THE USE OF THERMAL IMAGES TO INFER MARINE CIRCULATION FEATURES : MEDITERANEAN EXAMPLES

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ABSTRACT

The overall functioning of the Mediterranean Sea, which transforms Atlantic Water (AW) into Mediterranean Waters (MW), 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 controversies lies in the fact that most studies do not take into account the large spatio-temporal variability induced by the mesoscale dynamics, which is intense in the whole Mediterranean, especially in the southern parts of both basins. The flow of AW forms unstable currents that generate meanders and eddies along the Algerian and the Libyo-Egyptian slopes, 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 from month to year (up to 3 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 phenomena with a fine spatio-temporal interval. The medium-resolution satellite images (pixel ~ 1km, ~1 pass/day) are an extremely efficient tool in this regard. The most-widely used ones are the thermal infrared images from NOAA/AVHRR (thermal resolution ~0.1°C), which can be used to infer surface currents, provided some precautions are taken. Mediterranean examples are shown, from eddy tracking up to the new schema of the surface circulation in the eastern basin we deduced from images time series analysis. This schema has yet to be validated by in situ observations, which will be collected during a campaign guided in near real time by the thermal imagery. For more information see www.ifremer.fr/lobtln.

1. Introduction

The Mediterranean is an evaporation basin, meaning that it is loosing more water through evaporation that it is gaining through river runoff and rain. The loss of water is estimated to be equivalent to a sea-level decrease of 0.5 to 1m/year. As a result light water from the Atlantic (Atlantic Water, AW) is entering the Mediterranean through the strait of Gibraltar. It constitutes the surface circulation (Figure 1), flowing in counter-clockwise basin-scale gyres[1] in the western and the eastern basins (for a review see Millot and Taupier-Letage, 2005a[2], and references therein). In the southern parts of both basins the flow of AW successively forms the Algerian Current and the Libyo-Egyptian Current. Both are unstable, and generate meanders and anticyclonic mesoscale eddies (50-250 km in diameter) that propagate alongslope downstream (eastward) at a few km/day. Eddies are 100s to 1000s m deep (some algerian eddies (AEs) reach the bottom at ~3000 m), so that their trajectory can be constrained by the bathymetry. The larger AEs

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[1] see our terminology on www.ifremer.fr/lobtln/OTHER/terminolgy
[2] available on http://www.ifremer.fr/lobtln/OTHER/Millot_Taupier_handbook.pdf

thus cannot go further eastward through the channel of Sardinia, detach from their parent current and veer northward along the western Sardinian slope. AEs generally describe a counter-clockwise circuit in the eastern part of the Algerian sub-basin, including one or several loops. Eddies lifetimes have been observed to extend up to ~3 years. In the northern parts of the basins the surface circulation (Northern Current) is more stable (in the western basin it never generates eddies), but shows a strong seasonal variability related to winter dense water formation. Given this ubiquitous mesoscale variability, the description at high spatio-temporal resolution of the dynamic field will condition the correct interpretation of in situ observations.

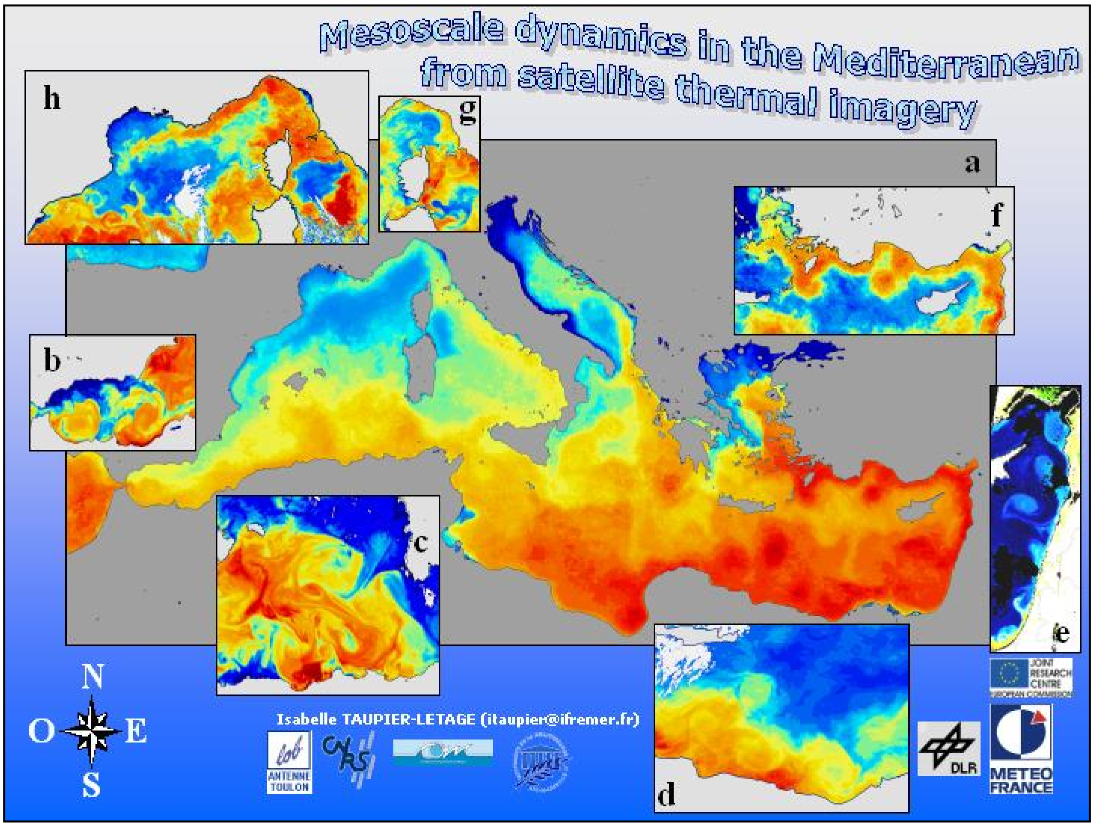

Figure 1. Illustration of the mesoscale dynamics in the Mediterranean with thermal NOAA/AVHRR images from SATMOS/MétéoFrance and DLR (but e: ocean colour/chlorophyll content from SeaWiFS, from ies/JRC). Images have been selected at different dates. Temperature increases from blue to red, but all images 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: 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. d: The western Levantine sub-basin, with libyo-egyptian eddies (accumulation zone ΣL_W). e: The Middle-East, with the current coastal instabilities revealed by their chlorophyll content (SeaWiFS "ocean colour" image; situation not characteristic of the accumulation zone ΣL_E). f: The Northern Current off Turkey, showing sharp meanders and an eddy pinching off. g: The Ligurian sub-basin, 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. h: the Liguro-Provencal sub-basin: 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).

2. The use of the thermal images to infer circulation features in the Mediterranean.

2.1 Principle

The infrared signal remotely sensed only comes from the few upper microns of the surface. Therefore the thermal signatures observed cannot be *a priori* related to the dynamics of the mixed layer. However very often (if not most often) the wind blows and mixes the upper layer, so that the temperature of the surface is representative of that of the mixed layer (which can be ~2000m deep in the Gulf of Lions when wintertime deep convection occurs!). In the Mediterranean, the surface circulation can be tracked most generally and in most places (see the following section for restrictions) by tracking the higher temperatures, which correspond to the lower salinity water, hence to the lighter AW. Such conditions are optimum in winter, when the 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 on Figure 1. The medium-resolution satellite NOAA/AVHRR images are an extremely efficient tool to track mesoscale features. The Mediterranean spatial coverage is provided by a swath wider than 2000 km. The fine temporal coverage is provided by 2 NOAA satellites flying simultaneously, yielding at least 4 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 not cloud-free simultaneously, the same area cloud-free intermittently).

The sea surface temperature (SST) is derived from a linear combination of 2 (day) to 3 (night) channels (*eg* 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 (“relative 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 even 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 shallow phenomenon will have a transient lifetime, of the order of day(s). Inversely, the 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, be the eddies cyclonic or anticyclonic. Most often the current is parallel to the isotherms. 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 perpendicular to the propagation direction. Most generally the inference of the currents is intuitive, as one can verify considering the sub-scenes of Figure 1.

2.2 Precautions

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 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, and are circumvented using nighttime images. During cloudy periods the mesoscale structures can be tracked using the sea level anomaly (SLA) they generate on altimetric tracks, and/or using composite thermal images (from weekly to monthly). However care must be taken when using composite images that 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). This damping effect is illustrated by the monthly composite in Figure

1a. Besides cloudiness, specific meteorological conditions can also impair or even prevent tracking mesoscale features. This is especially frequent during summertime. In the Ionian 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 the strong Etesian winds mix and cool the surface layer, possibly up to the Egyptian coast. 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. 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.

2.3 Validation

The use of thermal images to infer mesoscale dynamical structures and circulation features has been extensively validated in the western basin. In the surface layer the thermal signatures match the drifter trajectories (e.g. Salas *et al.*, 2001; 2002) the shipborne ADCP currents (Figure 2, see Taupier-Letage *et al.*, 2003), and the 100 m- currentmeters time series (Millot *et al.*, 1997).

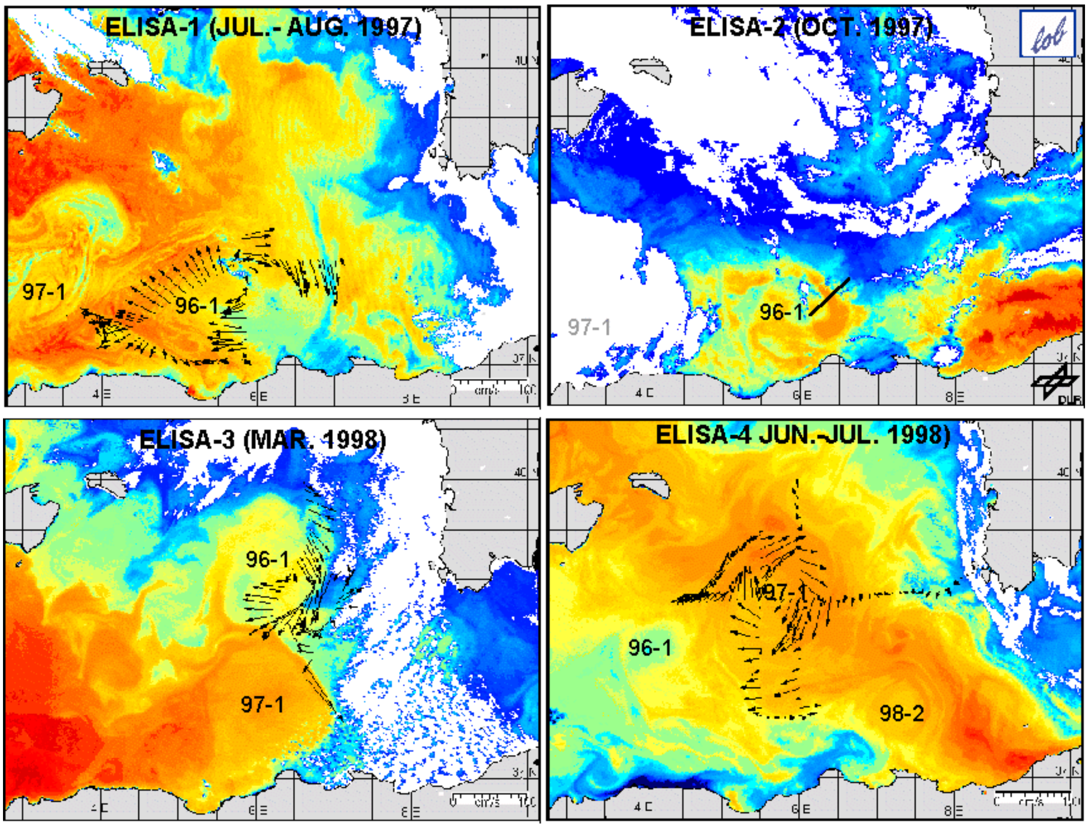

Figure 2. The positions and circuits of the AEs (96-1, 97-1 and 98-2) during the ELISA experiment (www.ifremer.fr/lobtln/ELISA) , and the associated surface ADCP current during the campaigns (from Taupier-Letage et al., 2003).

In the intermediate layer, the guiding of sampling in near-real time allowed to evidence that the AEs are responsible for the dispersion of recent Levantine Intermediate Water (LIW) in the Algerian sub-basin, settling by the negative the controversy about the existence of a LIW westward vein along the algerian slope (Millot and Taupier-Letage, 2005b). In the deeper layer (~3000 m), 1-year currentmeter time series have shown that AEs can locally and temporally modify the circulation over the bottom (Millot and Taupier-Letage, 2005b). In the eastern basin fewer in situ observations are available yet, however there is no objective reason to expect a different behaviour.

3. Application to the surface circulation in the eastern basin

While the historical schemata of the surface circulation in the eastern basin basically depicted the AW flowing in a counter-clockwise circuit around the basin (*e.g.* Nielsen, 1912; Lacombe and Tchernia, 1972), the recent schema issued from observations carried in the 1990s depicted the AW flowing as a series of jets meandering offshore across the sub-basins (*e.g.* Robinson and Golnaraghi, 1993). Specifically along the Libyan and Egyptian slopes, instead of the coastal circulation expected at least from the simple Coriolis force effect, the latter schema depicts the so-called Mid-Mediterranean Jet (MMJ). In situ observations in the southernmost part of the eastern basin are scarce, and no data set is adequate to describe the mesoscale activity that was evidenced for a long time (*e.g.* Le Vourch *et al.*, 1992; Millot, 1992).

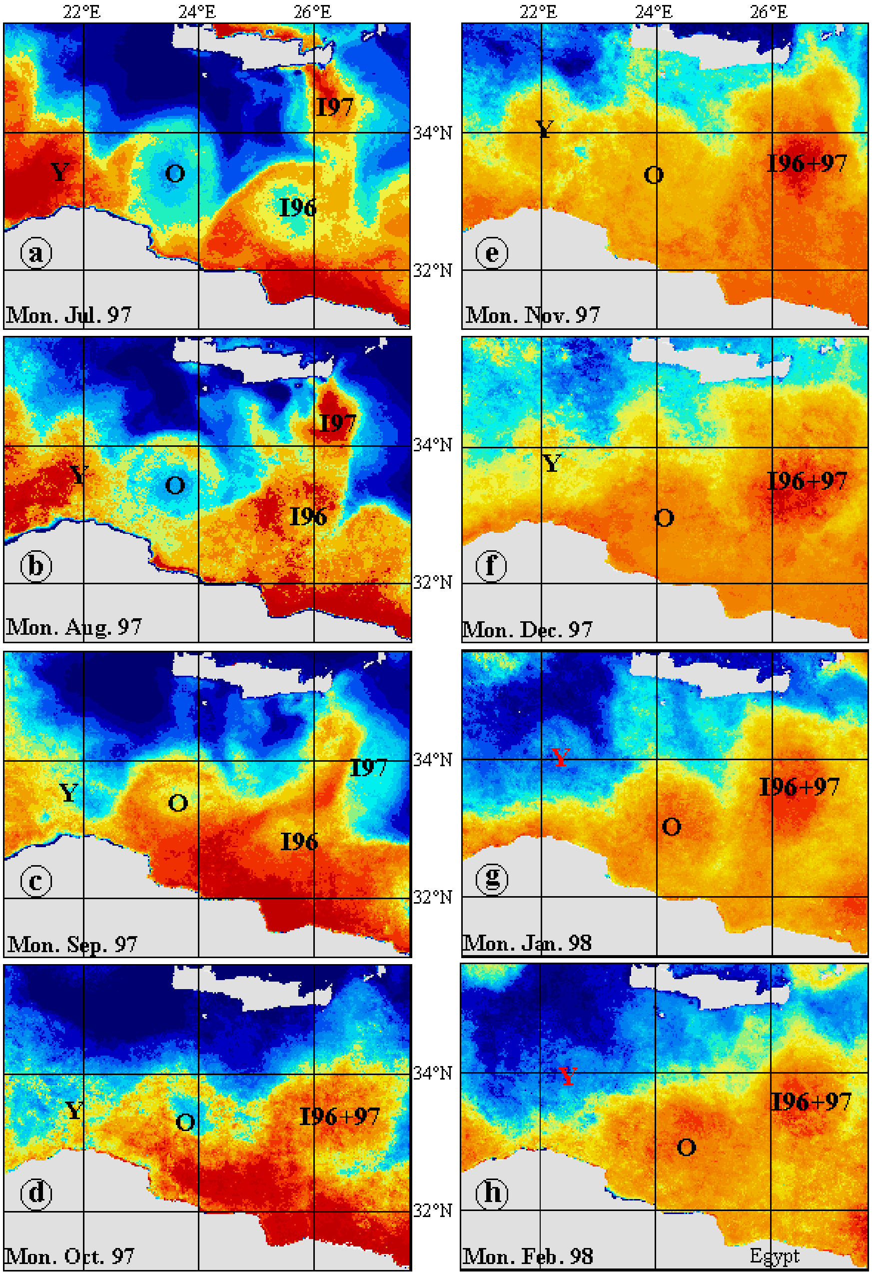

Figure 3. A 8-month time series of monthly SST composites showing the eastward propagation of the libyo-egyptian eddies “O” and “Y” (from Hamad et al., 2005b).

Thus an exhaustive analysis of thermal images (over 1000 daily, weekly and monthly composite images) spanning the period 1996-2000 was undertaken. Images times series showed that the AW flow is unstable and generates eddies that propagate along the Libyan and Egyptian slopes at 1-3 km/day (Figure 3). We hypothesise (Hamad et al., 2005a, b) 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.

4. Conclusion

Provided some precautions are observed, the use of thermal images prior and during campaigns at sea has proven an extremely efficient tool to study the circulation in the western basin of the Mediterranean, since it allows resolving the mesoscale activity. Based on our experience in the western basin, we have thus extended our schema of the surface circulation to the eastern one, where we hypothesise a circulation alongslope and counter-clockwise a basin scale (Millot and Taupier-Letage, 2005a). We are currently designing the EGYPT experiment (Eddies and GYres Paths Tracking, www.ifremer.fr/lobtln/EGYPT) to collect the in situ observations dedicated to test this hypothesis.

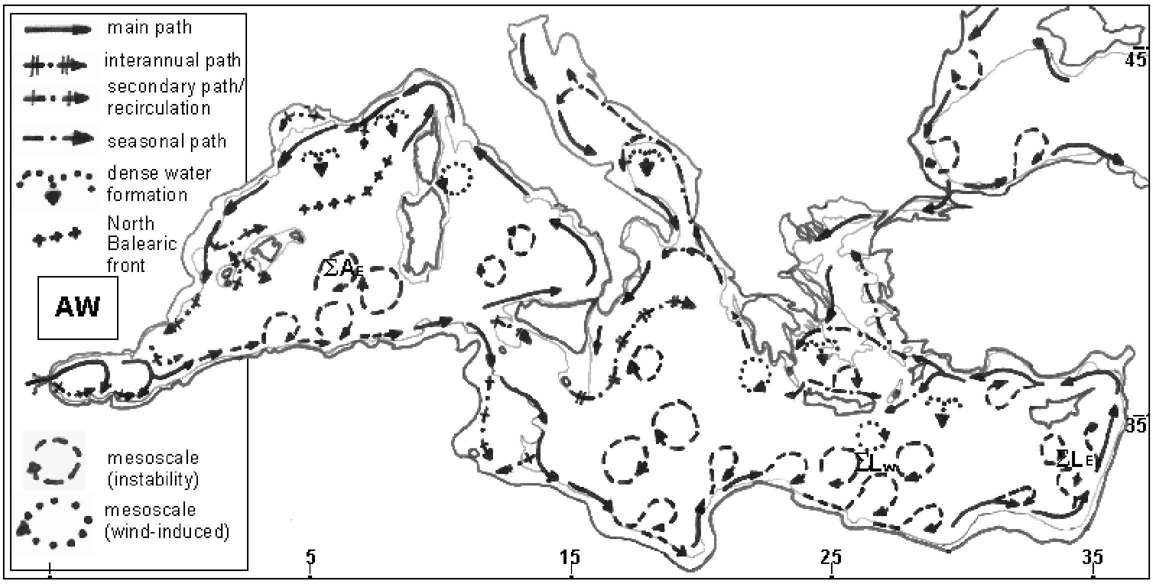

Figure 4. The schema of the surface circulation (Atlantic Water) in the Mediterranean (from Millot and Taupier-Letage, 2005a).

5. Acknowledgements

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