Large scale flow separation and mesoscale eddy formation in the Algerian Basin

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Abstract

During the ELISA/MATER experiment floats released at about 600 m depth in the Levantine Intermediate Water layer south of Sardinia in July 1997 have revealed the existence of a coherent eddy, approximately 50 km in diameter and lasting for several months. This anticyclonic eddy was first observed south-west of Sardinia in November 1997 and drifted inside the Algerian Basin during the following months until April 1998. This eddy contained Levantine Intermediate Water at intermediate level and seemed to be related to 2 main large scale features: (a) a cyclonic gyre (250 km in diameter and 3–4 months period) located in the Algerian Basin and (b) a boundary current located along the continental slope south and west of Sardinia and originating from the Sardinia–Tunisia channel. We will first describe the “Sardinian” eddy, from a kinematical point of view, and the Algerian Gyre and second, give some insights about the eddy origin and its importance for LIW large scale spreading in the Western Mediterranean Sea.

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1. Introduction

The main information regarding the Algerian Basin concerns the circulation of the surface modified Atlantic Water (AW) which has been intensively studied with satellite imagery, moored current meters (Millot, 1999; Puillat, Taupier-Letage, & Millot, 2002) and surface drifters (Font, Millot, Salas, Julia, & Chic, 2005 Elsevier Ltd. All rights reserved.

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The mean transport of AW associated with the Algerian current flowing along the north African continental slope, is 1.7 Sv (Benzhora & Millot, 1995). The current is unstable and generates large anticyclonic Algerian Eddies (AEs) around 1–2°E longitude. They are about 100 km in diameter and have a rotational period of order of a week corresponding to a relative vorticity of $-f/10$ and peak orbital surface velocities of about 50 cm s$^{-1}$. AEs generally extend from the surface down to about 350 m depth which corresponds to the maximum depth reached by AW, but they can episodically extend much deeper. They circulate cyclonically around the Algerian Basin at mean speed of few cm s$^{-1}$, detaching from the north African coast at about 8°00'E. Usually, the average time for AEs to move around the Algerian Basin is about 1 year. Their lifetime is usually greater than 1 year and can reach 3 years according to Puillat et al. (2002).

Deeper water masses circulation in the Algerian Basin and through the Channel of Sardinia–Tunisia are less well-known. This channel is deep (~1900 m) and wide (~70 km at 500 m depth) and provides a unique opportunity for intermediate and deep waters to communicate between the Algerian Basin and the Tyrrhenian Sea. At higher levels a main core of Levantine Intermediate Water (LIW), centered around 350 m depth and characterized by high temperature and salinity maxima, flows westwards from the Tyrrhenian Sea to the Algero-Provencal Basin along the northern side of the Channel of Sardinia–Tunisia. This flow also concerns the Tyrrhenian Deep Waters (TDW) which are situated below between approximately 700 and 1500 m depth. These waters result from the LIW and the Western Mediterranean Deep Water (WMDW) which would have mixed together in the Tyrrhenian Sea (at about a 2:1 rate) although these mixing processes are not yet well documented (Hopkins, 1988, Rhein, Send, Klein, & Krahmann, 1999).

The WMDW flowing in the Channel of Sardinia–Tunisia and entering the Tyrrhenian Sea balances this export of TDW (0.2 Sv according to Hopkins (1988)) in the Algerian Basin. Based on CFC measurements, Rhein et al. (1999) observed a TDW outflow of ~0.4 Sv between 600 and 1600–1900 m depth from the Tyrrhenian Sea through the Channel of Sardinia in the Algerian Basin.

On the southern side of the Channel of Sardinia–Tunisia and at intermediate levels, modified LIW follows the path of AW heading east (Benzhora & Millot, 1995) and enters the Tyrrhenian Sea where it mixes with the LIW outflow coming from the Eastern Mediterranean Sea through the Channel of Sicily (Bouzinac, Font, & Millot, 1999; Sammari, Millot, Taupier-Letage, Stefani, & Brahim, 1999). Note, these deep interbasin exchanges are well illustrated by CTD casts in the Channel of Sardinia–Tunisia (Figs. 2 and 3 in Bouzinac et al. (1999)) showing very clearly the main core of LIW-TDW flowing westwards south of Sardinia and WMDW flowing eastwards north of Tunisia at deeper levels. Nevertheless, these deep water masses exchanges have not been quantified since geostrophic calculations did not reveal any significant baroclinic currents and the barotropic component is unknown.

South of Sardinia, the LIW vein flowing westwards is relatively narrow (~50 km), reaching ~800 m and characterized by pronounced temperature–salinity maxima (13.9 °C) at about 300 m depth. The LIW core turns northwards when leaving the Channel of Sardinia–Tunisia following the continental slope west of Sardinia (Katz, 1972; Millot, 1999; Perkins & Pistek, 1990; Wüst, 1961). West of Sardinia, the vein is wider (~120 km) and temperature maxima of 13.9 °C are found locally between 250 and 350 m depth across a 10–20 km narrow section (Millot, 1999). In the center of the Algerian Basin, LIW is generally significantly modified with typical temperature maxima half a degree colder (around 13.35 °C) due to increased mixing with the surroundings. TDW evidenced by Rhein et al. (1999) and characterized by a minimum of CFC concentration centered around 1000 m depth, fills the layer between LIW and WMDW throughout a large part of the Algerian Basin. WMDW and TDW are the 2 main components of deep waters in the Algerian Basin. CFC measurements allowed to identify TDW more efficiently than temperature-salinity characteristics alone, TDW being situated on the mixing line between WMDW and LIW on a $\theta$–$S$ diagram. The lowest CFC concentrations (comparable with CFC values found in the Tyrrhenian Sea) characterizing TDW, are found along the continental slope of Sardinia under the main core of LIW. According to Millot (1999) and Rhein et al. (1999), TDW follows the general cyclonic boundary circulation around the Algero-Provencal Basin like LIW and mixes in the interior of the basin.
Patches of LIW have been observed in the interior of the Algerian Basin with temperature maxima around 13.8 °C (Fuda, Millot, Taupier-Letage, Send, & Bocognagno, 2000; Millot, 1999) giving evidence to a direct transport of LIW from the LIW vein off Sardinian continental shelf and slope, towards the deep basin. The mesoscale activity characterizing AW and evidenced with surface measurements, is able to slow down and even to reverse the along slope circulation in the Channel of Sardinia–Tunisia according to Bouzinac et al. (1999). Patches of LIW observed in the Algerian Basin interior (Millot, 1999) may result also from AEs entrapping patches of LIW from the LIW vein and advecting them towards the middle of the basin. These patches have also been described as filaments swirling around AEs (Emelianov, Millot, Font, & Taupier-Letage, 1999). Millot (1999) also considered that LIW vein could generate anticyclones (“Led-dies”) resulting from (1) the vein instability (Afanasiev & Fillipov, 1996; Baey, Renouard, & Chabert d’Hières, 1995) (2) an increase in the vertical density gradient between the Tyrrhenian Sea and the Algerian Basin that would reduce the LIW layer thickness and create negative vorticity in accordance with potential vorticity conservation and (3) the momentum conservation of a flow following a continental slope presenting an angle to the right (Pichevin & Nof, 1995).

During MATER/LIWEX, Gascard et al. (1999) observed a deep cyclonic gyre circulation at 600 m depth in the Algerian Basin (Fig. 1). This gyre type circulation is different from the well-known general cyclonic alongslope circulation in the whole Algero-Provençal Basin since this cyclonic gyre also concerns waters in the interior of the basin. This large scale steady circulation revealed by Lagrangian floats from July 1997 to July 1998, has been defined as the Algerian Gyre. The Algerian Gyre extension is variable approximately 250 km in the East–West direction and 100–200 km in the South–North direction, occupying a large part of the Algerian Basin between the Balearic Islands, Sardinia and North Africa. This gyre is characterized by

Fig. 1. Trajectories of floats #09, #11, #14, #39 and #88 from 31 September 1997 to 26 December 1997 color-coded according to in situ potential temperature. Locations of moorings (crosses) equipped with currentmeters at 100, 350, 1000 and 1800 m depth.
horizontal velocities of 5–10 cm s\(^{-1}\) as indicated by floats drifting at its periphery and completing a full loop in 3–4 months. This is 3–4 times faster than the time needed by AEs (about 1 year) to circulate around the Algerian Basin (Puillat et al., 2002). During the same experiment, an eddy characterized by a strong LIW signature was also revealed by Lagrangian floats at the periphery of the Algerian Gyre and was first presented by Testor and Gascard (2003) as a LIW eddy. In this paper, we will mainly present a kinematical analysis of this eddy, based on data obtained during MATER/LIWEX experiment and will propose new insights about the origin of this eddy and its importance for LIW circulation in the Western Mediterranean Sea. We conclude that this eddy, hereafter named “Sardinian Eddy”, has a distinct origin from the Leddies hypothesized by Millot (1999) and are also quite different from Meddies observed in the North Atlantic (Richardson, Walsh, Armi, Schröder, & Price, 1989).

2. MATER experiment general presentation

During the MATER experiment, 15 subsurface Lagrangian floats have been located acoustically from July 1997 until July 1998 in the Algerian Basin. These so-called RAFOS floats are isobaric like Swallow floats (Swallow, 1955) and drift according to horizontal currents at a predetermined and quasi-constant depth. They are localized by acoustic triangulation using an array of moored acoustic sources transmitting long range propagating signals. Floats receive signals transmitted by acoustic sources every 4 h. The mean absolute accuracy for floats positioning is about 2 km but relative precision is better than 300 m. They also measure in situ temperature and pressure every 4 h. At the end of their mission they ascend to the surface and start transmitting data to satellites (NOAA/ARGOS). Twelve floats were recovered during LIWEX in July 1998 and deep CTD casts were taken at the locations where floats had been recovered.

Floats were ballasted to drift in the intermediate layer to document the subsurface general circulation of this basin and to complement other observations of ocean circulation carried out during the MATER/ELISA operation (MAST3 – EU final scientific report, 1999). During MATER/ELISA 1 cruise in July 1997, 10 floats had been launched in the center of the Algerian Basin and 5 floats had been launched south of Sardinia in the Levantine vein; the 15 drifting floats remained in the water at about 600 m depth for one full year (until July 1998).

3. Description of large and mesoscale features revealed by the MATER Lagrangian float experiment

We will focus on the autumn 1997–spring 1998 period during which floats highlighted an eddy-like flow field of marked LIW that we named Sardinian Eddy and also a gyre-like circulation that we named Algerian Gyre.

3.1. Deep cyclonic circulation in the Algerian Basin: the Algerian Gyre

Floats #09 and #11 launched in the center of the Algerian Basin in July 1997 clearly show the large cyclonic gyre deep circulation in the Algerian Basin (Fig. 1), the so-called Algerian Gyre (Gascard et al., 1999). They drifted in the Gyre throughout the whole experiment and measured velocities of 5.6 ± 2.2 and 5.1 ± 1.8 cm s\(^{-1}\), respectively. The Algerian Gyre was very energetic between November 1997 and January 1998 with velocities up to 8 cm s\(^{-1}\) at the periphery (float #09, Fig. 2). Floats drifting in the gyre measured potential temperatures around 13.1 °C at about 600 m depth in contrast to the high temperatures recorded in the Sardinian Vein west of Sardinia or in the Sardinian Eddy at the periphery of the gyre by other floats.
The Algerian Gyre was revealed by other floats (Fig. 3) and has a strong seasonal variability: it is stronger in winter ($U \sim 10 \, \text{cm s}^{-1}$) than in summer ($U \sim 5 \, \text{cm s}^{-1}$). Fig. 3 also shows $fH$ contours which are closed in the Algerian Basin and which coincide with the structure of the gyre as revealed by floats, both in summer and winter. This configuration is in favor of a barotropic gyre circulation.
3.2. Flow separation south-west of Sardinia

CTD casts 048–057 undertaken during the ELISA experiment (Fig. 4) document the structure of the fluid flowing northward along the western slope of Sardinia and in the Algerian Gyre. South-west of Sardinia, geostrophic calculations referenced to 1000 m depth on the ELISA CTD casts 048–057 are presented in Fig. 4. They do not indicate any current greater than 0.5 cm s\(^{-1}\) below 300 m depth (AW layer). In contrast, south-west of Sardinia, velocities at 600 m depth are larger (order of 5 cm s\(^{-1}\)) which implies that currents are mainly constant along the vertical below the AW layer.

Velocities at float #88, reached a peak value of about 10 cm s\(^{-1}\) (Fig. 2) when it was the closest to the 2000 m isobath. At this time, float #09 velocities (Fig. 2) drifting nearby float #88, are about the same as float #88 velocities. There is a strong temperature gradient between these two floats (Fig. 4). Being less than 10 km away from each other, float #88 measured a temperature \(~0.4\) °C greater than float #09, indicating that float #09 was in the Algerian Gyre whereas float #88 was in LIW that had recently come from the Tyrrhenian Sea (Fig. 1). Around 39°00' N, 7°30' E the two float paths separated; float #88 followed the continental slope, and float #09 remained in the cyclonic Algerian Gyre, detaching from the continental slope.

South-west of Sardinia, the LIW core is characterized by anticyclonic horizontal shear between the Algerian gyre and the continental slope (Fig. 5). This shear is evaluated to be about \(-0.9\) to \(-0.4 \times 10^{-5}\) s\(^{-1}\).
Note that the assumption of homogeneity for alongslope projection is justified as along slope velocities measured by float #88 are about the same before and after the float detected the maximum velocity allowing us to define the new referential.

In this region, the LIW circulating along the continental slope south and west of Sardinia, is confined between the energetic cyclonic Algerian Gyre and the continental slope (Fig. 4).

### 3.3. LIW Sardinian vein west of Sardinia

Float #88 at 600 m depth remained in marked LIW until 28 January 1998 indicating deep currents flowing along the slope of Sardinia. During all its journey, it measured potential temperatures of 13.5–13.6 °C at 600 m depth (Fig. 2) and closely followed the 1000 m isobath (Fig. 1). Velocities measured by this float were $2.8 \pm 2.4$ cm s$^{-1}$.

The waters coming directly from the Tyrrhenian sea have their TS characteristics modified while flowing northwards along the slope as indicated by CTD casts 908–910 (Fig. 4). This shows, as already suggested by Millot (1999), that some dramatic change in the structure of the alongslope flow occurs south-west of Sardinia.

Geostrophic calculations with reference at 1000 m depth on the LIWEX CTD casts 908–910 presented in Fig. 4 do not indicate any current greater than 0.5 cm s$^{-1}$ below 300 m depth either. Accordingly, the Sardinian Vein is composed of waters coming directly from the Tyrrhenian Sea mainly confined between 1000 and 2000 m isobaths. It flows northwards west of Sardinia and seems to be a sluggish circulation characterized by no vertical shear below the surface layer of AW.
3.4. Sardinian Eddy

In November 1997, two floats (#39 at 700 m depth and #14 at 600 m depth launched south of Sardinia in July 1997) began to describe anticyclonic loops of 3–4 weeks period, indicating that they were both drifting in the same mesoscale eddy. Both floats measured very high temperatures (\(\sim 13.6^\circ C\) at 600 m depth and \(\sim 13.4^\circ C\) at 700 m depth) typical of LIW off the coast of Sardinia. Float #39 left the Sardinian Eddy on 26 December 1997 and float #14 remained within the eddy until April 1998, indicating an eddy life-time greater than 5 months. Since low-pass filters applied to floats fixes allow to have an estimation of the vortex center locations, the relative positions of floats to the estimated center of rotation of the Sardinian Eddy were computed as well as the corresponding orbital velocities considering this eddy was axisymmetric. Thus, a radial distribution of orbital velocities (Fig. 6) could be estimated. This gives a typical Sardinian Eddy radius length scale of about 25–30 km (defined as the distance of maximum orbital velocity) confirmed by an upper bound of the eddy radius according to a float passing...
nearby at the same depth (#09 at 40 km from the center, Fig. 1) and not influenced by the vortex rotations. The eddy core was in quasi solid body rotation and had a relative vorticity $\zeta \sim -f/16$ leading to a Rossby number of 0.06.

Three phases can be identified from floats trajectories (Fig. 7):

- **Phase 1**: First, floats #14 and #39 drifted in the LIW core south-west of Sardinia (Figs. 7 and 2). Both measured high temperatures and low velocities typical of LIW off Sardinia. Temperatures decreased slowly until the beginning of November, indicating they were drifting in a slightly modified LIW while velocities increased. Floats #11 and #09 were embedded in the Algerian Gyre and measured temperatures and velocities (Fig. 2), in contrast to floats #14 and #39.

- **Phase 2**: At the beginning of November, floats #39 (around 700 m depth) and #14 (around 600 m depth) detached from the continental slope and began to describe anticyclonic loops of about 3–4 weeks period while still drifting in warm waters typical of LIW. At this time, they were clearly trapped in the Sardinian Eddy. The two floats drifted almost diametrically opposed and at about the same distance from the eddy.

![Fig. 6](image-url)
center for 2 complete eddy revolutions. During this period, the Sardinian Eddy translated at a velocity of about 3 cm s\(^{-1}\) at the periphery of the Algerian Gyre as shown by time series of floats velocities indicating oscillations of 3–4 weeks periods and amplitudes about 5 cm s\(^{-1}\), centered around 3 cm s\(^{-1}\) (Fig. 2). Temperatures decreased significantly when the eddy detached from the Sardinian Vein, indicating an overall response to a colder environment.

- **Phase 3:** At the end of December, the Sardinian Eddy remained on a steady position north of the Algerian Gyre for several weeks. At the same time, float #39 drifted away from the Sardinian Eddy center while float #14 went closer to the center. Float #14 remained in the eddy until mid April 1998 while float #39 moved away from it and began to drift without transition in a very distinct, much smaller and coherent vortex advecting newly formed WMDW (SCV-S1, in Testor & Gascard (2003)). At the end of March, the Sardinian Eddy started to propagate southwards with advection speeds about 3 cm s\(^{-1}\) and, finally float #14 left the Sardinian Eddy around mid-April.
4. Differential kinematic parameters

4.1. Estimation of differential kinematic parameters

A method based on the works of Molinari and Kirwan (1975) and Sanderson (1995) allows to analyse float trajectories in terms of differential kinematic parameters (DKPs)-relative vorticity (vor), divergence (div), shear (shr) and stretch (str)- for a water parcel defined by a cluster of floats, by computation of horizontal velocity gradients (Eq. (1)). For a water parcel with velocities \((\vec{u}(x, y), \vec{v}(x, y))\),

\[
g_{11} = \frac{\partial \vec{u}}{\partial x}; \quad g_{12} = \frac{\partial \vec{u}}{\partial y}; \quad g_{21} = \frac{\partial \vec{v}}{\partial x}; \quad g_{22} = \frac{\partial \vec{v}}{\partial y},
\]

and \(\text{vor} = g_{21} - g_{12}; \text{div} = g_{11} + g_{22}; \text{shr} = g_{21} + g_{12}; \text{str} = g_{11} - g_{22}\).

A cluster of \(N\) floats drifting close to each other, is taken as a water parcel in which we assume that horizontal speed gradients are homogeneous. Then, these gradients can be estimated by inverting (using least squares method) the system (Eq. (2)) in which we express the velocity of each float in a Taylor expansion about the center of mass of the cluster.

\[
\begin{align*}
\{ \quad & u_i = U + g_{11}(x_i - X) + g_{12}(y_i - Y) + u'_i, \\
& v_i = V + g_{21}(x_i - X) + g_{22}(y_i - Y) + v'_i,
\end{align*}
\]

where \((x_i, y_i)\) are the floats positions, \((u_i, v_i)\) are the floats velocities, \((X, Y)\) is the position of the mass center of the cluster of floats \((x_i, y_i)\), \((U, V)\) is the velocity of the center \((X, Y)\) (mean velocity of the parcel) and \((u'_i, v'_i)\) are residual velocities.

Assuming that velocity gradients linked to the water column are constant during \(T\) time steps and defining a cluster centre as \((X, Y) = \frac{1}{N} \sum_{k=1}^{N} \sum_{i=1}^{T} (x_i(k), y_i(k))\), we can increase the number of equations used for the linear trend (Eqs. (3) and (4)). We can rewrite all these equations using matrices:

\[
\begin{align*}
U &= RA + E, \\
R &= \begin{pmatrix}
(u_1(t_1) - U) & v_1(t_1) - V \\
\vdots & \vdots \\
(u_N(t_1) - U) & v_N(t_1) - V \\
\vdots & \vdots \\
(u_1(t_T) - U) & v_1(t_T) - V \\
\vdots & \vdots \\
(u_N(t_T) - U) & v_N(t_T) - V
\end{pmatrix}, \\
E &= \begin{pmatrix}
x_1(t_1) - X & y_1(t_1) - Y \\
\vdots & \vdots \\
x_N(t_1) - X & y_N(t_1) - Y \\
\vdots & \vdots \\
x_1(t_T) - X & y_1(t_T) - Y \\
\vdots & \vdots \\
x_N(t_T) - X & y_N(t_T) - Y
\end{pmatrix},
\end{align*}
\]

and \(A = \begin{pmatrix} g_{11} & g_{21} \\
g_{12} & g_{22} \end{pmatrix}\).

Thus, we can determine \(A\) and the residual matrix by calculating the linear trend every \(T\) time steps:

\[
A = (R^+R)^{-1}R^+U; \quad E = U - RA.
\]
4.2. Okubo–Weiss criterion

A criterion addressing how to partition the fluid into regions with different dynamical properties has been derived by Okubo (1970) and Weiss (1991). With this criterion and the knowledge of the differential kinematical parameters of a water parcel, one can determine if this parcel is more typical of a vortex or a filament:

\[
\lambda = (\text{shr}^2 + \text{str}^2) - \text{vor}^2 \begin{cases} < 0 & \Rightarrow \text{vortex}, \\ > 0 & \Rightarrow \text{filament}. \end{cases}
\]

To increase the number of data used for the linear regression presented in Section 4.1, as we have generally only 2–3 floats in the water parcel, 5 time steps (20 h) have been used for the computations, low compared to the time scale of the mesoscale phenomena which are studied hereafter. Every phenomena characterized by smaller time scales are filtered out by this method. Computations were repeated 5 times (shifting time from 0 to 4 time steps), and the scatter of these 5 different estimates indicate the accuracy of the results.

Fig. 8 shows computations of differential kinematic parameters for the situation presented in Fig. 5, involving floats #09 and #88 from 15 to 18 November 1997. Estimates of the shear are about \(-0.5 \times 10^{-5} \text{ s}^{-1}\) and agree with previous estimates (Section 3.2). The Okubo–Weiss criterion also revealed that floats were drifting in a region dominated by filamentation (shear and stretch, \(\lambda > 0\)) during that period.

This criterion was also applied to the water parcel represented by floats #39 and #14 (Fig. 9). One can clearly see two different dynamical regimes. The two floats were first drifting in a region dominated by filamentation (\(\lambda > 0\)) which corresponds to the LIW flow south-west of Sardinia and then passed to an eddy flow field (\(\lambda < 0\)) around 8 November 1997 when the two floats left the vicinity of the continental slope to drift in the Sardinian Eddy. Note that from that date, estimations of the relative vorticity \(\zeta\) gives \(\zeta/f\) about \(-0.05\), consistent with previous estimations of relative vorticity associated to the Sardinian Eddy (Section 3.4).

The same computations were carried out using floats #39, #14 and #09 between 20 November 1997 and 12 December 1997 (Fig. 10). The definition of the water parcel in this case is more tricky, but it shows interesting results as calculations are almost unchanged for relative vorticity (about \(-0.5 \times 10^{-5} \text{ s}^{-1}\)) with or without adding float #09. Peak values are due to numerical limitations, when the surface of the parcel nears 0, the three floats being on a line. Between these peaks, float #09 acted as if it belonged to the Sardinian Eddy from a vorticity point of view. Velocities measured by floats #09, #14 and #39 during that period also suggest that float #09, defining the periphery of the gyre, can also define the periphery of the Sardinian Eddy (Fig. 11). Indeed, velocities at floats #14 and #39 were about the same as velocities at float #09, when they were the closest to float #09.

5. Discussion

5.1. Algerian Eddies

Long-lived AEs were followed in the Algerian Basin during the whole experiment (July 1997–July 1998). They formed along the African coast around 1–2°E longitude by instabilities of the Algerian Current and then propagated eastwards until they reached about 8°00′ E longitude. Here they detached from the coast and moved cyclonically around the basin. They have a clear sea surface temperature signature and Puillat et al. (2002) described in great detail the paths of AEs during the ELISA experiment (July 1997–July 1998).
based on AVHRR images. SST images allow the positioning of AEs only in clear sky conditions. We checked that other data (TOPEX/POSEIDON tracks and ELISA current meters; non-published yet) can also be used to localize AEs with a better time resolution than with SST images only. CTD casts (geostrophic computations), current meters records at 100, 350, 1000 and 1800 m depth and floats trajectories (around 600 m depth) showed that their vertical extension varied a lot. It appeared that 600 m deep floats did not generally show any influence of the large anticyclonic AEs up above. Current meters at 100 m always showed the signature of these eddies, but for deeper current meters, it was in agreement with floats.

Between September 1997 and January 1998, two AEs (96-1 and 97-1) were identified and located along the Algerian coast, quite far away from Sardinia (Puillat et al., 2002). 96-1 circulated from 6°E to 8°E during that period and 97-1 from 3°E to 4°E along the north African coast with advection speed of few cm s$^{-1}$. Their diameter varied between 100 and 170 km and they were limited to the AW layer during that period.

They remained quite far away from the south-west corner of Sardinia and consequently they could hardly have been involved in the formation of the Sardinian Eddy revealed by floats #14 and #39. On the other hand, AEs seem to participate to some LIW transport across the Algerian Basin. Indeed, by the time AEs reach the south-west corner of Sardinia, LIW filaments appeared swirling around AEs as described by Emelianov et al. (1999).
5.2. Barotropic motions

5.2.1. Algerian gyre

The ELISA current meters deployed at 1800, 1000 and 350 m depth in the Algerian Basin (MAST3 – EU final scientific report, 1999, see Fig. Sa1 for the position of the moorings) confirm that the cyclonic large scale gyre circulation is barotropic. In the surface layer (ELISA currentmeters at 100 m depth), the gyre is hidden by strong mesoscale currents due to AEs (orbital velocities \( \sim 50 \text{ cm s}^{-1} \)) which were generally limited to the surface AW layer during this experiment.

AEs migrate cyclonically around the Algerian Basin more slowly (\( \sim 1 \text{ year} \)) than the floats below (\( \sim 3–4 \text{ months} \)) and this is largely due to AEs being blocked several weeks along the African slope. This indicates that the cyclonic Algerian Gyre is strongly influencing the general movement of AEs around the basin.

CTD casts carried out during ELISA experiment were mainly limited to 0–1000 m depth so they could not give a good representation of deep circulation. Nevertheless, no doming of isopycnals between 0 and 1000 m depth was observed, which is consistent with a barotropic gyre.

So, these arguments are all in favor of a barotropic Algerian Gyre strongly influenced by the bottom topography and earth rotation (see Section 3.1).
5.2.2. Alongslope current south-west of Sardinia

It has to be pointed out that the velocity (LADCP measurements) and CFC measurements presented by Rhein et al. (1999) were undertaken approximately at the same time as our observations (Figs. 4, 8 and Plate 1 in their paper). Rhein et al. (1999) showed that TDW coming from the Tyrrhenian Sea extended from 700 down to 1500 m depth just below the LIW layer in the whole basin. Our Fig. 5 deduced from floats drifting around 600 m depth is quite similar to Fig. 8 in Rhein et al. (1999) representing the mean velocity between 800 and 1500 m depth. It indicates that currents beneath the AW surface layer (0–350 m) and down to 1800 m depth or to the bottom when it is shallower, are almost constant with depth, south-west of Sardinia. Thus, the circulation south-west of Sardinia appears to be mainly barotropic as the Algerian Gyre.

In this region, the Algerian Gyre and the circulation originating from the Tyrrhenian Sea and following the continental slope south of Sardinia, merge and correspond to a maximum velocity of about 10 cm s\(^{-1}\). This maximum velocity extends over a large depth range in the LIW-TDW layer and is situated above the 2500 m isobath (compare Figs. 5 and 4 with Figs. 5 and 8 in Rhein et al. (1999)). The LIW and TDW cores coming directly from the Tyrrhenian Sea through the Channel of Sardinia–Tunisia and characterized by high temperature/salinity and low CFC values (<0.7 pmol kg\(^{-1}\)) respectively, are mainly confined to the right-hand side of the velocity maximum in a region dominated by an horizontal anticyclonic shear.
Indirect estimates of Rhein et al. (1999) from tracers lead to an annual mean inflow of TDW from the Tyrrhenian sea of 0.4 Sv. Fig. 5 (as well as with Fig. 8 in Rhein et al. (1999)) would indicate an instantaneous transport of about 0.8 Sv with mean velocities of 4 cm s\(^{-1}\) between 600 and 1600 m depth across a section 20 km wide crossing the region of pronounced LIW and TDW influence. In comparison, the Algerian Gyre involves a mean recirculation of 4 Sv which is one order of magnitude higher, considering a mean orbital velocity of 4 cm s\(^{-1}\) across a section 1000 m high (between 600 and 1600 m depth) and 100 km wide (between the center and the periphery of the gyre). Also, in contrast to the Algerian Gyre, which appears very energetic, the Sardinian Vein west of Sardinia appears as a more sluggish circulation closely following the continental slope northwards.

5.3. Sardinian Eddy formation

Concerning the origin and formation of the Sardinian Eddy, several relevant aspects have to be examined. As mentioned in Section 1, Millot (1999) proposed 3 mechanisms for the formation of eddies south-
west of Sardinia. We propose another one due to the Algerian Gyre, which separates from the slope and was never observed before.

5.3.1. Gyre flow separation

The Algerian Gyre (approximately 250 km diameter and 3–4 months period) appears as a dominant and permanent feature in the Algerian Basin. It seems to extend down to the bottom having maximum intensity at great depths (500–1800 m depth), but also influences the AEs in the surface layer as well. It is characterized by a seasonal variability in horizontal extension and intensity. It reaches its maximal intensity of 8–10 cm s\(^{-1}\) at its periphery in late autumn-winter. This gyre implies that a large amount of water separates from the continental slope at about 39°00′ N, whereas the Sardinian Vein flows along the slope west of Sardinia.

The analysis of differential kinematic parameters (Section 4.2) indicates that the LIW flow south-west of Sardinia is a region dominated by filamentation (mainly anticyclonic shear). The Sardinian Eddy characteristics seem to be mainly due to the anticyclonic shear in this region, as the relative vorticity of the eddy was about equivalent to the shear vorticity (~0.5 × 10\(^{-3}\) s\(^{-1}\)) near the continental slope, (Sections 3.2 and 4.2). Part of the shear would have been transferred to curvature vorticity (about half) and the other part to shear vorticity, as the eddy is in quasi-solid body rotation, once the water parcel had left the vicinity of the Sardinian slope. This is illustrated by Okubo–Weiss criterion evidencing 2 regimes, before (filaments) and after (vortex) November 8, 1997 (Figs. 8 and 9). Time series of velocities from floats and differential kinematic parameters indicate that parcels at the periphery of the Algerian Gyre could also characterize the edge of the Sardinian Eddy from kinetic energy and relative vorticity points of view (Section 4.2). That suggests that the flow separation south-west of Sardinia is certainly involved in the formation of the Sardinian Eddy.

Marshall and Tansley (2001) derived an implicit formula for the separation of a current from the coast. Scaling analysis indicates that the condition for a current separating from a vertical wall is

\[
r < \left( \frac{U}{\beta} \right)^{1/2},
\]

where \(r\) is the radius of curvature of the coast, \(U\) the speed of the boundary current and \(\beta\) the gradient of the Coriolis parameter in the downstream direction. For \(\beta \approx 10^{-11} \text{ m}^{-1} \text{ s}^{-1}\), \(U \approx 0.1 \text{ m s}^{-1}\) (which are values corresponding to the gyre in winter when it is fully developed), it requires \(r < 100 \text{ km}\). The separation from the coast of a jet or a gyre would require the generation of eddies to maintain the separation according to Tansley (2001). Around the south-west corner of Sardinia (Fig. 7(c)) the continental shelf and slope form a bulge characterized by a radius smaller than 100 km satisfying the Marshall and Tansley (2001) criterion for flow separation and eddy formation.

We propose the Sardinian Eddy first observed on November 8, 1997 exactly at the separation location and then migrating on the edge of the Algerian Gyre, is generated according to this process.

We have no precise indication about the vertical structure of this Sardinian Eddy since float #14 drifted at about 600 m depth and float #39 at about 700 m depth. NOAA/AVHRR SST or SEAWIFS images could not be used intensively due to a strong cloud cover during the autumn–winter season in this region. But, the formation mechanism we propose suggests this would be a strongly barotropic eddy. However, no surface signature of this eddy could be found neither on the few SST images, nor on TOPEX/POSEIDON tracks due to sampling and resolution problem.

5.3.2. Other mechanisms

LIW and TDW flow south of Sardinia, join the Algerian Gyre south-west of Sardinia and may continue to flow along the western Sardinian slope (float #88, Section 3.2). Could an internal dynamic stability of this flow be involved in the generation of Sardinian Eddies? The horizontal structure of isopycnals is very
weak in the LIW–TDW layer (300–1600 m) and geostrophic calculations do not show any significant vertical shear along the slope of Sardinia. So, the hypothesis of Millot (1999) assuming that LIW eddies are generated by an unstable intermediate jet of LIW seems improbable. If an instability process was involved in the generation of LIW eddies, it would rather involve a horizontal shear as for a barotropic instability. However, second-order derivatives of velocities are needed to estimate a criterion of barotropic instability.

Another hypothesis of Millot (1999) considers that an increase in the vertical density gradient would produce anticyclonic vorticity. A production of anticyclonic vorticity of $-f/16$ requires a shrinking of 10 m for a water parcel initially at rest and extending over 160 m according to the conservation of potential vorticity. This had not been observed on CTD casts carried out along the slope, but the CTD array was certainly not sufficient to detect such shrinking.

The effect of a sharp slope angle to the right, so-called “eddy-gun” (Pichevin & Nof, 1995), could also generate an eddy as a result of momentum conservation and requires an agent responsible for the removal of the eddy from the generation area – this is provided by $\beta$-effect or advection (or both).

So, while we cannot exclude these effects, the Sardinian Eddy formation mechanism we propose is different and involves the newly discovered Algerian Gyre circulation feature which is far more energetic than the circulation associated with LIW and TDW south-west of Sardinia.

5.4. Comparison with Meddies

The situation met south-west of Sardinia is really different from the situation met south-west of Spain and links between the generations of Meddies and Sardinian Eddies (as sometimes it has been suggested for Meddies and Leddies) are not likely. The presence of an energetic cyclonic flow (which seems to contribute actively to the generation of LIW eddies) is also in contrast with the general circulation south of Spain. Even if Meddies and Sardinian Eddies had about the same radius of about 25–30 km (Richardson et al., 1989), their density structures and relative vorticities are very different. Indeed, Mediterranean Water composing the core of Meddies has a strong density signature (almost constant potential density) due to homogenization and entrainment while cascading from Gibraltar Strait. This is in contrast to LIW flowing along the slope of Sardinia in a strongly barotropic flow, presenting typical temperature–salinity characteristics which compensate so that there is almost no density difference between the modified LIW in the Algerian Basin and the LIW coming recently from the Tyrrhenian Sea. Also, a Meddy has about $-f/2$ relative vorticity due to the density distribution (Richardson et al., 1989), which is a very strong anomaly compared with the $-f/16$ of the Sardinian Eddy. In summary, this clearly shows that these two kinds of eddies are very different dynamical features: the Meddies belong to the Submesoscale Coherent Vortex category (McWilliams, 1985) in contrast to Sardinian Eddies.

6. Conclusion

The anticyclonic Sardinian Eddy revealed by the MATER (ELISA-LIWEX) experiment is characterized by a radius of about 30 km, a rotational period of 3–4 weeks and if we approximate it with a quasi-solid body rotation, a mean relative vorticity of about $-f/16$ corresponding to a Rossby number $R_0 \sim 0.06$. The origin of this Sardinian Eddy seems to be strongly related to some interactions between the large scale cyclonic Algerian Gyre and the general boundary circulation entraining LIW along the continental slope of Sardinia. The Sardinian Eddy appeared precisely at the separation location between these two large scale features and evolved later on at the periphery of the Algerian Gyre. The Sardinian Eddy has a strong LIW signature as the water at 600 m depth in the core of the eddy has the same characteristics as the LIW found along the slope West of Sardinia. Its relative vorticity may be due to the anticyclonic shear between the Algerian Gyre and the circulation along the continental slope south-west of Sardinia where the Algerian
Gyre and the Sardinian Vein merge and split. The formation mechanism seems mainly due to the energetic cyclonic Algerian Gyre separating from the continental slope south-west of Sardinia and as a result of (1) the geometry of the continental slope, (2) the speed of the flow intensified by the gyre at this location and (3) the planetary vorticity gradient along the direction of the flow. The flow separating from the slope generates eddies like Sardinian Eddies according to a process similar to the one described by Tansley (2001) and Marshall and Tansley (2001), dealing with the Gulf Stream separating from the east north American coast near Cape Hatteras.

This observation of a Sardinian Eddy is a valuable information concerning the pending question of how the LIW spreads in the Algerian Basin. Our findings contribute (1) to characterize Sardinian Eddies from an eddy-structure point of view (kinematics and dynamics) (2) to shed light on the origin of such eddy and (3) to estimate how important are Sardinian Eddies for the general circulation of LIW and TDW in the Mediterranean Sea. The Sardinian Eddy structure described is noticeably distinct from Meddies and Leddies previously reported in the literature.

In addition, the MATER 1997/98 experiment indicated a Submesoscale Coherent Vortex composed of newly formed WMDW (SCV-S1) interacting with the Sardinian Eddy (Testor & Gascard, 2003) indicating that Sardinian Eddies can also have a significant role influencing the spreading of newly formed WMDW in the Algero-Provençal Basin and vice versa.

The vertical extension of the Sardinian Eddy could not be precisely specified but it may have well concerned the whole water column. Each Sardinian Eddy would amount to about \(3 \times 10^{12} \text{ m}^3\) of LIW and TDW leaving the boundary circulation towards the interior of the Algero-Provençal Basin. This is equivalent to a volume of water passing through a section 30 km wide and 1 km high, with a mean velocity of about 4 cm s\(^{-1}\) during 1 month. In other words, a single Sardinian Eddy can account for as much as 1 month of the inflow of waters coming from the Trrhenian Sea, which is quite significant and should have important consequences on the Sardinian Vein flowing northwards west of Sardinia. The Algerian Gyre is characterized by a strong seasonal variability and Sardinian Eddies will mainly be formed in winter when the gyre has its greatest intensity. Accordingly, 4–5 Sardinian Eddies may very well be formed each year and can account for almost 50% of the waters entering into the Algero-Provençal Basin through the Channel of Sardinia.

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