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Additional evidence of LIW entrainment across the Algerian subbasin by mesoscale eddies and not by a permanent westward flow

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Abstract

The circulation of the Levantine Intermediate Water (LIW) in the Algerian subbasin (western basin of the Mediterranean sea) has been much debated for more than fifteen years now. Together with the old circulation diagrams, several numerical models claim that a branch of LIW is permanently flowing westwards across the Algerian subbasin, i.e. directly from the Channel of Sardinia towards the Strait of Gibraltar. Only a few models support the fact that the unique continuous flow of LIW is structured as an alongslope counterclockwise vein, which is thus directed northwards off Sardinia in the Algerian subbasin, and hence support the diagram published by Millot in 1987 [Millot, C. (1987a) Circulation in the Western Mediterranean. Oceanologica Acta *10*(2), 143–149]. According to this diagram, any little mixed LIW found in the central subbasin corresponds to fragments which have been pulled away from the vein and entrained there by mesoscale eddies originated from the Algerian Current. The ELISA experiment (1997–1998), as a follow-up of other ones conducted since about 15 years, was designed partly to validate the diagram. In addition to about 40 current meters set in place for one year, four main campaigns were conducted with a sampling strategy guided in real time by infrared satellite information. The data set we present clearly provides additional evidence that the little mixed LIW found in the central Algerian subbasin has been entrained there by the mesoscale eddies and not by a permanent westward flow.

Keywords: General circulation; LIW; Mediterranean Sea; Algerian subbasin; Mesoscale eddies

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1. Introduction

Most probably because the study of the general circulation began very early in the western basin of the Mediterranean sea, the circulation diagrams proposed by Nielsen (1912), reassessed later by Wüst (1961) and Ovchinnikov (1966), were given for "classical". Despite the very scarce in situ data available at that time, they schematised some circulation features in a way that has been accepted by most of the scientific community, particularly in the surface layer. It is only relatively recently that these diagrams were contradicted. In the light of infrared satellite information and on account of basic considerations, the analysis of roughly the same in situ data set was reconsidered by Millot (1987a) who proposed diagrams substantially different for surface (mainly Atlantic Water, AW, http://ciesm.org/events/RT5-WaterMassAcronyms.pdf), intermediate (mainly Levantine Intermediate Water, LIW) and deep waters (mainly Western Mediterranean Deep Water, WMDW). Basically, these diagrams depict water masses flowing mainly counterclockwise and alongslope at all depths. Surface currents were said to be generally unstable and, for the Algerian Current in particular, to generate mesoscale phenomena that could extend down to the bottom, thus sometimes affecting the circulation at intermediate and greater depths. More recently, intermediate veins such as LIW were said to be possibly unstable too, and the occurrence of Leddies – by analogy with the Meddies – was hypothesised (Millot, Taupier-Letage, & Benzohra, 1997). The LIW circulation diagram is very explicit in this respect (Fig. 1).

LIW is a relatively warm and saline water that has always been recognised to flow into the Western Mediterranean Sea through the Channel of Sicily (characteristic core values there are $\Theta > 14.5$ °C and $S > 38.75$). Within the Tyrrhenian subbasin, the LIW circulation is still debated. Even though recent papers claim that there is a LIW vein extending directly west from the Channel of Sicily under special conditions (e.g. Onken & Sellschopp, 2001) or according to the season (e.g. Zavatarelli & Mellor, 1995), an increasing number (e.g. Sparnocchia, Gasparini, Astraldi, Borghini, & Pistek, 1999) agrees with the diagram in Fig. 1. Whatever, it is clear that LIW flows westwards through the Channel of Sardinia at ~200–600 m with $\Theta \sim 13.90$–13.95 °C and $S \sim 38.65$–38.70.

Sampling in most of the Mediterranean has generally not been adequate due to (i) time and space intervals too large with respect to the mesoscale phenomena and (ii) to a recurrent interest for the central part of the basins and subbasins when the water masses mainly circulate along their edges. This has been especially misleading in the Algerian subbasin, since little mixed LIW ($\Theta > 13.8$ °C and $S > 38.6$) was sometimes encountered in the central part whilst not tracked on edges. The westward route across the subbasin that was thus inferred was attractive, since it was directed towards the Strait of Gibraltar where LIW has always been iden-

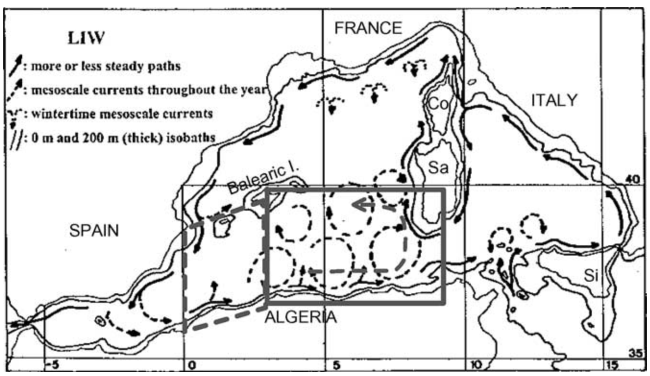

Fig. 1. The LIW circulation in the western basin of the Mediterranean sea according to Millot (1999). The grey frame indicates the area concerned by the present data analysis (solid frame: data shown in this paper; dashed frame: data considered but not shown). The arrow schematises the counterclockwise circuit of the Algerian eddies in the eastern Algerian subbasin. Co, Corsica; Sa, Sardinia; Si, Sicily.

tified and where it must flow out from the sea. General circulation models have maintained this misinterpretation of the in situ data. Indeed, although results of such models are often difficult to understand and moreover contradictory, a permanent westward flow of LIW across the whole Algerian subbasin was indicated by many of them (see Section 4).

Now, as explained by, e.g., Griffiths (1986), such a flow crossing a basin disagrees with basic considerations about fluids spreading under gravity in rotating systems. ‘‘Motions normal to the rotation vector induce Coriolis forces that tend to oppose the spreading. However, near a boundary, the requirement that angular momentum be conserved is removed, the constrains imposed by the rotation are broken, and a gravity current flows along the boundary. In case of a fluid injected, like a river, from a small source at the surface of a denser stationary fluid, the buoyancy force driving the injected fluid along the boundary is proportional to the slope of the interface parallel to that boundary’’. Such considerations apply to other gravity currents of importance such as those of intermediate density that flow along sloping boundaries at their own density level in a stratified ocean. They are clearly supported by all experimental studies about intermediate currents along bottom slopes (e.g. Jacobs, Guo, & Davies, 1999 and Sadoux, Baey, Fincham, & Renouard, 2000) . . . and by most of the numerical models discussed in Section 4. Let us specify that these notions apply to an *f*-plane domain, so that it is not relevant to consider neither the conservation of potential vorticity nor the orientation of both the injection and the slope with respect to North.

In an enclosed domain such as the Mediterranean Sea, such a buoyancy spreading clearly leads to an counterclockwise alongslope circulation. The normal, expected route for the LIW exiting from the Channel of Sardinia is thus northwards, along the western Sardinian slope, and then all along the French and Spanish slopes up to the Alboran subbasin (where $\Theta < 13.5$ °C and $S < 38.5$). From there, its normal route is to exit through the Strait of Gibraltar, at least for the upper part of the vein. Now, some LIW can be entrained from the Alboran subbasin along the African slope instead of exiting. If it still associated there with a buoyancy gradient, this old LIW will flow eastwards along that slope, i.e. eastwards off Algeria.

In addition to these general circulation features, the Algerian subbasin is now recognised to be, at least from an altimetric point of view (Ayoub, Le Traon, & De Mey, 1998), the most energetic Mediterranean subbasin at mesoscale. Since mesoscale phenomena and eddies are evident on infrared images and seemingly energetic, Millot (1987a, 1987b) hypothesised that they were able to pull LIW fragments away from the Sardinian slope and to entrain them in the central subbasin. The relatively large temperature and salinity values ($\Theta > 13.8$ °C and $S > 38.6$) spotted there might be interpreted thus not as the signature of a permanent westward flow of LIW, but as the result of a disrupted and intermittent entrainment. Since then, data supporting these main circulation features and the role of the mesoscale have been collected and the diagram has been complemented, focussing on the Algerian subbasin where the eastward flow of heavily mixed LIW off Algeria and the determining role of the mesoscale have been specified (Millot, 1999). The data set collected during the 1997–1998 ELISA experiment (Eddies and Leddies Interdisciplinary Study in the Algerian basin, www.com.univ-mrs.fr/ELISA/) brings further supporting evidence to this scenario.

The characteristics of the Algerian mesoscale phenomena and eddies are described in Section 2. An updated review of the in situ and experimental published results is made in Section 3. A review of the modelling results is made in Section 4. The ELISA results are presented in Section 5 and the conclusion is drawn in Section 6.

2. The Algerian mesoscale eddies

The Algerian Current, as was named the flow of AW off Algeria where its characteristics are specific (Millot, 1985), is a coastal current initially (near 0°) few 10’s (~50) km wide and a few 100’s (~200) m thick. This current is markedly unstable and, as first deduced from the current time series and satellite images collected during the Mediprod-5 experiment (Millot et al., 1997), it often generates two kinds of mesoscale phenomena.

Most of the time, the Algerian Current generates series of relatively small (few 10's km in diameter) and shallow (100–200 m) eddies that do not have significant consequences on the circulation of the water masses. However, on some occasions, this current forms a relatively large meander that actually has dramatic consequences for the circulation of all water masses as shown in the following. This occurred once during the 9-month Mediprod-5 experiment, whilst several serial eddies were observed (note that the serial eddies are no more considered hereafter). Inside the meander, a mesoscale anticyclonic eddy develops at surface (as described by Font, Millot, Salas, Julia, & Chic, 1998; Salas, Millot, Font, & García-Ladona, 2002). This embedded eddy can reach 50–100 km in diameter and ~200 m in depth, and both features generally propagate downstream at a few km/day (when the current speed is several 10's (~50) km/day). These eddies and their associated meander can temporarily reduce in size and even disappear, but the most energetic ones generally increase in size, thus leading to an overall seaward spreading of the AW flow. In the end, this turbulent spreading is mimicked by the smooth spreading schematised by the former circulation diagrams (Nielsen, 1912; Ovchinnikov, 1966; Wüst, 1961).

Even though analytical computations for two-layer systems (Millot, 1985) and dedicated numerical models (e.g. Mortier, 1992) suggest that baroclinic instability is the major process destabilising the Algerian Current, in situ data reveal an unexpected deep structure which is not reproduced by the models. In particular, each energetic meander-surface eddy is associated with a larger anticyclonic eddy in the deeper layer (Millot, 1994). The three components are roughly in phase in an alongslope direction and their ensemble has been named "event" (Millot et al., 1997). Information published up to now about the structure and large vertical extent of these events was mainly based on current meter (down to ~1000 m) and hydrological data (down to the ~3000-m bottom) in the western part of the Algerian subbasin. In the laboratory, events very similar to the ones observed in nature are also generated (Obaton, Millot, Chabert D'Hières, & Taupier-Letage, 2000).

Most events propagate for months along the Algerian slope until they reach the Channel of Sardinia that they cannot cross due to their relatively large size and vertical extent (see Fig. 2). Thus, they continue propagating along the deeper slope, i.e. towards Sardinia, and they pinch off from the Algerian Current per se, which continues propagating along the upper slope, i.e. eastwards towards Tunisia (Salas et al., 2002; Sammari, Millot, Taupier-Letage, Stefani, & Brahim, 1999). After pinching off, the meander is no longer differentiated from the surface eddy, and both surface and deep eddies come to be aligned, constituting what has been named an "open-sea eddy". The open-sea eddies first propagate towards north/north-west (as confirmed statistically by Vignudelli, 1997, and Iudicone, Santoleri, Marullo, & Gerosa, 1998). Before reaching ~40°N, they leave the Sardinian slope and propagate towards west/south-west in the open subbasin. Hence open-sea eddies in the eastern part of the Algerian subbasin generally describe an anticlockwise circuit (Fuda, Millot, Taupier-Letage, Send, & Bocognano, 2000). Reasons for this are not clear. Taupier-Letage and Millot (1988) hypothesised that this could be due to the planetary β-effect, but the topographic β-effect could be a plausible candidate as well (in such a case, this would account for the down-to-the-bottom extension of the eddies). Some of these eddies have been tracked during several years (up to 3) along several loops (up to 3) (Puillat, Taupier-Letage, & Millot, 2002). Note that both events and open-sea eddies are large, deep and energetic phenomena. Since they cannot always be differentiated from space (in Fig. 2(a), 97-1 is an event when 96-1 is an open-sea eddy that already described one loop), both are named AEs (Algerian Eddies) in the following. Their propagation speed is usually a few km/day, but they can remain motionless for weeks to months (up to 9) (Taupier-Letage & Millot, 1988). In such a case, the Algerian Current must bypass the AEs since AW is still required in the remainder of the sea to compensate for the deficit due to the evaporation.

AEs can increase in size up to ~250 km, so that two of them can roughly fill the whole Algerian subbasin. Such huge AEs dramatically disturb the parent Algerian Current which can then spread towards the central subbasin for a long time (up to 9 months at least) and they can destroy or divert seaward AEs propagating along the slope (Millot et al., 1997; Taupier-Letage & Millot, 1988). Such an AE (98-1) diverted from the slope

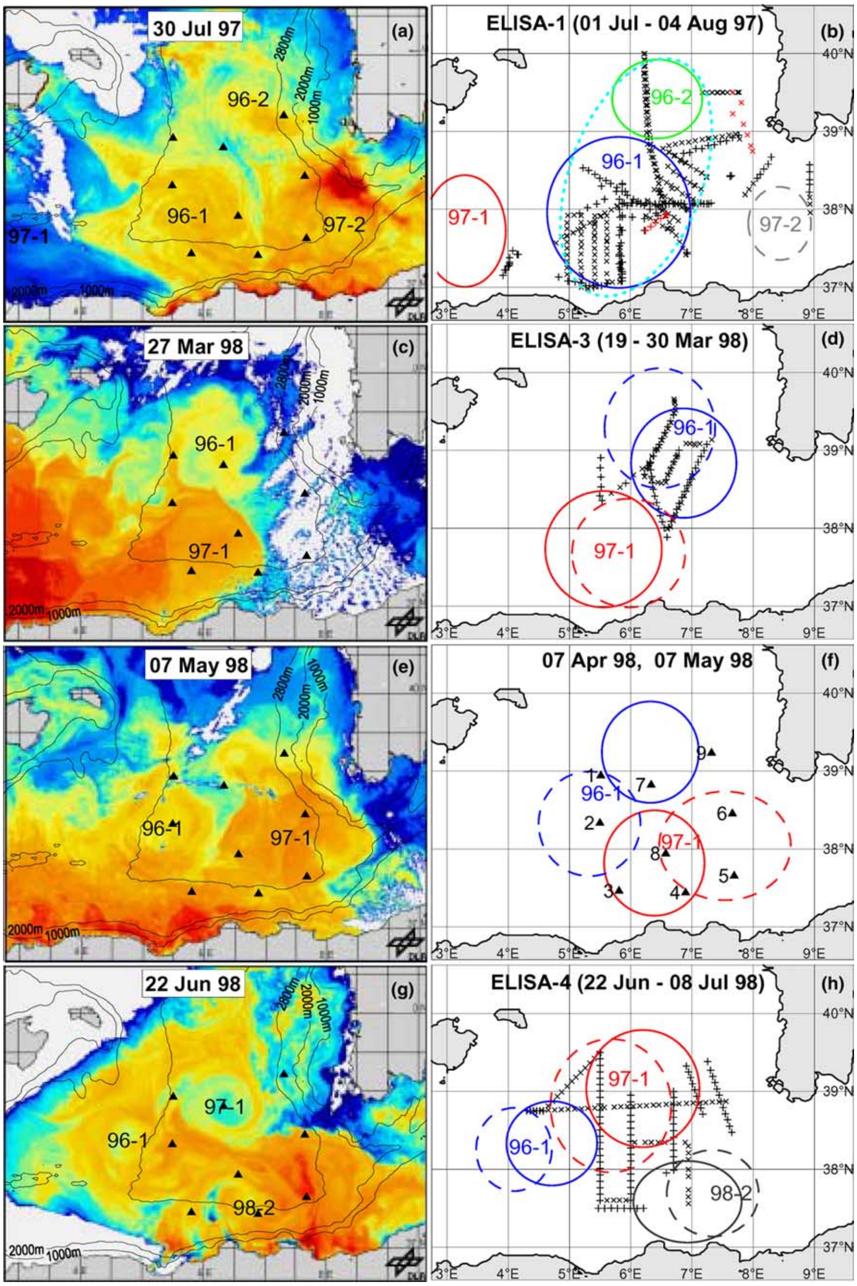

Fig. 2. Synopsis of the one-year ELISA experiment. (a,c,e,g) NOAA–AVHRR infrared images (temperature increases from blue to red: ∼13–15 °C in winter, ∼17–25 °C in summer) representative of the eddy field schematised in b,d,f,h, together with sampling (moorings (▲), CTD (+) and XBT (*x*) casts). (b): ELISA-1 cruise; the schematised positions of the AEs are representative of summer 97: eddies did not move significantly (97-2 in dashed line since not clearly tracked with time), but for the temporary interaction between 96-1 and 96-2 (light blue dots); the ELISA-1 casts are in black, whilst the ELISA-1.33 (5–8 September; *x* only) and ELISA-2 (20-29 October; + only) casts are in red. (d): ELISA-3 cruise; eddies positions on March 18 (solid line) and on March 27 (dashed line). (f): moorings identification (▲) and eddies positions on April 07 (solid line) and May 07 (dashed line). (h): ELISA-4 cruise; eddies positions on June 22 (solid line) and on July 06 (dashed line) (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

near 3°E and sampled near the Balearic Islands (Ruiz et al., 2002), displayed characteristics similar to AEs sampled elsewhere in the subbasin. This seaward drift of AEs before they reach the Channel of Sardinia is consistent with the statistical analysis of altimetric data (Bouzinac, Vazquez, & Font, 1998). However, AEs have never been observed leaving the slope before reaching the Channel of Sardinia without any interaction with another AE, even though this has been suggested by numerical models (Gervasio, 1997). Unlike mesoscale structures in the open ocean (e.g., the Gulf Stream rings, the Meddies) which drift away from their parent current for years, and thus continuously decay, the AEs are constrained in a relatively small subbasin, so that complex and probably essential interactions certainly occur with their parent current.

Since (i) theoretical analyses dealing with the interactions between a propagating eddy and an independent vein of intermediate water are lacking, (ii) the SST signature of an AE does not markedly change when it interacts with the LIW vein around Sardinia, (iii) the characteristic speed of the vein is a few km/day only, we assume that the vein cannot dramatically modify the AEs dynamics. To explain how drifting AEs can pull away water fragments from an alongslope intermediate vein and entrain them seawards, the expected structure of the AEs must first be specified. An important point to have in mind is that the currents at different levels in the deeper part of an AE (i.e. in the Mediterranean water) are similar in both amplitude and phase (Millot et al., 1997); this point can be ascertained from the moorings E2, E3 and E8 records in Fig. 8 at the beginning of the experiment. Therefore, the deeper part of an AE is clearly not entrained by the upper (i.e. AW) part through friction (if this were the case, the current amplitude would decrease with depth and the phase would change).

To our knowledge, there are no models that reproduce such similar currents in the deeper part of an eddy so that we have had to put forward our own hypothesis about the mechanism driving Mediterranean water within an AE (Obaton et al., 2000). If the Algerian Current can reasonably be considered as in geostrophic equilibrium when it quietly flows alongslope over a Mediterranean water supposed at rest, we hypothesise this is no longer the case when it forms a huge meander. In other words, we hypothesise that AW within a meander is added like a bump on top of the water underneath, being thus in excess with respect to geostrophic equilibrium. The pressure gradient that is therefore induced over the whole water column generates an anticyclonic deep motion, the size of which is roughly equal to that of the bump. Note that the less stratified the deeper layer, the more similar the currents at different levels within the whole layer. We also hypothesise that this characteristic is maintained after the AE pinches off (i.e. this is a characteristic of both the events and the open-sea eddies).

For what concerns LIW, the major point is that any water located below the surface water bump, i.e. below the surface eddy of AW as recognised from space, is immediately entrained within the AE itself. The amount of LIW entrained into such an anticyclonic motion depends on the overlapping of the vein by the AE. Indeed, the amount is small when the overlapping starts or stops while it is larger in-between (maximum overlapping). Would the eddy remain over the vein without propagating, LIW would be entrained within the whole eddy up to a theoretical annular or spiral shape. In fact, the overlapping varies continuously, clearly while the AE propagates over the vein and/or possibly when the vein meanders below the AE. Hence, we expect the LIW fragments within an AE to be shaped as crescents (Fuda et al., 2000; Millot, 1987b). Note that LIW fragments can thereafter be trapped or released by a drifting AE, depending on its kinematics (McCartney & Woodgate-Jones, 1991). Let us specify that both the crescent-shape of the LIW fragments and their location within the AE (not around it) are essential features to better understand the AEs dynamics. Indeed, would viscosity be important on both the vertical and the horizontal, a cylindrical eddy approaching the vein would entrain LIW mainly around it, which is clearly not the case (see Section 5).

3. Review of the mesoscale-dedicated in situ experiments

For the sake of homogeneity, we transformed all XBT in situ temperatures into potential temperatures using a simple linear relationship computed from the contemporaneous CTD data sets. All data analyses in the Algerian subbasin published before 1986, which were not dedicated to the mesoscale, have already been reviewed by Millot (1987b).

The Mediprod-5 experiment (1986–1987) was the first to be conducted in order to check the proposed circulation diagrams (i.e. Fig. 1). Hydrological data (∼100 CTD casts) were mainly collected off Algeria between ∼0 and 5°E and south of ∼38°N in June 1986. They evidence highly mixed LIW ($\Theta \sim 13.07$–13.24 °C, $S \sim 38.47$–38.51) in the whole coastal zone south of ∼37°30′N (Benzohra & Millot, 1995a). Hydrological data collected at the same time crossing the whole Algerian subbasin (Perkins & Pistek, 1990) support the occurrence of a LIW vein along the western slope off Sardinia. Fragments of less mixed LIW ($\Theta \sim 13.30$–13.45 °C, $S \sim 38.52$–38.57) were found trapped within an AE centred near 5°E–38°N (Benzohra & Millot, 1995b; Millot, 1987b). Nine-month mean currents collected on 8 moorings in the whole coastal zone (50–100-km wide) at 300, 1000 and 2000 m were directed eastwards and reached ∼3 cm/s at all depths (Millot et al., 1997).

The Mediprod-6 experiment, conducted in the same area in June 90, was mainly devoted to study biological processes (Raimbault, Coste, Boulhadid, & Boudjellal, 1993). At that time, the Algerian Current was only generating serial eddies, and sampling barely reached the western edge of an AE at ∼3°30′E. The overall distribution of LIW, specified with ∼40 (out of ∼100) deep enough CTDs, shows again that it was highly mixed ($\Theta \sim 13.10$–13.39 °C, $S \sim 38.47$–38.51) in the whole coastal zone south of ∼37°30′N. It was more heterogeneous along 3°30′E near 38°N, where an isolated maximum reached $\Theta \sim 13.57$ °C, $S \sim 38.55$.

During the PRIMO-1 experiment (1993–1994), currents were measured at four locations in the eastern part of the Algerian subbasin, especially on the Algerian and Sardinian continental slopes at 8°E (Bouzinac, Font, & Millot, 1999). Off Algeria, 6-month mean currents were eastwards at 450 m (∼1 cm/s) and 2500 m (∼4.5 cm/s). Off Sardinia, they were north-westwards (i.e. alongslope) at 300, 1000 and 2000 m with mean speeds ranging from 1 to 3 cm/s (Millot, 1994). A CTD transect (Bouzinac et al., 1999), consistently with previous ones (Garzoli & Maillard, 1976; Sammari et al., 1999; Sparnocchia et al., 1999), evidenced the LIW vein along the Sardinian slope with core values of $\Theta \sim 13.95$ °C, $S \sim 38.67$.

During the 1994 Thetis-2 experiment, currents were measured at seven locations in the western basin of the Mediterranean sea (Send et al., 1997). In the Algerian coastal zone, 9-month mean currents (Millot, 1994) were eastwards at 350 m (∼3 cm/s) and 2600 m (∼4 cm/s). Meanwhile, 14 XBT transects were made every ∼2 weeks from February to September with a cargo ship between Marseilles, France, and Skikda, Algeria, i.e. roughly at 6–7°E in the Algerian subbasin (Fuda et al., 2000). Specially calibrated T7 probes (accuracy of ∼0.05 °C, i.e. twofold the standard one) generally launched ∼28-km apart evidenced, consistently with one CTD transect, an extremely large mesoscale variability at the LIW level in the central subbasin. For instance, a big (∼100-km wide, ∼200-m thick) LIW fragment that is the warmest (up to 13.95 °C) ever found, was located near 39°N on May 2. On May 21, XBTs were launched with a frequency doubled (∼14-km apart) to try sampling this fragment again and better describe its structure, exactly along the same route between 40 and 37°30′N: there was no longer any little modified LIW, and Θ were <13.40 °C in the whole area. Most often, such LIW fragments were located in the southern part of AEs that were recently in a position to pull LIW away from the Sardinian vein. When all 14 transects evidenced the LIW vein along the French slope ($\Theta \sim 13.4$–13.6 °C), no maximum was found along the Algerian one ($\Theta \sim 13.3$ °C). The maximum values of the averaged transect ($\Theta \sim 13.5$ °C) were found near 39°N, which might have been interpreted as the signature of a permanent westward flow of LIW, and was in fact very demonstrative of the misinterpretation that could result from an unsupervised analysis and/or inadequate sampling.

The ALGERS-96 experiment was conducted along the Algerian slope near 0° mainly to launch drifters in a newly generated AE (Salas et al., 2002). All casts (31 CTD, 22 XCTD and 131 XBT) were performed south of 37°30′N and west of 3°E. Isolated LIW maxima there were $\Theta \sim 13.55$ °C, $S \sim 38.56$. The ALGERS-98 experiment sampled, in the south of the Balearic Islands, AE 98-1 that left the Algerian slope near 3°E and then described a loop along the Balearic and mainland Spanish slopes before decaying (Ruiz et al., 2002). Isolated LIW maxima ($\Theta \sim 13.48$ °C, $S \sim 38.56$) were found within the AE. Compared to the LIW background values ($\Theta < 13.3$ °C, $S < 38.5$), these maxima account for a weak mixing of the fragments during their entrainment (more exactly, the actual process should be re-entrainment of fragments released in the west by another AE that previously interacted with the vein in the east).

Within the MFSPP project, another XBT monitoring was performed between Sète, France, and Tunis, Tunisia, in 1999–2000 (Manzella et al., 2001). The 15 transects crossed the south-western continental slopes of Sardinia, and thus sampled the LIW vein twice as it goes round the corner of Sardinia. Within the Channel of Sardinia, the vein was relatively large with core values of 13.8–14.0 °C whilst, west of Sardinia, it was relatively narrow with core values of 13.7–13.9 °C. Differences in core values were most likely due to mixing processes within the vein itself. Differences in width (also observed during the ELISA experiment – see below) could be due to the erosion of the vein by the AEs, but this would occur occasionally and does not seem to represent a sufficient amount. We believe that a relatively stagnant LIW fills the Tyrrhenian subbasin and most of the Channel of Sardinia and that only part of the LIW found in the channel enters the Algerian subbasin and flows round the Sardinian slope. Therefore, differences in shape are likely due to differences in dynamics.

Apart from the experiments listed above, "the few relevant data collected by other teams in the Algerian subbasin are not large enough yet to give a clear answer on that issue (Rhein, Send, Klein, & Krahmann, 1999)". In addition, most of the data collected by Onken and Sellschopp (2001) in the Channel of Sardinia are consistent with the diagram in Fig. 1.

Therefore, all these results from mesoscale experiments relevant to study the LIW distribution in the Algerian subbasin: (i) agree with the data sets available in all data banks, (ii) do not evidence any permanent westward flow of LIW and (iii) support both the LIW overall counterclockwise circuit and the LIW entrainment by mesoscale AEs, as described by the diagram in Fig. 1.

Nevertheless, this diagram has been refuted by most of the numerical modellers, which is disturbing since (i) basic considerations (e.g. Griffiths, 1986) ought to be questioned then and (ii) the synergy between observations/observers and models/modellers failed. Because we (observers) are unable to specify where the weaknesses of the numerical computations are, we have chosen to report precisely the numerical results analyses of all the major teams. We hope that pinpointing the contradictions between observations and OGCMs results will help improving the models and activate the necessary synergy.

4. Review of modelling results

In the whole section, the "diagram" is the one in Fig. 1. The Alvarez, Tintoré, Holloway, Eby, and Beckers (1994) model shows that a parameterisation of the eddy-topography interaction (the Neptune effect) can be used in large scale OGCMs. With climatological wind and buoyancy forcings, and be the straits open or closed, "...where LIW is found, a wide eastward current is shown off Africa ...that is basically in accordance with the diagram". The Zavatarelli and Mellor (1995) model run with climatological forcings shows "...a LIW flow pattern similar to the diagram". These two relatively old models are close to our diagram for the fundamental aspect of an eastward flow along the Algerian slope. However, the former also gives a wider and smoother westward flow in the central Algerian subbasin, and the latter indicates a seasonal reversal of the circulation in the Tyrrhenian subbasin.

Roussenov, Stanev, Artale, and Pinardi (1995) use heat fluxes computed from realistic air–sea interaction physics. They find that "...LIW branches south of Sardinia and part of it goes directly towards the Strait of Gibraltar".

Wu and Haines (1996) study the importance of LIW in the deep-water formation process. They find that, "...two LIW boundary currents are formed..., one flows northward...and one westward along the northern African coast. The northward current is consistent with observations, whilst the westward current is intermittent for the first 10 years, often breaking up into eddies which enter the basin interior''. Their analysis is that ''…it is possible to have a boundary current at intermediate depth in the northern hemisphere with topography on the left …and to have multiple circulation regimes in the real sea''.

Herbaut, Mortier, and Crépon (1996) study the influence of the density gradients at Gibraltar and Sicily on the large-scale circulation of the sea. They find that ''…LIW splits into two branches. One flows northward along the west coast of Sardinia, whilst the other follows the Algerian coast straight from the Channel of Sardinia to the Strait of Gibraltar. The transport along the Algerian coast integrated between the bottom and 200 m is to the west and reaches 0.8 Sv. This circulation does not correspond to the diagram''.

Horton, Clifford, Schmitz, and Kantha (1997) describe a nowcast/forecast system with data-assimilation for the entire sea resembling weather prediction models. They find that ''…south–southwest of Sardinia a LIW westward current forms along the African coast which continues to the Strait of Gibraltar …The LIW paths are more consistent with Wüst than with the diagram''.

Brankart and Brasseur (1998) performed a climatological analysis at seasonal and monthly scales of ~100,000 CTD profiles in the whole sea, using a variational method and a finite element technique. They ''…suggest a slight revision of the diagram…The 38.5 isoline drawn to the west of Sardinia and Corsica illustrates the predominant pathway chosen by LIW to proceed to the Strait of Gibraltar. As already pointed by Brasseur, Beckers, Brankart, and Schoenauen (1996), part of LIW also displays some tendency to flow along the African coast in a fairly spread current …The temperature field supports the hypothesis of a double pathway for LIW to propagate towards the Strait of Gibraltar''.

Korres, Pinardi, and Lascaratos (2000) investigate the low-frequency interannual variability in atmospheric forcing for the period 1980–1988. They find that ''After the southern tip of Sardinia, the flow of LIW splits into two branches, the strongest going northward and the other westward into the Alboran Sea. This is in agreement with the climatological picture presented by Wüst and Ovchinnikov. The western branch of the LIW path is called the Algerian undercurrent…In winter, LIW turns to the north around Sardinia …In summer, LIW progresses directly to the Alboran Sea flowing along the North African coast. The branch that during winter months goes to the north is now very weak whilst the Algerian undercurrent is well developed''.

Korres et al. add: ''…our results are in partial disagreement with Millot (1994). He in fact shows that from June 1986 until March 1987 there is no Algerian undercurrent at 300 m at some locations along the Algerian coastlines. In our case, the weakening of the Algerian undercurrent happens only in winter 1986. However, it is also evident that from January 1986 to 1988 we reach the minimum values of Algerian undercurrent transport''. The reader must realise that ''some locations'' actually represent current meters set on 8 moorings from 0 to 5°E (Mediprod-5 data). He/she must also remind (see Section 3) that the mean flow during PRIMO-1 (6 months in 1993–1994), Thetis-2 (9 months in 1994) and ELISA (12 months in 1997–1998; see Section 5) was clearly eastwards. This data set does not evidence any seasonal variability so that, even if such a variability were to exist, it would be very weak. Whatever, such a seasonal variability would definitely not be that of an ''Algerian undercurrent'', which is clearly no more than a pure model construction.

To summarise this review of modelling results, we note that several modelling teams (Herbaut et al., 1996; Horton et al., 1997; Korres et al., 2000; Roussenov et al., 1995; Wu & Haines, 1996) claim that it is possible to have in the Algerian subbasin a boundary current at intermediate depth with topography on the left, what we consider inconsistent with basic considerations (e.g. Griffiths, 1986). We also note (and will demonstrate in Section 5) that any unsupervised statistical data analysis (e.g. Brankart & Brasseur (1998) and the several-decade old analyses) gives the visual impression that LIW could flow westwards across the Algerian subbasin. This general disbelief in our diagram partly prompted us to conduct a mesoscale-dedicated experiment in the key-area that is the eastern Algerian subbasin.

5. The ELISA experiment

The ELISA experiment (Taupier-Letage, Puillat, Raimbault, & Millot, 2003) was conducted in 1997–1998. Its aims relevant to this paper were to specify the structure of the AEs and their role in entraining LIW away from the Sardinian vein, as well as to investigate the hypothetical existence of Leddies. An array of 9 moorings (Ei) equipped with ~50 instruments including 41 AANDERAA (RCM5-8 and RCM9) and MORS current meters was set in place for one year. Seven campaigns (more than 100 days at sea) were conducted with a sampling strategy based on infrared satellite images received onboard in near real time (Fig. 2(a), (c), (e) and (g)). In total, 313 CTDs and 353 T7,5-XBTs profiles were collected at a fine interval of 5–10 km. The locations of the casts are given in Fig. 2(b), (d), (f) and (h), together with the Ei positions and the schematised eddy field.

Two AEs (96-1 and 97-1) dominated the eddy field during the experiment. Other AEs (96-2, 97-2 and 98-2) temporarily interacted with the formers. In particular, during the first half of July 97, the interaction between 96-1 and 96-2 resulted in a single elliptical structure (Fig. 2(b), corresponding signature on infrared images not shown). All AEs described the classical counterclockwise circuit (see Section 2 and Puillat et al., 2002). As will be detailed later, both 96-1 and 97-1 clearly extended down to the bottom (~3000 m), at least during parts of the experiment.

The ELISA and Mediprod-5,6 temperature and salinity maxima characterising the LIW core in the eastern Algerian subbasin are plotted in Fig. 3. The choice to restrict the plot to those stations located east of 3°E allows evidencing details of the maxima distribution. Note however that the data located west of 3°E (part of the Mediprod-5,6 data and all Algers-96,98 data) as well as the Thetis-2 and MFSPP data (located at 6–9°E but not shown since the superposition of 14–15 values would not be legible) are consistent too. Fig. 3 shows: (i) the large amount of LIW within the Channel of Sardinia, (ii) the continuity with the vein flowing from there along the Sardinian slope, first westwards and then northwards, and (iii) the non-occurrence, along the Algerian slope, of any continuous maximum that would sign a westward flow. In the central Algerian subbasin, the large heterogeneity results from the AEs carrying LIW fragments. Obviously, the unsupervised interpolation of this data set represented by the black dashed isolines mimics a westward flow across the subbasin.

Transects were performed ~3 days apart in July 1998 to investigate 97-1. The CTD transect 1 and XBT transect 3 are extended to the slopes in Fig. 4 to evidence the general alongslope circulation pattern of LIW, and hopefully persuade the not-yet-convinced colleagues (see the analyses of modelling results reported in Section 4). The easternmost part of transect 3 evidences the LIW vein along the Sardinian slope. Temperatures higher than 13.5 °C that are found deeper than the LIW nominal lower limit (~600 m) are associated with Tyrrhenian Deep Water (TDW), a water with similar characteristics which follows the same route underneath (down to ~2000 m). Transect 2 accounts for the non-existence of any alongslope vein off Algeria. The trough in transects 1 and 3 corresponds to 97-1. Fragments of little mixed LIW (>13.8 °C) are all found within its southern part (near 75 naut. miles (nm) on transect 1), but for one more mixed (<13.7 °C) fragment east of 97-1, close to the vein (near 140 nm on transect 3). Such a limited LIW distribution is peculiar for an AE so far from the Sardinian slope since it is usually more widespread (see Figs. 6,7). This is most likely due to the unusually fast (~8–10 km/day; see Fig. 2(f) and (h)) propagation of 97-1 along its counterclockwise loop, so that the fragments have been pulled away: (i) during a short time only (short fragment), and (ii) a few weeks ago only (entrainment around reduced).

Fig. 5(a) schematises the anticyclonic elliptical structure resulting from the interaction between 96-1 and 96-2 during the first half of July 1997. The XBT transects 1 and 2 were performed on July 8–9 and 11, i.e. only ~2–3 days apart, along the same route across both AEs (see Fig. 2(b)). Note that these transects only display one trough (Fig. 5(b) and (c)) thus supporting, in addition to shipborne ADCP currents (not shown), the elliptical structure. Being performed with a sampling interval <10 km, these transects ascertain the fragmentary distribution of LIW. On image of July 9 (not shown), a cooler surface filament (similar to

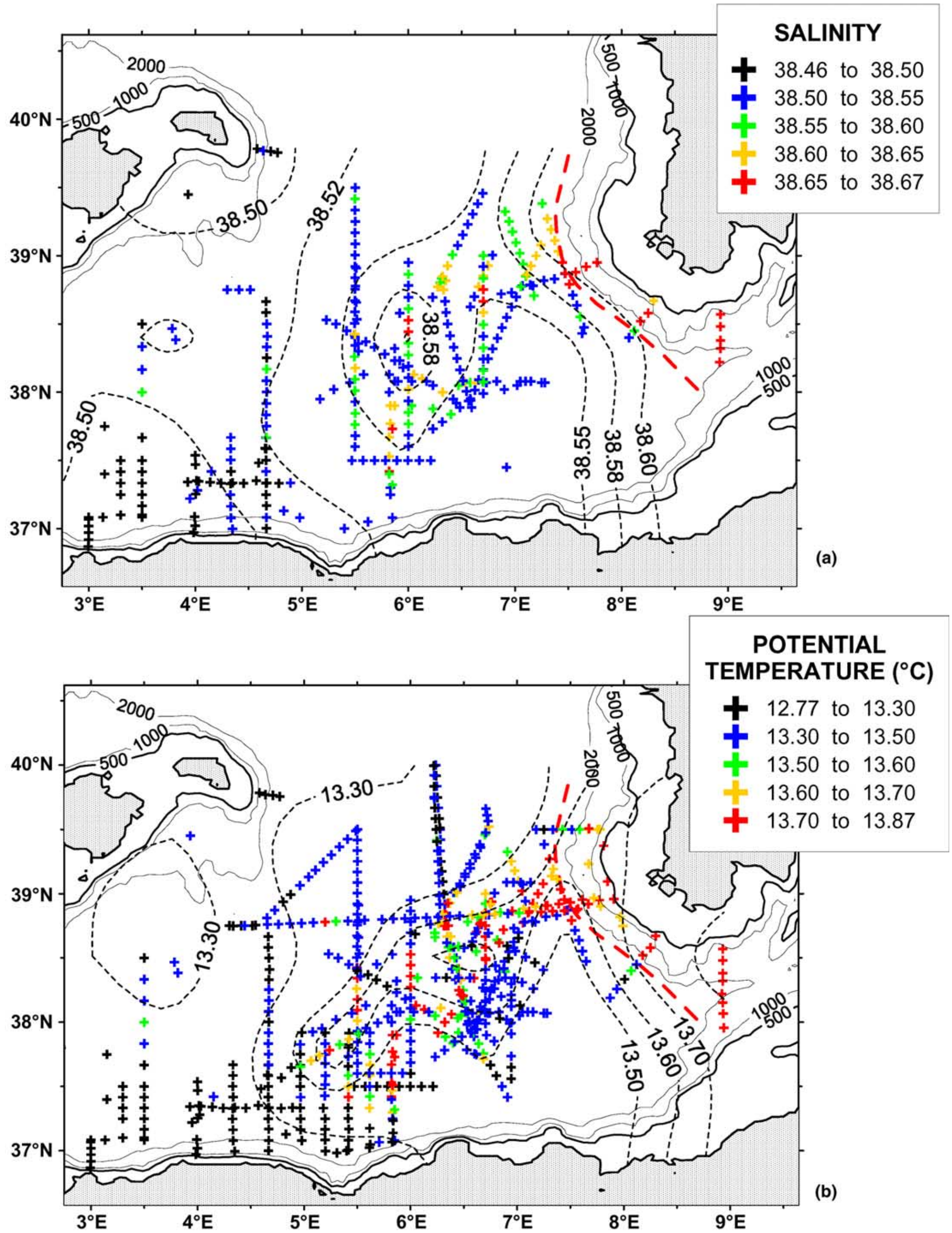

Fig. 3. Distribution of the salinity (a) and potential temperature (b) maxima associated with LIW from the Mediprod-5,6 and ELISA (CTD and XBT casts) in the eastern Algerian subbasin. Associated depths range from ~250 to 650 m for salinity and from ~250 to 550 m for temperature. The dashed black line would result from the unsupervised interpolation of this data set. The dashed red line figures the LIW vein external edge (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

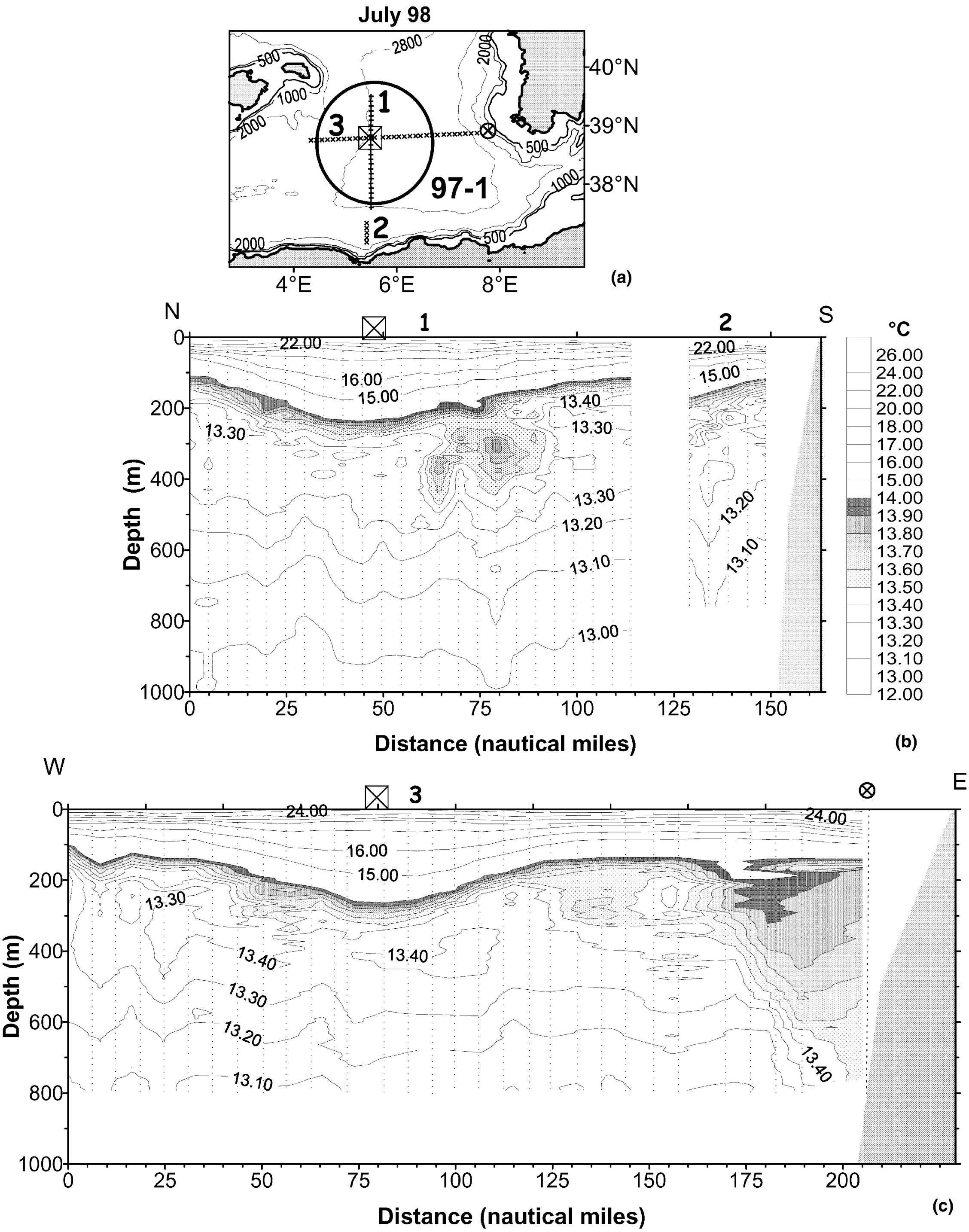

Fig. 4. (a) Schematised position of 97-1 in July 98; (b,c) transects 1 (CTD, 3-4 July 98) and 3 (XBT, 1-2 July 98) completed with casts close to Algeria (XBT transect 2, 17 July 97) and close to Sardinia (XBT cast, 7 September 97).

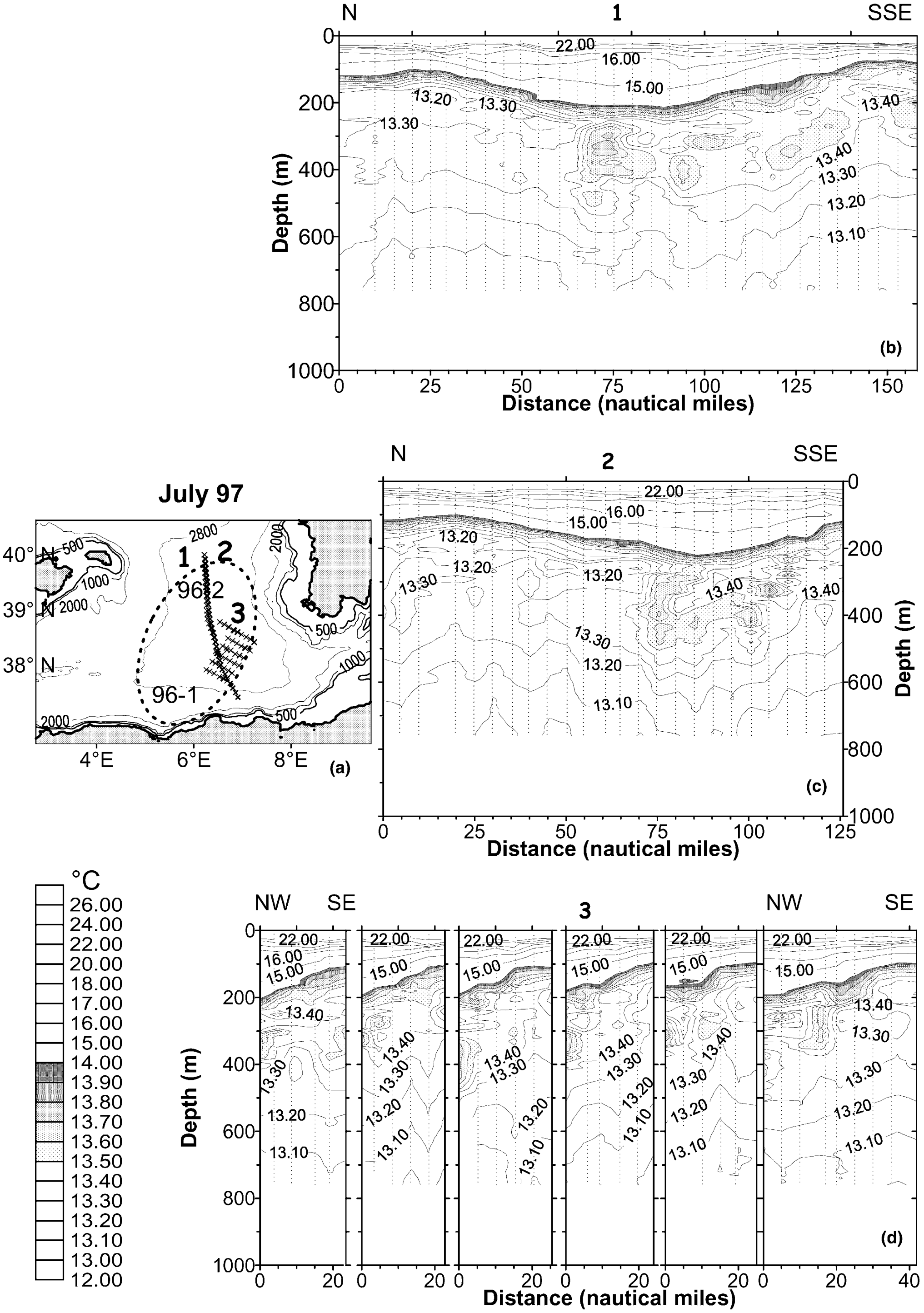

Fig. 5. (a) Schematised position of the elliptical structure resulting from the interaction between 96-1 and 96-2 during the first half of July 97. (b,c) XBT transects 1 and 2 performed on July 8–9 and 11, respectively. (d) XBT transect 3 performed on July 12–13.

that originating from Sardinia on Fig. 2(g)) underlined the south-eastern part of the elliptical structure, so that we decided to perform the series of transects 3 (~20-km apart, ~10-km sampling interval) on July 12–13 (Fig. 5(d)). The slope of the upper isotherms confirms that we were still sampling inside the elliptical structure. Underneath, the LIW fragments corresponding to those described on transects 1–2 were found on all transects 3. Note that the maximum values of 13.7–13.8 °C on transects 1, 2 and 3 are in the range of those in the core of the vein off western Sardinia, that is ~100 km to the east.

To continue the survey of these LIW fragments, XBT transects 1–5 (Fig. 6) were performed soon after, on July 17–18 (at that time, 96-1 and 96-2 started to separate again). The small sampling interval along each transect (<10 km) and the small spacing between the transects (<25 km) guarantee that the fragments are well described again. Close to the Algerian slope, maximum values were still >13.7 °C at ~6°E (transect 1), whilst no more LIW fragments were detected at ~5°E (transect 5). This shows that the amount of LIW and the maximum values are diminishing and even vanishing from transect 1 to transect 5, i.e. downstream within the anticyclonic eddy. It supports the fact that LIW fragments are actually crescent-shaped.

An additional south-west to north-east XBT transect (6, Fig. 6(e)) was made ~12 days after (on July 29) crossing the transects 2–5 from which a recombined transect (Fig. 6(d)) has been drawn. Although the transects in Figs. 6(d) and (e) have exactly the same location, the former (d) does not show any significant amount of LIW, whilst the latter (e) does show a significant one. This documents the extremely large temporal variability at mesoscale. In addition, assuming that the LIW fragment (>13.7 °C) evidenced on July 29 near 38°30′N corresponds to that evidenced on July 17 near 37°30′N (at least, i.e. or further upstream) and assuming that it was entrained by 96-1 along a circular path, an entrainment speed can be computed. Obviously, the AE is not circular, it changed shape and moved, so that a radius of ~70 km (from an AE centre near 38°N–6°E) and a path of ~ 100 km (a quarter of a circle) described by the LIW fragment are rough estimates only. Considering that both fragment cores were sampled exactly 12 days apart, we come with a minimum speed of ~10 cm/s, which is well in the range of the shipborne ADCP values measured at 350–400 m at that time (not shown).

The three CTD transects in Fig. 7 were performed across 96-1 within 2 days, on 26–28 March 98. AE 96-1 was propagating along the Sardinian slope (see Fig. 2(d)), and the northern end of transect 1 reached the outer part of the LIW vein (with TDW underneath, as mentioned for Fig. 4). Further downstream, transect 2 shows an isolated fragment with a Θ maximum > 13.7 °C, whilst the southern end of transect 3 shows patchy smaller maxima of ~13.7 °C (near 55 nm). In the northern part of the eddy (northern end of transect 3), both the amount of LIW and the value of the maximum (<13.6 °C near 10 nm) are lower. Such features are perfectly coherent with LIW entrainment within the whole AE. Considering that: (i) it takes 10–15 days at most for a fragment to be entrained along a quarter of a circle (see Fig. 6), and thus 1.5–2 months along a full circle, and (ii) 96-1 interacted with the vein since 2 months at least (Puillat et al., 2002), we can assume that the northern fragment has completed nearly one full circle (a spiral/annular shape is even conceivable).

Current meters were set at nominal depths of 100, 350, 1000, 1800 and 2700 m on most moorings Ei from July 1997 to July 1998. Due to defects of some instruments (the MORSs and the RCM9s), the data set at the deepest levels is incomplete. Nevertheless, significant results can be inferred from the 1-year progressive vector diagrams (pvds) at intermediate and greater depths shown in Fig. 8. Let us remind that the sense of rotation and trajectory of a propagating eddy can be defined unambiguously with one moored current meter only. For instance, the pvd of a current meter located in the southern part of an anticyclonic eddy propagating eastward in the direction of the general circulation will display a loop to the south (details are given in Millot et al., 1997). In the case of an AE, both the eddy current induced by a pressure force (as we hypothesise for the deeper part of the AEs) and the overall current (the general circulation) are to be vectorially combined. The most striking signature on a pvd is when the eddy current is larger and in the direction opposite to the general circulation. This occurred at the beginning of the experiment (summer 1997) due to 96-1 which was not propagating then (thicker segments in Fig. 8; see Fig. 2(a) and (e)), so that the pvds were towards west at E3 (located in the south of 96-1 where the general circulation was towards

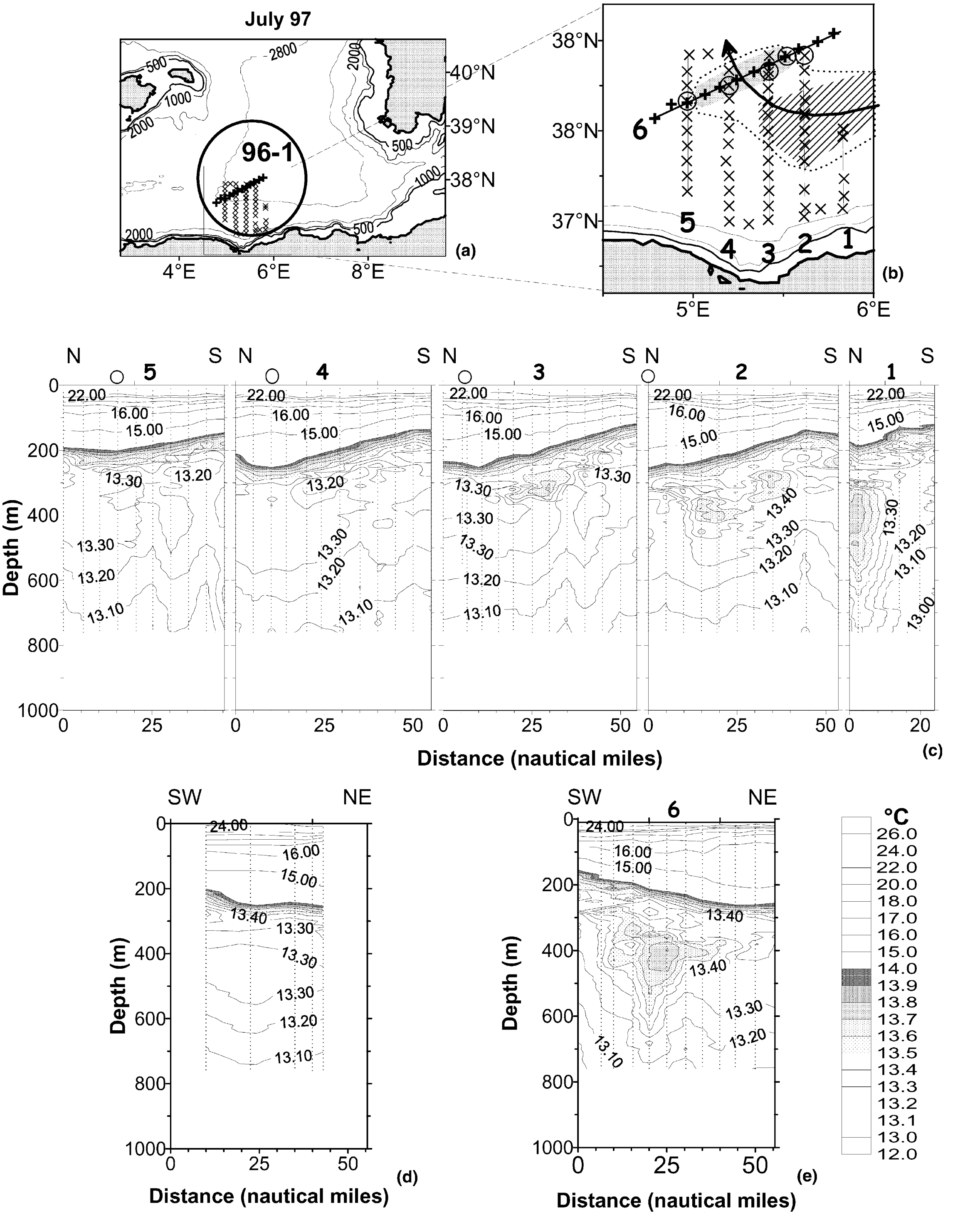

Fig. 6. (a) Schematised position of 96-1 in the second half of July 97. (b) XBT transects 1–5 (July 17–18, plotted in (c); circles indicate the casts used to construct the transect plotted in (d)) and 6 (July 29, plotted in (e)); the hachured (resp. grey) area in (b) figures the LIW fragments extent on July 17–18 (resp. 29).

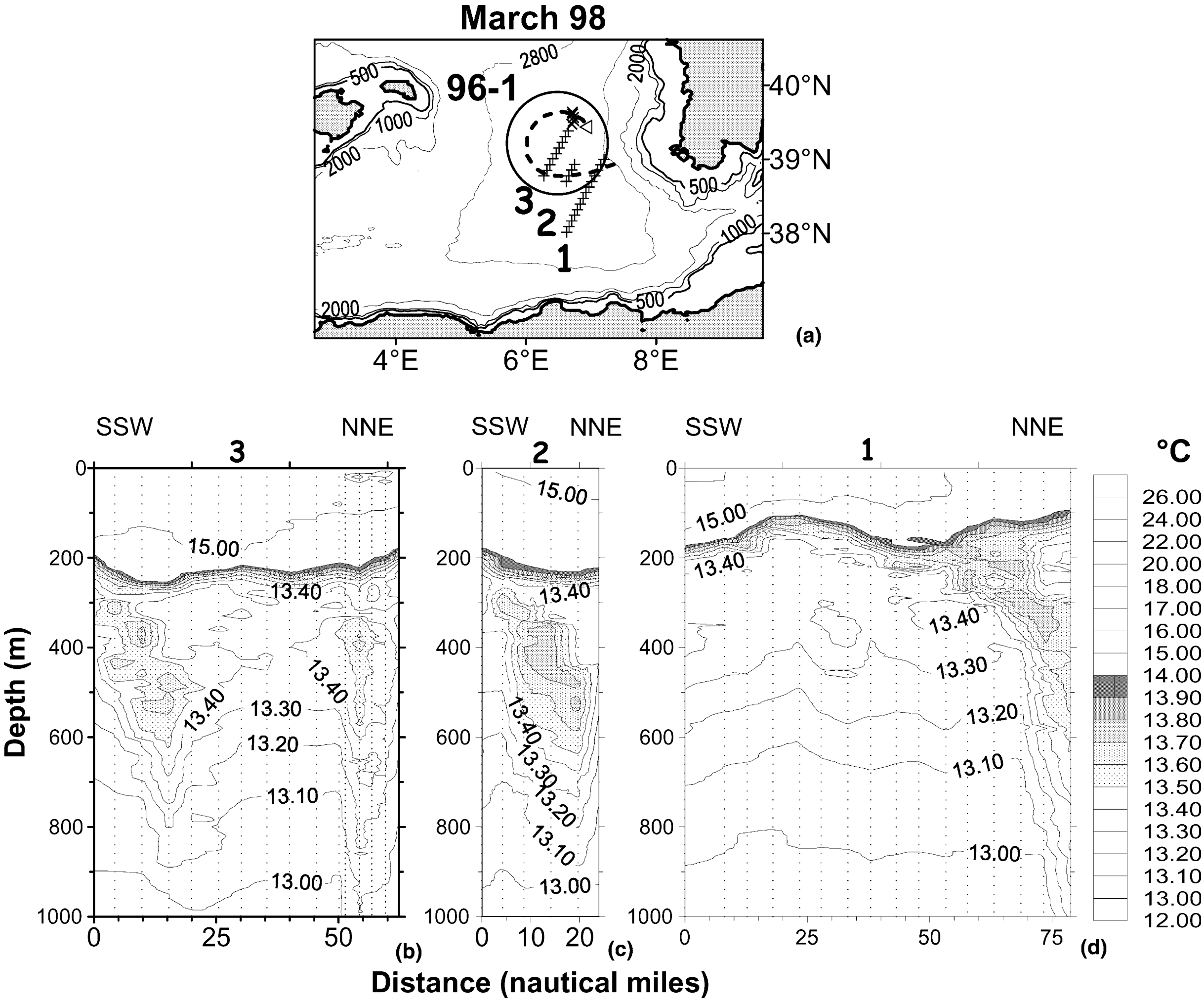

Fig. 7. (a) Schematised position of 96-1 in late March 98 together with the CTD transects 1–3 (b–d) performed on 26–28.

east) and towards north-east at E2 (located in the north-west of 96-1 where the general circulation was towards south-west). Signatures of 96-1 at that time were also significant at E8 (located in the north-east of 96-1 where the general circulation was towards east) since the pvd were diverted southward. AE 96-1 then propagated eastwards and reduced in both size and intensity, thus leading to a decrease of the eddy current at depth: when 96-1 overlapped E4, the pvd (dashed segments) mainly resulted from the general circulation, but the eddy influence can still be identified by the southward curvature. Similar curvatures were induced down to the bottom at least at E3 and E4 (dotted segments) in winter-spring 1998 by 97-1 (see Fig. 2c-f).

After the passage of 96-1, the flow was eastward down to the bottom along the Algerian slope at E3, E4 and E8 for the rest of the experiment, which contradicts the models results (see Section 4). The circulation was clearly alongslope and counterclockwise at all levels, not only along the Algerian and Tunisian slopes (E3, E4 and E5), but also along the Sardinian one (E6 and E9). Finally, note the relatively intense circulation at greater depths (up to a yearly mean speed of ~10 cm/s at 2700 m at E4). The intense, alongslope

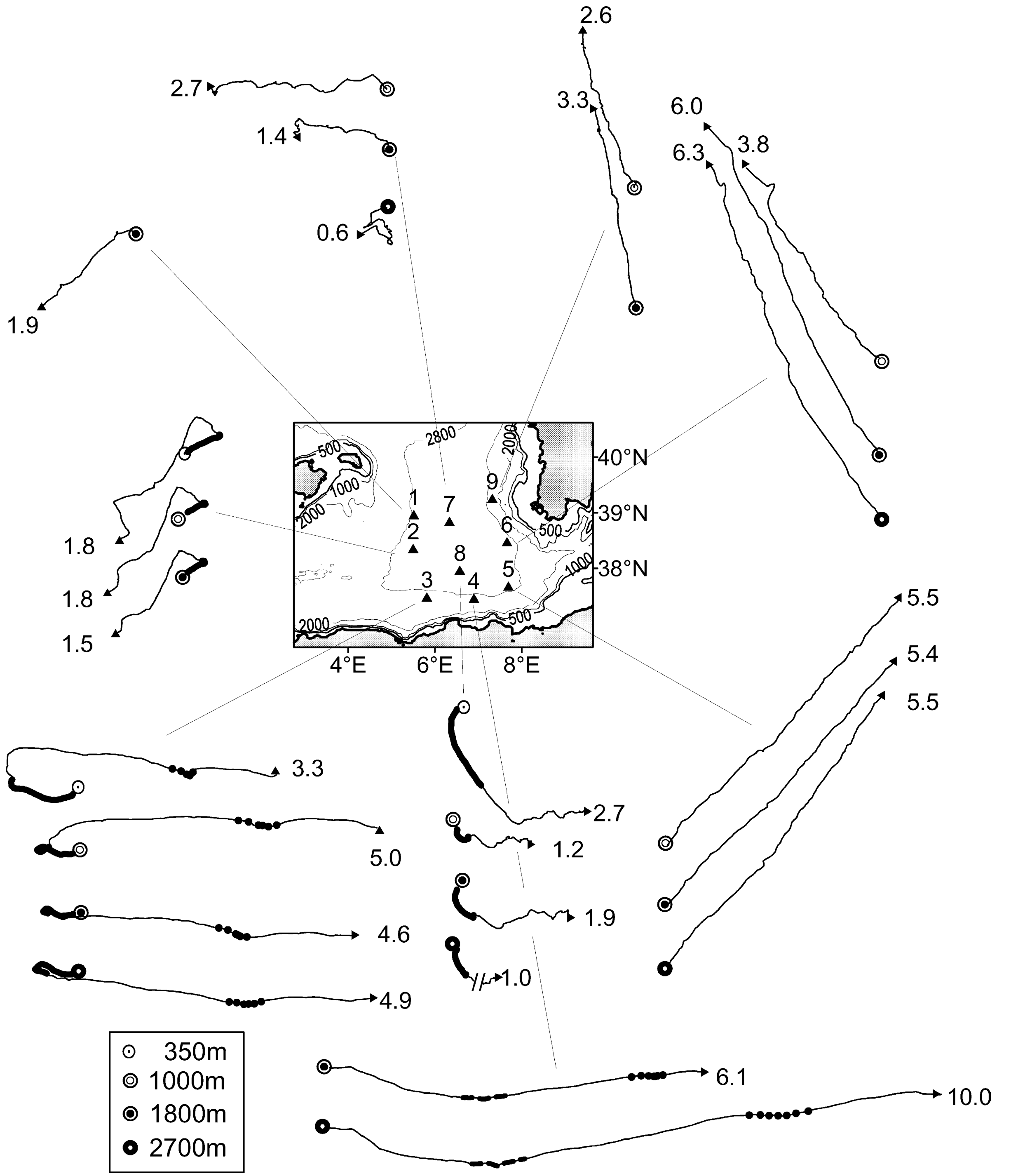

Fig. 8. One-year progressive vectors diagrams at 350, 1000, 1800 and 2700 m together with the mean speed in cm s^{-1}; see text for explanations of thickened parts.

and counterclockwise circulation down to the bottom agrees with the previously published data (Millot, 1994).

6. Conclusion

All in situ data available in all data banks, and in particular those we collected in 1986–1987, 1990, 1993–1994, 1996, 1997–1998, and 1999–2000 (our data set representing about 80 current time series of 9–12 months in length, about 500 CTD and about 1000 XBT profiles) agree with the schematic diagrams proposed by Millot (1987a, 1999) for the circulation features of all water masses, particularly those concerning LIW in the Algerian subbasin (Fig. 1). We summarise the scenario emerging from our analysis.

LIW generally circulates anticlockwise alongslope, consistently with basic theoretical arguments. It amasses in the Tyrrhenian subbasin from which it exits partly through the Channel of Corsica and mostly through the Channel of Sardinia on its northern side. From there, it forms a vein that flows alongslope, i.e. northwards west of Sardinia. Some LIW is pulled away from the vein by Algerian mesoscale eddies (the AEs) passing by. Since there is nearly always an AE interacting with the vein, fragments are nearly permanently entrained within the eddies, eventually across the central Algerian subbasin. The fragments are shaped like crescents, since the overlapping of the vein by the AE varies with the propagation of the latter, essentially. Fragments are finally released in the central subbasin, possibly before the AE decay. Fragments can be identified for a long time and/or far westwards, which means that mixing within an AE is weak. Such a fragmentary distribution will lead any unsupervised statistical analysis to conclude mistakenly to a permanent westward flow. Except when disturbed by an AE, the general circulation at all levels down to the bottom is intense, alongslope and counterclockwise. Along the Algerian slope and at the LIW level, water (that is either strongly modified LIW closing there its counterclockwise circuit in the whole western basin of the Mediterranean sea or any other water) flows eastward on a yearly mean. However, most of the models do not reproduce this eastward circulation at the intermediate level off Algeria and none examines the deep intense circulation.

Data such as the ones presented in this paper were collected in order to understand the processes. Nevertheless, since in situ experiments are necessarily limited in time, locations and parameters, and because of the natural variability, the description of the phenomena and consequently the understanding of the processes are limited too. Therefore, with basic considerations in mind, an observer can only put forward hypotheses (about the structure of the phenomena and about the associated processes) consistent with all – or at least most of – the available data. Now, to definitively validate these hypotheses and finally clearly understand the processes, data will hardly be sufficient or would be tremendously expensive. That is why observers need modellers. However, models first have to be improved until they achieve coherence with the available data, not to be considered as more reliable than the data. Then, modellers could suggest the collection of complementary data, which would obviously be much appreciated by the observers to define their sampling strategy.

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References

Alvarez, A., Tintoré, J., Holloway, G., Eby, M., & Beckers, J. M. (1994). Effect of topographic stress on circulation in the Western Mediterranean. *Journal of Geophysical Research, 99*, 16053–16064.

Ayoub, N., Le Traon, P. Y., & De Mey, P. (1998). A description of the Mediterranean surface variable circulation from combined ERS-1 and TOPEX/POSEIDON altimetric data. *Journal of Marine Systems, 18*, 3–40.

Benzohra, M., & Millot, C. (1995a). Characteristics and circulation of the surface and intermediate water masses off Algeria. *Deep-Sea Research, 42*(10), 1803–1830.

Benzohra, M., & Millot, C. (1995b). Hydrodynamics of an open-sea eddy. *Deep-Sea Research, 42*(10), 1831–1847.

Bouzinac, C., Vazquez, J., & Font, J. (1998). Complex empirical orthogonal functions analysis of ERS-1 and Topex/Poseidon combined altimetric data in the region of the Algerian Current. *Journal of Geophysical Research, 103*(C4), 8059–8071.

Bouzinac, C., Font, J., & Millot, C. (1999). Hydrology and currents observed in the Channel of Sardinia during the PRIMO-1 experiment from November 1993 to October 1994. *Journal of Marine Systems, 20*(1–4), 333–355.

Brankart, J., & Brasseur, P. (1998). The general circulation in the Mediterranean Sea: a climatological approach. *Journal of Marine Systems, 18*, 41–70.

Brasseur, P., Beckers, J. M., Brankart, J. M., & Schoenauen, R. (1996). Seasonal temperature and salinity fields in the Mediterranean Sea: climatological analysis of a historical data set. *Deep-Sea Research, 43*(2), 159–192.

Font, J., Millot, C., Salas, J., Julia, A., & Chic, O. (1998). The drift of modified Atlantic water from the Alboran Sea to the eastern Mediterranean. *Scientia Marina, 62*(3), 211–216.

Fuda, J.-L., Millot, C., Taupier-Letage, I., Send, U., & Bocognano, J. M. (2000). XBT monitoring of a meridian section across the Western Mediterranean Sea. *Deep-Sea Research, 47*, 2191–2218.

Garzoli, S., & Maillard, C. (1976). Hydrologie et circulation hivernales dans les canaux de Sicile et de Sardaigne. Int. rep. of the Laboratoire d'Océanographie Physique du Museum, Paris.

Gervasio, L. (1997). Instabilités des courants côtiers en présence de topographie. Application au courant algérien (p. 299). Thèse de Doctorat de l'Université de Paris VI.

Griffiths, R. W. (1986). Gravity currents in rotating systems. *Annual Review of Fluid Mechanics, 18*, 59–89.

Herbaut, C., Mortier, L., & Crépon, M. (1996). A sensitivity study of the general circulation of the western Mediterranean Sea. Part I: The response to density forcing through the straits. *Journal of Physical Oceanography, 26*(1), 65–84.

Horton, C., Clifford, M., Schmitz, J., & Kantha, L. (1997). A real-time oceanographic nowcast/forecast system for the Mediterranean Sea. *Journal of Geophysical Research, 102*(C11), 25123–25156.

Iudicone, D., Santoleri, R., Marullo, S., & Gerosa, P. (1998). Sea level variability and surface eddy statistics in the Mediterranean Sea from TOPEX/POSEIDON data. *Journal of Geophysical Research, 103*(C2), 2995–3011.

Jacobs, P., Guo, Y., & Davies, P. A. (1999). Boundary currents over shelf and slope topographies. *Journal of Marine Systems, 19*(1–3), 137–158.

Korres, G., Pinardi, N., & Lascaratos, A. (2000). The ocean response to low-frequency interannual atmospheric variability in the Mediterranean Sea Part I: Sensitivity experiments and energy analysis. *Journal of Climate, 13*(4), 705–731.

Manzella, G., Cardin, V., Cruzado, A., Fusco, G., Gacic, M., Galli, C., et al. (2001). EU-sponsored effort improves monitoring of circulation variability in the Mediterranean. *EOS, Transaction AGU, 82*(43), 497–504.

McCartney, M., & Woodgate-Jones, M. (1991). A deep-reaching anticyclonic eddy in the subtropical gyre of the eastern South Atlantic. *Deep Sea Research, 38*, S411–S443.

Millot, C. (1985). Some features of the Algerian Current. *Journal of Geophysical Research, 90*(C4), 7169–7176.

Millot, C. (1987a). Circulation in the Western Mediterranean. *Oceanologica Acta, 10*(2), 143–149.

Millot, C. (1987b). The circulation of the Levantine Intermediate Water in the Algerian Basin. *Journal of Geophysical Research, 92*(C8), 8265–8276.

Millot, C. (1994). Models and data: A synergetic approach in the western Mediterranean Sea. In P. Malanotte-Rizzoli & A. R. Robinson (Eds.), *Erice School proceedings, ocean processes in climate dynamics: Global and Mediterranean Examples* (pp. 407–425).

Millot, C. (1999). Circulation in the Western Mediterranean sea. *Journal of Marine Systems, 20*(1–4), 423–442.

Millot, C., Taupier-Letage, I., & Benzohra, M. (1997). Circulation off Algeria inferred from the Médiprod-5 current meters. *Deep Sea Research, 44*(9–10), 1467–1495.

Mortier, L. (1992). Les instabilités d'un courant côtier de densité. Application au courant algérien (p. 326). Thèse de doctorat de l'Université d'Aix Marseille II.

Nielsen, J. (1912). Hydrography of the Mediterranean and adjacent waters. *Report of the Danish Oceanographic Expedition 1908–1910 to the Mediterranean and Adjacent waters, Copenhagen, 1*, 77–192.

Obaton, D., Millot, C., Chabert D'Hières, G., & Taupier-Letage, I. (2000). The Algerian Current: comparisons between in situ and laboratory measurements. *Deep-Sea Research I, 47*, 2159–2190.

Onken, R., & Sellschopp, J. (2001). Water masses and circulation between the eastern Algerian Basin and the Strait of Sicily in October 1996. *Oceanologica Acta, 24*(2), 151–167.

Ovchinnikov, I. (1966). Circulation in the surface and intermediate layers of the Mediterranean. *Oceanology, 6*, 48–59.

Perkins, H., & Pistek, P. (1990). Circulation in the Algerian Basin during June 1986. *Journal of Geophysical Research, 95*, 1577–1585.

Puillat, I., Taupier-Letage, I., & Millot, C. (2002). Algerian eddies lifetimes can near three years. *Journal of Marine Systems, 31*(4), 245–259.

Raimbault, P., Coste, B., Boulhadid, M., & Boudjellal, B. (1993). Origin of high phytoplankton concentration in deep chlorophyll maximum (DCM) in a frontal region of the south-western Mediterranean Sea (Algerian Current). *Deep Sea Research, 40*(4), 791–804.

Rhein, M., Send, U., Klein, B., & Krahmann, G. (1999). Inter-basin deep water exchange in the western Mediterranean. *Journal of Geophysical Research, 104*(C10), 23495–23508.

Roussenov, V., Stanev, E., Artale, V., & Pinardi, N. (1995). A seasonal model of the Mediterranean Sea general circulation. *Journal of Geophysical Research, 100*(C7), 13515–13538.

Ruiz, S., Font, J., Emelianov, M., Isern-Fontanet, J., Millot, C., & Taupier-Letage, I. (2002). Deep structure of an open sea eddy in the Algerian Basin. *Journal of Marine Systems, 33–34*, 179–195.

Sadoux, S., Baey, J. M., Fincham, A., & Renouard, D. (2000). Experimental study of the stability of an intermediate current and its interaction with a cape. *Dynamics of Atmosphere and Oceans, 31*(1–4), 165–192.

Salas, J., Millot, C., Font, J., & García-Ladona, E. (2002). Analysis of mesoscale phenomena in the Algerian Basin observed with drifting buoys and infrared images. *Deep-Sea Research, 49*(2), 245–266.

Sammari, C., Millot, C., Taupier-Letage, I., Stefani, A., & Brahim, M. (1999). Hydrological characteristics in the Tunisia–Sicily–Sardinia area during spring 1995. *Deep-Sea Research, I-46*, 1671–1703.

Send, U., Krahmann, G., Mauuary, D., Desaubies, Y., Gaillard, F., Terre, T., et al. (1997). Acoustic observations of heat content across the Mediterranean Sea. *Nature, London, 385*, 615–617.

Sparnocchia, S., Gasparini, G.-P., Astraldi, M., Borghini, M., & Pistek, P. (1999). Dynamics and mixing of the Eastern Mediterranean Outflow in the Tyrrhenian Basin. *Journal of Marine Systems, 20*, 301–317.

Taupier-Letage, I., & Millot, C. (1988). Surface circulation in the Algerian Basin during 1984. *Oceanologica Acta*(9), 119–131.

Taupier-Letage, I., Puillat, I., Raimbault, P., & Millot, C. (2003). Biological response to mesoscale eddies in the Algerian Basin. *Journal of Geophysical Research 108, C8*, 3245. doi:10.1029/1999JC000117.

Vignudelli, S. (1997). Potential use of ERS-1 and Topex/Poseidon altimeters for resolving oceanographic patterns in the Algerian Basin. *Geophysical Research Letters, 24*(14), 1787–1790.

Wu, P., & Haines, K. (1996). Modelling the dispersal of Levantine Intermediate Water and its role in Mediterranean deep water formation. *Journal of Geophysical Research, 101*, 6591–6607.

Wüst, G. (1961). On the vertical circulation of the Mediterranean Sea. *Journal of Geophysical Research, 66*, 3261–3271.

Zavatarelli, M., & Mellor, G. (1995). A numerical study of the Mediterranean Sea circulation. *Journal of Physical Oceanography, 25*(6), 1384–1414.