

Isopycnic Study of the Circulation in the Different Water Layers of the Eastern Mediterranean Sea

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ABSTRACT. The large scale circulation in three different water layers, namely; intermediate water, mid-depth water and deep water, in the Eastern Mediterranean Sea was inferred using an isopycnal analysis technique applied to a relatively homogeneous and up-to-date data set.

The $\sigma_0 = 29.03$ surface was selected to examine the circulation in the Levantine intermediate water. The $\sigma_1 = 33.55$ and $\sigma_2 = 37.84$ surfaces (potential densities referred to 1000 and 2000 db respectively) were selected to examine the circulation in the mid-depth and deep layers.

Some new features in the water circulation pattern were observed.

The main regime of the Mediterranean Sea, in the western as well as in the eastern basin is controlled by intense surface transfer of heat, momentum from water across the sea surface. In some areas, the surface waters become more saline, somewhat colder and consequently more dense than their surroundings as a consequence of latent and sensible heat loss when cold dry air (often 10°C colder than the surface temperature of the ocean) blows over the surface. These waters sink to depths ranging from 200-250 m for Levantine intermediate water, to 1000-1200 m in the Adriatic Sea and the North Aegean Sea and down to 2000 m in the NW Mediterranean (UNESCO Rep. 1984).

Levantine intermediate water, characterized by the maximum of salinity, is found in the whole Mediterranean at various depths between 200 and 600 m (Wüst 1960). Regions of formation of the Levantine intermediate water mass have more or less been identified in the Eastern Mediterranean (Wüst 1960, Morcos 1972, Ozsoy *et al.* 1981, Ovtchinnikov 1984, and Said 1985).

The process of deep water formation in the Eastern Mediterranean was studied by Nielsen (1912). He suggested that there are two main sources of formation. The first one exists in the southern Adriatic Sea from where a

southward flux takes place through the Otranto strait to fill the deep Ionian Basin. The other one lies in the southern Aegean Sea which supplies the Levantine Basin with deep waters through the southeastern straits. Contrary to Nielsen's thesis, none of this water is formed in the southern Aegean Sea (Pollak 1951). Lacombe and Tchernia (1958), Wüst (1960), Moskalenko *et al.* (1976) and El-Gindy and Sharaf El-Din (1986) all support the idea that it is Adriatic and Levantine water types which are responsible for the formation of the deep waters of the Eastern Mediterranean. Zore-Armanda (1972), by using T-S diagram analysis, found that, in the Otranto strait, the dense Adriatic surface water meets lighter Ionian water. It sinks and mixes with the more saline eastern water of the intermediate layer which comes from the Levantine basin. The upper layer of mixed water proceeds from the Otranto area into the Adriatic and the mixed water of deeper layers is deflected to the Ionian side and later to the Levantine basin as bottom water.

The aim of this work was to study the large scale circulation in three different water layers, namely; intermediate water mid-depth water and deep water, in the Eastern Mediterranean using an isopycnal analysis technique with a relatively homogeneous and up-to-date data set.

The data used in this study were collected from the Eastern Mediterranean by the Russian R/V Vasily Golovnin and R/V Akademik Petrovsky during March 1977 (obtained from hydrographic Data Centre B, Moscow). Figure 1 illustrates the area of investigation and the locations of the hydrographic stations. Vertically unstable stations were either corrected for temperature or salinity or rejected if many levels of instability were observed.

The data were filtered from outliers due to bad temperature and/or salinity measurements were filtered from the data set by using scatter diagrams such as those shown in Fig. 2 (a,b,c). These diagrams were selected from 16 diagrams and represent the relation between the corresponding upper and lower σ value at the 300, 800 and 1500 m levels. Straight lines were then fitted to all points of each diagram, and the points which deviated from the best-fit straight line by more than twice the standard deviation were removed from the analysis.

Method of Analysis

The method used, in this study, is called "isopycnal" analysis. It is predicated upon the assumption that the flow and the lateral mixing take place along surfaces of constant potential density to a much greater extent than across them. The direction of flow is deduced by contouring tracer quantities (*e.g.* salinity and oxygen) on such surfaces. Contours of tracer quantities frequently have a tongue-like distribution as a result of the combined effect of advection by the mean

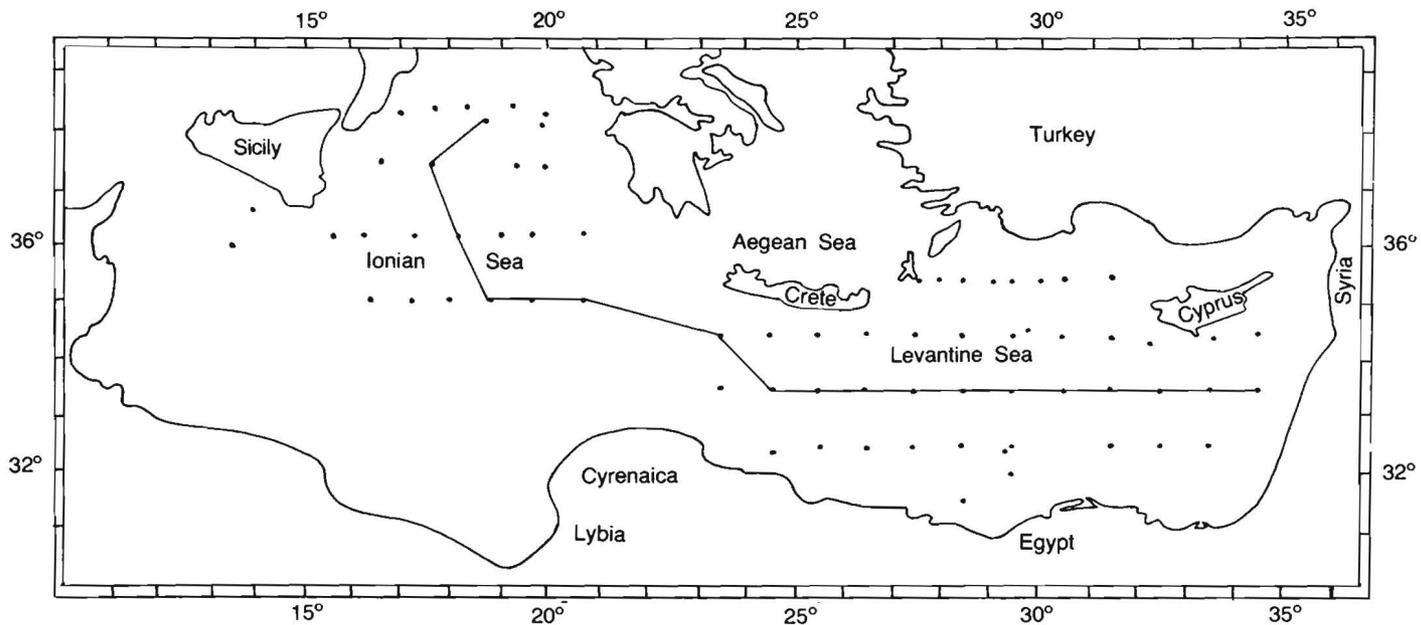


Fig. 1. Eastern Mediterranean Sea and the locations of the stations used in the isopycnal analysis. The solid line represents a section used to study the Levantine, mid-depth and deep waters.

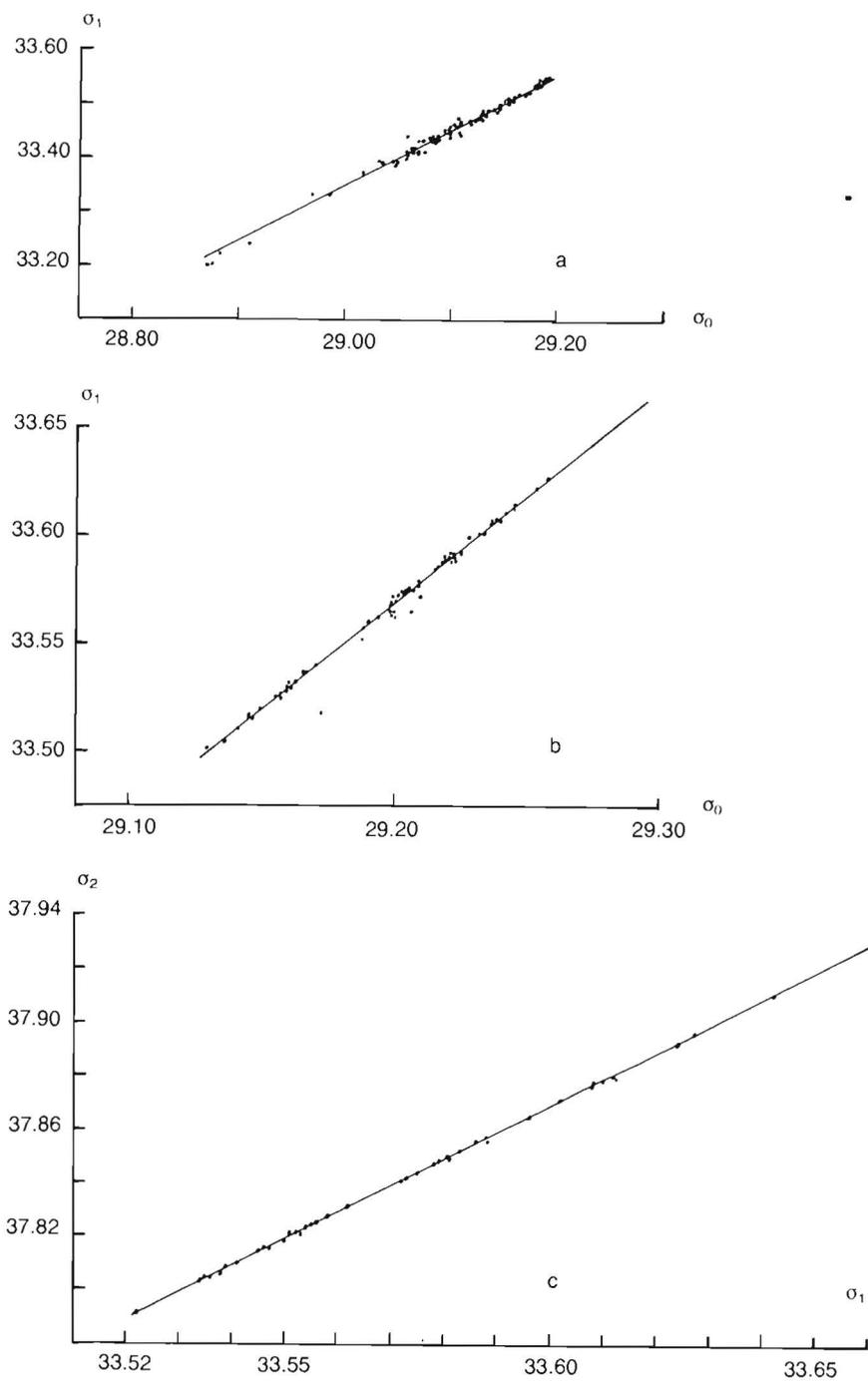


Fig. 2. Local potential density relationship at: a=300 m, b=800 m and c=1500 m.

flow and cross-flow diffusion. The direction of flow is usually taken to be along the axis of the tongue.

The method was first used by Montgomery (1938) and Parr (1938), who examined the distribution of various conservative and nonconservative properties on surfaces of constant σ_t to determine the circulation in the Atlantic Ocean. More recently, the method was widely applied by numerous authors, among them Clowes (1950), Taft (1963), Reid (1956, 1981), Lynn and Reid (1968), Reid and Lynn (1971) and Karam (1986). The method was successful in interpreting the large-scale flow. It has the added advantage that the complicated three-dimensional distribution of a property can be reduced to a more comprehensible map of that tracer on an isopycnal.

Results

A vertical salinity section Fig. 3 was chosen, extending from south of the Otranto strait to the far east of the Levantine basin (Fig. 1). By superimposing the density field on this section it was found appropriate to select the $\sigma_0 = 29.03$ surface to represent the circulation of the intermediate Levantine water. The $\sigma_1 = 33.55$ and $\sigma_2 = 37.84$ surfaces (potential densities referred to 1000 and 2000 decibars respectively) were selected to examine the circulation in the mid-depth and deep layers.

Circulation in the Intermediate Levantine Layer

a) Depth of $\sigma_0 = 29.03$ surface

The depth pattern Fig. 4 is characterized by a large trough occupying most of the northern Ionian basin which might reflect an anticyclonic movement. In the southern part of the Levantine basin and south of Crete small troughs exist. However, in the region between Crete and Cyprus there is a large ridge which reflects a cyclonic motion. The surface generally shoals toward the northern borders of the Eastern Mediterranean Sea. The surface shows depth values as shallow as 28 and 118 m in the northern parts of the Levantine and Ionian basins respectively but extends to 475 m in the middle of the Ionian basin. This pattern is quite similar to that presented by Ovtchinnikov (1966).

b) Salinity on $\sigma_0 = 29.03$ surface

The salinity distribution on this surface Fig. 5 reveals that in the Levantine basin there are two main regions of high salinity in the northern part (39.148‰) southeast of Crete and of 39.135‰ west of Cyprus). From the region near Crete, the high-salinity water seems to flow southwards in a high-salinity tongue. Parallel

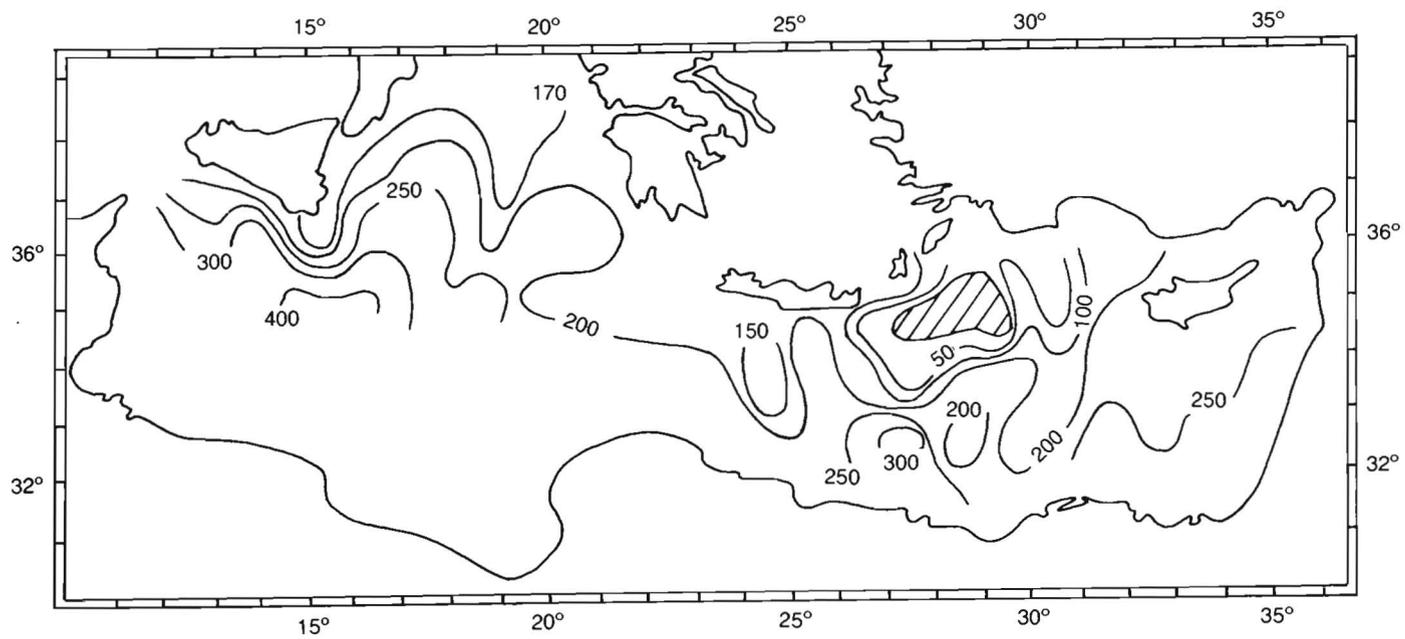


Fig. 4. Depth (m) of the surface where $\sigma_0 = 29.03$ in winter of 1977. The hatched area indicates nonexistence of the surface.

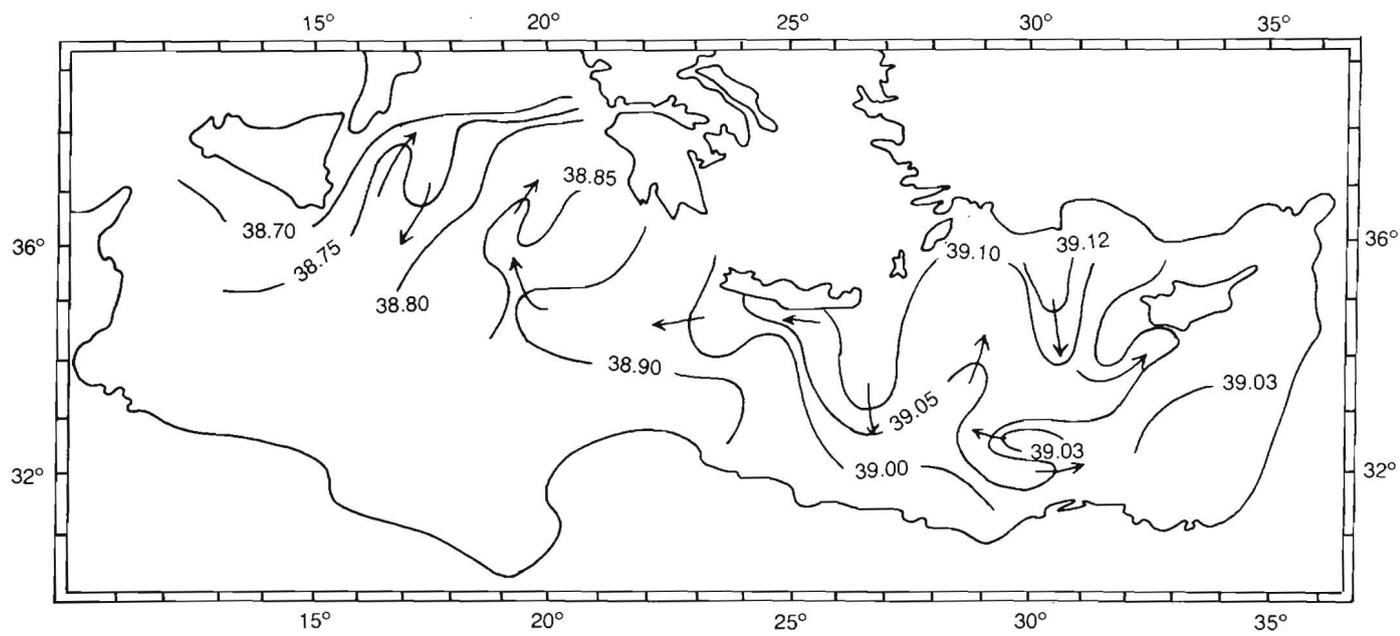


Fig. 5. Salinity (‰) on the $\sigma_0 = 29.03$ surface in winter of 1977.

to this tongue along approximately the 28°E parallel less-saline water flows to the north. These two tongues might reflect a cyclonic movement as revealed from the topographic map (Fig. 4). From the second region near Cyprus, the saline water proceeds to the south in a high-salinity tongue until 34°N where it deflects to the south of Cyprus. The Levantine intermediate water flows from southeast of Crete to the north, parallel to the eastern borders of the Ionian Sea. In addition, there is an indication of a small anticyclonic movement east of Sicily as reflected by the shape of the isohalines in this region. Generally speaking, the circulation of the Levantine water is quite complicated, particularly, in the Levantine Sea where many tongues appear. It is important to mention that there is a little indication of a direct spreading of the intermediate water from the Levantine to the Ionian basin which is hardly might be consistent with the old picture of Wüst (1960).

c) Potential temperature on $\sigma_0 = 29.03$ surface

The potential temperature map Fig. 6 does not show a great discrepancy from that of salinity except in the Ionian Sea (particularly toward the center) where the relatively warm water deviates from that indicated by the salinity map (Fig. 5).

Circulation in the Mid-depth Layer

a) Depth of the $\sigma_1 = 33.55$ surface

The topographic map of this surface Fig. 7 shows that it is generally shallower in the Levantine basin (400-700 m) than in the Ionian basin (1200-2000 m). The pattern is more intricate than that in the intermediate layer, with many more troughs and ridges. In the Levantine basin four large troughs can be clearly seen in which the surface deepens to about 700 m. These are located south of Cyprus and of Crete and off the Egyptian and Lybian coasts. In the Ionian Sea, two troughs appear in the western and eastern parts at which the surface deepens to about 2000 m, and in the middle of the basin two ridges exist at which the surface shoals to about 1200 meters.

b) Salinity on the $\sigma_1 = 33.55$ surface

The gross features of the salinity distribution on this surface Fig. 8 is that the salinity values in the Levantine basin are generally higher than those in the Ionian basin as expected from the depth map (Fig. 7). A region of high-salinity water (> 38.95‰) exists close to the eastern straits of the Aegean Sea from where the saline water spreads to the south in two high salinity tongues whose main axes run roughly along 26° and 29° E. Between these tongues and parallel to them relatively low-salinity water flows to the north in a tongue whose apex runs approximately along 27° 30' E. According to the depth map (Fig. 7), this system of tongues reflects an anticyclonic eddy between about 27° and 29° E. The tongue along 26° E might indicate an outflow from the eastern Aegean Sea straits since the isohaline

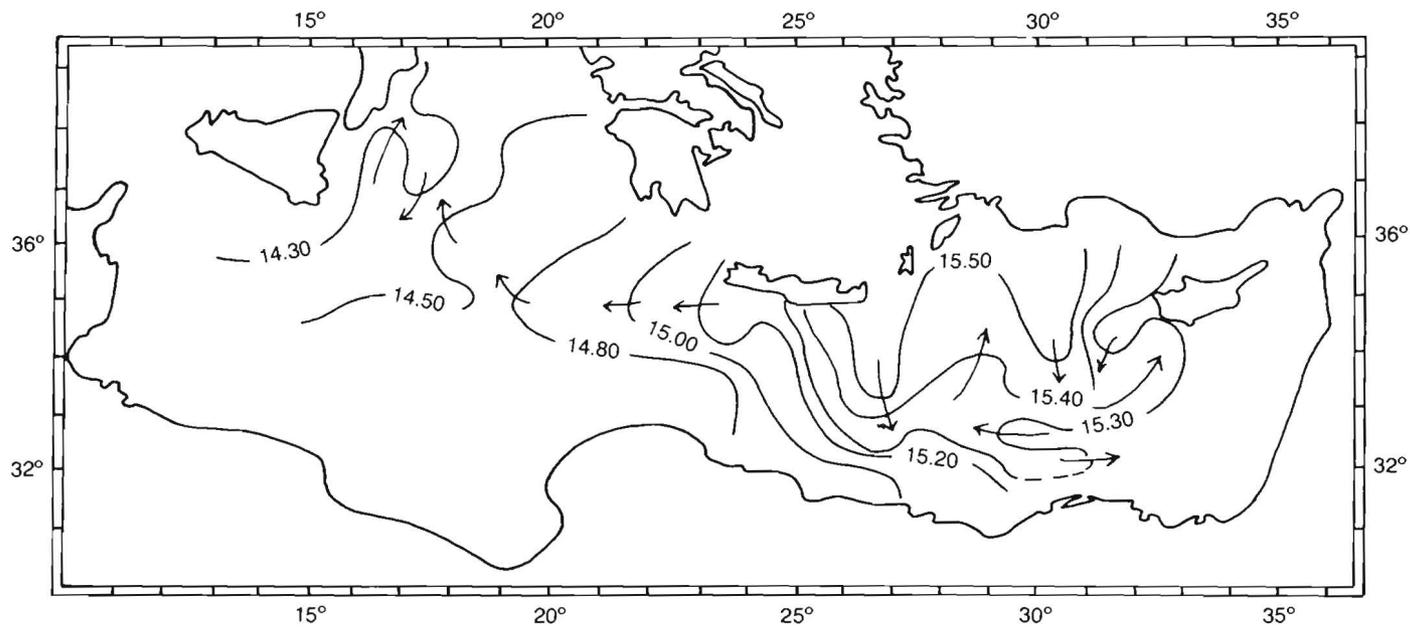


Fig. 6. Potential temperature on the $\sigma_0 = 29.03$ surface in winter of 1977.

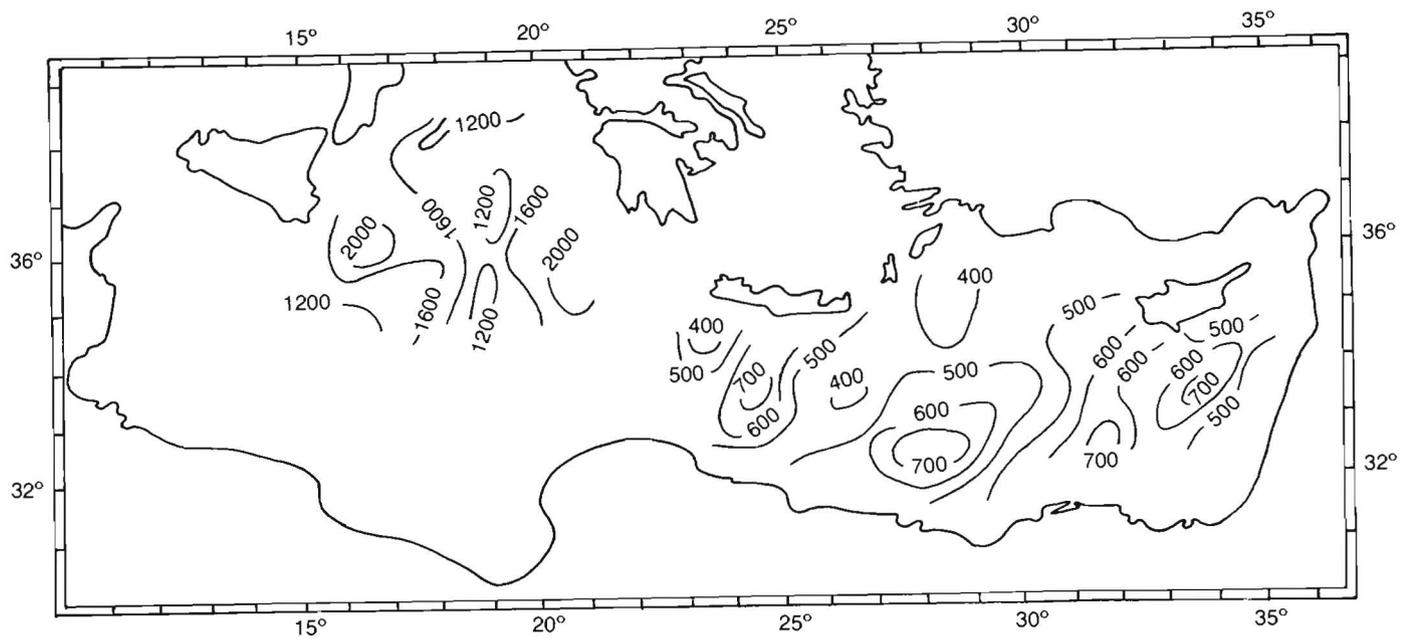


Fig. 7. Depth (m) of the surface where $\sigma_t = 33.55$ in winter of 1977.

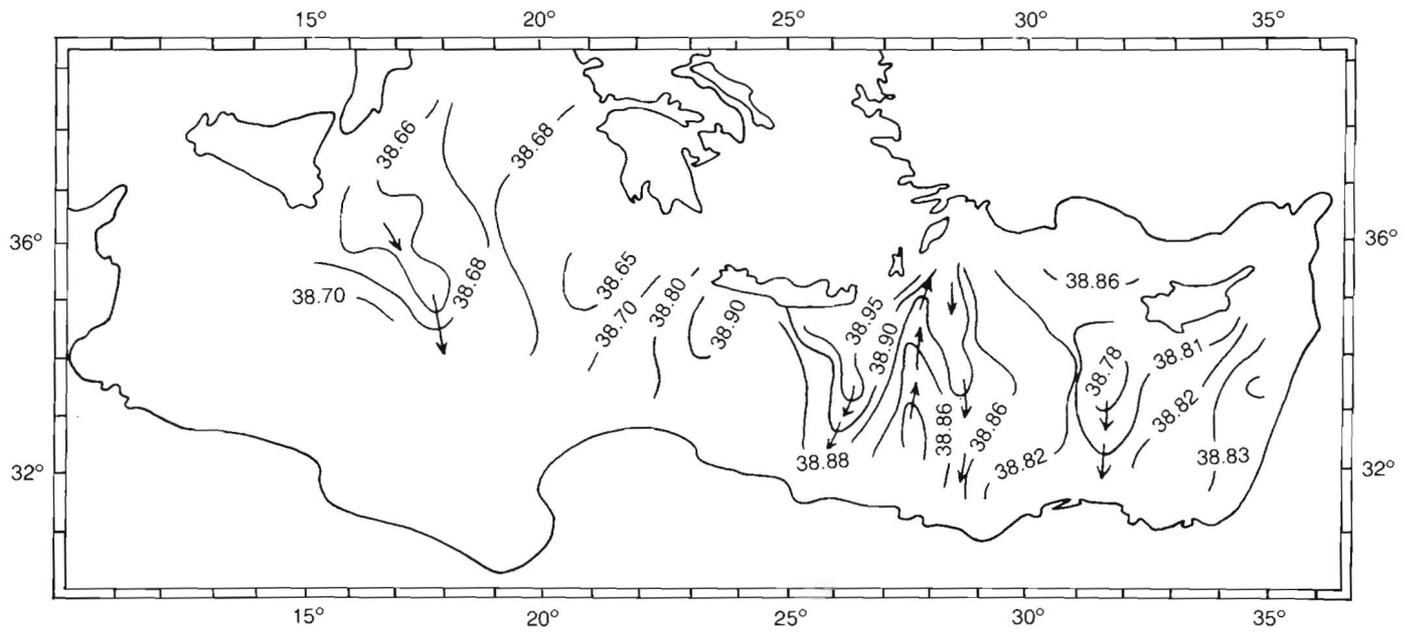


Fig. 8. Salinity (‰) on the $\sigma_1 = 33.55$ surface in winter of 1977.

38.95‰ hugs them. The outflow appears at depths of about 500 m near the straits, deepening to about 700 m south of Crete. Southwest of Cyprus there is an indication of flow of low-salinity water to the south in a low-salinity tongue extending along approximately 32° E. In the Ionian Sea, however, the pattern is characterised by only one low-salinity tongue which indicates a flow of relatively low-salinity water from a region southeast of Sicily to the middle of the Ionian basin. This water might be formed locally where the isopycnal surface deepens to about 2000 meters.

c) Potential temperature on the $\sigma_1 = 33.55$ surface

The potential temperature distribution on this surface (Fig. 9) shows most of the features in the Levantine basin, particularly the anticyclonic eddy which appears more clearly between 27° and 30° E. In addition, a limited flow appears to the west along roughly 33°N (south of Cyprus), which then turns toward the south at 32° E. In the Ionian Sea, however, the flow system is somewhat different from that deduced from salinity. The flow is generally from the north and west towards the middle region of the Ionian basin.

Circulation in the Deep Layer

a) Depth of $\sigma_2 = 37.84$ surface

South and east of the eastern Aegean straits Fig. 10 the depth of the $\sigma_2 = 37.84$ surface is fairly uniform at 600-700 m. This area of uniformity lies roughly between 26° and 31° E and extends south to about 33° N. South and east of this area, the depth rapidly increases to about 1200 m off the western coast of Egypt and south of Cyprus, respectively. From the maximum south of Cyprus the surface slopes downward to about 600 m towards the coasts of Lebanon and Sinai. In the Ionian Sea, the surface goes as deep as 3000 m southeast of Sicily from where the surface slopes upwards in a large trough which occupies the whole area. Between the two basins, the surface shoals from 1000 m south of Crete to about 600 m near the Cyrenaica Peninsula.

b) Salinity on the $\sigma_2 = 37.84$ surface

Figure 11 shows the salinity distribution along this surface, the major feature of the pattern being the low-salinity tongue. This extends southwest from Cyprus to 32°N and 30°E where it becomes parallel to the western coast of Egypt to 25°E. At this point it deviates to the northwest where it might enter the Ionian Sea. This tongue indicates a spreading of low-salinity water (< 38.75‰) from west of Cyprus to the southwest and then westwards to the Ionian Sea where, after mixing with high salinity water, its salinity reaches about 38.80‰. Another two limited high-salinity tongues appear in the Levantine basin indicating another two branches of flow: the first shows a flow of high-salinity water (with salinity starting at about 38.83‰) south of Crete which extends southwards roughly along 26°E to

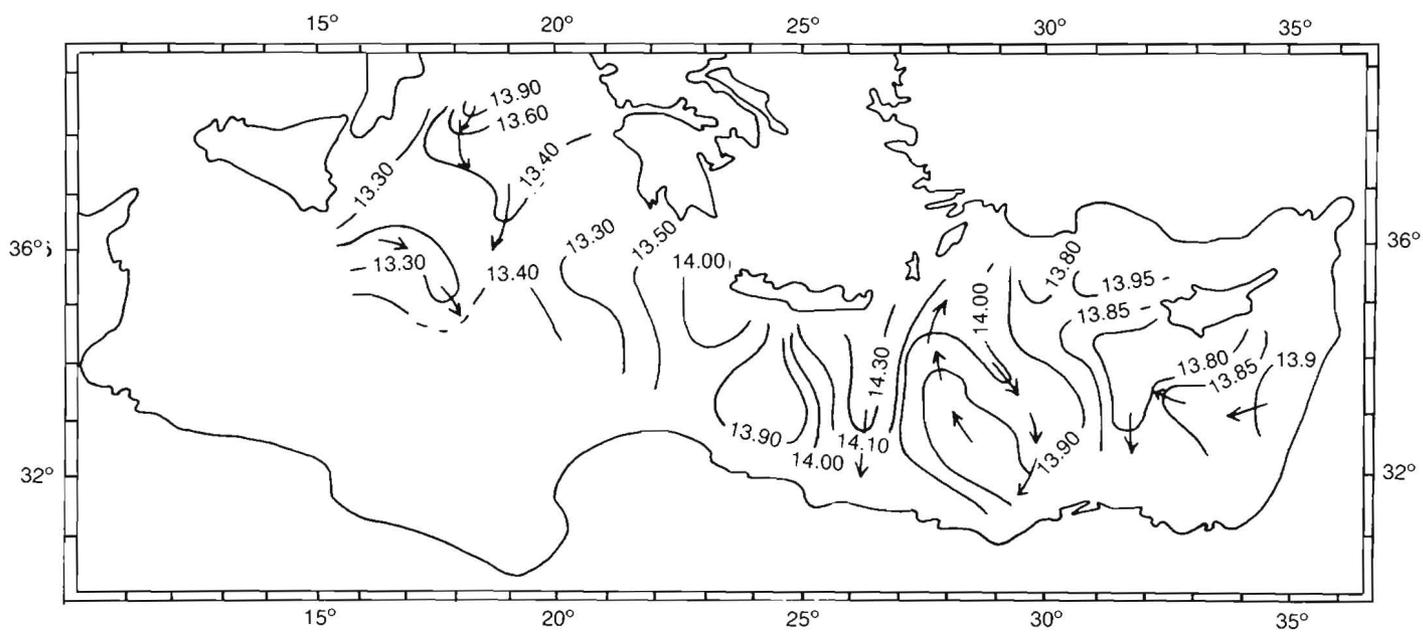


Fig. 9. Potential temperature on the $\sigma_1 = 33.55$ surface in winter of 1977.

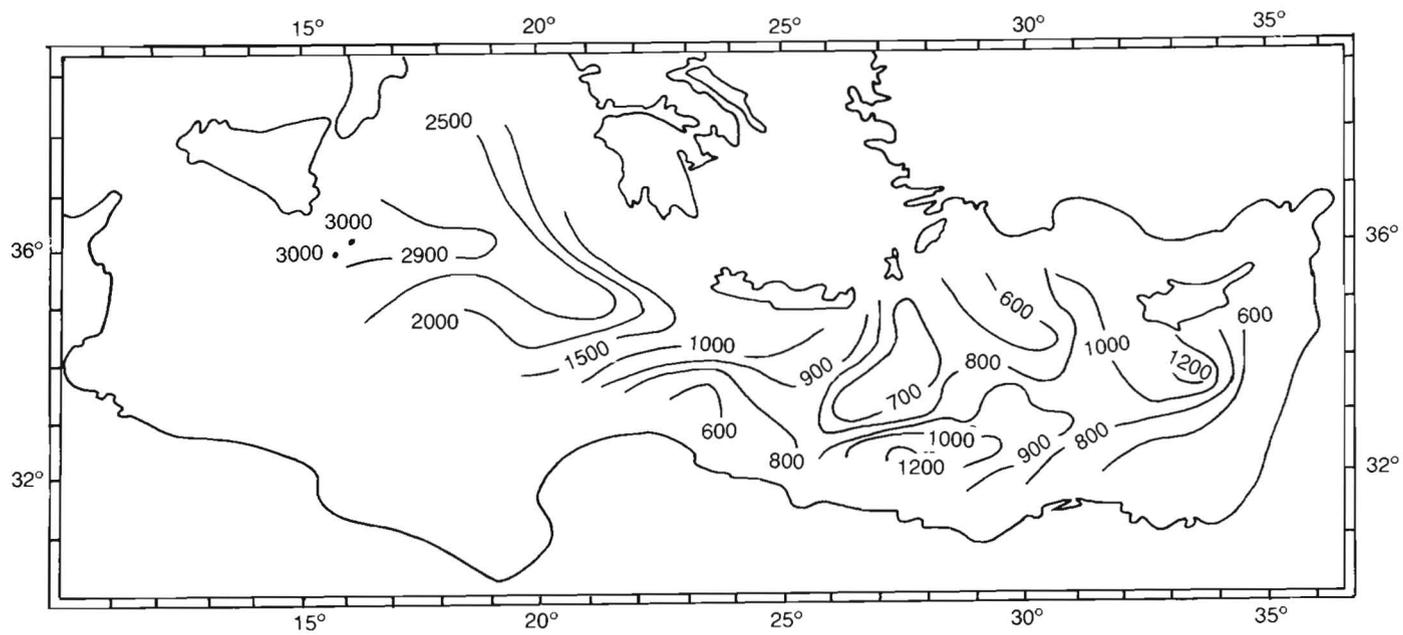


Fig. 10. Depth (m) of the surface where $\sigma_2 = 37.84$ in winter of 1977.

meet the main water of low salinity approximately at 32°N, 25° 30'E. The second branch of flow appears as a limited high-salinity tongue in which the relatively high-salinity water (> 38.80‰) spreads from about 35°, 30'N, 29°E to the southeast.

In the Ionian basin, the salinity is generally lower than that of the Levantine basin as expected from the depth map (Fig. 10). A low-salinity tongue exists in the middle of the basin whose apex indicates a limited flow to the west along approximately 36°N. From the above description, the general features of the water movement in both basins differ entirely from those produced by Pollak (1951) and Wüst (1960) for the deep water. Their maps showed a significant flow from the Ionian to the Levantine basin which is not found on deep isopycnals.

c) Potential temperature on the $\sigma_2 = 37.84$ surface

The potential temperature distribution Fig. 12 resembles that of salinity (Fig. 11) in most of the tongue-like distribution except for the third branch of flow in the Levantine Sea, where its axis is directed towards the south.

Conclusion

The circulation of the intermediate water, mid-depth water and the deep water in the Eastern Mediterranean were studied using isopycnal analysis in the winter of 1977.

The topographic map and salinity distribution in the intermediate layer reveal a cyclonic gyre in the central Levantine basin and an anticyclonic gyre in the Ionian basin east of Sicily. These features are in general agreement with the findings of Ovtchinnikov (1966) whose dynamic height chart was dominated by gyres. The distribution of salinity and potential temperature indicate that the main westward flow is from the Levantine Sea to the south of the Ionian Sea with a part of the flow directed to the north, parallel to the eastern boundary of the Ionian Sea. This latter flow then turns to the west in the northern part of the sea. This seems somewhat consistent with the gross features of Wüst's map (1960) which showed a clear direct spreading of the intermediate water from the Levantine to the Ionian basin. These features were also observed by Karam (1986).

The gross feature for the mid-depth water as indicated from the depth map and salinity distribution is the existence of an anticyclonic eddy between about 27° and 29°E. An outflow from the eastern Aegean Sea straits appears at depths near 500 m near the straits and goes deeper, to about 700 m, south of Crete.

In the Ionian Sea, there is a flow of relatively low-salinity water from a region southeast of Sicily to the middle of the Ionian basin. This water might be formed

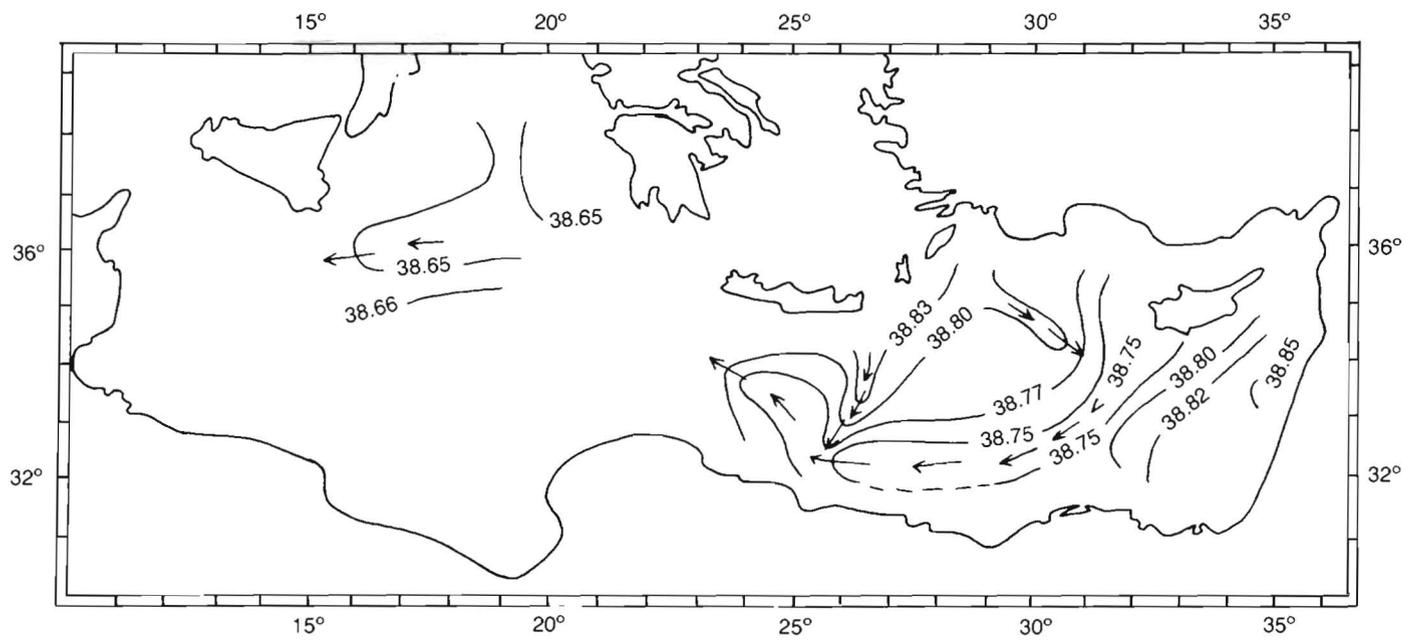


Fig. 11. Salinity (‰) on the $\sigma_2 = 37.84$ surface in winter of 1977.

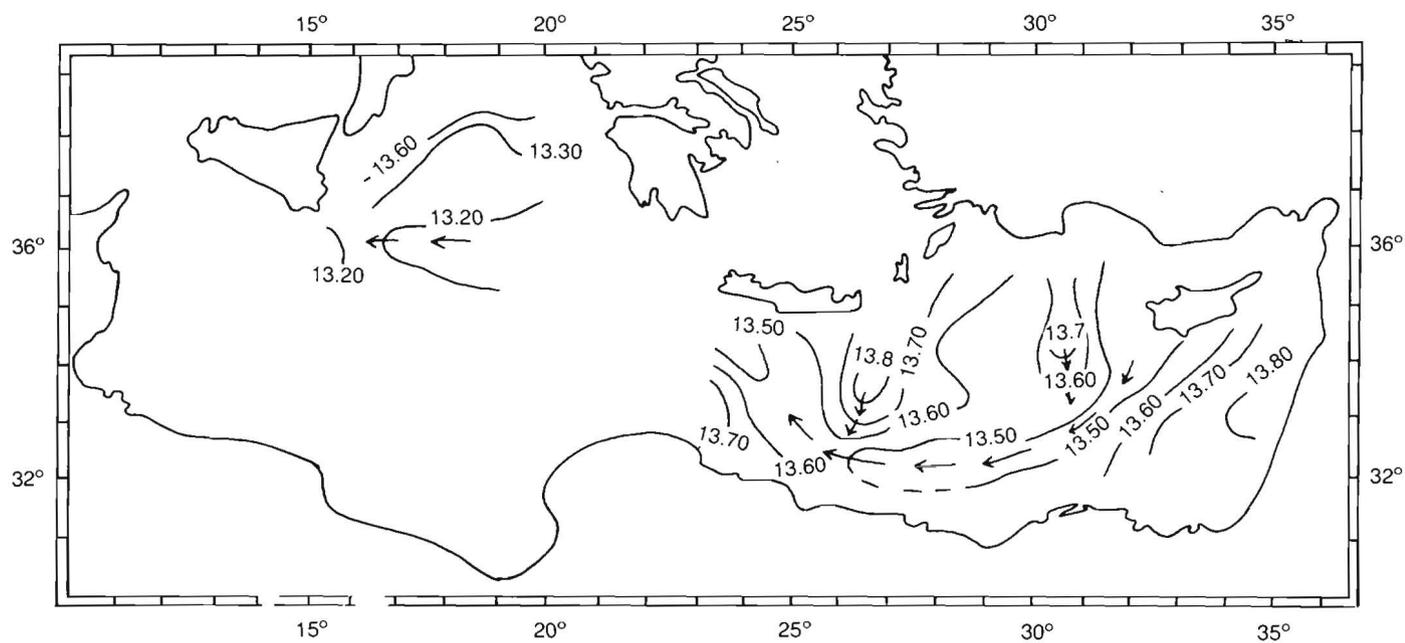


Fig. 12. Potential temperature on the $\sigma_2 = 37.84$ surface in winter of 1977.

locally where the isopycnal surface deepens to about 2000 meters.

The major features of the circulation pattern in the deep layer is the spreading of low-salinity water (38.75‰) from west of Cyprus to the southwest and then westward to the Ionian Sea, where after mixing with high salinity water its salinity reaches about (38.80‰). There are another two branches of flow: the first one of high-salinity water (starting at about 38.83‰) south of Crete extends southwards roughly along 26°E to meet the main water of low salinity approximately at 32°N, 25° 30'E. The second branch of flow spreads from about 35° 30'N, 29°E to the southeast.

In the Ionian basin, the salinity is generally lower than that of the Levantine basin. A limited flow of low-salinity water (38.65‰) from the middle of the basin to the west along approximately 36°N was observed. The results presented here for the deep water based on isopycnal analysis are not in agreement either with those deduced by Pollak (1951) from O₂ minima or with those inferred by Wüst (1960) using the core-method.

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دراسة أيزوبيكنية للتيارات في مختلف الطبقات المائية بشرق البحر المتوسط

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يتميز شرق البحر المتوسط، وخاصة المنطقة الواقعة ما بين الساحل الشرقي للبحر المتوسط وخط طول ١٥° شرق بالتعقيدات في نظام التيارات البحرية بها. لذلك تركز البحث على دراسة نظام التيارات البحرية عند ثلاث طبقات مائية مختلفة العمق وذلك باستخدام التحليل الأيزوبيكني. وطبقاً لهذه الطريقة فقد تم اختيار ثلاثة أسطح ايزوبيكنية (اسطح ذات كثافات ثابتة). وتتميز هذه الطريقة بأن تدفق المياه يكون موازياً لهذه الأسطح وبالتالي يمكن استنتاج اتجاه التيار وذلك برسم المتغيرات (ملوحة المياه، درجة الحرارة الوضعية، العمق) على هذه الأسطح.

وقد تم رسم ملوحة المياه ودرجة الحرارة الوضعية والأعماق على الأسطح التالية:

- $\sigma_0 = 29,03$ ليمثل طبقة المياه تحت السطحية.

- $\sigma_1 = 33,55$ ليمثل طبقة المياه متوسطة العمق.

- $\sigma_2 = 37,84$ ليمثل طبقة المياه العميقة.

تم هذا العمل باستخدام بيانات هيدروجرافية جمعت بوساطة مراكب الأبحاث السوفيتية (فاسيلي جولوفيني وأكاديميك بيتروفيسكي) في شتاء سنة ١٩٧٧م. وقد وجد أن:

١ - نظام التيارات في طبقة المياه تحت السطحية عبارة عن دوامة سيكلونية ذات اتجاه في عكس عقرب الساعة) في منتصف حوض الليفانتين وكذلك دوامة أخرى انتيسيكلونية (ذات اتجاه مع عقرب الساعة) في حوض البحر الأيوني.

٢ - تميز نظام التيارات في طبقة المياه متوسطة العمق بوجود دوامة أنتيسيكولوجية بين خطي طول ٢٧° و ٢٩° شرق في بحر الليثانيتين . وكذلك ظهرت مياه خارجية من بحر إيجه عند عمق ٥٠٠ متر عند المضائق ثم غاصت إلى أعماق ٧٠٠ متر عند جنوب كريت . أما في البحر الأيوني فلقد وجد تيار من المياه ذات الملوحة المنخفضة والذي اتجه من جنوب شرق سيسيل إلى منتصف البحر الأيوني .

٣ - أما عن نظام التيارات في الطبقة العميقة فلقد اختلف اختلافاً تاماً عن نظيره في الطبقتين العلويتين حيث ظهر تيار يحمل مياه منخفضة الملوحة والذي اتجه من غرب قبرص إلى الجنوب الغربي ثم اتجه بعد ذلك غرباً إلى البحر الأيوني . ولقد وجد أيضاً فرعان من التيار: الأول يحمل مياه ذات ملوحة عالية ويمتد من جنوب كريت جنوباً تقريباً على خط طول ٢٢° شرق ، أما الفرع الثاني للتيار فيمتد من حوالي ٣٢° شمال ، ٢٥ . ٣° شرق إلى الجنوب الشرقي . ولقد تميز نظام التيار في البحر الأيوني بوجود تيار يحمل مياه ذات ملوحة منخفضة ويمتد من منتصف البحر الأيوني إلى الغرب .