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Progress in Oceanography 66 (2005) 287–298
Progress in Oceanography
www.elsevier.com/locate/pocean

A new hypothesis about the surface circulation in the eastern basin of the mediterranean sea

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Received 6 November 2002; received in revised form 1 April 2005; accepted 25 April 2005
Available online 1 July 2005

Abstract

In time, the circulation of the Atlantic Water (AW) in the eastern basin of the Mediterranean Sea has been described differently, according to two major representations. The historical one, which began with the scheme from Nielsen in 1912 and has been refined up to the 1980s, favours a counterclockwise circulation in the whole basin, with AW flowing in its southern part as a broad flow off Libya and Egypt (from the Ionian to the Levantine subbasins), then continuing along Middle-East and Turkey before flowing back westwards. The more recent one, issued in the 1990s, favours a clockwise circulation in the northern part of the Ionian continuing offshore across the basin from the Cretan to the central part of the Levantine as the so-called "Mid-Mediterranean Jet". This jet is depicted then as splitting both clockwise in the southeastern part of the basin and counterclockwise off Turkey (where this representation agrees with the former). Because the recent representation cannot be considered as a refinement of the historical ones, we have been interested in understanding why a given data set available to everybody is interpreted in such different ways.

In the Algerian subbasin, the combined use of satellite infrared images and a significant amount of in situ data sets (hydrology and both Eulerian and Lagrangian current measurements) allowed us to solve a similar controversy. Therefore, we examined the circulation features in the eastern basin, undertaking the detailed analysis of ~1000 daily and weekly composite images spanning the period 1996–2000, and of monthly composite images available since 1985. Whenever in situ observations were available, we have confronted them with the satellite thermal signatures and have shown that both are consistent. This paper focuses on the overall (basin scale) results while the detailed ones are published in an other paper. The new scheme we propose is basically a refined version of the historical ones: the circulation of AW is counterclockwise in the whole eastern basin but it is more constrained alongslope than previously thought, and the broadening historically schematised appears to be due to intense mesoscale eddies mainly generated by the instability of this circulation.

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doi:10.1016/j.pocean.2005.04.002

Keywords: Mediterranean sea; Eastern basin; Surface circulation; Infrared satellite imagery; Mesoscale eddies; 30–46°N and 10–36°E

1. Introduction

The circulation of the Atlantic Water (AW, http://www.ifremer.fr/lobtln/OTHER/WaterMassAcronyms.pdf) in the eastern basin of the Mediterranean Sea is still debated. Several schemes have been proposed up to now: Nielsen (1912), Ovchinnikov (1966), Lacombe and Tchernia (1972) and Robinson et al. (1991) completed by Robinson and Golnaraghi (1993) and by Malanotte-Rizzoli et al. (1997); these schemes are represented in Fig. 1.

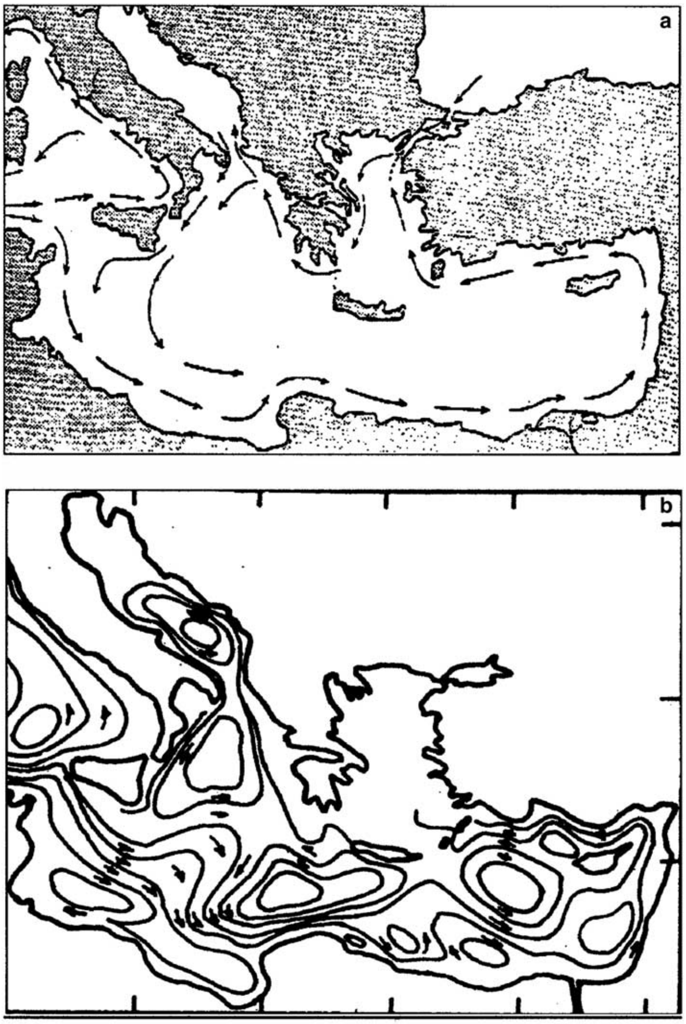

Fig. 1. Schemes of the surface circulation at basin scale: (a) from Nielsen (1912), (b) Ovchinnikov (1966), (c) Lacombe and Tchernia (1972), (d) Robinson and Golnaraghi (1993).

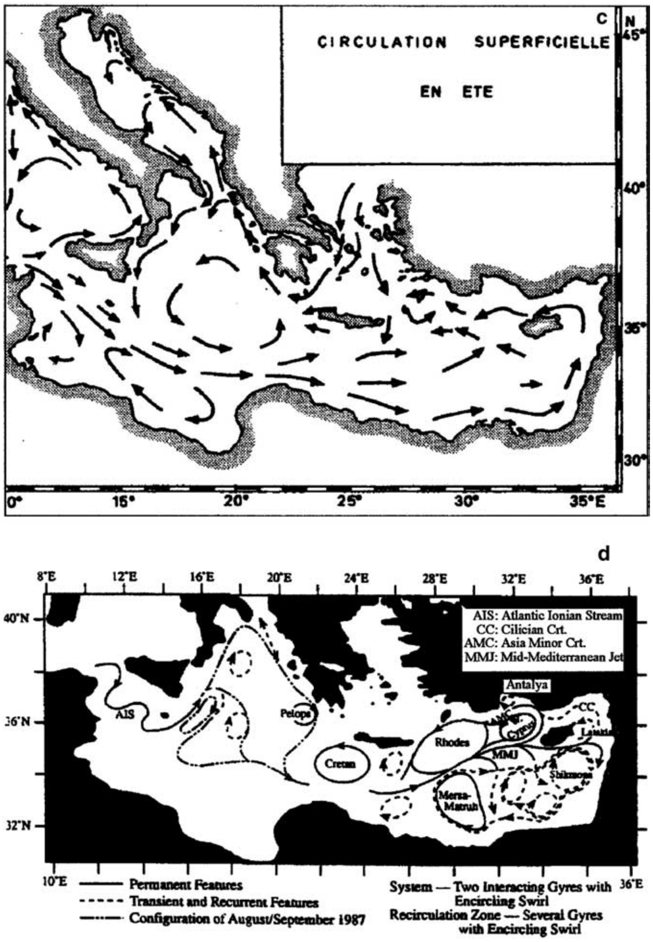

Fig. 1 (*continued*)

The three older (historical) ones could not be very accurate or detailed because of the limited number of in situ data and the non-availability of remotely sensed information at these times, which prevented a correct awareness of features having a relatively small scale, namely the mesoscale features. The scheme from Nielsen (Fig. 1(a)), even though based on very few hydrological data and hence necessarily coarse, clearly specifies an overall counterclockwise circulation in the whole basin. The scheme of Ovchinnikov (Fig. 1(b)), based on geostrophic computations from a larger set of hydrological data, as well as the scheme of Lacombe and Tchernia (Fig. 1(c)), based on complementary hydrological data, provide more details than Nielsen's one and can be considered as continuous refinements. These historical schemes describe, in particular in the southern and eastern parts of the basin, an overall circulation that is essentially counterclockwise around the basin.

The three most recent schemes, elaborated by the POEM (Physical Oceanography of the Eastern Mediterranean) group from both in situ data sets (collected during specific campaigns) and numerical simulations, are basically similar to each other (therefore we deal hereafter with "the" POEM scheme), but differ markedly from the former three. The POEM scheme (Fig. 1(d)) typically describes a flow (i) crossing the central part of the Ionian subbasin[1] or spreading clockwise in its northern part (the "Atlantic Ionian Stream, AIS" and the "Mid-Ionian Jet, MIJ"), (ii) crossing the southern Cretan subbasin (i.e., the Cretan passage; the "North African Current, NAC") and (iii) crossing the Levantine subbasin offshore (the "Mid-Mediterranean Jet, MMJ") before (iv) branching off Middle East and flowing either counterclockwise up to Turkey and Crete (the "Cilician Current, CC" and the "Asia Minor Current, AMC") or clockwise down to Egypt. Because the POEM scheme cannot be considered as a refinement of the historical ones, we have been interested in understanding why a given data set available to everybody is interpreted in such different ways.

Infrared (IR) satellite imagery provides information on the sea surface temperature (SST) and can efficiently be used to infer circulation features. This was shown for the western basin, where a similar controversy about the circulation (cross-basin vs. around-basin) existed (see illustrations in, e.g., Millot, Benzohra, & Taupier-Letage, 1997; Millot & Taupier-Letage, this issue; Puillat, Taupier-Letage, & Millot., 2002; Taupier-Letage, Puillat, Raimbault, & Millot, 2003). Here, the circulation patterns were shown to be fully consistent with all in situ data sets, which is why we chose to analyse IR images for the eastern basin too. At the time the POEM scheme was elaborated, an analysis of satellite images spanning the eighties (Le Vourch, Millot, Castagné, Le Borgne, & Olry, 1992) and a preliminary comparison between the western and the eastern basins (Millot, 1992) both accounted for a counterclockwise circulation of AW around the whole eastern basin. We have now extended our preliminary 1992-analysis and have analysed ~1000 IR daily and weekly composites spanning the period 1996–2000 together with monthly composites available from the German Aerospace Centre (http://eoweb.dlr.de/) at full (1 km × 1 km) resolution and from the PODAAC Pathfinder Archives (http://podaac.jpl.nasa.gov/sst/) at a 9 km × 9 km resolution since 1985. In order to avoid dealing with the SST seasonal variability, we present images with a colour scale spanning the actual temperature range (hence changing from an image to another): we thus consider, on a given image, only the spatial SST distribution, i.e., the relative values.

A large amount of papers account for the efficiency of IR images to provide reliable SST information and to depict oceanic phenomena, based on the comparisons with in situ data sets. They concern the eastern basin (e.g., Horton, Kerling, Athey, Schmitz, & Clifford, 1994; Marullo, Santoleri, Malanotte-Rizzoli, & Bergamasco, 1999a, Marullo, Santoleri, Malanotte-Rizzoli, & Bergamasco, 1999b; Ozsoy et al., 1993; Zodiatis, Theodorou, & Demetropoulos, 1998) and the global ocean, so that we do not detail the validation we made in the western basin (see references above). For what concerns the comparisons we made in the eastern basin (in addition to those made hereafter), we can emphasise the excellent correlation of SST and ocean colour (SeaWiFS) patterns at mesoscale, as well as with a large XBT data set collected during the Mediterranean Forecasting System Pilot Project (MFSPP, e.g., Fusco et al., 2003; Manzella et al., 2001; Zervakis, Papadoniou, Tziavos, & Lascaratos, 2003). Agreement with altimetric data (Larnicol, Ayoub, & Le Traon, 2002) is also excellent, provided that the artefact of the cyclonic feature computed between anticyclonic eddies from sea level anomalies be disregarded (see Hamad, Millot, & Taupier-Letage, 2004; Hamad, Millot, & Taupier-Letage, in press, for details). Finally, we can emphasise the agreement with the most recent numerical simulations (e.g., Alhammoud, Béranger, Mortier, & Crépon, 2004; Alhammoud, Béranger, Mortier, Crépon, & Dekeyser, this issue). It is clear that remotely sensed data sets, in situ data sets and recent numerical simulations basically agree. But differences can arise from the interpretations of the data sets, hence resulting in different inferred circulation schemes. This is what we try to emphasize hereafter.

In Section 2, we compare the large POEM in situ data set with the IR satellite imagery. We show: (i) that both in situ and satellite observations are fully consistent, which validates our use of the remotely sensed data to infer circulation features in the eastern basin too, and (ii) that the situation encountered during the POEM campaigns did not vary interannually much from 1985 to 1996, at least as described from space. We

[1] We reserve the term "sea" for the Mediterranean and "basin" for the eastern and western parts of the sea. Any smaller entity is a subbasin, this term being possibly omitted. Our terminology is on: http://www.ifremer.fr/lobtln/OTHER/Terminology.html.

discuss in Section 3 the reasons that could have led to different interpretations of a unique (i.e., both in situ and remotely sensed) data set, and we propose our own circulation scheme.

2. The available data sets and their analyses

Four major operations at sea, involving several campaigns, each spanning several weeks/months periods, have been conducted by the POEM group. Fig. 2 shows the surface dynamical patterns that the group described and the corresponding SST composites that we got from PODAAC. We chose either weekly or monthly composites to fit the campaigns' duration at best.

All major features evidenced from in situ (hydrological) data sets are seen from space. For POEM ON 85 (Fig. 2(a) and (b)): the cool "West Cretan Gyre" (WCG), the warm "Mersa-Matruh" (MM) in the southwestern Levantine, the 3-pole structure of "Shikmona" (S), the "Rhodes Gyre" (RG) and its southeastern extension, the "Asia Minor Current" (AMC) and its associated eddy (AE). For POEM MA 86 (Fig. 2(c) and (d)): the warm "MM" in the central Levantine, the 2-pole structure of "S", the progression of the "AMC" towards Crete. For POEM AS 87 (Fig. 2(e) and (f)): the "Atlantic Ionian Stream" (AIS) in the channel of Sicily and the northern Ionian, a coastal eddy (E) off Libya and Egypt and the "WCG", Ierapetra (I), "MM" and the multi-pole structure of "S", the large "AMC" meander and its associated AE, the "RG" and its northeastward extension. For POEM O 91 (Fig. 2(g) and (h)): the "AIS" (different from POEM AS 87) around Sicily and in the northern Ionian, Pelops (P) and I, "MM", an eddy (E) in the central Levantine, the one-pole structure of "S", the "Cyprus Anticyclonic Eddy" (CAE), the "AMC", the "RG" and its extensions towards both northeast and southeast. This confirms that both in situ and remotely sensed observations (as well as other data sets: e.g., Fusco et al., 2003; Manzella et al., 2001; Zervakis et al., 2003) basically agree.

Even though the above-mentioned features (gyres, eddies, branches) will not be analysed hereafter (see for that the preliminary analysis of Hamad et al., 2004; and/or the detailed one of Hamad et al., in press) many papers have shown that these features have generally a deep extent, most probably deeper than the sampled ~2000 m (e.g., Brenner, 1989, 1993; Feliks & Itzikowitz, 1987; Horton et al., 1994; Ozsoy et al., 1991; Ozsoy et al., 1993; Zodiatis et al., 1998). This is another evidence of the reliability and efficiency of IR satellite imagery, if required.

The major point we want to address with Fig. 2 is that the POEM campaigns do not cover the regions of highest SSTs: in most of the Ionian and the Levantine, particularly off Tunisia, Libya and Egypt, warmest waters are found south of the POEM investigations. The POEM scheme (Fig. 1(d)), notwithstanding this lack of data, neither shows nor infers any circulation feature in these southernmost areas, while a circulation was depicted there in historical schemes (Fig. 1(a)–(c)). In the southeastern Levantine, off eastern Egypt and southern Middle East, warmer waters are found close to the coast/slope. There, the POEM data coverage is poor, and a clockwise circulation is schematised in Fig. 1(d). This is in contrast to the counterclockwise circulation schematised in Fig. 1(a)–(c) too. In the northern Levantine, off northern Middle East and southern Turkey up to Crete, the warmer waters were correctly sampled during the POEM campaigns and the features schematised in Fig. 1(d) are consistent with the historical ones (Fig. 1(a)–(c)).

Differences between the POEM and the historical schemes may of course be due to interannual variability. This can be estimated using the SST data set, i.e., a data set providing a basin-wide overview since about two decades. We analysed all available monthly composites and found that the overall features previously described (Fig. 2) can still be identified, in particular the permanent location of warmest waters in the southern and eastern parts of the basin. For space's sake we just show in Fig. 3, the November series from 1985 to 1996 that covers all POEM experiments and matches the average duration of these experiments. Additional information on SST distribution during fall spanning the years 1983–1992 can be found in Marullo et al., 1999a (plate 4). All other months display similar overall features, except for those linked to the seasonal variability.

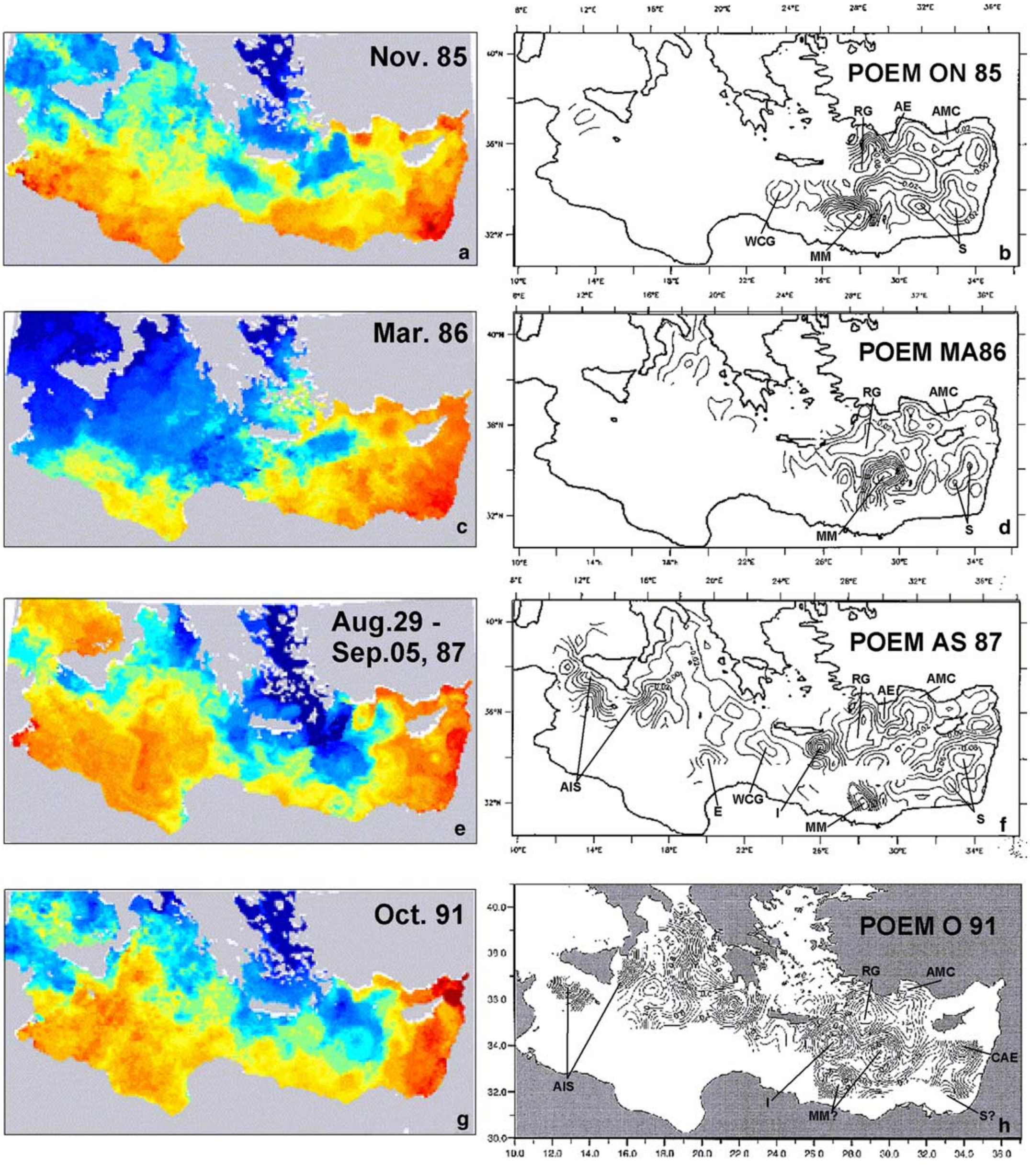

Fig. 2. Comparison of satellite (IR composites) and in situ observations (dynamics heights anomaly at the surface during the POEM cruises, from Robinson et al. (1991) and from Malanotte-Rizzoli et al. (1999)): a, b (November 1985, POEM ON 85), c, d (March 1986, POEM MA 86), e, f (August – early September 1987, POEM AS 87), g, h (October 1991, POEM O 91). The main features are identified, using the POEM nomenclature (AIS: Atlantic Ionian Stream, AMC: Asia Minor Current, AE: Antalya Eddy, CAE: Cyprus Anticyclonic Eddy, E: Eddy not named, I: Ierapetra, MM: Mersa Matruh, P: Pelops, RG: Rhodes Gyre, S: Shikmona, WCG: West Cretan Gyre).

All maps show the continuity and permanency of higher SSTs from the Channel of Sicily up to southern Turkey and Crete. In these latter places, all schemes (including the POEM one) link these higher temperatures with AW, consistently with associated lower salinity values (as can be evidenced from any data set, e.g., MEDAR Group, 2002). At least for what concerns this particular point, it is clear that the IR images such as

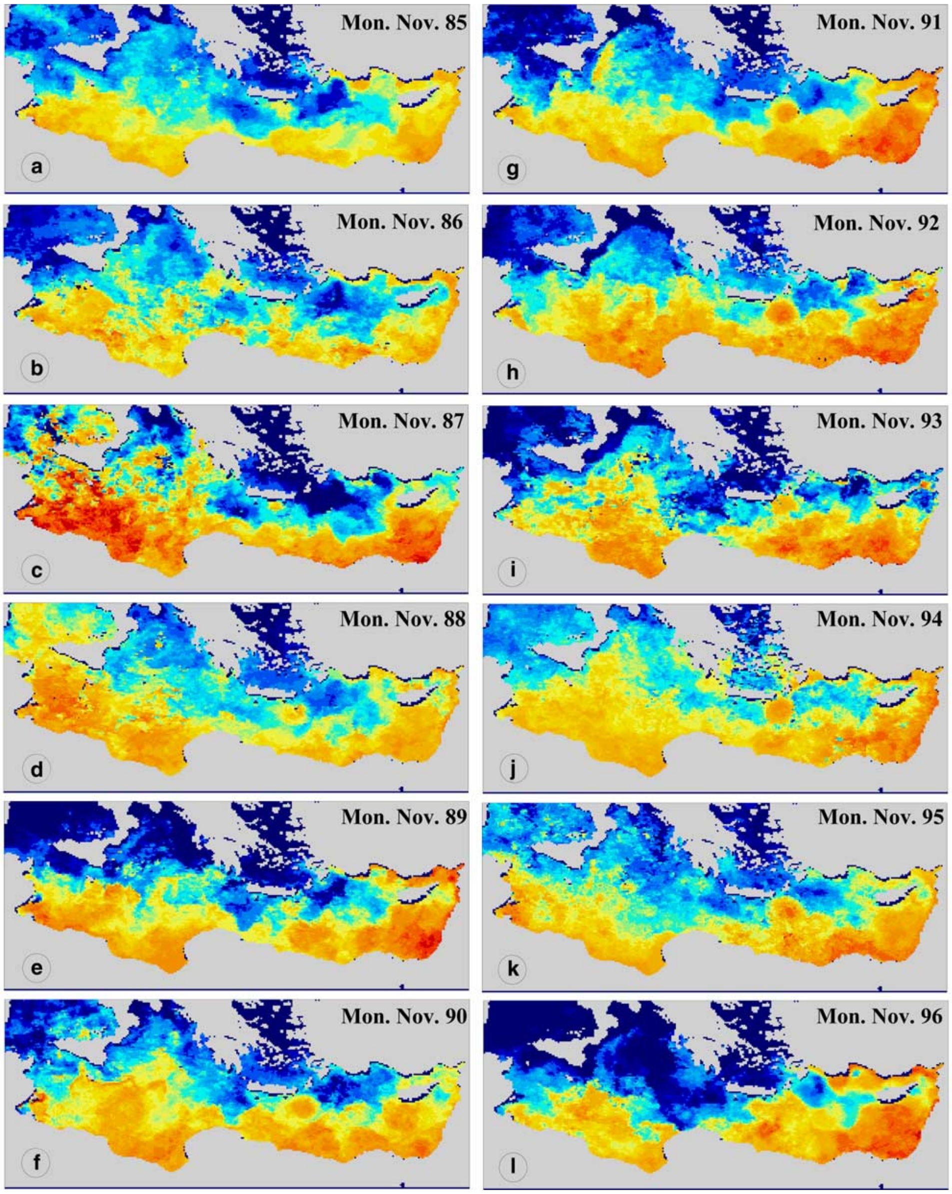

Fig. 3. The eastern basin of the Mediterranean Sea in November from 1985 to 1996 (SSTs).

the ones shown in Figs. 2 and 3 are more consistent with the historical schemes than with the POEM one. It is also clear that the POEM scheme is consistent with both SSTs and historical schemes at places where the POEM sampling coverage was adequate.

3. Discussion

Inferring circulation features in the eastern basin from SSTs cannot be made without considering the specific meteorological conditions. Essentially, northwesterly winds frequently blowing through the relatively shallow Channel of Sicily induce intense mixing and upwelling off Sicily, hence relatively low SSTs (see all IR images in Figs. 2 and 3). From there, and during about half of the AW basin-wide circuit schematised in Fig. 1(a)–(c), i.e., towards south (up to Libya), east (up to Middle East) north and west (up to western Turkey), SSTs generally increase, whatever the season. Then, due to the Etesian in summer and northerly winds in winter, mixing decreases SSTs from the Aegean to the Ionian and the Adriatic. In addition, cooler fresh water comes from both the Black Sea and rivers. Off southern continental Italy and Sicily, according to the historical schemes and consistently with the images in Figs. 2 and 3, relatively old and cool AW encounters relatively young and warm AW. One can notice at the basin scale the discrepancies in the Ionian between the POEM scheme, which represents a clockwise circulation, and the historical schemes, which represent a counterclockwise circulation.

It is beyond the scope of this paper to weigh the theoretical arguments supporting or contradicting either a cross-basin (even clockwise in a subbasin) circulation or a counterclockwise basin-wide one. However, based on our experience as experimentalists and our previous work in the western basin, we think that the circulation of AW can be explained by considering the thermohaline forcing that is linked to the proper functioning of the Mediterranean Sea. Indeed, due to differences in density between the sea and the ocean, which leads to a Mediterranean level lower than that of the Atlantic, AW tends to flow into the sea. Then, having entered the basins through the Strait of Gibraltar or the Channel of Sicily, AW flows towards the zones of dense water formation, following a path more or less direct. One argument accounting for an overall permanent counterclockwise and alongslope circulation of AW is the one first given by Nielsen (1912) who says (p. 134) that it is "*due in the first place to the earth's rotation, which bends the current to the right and thus forces the inflowing AW up against the coast of Africa and constantly maintains the current system*". It is with such an argument that we personally analyse the fact that, in an idealized semi enclosed marginal sea subject to a surface cooling, the thermohaline circulation is basically a counterclockwise rim current (Spall, 2004).

Even though this is an argument that has been more or less disregarded in the 1990s and that is sometimes considered as "simplistic", it is the argument that we presently consider as fundamental for explaining the consistency between our interpretation of the remotely sensed and in situ data sets and the historical schemes. This is an argument that we previously (e.g., Millot, 1992) extended to all parts of the basins, i.e., not only to the coasts of Africa, (and to deeper layers too, see Millot & Taupier-Letage, in press), when we introduced the notion of a "Northern Current", a rim current in the northern parts of the basins. In the western basin for instance, the AW flows from Gibraltar and the Alboran subbasin to the offshore area of the Gulf of Lions, a zone of dense water formation, successively along Africa, Sicily, continental Italy, France and Spain. We strongly believe that similar processes and features occur in the eastern basin, and remotely sensed information suggest that the mean flow (see below) of AW in both basins is in fact concentrated much more alongslope (a few tens of km wide) than thought by Nielsen and indicated by the historical schemes (Millot & Taupier-Letage, in press). A major consequence of such a narrow alongslope counterclockwise basin-wide circulation of AW is that it can be correctly described only with in situ data collected at the rim of the basin, in the coastal zones and over the continental slopes, with a fine sampling interval (few km). So far, most in situ data in the eastern basin have been collected in the basin interior, most often with a large sampling interval (tens of km), so that they do not resolve the boundary flow. In situ data in the ~50 km wide coastal zone in the southern part of the basin are extremely scarce; the few available ones strongly suggest that the core of the AW circulation has been sampled there (Abdel-Moati & Said, 1987).

Another reason for diverging interpretations of the mean circulation is the existence of the strong mesoscale variability being extremely high in the southern parts of both basins (Millot & Taupier-Letage, in press). The January-1998 IR composite image in Fig. 4(a), that we consider as typical for the ~1000 images analysed, shows this dilemma. In addition to the Pelops and Ierapetra mesoscale anticyclonic eddies that were induced by the Etesians during the previous summer, this winter image clearly evidences other types of

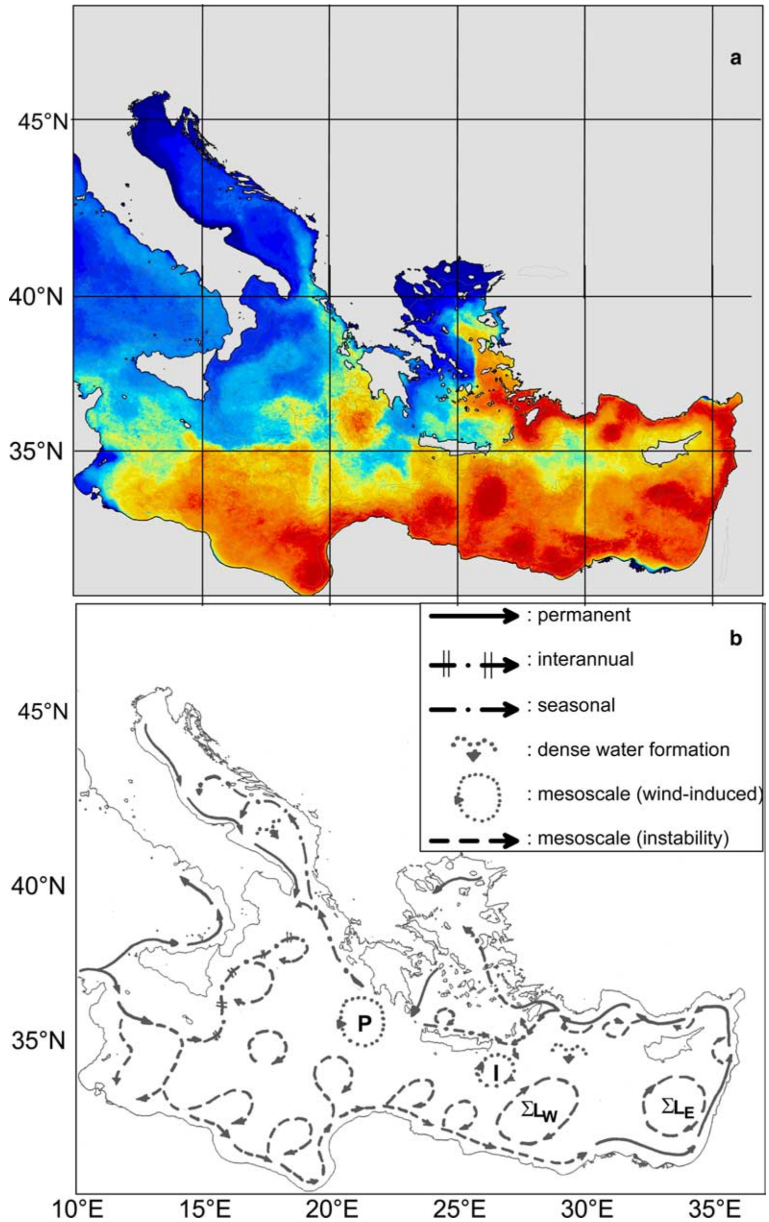

Fig. 4. The eastern basin of the Mediterranean Sea in January 1998 (SST, a), and our surface circulation scheme (b).

mesoscale anticyclonic eddies. A relatively large one can be seen off eastern Libya while a smaller one can be seen off southern Turkey. The former can be considered (Millot & Taupier-Letage, in press) as the counterpart of an Algerian eddy, while the latter is specific to the eastern basin. As clearly suggested by this image, both eddies are closely linked to higher SSTs that are evidenced all around the basin and that we link to the alongslope counterclockwise circulation of AW. We have shown (Hamad et al., 2004, in press) that such eddies are generated by the instability of this alongslope circulation, as occurs in Algerian subbasin; these instabilities lead to the seaward spreading of AW in both the southern Ionian and off Middle East, the Shikmona zone. The situation in Fig. 4(a) illustrates that sampling only the northern parts of the Ierapetra anticyclone and of the Libyan eddy may mislead into interpreting a jet of AW (namely the "MMJ") meandering across the central part of the Levantine.

The synthetic analysis of the available remotely sensed and in situ data sets has led us to propose a new scheme for the circulation of AW in the eastern basin. After "branching" in a more or less complex way at the entrance of the Channel of Sicily (see drifters trajectories on Fig. 15 of Lermusiaux & Robinson, 2001), which is consistent with numerical simulations (e.g., Molcard et al., 2002), we think that AW circulates mainly along Tunisia (see drifters trajectories on Fig. 1 of Salas, Millot, Font, & García-Ladona, 2002). Then, part of the AW continues along the Tunisian coast while the other, probably larger part, follows the Tunisian continental slope (e.g., Pierini & Rubino, 2001). From there, a northern interannual branch has been observed up to early 1998, both in IR images (see Hamad et al., in press) and with in situ data including drifter trajectories as shown by, e.g., Poulain (1998) and Robinson et al. (1999). Off Libya and Egypt, we observe that the circulation of AW is markedly unstable (as off Algeria and in agreement with numerical simulations, e.g., Alhammoud et al., this issue), generating mesoscale anticyclonic eddies that are expected to extend down to the bottom (as Algerian eddies, see Millot & Taupier-Letage, this issue). We think that these eddies then accumulate in the Herodotus bathymetric trough (depths > 3000 m in the Levantine), interacting there up to merging, and hence forming a specific area that we name ΣL_W. This area corresponds to the so-called "Mersa Matruh Gyre", but the processes and features we invoke are very different. Supposedly because of much shallower depths, instability of the circulation of AW off Middle East generates eddies that have smaller space and time scales and accumulate in the specific area that we name ΣL_E, the so-called "Shikmona Gyre" area. In the northern part of the basin, the IR image in Fig. 4(a) suggests clear links between the circulation of AW and the zones of dense water formation. Note that AW surrounds such a zone in the southern Adriatic, due to the reduced size of this subbasin, but does not seem to surround the zone southeast of Rhodes Island where the Levantine Intermediate Water is formed, so that the existence of the "Rhodes Gyre" might be questioned (AW has very different characteristics north and south of the zone).

4. Conclusion

Several schemes have been proposed to describe the circulation of the Atlantic Water (AW) in the eastern basin of the Mediterranean Sea. The three former ones from 1912 to the 1980s show a round-basin circulation whereas the most recent one introduced a cross-basin circulation. To better understand this controversy, we have analysed infrared (IR) composite images computed from specialised centres, namely all monthly composites available from 1985 and weekly and daily composites during the period 1996–2000. We have shown that the overall distribution of the sea surface temperatures (higher SSTs, linked to lowest densities, at the rim of the basin), whatever the year and the season, was more consistent with the historical schemes than with the most recent one. Essentially, our results confirm that AW circulates counterclockwise in the basin. However, the historical schemes represent a broad flow while we think that the circulation is essentially constrained alongslope, being markedly unstable and generating mesoscale eddies. Sampling with too large spacing or considering climatological averages leads to a flow misleadingly much broader and smoother (for a detailed description of these mesoscale eddies, see Hamad et al., 2004, in press). The new scheme that we propose can be considered as a refinement of the historical ones. Doing so, we end up displaying features very similar to the features now widely accepted for the western basin. This new scheme is consistent with all the available in situ and remotely sensed data sets, with recent numerical simulations and with theoretical arguments such as the Coriolis effect, as initially invoked by Nielsen (1912).

Acknowledgements

We thank the editors and some of the referees for having allowed the publication of such a controversial analysis. Najwa Hamad received support for her PhD from the High Institute of Marine Research/University of Tishreen/Syria. Assef Abbas, Jean-Luc Fuda and Gilles Rougier are warmly acknowledged for their help. We used satellite IR images from the German remote sensing centre, from the SATMOS (agreement INSU/METEO-FRANCE October 2001-present), and from the PODAAC Pathfinder Archive.

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