On the Use of Thermal Images for Circulation Studies: Applications to the Eastern Mediterranean Basin

Isabelle Taupier-Letage

Centre National de la Recherche Scientifique et Université de la Méditerranée, Laboratoire d'Océanographie et Biogéochimie, La Seyne/Mer, France

Abstract. The use of satellite thermal infrared images to infer marine circulation features is presented, here in the case of the eastern basin of the Mediterranean Sea. Although the first schema of the surface circulation for Atlantic Water in the Mediterranean Sea is one century old, its real path in the Eastern basin is still debated nowadays. Does it flow along the Libyan and Egyptian slopes in a counterclockwise circuit at basin scale, or as an offshore jet that crosses the basin in its central part (the "Mid-Mediterranean Jet")? In this paper we describe the use and contribution of the thermal images for the study of the surface circulation in the Eastern basin, currently underway within the framework of the programmes EGYPT and EGITTO (2005-2008).

1. Introduction

The water lost by evaporation in the Mediterranean is compensated by light Atlantic Water (AW). AW flows over the saltier – hence denser – Mediterranean Waters (MWs), and determines the surface circulation (for a review of the general circulation in the Mediterranean see Millot and Taupier-Letage (2005a) and references therein). Overall, and due to the earth rotation, AW and MWs are expected to follow the bathymetry and describe quasi-permanent counterclockwise circuits, in both the western and the eastern basins. The first schema of the surface circulation dates back to the early 1910s: it showed counterclockwise circuits in both basins (Figure 1a). In the 1990s, the experiment Physical Oceanography of the Eastern Mediterranean (POEM) issued a schema (Figure 1b) depicting the AW path as an offshore jet, crossing the basin in its central part (the so-called Mid-Mediterranean Jet, MMJ), and feeding mesoscale circulations on both sides (Robinson *et al.* 1991). That latter representation has been questioned (Millot 1992). Firstly because satellite thermal images display features analogous in both basins (Figure 2), and secondly because no *in situ* observations were available in the southernmost part of the Eastern basin. The thermal signature of AW (warmer in winter; Figure 2a) can be tracked along the southern continental slopes of both basins. In both basins the flow of AW in the South forms currents that are unstable at mesoscale (Figure 2c-f). They meander and generate anticyclonic eddies that often extend down to the bottom and have lifetimes of several months. Eddies propagate usually downstream or in the basins interior at a few km per day, and are thus likely to interact with their parent current or other eddies.

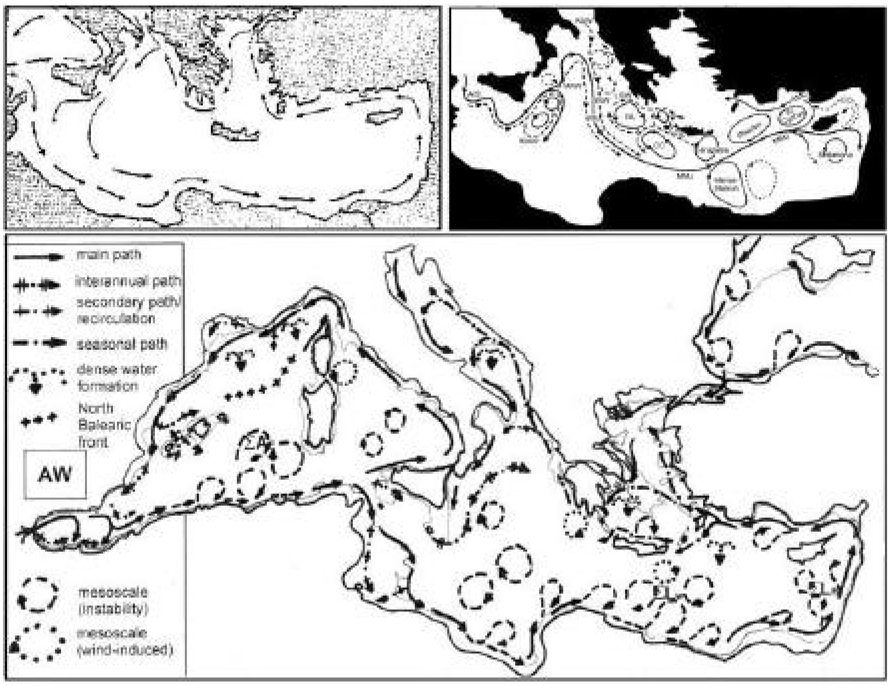

Fig. 1. Schema of the surface circulation in the (eastern) Mediterranean Sea, according to: Nielsen (1912), upper left panel; Robinson *et al*. (1991), upper right panel; Millot and Taupier-Letage (2005a), lower panel.

This intense mesoscale activity induces a very high variability in both space and time, which impairs interpreting the observations that do not resolve mesoscale properly. By combining thermal (mainly) satellite images and *in situ* observations, Millot *et al.* (1997) and Taupier-Letage *et al.*

(2003) showed the role of such mesoscale eddies in entraining AW and MWs from the periphery towards the central part of the Algerian subbasin, and thus in diverting potentially (part of) the flow from its expected path. This allowed solving a similar controversy about the path of the Levantine Intermediate Water in the southern part of the Western basin (Millot and Taupier-Letage, 2005b). Hamad *et al.* (2005) have analysed a 4-year time series of thermal images covering the Eastern basin, and confronted the *in situ* observations (among which the POEM data and repeated XBT transects) with their thermal signatures. They observed a permanent eastward circulation in the south, that they named the Libyo-Egyptian Current (Figure 1c, Figure 2f). Zervakis *et al.* (2003) and Fusco *et al.* (2003) also concluded that there was a permanent coastal flow (the MMJ in the latter case, *cf* their Figure 10). Given the presence of coastal libyo-egyptian eddies at the time of POEM, Hamad *et al.* (2005, 2006) suggested (*i*) that these eddies were responsible for spreading the AW found offshore, and (*ii*) that the meandering MMJ was a misinterpretation of the AW found on the northern edges of successive eddies. The joint programmes EGYPT[1] and EGITTO[2] are currently (2005-2008) collecting *in situ* observations to study the circulation in the Eastern basin, with focus on its southernmost part. The methodology to infer circulation features from the thermal imagery is described in section 2. The first results of the confrontation between *in situ* and satellite observations are described in section 3 and discussed in section 4, together with the conclusion.

2. Inferring circulation features from thermal imagery

The retrieval of the sea surface temperature (SST) from remote sensing in the thermal infrared is routine work. The detailed principles are beyond the scope of this paper; therefore the reader is referred to other chapters of this book or for instance to the site of the Medspiration[3] project.

2.1 The eligible products and selection criteria

The most adequate products to track (mesoscale) circulation features are infrared thermal images derived from the Advanced Very High Resolution Radiometer (AVHRR) sensor. The temporal coverage is ensured by two

[1] http://www.ifremer.fr/EGYPT
[2] http://doga.ogs.trieste.it/sire/drifter/egitto_main.html
[3] http://www.medspiration.org/science

(at least) satellites flying simultaneously and providing at least 4 images/day over the Mediterranean, the synoptic view by a swath >2000km, the spatial resolution by a pixel of ~1km, and the detection of the features by a ~0.12°C thermal resolution (Figure 2-5). The typical processing includes the retrieval of the SST from the combination of 2 to 3 infrared channels, the geographical registration, with possibly the generation of cloud and land masks. Images can be then composed into daily to monthly products. SST images are routinely generated and made available on numerous data centers for free.

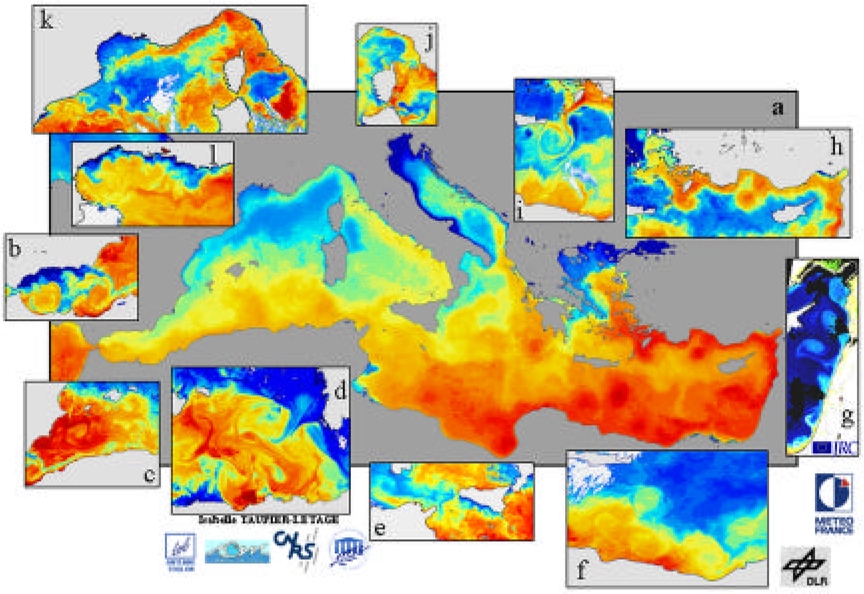

Fig. 2. The surface circulation in the Mediterranean Sea seen with thermal images. (*a*) Atlantic Water (warmer) can be tracked all around the continental slopes in a counterclockwise circuit; (*b-l*) the mesoscale dynamics and associated variability. Temperature increases from blue to red. Image credits: (*a, h*) monthly SST composite for January 1998 (DLR imagery); (*b-f* and *i-l*) single AVHRR images (SATMOS imagery); (*g*) ocean colour from SeaWiFS (JRC imagery).

Although the circulation features can be detected from SST images (see Figure 2a, h and Figure 4e-f), a tailored product has been determined and generated[4] to meet the needs for a fine resolution in both space (1km) and

[4] By the SATMOS/INSU-Méteo France facility (http://www.satmos.meteo.fr/), and used throughout this paper unless otherwise stated.

time (single pass, every day) and for near-real time availability, as required to sample *in situ* mesoscale features (that may be propagating). This product is the image of the channel 4[5] (brightness temperatures, hereafter called thermal image). The image is extracted from of a single pass, at a 1-km resolution, and geographically registered. The size of the file is decreased by recoding the image over 8 bits (10 bits originally); the original thermal dynamics is preserved by keeping only the numerical counts that correspond to marine temperatures (usually from 5 to 32°C). To decrease the size further the land is masked, the larger clouds too (flagged by a simple threshold, usually temperatures <5°C), and the file is compacted with a lossless algorithm. If the file is an image a grayscale is used to preserve the possibility to adjust the contrast specifically. The generation of such products is fully automated, cheap, and easily completed within one hour after the satellite pass.

The infrared signal only comes from the upper few microns (the "skin" temperature; see *e.g.* Buongiorno Nardelli *et al.* 2005 for more details). Therefore the thermal signatures cannot be, *a priori*, related to the dynamics of the mixed layer[6]. This is the case when solar heating creates a shallow (and temporary) thermocline, which caps the thermal patterns of the mixed layer. Nighttime passes are thus preferred. On the other hand the wind blows very often and mixes the upper layer, so that the surface temperature is representative of that of the mixed layer[7].

2.2 The link between thermal signature and ocean dynamics

In the Mediterranean, the surface circulation can be tracked most generally by tracking the higher temperatures, which correspond to the lower salinity –and thus lighter- AW[8]. Such conditions are optimum in winter, as seen on Figure 2a. Note that this is also true independently of the latitude, as shown by the AW warmer current flowing along the northernmost parts of both basins on Figure 2a, h and k.

The tracking of the mesoscale features from their thermal signature relies on the fact that there must be coherence between the temporal and the

[5] A single channel is preferred for delineating features since the multi-channel combination increases the noise in the SST image.

[6] Ocean colour images are better since the signal comes from a thicker layer. But their processing is no real routine, and the temporal coverage is much less.

[7] Possibly even under summertime conditions at noontime, as shown by Figure 4a: the northerly winds mix and cool the surface layer on both sides of Crete, clearly revealing anticyclones.

[8] Isopycnals and isotherms mostly co-vary.

spatial scales. Indeed, the infrared signature of a shallow phenomenon will have a transient lifetime, of the order of hour(s) or day(s). This is the case for diurnal heating or some wind-induced phenomena. Conversely, the thermal signature that can be tracked for months -up to years- necessarily corresponds to a structure having deep vertical extent, a condition required to maintain the signature over time, especially to survive winter mixing (see *e.g.* the 3-year tracking of algerian eddies in Puillat *et al.* 2002, and of libyo-egyptian eddies in Hamad *et al.* 2006). But there is no direct relation between the intensity (*i.e.* the thermal gradient) of a signature and the intensity of the structure itself (vertical extent or current speed).

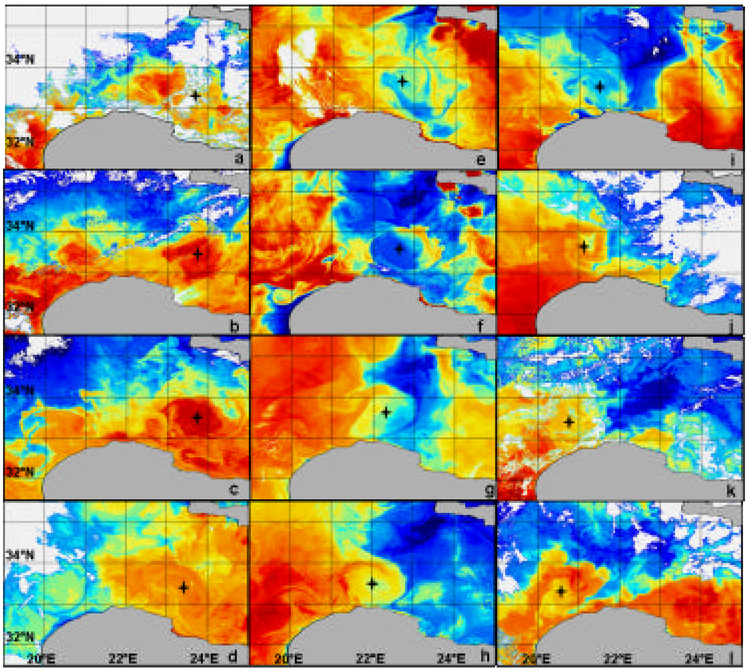

Fig. 2. Time series used to track the libyan eddy (+) during 2006: *a*) 08 Jan.; *b*) 10 Feb.; *c*) 06 Mar.; *d*) 26 Apr.; *e*) 28 May; *f*) 17 Jun.; *g*) 23 Jul.; *h*) 18 Aug.; *i*) 14 Sep.; *j*) 26 Oct.; *k*) 08 Nov.; *l*) 19 Dec. 2006. Δ: an other libyan eddy.

For instance a cyclonic eddy is associated with a doming of the isopycnals, so that deeper/colder water intersect the surface in the centre and delimit an intense thermal gradient: the resulting small cold spots will always be detected (Figure 2d, 3i). However such cyclonic eddies[9] are known to be shallow and transient. Conversely, an anticyclonic eddy is associated

[9] Cyclonic eddies are secondary phenomena, induced by the shear.

with a depression of the isopycnals, and its generic signature is a warmer (lighter water) central area. While this is always verified during wintertime because of mixing (*e.g.* Figures 3b-c, 5b), under stratified conditions the isotherms may not intersect the surface, and hence anticyclones may not exhibit any intrinsic signature. They are detected then indirectly by the superficial water they entrain, up to displaying a colder central area. The resulting variability of an eddy's signature is illustrated by the Figures 3 and 4[10]. Finally, the temperature difference between AW and MW reverses on a yearly cycle: thus, spring and fall are less favourable periods for tracking thermal patterns, and even a difference of ~ 0.1°C (thermal resolution) can sometimes trace a structure and be significant (see eddy Δ in Figure 3d).

Most often the current is parallel to the isotherms, and generally the inference of the currents is intuitive. One image allows deducing the current direction associated with the eddies, since the isotherms always spiral inside. One can estimate their diameter and centre location, even from segments of isotherms on images partially cloud-covered (Figures 3a, k). But since the eddy's signature may vary according to the water its entrains, estimates of its size can hardly be precise, but in winter when the mixed layer is thick. Time series of images allow deducing the trajectory and the propagation speed from the successive positions of the features (isotherms are then perpendicular to the propagation direction).
During cloudy periods the dynamical features can be tracked using the anomaly they generate on the sea level with altimetric tracks (*e.g.* Pujol and Larnicol 2005), and/or using composite thermal images. But care must be taken when using interpolated or composite images that the longer the time span the smoother the signature of a propagating structure, up to potentially yielding a misleading picture. Indeed, where successive eddies propagating along the coast mainly induce cross-shore gradients (*cf* Figure 2d, f), the image resulting from a long-time average will display a smooth band parallel to the coast, with gradients mainly oriented along-shore.

2.3 The interpretation of the thermal signatures

The first step is to discriminate between oceanic and atmospheric signatures. This is relatively easy because both types of phenomena have different space and time scales. Clouds are changing and moving more rapidly than any oceanic phenomena, so that comparing two images prevents from mistaking the limits of a cloud or haze for those of an eddy. Patterns too are characteristic: isotherms associated with oceanic phenomena are

[10] Symmetrically, 2 cyclonic shear eddies display a warmer signature in Figure 2d

smoother and less patchy, and are mostly tangential: one should suspect atmospheric contamination wherever isotherms intersect.

The second step is to detect and evidence the circulation features. As shown above the temperature is not a sufficient criterion, as its value and the gradient it determines vary with its environment, the season, the meteorological conditions and the time of day. This requires stretching the colour scale to adjust the contrast for each image, sometimes even differently for the same image to evidence circulation features at the Mediterranean (Figure 2a) and sub-basin (Figure 2h) scales. If the retrieval of accurate temperature (SST) is crucial for climatological studies, it is not an issue for process studies so that colour-temperature scales are not relevant.

The third step is to check whether the thermal signature corresponds to an actual dynamical structure. Its presence and lifetime must be verified on several images, possibly using other satellite information too (*e.g.* visible imagery, or altimetry to establish the continuity during cloudy periods).

The final step is to characterize the circulation features: one considers the shape, location and consistency of isotherms. The most common analysis consists in reporting the isotherms (possibly segments only) delineating a circulation feature, and in superimposing its successive signatures (as illustrated by the Figure 3 of Marullo *et al.* 2003). The recurrence of contours ends up in delineating the whole feature, its centre in the case of an eddy, and, should it move, its direction and propagation speed.

3. New results on the circulation in the Eastern Basin

The EGYPT and EGITTO experiments provide a new insight in the surface circulation. The confrontation of concurrent *in situ* with remotely sensed observations is focused here on the year 2006. Note that the data sets analysis is currently underway and related paper still in preparation[11].

3.1 A newly observed drift for libyan eddies

In the previous study spanning 4 years, eddies along the Libyan slope had only been observed drifting eastward (Hamad *et al.* 2006). Figure 3 (d-l) shows 2 libyan eddies drifting westward: one (+) from April during 9 months at least (detailed tracking interrupted after December 2006), the other one upstream (Δ) during 3 months at least (no specific tracking).

[11] References of papers will be available on the EGYPT and EGITTO web sites.

3.2 Few-days temporal variability: the merging of eddies

The northerly Etesians winds blowing in summer generate eddies. The anticyclone induced Southwest of Crete is called Ierapetra. Several authors have reported its persistence after the decay of the Etesians, and the fates of successive generations of Ierapetra are described in Hamad *et al.* (2006). The situation of summertime 2006 is detailed in Figure 4.

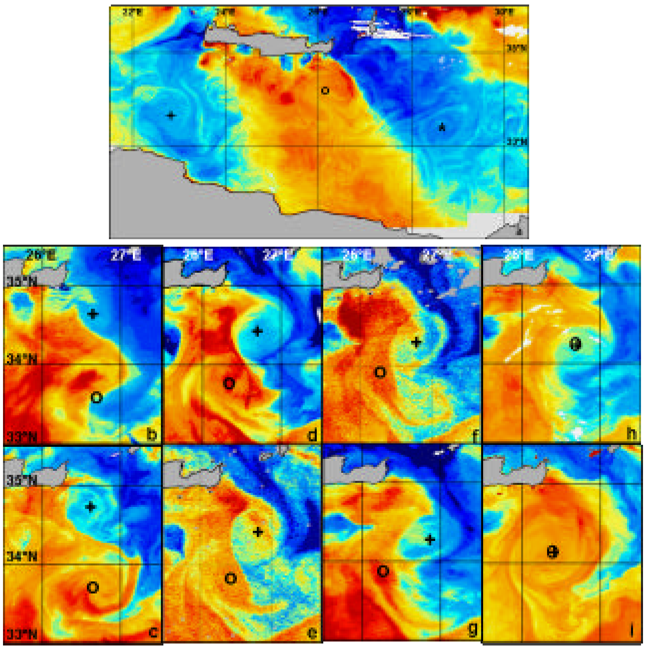

Fig. 4. Summer 2006: the merging of the Ierapetra eddies created respectively in 2005 (I05: **o**) and 2006 (I06: **+**) : *a*) situation on 28 May 11:59; *b*) 05 Jul. 20:52 ; *c*) 10 Jul. 20:38; *d*) 19 Jul. 20:31; *e*) 20 Jul. 16:09; *f*) 21 Jul. 15:30, *g*) 22 Jul. 01:07; *h*) 23 Jul. 20:39; *i*) 27 Jul. 11:48 2006. *e* and *f*: SST from Remote Sensing Group of the Department of Oceanography (OGS)[12].

In May the Ierapetra generated in summer 2005 (I05, o) appears as a large anticyclone. By 5 July the signature of Ierapetra 2006 (I06, +) is definitely established, and both signatures co-exist. The size of I06 doubles in 5 days, and by 19 July I06 is larger than I05. I06 moves to the South and begins interacting strongly with I05: their merging takes less than 4 days, and by 23 July there is only one anticyclone signature. So that by 27 July

[12] http://poseidon.ogs.trieste.it/sire/satellite/

(Figure 4j) the situation appears similar to that of late May (Figure 4a), but the Ierapetra eddy is different.

3.3 The sampling strategy dedicated to mesoscale processes

The analysis in near-real time of thermal images transmitted on board allowed crossing several eddies (Figure 5a), and seeding them with surface drifters. The 3 drifters seeded in April in the libyan eddy (+) remained trapped inside at least till early October, and their trajectories materialize its eastward drift, as already inferred from the thermal images (Figure 3).

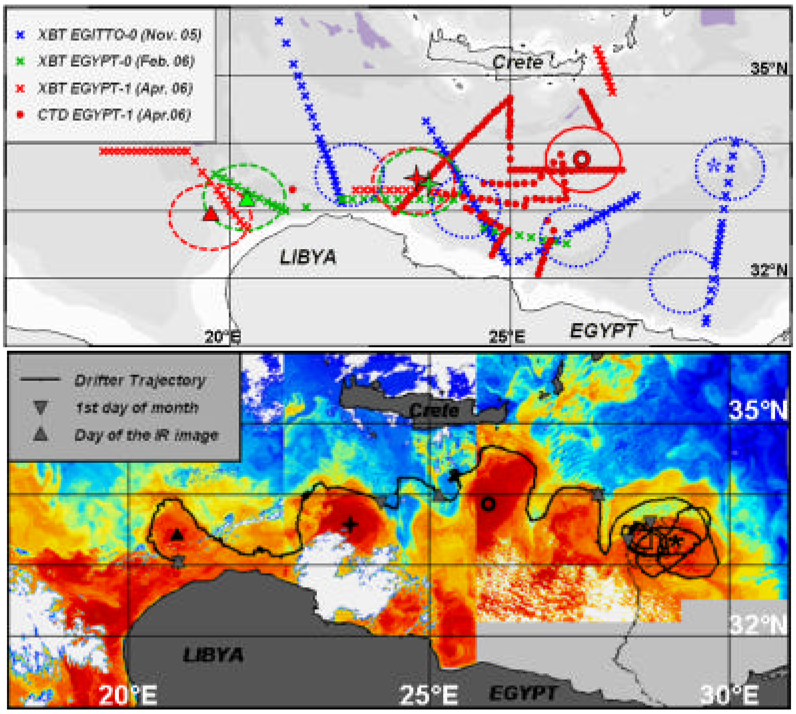

Fig. 5. Upper panel: the strategy of the EGYPT and EGITTO campaigns and positions of the eddies sampled. Lower panel: trajectory of a surface drifter, traced from 1 February to 18 May 2006, superimposed on images from 10 February (left), 10 March (middle) and 1 April 2006 (right).

The CTD transect that crossed it from the Libyan shelf to the Cretan one (Figure 5a) showed[13] that the minimum of salinity (indicating the most re-

[13] It also showed a vertical extent > 1000m

cent/less modified AW) was found on -and limited to- its northern edge. The trajectory (Figure 5b) of the drifter released upstream on the southern periphery of the libyan eddy (Δ) in February demonstrates how successive eddies act as paddle-wheels to transport water offshore.

4. Discussion and conclusion

The good correlation between *in situ* and satellite observations has been demonstrated again. The libyan eddy (+) has been tracked for 9 months with drifters, up to 1 year with thermal images. In February and March (Figure 3b-c) the continuity of the warmer signature from the eddy (Δ) to the eddy (+) shows that AW is first flowing alongslope. Then the paddle-wheel effect illustrates the mechanism of its offshore spreading, and explains why, on the CTD transect, recent AW has only been found on the northern edge of the eddy (+). Although the resulting drifter trajectory (Figure 5b) evokes a MMJ, the underlying processes are different.

Knowing the history of the mesoscale phenomena with a fine spatio-temporal interval is also important since situations looking similar can be achieved with different eddies, and since merging of eddies can be completed within few days. This also concerns other disciplines, as for instance the distribution of nutrients not only differs in and out of an eddy, but also in a one-year old eddy (as I05 in 2006) and in a newly formed one.

Provided some precautions are taken, the study of the circulation based on thermal images is efficient in the eastern basin of the Mediterranean too. However there are no constant criteria to characterise the eddies signatures, which are difficult to detect and track automatically. Such studies remain thus rather descriptive, but they are easy to carry, cheap, especially cost-efficient for *in situ* sampling –and indispensable for data interpretation wherever the mesoscale dynamics plays a pivotal role.

Acknowledgments

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