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A review of the Levantine Basin circulation and its variability during 1985–1988

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ABSTRACT

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The variability of the Levantine Basin circulation and hydrography is reviewed based on a collection of recent data sets. The major emphasis is placed on the complexity of the associated dynamics. The region is shown to be populated with synoptic and mesoscale dynamic features. In addition to the complexity arising due to the heterogeneity of water masses and the variability of the atmospheric and thermohaline forcing, the confines of the relatively small basin causes the sub-basin-scale gyres to be in close contact with each other, resulting in interacting, basin-wide turbulent features. The bifurcation of the mid-Levantine jet near Cyprus is variable on interannual time-scales, the amount of bifurcation of the fluxes being dependent on the evolution of the circulation in the multi-connected domain and the relative intensities of the sub-basin-scale gyres. During the 3-year observation programme, qualitative changes are identified in the general circulation. The flow encircling Cyprus is partially blocked in the first phase of the experiments. Later, the two basins on the north and east sides of Cyprus are flushed with new water masses carried in the cores of incident eddies, and a new pattern of basin-wide circulation is established, with a major part of the mid-basin jet flowing coherently along the mainland coasts and cyclonically around Cyprus. As a consequence, the general circulation of the Levantine Basin appears considerably different and more complex than the traditional descriptions of it.

1. INTRODUCTION

Until recent years, the Eastern Basin of the Mediterranean Sea and in particular the Levantine Basin (the eastern half of the Eastern Basin, Fig. 1) have remained one of the least understood parts of the world ocean. The inferences that could be drawn from the various fragmentary sets of data in the past could not be reconciled to yield a coherent description of the circulation and the water mass source mechanisms of the Levantine Basin. It came to be accepted that the insufficiency of the oceanographic database

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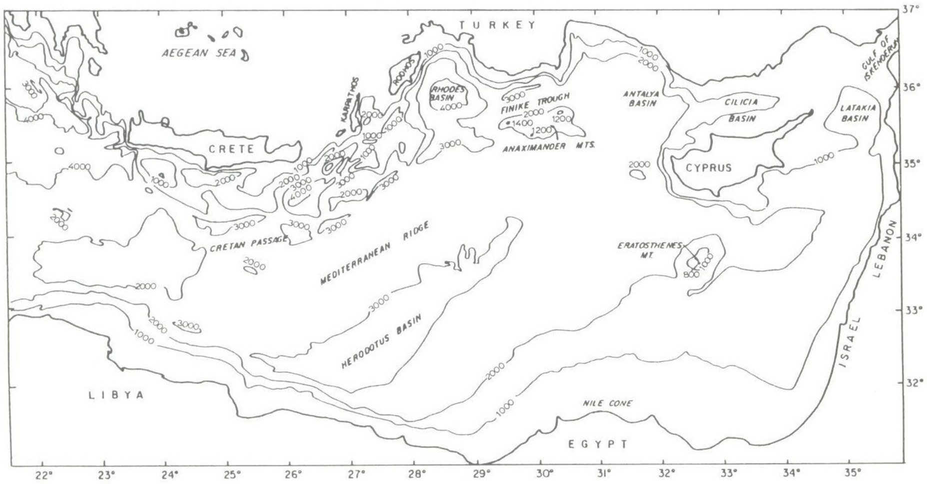


Fig. 1. Location map and bathymetry of the Levantine Basin, eastern Mediterranean Sea.

was the major barrier to a better understanding of the region. It now appears, after we have gained the minimum amount of data coverage during the Physical Oceanography of the Eastern Mediterranean (POEM) research programme designed for the cooperative investigation of the eastern Mediterranean (UNESCO, 1984, 1985), that the often contradictory nature of the earlier conjectures based on limited data were only manifestations of the real natural variability and complexity in the region. A thorough understanding of these complex processes remains to be reached through continuing challenges for determining the underlying dynamics. In the following, we review the essential elements of the historical development of the general circulation concepts (Section 2). We then attempt to update the circulation concepts by displaying its evolution within the POEM observational period (Section 3). The properties and transport of water masses embedded in this general circulation are then used in Sections 4 and 5 to demonstrate secular changes in the circulation by displaying some of the long-term features of the water mass distribution. A review of the results is given in Section 6. Pertinent details of the methodology are described in Appendix A.

2. DEVELOPMENT OF THE GENERAL CIRCULATION CONCEPTS

The first major scientific investigation of the Levantine Basin was carried out in 1890 during the cruise of the Austro-Hungarian ship Pola, followed in 1910 by the Danish ship Thor. In the Levantine Basin, the Thor collected data at nine stations only, four of them within the southern side of the Cretan Passage, and five of them approximately along the 27°30′E longitude (at the entrance region of the Levantine Basin). Nevertheless, it was the subsequent publication of Nielsen's (1912) Mediterranean currents map, based on these data, that for many years left the most indelible mark on the depiction of the Levantine Basin circulation. Nielsen ventured to depict eastward currents flowing into the Levantine Basin through the southern section of the Cretan passage, which then followed a counter-clockwise path continuously along the eastern Levantine shores. A later sophistication of this map (e.g. Lacombe, 1975) shows some of the currents branching southeast of Cyprus, with one branch continuing northward into the Cilician Basin as in Nielsen (1912), while the other branch turns westward, south of Cyprus.

The next major investigation of the Levantine Basin was carried out in 1948 by the USA ship Atlantis. This was followed by the cruises of the French Calypso in 1956, the Japanese Shoyo-Maru in 1959, The USA Atlantis in 1961 and again in 1962, the USA Chain in 1961, and the USA Pilsbury in 1965. The data from all these cruises contributed some additional details to the schematic Nielsen map but it did not drastically change the general circulation concept.

In the sixties, Russian scientists carried out a particularly intensive investigation of the entire Mediterranean Sea. The data collected by the six extensive Vavilov cruises (1959–1963) as well as by the Ichteolog cruise in 1966 was analysed and summarized by Ovchinnikov et al. (1966, 1976). The Russian oceanographers described in detail some of the processes driving the circulation of the Mediterranean Sea and in particular the circulation of the Atlantic Waters (AW) and the Levantine Intermediate Waters (LIW). Moreover, they presented new and enhanced geopotential anomaly maps at a number of levels and, most important, they revealed some of the differences between the summer and the winter circulation. However, as far as the Levantine Basin circulation was concerned, they continued to retain the traditional Nielsen cyclonic pattern.

Since the beginning of the sixties the reasonably extensive Israeli data have provided the first indications that there may be no foundation to the traditional cyclonic circulation in that region (e.g. Engel, 1967; Oren, 1970). Such conjectures at the time ran contrary to the much simpler pattern of cyclonic circulation inspired by the map of Nielsen (1912); in addition the distribution and accuracy of the new data were still far from providing anything more than a partial description. As a consequence, these results which gave clear indications of an anticyclonic circulation in the southeastern Levantine Basin were not given sufficient recognition.

During the mid-seventies Israel utilized modern conductivity-temperature-depth (CTD) based methodology, and over a period of 5 years carried out an intensive investigation of the southeastern Levantine Basin (the

'Marine Climate' or MC series of cruises). This data set has shown the abundance of mesoscale eddies, jets and filaments embedded in the circulation, and a patchy distribution of water masses (Hecht et al., 1988). Perhaps more important within the context of the present discussion, the MC data provided additional indications that the anticyclonic structure south of Cyprus, which we refer to as the Shikmona gyre in the POEM observations, appeared in this region also during the earlier periods of the MC cruises. The overall persistence of anticyclonic features in the region during extended periods (such as October 1983–August 1984) in spite of the limited area covered (Hecht et al., 1988), lends further credence to a persistent feature, which, on the other hand, seems to display long-term variations in its structure, position and intensity.

Within the POEM framework, the combined data of the Israeli RV Shikmona and the Turkish RV Bilim presented us with the unique opportunity to obtain detailed descriptions of the general circulation of the Levantine Basin (Özsoy et al., 1989). The qualitative aspects of the results derived from these surveys differed significantly from the most detailed prior analyses of the general circulation, e.g. Ovchinnikov et al. (1976). It was shown that the circulation consisted of quasi-permanent sub-basin gyres, various eddies interspersed in between the gyres, and an intense jet flow in the middle of the basin which bifurcated several times as it moved along in between the gyres towards the eastern boundary of the basin. A detailed description of the Atlantic and Levantine Intermediate Waters was also provided, showing their presence throughout the year and their patchy distribution and entrapment by eddies throughout the basin. The analysis of the combined data from more extensive surveys of the Eastern Basin (e.g. POEM-V, see The POEM Group, 1991) supported these findings and extended them to the qualitative description of the general eastern Mediterranean circulation and dynamics.

3. VARIABILITY OF THE CIRCULATION DURING 1985–1988

The cruises carried out during the first phase of the POEM programme and referred to in the following did not necessarily cover the entire basin. The cruises POEM-I of October–November 1985, POEM-II of March–April 1986, and POEM-V of August–September 1987 (Özsoy et al., 1989; The POEM Group, 1990) covered almost the entire Levantine Basin. Other cruises—mainly those carried out by the Bilim in the northern Levantine Basin—were less extensive, but nevertheless yielded valuable information which bridged the gaps between the periods of more extensive coverage and helped towards a better understanding of the processes leading to temporal changes.

The motions in the Levantine Basin are characterized by a wide range of scales, amongst which we distinguish the synoptic, meso and sub-mesoscale as the major horizontal length scales. Since the motions are confined by geometry, the synoptic scales essentially cover the basin and sub-basin ranges of the scales of motion. The mesoscale is defined with the help of the first baroclinic radius of deformation; it covers the range of length scales from several deformation radii down to a fraction of this quantity. In the Levantine Basin the first baroclinic deformation radius is in the order of 10–15 km, and a part of the mesoscale spectrum is always difficult to detect in experiments unless they are specifically designed for this purpose. In basin-wide experiments, the mesoscale information is often compromised in favour of greater synoptic coverage. In the present experiments, the nominal station spacing has been 0.5° latitude/longitude (~ 50 km), so that we can only map the basin-wide general circulation, the sub-basin-scale motions and only the coarser elements of the mesoscale motions. Depending on the horizontal resolution of the measurements, motions with mesoscale and sub-mesoscale signatures superposed on top of the general circulation features have consistently been identified in the region (Özturgut, 1976; Özsoy et al., 1986; Robinson et al., 1987; Tziperman and Hecht, 1988; The POEM Group, 1991). Those motions, while being beyond our present scope, play important roles in the dynamics and certainly deserve more attention.

A review of the best available information over the total observation period suggests that some of the features are quasi-permanent (i.e. they appear to be present throughout the observation period although these features undergo dynamical and transient deformations and oscillations), some others are recurrent (they appear to be persistent for extended periods, and although they disappear during certain periods, they have a tendency to reappear), while others are simply transient. These characterizations, which are primarily based on the available period of observation, follow the earlier conclusions of Özsoy et al. (1989) and are parallel to the syntheses of Robinson et al. (1991).

In the following, we first present the surface and intermediate depth circulation derived from the available observations of 1985–1988. Later we describe water mass distributions insofar as their advection and local characteristics relate to the circulation. In particular, we emphasize secular evolution in which the major qualitative changes are detected to occur between the periods of 1985–1986 and 1987–1988.

3.1. Surface circulation

October–November 1985 (POEM-I)

The general circulation (Özsoy et al., 1989) consists of three major elements: the Rhodes gyre, a large feature with two eddy centres located approximately at the deep basin south of Rhodes, and a third one extending eastward toward Cyprus; the Mersa–Matruh gyre, the intense feature located to the south of the Rhodes gyre; the Shikmona gyre, the large cell with three separate centres and occupying the rest of the southeastern part of the Levantine basin (Fig. 2). In between the cyclonic Rhodes gyre and the anticyclonic Mersa–Matruh and Shikmona gyres, there is an eastward-flowing coherent jet, the central Levantine Basin current, which appears to be the continuation of the North African current. On its course the central Levantine Basin current bifurcates more than once, and becomes partially entrained in the gyral circulations. The first of these bifurcations occurs between the Rhodes gyre and the Mersa–Matruh gyre, where part of the jet encircles the Mersa–Matruh gyre and the other part flows along the southern rim of the Rhodes gyre to encircle the two cyclonic centres of the Rhodes gyre and eventually to join with the westerly flow along the southwest Anatolian coast. The remaining core of the jet branches once

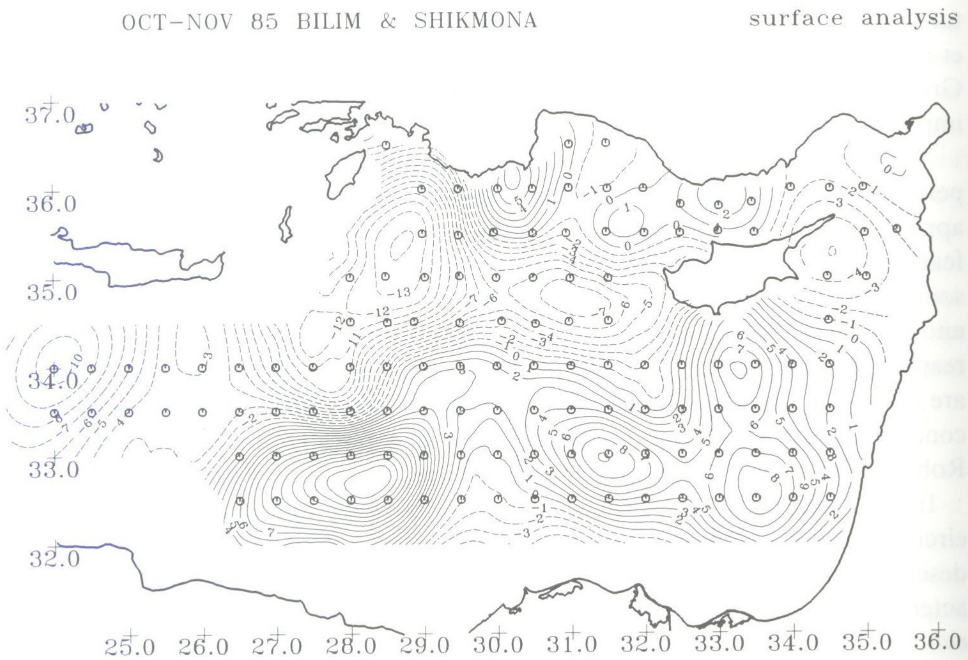


Fig. 2. Surface geopotential anomaly referenced to 800-dbar level of no motion, October–November 1985.

In Figs. 2–10 the contours are in units of dynamic centimetres; the positive contours are shown with bold lines and the negative contours with dashed lines. In order to mask out the regions of low confidence, the analysis field is displayed only in areas where the normalized error variance is larger than 0.5. The contour interval is 1 cm in the surface maps of Figs. 2–9 and 0.25 in the 300-m maps of Fig. 10.

more southwest of Cyprus, this time part of it to encircle the eastern extension of the Rhodes gyre, while the other part bypasses Cyprus on the south and, upon impinging on the eastern boundary of the basin, turns mainly southward while only a small part of the jet flow appears to be diverted, if at all, anticlockwise around Cyprus. This latter diversion as well as the flow immediately south of Cyprus appear uncertain because of the lack of data close to the coast in both areas (see Fig. A1 for the error distribution). Nevertheless, the Lattakia and Cilicia basins to the east and north of Cyprus appear to be blocked off from the mainstream flows and are occupied by a number of weaker eddies. An anticyclonic eddy is located between the Rhodes gyre and the Turkish coast (centred at 30 ° E and 36 ° N) where it appears to be locked on to the Anaximander Seamounts; we will call this eddy the Anaximander anticyclonic eddy. To the east of this anticyclonic eddy, but not sufficiently displayed in Fig. 2, another anti-cyclonic eddy appears in Antalya Bay (centred around 31° 30′E and 35°45′N), the Antalya anticyclonic eddy, located immediately west of the entrance to the Cilician Basin. This latter eddy appears relatively more intense (see Sections 3.2 and 4).

March–April 1986 (POEM-II)

This survey was almost entirely a repetition of the previous one (Fig. 3), about six months later and immediately after the winter season. In comparison with the previous survey, the three main features of the Levantine Basin circulation, the Rhodes, the Mersa–Matruh, and the Shikmona gyres, are still easily recognized, although their shapes have changed to some degree. In particular, the Rhodes gyre has acquired a crescentic form which almost engulfs the Mersa–Matruh gyre, its two ‘arms’ almost reaching the North African coast.

The central Levantine Basin current, which primarily had a zonal structure in the previous survey is also present in this survey, but it is meandering strongly. It first veers southward southeast of Crete, then makes a sharp turn north close to the African coast where it proceeds to make its way between the Mersa–Matruh and Rhodes gyres. Then, for the second time, it makes an excursion towards the African coast, turns north again, and traces the rim of the Rhodes gyre afterwards. In fact the central Levantine Basin current does not seem to reach the eastern coast of the basin because it simply continues north along the eastern edge of the Rhodes gyre. In the vicinity of the southwestern shores of Cyprus, where the central Levantine Basin current had displayed a bifurcation before, it seems to have broken apart, the remaining part of the jet forming a second loop around the warm core ring in the east (i.e. around the Shikmona gyre). There are other indications of the incipient breakdown of the meandering jet flow into separate loops at

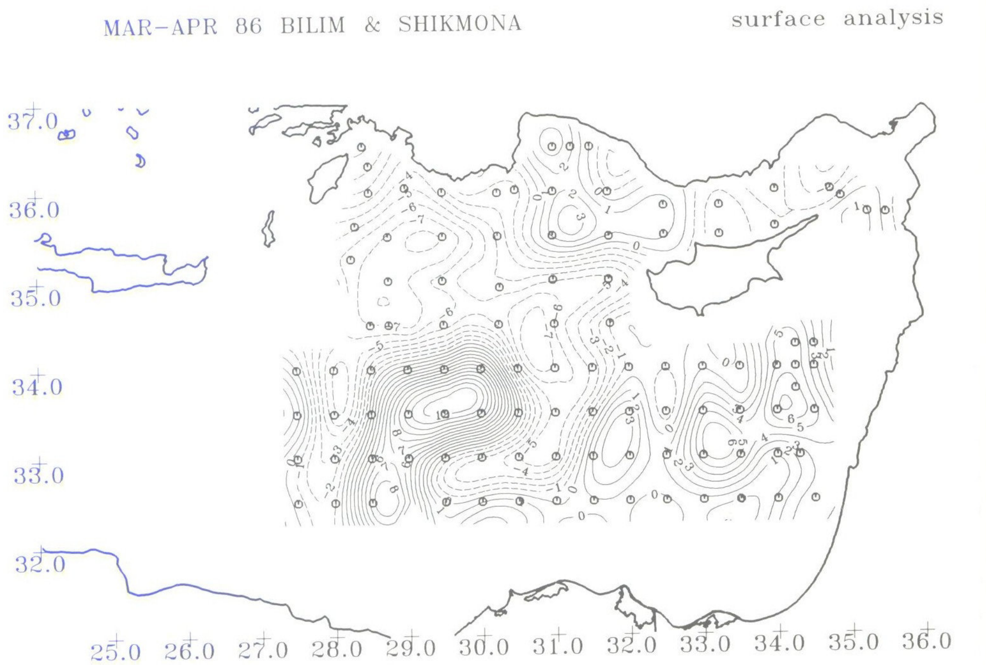


Fig. 3. Surface geopotential anomaly referenced to 800-dbar level of no motion, March–April 1986.

~ 35° N, 30° E where a deep structure is embedded within the Rhodes gyre (Özsoy et al., 1989).

In this survey as well as the previous cruise, there is no sign of a net flow forming a closed circuit around Cyprus. The Lattakia and Cilicia basins appear to be blocked to the mainstream flows to pass through them. Although the Anaximander or the Antalya anticyclonic eddies cannot be identified at the surface, a general anticyclonic region with two eddy centres can be discerned in Antalya Bay. The southerly one of the pair is located only slightly west of the former position of the Antalya eddy, and is conjectured to correspond to that eddy, since it persists till the next cruise of June 1986. The northerly member of the anticyclonic pair is conjectured to be related to the Anaximander eddy displaced to the northeast of its former position.

June 1986

During this cruise (Fig. 4), which covered only the northern part of the basin, a series of regularly spaced anticyclonic eddies were observed in the region extending from the Cilician Basin to the Anaximander Seamounts. The presence of the Rhodes gyre is indicated by the cyclonic circulation at

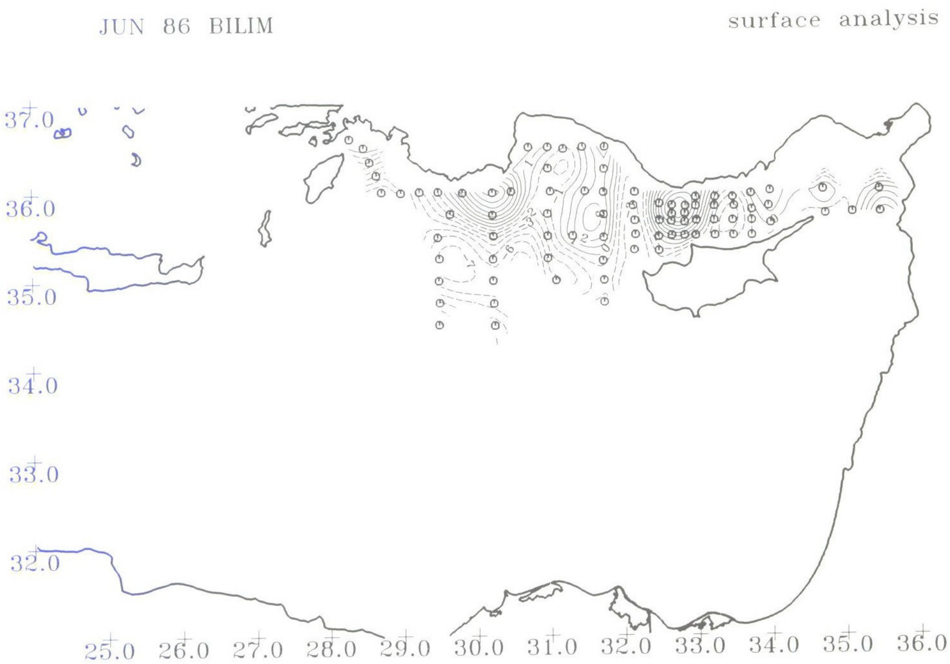


Fig. 4. Surface geopotential anomaly referenced to 800-dbar level of no motion, June 1986.

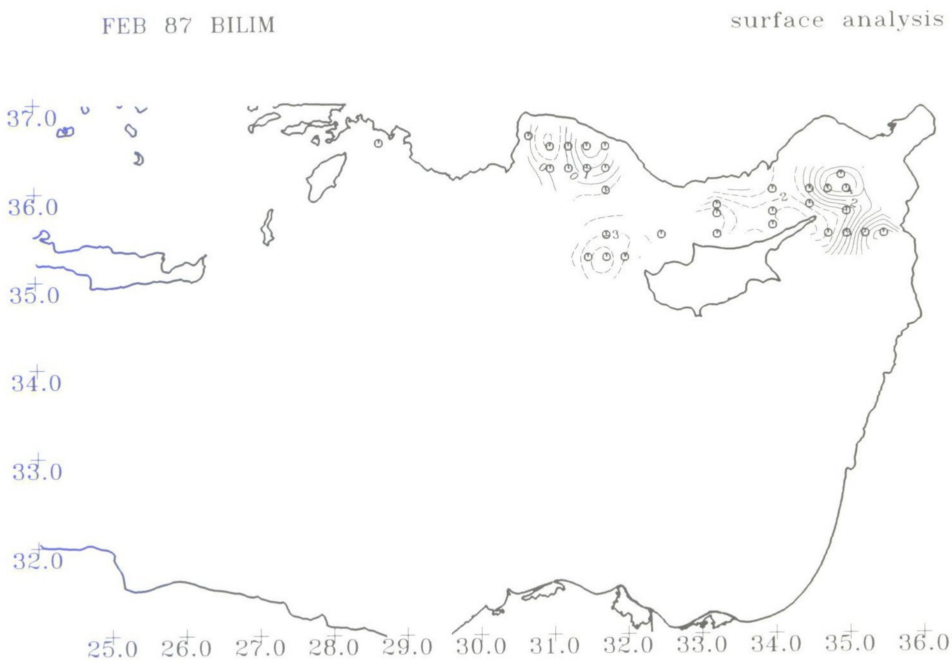


Fig. 5. Surface geopotential anomaly referenced to 800-dbar level of no motion, February 1987.

the western edge of the domain. The Anaximander and Antalya anticyclonic eddies are persistent and appear again at the locations at which they were identified in the October–November 1985 survey.

February 1987 (POEM-IV)

This cruise partially covered the northern part of the basin (Fig. 5). In contrast to the previous cruises, the circulation observed in the Cilician Basin during this survey is mainly cyclonic. However, a distinctly new development can be associated with the two anticyclonic eddies observed in the Lattakia Basin and the eastern part of the Cilician Basin. These particular eddies seem to be new arrivals in the region from afar, advecting with them Atlantic waters with an abundance which largely contrasts the previous surveys (see Section 4).

Although the survey does not cover the western part of Antalya Bay, it appears that the Antalya anticyclonic eddy formerly occupying the eastern part of the Antalya Bay at the entrance to the Cilician Basin is not detected at the same location in this survey.

June 1987

In Fig. 6 the Rhodes gyre appears to have retreated west, and an anticyclonic eddy occupies part of the Antalya Basin regularly occupied by

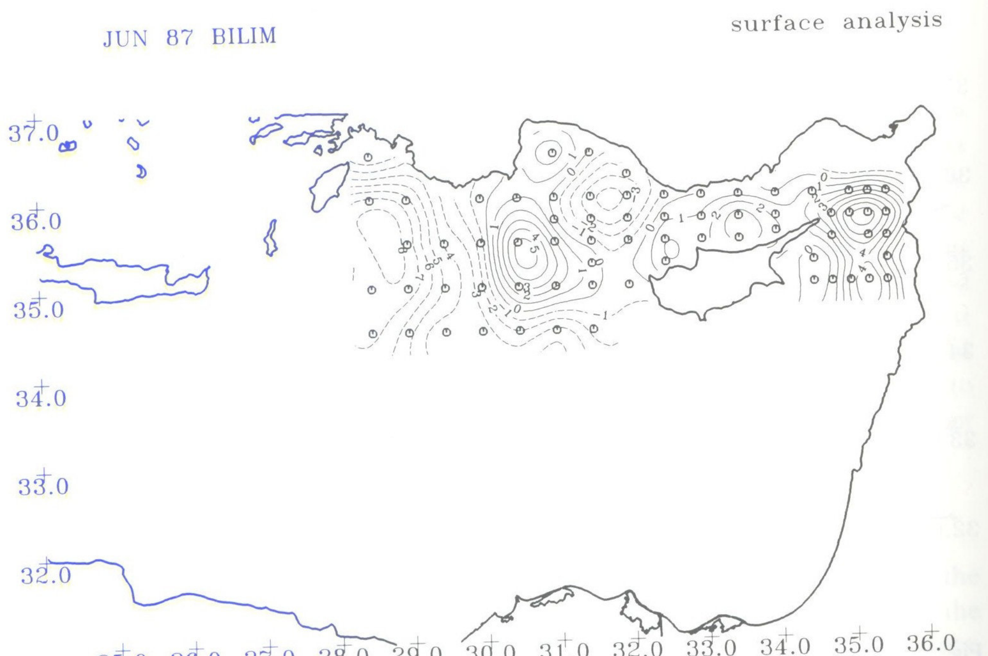


Fig. 6. Surface geopotential anomaly referenced to 650-dbar level of no motion, June 1987.

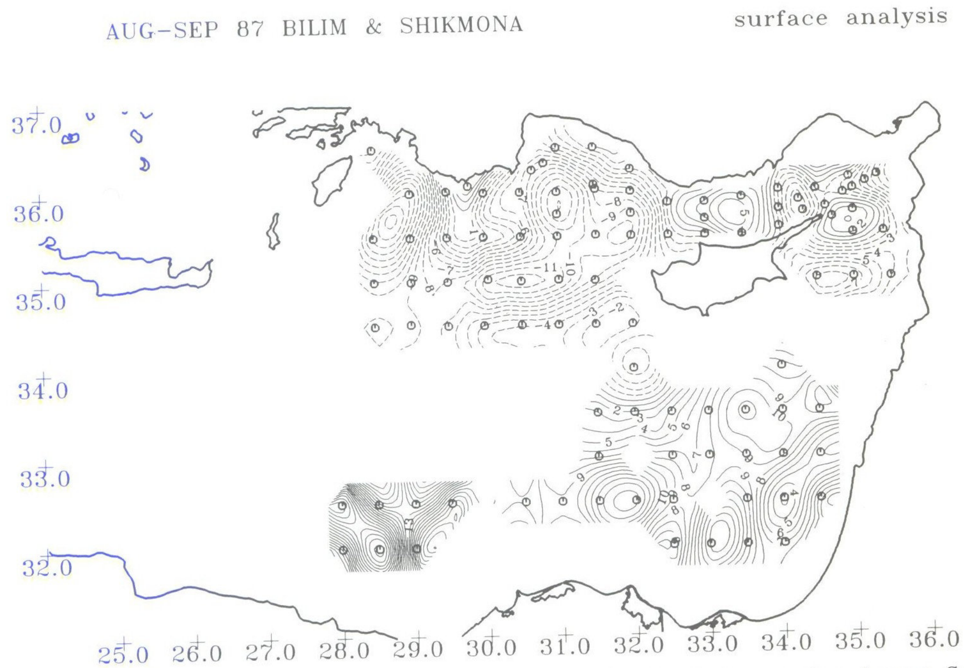


Fig. 7. Surface geopotential anomaly referenced to 450-dbar level of no motion, August–September 1987.

the Rhodes gyre easterly extensions in the surveys. In fact, the Anaximander and Antalya anticyclonic eddies of the first three surveys appear to be replaced by a single anticyclonic eddy (centred at 30°30′E, 35°30′N) to the south of the former positions of both eddies. Consequently, the currents on the outer edge of the Rhodes gyre flow west-southwest of Cyprus, later to turn north and follow the Anatolian coast. A cyclonic eddy appears in the eastern part of the Antalya Basin and the region east of this feature, the Cilicia and Lattakia basins, are occupied by anticyclonic circulation: the Cilician Basin circulation has reversed its direction once more to anticyclonic, and the twin eddy centres of the Lattakia Basin are still present. We only note here, and will demonstrate later, that the Atlantic Waters brought into the region of these anticyclones at the time of the previous survey survive also in this cruise.

August–September 1987 (POEM-V)

During August–September 1987 (Fig. 7), the POEM group attempted the coordination of cruises to obtain quasi-simultaneous data in the entire eastern Mediterranean basin (POEM-V). In addition to the Turkish and

Israeli cruises, POEM scientists from Italy, Greece, Yugoslavia, Germany and the USA collaborated in the data collection aboard various ships and later in the processing, intercalibration and analyses of the data (Pinardi, 1988). Analyses of the collective POEM data sets in the eastern Mediterranean including POEM-V are given by The POEM Group (1991) and Robinson et al. (1991). We present analyses based on Israeli and Turkish data collected in the Levantine Basin alone.

Technical problems prevented both the RV Bilim and the RV Shikmona from carrying out the full survey. The RV Bilim collected data only to a depth of 450 m and the RV Shikmona had to abort the cruise after carrying out only a limited number of its planned stations. Because the Shikmona CTD data could not be recovered for this cruise (Pinardi, 1988), temperature and salinity measurements obtained at selected depths for calibration purposes have been used in the dynamic height calculations.

The results (Fig. 7) show the Rhodes gyre extending into the Antalya Basin, and the anticyclonic circulation in the Cilician Basin persisting in the same way as during the previous cruise. The Antalya anticyclonic eddy has completely disappeared, not to reappear within the rest of the observational period. The Anaximander eddy survives in its most persistent position adjacent to the Turkish coast. It must be noted that the Anaximander and Antalya eddies had been formerly identified as quasi-permanent features, because they were persistent from October–November 1985 to June 1986. It appears from later surveys of February and June 1987 that the features identified as the Antalya and Anaximander eddies may have been first merged and then shifted to the Anaximander eddy identified in the present survey.

In the southern part of the basin, and about two years after they were first identified, structures reminiscent of the earlier depictions of the Mersa–Matruh gyre and the Shikmona gyre are observed once again (cf. Robinson et al., 1990). The Mersa–Matruh gyre domain is occupied by two intense anticyclonic eddies nearer to the coast than had been observed before. Intrinsic in the Shikmona gyre are two anticyclonic eddies: the intense northerly member of this pair is located more to the south of that observed in the earlier cruises. To the extent allowed by the scarcity of data in the region, it appears that the central Levantine Basin current, between the Rhodes gyre and the Mersa–Matruh gyre bifurcates well west of Cyprus, the divergence occurring at $\sim 28°$E, $34°$N. One branch then proceeds northeastward and then westward along the rim of the Rhodes gyre, the other branch flows south of Cyprus then turns southward and eventually westward to flow along the northern rim of the Shikmona gyre (The POEM Group, 1991; Robinson et al., 1991). None of the central Levantine Basin current waters appear to penetrate into the Cilician Basin.

May 1988

This cruise covers a very restricted area in the northern Levantine Basin. It reveals that (not shown here) at the time the anticyclonic circulation of the Cilician Basin still persisted.

July 1988

Once more a cruise limited to the northern basin alone (Fig. 8), reveals significant changes as compared with previous circulation patterns. The flow along the Turkish coast is intense and coherent, meandering strongly in the entire region from the Lattakia–Cilicia basins to Rhodes. The only break in the continuity of the jet occurs near Cape Andreas (the 'tip' of Cyprus), and can be ascribed to the steep topography (Fig. 1) associated with the sill between Cyprus and the Gulf of Iskenderun.

The Rhodes gyre covers an extensive area, and appears to engulf an anticyclonic eddy in the south, perhaps part of the Mersa–Matruh Gyre—resembling the situation observed in POEM-I and POEM-II. An intense anticyclonic eddy (presumably part of the Shikmona gyre) is observed south of Cyprus.

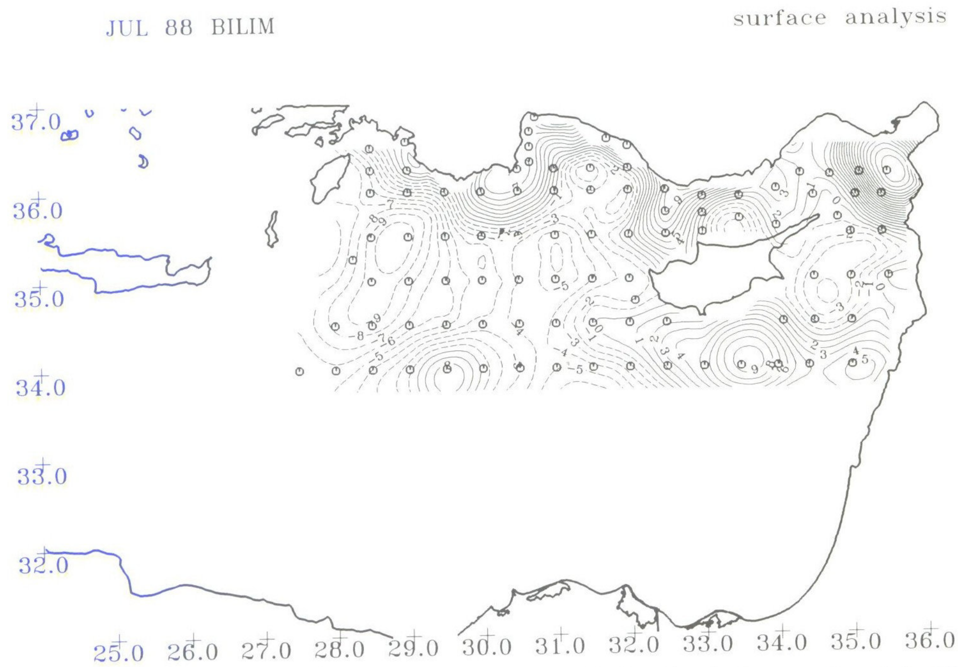


Fig. 8. Surface geopotential anomaly referenced to 800-dbar level of no motion, July 1988.

While the presence of a feature like the central Levantine Basin current cannot be identified due to the partial coverage in this survey, the flow approaching Cyprus from the south bifurcates to the island's southwest. One of the branches flows northward and finds its way to the Antalya Basin. The other branch, which appears to carry the larger part of the fluxes flows between the Shikmona gyre and the island of Cyprus and turns northward to join the meandering jet flow in the Cilician Basin. This pattern is radically different from all previous observations since the earlier surveys indicated that none of the flow, or at best a small fraction of the total flow was able to penetrate into the Cilician Basin through the passage east of Cyprus.

October 1988

Another limited extent cruise which, once more, showed a meandering jet flow extending from the Lattakia and Cilician basins to the Antalya and Rhodes basins (Fig. 9). Since the southern and eastern parts of Cyprus were not covered, and since we do not see much of a northerly flow west of Cyprus, continuity would indicate that the main part of the flow be diverted

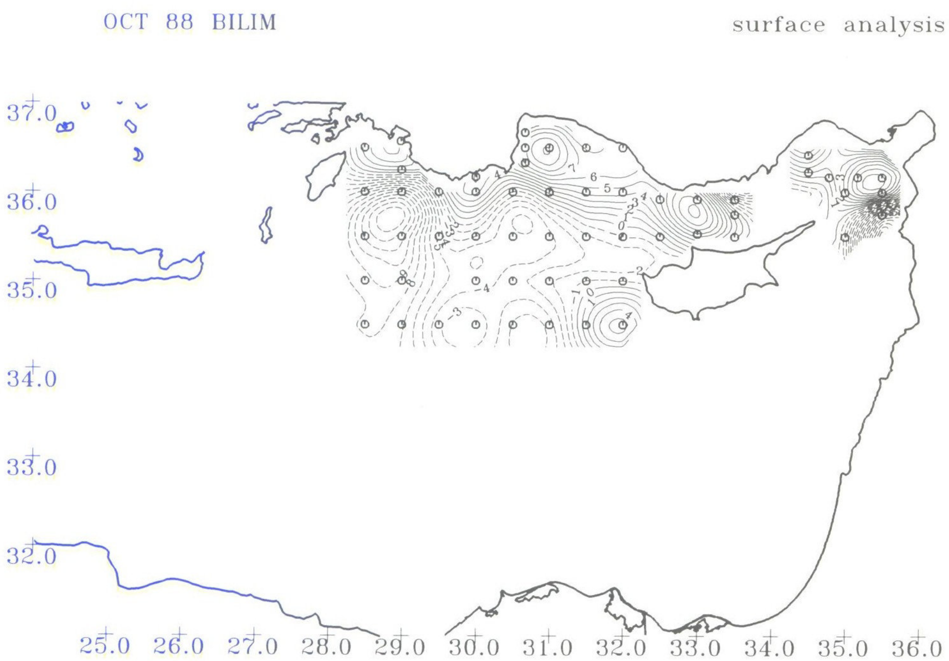


Fig. 9. Surface geopotential anomaly referenced to 800-dbar level of no motion, October 1988.

to pass east of Cyprus in order to join in with the meandering jet issuing west from the Cilician Basin.

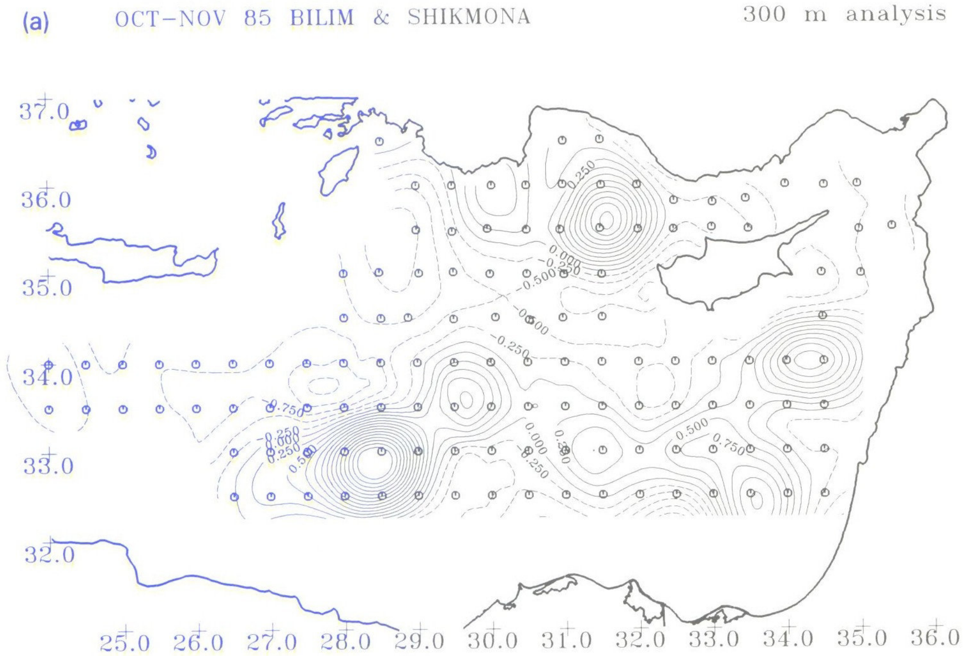
3.2. Circulation at intermediate depths

The description of the intermediate-depth circulation will be based on the 300-m depth anomaly maps corresponding to the periods of surface circulation maps presented above. In addition to providing a description of the vertical structure of the circulation, the series of maps given in Fig. 10a–h are also instrumental in identifying the changes in the positions and structure of the persistent eddies. The analyses of the POEM-I and POEM-II experiments (Özsoy et al., 1989) have indicated significant vertical structure, with horizontal shifts and relative intensifications of the eddy centres. Moreover, some of the coherent anticyclonic eddies were shown to persist with depth.

Comparing the maps for the POEM-I and POEM-II (Fig. 10a,b), the persistent anticyclonic vortices are identified as the Mersa–Matruh, Shikmona gyres and Anaximander and Antalya eddies, which preserve their identities in spite of a variety of changes in their structures. In June 1986 (Fig. 10c) we continue to identify the Anaximander and Antalya eddies in the northern Levantine. In fact, the Antalya eddy identified as a deep coherent anticyclone east of the Antalya Basin and blocking the entrance to the Cilician Basin ceases to exist in the same region some time between June 1986 and February 1987. In February 1987 (Fig. 10d), as far as the coverage permits, we do not find any evidence for the Antalya eddy. Instead, we observe a cyclonic circulation in the Cilician Basin, and a small anticyclonic eddy entering the Lattakia Basin.

In June 1987 (Fig. 10e), the Cilician Basin circulation switches to become anticyclonic and two anticyclonic eddies are detected in the Lattakia Basin. At the same time we find a deep, coherent anticyclonic eddy in the west, which is located in the vicinity of the Anaximander eddy observed in the earlier phase of the experiments. In the basin-wide experiment of POEM-V (Fig. 10f) it is evident that the coherent structure of the eddies in the Mersa–Matruh and Shikmona anticyclonic gyral regions preserve their depth structure, and in the case of the Shikmona eddy, become more intense at the 300-m depth. The only other persistent features with depth are the small Anaximander anticyclonic eddy and the anticyclonic eddy near the tip of Cyprus. In July 1988 (Fig. 10g), the intermediate-depth signatures of the Anaximander eddy and two other anticyclonic eddies at 34° N latitude are significant. In October 1988 (Fig. 10h), the two relatively strong eddies appear, one at the familiar position of the Anaximander eddy and the other one extending into the western part of Antalya Bay.

(a)



(b)

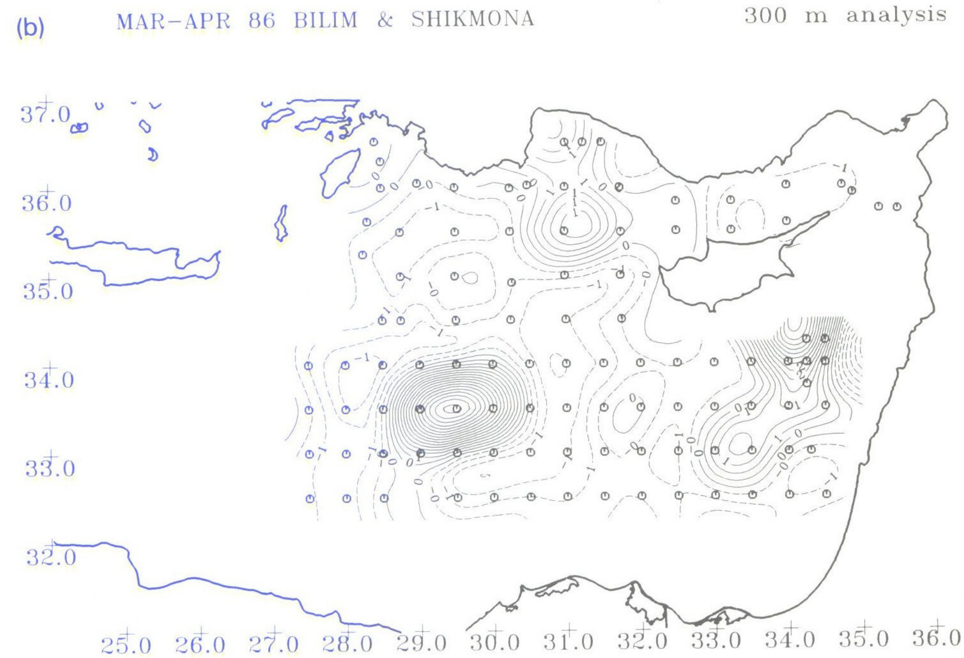
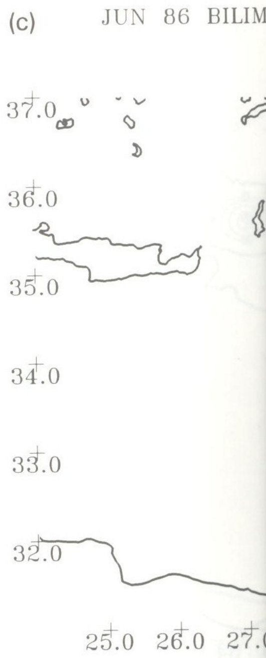
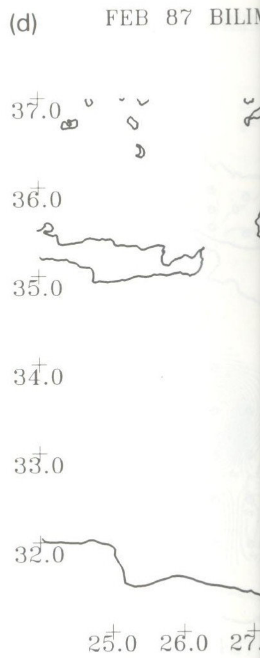


Fig. 10. Geopotential anomalies at the 300-dbar level for the experiments of: (a) October–November 1985; (b) March–April 1986; (c) June 1986; (d) February 1987; (e) June 1987; (f) August–September 1987; (g) July 1988; and (h) October 1988. The units and the reference levels are the same as in Figs. 2–9.

(c)



(d)



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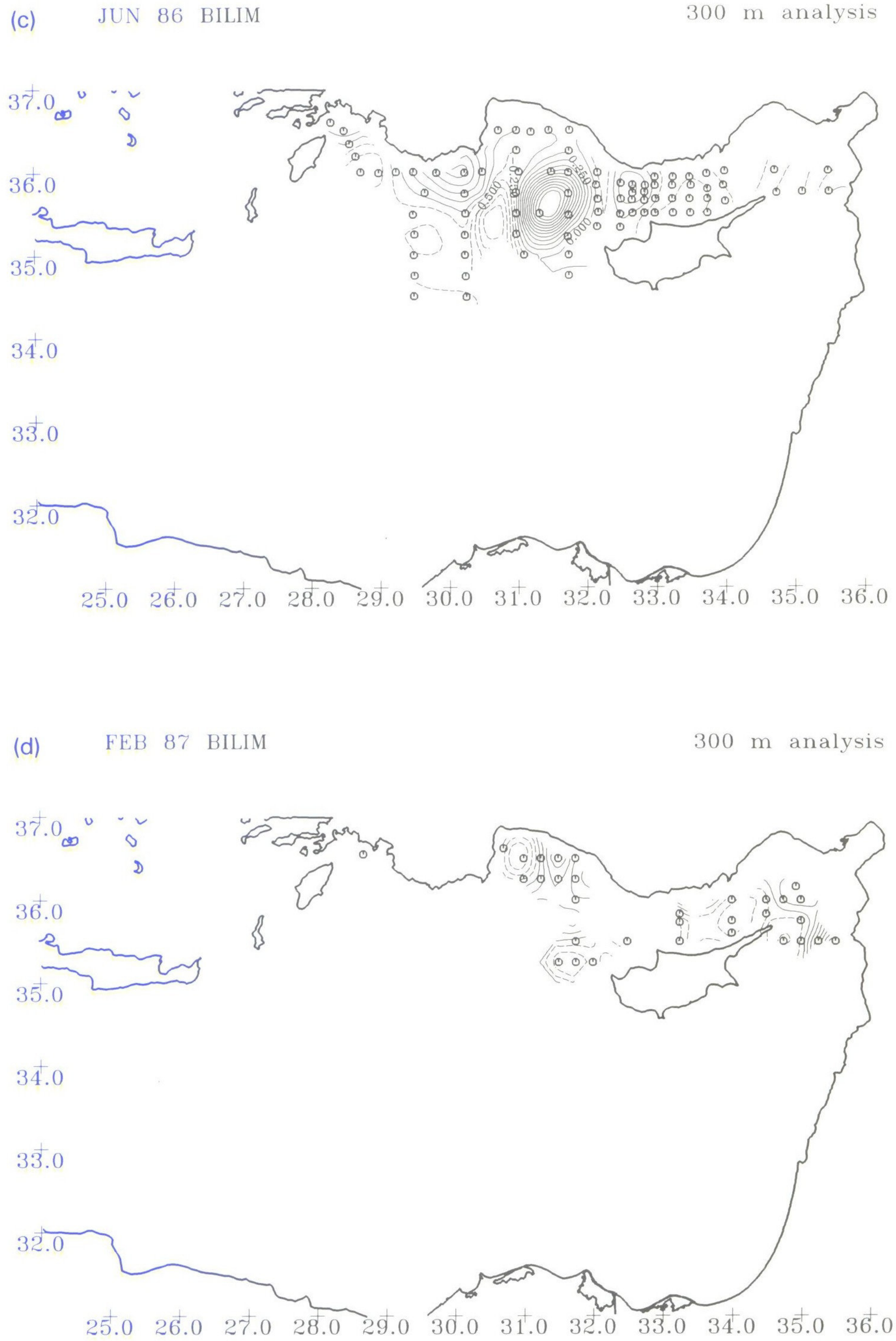

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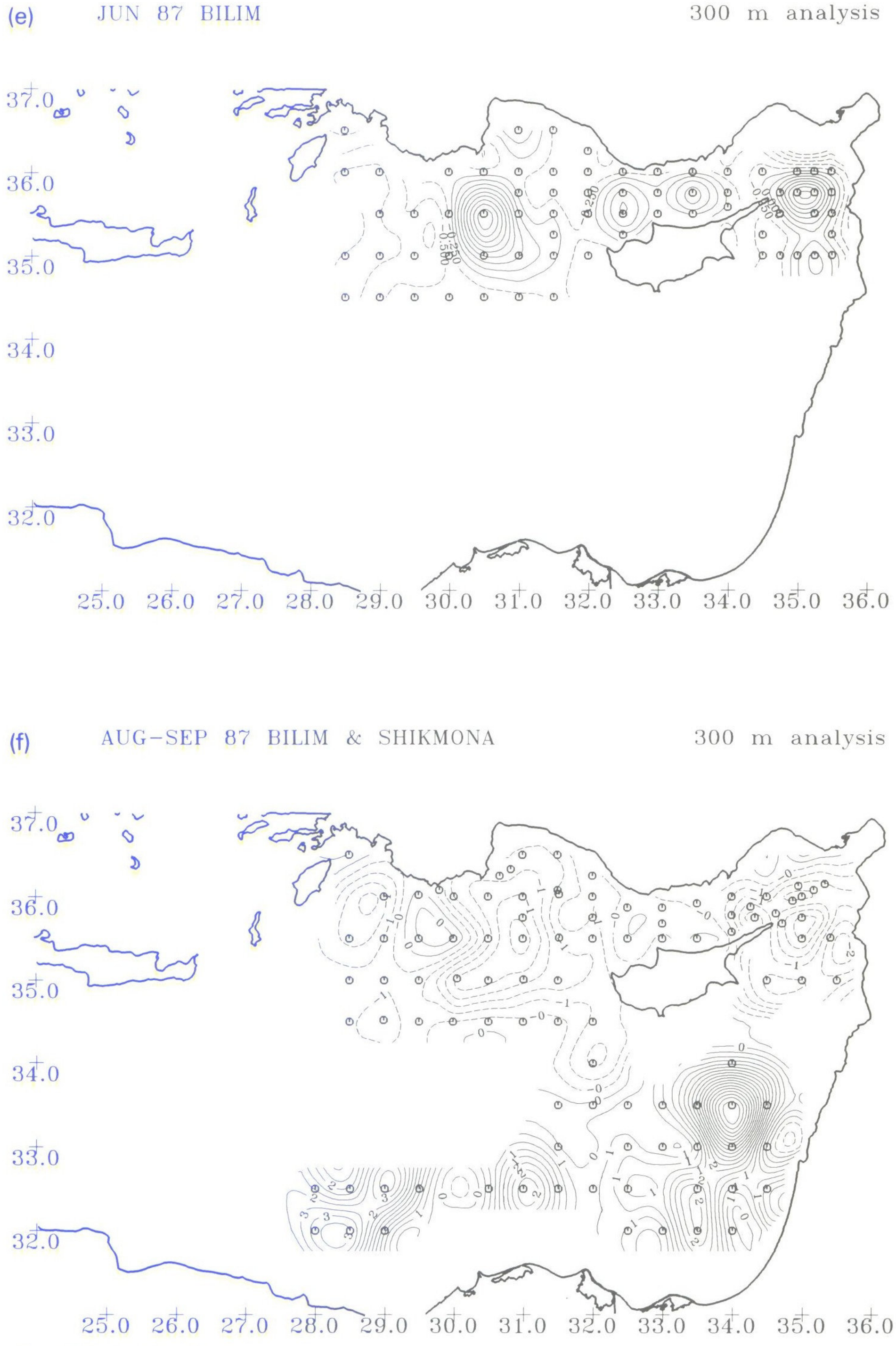
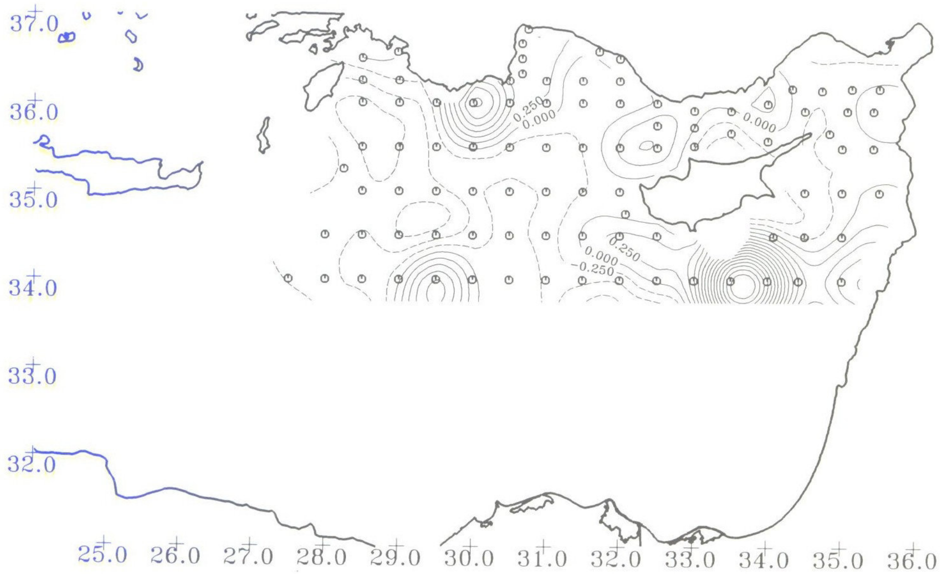


Fig. 10 (continued).

(g) JUL 88 BILIM 300 m analysis



(h) OCT 88 BILIM 300 m analysis

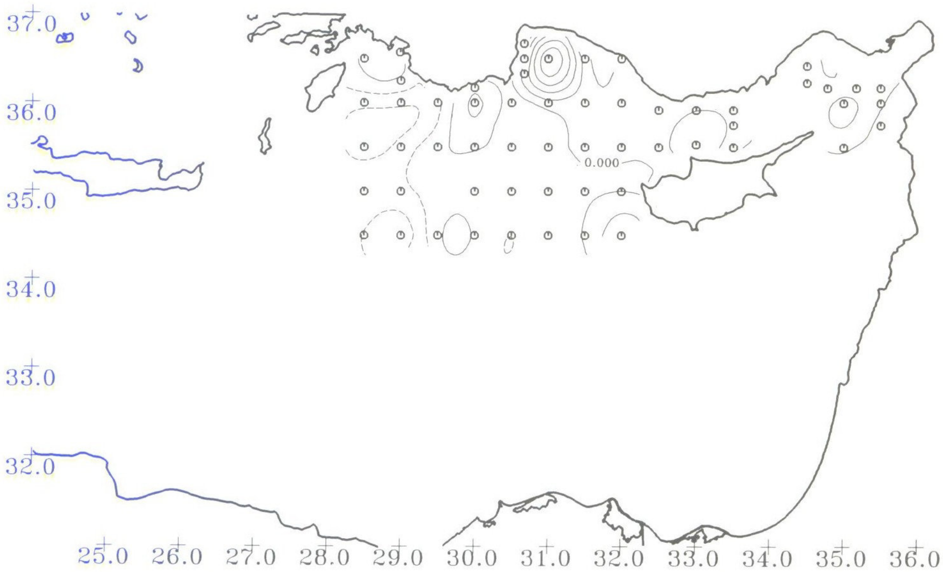


Fig. 10 (continued).

4. ADVECTION OF ATLANTIC WATER MASSES

We will use the salinity distribution, in particular, that of the anomalous Atlantic waters, as a tracer to support some of the above observations. The Atlantic Water (AW) enters the Levantine Basin through the Cretan Passage; it is then carried around by the jet flow with which it is associated, and depending on the fate of the jet and entrainment into the various nearby eddies, it finds its way into the northern Levantine region in the form of subsurface filaments (Özsoy et al., 1989). To emphasize the variations in its abundance, and thereby to aid in the interpretation of the circulation variability observed above, we will plot sections located approximately along the 35°30′N latitude (Fig. 11) to show the salinity distribution at the time of each survey. In each plot, the near-surface (40–50 m) solid line contours with salinities of $\leqslant 38.9$ are used to identify the AW masses.

In the October–November 1985 cruise (Fig. 12a), there are some filaments of AW which manage to reach to the northern Levantine; but generally, high-salinity LIW occupies the whole section. The rising of the isohalines to the west of the section (left-hand side) corresponds to the Rhodes gyre. The deepening of the isohalines and the maximum salinities

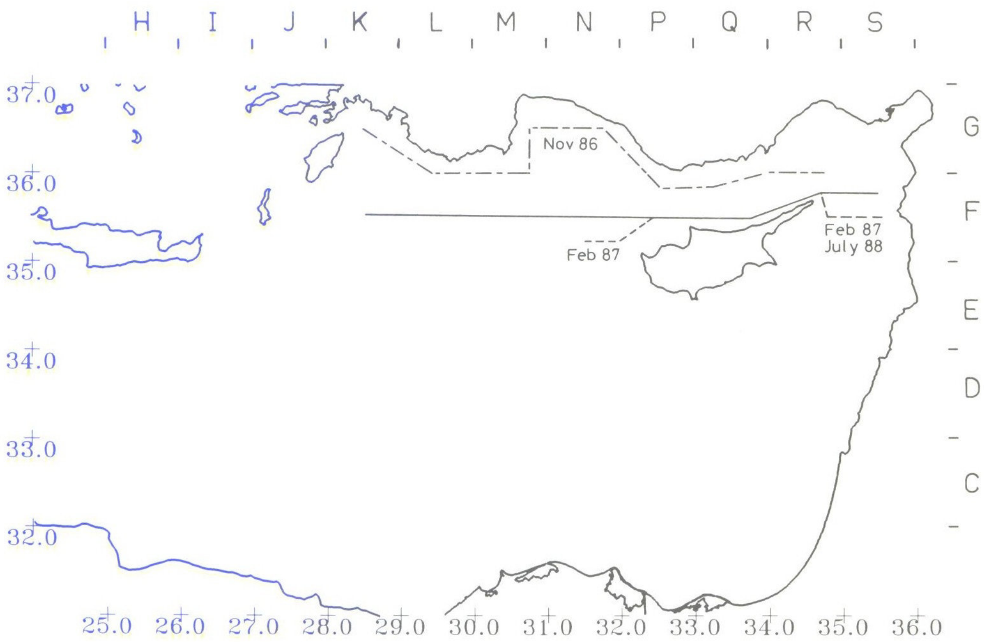


Fig. 11. Locations of the transects of stations for which the salinity distributions are plotted in Fig. 12a–i. The solid line marks the locations of most of the transects, and the dashed lines indicate the occurrences other than the main west–east transect. Letter codes for one degree square grids are marked to specify the locations of stations in Fig. 12a–i.

observed at about the midpoint of the section marks the location of the intense Antalya anticyclonic eddy at ~35°30′N, 31°30′E, which persisted at this location from October 1985 till at least June 1986. The filaments of AW are observed to partly encircle the Rhodes gyre and partly wrap around this anticyclonic eddy. The AW that leaks into the region has been transported as filaments mainly by the bifurcating branch of the central Levantine Basin current which advects them north from west of Cyprus.

In the April–March 1986 survey (Fig. 12b), the AW signature in the northern part of the Levantine Basin is lost because of wintertime mixing. It appears as a distinct water mass extending from the surface down to depths of 200 m in the Mersa–Matruh gyre (Özsoy et al., 1989), but the mixing of the surface waters and the extreme undulations of the jet flow (see last section) inhibit the AW filaments in the north. It is, however, quite clear from the circulation derived from this extensive survey that the circulation features have not changed significantly as compared with the October–November 1985 cruise. The deepening of the isohalines at about mid-section again marks the Antalya eddy, which has shifted slightly to the west of its former position.

In June 1986 (Fig. 12c), the structure of the intense Antalya anticyclonic eddy is evident in the salinity section, the eddy being located at the exact position that it had been observed in October–November 1985. An AW filament is found west of the Antalya anticyclonic eddy, and it is conjectured to have arrived there from the western side of Cyprus. There is also an AW trace at the easternmost station of the section, showing a partial penetration by way of the connection east of Cyprus.

The next section (Fig. 12d) represents the only set of data available during November 1986, when a single transect of stations was visited more to the north than that presented in the other sections (Fig. 11). The only trace of an AW filament appears at the eastern part of the Cilician Basin, suggesting some penetration of these waters from the eastern side of Cyprus.

It is only in February 1987 (Fig. 12e) that we see voluminous amounts of AW penetrating the region east of Cyprus. For the first time in this region we observe a layer of AW extending from the surface down to depths of 200 m. The AW appears to be trapped in the anticyclonic eddies which present themselves at the Lattakia Basin and the Gulf of Iskenderun region during this survey.

In the following June 1987 survey (Fig. 12f), the abundance of the AW in the northern Levantine has increased dramatically. The pool of AW which appeared in the Lattakia Basin for the first time in February 1987 now extends west to cover the Cilician Basin as well, associated with the extension of anticyclonic eddies to cover both of these basins. An additional patch of AW appears in the anticyclonic eddy located in the Antalya Basin.

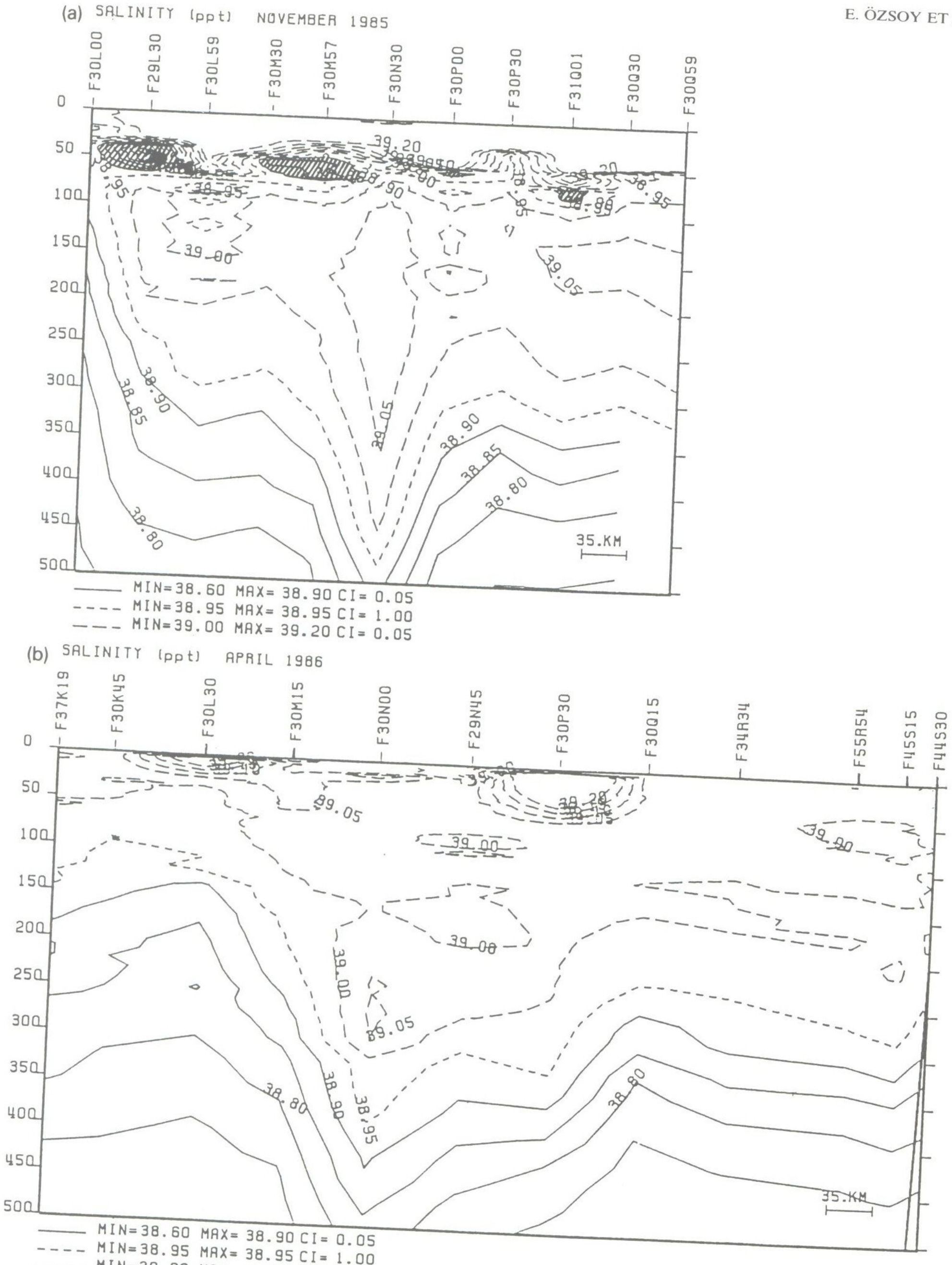
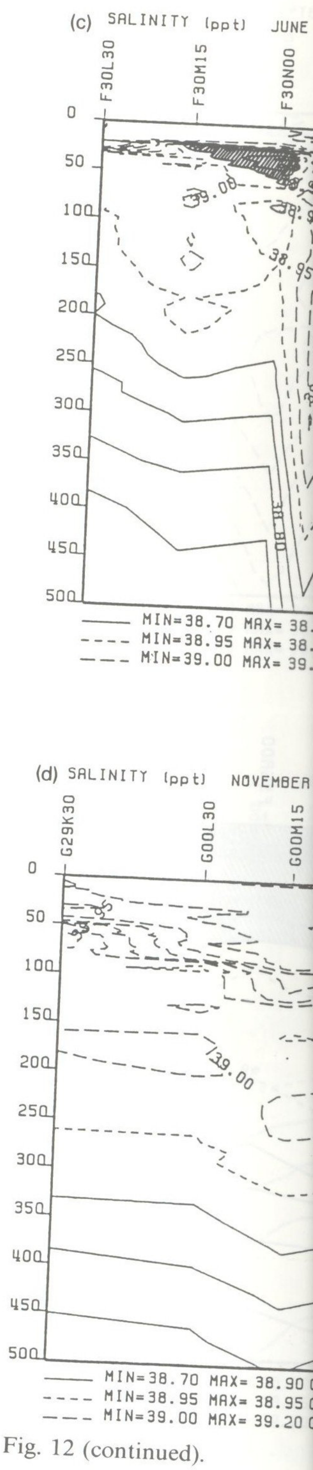


Fig. 12. West–east cross-sections of salinity in the northern Levantine at the transects shown in Fig. 11. (a) November 1985; (b) March–April 1986; (c) June 1986; (d) November 1986; (e) February 1987; (f) June 1987; (g) September 1987; (h) July 1988; (i) October 1988. The contour spacing is 0.05 with solid lines for $S < 38.90$, small dashes for $S = 38.95$ and long dashes for $S > 39.00$. The water masses with AW signature ($S < 38.90$) are shaded in the figures. The station identifiers are coded such that the letters represent the grid degrees latitude and longitude (see Fig. 11), and the subsequent two-digit numbers give the minutes of degree displacements in that grid.



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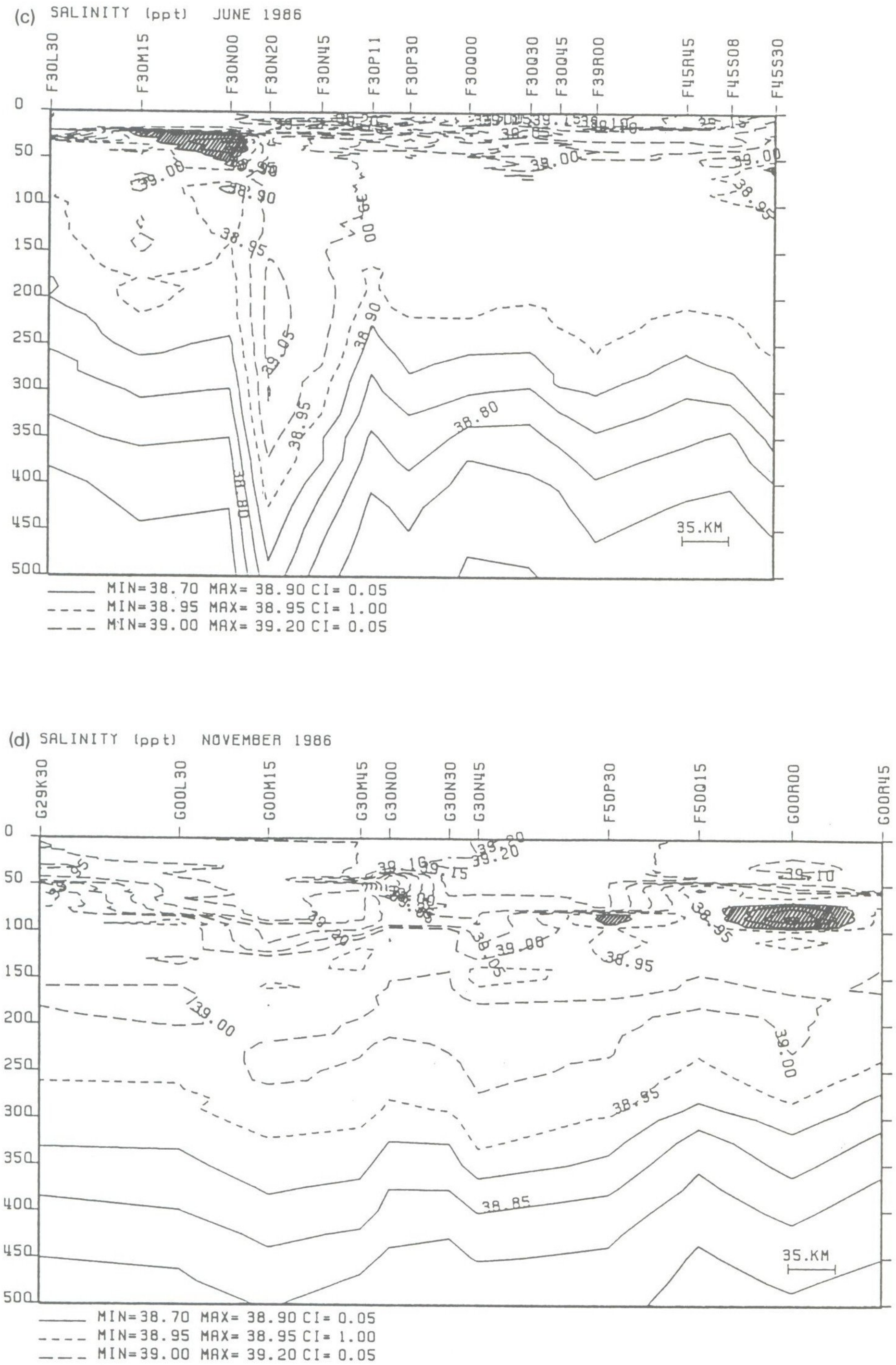

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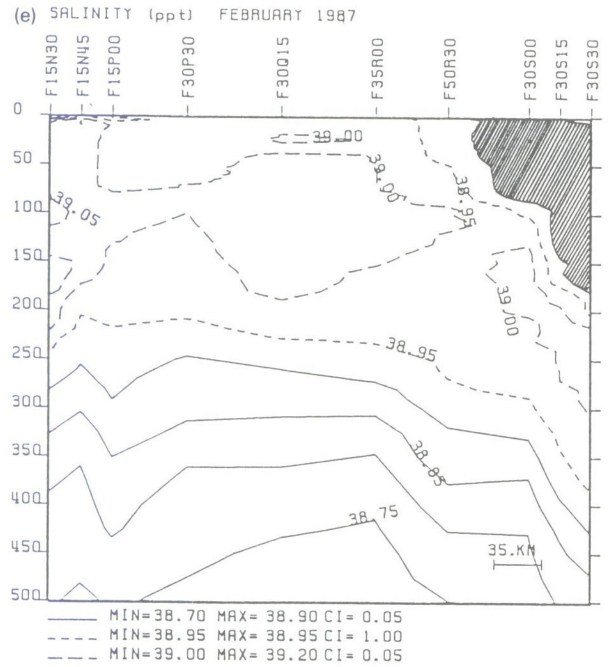

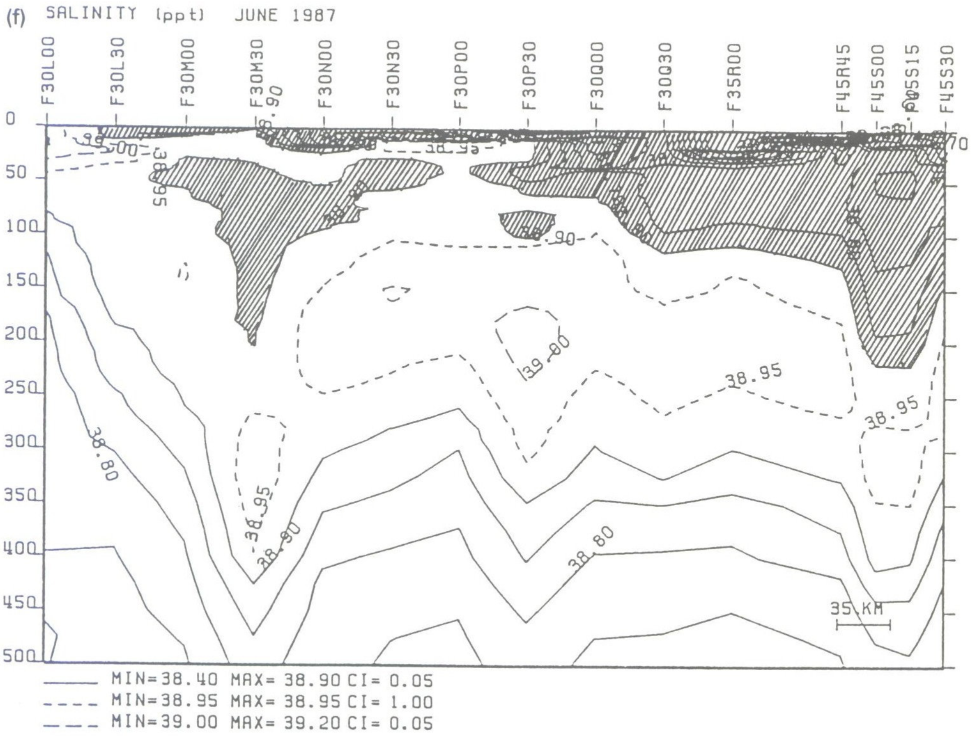

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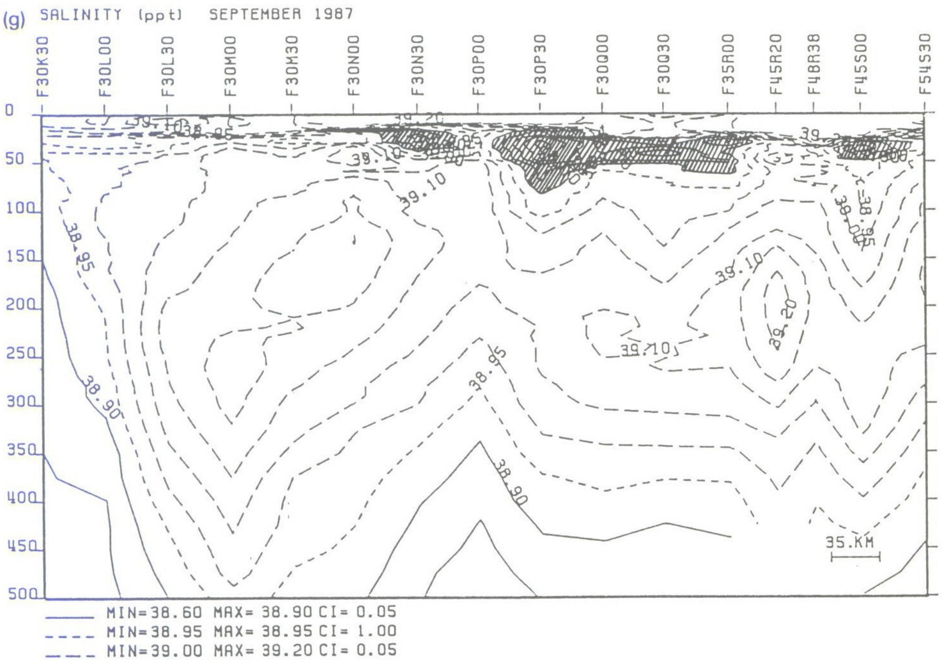

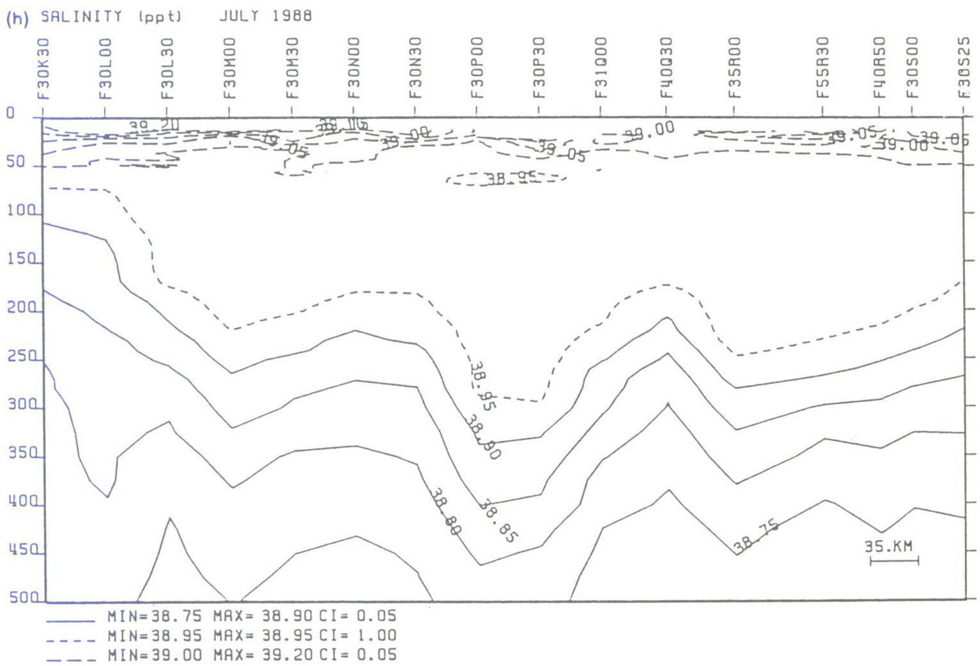

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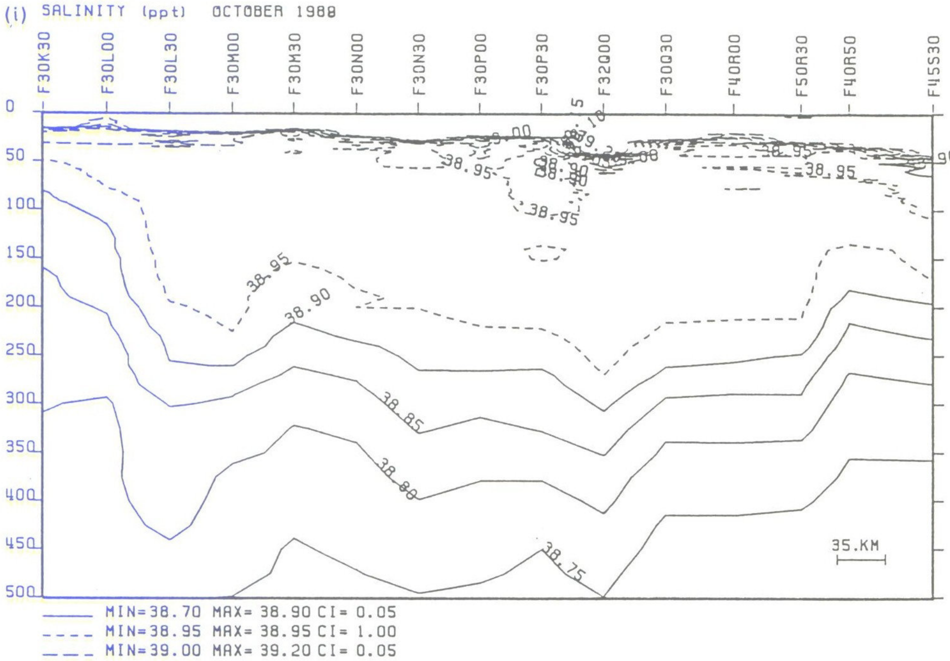

Fig. 12 (continued).

It is not clear how the patch in the Antalya Basin eddy was entrained; whether it was entrained from the Cilician Basin AW pool or from south of Cyprus. What is clear, however, is that both the Antalya Basin patch and the Cilician and Lattakia basin patches of AW were not observed there before February 1987.

In the following survey of September 1987 (Fig. 12g) the AW continues to persist in the Cilician Basin, although it now appears as a much thinner layer below the more saline mixed layer. Filaments appear in the Antalya Basin and the Gulf of Iskenderun regions.

In the two surveys of July and October 1988 (Fig. 12h,i), there is much less of an indication of AW filaments, except for certain traces of it in the eastern and western extremities of the Cilician Basin.

5. WATER MASS SIGNATURE OF THE SHIKMONA GYRE

The four distinct water masses that occur in the Levantine Basin (Levantine surface water, Atlantic water, Levantine intermediate water and deep water) can be distinguished primarily through the vertical structure of the water column. Horizontal contrasts that are associated with various circulation features often appear in terms of large vertical displacements of these water masses, as shown in the previous section. By taking advantage of this fact, Brenner (1989) was able to show that the cores of the Mersa–Matruh and Shikmona gyres could be identified by unique *T–S* signatures. While both cores consisted of a trapped patch of LIW the core of the Mersa–Matruh gyre was 80 m deeper, 0.21° C cooler, and 0.12 less saline than the core of the Shikmona gyre. Furthermore, at depths below the seasonal thermocline, each eddy maintained its unique *T–S* signature at least over the 6-month period covered by cruises POEM-I and POEM-II.

In addition to the POEM cruises, a series of five intensive cruises (referred to as EDDY cruises) has been conducted with the RV Shikmona in the vicinity of the Shikmona gyre. During each of these cruises an attempt was made to sample the eddy along at least one north–south section and one east–west section. A typical cruise consisted of 30 stations with a nominal spacing of 20 km. Further details of the cruises are given in Brenner et al. (1991).

Following Brenner (1989) we have examined the *T–S* properties from the central station of the eddy during the various cruises beginning with POEM-II (April 86) through EDDY-05 (May 89). The location of the core and various properties of the thermostad including the depth of its base, its temperature, and its salinity are summarized by Brenner et al. (1991). From their data we can see that the eddy has appeared in two distinct locations. Until June 1986 it was located further to the northeast while from August 1987 onward the preferred location has been further south. Associated with this shift in location we also notice an increase in the temperature of the thermostad from 16.15° C to 16.43° C. The latter value has been maintained since August 1987.

The salinity of the thermostad has undergone three changes. Until June 1986 the value was typically 39.12. With the southward shift and the rise in temperature observed in August 1987, the salinity dropped to 39.08. While the temperature remained virtually unchanged between August 1987 and September 1989, the salinity rose to 39.15 during the winter of 1988–1989 and remained at that value through September 1989.

Accordingly we have grouped the *T–S* curves into three periods. In Fig. 13a we show the *T–S* curves for POEM-II (April 1986) and EDDY-01 (June 1986) when the eddy was cooler and to the northeast. Figure 13b shows the curves for POEM-V (August 1987) and EDDY-02 (April 1988) with the warmer but less saline thermostad. Figure 13c shows the curves for EDDY-03 (February 1989), EDDY-04 (May 1989), and EDDY-05 (September 1989) with the warmer more saline thermostad. Focusing our attention on depths from the thermostad and below, we find that in each figure the curves coincide indicating that the water mass properties are preserved during the respective periods. Based on this, we believe that some time during the first

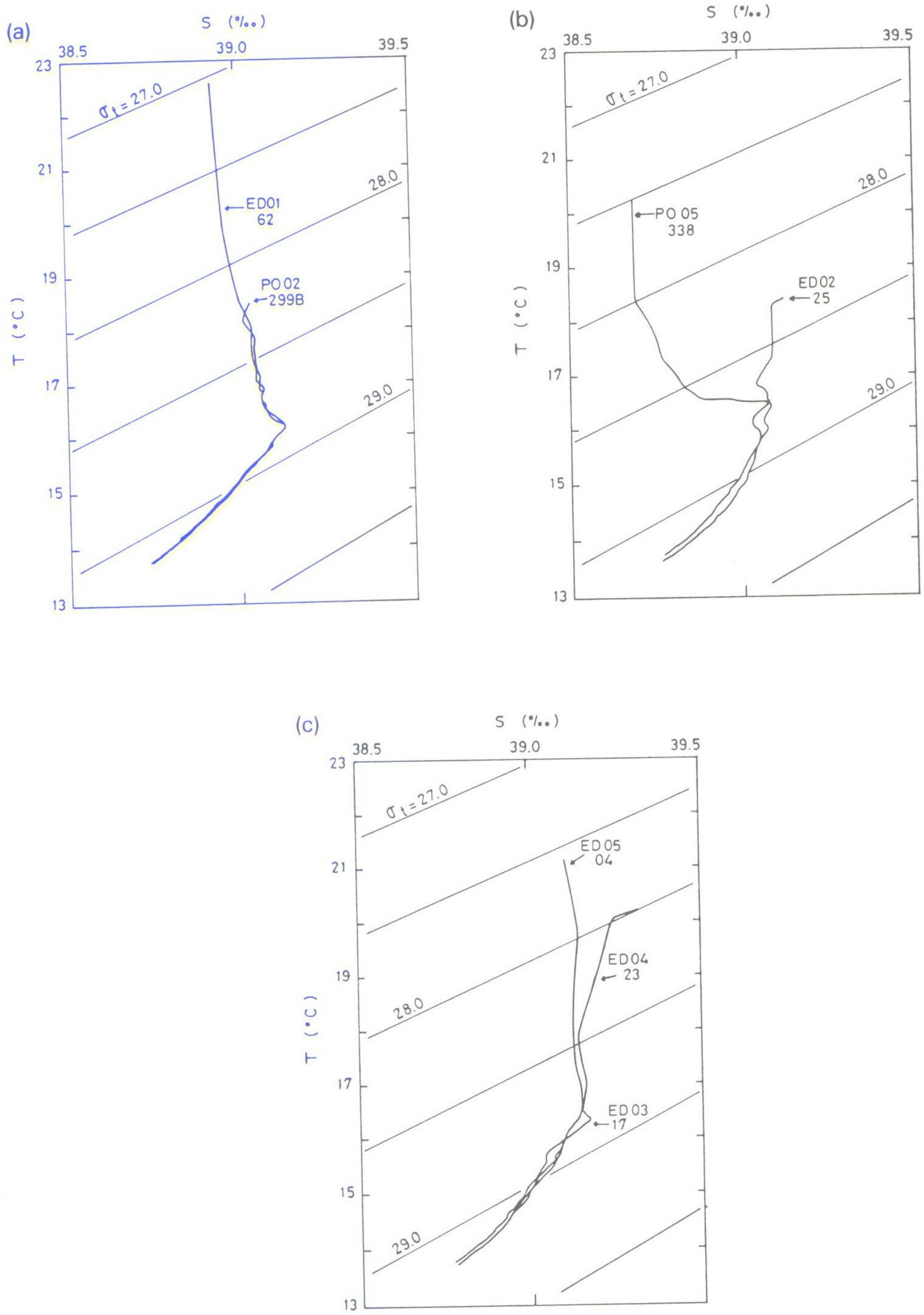

Fig. 13. Temperature versus salinity in the core of the Shikmona gyre sampled in the periods: (a) April–June 1986; (b) August 1987–April 1988; and (c) February–September 1989.

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half of 1987, the eddy experienced a major change in its water mass structure. Whatever the cause of this change may be, it is consistent with the changes occurring in the circulation patterns reviewed above.

6. SUMMARY AND CONCLUSIONS

The recently available sets of oceanographic data show that the Levantine Basin acts as the stage for complex dynamical events of significance in modern ocean science. The region is characterized by quasi-permanent, recurrent and transient features such as eddies, jets and filaments which are in continuous communication and interaction with each other. A wide range of scales and associated dynamical processes are evidently embodied by these features.

In reviewing the structure and characteristics of some of these features and the seasonal and longer term variability in the general circulation of the Levantine Basin, we have attempted to extract a maximum amount of information by patching together the interpretations obtained from individual data sets.

Various qualitative changes in the long-term behaviour of the circulation are detected and appear to be related to each other. In particular, we find that the circulation pattern in 1985–1986 essentially consisted of a jet flow in the middle of the basin which meandered and bifurcated several times to contribute to the flows around the three main sub-basin-scale gyres. The particular pattern of diversion of the jet flow into the gyres resulted in weak flows in the Cilician Basin. During this period, the AW filaments, which indicate the degree of penetration of the jet flow into the northern Levantine, were common in the region between the islands of Rhodes and Cyprus. One of the conspicuous features of the circulation during the same period was the intense Antalya anticyclonic vortex which persisted at the western entrance to the Cilician Basin.

In the following period of 1987–1988, the general circulation pattern is observed to undergo several important changes. First, early in 1987, we observe anticyclonic eddies entering the Lattakia Basin, east of Cyprus. For the first time in the detailed observation period, significant quantities of AW, trapped in these anticyclonic eddies, are transported first into the Lattakia Basin in February 1987, and then into the Cilician Basin in June 1987, lasting in some trace amounts until September 1987. Moreover, the Antalya anticyclonic eddy, which, in the earlier period appeared to occupy the entrance to the Cilician Basin in the west, seemed to have been either displaced from its location or to have disintegrated. An anticyclonic eddy was observed further to the west in June 1987, but its water mass characteristics significantly differed from the former Antalya eddy: it trapped a large amount of AW above a layer of LIW trapped deeper in its core, whereas the Antalya eddy had a core with LIW and thin filaments of AW wrapped around it. Since the Cilician Basin was flooded with AW and the Antalya eddy seems to have been pushed to the west it seems likely that the AW trapped in this eddy in June 1987 have arrived there by way of the Cilician Basin. In fact, this is consistent with the fact that later in 1988 the circulation pattern has dramatically organized itself into a coherent, though meandering, jet flow located all along the Anatolian coast.

A review of the relatively short period of recent systematic observations in the Levantine Basin provides a detailed description of some of its complex oceanographic characteristics. This description is quite different from any pre-existing knowledge of the basin circulation. Furthermore, these observations motivate an outlook into the future which is fully expectant of significant efforts to understand the underlying dynamics.

ACKNOWLEDGEMENTS

The oceanographic data collection of the RV Bilim was supported by the Turkish Scientific and Research Council (TÜBITAK) under the National Oceanography Program. Part of this work was completed during a visit by the first author to Harvard University, initially as a grantee of the UNESCO Division of Marine Sciences and later as a Fulbright scholar during 1989–1990. The first author acknowledges the encouragement and constant support given by Prof. Allan Robinson of Harvard University. We also express our thanks to various individuals from our institutions (the IMS–METU and the IOLR) who accompanied us in the collection and processing of the data presented in this paper. This work would not be possible without their enduring contributions.

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APPENDIX A: METHODS

The analyses are based on CTD data collected aboard the RV Bilim and RV Shikmona, respectively, by the Institute of Marine Sciences, Middle East Technical University (IMS–METU) and the Israel Oceanographic and

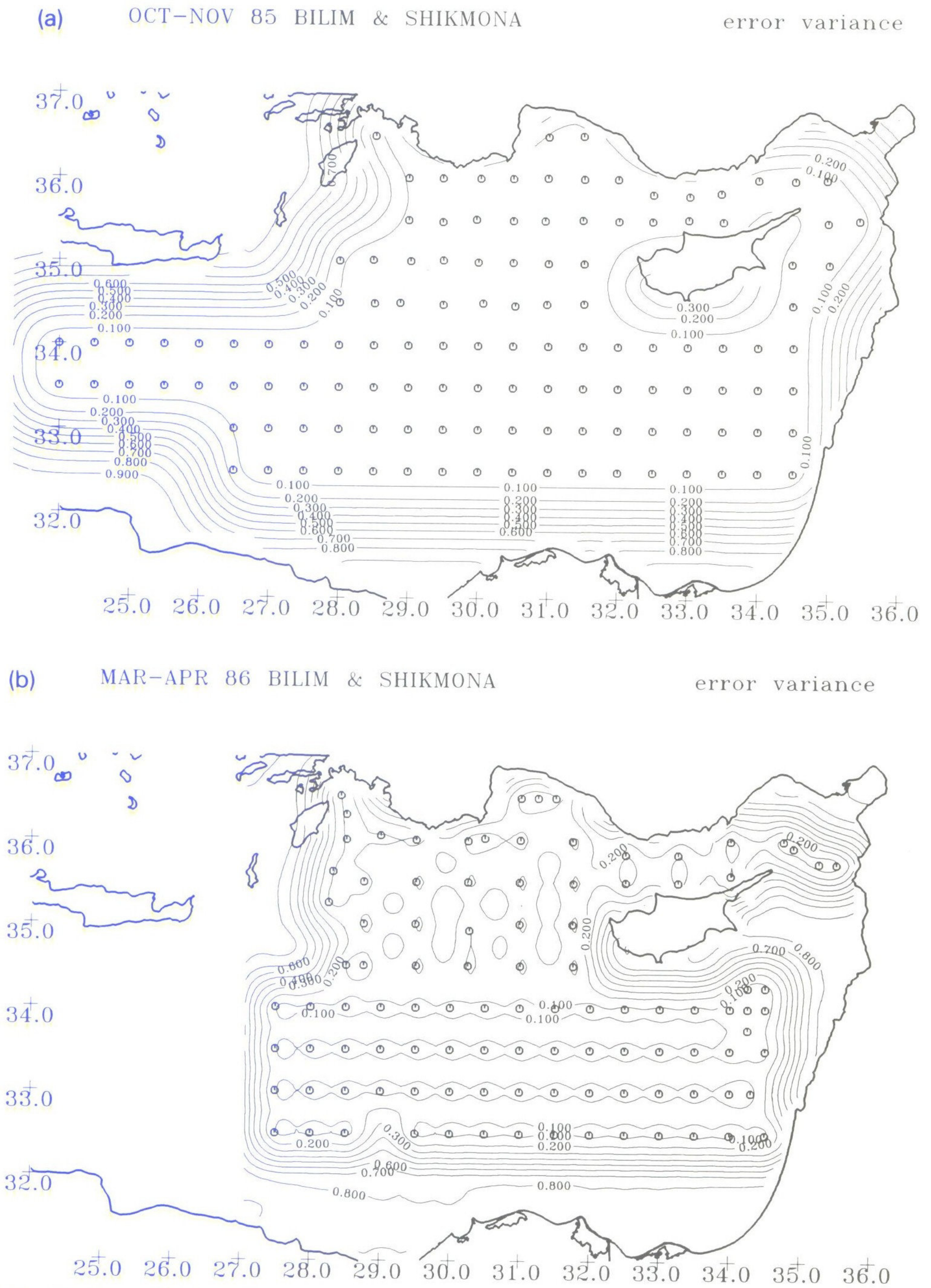


Fig. A1. Normalized error variance distribution maps for the objective analyses of Figs. 2–9: (a) October–November 1985; (b) March–April 1986; (c) June 1986; (d) February 1987; (e) June 1987; (f) August–September 1987; (g) July 1988; (h) October 1988.

(c) JUN 86 BILIM error variance

(d) FEB 87 BILIM error variance

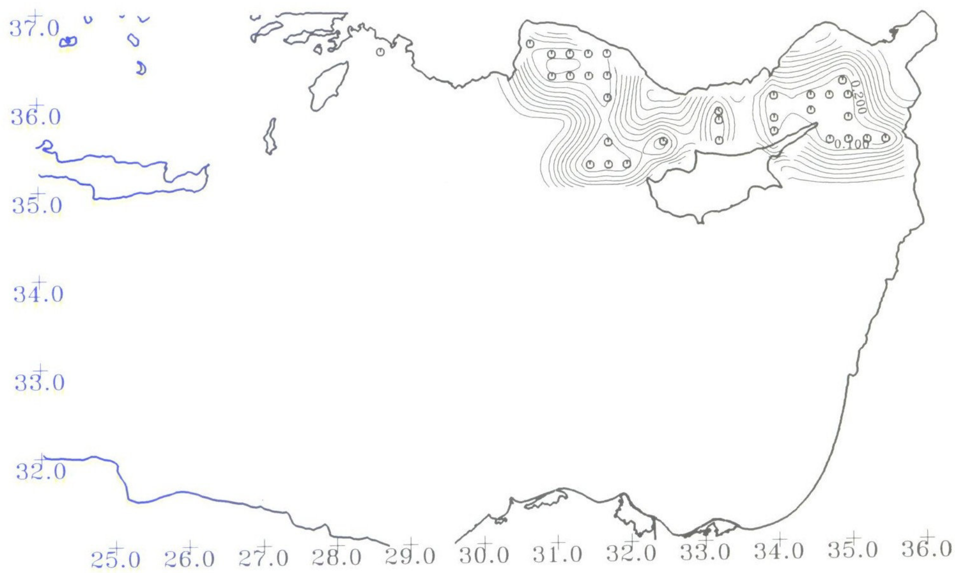
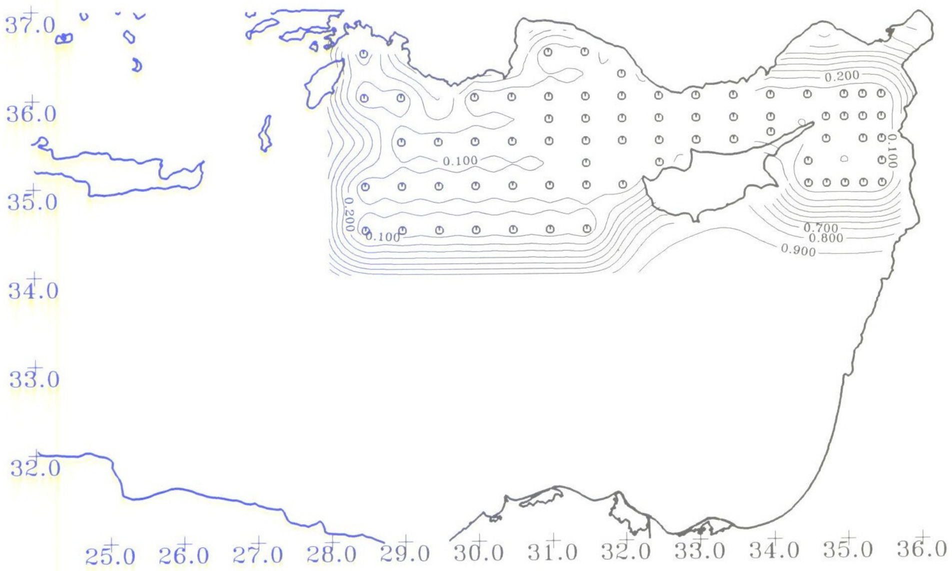
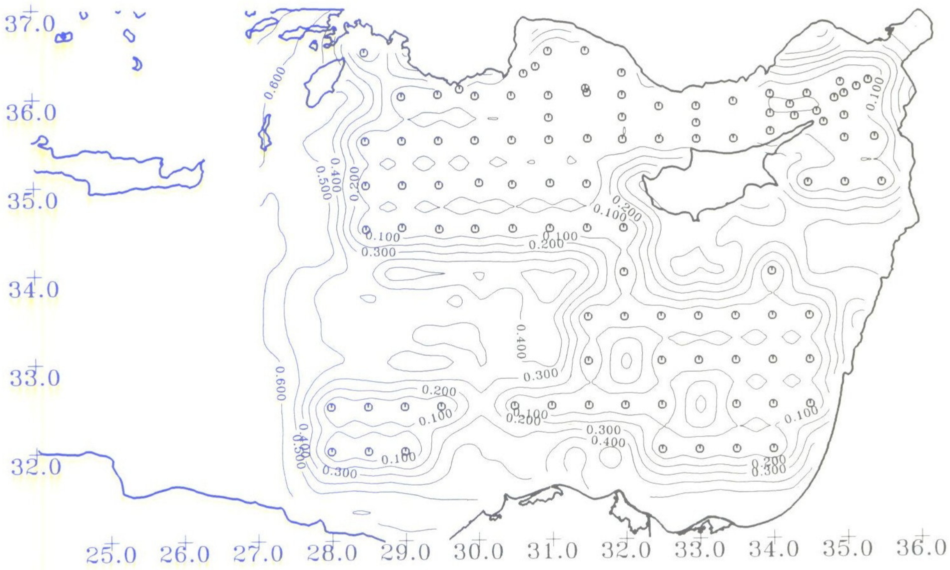


Fig. A1 (continued).

(e) JUN 87 BILIM error variance



(f) AUG-SEP 87 BILIM & SHIKMONA error variance



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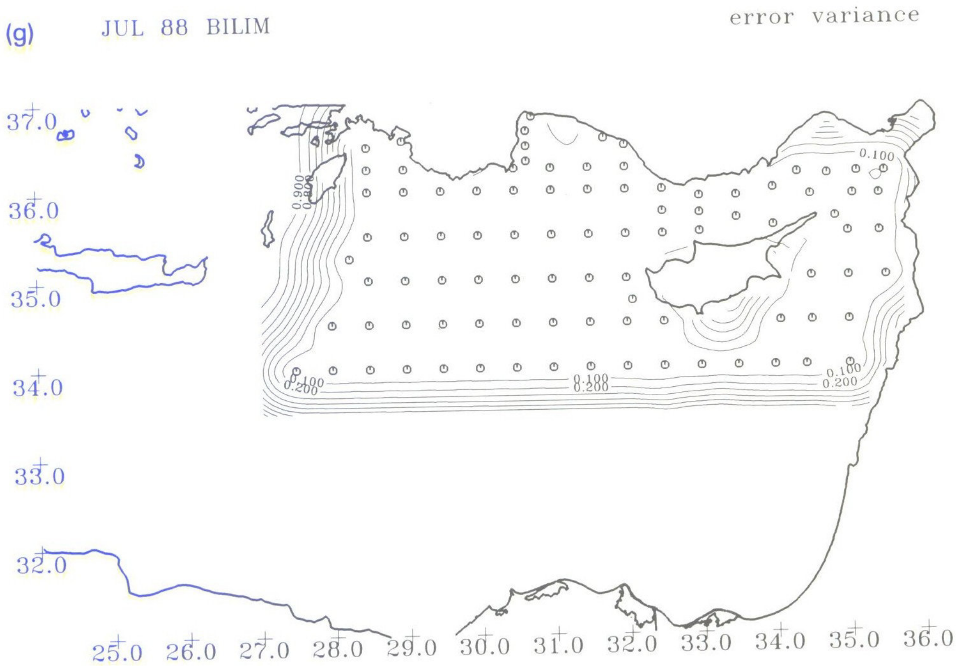

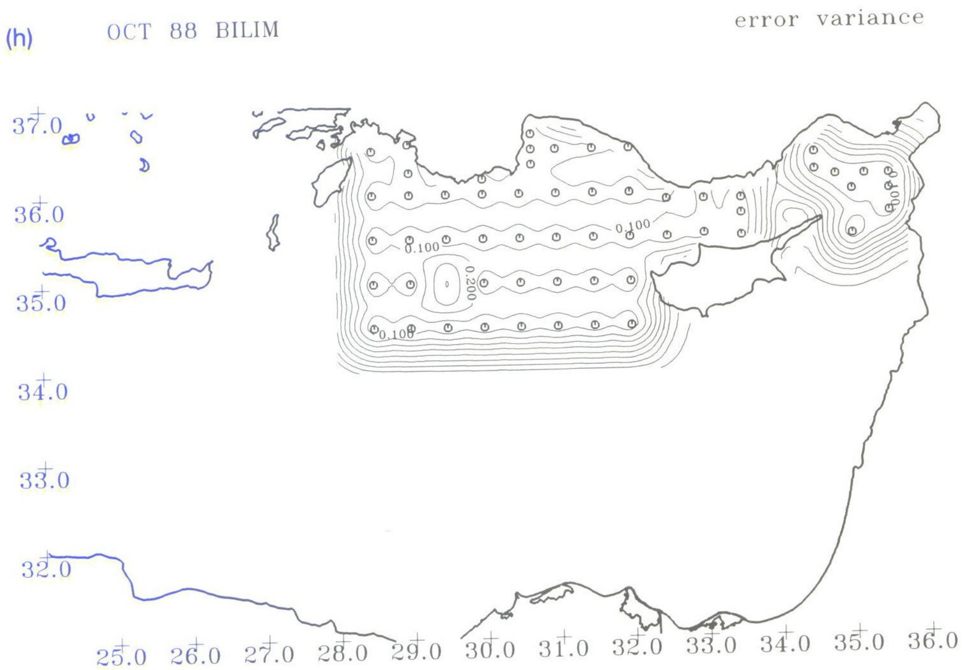

Fig. A1 (continued).

Limnological Research Ltd. (IOLR). An SBE Model 9 CTD system was employed on the Bilim, while a Neil-Brown CTD was used on board the Shikmona.

The data sets were processed separately by each group, the details of which are given in Özsoy et al. (1989). The method of intercalibration between the Israeli and Turkish data sets consisted of comparing the temperature and salinity measurements below 500 m at common intercalibration stations and applying a constant correction value to each parameter when any consistent differences were found between the data sets. The corrections applied to the Turkish data were $\Delta T = +0.04, +0.02, 0.0\,^\circ\mathrm{C}$ and $\Delta S = +0.03, +0.06, -0.04$ respectively for the three combined surveys of October–November 1985, March–April 1986 and August–September 1987 (Pinardi, 1988; Özsoy et al., 1989).

The dynamic computations are based on a reference level of 800 dbar for all surveys, except in June and August–September 1987 cruises. Because the CTD cable on the RV Bilim had to be shortened due to deterioration, the Turkish CTD casts were shallow and the dynamic calculations for the joint data were based on reference levels of 650 dbar in the former and 450 dbar in the latter of these two surveys.

The objective analyses of the dynamic height anomaly derived from the measurements was made following Özsoy et al. (1989), who used a correlation model of

$$C(r) = \left(1 + a_2 r^2 + a_3 r^3\right) \exp(-br^2).$$

as a function of the horizontal distance r between observation points. The scales a_2, a_3 and b are determined by least squares fitting of the correlation data to the model. The decorrelation scale (first zero-crossing of the correlation function) was typically on the order of 125–150 km. The radius of influence for interpolation was chosen as 200–250 km and the number of influential points for each interpolation was limited to 12.

The normalized error variance maps for each of the objective analysis maps in Figs. 2–9 are provided in Fig. A1.

Figures 2–10 are based on open sea observations only, and do not consider any effects of the coasts apart from what can be inferred from the observed fields themselves. Analyses based on a method of coastal stream lines have been used by the POEM Group (1991) and Robinson et al. (1991). We preferred to leave the analyses as they are, i.e. without any coastal corrections.