The use of the satellite thermal imagery to track mesoscale features and infer circulation in the Mediterranean

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ABSTRACT

The overall functioning of the Mediterranean Sea, which transforms Atlantic Water (AW) into Mediterranean Waters (MWs), has been comprehended for decades now, and so is the process of dense water formation, which leads AW to sink in specific offshore northern zones of both basins. However, some circulation features are still being debated in the western basin, while a similar debate is currently being initiated in the eastern one.

One main reason for these debates lies in the fact that most studies do not take into account the large spatio-temporal variability induced by mesoscale dynamics, which is intense in the whole Mediterranean, especially in the southern parts of both basins. The flow of AW forms alongslope unstable currents that generate meanders and eddies along the Algerian and the Libyo-Egyptian subbasins (respectively). These eddies have diameters ranging from 50 to 150 km (up to 250 km), vertical extents from 100s to1000s of metres (down to the bottom: ~3000m), and lifetimes ranging from month to year (up to three years at least). These eddies propagate alongslope downstream (eastward) at a few km/day, can detach from the current to drift in the open sub-basin, and can have an impact on the general circulation. In order to interpret correctly the *in situ* observations, it is thus of the utmost importance to locate and track these mesoscale phenomena with a fine spatio-temporal interval. The medium-resolution satellite images (pixel ~ 1 km, ~1 pass/day) are an extremely efficient tool in this regard, the most-widely used being the thermal infrared (IR) images from NOAA/AVHRR (thermal resolution ~0.1°C). Provided some precautions are taken, IR images can be used indeed to infer surface currents. Mediterranean examples of the use of IR images to infer circulation features will be shown, from filaments to eddy tracking, up to the results of the analysis of a time series of images spanning ~4 years, from which we inferred a new schema of the surface circulation in the eastern basin. The use of IR imagery in near-real time will play a key-role in the sampling strategy of future cruises dedicated to test these hypotheses.

1. INTRODUCTION

The Mediterranean Sea is a domain where evaporation exceeds the water inputs by rivers and precipitations. As a result the Mediterranean sea level is lowered, and lighter (less salty) Atlantic Water (AW[1]) enters at Gibraltar at the surface. AW is made denser along its circuit in the western

1 See the water masses acronyms on http://www.ciesm.org/catalog/WaterMassAcronyms.pdf

and eastern basins through evaporation and mixing with resident Mediterranean Waters (MWs), all year long. During wintertime, cooling and intense mixing with deeper (saltier) MW in the northern parts of both basins lead to dense water formation processes. So that surface/lighter incoming AW is transformed into deeper/denser MWs, which will eventually exit at depth through the strait of Gibraltar (for a recent review of the circulation in the Mediterranean see Millot and Taupier-Letage, 2005a[2]). The agreement around this basic functioning of the Mediterranean is general. But when it comes to detail the circulation paths of the water masses, some features are still fiercely debated nowadays. It is all the more amazing when thinking that the first schema of the circulation (for both surface and intermediate layers) was issued nearly a century ago (Nielsen, 1912). He mainly considered the effect of the Coriolis force, and as a result the general circuit was mainly counter-clockwise around the basins. However some features raised questions: how to explain the "branching" of the AW circulation in the eastern part of the Algerian subbasin[3], one flowing "normally" eastward through the Channel of Sardinia, and the other flowing northward along the western slope of Sardinia? In the same way, some Levantine Intermediate Water (LIW) was found hardly modified at all in the central part of the Algerian subbasin: in addition to the vein flowing "normally" northward west of Sardinia, a vein of LIW was also drawn flowing westward across the subbasin at intermediate depth, in contradiction with the effect of the Coriolis force.

In the eastern basin this schema depicted a surface circulation around the basin in a counter-clockwise circuit. In the 1960s-1970s (Ovchinnikov, 1966; Lacombe and Tchernia, 1972) the diagrams still depicted a surface circulation around the basin in a counter-clockwise circuit, but in the southern part it was more widespread and included subbasin circulations. Between 1985 and 1990 intensive fieldwork was organized within the framework of the POEM experiment (Physical Oceanography of the Eastern Mediterranean, e.g. Robinson *et al.*, 1991). The interpretation of this data set combined with modelling resulted in a schema (e.g. Robinson and Golnaraghi, 1993) showing a surface circulation crossing the basin with jets meandering offshore (among which the so-called "Mid Mediterranean Jet": MMJ), splitting in a complex system of swirls encircling mesoscale eddies and/or gyres, that were characterized as permanent, recurrent, and/or transient. Briefly stated, while the historical schemata represented a circulation mainly counter-clockwise "round-basin", the POEM schema switched to a circulation mainly "cross-basin", superseding the simple effect of the Coriolis force.

The satellite imagery, and especially the thermal NOAA/AVHRR (National Oceanic and Atmospheric Administration/ Advanced Very High Resolution Radiometer) imagery, provides since the late 1970s i) a synoptic view of the basin ii) at a spatio-temporal scale that allows to evidence the mesoscale phenomena, its ubiquity and its impact on the circulation of the water masses. Thus it offered the possibility to investigate and understand the high spatio-temporal variability of *in situ* observations, and to propose explanations and/or alternate interpretations to reconcile *in situ* observations and theory or basic principles, since numerical hence theoretical models can show cross-basin jets.

2. The use of satellite thermal images for circulation studies

a. Principle

The infrared signal remotely sensed only comes from the few upper microns of the surface (for the theory of thermal remote sensing see e.g. http://rst.gsfc.nasa.gov/Sect9/Sect9_1.html). Therefore the thermal signatures observed cannot be *a priori* related to the dynamics of the mixed layer. However very often the wind blows, so that the temperature of the surface is representative of a mixed layer that can reach a few 10s of metres due to the seasonal stratification, down to 1000s of metres where MWs are formed in winter.

In the Mediterranean, the surface circulation can be tracked most generally and in most places (see the following paragraph for restrictions) by tracking the higher temperatures, which correspond to the lower salinity water. Such conditions are optimum in winter, when the

2 Available on http://www.ifremer.fr/lobtln/OTHER/Millot_Taupier_handbook.pdf

3 See our terminology on http://www.ifremer.fr/lobtln/OTHER/Terminology.html

inflowing AW temperature is ~16°C and that of the MW ~13°C. Note that this can also be true independently of the latitude, as shown by the warmer current flowing along the northernmost parts of both basins in Figure 1a.

The medium-resolution satellite NOAA/AVHRR images are an extremely efficient tool to track mesoscale features. The Mediterranean basin-wide spatial coverage is provided by a swath wider than 2000 km. The fine temporal coverage is provided by two NOAA satellites flying simultaneously (for evolution see http://www.ipo.noaa.gov/), yielding at least four passes per day over the Mediterranean. The pixel is ~1 km, and the thermal resolution ~ 0.1°C (for more details see http://noaasis.noaa.gov/NOAASIS/ml/avhrr.html). The relatively weak cloudiness and the dimension of the Mediterranean thus let expect a coverage adequate at meso- spatial and temporal scales, even though possibly patchy (the whole sea is not cloud-free simultaneously, the same area cloud-free intermittently).

The sea surface temperature (SST) is derived from a linear combination of two (day) to three (night) channels (e.g. see http://www.ghrsst-pp.org/), which increases the noise in the resulting image. Although this is not a serious drawback, the preferred product to track the thermal signatures is the channel 4 image. The geophysical data are brightness temperatures, that are “relative temperatures”, as opposed to SSTs, which are “absolute temperatures”.

In order to optimise the visualisation of the thermal signatures it is necessary to use a colour table specifically adjusted for each image/area. This is required mainly because the marine thermal dynamics is usually very weak (few °C), so that a colour scale spanning temperatures lower than 10°C to more than 25°C results in a nearly colour-uniform image showing little, if any, dynamical information. This is also required because the temperature at the ocean-atmosphere interface can differ markedly between day and night, a temporal scale at which no significant variation occurs for the mesoscale phenomena. So if the temperatures cannot be compared from one image to the other, the evolution of the signature can be analysed. Following the conventions, the images will be presented with temperatures increasing from blue to red.

The tracking of mesoscale features from their thermal signature relies on the fact that there must be coherence between the temporal and the spatial scales. Indeed, the thermal signature that corresponds to a (small) shallow phenomenon will have a transient lifetime, of the order of day(s). Inversely, the (large) thermal signature that can be tracked for months up to years necessarily corresponds to a structure having a deep vertical extent, a condition required to maintain the signature over time, especially to survive winter mixing.

One image allows to deduce the current direction associated with the mesoscale eddies, since the isotherms always spiral inside, whether the eddies are cyclonic or anticyclonic. Most often the current is parallel to the isotherms because the latter are parallel to isohalines, hence isopycnals, so that geostrophic approximation is satisfied. Time series of images allow deducing a propagation speed from the successive positions of a feature such as an eddy, an upwelling cell, a front, or a filament. Isotherms are then generally perpendicular to the propagation direction. Most generally the inference of the currents is intuitive (cf meteorological scenes shown on TV), as one can verify considering the sub-scenes of Figure 1 (see legend for interpretation).

b. Precautions

First one must discriminate between marine signal and atmospheric contamination from water vapour and dust, in case the images are delivered without a cloud-mask. Most of the time it is fairly easy, since the atmospheric temperatures are much lower than the marine ones. In the case of light haze (when these temperatures can be in the same range), the atmospheric isotherms can be identified by their pattern, the fact that they cut the marine isotherms at any angle (see Figures 1f, i, k), and if there is any doubt, by looking at the signature on a previous or following image.

Then, in order to assign a thermal signature to an actual mesoscale dynamical structure, the presence and lifetime of the thermal pattern must be verified on several images, possibly using other satellite information too (e.g. visible images: cf Figure 1g, or altimetry).

Under calm wind conditions, the superficial microlayer can heat up due to solar heating. Then the “skin” temperature is higher (up to a few °C) than the “bulk” temperature, and the thermal

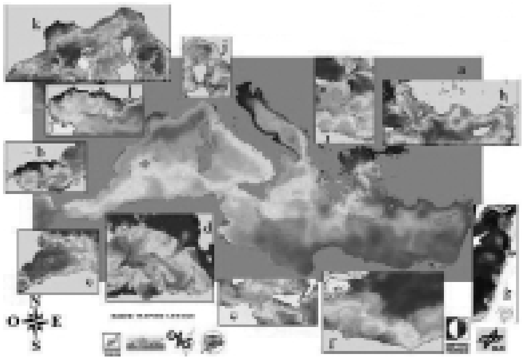

Fig. 1. (See page 108 for original color plate) Illustration of the mesoscale dynamics in the Mediterranean with thermal NOAA/AVHRR images from SATMOS/ MétéoFrance and DLR (but **g**: ocean colour/ chlorophyll content from SeaWiFS, from *ies*). Images have been selected at different dates. Temperature increases from blue to red, but all images have an independent colour scale. **a**: the monthly composite of January 1998 for the whole Mediterranean. **b**: the Alboran, in its classic situation of two gyres filling the sub-basin. **c**: the jet of AW on the western half of the eastern Alboran gyre reaches the algerian slope near 0° and continues as the Algerian Current, which can be seen (colder signature) propagating alongslope as far as ~4°E (south of Menorca), where it veers offshore (due to eddies interactions, not shown). An algerian eddy (warmer isotherms) can be seen south of Ibiza. **d**: Algerian eddies interacting strongly in the eastern part of the Algerian sub-basin, the accumulation zone ΣA_E. The strong shear between 2 close anticyclones creates small cyclonic shear eddies. Upwelling cells (dark blue tongues) are generated on the southwestern side of the AEs, where the current is directed offshoreward. **e**: the channel of Sardinia with an AE (blocked) at the entrance, and the channel of Sicily (the upwelling cells along the southern coast of Sicily are typical of summertime conditions). **f**: the western Levantine, with libyo-egyptian eddies (accumulation zone ΣL_W). **g**: the Middle-East, with coastal instabilities revealed by their chlorophyll content (SeaWiFS "ocean colour" image; situation not characteristic of the accumulation zone ΣL_E). **h**: the Northern Current off Turkey, showing sharp meanders and an eddy pinching off. **i**: most of the Northern Current is feeding the wind-induced Ierapetra eddy, east of Crete. **j**: the Ligurian subbasin, with a vortex dipole (mushroom-like structure) north of Corsica; the cold patch east of the strait of Bonifacio reveals the divergence induced by a strong (past) mistral wind event. **k**: the Liguro-Provencal subbasin: the Northern Current flows close to the coast since the slope is steep east of the gulf of Lions; there it skirts the continental shelf along the ~200m isobath, and thus crosses the gulf; the cold area off the gulf of Lions (and probably the one east of the strait of Bonifacio too) reveals the area where wintertime deep convection occurs, forming dense water (image typical of wintertime situation). **l**: upwelling cells in the gulf of Lions induced by strong Mistral events.

patterns are no longer representative of those of the mixed layer. Therefore it prevents, locally and temporally, any interpretation in terms of current. However such unfavourable conditions are easily detected thanks to their usual elliptic and concentric shape, and are circumvented by using nighttime images.

During cloudy periods the mesoscale structures can be tracked using the sea level anomaly (SLA) which they generate on altimetric tracks, and/or using composite thermal images (from weekly to monthly ones). However care must be taken when using composite images as the longer the time interval the smoother the signature of a propagating structure, up to potentially yielding a misleading picture. Indeed, the image resulting from the time-composition of eddies (thus inducing thermal gradients mainly cross-shore) propagating along a coast will present a smooth band parallel to the coast (thermal gradients mainly along-shore).

Besides cloudiness, specific meteorological conditions can also impair or even prevent tracking mesoscale features. This is especially frequent during summertime. In the Ionian especially the alternation of strong wind events and high warming calm periods in an orographically complex area leads to thermal patterns difficult to interpret. In the Aegean, possibly up to the Egyptian coast, the strong Etesian winds mix and cool the surface layer. The resulting strong gradients oriented north-south that delimit this cooler band will appear and supersedes thermal patterns linked to mesoscale dynamics in any automatic image processing. In the southeastern Levantine warming is such that a superficial warm layer usually caps the layer containing the dynamical information. Moreover, the dynamical features there tend to be of smaller size and to have a rapid evolution/propagation. Therefore statistical and climatological analyses of thermal images (e.g. Marullo *et al.*, 1999a-b) do not provide adequate information on the mesoscale dynamics or on the general circulation. The visual analysis of (portions of) images remains, up to now, the unique way to make a detailed analysis and to track the eddies on the long term (years).

c. Validation

The use of thermal images to infer mesoscale dynamical structures and circulation features has been extensively validated in the western basin. In the eastern basin fewer observations are available yet, there is no objective reason to expect a different behaviour.

3. THE RESULTS OBTAINED ON THE MESOSCALE DYNAMICS AND THE GENERAL CIRCULATION IN THE MEDITERRANEAN

A review of our present understanding of the circulation is presented in Millot and Taupier-Letage (2005a). The progressive steps that led to our current view of the surface circulation (Figure 2) are briefly described here below.

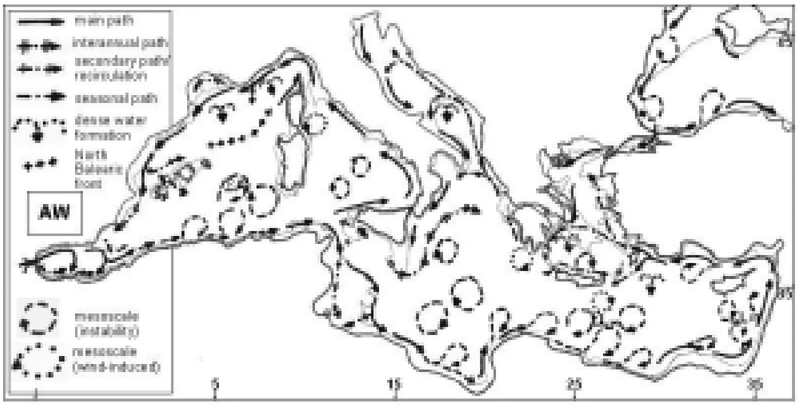

Fig. 2. The schema of the surface circulation (from Millot and Taupier-Letage, 2005a).

a. Definitive results in the western basin

The first analysis of thermal images (Millot, 1985) showed that the flow of recent AW along the Algerian slope -namely the Algerian Current (Figure 1c)- is unstable, giving rise to an intense mesoscale activity (Figure 1d). It generates meanders (width ~50km), which enclose a mesoscale anticyclonic eddy ~50 km in diameter. Meanders and enclosed eddies propagate downstream, i.e. eastward along the slope, at few km/day. The larger (diameter up to ~200km) and deeper (some can reach the bottom at ~3000m, see Ruiz *et al*., 2002, Millot and Taupier-Letage, 2005b) Algerian eddies (AEs) cannot go on eastward through the channel of Sardinia (Figure 1e), and are constrained to follow the Sardinian slope northward. This is illustrated by the trajectories of the drifters released upstream in a young AE and their various fates (see Salas *et al*., 2001, 2002). AEs generally follow a counter-clockwise circuit in the eastern part of the Algerian subbasin (Puillat *et al*., 2002; Isern-Fontanet *et al*., 2003), thus transporting recent AW offshore, which is released upon their decay (lifetimes can exceed three years). The AEs (enclosing AW), observed drifting in the open basin, provide the (simple) explanation to the AW branching in the eastern Algerian. Thus the Algerian subbasin acts as a buffer zone for AW, disconnecting the flux coming in at Gibraltar from the flux exiting the subbasin through the channel of Sardinia and along the southwestern coast of Corsica.

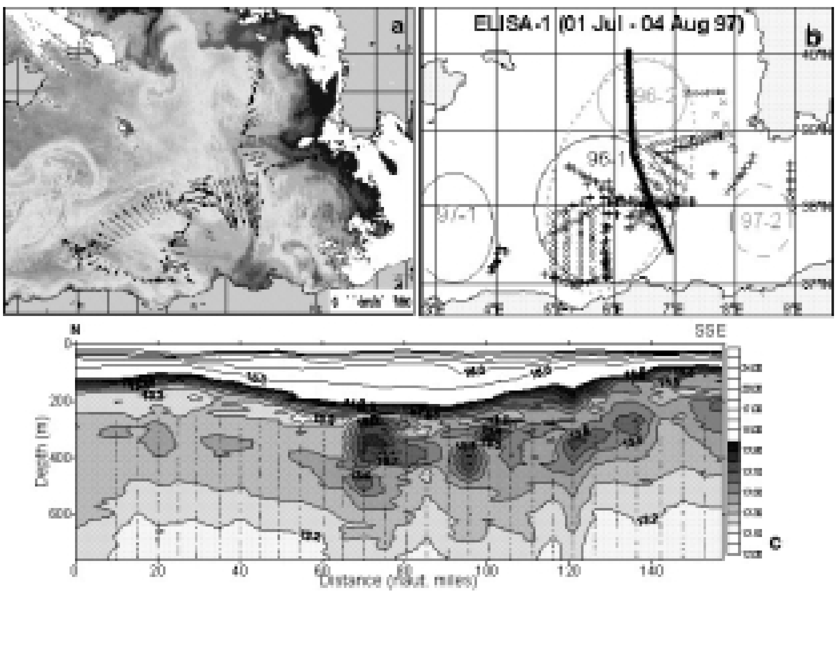

Fig. 3. The sampling at mesoscale during the ELISA-1 campaign. **a)** the associated surface ADCP current overlaid on a thermal infrared image of late July 1997. ; **b)** contours of the AEs and locations of the CTD and XBT casts; thick line: section detailed below; **c)** XBT transect showing several lenses of LIW trapped in 96-1.

It was then hypothesized that the AEs drifting along the Sardinian slope could catch lenses of LIW from the "normal northward flowing" vein, and transport it in the subbasin interior along their circuit (Millot, 1985). Thus there would be no vein of LIW flowing westward, but a patchy distribution of recent LIW in the subbasin, the most recent LIW values being related to AEs (as now shown in Millot and Taupier-Letage, 2005b).

Given the role assigned to the mesoscale phenomena in that region, the *in situ* sampling strategy had to be guided with satellite information in (near) real time, and required a fine (~ 10 km) sampling interval. Such a strategy has been successfully used in all our experiments, most recently in 1997-1998 during the experiment ELISA (Eddies and Leddies Interdisciplinary Study off Algeria, http://www.ifremer.fr/lobtln/ELISA). As an example of the data collected, the transects made across the southern part of AE 96-1 in summer 1997 (Figure 3) show that the LIW distribution is patchy, and restricted to the AE 96-1. Moreover, the LIW found close to the Algerian slope is related to the AE, since it has been shown that LIW progresses with the anticyclonic rotation (see Millot and Taupier-Letage, 2005b for detailed results).

A network of nine moorings was set in place for one year, equipped with ~ 40 currentmeters from the surface (~100m) to the bottom (~3000m). The time series (Figure 4) confirmed that the AEs can interact with the general circulation and modify it (e.g. Taupier-Letage and Millot, 1988), even revert it, locally and temporally, down to the deeper layer.

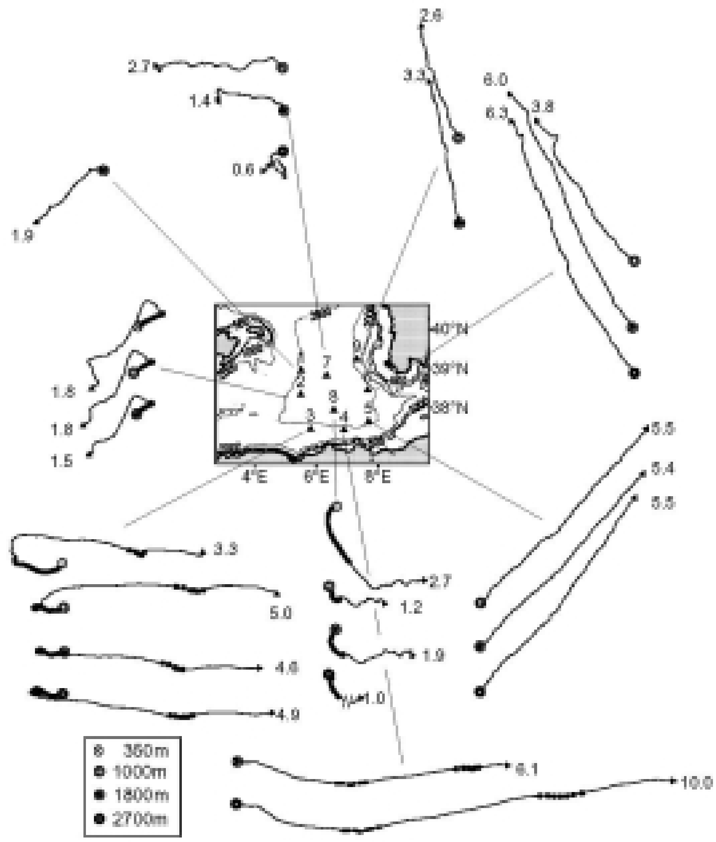

Fig. 4. The ELISA one-year progressive vectors diagrams at 350, 1000, 1800 and 2700 m together with the mean speed in cm/s. At the beginning of the record of mooring 3, at least, the circulation, normally eastward, has been reversed by the AE 96-1 on the whole water column (from Millot and Taupier-Letage, 2005b).

b. Recent results in the eastern basin

The dynamical phenomena in the eastern basin as seen on thermal images (see Le Vourch *et al.*, 1992) do not differ markedly from their analogues in the western basin, and Millot (1992) disagreed with the main feature of the POEM schema (Robinson *et al.*, 1991; Robinson and Golnaraghi, 1993) of an offshore cross-basin circulation with the MMJ. The eastern basin is an area where *in situ* data are scarce, especially in the southern part. The detailed analysis of ~1000 SST images spanning 1996-2000 (see details in Hamad *et al.*, 2004, 2005a,b, available on www.ifremer.fr/lobtln/EGYPT) showed that the flow of AW along the Libyan and Egyptian slopes (the Libyo-Egyptian current) is unstable, and generates mesoscale anticyclonic eddies (diameter ~100-200km, Figure 1f) that propagate downstream eastward alongslope, at 1-3 km/day, as illustrated by Figure 5. Each summer the Meltem generates, through the wind stress curl east of Crete and Peloponnese, two anticyclonic eddies: "Ierapetra" southeast of Crete, and "Pelops" southwest of Peloponnese. Based on our observations in the western basin, and on XBT data which show that eddies in the eastern basin are signed at least down to 700 m (Fusco *et al*., 2003), we hypothesise that some of these eddies have a deep extent (>3000m), and that they might be guided offshore by the bathymetry (the Herodotus trough). There (between ~27- 29°E) they would be trapped and accumulate, interacting up to merging and/or decaying. As a consequence there are always anticyclonic eddies in this area, which is where the POEM group observed a permanent/recurrent "Mersa-Matruh" gyre/eddy/anticyclone. To specify that the eddies observed at this location are not permanent, but that there are eddies permanently, we call this area ΣLw (for accumulation zone Levantine west). Along the Middle-East slope (Figure 1g) the mesoscale activity is also intense, although with smaller diameters and lifetimes (and thus probably shallower). In the easternmost part of the Levantine subbasin eddies also tend to accumulate, generally with a larger anticyclonic structure being fed by smaller ones (see Figures 14 and 15 of Hamad *et al*., 2005b). This area corresponds to that where the POEM group observed a permanent/recurrent/transient "Shikmonah" gyre/eddy/anticyclone. For the same reasons as mentioned earlier we name this area ΣL_E (for accumulation zone Levantine east). Overall, we infer from the images a circulation which is alongslope and counterclockwise at basin scale. And we hypothesise that what has (mis)led to conceive a Mid Mediterranean Jet are the facts that no *in situ* observations were made in the southernmost part of the basin, that no circulation was inferred there (although the historical schemes depicted one), and finally that sampling only on the northern edges of successive anticyclonic eddies does produce a meandering jet.

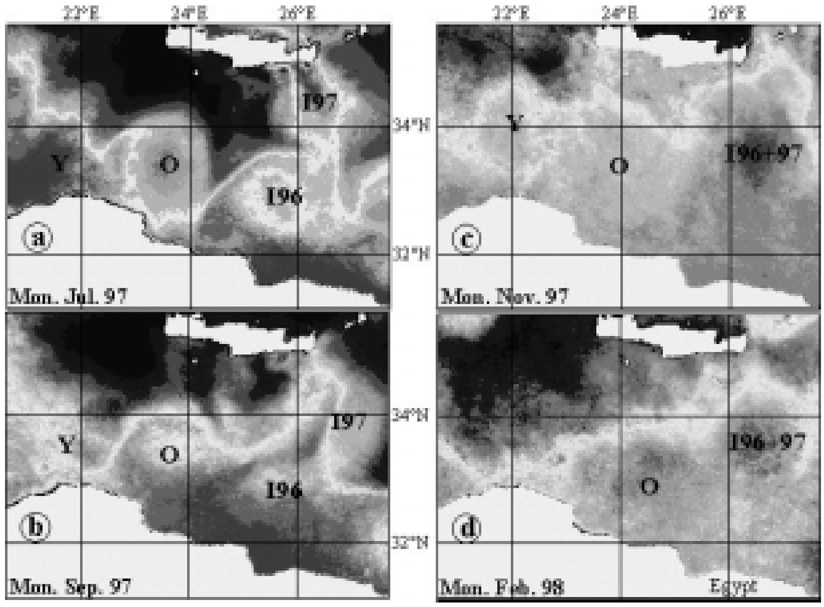

Fig. 5. A 8-month time series of monthly SST composites showing the eastward propagation of the libyo-egyptian eddies "O" and "Y", and the merging of the wind-induced anticyclones Ierapetra generated in 1996 (I96) and in 1997 (I97) (from Hamad *et al.*, 2005b).

4. CONCLUSION

On average we depict a surface circulation alongslope, following a counter-clockwise circuit in both basins. The situation is generally more complex in the south of the sea, where both the Algerian and the Libyo-Egyptian currents are unstable and generate mesoscale phenomena. It is thus of the utmost importance to sample with a knowledge of the actual eddy field (reception and analysis of images in (near) real-time), having a reasonably good knowledge of the space and time scales and movements characterising the mesoscale activity (possibly gained from a preliminary analysis of the time series of images).

This is also important when using data from climatological atlases. As an example, Figure 6 shows the result of a simple interpolation of all intermediate maxima of salinity and temperature (corresponding to the LIW signature) available from the MEDATLAS data base (see

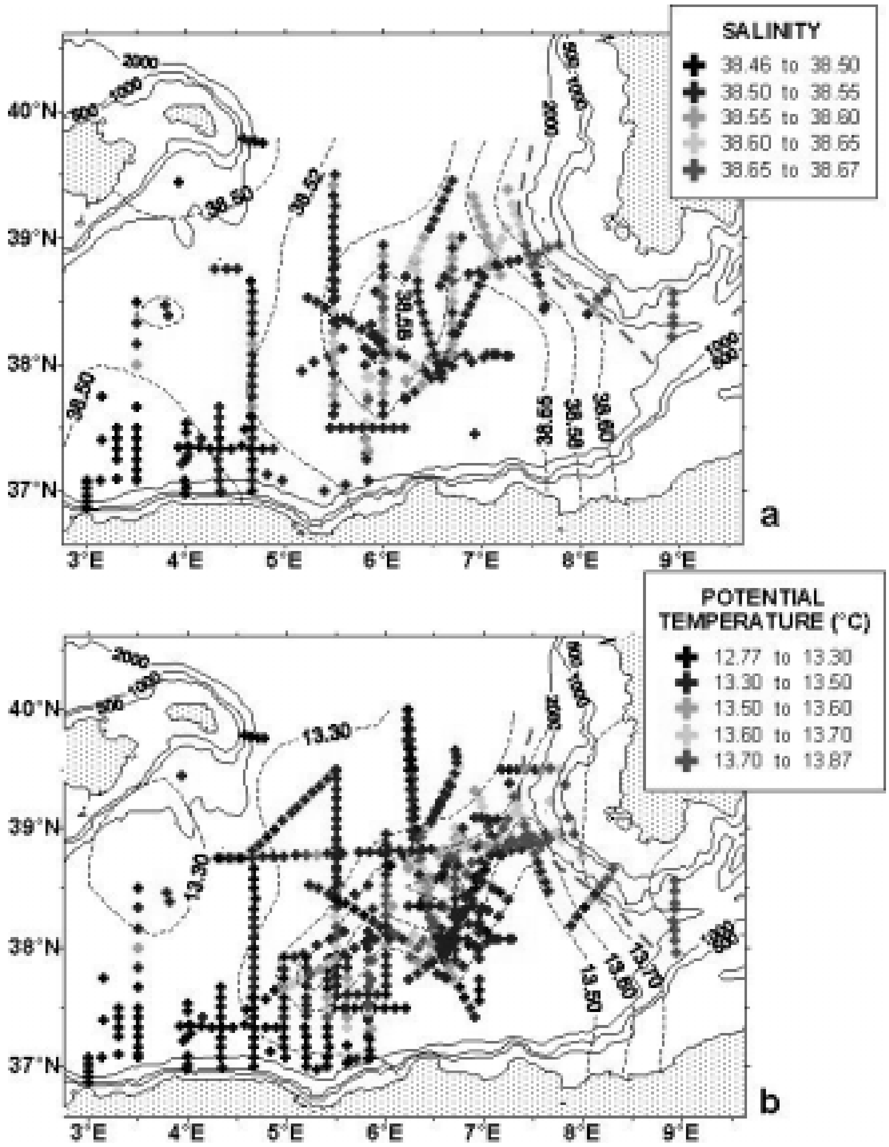

Fig. 6. Distribution of the salinity (**a**) and potential temperature (**b**) maxima associated with LIW from the MEDIPROD-5,6 and ELISA (CTD and XBT casts) in the eastern Algerian subbasin. Associated depths range from ~250 to ~650 m for salinity and from ~250 to ~550 m for temperature. The dashed black line would result from the unsupervised interpolation of this data set. The dashed red line figures the LIW vein external edge (from Millot and Taupier-Letage, 2005b).

www.ifremer.fr/sismer). Because CTD casts have been obtained at different times the data set is not coherent (AEs move), and the interpolation suggests a westward vein. But using individual data, campaign by campaign, and linking the hydrology to the AEs, we have concluded that this vein does not exist.

Now, the best would be to combine *in situ* and satellite information, in a multiplatform experiment. Whenever possible, several types of satellite observations should be used: altimetry and ocean colour efficiently complement the SST images. Combining time series from moored (Eulerian) and drifting (Lagrangian) instruments is especially efficient too, and must be confronted to the dynamical situation of their environment, using satellite images. Finally, an eddy-resolving sampling using a fine sampling interval (~10 km) must be adopted. Such an experiment (EGYPT: Eddies and GYres Path Tracking: www.ifremer.fr/lobtln/EGYPT) is currently being planned to investigate the southern Levantine at mesoscale, in order to possibly validate our hypotheses for the circulation there.