PHYSICAL OCEANOGRAPHY OF THE EASTERN MEDITERRANEAN

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ABSTRACT

The Eastern Mediterranean, and in particular the Levantine Basin, has been one of the least understood parts of the world ocean. The new and definitive synthesis of the Eastern Mediterranean circulation is based on the comprehensive hydrographic data base formed through the national programs of the bordering countries. The POEM research program designed for the cooperative investigation of the physical oceanography of the Eastern Mediterranean has played a central role in the success of these efforts. A new synthesis of Eastern Mediterranean circulation is presented based on the recent data sets. Special emphasis is given to the Levantine Basin, where the data are most abundant. The existence of a series of interacting mesoscale/synoptic eddies and jets, and general circulation features with seasonal and interannual time scales are demonstrated. Long-term qualitative changes in the circulation are reflected in the evolving bifurcation patterns of a mid-basin jet, the abundance, relative strength, and shape of some eddies, and the hydrographic properties of the water masses at the core of these eddies. The confinement of these features within the Basin, and their dynamical interactions with each other appear to dominate the evolution of the circulation. A complete range of scales are observed in the region. The complexity of the circulation is well correlated with the basin-wide and smaller scale heterogeneity of the hydrographic properties. The formation of Levantine Intermediate Water (LIW) in the region appears to be correlated with the interannual evolution of the circulatory features. Wintertime convective overturning and intermediate depth mixing appear to be a dominant mechanism of LIW formation in anticyclonic eddies. Applied results emerging from the synthesis of observations can have important applications, especially in regard to the transport of pollution, biochemical structure, coastal interactions, water mass transformation and current systems.

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INTRODUCTION

The Eastern Mediterranean deserves attention not only because of its role in providing an observation ground and a model basin for interesting oceanic processes, but also because of the yet unresolved local scientific questions, e.g. the driving mechanisms of the regional circulation and water mass formation, with their far-reaching impacts in the entire Mediterranean and parts of the Atlantic Ocean. Reviews of the Eastern Mediterranean oceanography based on historical information are given (Lacombe and Tchernia, 1974, 1960; Miller, 1963; Hopkins, 1978, 1985; Ünlüata, 1986; Hecht, 1986; Malanotte Rizzoli and Hecht, 1988).

In the past, the lack of a coherent description of the circulation and the water mass production in the Eastern Mediterranean has often been attributed to the insufficiency of the data base. It is only after the availability of the recent observations that we have started to understand complexity and natural variability are inherent features of the circulation, and much remains to be done before a thorough understanding of the underlying dynamics is reached.

The international cooperative research programme of POEM (Physical Oceanography of the Eastern Mediterranean) has resulted in a new picture of the dynamical variability of the Eastern Mediterranean to emerge (UNESCO, 1984, 1985, 1987, 1989; Malanotte Rizzoli and Robinson, 1988; Özsoy, Hecht and Ünlüata, 1989; Robinson et al., 1991; Özsoy et al., 1989, 1991, 1992; Robinson, 1992; The POEM Group, 1992). This new description of the phenomenology of the Eastern Mediterranean is based on the POEM first phase data obtained during 1985−1987. These and some additional cruises carried out in the Levantine Basin from 1985 till the present have led to valuable information on the space-time variability of the circulatory features of the Basin.

The Eastern Basin of the Mediterranean is comprised of the Ionian and Levantine Basins, connected by the wide and relatively shallow waters of the Cretan Passage (Fig. 1). In this review, we exclude the specific details of sub-basins and connected bodies of water such as the Adriatic, the Aegean and the Black Seas, and concentrate on specific characteristics of the Ionian and Levantine Basins.

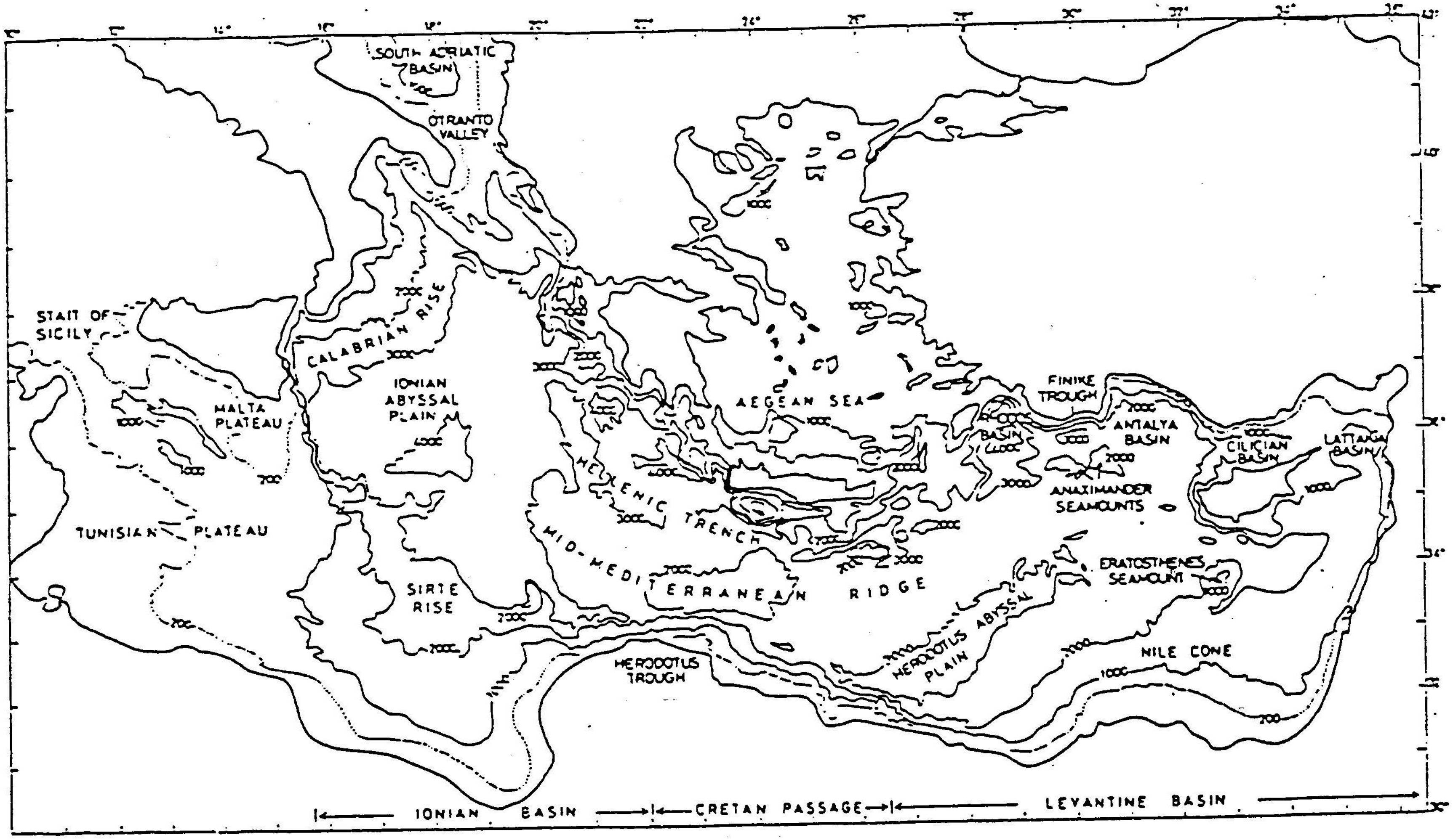

Fig. 1. Bottom topography and geographic features of the Eastern Mediterranean.

REGIONAL CHARACTERISTICS AND DATA SETS

Bottom topography

The bottom topography of the Eastern Mediterranean Basin is shown in figure 1. The Ionian Basin is connected to the Western Basin by the Strait of Sicily (1000 m), and to the Adriatic Sea by the Otranto Passage. The deep Ionian Abyssal Plain (4000 m) is bounded in the west by the shallow Tunisian and Malta Plateaus and by the Calabrian and Sirte Rise regions respectively to its north and south. The Hellenic Trench outlines the Cretan Archipelago with deepest regions of up to 5000 m southwest of Greece and 4300 m in the Rhodes Basin at its eastern most extension. The Mid-Mediterranean Ridge runs from the Ionian Basin into the Levantine Basin south of the Hellenic Trench, and has its shallowest region at the Herodotus Rise (1600 m) in the Cretan Passage. South of the Mid-Mediterranean Ridge, the Herodotus Trough occupies the southern part of the Cretan Passage, and the Herodotus Abyssal Plain (3000 m) occupies the southwestern part of the Levantine Basin.

The smaller scale bathymetric features of the Levantine Basin are the Lattakia (1000–1500 m), Cilician (1000 m), Antalya (2000–3000 m) and Rhodes (4000 m) Basins and the Anaximander (1500 m) and Eratosthenes *(1000 m) Seamounts. The relatively shallow* Lattakia and the Cilician Basins communicate with each other through a narrow channel of 700 m depth located nearly midway between the sill extending from the northeastern tip of Cyprus to the mouth of the Gulf of Iskenderun.

Meteorology and surface forcing

The frequent incidence in winter and spring of extratropical cyclones in the Eastern Mediterranean results in significant variability of the meteorological conditions in the region (Reiter, 1975; Mediterranean Pilot, 1976; Karein, 1979; Brody and Nestor, 1980; Özsoy, 1981). The Ionian and the Levantine Basins are significant regions of cyclogenesis. Local wind systems with significant space-time variability are generated in the region as a result of the climatic contrasts maintained by the land topography. Some examples are Sirocco and Khamsin along the African coast, Bora on the Dalmatian coast, Etesians over the Aegean Sea and Poyraz along the Anatolian coast (Reiter, 1975; Özsoy, 1981). In addition, intense sea-breezes in the summer and autumn accompany the seasonal wind systems.

Climatological mean flows in the Eastern Mediterranean can basically be described as predominantly westerly winds in winter, and northwesterly winds strengthened by the Aegean Etesian regime in summer (Middelandse Zee, 1957; Brody and Nestor, 1980). The monthly mean wind-stress distributions of May (1982) also display this seasonal pattern.

The intense outbreaks of cold and dry air into the Eastern Mediterranean from the northern continental regions play an important role in the oceanography of the region. Dense water formation and deep convection accompany similar outbreaks in the Adriatic and the Western Mediterranean basins. In the Eastern Mediterranean, the significant buoyancy losses generated by the cold and dry outbreaks have been recognized as the predominant source for the formation of the Levantine Intermediate Water (Wüst, 1961; Morcos, 1972).

Estimates of the various components of the fluxes at the air-sea interface have been compiled by Bunker (1972), Bunker et al. (1982), Colacino and Dell'Osso (1975, 1977), Metaxas and Repapis (1977), Bethoux (1979, 1980), May (1982), Peixoto et al. (1982), Hellerman and Rosenstein (1983), Goossens (1985), Navarra (1986), Navarra et al. (1987), Malanotte Rizzoli and Capotondi (1991). Some of these estimates of surface fluxes have been compiled and used recently in the numerical model studies of Pinardi and Navarra (1988, 1991), and Malanotte Rizzoli and Bergamasco (1989, 1991), and Pinardi and Navarra (1991), all of which found the surface fluxes to be important in driving the circulation.

The data sets

The first hydrographic measurements in the Eastern Mediterranean have been obtained by Captain Beaufort in 1811–1812 (along the Anatolian coast), by Captain Spratt in 1845, and by Carpenter in 1871, aboard British ships. The first scientific investigation of the Levantine Basin was carried out in 1890 by the Austro–Hungarian ship POLA, followed in 1910 by the Danish ship THOR. These early measurements were far from being sufficient, but they provided the first glimpse into the oceanography of the region. Since then, and before the 1970's, the USA ship ATLANTIS (1958), the French CALYPSO (1956) and JEAN CHARCOT (1967), the Japanese SHOYO–MARU (1959), the USA ATLANTIS (1961 and 1962), the USA CHAIN (1961), and the USA PILLSBURY (1965), the Soviet VAVILOV (1959–1963) and ICHTEOLOG (1966) and the Turkish CARSAMBA (1968) have collected data in the region.

Mediterranean Sea Atlases containing some of the historical data have been prepared by Miller et al. (1970) and Guibout (1987). Selected historical data from the various cruises in the Eastern Basin are included in the climatological archive of Levitus (1982), and have been used in the numerical modeling studies of Pinardi and Navarra (1988, 1991), and Stanev et al. (1989, 1991). The MOODS data set of the U. S. Fleet Numerical Oceanography Center is believed to partly cover the same data, and has been utilized by Feliks and Itzikowitz (1987). Seasonally averaged climatological data of the U.S. Naval Oceanographic Office (1989) have been used by Tziperman and Malanotte Rizzoli (1991), who report noisy data in the deeper levels of the Levantine Basin. Separate analyses of seasonal climatological fields based on the Bureau National de Donnees Oceanographiques (BNDO), Brest, data set have been made by Roussenov and Brasseur (1991).

The more recent MC (" Marine Climate ") data set collected by the Israeli ships has been described extensively by Hecht et al. (1985, 1988) and has been used by Feliks and Itzikowitz (1987) and Tziperman and Hecht (1988) in their analyses.

The much needed recent data in the Eastern Mediterranean have been collected by a number of institutions on an extensive network of stations. The national programmes of the bordering countries formed the main framework of the research, and the POEM programme ensured the synthesis of the results from planned scientific experiments. In spite of attempts to obtain complete synoptic coverage of the Eastern Mediterranean during the POEM multi-ship cruises, and the maximum coverage obtained during POEM 05 (August–September 1987) (Pinardi, 1988; Robinson et al., 1991a), major data gaps remained in the southern Ionian Basin. Almost complete coverage of the Levantine Basin (excluding minor gaps south of Cyprus and along the African coast) was obtained in the POEM 01 (October–November 1985), POEM 02 (March–April 1986), POEM 05 (August–September 1987) and the July–August 1988 surveys (Özsoy, Hecht and Ünlüata, 1989; The POEM Group, 1992; Özsoy et al., 1991, 1992; Robinson et al., 1991). The increased coverage obtained from some extra cruises of the BILIM in the northern Levantine aided the interpretations. At present, post-POEM basin-wide surveys are being continued in the context of the Levantine Basin Dynamical Studies (LBDS). Two surveys, the LBDS 01 of March 1989 and LBDS 02 of August 1990 have been completed to date (Özsoy et al., 1992).

CIRCULATION AND INTERNAL DYNAMICS

THE GENERAL CIRCULATION

The Levantine Basin

The Nielsen (1912) scheme of well defined cyclonic circulation in the Levantine Basin has left an indellible mark on the oceanography of the region. In spite of later modifications (e.g. Lacombe, 1975) the concept of cyclonic circulation in the Levant survived till the 1980's with contributions of additional details derived from other cruises up to the 1960's. The intensive Russian studies of the Mediterranean Sea during the 1960' s could not alter the basic scheme of circulation derived in the first half of the century. On the other hand, these studies, for the first time, provided details of the circulation for the entire Mediterranean Sea (Ovchinnikov, 1966; Ovchinnikov et al., 1976) based on geostrophic calculations (Fig. 2).

In the past two decades, scientific views have evolved, so that the Eastern Mediterranean is now perceived as a complex dynamical system.

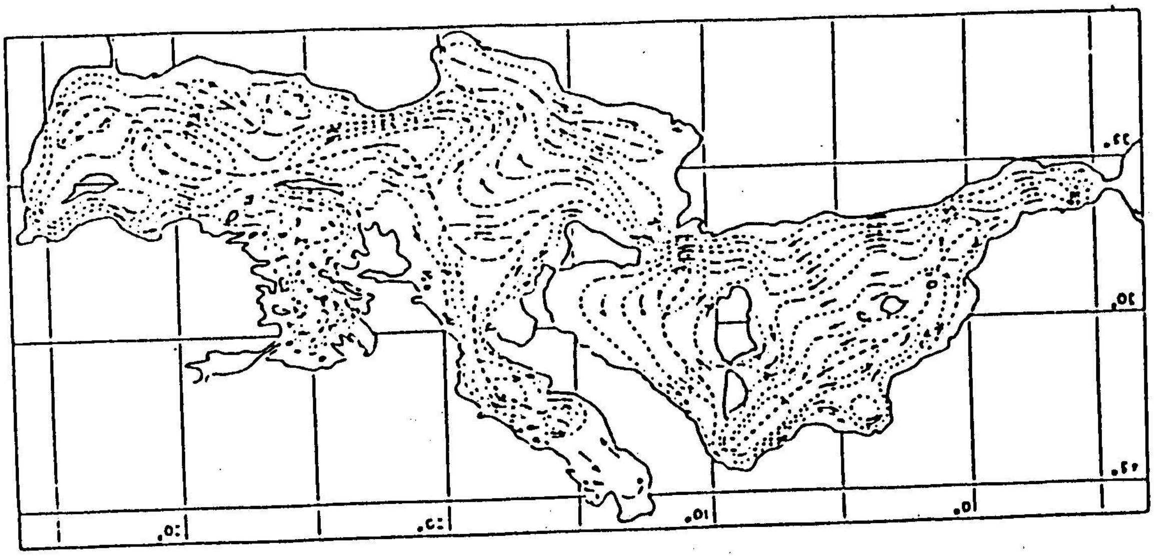

Fig. 2. The winter circulation of the Meditarranean Sea according to Ovchinnikov (1966).

The first contradictions between the new results and the earlier schemes, at least in the southestern Levantine, appeared in the studies of Engel (1967) and Oren (1970), who found anticyclonic circulations in the region. In fact, anticyclonic eddies in the southern part of the Levantine basin were also indicated by Ovchinnikov et al. (1976) in some of their data but were not sufficiently emphasized. A Russian survey in 1977 also differed from the analyses of the earlier data and indicated anticyclonic circulations in the southern Levantine in the positions of the Mersa Matruh and Shikmona Gyre complexes (Ovchinnikov, 1984a).

It is interesting to note that, in recent years, the renewed analyses of the historical data for identification of eddies (Feliks and Itzikowitz, 1987) and the climatological mean circulation (Fig. 3) derived from an inverse model using

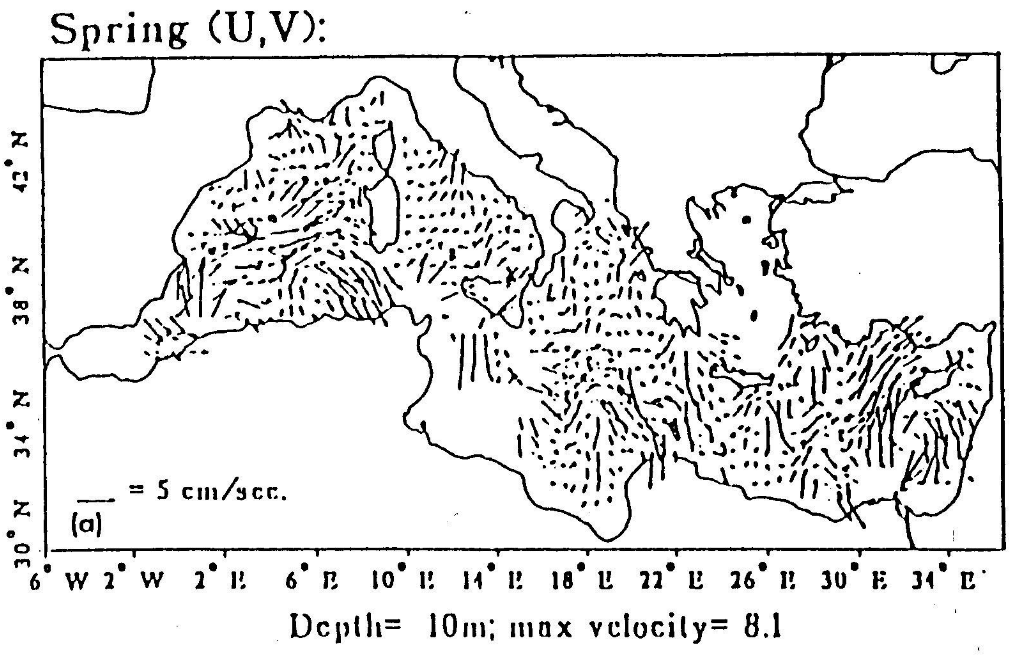

Fig. 3. Surface (a) and 700 m depth (b) circulation derived from climatological data with an inverse model, after Tziperman and Malanotte Rizzoli (1991).

historical data (Tziperman and Malanotte Rizzoli, 1991) reveal the abundance of anticyclonic eddies in the southern Levantine and in some parts of the northern Levantine (excluding the domain of influence of the Rhodes Gyre).

New and more adequate experimental designs such as the MC (" Marine Climate ") cruises of the 1970's and 1980's and the recent POEM surveys have made possible a more detailed identification of the circulation features. A synthesis of the Eastern Mediterranean circulation has been made by Robinson et al. (1991) and The POEM Group (1992), and a synthesis of the Levantine Basin circulation based on more detailed coverage of the region by the Israeli SHIKMONA and the Turkish BILIM has been made by Özsoy, Hecht and Ünlüata

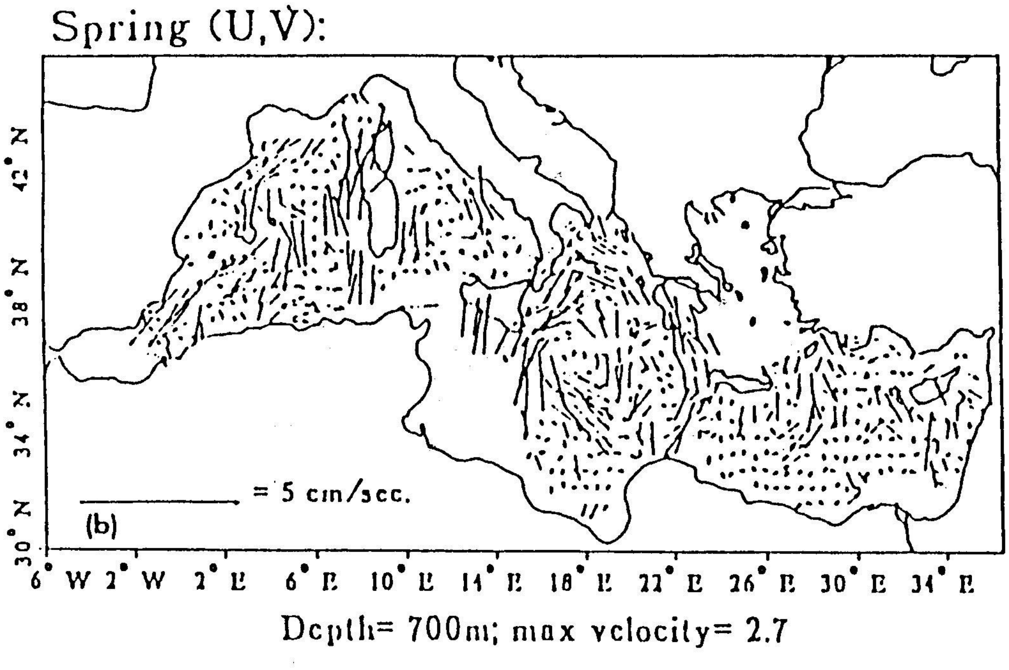

Fig. 3. Surface (a) and 700 m (b) depth circulation derived from climatological data with an inverse model, after Tziperman and Malanotte Rizzoli (1991).

(1989) and Özsoy et al. (1991, 1992). Figure 4 outlines the persistent and recurrent features observed during POEM.

The details of the Levantine surface circulation can be observed from the October–November 1985 (ON 85) and March–April 1986 (MA 86) data sets (POEM 1 and POEM 2 surveys). Dynamic height anomaly computations

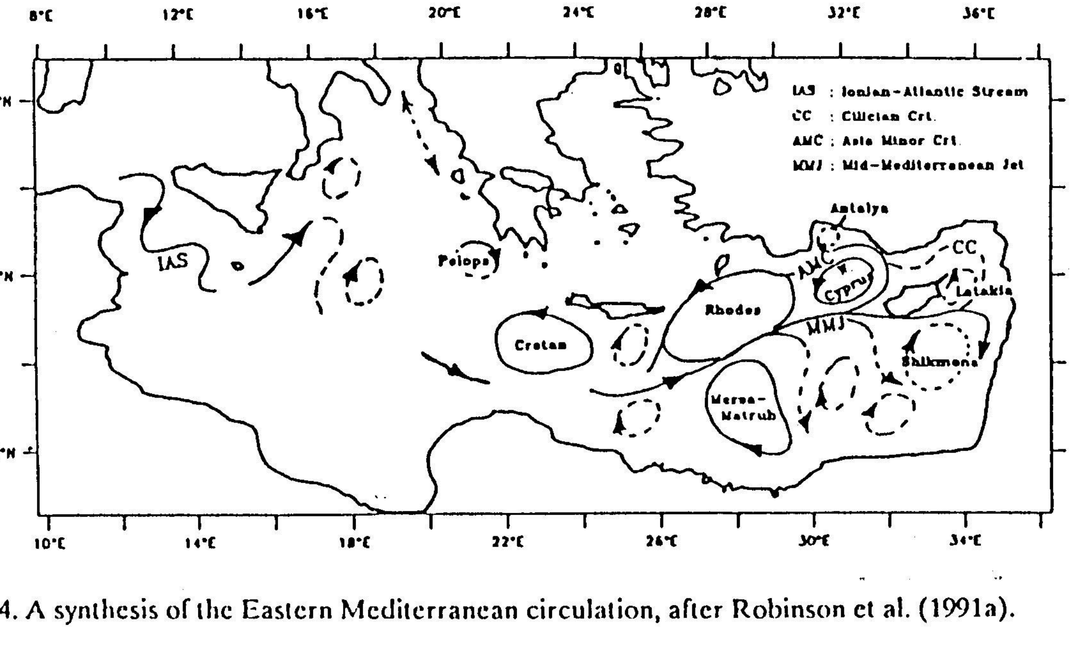

Fig. 4. A synthesis of the Eastern Mediterranean circulation, after Robinson et al. (1991a).

referenced to 800 decibars (Özsoy, Hecht and Ünlüata, 1989) are given in figures 5 a–d. These two experiment periods respectively correspond to the summer and winter conditions in the Levant (Hecht, Pinardi and Robinson, 1988).

The circulation in either survey had three major elements: the Rhodes Gyre with a number of centers located southeast of Rhodes and an extension towards Cyprus; the intense Mersa Matruh Gyre south of the Rhodes Gyre; and the Shikmona Gyre with multiple centers occupying the southeastern Levantine Basin (Fig. 5 a–d). The twin centers of the Mersa Matruh Gyre and the northerly member of the Shikmona Gyre complex (i.e. the Shikmona eddy) were coherent at the depths of the thermocline. A persistent anticyclonic eddy was indicated in the Finike Trough between the Anaximander Seamounts and the Turkish coast. Another anticyclonic eddy with intensifying deeper structure appeared at the junction of the Cilician Basin and Antalya Bay and was referred to as the Antalya eddy. In the ON 85 a coherent surface jet (the Central Levantine Basin Current) flowed towards the east and bifurcated several times to become entrained in sub-basin scale gyres.

Comparison of the circulation in the ON 85 and MA 86 surveys shows temporal variability of the features, including the shifting of the centers of the gyres and deformation and undulation of their boundaries. In MA 85 the Rhodes Gyre is in the form of a crescent engulfing the Mersa Matruh Gyre. The jet system encircling the Mersa Matruh gyre undergoes large north-south excursions, with intense currents along the periphery of the mid-basin gyres.

A permanent feature of the general circulation is the meandering flow along the southern coast of Turkey, called the Asia Minor Current (AMC). This current did not extend to the Cilician Basin (northeast corner of the Levant) in the ON 85 and MA 86 surveys, but the well developed case with the coherent and intensely meandering structure of the AMC along the entire Anatolian coast is illustrated for other realizations (Fig. 8 and Fig. 9).

The continued measurements by joint surveys, and the partial coverage provided by northern Levantine data were used to study long-term variations. A detailed description of the observed changes can be found in Özsoy et al. (1991, 1992), and forms the basis for the following discussion.

One of the important features of the northern Levantine is the deep and coherent Antalya anticyclone persistent in the first two POEM surveys (Fig. 5 a–d). It persists in the same position during October 1985 – June 1986, and contains high salinity LIW trapped in its core. West-east salinity sections along the Anatolian coast in figures 6 a and b display the intense structure of this eddy

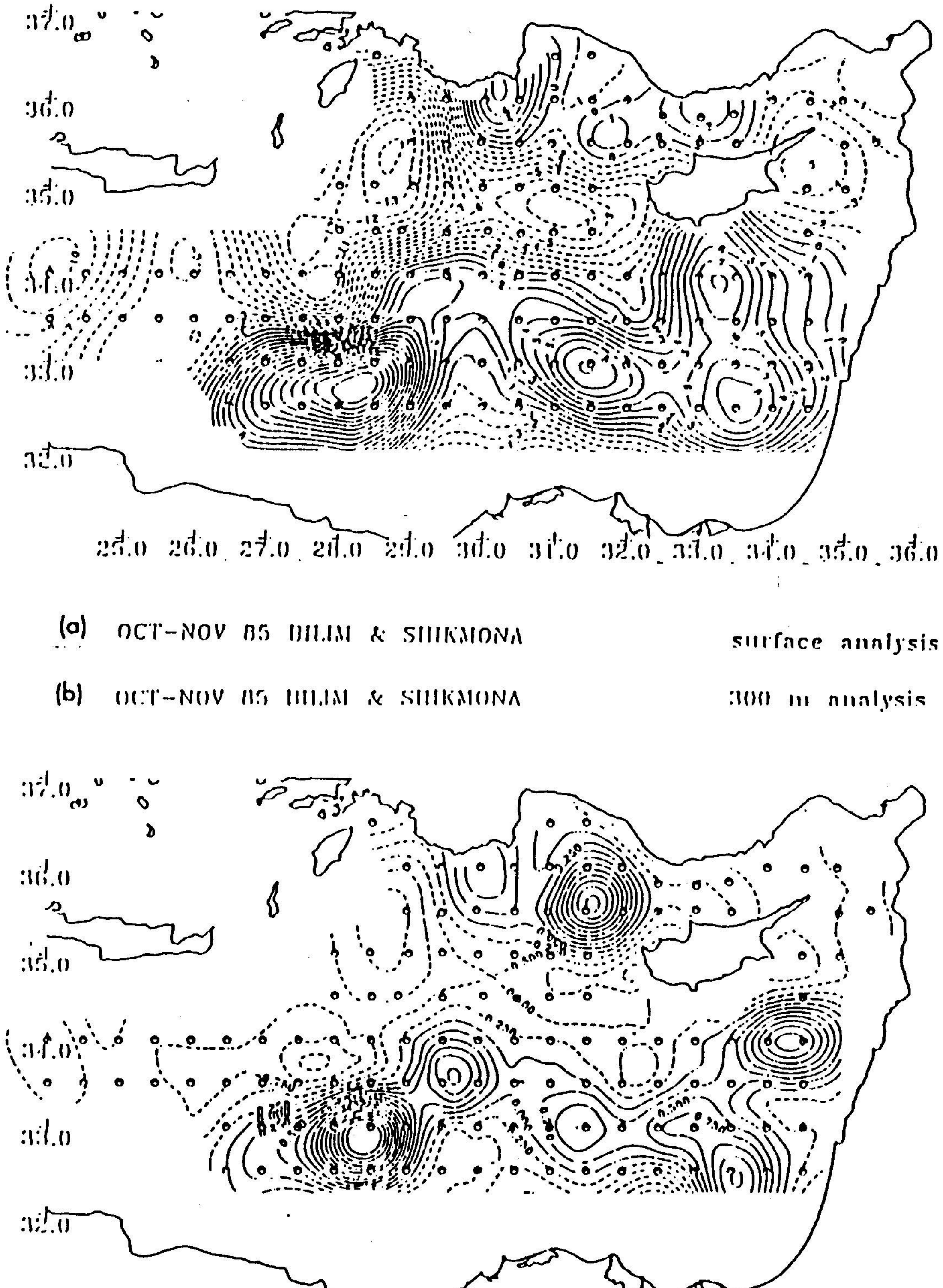

Fig. 5. Surface (a) and 300 m (b) dynamical topography during October–November 1985 surveys of the Levantine Sea, after Özsoy et al. (1989).

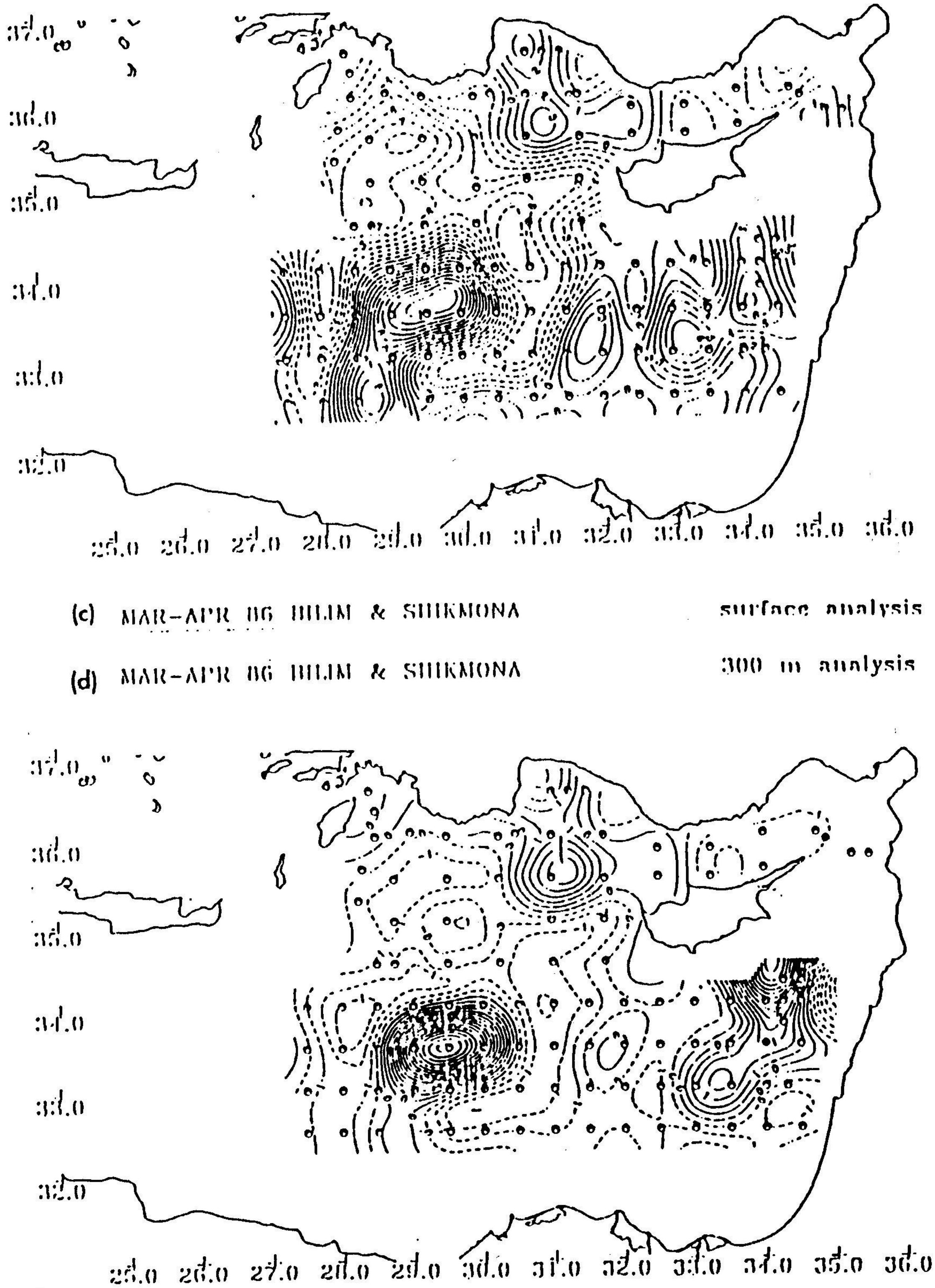

Fig. 5. Surface (c) and 300 m (d) dynamical topography during March–April 1986 (POEM 02) surveys of the Levantine Sea, after Özsoy et al. (1989).

during this period. A series of significant changes take place in 1987. In February 1987, two eddies carrying Atlantic Water (AW) in their cores were observed to enter the Lattakia Basin from the south (Özsoy et al., 1991). Shortly thereafter, the Antalya anticyclone appeared to change form, shifted its position and entrained a large pool of AW in June 1987, due to a possible merger of the

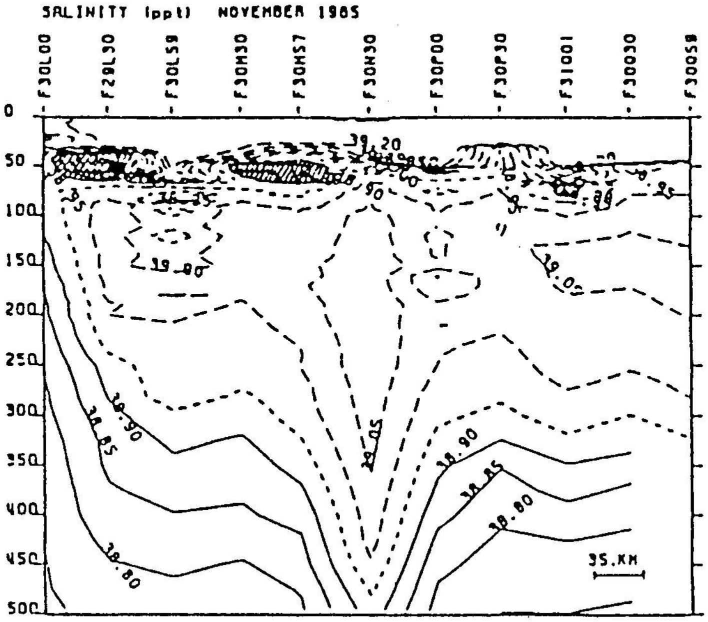

Fig. 6a. West-east sections of salinity in the northern Levantine during October–November 1985, after Özsoy et al. (1989).

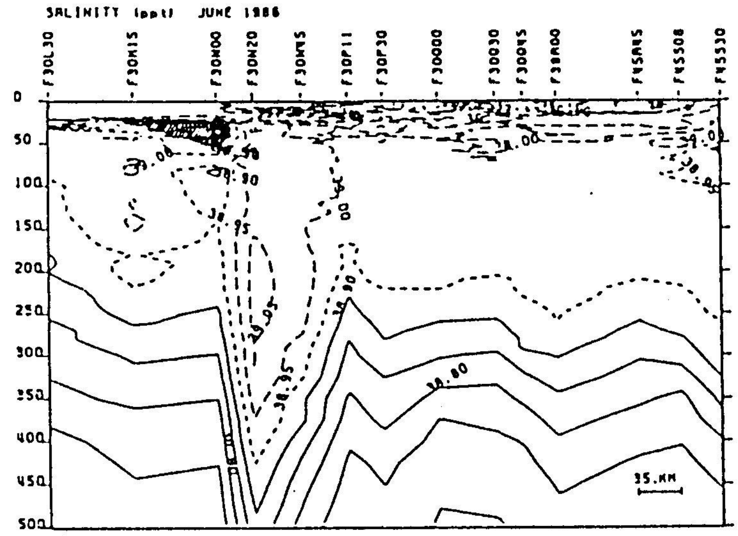

Fig. 6b. West-east sections of salinity in the northern Levantine during June 1986, after Özsoy et al. (1989).

Anaximander and the Antalya anticyclonic eddies (Fig. 6c). The upper part of the newly merged eddy is dominated by Atlantic Water entrained into its core in the course of the merger. In about the same period (September 1987) Brenner et al. (1990) report extensive penetration of AW into the core of the

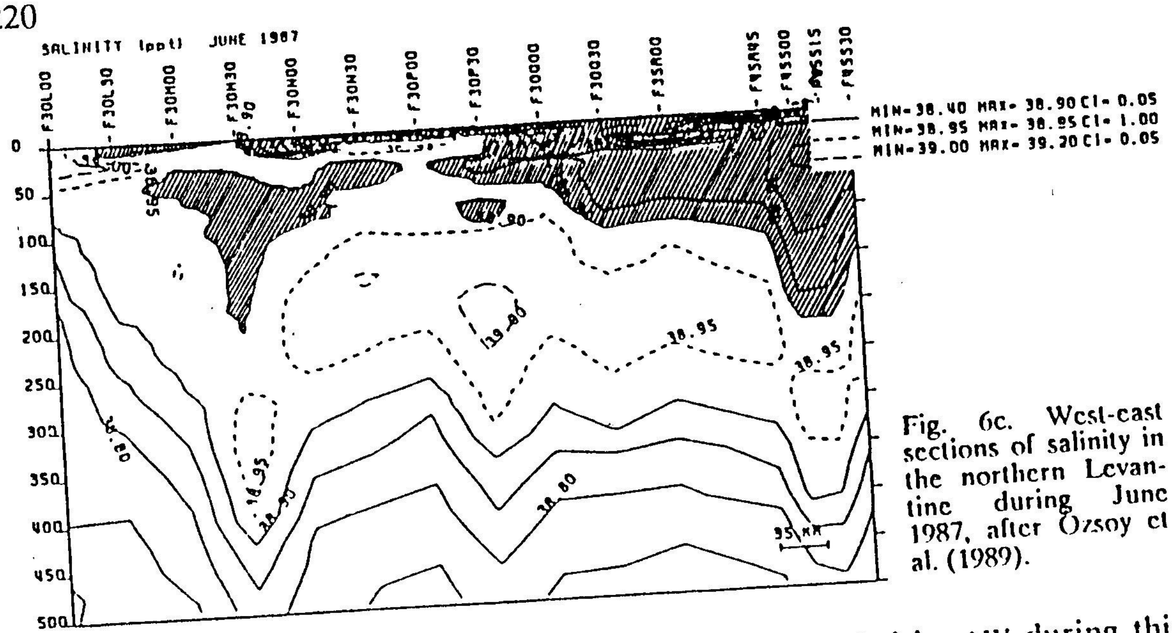

Fig. 6c. West-east sections of salinity in the northern Levantine during June 1987, after Özsoy et al. (1989).

Shikmona eddy. It is significant that the region is flooded by AW during this period, and that this change is associated with changes in the circulation patterns in 1987 and 1988.

Based on the analysis of additional ship data in the region from the POEM 05 (August–September 1987) combined survey, The POEM Group (1992) and Robinson et al. (1991) indicate (Fig. 7 a and b) parts of the Mersa Matruh and Shikmona Gyre complex, and the bifurcating flow of the Central Levantine

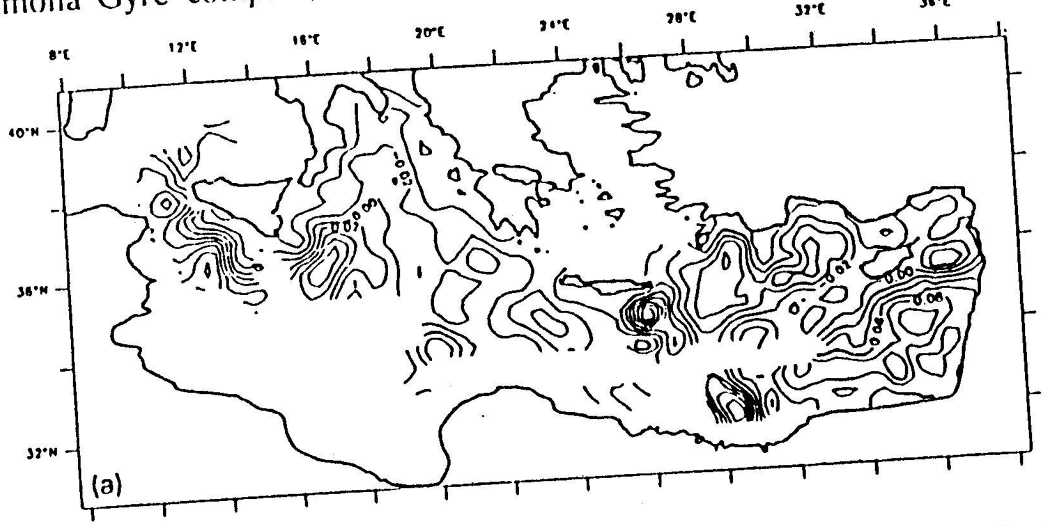

Fig. 7a. Surface dynamical topography in the Eastern Mediterranean during August–September 1987, POEM 05, after Robinson et al. (1991a).

Basin Current with minor penetration into the Cilician Basin. During this period, the Antalya anticyclonic eddy has disappeared, but the Anaximander anticyclonic eddy is persistent in its position adjacent to the Turkish coast. The

Rhodes gyre occupies a large area west of Cyprus. The intense Shikmona eddy is located more to the south of its location than in the POEM 01 and POEM 02 observations, as indicated by Brenner et al. (1990). A new feature that can be identified in September 1987 is the intense anticyclonic eddy southeast

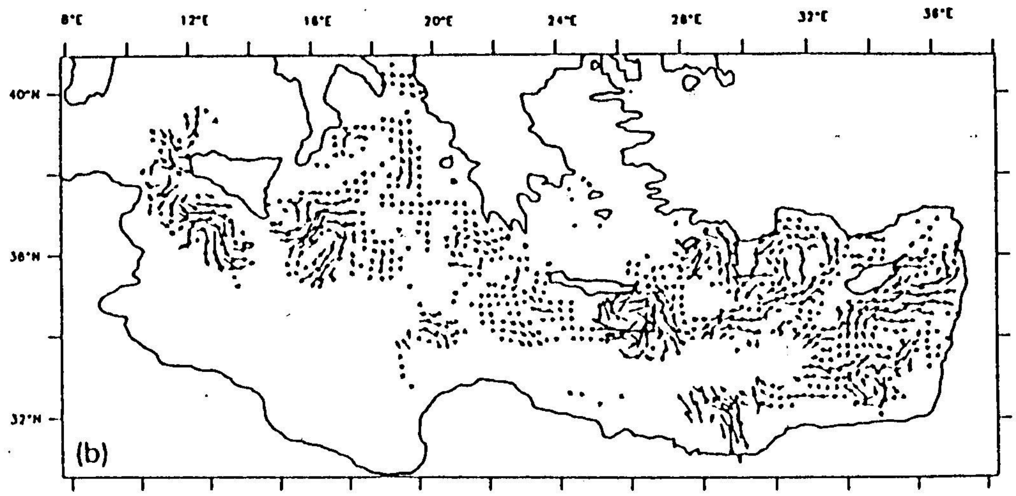

Fig. 7b. Currents in the Eastern Mediterranean during August–September 1987, POEM 05, after Robinson et al. (1991a).

of the island of Crete. It is also worthy of note that the AW penetrating the northern Levantine in June 1987 is largely diminished in September 1987 (Özsoy et al., 1991).

In the next combined Israeli and Turkish cruises in July 1988 (Özsoy et al., 1992), significant changes are revealed in the circulation (Fig. 8a), with a large part of the jet flow south of Cyprus reaching the Syrian and Turkish coasts, to form the Asia Minor Current. A coherent flow is observed along the Turkish coast, meandering strongly in the entire region from the Lattakia–Cilicia Basins to the Island of Rhodes, in a pattern characteristically different from the earlier period shown in figure 5. The Rhodes Gyre with multiple cyclonic centers engulfs an anticyclonic extension of the Mersa Matruh Gyre. The Shikmona Gyre complex with the anticyclonic Shikmona eddy is also present.

From July 1988 until 1990, the same pattern of penetration into the Cilician Basin and the flow of the meandering Asia Minor Current along the Anatolian coast continue to exist in the Levantine Basin (Özsoy et al., 1991, 1992). In repeated cruises in July, October 1988, and March 1989, the Antalya anticylone can not be observed in its position prior to 1987.

In the March 1989 joint cruise (Özsoy et al., 1992), the Rhodes Gyre, anticyclonic eddies south of Crete, and the Mersa Matruh–Shikmona Gyre

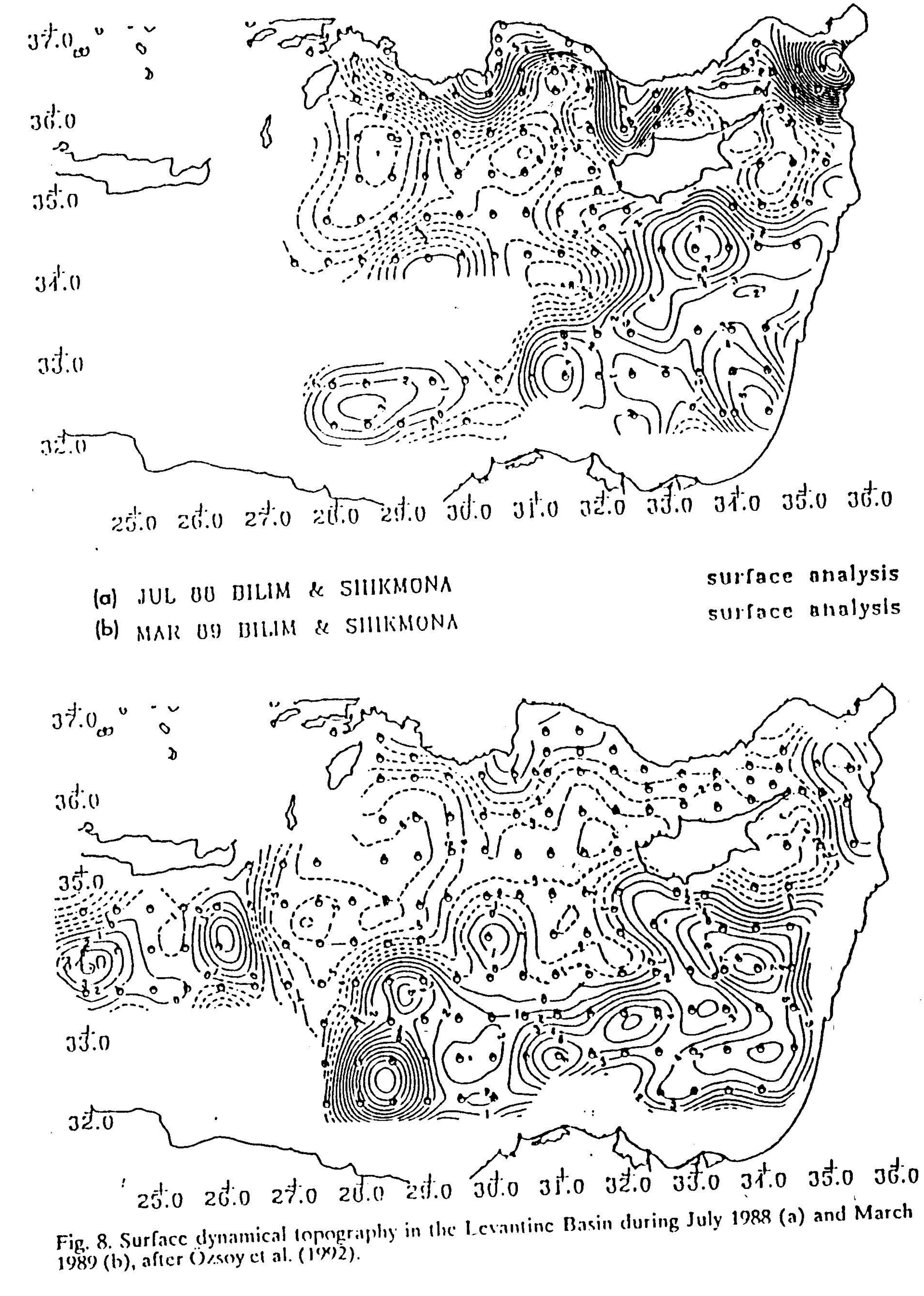

Fig. 8. Surface dynamical topography in the Levantine Basin during July 1988 (a) and March 1989 (b), after Özsoy et al. (1992).

complexes are present (Fig. 8b). The Central Levantine Basin Current developing near the Shikmona Gyre divides into two parts; one branch circulates cyclonically around Cyprus and joining the Asia Minor Current, and the other branch loops around the Shikmona complex. There is almost no flow reaching the Anatolian coast from west of Cyprus. The Asia Minor current along the Turkish coast is weaker than that observed in figure 8a. This is due to the erosion of the temperature stratification by convective overturning, leading to formation of LIW adjacent to the coast, where a uniform layer with LIW properties extending to depths of 400–500 m is formed (Özsoy et al., 1992). The intense anticyclonic vortex southeast of Crete is also found in this cruise.

In August 1990, available data in the northern Levantine indicate coherent flow of the Asia Minor Current along the full length of the Anatolian coast, the Rhodes Gyre, and isolated anticyclonic eddies near the Anaximander Seamounts and in the Antalya Bay region (Fig. 9a). The recurrent Antalya anticyclone is once again observed at its preferred position and at depth (Fig. 9b), about four years after when it was last observed. The anticyclone occupies the same position as in October 1985 – June 1986, and has the same water mass signature as before; its core contains high salinity LIW. Satellite data for the

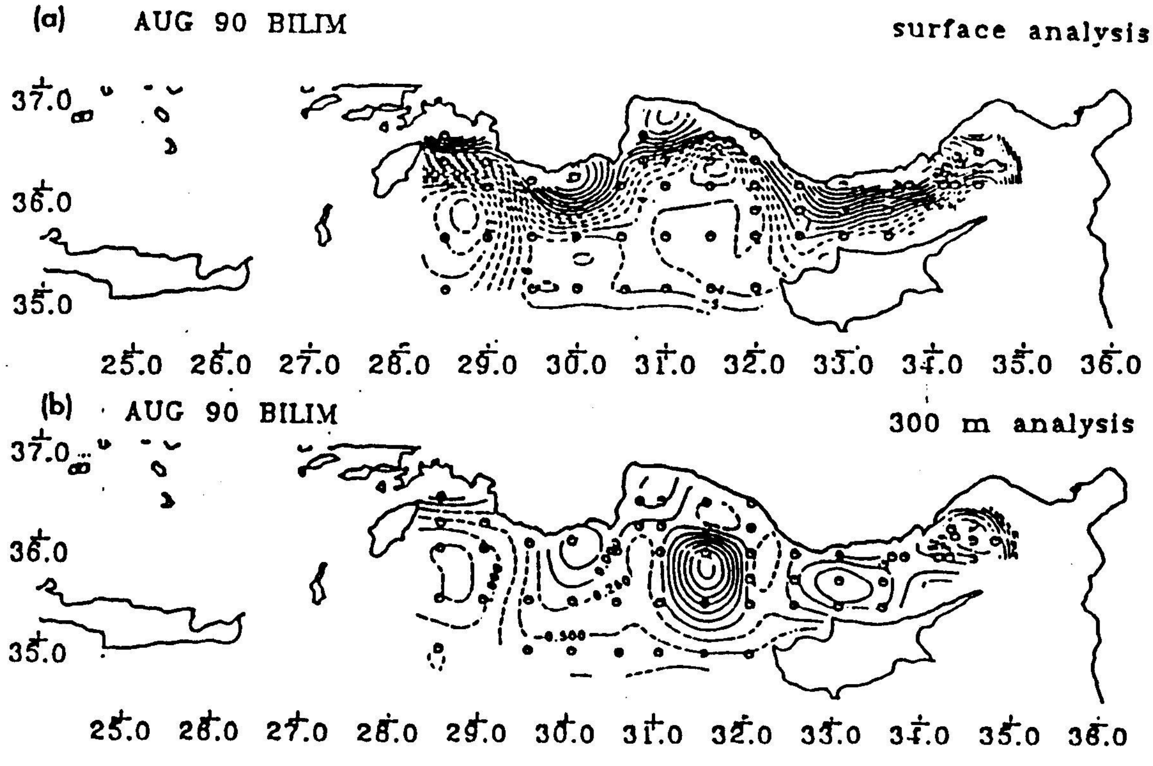

Fig. 9. Surface (a) and 300 m (b) dynamical topography in the northern Levantine Basin, August 1990, after Özsoy et al. (1992).

same period (Fig. 10) shows the Rhodes Gyre, the Asia Minor Current, and anticyclonic coherent eddies southeast of Crete and in the southern Basin. Mesoscale filaments and oscillatory features are also evident.

The southeast Cretan eddy has been found in three different surveys (Figs. 7, 8b and 10) and these data alone indicate that it may have persisted at the same

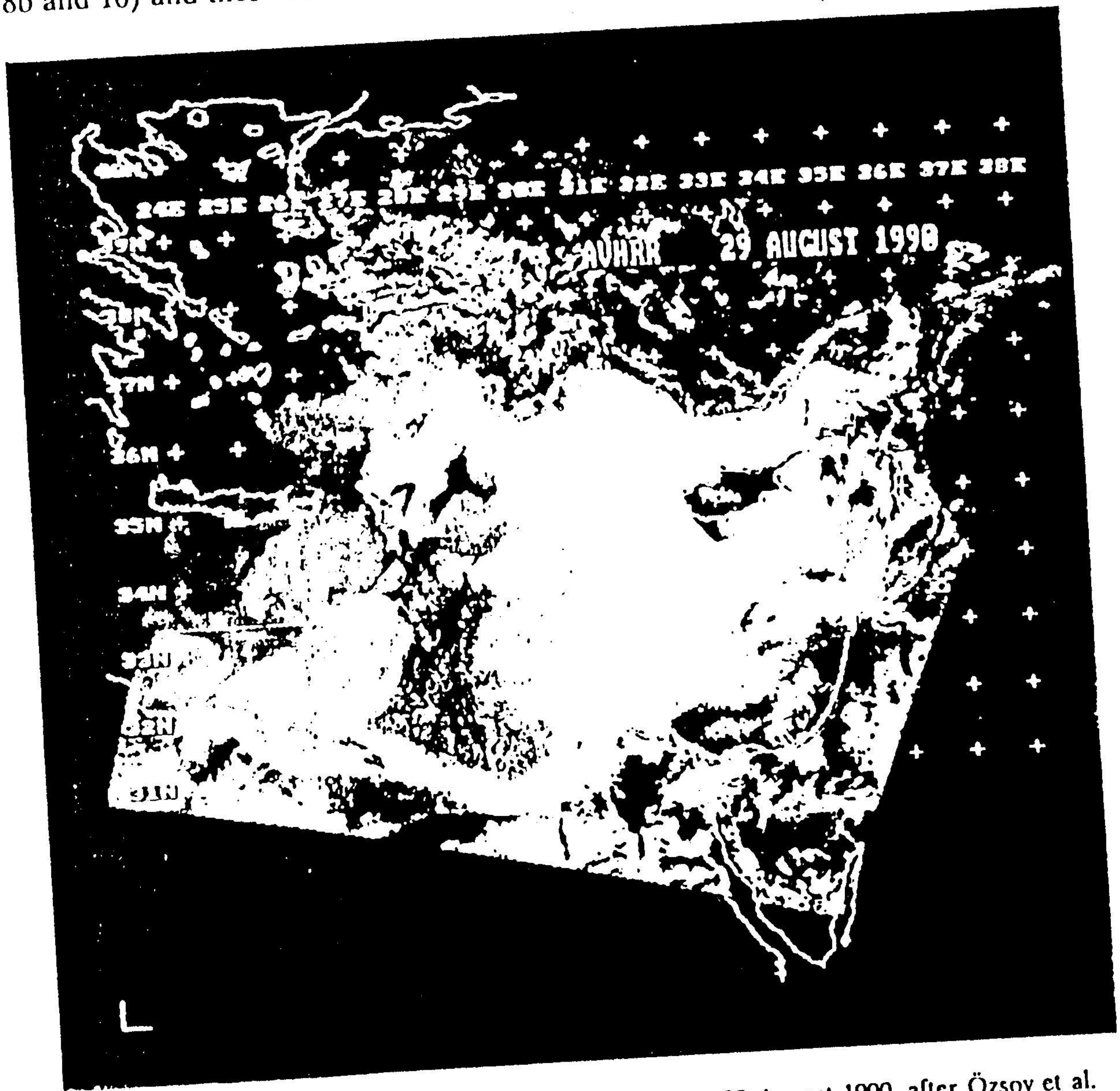

Fig. 10. AVHRR satellite image of the Levantine Basin on 29 August 1990, after Özsoy et al. (1989).

position during the 1987–1990 period. It is also interesting to note that this eddy has a deep structure, and in September 1987 appaears to be associated with a salt anomaly originating from the Aegean Sea (Schlitzer et al., 1991).

The limited data obtained near the Turkish coast during November 1990 and March 1991 indicate the continued presence of a deep structure in the Antalya anticylone region, but the amount of data is insufficient to infer the circulation. A synoptic survey in October 1991 (unpublished analyses at this time) has shown a return to the case with a mid-basin flow joining the Asia Minor Current west of Cyprus, and no evidence of the Antalya anticyclone.

A number of modelling studies are now in progress, though we consider it premature to report on the modelling aspects at present, because of the continuing nature of the research, and because of further developments needed for accurate reproduction of the observed features. However, we note a number of recent contributions to model developments and simulations with relevance to the Eastern Mediterranean dynamics. The Harvard quasigeostrophic baroclinic model (open ocean version) has been used by Robinson et al. (1983) for process studies based on the MC data. The developments of Milliff (1990), and Özsoy, Lozano and Robinson (1992) have generalized this model to include coasts and islands with semi-enclosed or closed basin geometries. The coastal version has been used by Milliff and Robinson (1991) and Robinson et al. (1991b) to model the Eastern Mediterranean dynamical processes based on initializations with POEM data. Primitive equation models have been used by Stanev et al. (1989, 1991), Malanotte Rizzoli and Bergamasco (1991) and Pinardi and Navarra (1991) to study the Eastern Mediterranean circulation under various forms of inflows, thermohaline fluxes and wind forcing. Brenner et al. (1990) and Feliks (1991) have experimented with models of mixed layer convection and seasonal evolution, to explain LIW formation at the centers of anticyclonic eddies and along the coast. Most of these models are successful in producing partial results for process studies, but further development has yet to occur before observed structures can be generated from arbitrary initial conditions by the action of major forcing mechanisms.

The Ionian Basin

With regard to its detailed circulation, the Ionian Basin remains largely unexplored even today. The POEM experiments covered the northern parts, but could not totally eliminate large data gaps south of the basin.

A cyclonic circulation in the Ionian Basin, with the eastward flowing North African Current bypassing the anticyclonic region of Sirte has been indicated by Nielsen (1912). The Ovchinnikov (1966) circulation scheme for winter (Fig. 2) shows the North African Current (Ionian–Atlantic Stream) flowing towards the Levantine Basin. On its south, an anticyclonic circulation is displayed in the

The limited data obtained near the Turkish coast during November 1990 and March 1991 indicate the continued presence of a deep structure in the Antalya anticylone region, but the amount of data is insufficient to infer the circulation. A synoptic survey in October 1991 (unpublished analyses at this time) has shown a return to the case with a mid-basin flow joining the Asia Minor Current west of Cyprus, and no evidence of the Antalya anticyclone.

A number of modelling studies are now in progress, though we consider it premature to report on the modelling aspects at present, because of the continuing nature of the research, and because of further developments needed for accurate reproduction of the observed features. However, we note a number of recent contributions to model developments and simulations with relevance to the Eastern Mediterranean dynamics. The Harvard quasigeostrophic baroclinic model (open ocean version) has been used by Robinson et al. (1983) for process studies based on the MC data. The developments of Milliff (1990), and Özsoy, Lozano and Robinson (1992) have generalized this model to include coasts and islands with semi-enclosed or closed basin geometries. The coastal version has been used by Milliff and Robinson (1991) and Robinson et al. (1991b) to model the Eastern Mediterranean dynamical processes based on initializations with POEM data. Primitive equation models have been used by Stanev et al. (1989, 1991), Malanotte Rizzoli and Bergamasco (1991) and Pinardi and Navarra (1991) to study the Eastern Mediterranean circulation under various forms of inflows, thermohaline fluxes and wind forcing. Brenner et al. (1990) and Feliks (1991) have experimented with models of mixed layer convection and seasonal evolution, to explain LIW formation at the centers of anticyclonic eddies and along the coast. Most of these models are successful in producing partial results for process studies, but further development has yet to occur before observed structures can be generated from arbitrary initial conditions by the action of major forcing mechanisms.

The Ionian Basin

With regard to its detailed circulation, the Ionian Basin remains largely unexplored even today. The POEM experiments covered the northern parts, but could not totally eliminate large data gaps south of the basin.

A cyclonic circulation in the Ionian Basin, with the eastward flowing North African Current bypassing the anticyclonic region of Sirte has been indicated by Nielsen (1912). The Ovchinnikov (1966) circulation scheme for winter (Fig. 2) shows the North African Current (Ionian–Atlantic Stream) flowing towards the Levantine Basin. On its south, an anticyclonic circulation is displayed in the

Tunisian Plateau and the Gulf of Sirte regions. The Ionian–Atlantic Stream makes an anticyclonic excursion towards north of the Ionian Basin and two cyclonic gyres, one in the northern part of the Basin and the other in the east towards the Cretan Passage are indicated.

Ovchinnikov and Fedoseyev (1965) show cyclonic circulation in the Ionian Basin in winter, but the sense of rotation of the circulation was indicated to become anticyclonic in summer in a large area of the Basin including the western part of the Cretan passage. The reversal of the Ionian gyre has been a puzzling aspect of the circulation (Malanotte Rizzoli and Hecht, 1988). An indicator for the reversal of the Ionian gyre may be the reversing vortex in the sub-domain of Taranto Gulf (Accerboni et al., 1975), although its seasonal sense of rotation is opposite that of the main Ionian gyre. A barotropic reversing gyre in the Ionian Sea is indicated in the model results of Pinardi and Navarra (1989, 1991), who explain this feature partially by seasonally forced Rossby basin modes. On the other hand, the deep (700 m) circulation inferred from seasonally averaged climatological data, using inverse methods (Tziperman and Malanotte Rizzoli, 1991) indicate an anticyclonic gyre, without any reversals throughout the year (Fig. 3b). The more intense surface circulation (Fig. 3a) in the same study shows a reversing gyre only in the northern part of the Basin, cyclonic in winter, and anticyclonic in spring and summer. The undulating Ionian–Atlantic Stream hugs the African coast in winter and shifts north in summer (Tziperman and Malanotte Rizzoli, 1991). Similar results are indicated in the surface flows of Pinardi and Navarra (1991). The meandering Ionian–Atlantic Stream exiting from the Sicily Strait is also indicated by Ovchinnikov (1966), Robinson et al. (1991a), as well as the model results of Malanotte Rizzoli and Bergamasco (1991).

POEM surveys have covered the northern parts of the Ionian Basin and the Strait of Sicily regions. The most extensive coverage obtained in the August–September 1987 (POEM 05) survey (Fig. 7a and b; Robinson et al., 1991a) indicates anticyclonic circulation in the region following the northerly extension of the North African Current after entering from the Sicily Channel. A smaller eddy called the Pelops anticyclone was observed near the southwest of the Peleponissos and a cyclonic eddy occupied the region southwest of Crete. Another cruise during March–April 1986 indicated northerly flows along the Greek coast of the Ionian Basin and the presence of the Pelops anticyclone (Theodorou, 1991; Robinson et al., 1991a).

Interconnecting straits and passages

The connections to the Western Basin at the Strait of Sicily, to the Adriatic Sea at the Otranto Strait, to the Aegean Sea at three major Aegean Straits, and the communication of the Levantine and Ionian Basins through the wide Cretan Passage play important roles in the general circulation of the Eastern Mediterranean.

The surface flow through the Strait of Sicily imports Atlantic Water from the Western Basin and the intermediate depth outflow exports Levantine Intermediate Water. Garzoli and Maillard (1979) estimated both flows to be on the order of 1 Sv (1 Sv = 10^6 m^3/s). According to Manzella et al. (1988) the summer fluxes (both ways) are about 1.5 Sv, and in winter they increase to 3 Sv. Grancini and Michelato (1987) also find increased mean flows in winter, and increased eddy kinetic energy (low-frequency, tidal and inertial motions) superposed on the mean motion in the entire cross-section of the Sicily Channel. In contrast, De Maio et al. (1990) find an increased volume of LIW in summer, but no flux estimates are given.

The surface water flow through the Otranto Strait is towards the Adriatic along the Greek coast, and towards the Ionian Basin along the Italian coast (Ferentinos and Kastanos, 1988). The northerly flow along the Greek coast is continuous and intense, extending to about mid-depth. Below this flow, and occupying the rest of the Strait section, the southerly currents are less intense and display fluctuations. The currents become more coherent and developed near the bottom, and on the Italian continental shelf, where the dense water formed in the Adriatic flows out into the Ionian Basin.

The Straits of Rhodes, Karpathos, Cassos (east of Crete) and Antikithira (west of Crete) are the major passages between the Aegean and the Eastern Mediterranean Seas. Nielsen (1912) proposed surface inflow into the Aegean Sea and deep outfow to the Eastern Mediterranean through these straits. There has been a number of current measurements made in the straits (Pollak, 1951; Bruce and Charnock, 1965; Burman and Oren, 1970; Accerboni and Grancini, 1972) in later years, which indicate a main pattern of surface inflow through the eastern straits and outflow through the western straits, subject to seasonal and short-term changes. Recent current-meter measurements during POEM (Lascaratos et al., 1989) indicate variable surface currents subject to wind and barometric forcing, and a consistent outflow of the Aegean deep water into the Eastern Mediterranean.

The wide Cretan Passage circulation apparently shows a great amount of variability. The Ovchinnikov (1966) winter circulation (Fig. 2) shows a cyclonic gyre filling the region, while the Ovchinnikov and Fedoseyev (1965) summer circulation indicates anticyclonic patterns. The POEM surveys (Figs. 5, 7 and 8) indicate variable structures in the region. One of the most significant structures is the deep coherent anticyclonic eddy southeast of Crete covered in the September 1987 and March 1989 experiments (Figs. 7 and 8).

Mesoscale motions

The motions in the Levantine Basin are characterized by a wide range of scales. Meso-scale motions (corresponding to an internal radius of deformation of about 10–15 km) are often not detected with the nominal station spacing of about 0.5° (≅50 km) used for maximum synoptic coverage in the POEM surveys. Mesoscale and sub-mesoscale features have been identified by Özturgut (1976), Özsoy et al. (1986), Robinson et al. (1987), The POEM Group, (1992), and are also evident in satellite data (Fig. 10).

The continuous sampling of surface features along the course of the BILIM in the northern Levantine (Özsoy et al., 1986) yielded information on small scale variability. The continuous surface measurements in figure 11 show fine mesoscale variability between hydrographic stations. Frontal regions with temperature gradients exceeding 0.1° /km are evident in many areas. Horizontal

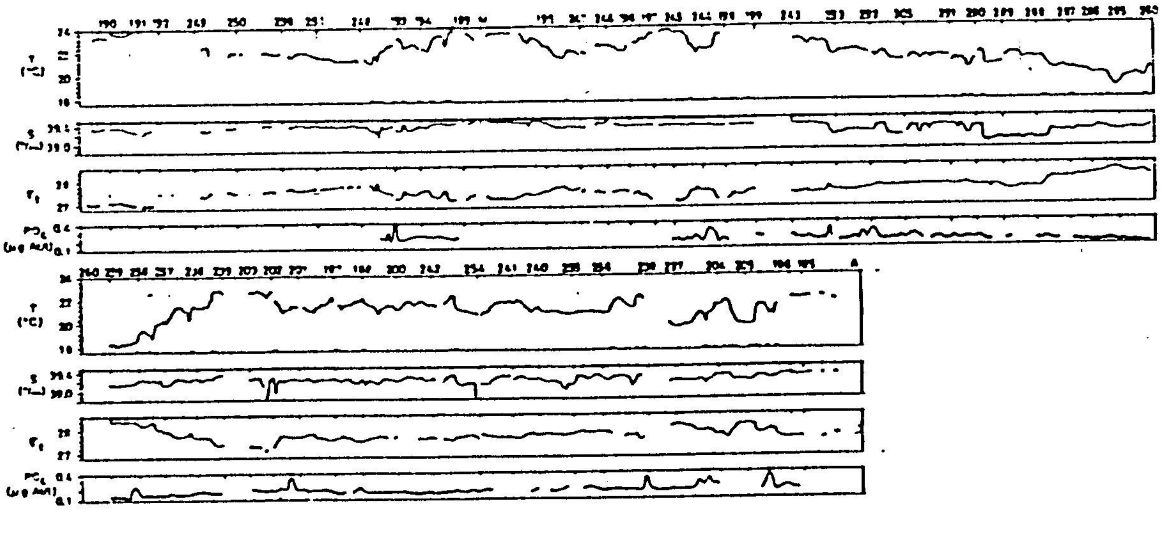

Fig. 11. Continuous surface temperature, salinity, σ_t and PO_4 measurements along the cruise track of RV BILIM (Fig. 12a), October–November 1985.

distributions of temperature and salinity interpolated along the ship route are plotted in figure 12. The surface temperature is in harmony with the circulation features, with a meandering frontal structure. The mixed layer salinity is

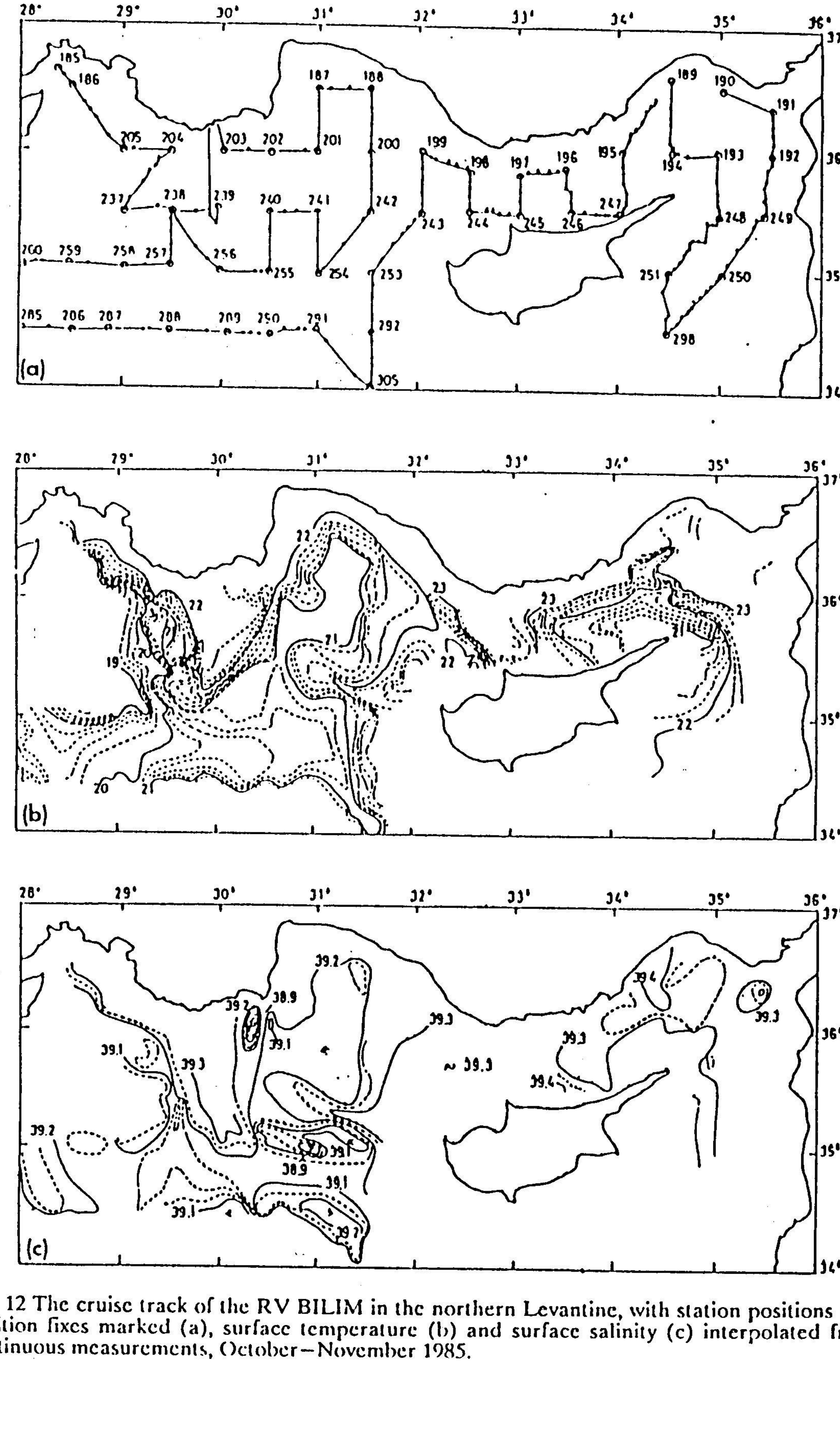

Fig. 12 The cruise track of the RV BILIM in the northern Levantine, with station positions and position fixes marked (a), surface temperature (b) and surface salinity (c) interpolated from continuous measurements, October–November 1985.

uniform in most of the region, excluding frontal regions, where sharp variations were encounterd due to the surfacing of the low salinity Atlantic Water from below the mixed layer. Interleaving water masses are evident from T−S diagrams in the frontal regions, and often display characteristics of oceanic fronts (Bowman and Esaias, 1978). Such major fronts are often identified from satellite images (Philippe and Harang, 1982).

Small mesoscale eddies and oscillatory features are evident in measurements with adequate resolution (Robinson et al., 1987; Leslie and Robinson, 1990), and the coarser mesoscale features appear with horizontal scales of up to 5−6 times the first internal radius of deformation and vertical scales of up to 50−400 m. The mean transport by the larger-scale general circulation is often masked by mesoscale eddies, jets and filaments. Over time scales of six months to a year, the southern Levantine eddies were stationary, with little westward propagation, but changed intensity and shape (Robinson et al., 1988). The same appears to be true in the northern Levantine, except for a few westward propagating anticyclonic eddies observed along the Asia Minor Current in the Cilician Basin region. Structurally, the small mesoscale features exhibit strong shear in the vertical and appear to be intensified at the levels of LIW. Within the jet flows near the surface, geostrophically computed currents are up to 30−40 cm/s (Robinson et al., 1987, 1988; Özsoy et al., 1989).

Shelf seas and coupling with the deep sea

In the Levantine Basin, current meter measurements of sufficient duration are virtually non-existent. The only long term (up to 5 months) current measurements are reported by Ünlüata et al. (1978, 1980), and Özsoy and Ünlüata (1983). Mean westerly currents of the order of 10 cm/s were found along the straight coastline regions of the Cilician Basin. The mean flow was fouhd to be significantly reduced adjacent to rugged coastlines where topographic steering limited its penetration along the coast (Ünlüata et al., 1983).

Due to strong coupling between the narrow shelf and the deep waters, current measurements on the shelf partially reflect the effects of Cilician Basin dynamics (Ünlüata, 1982). The measurement of strong reversing currents (of up to 50 cm/s) with periods ranging from several weeks to diurnal and shorter time scales indicate energetic motions in the region (Ünlüata, et al., 1978, 1980; Özsoy and Ünlüata, 1983). The current spectra have sharp peaks at 16d, followed by peaks at 40d, 10d, 6d, and 4d periods. The 16d and longer periods in the spectra are explained by the shelf reponse to the topographic Rossby wave modes supported by Cilician Basin topography (Ünlüata, 1982). The other oscillations with shorter periods could be explained by baroclinic shelf waves with topographic coupling to the interior. The wavelengths of the first mode barotropic Rossby wave (Cilician Basin) and the barotropic shelf wave are estimated as 100 km and 15–20 km respectively. The first mode baroclinic motions (internal radius of deformation), and the inertial-internal oscillations would have length scales of 15 and 45 km respectively (Ünlüata, 1983).

Diurnal and inertial oscillations connected to the strong sea-breeze system of the summer season (Özsoy and Ünlüata, 1983) are detected in the high frequency range. The closeness of the diurnal (20 h) and the inertial (20.4 h) periods makes possible the near resonant tuning of the latter by the sea-breeze forcing.

Deep ocean mesoscale eddies and meandering boundary currents can transfer energy to the shelf motions (Smith, 1983). Similarly, shelf processes can induce exchanges with the deep waters, including those of the biological and chemical nature (Smith, 1983; Brink, 1987; Brink et al., 1990). Similar results were predicted by Ünlüata et al. (1985) for steady circulation in the Cilician Basin. It is shown that the motions off the shelf provide additional forcing to the shelf waters, but because they can not fully penetrate into the shelf region due to the insulating effect of a steep shelf slope, they are mainly concentrated near the shelf edge. Similar situations have been reported for wide shelf regions rapidly joining to abyssal depths (Wang, 1982; Csanady and Shaw, 1983). Depending on the currents specified at the eastern boundary, a net cross-shelf transfer of mass of 0 (shelf width/basin width) $\cong 1/10$ is found to be possible. This transport is significant relative to the shelf transport, but insignificant in terms of the interior motions of the Cilician Basin.

A prototype example of shelf convection leading to mass formation and interaction with deep waters takes place in the northern part of the Adriatic Sea (Malanotte Rizzoli, 1991), where the weather conditions, shallow mixing, and the effects of topography are important. The dense waters formed in the north flow along the shelf region and fill the south Adriatic Basin. The sinking of the vein of dense water in the southern Adriatic is aided by topographic effects at the Bari Canyon (Bignami et al., 1990).

Similar dense water formation takes place in the Aegean Sea in winter (Miller; 1972, 1974; Lascaratos, 1983) through mixing processes on the shallow continental shelf. Dense bottom waters are found in the three deep troughs of the Aegean Sea with the highest density values occuring in the northern Aegean.

PROCESSES OF WATER MASS FORMATION AND MAINTENANCE

The major water masses existing on the scale of the Eastern Mediterranean Basin are: (a) the Atlantic Water (AW), (b) the Levantine Intermediate Water (LIW), and (c) the Deep Water (Wüst, 1961; Hopkins, 1978). The different water masses, their depth ranges and seasonal variations have been characterized (Hecht, Pinardi and Robinson, 1988), based on sufficiently long coverage of the MC cruises available in the southern Levantine Basin.

Atlantic Water

The existence of AW is due to the influx of the Atlantic water through the Gibraltar and in the Western Mediterranean it is primarily found within the surface layers with salinities 36.15–37.15 ppt (Morel, 1971). On its route from Alboran Sea to past Strait of Sicily its vertical extent changes from 150–200 m to 200–300 m (Lacombe, 1974). In the Levantine, it is overtopped in summer by surface waters with higher temperature and salinity, so that it is often characterised by a subsurface minimum in salinity (Lacombe and Tchernia, 1974; Oren, 1971; Morcos, 1972).

From late spring to autumn, AW is overtopped by warmer and more saline Levantine Surface Water (LSW), which evolves through surface heating and evaporation. The LSW typically extends to a depth of about 40 m in autumn, with salinity values as high as 39.5 and temperatures of 16–27.8 °C. In winter, the surface layer extends deeper and the subsurface salinity minimum vanishes as a result of vertical convective processes.

The salinity and temperature properties of AW are variable in the Levantine Basin, reflecting seasonal and interannual changes and internal dynamics (Ünlüata, 1986; Hecht, Pinardi and Robinson, 1988; Öszoy, Hecht and Ünlüata, 1989; Özsoy et al., 1989, 1991, 1992). The depth of the salinity minimum varies between 20 to 100 meters at different regions and lies within the seasonal thermocline extending down to 100 m. The salinity minimum at any particular location can be as low as 38.5 and as high as 39. Large pools of AW can be found in the Ionian Basin and the southern Levantine Basin, transported by the North African Current and its breakaway anticyclonic eddies. It is almost never observed at the center of Rhodes Gyre because of the homogenization of the water mass properties by upwelling. In some years (1985–1986) the AW enters the northern Levantine in the form of subsurface filaments (Figs. 6a and b), following the northwest branch of the jet flow bifurcating southwest of Cyprus and can not enter the Cilician Basin in large volumes (Özsoy, Hecht and Ünlüata, 1989). In other years (1987–1990), the AW enters into the Cilician Basin through the passage east of Cyprus, following flooding of the Lattakia Basin and the Gulf of Iskenderun by AW pools (Fig. 6c) trapped in a series of anticyclonic eddies which later propagate into the Cilician Basin. The AW appearing in the Cilician Basin is flushed out within a year by the intensification of the Asia Minor Current (Özsoy et al., 1991, 1992).

Levantine Intermediate Water

The LIW is a peculiar water mass affecting the oceanography of the entire Mediterranean. It has been schematized in the form of a high salinity tongue originating from the Levantine Basin at depths of 100–250 m and extending through the Eastern and Western Basins with an intermediate depth salinity maximum shallower than 400 m. In the Levantine Basin, the LIW is found within the permanent thermocline, which extends to a depth of 500 m. Traditionally, a salinity of 39.1 and a temperature of 15.5 °C ($\sigma_t \cong 29$) have been accepted as its signature in the source region. The saline tongue extends west to exit into the Atlantic Ocean through the Gibraltar Strait. It reaches the Alboran Sea with a salinity of 38. 4 and temperature of 13 °C (Nielsen, 1912; Wüst, 1959; Morcos, 1972; Miller et al., 1970).

The formation of LIW is a complex process that is not sufficiently understood. Conventionally, its formation has been linked with the upper ocean convective processes in the northern part of the Levantine Basin, where dry and cold atmospheric outbreaks from the north are capable of boosting surface buoyancy fluxes (latent and sensible heat, evaporation) in winter (Morcos, 1972), though evidence for some LIW in the southern Levantine Basin is not lacking (Morcos and Hassan, 1976). Özsoy, Hecht and Ünlüata (1989) showed basin-wide patchiness of LIW and persistence throughout the year. The dominant role of surface fluxes is clear, but the basin internal dynamics also seems to exert important influences in the formation, storage and transport of LIW.

The Poyraz wind regime formed by intensification of northerly flows at the major mountain passes along the Turkish coast seems to create favorable conditions for surface cooling in the northern Levantine (Özsoy, 1981; Özsoy and Ünlüata, 1983). The Gulf of Antalya and the regions to its southwest are well documented formation regions of LIW (Nielsen, 1912; Wüst, 1959; Özturgut, 1976; Ovchinnikov, 1984).

Much is yet to be learned on the exact mechanisms through which LIW is formed. The complexity of the basin dynamics have precluded the construction of a valid and simple theory. Of the various theories advanced to date, three basic trends can be identified: (i) isopycnal sinking into anticyclonic eddies from convection regions within the cyclonic Rhodes Gyre (Ovchinnikov, 1984; Ovchinnikov and Plakhin, 1984), (ii) continental shelf/slope convection processes as observed in the Cretan Sea (Georgopoulos et al., 1989), (iii) convective overturning directly occurring in anticyclones (Brenner et al., 1990).

Large scatter found in the T−S values of the LIW suggests multiple sources (Morcos, 1972). Homogeneity in the T−S properties is only achieved in the west, by smoothing of the differences in the multiple source regions in the Levantine, subject to annual variations in the volume of LIW formed. As pointed out by Hopkins (1978), the transit time out of the source region must be sufficiently long for this to happen. Indeed, Ovchinnikov (1984) shows that the spreading is so slow that the LIW in the west can be regarded as " stale ". Contrary to Wüst's (1961) earlier claims, Katz (1972) did not find seasonal dependence of LIW outflow, but, recent results (Grancini and Michelato, 1987; Manzella et al., 1988; De Maio et al., 1990) show seasonal and low-frequency variations in the LIW outflow through the Strait of Sicily. The efflux appears to increase in winter, despite some conflicting reports (De Maio et al., 1990) of increased volumes of saline water in summer. Independent of the fluxes, the salinity of the LIW core near Sicily Strait always seems to have a constant value of about 38.75, without any seasonal variability. This steady supply of LIW, despite changes in its efflux, could indicate continuous annual production or a slow release due to a storage mechanism.

Özsoy, Hecht and Ünlüata (1989) and Özsoy et al. (1991) emphasized a strong relationship between water mass formation/transport and the internal dynamical processes of the Levantine Basin circulation. The LIW is often found to be trapped (Figs. 6a−c) within anticyclonic eddies (Ünlüata, 1986; Hecht, Pinardi and Robinson, 1988; Özsoy, Hecht and Ünlüata, 1989, Brenner et al., 1990) and, as a result, the rate at which LIW disperses is expected to be very small, reflecting the sluggish motion of the eddy field. These observations are consistent with the conclusions of Hopkins (1978) and Ovchinnikov (1984a,b), and with theoretical results applied to the stirring of a passive tracer in eddy fields (Holloway et al., 1986). Özsoy, Hecht and Ünlüata (1989) suggest that the LIW could be maintained continuously within the Basin. It appears that the multiplicity of sources, the slow spreading due to entrainment into anticyclonic eddies, and almost continuous generation throughout the year are typical of LIW.

The analysis of water mass properties in the region indicates that the AW and LIW are simultaneously found in small patches and filaments within the coarse mesoscale eddy field. Özsoy, Hecht and Ünlüata (1990) show that the spatial distribution of LIW is highly correlated with mesoscale variability in the stream function field. Moreover, intrusive filaments of AW (Figs. 6a and b) entrained into coherent eddies causes time dependent dilution of the LIW salinity characteristics (Özsoy et al., 1991). Therefore, assessments of the abundance of water mass species based on average or climatological water mass properties alone, could often be unjustified or misleading.

Of the various mechanisms proposed for LIW formation, local formation by convective overturning in the anticyclonic eddies has been demonstrated to be a dominant mechanism in the Shikmona Gyre by Brenner et al. (1990) who successfully simulated the observed properties in anticyclones with a one dimensional model of the mixed layer driven by surface fluxes of buoyancy. Based on the uniformity of properties above a deep thermocline at the centers of anticyclonic eddies, such as warm core rings, one dimensional mixed layer formulations have been widely used to study convection (e. g. Schmitt and Olson, 1985; Dewar, 1986).

Winter recurrence of cyclonic winds, downwelling circulation along the periphery of the Levantine Basin, and a parameterization of vertical mixing has been combined in a two-dimensional model by Feliks (1991). In this model, it is suggested that LIW can be formed by open ocean mixing and downwelling, producing a deep layer of uniform properties near the coast.

In our observations of March 1989 the convective overturning mechanism was found in a larger area of the northern Levantine (Özsoy et al., 1992). Temperature and salinity adjacent to the Anatolian coast (Figs. 13a and b) and within the core of the Shikmona eddy showed almost uniform properties with a salinity of 39.15 down to the base of the deep mixed layer (to depths of 500 m). Mixed layer deepening could be a valid model of convection in these two regions, and the results are in partial agreement with the models of Brenner et al. (1990) and Feliks (1991), who shows that the downwelling region adjacent to the Anatolian coast is a preferential area of LIW formation. In other parts of the Levantine Basin, excluding the Turkish coast and the Shikmona eddy, deep saline and warm pools were found within anticyclonic eddies, but the temperature and salinity deviated from a vertically uniform distribution,

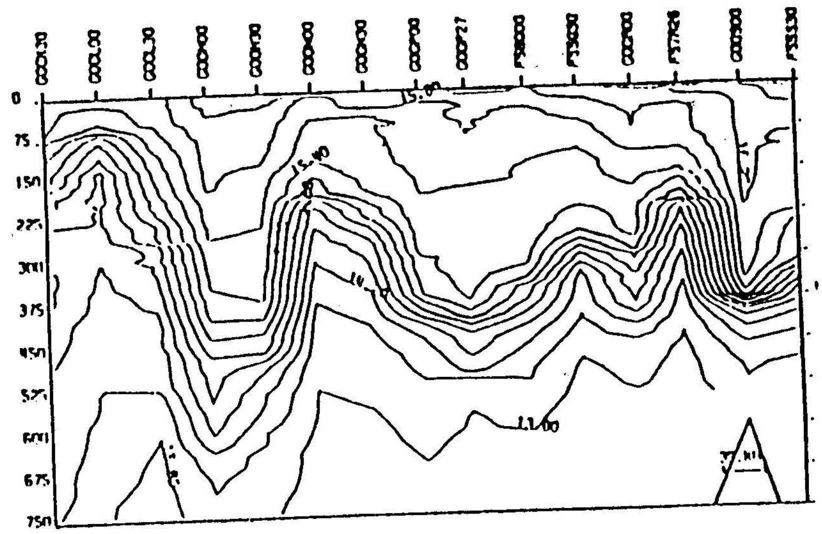

Fig. 13. (a) Temperature west-east sections adjacent to the Anatolian coast in March 1989, after Özsoy et al. (1992).

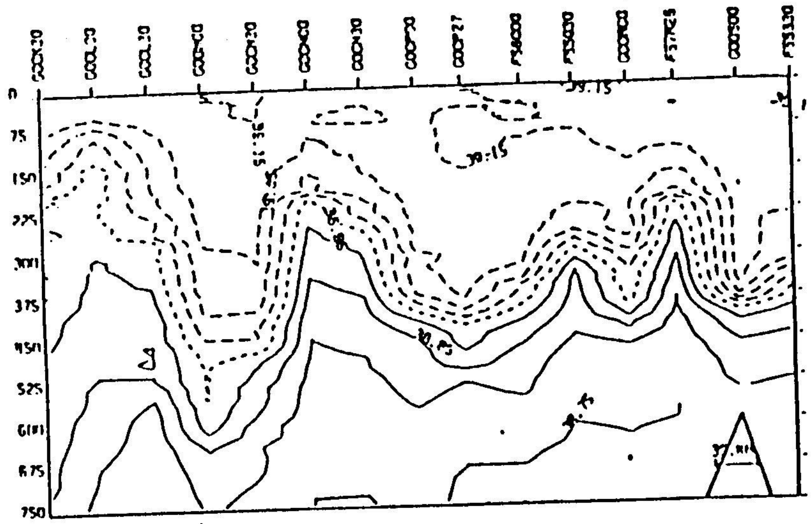

Fig. 13. (b) Salinity west-east sections adjacent to the Anatolian coast in March 1989, after Özsoy et al. (1992).

implying additional convection processes in these regions possibly with isopycnal (e.g. Ovchinnikov, 1984) and three-dimensional components.

Deep Water

The deep water of the Levantine basin is characterized by a temperature of 13.6 °C and a salinity of 38.7 ppt, and is found at depths in excess of 700 m (Wüst, 1961; Moskalenko and Ovchinnikov, 1965; Hecht, Pinardi and Robinson, 1988). Based on tracer characteristics, Schlitzer et al. (1991) defined the oldest Deep Water to be in the depth range of 1200–2800 m, with an intermediate layer above, and recently formed bottom waters occupying the depths below 2800 m.

Both the southern Aegean and the Adriatic have been suggested as the source areas for the Deep Water (Nielsen, 1912; Schott, 1915; Pollak, 1951; Wüst, 1961; Miller, 1963, 1972). A review of these studies has led Hopkins (1978) to conclude, on the lines of Pollak (1951), that the Adriatic is the main source. Tracer studies using Tritium, chlorofluoromethane (CFM−12) and oxygen have shown that the Adriatic is the only source of deep water with an influx of about 0.3 ± 0.1 Sv. (Roether et al., 1983; Roether and Schlitzer, 1991; Schlitzer et al., 1991; The POEM Group, 1992). Figures 14a and b show the oxygen and CFM−12 distributions below a depth of 1500 m, indicating

Fig. 14. The distribution of bottom water oxygen (μmol kg^{-1})(a) and bottom water CFM−12 (pmol kg^{-1})(b) in the Eastern Mediterranean during August− September 1987 (POEM 05) cruise of the RV METEOR, after Schlitzer et al. (1991).

enrichment in the western side of the Ionian Basin due to inflow from the Adriatic. It is uncertain whether the dense water formed in the northern Adriatic and stored at the bottom of the Southern Adriatic Basin eventually overflows the Otranto sill to feed the Deep Waters of the Eastern Mediterranean. The various hypotheses are revieved by Ovchinnikov et al. (1985), who argue that the dense waters feeding the Eastern Mediterranean must be formed locally in the southern Adriatic.

The 1987 measurements show a saline lense of Aegean water south of the Island of Crete, and lying between the LIW and DW at depths of about 700 m (Schlitzer et al., 1991). However, the Aegean contribution to the Deep Water is estimated to be minimal.

An alternative mechanism of deep water formation has been proposed by Gertman et al. (1991), based on observations of intense convective mixing at the center of the Rhodes Gyre in March 1987, when the temperatures at the center were found to be as low as 14 °C. The thin layer of stratified water normally covering the cold dome of the Rhodes Gyre is reported to have disappeared temporarily, giving way to deep convection to depths of 800–1000 meters. Convective overturning at the center is likely to have occurred in view of the weak stratification at the center of the gyre, but the net contribution of such isolated events to deep water formation is expected be small.

SOME ASPECTS OF PRIMARY PRODUCTIVITY IN THE LEVANTINE BASIN

Most primary productivity measurements in the Eastern Mediterranean have been made in the neritic waters, and few measurements exist for the pelagic open sea waters. Based on indirect measurements, the classical data compiled by Koblentz–Mishke et al. (1970) suggested 50–100 g C m^{-2} yr^{-1} for most of the Mediterranean open waters. Berman et al. (1984, 1986) indicate that the actual value is much lower, in the range of 6–40 g C m^{-2} yr^{-1} for the open waters of the southeast Levantine Basin. Average values of about 16–25 g C m^{-2} yr^{-1} are indicated for the northern Levantine Basin (Gocmen, 1988).

Both Göcmen (1988) and Yilmaz et al. (1988) indicate a deep (80–150 m) euphotic zone in the northern Levantine based on light penetration measurements. It appears that the deep penetration of sunlight combined with low concentrations of nutrients in the euphotic zone leads to the " deep chlorophyll maximum ", at depths of 1–10 % penetration of the incident solar radiation in the open-sea regions.

The thermohaline circulation of the Mediterranean has significant impact on the productivity of the region. The sinking of LIW in the Eastern Mediterranean and the high salinity tongue exiting into the Atlantic Ocean at Gibraltar Strait is known to create a nutrient deficit (McGill, 1965, 1969; Coste et al., 1988) in the region. The river discharges and Atlantic inflow are insufficient to balance this deficit. As a result, the Eastern Mediterranean is one of the world's few oligotrophic basins (McGill, 1965) due to nutrient limitation of primary production. On the other hand, the subtle schemes of " new production " available to the system is still sufficient to support a certain level of biological productivity (Dugdale and Wilkerson, 1988).

Dugdale and Wilkerson (1988) indicate that 20–40 % of the new production in the Eastern Mediterranean is of terrestrial origin, though from few sources (Bethoux, 1981). The remaining new production is estimated to be generated by the vertical transport of relatively richer deep waters into the euphotic zone.

One of the possible mechanisms leading to new production is the transient vertical transports near the shelf and open-ocean fronts (Bowman and Esaias, 1978; Lohrenz et al., 1988a,b). In the northern Levantine, Özsoy et al. (1986) obtained continuous samples of temperature, salinity and phosphate at the sea surface (Figs. 11 and 12a–c). Because of calibration errors in an early phase of the POEM programme, the average phosphate levels in these measurements are probably biased (much higher than present measurements), but they are the only continuous measurements to date. In figure 11, surface phosphate concentrations are uniform in the whole region, except near frontal regions and on the periphery of eddies, where the mixing with the subsurface AW filaments is suggested. The meso-scale eddy field alone is not capable of creating an outcropping nutricline, but the ageostrophic frontal dynamics seems to achieve surface injections of nutrients. The net influence of this mechanism may be limited, though it could have regional significance.

There is evidence that the shallowing of the nutricline at the centers of cyclonic eddies, such as the Rhodes gyre and its extensions, leads to increased primary production at the nutricline levels, due to simultaneous availability of nutrients and light. This increase is evidenced by the shallowing of the chlorophyll maximum and an increase in the total chlorophyll (Salihoglu et al., 1990; Bastürk et al., 1988). Biological productivity at higher trophic levels also appears to increase, indicated by the higher yields from neuston net hauls of zooplankton, fish larvae, small shrimp (Salihoglu et al., 1990), and visual sightings of seabirds, squid and dolphins in the Rhodes gyre region. Light penetration measurements indicate higher turbidity (light extinction of 0.20–0.5 m^{-1}) in the upwelling zone of the Rhodes Gyre as compared to the warm core Antalya eddy (0.01–0.1 m^{-1}). Much remains to be learned on the role of meso-scale motions in influencing the biochemistry of the Basin waters.

SUMMARY AND CONCLUSIONS

Observational evidence for the Eastern Mediterranean processes and their variability have been reviewed. The weight of our review has been placed in the Levantine Basin because this is where the data are more frequent and extensive. We hope that it is not our bias that creates this weighting.

The dynamical structure of the circulation consists of basin-wide wind and thermohaline driven circulation cells (the basic gyres) fed by jet flows, with embedded coherent eddies. The dynamical significance of the observed complex features lies in the fact that a high level of organization is displayed by them. Qualitative changes in the modality of the circulation, penetration of the AW, and the storage and leakage of LIW in mesoscale features characterize the long term behaviour of the circulation.

The recurrent organization of coherent eddies is akin to the subject of geophysical turbulence (McWilliams, 1984). The effects of planetary vorticity variations in a semi-enclosed geometry could also aid such structured formations (Larichev, 1989). The modelling experiments show complex influences due to wind stress, topography, and surface fluxes. The long-term survival of eddies and major circulation features despite the modulating effects of the driving forces is a unique feature of the Eastern Mediterranean, and seems to be reproduced in model studies (Robinson et al., 1991b). These and other aspects of the underlying dynamics can only be resolved by continuing studies.

Preliminary measurements suggest that a better understanding of the evolutionary and transport characteristics of the eddy circulations can lead to a detailed assessment of subtle yet significant processes that appear to dominate the biogeochemical cycles, biological mechanisms, and the basin-wide transport of seawater properties, pollutants and other waterborne constituents.

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MINAS: Comments and questions.

BRYDEN: I wasn't clear where you now think the Levantine Intermediate Water is formed (Özsoy: I'm not clear either) but it looked to me as it wasn't just near Rhodes that it was more along the coast of Turkey.

ÖZSOY: We have also early evidence that you can find Levantine Intermediate Water most abundantly near the coast; so it's since history or our interpretation was that it forms in the Rhodes gyre and sinks isopycnically and gets trapped along the coast, but now we see this intersected horizon having been formed in there, but this trapped region along the coast anyway is the deepest in this March '89 cruise, and we know it was formed there. But either than that it's been formed but for long time it can be trapped within ... I guess; that's our interpretation. It's not omogeneous, it's formed and kept there, maintained for a long period in summer; it's formed in winter but then it leaks slowly out of the basin through these eddies ... complicated.

AUBREY: Managers are always who to want to know about prediction. Can you predict many of the features that you see here; particularly the major features, like the major currents circumvaning Crete or going around Crete? Do you know what the major forcing is that causes that, the current can circumvent Crete or go around Crete and how successfully you think the modelling is going to be for those predictions?

ÖZSOY: The answer is that we don't know yet; but we are working on it. About Cyprus problem, it's much like an aeroplane wing where you have a circulation modified by frictional forces or perhaps in other mechanism, you know, persistant coherent gyres, like the Shikmona Gyre, can force the jets to go around and at some instances it can cause ... the eddy gets stronger and when it gets stronger it entrains these jets towards the eastern coast. I can't explain it fully, we have not yet done detailed studies, but the studies by Rizzoli, for example, they show that all of the factors are important, wind stress is definitely important but, you know, lateral forcing, buoyancy and thermoaline, they are also important. So, it's a complex area and that's the reason why for many years we looked at the data and we couldn't enter; the data being collected for many years were not instantaneous. We thought it was just the quality of the data was wrong, was bad, so that we could not interprete it. We know now that it's too complex to interprete from such scarce data.

DELLA CROCE: I'm not a physical oceanographer but, studying physical oceanography, I'm still accustomed to see in books description of current completely different from those I have seen today. The jets and vortexes you speak about, moving around on the eastern basin, seem to use a lot of energy, much more than on the western (voice: much more ...). The question is where it gets all of this energy the Eastern Mediterranean to be so much full of jets and the vortexes. For us, as biological oceanographers, it could be interesting to know just if we have indicators of these water masses moving on this way. In such almost steady situation it could be very interesting to know what could be the dynamics of a species staying for one year or two years in the same vortex or what it is. Thank you.

ÖZSOY: In fact this is very energetic, and the energy comes from the atmosphere and perhaps through this lateral forcing through the Straits, but the thing is that once the energy is in there it's in the form of a basin wide turbolence and that turbolence is driven by these forces, but eventually these eddies also contribute to the vertical circulation in that Levantine Intermediate Water is formed and sinks through these eddies and finally leaks out of the basin. We look, I can say, at it from the point of view basin wide turbolence and you are right about the role of these eddies in maintaining perhaps fish or other forms of life: we have consistently observed, for example, near the Rhodes Gyre, dolphins and large animals like these and birds, seabirds out in open sea so it has to have some role.

VAGN HANSEN: I noticed the map with all the stations operated and then when we came south to the Egyptian national territory, there was the abrupt line; now, if I recall correct, POEM is an international programm of IOC and certainly also of the CIESM. Why is it that Egypt has not been cooperating in this? It's just by curiosity because you would need data on the flow of the Nile ...

ÖZSOY: There have been attempts to include Egyptian scientists and one reason, perhaps, is that they don't have a ship to cooperate in this research. Another reason why you see a gap there is because of the Nile cones, we cannot include shallow stations in our analysis. I think I don't need to say anything about the Lybian side; there are no data in there. It is a wide gap in the Southern Ionian.

VAGN HANSEN: I have asked that question, because Egypt didn't partecipate, but were you not admitted to operate in their waters with your ship or ...

ÖZSOY: No.

BASCOM: They wouldn't allow you to operate in their waters.

ÖZSOY: No, we didn't ask for it.

MINAS: Any more question? So, I close the session and I thank you very much.