Pergamon

Progress in Oceanography 45 (2000) 209–250

Progress in Oceanography

A census of Meddies tracked by floats

P.L. Richardson [a,*], A.S. Bower [a], W. Zenk [b]

[a] *Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, MA, USA*

[b] *Institut für Meereskunde, an der Universität Kiel, Kiel, Germany*

Abstract

Recent subsurface float measurements in 27 Mediterranean Water eddies (Meddies) in the Atlantic are grouped together to reveal new information about the pathways of these energetic eddies and how they are often modified and possibly destroyed by collisions with seamounts. Twenty Meddies were tracked in the Iberian Basin west of Portugal, seven in the Canary Basin. During February 1994 14 Meddies were simultaneously observed, 11 of them in the Iberian Basin. Most (69%) of the newly formed Meddies in the Iberian Basin translated southwestward into the vicinity of the Horseshoe Seamounts and probably collided with them. Some Meddies (31%) passed around the northern side of the seamounts and translated southwestward at a typical velocity of 2.0 cm/s into the Canary Basin. Some Meddies observed there were estimated to be up to ~5 yr old. Four Meddies in the Canary Basin collided with the Great Meteor Seamounts and three Meddies were inferred to have been destroyed by the collision. Overall an estimated 90% of Meddies collided with major seamounts. The mean time from Meddy formation to a collision with a major seamount was estimated to be around 1.7 yr. Combined with the estimated Meddy formation rate of 17 Meddies/yr from previous work, this suggests that around 29 Meddies co-exist in the North Atlantic. Therefore during February 1994 we observed about half of the population of Meddies.

Contents

1. Introduction 210

2. Scientific background 212
   2.1. History of Meddies 212

* Corresponding author. Fax: +1-508-457-2181.
E-mail address: prichardson@whoi.edu (P.L. Richardson).

PII: S0079-6611(99)00053-1

2.2. Meddy definition . . . 213
2.3. Meddy velocity structure . . . 214
2.4. Meddy distribution . . . 214
2.5. Meddy formation . . . 214
2.6. Methods . . . 216
2.7. Meddy float tracking experiments . . . 217

3. Results . . . 218
3.1. Iberian Basin Meddies . . . 218
3.1.1. Meddy formation and characteristics . . . 218
3.1.2. Meddy pathways and translation velocities . . . 220
3.1.3. Some case histories . . . 224
3.1.4. Meddy lifetimes . . . 233
3.2. Canary Basin Meddies . . . 233
3.2.1. Some case histories . . . 235
3.2.2. Mean Meddy lifetimes . . . 239
3.3. Census of Meddies in the Iberian and Canary Basins . . . 240

4. Overall Meddy lifetimes . . . 242

5. Discussion . . . 242
5.1. Collisions with seamounts . . . 242
5.2. Detrainments near eastern boundary . . . 244

6. Summary . . . 244

Acknowledgements . . . 245

Appendix A . . . 245

References . . . 248

1. Introduction

The Mediterranean salt tongue is one of the most prominent hydrographic features of the mid-depth North Atlantic. The salty water originates in the Mediterranean Sea from excess evaporation which increases the water's salinity and density. The dense water overflows the Strait of Gibraltar, cascades down the continental slope and equilibrates at depths of 500–1500 m in the northern Gulf of Cadiz as a westward flowing boundary current called the Mediterranean Undercurrent (Madelain, 1970; Ambar & Howe, 1979a,b; Baringer & Price, 1997). The Undercurrent flows around Cape St Vincent at the southwestern corner of the Iberian Peninsula and continues northward along the continental slope as an eastern boundary current. Large segments of the Undercurrent separate from the boundary in the form of 40–100 km diameter lenses of warm, salty Mediterranean Water. These Mediterranean Water eddies (Meddies) rotate anticyclonically (clockwise) with azimuthal velocities up to 30 cm/s and translate westward into the eastern Atlantic where they are observed as large temperature, salinity and velocity anomalies. Compared to background water in the Canary Basin Meddy salinity and temperature anomalies reach 1 psu and 4°C. Because of the difficulty of following these subsurface eddies continuously, knowledge of where they form and their life histories has remained rudimentary until recently.

The formation and westward translation of Meddies is thought to be important in maintaining the Mediterranean salt tongue, but how important is not yet clear. For example, Arhan, Colin de Verdiere and Memery (1994) suggested that Meddies may be responsible for more than 50% of the westward salt flux at the level of the Mediterranean Water based on a hydrographic section near 15°W that crossed three Meddies. Mazé, Arhan and Mercier (1997) found that the westward transport of Mediterranean Water at Iberian latitudes could be totally accounted for by mescoscale fluxes and the westward translation of Meddies. Richardson, Walsh, Armi, Schröder and Price (1989) found that Meddies in the Canary Basin translated through a nearly zero mean background velocity at 1000 m which suggests that the mean velocity in the salt tongue is less important than Meddies and other low frequency fluctuations (see Spall, Richardson & Price, 1993). Stephens and Marshall (1999) modelled the effect of Meddies dissipated locally by collisions with topographic seamounts and found that they may generate large recirculations which extend across to the western boundary and shift the salinity tongue equatorward. In order to clarify the role of Meddies we need good information on the number of Meddies that form per year, their sizes, and life histories.

Since 1984 several experiments have tracked 27 Meddies in the Iberian and Canary Basins using freely drifting subsurface floats. When floats become trapped in the rotating swirl motion around the Meddies' centers their paths can be inferred from the looping float trajectories. Although some subsets of the Meddy float data have been published, the results are somewhat contradictory. Some of the Meddies, which appeared to decay slowly, were inferred to survive 4–5 yr. But others collided with seamounts which disrupted their normal Meddy structure and may have shortened their lifetimes. The persistent Meddies presumably leave a dilute trail of warm salty water in their wake (Käse & Zenk, 1987). In the second case a much stronger concentration of warm salty water may be injected locally in the vicinity of the seamounts. These two very different kinds of life histories raise questions about the usual fate of Meddies.

New information about Meddies can be obtained by compiling all available Meddy float data and analyzing them together. The period 1993–1994 was particularly interesting because three different experiments collected float data on 21 Meddies. The objective of this paper is to use the new merged data set to describe results concerning the standing population of Meddies, their typical paths through the ocean, how long they typically survive and what ultimately happens to them. The results suggest that many Meddies collide with seamounts and are possibly destroyed by the collision. Other results imply that there are Meddy bifurcations and mergers.

2. Scientific background

2.1. History of Meddies

The term ‘Meddy’ originated with the discovery by McDowell and Rossby (1978) of a subsurface eddy containing a clockwise rotating core of warm salty water in the western North Atlantic, north of Hispanola. They concluded that the eddy water had characteristics of Mediterranean Water from the eastern Atlantic (hence Meddy), and they posed the question as to how the eddy could have translated 6000 km from its parent water mass. This early report created significant interest in these eddies, and led to studies of their physical characteristics and distribution in the ocean. The hydrographic properties of several Meddies have now been measured in detail (Armi & Zenk, 1984; Armi et al., 1989; Hebert, Oakey & Ruddick, 1990; Schultz Tokos & Rossby, 1991; Pingree & LeCann, 1993a,b; Prater & Sanford, 1994; Pingree, 1995; Tychensky & Carton, 1998) along with their velocity structures measured with current meters (Siedler, Zenk & Emery, 1985; Käse & Zenk 1987, 1996; Armi et al., 1989), velocity profilers (Schultz Tokos & Rossby, 1991; Pingree & LeCann, 1993b; Prater & Sanford, 1994), and floats (Armi et al., 1989; Richardson et al., 1989; Zenk, Schultz Tokos & Boebel, 1992; Schultz Tokos, Hinrichsen & Zenk, 1994; Käse & Zenk, 1996; Bower, Armi & Ambar, 1997; Richardson & Tychensky, 1998). Studies of temperature and salinity anomalies in historical data have identified numerous other possible Meddies which helped show their distribution in the eastern Atlantic (Armi & Zenk, 1984; Belkin & Kostianoy, 1988; Richardson, McCartney & Maillard, 1991; Shapiro & Meschanov, 1996).

In 1984–1987 SOFAR floats were used for the first time to track three Meddies in the Canary Basin (Richardson et al., 1989). One Meddy was tracked for 27 months and observed by shipboard measurements four times during two years which documented its changes with time and its gradual decay (Armi et al., 1989; Hebert et al., 1990; Schultz Tokos & Rossby, 1991). More recent float experiments during 1991–1995 tracked four more Meddies in the Canary Basin (Richardson & Tychensky, 1998) and 14 Meddies in the Iberian Basin (Käse & Zenk, 1996; Bower et al., 1997). Some of these Meddies and the float measurements in them have not previously been described in detail. This paper combines all these float measurements in Meddies and summarizes the Meddy characteristics revealed by the data.

In a curious turn of events Prater and Rossby (1999) conclude that eddies with temperature–salinity properties similar to those in the McDowell and Rossby (1978) eddy, form near the northwestern corner of the North Atlantic Current to the east of Newfoundland and that these eddies may be advected south and west by Gulf Stream recirculations to end up near the McDowell and Rossby eddy site. Prater and Rossby argue that the McDowell and Rossby eddy was not a Meddy. However the long westward trajectory of one of the Canary Basin Meddies to 43°W (see below) suggests some may continue on into the western Atlantic and adds supporting evidence to the original McDowell and Rossby hypothesis. The real origin of the McDowell and Rossby eddy remains in dispute, as is the possibility that Meddies translate across the mid-Atlantic Ridge into the western Atlantic.

2.2. Meddy definition

A Meddy is a coherent clockwise-rotating lens of warm salty Mediterranean outflow water. Meddies are typically 40–150 km in diameter and contain maximum salinities of around 36.5 psu and maximum temperatures of around 13.0°C in the depth range 800–1400 m (Fig. 1). Some Meddies contain two vertically aligned maxima in salinity and temperature similar to the double core structure observed in the Mediterranean Undercurrent near Cape St Vincent (Zenk, 1975; Daniault, Mazé & Arhan, 1994; Bower, Armi & Ambar, 1995). As Meddies translate westward from the eastern boundary into cooler and fresher water, their core waters become apparent as large anomalies that can reach 1 psu and 4°C.

Hydrographic sections through Meddies reveal that the anomalously warm and salty core water extends vertically from around 600 to 1700 m and the larger features can have diameters of around 100 km (Fig. 1). Density sections show that the Meddy lens shape frequently extends from the ocean surface down to at least 2000 m depth (the maximum depth of most sections) and that the dynamical structure extends beyond the layers occupied by temperature and salinity anomalies. They are often found in the vicinity of the Azores Current which flows eastward near 34°N, its cutoff current rings, and other eddies. This suggests that Meddies are not isolated vortices and complicates the interpretation of their hydrography.

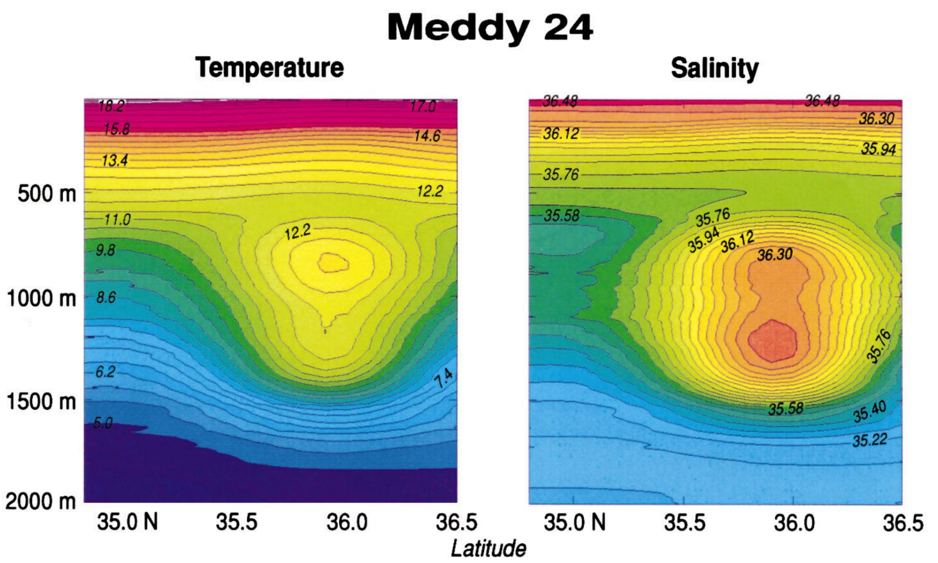


Fig. 1. Vertical sections of temperature and salinity through Meddy 24 in the Canary Basin near 36°N 28°W measured during July 1993 (Tychensky & Carton, 1998). Meddy 24 contained double maxima in the vertical of both temperature and salinity. Values reached 13.2°C and 36.4 psu at 850 m and 12.3°C and 36.5 psu at 1250 m. Maximum anomalies compared to background values were 4.1°C and 1.1 psu at 1250 m. The overall diameter of Meddy 24 was around 120 km. Repeated sections through a Meddy during two years have been shown by Armi et al. (1989) and Hebert et al. (1990), see also Schultz Tokos et al. (1994).

2.3. Meddy velocity structure

The central core region of a Meddy rotates with nearly solid body rotation at each depth between roughly 500 and 1500 m (Armi et al., 1989; Richardson et al., 1989; Schultz Tokos & Rossby, 1991). Maximum rotation rate and maximum swirl velocity ~30 cm/s are located near the central depth of the core, ~1000 m, but the central depth of different Meddies varies from 700 to 1200 m depending on density structure. The diameter of maximum swirl velocity ranges from 20 to 50 km depending on the overall Meddy diameter. Beyond the region of solid body rotation swirl velocities appear to decay exponentially with radius. There is some evidence that their rotation axes tilt and that the tilt is caused by the background geostrophic shear (see Rossby, 1988; Schultz Tokos et al., 1994; Walsh, Richardson & Lynch, 1996).

The swirl velocity of a Meddy can extend over a large fraction, if not the whole, water column. The surface swirl velocity has been observed with surface drifters (Schultz Tokos et al., 1994; Tychensky, Le Traon, Hernandez & Jourdan, 1998) and by altimetry (Stammer, Hinrichsen & Käse, 1991). The deep swirl velocity has been measured to 1500 m by velocity profilers (Armi et al., 1989; Schultz Tokos & Rossby, 1991; Prater & Sanford, 1994) and to 3000 m by moored current meters (Siedler et al., 1985). Siedler et al. (1985) showed a vertical profile of swirl velocity in a Meddy peaking at 30 cm/s near 700 m and extending below (1600–3000 m) with a velocity of around 7 cm/s.

2.4. Meddy distribution

The geographical distribution of proven Meddies and other possible Meddy structures recorded in historical data extend southwestward from the Iberian Peninsula out to 37°W and south to 20°N (Fig. 2). Some possible Meddy observations near 45°N have recently been confirmed with detailed shipboard and float measurements (Paillet, LeCann, Serpette, Morel & Carton, 1999). The temperature and salinity anomalies continue to be large in the western and southern Meddies because they are translating into cooler and fresher background water. Meddies are embedded in and are part of the large scale Mediterranean salt tongue which extends from the Iberian Peninsula, where maximum salinity outside of Meddies is around 36.5 psu, westward through the Canary Basin where salinities are of around 35.5 psu. The pronounced zonal alignment of the tongue south of the Canary Islands favors the apparent salinity contrast between southward roving Meddies and the background water in the southern Canary Basin.

2.5. Meddy formation

The formation of Meddies was recently documented with RAFOS floats launched in the Mediterranean Undercurrent south of Portugal (Bower et al., 1997). Six Meddies were observed to form near Cape St Vincent at the southwestern corner of the Iberian Peninsula, and three Meddies formed in the vicinity of the Tejo Plateau to the west of Lisbon. The formation events were identified when the floats began

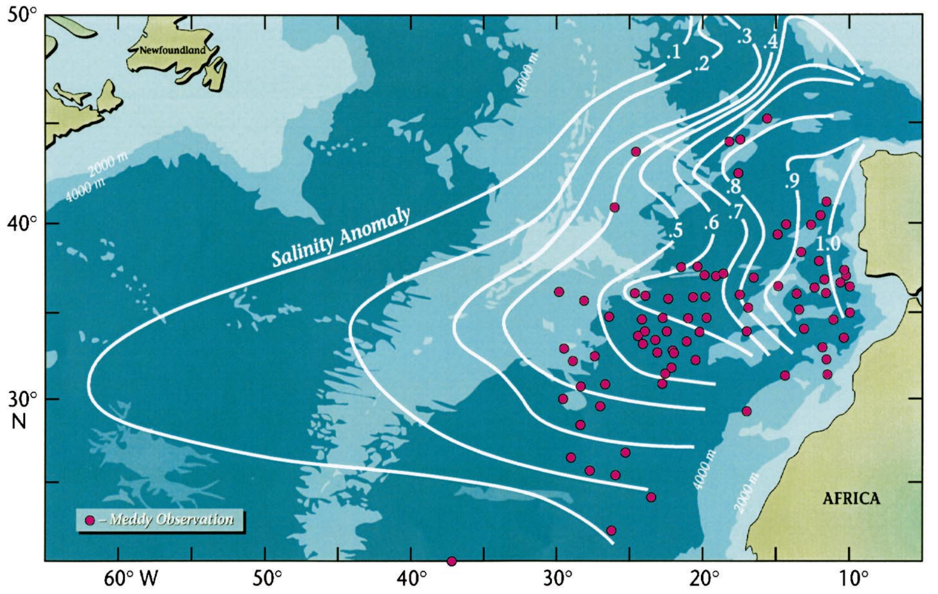


Fig. 2. Summary of historical Meddy observations listed by Richardson et al. (1991) and Shapiro and Meschanov (1996) and shown by Richardson and Tychensky (1998). The diameter of the dots in this figure is approximately 50 km, somewhat smaller than the diameter of a typical Meddy which is around 100 km. Contours of the salinity anomaly of the Mediterranean Water relative to 35.01 psu near a depth of 1100 m are based on a figure by Needler and Heath (1995) and shown by Joyce (1981).

to loop clockwise with looping periods typical of previously documented Meddies. Confirmation that these floats ended up in Meddies came from the relatively warm float temperatures (>12°C) near 1100 m that are indicative of the anomalously warm (and salty) Meddy core. At both the main formation sites facing downstream in the Undercurrent the continental slope turns sharply to the right. The sharp bend (and some major canyons cutting into the slope) seems to initiate Meddy formation by causing the Undercurrent to separate from the boundary. Based on the proportion of floats that were launched in the Undercurrent and those that ended up in Meddies, Bower et al. (1997) estimate that about 10 Meddies form per year near Cape St Vincent and seven near the Tejo Plateau, a total of 17/yr.

Some very recent float and hydrographic measurements show that Meddies also form north of the Tejo Plateau. Three Meddies were observed between 41°N and 45°N, one of which was tracked for 390 days (Paillet et al., 1999). The implication of these new observations and some earlier possible Meddy observations seen in historical data is that Meddies also form off Cabo Finisterre at the northwestern corner of Spain. These northern Meddies seem to have lower temperature and salinity maxima than the Meddies forming farther south, in accord with the decrease in temperature and salinity of the Mediterranean Undercurrent as it flows northward (Daniault et al., 1994).

Farther north, some floats were launched recently (~900 m) in the relatively warm and salty water lying along the eastern boundary near Porcupine Bank at 48°N–52°N (southwest of Ireland). Floats in four eddies looped clockwise and translated westward to southwestward away from the boundary (Bower, Richardson & Hunt, 1999). The implication is that Meddies or Meddy-like anticyclonic eddies can form at several places along the eastern boundary at least as far north as 50–52°N. These new float trajectories are still being analyzed and have not been included here. Hence the Meddy formation rate determined by Bower et al. (1997) is a lower bound of the total Meddy formation rate. However, it remains an open question whether or not these northern Meddy-like eddies can be classified as Meddies according to our earlier definition.

2.6. Methods

The Meddies described here were all tracked using freely drifting subsurface RAFOS (Ranging and Fixing of Sound) floats except for the three tracked earlier by SOFAR floats (Meddies 21–23, see Appendix A). RAFOS floats record temperature, pressure and times of arrival of acoustic signals transmitted by an array of moored sound sources. SOFAR floats are the reverse of RAFOS; they emit acoustic signals, which are recorded by moored listening stations. The signals travel in the deep sound channel, a zone of minimum sound speed centered just below the main salinity maximum of the Mediterranean Water tongue. This layer traps acoustic energy and permits tracking ranges of 1000–2000 km. The distance between a float and a sound source is calculated using the measured time of arrival and the speed of sound. A float position is calculated by triangulation from the locations of sound sources and the distances to the float.

Absolute position errors depend on many factors such as the number of sources and their configuration in the array, the location of a float with respect to the array, clock drift errors, etc., but is usually around 10 km or less. Fix-to-fix relative errors tend to be smaller than this. Absolute errors can be larger than 10 km when either a float is located outside a source array or if the tracking geometry is poor. Seamounts and other topographic features can block the acoustic signals and so can cause gaps in the trajectory records. Short gaps of a few days were usually filled in by interpolation.

Most of the RAFOS floats described here were ballasted to be neutrally buoyant near the core depth of Meddies, around 1000 m (see Appendix A for float depths). The floats have glass pressure hulls and are nearly isobaric. They tend to remain close (within 100 m) to their initial equilibrium depth, but for unexplained reasons some floats rose slowly and others sank slowly (possibly as a result of slow leaks). Preset float missions usually ranged from a few to 18 months. At the end of its mission a float drops a weight and rises to the ocean surface. It then transmits its stored data to the laboratory via ARGOS satellites. Data are transmitted over 4–6 weeks while the float drifts at the surface. For more details see a description of RAFOS floats by Rossby, Dorson and Fontaine (1986).

Most of the floats recorded position data two to three times per day. Floats in Meddies 1, 4, 5, 6 had limited memory and so recorded data only once per day.

Fast float loops with a 2–3 day period of rotation (Meddies 4, 5, 6) are poorly resolved with a single daily position so that the resulting trajectories can look erratic.

2.7. Meddy float tracking experiments

Two experiments have tracked Meddies in the Canary Basin. During the first in 1984–1987 two Meddies were surveyed by shipboard measurements and seeded with six SOFAR floats (Armi et al., 1989; Richardson et al., 1989) near a depth of 1100 m. A third Meddy (23) was tracked when a float was launched into it by chance. The longest tracked of these three (~27 months) was observed to be eroding from its edges, top and bottom and to be losing salt with an e-folding time of about one year (Armi et al., 1989). During 1993–1995 four further Meddies (24–27) were surveyed in the Canary Basin by ship during the Semaphore experiment (Tychensky & Carton, 1998) and seeded with 10 RAFOS floats (Richardson & Tychensky, 1998). The typical float mission was 18 months and depths ranged from 750 to 1250 m. Three floats were deployed at different depths (near 950, 1050 and 1250 m) in Meddy 24, but this feature drifted far to the west of the main sound source array and west of numerous seamounts which caused problems in tracking. In both of these experiments, two float positions per day were obtained.

Two main experiments tracked floats in the Iberian Basin. The first was a German program, the Iberian Basin Experiment, which surveyed six different Meddies (Meddies 1–6) and tracked 19 floats in them during 1991–1994 (Käse & Zenk, 1996). Meddies 4 and 6 were successfully reseeded by relocating the Meddy shortly after a float surfaced. The float depths ranged from 700 to 900 m, typical missions lengths varied from 1 to 9 months, with either one or three fixes being recorded per day. During the second experiment, AMUSE (Bower et al., 1997), 49 floats were launched at a typical depth of 1100 m in the Mediterranean Undercurrent south of Portugal. Two floats were usually launched each week during a series of 25 cruises, and were tracked up to 11 months throughout 1993–1995. Some of the floats were caught up in nine Meddies as they formed, and other floats became entrained into five Meddies, which had already formed. One of these Meddies (13) was also observed by shipboard measurements and seeded with floats by Pingree (1995). No description of the hydrographic properties and overall size of the other AMUSE Meddies is available except for what data can be gleaned from the float temperatures, pressures, and trajectories.

Three experiments, Semaphore, Iberian Basin, and AMUSE, overlapped during 1993–1994 and resulted in the tracking of 21 Meddies, 14 of which were observed simultaneously. Of the total 27 Meddies tracked by floats during 1984–1995, 13 were directly seeded with floats and studied by shipboard measurements. The others were not surveyed by ship.

In the following discussion, floats are identified by two letters and a number. The letters refer to the three main experiments—AM for AMUSE (Bower et al., 1997), IB for Iberian Basin (Käse & Zenk, 1996) and MD for Meddyphore/Semaphore (Richardson & Tychensky, 1998). Further information about the floats is available in the papers cited and in the other references given for each Meddy in Appendix A.

3. Results

We will first present results concerning Meddies in the Iberian Basin, because this is where they are generated and so where the youngest ones are located. Then we will discuss the older Meddies that occur in the Canary Basin.

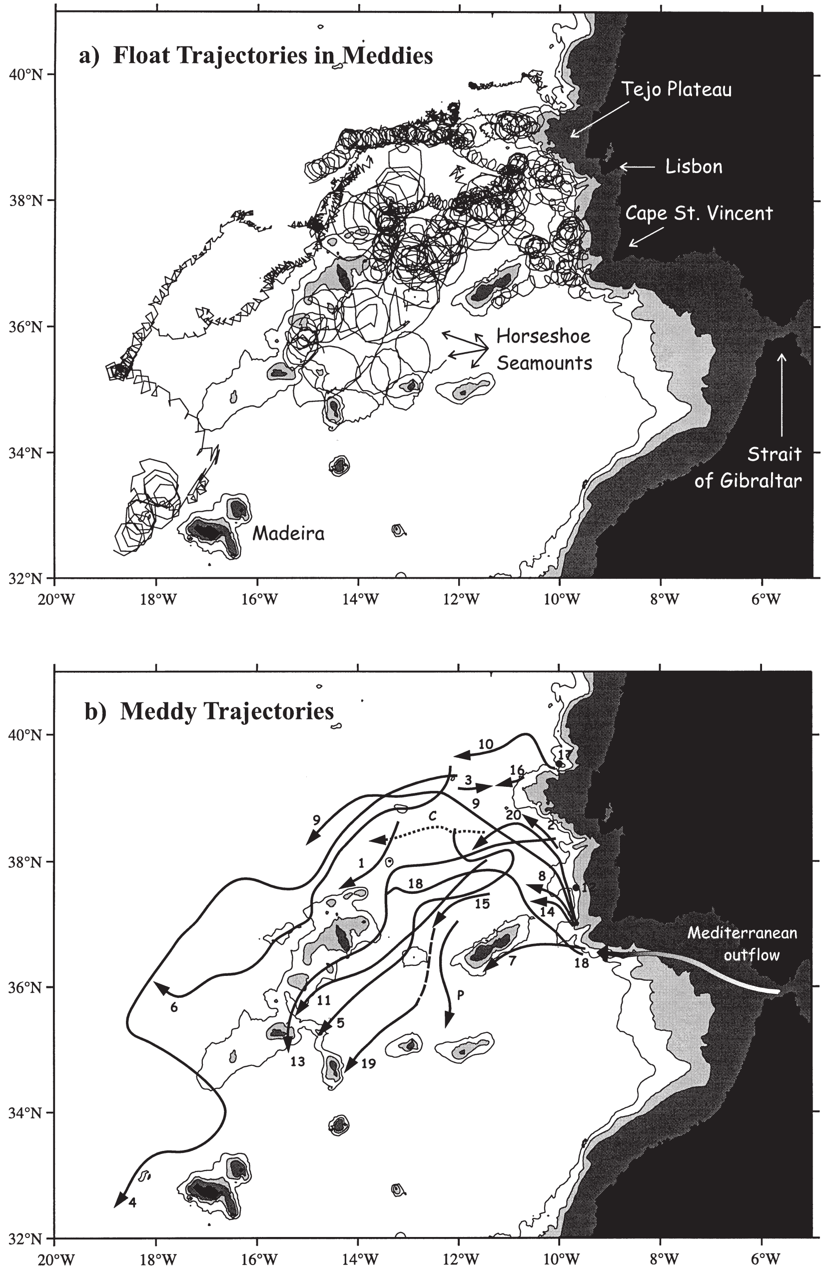
3.1. Iberian Basin Meddies

3.1.1. Meddy formation and characteristics

Twenty Meddies were tracked with RAFOS floats in the Iberian Basin between May 1991 and February 1995 (see Appendix A). Fig. 3(a) shows the trajectories of the RAFOS floats that were trapped in each Meddy for the longest period of time, and Fig. 3(b) shows the Meddy trajectories that have been smoothed subjectively. Six of the Meddies (7, 8, 9, 14, 18, 20) formed near Cape St Vincent, at the south-western corner of the Iberian Peninsula, and three (10, 16, 17) formed in the vicinity of the Tejo Plateau west of Lisbon [Bower et al., 1997, Fig. 3(b)].

Some floats that did not end up in newly formed Meddies became entrained into five pre-existing Meddies (11, 12, 13, 15, 19) in the Iberian Basin, whereas other floats were seeded directly into other Meddies (1–6, 13), four of which (2, 3, 12, 13) were located next to the eastern boundary and had probably only just formed. About 20% of all the AMUSE float data consisted of looping trajectories in Meddies. None of the floats was located in Meddies north of 40°N, although Meddies (or Meddy-like eddies) have been identified there recently and tracked with floats (Paillet et al., 1999; Bower et al., 1999). These new float data have not been included here. Some observations of possible Meddies from historical hydrographic data come from positions to the south of these data and east of Madeira (Fig. 2) suggesting that Meddies or salty blobs of Mediterranean Water may also occasionally translate into that region.

The looping float trajectories were used to obtain information about Meddy size, rotation period, translation velocity and pathways through the ocean (Appendix A, Fig. 3). Float trajectories with looping diameters of less than 20 km were probably close to the central core region of a Meddy and had the fastest rotation periods, 2.5–3.0 days (Meddies 3, 4, 6, 7, 9, 10, 13, 20). Prater and Sanford (1994) surveyed a newly formed Meddy near Cape St Vincent and measured a similar core rotation period of 2.5 days. Floats in one of the fastest rotating Meddies (4) for a record 159 successive loops over 553 days [Fig. 4(a)]. The fast loops were poorly resolved, because the floats involved only recorded one position per day. The longest rotation periods, >20 days, corresponded to the features with the largest looping diameters of around 120 km, and were observed in the outer periphery of Meddies (1, 5, 19). Several of the Meddies were only measured by floats trapped in their core region, notably those observed to form near Cape St Vincent. The overall size of these Meddies cannot be accurately estimated in the absence of further in situ measurements, but it is likely that their diameters were larger than the maximum loop diameters of the float trajectories (see Appendix A). Maximum swirl velocity of Meddies was around 30 cm/s at diameters of 30–60 km (Meddies 1, 12, 13, 16, 20), which


a) Float Trajectories in Meddies
Tejo Plateau
Lisbon
Cape St. Vincent
Horseshoe
Seamounts
Strait
of Gibraltar
Madeira
40°N
38°N
36°N
34°N
32°N
20°W
18°W
16°W
14°W
12°W
10°W
8°W
6°W
b) Meddy Trajectories
Mediterranean
outflow
40°N
38°N
36°N
34°N
32°N
20°W
18°W
16°W
14°W
12°W
10°W
8°W
6°W

is much faster than typical background velocities of approximately 5–10 cm/s that were measured by floats in the Iberian Basin (see below).

3.1.2. Meddy pathways and translation velocities

Meddies near the eastern boundary tended to translate initially in either a northward or northwestward direction, whereas those farther offshore tended to drift southwestwards [Fig. 3(b)]. This is illustrated in detail by the trajectories of the three Meddies that formed near Cape St. Vincent [Fig. 4(b–d)]. All three of these Meddies followed a curved path, initially moving northward or northwestward, but eventually southwestward. Meddy 9 reached the highest latitude, 39°N, before turning southwestward. The relatively rapid northward translation velocity of these Meddies along the eastern boundary is evident from the wide spacing between float loops, and was estimated by low-pass filtering the float tracks to obtain the trajectories. Meddies 9 and 18 translated along the continental slope at 8–10 cm/s immediately after their formation. However, Meddy 20 translated the most rapidly along the slope, with an initial speed of about 17 cm/s. Until they reached their maximum of latitude, the mean along-boundary speed of Meddies 9, 18 and 20 were 4.5, 2.3 and 6.4 cm/s respectively.

The northward along-boundary velocity calculated from floats in these three and four other Meddies (2, 8, 10, 14) appears to have been caused by the general northward flow along the eastern boundary. This poleward current is also evident in the trajectories of the seven floats launched to the south of Portugal at various times that rounded Cape St Vincent within a remarkably narrow (~10 km wide) band, and then closely followed the western Portuguese slope northward toward the Tejo Plateau (Fig. 5). In the vicinity of Setubal and Lisbon Canyons (38.3°N), the tracks of these diverged; four of them continued along the slope but the three others drifted offshore into deeper water. A similar divergence of Meddy trajectories was observed near these canyons [Fig. 3(b)]. All but one of the seven floats left the boundary in the vicinity of the Tejo Plateau and drifted generally westward (between northwestward and southwestward).

The mean speed of the poleward Undercurrent measured by floats is similar to the mean translation speed of Meddies near the slope, further evidence that the Meddies are being advected northward by this current. The mean northward velocity of the seven floats in Fig. 5 between 36.7°N and 38.0°N is 11.0±0.8 cm/s, the standard

Fig. 3. (a) Trajectories of floats that looped clockwise in 20 Meddies in the Iberian Basin. These floats remained in the Meddies for the longest period of time. Other floats that also looped in the Meddies are not shown in order to avoid clutter. Note the numerous seamounts in the Horseshoe Seamount Chain southwest of Cape St Vincent, many of which reach up to the depth of Meddies. Names of the major seamounts are given in Fig. 4. (b) Trajectories of the same Meddies in (a), obtained by subjectively smoothing the float tracks to emphasize large scale patterns. Eighteen Meddy trajectories were obtained from the translation of looping floats, and two Meddies (12 and 16) were stationary during the period of observation. An additional Meddy (P) was tracked with surface drifters by Pingree and LeCann (1993a). Five Meddies (4, 5, 6, 9, 13) were continuously tracked for roughly a year, two (4, 6) for a year and a half. The trajectory of a coherent cyclone (C) is shown by a dotted line. The coastline and 1000, 2000 and 3000 m isobaths are superimposed.

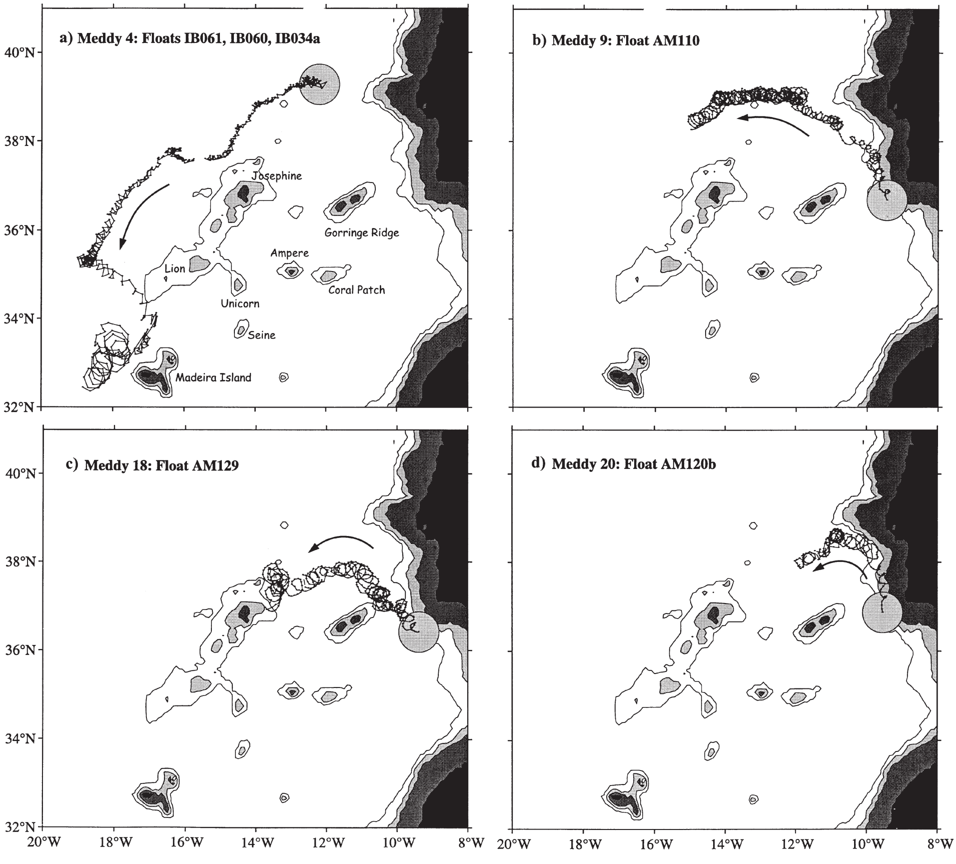


Fig. 4. Trajectories of four representative Meddies in the Iberian Basin. A circle of diameter 100 km was added to each Meddy to show its approximate overall size. Meddies formed near Cape St Vincent are probably smaller than this and do not overlap the topography as it appears in the figure. In all panels, the coastline and 1000, 2000 and 3000 m isobaths are indicated. (a) Three floats (IB61, IB60, IB34) pieced together to show the overall trajectory of Meddy 4 (see Appendix A) from September 23, 1992, to April 21, 1994. This is the longest tracked (1000 km, 1.6 yr) of the Iberian Basin Meddies. Meddy 4 was surveyed three times by ship in September 1992, March and July 1993 and seeded with floats each time. Many float loops were around 10 km in diameter, much smaller than the Meddy's overall diameter of around 80 km. Larger diameter loops up to 70 km appeared after Meddy 4 interacted with the Azores Current and brushed past (at a distance of ~40 km) Madeira Islands in mid January 1994. (b) Trajectory of float AM110 which looped in Meddy 9 for 328 days, starting at its formation near Cape St Vincent on July 20, 1993 and continuing until the float surfaced on June 13, 1994. Of the six Meddies observed to form at Cape St Vincent, this one drifted the farthest north before turning toward the southwest and drifting around the Horseshoe Seamounts. (c) Track of AM129, which looped in Meddy 18 from March 3, 1994 to September 16, 1994. The loops of float AM126b suggest that this Meddy's overall diameter was greater than 90 km. In July and early August Meddy 18 coalesced with Meddy 13, then collided with several seamounts in the Horseshoe chain. (d) Meddy 20, as revealed by float AM120b, translated rapidly (17 cm/s) northward along the eastern boundary before turning westward away from the slope and into deeper water. This Meddy was tracked from October 14, 1994 to January 31, 1995.

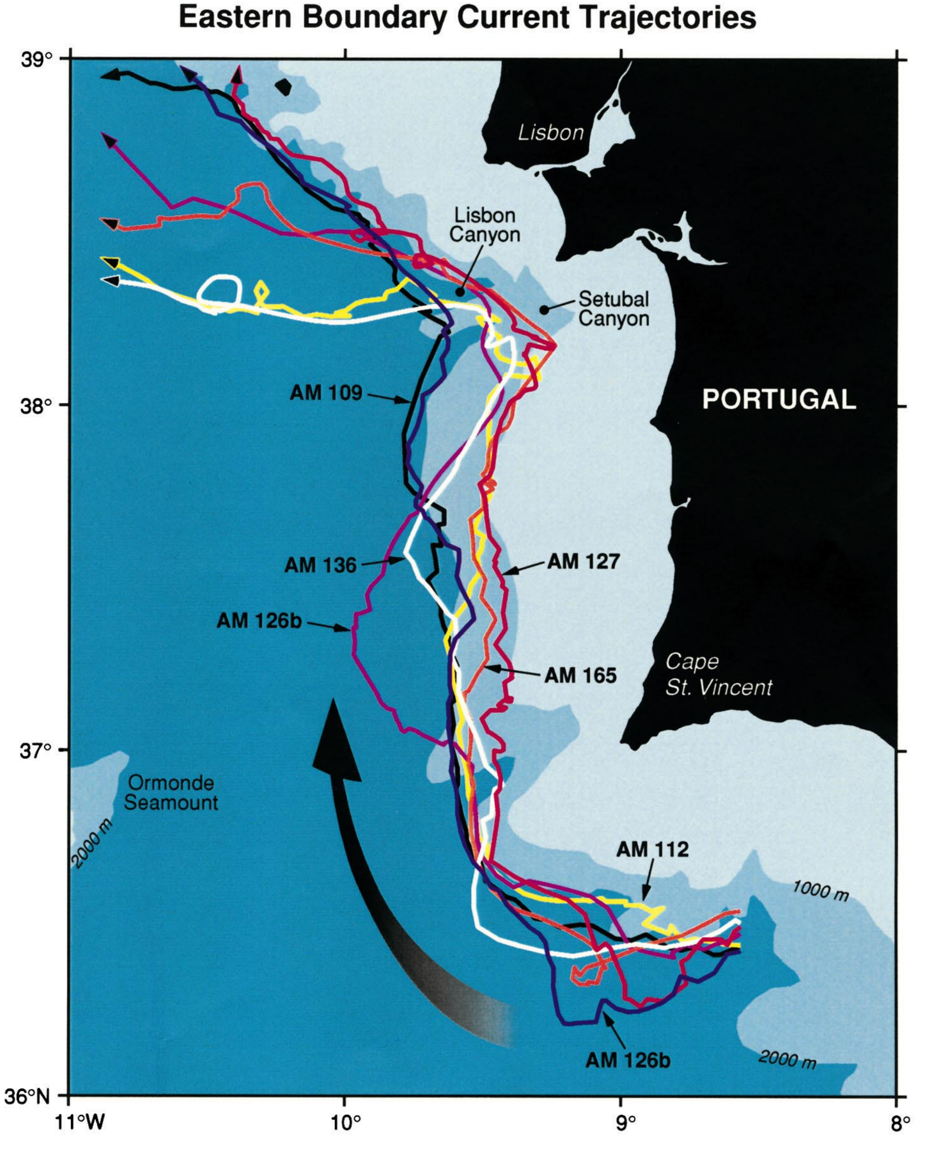


Fig. 5. Trajectories of seven floats deployed in the Mediterranean Undercurrent south of Portugal that followed the continental slope around Cape St Vincent and northward to the Tejo Plateau. These floats clearly indicate the presence of a well-defined boundary current that could advect newly formed Meddies northward. The mean depth of these seven floats is 1123 m.

error is being combining the mean velocity of each of the seven floats. Grouping all the non-Meddy float velocities near the boundary reveals that there is a northward mean flow extending about 100 km from the 1000 m isobath, with a peak mean value of about 6 cm/s located 20 km from the 1000 m contour [Fig. 6(a)]. Instantaneous velocities in the eastern boundary current are faster than this and reach 25–30 cm/s, which probably accounts for the higher instantaneous Meddy translation speeds. The variability in along-boundary speed is relatively large, with standard deviation within the eastern boundary current of 8–10 cm/s [Fig. 6(b)]. Note this implies that there are occasional reversals in the boundary flow as is also seen in a few float trajectories (not shown).

The mean velocity of all the Meddies from start to end and weighted by number of days tracked was 2.0 cm/s towards 227°T (southwestward). Three Meddies (3, 16, 17) stagnated for a month or two in the vicinity of the Tejo Plateau and did not

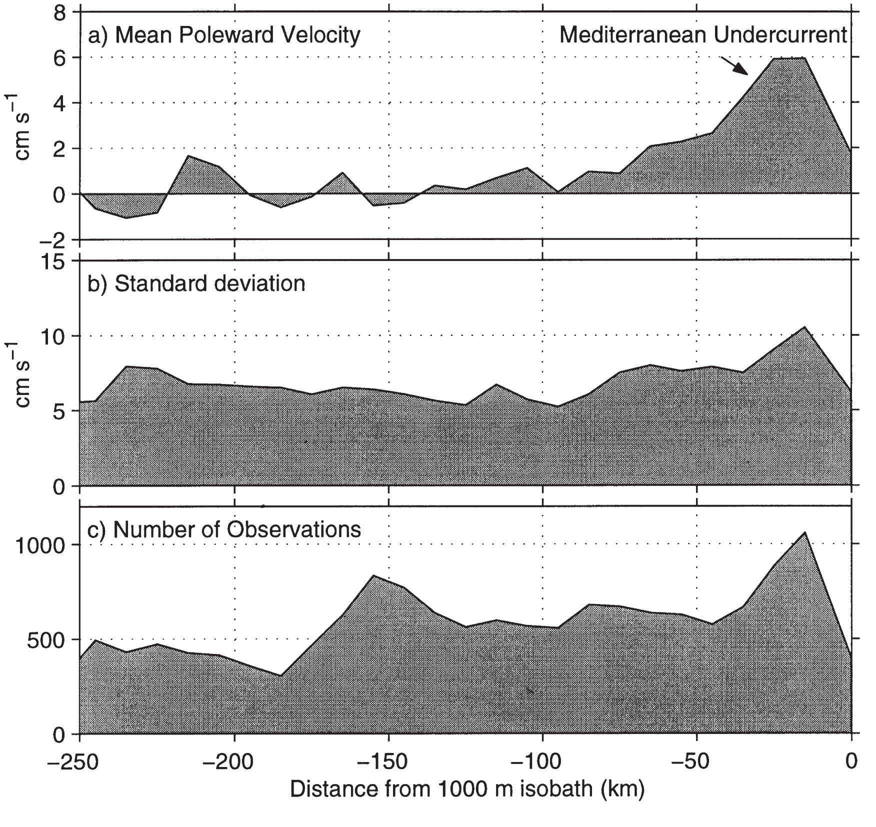


Fig. 6. (a) Mean poleward along-boundary velocity within 250 km of the 1000 m isobath based on all float data except those clearly in the cores of Meddies and those east of 9.25°W in the Gulf of Cadiz. Individual float velocities were grouped and averaged in 10 km wide bins parallel to the 1000 m depth contour which was obtained from ETOPO2 data. A poleward flowing eastern boundary current, the Mediterranean Undercurrent, has a peak mean speed of about 6 cm/s, and occupies the nearest 100 km to the slope. (b) Standard deviation in the 10 km wide bins, and (c) number of observations in each bin.

translate significant distances, at least while they were being tracked by floats. Some other Meddies alternated between periods of relatively fast translation and periods of stagnation. Käse and Zenk (1996) suggested that the fast translation is the result of a dipole structure in which an anticyclonic Meddy is associated with a cyclonic partner eddy. The period of stagnation results from an instability, which leads to the separation of anticyclonic and cyclonic components.

Shapiro and Meschanov (1996) used historical data to map the spreading cores of Mediterranean Water in the Iberian Basin. The main core turns northwestward between Cape St Vincent and Gorringe Ridge which is in agreement with Zenk and Armi (1990) and Daniault et al. (1994). Near 38°N their main core splits into three branches going (1) northward, (2) northwestward, and (3) westward around the Horseshoe Seamounts then southwestward. A secondary core spreads southwestward from Cape St Vincent splitting into two branches. The swath of trajectories tracked by floats [Fig. 3(b)] roughly coincides with the southern branch of the main (northern) core and the northern branch of the southern core. A composite of displacement vectors from start to end of the trajectories of all the floats launched in the Mediterranean Undercurrent (Hunt, Wooding, Chandler & Bower, 1998) roughly agrees with the area covered by spreading paths shown by Shapiro and Meschanov, although the displacement vectors do not seem to reveal preferred branches.

3.1.3. Some case histories

Meddy Coalescence: During July and early August 1994 Meddy 18 collided and coalesced with Meddy 13 (Fig. 7) just northeast of Josephine Seamount [see Fig. 4(a) for location]. The coalescence was documented by four floats, floats MD136 and MD137 in Meddy 13 and floats AM126B and AM129 in Meddy 18. The trajectories of three of the four floats are illustrated in Fig. 7. The fourth, MD136, is not shown because it is very gappy. The close correspondence between the overall trajectories of MD136 and MD137 and their similar decrease in temperature when MD137 ceased looping shows that they both remained in Meddy 13 until December 1994. Before the collision, Meddy 18 was translating rapidly southwestwards along the southeastern edge of Meddy 13, which at the time was nearly stationary [Fig. 7(a–b)]. The start of the coalescence was evident during 21–31 July when float AM126b moved from the periphery of Meddy 18 to the periphery of Meddy 13 [Fig. 7(b–c)]. Float MD137 in Meddy 13 then switched abruptly from small diameter (<10 km) loops with a three-day period to larger (40 km) loops with a 4–5 day period [Fig. 7(b–c)]. The track of float MD136 agreed with these loops but failed to resolve them. Float AM129 in Meddy 18 maintained a 4–5 day looping period during the coalescence. During August 10–20 these two floats closest to the Meddy center (plus MD136, not shown) continued to loop as the composite Meddy began to translate southward.

Float temperatures remained warm (T>12°C) during the coalescence (Fig. 8) which implies that the warm core waters from the two Meddies merged. Thus the floats did not leave one Meddy, travel through cooler background water, and subsequently enter the other Meddy. Float MD137 did measure a slow decrease in temperature (~0.1°C) after the coalescence, but this decrease was small compared to the

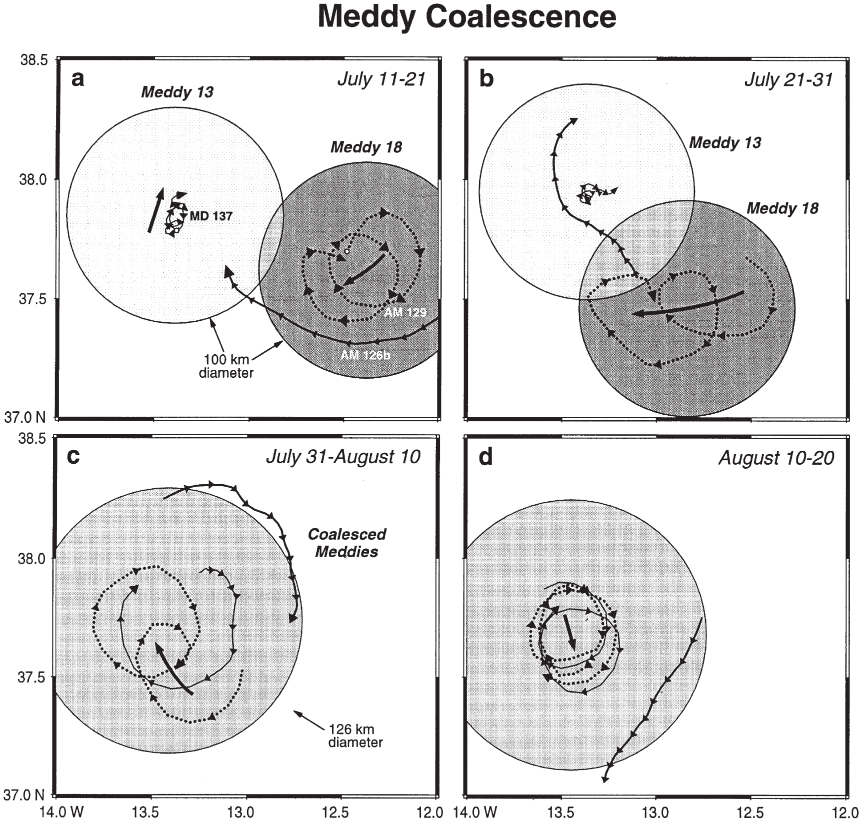


Fig. 7. Coalescence of Meddies 13 and 18 as shown by the trajectories of floats MD137 in Meddy 13 and, AM129, and AM126b in Meddy 18 (near depths of 930, 1170 and 1160 m respectively). Circles have been added to illustrate the approximate overall size of the Meddies. During July 11–21, 1994, the Meddies began to coalesce as Meddy 18 approached from the east toward a nearly stationary Meddy 13. During July 21–31 the central region of Meddy 18 (float AM129) began to turn northward. At this time the trajectory of float AM126b showed the connection between Meddies. During July 31–August 10 the Meddies completely coalesced as shown by all three floats which began looping around a common center. Further evidence is provided by another float, MD136, at 1120 m which was launched along with MD137 in Meddy 13 and remained in it and the merged Meddy until December 1994. The trajectory and temperature series of MD136 are not shown because they are very gappy and the loops were not resolved. The data are consistent with the coalescence of two Meddies.

overall temperature anomaly of Meddy 13 (which was around 3°C) or that associated with a seamount collision (see below). The warm temperature and the increase in the looping diameter of float MD137, combined with the steadiness of looping period and temperature of float AM129, implies that the core water of Meddy 13 coalesced with the core of Meddy 18. The overall size of the Meddies before they coalesced was around 100 km, based on the largest float loops in both Meddies (~80 km diameter) and some additional measurements of Meddy 13 (Pingree, 1995). The diameter of the composite Meddy was not evident from the float data, but we can

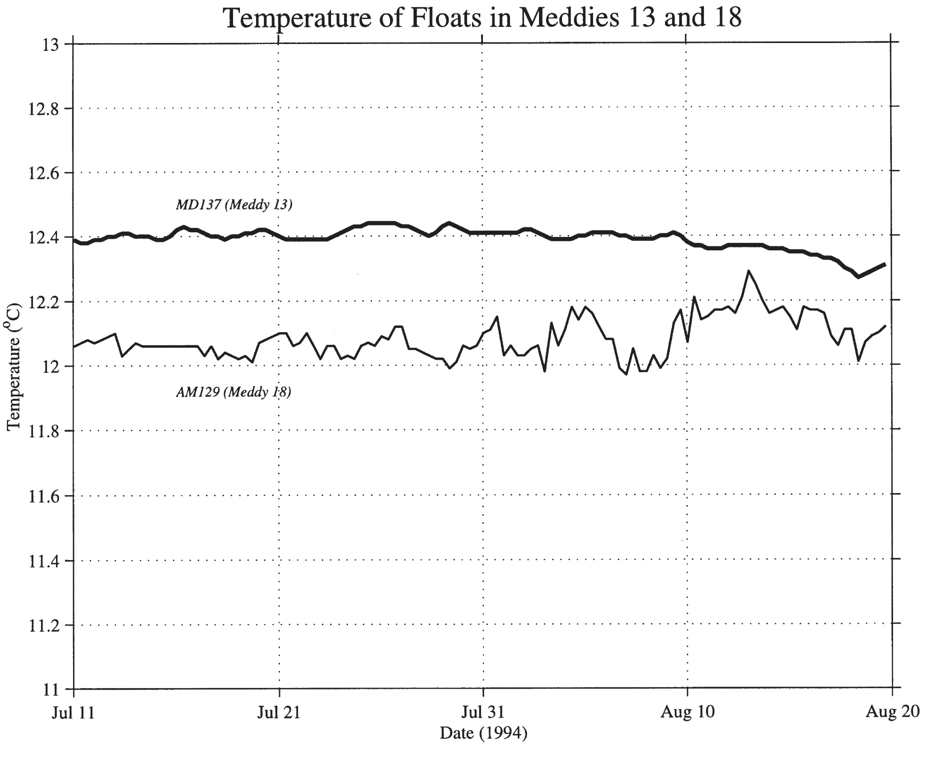


Fig. 8. Temperature measured by floats MD137 at a depth of 930 m and AM129 at 1170 m during the coalescence of Meddies 13 and 18. Temperature remained greater than 12°C throughout the coalescence, and in the case of MD137, did not drop significantly until the composite Meddy collided (possibly fatally) with Lion Seamount. Float MD137 was warmer and shallower than float AM129 and closer to the warmer, less saline upper core water originating in the Mediterranean Undercurrent. The temperature of float MD136 at a depth of 1120 m was around 12.2 during the coalescence but gappy and therefore not shown.

estimate it crudely as follows. Assuming that the volume of the new composite Meddy is simply the sum of the volumes of Meddies 13 and 18, and also that its aspect ratio (thickness/diameter) remained the same as that of the original ones (justified by the constant looping period and radius of float AM129 throughout the coalescence), then the diameter of the composite Meddy is equal to 2.3 times the diameter of the original Meddies, i.e. 126 km. The new composite Meddy which was formed is now referred to as Meddy 13 simply because the original Meddy 13 floats (MD136 and MD137) continued to loop for longer than those floats originally in Meddy 18. This coalescence was similar to that of two other Meddies each around 75 km in diameter which were observed by Schultz Tokos et al. (1994) to coalesce into Meddy 1. This latter coalescence was followed by four RAFOS floats, three surface drifters, and a hydrographic survey. During the coalescence the centers of the original two Meddies revolved clockwise around a common center of rotation and the distance between centers gradually decreased over a three-week period. The period of rotation of the core of one Meddy was 4.3 days. However, the core rotations of the other Meddy and the coalesced Meddy were not measured. Largest loops of a drifter and a float in the composite Meddy were around 100 km in diameter. These two examples of Meddy coalescence imply that some of the larger Meddies in the Canary Basin may have formed from the merging of smaller Meddies.

Collisions with Topography: There are major obstructions to the southwestward translation of Meddies away from the eastern boundary in the form of the Horseshoe Seamounts, a curved line (~500 km) of seamounts located southwest of Cape St. Vincent [Figs. 3 and 9(a)]. At least nine of these seamounts rise above the mid-depth (1100 m) of a typical Meddy and five of them rise to within a few hundred

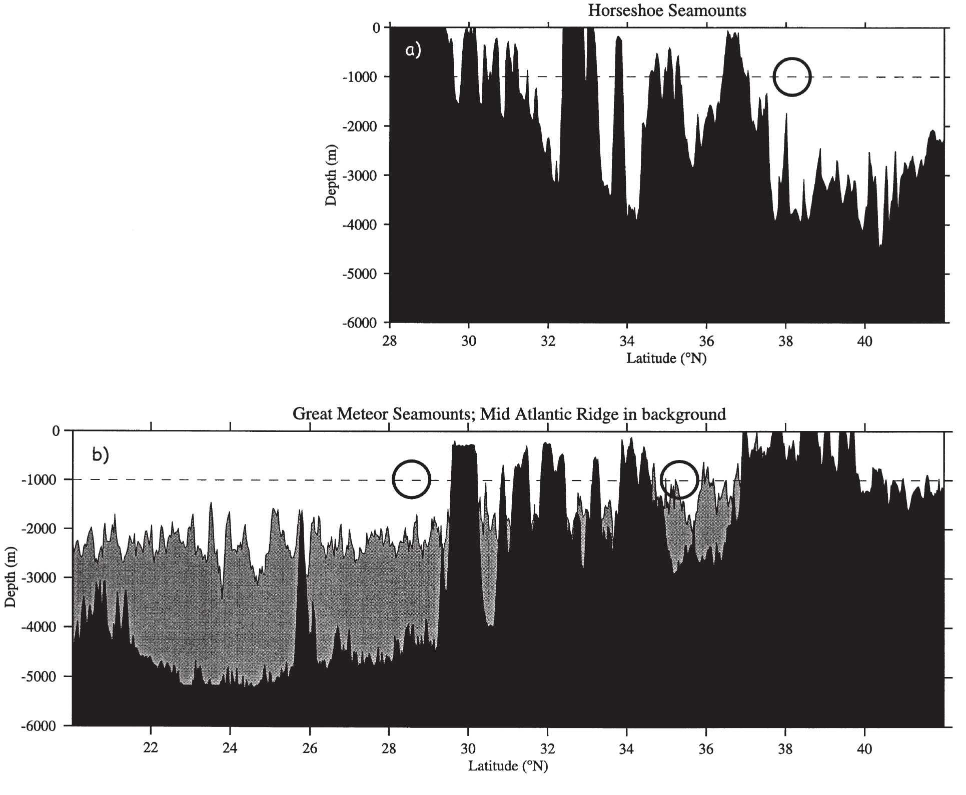


Fig. 9. North–south sea floor depth profiles showing (a) the Horseshoe Seamounts, and (b) the Great Meteor Seamounts and the Azores Plateau (black), and the mid-Atlantic Ridge (grey). The Great Meteor Seamounts are a line of seamounts extending north and a little west of Great Meteor Seamount as shown in detail in later figures. These are major obstacles faced by a Meddy translating westward in the Atlantic. Typical Meddies are shown schematically to be 800 m in vertical extent and 100 km in diameter. The Meddies are shown centered where they could possibly translate westward without colliding with seamounts. Depth profiles were created by plotting the shallowest depth at each latitude using ETOPO2 data (Smith & Sandwell, 1997) in meridional swaths in the Iberian Basin 11°W–17°W (Horseshoe Seamounts), in the Canary Basin 25°W–32°W (Great Meteor Seamounts), and along the mid-Atlantic Ridge 32°W–45°W.

meters of the sea surface. Four Meddies skirted around the northern and western limits of these seamounts (4, 6, 9, 10—assuming that Meddy 10 would follow the trajectories of Meddies 4, 6 and 9) [Fig. 3(b)]. Once clear of the seamounts, these Meddies would then have had an unrestricted path into the Canary Basin. However, one Meddy (4) that had successfully passed to the north of the seamounts then jogged eastward near 34–35°N and made a glancing collision with Madeira Island [Fig. 4(a)]. The eastward jog is interpreted to be the result of the Meddy's interaction with the Azores Current, which is normally located near this latitude (see Käse & Zenk, 1996; Tychensky et al., 1998 and Sparrow et al., personal communication). The closest approach of the Meddy center to the 1000 m isobath of Madeira was around 40 km, so the outer edge of this Meddy's circulation is interpreted to have impinged on the continental slope of the island; this disrupted its normal pattern of circulation so that the two floats which had been looping in its core shifted from undertaking small (<20 km diameter) loops to larger (>50 km) loops. Fig. 3(a) shows the trajectory of one of the floats in Meddy 4. At the time the feature increased in diameter, the float temperature dropped by 1°C. Both floats continued to loop until they completed their missions and surfaced, one about two weeks and the other three months after the collision.

Nine Meddies translated directly into the vicinity of the Horseshoe Seamounts. Seven of these Meddies (1, 5, 7, 11, 13, 18, 19) collided with seamounts and in six cases (1, 5, 11, 13, 18, 19) the float looping characteristics were either modified or the floats ceased to loop; implying there had been a disruption or even perhaps total destruction of the normal coherent Meddy circulation. We assume that if floats in a Meddy suddenly cease looping, that the Meddy has been destroyed. But until confirmatory evidence is obtained, this must remain a hypothesis. Meddies 13 and 18 were counted as two Meddies even though they coalesced before colliding with the seamounts. A particularly clear example of a collision is given by Meddy 13 (Fig. 10) which collided with several seamounts including Josephine (<200 m minimum depth) and Lion (<600 m depth). At the time of impacts the looping period of the two floats, MD136 and MD137, increased (one is shown in Fig. 10). In late September 1994, the temperature of float MD137 dropped suddenly by about 0.5°C, and temperature fluctuations increased, indicating that the core water was mixing with its surroundings (Fig. 10). Float temperatures continued to decrease until just after the feature had collided with Lion Seamount in December 1994 when both of the floats ceased to loop. Floats in two other Meddies (1, 11) also stopped looping following a collision with a seamount. Schultz Tokos et al. (1994) reported that when Meddy 1 collided with Josephine Seamount both the float and a surface drifter were expelled "as if the seamounts acted as a wedge to break off the outer pieces" of this Meddy.

None of the Iberian Basin Meddies was tracked completely through the seamounts and out the other side, implying that the seamounts are a major impediment to the passage of the Meddies. However, many of the floats reached the end of their missions and surfaced near the time of collision which curtailed the trajectories and made it impossible to discriminate details of many post-collision disruptions. It remains possible that after colliding with seamounts, Meddy remnants may have

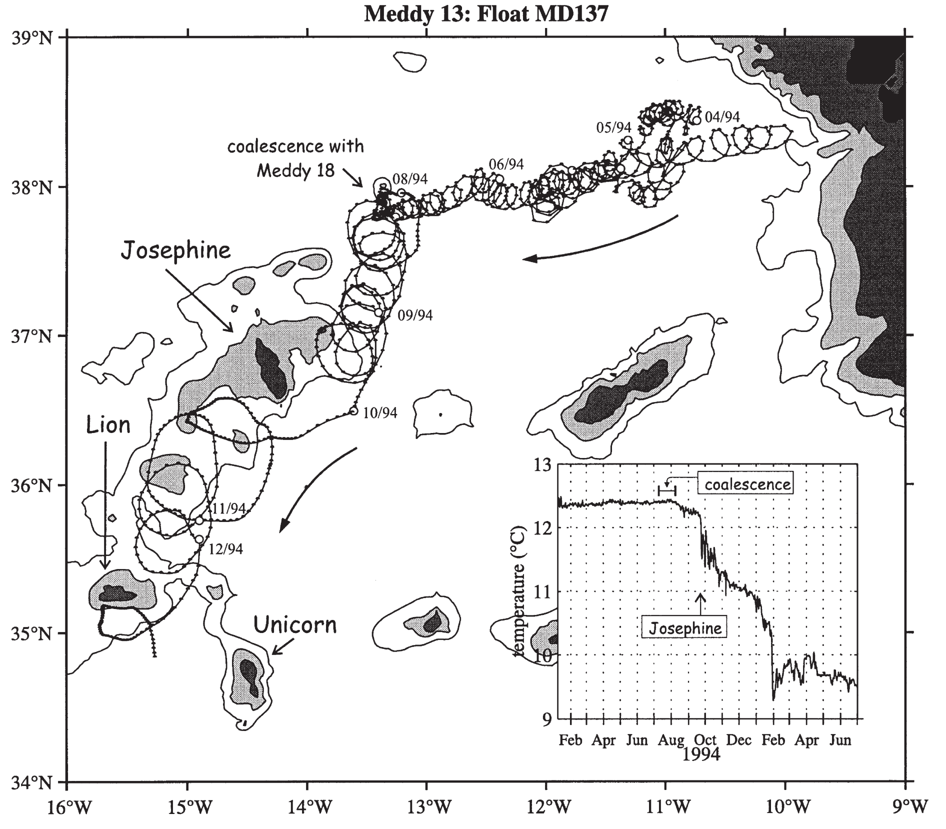


Fig. 10. Trajectory of float MD137 in Meddy 13 from January 1 to December 25, 1994. Meddy 13 was discovered by Pingree (1995) near 38.4°N 10.0°W adjacent to the continental slope near Lisbon Canyon and had presumably just formed. Pingree launched two surface drifters, two ALACE floats and two RAFOS floats into this Meddy. In July and early August Meddy 13 collided and coalesced with Meddy 18 (see Fig. 7). In September and October 1994 Meddy 13 skirted around the southeastern side of Josephine Seamount (<200 m depth) and then translated over or near two other seamounts southwest of Josephine (one <800 m depth and the other <1600 m depth). In December Meddy 13 passed over or around Lion Seamount (<600 m). The loops of float MD137 increased in diameter from 10 to 40 km during the coalescence with Meddy 18 and to 50 km after colliding with Josephine Seamount. Both floats MD136 and MD137 stopped looping in December 1994 after passing over or around Lion. The cessation of looping after the final collision implies that Meddy 13 was severely disrupted if not totally destroyed by its collisions with the Horseshoe Seamounts. The inset shows temperature time series measured by float MD137 near a depth of 930 m in Meddy 13. On September 20, 1994, as Meddy 13 collided with Josephine Seamount the temperature dropped from 12.1 to 11.6°C. From September 20 into January 1995 as Meddy 13 passed over several seamounts the temperature gradually decreased to 10.5°C accompanied by temperature fluctuations up to 0.5°C. During this time the float was looping at a diameter of 50–80 km. Float MD137 stopped looping on December 25, 1994, just after passing over Lion Seamount. Afterward (not shown) float MD137 slowly translated south to around 31N. At the end of January the temperature dropped to 9.4°C and then stabilized near 9.7°C. The cooling after December 25 occurred after the float stopped looping, possibly indicating the mixing of a Meddy remnant with the background fluid.

translated southwestward, but there is no supporting evidence. It is not surprising that collisions with tall and even not-so-tall seamounts seem to have an important effect on the Meddies' structure considering the deep extension of swirl velocity.

Observations of a Cyclone: Six floats looped counterclockwise at various times in a large cyclonic eddy which was first observed in April 1993 southwest of the Tejo Plateau. It was followed for about six months, and Fig. 11 shows the tracks of all the floats in and around the cyclone in monthly segments, and includes floats in nearby Meddies. Fig. 12 also shows some detailed trajectories in the cyclone and Meddy 6. The smallest loops in the cyclone had a diameter of 30 km and period of rotation of 7.5 days [Fig. 12(d)]. Largest loops had a diameter of 140 km and rotation period of over two months. Maximum swirl speed in the cyclone was around 10 cm/s, about one-third that of Meddies. During the six months it was tracked, the cyclone translated westward along 38.5°N from 11.5°W to 13.5°W at a mean velocity of 1.1 cm/s [Figs. 3(b) and 12(a)]. During this time the cyclone's center was about 115 km from the center of Meddy 6 which was translating southwestward at 1.9 cm/s at the same time [Fig. 12(a)]. As a result, the line from the cyclone's center to the Meddy's center rotated counterclockwise about 95°, from 330° to 235° [Fig. 12(a)]. This rotation direction is consistent with simple inviscid vortex kinematics if the relative vorticity of the cyclone was larger than that of the Meddy. Although the maximum swirl velocity in the Meddy was larger than that in the cyclone (about 30 versus 10 cm/s), the latter may have had faster swirl velocities than the Meddy at larger radii, thus giving the cyclone the larger circulation overall.

The Meddy and cyclone exchanged water around their peripheries as documented by four floats (IB39, IB44, IB45, IB49) which moved from one eddy to the other. The track of one of these, IB39, is shown in Fig. 12(c). Float IB39 made a partial loop in the cyclone during April, then looped twice in Meddy 6 in May and June, and then looped twice back in the cyclone during July–October. Floats IB49 and IB44 looped in Meddy 6 in April–early June and switched to the cyclone in mid June. Float IB44 left the cyclone in July, but float IB49 continued to loop in it through September. The trajectory of IB44 in the cyclone is shown along with three others in Fig. 12(d). Three floats (IB44, IB45, IB49) left Meddy 6 and entered the cyclone in June, the month that the centers of the two eddies were the closest (~90 km). The temperature measured by floats in the cyclone was colder than in the Meddies but similar to background water, to the extent it could be measured by a few floats.

The exchange of water and the rotation of the line between their centers suggest that the two eddies were interacting. It is also possible that the cyclone was interacting with Meddy 5 during April and May 1993, but only one float was in Meddy 5 and no floats were exchanged between eddies (Fig. 11). The center of Meddy 5 was 60 km from the cyclone's center and was translating in a counterclockwise direction relative to the cyclone from mid April–mid May in accord with the cyclone's swirl rotation. Later, during September and October, the cyclone was surrounded on three sides by Meddies 5, 6 and 9 at distances of 120 to 180 km (Fig. 11). The counterclockwise circulation in the cyclone may have advected Meddy 9 farther to the north than it would have gone otherwise and far enough north to avoid collision with the Horseshoe Seamounts.

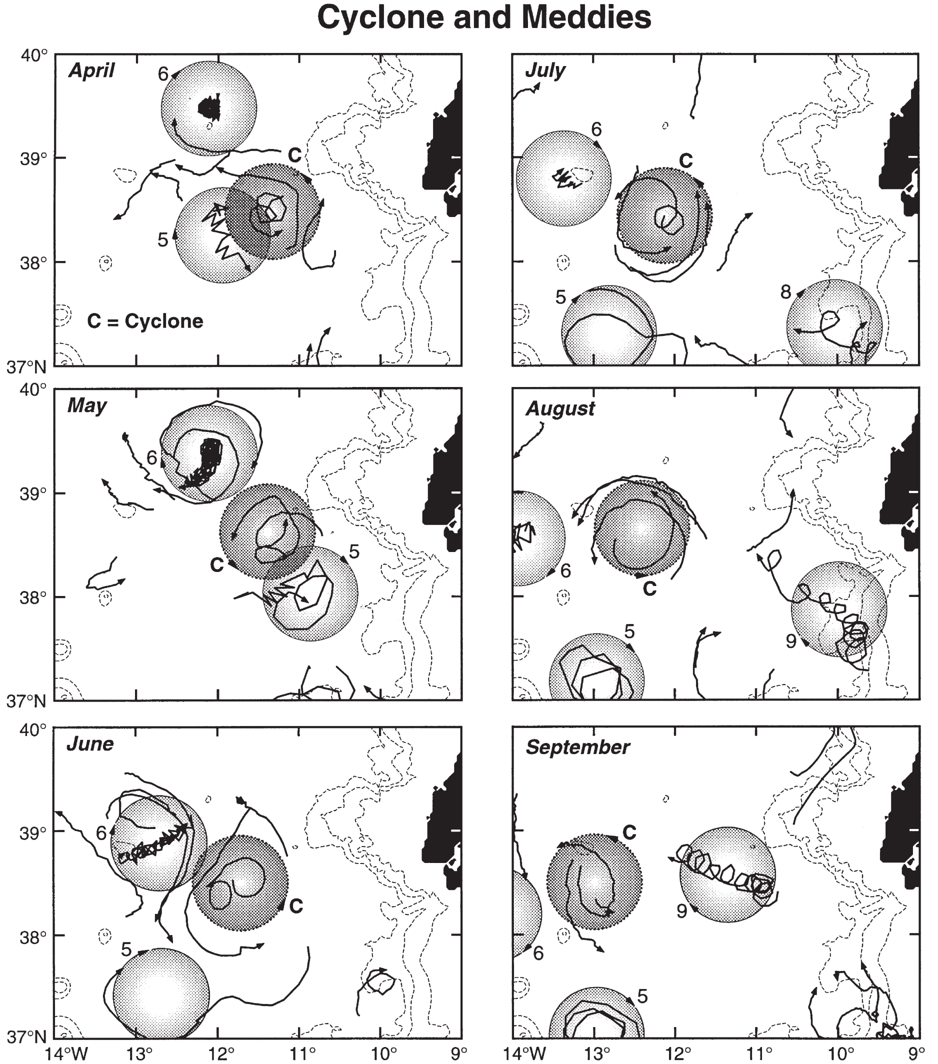


Fig. 11. Time sequence showing month-long segments of all floats in and around a coherent cyclone observed between April and September 1993 southwest of the Tejo Plateau. The Meddies and cyclone are indicated schematically here with circles 100 km in diameter which show the approximate overall size of the eddies. The circles overlap at times (April–June) which implies that the eddies were probably connected and interacting.

This well-documented large cyclone and a few other counterclockwise loops in other cyclones suggests that they could be relatively common features and possibly important to Meddies. These data raise several questions about the cyclones—what is their origin and structure? How frequent are they? What is their connection to

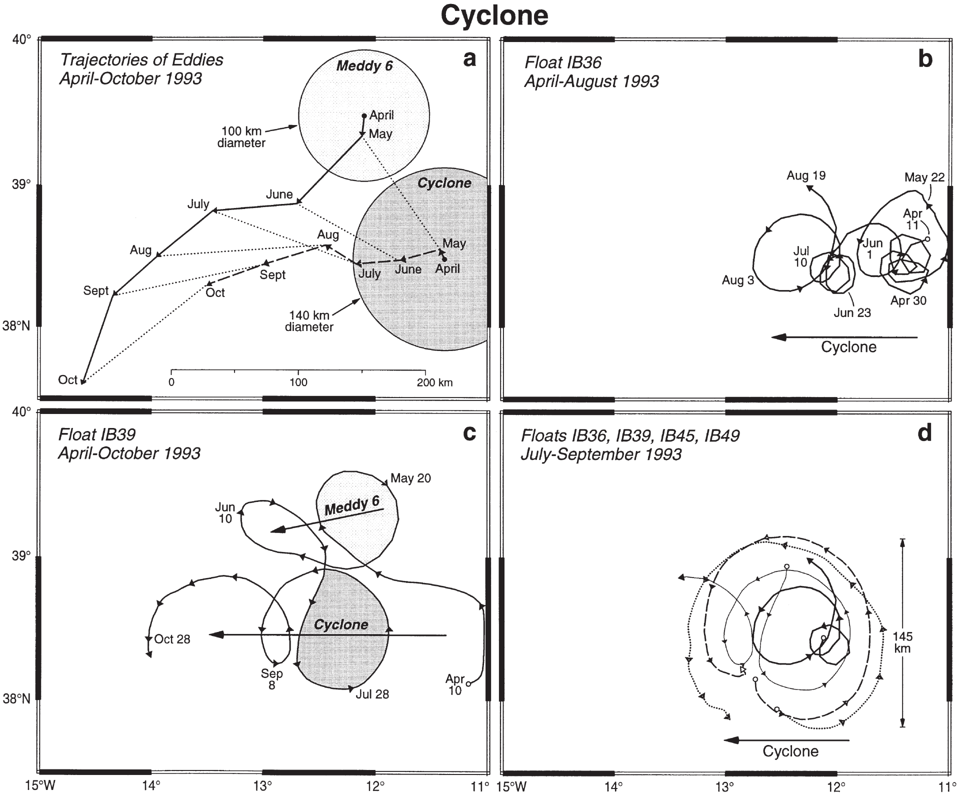


Fig. 12. Detailed observations of a large cyclonic eddy. (a) Monthly positions of Meddy 6 and the cyclone based on looping float trajectories. The circles added to the April positions indicate the eddies' overall size. Meddy 6 translated counterclockwise relative to the cyclone and was possibly advected by it. (b) Trajectory of float IB36 as it looped in the cyclone from April 11 to August 19, 1993. (c) Trajectory of IB39 from April 10 to October 31, 1993, as it looped alternately in the Meddy and cyclone. One loop in each eddy was shaded to differentiate them. (d) Four floats (IB36, IB39, IB45, IB49) looped in the cyclone during July to September 1993.

Meddies? Do the cyclones and Meddies interact and so advect each other as implied by the relatively persistent linking between the cyclone and Meddy 6?

Some information about the relative population of cyclones at the depth of the Mediterranean Water can be inferred from AMUSE floats. These floats looped in 24 eddies as defined by at least two consecutive float loops in the same direction. One-third of the eddies were cyclonic, and roughly 10% of the total number of loops were cyclonic. Several floats became trapped in Meddies (9, 10, 18) for long periods during which they made many loops and this increased the total number of anticyclonic loops observed. This was not the case for floats in cyclones. The AMUSE floats were launched in the warm salty Mediterranean Undercurrent and so they were biased in favor of anticyclone (Meddy) formations. A similar seeding strategy was applied during the preceeding Iberian Basin Experiment cruises when floats were launched intentionally in Meddies. Thus, these floats probably also give an underestimate of the population of cyclones in the Iberian Basin.

3.1.4. Meddy lifetimes

Four of the 13 longest tracked Meddies in the Iberian Basin skirted around the northern side of the Horseshoe Seamounts and the other nine translated into the seamounts. This suggests that roughly 70% of Meddies entering the Iberian Basin collide with the Seamounts reducing the numbers of pristine Meddies that move on into the Canary Basin to 30% of the original numbers. The typical lifetime of Iberian Basin Meddies, inferred by piecing together trajectories of newly formed Meddies with those that collided with seamounts, is around 0.7 yr. One Meddy (7) was tracked only 26 days before it collided with Gorringe Ridge ($<$100 m deep) at which time the float finished its mission and surfaced. Four other floats had estimated lifetimes of 0.5–1.2 yr. The average lifetime of 0.7 yr is, therefore, probably an underestimate of the lifetime of Iberian Basin Meddies, especially as some may continue to exist as remnant features after collision.

The large number of Meddy collisions with seamounts and the inferred dispersal of Meddy floats during and after collisions is evidence that much of the salty Mediterranean outflow water advected by these Meddies is dispersed into their surrounding region as suggested by Käse and Zenk (1996) from a smaller data set. The frequent collision of Meddies with the Horseshoe Seamounts could be partly responsible for the very salty water located in the Mediterranean tongue there (see, e.g. Lozier, Owens & Curry, 1995).

3.2. Canary Basin Meddies

Seven Meddies were tracked in the Canary Basin, Meddies 21–23 during 1983–1985 (Richardson et al., 1989) and Meddies 24–27 more recently during 1993–1995 (Richardson & Tychensky, 1998). Their overall diameters measured hydrographically ranged from 100 to 150 km and their periods of rotation measured with floats ranged from 3.6 to 6.0 days. Meddy 26, which had the fastest period of rotation of 3.6 days and largest diameter of approximately 150 km, contained a core of very warm (13.1°C) and salty (36.4) water with characteristics similar to those found in newly formed Meddies. This implies that Meddy 26 and also Meddy 24 (see Fig. 1) had not been modified significantly prior to reaching the Canary Basin.

Canary Basin Meddies generally translated southwestward although some translated southward and others westward (Fig. 13). Two Meddies (21, 23) translated southward at 1–2 cm/s into the southern Canary Basin where they slowly decayed (Armi et al., 1989; Hebert et al., 1990; Richardson et al., 1989). One of these (Meddy 21) was tracked by a float for 2.3 yr, the longest time a Meddy has been continuously followed. Meddy 4 seemed to be headed in this same direction when tracking stopped. Combining the trajectories of Meddy 4 and 21 suggests a total Meddy lifetime of around 4.1 yr, possibly longer considering the long life (1.5 yr) of Meddy 23 near 22°N 26°W. Meddy 23 was still quite energetic based on its fast rotation period ~5 days just before the SOFAR float stopped transmitting. Several Meddies

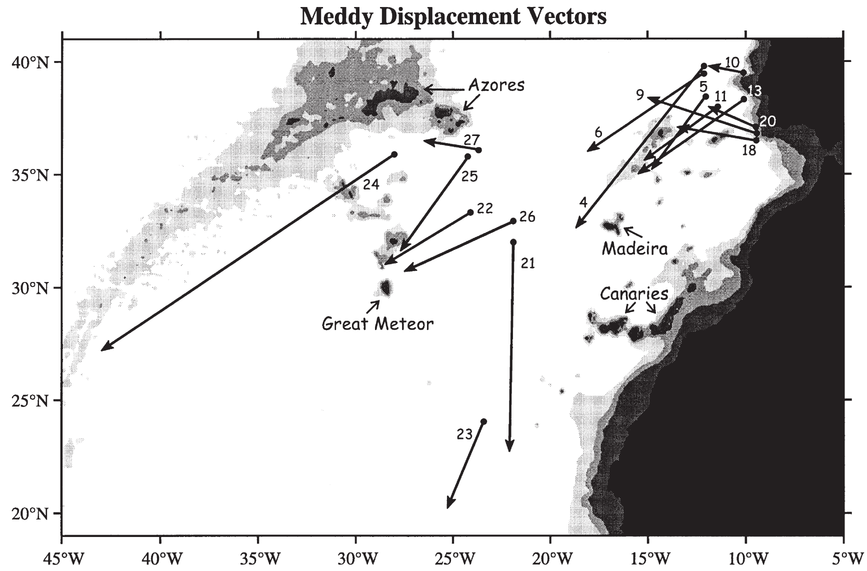


Fig. 13. Overall displacement vectors for 16 Meddies continuously tracked for at least 100 days. Depth contours (1000 and 2000 m) show the Horseshoe Seamounts, the Great Meteor Seamounts and the mid-Atlantic Ridge. The displacements of Canary Basin Meddies 22, 25, 26 all stop where their floats ceased to loop after the Meddies collided with seamounts. Meddy 24 collided with Plato Seamount but continued for at least another 1.2 yr despite significant changes of the Meddy's swirl velocity and temperature during the collision.

were observed hydrographically west of Meddies 21 and 23 in the area 25–30°W, 20–30°N providing further evidence that Meddies translate into this region (Richardson et al., 1991; Shapiro & Meschanov, 1996).

Five Canary Basin Meddies translated westward into the area just south of the Azores (31°N–37°N). Four of these collided with the Great Meteor Seamounts (22, 24, 25, 26) and the remaining one (27) made a glancing collision with the Azores Plateau near Santa Maria Island. The four that collided with seamounts appeared to be severely disrupted, and three (22, 25, 26) were possibly obliterated. At the time of the collisions, floats in the Meddies suddenly changed their looping characteristics and floats in three of the Meddies ceased looping altogether after periods of 1–3 months. The float temperatures decreased rapidly showing that colder fresher background water had become entrained into the Meddies reducing their temperature and salinity anomalies.

Below we describe some details of the collisions including temperatures measured by the floats. Some of this information, but not the temperature series, was presented and briefly discussed by Richardson and Tychensky (1998). Descriptions of Meddies crossing the Azores Current have been given by Käse and Zenk (1987), Tychensky and Carton (1998) and Tychensky et al. (1998).

3.2.1. Some case histories

Case histories of three Meddies reveal details of collisions with seamounts and show some important differences. Meddy 24 was a large and energetic Meddy with an overall diameter of 120 km measured hydrographically (see Fig. 1). Its track was being followed by three floats each of which had rather similar trajectories, one of which is shown in Fig. 14. Meddy 24 passed over a moderately sized seamount, Plato, which has a minimum depth of 476 m. After the collision the three floats, which had looping diameters of around 15 km, suddenly increased these diameters to 25–60 km and the float temperatures dropped abruptly over approximately three weeks. All three floats continued to loop for a long time ($>$1 yr) after the collision. The float temperatures, coupled with a previous shipboard survey of the Meddy, suggest that it cooled by 1.0–1.5°C (~1/3 to 1/2 of its temperature anomaly) during the collision, but thereafter its temperature remained fairly constant. This shows that it is possible for a Meddy to survive a collision with a moderately-sized seamount and to continue in a modified form for a long time afterwards. Despite this collision, disruption and cooling, Meddy 24 set the record for having the fastest long term mean velocity, 3.9 cm/s (over 1.5 yr), and moving the longest distance, ~1700 km, over which a Meddy has been continuously tracked. By the time the tracking floats surfaced, this Meddy had traveled almost 60% of the distance across the Atlantic (from the Iberian Peninsula toward the Caribbean Sea in the direction of the Meddy's mean velocity). Combining the trajectories of Meddies 6 and 24 and filling in the gap with typical Meddy velocities suggests that Meddy 24 was around 4.0–4.6 yr old when the floats tracking it surfaced. At that time it was still quite an energetic Meddy (period of rotation of 6.2 days at 30 km diameter),so its total lifetime could have been $>$5 yr and long enough for it to cross over the mid-Atlantic Ridge into the western North Atlantic.

Meddy 25 was a rather modest feature with a 100 km overall diameter that collided with two major seamounts, Cruiser and Irving (Fig. 15). Cruiser has two peaks extending above 800 m and Irving has a minimum depth of 262 m (Hunter, Searle & Laughton, 1983). Two floats with very similar trajectories tracked Meddy 25; one is shown in Fig. 15. Both floats had been looping in the core of Meddy 25 before the collision and both ceased looping within three weeks of the collision, during which time float temperatures rapidly cooled by 2–3°C. An earlier Meddy (22) collided with another major seamount, Hyeres, and its two floats also abruptly stopped looping and cooled rapidly (Richardson et al., 1989). These records are interpreted to show how collisions with seamounts can be rapidly fatal to Meddies.

Two months after Meddy 22 had collided with Hyeres Seamount the regions near the seamounts and the two floats (which had been looping in the Meddy) were surveyed by XBT and CTD (Richardson et al., 1989). No obvious remnant salty water from the Meddy was found showing conclusively that the floats were no longer in the Meddy. However, it is possible that a remnant of the Meddy could have translated out of the region before the survey began.

Meddy 26 was an unusually large (150 km diameter) and energetic feature that also collided with Cruiser and Irving Seamounts in June and July 1994 (Fig. 16). At the time of the collisions this Meddy appeared to have been cleaved by the sea-

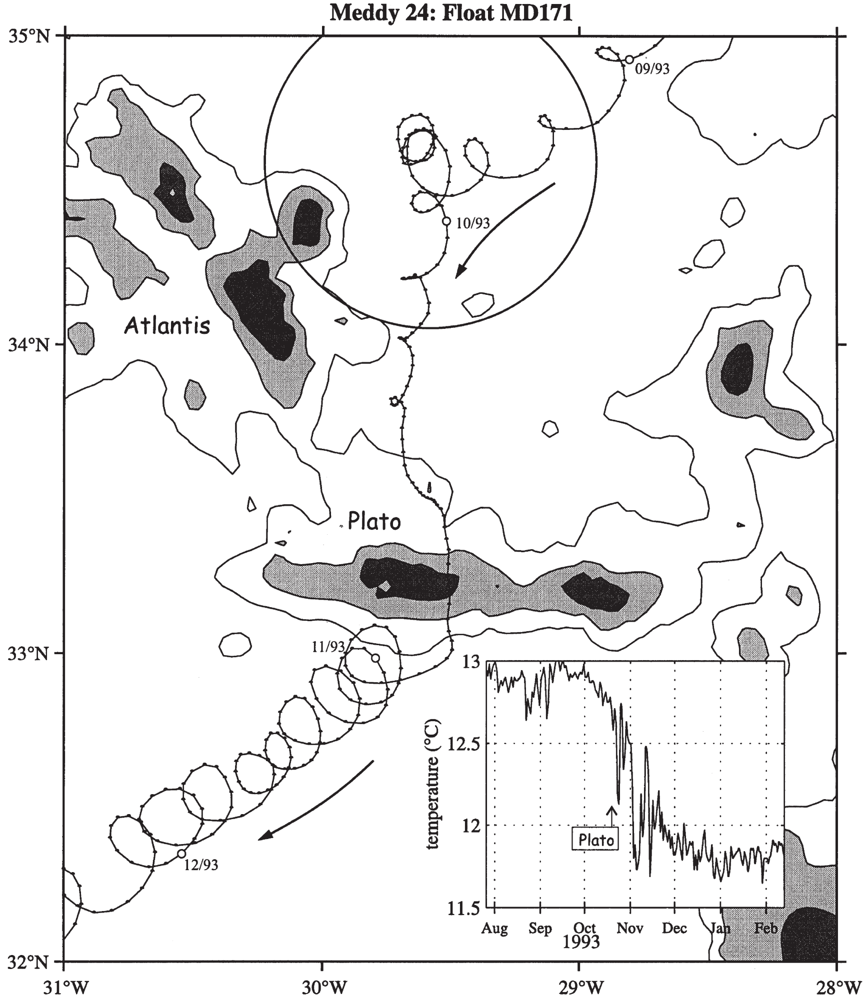


Fig. 14. Trajectory (September–December 1993) and temperature of float MD171 (near 900 m) in Meddy 24 as it stopped just east of Atlantis Seamount, then translated southward over Plato Seamount (476 m minimum depth), and then southwestward. As the Meddy passed over Plato on October 21, 1994, the float loops increased in diameter from around 15 to 25 km. From October 21 to November 3 the float temperature decreased around 1°C accompanied by temperature fluctuations up to around 0.8°C. All of the decrease in temperature was due to the Meddy cooling (versus radial float displacement) as determined by comparing the float temperature, diameter and depth (~900 m) with a temperature survey at the time of float launch. Float MD171 continued to loop in Meddy 24 until the float surfaced at the end of its mission on January 15, 1995. Float MD171 completed 102 loops at an average period of rotation of 5.2 days. The overall diameter of this Meddy based on a hydrographic survey before the collision (Fig. 1) was around 120 km as shown by the circle.

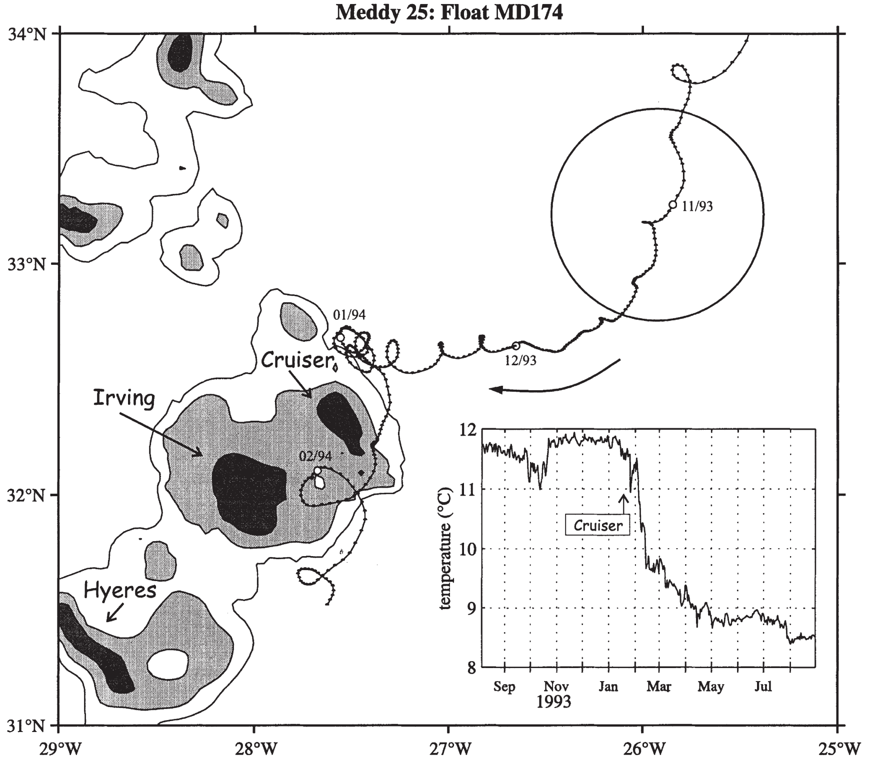
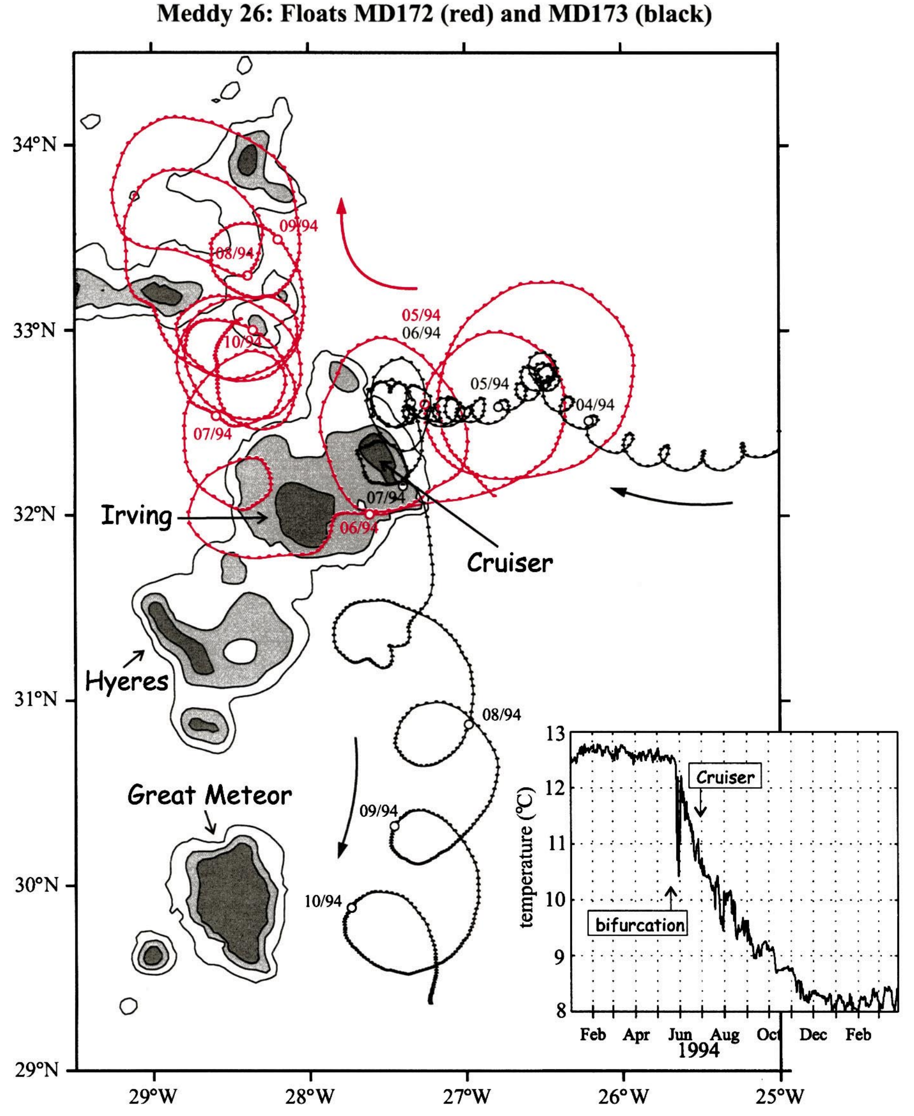


Fig. 15. Trajectory and temperature of float MD174 in Meddy 25 as it translated over Cruiser Seamount on January 26, 1994, and made a close pass to Irving Seamount. Float MD174 stopped looping on February 13, 1994. The trajectory is terminated in the figure where the loops stop. A second float (MD172) in Meddy 25 with a similar trajectory stopped looping on February 6. The main decrease in temperature of these two floats at depths of 1000–1050 m was over a three week period, January 26–February 15, although the temperature of float MD174 continued to decrease at least through March as the float remained in the same general area and depth but did not loop. The total decrease in temperature was around 3°C. The overall diameter of Meddy 25 measured hydrographically before the collision was around 100 km as shown by the circle.

mounts into two roughly equal-sized smaller Meddies. The larger remnant was shown by float MD173, which had been looping in the core before the collision, to translate southward over Cruiser Seamount into the area just east of Great Meteor Seamount; the float stopped looping on October 15 (Fig. 16). The bifurcation of Meddy 26 was revealed by float MD172 which had been looping in the outer part of Meddy 26 but was diverted around the south side of Cruiser and Irving Seamounts, where it began looping in a separated feature west of Irving (Richardson & Tychensky, 1998). Float MD172 then looped and translated northward to 34°N, then back south. This float also stopped looping on October 15 but continued to drift (not shown).

Floats in Meddy 26 revealed several interesting features. First they show that Meddies can be broken into large pieces, which can survive as separate entities for



Meddy 26: Floats MD172 (red) and MD173 (black)
34°N
33°N
32°N
31°N
30°N
29°N
29°W
28°W
27°W
26°W
25°W
09/94
08/94
10/94
07/94
05/94
06/94
05/94
04/94
07/94
06/94
Irving
Cruiser
Hyeres
Great Meteor
08/94
09/94
10/94
temperature (°C)
13
12
11
10
9
8
Cruiser
bifurcation
Feb
Apr
Jun
Aug
Oct
Dec
Feb
1994

several months before the floats stopped looping. This was for much longer than the floats in Meddies 22 and 25 continued to loop after their collisions with seamounts. Perhaps the very large size and strength of Meddy 26 resulted in its slower decay after its collision.

Secondly, some cold water intrusions, 2°C cooler than the Meddy core temperature, were recorded at the time the Meddy 26 bifurcated, which are interpreted to be intrusions of background water.

Thirdly, the small loops east of Hyeres Seamount (near 31.3°N 27.5°W) embedded in a large loop of the trajectory (Fig. 16) could be indicative of a piece of the original Meddy core continuing to rotate with the original core rotation rate, but having been displaced radially to a much larger diameter by the collision. The small rapidly rotating piece might also have been generated directly by the seamounts as the Meddy circulation passed over or around them. At the time of the small loops, the float temperature had decreased to around half of the Meddy temperature anomaly which had been around 4°C before the collision. It is possible that smaller scale embedded eddies like this one could enhance the stirring and mixing of Meddy water with background water and be partially responsible for rapid post-collision decay.

3.2.2. Mean Meddy lifetimes

Taken together the fates of the three Meddies (22, 25, 26) show that the Great Meteor Seamounts are a major obstacle to Canary Basin Meddies freely translating westward between 29°N and 35°N. The estimated lifetimes of these three Meddies up until the time of impact was about 3.0 yr based on the velocity of Iberian Basin Meddies. The estimated lifetimes of the two Meddies (21, 23) that translated southward and so avoided the seamounts, and also of Meddy 24, which survived its collision with Plato, was around 5 yr.

Fig. 16. Trajectory (March–October 1994) and temperature of float MD173 at a depth of 1080 m in Meddy 26 as it translated westward between 32°N and 33°N, and collided with and stopped (June 1) just north of Cruiser Seamount. On July 1, 1994, Meddy 26 translated southward over Cruiser Seamount and next to Irving Seamount and continued south until the loops stopped on October 15. Near 31.2°N 27.5°W float MD173 made three small clockwise loops (~10 km diameter, 4 day period) embedded in a larger scale loop (~60 km, 25 day). The temperature remained at around 12.5°C until May 28 when several cold temperatures were recorded. The minimum temperature was 10.4°C, 2° colder than the Meddy core. These cold temperatures occurred just as Meddy 26 bifurcated into two smaller Meddies. The temperature gradually decreased to ~9°C as float MD173 looped at a roughly constant diameter. The temperature continued to decrease somewhat after the float stopped looping where the trajectory was terminated. The trajectory of float MD172 during April 4–October 15, 1994, is shown in red. This float made concentric loops around float MD173 and the Meddy center during April and May. In June MD172 was diverted south of Irving Seamount and began looping west of Irving in what is interpreted to be a piece of the original Meddy which bifurcated in early June and which appeared to be topographically trapped near 33.0°N 28.5°W. The overall diameter of Meddy 26 before it bifurcated was around 150 km or 1.4 degrees of latitude.

3.3. Census of Meddies in the Iberian and Canary Basins

During 1993 and 1994, 21 Meddies were observed by looping floats. The number of Meddies tracked at the same time reached a peak of 14 in February 1994 when 11 Meddies were observed in the Iberian Basin area and three more in the Canary Basin (Fig. 17). Four of the Meddies (11, 13, 14, 15) were located close to each other west of Cape St Vincent.

Large numbers of Meddies were observed simultaneously in the Iberian Basin during November 1993–April 1994 (Fig. 18). During this time the formation of six new Meddies were observed (13–18); two of these (14, 18) were newly formed near Cape St Vincent and two (16, 17 possibly also 13) near the Tejo Plateau west of Lisbon (Bower et al., 1997). Floats were launched directly into Meddy 13 near the eastern boundary (Pingree, 1995) and a float was entrained into Meddy 15. At the same time five Meddies were lost track of, three (5, 10, 17) because the floats completed their missions and surfaced, and two (12, 14) because the floats left the Meddies when near the eastern boundary. These observations are remarkable for showing the large population of Meddies in the Iberian Basin, and their distribution and movement over a six month period. Aside from the erratic behaviour of Meddy 4 in November and January and Meddy 13 in February and March, the Meddies translated northwestward along the western Iberian coast and southwestward in the interior Iberian Basin. Our census, which relies exclusively on Meddies tracked by floats, supplements an earlier inventory compiled by Shapiro, Zenk, Meschanov and Schultz Tokos (1995) which was based primarily on hydrographic surveys in the Iberian and Canary Basins.

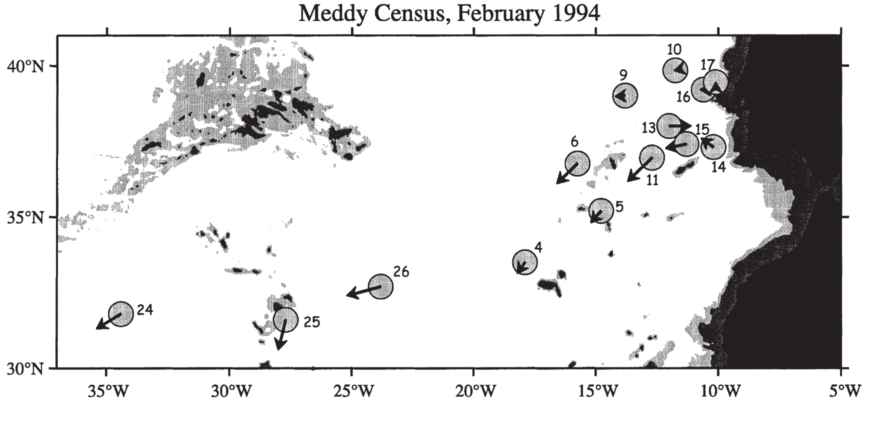


Fig. 17. A census of Meddies in February 1994, the month with the most observed Meddies. Fourteen Meddies were tracked, eleven east of 18°W and three in the Canary Basin, 23°W–35°W, with at least one float looping in each Meddy. Vectors show the translation of Meddies between February and March 1994. Circles with a diameter of 100 km show the location and typical overall size of the Meddies. Some Meddies could be smaller than 100 km and others larger. Our interpretation is that two different Meddies coexisted where 16 and 17 are shown, and that at least Meddy 17 was much smaller than the schematic 100 km diameter.

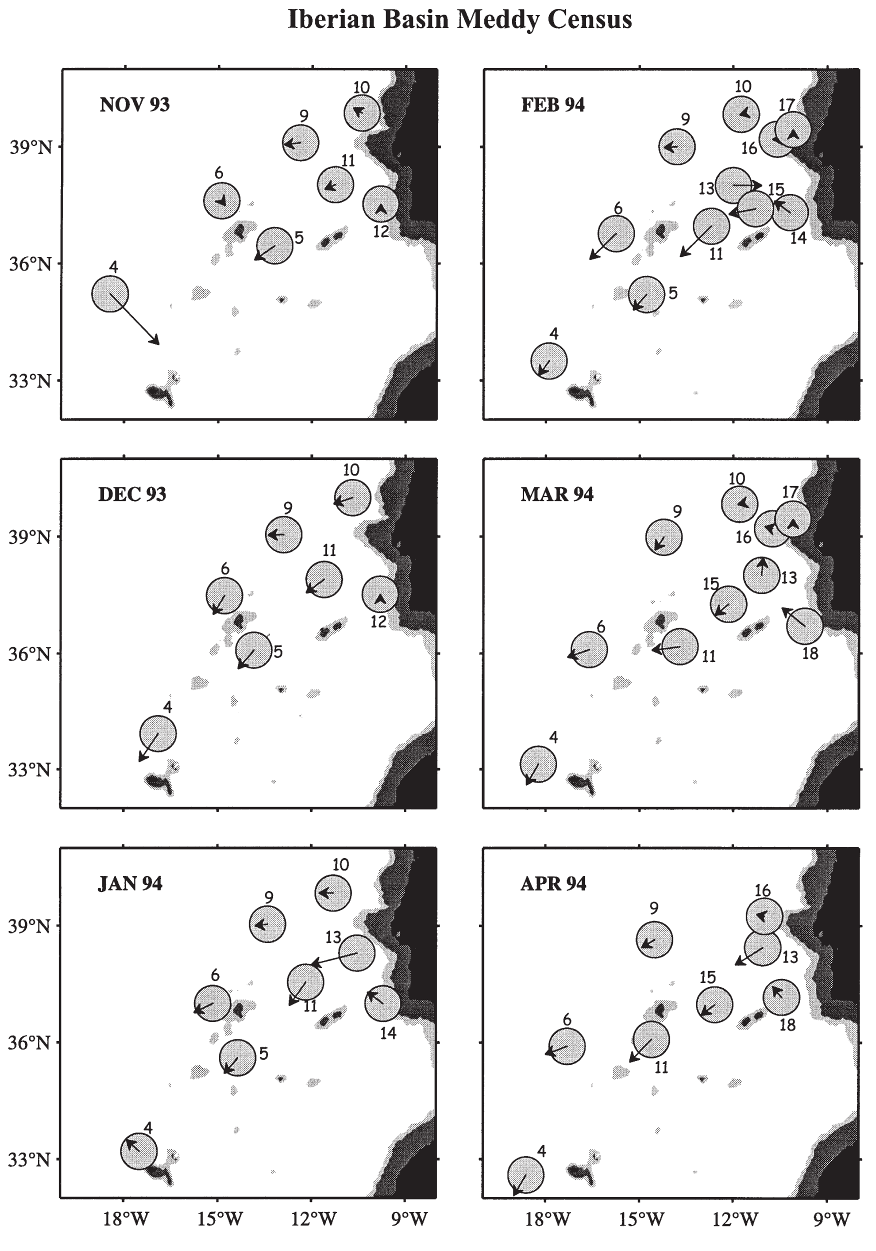


Fig. 18. Sequence of Meddies observed by looping floats in the Iberian Basin November 1993–April 1994. Meddies are indicated schematically by 100 km diameter circles. Some Meddies such as 12, 14, and 17 near the eastern boundary were probably smaller than 100 km as implied by the circles which overlap the 1000 m depth contour (see Appendix A for diameter). The velocity of each Meddy between positions one month apart is shown by vectors. Fig. 17 is an expanded area version of the February 1994 subplot.

It is possible that a few Meddies may have been counted twice, which would reduce the total number of tracked Meddies during 1993–1994. For example, Meddy 19 could have been a subsequent observation of Meddy 15 [Fig. 3(b)]. There was a two-month gap between the end of April 1994 when float AM103b stopped its regular looping in Meddy 15 and the end of June when float AM115 to loop in Meddy 19, but its estimated velocity during the gap in observations from mid April to mid July ~2.3 cm/s southward was similar to the mean velocities of Meddy 15 (1.8 cm/s) and Meddy 19 (2.5 cm/s). In addition, during May 1994 float AM103b made one final but slower loop which was consistent with a southward Meddy translation, and during June three float trajectories suggest a general clockwise circulation centered along the inferred southward translation between Meddies 15 and 19. Since it seems probable that these two Meddies were the same, their two trajectories are shown connected by a dashed line in Fig. 3(b). If indeed they are the same Meddy, then this Meddy was tracked a total of 9 months over 385 km. There is also a remote possibility that in the Canary Basin, Meddy 27 may have been a subsequent observation of Meddy 6, but there was a 4.6 month and 500 km gap between the two series. If they were the same feature the inferred velocity between the end of the trajectory of Meddy 4 and the beginning of Meddy 27 is westward at 4 cm/s which is roughly double the mean velocities of Meddies 6 and 27, so the evidence connecting these two Meddies is poor.

4. Overall Meddy lifetimes

The mean lifetime of a newly formed Meddy was crudely estimated to be 1.7 yr by combining the ratios of Meddies that hit seamounts with the times to collision (Meddy 27 was excluded as being too short to be informative). Since warm salty remnants of Meddies (less warm and salty than typical Meddies) could possibly continue undetected after the collisions, the mean lifetime of 1.7 yr could underestimate the total lifetime including Meddy remnants. This estimate coupled with the estimated 17 Meddies which form each year (Bower et al., 1997) suggests that at least 29 Meddies coexist in the North Atlantic. Coalescence of some Meddies (as reported here and by Schultz Tokos et al., 1994) would reduce this estimate, conversely the splitting of other Meddies (Richardson & Tychensky, 1998) would tend to compensate this reduction. The recent observations of Meddies and Meddy-like eddies to the north of those reported here (Paillet et al., 1999; Bower et al., 1999) would increase the estimate of co-existing Meddies.

5. Discussion

5.1. Collisions with seamounts

Floats in the core regions of Meddies that remained clear of seamounts, islands and the eastern boundary continued to loop for long times in a very regular pattern of nearly constant diameters and periods and showing persistent temperatures (Meddies 4, 6, 9, 10, 13, 18, 20–26). In contrast, floats in these Meddies that collided with seamounts rapidly changed their looping characteristics and showed rapid cooling; in at least four cases (Meddies 13, 22, 25, 26) their looping ceased altogether. These observations are interpreted to show that the normal roughly circular swirl circulation around the anomalously warm and salty Meddy core is disrupted by the seamounts. When collisions are either glancing or off-centered (Meddy 4) or are with smaller seamounts (Meddy 24) the Meddy may not be destroyed as demonstrated by floats continuing to loop for long times afterward. However, when the collisions are with major seamounts like Lion, Cruiser, Irving, and Hyeres, the disruption can be severe or fatal, as was implied by eight floats in four Meddies (13, 22, 25, 26) that ceased looping altogether. In each of these Meddies, two floats located at different locations within the Meddy core prior to the collision and which ceased looping, cooled more or less simultaneously implying that most if not all the core had been suddenly disrupted. After a few weeks (Meddies 22, 25) to a few months (Meddies 13, 26) the core water in these features had been dispersed into the background. There is the possibility that an unobserved remnant Meddy could have continued after the floats stopped looping, but there are no data from any of the four Meddies (13, 22, 25, 26) to confirm this hypothesis.

At the time that five Meddies (4, 13, 24–26) collided with seamounts the float temperature decreased accompanied by rapid (few days) fluctuations typically of 0.5–1.5°C. Some of the observed temperature decrease occurred while the floats continued to loop at a nearly constant diameter and depth (Meddies 4, 13, 26) showing that the whole Meddy was cooling. These observations are interpreted as showing that colder and fresher background water had been entrained into the Meddies and mixed with core water, and this cooled and freshened the whole Meddy structure and decreased its anomalous characteristics of heat and salinity. The decreased temperature and salinity anomalies imply decreased radial density gradients between the Meddy core and background water. Reduced gradients are consistent with decreased swirl velocity and increased period of rotation. This cooling occurred very rapidly, over a few weeks in the case of Meddies 22 and 25, which was much shorter than the 5 yr lifetime of these Meddies that remain clear of seamounts. In several cases (Meddies 13, 25, 26) the floats continued to show temperatures continued to decrease even after they had stopped looping. This implies that pieces of the Meddy too small or weak to rotate, or rotating too slowly to be detected by floats, were being dispersed into background water, gradually eroding any remaining Meddy temperature and salinity anomaly.

Four Meddies (13, 24, 25, 26) briefly stopped translating after colliding with seamounts and then turned left and continued to translate southward around the seamounts or clusters of seamounts. Examples include Meddy 13 near the Horseshoe Seamounts (Fig. 10), Meddy 24 near the Atlantis Seamount cluster (Fig. 14), and Meddies 25 and 26 near the Cruiser–Irving cluster (Figs. 15 and 16). This sense of translation is in accord with models of barotropic anticyclonic eddies which tend to translate in a clockwise sense (and also downslope) around a broad topographic hill (Carnavale, Kloosterziel & van Heijst, 1991). The implication is that a barotropic component of

Meddy swirl velocity extended deeply enough to impinge on the seafloor topography and hence steer the Meddy around the seamount cluster and into deeper water. Although many seamounts are smaller than the Meddies, it is possible that the Meddies may be responding to the integrated effect of the seamount clusters.

5.2. Detrainments near eastern boundary

Some floats detrained out from Meddies that had not collided with seamounts. These detrainments (Meddies 2, 3, 8, 14, 16) occurred preferentially in the vicinity of the eastern boundary, sometimes shortly after a Meddy had formed (Meddies 8, 14, 16). Losses of floats from these Meddies may occur for several reasons: (1) the expulsion of water from the Meddies as they undergo initial adjustment, (2) interaction of Meddies with the northward flowing Mediterranean Undercurrent (or other Meddies), (3) distortions caused by the impingement of the Meddy swirl velocity against the boundary, and (4) rapid translation of the Meddy which may result in the loss of water that is not trapped in the central core region.

6. Summary

At least 17 times each year Meddies are generated along the southwestern boundary of the Iberian Peninsula. They usually translate northwestward near the boundary, then more westward and finally southwestward with a typical speed of 2 cm/s. Roughly 70% of the Meddies are inferred to collide with the Horseshoe Seamounts, sometimes fatally: the remaining 30% pass northward around the seamounts and on into the Canary Basin. Four of the seven Meddies tracked in the Canary Basin collided with the Great Meteor Seamounts, three fatally. Overall, an estimated 90% of the Meddies collided with major seamounts after a mean lifetime of around 1.7 yr. Although some of these Meddies could have survived for some time after colliding with smaller seamounts, we consider the usual fate after a collision with a major seamount is for Meddy decay to accelerate foreshortening their lifetime relative to the estimated 5-yr (or more) lifetime of these Meddies that avoid impact with seamounts.

Eight floats originally looping in the cores of four Meddies that collided with seamounts were dispersed into the background water and ceased looping. This was interpreted as Meddies breaking up and their warm salty core waters being dispersed. The fall in the temperatures measured by floats previously looping in Meddies, especially the occurrence of cold spikes observed during collisions, is interpreted to be the entrainment of colder background water into the cores of the Meddies where it is rapidly mixed with warmer Meddy water. Therefore the floats were measured two processes—(i) the detrainment or dispersal of what was originally Meddy core water into background water and (ii) the entrainment and mixing of background water into the Meddy core. Some decrease of temperature continued to be detected by floats even after they had stopped looping, implying that pieces or blobs of Meddy water too small or weak to rotate had been dispersed into background water where their temperature and salinity anomalies decayed. The interference is that the large number of Meddy collisions with seamounts and their subsequent disruption is dispersing large amounts of the warm salty Mediterranean water carried into the vicinity of the Horseshoe and Great Meteor Seamounts by the Meddies. This dispersal of Meddy water is considered to be important process maintaining the high salinities located in the vicinity of the Horseshoe Seamounts.

The amount of data in Meddies during their collisions with Seamounts is limited so we recommend that more numerical and laboratory experiments are conducted to explore the physical processes that occur during these collisions. Model simulations could shed light on how much core water is expelled and how long remnant Meddies can exist. We expect that simulated float trajectories during collisions could help us further to interpret the RAFOS float trajectories and temperatures and to learn more about what occurs in the real ocean.

Acknowledgements

Contribution number 9910 from the Woods Hole Oceanographic Institution. Funds were provided by the US National Science Foundation grants OCE91-01033, OCE96-16952 and OCE93-01234 and the Deutsche Forschungsgemeinschaft (SFB 133), Bonn. An embryonic version of this paper was written while PLR was a visiting scholar at the Rockefeller Study Center in Bellagio, Italy. Heather Hunt, Christine Wooding and Jayne Doucette created most of the illustrations. Mary Ann Lucas typed the manuscript. Audrey Rogerson and two anonymous reviewers provided helpful comments on an earlier version. We are indebted to our many colleagues and shipmates who launched the floats and sound sources, tracked the floats, and created the valuable data used in this paper, especially Isabel Ambar, Larry Armi, Olaf Boebel, Yves Camus, Brian Guest, Heather Hunt, Bruno LeSquere, Kathy Schultz Tokos, Bob Tavares, Aude Tychensky, Jim Valdes, and Chris Wooding.

Appendix A

Table 1, see over.

Table 1
Summary of 27 Meddies[a]

Meddy number	Dates tracked (mo, day, yr)	Start N	Start W	End N	End W	Days tracked	Mean float depth (m)	Number of loops	Mean looping period (days)	Core looping period (days)	Mean velocity (cm/s)	Direction	Overall diameter (km)	References	Comments
Iberian Basin															
1	05 27 91–09 25 91	38.7	13.1	37.6	14.2	121	900	9.5	13	–	1.5	219	120	SH, KZ	
2	11 16 91–12 13 91	38.2	10.0	38.6	10.4	27	850	4.0	6.8	–	2.4	322	50	ZS, KZ	
3	05 19 92–08 05 92	39.1	11.8	39.1	11.2	78	800	5.0	12	2.5	0.8	90	50	KZ, O	
4	09 24 92–04 21 94	39.3	12.1	32.6	18.6	574	900	159	3.5	2.7	1.9	220	70	KZ	
5	04 12 93–02 23 94	38.5	12.0	35.2	14.8	317	700	(16)	(17)	–	1.6	215	120	KZ	
6	04 13 93–04 25 94	39.5	12.1	36.0	18.1	377	800	122	2.9	2.6	2.0	235	100	KZ	
7	07 09 93–08 04 93	36.7	9.6	36.4	11.3	26	1150	8.8	3.0	3.0	6.9	258	30	BA	CSV formation
8	07 19 93–07 30 93	37.0	9.7	37.5	10.3	11	1100	2.0	5.5	–	8.1	316	30	BA	CSV formation
9	07 20 93–05 01 94	36.8	9.4	38.4	15.0	285	(1200)	84	3.4	2.9	2.1	292	40	BA	CSV formation, followed 328 days
10	11 06 93–03 11 94	39.5	10.1	39.8	11.8	125	1000	(50)	2.5	2.5	1.4	283	15	BA	TP formation
11	11 09 93–05 23 94	38.0	11.4	35.6	15.2	195	(700)	(16)	(12)	–	2.6	233	80	BA	
12	11 19 93–12 09 93	37.5	9.8	37.5	9.8	20	1100	3.5	5.7	–	(0)	–	40	BA	Stationary
13	01 07 94–12 25 94	38.3	10.1	35.0	15.5	352	950	93	3.8	2.5	2.0	234	80(120)	BA,P	Merged with 18
14	01 27 94–02 07 94	37.0	9.6	37.3	10.2	11	1200	3.0	3.7	–	6.6	302	30	BA	CSV formation
15	02 20 94–04 26 94	37.5	11.6	37.0	12.6	65	1150	6.8	9.6	—	1.9	238	80	BA	Same as 19?
16	02 26 94–05 11 94	39.2	10.5	39.2	11.0	64	850	9.5	6.7	–	0.8	270	50	BA	TP formation
17	02 26 94–03 28 94	39.4	10.1	39.4	10.1	30	1100	(9.0)	3.3	3.3	(0)	–	(15)	BA	TP formation, stationery

(continued on next page)

Table 1 (*continued*)

Meddy number	Dates tracked (mo, day, yr)	Start N	Start W	End N	End W	Days tracked	Mean float depth (m)	Number of loops	Mean looping period (days)	Core looping period (days)	Mean velocity (cm/s)	Direction	Overall diameter (km)	References	Comments
18	03 03 94–09 16 94	36.5	9.5	37.1	13.6	197+	1200	46	4.3	3.2	2.2	282	80	BA	{CSV formation, merged with 13}
19	06 26 94–09 14 94	35.6	12.7	34.7	14.2	80	1100	4.0	20	–	2.4	234	100	BA	
20	10 14 94–01 31 95	37.1	9.5	38.0	11.9	109	1100	(31)	(3.5)	2.8	2.5	296	40	BA	{CSV formation, same as 15?}
Canary Basin															
21	09 29 84–01 14 87	31.9	21.9	22.7	22.1	837	1100	114	7.2	6.0	1.4	181	50(100)	RW, AH	See also SR, HO, R
22	11 11 85–07 18 86	33.3	24.2	31.2	28.4	249	1050	62	4.0	4.0	2.1	241	50(100)	RW, R	
23	09 17 85–03 21 87	24.2	23.2	20.2	25.3	550	(1100)	56	9.8	5.0	1.0	206	60	RW, R	
24	07 24 93–01 15 95	35.9	28.0	27.2	43.0	540	1050	101	5.3	4.4	3.7	240	60(120)	RT, TC	
25	07 28 93–02 13 94	35.8	24.2	31.6	27.7	200	1050	29	6.9	5.6	3.3	216	35(100)	RT, TC	
26	11 12 93–10 15 94	32.9	21.8	29.5	27.6	337	1100	63	5.3	3.6	2.3	237	110(150)	RT, TC	
27	09 09 94–02 13 95	36.2	23.7	36.5	26.5	167	750	20	8.4	–	1.8	278	60(100)	RT, TC	

[a] The start and end positions of each Meddy trajectory were estimated from the float loops. The days tracked are from the start to end including some tracking gaps. Some Meddies were tracked by more than one float. The approximate mean depth of the primary tracking float in each Meddy is given to the nearest 50 m. Floats usually remained within 100 m of their launch depth. The depths of those that did not are enclosed by parentheses. The number of loops was estimated from the trajectories, velocity time series and times of arrival. Mean looping period was calculated from the number of looping days divided by the number of loops. Parentheses indicate less accurate estimates. Core looping period was estimated from the smallest (<20 km diameter) and quickest loops. Mean velocity was calculated from the start to end position of each Meddy trajectory. The overall diameter was estimated from the largest loops in each Meddy. The diameters in parenthesis were estimated using shipboard hydrographic measurements (see references). CSV is an abbreviation of Cape St. Vincent. TP refers to Meddies formed near the Tejo Plateau. The following papers describe aspects of the Meddies where the letters designate the relevant references :AH=Armi et al. (1989); RW=Richardson et al. (1992); HO=Hebert et al. (1990); SR=Schultz Tokos and Rossby (1991); ZS=Zenk, Schultz Tokos and Boebel (1992); O=Ollitrault (1993); R=Richardson (1993); SH=Schultz Tokos et al. (1994); P=Pingree (1995); KZ=Käse and Zenk (1996); BA=Bower et al. (1997); RT=Richardson and Tychensky (1998); TC=Tychensky and Carton (1998). Details of some of the float data have been described in the following technical reports: Price, McKee, Valdes, Richardson and Armi (1986) (Meddy 21); Zemanovic, Richardson and Price (1990) (Meddies 21–23); Richardson and Wooding (1999) (Meddies 13, 24–27); Hunt et al. (1998) (Meddies 7–20).

References

Ambar, I., & Howe, M. R. (1979a). Observations of the Mediterranean outflow—I. mixing in the Mediterranean outflow. *Deep-Sea Research I*, *26*, 535–554.

Ambar, I., & Howe, M. R. (1979b). Observations of the Mediterranean outflow—II. the deep circulation in the vicinity of the Gulf of Cadiz. *Deep-Sea Research I*, *26*, 555–568.

Arhan, M., Colin De Verdiere, A., & Memery, L. (1994). The eastern boundary of the subtropical North Atlantic. *Journal of Physical Oceanography*, *24*, 1295–1316.

Armi, L., & Zenk, W. (1984). Large lenses of highly saline Mediterranean Water. *Journal of Physical Oceanography*, *14*, 1560–1576.

Armi, L. D., Hebert, D., Oakey, N., Price, J. F., Richardson, P. L., Rossby, H. T., & Ruddick, B. (1989). Two years in the life of a Mediterranean salt lens. *Journal of Physical Oceanography*, *19*, 354–370.

Baringer, M. O., & Price, J. F. (1997). Mixing and spreading of the Mediterranean outflow. *Journal of Physical Oceanography*, *27*, 1654–1677.

Belkin, I. M., & Kostianoy, A. G. (1988). *Lenses of Mediterranean Water in the North Atlantic. Hydrophysical Investigations on the MEZOPOLYGON Program.* Moscow: Nauka (in Russian).

Bower, A. S., Armi, L., & Ambar, I. (1995). Evidence of Meddy formation off the southwest coast of Portugal. *Deep-Sea Research I*, *42*, 1621–1630.

Bower, A. S., Armi, L., & Ambar, I. (1997). Lagrangian observations of Meddy formation during a Mediterranean undercurrent seeding experiment. *Journal of Physical Oceanography*, *27*, 2545–2575.

Bower, A. S., Richardson, P. L., & Hunt, H. D. (1999). Warm water pathways in the northeastern North Atlantic (Abstract). *EOS Transactions American Geophysical Union*, *80* (14 (Suppl)), S181.

Carnavale, G. F., Kloosterziel, R. C., & van Heijst, G. J. F. (1991). Propagation of barotropic vortices over topography in a rotating tank. *Journal of Fluid Mechanics*, *233*, 119–139.

Daniault, N., Mazé, J. P., & Arhan, M. (1994). Circulation and mixing of Mediterranean Water west of the Iberian Peninsula. *Deep-Sea Research*, *I 41*, 1614–1685.

Hebert, D., Oakey, N., & Ruddick, B. (1990). Evolution of a Mediterranean salt lens: scalar properties. *Journal of Physical Oceanography*, *20*, 1468–1483.

Hunt, H. D., Wooding, C.M., Chandler, C. L., & Bower, A.S. (1998). A Mediterranean undercurrent seeding experiment (AMUSE): Part II: RAFOS float data report May 1993–March 1995. *Woods Hole Oceanographic Institution Technical Report* WHOI-98-14.

Hunter, P.M., Searle, R.C., & Laughton, A.S. (1983). *Continental margin off northwest Africa, bathymetry of the northeast Atlantic, sheet 5*. Published at Taunton, UK, under the superintendence of Rear-Admiral D.N. Haslam, Hydrographer of Navy.

Joyce, T. M. (1981). Influence of the mid-Atlantic Ridge upon the circulation and the properties of the Mediterranean Water southwest of the Azores. *Journal of Marine Research*, *39*, 31–52.

Käse, R. H., & Zenk, W. (1987). Reconstructed Mediterranean salt lens trajectories. *Journal of Physical Oceanography*, *17*, 158–163.

Käse, R. H., & Zenk, W. (1996). Structure of the Mediterranean Water and Meddy characteristics in the northeastern Atlantic. In W. Krauss, *Warmwatersphere of the North Atlantic Ocean* (pp. 365–395). Berlin: Gebrüder Borntraeger.

Lozier, M. S., Owens, W. B., & Curry, R. G. (1995). The climatology of the North Atlantic. *Progress in Oceanography*, *36*, 1–44.

Madelain, F. (1970). Influence de la topographie du fond sur l'écoulement méditerranéen entre le Détroit de Gibraltar et le Cap Saint-Vincent. *Cahiers Océanographie*, *22*, 43–61.

Mazé, J. P., Arhan, M., & Mercier, H. (1997). Volume budget of the eastern boundary layer off the Iberian Peninsula. *Deep-Sea Research I*, *44*, 1543–1574.

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

Needler, G. T., & Heath, R. A. (1995). Diffusion coefficients calculated from the Mediterranean salinity anomaly in the North Atlantic Ocean. *Journal of Physical Oceanography*, *5*, 173–182.

Ollitrault, M. (1993). The SAMBAO experiment: a comparison of subsurface floats using the RAFOS technique. *WOCE Newsletter*, *14*, 28–32.

Paillet, J., LeCann, B., Serpette, A., Morel, Y., & Carton, X. (1999). Real-time tracking of a Galician Meddy. *Geophysical Research Letters*, *26*, 1877–1880.

Pingree, R. D. (1995). The droguing of Meddy Pinball and seeding with ALACE floats. *Journal of Marine Biological Association of United Kingdom*, *75*, 235–252.

Pingree, R. D., & LeCann, B. (1993a). A shallow Meddy (a Smeddy) from the secondary Mediterranean salinity maximum. *Journal of Geophysical Research*, *98*, 20169–20185.

Pingree, R. D., & LeCann, B. (1993b). Structure of a Meddy (Bobby 92) southeast of the Azores. *Deep-Sea Research I*, *40*, 2077–2103.

Prater, M. D., & Sanford, T. B. (1994). A Meddy off Cape St. Vincent. Part I: description. *Journal of Physical Oceanography*, *24*, 1572–1586.

Prater, M. D., & Rossby, T. (1999). An alternative hypothesis for the origin of the 'Mediterranean' salt lens observed off the Bahamas in the fall of 1946. *Journal of Physical Oceanography*, *29*, 2103–2109.

Price, J. F., McKee, T.K., Valdes, J.R., Richardson, P.L., & Armi, L. (1986). SOFAR float Mediterranean outflow experiment: data from the first year, 1984–1985. *Woods Hole Oceanographic Institution Technical Report* WHOI-86-31.

Richardson, P. L. (1993). A census of eddies observed in North Atlantic SOFAR float data. *Progress in Oceanography*, *31*, 1–50.

Richardson, P. L., & Tychensky, A. (1998). Meddy trajectories in the Canary Basin measured during the Semaphore Experiment, 1993–1995. *Journal of Geophysical Research*, *103*, 25029–25045.

Richardson, P. L., & Wooding, C.M. (1999). RAFOS float trajectories in Meddies during the Semaphore experiment, 1993–1995. *Woods Hole Oceanographic Institution Technical Report*, WHOI-99-05.

Richardson, P. L., McCartney, M. S., & Maillard, C. (1991). A search for Meddies in historical data. *Dynamics of Atmospheres and Oceans*, *15*, 241–265.

Richardson, P. L., Walsh, D., Armi, L., Schröder, M., & Price, J. F. (1989). Tracking three Meddies with SOFAR floats. *Journal of Physical Oceanography*, *19*, 371–383.

Rossby, T. (1988). Five drifters in a Mediterranean salt lens. *Deep-Sea Research*, *35*, 1653–1663.

Rossby, T., Dorson, D., & Fontaine, J. (1986). The RAFOS system. *Journal of Atmospheric and Oceanic Technology*, *3*, 672–679.

Schultz Tokos, K., & Rossby, H. T. (1991). Kinematics and dynamics of a Mediterranean salt lens. *Journal of Physical Oceanography*, *21*, 879–892.

Schultz Tokos, K. L., Hinrichsen, H.-H., & Zenk, W. (1994). Merging and migration of two Meddies. *Journal of Physical Oceanography*, *24*, 2129–2141.

Shapiro, G. I., & Meschanov, S. L. (1996). Spreading pattern and mesoscale structure of Mediterranean outflow in the Iberian Basin estimated from historical data. *Journal of Marine Systems*, *7*, 337–348.

Shapiro, G. I., Zenk, W., Meschanov, S. L., & Schultz Tokos, K. L. (1995). Self-similarities of the Meddy family in the eastern North Altantic. *Oceanologica Acta*, *18*, 29–42.

Siedler, G., Zenk, W., & Emery, W. J. (1985). Strong current events related to a subtropical front in the northeast Atlantic. *Journal of Physical Oceanography*, *15*, 885–897.

Smith, W. H. F., & Sandwell, D. T. (1997). Global sea floor topography from satellite altimetry and ship depth soundings. *Science*, *277*, 1956–1962.

Spall, M. A., Richardson, P. L., & Price, J. (1993). Advection and eddy mixing in the Mediterranean salt tongue. *Journal of Marine Research*, *51*, 797–818.

Stammer, D., Hinrichsen, H.-H., & Käse, R. H. (1991). Can Meddies be detected by satellite altimetry? *Journal of Geophysical Research*, *96*, 7005–7014.

Stephens, J. C., & Marshall, D. P. (1999). Dynamics of the Mediterranean salinity tongue. *Journal of Physical Oceanography*, *29*, 1425–1441.

Tychensky, A., & Carton, X. (1998). Hydrological and dynamical characterization of Meddies in the Azores region: a paradigm for baroclinic vortex dynamics. *Journal of Geophysical Research*, *103*, 25061–25079.

Tychensky, A., Le Traon, P.-Y., Hernandez, F., & Jourdan, D. (1998). Large structures and temporal change in the Azores Front during SEMAPHORE experiment. *Journal of Geophsyical Research*, *103*, 25009–25027.

Walsh, D., Richardson, P. L., & Lynch, J. (1996). Observations of tilting Meddies. *Journal of Physical Oceanography*, *26*, 1023–1038.

Zemanovic, M.E., Richardson, P.L., & Price, J.F. (1990). SOFAR float Mediterranean outflow experiment: summary and data from 1986–1988. *Woods Hole Oceanographic Institution Technical Report*, WHOI-90-01.

Zenk, W. (1975). On the origin of intermediate double maxima in T/S profiles from the North Atlantic. *Meteor Forschungen Ergebnisse*, *A16*, 35–43.

Zenk, W., & Armi, L. (1990). The complex spreading pattern of Mediterranean Water off the Portuguese continental slope. *Deep-Sea Research*, *37*, 1805–1823.

Zenk, W., Schultz Tokos, K., & Boebel, O. (1992). New observations of Meddy movement south of the Tejo Plateau. *Geophysical Research Letters*, *19*, 2389–2392.