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Arms winding around a meddy seen in seismic reflection data close to the Morocco coastline

C. Ménesguen,[1] B. L. Hua,[2] X. Carton,[2] F. Klingelhoefer,[1] P. Schnürle,[1] and C. Reichert[3]

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[1] The North Atlantic temperature and salinity distributions are strongly influenced by the existence of Mediterranean eddies (meddies) which significantly contribute to the transport of the warm and salty Mediterranean Water along different pathways. The most common pathways are observed to be North and West of the Canary Current. However, a 2011 seismic reflection cruise conducted by BGR and Ifremer near the North–Western African margin of Morocco, MIRROR Leg 2, revealed the presence of a meddy south of the Azores front and very close to the Morocco coastline. This unusual location of a strong Mediterranean Water anomaly is confirmed by other data. Moreover, meddies are long-lived structures whose dynamics and dissipation are not yet completely understood. Recently, theoretical studies have revealed critical-level baroclinic instabilities of compact, lens-like vortices. This theory supports the slow growth of azimuthal eigenmodes along critical surfaces which leads to the formation of arms winding around the vortex developing sharp internal fronts. These structures are very thin and spatially intermittent and are identified for the first time in a seismic dataset; this is made possible by the length of seismic sections at high lateral resolution. **Citation:** Ménesguen, C., B. L. Hua, X. Carton, F. Klingelhoefer, P. Schnürle, and C. Reichert (2012), Arms winding around a meddy seen in seismic reflection data close to the Morocco coastline, *Geophys. Res. Lett.*, *39*, L05604, doi:10.1029/2011GL050798.

1. Introduction

[2] The Mediterranean Sea is an evaporation basin which produces warm and salty waters which exit into the Atlantic Ocean via the Straits of Gibraltar. On the Iberian continental slope in the Gulf of Cadiz, these waters undergo strong diapycnal mixing with the surrounding North Atlantic Central Waters, and also the influence of the Coriolis force. These two influences modify both the vertical and horizontal position of the outflow until it forms three undercurrents, hydrostatically balanced and flowing westward along the southern Iberian slope at 400, 800 and 1200 m depths. The two deeper cores of Mediterranean Water (MW) feel the influence of the Portimão and Saõ Vicente canyons and also of Cabo Saõ Vicente around which they veer to the North. These topographic irregularities impart to the deep cores of MW, noticeable perturbations which can amplify into eddies [*Bower et al.*, 1997; *Ambar et al.*, 2008]. These eddies are predominantly anticyclones (called meddies), but cyclones have also been observed. Meddy pairing with MW cyclones can occur in their early stages of evolution [*Serra and Ambar*, 2002; *Carton et al.*, 2002]. The MW cores continue their route towards the Bay of Biscay, and along the way, the Estremadura Promontory and Cabo Ortegal are other sites of meddy generation.

[3] Depending on the generation site, meddies follow different trajectories into the Atlantic Ocean. Globally, they are influenced by beta-effect and by large-scale currents. Locally, they can be steered by topography. When generated at Portimão Canyon, meddies often drift in the Gulf of Cadiz either to the Southwest or cyclonically to the Southeast along the mean circulation [*Alves et al.*, 2011]. The further evolution of meddies exiting the Gulf of Cadiz southwestward has not yet been observed. When generated near Cabo Saõ Vicente, meddies can either move southwestward and become trapped between the Horseshoe seamounts (for up to 70% of them *Richardson et al.* [2000]) and be substantially eroded by their interaction with topography, or circle north of the Gorringe Bank and then drift in the open ocean towards the Azores.

[4] Once in the open ocean, meddy lifetime can reach 3–4 years. Though meddies are long-lived, theory has identified weak modes of instability which may modify their structure and lead to the shedding of spiral arms. But this evolution has not been observed either.

[5] In this paper, we present recent observations which shed new light on the possible southern route of meddies along the African coast and on the formation of arms winding around these anticyclones.

2. Data and Processing

[6] In this paper, we make use of seismic reflection data, of altimetric data, of ARGO floats data and of deep drogued buoy trajectories.

[7] Two sections, illustrated in Figure 1 of multi-track seismic reflection measurements were acquired by the R/V Atalante during the MIRROR Leg 2 cruise conducted by BGR and Ifremer in June 2011, close to the Moroccan continental margin (see Figure 2).The seismic device used during this experiment included 14 airguns with a total volume of 2765 cubic inches and a streamer with 360 hydrophones spaced by 12.5 m. Special attention was given to an accurate positioning of the sources and receptors, and to the pre-processing of seismic data, which notably included the damping of the direct wave via a SVD filter [*Golub and Van Loan*, 1996]. In order to increase the signal to noise ratio, the processing bin size was enlarged from 12.5 m to 50 m in the horizontal. The classical seismic data

[1]Laboratoire de Géophysique et Géodynamique, IFREMER, Plouzané, France.
[2]Laboratoire de Physique des Océans, IFREMER, Brest, France.
[3]Marine Resource Exploration, BGR, Hannover, Germany.

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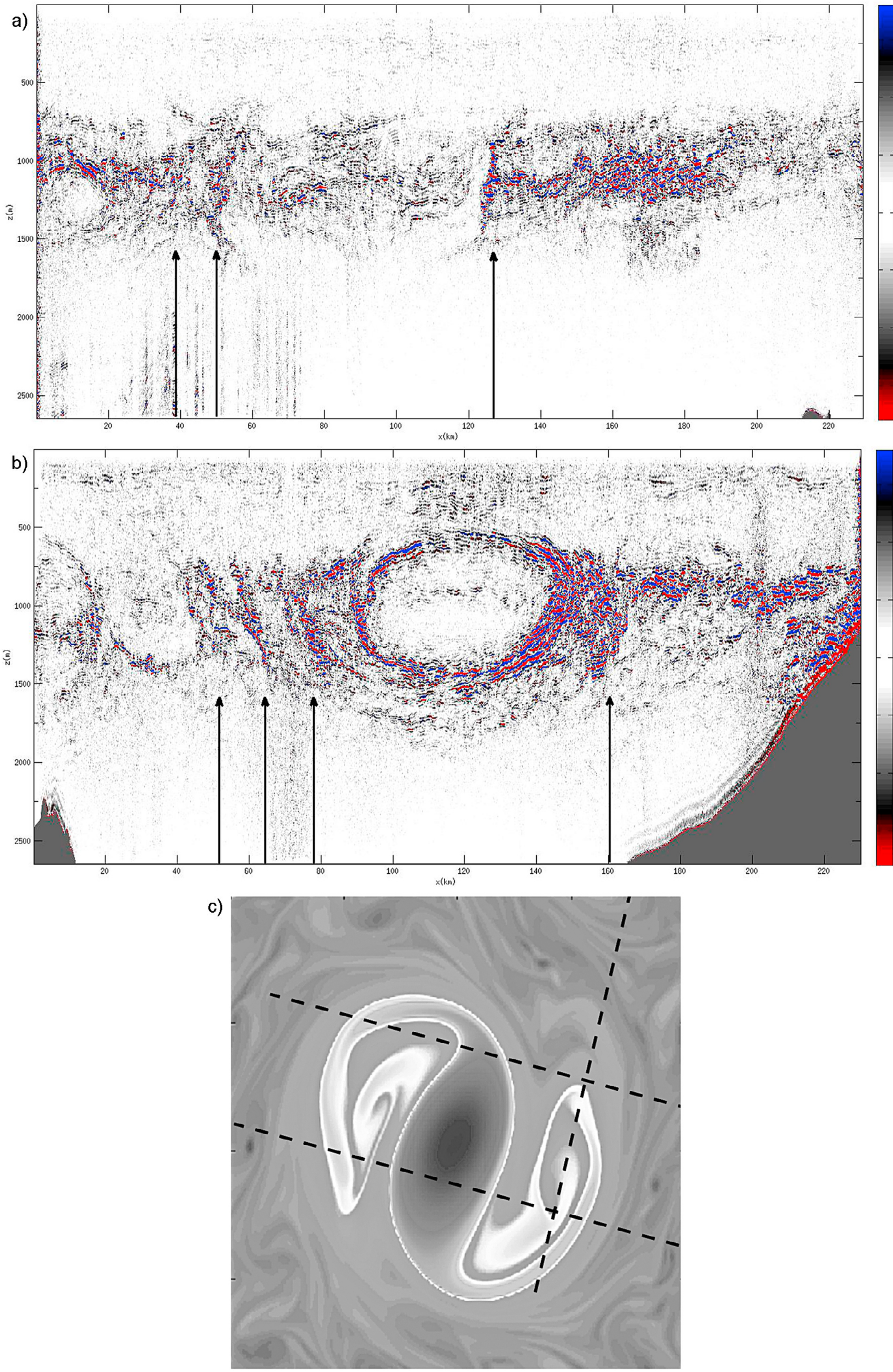

Figure 1. (a, b) Two parallel seismic sections from MIRROR cruise, June, 5 and 7, 2011 near 32°N latitude. (c) Horizontal section of potential vorticity of a baroclinically unstable anticyclonic lens, obtained from a numerical, quasi-geostrophic model of a continuously stratified fluid. The dashed lines indicate the two MIRROR sections (Figures 1a and 1b) and a perpendicular section shown in Figures S1–S3.

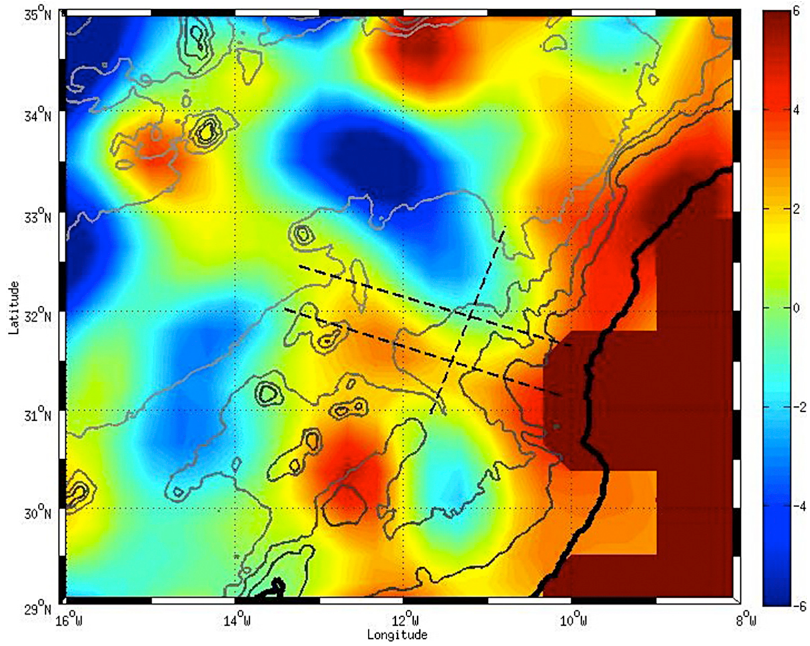

Figure 2. Sea Level Anomaly in cm, for the 7th of June 2011, computed with respect to a seven-year mean sea-surface. AVISO merged satellite data were provided on a 1/3 degree of resolution Mercator grid. Black dashed lines are the three seismic sections from MIRROR. Coastline is in black and bathymetry in grey (indicating depths of 1000 m, 2000 m, 3000 m, 4000 m and 5000 m).

processing then included a NMO-stack-constant speed migration sequence.

[8] Delayed-time sea-level anomalies regularly gridded in space (1/3° × 1/3° on a Mercator grid) and time (every day) were obtained from the AVISO satellite data center for the period of the cruise. The Sea Level Anomaly (SLA) was computed with respect to a seven year mean of the Sea Surface Height (SSH).

[9] ARGO floats data were sampled from the Coriolis data center, one of the two Argo Global Data Assembly Centers. ARGO floats are free-drifting profiling floats which measure the temperature and salinity of the upper 2000 m of the ocean. ARGO floats deployment began in 1997 and is still active today.

[10] Finally, surdrift buoys from the SEMANE experiments at sea (carried out by SHOM in 1999 and 2000) were also used. These surface drifters were tethered by 2.5 mm thin Kevlar cables to a 10 m high x 1 m diameter holeysock drogue. The cable length varied between 700 and 1200 m. The buoy nominal mission was 180 day long. They were positioned via Argos. Their trajectories were re-sampled every 8 h. A test on relative acceleration was performed to detect a possible loss of the drogue; in that case, their mission was terminated.

3. A Pathway for Meddies Close to the Morocco Coastline

[11] On Figure 1, we show seismic reflectivity on two of the three MIRROR sections performed on June 5th and 7th 2011. One of the sections clearly evidences a lens between 600 m and 1400 m depth; this lens has a diameter of about 50 km. Its depth range and size make it likely to be a meddy, though the sections lie close to the African coast, south of the Gulf of Cadiz. Figure 3 illustrates how rare the southern route is for meddies. 54,000 ARGO float profiles, from 1997 to 2011, have been used to identify salinity anomalies between 800 and 1400 m depths in the Northern Atlantic ocean. To identify meddies, we used historical measurements which show that their salinity is usually above 36.2 psu and their temperature above 11.7°C (Figures S1–S3 in the auxiliary material).[1] With these criteria, many anomalies are found close to the southwestern tip of the Iberian peninsula, but only four meddies have been identified in the database south of 34°N and west of 14°W. No meddy was observed, east of 14°W, so close to the Moroccan coast. A few anomalies are observed in the Gulf of Cadiz and a few others are seen between the Horseshoe seamounts but none south of them. In *Richardson et al.*'s [2000] meddy census, only six meddies out of eighty lay directly south of the Horseshoe seamounts. Figure 3b presents a zoom of Figure 2 close to the coast. Clearly, the closest meddies in the ARGO profiles lie at least 500 km away from the MIRROR sections.

[12] Figure 4 shows the trajectories of 11 surdrift buoys drogued between 900 and 1200 m depths, released during the SEMANE experiments. Most of them remain in the Gulf of Cadiz but two drift southward along the coast. A cycloidal motion, but no large loop can be seen on these trajectories. Thus, though these buoys may not be trapped in meddies, they illustrate a southern pathway for the Mediterranean Water. These buoys took three to five months to reach the location of the MIRROR sections, starting from their release position.

[13] Several previous studies have shown that meddies can have a surface signature, either in SLA [*Stammer et al.*, 1991; *Carton et al.*, 2010] or in SST [*Pingree and Le Cann*, 1993; *Oliveira et al.*, 2000]. Figure 2 shows the

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL050798.

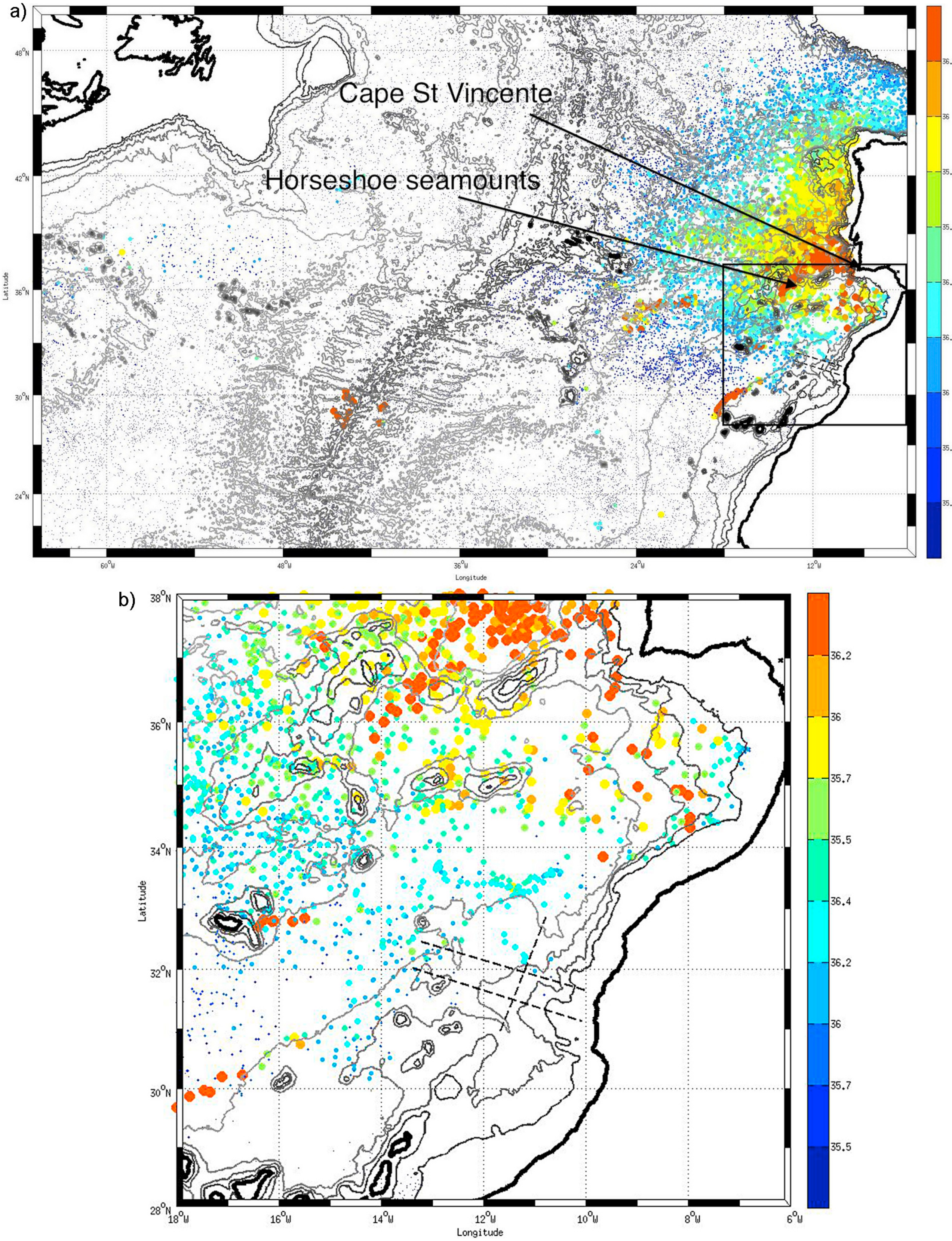

Figure 3. (a) Map of salinity maxima between 800 and 1400 m depths obtained from about 54000 ARGO floats profiles, from 1997 to 2011. (b) Zoom of the black box in Figure 3a. Red color and big marker size are given to high values of salinity, blue color and small marker size are given to low values. Three meddies were sampled south and west of this area within the mapped region. The black dashed lines are the three seismic sections from MIRROR. The coastline is in black and the bathymetry in grey (isobaths of 1000 m, 2000 m, 3000 m, 4000 m and 5000 m are indicated).

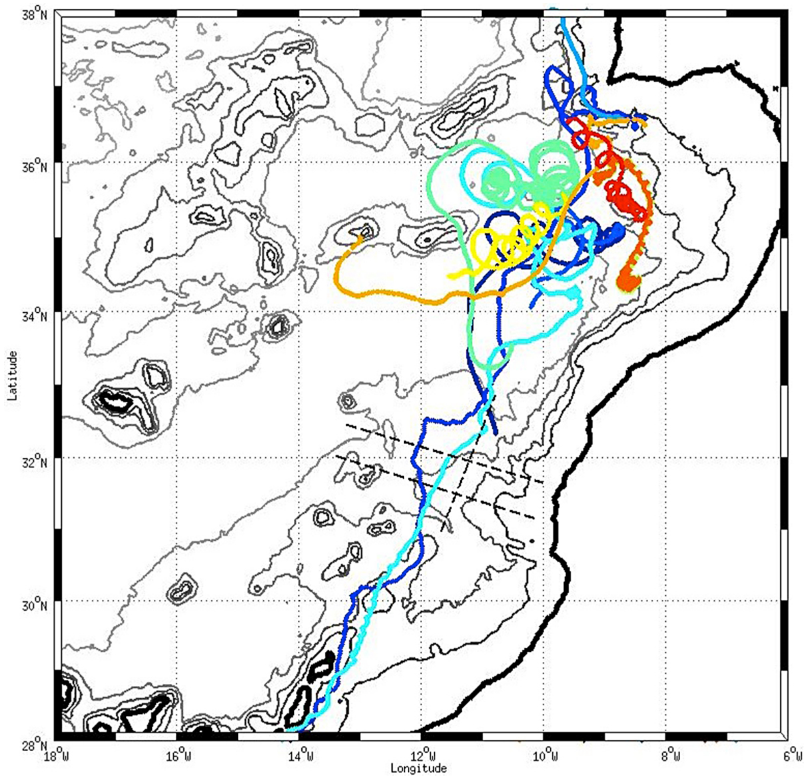

Figure 4. Trajectories of 11 surdrift floats drogued between 900 m and 1200 m. They were launched in the Gulf of Cadiz during the SEMANE 1999, 2000(1) and 2000(2) cruises.

positive SLA, in the altimetric map, above the MIRROR sections, at the time of the cruise. A time sequence of altimetric maps before the cruise shows that this anomaly may have drifted from a position to the North, along the coast, or may have resulted from a splitting of another positive anomaly, previously located to its northwest (Animation S1). Therefore, it is difficult to assess the exact origin of this meddy. This is also in agreement with *Carton et al.* [2010] who showed the difficulty of continuously following a meddy in altimetric maps.

4. Meddy Structure

[14] On this same map, the anticyclonic lens of the MIRROR sections corresponds to a positive sea-level anomaly of a few centimeters over a horizontal distance of about 100 km. There is a good agreement between the structure identified on the MIRROR sections and the SLA. The southern section (Figure 1b) encompasses the meddy, while the northern (Figure 1a) and eastern (Figures S1–S3) sections lie on its periphery. This is summarized and illustrated on Figure 1c. This snapshot of potential vorticity indicates that the meddy is perturbed elliptically and has arms winding around it. These arms can clearly be seen as lateral stacks of reflectors on all sections. These stacks have a height of about 700 m (the same as the meddy) and are quasi-regularly spaced laterally by about 12 km (see in particular Figure 1b). Furthermore, strong reflectors are found at the meddy boundary, both above, below and around it. Seismic reflection measurements capture part of the vortex stretching which is proportional to dT/dz, the vertical derivative of temperature. In the QG approximation, potential vorticity is the sum of vortex stretching and of relative vorticity. Thus, insofar as the arms winding around the meddy have a vortex stretching component which is dominating over relative vorticity, seismic reflection measurements can be interpreted as potential vorticity fronts. This is in agreement with the study of *Nguyen et al.* [2012, hereinafter N2012] of the destabilization of a vortex in a continuously stratified flow, showing the growth of slow unstable modes confined on critical surfaces at the meddy periphery and leading to the formation of sharp potential vorticity interfaces. At the depth of the meddy, the Brunt-Väisälä frequency is $N \sim 2.10^{-3}s^{-1}$ and the Coriolis parameter is $f(32°N) = 7.7.10^{-5}s^{-1}$. The characteristic height H and width L of the meddy can be obtained by identifying the seismic reflection at the periphery of the meddy to the critical layers of Figure 4 of N2012, yielding H = 270 m, L = 17 km and a Burger number $Bu \equiv (NH/fL)^2 = 0.17$. Furthermore, thermal wind and hydrostatics imply $Ro \sim 2Bu$, where the Rossby number is $Ro \equiv \zeta/f$, with ζ the relative vorticity. The growth rate σ can then be estimated from Figure 1a of N2012: $\sigma^{-1} \sim 70$ days. This is compatible with the age of the meddy which is about 4–5 months old. In laboratory experiment, incipient formation of arms winding around a vortex has been described by *Hedstrom and Armi* [1988] for a zero potential vorticity vortex. Arms winding around vortices have also been observed to form in the nonlinear evolution of unstable baroclinic vortices, idealizing meddies, in numerical simulations by *Tychensky* [1999]. In these five-layer quasi-geostrophic simulations, the meddy was represented as an isolated vortex in potential vorticity in the three intermediate layers. The barotropic and baroclinic instability of this vortex could either lead to the formation of a tripole, for weak instability,

or to the splitting of the vortex into two dipoles, for strong instability. The formation of a tripole involved an intermediate stage with the growth of arms and their wrapping into satellite vortices around the meddy.

5. Discussion

[15] The observations reported here indicate that meddies can drift south–southwestward from the Gulf of Cadiz along the African coast. Topographic steering and regional currents (the Canary current) undoubtedly play a role in guiding meddies along this path.

[16] Concerning the meddy structure, the seismic reflection section shows that despite the presence of arms, the meddy core is very coherent. This leads to several conclusions.

1. The instability underlying the formation of arms is weak baroclinic instability, as described by theory. Otherwise, strong barotropic or baroclinic instability of the meddy would lead to its dipolar splitting and the average meddy lifetime would be much shorter.

2. Furthermore, arms winding around the meddy may be the consequence of the growth of a low azimuthal mode disturbance, which forms sharp fronts near the critical radius, as in the study of *Balmforth et al.* [2001].

3. The formation of arms may have been triggered by surrounding flows or by topographic anomalies, which slightly modify the meddy potential vorticity distribution. Since the meddy is quite young (few months), arms shedding may also be an early adjustment process in the meddy life.

[17] As stated above, more numerous and more detailed measurements of such southern meddies shedding arms would be necessary to quantify the flux and reach of this turbulent MW route.

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References

Alves, J., X. Carton, and I. Ambar (2011), Hydrological structure, circulation and water mass transport in the Gulf of Cadiz, *Int. J. Geosci.*, *2*, 432–456.

Ambar, I., N. Serra, F. Neves, and T. Ferreira (2008), Observations of the Mediterranean Undercurrent and eddies in the Gulf of Cadiz during 2001, *J. Mar. Syst.*, *71*, 195–220.

Balmforth, N. J., S. L. Smith, and W. R. Young (2001), Disturbing vortices, *J. Fluid Mech.*, *426*, 95–133.

Bower, A. S., L. Armi, and I. Ambar (1997), Lagrangian observations of meddy formation during a Mediterranean Undercurrent seeding experiment, *J. Phys. Oceanogr.*, *27*, 2545–2575.

Carton, X., L. Chérubin, J. Paillet, Y. Morel, A. Serpette, and B. L. Cann (2002), Meddy coupling with a deep cyclone in the Gulf of Cadiz, *J. Mar. Syst.*, *32*, 13–42, doi:10.1016/S0924-7963(02)00028-3.

Carton, X., N. Daniault, J. Alves, L. Cherubin, and I. Ambar (2010), Meddy dynamics and interaction with neighboring eddies southwest of Portugal: Observations and modeling, *J. Geophys. Res.*, *115*, C06017, doi:10.1029/2009JC005646.

Golub, G. H., and C. F. Van Loan (1996), *Matrix Computations*, vol. 10, 48 pp., Johns Hopkins Univ. Press, Baltimore, Md.

Hedstrom, K., and L. Armi (1988), An experimental study of homogeneous lenses in a stratified rotating fluid, *J. Fluid Mech.*, *191*, 535–556.

Nguyen, H. Y., B. L. Hua, R. Schopp, and X. Carton (2012), Slow quasigeostrophic unstable modes of a lens vortex in a continuously stratified flow, *Geophys. Astrophys. Fluid Dyn.*, doi:10.1080/03091929.2011.620568, in press.

Oliveira, P. B., N. Serra, A. F. Fiùza, and I. Ambar (2000), A study of meddies using simultaneous in-situ and satellite observations, in *Satellites, Oceanography and Society*, *Elsevier Oceanogr. Ser.*, vol. 63, edited by D. Halpern, chap. 7, pp. 125–148, Elsevier, Amsterdam, doi:10.1016/S0422-9894(00)80008-2.

Pingree, R. D., and B. Le Cann (1993), A shallow meddy (a smeddy) from the secondary Mediterranean salinity maximum, *J. Geophys. Res.*, *98*, 20,169–20,185, doi:10.1029/93JC02211.

Richardson, P., A. Bower, and W. Zenk (2000), A census of Meddies tracked by floats, *Prog. Oceanogr.*, *45*, 209–250, doi:10.1016/S0079-6611(99)00053-1.

Serra, N., and I. Ambar (2002), Eddy generation in the Mediterranean Undercurrent, *Deep Sea Res., Part II*, *49*, 4225–4243, doi:10.1016/S0967-0645(02)00152-2.

Stammer, D., H.-H. Hinrichsen, and R. H. Käse (1991), Can meddies be detected by satellite altimetry?, *J. Geophys. Res.*, *96*, 7005–7014, doi:10.1029/90JC02740.

Tychensky, A. (1999), Les meddies: Observation et modélisation de leurs interactions avec le courant des Açores et étude de leurs propriétés de stabilité, PhD thesis, Univ. de Toulouse III, Toulouse, France.

X. Carton and B. L. Hua, Laboratoire de Physique des Océans, 6 avenue Le Gorgeu, F-29200 Brest CEDEX, France.

F. Klingelhoefer, C. Ménesguen, and P. Schnürle, Laboratoire de Géophysique et Géodynamique, IFREMER, BP70, F-29280 Plouzané CEDEX, France. (cmenesg@ifremer.fr)

C. Reichert, Marine Resource Exploration, BGR, Stilleweg 2, D-30655 Hannover, Germany.