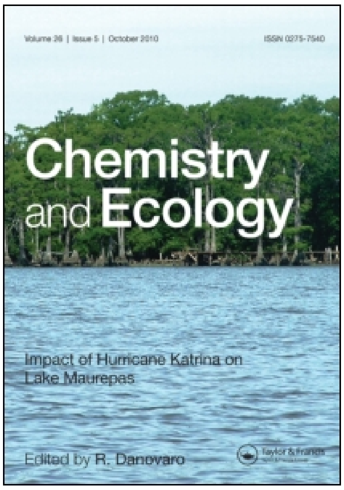

Chemistry and Ecology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713455114

Westward branching of LIW induced by Algerian anticyclonic eddies close to the Sardinian slope

I. Puillat[ab]; R. Sorgente[a]; A. Ribotti[a]; S. Natale[a]; V. Echevin[b]
[a] Fondazione IMC ONLUS, Italy [b] Laboratoire d'Océanographie et du Climat: Expérimentations et approches numériques (LOCEAN-exLODyC), Université Pierre et Marie Curie, Paris cedex 05, France

To cite this Article Puillat, I. , Sorgente, R. , Ribotti, A. , Natale, S. and Echevin, V.(2006) 'Westward branching of LIW induced by Algerian anticyclonic eddies close to the Sardinian slope', Chemistry and Ecology, 22: 4, S293 — S305
To link to this Article: DOI: 10.1080/02757540600670760
URL: http://dx.doi.org/10.1080/02757540600670760

Chemistry and Ecology
August 2006, Vol. 22 (Supplement 1), pp. S293–S305

Westward branching of LIW induced by Algerian anticyclonic eddies close to the Sardinian slope

I. PUILLAT†‡, R. SORGENTE†, A. RIBOTTI†, S. NATALE*† and V. ECHEVIN‡

†Fondazione IMC ONLUS, loc. Sa Mardini, 09170 Torregrande (OR), Italy
‡c/o V. Echevin, Laboratoire d'Océanographie et du Climat: Expérimentations et approches numériques (LOCEAN-exLODyC), Université Pierre et Marie Curie T26 4E Boite 100, 4 place Jussieu, 75252 Paris cedex 05 France

(Received 15 March 2005; in final form 3 March 2006)

The interaction between anticyclonic Algerian eddies and Levantine Intermediate Water (LIW) flow is investigated along the western Sardinian slope by analysing *in situ* data and model results. In March–April 2001, LIW flowed northward inshore the isobath 2000 m. At about 30 km far offshore, LIW was more distributed in patches than in a vein, and there this variability was associated with a distant anticylonic eddy. In May 2002, the situation was very different: LIW was also patchy inshore from the 2000 m isobath. On horizontal sections, LIW was observed in a relative wide latitudinal band (∼50 km) centred on ∼40° N, in the southern part of an anticyclonic eddy located over the slope. This study shows that mesoscale structures can disturb the LIW flows along the Sardinian slope by diverting a part of LIW flow westward.

Keywords: Sardinian Sea; Antycyclonic eddies; LIW flow; Mesoscale activity

1. Introduction

The area investigated is the Sardinian Sea (figure 1), located west off Sardinia, from the coast to ∼7° E. It is directly connected to the Algerian basin where mostly anticyclonic Algerian Eddies (AEs [1]) drive the circulation [2]. Their diameter varies between ∼50 and ∼250 km [3], and their vertical extent ranges from hundreds of metres to the bottom (1000–3000 m). They can last 2–3 yr in the basin [4] propagating along a counter-clockwise trajectory in the eastern Algerian basin [5]. Some AEs break off from the Algerian current and slope to follow the Sardinian slope northward and then, eventually, propagate inside the basin.

Consequently, in the surface layer, AEs transport relatively fresh Atlantic Water (AW) with a salinity lower than 38.0 in the centre of the basin where modified AW stays with a typical salinity higher than 38.0. When passing close to or in the Sardinian Sea, AEs drive or strongly disturb the circulation over the slope and the shelf [6]. At an intermediate level, along the western Sardinian slope, the Levantine Intermediate Water (LIW), which enters the western basin

*Corresponding author. Email: s.natale@imc-it.org

Chemistry and Ecology
ISSN 0275-7540 print/ISSN 1029-0370 online
http://www.tandf.co.uk/journals
DOI: 10.1080/02757540600670760

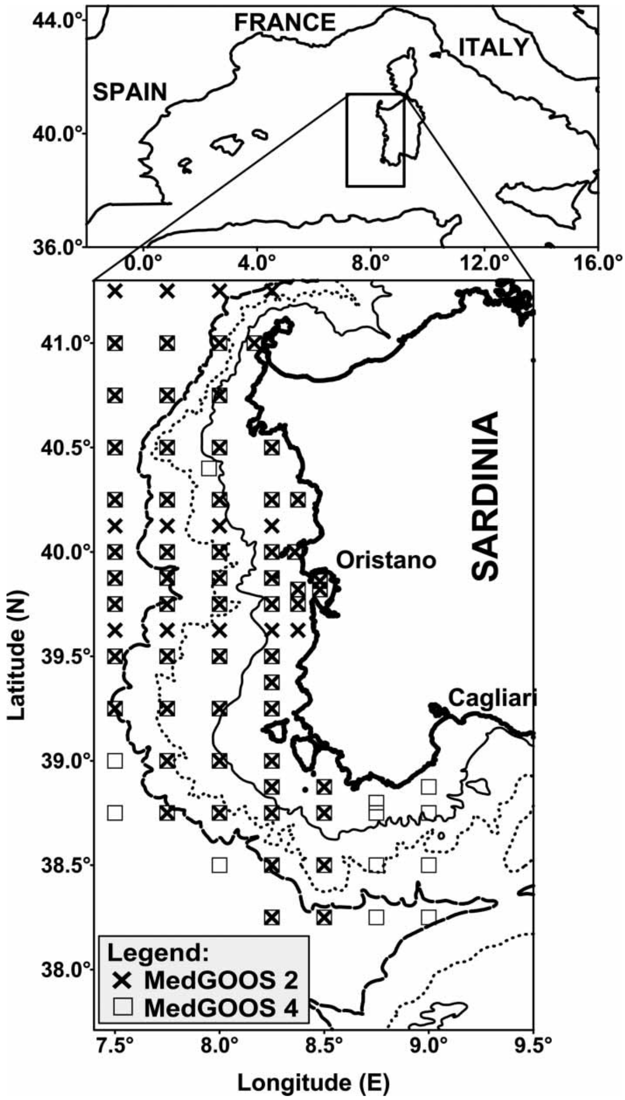

Figure 1. Localization of the CTD stations during the two cruises in the Sardinian Sea (Western Mediterranean Sea).

through the Channel of Sardinia between ~300 m and ~800 m [7], is subject to controversies. For instance, analysis of modelling results by Wu and Haines [8] and Korres *et al.* [9] depicted a northward LIW flow on the western Sardinia slope and a westward mean LIW undercurrent flowing directly to Gibraltar. Korres *et al.* found an inverse dependence of the LIW flow on the wind curl forcing in the western Mediterranean. By contrast, by running a higher-resolution model, Demirov and Pinardi [10] suggested a possible effect of eddies to deviate the LIW flow. In addition, from *in situ* measurements, LIW is expected to be partly deviated by AEs from its northward flow along the western Sardinian slope, but this has never been directly observed. Indeed, Millot [2, 11, 12] and Millot and Taupier-Letage [13] demonstrated that masses of little mixed LIW observed in the open Algerian basin are patches of recent LIW trapped from the Sardinian vein by anticyclonic eddies which passed near the western Sardinian slope. At the same time, they contested the existence of an hypothetic permanent westward LIW branch coming from the Sardinian Channel [7, 14]. According to Millot and Taupier-Letage, those eddies may be AEs or other eddies due to the instability of the LIW vein off Sardinia, but these last ones had never been evidenced by *in situ* experiments. Eddies that have already been observed *in situ* with recent LIW trapped inside are AEs [5, 11–13, 15, 16]. Nevertheless, these eddies were mainly observed in the open basin but never observed while directly catching recent LIW.

The aim of this paper is to show an AE catching LIW on the western Sardinian slope and diverting LIW westward, confirming the key role of AEs on LIW distribution. In contrast with previous *in situ* studies located off southern Sardinia, here almost all the western slope is investigated. All the involved supports and methods are described in section 2, and section 3 presents the results.

2. Methods

This study combines *in situ* observations, a numerical circulation model simulation and infrared satellite images. During two surveys, named Medgoos 2 (23 March to 3 April 2001) and Medgoos 4 (4–23 May 2002), the hydrological variability was investigated by CTD measurements. The selected points covered the whole area quite regularly with a 25 km grid. This was a good compromise between the need to have a fine enough spatial sampling to study mesoscale phenomena over the whole area and the available vessel time. Data were quality-checked and processed following the MODB quality-control procedures [17] and using SeaBird SBE software. Data were directly analysed using interpolation software, providing a description of the hydrology, but also interpolated using the Objective Analyses Method [18] on a regular 2 km grid in order to initialize the three-dimensional, free surface, ocean model based on the Princeton Ocean Model (POM) [19], using the Boussinesq approximation and the hydrostatic equilibrium. The model has been implemented within the study area at 7.4–8.5° E and 38.7–40.6° N, with a spatial resolution of $1/60° \times 1/60°$ (about 2 km), lower than the first internal Rossby radius of deformation (15–20 km). In the vertical, the model has 24 sigma (bottom following) layers with a logarithmic distribution near the surface. A detailed description of the model set-up is given by Sorgente *et al.* [20]. The model was integrated in diagnostic mode for 10 d, *i.e.* it calculated the velocity field in nearly geostrophic balance with the *in situ* T/S data interpolated into the model grid. In order to allow the observed density field to be adjusted to the model topography, an additional 2 d of prognostic calculation was carried out. This kind of approach has also been used by Mellor and Ezer [21] to diagnose the Atlantic Ocean circulation.

In order to validate the mesoscale structure depicted by the model and to interpret the hydrological variability in the surface layer, several NOAA/AVHRR daily Sea Surface Temperature (SST) composites satellite images were used from the German Aerospace Centre DLR (http://eoweb.dlr.de) database. Land and clouds are masked. For each image, the greyscale was adjusted to evidence eddies, and so absolute temperatures could not be compared between images. Grey tones, dark to light, gradually correspond to cold to less cold water. Note that during the spring and autumn, thermal gradients between different surface waters were low so that anticyclonic eddies were hardly visible. For this reason, during the Medgoos 2 period, the only available good SST image was that of 14 March 2001, 10 d before the beginning of the cruise. Altimetry data from Topex/Poseidon and ERS1/2 satellites also help to fill this gap. Maps of Seal Level Anomaly (SLA) were provided by collaboration with a LODYC team. These maps were calculated over a 10 d period and have already allowed AEs [4, 22] to be detected, and so this method is not detailed here.

3. Results and discussion

3.1 *Mesoscale eddies identification*

During each cruise, two eddies were characterized by low-salinity cores: 37.2–37.3 in eddies A1 and A2 during Medgoos 2 and 37.0–31.1 in A3 and A4 during Medgoos 4 (figures 2a and d). Anticyclonic rotation is observed (figures 2b and c), with calculated absolute velocity significantly higher in A3 and A4 (max: $\sim$40 cm s^{-1}, $\sim$55 cm s^{-1}) than in A1 and A2 (max: $\sim$30 cm s^{-1} and $\sim$15 cm s^{-1}). Maxima were observed in the periphery, by opposition to the core where the velocity was lower ($<$15 cm s^{-1}) in agreement with past current measurements [16].

Those eddies were also observed on satellite data (figures 3 and 4). Indeed, A3 and A4 were identifiable on the 9 May 2002 image (figure 3b) and were also well signed on the altimetry map with more than 2 cm of sea level anomaly (SLA, figure 4b). Concerning A1 and A2 on the 14 March 2001 SST image (figure 3a), the thermal gradient was not intense enough to identify eddies contours. This is a recurrent problem in spring and summer, when thermal gradients weaken. On the corresponding altimetry map (figure 4a), A2 corresponds to the south-western eddy, implying that only the north-eastern edge of A2 had been sampled during Medgoos 2 and that data extrapolated by the model in the south-western must be carefully interpreted. Also, in a general way, the position and diameter of eddies depicted by SLA should be carefully interpreted because SLA are anomalies compared from a climatologic geoids and thus are relative values, implying that the edge of eddies can be different. In addition, maps were calculated over a 10 d period, during which eddies were moving, thus distorting the observation of eddies. These maps were spatial interpolations that could not visualize structures smaller than $\sim$50 km width, the approximate distance between two ERS passes. For this reason, and if we consider the 37.3 isohaline, the A1 diameter was $\sim$30 km and could not be seen by altimetry. Nevertheless, A1 is correctly depicted by the deepening of isohalines from the CTD data analysis, even if the A1 was at the edge of the surveyed area (figure 5).

Thus, while the eddies A1 and A4 were relatively far away from the slope, A3 was the closest and coming over it, thus acting on the shelf circulation and inducing a south-south-westward current (figure 2c). Eddy A2 seemed to be at an intermediate distance from the coast if *in situ* data were considered.

Considering observed and calculated values (salinity, density, and velocity) and their features on satellite images, the A1–A4 eddies were Algerian anticyclonic eddies detached from the Algerian current.

3.2 *Influence of anticyclonic eddies on LIW flow*

First, the LIW horizontal distribution was studied by comparing three parallel south–north vertical sections at increasingly longer distances from the coast (figures 6 and 7). These sections are called 'slope', 'halfway', and 'offshore' sections, and are numbered 1, 2, and 3, respectively, on figures 2a and d.

On these sections, A1–A4 can be identified by the deepening of salinity isolines well depicted in the halocline, but not so well deeper down because of the increasing homogenization. Consequently, the vertical extension of eddies cannot be given, only their minimum extension. Considering the deepening of the 38.5 isohaline, the minimum depth in A1 and A3 was about 1500 m and about 1000 m in A4 (figures 6c and 7b and c). A2 was at least 200–300 m deep, but data were missing in the eddy core on the offshore section.

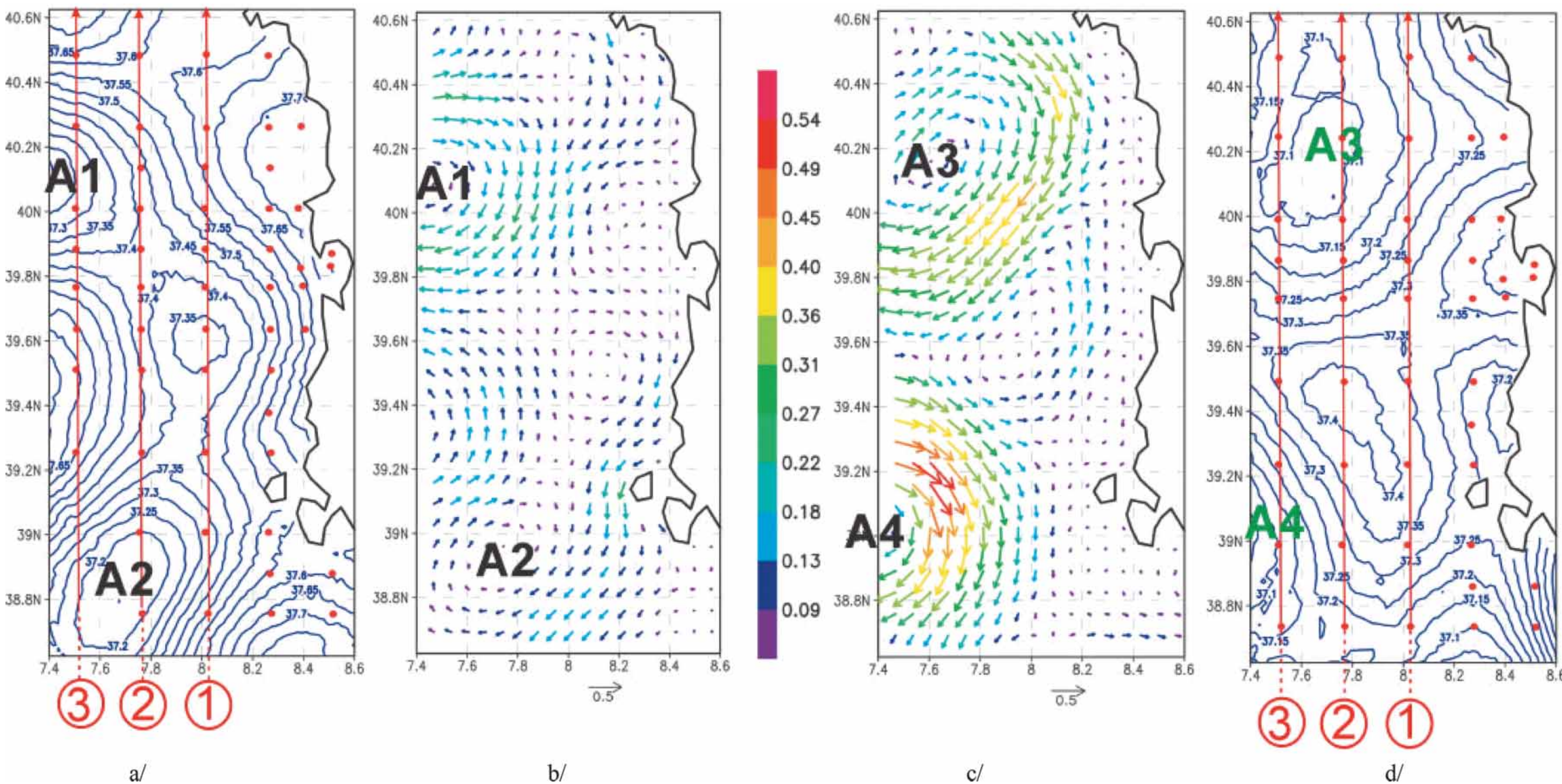

Figure 2. Horizontal distribution of salinity and velocity during Medgoos 2 (a, b) and during Medgoos 4 (c, d) at a depth of 5 m.

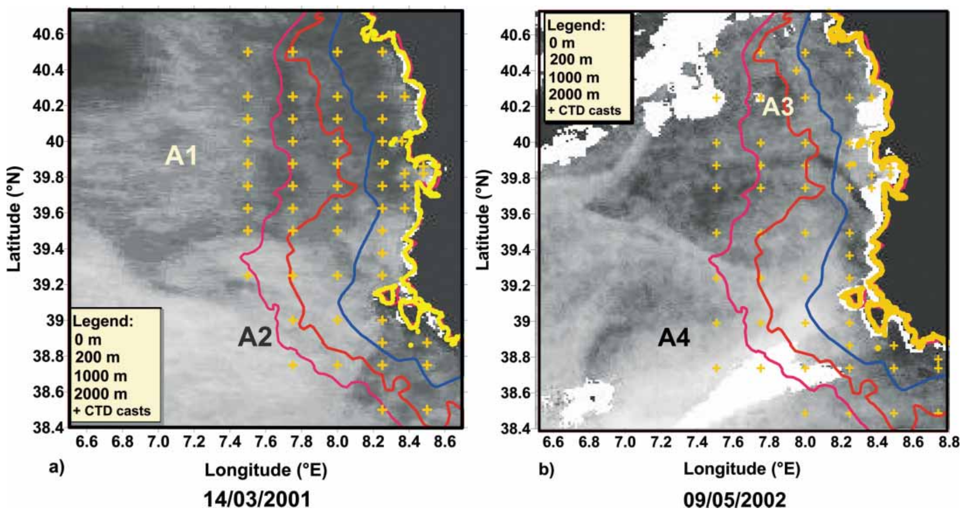

Figure 3. Composite NOAA/AVHRR sea-surface-temperature satellite images on 14 March 2001 (a) and 9 May 2002 (b) with the overlaid sampling field performed during Medgoos 2 (a) and Medgoos 4 (b).

For both cruises, on the slope sections (figures 6a and 7a), LIW was observed as a vein between ∼300 and ∼1000 m with a salinity of ∼38.60–38.67, and maxima at ∼450–500 m, in agreement with values found southernmost during those cruises (not shown) and in literature (*e.g.* [23, 24]). Farther from the coast, on the halfway sections, LIW was still distributed as a vein during Medgoos 2 but was patchy during Medgoos 4 (figures 6b and 7b). One patch was located over ∼39.75–40.50° N in the southern half of A3, the other being over

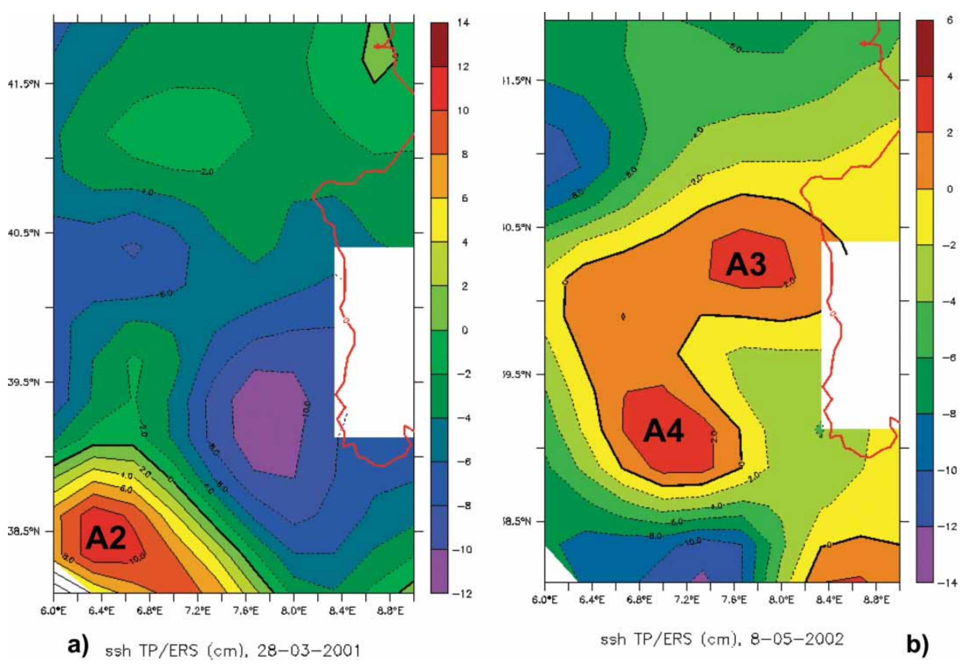

Figure 4. Sea-level anomaly (cm) maps calculated from TOPEX/Poseidon and ERS altimetry data for two 10 day periods centred on 23 March 2001 (a) and 8 May 2002 (b).

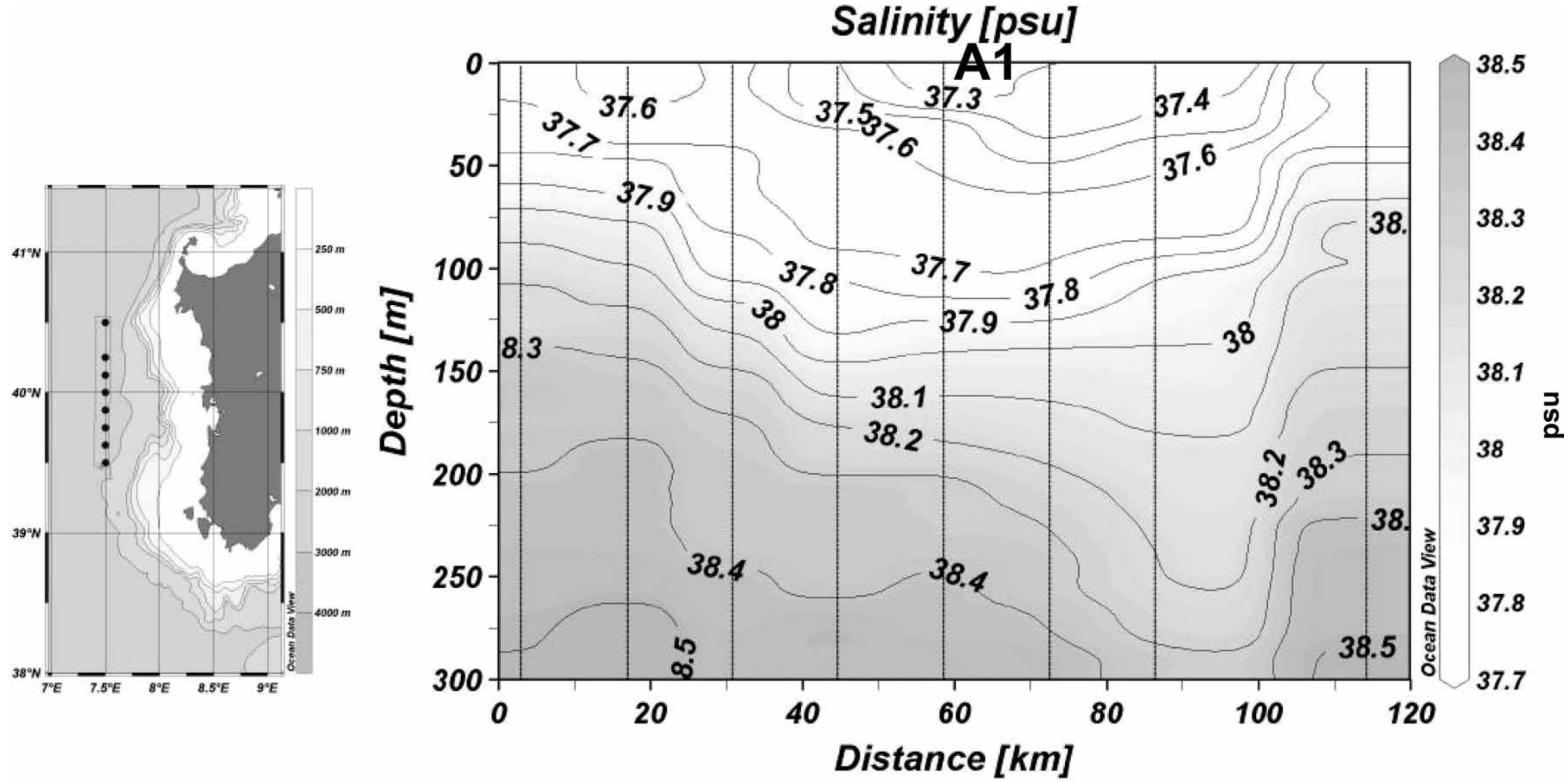

Figure 5. *In situ* CTD data analysis during the Medgoos 2 cruise in the area where the eddy A1 was located. Here, a salinity section from the surface to a depth of 300 m is plotted. A deepening of isohalines is visible.

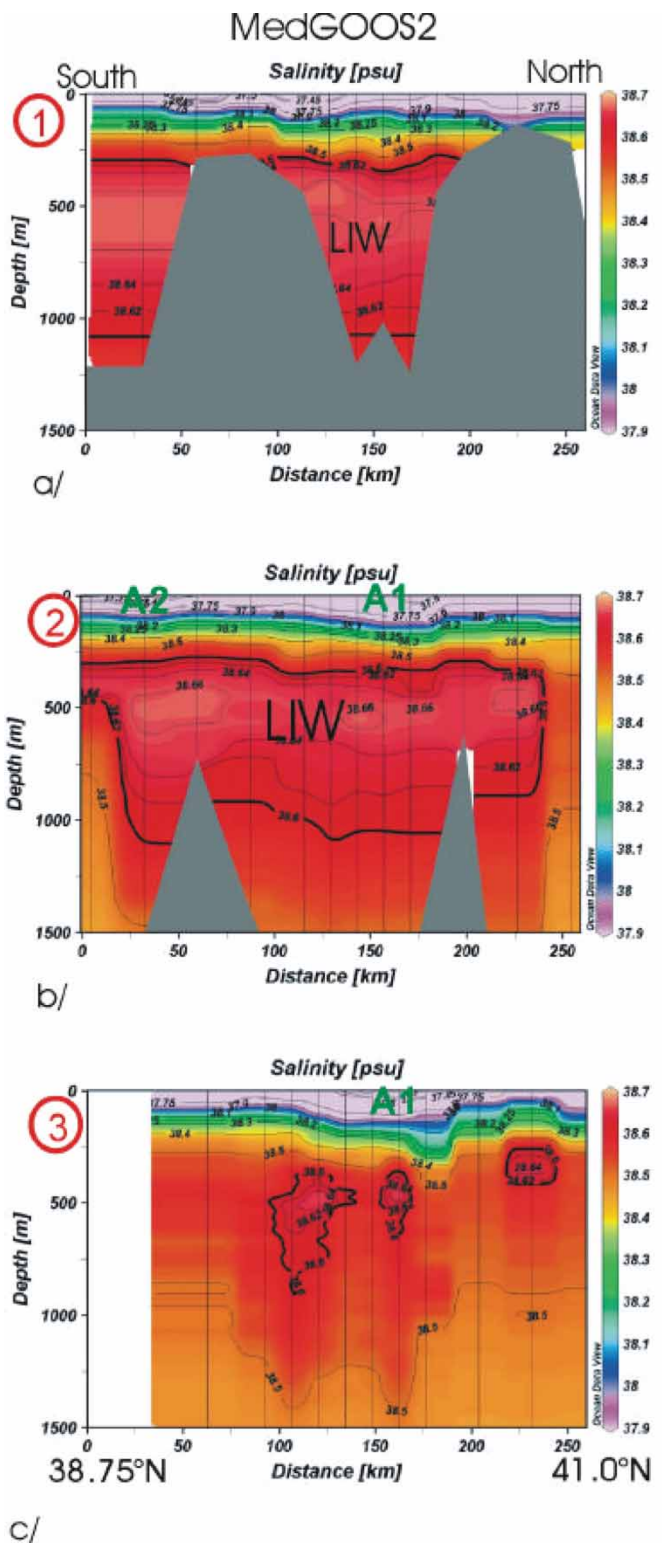

Figure 6. *In situ* salinity vertical distribution on south–north sections from Medgoos 2 data referenced on figure 2a by the numbers 1/, 2/, 3/ corresponding to (a), (b), and (c), respectively.

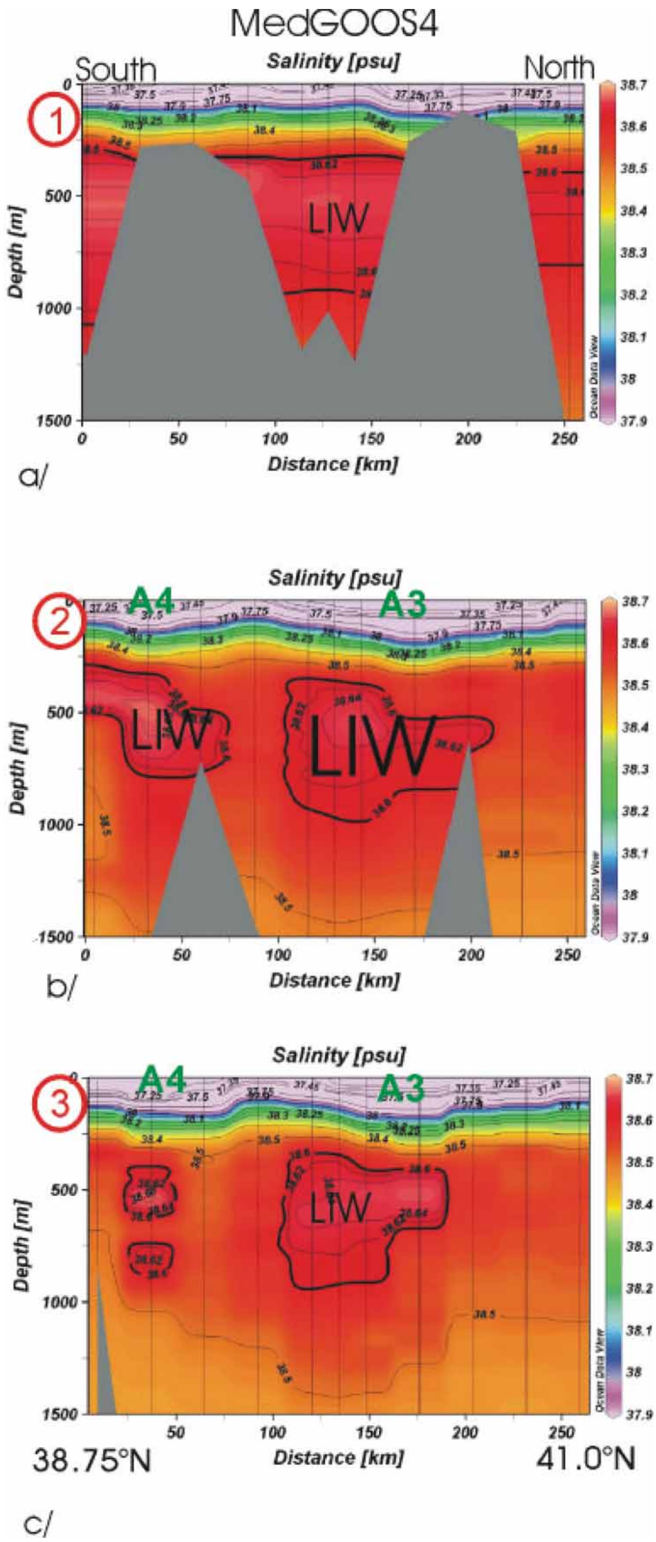

Figure 7. *In situ* salinity vertical distribution on south–north sections from Medgoos 4 data referenced on figure 2d by the numbers 1/, 2/, 3/ corresponding to (a), (b), and (c), respectively.

∼38.75–39.25° N in the eastern periphery of A4. On the offshore sections, LIW was patchy for both cruises (figures 6c and 7c) but with larger patches for Medgoos 4. During Medgoos 2, the deepest patches were in the southern part of A1, while in the northern part, patches were more superficial. The largest Medgoos 4 patch was in the south-western part of A3, and the other one was in the south-eastern part of A4. Comparing with the Medgoos 4 halfway section (figure 7b), both patches had a similar distribution regarding values, forming shape, and localization on a latitudinal band. Consequently, during Medgoos 4, halfway and offshore sections with two patches each should have vertically crossed two westward LIW branches.

On the Medgoos 4 horizontal salinity distribution at 520 m, isohalines >38.60 were mainly cross-shore between ∼39.7 and ∼40.1° N, suggesting that LIW spreads offshore (figure 8b) in the southern part of A3 up to 39.7° N. In contrast, during Medgoos 2, these isohalines were alongshore, suggesting that LIW flowed continuously along the Sardinian slope as a vein (figure 8a). This difference was confirmed on the latitudinal vertical sections where LIW flowed as a vein 60 km wide at ∼500 m during Medgoos 2, whereas the LIW offshore boundary was not visible during Medgoos 4 (figures 9a,b). In a same way, the southern Medgoos 4 patch should be a body of water entrained by A4.

Therefore, in March–April 2001, LIW's flow is almost not disturbed by AEs, more flowing as an along-slope vein inshore the isobath 2000 m with a lower westward flow at about 39.8° N (maximum of ∼0.08 Sv) deduced for a water mass with $S > 38.6$ but more localized. In contrast, in May 2002, the LIW vein was diverted westward by A3 between ∼39.7° N

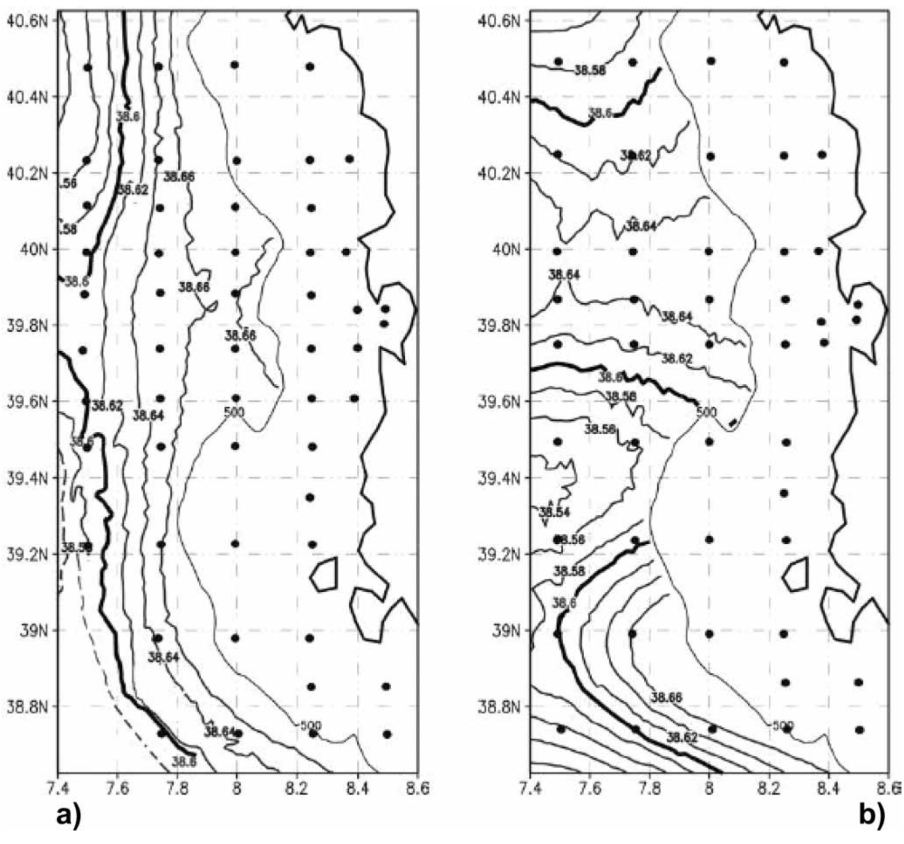

Figure 8. Horizontal salinity distribution at 520 m calculated by the Objective Analysis Method from Medgoos 2 (a) and Medgoos 4 (b). The bold isoline corresponds to a salinity of 38.6.

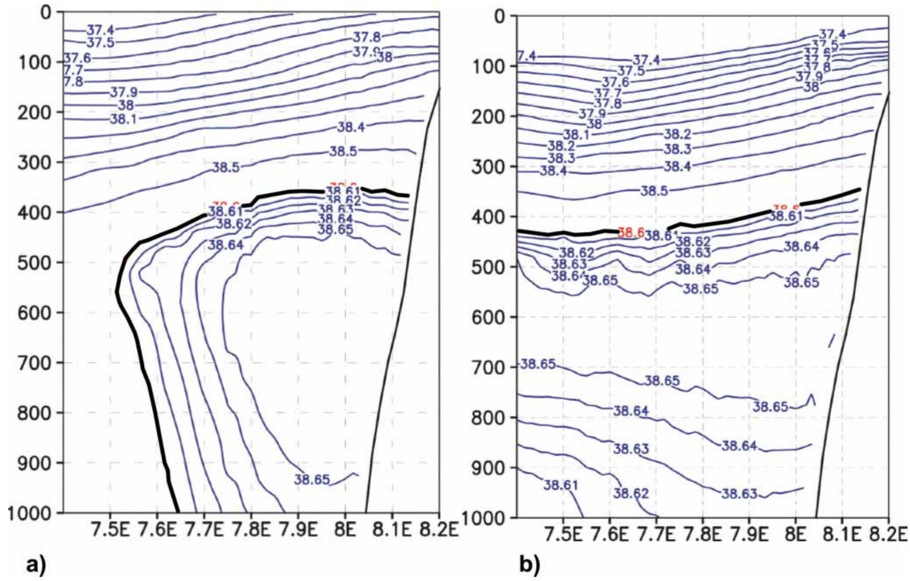

Figure 9. Vertical salinity section at 40° N calculated by the Objective Analysis Method from Medgoos 2 (a) and Medgoos 4 (b). The bold isoline corresponds to a salinity of 38.6.

and ~40.1° N. A similar westward branch can be entrained south-westward by A4. Fluxes always deduced from Medgoos 4 velocity field for a water mass with $S > 38.6$ also depicted a westward flow in the southern parts of A3, significant from 8.1° E and maximum near 7.5–7.6° E with 0.15 Sv. Of course, these branches cannot be permanent as eddies move at ~3–10 km d^{-1} and do not remain close to the slope and the LIW vein.

These observations confirm Millot's theory about LIW diversion by AEs close to the western Sardinia [2, 11–13]. Nevertheless, it seems that patches of little mixed LIW observed in the open basin can be due to another kind of anticyclonic eddies. Recently, drifting floats ballasted in LIW layer depicted smaller anticyclonic eddies of diameter 50–60 km observed in the intermediate layer, and not in the surface layer [25]. These are thought to be created by horizontal shear between the recent LIW vein flowing along the south-western Sardinian slope and a cyclonic flow of old LIW (~13.1 °C) passing also close to the south-western Sardinian slope. The gyre of old LIW was observed within the Algerian basin and is the so-called Algerian Gyre [26].

4. Conclusion

The analysis of CTD data acquired in the Sardinian Sea during two cruises in March–April 2001 and in May 2002 showed the presence of Algerian anticyclonic eddies (AEs) during each cruise. Those eddies were expected to strongly disturb the LIW vein on the western Sardinian slope.

In March–April 2001, the LIW flowed northward along the Sardinian slope as a relatively narrow and thick layer. This can be considered as the LIW path without significant perturbation by AEs. In contrast, in May 2002, LIW was diverted westward by an AE that came over the Sardinian slope near 40° N (figure 10). The difference between those two situations underlines the temporal variability of the LIW flow direction off the western Sardinia, and thus the variability of the westward LIW branching. Nevertheless, in the middle of the eastern

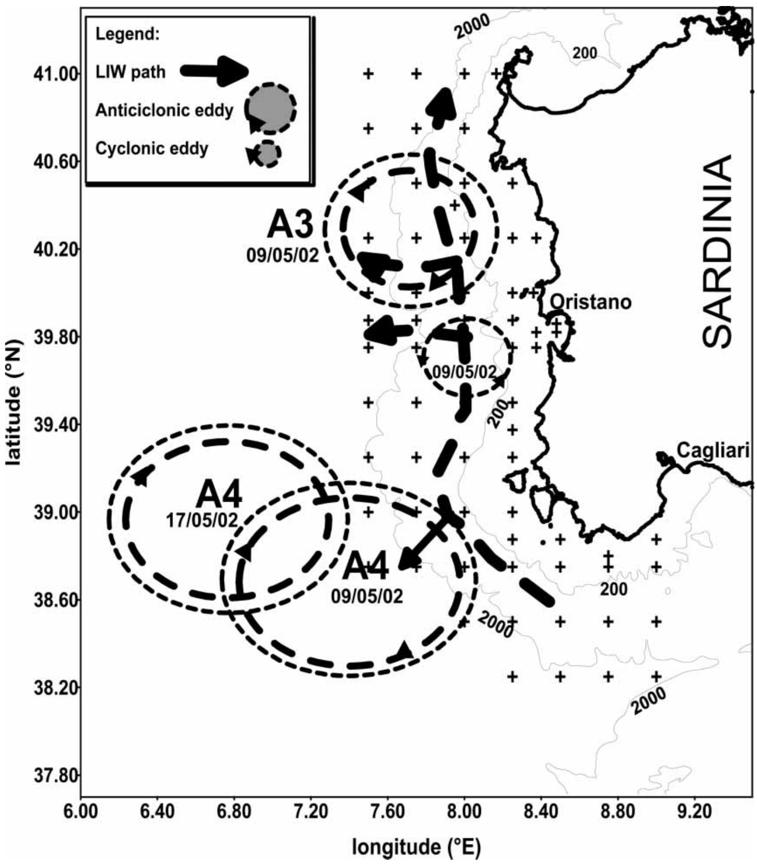

Figure 10. Mesoscale activity, during the Medgoos 4 cruise in May 2002 in the Sardinian Sea, based on the analysis of satellite images and its interaction with the LIW flow.

Algerian Basin, the total time spent by AEs passing successively over a fixed mooring was about 9 months between August 1997 and July 1998 (ELISA experiment [13]). Consequently, AE-induced branching could be more frequent than the northward LIW flow, but AEs seem to drift faster off western Sardinia than along the Algerian slope [4], so they should spend less time off Sardinia. A statistical analysis of the time spent by AEs along the western Sardinia slope would clarify this issue. In any case, regardless of the number of eddies involved and the time spent off Sardinia, AEs can be definitively considered as one of the main structures that spreads LIW from the Sardinian slope to the open basin. A process study should be set on after this work to determine diversion mechanisms of LIW by AEs.

Acknowledgements

We thank GianPietro Gasparini from ISMAR-CNR in La Spezia (Italy) for his important suggestions. This work was financially supported by: the Italian MIUR in the frame of the project SIMBIOS (SIstema per lo studio del Mare con Boa Integrata OffShore (Operative Programme of the Marine Environment Plan, Cluster C10, Project n. 13 – D.n. 778.RIC); the EU Marie Curie Host Fellowship: project ODASS (contract n. HPMD-CT-2001-00075); and the EU project MAMA (contract n. EVR1-CT-2001-20010 MAMA). We would especially like to thank the German Aerospace Centre DLR (http://eoweb.dlr.de) for the infrared images, the AVISO/Altimetrie team that provided the altimetry data (http://www.jason.oceanobs.com/html/presentation/welcome_fr.html) and R. Schlitzer, for the Ocean Data View freeware program (http:/www.awi-bremerhaven.de/GEO/ODV/2003).

References

[1] I. Taupier-Letage, I. Puillat, P. Raimbault, C. Millot. Biological response to mesoscale eddies in the Algerian basin. *J. Geophys. Res*. **108**, 3245–3255 (2003).
[2] C. Millot. Circulation in the western Mediterranean Sea. *J. Mar. Sys.*, **20**, 423–442 (1999).
[3] I. Taupier-Letage, C. Millot. Surface circulation in the Algerian Basin during 1984. *Oceanol. Acta*, **9**, 119–131 (1998).
[4] I. Puillat, C. Millot, I. Taupier-Letage. Algerian Eddies lifetime can near 3 years. *J. Mar. Syst.*, **31**, 245–259 (2002).
[5] J.L. Fuda, C. Millot, I. Taupier-Letage, U. Send, J.M. Bocognano. XBT monitoring of a meridian section across the western Mediterranean sea. *Deep-Sea Res.*, **47**, 2191–2218 (2000).
[6] A. Ribotti, I. Puillat, R. Sorgente, S. Natale. Mesoscale circulation in the surface layer off the southern and western Sardinia island in 2000–2002. *Chem. Ecol.*, **20**, 345–363 (2004).
[7] G. Wust. On the vertical circulation of the Mediterranean Sea. *J. Geophys. Res.*, **66**, 3261–3271 (1961).
[8] P. Wu, K. Haines. Modeling the dispersal of Levantine Intermediate Water and its role in the Mediterranean deep water formation. *J. Geophys. Res*., **101**, 6591–6607 (1996).
[9] G. Korres, N. Pinardi, A. Lascaratos. The Ocean Response to Low-Frequency Interannual Atmospheric Variability in the Mediterranean Sea. Part I: Sensitivity Experiments and Energy Analysis. *J. Climate*, **13**, 705–731 (2000).
[10] E. Demirov, N. Pinardi. Simulation of the Mediterranean Sea circulation from 1979 to 1993: Part I. The interannual variability. *J. Mar. Syst*., **33–34**, 23–50 (2002).
[11] C. Millot. Circulation in the Western Mediterranean Sea. *Oceanol. Acta*, **10**, 143–149 (1987a).
[12] C. Millot. The circulation of Levantine Intermediaite Water in the Algerian Basin. *J. Geophys. Res.*, **92**, 8265–8276 (1987b).
[13] C. Millot, I. Taupier-Letage. Additional evidence of LIW entrainment across the Algerian Basin by mesoscale eddies and not by a permanent westward flow. *Prog. Oceanogr.*, **66**, 231–250 (2005).
[14] I.M. Ovchinnikov. Circulation in the surface and intermediate layers of the Mediterranean. *Oceanology*, **6**, 48–59 (1966).
[15] M. Benzohra, C. Millot. Characteristics and circulation of the surface and intermediate water masses off Algeria. *Deep-Sea Res. I*, **42**, 1803–1830 (1995a).
[16] M. Benzohra, C. Millot. Hydrodynamics of an open sea Algerian eddy. *Deep-Sea Res.*, **42**, 1831–1847 (1995b).
[17] J.M. Brankart. The MODB local quality control. Technical report of Liège University (Belgium) (1994). Available online at: http://modb. oce. ulg. ac. be/modb/modb_products.htm (accessed 1999).
[18] E.F. Carter, A.R. Robinson. Analysis models for the estimation of oceanic fields. *J. Atmosph. Ocean. Technol.*, **4**, 49–74 (1987).
[19] A.F. Blumberg, G.L. Mellor. A description of a three-dimensional coastal ocean circulation model of the Mediterranean Sea. In *Three-Dimensional Coastal Ocean Models*, N.S. Heaps (Ed.), pp. 1–16, American Geophysical Union, Washington, DC (1987).
[20] R. Sorgente, A. Ribotti, I. Puillat. Water masses and diagnostic circulation west off Sardinia from March 23rd to April 4th, 2001, paper presented at *Building the European Capacity in Operational Oceanography, Proceedings of the Third International Conference on EuroGOOS Conference*, Athens, 1–6 December 2002, pp. 100–104 (2003).
[21] G.L. Mellor, T. Ezer. A Gulf Stream model and an altimetry assimilation scheme. *J. Geophys. Res.*, **96**, 8779–8795 (1991).
[22] C. Bouzinac, J. Vazquez, J Font. Complex empirical orthogonal functions analysis of ERS-1 and TOPEX/POSEIDON combined altimetric data in the region of the Algerian current. *J. Geophys. Res.*, **103**, 8059–8071 (1998).
[23] C. Bouzinac, J. Font, C. Millot. Hydrology and currents observed in the channel of Sardinia during the PRIMO-1 experiment from November 1993 to October 1994. *J. Mar. Sys.*, **20**, 333–355 (1999).
[24] C. Sammari, C. Millot, I. Taupier-Letage, A. Stefani, M. Brahim. Hydrological characteristics in the Tunisia–Sicily–Sardinia area during spring 1995. *Deep-Sea Res*., *J. Mar. Sys.*, **46**, 1671–1703 (1999).
[25] P. Testor, J.C. Gascard. Large-scale spreading of deep waters in the western Mediterranean Sea by submesocale coherent eddies. *J. Phys. Oceanogr.*, **33**, 75–87 (2003).
[26] J.C. Gascard, C. Rouault, P. Testor. General ocean circulation and subsurface mesoscale eddies in the Algerian Basin, paper presented at *4th Mediterranean Target Project Workshop*, pp. 50–51, MATER, Perpignan, France (1999).