

## The Atlantic water mesoscale hydrodynamics in the Levantine Basin

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### ABSTRACT

The spatial and temporal variability of the Atlantic Water (AW) and the mid-Mediterranean jet (MMJ) in the Eastern Mediterranean Levantine basin is investigated using *in-situ* data sets collected between 1995 and 2005. The data provide insight on the mesoscale spatial variability, the seasonal and even the hourly variability of the AW in the area of interest. Synoptic and high frequency *in-situ* data from hydrological surveys and an open sea observatory indicate the MMJ meanders eastward, between the southern shore of Cyprus and the northern periphery of the Cyprus warm core eddy or the Shikmona gyre. The MMJ is documented to transfer eastward the AW, both at surface and subsurface layers. The results confirm that the MMJ, as an offshore cross-basin jet, is indeed the major driving force responsible for the eastward spreading of the main volume of the AW in the SE Levantine basin, while *in-situ* data closer to Egypt provide evidence of a westward recirculation offshore Egypt.

### INTRODUCTION

The most variable water mass of the Levantine basin (Figure 1) is the relatively low salinity Atlantic Water (AW). The inflow of the AW in the Mediterranean compensates for the high rates of the sea water evaporation in the Levantine basin and of the outflow of the Levantine Intermediate water (LIW) into the North Atlantic (Ovchinnikov *et al.*, 1976). The estimated AW inflow through the Strait of Gibraltar (1.01 Sv) exceeds the total mean outflow fluxes (0.97 Sv) of the Mediterranean waters (Astraldi *et al.*, 1999). The AW, after its entry into the Mediterranean through the Strait of Gibraltar, with salinity as low as 36.3 psu, follows a complicated pathway eastwards, as far as the Levantine basin (Figure 1). There the AW is most often well-pronounced as a subsurface layer with minimum salinity, spanning 40 to 80 meters, with salinity as low as 38.60-38.95 psu (Ovchinnikov *et al.*, 1976; Hecht *et al.*, 1988; Ozsoy *et al.*, 1991). However, periodically surface AW has also been found in the western part of the Levantine with similar salinity values.

The high rates of heating and evaporation, which prevail over the Levantine basin during summer, are able to transform the surface layer of the AW to the warmest and most saline (up to 29 deg. C

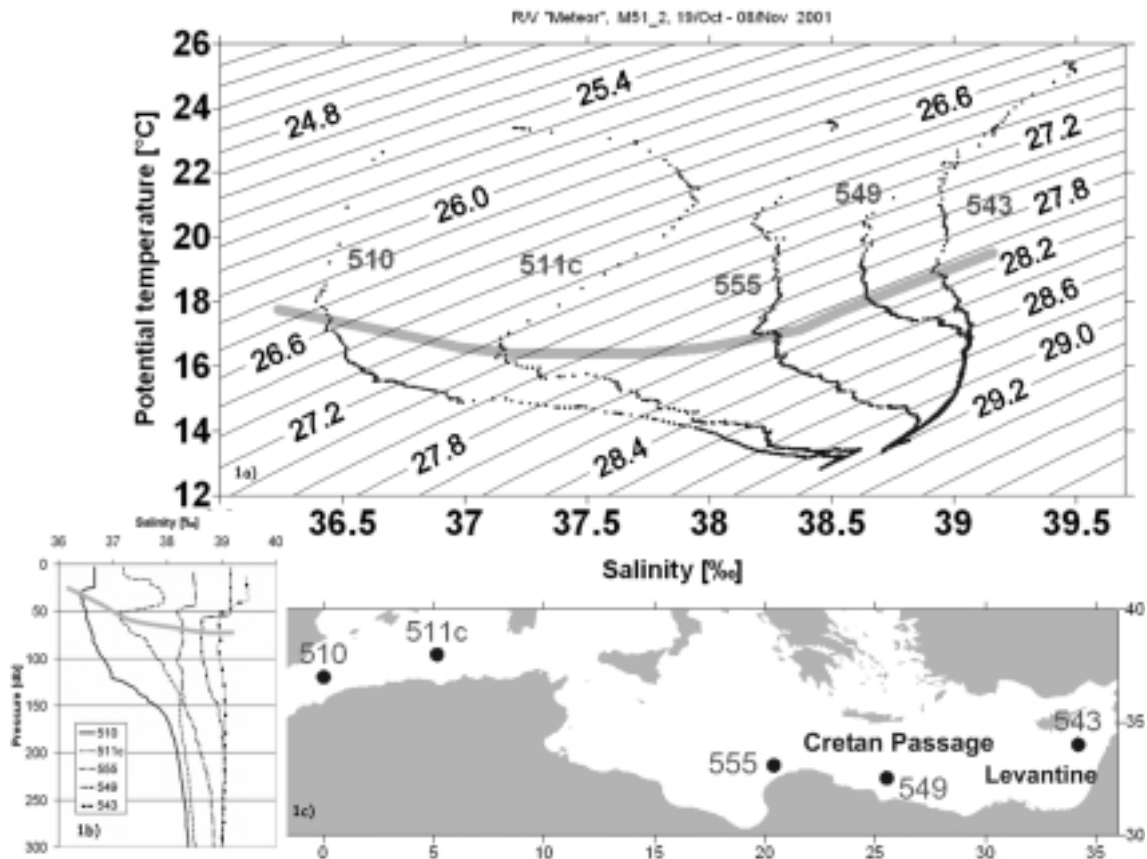


Fig. 1. **a**) T/S diagrams across the Mediterranean showing the transformation of the AW (obtained during a cruise of the R/V METEOR, between Oct.-Nov. 2001). **b**) Associated salinity profiles at selected stations across the Mediterranean. **c**) Associated station locations.

and 39.6 psu) surface waters in the Mediterranean, as observed during the summer 2003 CYBO cruise (Zodiatis *et al.*, 2004). In winter, convection mixing processes in the SE Levantine usually initiate the homogenization of the water column from the surface down to subsurface and intermediate layers, in some cases even down to 200–350 m (Zodiatis *et al.*, 2001). Consequently, the salinity of the mixed water mass at the typical depths of the AW increases, and the AW is not evident. The spatial variability of the MMJ (mid-Mediterranean jet) in the Levantine basin is also influenced by the local surface processes (summertime evaporation, winter mixing) and by the fluctuations of the local flow dynamics dominating the area (Ozsoy *et al.*, 1991).

The general circulation in the Eastern Mediterranean as inferred in the 1960s and 1970s (Ovchinnikov *et al.*, 1976) shows an anticlockwise flow with sub-basin features in the Levantine basin (Figure 2a). In the 1980s, the POEM (Physical Oceanography of the Eastern Mediterranean) mesoscale field experiments (Ozsoy *et al.*, 1991; POEM Group, 1992), showed that the AW is transferred within the Levantine by the MMJ (Figure 2b). This offshore cross-basin jet is generated as a result of the interaction between the mesoscale cyclonic (Rhodos gyre) and anti-cyclonic (Mersa Matruh and Shikmona gyres) flow features during the eastward spreading of the surface and subsurface waters of Atlantic origin, after passing the Cretan passage.

The use of satellite sea level anomaly (SLA) nowadays is documented to provide a true background of the sea surface circulation. This is the main reason that these remote sensing data are assimilated into the numerical models producing the operational flow forecasts in the Mediterranean Sea (MFSTEP) and elsewhere. It should be noted that remotely-sensed sea surface temperature (SST) is not generally assimilated in numerical models, but is used to relax the heat

fluxes used at the surface boundaries of the models. Recently, the use of a series of SLA patterns of the Mediterranean Sea has made possible the direct estimation of the general sea surface circulation (Pascual *et al.*, 2005). This SLA-derived circulation has been used for simulating the pathways of passive tracers in the Mediterranean: particles released in the Western Mediterranean spread after traversing the Cretan Passage, diverging from the south-western coast of the Levantine basin, from where they crossed the Levantine basin, more or less in a similar way as that followed by the MMJ crossing the basin during the POEM experiments in the 1980s.

The present work makes use of new *in-situ* data sets obtained from different observing platforms (synoptic oceanographic surveys and continuous records from an open sea observatory) and provide the most recent evidence of the presence of AW and MMJ in the SE Levantine basin. This supports the earlier schema of the MMJ as an offshore cross-basin flow, depicted in the 1980s within the framework of the POEM experiment.

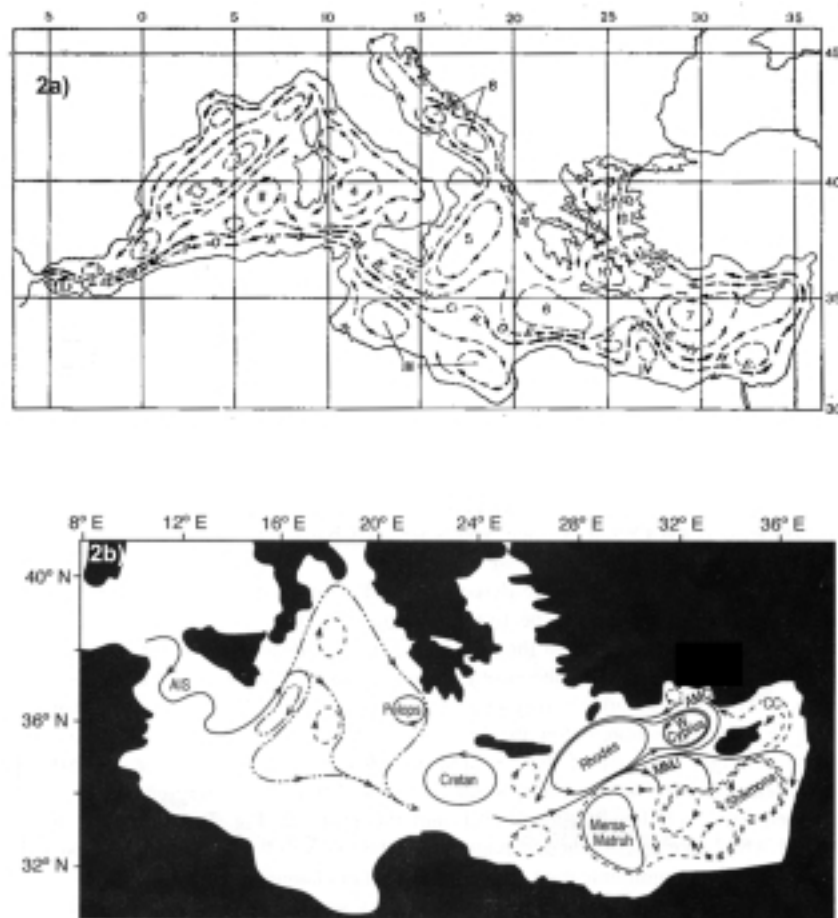


Fig. 2. **a)** The general circulation as depicted during the 1960s and early '70s by Ovchinnikov *et al.* (1976). The prominent feature in the Levantine basin is the Rhodos gyre, labeled "7". **b)** The SE Levantine dynamics during the 1980s consisted of a mesoscale flow structure with anticyclonic eddy activity south of Cyprus and the MMJ meandering eastward transferring the AW (POEM Group, 1992).

## DATA AND METHODS

The existence of the AW and of the MMJ in the SE Levantine are documented on the basis of *in-situ* data collected seasonally from more than 20 quasi-synoptic oceanographic cruises. The cruises usually lasted not more than 10 days each and were carried out in winter or late winter-early spring and in summer periods from 1995 to 2005. The *in-situ* data for the CYBO (Cyprus basin oceanography), CYCLOPS (Cycling of phosphorous in the Mediterranean) and HaiSec (Long-term Haifa section) projects were gathered from a telescopic grid of stations (with a grid

station spacing from 30 nautical miles in the open sea to 5 nautical miles closer to the coastal zone), using Sea Bird Electronics (SBE 911plus) profilers. An SBE 19plus profiler was used for the CYCO (Cyprus coastal oceanography) cruises. The measurements were sampled at a rate of 24 Hz for the 911plus and 4 Hz for the 19plus, and they were averaged *in-situ* over 1 s intervals. The CTD sensors were calibrated annually, prior to the winter cruises, by Sea Bird Electronics.

Continuous measurements of temperature, conductivity and pressure at five subsurface water layers (at 17, 22, 27, 33, 38 m depths) were obtained at a half-hour interval for the period June 2004 to June 2005, from the SBE 16 CT and SBE 16 CTD profilers of the ocean observatory of the Cyprus coastal ocean forecasting and observing system (CYCOFOS). The ocean observatory is located at the open deep sea area of the SE Levantine, west of Eratosthenes seamount, at the location 33° 41'N and 32° 07.5'E, at about 70 nautical miles southwest of Cyprus. The area of the deployment of the CYCOFOS ocean observatory is considered a passage for the MMJ, during its offshore crossing from the southern part of the western Levantine basin.

In order to complement the hydrodynamic patterns obtained from the above *in-situ* data sets, a corresponding time series of daily remote sensing satellite SST images of the Levantine and of the Eastern Mediterranean, with a spatial and thermal resolution of about 1 km and 0.1 °C, respectively, were utilised. The single night passage thermal infrared (IR) satellite images, obtained from NOAA-AVHRR were received and processed by the HRPT receiving station operated at the Oceanography Centre, University of Cyprus.

## RESULTS AND DISCUSSION

The renewed investigations of the SE Levantine, from 1995 to 2005, within the framework of CYBO, CYCO, CYCLOPS, and HaiSec projects, provided strong evidence about the existence, the spatial and temporal fluctuation of the MMJ, the AW, and of the dominating flow features of the area. The current analyses of the *in-situ* data confirm earlier works (Ozsoy *et al.*, 1991; POEM Group, 1992) that the MMJ, which carries the AW in the area, enters the study area from the southwest, at surface and subsurface layers, after crossing the basin from the southwest part of the Levantine and then meanders mainly eastward. The present work confirms that the jet meanders between Cyprus and the northern periphery of the Cyprus warm core eddy (Zodiatis *et al.*, 1998). The latter is revealed as the dominant flow feature of the study area. Periodically the MMJ bifurcates southwest of Cyprus, generating a secondary branch flowing northward along the western coast of Cyprus. The Cyprus warm core eddy and Shikmona gyre (when present), as well as smaller-scale cyclonic and anticyclonic eddies, increase the complexity of the flow path of the MMJ and subsequently of the AW transport in the SE Levantine (Ozsoy *et al.*, 1991; POEM Group, 1992). Throughout the period of study the fluctuation of the MMJ was found to be connected with the Cyprus warm core eddy. The latter undergoes strong seasonal variability, for example the westward shift of the Cyprus warm core eddy during the period 2000-2001 and the re-establishment of the Shikmona gyre during the period summer 2001-2003 (Zodiatis *et al.*, 2005).

During summer 1998, as in all summer cruises from 1995 to 2004, the composite T/S diagram of the area shows the well know “S” shape of the temperature and salinity relationship (Figure 3a). The minimum subsurface salinity was quite well defined at a depth below the thermocline (about 40-50 m) with salinity as low as 38.65-38.75 psu. North-south and west-east salinity sections, south of Cyprus, such as those carried out in summer 2003, show the AW in the form of less saline subsurface lenses with salinity as low as 38.67 psu. These water lenses were attributed to the stream of the MMJ that transferred the AW eastward (Figures 4a,b).

During severe winter weather conditions the presence of the AW is difficult to detect, often being eradicated by winter mixing processes, as shown in the composite T/S during winter 2002 (Figure 3b). However, in milder winter conditions, such as in January 1999 and in early spring, as in May 2000, the AW has been found very well pronounced with salinity values comparable to those observed during summer periods. Periodically the AW has been found at the south-western part of the study area, from the surface down to 100 meters.

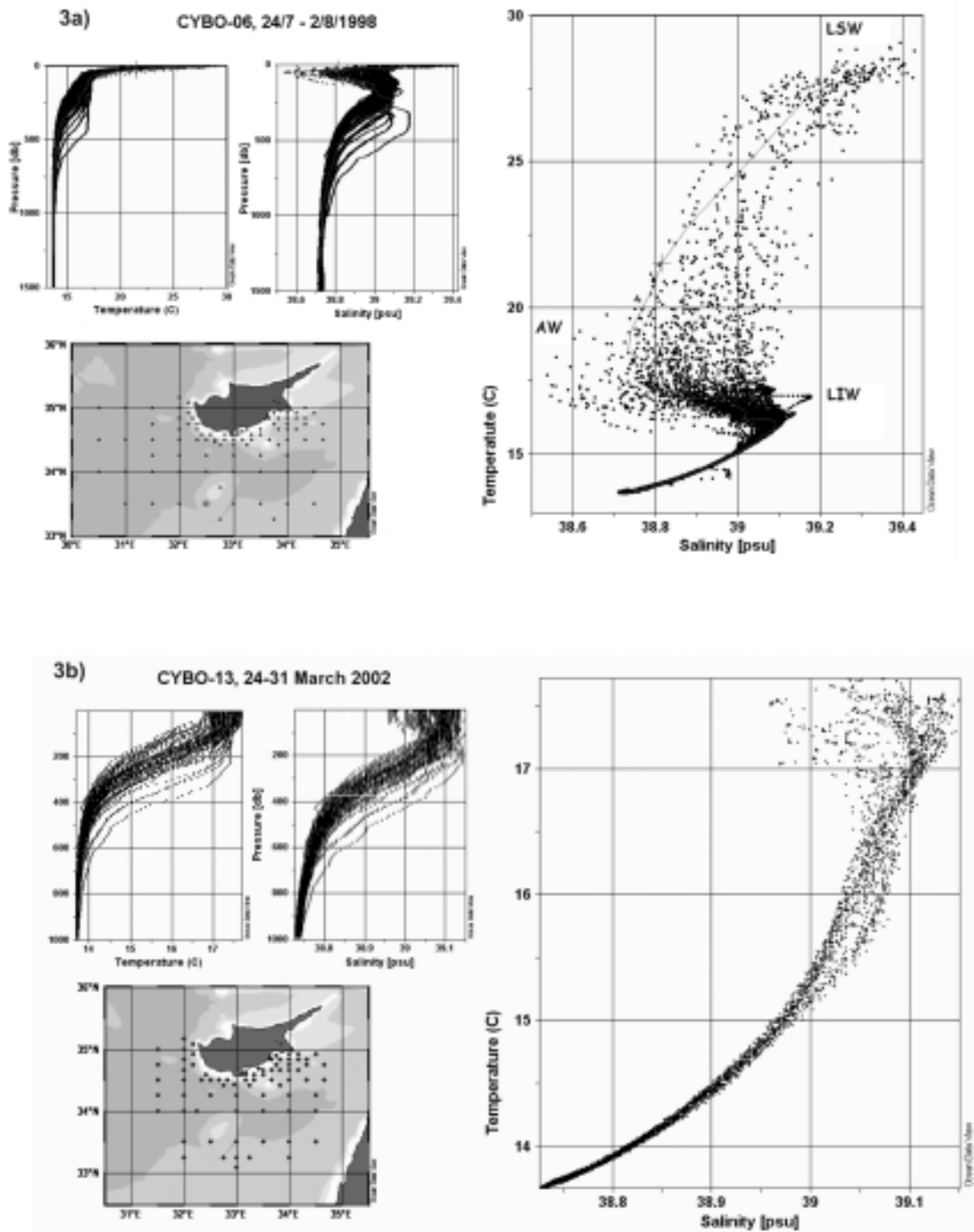


Fig. 3. **a)** *In-situ* data from Cyprus basin Oceanography cruise CYBO-06 in July and August 1998 (all stations are indicated in the location map), showing temperature and salinity profiles, as well as the T-S diagram. **b)** *In-situ* data from Cyprus basin Oceanography cruise CYBO-13 during March 2002 (all stations are shown in the location map), showing temperature and salinity profiles, as well as the T-S diagram. Note the absence of Atlantic Water as a subsurface layer (due to strong vertical mixing).

In early spring 2000 the north-south salinity section south of Cyprus, which crossed the eastward pathway of the MMJ, showed a very well pronounced lens of AW origin (Figure 5). The lens was found to extend from the surface down to the depth of 90 m and from north to south for about 40

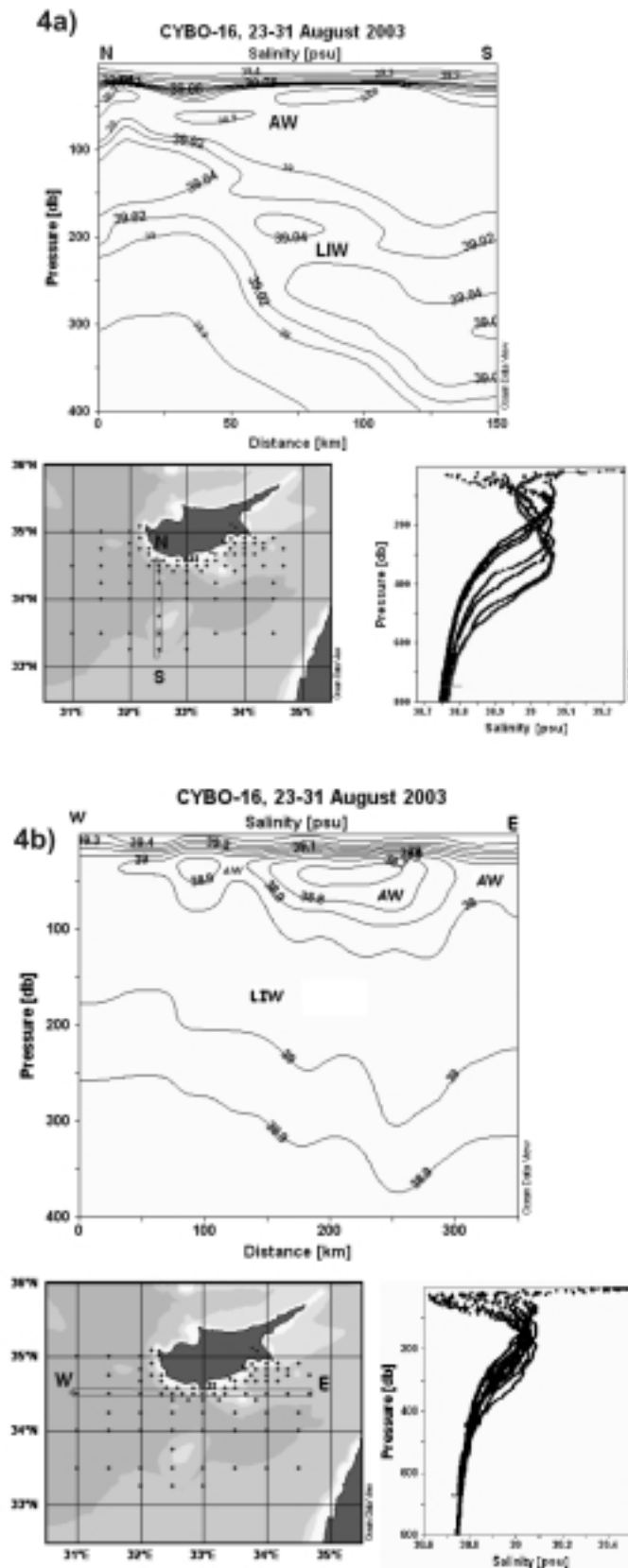


Fig. 4. **a)** *In-situ* data from Cyprus basin Oceanography cruise CYBO-16 in August 2003 (all stations are shown in the location map), showing salinity profiles for a meridional section south of Cyprus, as well as the vertical section (top 400 m only). Atlantic Water (AW) and Levantine Intermediate Water (LIW) are indicated. **b)** As in Figure 4a, but for a zonal section south of Cyprus.

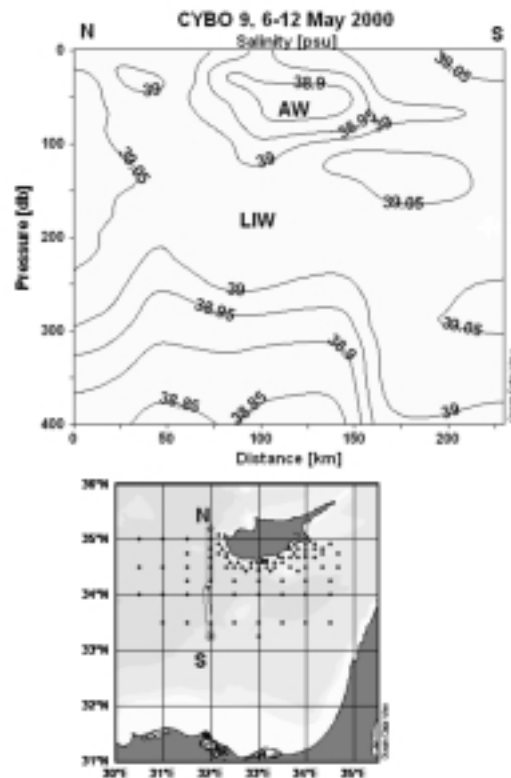


Fig. 5. As in Figure 4a, but for CYBO-09 in May 2000. The core of the AW extended from the surface down to 100 meters and spanned up to 75 km horizontally. Vertical profiles are not shown.

nautical miles, with salinity between 38.85-38.95 psu. The lens is attributed to the MMJ. In this region eastward geostrophic velocities of 30-35 cm/s were observed, transferring the AW through the saline waters of the Levantine basin.

During the CYBO and CYCLOPS experiments carried out in 2001 and 2002, it was found that the significant seasonal spatial displacement of the Cyprus warm core eddy to the west (about 60-80 nautical miles from its original position, Zodiatis *et al.*, 2001, 2005) caused an even more complicated flow path for the MMJ. In particular, in April-May 2001 the northward extent of the Cyprus eddy caused for a short period the restriction of the eastward transfer of the AW. The main flow path of the MMJ became northward offshore west Cyprus, as opposed to its usual eastward direction offshore south Cyprus. In August 2001, the southern relaxation of the Cyprus warm core eddy for about 20 nm and a secondary new anticyclonic eddy, between southeast of Cyprus and offshore Lebanon, resulted in the re-establishment of the eastward MMJ flow, with velocities up to 45 cm/s, along the northern peripheries of these two warm core eddies. The co-existence of these two warm anticyclones until summer 2003, contributed to the re-appearance of the well known Shikmona gyre (Zodiatis *et al.*, 2005). During this period the AW was observed also below the secondary anticyclone, at greater depth than usual, down to 200 m. The latter suggests that the AW after its eastward advection along the Cyprus eddy was then picked up by the new (secondary) anticyclone, which was more intense at the upper surface layers comparable to the Cyprus eddy.

The spatial and temporal variations of the dominating dynamic flow features of the SE Levantine are illustrated in the three circulation diagrams (Figures 6a,b,c), characterizing the periods: a) 1995-1999, b.) 2000-2001, c) summer 2001-2003. Figure 6a shows the Cyprus warm core eddy to be located east of the meridian of 33 00.E, while Figure 6b shows the significant westward shift (about 60-80 nm) of the Cyprus eddy at the end of 2000-early 2001. Finally, Figure 6c shows the re-establishment of the Shikmona gyre that constituted from warm core eddies, similar to

those found during the 1980s. A detailed description of the circulation during the CYCLOPS experiments will be found in Zodiatis *et al.* (2005).

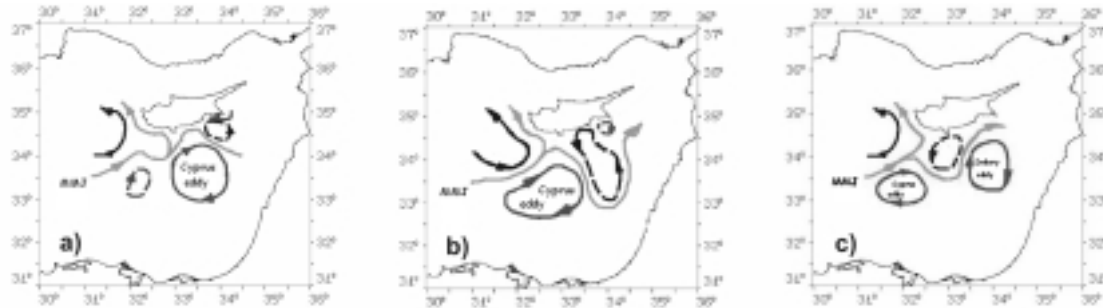


Fig. 6. Diagrams of the prevailing general circulation in the SE Levantine, based on CYBO and CYCLOPS cruises. **a)** For the period 1995-1999; **b)** for the period 2000-2001; **c)** for the period summer 2001-2003.

In summer 2004, the north-south salinity section, between south Cyprus and offshore Egypt, shows the AW to be transferred within the pathway of the MMJ, with salinity as low as 38.8 psu, between the depths 30-100 m (Figure 7). The geostrophic flow at the same section indicated that the MMJ flowed eastward along the northern periphery of the well-established Cyprus warm core eddy, transferring the AW. Moreover, the current intensity of the eastward flow in general was greater, particularly at the most northern part of the section, comparable to the westward flow in the southern part of the section (offshore Egypt). These results give additional evidence that during summer 2004 there was no significant eastward current offshore Egypt. On the contrary, the AW is mainly transferred eastward by the MMJ, flowing between south offshore Cyprus and the northern periphery of the Cyprus warm core eddy, after crossing the basin from the south-western part of the Levantine basin.

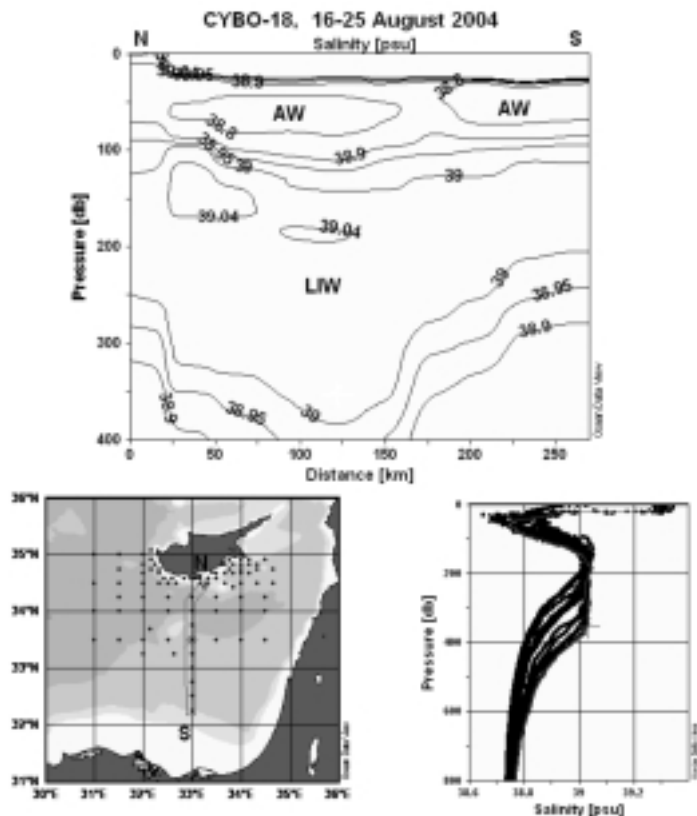


Fig. 7. *In-situ* data from Cyprus basin Oceanography cruise CYBO-18 in August 2004 (all stations are shown in the location map), showing salinity profiles for a meridional section from Cyprus as far south as offshore Egypt.

A series of daily single passage satellite SST images were used to complement our knowledge on the daily variability of the general flow dynamics of the broader Levantine region during the synoptic oceanographic surveys discussed here. It was possible to define the main flow features of the broader area of interest using the remote sensing IR images, but the AW pathways could not be identified without the use in parallel of *in-situ* data. The main reason is that the AW usually appears as a subsurface salinity minimum in the Levantine basin. However, in cases when the transferred AW by the MMJ was cooler than the surrounding surface waters of the Levantine, then the pathway of the MMJ appeared in SST images. As an example the geostrophic flow pattern derived from *in-situ* density profiles in the SE Levantine during the CYBO experiment, in March 2002, two months prior to CYCLOPS (Figure 8) indicated a jet flowing along the periphery of the Cyprus warm core eddy and of the secondary anticyclone offshore eddy that was located between SE Cyprus and Lebanon.

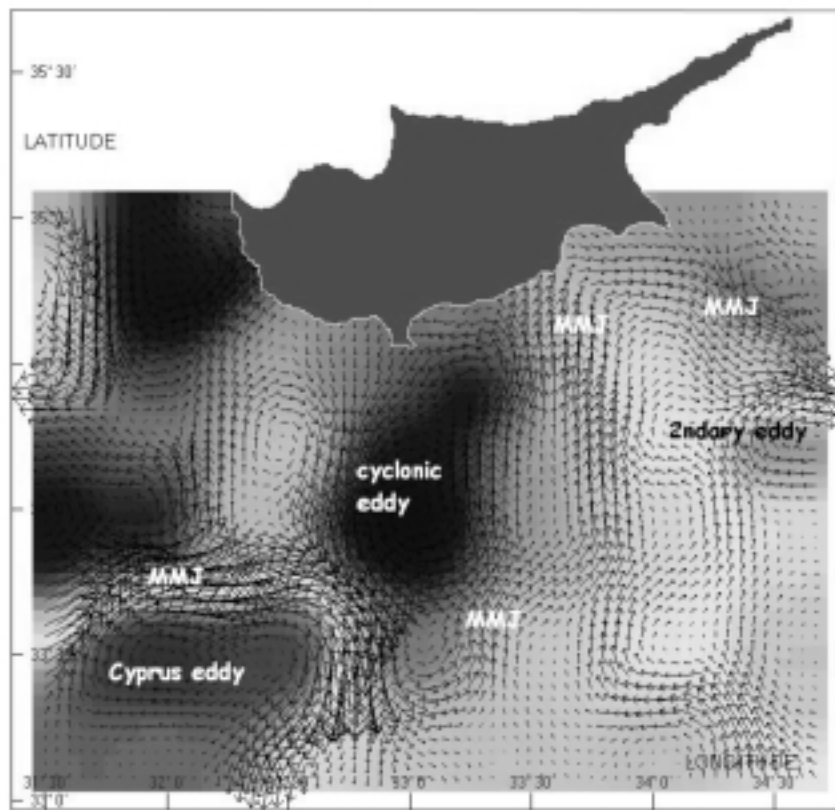


Fig. 8. The general geostrophic circulation pattern estimated using *in-situ* data obtained during the CYBO experiment, late March 2002, in order to support the forthcoming CYCLOPS experiment in May 2002.

High frequency *in-situ* data from the CYCOFOS ocean observatory, located at the open deep sea southwest of Cyprus, provide unique evidence for the half-hourly variability of AW in this particular area, which is considered a passage of the MMJ. From June through October 2004, the 38 m sensors indicated the presence of AW. The salinity at 38 m was nearly always below 38.8 psu and temperatures were 3-6 C° lower than the 17 m values where salinity was above 39 psu. In winter 2004-2005, the mixed layer extended deeper than the deepest (38 m) ocean observatory sensor (Figures 9a,b). Salinities in the mixed layer were greater than 39 psu. From May to June 2005 the salinity at 38 m showed again the intrusion of the AW with salinity to be fluctuating between 38.8-38.98 psu. The sensors at the depth of 17 m showed the salinity to increase gradually during the same period, with values above 39 psu.

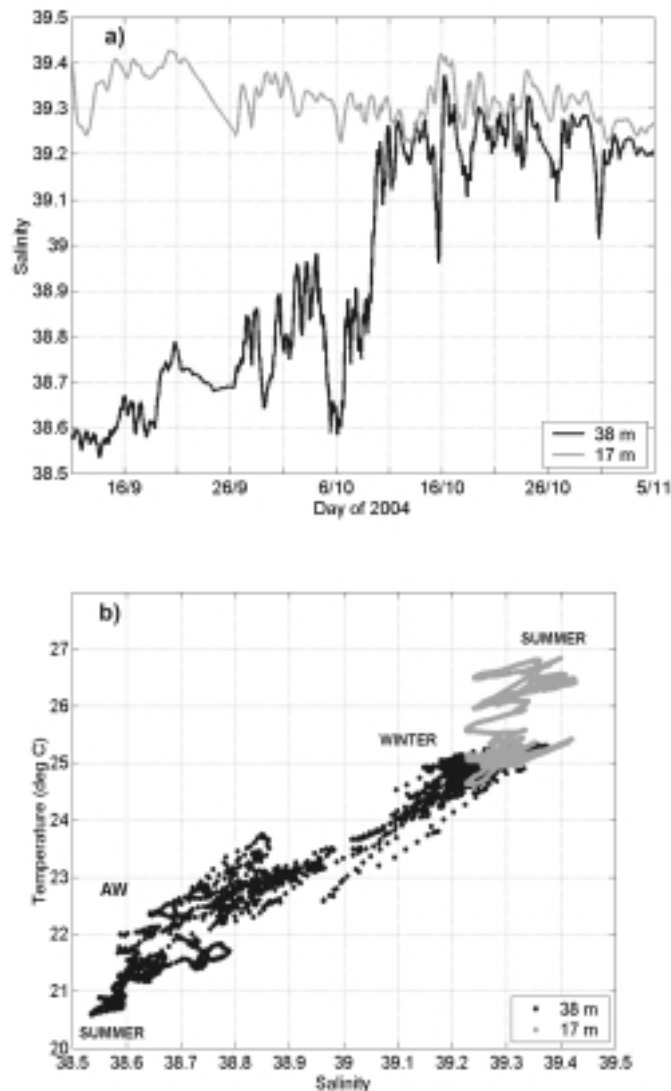


Fig. 9. Data from MedGOOS-3 Buoy, part of the Cyprus Coastal Observing and Forecasting System (CYCOFOS). **a)** Salinity time series at two of the five observed depth levels (17 m and 38 m) for the late-summer period September to November 2004 showing transition to well-mixed conditions in early October 2004. **b)** Temperature-Salinity diagram for the same period and same two depths showing the presence of Atlantic Water (AW) at 38 m during the summer stratified period but not at 17 m.

## CONCLUSIONS

The analyses of *in-situ* data sets collected over a ten-year period from two different observing platforms, with different sampling time and spatial scale, provide strong evidence that the MMJ transfers the main volume of the AW in the SE Levantine basin. These *in-situ* data confirm that the MMJ, after crossing the basin from the offshore southwest part of the Levantine, meanders eastward between offshore Cyprus and the northern periphery of the Cyprus warm core eddy or the Shikmona gyre (when present). Moreover, at a certain period *in-situ* data closer to Egypt provide evidence of a westward re-circulation offshore Egypt.