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Variability of the Cyprus warm core Eddy during the CYCLOPS project

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Abstract

The circulation of the southeastern Levantine Basin (Eastern Mediterranean) as determined from several oceanographic cruises carried out in April, May, and August 2001 and in March, May, and August 2002 was investigated within the framework of the CYCLOPS experiment. The May cruises were part of CYCLOPS while the others, which provide supporting data, were part of the ongoing CYBO project. The May 2002 data provided the location of the eddy and physical description of the circulation, which were crucial for the in situ phosphate/SF_6 addition experiment of CYCLOPS. The major flow features observed in the region south of Cyprus displayed strong variability within the period of the observations. Throughout the entire study period, the warm core, anticyclonic eddy, known as the Cyprus eddy, was a dominant component of the circulation. During the 18 months covered by the cruises, the eddy drifted slowly to the southwest. At the end of the CYCLOPS cruises, the center of this persistent, recurrent eddy was found approximately 100–150 km west of its previously observed location since the 1980s. The mid-Mediterranean jet (MMJ), associated with the rim of this eddy, followed a complex path south of Cyprus depending upon the eddy's shape and location. During most of the study period the MMJ surface currents near the northern periphery of the rim of the eddy were as high as 35–45 cm/s. In May 2002, during the in situ experiment, the near surface seasonal thermocline inhibited downward mixing of the added tracers while the strong horizontal current around the rim of the clearly defined eddy core limited the lateral spreading and dilution of the patch. Finally, the westward shift of the Cyprus eddy allowed space for the generation of a secondary anticyclonic eddy in the eastern part of the domain. The co-existence of the two anticyclonic eddies during 2002 along with the development of a third anticyclonic eddy closer to the coast of Egypt provides strong evidence for the re-establishment of the previously observed, multi-pole, sub-basin scale Shikmona gyre.

Keywords: Eastern Mediterranean Levantine Basin; Cyclops project; Circulation; Warm core eddy; Satellite imagery

1. Introduction

The general features of the hydrodynamic conditions of the Levantine Basin have been known for some time (Ovchinnikov et al., 1976). During the

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second half of the 80s and the beginning of 90s, a more detailed picture of the water masses distribution and the general circulation has emerged (Ozsoy et al., 1991; POEM Group, 1992; Malanotte-Rizzoli et al., 1999). The general circulation of the Levantine Basin consists of a complicated, energetic flow pattern, with strong currents and several multi-scaled eddies, dominated to the west by the sub-basin multilobe cyclonic Rhodes gyre. This is flanked to the north by the westward meandering Asia Minor current (AMC) and to the south by the eastward flowing mid-Mediterranean jet (MMJ). The Rhodes gyre can extend eastward towards the western coast of Cyprus, thereby forming a secondary eddy center, known as the Western Cyprus Cyclonic eddy.

Another important, recurrent dynamic feature in the southeastern Levantine Basin is the anticyclonic Shikmona gyre, consisting of several eddies (POEM Group, 1992). During the late 80s the warm core Cyprus eddy was activate and quite persistent south of Cyprus (Hecht et al., 1988; Brenner, 1989). During the Physical Oceanography of the Eastern Mediterranean (POEM) project this eddy was shown to be the northernmost lobe of the Shikmona gyre. In the late 90s, based on several seasonal field experiments carried out in the frame of the Cyprus Basin Oceanography (CYBO) project, it was shown that the Cyprus eddy is recurrent and persistent for long periods, dominating the general circulation of the entire southeastern Levantine Basin. In particular, it controls the direction of the MMJ south of Cyprus as well as the bifurcation of the MMJ southwest of Cyprus (Zodiatis et al., 1998).

The Cyprus eddy, whose influence extends to depths of about 400 m, constitutes one of the most intense (current speeds up to 30–35 cm/s) dynamic features of the open sea in the southeastern Levantine Basin. The seasonal fluctuation of the Cyprus eddy shows that the baroclinic instability of the eastward flow along its periphery causes the formation of a secondary, smaller anticyclonic eddy, which circulates west of the main eddy center, contributing to an even more complex meandering flow path of the MMJ. Moreover, within the framework of the EU Mediterranean Forecast System Pilot Project (MFSPP), the XBT data collected bi-weekly (Manzella et al., 2003) along the Limassol–Port Said track, followed the quasi-synoptic evolution of the temperature associated with the Cyprus eddy center (Zodiatis et al., 2001).

This paper provides new evidence for the strong seasonal variability of the Cyprus eddy, the MMJ south of Cyprus and the re-establishment of the Shikmona gyre over a sixteen-month period. The results presented were acquired from hydrographic cruises conducted during the EU CYCLOPS project in 2001 and 2002. The principal goal of CYCLOPS was to investigate the in situ role of phosphorous as a growth-limiting nutrient in the oligotrophic Levantine Basin through the fertilization of a small area in the core of the Cyprus eddy with dissolved phosphate. The purpose of the physical oceanographic investigations in this project was to locate the center of the eddy and to study the hydrodynamic regime in support of the in situ biogeochemical experiments during the addition of phosphate and an inert tracer, SF_6 (Law et al., 2005). The latter tracer was used to follow the dispersion of the injected material and to help differentiate between the processes of P loss due to biological uptake as opposed to dilution and mixing (Law et al., 2005). Due to its persistence, intensity, and long-term stability, the eddy center was deemed to be an ideal location for the experiment since over the period of the experiment (up to 10 days) the tracer patch was expected to be contained with limited lateral spreading. While for the specific purposes of CYCLOPS it would have sufficed to present results only from the two May cruises, for completeness, we also present results from CYBO cruises that preceded and followed the CYCLOPS cruises in both years. Thus, we were able to assess both the seasonal evolution and to a lesser extent interannual variability of the Cyprus eddy.

2. Data and methods

The circulation pattern is described on the basis of in situ data collected in the southeastern Levantine Basin in April, May, and August 2001, and again in March, May, and August 2002 on board the R/V AEGAEO. The data were gathered using a Sea Bird Electronics (SBE911+) CTD profiler, equipped with an oxygen sensor and a fluorometer. The measurements were sampled at a rate of 24 scan/s and were averaged in situ over 1 s intervals. In early 2001 and 2002, before each series of cruises, the CTD sensors were calibrated at the metrological facilities of the manufacturer to ensure the quality and accuracy of the data. The sensors exhibited no significant change or drift between calibrations. Salinity spikes were eliminated by passing the raw data through a forward and backward low pass filter.

In order to complement the hydrographic data obtained from above cruises data, a corresponding time series of NOAA–AVHRR and SeaWIFS images and Topex/Poseidon and ERS-2 dynamic topography data of the Levantine Basin was utilized. The NOAA–AVHRR data were received and processed by the HRPT receiving stations operated at the Oceanographic Centre of Cyprus University and at the Plymouth Marine Laboratory (PML) while the altimeter data were processed by

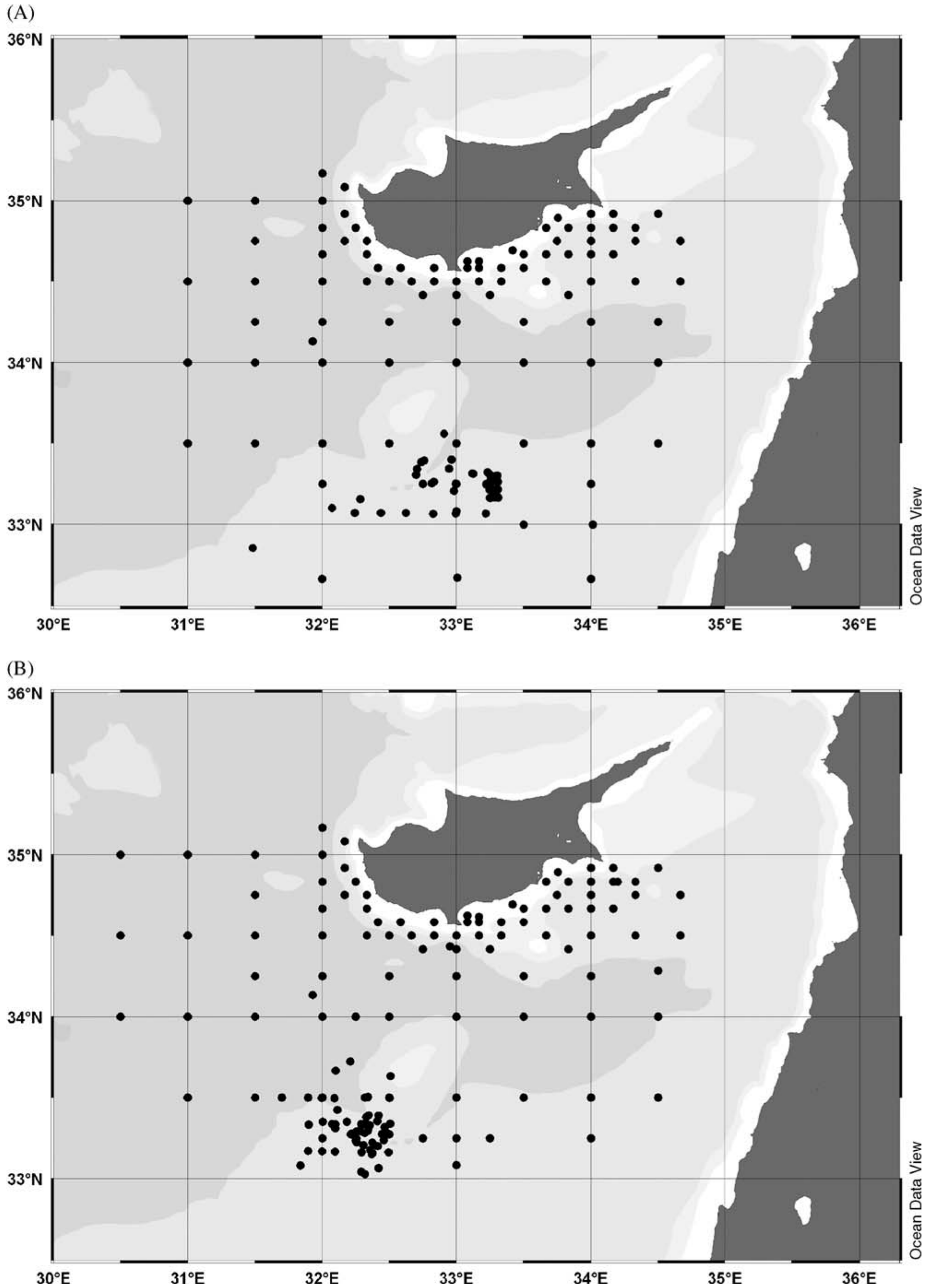

Fig. 1. (A) Stations sampled during the April, May and August 2001 CYCLOPS and CYBO cruises, (B) stations sampled during the March, May and August 2002 CYCLOPS and CYBO cruises.

PML only. In addition, MFSPP quasi-operational daily hindcasts of temperature, salinity, and currents, produced by a data assimilation system, (Pinardi et al., 2003) were used to view the eddy within the framework of the overall, basinwide circulation. Similarly, trajectory data from a subsurface drifter deployed at the depth of 15 m, by the PML group were used to assess the eddy's time variability immediately before and during the biogeochemistry in situ experiments in May 2001 and 2002.

During the first CYCLOPS cruise, CTD data were collected from 69 casts in and around the center of the Cyprus eddy, between 5 and 17 May 2001 (Fig. 1A). Most of the casts during this cruise were shallower than 200 m. The shallow casts were carried out primarily for water biogeochemistry sampling within the upper water layer, while the deep casts were carried out in order to define the exact location of the eddy center. In order to more clearly define the dynamical features of the area under investigation, these data were used together with the data collected from 81 deep (>1000 m) stations of the CYBO cruise conducted from 6 to 11 April 2001 in the broader area south of Cyprus, (Fig. 1A). After the first CYCLOPS cruise, the area of interest was re-surveyed between 23 and 30 August 2001, for the CYBO project, collecting samples from 89 deep casts, on approximately the same sampling grid of April 2001 (Fig. 1A).

During the second CYCLOPS cruise, data from 68 casts were collected on a telescoping grid in the area of the Cyprus eddy center, between 11–26 May 2002 (Fig. 1B). The sampling interval was refined from 20 to 5 km closer to the eddy, in order to help define the exact position of the eddy center. Prior to this cruise, the broader sea area south of Cyprus was surveyed between 24 and 31 March 2002. Samples were obtained from 78 deep stations (Fig. 1B). Following the sampling strategy of the 2001, after the second CYCLOPS cruise the area south of Cyprus was re-surveyed between 25 August–1 September 2002 for the CYBO project, collecting data from 87 deep casts (Fig. 1B).

3. Results and discussion

The analysis of the data from the six cruises described above allowed us to define the circulation before, during, and after the two CYCLOPS in situ experiments. In particular, we were able to assess the persistence, seasonal evolution and, to a lesser extent, the interannual variability of the warm core Cyprus eddy (Zodiatis et al., 2001; Zodiatis et al., 2003). The accurate determination of the location of the eddy center and a description of the local flow pattern was of primary importance for the successful containment and tracking of the tracers injected into the water column during the biogeochemical in situ experiments. It should be noted that of the two experiments, the second (May 2002) was more successful and therefore is the focus of most of the other papers in this volume (e.g., Law et al., 2005). Nevertheless, for completeness, we describe the results from both 2001 and 2002.

3.1. April, May, August 2001

In early April 2001, one month before the first CYCLOPS experiment we surveyed the broad area of interest in the southeastern Levantine Basin. On a west–east section along 33°30′N a clearly defined depression of the isotherms and isohalines, typical of a warm core eddy, was found (Fig. 2). Below the weak, near surface, seasonal thermocline, a homogeneous lens of relative warm (17.25 °C) and saline (39.12 psu) water was located between 40 and 270 m. A similar well mixed lens was found in the Cyprus eddy center during the bi-weekly XBT surveys carried out in this region, from September 1999 to June 2000 (Zodiatis et al., 2001, 2003; Manzella et al., 2001; Fusco et al., 2003). At the surface, relatively cool (18.1–8.5 °C) and fresher (38.92–8.95 psu) water occupied the western part of the domain, while in the southeast the water was significantly warmer and more saline with temperature and salinity of up to 19.2 °C and 39.15 psu, respectively (horizontal map not shown). Below the weak upper thermocline, the horizontal maps of the waters characteristics at the depth of 100 m, clearly showed the horizontal extent of the warm, saline lens forming the eddy core that appeared in the vertical cross sections (Fig. 2). From the horizontal maps (not shown) we concluded that the eddy center was located near 33°30′N, 33°E. This warm core, Cyprus eddy was the dominant circulation feature at this time with a clearly defined anticyclonic center and an elongation to the northwest. This pattern restricted the eastward flow of the MMJ south of Cyprus. A similar pattern was also suggested by the satellite altimeter images received during the same period, although the sea surface height (SSH) images placed the eddy center about 30 km to the west relative to the in situ data. This discrepancy is

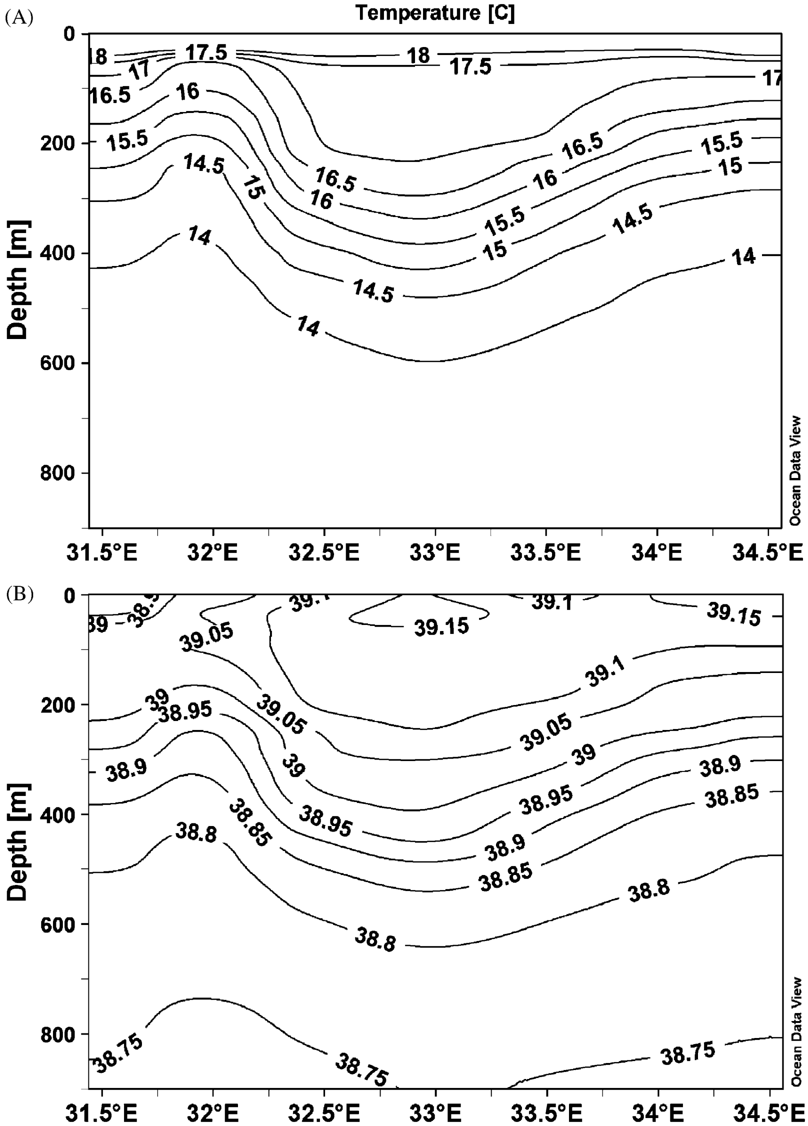

Fig. 2. Vertical distribution of (A) the temperature and (B) salinity on a W–E section along 33°30′N south of Cyprus, April 2001.

probably due to the limited number of satellite tracks and relatively long repeat time of nearly ten days in this region. It is interesting to note that the MFSPP hindcasts in which both XBT, sea surface temperature (SST) and SSH data were assimilated also showed this shift of the eddy position.

One month later, in early May 2001, during the first CYCLOPS experiment, the data from the additional CTD casts allowed us to more precisely locate the eddy core near 33°10′N, 33°E. Moreover, it was also possible to now define the southern boundary of the eddy as far south as 32°30′N.

The composite circulation pattern in April–May 2001, as shown by the 0/700 m dynamic height (Fig. 3), again indicated that that the dominant flow feature in this region was the single large warm core eddy, known as the Cyprus eddy. The 700 m level of no motion was chosen to be consistent with previous studies of this region (e.g., Ozsoy et al., 1991). It also allowed us to fully use the data that were collected closer to the coast of Cyprus. It is interesting to note, however, that its center was located about 100 km to the west of its previously observed location in the 80s and 90s (Brenner et al., 1991; Brenner, 1993). The

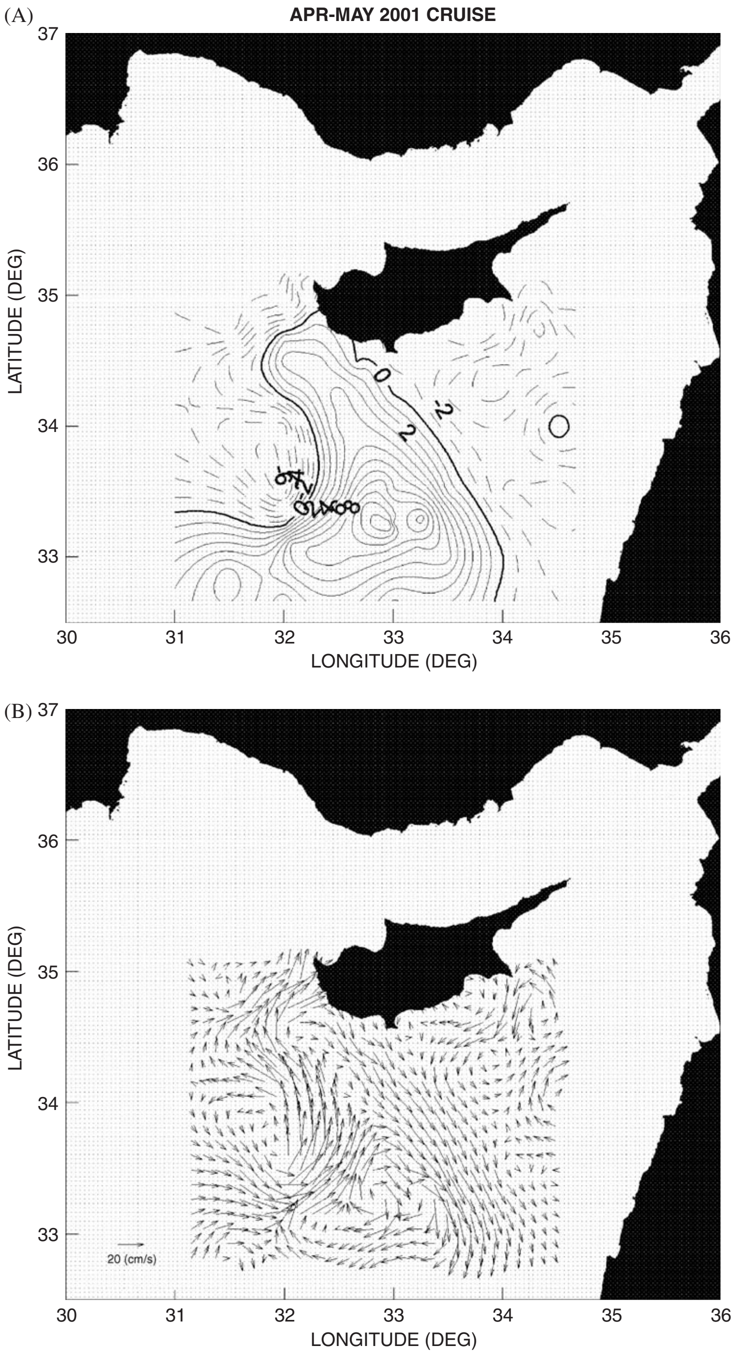

Fig. 3. Dynamic height (0/700 m) and corresponding circulation during April–May 2001.

chlorophyll concentrations from the SeaWifs image of 19 May 2001 (Fig. 4) suggests a similar pattern with filaments of water spiralling anticyclonically into the eddy center, as well as a northwestward elongation of the eddy. The SST image from 24 May 2001 (Fig. 5) also shows the intense anticyclonic eddy south of Cyprus, although the center has shifted slightly to the east relative to the SeaWifs image from five days earlier.

The geostrophic currents (Fig. 3B), computed from the dynamic height field, were as high as 30–40 cm/s around the rim of the eddy in the near

Fig. 4. SeaWifs Chlorophyll concentration on 19 of May 2001.

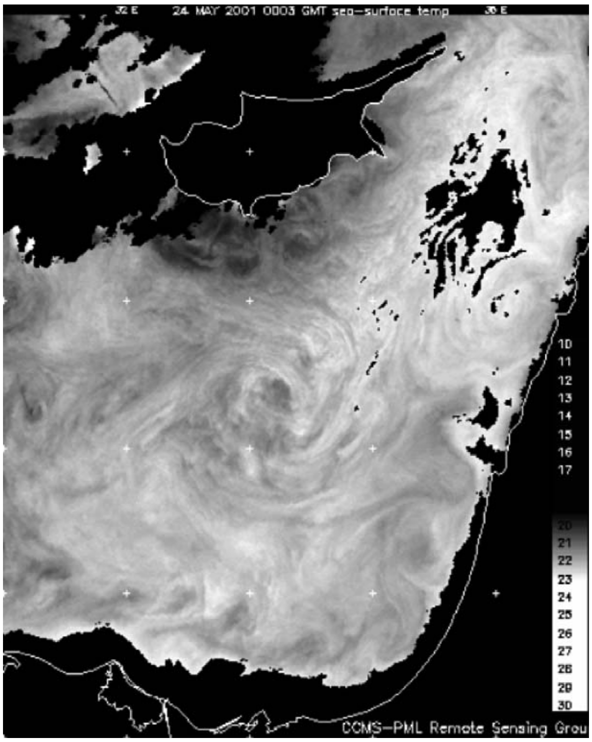

Fig. 5. Sea surface temperature (NOAA–AVHRR images) on 24 May 2001.

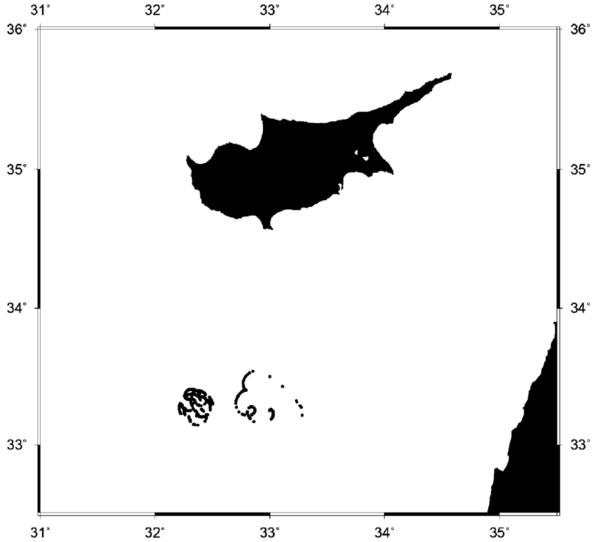

Fig. 6. The subsurface drifter trajectory at 15 m, superimposed during May 2001 (east) and May 2002 (west).

surface layer. The computed geostrophic velocities were comparable to the velocity values estimated from the displacement of a subsurface drifter deployed at the depth of 15 m by the PML group during the first CYCLOPS cruise. The drifter was tracked for a period of 4 days after the phosphorus and the SF_6 infusion. The trajectory of the drifter (Fig. 6—eastern trace), suggests a general clockwise flow around the eddy with a rotation period of about six days with superimposed inertial motions with a period of 23.5–24 h. The shape of the drifter trajectory further confirms the location of the eddy center and determined from the CTD data and from the satellite images. The mean Lagrangian drifter velocity was found to be about 32 cm/s as compared to the geostrophic estimates of 30–40 cm/s.

The westward shift of the Cyprus eddy in April–May 2001, as compared to its historical location, caused the restriction of the eastward flow of the MMJ, thereby reducing the eastward transport of the relatively fresh Modified Atlantic Water (MAW) south of Cyprus. The MMJ turned northward along the western periphery of the Cyprus eddy without any eastward bifurcation south of Cyprus, as was reported to occur in the past (POEM Group, 1992). The usual eastward flow path of the MMJ was restored by the end of May 2001 as revealed by a nearly daily series of SST images obtained during the first CYCLOPS experiment.

This is already noticeable in the 24 May 2001 image (Fig. 5).

By August 2001, three months later, the northwestward elongation of the eddy completely disappeared and a clear eastward path of the MMJ with its associated eastward advection of MAW was restored as shown in Fig. 7. The other important feature that appears here is an intense, well defined warm core Eddy located in the eastern most part of the region. Surface temperatures in the center of this eddy were as high as 29 °C. The earlier SewWifs image (Fig. 4) suggests that this eddy may have

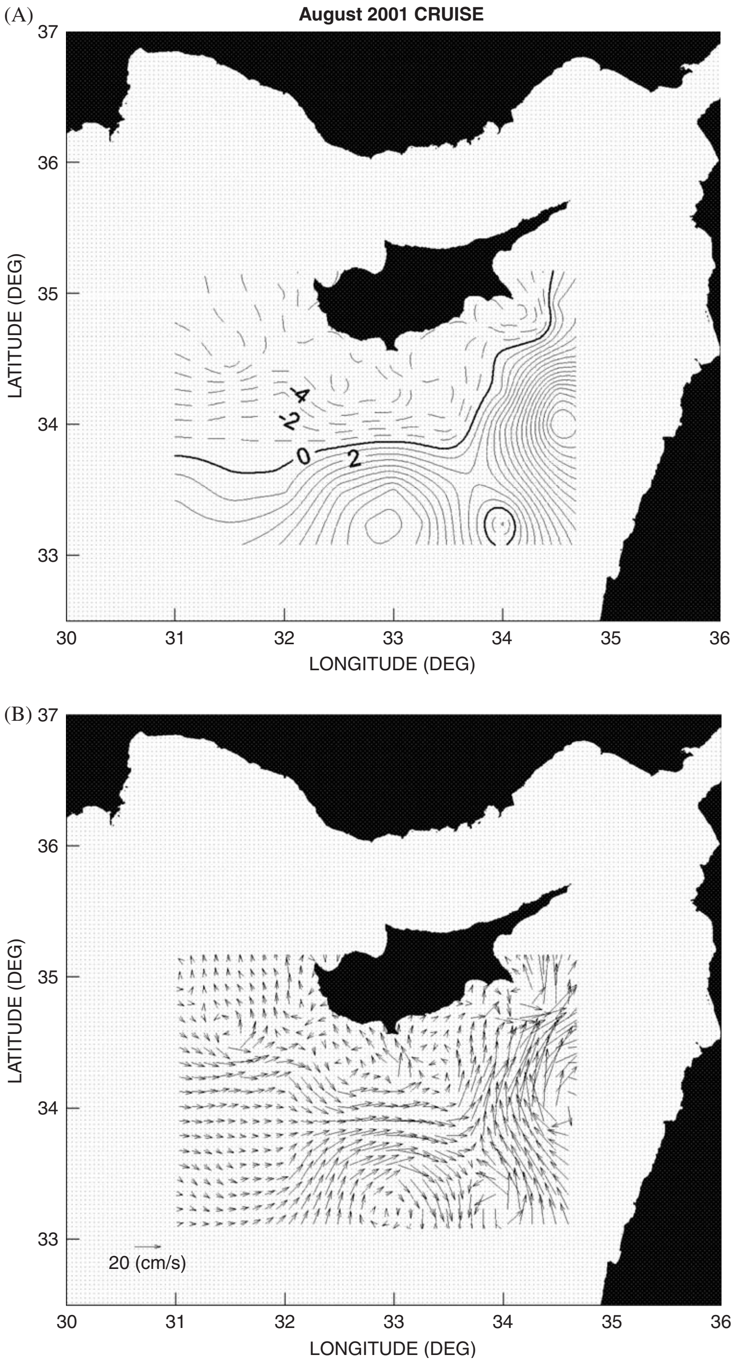

Fig. 7. Dynamic height (0/700 m) and corresponding circulation during August 2001.

formed as a pinched off meander that separated from the shelf break jet along the coasts of Israel and Lebanon. Eddies of this type, which transport relatively warm shelf water into the open sea, have been found to occur frequently in recent high resolution, numerical modelling studies of this region (Brenner, 2003).

3.2. March, May, August 2002

In early March 2002 the hydrographic survey of the region of study provided vital information concerning the structure of the Cyprus eddy (Fig. 8). In particular, its latest location was determined in preparation for the upcoming second

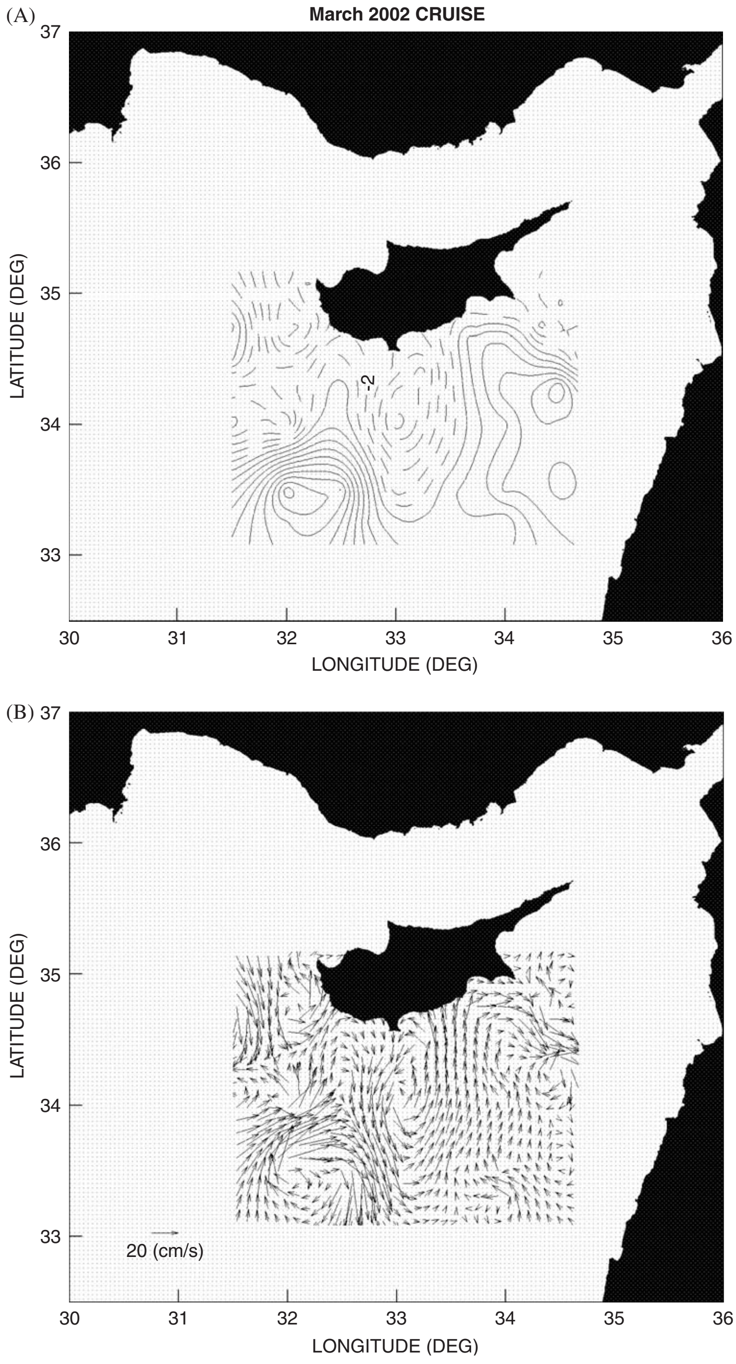

Fig. 8. Dynamic height (0/700 m) and corresponding circulation during March 2002.

CYCLOPS experiment. In comparison to the preceding summer, the center was shifted approximately 80 km to west. The water in the core of the eddy was homogenous from the surface down to 300 m depth, with a temperature of 17.25 °C and salinity of 39.1 psu, similar to the characteristics of the subsurface lens a year earlier. This is consistent with the results of Brenner et al. (1991) and Brenner (1993) who showed that the Cyprus eddy is able to maintain the core temperature and salinity characteristics for periods of up to two years. The thermohaline signal of the eddy's depression of the permanent thermocline was quite discernible down to 600 m, which is also consistent with previous studies of the recurrent eddy in this region. The intense anticyclonic eddy to the east, which appeared in late August 2001 weakened significantly, leaving only a minor remnant. The general direction of the MMJ was still eastward although it formed a large meander that connected the Cyprus eddy and a cyclonic eddy located to its northwest, adjacent to the southern coast of Cyprus.

A similar flow pattern, with two anticyclonic eddies surrounding a single cyclonic was also revealed from the satellite images of SSH in early May 2002 as well as from the operational MFSPP hindcasts for this period. However, an erroneous displacement of the eddy center appeared in these two data sets, similar to the error found in May 2001. Nevertheless, their valuable contribution in defining the eddy variability before the second CYCLOPS experiment was significant in terms of reducing the ship time required to locate the eddy center in May 2002.

Prior to the second CYCLOPS experiment, the center of the eddy, as determined by the CTD casts and supporting satellite images, was located near 33°20′N, 32°22′E which was roughly 40 km west of its location a year earlier. Fig. 9 shows the west–east vertical cross sections of temperature and salinity along 33°50′N, which passes through the northern part of the eddy. The subsurface signal of the core of the eddy is especially noticeable in the salinity section as indicated by the closed 39.12 isohaline. During the in situ experiment, a phosphate/SF_6 solution was pumped into the surfaced mixed layer at a depth of 10 m over a 6 h period (Law et al., 2005). Consequently, in addition to the lateral structure of the eddy, the other important hydrographic feature is the intensifying, near surface seasonal thermocline, which is displaced upward in the center of the eddy. From the results of Law et al. (2005) it is clear that the stratification was strong enough to inhibit any significant downward mixing of the tracers, which remained concentrated in the upper 15 m throughout the nine days of the experiment.

The intensity of the horizontal circulation of the eddy was similar to the previous year with geostrophic velocities along the rim reaching values of 40 cm/s. The high spatial resolution of the casts

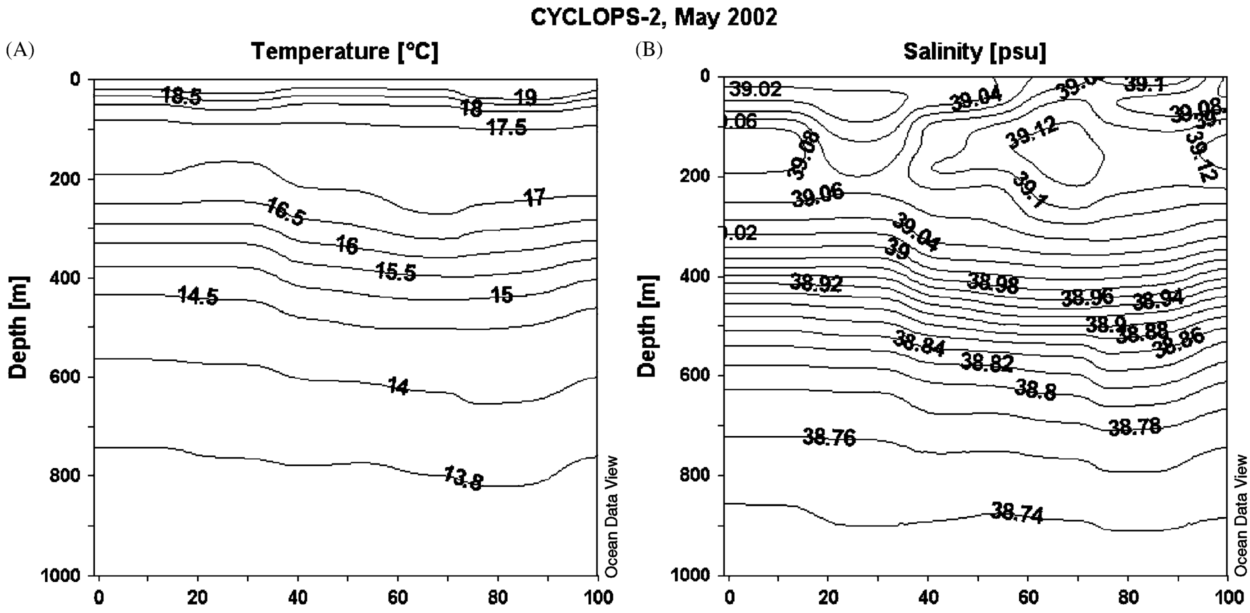

Fig. 9. Vertical distribution of (A) the temperature and (B) salinity on a W–E section along 33°30′N south of Cyprus, May 2002.

on a telescoping grid of stations with the spacing decreasing from 20 to 5 km closer to the eddy center, helped reveal the existence of small-scale meandering structures around the core of the eddy as seen in the dynamic height/geostrophic velocity plots in Fig. 10. These features may play an important role in the lateral spreading of the infused phosphorous and the SF_6 during the in situ biogeochemistry experiment.

During this cruise the PML group also deployed a subsurface drifter at 10 m, which was followed for a period of nine days after the phosphate/SF_6 addition (Law et al., 2005). The trajectory of the drifter is shown in the western trace of Fig. 6. The general behavior of the trajectory was similar to that of the previous year, i.e. a general clockwise rotation with a period of one week with superimposed inertial oscillations with a period of roughly 24 h (Law et al., 2005). Over the period of deployment, the drifter was confined to a much smaller area than during the previous year's experiment. This smaller, more tightly defined vortex was also reflected in the containment of the SF_6 in a clearly identifiable patch throughout the experiment (see Fig. 4 in Law et al., 2005). The tangential velocities of the drifter were between 20 and 40 cm/s, similar to the computed geostrophic flow.

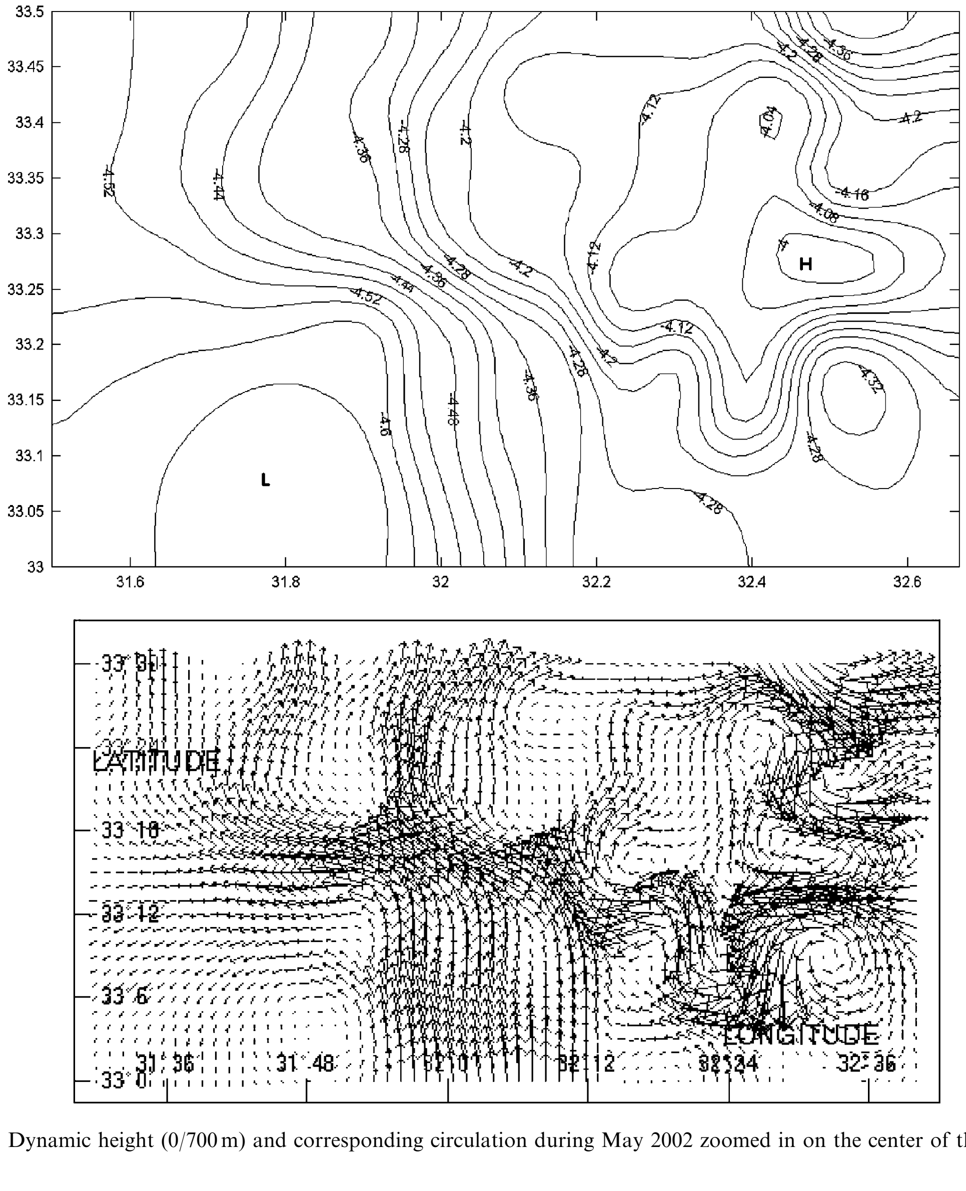

Fig. 10. Dynamic height (0/700 m) and corresponding circulation during May 2002 zoomed in on the center of the eddy.

During the late August 2002 re-survey of the broader area south of Cyprus, the upper 40 m was strongly stratified and contained unusually warm (28–29 °C) and saline (39.4–39.6 psu) water. The subsurface MAW, with salinities as low as 38.9 psu, occupied the entire southern study area down to 80–100 m, while the layer between 100–300 m contained Levantine Intermediate Water (LIW) with salinities as high as 39.05 psu. The dynamic height and geostrophic velocity maps (Fig. 11) again showed a general circulation pattern consisting of two anticyclonic eddies (the Cyprus eddy in the

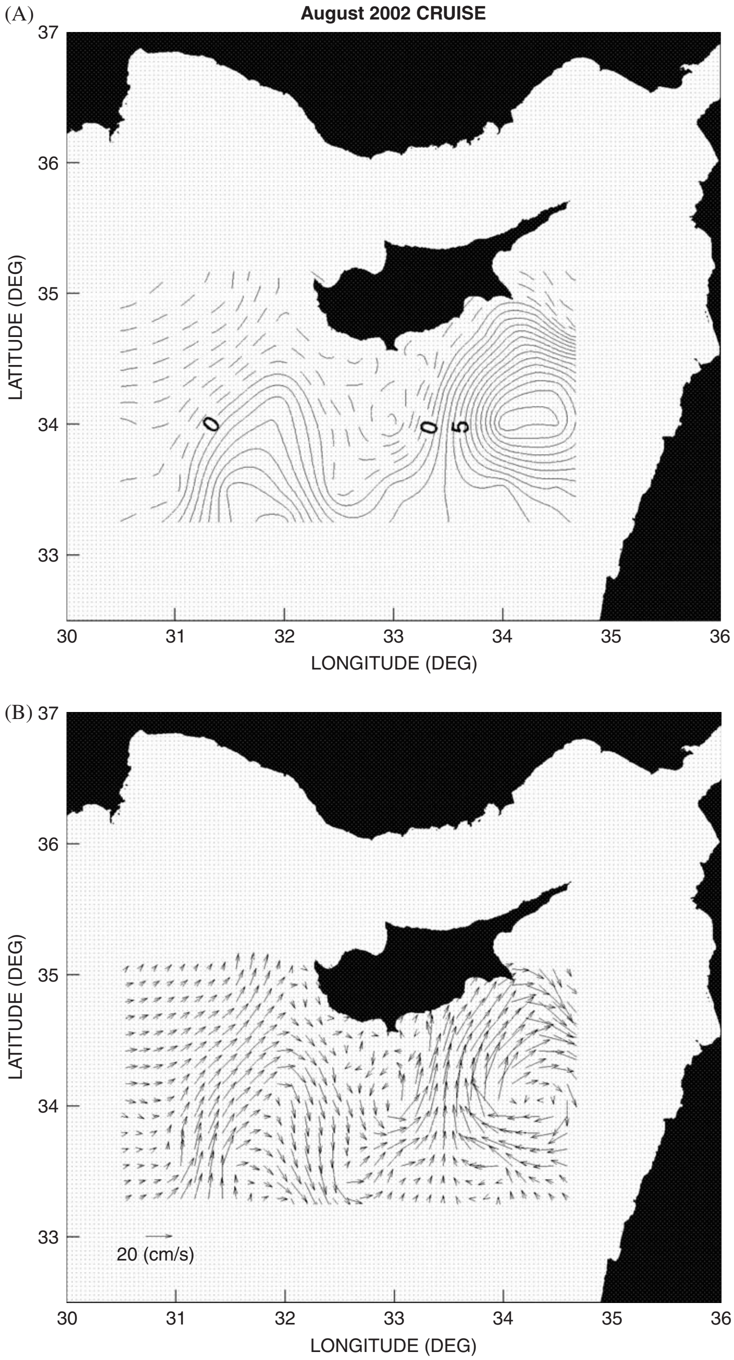

Fig. 11. Dynamic height (0/700 m) and corresponding circulation during August 2002.

southwest and a regenerated, intense eastern eddy) surrounding a cyclonic eddy off the south central coast of Cyprus. We also note that the Cyprus eddy drifted an additional 40 km to the west relative to its location three months earlier.

A similar flow pattern was also seen in several NOAA–AVHRR (an example is shown in Fig. 12) and SeaWIFs images received during the summer. These images show the two intense, warm core eddies mentioned above, as well the MMJ which meandered along their peripheries. In addition the satellite images revealed the existence of a third anticyclonic eddy further to the south of the area of interest, closer to the coast of Egypt (Fig. 12).

The strong fluctuations of the circulation in the southeastern Levantine Basin, the generation of a secondary anticyclonic eddy to the east, the co-existence of the Cyprus eddy with this newly formed eddy from May 2001 to August 2002, as well the appearance of a third anticyclonic eddy to the south, provide additional evidence for the re-establishment of the previously observed, non permanent, multilobe, sub-basin scale, anticyclonic Shikmona gyre. This is consistent with the results from other recent investigations of the southeastern Levantine Basin from 1995 to 2002 (Zodiatis et al., 1998a,b, 2001, 2003).

4. Summary and conclusions

Throughout the entire period of the CYCLOPS experiments in 2001 and 2002 the recurrent, anti-cyclonic Cyprus eddy was shown to be a dominant feature the circulation pattern of the southeastern Levantine Basin. In the first half of 2001 this warm core eddy appeared as a single, large and intense anticyclonic flow feature south of Cyprus, located some 100 km west of its previously observed location in 1980s and mid to late 1990s. In April–May 2001 the eddy was elongated to the northwest, thereby restricting the eastward flow of the MMJ and advection of MAW south of Cyprus. From the

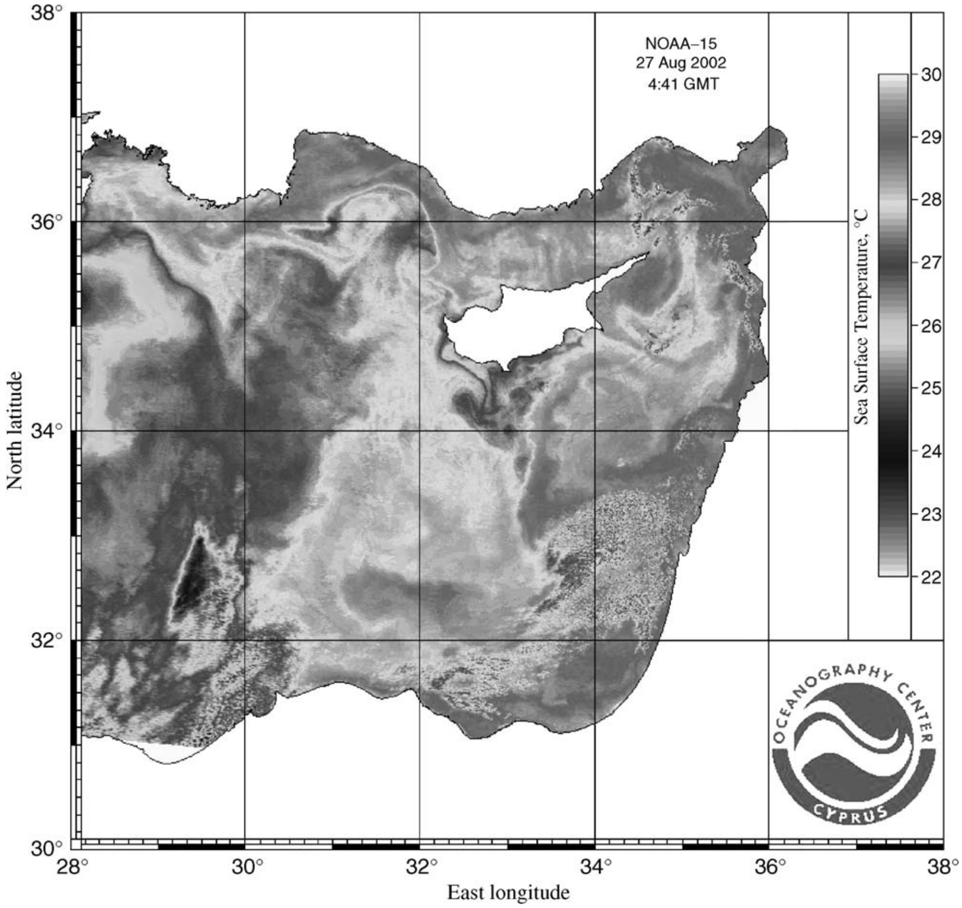

Fig. 12. Sea surface temperature (NOAA–AVHRR images) during August 2002.

second half of the 2001 and through the summer of 2002 the eddy drifted southward by 30–40 km and laterally contracted, thereby allowing the re-establishment both the MMJ and the eastward transfer of MAW south of Cyprus. In the course of 2001 a second eddy developed to the east, apparently as a pinched off meander of the northward flowing shelf break jet along the coasts of Israel and Lebanon. The co-existence of these two warm core eddies south of Cyprus in 2002, as well the appearance of a third warm core eddy closer to Egypt provides strong evidence for the reappearance of the previously observed, multi-pole, sub-basin scale Shikmona gyre in the southeastern Levantine Basin.

In May 2002, the accurate determination of the eddy's location and physical structure, as ascertained from CTD casts and remotely sensed images, was crucial for the successful execution of the in situ phosphate/SF_6 addition experiment. The release and tracking of a subsurface drifter during the experiment further confirmed the flow pattern associated with the eddy. The relatively shallow seasonal thermocline restricted the downward mixing of the tracers while the tightly defined, intense lateral flow around the rim of the eddy contained the tracers in an identifiable patch throughout the experiment as had been anticipated.

Acknowledgements

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