Recent results and new ideas about the Eurafrican Mediterranean Sea.

Outlook on the similarities and differences with the Asian Mediterranean Sea.

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Abstract :

The overall functioning of the Eurafrican Mediterranean Sea, which transforms Atlantic Water (AW) into Mediterranean Waters (MWs), has been comprehended for a while, and the process of dense water formation, which leads AW to sink offshore in specific northern zones of the western and the eastern basins, has been studied in the world ocean. However, the circulation of the various waters from/to the basins openings to/from the zones of sinking is still debated in the western basin, while a similar debate is only being initiated in the eastern one. As earlier studies pointed out, considering properly the role of the mesoscale phenomena (eddies and gyres) is pivotal, and satellite images have become a fundamental tool. Based on the analysis of satellite (thermal) images time series and on their confrontation with the available in situ observations, we have recently proposed a new schema of the surface circulation in the eastern basin, and we are currently preparing the EGYPT in situ experiment for its validation. In the same way, results from the ELISA experiment recently settled the controversy about the circulation of the Levantine Intermediate Water (LIW) in the Algerian subbasin.

Most recently, hydrological time series newly recorded in the Strait of Gibraltar confronted to hydrological casts about 20 years old showed that the outflow's characteristics can vary more largely and rapidly than previously thought (trends ~0.03 °C and 0.01 per decade), depending on the relative amounts of the different waters formed from year to year.

Finally, as a call for potential collaboration, we point out some similarities and differences between the Eurafrican and Asian Mediterranean Seas.

1. Introduction

The overall functioning of the Eurafrican Mediterranean Sea (Fig.1.), which transforms Atlantic Water (AW) into Mediterranean Waters (MWs), has been comprehended for a while, and the process of dense water formation, which leads AW to sink offshore in specific northern zones of the western and the eastern basins and exit through the Strait of Gibraltar, has been studied in the world ocean. However, debates are still fierce around the circulation of the various waters (see Millot and Taupier-Letage, 2004a). We consider that, overall and due to the Coriolis effect, all waters (AW and MWs) that circulate at basin scale tend to follow, in the counter-clockwise sense, the isobaths at their own level (Fig. 2, 3, 4). Hence they tend to describe, in both the western and the eastern basins, quasi permanent gyres[1] (flow a few 10s km wide) a few 1000s km long along the continental slope. This simple schema is complicated by the fact that the southern parts of both gyres described by AW are markedly unstable, the AW inflow being hence identified with the so-called Algerian Current and Libyo-Egyptian Current and generating specific systems over the whole depth. Indeed, these currents (100-200 m deep, few tens km wide) meander and generate, a few times per year, anticyclonic eddies[2] that can reach diameters of 100-200 km (and even more), propagate downstream (i.e. eastward) at speeds up to a few km/day, and sometimes extend down to the bottom (2-3000 m). Hence, these eddies follow the deeper isobaths, separate from their parent current where these isobaths diverge from the upper continental slope, and drift for years (up to 3 at least) in the central part of the basins, possibly coming back shoreward where they interact with their parent current, sometimes in a dramatic way.

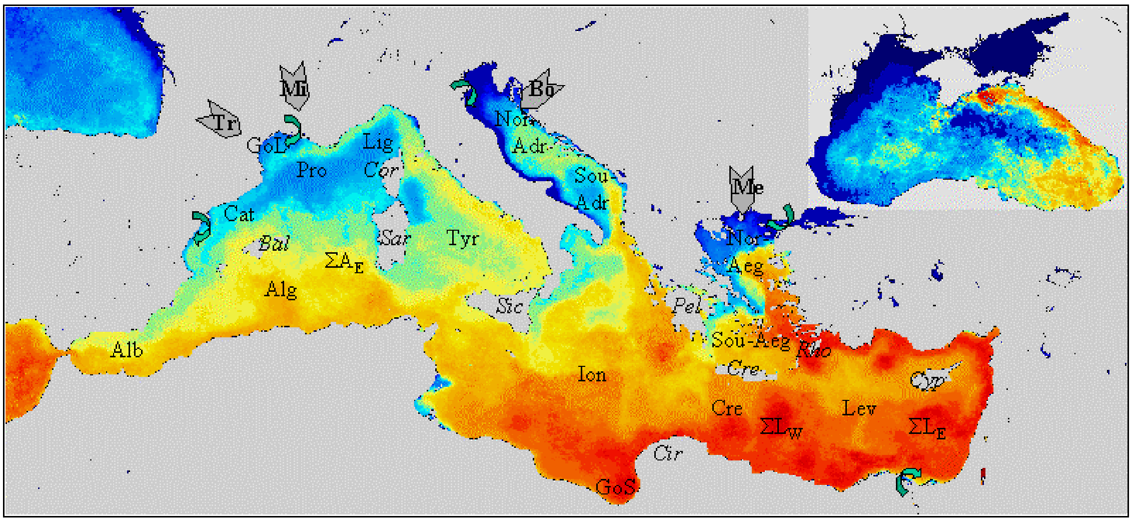

Figure 1: The Eurafrican Mediterranean Sea geography, superimposed on the Sea Surface Temperature monthly composite image of January 1998. The counter-clockwise circuit of the AW entering through the Strait of Gibraltar is illustrated by the continuity of the warmer temperature alongslope.

Nomenclature: The Eurafrican Mediterranean is divided into the western and eastern basins. Basins are divided into subbasins (following the AW circulation) : Alb: Alboran; Alg: Algerian; Tyr: Tyrrhenian; Ion: Ionian; Cre: Cretan: Lev: Levantine; Sou-Aeg: South-Aegean; Nor-Aeg: Nor-Aegean; Sou-Adr: South-Adriatic; Nor-Adr: North-Adriatic; Lig: Ligurian; Pro: Provencal; Cat: Catalonian. ΣA_E, ΣL_W and ΣL_E are areas where eddies tend to accumulate and interact, up to merging and/or decaying, in the east Algerian, west and east Levantine subbasins, respectively.

Bal: Balearic Islands; Sar: Sardinia; Sic: Sicily; GoS: Gulf of Syrte; Cir: Cirenaica; Cre: Crete; Cyp: Cyprus; Rho: Rhodes; Pel: Peloponnese; Cor: Corsica; GoL: Gulf of Lions.

The main wind systems are indicated with wide arrows: Tr: Tramontane; Mi: Mistral; Bo: Bora; Me: Meltem). Curved arrows represent the main river outflows.

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[1] *Gyres are circulation features induced by wind and/or thermohaline forcing and/or topographic features (such as straits) that are clearly constrained by the bathymetry (at basin and subbasin scales). They are characterised as clockwise in the Alboran (mainly due to the orientation of the Strait of Gibraltar) and everywhere else as counterclockwise (due to the Coriolis effect). Parts of the gyres can be unstable.*

[2] *Eddies are phenomena generated either by processes that destabilise alongslope currents (such as the Algerian Current) or by the wind stress curl locally induced by orographic effects (as described later on). They are characterised as cyclonic / anticyclonic, not constrained by the bathymetry and can move. Eddies are mesoscale (some 10s to a few 100s km) features that will be characterised as small (up to ~50 km), medium (50-150 km) or large (150-250 km).*

These eddies entrain AW and MWs from the peripheral part of the basins towards their central part, together with those eddies induced by the wind in the eastern basin only. In both basins, the northern parts of the gyres display specific features linking them to the zones of AW sinking, hence being identified (more easily in the western basin than in the eastern one due to the topography) with the so-called Northern Currents. In addition to these circulation features, and because the various openings are only a few 100s m deep, the deeper MWs must be uplifted before outflowing. This is achieved permanently and more or less everywhere through continuous mixing with less dense waters and uplifting resulting from sinking newly formed denser waters. This is also achieved when and where intense mixing with other waters (cascading from sills or sinking) and sucking upward straits occur.

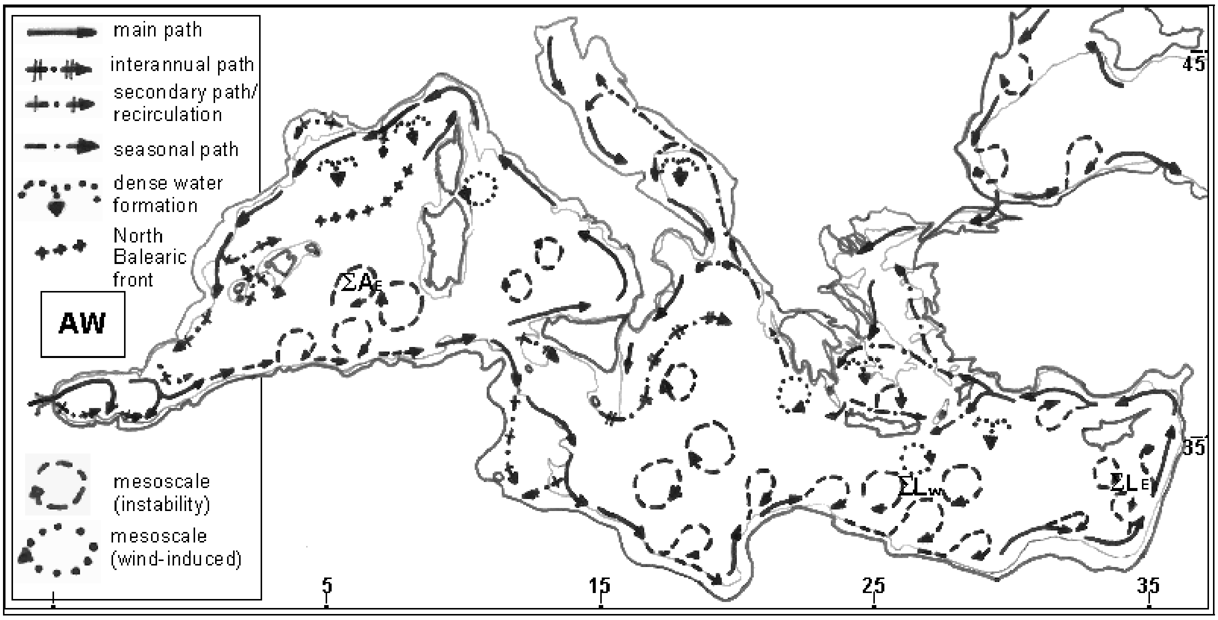

Figure 2: Circulation of the Atlantic Water (from Millot and Taupier-Letage, 2004a)

However, the circulation of the various waters from/to the basins openings to/from the zones of sinking is still debated in the western basin, while a similar debate is only being initiated in the eastern one.

2. *Recent results and new hypotheses*

a. <u>The surface circulation in the Eastern Basin</u>

The schemata of the AW circulation in the eastern basin of the Eurafrican Mediterranean Sea widely referred to nowadays represent, in particular, jets meandering offshore across the whole basin (Mid-Ionian Jet: MIJ; Atlantic Ionian Stream: AIS, and Mid-Mediterranean Jet: MMJ, *e.g.* Robinson and Golnaraghi, 1993). No mention is made of an overall anticlockwise and alongslope flow (100-200 m thick), as first indicated by Nielsen (1912), and as supported by a former analysis of thermal satellite images (Le Vourch *et al.*, 1992; Millot, 1992).

On average (cf. Fig.2, see Hamad *et al.*, 2004), AW does not cross the Ionian in its central and/or northern parts but finally concentrates, either as an alongslope anticlockwise flow or as anticyclonic eddies, in the southern Ionian along the western Libyan slope. The Libyan eddies then propagate downstream along the eastern Libyan slope (Fig.5). Some of them come to interact with the wind-induced Ierapetra eddy, which increases its interannual variability (hence not only dependent on the summertime-winds (Etesians) intensity). Ierapetra can survive more than one year, drift and reach the Libyan and Egyptian slopes or remain motionless, and/or merge with a former Ierapetra. At the entrance of the Levantine, most of the eddies (including Ierapetra) tend to follow the deep isobaths and thus detach from the current before spreading northeastwards. Therefore, contrary to what has been believed hitherto, the area known as “Mersa-Matruh” is not occupied by a recurrent / permanent feature but by slowly propagating anticyclonic eddies originated elsewhere. The northwestern edges of such mesoscale eddies have (most probably) been confused with a northeastward “Mid-Mediterranean Jet”.

The area known as Shikmona is in fact an offshore anticyclonic structure continuously fed by various kinds of eddies originated alongslope. The so-called “Cilician Current” and the “Asia Minor Current”, which clearly appear to be the continuity of the overall alongslope flow, generate eddies of medium size before flowing markedly into the Aegean, especially in winter, or southwestwards, up to feeding Ierapetra. North of Crete, most eddies propagate eastward. In the northern Ionian, the surface flow toward the Adriatic displays a marked seasonal variability, being especially intense in winter. In the Adriatic, the surface flow clearly surrounds the dense water formation zone.

Overall, AW clearly circulates mainly alongslope around the whole basin, as indicated by Nielsen (1912) who considered the Coriolis effect as dominant. Although mainly descriptive, this detailed analysis of infrared images of the whole eastern basin of the Eurafrican Mediterranean Sea has allowed proposing a realistic and coherent schema of the surface circulation there, which is coherent with all the observations available. It is thus concluded that schema presenting as a main feature a MMJ and permanent eddies resulted from i) a misinterpretation of the under-sampled features and ii) ignorance of any satellite information. We are thus currently setting an experiment in the key area that is the Levantine subbasin. EGYPT (Eddies and GYres Paths Tracking, see http://lobtln.chez.tiscali.fr/)

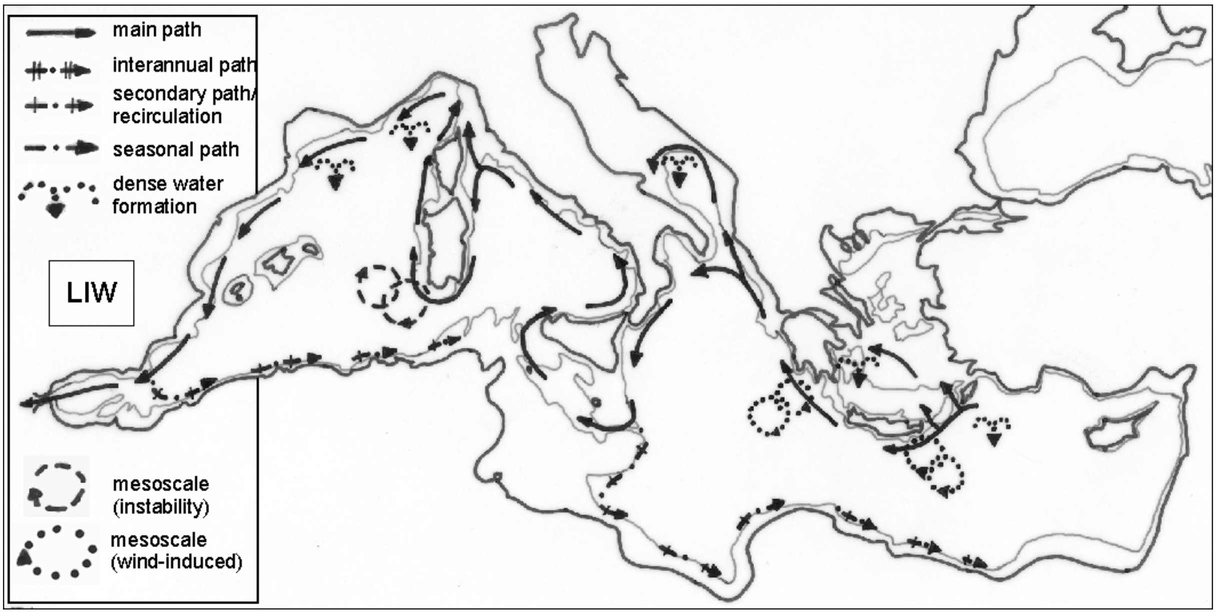

Figure 3: Circulation of the Levantine Intermediate Water (from Millot and Taupier-Letage, 2004a)

b. The circulation of the Levantine Intermediate Water (LIW) in the Algerian subbasin

The circulation of the Levantine Intermediate Water (LIW) in the Algerian subbasin (western basin) is another case-study in this regard, as it has been much debated for more than fifteen years now (Millot and Taupier-Letage, 2004b). Together with the old circulation diagrams, several recent papers claim that a branch of LIW is continuously flowing westwards across the Algerian subbasin, *i.e.* directly from the Channel of Sardinia towards the Strait of Gibraltar. Only a few papers support the fact that the unique continuous flow of LIW is structured as an alongslope counter-clockwise vein, which is thus directed northwards off Sardinia in the Algerian subbasin, and hence support the diagram published by Millot in 1987. According to this diagram, fragments of little mixed LIW found in the central basin have been pulled away from the vein and entrained there by mesoscale eddies originated from the Algerian Current. The ELISA experiment (1997-1998, http://www.com.univ-mrs.fr/ELISA/), as a follow-up of other ones conducted since about fifteen years, was designed partly to validate the latter diagram. The observations provide definitive evidence that the little mixed LIW found in the central Algerian subbasin has been entrained there by the mesoscale eddies and not by a permanent westward-flowing vein (Fig.2.). We expect similar effects of the Libyo-Egyptian eddies in the eastern basin.

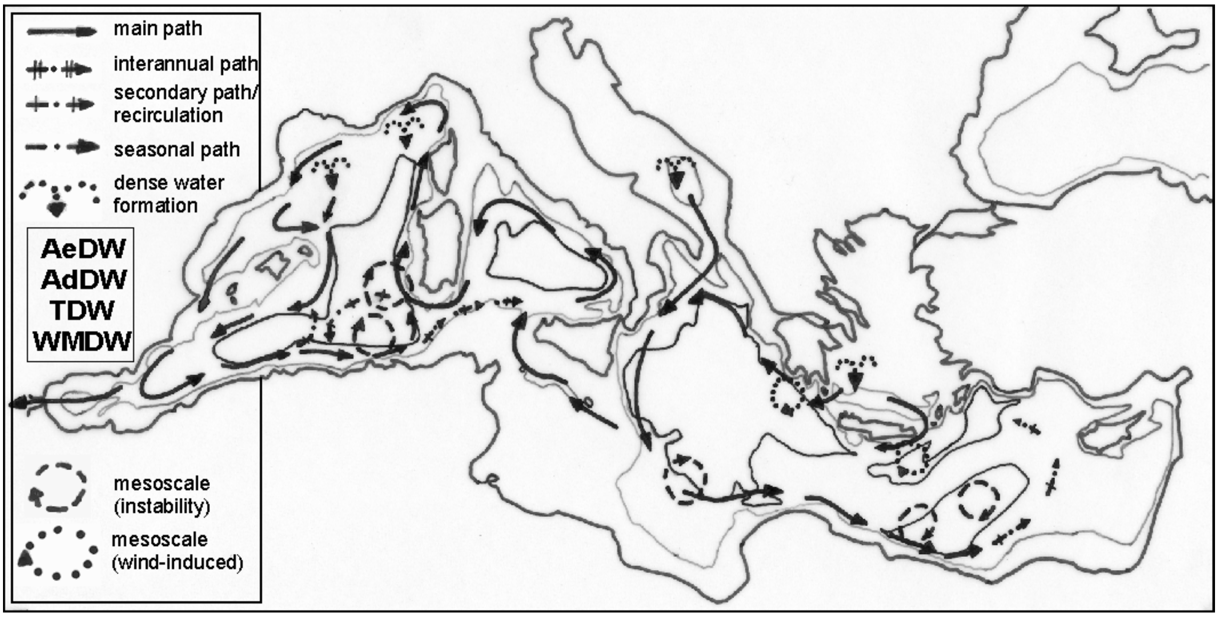

Figure 4: Circulation of the intermediate and deep waters (from Millot and Taupier-Letage, 2004a)

c. The changes in Eurafrican Mediterranean outflow

During wintertime AW is transformed into a set of cooler and saltier (hence denser) waters that, being formed in different sub-basins of the eastern and western basins, have different hydrological characteristics. Data from the 60s-80s have shown that the densest water outflowing at Gibraltar was a relatively cool and fresh one formed in the western basin, a situation generally thought as permanent. We have recently shown (Millot et al., 2004) that the densest waters mainly outflowing since the mid-90s were formed in the eastern basin

(LIW in particular), hence leading to an outflow actually much warmer (~0.3 °C) and saltier (0.06) than ~10 years

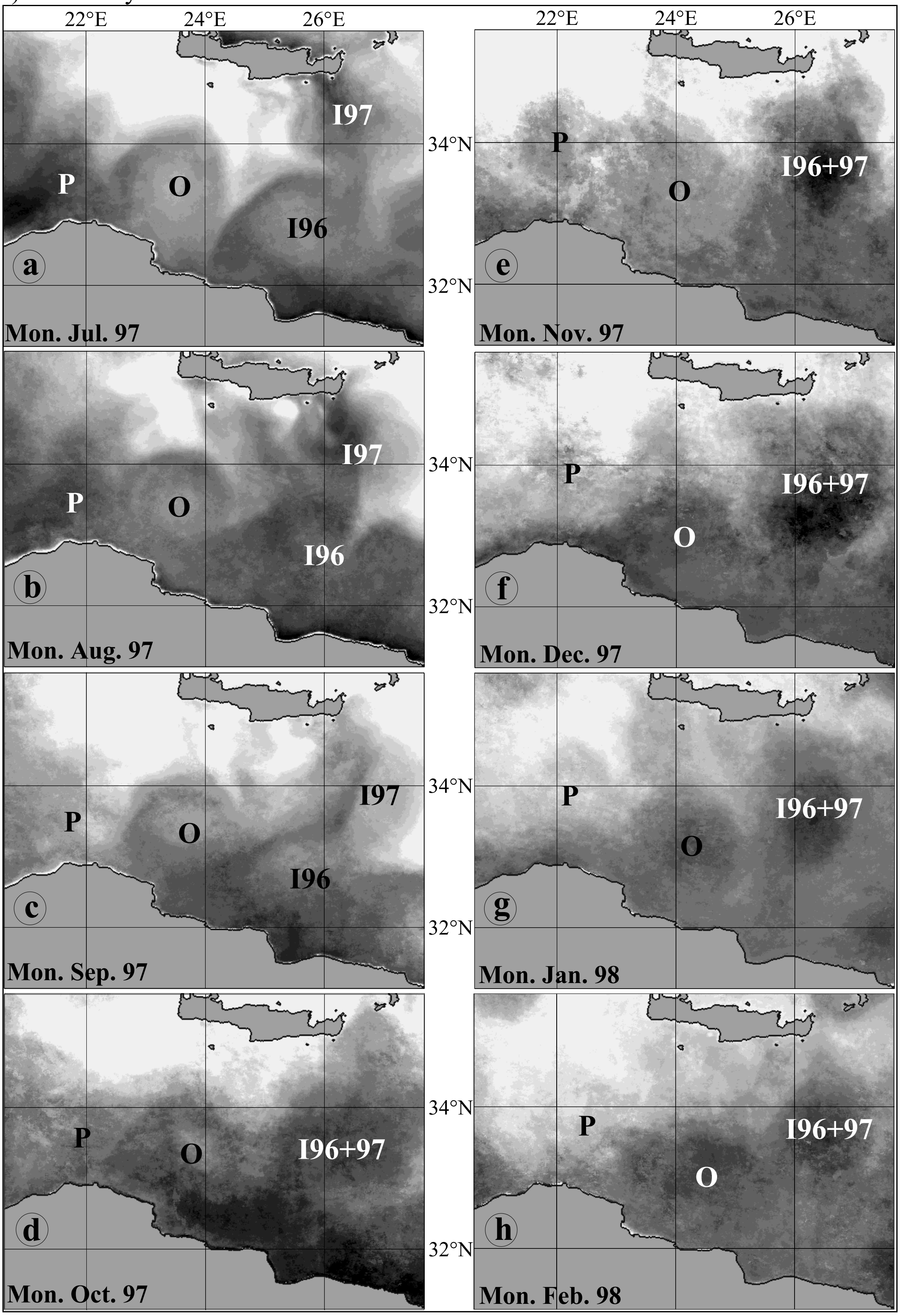

Figure 5: Time series of monthly SST composites of the southern Cretan subbasin. Eddies O and P progress downstream alongslope at a few km/day (a-h). During the summer 97 (a-c) the former wind-induced Ierapetra eddy (I96) interacts with the one being formed (I97). I97 drifts then southward and merges with I96, and this ensemble (I96+97) remains without propagating for several months (d-h). From Hamad et al. (2004).

ago. We conclude that the outflow's characteristics can vary more largely and rapidly than previously thought (trends ~0.03 °C and 0.01 per decade), depending on the relative amounts of the different waters formed from year to year. The consequence is that the Eurafrican Mediterranean Sea thus affects markedly the mid-depth waters characteristics in the North Atlantic.

3. Similarities and differences with the Asian Mediterranean Sea.

More than 10 years ago Millot (1992) wondered in a preliminary investigation whether there were major differences between the largest Mediterranean seas. He compared the Eurafrican Mediterranean, divided in 2 mediterranean seas (the western and eastern ones: WMS and EMS), to the Asian Mediterranean Sea (AMS). He reviewed the morphology, meteorology, hydrology and dynamics. A striking common feature is that the circulation in the southern parts of all 3 MSs (the Tsushima Current (Fig.6), the Algerian Current and the Libyo-Egyptian Current) are clearly turbulent, and the mesoscale eddies generated seem to have similar spatio-temporal scales. Are the reasons for such a turbulence similar and, if not, what are the major differences? As the waters transported by these currents spread into the interior of the seas, they appear to be amassed within some kinds of reservoirs. Are the frontal zones delimiting these reservoirs associated with some specific circulations, and is geostrophy responsible for their drainage through their northeastern corner? The other striking common feature is that the circulation in the northern parts of all 3 MSs (the Liman Cold Current and the 2 Northern Currents) are relatively stable and quiet currents, flowing westwards along northern slopes. Are the reasons for such a common feature similar and, if not, what are the major differences?

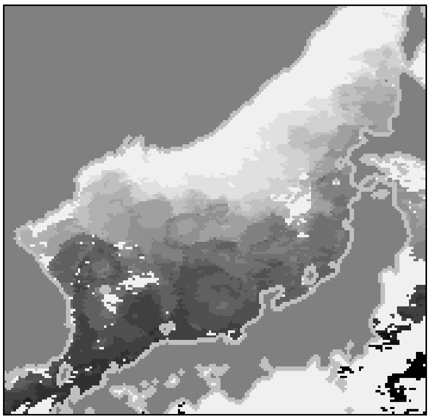

Figure 6: SST image of the Asian Mediterranean Sea (temperature increases from light to dark grey). The mesoscale turbulence along the southern slope (Tsuhima Current) is clearly evidenced.

A feature probably worth further investigation would be the potential similarity between the East Korean Warm Current and the interannual branch which can develop around the southeastern corner of Sicily, spreading northward before vanishing in a clockwise rotation (see Fig.3)[3] .

[3] In the Alboran subbasin thermal signatures sometimes also display a northward branch, but it is clearly entrained by a mesoscale eddy and is short-lived.

All 3 MSs have intermediate and deep waters formation in localized areas. A major difference, however, is that the circulation is essentially in the same directions in the straits in the AMS (Korea/Tsushima, Tsugaru, Soya Straits) while in the WMS the surface circulation (AW) is opposed to the intermediate and deep ones (Gibraltar Strait, Sardinian and Sicily Channels).
Given the amount of new data (see Chang et al. (2004) for the AMS, Millot (1999) and Millot and Taupier-Letage (2004b) for the western basin and Hamad et al. (2004) for the eastern basin of the Eurafrican Mediterranean), the comparison could be worth deepening, up to deciding whether it could be relevant to run a general model for mediterranean seas?

4. References.

Hamad N., C. Millot and I. Taupier-Letage (2004). The surface circulation in the eastern basin of the Mediterranean Sea as inferred from infrared images. Prog. Oceanogr., in press.

Le Vourch, J., Millot, C., Castagné, N., Le Borgne, P., & Olry, J.P. (1992). Atlas of thermal fronts of the Mediterranean Sea derived from satellite imagery. *Mémoires de l'Institut Océanographique, Monaco,* 16.

Millot C., 1987. The circulation of the Levantine Intermediate Water in the Algerian Basin. J. Geophys. Res., 92, C8, 8265-8276.

Millot, C. (1992). Are there major differences between the largest Mediterranean Seas? A preliminary investigation. *Bull. Inst. Oceanogr. Monaco*, 11, 3-25.

Millot, C. (1999). Circulation in the Western Mediterranean Sea. *J. Mar. Syst*., 20, 423-442.

Millot, C., J.-L. Fuda, J. Candela and Y. Tber. Large warming and salting of the Mediterranean outflow due to shifts in water formation zones within the sea. *Manuscript to be submitted.*

Millot C. and I. Taupier-Letage (2004a). Circulation in the Mediterranean Sea. The Handbook of Environmental Chemistry, Vol 1 (The Natural Environment and the Biological Cycles), Springer-Verlag Editor, *in press.*

Millot C. and I. Taupier-Letage (2004b). Additional evidence of LIW entrainment across the Algerian Basin by mesoscale eddies and not by a permanent westward-flowing vein. Prog. Oceanogr., *in press*

Nielsen, J.N. (1912). Hydrography of the Mediterranean and adjacent waters. *Rep. Dan. Oceanogr. Exp. Medit.,* 1, 77-192.

Puillat, I., Taupier-Letage, I., and C. Millot (2002). Algerian Eddies lifetime can near 3 years. *J. Mar. Syst.,* 31, 245-259.

Robinson, A.R. and M.Golnaraghi (1993). Circulation and dynamics of the Eastern Mediterranean Sea; Quasi-Synoptic data-driven simulations. *Deep Sea Res.,* 40 (6), 1207-1246.