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Direct evidence of meddy formation off the southwestern coast of Portugal

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Abstract—The formation of a Mediterranean Water eddy, or meddy, was observed directly for the first time off the southwestern coast of Portugal near Cape St. Vincent. The formation event is revealed in the 30-day trajectory of a RAFOS float deployed in the lower core of the Mediterranean Undercurrent in the Gulf of Cadiz. For the first several days after deployment, this float was advected westward in the Undercurrent at a speed of about 0.4 m s^{-1}, generally paralleling the topography. Just after passing Cape St. Vincent, where the coast turns abruptly northward, the float began looping anticyclonically, indicating that it had become trapped in the core of a new meddy. The meddy translated first westward, then southwestward along the southern flank of Gorringe Bank. The float rotated around the meddy center with azimuthal speeds of 0.20–0.25 m s^{-1} at a radius of about 10 km. The rotation period was on the order of three days, and the average translation speed of the meddy over 25 days was 0.08 m s^{-1}. Observations of this and four additional 30-day trajectories indicate (1) persistent westward flow of the Undercurrent along the south coast of Portugal, (2) a tendency for the lower core of the Undercurrent to separate from the continental boundary after passing Cape St. Vincent, and (3) evidence of anticyclonic looping west of Cape St. Vincent. These preliminary results confirm the speculation that the region off Cape St. Vincent is one site of meddy generation.

INTRODUCTION

Over the past 15 years, it has been increasingly recognized that coherent vortices play an important role in transporting water properties from source regions to the ocean interior (McWilliams, 1985). The relatively rapid azimuthal velocities associated with these eddies isolate the fluid inside, and inhibit mixing with the surrounding fluid. One of the best-known examples of such coherent vortices are Mediterranean Water eddies, commonly referred to as meddies. Since their initial discovery (McDowell and Rossby, 1978), these intrathermocline, rotating lenses of Mediterranean Water have been observed extensively in the eastern North Atlantic (see e.g. Armi and Zenk, 1984; Armi *et al.*, 1989; Prater and Sanford, 1994; Zenk *et al.*, 1992; Pingree and Le Cann, 1993). They vary in diameter from 20 to 100 km, and may contain fluid from one or both of the two cores that make up the Mediterranean outflow after it leaves the Strait of Gibraltar (Ambar and Howe, 1979a,b; Armi *et al.*, 1989; Pingree and Le Cann, 1993). Rotation periods of the core fluid range from two days (Prater and Sanford, 1994) up to 6–7 days (Richardson *et al.*, 1989).

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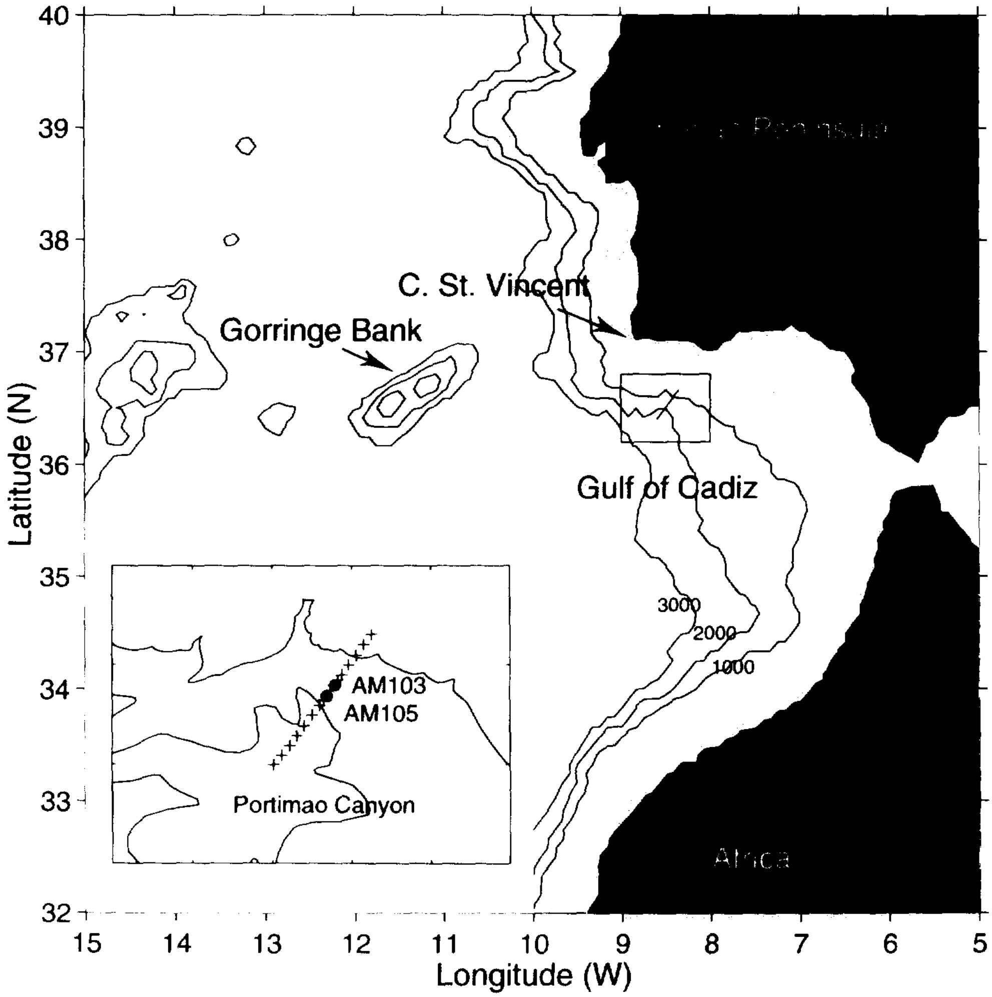

Fig. 1 Chart showing a portion of the Iberian Peninsula, the northwestern African coast and the Strait of Gibraltar. The small boxed region south of the Iberian Peninsula was the site of the AMUSE float deployments and XBT sections, and is enlarged in the inset to show the positions of XBT profiles (+) and launch sites for RAFOS floats AM103 and AM105 (solid circles) deployed on 5 July 1993. The 1000, 2000 and 3000 m isobaths are shown.

Although meddies vary somewhat in their physical characteristics, they are all similar in that their cores contain relatively warm and saline water of Mediterranean origin, which is several hundred meters thick and less stratified than the background fluid. This density structure supports an anticyclonic rotation that has been observed directly with floats and velocity profilers.

Our understanding of the structure and dynamics of meddies has steadily increased during the past decade, but some fundamental questions remain. In particular, where, how often, and by what mechanisms do meddies form? The water properties in the cores of meddies suggest that formation takes place along the coast of the Iberian Peninsula, where the Mediterranean Undercurrent flows along the continental boundary as a coherent,

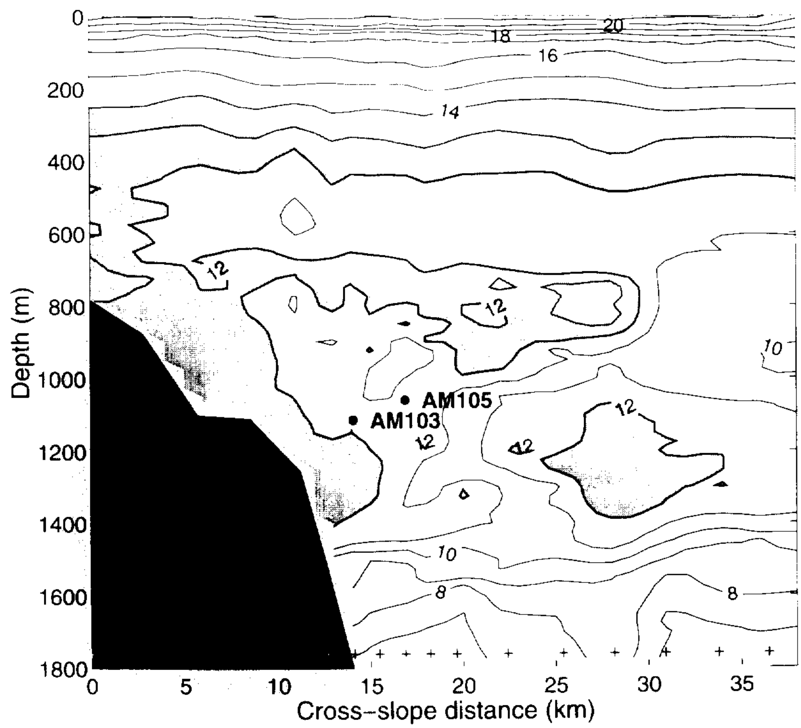

Fig. 2 Vertical temperature section from XBTs taken at locations shown in Fig. 1 inset. Contour interval is 1°C. The 12°C contour is darkened, and temperatures between 12 and 14°C are shaded. The two solid circles show the initial depths and cross-stream positions of AM103 and AM105. The locations of the XBT profiles along the section are shown by +'s at the base of the figure.

wall-bounded jet (Ambar and Howe, 1979a,b; Zenk and Armi, 1990; Daniault *et al.*, 1994). A number of mechanisms for meddy formation have been proposed (see review by Prater, 1992), but the cause of meddy generation has remained largely speculative since a formation event has not been observed directly.

A new experiment, called "A Mediterranean Undercurrent Seeding Experiment", or AMUSE, is underway to specifically address the issues of meddy formation and the spreading of Mediterranean Water away from the Iberian peninsula. Between May 1993 and March 1994, 40 RAFOS floats were deployed in the Mediterranean Undercurrent south of Portugal (for a description of the RAFOS float system, see Rossby *et al.*, 1986). The floats were launched in pairs about every seven days in the lower core of the Undercurrent (1200 m) from a chartered research vessel, and tracked acoustically by an array of French, German and U.S. sound sources moored in the Iberian and Canary Basins. Position fixes, with accompanying temperature and pressure measurements, were made three times daily. Most of the floats were programmed for a one year mission, and data from these floats are currently being analyzed. However, trajectories of five floats deployed for 30-day missions have already been analyzed, revealing some new results that are the subject of this preliminary report.

PRELIMINARY RESULTS

The floats were deployed along a transect across the Mediterranean Undercurrent in the Gulf of Cadiz south of Portugal (Fig. 1). The transect is aligned perpendicular to the isobaths near the eastern edge of Portimao Canyon (inset Fig. 1). Deep (1800 m) expendable bathythermographs (XBTs) were deployed on each float deployment trip to locate the core of the Undercurrent, and to provide a time series of the temperature structure of the Undercurrent over the period of the float launchings. During the first several cruises, the XBTs were deployed at 2.8 km intervals beginning at the 800 m isobath and extending about 40 km offshore (Fig. 1). On later cruises, the XBT line was extended onshore to the 300 m isobath, and offshore, to ensure that the entire Undercurrent was being sampled. In the center of the current, three extra XBTs were deployed between the standard stations to improve the resolution of the sampling. XBT positions were determined to within ± 0.18 km with the Global Positioning System (GPS).

The first XBT transect was made on 5 July 1993 (Fig. 2). The temperature structure is complex, reflecting the abundant interleaving of the relatively warm Mediterranean and cooler Atlantic waters. The two cores of the Undercurrent appear distinctly, however, as the temperature maxima ($T > 12$°C) at 800 and 1300 m. A ribbon of Mediterranean Water

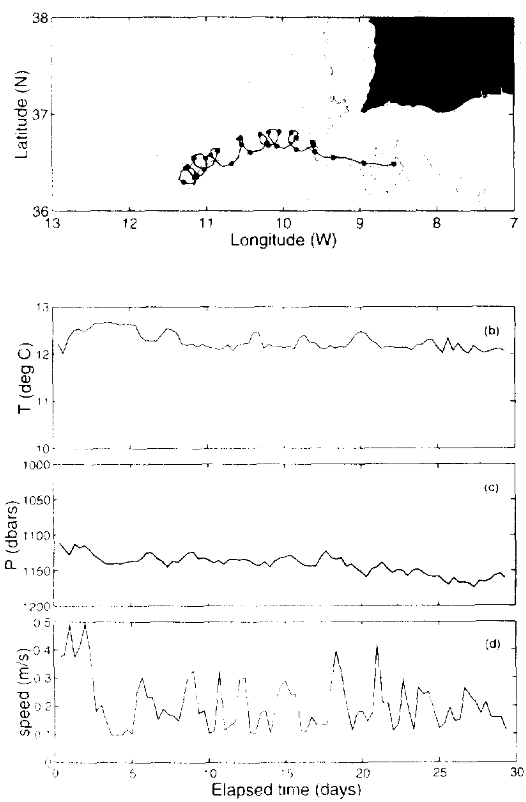

Fig. 3. (a) Trajectory, (b) temperature, (c) pressure and (d) speed for float AM103 deployed for 30 days on 5 July 1993. Solid dots on trajectory indicate daily position. Depth is contoured every 1000 m.

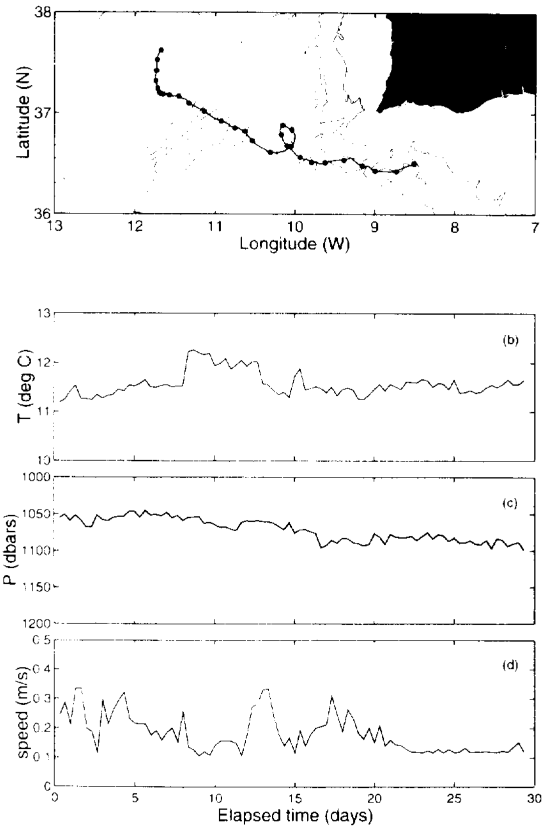

Fig. 4 Same as Fig. 3 but for AM105 deployed on the same day 3 km further offshore.

warmer than 12°C appears right against the boundary, and two somewhat isolated patches, one for each core, are located between 25 and 35 km from the origin of the transect.

At the beginning of the seeding experiment, the RAFOS floats were deployed at 1100 dbars, the average depth of the mid-depth salinity maximum in the open North Atlantic. Later, the target depth was changed to 1200 dbars to tag the high-temperature, high-salinity water of the lower core at the launch site. The temperature measured by the floats at this level indicates when the floats are in or out of the Mediterranean Water.

Floats AM103 and AM105 were deployed 3 km apart along the XBT section shown in Fig. 2. Their 30-day trajectories, and their temperature, pressure and speed records are shown in Figs 3 and 4. AM103 was launched inshore of AM105 at a pressure of about 1115 dbars (Fig. 3c), and temperature of 12.2°C (Fig. 3b). Its trajectory (Fig. 3a) indicates westward flow of the Undercurrent in the order of 0.4 m s^{-1} during the three days it took to reach Cape St. Vincent. After passing the Cape, the float's speed dropped to less than 0.10 m s^{-1}, then increased as the float began a series of anticyclonic loops. The persistent looping and the consistently high temperature measured by the float (> 12°C) indicate that it was trapped in the core of a meddy. This newly formed meddy moved westward, then southwestward along the southern flank of Gorringe Bank.

Float AM105 settled at a pressure of about 1050 dbars (Fig. 4c), and temperature of

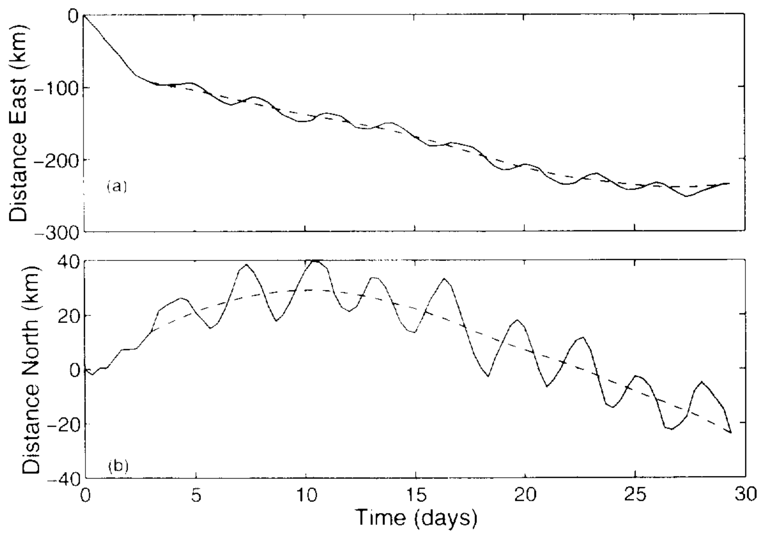

Fig. 5 The (x, y) coordinates of AM103 as a function of time relative to its initial position before (solid lines) and after (dashed lines) the data were smoothed with a low-pass Gaussian filter to remove the high-frequency motion associated with the meddy rotation.

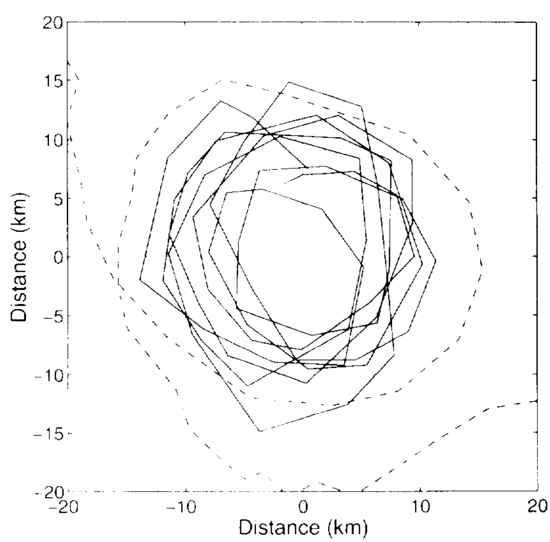

Fig. 6 The motion of AM103 (solid) and AM105 (dashed) relative to the meddy center.

11.2°C (Fig. 4b). It traveled downstream more slowly (0.25 m s^{-1}), as indicated by the closer spacing of the dots in Fig. 4a, compared to Fig. 3a. It decelerated briefly before reaching Cape St. Vincent, accelerated as it passed the Cape, then made one anticyclonic loop around the same meddy that AM103 was trapped in. Temperature increased to greater than 12°C during this loop. But AM105 did not remain with the meddy; instead it

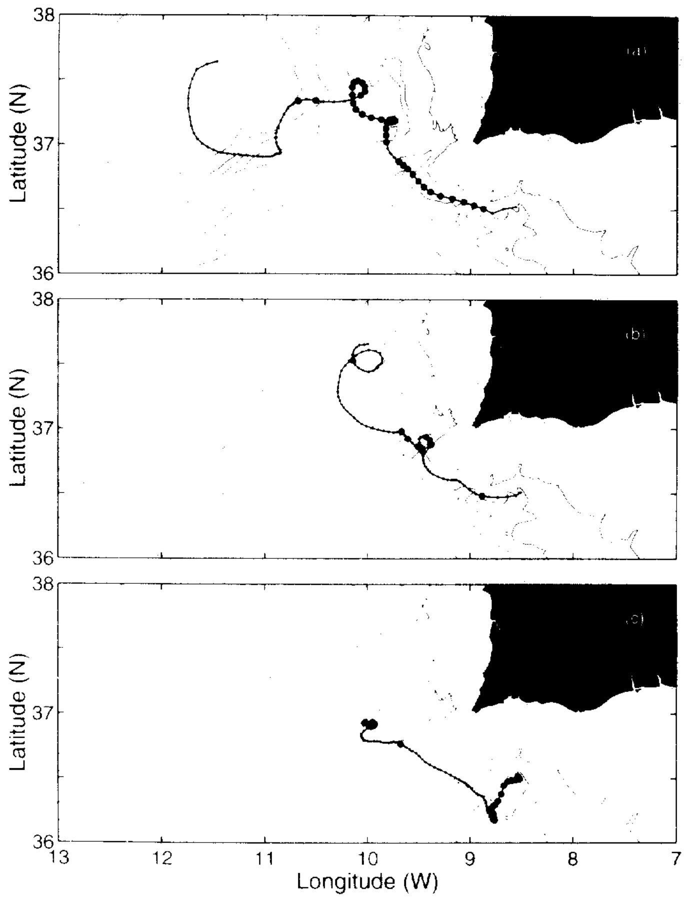

Fig. 7 Thirty-day trajectories of three floats launched as part of AMUSE: (a) AM116a deployed on 15 July 1993; (b) AM101 launched on 11 May 1993; (c) AM116b launched on 4 December 1993. Eight-hour fixes are indicated by small dots, or by large dots if temperature was greater than or equal to 12°C. Bathymetric contours are every 1000 m.

drifted off toward the northwest at an initial speed of about 0.20 m s^{-1}, passing just northeast of Gorringe Bank. Both trajectories indicate that at least some of the water carried by the Undercurrent along the continental slope south of Portugal left the slope and moved out into deep water after passing Cape St. Vincent.

The motion of AM103 was decomposed into two components, one related to translation of the meddy, and the other to its anticyclonic looping. These results are preliminary, and further refinement of the trajectories (e.g. removal of high frequency motions associated with near-inertial waves and tides) will be done later. Figure 5 shows the time series of (x, y) positions of AM103 (solid curves), which have been low-pass filtered to estimate the meddy translation (dashed curves), starting three days after the beginning of the trajectory, when the float began looping. The difference between the filtered and unfiltered curves (Fig. 6, solid line) gives the float coordinates relative to the center of the meddy. In 27 days, the float made eight complete, approximately circular loops around the meddy center at a radius of about 10 km, with azimuthal speeds between 0.20–0.25 m s^{-1}. The rotation period of the meddy was approximately three days.

The motion of AM105 relative to the meddy center (Fig. 6, dashed line) shows that it made one loop around the meddy in five days, at a radius of about 15 km. The longer rotation period of AM105, and its quick departure from the meddy, suggest that it was outside the core of the meddy, which is usually in solid body rotation (see e.g. Armi *et al.*, 1989). The radius of the core is thus bounded between 10 and 15 km.

This meddy was smaller than Meddy "Sharon", first observed in the Canary Basin with a rotation period of about six days and a core radius of about 25 km (Armi *et al.*, 1989; Richardson *et al.*, 1989). However, "Sharon" was first observed about 1300 km from Cape St. Vincent, and was estimated to be about two years old. Our new meddy is more comparable to the meddy studied by Prater and Sanford (1994) near Cape St. Vincent, which had a similar rotation period, about 2.5 days, and a core radius of 9 km.

The low-passed data in Fig. 5 indicate that our meddy did not translate away from the formation site at a uniform speed. The meddy left the boundary at a speed of about 0.10 m s^{-1}, but slowed down to about 0.05 m s^{-1} in the gap between Cape St. Vincent and Gorringe Bank. As it approached the Bank, the meddy accelerated briefly to over 0.10 m s^{-1}, but slowed again as it came into close proximity to the Bank. These features are also apparent in the trajectory in Fig. 3a. Gorringe Bank, which comes to within 50 m of the sea surface, may have had a role in separating the two floats: AM103 and the meddy passed south of the Bank, while AM105 drifted to the north.

The 30-day trajectories of three other floats (Fig. 7) give a measure of several other pathways of the Mediterranean Water. Here temperatures greater than or equal to 12°C are indicated by a large dot. AM116a (Fig. 7a) was deployed 10 days after AM103 and AM105, at a pressure of about 1050 dbars. It moved rapidly downstream at a speed of about 0.30 m s^{-1}, turned northwestward after passing Cape St. Vincent, then made two anticyclonic loops in a manner similar to AM103. The float did not stay trapped in this possible meddy (based on the discontinuation of the looping), but drifted away from the coast to the northeastern corner of Gorringe Bank, and made a broad anticyclonic loop north of the Bank. Temperature was above 12°C only when the float was near the boundary. At the end of the trajectory, the float had accelerated to about 0.30 m s^{-1}.

AM101 (Fig. 7b), deployed on 11 May 1993 during a CTD survey of the Undercurrent that preceded the start of the seeding program, settled at about 1250 dbars. It moved downstream toward Cape St. Vincent at about 0.25 m s^{-1}, but slowed to about 0.10 m s^{-1} at the point where the 1000 m isobath turns northward. It made a small loop in St. Vincent Canyon, southwest of Cape St. Vincent, where temperatures in excess of 12°C were observed. Temperature decreased when the float moved offshore in a broad anticyclonic arc that may indicate a meander of the Undercurrent. The trajectory ended with an anticyclonic loop of about 25 km diameter near the continental slope at about 37.5°N. Temperatures close to 12°C were detected when the float was making this loop.

Float 116a was recovered by the charter vessel and redeployed on 4 December 1993 at about 1150 dbars as AM116b (Fig. 7c). This is the only one of the five floats that did not proceed directly westward after deployment. During the first seven days of its trajectory, AM116b meandered gradually southwestward in water warmer than 12°C, then turned to a path toward Cape St. Vincent. It moved more slowly toward the Cape compared to the other floats, and measured cooler temperatures along this segment of its path. It apparently separated from the continental slope (based on the departure of the track from the 2000 m isobath), but unlike the others, it stagnated over the 3000 m isobath west–southwest of Cape St. Vincent until the end of its mission. During this period of little motion, the temperature increased to over 12°C, suggesting that the float was in a pool of purer Mediterranean outflow water.

CONCLUDING REMARKS

Preliminary float trajectories from the AMUSE experiment indicate directly that the region off Cape St. Vincent is one site of meddy formation. The evidence presented here also suggests that at least some of the lower core of the Mediterranean outflow can leave the continental slope at, or just past, Cape St. Vincent, and move out into deeper water, consistent with the spreading patterns Zenk and Armi (1990) and Daniault *et al.* (1994) proposed based on hydrographic data. These authors found that the lower core of the Undercurrent tends to leave the continental slope west or northwest of Cape St. Vincent, but the upper core is more likely to continue to follow the continental slope along the west coast of Portugal. Temperature observations from the floats reveal that the warmest temperatures are found along the boundary and in anticyclonic loops, probably indicating the presence of the most undiluted Mediterranean Water. As more float data become available, the details of the spreading of Mediterranean Water, including its time-dependent nature, its dependence on cross-slope position and the preferred site of meddy formation, will be investigated.

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