for SCVs.

The AMUSE float data provide velocity observations in the undercurrent that, with certain assumptions about the velocity structure, can be used to estimate relative vorticity in the undercurrent upstream of the meddy formation site at Cape St. Vincent. In Fig. 21a, average velocity vectors computed over the first three days after launch are plotted for the floats deployed on K01, K02, K18, and K23, when meddies were observed to form near Cape St. Vincent. From this figure, and the numerical values listed in Table 3, it can be seen that on the five occasions when meddies formed at Cape St. Vincent just

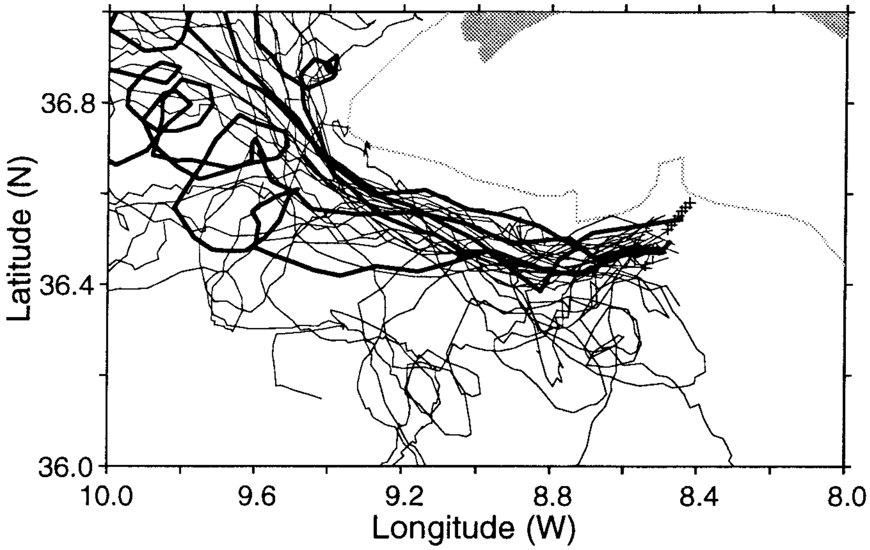

FIG. 19. Superposition of the first 30 days of tracks for 32 floats deployed at the level of the lower core of the Mediterranean Undercurrent ($P > 1000$ dbars). Tracks of the first five meddy floats are highlighted and the 1000-m isobath is also shown for reference.

after floats were launched, the float that was initially farther inshore was moving downstream faster than the offshore float(s), indicating that the latter were in a region of cyclonic shear. The position of the inshore floats relative to the cross-stream velocity structure cannot be determined directly, but we can use the velocity observed by the inshore float to estimate a lower bound for the average anticyclonic shear between the float and the boundary by first difference, assuming that the downstream velocity goes to zero at the boundary, as illustrated in Fig. 21b. In all cases, the inshore float was about 10 km from the slope [defined as the 1000-m isobath (Figs. 6–9)] and anticyclonic shears are thus estimated to be between -3.5 and -2.5×10^{-5} s^{-1}, or $-0.4f$ and $-0.3f$, where f is the Coriolis parameter [event 6 (Fig. 10) was not considered since only one float was in the undercurrent just prior to the meddy formation].

The float observations also allow us to estimate relative vorticity in the meddies to compare with the above values. If we assume that the meddy floats were trapped in the cores of the meddies (justified by the warm and relatively homogeneous temperatures measured by the floats while they were looping), which are in solid body rotation (Armi et al. 1989; Prater and Sanford 1994), the relative vorticity at the level of the float is given by $2\omega = 4\pi/T$, where T is the looping period of the float. For the meddies formed at Cape St. Vincent, T was 3–5 days, corresponding to relative vorticities between -5.0 and -2.8×10^{-5} s^{-1} ($-0.6f$ and $-0.3f$). These results suggest that some or all of the anticyclonic vorticity of the meddies could come from anticyclonic shear in the undercurrent. As mentioned earlier, several floats launched farther offshore (am 110, am166, and am129), apparently in a region of cyclonic shear, still ended up in meddy cores. This emphasizes the complexity of the formation process.

We would expect that meddies formed by separation of a frictional boundary layer would have a core radius on the order of the width of the boundary layer, which we have estimated to be about 10 km. Although the size of the observed meddies cannot be determined exactly from single float tracks alone, there is some evidence to suggest that these meddies are considerably smaller than the ~50 km radius meddies observed away from the slope in the Iberian and Canary Basins (see, e.g., Armi and Zenk 1984; Armi et al. 1989). First, as mentioned in the previous section, only one of the two or three floats launched together was trapped in each of the formation events, even though the partner float(s) passed nearby (within ~10 km), suggesting that the meddies may have radii on the order of only 10 km larger than the looping radius of the floats, 8–15 km, for a maximum radius of 18–25 km. Second, in the first meddy formation event (Fig. 6) the meddy float (am103a) was looping at a radius of 9 km when its partner float, am105, was temporarily entrained into the same feature and made one complete loop. This float thus approximately defines the outer edge of the meddy at about 15 km, the radius of its one loop (Bower et al. 1995). The Cadiz Meddy (Prater and Sanford 1994), which was surveyed extensively with CTD and velocity profilers, had a core radius of 9 km. These values are of the same order as the width of the anticyclonic shear zone of the undercurrent estimated above.

The formation time for the meddies observed during AMUSE is relatively short compared to the 10–20-day estimate of Armi and Zenk (1984), but this is consistent with the smaller size of the AMUSE meddies. Armi and

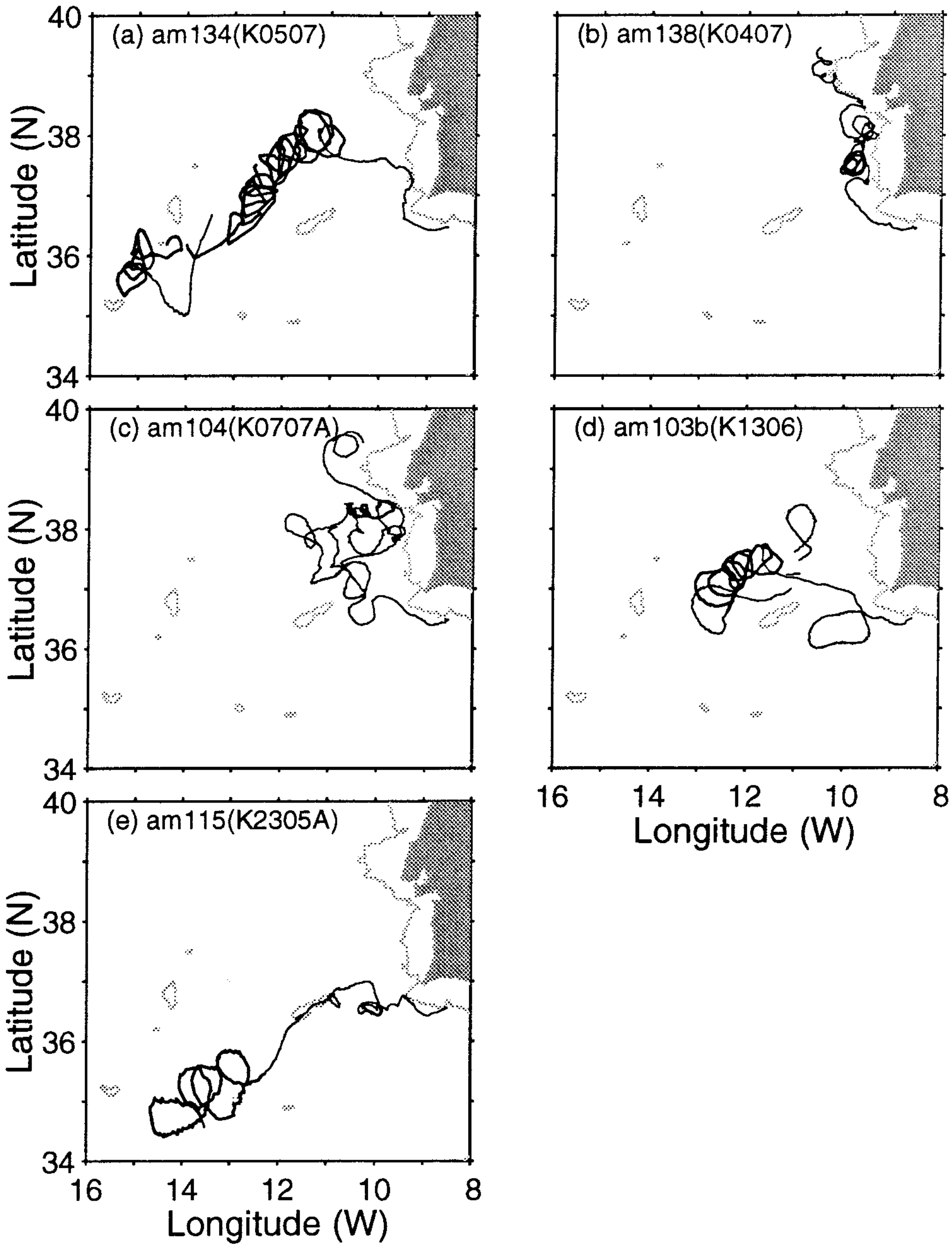

FIG. 20. Trajectories of five floats entrained into meddies during AMUSE: (a) am134 (K0507); (b) am138 (K0407); (c) am104 (K0707A); (d) am103b (K1306); and (e) am115 (K2305A). See Table 2 for statistical information.

Zenk's estimate represents the time necessary to generate a meddy of the size found in the Canary Basin from the MW volume transport in the Gulf of Cadiz, estimated to be 1.4–2.9 Sv (Sv ≡ 10^6 m^3 s^{-1}), depending on how much of the undercurrent was included. Using these values for the MW transport and the observed dimensions of meddies formed at the cape during AMUSE and the Cadiz experiment [radius ~15 km, thickness ~650 km (Prater and Sanford 1994)], we estimate that it would take only 1.1–2.3 days for a meddy to form, shorter than the 3–7 days that was observed. This suggests that even less of the undercurrent, about 0.5–1.1 Sv, is involved in meddy formation.

This analysis raises the question of how the larger meddies observed in the Canary Basin are formed. At least two possibilities exist. Either smaller meddies formed at Cape St. Vincent merge to form larger ones, as has been observed and modeled by Schultz Tokos et al. (1994), or

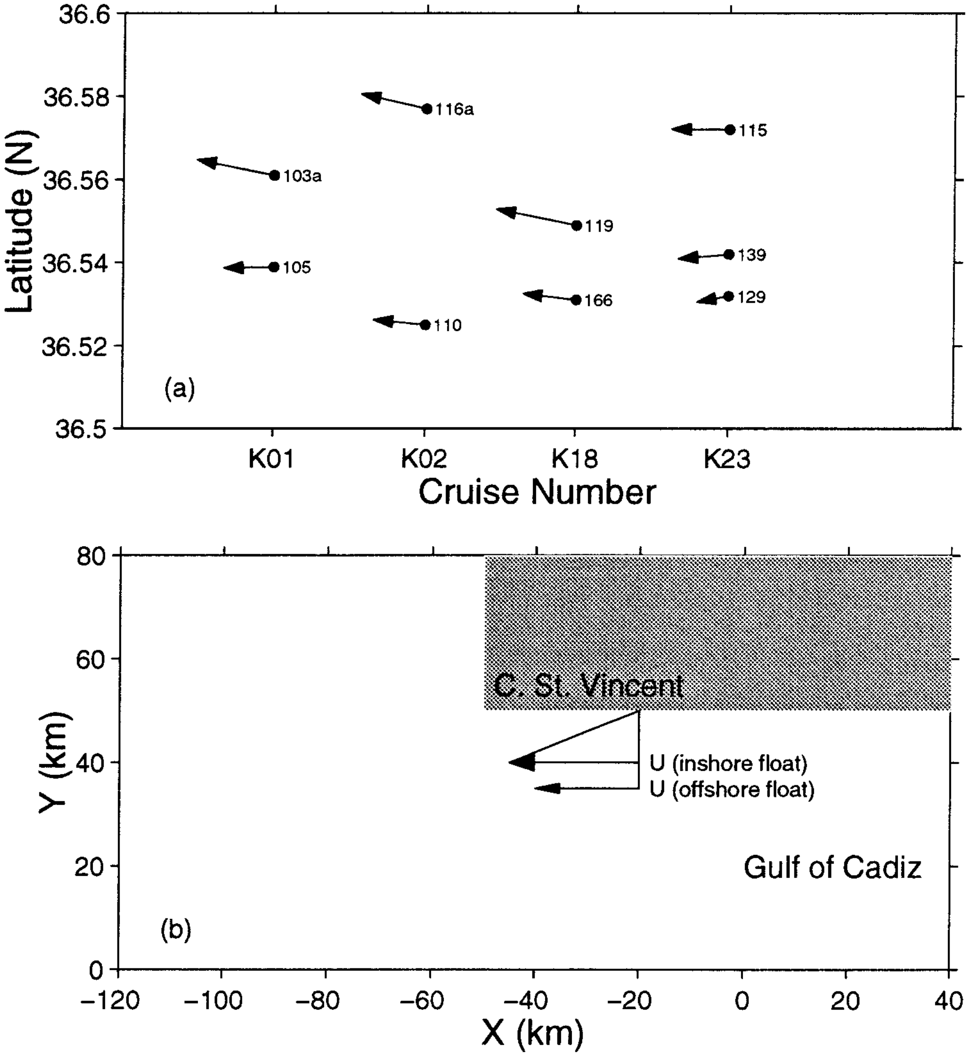

FIG. 21. (a) Mean velocity vectors measured over the first three days after the launch for floats deployed on K01, K02, K18, and K23 showing the relative speed of floats launched at different cross-slope positions. (b) Schematic view of the southwestern corner of the Iberian Peninsula and estimation of horizontal shear in undercurrent from float velocity observations. See text for explanation.

the larger meddies form at a site other than Cape St. Vincent. In the AMUSE data, the largest meddy was observed to form near Estremadura Promontory based on the track of am114, which looped in a meddy at a radius of about 20 km for almost two months (Fig. 15). Interestingly, this particular meddy never detached from the boundary during the observational period of AMUSE, but perhaps other large meddies form near the promontory and drift into the Iberian Basin.

7. Summary

A major field program, called A Mediterranean Undercurrent Seeding Experiment (AMUSE), was carried out to directly observe meddy formation and the spreading pathways of MW into the North Atlantic. Forty-nine RAFOS floats were deployed sequentially in the Mediterranean Undercurrent south of Portugal on 25 cruises between May 1993 and March 1994, accompanied by high-resolution XBT sections across the undercurrent. The floats were tracked acoustically for up to 11 months and position, temperature, and pressure data were collected three times daily. Forty-four trajectories were obtained, with an average length of 180 days, representing more than 20 float-years of data.

Nine meddy formation events were observed at two sites, one near Cape St. Vincent at the southwestern corner of the Iberian Peninsula, and the other near Estremadura Promontory, along the western Portuguese continental slope. In all cases, meddy formation seemed to be tied to specific locations along the slope where the coastline turns sharply to the right (when facing downstream), strong evidence that topography plays a critical role in meddy formation. Meddy formation was observed most frequently at Cape St. Vincent (six events). Considering only the floats that were successfully seeded in the lower core of the undercurrent, we have estimated that about 15–20 meddies form per year, assuming that each float represented an independent sample and that the time between independent sampling periods is about five days. Most meddies drifted away from their formation site within a few days of generation, transporting MW from the undercurrent into the North Atlantic. This implies a meddy formation timescale on the order of one week or less, less than the 10–20 days estimated by Armi and Zenk (1984) based on the volume of larger, Canary Basin meddies.

The float velocity observations revealed low-frequency (multimonth) variations in the speed of the Mediterranean Undercurrent south of Portugal, and meddies were observed to form most frequently when the current was relatively fast. Newly formed meddies that remained near the slope caused fluid particles approaching from upstream to be deflected off the slope, representing an indirect role of meddies in the spreading of MW away from the Iberian Peninsula.

Using the float velocities to estimate relative vorticity in both the undercurrent and the meddies formed at Cape St. Vincent, we found that much of the anticyclonic relative vorticity of the meddies could be accounted for in the anticyclonic shear zone of the undercurrent. This implies a formation mechanism most like that described by D'Asaro (1988), which relies on frictional torque along a boundary to generate the low potential vorticity found in the cores of submesoscale coherent vortices. Collapse and geostrophic adjustment of a vertically mixed water column injected into a stratified ocean, is probably not the principle mechanism at work in the formation of meddies at Cape St. Vincent.

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