Modeling the deep eddy field in the southwestern Mediterranean: The life cycle of Sardinian eddies

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[1] During the MATER experiment, an eddy characterized by marked Levantine Intermediate Water (LIW) in its core at intermediate depth, and called Sardinian Eddy (SE), has been observed in the Algerian Basin located in the western Mediterranean Sea. Here, results from a numerical simulation allow to investigate thoroughly such structures. The formation of SEs and their life cycle in the model are detailed and compared to in-situ observations. The formation of SEs is associated with the detachment from the continental slope of Sardinia of the large-scale cyclonic gyre found in the Algerian Basin. Once formed, SEs leave the slope westwards. They are strongly barotropic and about 3 to 4 SEs are created each year. At a later stage, SEs develop a baroclinic component as revealed by an emerging surface signature about 1 month after their formation. Coalescence processes and merging of these eddies are documented between Minorca and Sardinia where these eddies accumulate. **Citation:** Testor, P., K. Béranger, and L. Mortier (2005), Modeling the deep eddy field in the southwestern Mediterranean: The life cycle of Sardinian eddies, *Geophys. Res. Lett.*, *32*, L13602, doi:10.1029/2004GL022283.

1. Introduction

[2] The circulation of the Mediterranean Sea is mainly thermohaline [*Robinson and Golnaraghi*, 1994]. The inflowing water from the Atlantic circulates at the surface along the continental slope through the Mediterranean, following an anticlockwise circuit and increasing its density. In winter, the air-sea fluxes generate intermediate and/or deep waters in the Aegean Sea, the Adriatic Sea, the Gulf of Lions, and in the Levantine Basin. They circulate below the Atlantic Water (AW) and ultimately return to the Atlantic ocean at intermediate level through the Strait of Gibraltar under the inflow of Atlantic waters. In the western Mediterranean Sea, it is now well-established [*Millot*, 1999] that the Levantine Intermediate Water (LIW), the Tyrrhenian Deep Water (TDW) and the Western Mediterranean Deep Water (WMDW) flow anticlockwisely along the continental slope from their source region (the eastern Mediterranean Sea, the Tyrrhenian Sea, and the Gulf of Lions, respectively).

[3] At sub-basin scale, a cyclonic gyre encompasses the whole Liguro-Provençal basin [*MEDOC*, 1970] and more recently, another cyclonic gyre, so-called the Algerian Gyre, has been mapped by sub-surface floats from July 1997 to July 1998 during the MATER experiment [*Gascard et al.*, 1999; *Testor and Gascard*, 2003] which seems to be strongly barotropic and occupies the whole eastern part of the Algerian Basin, with an average diameter of around 200 km.

[4] In addition to this general picture, an intense eddy activity has been observed which appears to be essential for the thermohaline circulation of the Mediterranean Sea as indicated by [*Spall*, 2004] in a more general context for semi-enclosed basins. Thanks to satellite imagery, significant progress could be achieved in characterizing this turbulence but still, obvious observational difficulties strongly limit what can be deduced from in-situ measurements at depth and despite considerable effort, little is known on the deep eddy field characteristics and implications for the general circulation.

[5] It is now well-established that the northward surface flux of AW is not only due to a boundary current flowing anticlockwise around the basin but also to the eddies formed in the Algerian Basin along the African coast through the instabilities of the boundary current. These so-called Algerian Eddies (AEs), migrate offshore transporting and mixing the fresh AW in the basin interior. This mesoscale activity is expected to influence the intermediate and deep circulations as well, since some offshore AEs that have a deep signature (sometimes down to the bottom) could be observed [*Taupier-Letage et al.*, 2003]. Recently, another kind of mesoscale structure has been observed. Close to the Sardinian continental slope, the LIW and TDW coming from the Channel of Sardinia, flow northwards in a well marked vein [*Send et al.*, 1999] and interactions between this vein and the Algerian Gyre are supposed to generate Sardinian Eddies (SEs) [*Testor and Gascard*, 2003].

[6] Based on this fragmentary observational evidence with respect to the origin and life cycle of the SEs, and their possible role in the transport of water masses in the Algerian Basin, we present here results from the eddy-resolving ocean general circulation model (OGCM) developed by [*Béranger et al.*, 2005], aiming to contribute to a better understanding of the processes governing the general circulation in the western Mediterranean Sea. The size of the basin relative to the first radius of deformation is such that it allows fairly high horizontal resolution model to be run for decades at a moderate cost. Thus, an accurate description of generation mechanisms, life stages of these mesoscale eddies are affordable and their overall role in the basin circulation can be investigated.

2. Numerical Simulation

[7] The MED16 model of the Mediterranean Sea [*Béranger et al.*, 2005] is derived from the PAM model

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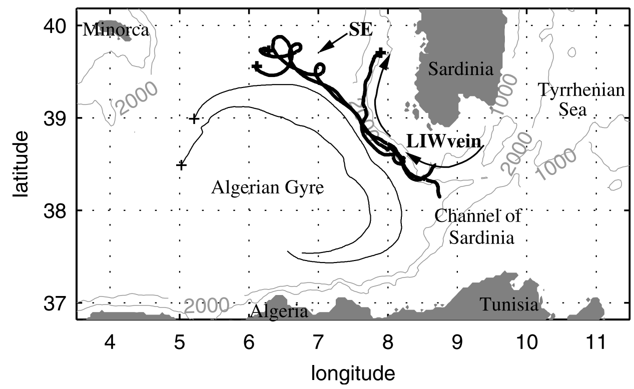

Figure 1. Trajectories of floats drifting at around 600 m depth between 27/09/1997 and 26/12/1997 (a + indicates the last position). Thick lines correspond to marked LIW signal [from *Testor and Gascard*, 2003].

developed in the framework of the MERCATOR project [*Drillet et al.*, 2005]. It is a primitive equations model with a biharmonic formulation of diffusion based on the OPA code [*Madec et al.*, 1998]. Its domain covers the whole Mediterranean Sea and a part of the Atlantic Ocean to 11°W. Its horizontal resolution (5 to 6 km) is well adapted to study mesoscale features that have a horizontal scale higher than 30 km. On the vertical, MED16 has 43 levels with a stretched grid from 6 m at the surface to 200 m at the bottom.

[8] The initial conditions of temperature and salinity were provided by the monthly climatology MEDATLAS for the Mediterranean Sea [*Mediterranean Data Archaeology and Rescue*, 2002]. The model was forced by recent daily atmospheric forcing from the analyses of the European Centre for Medium-range Weather Forecast. The model was first forced in a yearly perpetual mode during 8 years with year 2000 for adjustment, and then from year 1998 to year 2002.

3. Observations in the Algerian Basin

[9] Floats released in this region (Figure 1) showed 3 kinds of trajectories: 1) at the periphery of the Algerian Gyre, 2) in the LIW vein along the Sardinian continental slope, and 3) between these two pathways. It the last one, floats exhibited a cycloidal trajectory revealing an anticyclonic structure traveling northwestward.

[10] This eddy was observed during 5 months implying an even longer lifetime [*Testor and Gascard*, 2003]. It was characterized by a radius of around 30 km in a quasi-solid rotation corresponding to a Rossby number of 0.06 at 600 m. The temperature measured by the floats drifting in this eddy at 600 m was similar to the one observed in the main LIW vein. Because of the location where this eddy was observed, this kind of eddies is called Sardinian Eddies (SEs).

[11] The cyclonic gyre detaches from the continental slope southwest of Sardinia. This large-scale flow separation appears to be the main responsible for SE formation [*Testor and Gascard*, 2003]. The gyre appears to be characterized by a maximum speed, up to 10 cm/s at approximately 15 km far from the Sardinian continental slope at all depths below the surface layer (which is dominated by transient and mesoscale features hiding this barotropic component). There is an anticyclonic horizontal shear between this maximum and the slope where the current vanishes. This vorticity component is conserved downstream and mainly determines the relative vorticity of the eddy formed at the separation location. Considering this formation mechanism, SEs are expected to be strongly barotropic like the Algerian Gyre.

[12] So, in addition to AEs, this very different kind of eddies could strongly influence the water mass properties and the circulation in the Algerian Basin.

4. Life Cycle of Sardinian Eddies

[13] The analysis and intercomparison of observations and model outputs based on kinematic properties is particularly effective at mesoscale, where kinematic properties like strain (str), shear (shr), and vorticity (vor) are well defined. The Okubo-Weiss criterion [*Okubo*, 1970; *Weiss*, 1991] is useful to identify eddies from their surroundings and to follow their evolution. It examines the sign of $\lambda = str^2 + shr^2 - vor^2$. If the shear and the strain are more important than vorticity ($\lambda > 0$), the fluid parcel belongs to a filament. On the opposite ($\lambda < 0$), the parcel is in an eddy. The criterion was computed from the Eulerian velocity fields of the model and compared to the equivalent computations from float observations done by [*Testor and Gascard*, 2003].

[14] Numerous SEs are formed at the southwestern corner of Sardinia in the model and are similar to the one observed in 1997–1998. The Algerian Gyre is mainly barotropic in the model and separates there from the continental slope inducing the formation of these eddies. In the model, SEs are strongly barotropic, their radius is order of 30 km, and the rotation velocities in the eddy core are order of 10 cm/s at 600 m depth. They are characterized by a marked core of LIW, presenting high temperature at intermediate depths similar to the ones that can be found in the LIW vein along the Sardinian continental slope. Their lifetime is order of several months.

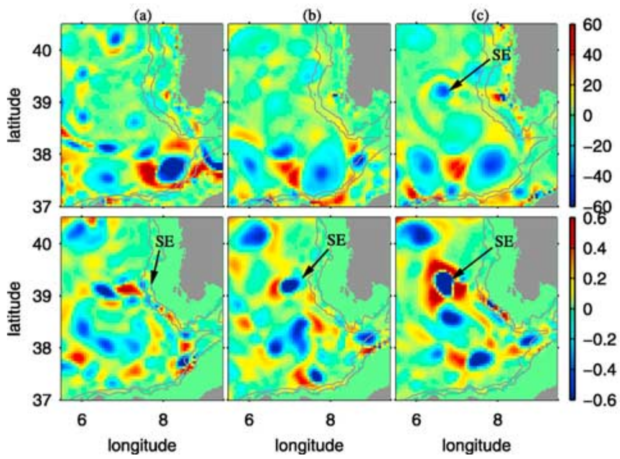

Figure 2. The 3 stages of the formation of a SE: (a) 08/05/08, (b) 27/06/08, and (c) 17/07/08. Okubo-Weiss criterion ($\times 10^{11}$ s^{-2}): (top) at surface and (bottom) at 600 m depth.

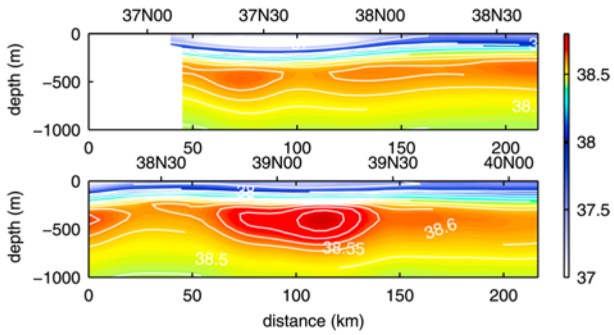

Figure 3. Meridional sections of salinity in MED16 typical of: (top) an AE and (bottom) a SE.

[15] Figure 2 shows one of these SEs at 3 different stages of its evolution in the simulation, at surface and at intermediate depths. The region between the gyre and the slope is dominated by shear and strain and is characterized by high temperature typical of water coming from the Tyrrhenian Sea. It develops downstream into an eddy-like flow, which is the SE growing at the separation location. Then, the SE detaches from the slope and propagates first northwestwards, as observed.

[16] The SEs are clearly identifiable at depth while their signature (~10 cm/s) is first hidden by strong mesoscale activity in the surface layer (~50 cm/s). Finally, the SE starts to develop a baroclinic component as revealed by an emerging surface signature (Figure 2c). At this stage, the orbital velocities of SEs are about 30 cm/s at surface, and 10 cm/s below 300 m depth.

[17] In the model, some SEs are more intense and have dynamical characteristics very similar to AEs. Their radius (~50 km) and orbital velocities (50 cm/s in the surface layer) are close to the ones observed by *Millot* [1991] and *Taupier-Letage et al.* [2003]. However, the water masses composing both kind of eddies are significantly different. Vertical sections of salinity through an AE and a SE highlight these differences (Figure 3). In the surface layer, AEs are mainly composed of fresh AW while SEs do not show a clear AW signature. In addition, in the intermediate layer, a core of LIW is found in SEs on the contrary to AEs for which marked LIW is located mostly at their periphery, in filaments swirling around them as observed by *Emelianov et al.* [1999]. Another important point is that SEs always show a strong barotropic structure in the model on the opposite to AEs for which the signature is largely baroclinic and concentrated in the surface layer, even if sometimes they can have a larger vertical extent, even down to the bottom as observed by *Taupier-Letage et al.* [2003].

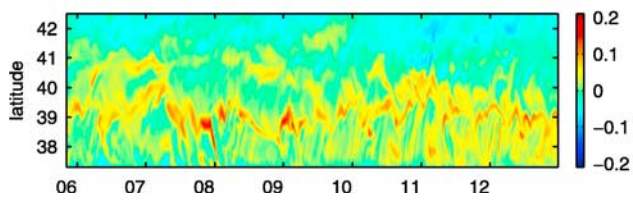

Figure 4. Hovmoller diagram (time in years-latitude in degrees) of the salinity anomaly along 7°E at 600 m depth.

[18] The formation of these eddies is rather frequent in the model. Around 3 to 4 SEs are formed at the southwest corner of Sardinia every year (Salinity maxima around 39°N, Figure 4) and propagate to the west. These SEs are characterized by an extent of about 60 km, a period of rotation of around 20–30 days and an average translation velocity of 2–3 cm/s.

[19] On average, an anticyclonic circulation pattern appears north of the Algerian Gyre between Minorca and Sardinia. The time-series of the model show that this circulation is due to the merging of several SEs (Figure 5). The resulting eddies are of larger dimension. Once their extent reaches around 60–80 km of diameter, these big SEs dissipate or leave this preferred location to move towards Africa while new SEs accumulate there again. Then, these old SEs evolve in the Algerian Basin together with AEs (Figure 5) and since they have a sea surface signature in temperature and height similar to the AE ones, they may be confused with them if they are observed from the surface only.

5. Discussion

[20] At depth, the eddy signature in the model looks very similar to the one observed by the floats at 600 m during the MATER experiment. They are similar with regards to the temperature signal (typical of LIW with marked properties, as along the Sardinian slope), to the radius, and to the relative vorticity.

[21] In addition, the model confirms the strong barotropic component of SEs suggested by the observations. Actually, the formation of the SEs appears to be directly related to the separation of the barotropic gyre from the slope southwest of Sardinia. The relative vorticity of the SEs is equivalent to the anticyclonic shear between the slope and the gyre, where the flow is dominated by filamentation. During the formation process, part of this shear is transferred to the vorticity associated with the curvature of the eddy and the other part, to the vorticity associated with the shear of the orbital velocities.

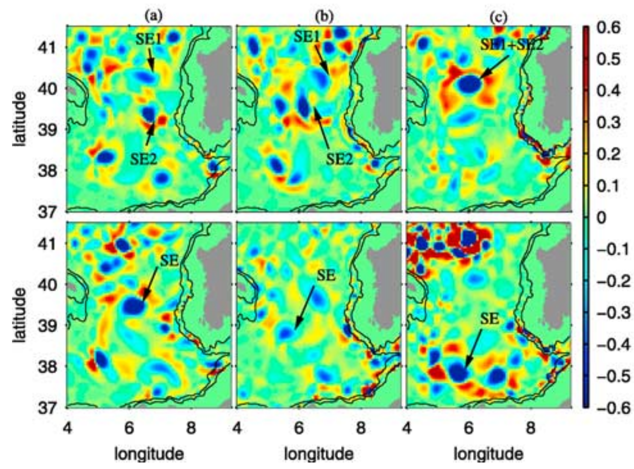

Figure 5. Okubo-Weiss criterion ($\times 10^{11}$ s^{-2}) at 600 m depth. (top) 2 SEs merging: (a) 03/11/08, (b) 23/11/08, and (c) 21/01/09. (bottom) 1 old SE traveling southwestward toward Africa: (a) 25/10/07, (b) 23/01/08, and (c) 07/04/08.

[22] *Tansley and Marshall* [2001] argue that a current detaching from a slope must emit eddies to maintain stationarity. This is a process very similar to the generation of a Von Karman street of eddies downstream an obstacle. *Marshall and Tansley* [2001] have shown that the current flowing along a wall can detach provided $r < \left(\frac{U}{\beta}\right)^{1/2}$, where U is the speed of the current, r the curvature of the wall and β the planetary vorticity gradient in the downstream direction. Here, $\beta \sim 10^{-11}$ m^{-1} s^{-1}, $U \sim 10$ cm/s and $r < 100$ km, which fulfills this relation. In addition, *Tansley and Marshall* [2001] suggest that OGCMs must use biharmonic operator to raise the Reynolds number in order to allow detachment and eddy formation. Following these authors, the effective Reynold number in MED16 is 10^5 while the non dimensional Rhines scale is only 1, which allow detachment and maintenance of the gyre by the eddy fluxes.

[23] MED16 appears to represent the formation of SEs in a realistic way compared to observations and thus is a powerful tool to study their life cycle. Our results suggest that SEs have a significant impact on the general circulation of the western Mediterranean Sea.

[24] (i) 3 to 4 SEs are created every year. LIW and TDW, that are captured in the intermediate core of SEs from the northward along slope vein, are exported toward the interior of the Algerian Basin. Owing to the amount of LIW carried in a single SE, the fluxes toward the basin interior due to 3 or 4 SEs may reach 50% of the flow through the Channel of Sardinia.

[25] (ii) SEs can develop a clear surface signature few months after their detachment southwest of Sardinia and thus could have a significant impact on the surface circulation.

[26] (iii) SEs accumulate and merge between Minorca and Sardinia. The coalescence processes inducing the growth of an eddy there, appear to be constrained at a scale determined by the distance between these islands and by the presence of the Algerian Gyre to the south and the North Balearic Front to the north [*Millot*, 1999].

[27] The average anticyclonic circulation resulting in this region, may have several important consequences for the general circulation. This anticyclone is squeezed between the Northern and the Algerian gyres. The boundary flows along Sardinia and Minorca may also be deviated toward the interior due to the increased shear. This situation appears to be unstable since the anticyclone can migrate to the south.

[28] In a more general framework, this study underlines the usefulness of eddy-resolving OGCMs to investigate the role of the deep eddy field in the general circulation. However, further improvements are necessary to study it thoroughly. In particular, submesoscale eddies (SCVs, 5–10 km radius) involved in the spreading of the newly formed deep waters [*Testor and Gascard*, 2003] demand higher horizontal resolution (∼1 km or less), improved vertical resolution or isopycnal formulation. The parameterization of such eddies in OGCMs of lower resolution is not easy due to the large distance covered by such eddies transporting significant amount of specific waters, which is a non-local process.

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