Distribution and seasonal variability of nutrients and dissolved oxygen in the northeastern Ionian Sea

Eastern Mediterranean
Ionian Sea
Nutrients
Oxygen
Distribution

Méditerranée orientale
Mer Ionienne
Sels nutritifs
Oxygène
Répartition

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ABSTRACT

In this paper we present for the first time detailed nutrient and oxygen figures for the Ionian Sea. The data were collected during cruises in March-April 1987 and August-September 1987, in the framework of the multi-nation research programme for the exploration of the Eastern Mediterranean, POEM.

The oxygen and nutrient pattern is affected by the presence of mesoscale cyclonic and anticyclonic gyres in the area, the most interesting feature of which is the large anticyclonic flow region southwest of Peloponnesus (Pelops gyre).

The chemical characteristics of the main water masses were also determined. In the deep layer of the stations near the Otranto Strait we have found, in winter, newly formed Adriatic Bottom Water (O_2 : 5.3 ml/l). This water mass has a clear evolution between winter and summer, whereas the Deep Water of the Eastern Mediterranean shows a very small seasonal variation in oxygen and nutrients. The Levantine Intermediate Water is slightly poorer in nutrients and richer in oxygen in summer. A study of the spatial evolution of water masses is also presented.

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RÉSUMÉ

Répartition et variation saisonnière des éléments nutritifs et de l'oxygène dissous dans la partie nord-est de la Mer Ionienne

Dans cet article, nous présentons pour la première fois des résultats détaillés des sels nutritifs et de l'oxygène dissous pour la Mer Ionienne. Les données ont été collectées pendant les deux campagnes océanographiques en mars-avril 1987 et en août-septembre 1987, dans le cadre du programme de recherche multinational pour l'exploitation de la Méditerranée orientale (Physical Oceanography of the Eastern Mediterranean, POEM).

Les répartitions des sels nutritifs et de l'oxygène dissous sont perturbées par la présence des tourbillons cycloniques et anticycloniques de la région. La plus intéressante structure sur ces distributions est le grand courant anticyclonique au sud-ouest du Péloponnèse.

Nous avons déterminé les caractéristiques chimiques des masses d'eau qui dominent cette région. En hiver, nous avons trouvé de l'eau de fond adriatique nouvellement formée (O_2 : 5.3 ml/l) dans la couche profonde des stations proches du détroit d'Otrante. Cette masse d'eau a une évolution nette entre l'hiver et l'été. A l'inverse, l'eau profonde de Méditerranée orientale varie très peu entre l'hiver et l'été. L'eau intermédiaire levantine est légèrement plus pauvre en sels nutritifs et plus riche en oxygène en été. Nous présentons aussi une étude d'évolution spatiale de ces masses d'eau.

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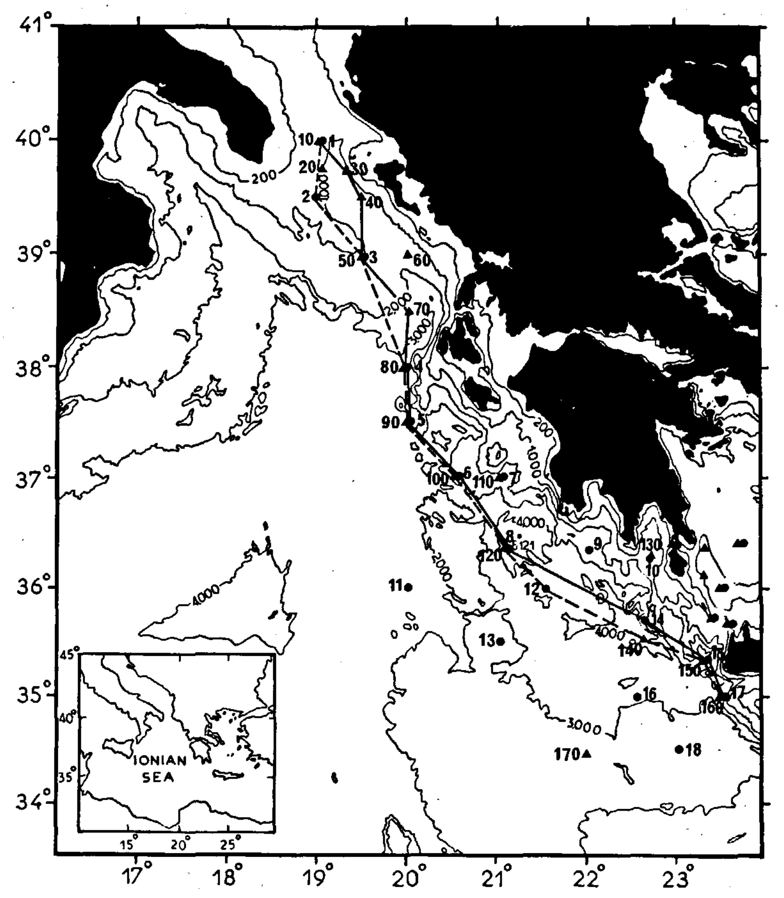
Figure 1

Bathymetric chart (depths in metres) and sampling stations: 10-180 (solid triangle) March-April 1987 cruise, 1-19 (solid circle) August-September 1987 cruise.

Carte bathymétrique (profondeurs en mètres) et stations de prélèvement: 10-180 (triangle plein) campagne de mars-avril 1987, 1-19 (cercle plein) campagne d'août-septembre 1987.



INTRODUCTION

The Ionian Sea, the largest in volume and the deepest area of the Eastern Mediterranean basin, is surrounded by the north African coast, the southern coasts of the Italian peninsula and Sicily and the west coast of Greece. Its greatest depths are found along the Hellenic Trench, just southwest of Peloponnesus (Vavilov, depth 5121 m). It communicates directly with the Western Mediterranean through the strait of Sicily, with the Adriatic Sea through the strait of Otranto and with the Aegean Sea through the three western straits of the Cretan Arc (Fig. 1).

The multi-nation research programme for the exploration of the Eastern Mediterranean, POEM (Physical Oceanography of the Eastern Mediterranean), began in 1984 with the objective of understanding the dynamics, variability and energetics of its general circulation, explaining physical processes such as deep convection and water mass formation occurring there and obtaining comprehensive knowledge of the chemical and biological oceanography of this sea. The ultimate scientific goal is to construct a general circulation model of the Eastern Mediterranean adequate for biological and chemical transport and for climate study.

The chemical oceanography of the Eastern Mediterranean at the time of initiation of the project was poorly known. Prior to that, information concerning the nutrient salts and oxygen distribution in the Eastern Mediterranean Sea was scanty. The number of oceanographic cruises in the Mediterranean had included the Eastern Mediterranean and Ionian Sea (cruise 151 of R/V *Atlantis 1948*, cruise 21 of R/V *Chain 1961*, cruise 275 of R/V *Atlantis 1962*). However, their main aim was the hydrological study of the region, and only during a few of them were chemical measurements carried out (Pollak, 1951; Miller *et al.*, 1970).

McGill (1961) presented a summary of the seasonal patterns of oxygen and phosphorus distribution in the Eastern and Western Mediterranean Sea, based on the observations of these cruises. The results indicate the low level of biological activity and the oligotrophic character of Mediterranean Sea. In 1965, the same author, summarizing the nutrient data collected from the *Atlantis* and *Chain* expeditions, with particular emphasis on the latest data from the Eastern Mediterranean, and comparing them with available data for Western Mediterranean and Atlantic Ocean, noted a considerable depletion of nutrient salts from the western to the eastern part of Mediterranean. Concentrations of nutrients in the Aegean Sea are twelve times lower than in the Atlantic Ocean, eight times lower than in the Alboran Sea and three times lower than in the Ionian Sea. This depletion is related to the mixing of the inflowing oceanic water with the nutrient-poor water of the basin, to biological activity and to the existence of successive sills.

The bulk of existing information concerning the physical characteristics of the different water masses in the Ionian Sea, the spreading of surface water of North Atlantic origin, the role of the Adriatic and Levantine water types in the formation of deep water of Eastern Mediterranean and the circulation patterns of the region has been provided by

Pollak (1951), Wüst (1961), Lacombe and Tchernia (1960 and 1972), Zore-Armanda (1969 and 1972), El-Gindy and El-Din (1986).

CTD data collected during March-April 1986, March-April 1987 and September-October 1987 cruises have been used for the water mass analysis and circulation study of this region (Georgopoulos *et al.*, 1986; Theodorou *et al.*, 1988; Artegiani *et al.*, 1988). The main results are the following :

The surface layer in the Ionian Sea is occupied by water originating from the North Atlantic. This water mass extends from the surface to about 60-140 m and is less saline and warmer than the Levantine Intermediate Water (LIW). In the subsurface layer the LIW is transformed along its northward route close to the coast from the Levantine to the Ionian Sea due to spreading and mixing processes. The region is dominated by mesoscale eddies with cyclonic circulation in the northern part and a large anticyclonic gyre in the west of Peloponnesus. The distribution of hydrological characteristics reveals the existence of a thermohaline front near the Otranto Strait, where Ionian and Adriatic waters meet. Temperature and salinity inversions are observed throughout the water column. Near the bottom of the sill, dense water (σ_θ: 29.17) was found to outflow towards the Ionian Sea.

We present here detailed nutrient and oxygen figures for the Ionian Sea (east of 190 E and between the latitudes 36° and 40° N). The nutrients measured were (PO_4-P, SiO_3-Si, NO_3-N, NO_2-N). This is the first time that relatively complete chemical results for the region are presented. A study of the seasonal variation of these parameters is derived from data collected during the cruises in March-April 1987 and August-September 1987. An interpretation of the distributions observed in relation to the water masses and their circulation inside the basin is also proposed.

MATERIALS AND METHODS

During the cruise of March-April 1987, samples from 54 chemical stations were collected in the regions of the northeastern and southeastern Ionian Sea, the Cretan Sea, the eastern straits of the Cretan Arc and the North Aegean Sea. During the August-September 1987 cruise, samples from 51 chemical stations were collected in the same regions and also in the western straits of the Cretan Arc. For each of the two cruises, about twenty of these stations are situated in the Ionian Sea (Fig. 1).

Samples for the determination of chemical parameters were collected from depths down to 2 100 m with rosette (12 Niskin bottles of 8 l) fixed on a CTD. Below 2 000 m, the samples were collected using NIO bottles carrying protected and non-protected thermometers. For stations deeper than 1 000 m, two rosette samplings were performed, in order to obtain a dense sampling.

Samples for the determination of oxygen were the first to be taken from the sampling bottle. These were analysed immediately after collection on board with the Winkler method according to Carpenter (1965 *a*; 1965 *b*).

Samples for the determination of nutrients were collected in 100 ml polyethylene bottles and kept continuously under deep freeze (- 20° C) until analysis in the laboratory by a Technicon CSM6 autoanalyser. The methods described by Murphy and Riley (1962) for phosphates, Mullin and Riley (1955) for silicates, Shinn (1941) and Strickland and Parsons (1968) for nitrites and nitrates were employed. Phosphates were measured on board RV *Aegaio* by a Hitachi 100-60 spectrophotometer, in order to improve reliability.

RESULTS AND DISCUSSION

Winter

Over the region of the northeastern Ionian Sea we have selected twelve stations from Otranto to the west of Crete to demonstrate the distribution of the chemical characteristics along a section parallel to the coastline (Fig. 1).

The surface layer is almost saturated with oxygen and the values fluctuate between about 6.2 and 6.0 ml/l in the north and 5.6 to 5.5 ml/l in the south in relation with the increase in temperature (Fig. 2). The nutrient poor surface layer extends down to 60 m in the north, while in the south, it reaches about 120 m. This surface layer is separated from the lower layers of intermediate and deep water by a transition layer 100-200 m thick within which the concentration

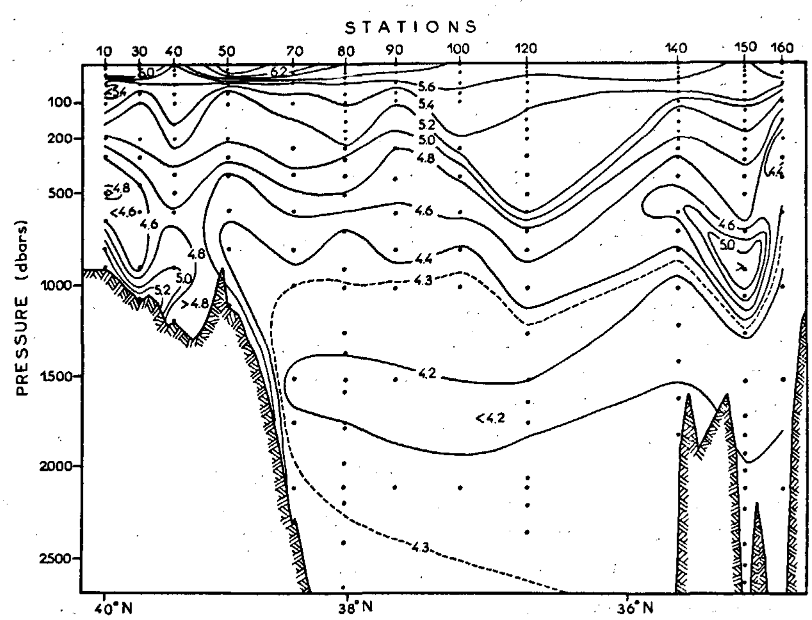


Figure 2

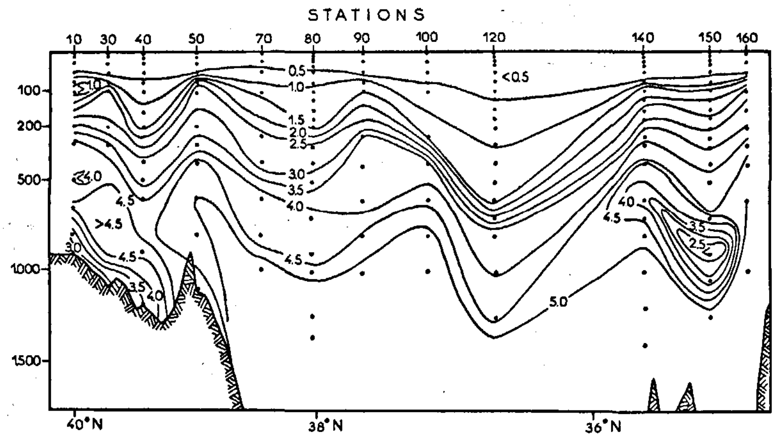
Vertical distribution of oxygen (ml/l) along a transect in the Ionian Sea (April 1987).

Distribution verticale de l'oxygène (ml/l) le long d'une section à travers la Mer Ionienne (avril 1987).

Figure 3

Vertical distribution of nitrates (µgat/l) along a transect in the Ionian Sea (April 1987).

Distribution verticale des nitrates (µgat/l) le long d' une section à travers la Mer Ionienne (avril 1987).



of nutrients increases quickly (Fig. 3).The thickness and the height of this layer is variable even for closely separated stations.

Figure 4 represents the distribution of salinity, temperature, oxygen and nitrate, *versus* sigma-theta, of two stations situated at 39° N latitude with a distance of 24 nautical miles between them. At station 50, the nitrates reach 3.3 µgat/l at about 200 m, while in the eastern station 60 we found such concentration at about 500 m. Oxygen decrease follows the increase of nutrients, and we have 5 ml/l at about 200 m at station 50 and at about 500 m at station 60. The corresponding isopycnal at these depths is 1.0291 .

The above observations show clearly that the oxygen and nutrient patterns are affected by the presence of mesoscale cyclonic and anticyclonic gyres in the area. From the north to the south we can follow a succession of cyclonic and anticyclonic disturbances which appear in the same locations and with the same intensity over the vertical sections of salinity, temperature, oxygen and nutrients (Fig. 2 and 3). The most interesting feature in these sections is the warm core eddy near station 120. The thermocline, isohaline, oxygen and nitrate isoconcentration lines at station 120 (36°32 N, 21°05 E) are depressed about 400 m below those in the adjacent areas.Surface waters up to a distance of 200 m within the gyre are very poor in nutrients (NO_3 < 1 µgat/l). This eddy is related to the anticyclone found in the same location in winter 1986 by Theodorou *et al.* (1988).

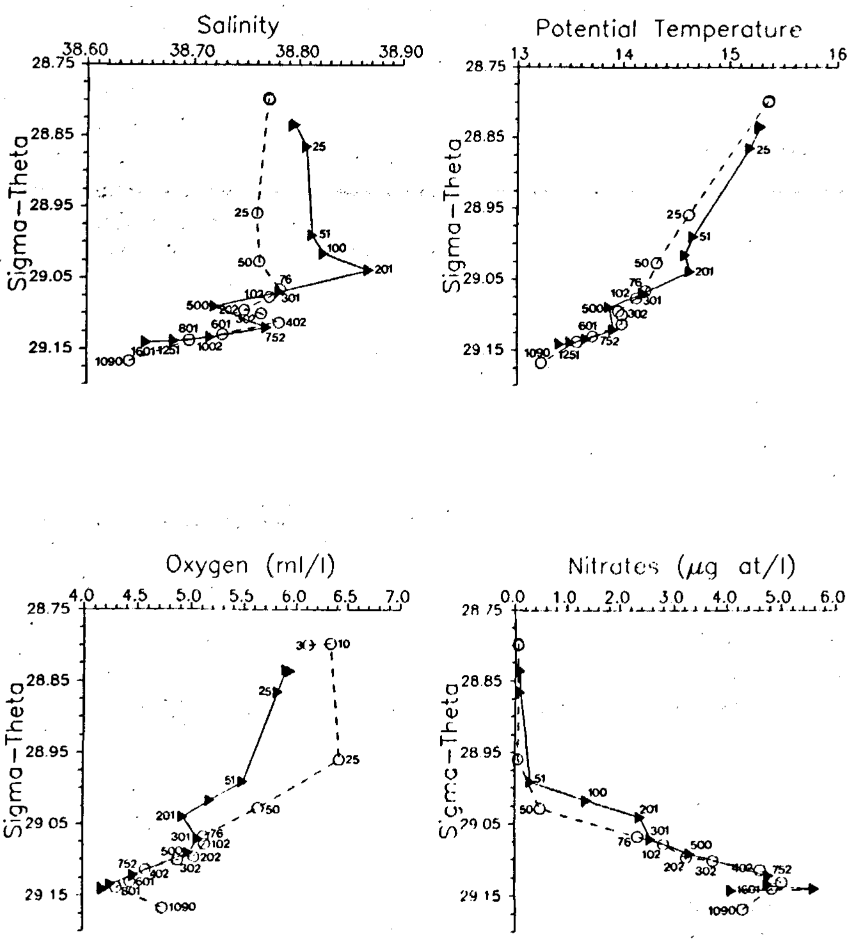


Figure 4

Distribution of salinity, temperature °C, oxygen (ml/l) and nitrate (µgat/l) versus *sigma-theta of two stations, 50 (empty circle) and 60 (solid arrow), situated at 39°N latitude (April 1987).*

Distribution de la salinité, de la température (°C), de l' oxygène (ml/l) et des nitrates (µgat/l) en fonction du sigma-theta de deux stations, 50 (cercle vide) et 60 (flèche pleine) situées à 39°N latitude (avril 1987).

The Adriatic Sea is well known as the main source region, in the Eastern Mediterranean, of high-oxygen deep water (Pollak, 1951; Wüst, 1961; Zore-Armanda, 1969; Lacombe et Tchernia, 1972). Wüst (1961) notes that a bottom water of very high oxygen content and density is formed in February and March in the southern Adriatic by vertical convection and mixing of surface and saline intermediate water. Recently, in April 1986 during the POEM cruise, Georgopoulos *et al.* (1986) observed dense water ($\sigma_\theta = 29.17$) near the bottom of a station situated in the south of the Otranto Strait. Based on data from the same cruise Theodorou *et al.* (1988) found large thermohaline gradients in the vicinity of the Otranto Strait.

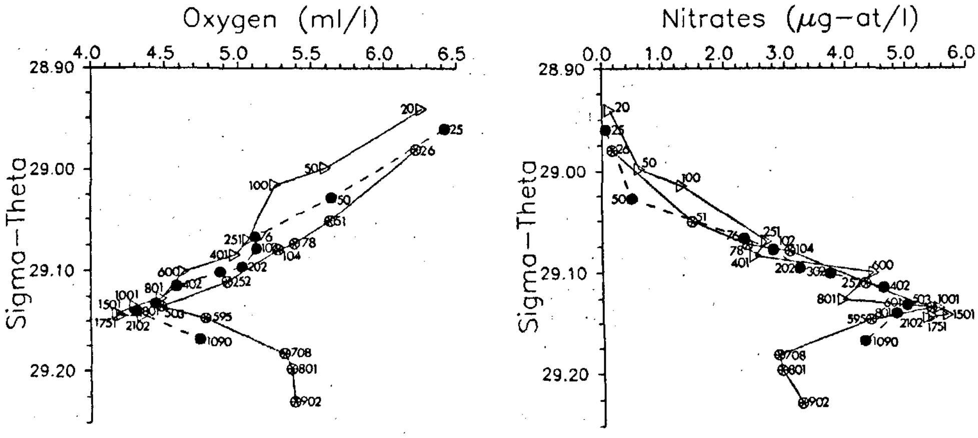


Figure 5

Distribution: a) of oxygen; and b) of nitrates versus sigma-theta for three stations: 20 (starry circle), 50 (solid circle) and 70 (empty arrow), in the Northeastern Ionian Sea (April 1987). The numbers next to the symbols correspond to the pressure in dbars.

Distribution : a) de l'oxygène ; et b) des nitrates en fonction de sigma-theta des trois stations, 20 (cercle étoilé), 50 (cercle plein) et 70 (flèche vide), dans la partie nord-est de la Mer Ionienne (avril 1987).Les chiffres près des symboles correspondent à la pression en dbars.

Also in the vicinity of the Otranto Strait (northernmost part of the oxygen and nitrate sections) we observe the well oxygenated and relatively nutrient-poor AdBW (Adriatic Bottom Water) close to the bottom (Fig. 2 and 3) . The core of this water has an oxygen concentration higher than 5.2 ml/l, nitrate lower than 3.0 µgat/l, phosphate lower than 0.1 µgat/l and silicates lower than 3.5 µgat/l.

The depletion of oxygen and the increase of nutrients in the deep waters of the stations south of the Otranto Strait is attributed to the mixing of the AdBW outflowing over the sill, with the Ionian waters moving towards the Adriatic. This evolution in the deep waters towards the south is illustrated in Figures 5 *a* and *b*, where oxygen and nitrate are plotted as a function of sigma-theta. The oxygen content of the deep waters neighbouring the Otranto Strait (station 20) is about 5.5 ml/l and nitrate ranges around 3 µgat/l. At the southernmost station (station 70), oxygen has been reduced to 4.2 ml/l , whereas nitrates are enhanced to about 5.6 µgat/l. Station 50 located in the middle of stations 20 and 70 has intermediate values O_2: 4.3 ml/l at 800 m, 4.8 ml/l at 1 100 m, NO_3: 4.9 µgat/l at 800 m and 4.3 µgat/l at 1 100 m.

South of 39° N latitude the deep waters (below 600 m) in the Ionian become homogeneous. This homogeneous water with an oxygen content lower than 4.4 ml/l and nitrate greater than 5.0 µgat/l is the Deep Water of the Eastern Mediterranean formed by mixing of the AdBW with the LIW. The concentration of oxygen is a little higher than and that of nitrate very similar to those published by Mc Gill (1961 and 1965).

A manifestation of the penetration of the Aegean waters into the Eastern Mediterranean is found to the west of the Cretan Arc, at stations 140 and 150 (Fig. 2 and 3). We observed a water mass with low nutrient and high oxygen content ($O_2 > 5.0$ ml/l, $NO_3 < 2.5$ µgat/l) at a depth of 900 m. This water mass also presented high salinity $S > 38.9$, and temperature $T > 14.4$. In fact the Ionian Sea communicates in the south with the Aegean Sea through the western straits of the Cretan arc, which plays a crucial role in the dynamics and the exchange of sea water. It is well known (Mc Gill, 1965; Souvermezoglou, 1989) that among the principal basins of the Mediterranen Sea, the intermediate and deep water of the Aegean Sea have the lowest concentration of nutrients and the highest of oxygen.

Summer

In summer we followed approximately the same stations (Fig. 1). We have also chosen ten stations to present the vertical distribution of oxygen and nitrates. Generally the summer patterns are similar with those of winter .

Due to the warming of the surface layer, we observe in this layer lower concentrations of oxygen in summer than in winter. The subsurface layer conserves the high winter concentrations of oxygen. The augmentation of temperature in the surface layer causes very strong gradients of oxygen between 30 and 100 m (Fig. 6 and 8). This subsurface maximum exceeds by about 1.3 ml/l the surface concentration.The maximum is widespread over the greater part of the ocean in summer. Its presence is attributed principally to the warming of the surface waters,the contribution of the biological processes being less effective (Reid, 1962; Minas, 1970).

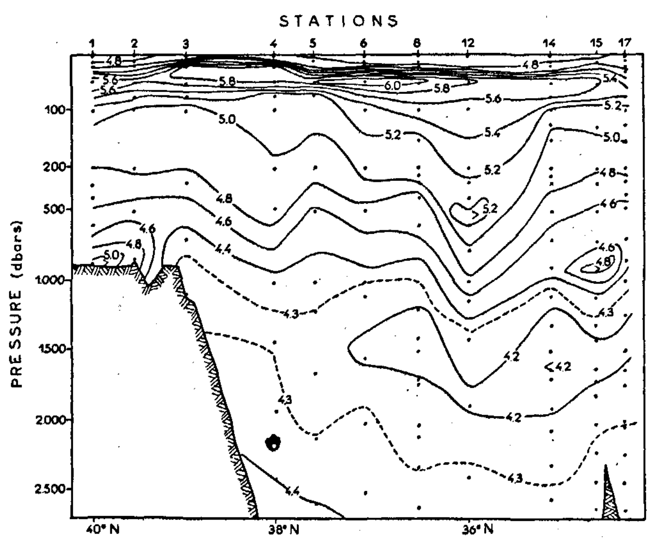


Figure 6

Vertical distribution of oxygen (ml/l) along a transect in the Ionian Sea (September 1987).

Distribution verticale de l'oxygène (ml/l) le long d'une section à travers la Mer Ionienne (septembre 1987).

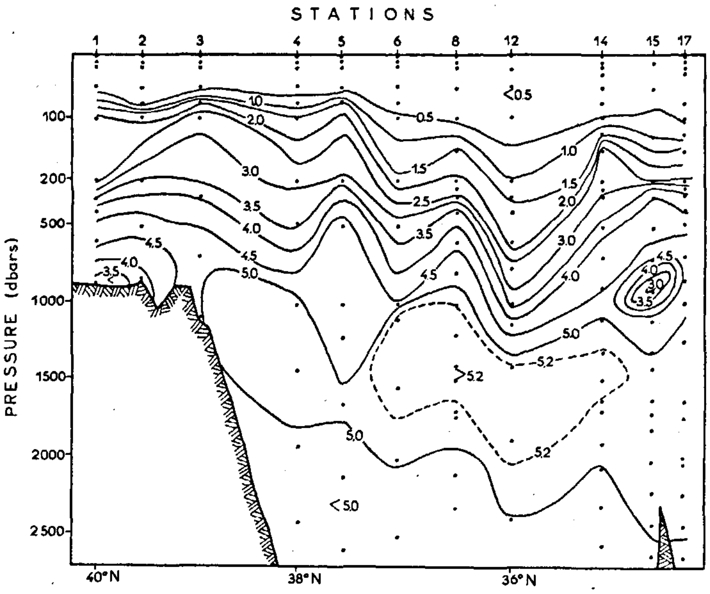


Figure 7

Vertical distribution of nitrates (µgat/l) along a transect in the Ionian Sea (September 1987).

Distribution verticale des nitrates (µgat/l) le long d' une section à travers la Mer Ionienne (septembre 1987).

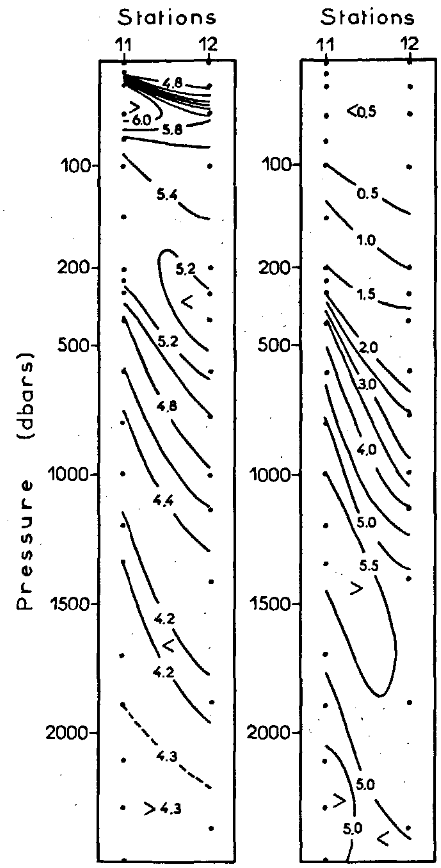


Figure 8

Vertical distribution of oxygen (ml/l) and nitrate (µgat/l) along a latitudinal transect (September 1987).

Distribution verticale de l' oxygène (ml/l) et des nitrates (µgat/l) le long d'une section latitudinale dans la Mer Ionienne (septembre 1987).

As in the winter pattern, the nutrient poor surface layer extends down to 60 m in the north and down to 150 m in the south (Fig. 7 and 8).

In the north of the sections (Fig. 2, 3, 6 and 7), the layer between 100 and 200 m is less oxygenated and richer in nutrients in summer [winter (April): oxygen 5.2 -5.4 ml/l, nitrate 1.5-2.5 µgat/l, summer (September): oxygen 4.9 - 5.0 ml/l, nitrate 2.5-3.0 µgat/l]. The degradation of the organic materials created during the spring-summer period can be a possible explanation for the lower oxygen concentrations observed in this layer in late summer.

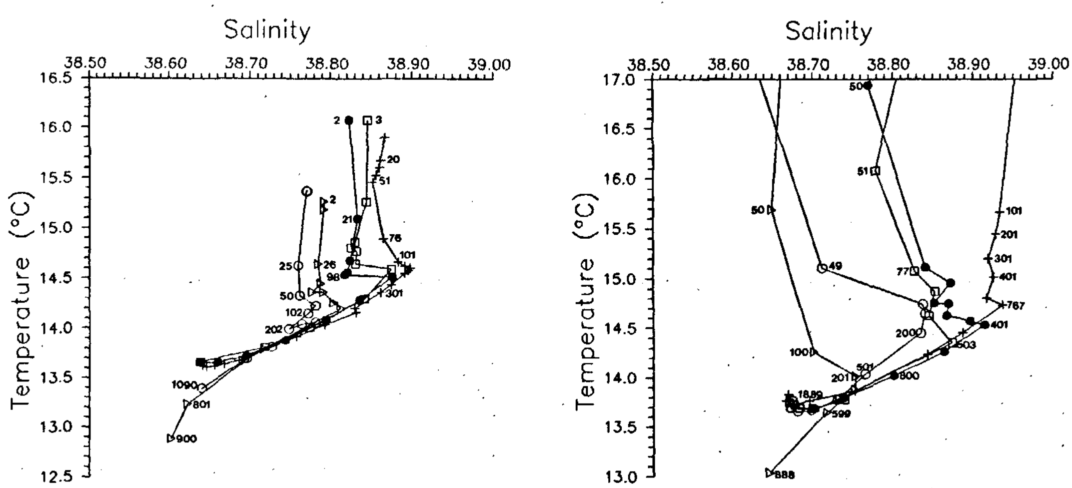


Figure 9

T-S diagrams of selected stations in the Ionian Sea: a) April 1987, stations 10 (empty arrow), 50 (empty circle), 90 (solid circle), 100 (empty square), 140 (+); b) September 1987, stations 1 (empty arrow) 4 (empty circle), 6 (empty square), 12 (+), 13 (solid circle). The numbers next to the symbols correspond to the pressure in dbars.

Diagrammes T-S des stations sélectionnées dans la Mer Ionienne : a) avril 1987, stations 10 (flèche vide), 50 (cercle vide), 90 (cercle plein), 100 (carré vide), 140 (+) ; b) septembre 1987, stations 1 (flèche vide), 4 (cercle vide), 6 (carré vide), 12 (+), 13 (cercle plein). Les chiffres près des symboles correspondent à la pression en dbars.

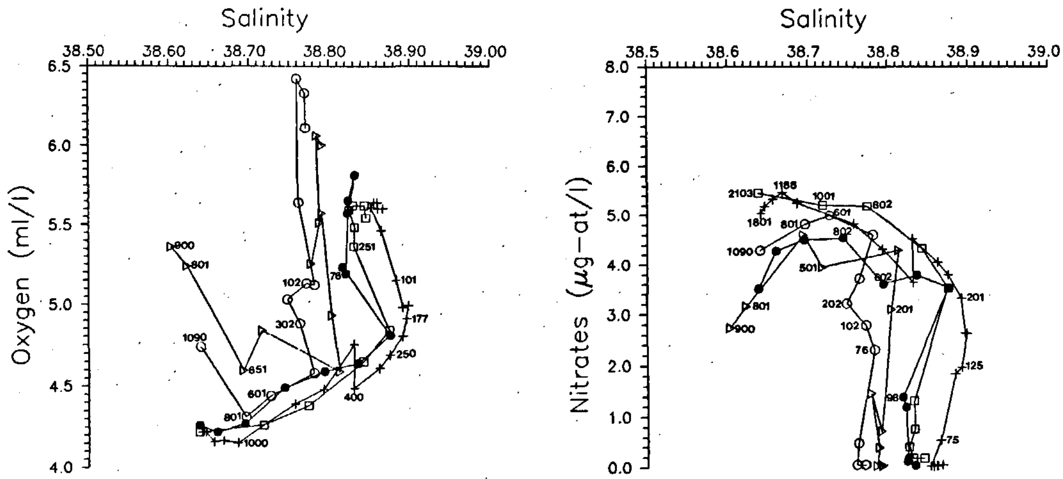


Figure 10

O_2-S, NO_3-S diagrams of selected stations in the Ionian Sea.(April 1987). Stations 10 (empty arrow), 50 (empty circle), 90 (solid circle), 100 (empty square), 140 (+). The numbers next to the symbols correspond to the pressure in dbars.

Diagrammes O_2-S et NO_3-S des stations sélectionnées dans la Mer Ionienne.(avril 1987), stations 10 (flèche vide), 50 (cercle vide), 90 (cercle plein), 100 (carré vide), 140 (+). Les chiffres près des symboles correspondent à la pression en dbars.

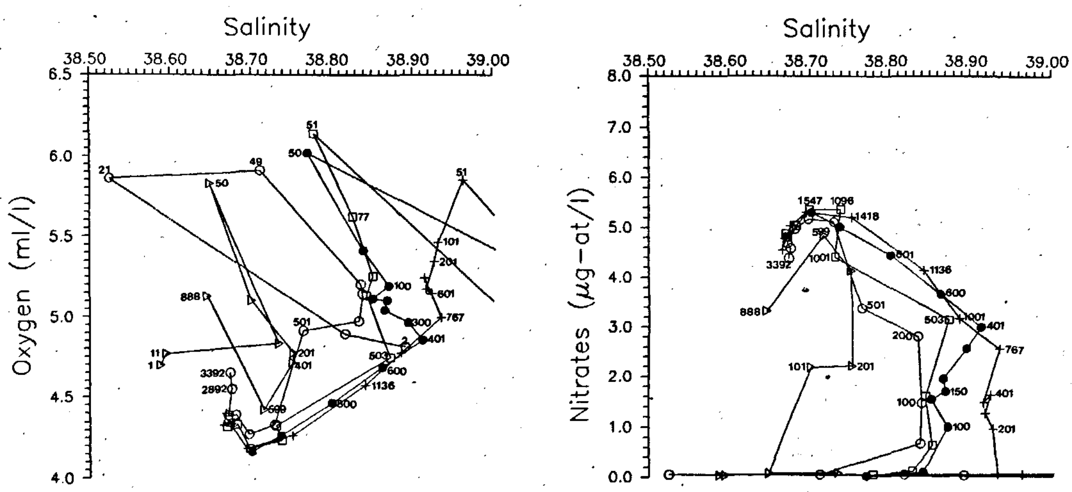


Figure 11

O_2-S, NO_3-S diagrams of selected stations in the Ionian Sea. September 1987, stations 1 (empty arrow), 4 (empty circle), 6 (empty square), 12 (+), 13 (solid circle). The numbers next to the symbols correspond to the pressure in dbars.

Diagrammes O_2-S et NO_3-S des stations sélectionnées dans la Mer Ionienne (septembre 1987), stations 1 (flèche vide), 4 (cercle blanc), 6 (carré vide), 12 (+), 13 (cercle plein). Les chiffres près des symboles correspondent à la pression en dbars.

The LIW in the Ionian Sea is generally poorer in nutrients and richer in oxygen in summer than in winter.

The oxygen and nutrient concentration of the deep water presents very small seasonal variations, being of the same order of magnitude as the winter concentration.

The isotherms, isohalines, oxygen and nitrate isoconcentration lines show the large anticyclonic flow region southwest of Peloponnesus. The location of the anticyclone in summer is about half a degree further towards the south than in winter at the level of station 12 (36°00 N, 21°30 E). A latitudinal section of oxygen and nitrates near this anticyclone is represented in Figure 8. The depth of the oxygen minimum (< 4.2 ml/l) at about 1 500 m fits very well with the depth of the maximum of nitrates (> 5.5 µgat/l).

Near the Otranto Strait, the well-oxygenated and relatively nutrient-poor AdBW makes a front with the water of Levantine origin, richer in nutrient and poorer in oxygen. The AdBW formed in winter in the Adriatic Sea flows over the Otranto sill to the Ionian. Pollak (1951) notes that during most of the time there will exist at least a thin layer of water at the bottom of the Adriatic Sea which has sufficiently high density to sink to those depths of Eastern Mediterranean at which the deep oxygen maximum is found. Zore-Armanda (1969) describes the two different water regimes of the Adriatic Sea in summer and winter. In summer, the Adriatic surface layer flows into the Ionian Sea and the outflowing bottom layer is thinner than in winter. Our results show that in summer the outflowing Adriatic water over the sill is thinner (Fig. 2, 3, 6 and 7), its chemical composition changing and becoming richer in nutrients and poorer in oxygen ($O_2 < 5.1$ ml/l, $NO_3 > 3.3$ µgat/l, $PO_4 > 0.2$ µgat/l and $SiO_4 > 3.8$ µgat/l). This evolution is related to the biogeochemical process such as the oxidation of organic materials and the seasonal variation of the soutward flow of AdBW through the Otranto Strait (Ovchinikov *et al.*, 1985).

We can identify the distinct patch of Cretan Water to the west of Crete, localized between stations 15 and 17. It is less pronounced in summer than in winter, with an oxygen content higher than 4.8 ml/l and nitrate less than 3.0 µgat/l (Fig. 6 and 7). Long data series in different seasons are needed to study the influence of the exchanges in the straits on the distribution of nutrients and oxygen.

Water mass analysis

The T-S diagrams of winter and summer (Fig. 9 *a*, 9 *b*) show that the area is dominated by four distinct water masses. We use the collected nutrient and oxygen data of the same stations during these two cruises, winter (Fig. 10 *a*, 10 *b*) and summer (Fig. 11 *a*, 11 *b*), for detailed analysis and determination of the chemical characteristics of the water masses.

The physical and chemical characteristics of these four water masses are the following:

- The surface water corresponds to the set of dispersed points, of high temperatures and salinities on the T-S diagrams. In winter we observe a gradual increase of salinity and temperature in the north-south direction. We utilize the same scale for the summer diagrams (Fig. 9 *b* and 11) in order to compare with those for winter.

This surface layer (< 75 m) is very poor in nutrients in winter and summer, with concentrations lower than 0.1 for phosphate, 0.5 for nitrate and 1.0 for silicate. The surface layer is almost oxygen-saturated (about 6 ml/l in winter and 4.8 µgat/l in summer).

- The LIW, which is characterized by high salinity, originates outside the area under investigation and can be found at depths from the surface down to 600 m in the Mediterranean basin. Its salinity over the Levantine basin, where the source areas of LIW are located, reaches 39.1 (Hopkins, 1978), while in the southern Ionian Sea we have found about 38.9. A decrease of temperature is also observed in the south-north direction (Fig. 9 *a*, 9 *b*). This transformation of LIW is due to spreading and mixing processes.

In winter the concentration of oxygen in the LIW varies between 4.75-5.0 ml/l and that of nitrate between 2.2-3.8 µgat/l. This water mass is found with slightly modified chemical characteristics in summer: the concentration of oxygen varies between 5.0-5.25 ml/l and that of nitrates between 1.6-3.0 µgat/l.

- The AdBW exhibits slightly different physical characteristics in summer and in winter. In winter, newly formed Adriatic Water was found near the Otranto Strait below 800 m, with salinity 38.6 and temperature 12.9-13°C, σ_θ 29.2. In summer it is saltier (S: 38.64-38.70) and warmer (T: 13-13.6° C). This well-oxygenated and relatively nutrient-poor water mass has in winter (O_2 5.3 ml/l NO_3 2.7 µgat/l, PO_4 0.07 µgat/l and SiO_4 2.8 µgat/l; Fig. 10 *a*, 10 *b*). In summer, it is poorer in oxygen (O_2< 5.1 ml/l) and richer in nutrients (NO_3> 3.5 µgat/l, PO_4> 0.2 µgat/l and SiO_4> 4 µgat/l).

- The DWEM formed by the mixing of the AdBW slightly further south with LIW. This water mass has S: 38.65, T: 13.7. It conserves almost the same physical characteristics in summer and almost the same chemical characteristics in winter and summer, with O_2: 4.2 ml/l, NO_3: 5.0 µgat/l, PO_4: 0.2 µgat/l.

The Mediterranean waters, besides their relative poverty in nutrients, are characterized by a nitrate-phosphate atomic ratio different from that in the open ocean, the Atlantic in particular. Thus, in the region under study, it ranges between 20 and 26, which is much higher than that in the Atlantic Ocean, in conformity with Redfield's ratio N:P = 16:1 (Redfield *et al.*, 1963). These ratios are very close to that given by Mc Gill [1965 (Tab. 2)] for the Strait of Otranto and two sections in the Ionian Sea (19.66 ± 1.87 at 38°N latitude, 18.49 ± 1.69 at 20°E longitude).

It is interesting to remark that the N/P ratio varies in the different water masses of the Eastern Mediterranean. An example of this is observed in the Ionian Sea. The stations near the Otranto Strait have an N/P ratio of 26.4, while the ratio at the stations situated south of 39°N is 20.9 owing to the different proportions of AdBW and LIW in the two groups of stations.

Spatial evolution

The composition in oxygen and nutrients of the two principal water masses in the Ionian Sea, the Deep Water of the Eastern Mediterranean (DWEM) and the LIW, gradually changes as they spread from the source areas.

It is well known from previous investigators that the DWEM is formed in the northern Ionian Sea and spreads to the south Ionian and Levantine Seas. Recently El-Gindy *et al.* (1986), by the horizontal distribution of different hydrographic parameters, have demonstrated that the cold and low saline waters come from the north of the Ionian Sea, toward the south and are deflected to the west of the Ionian Sea. Schlitzer *et al.* (1991) conclude that the AdBW is the only subtantial source of deep and bottom water in the Ionian and Levantine Seas. The very small CFM-12 concentrations in the minimum layer (at about 1 500 m in their west-east section along 35°N latitude) indicates that the vertical mixing with the underlying (rich in CFM-12) water of Adriatic origin, is minimal. As the amount of oxygen in the deep waters diminishes due to the decomposition of organic materials, we expect to find an inverse correlation between the dissolved oxygen and the time elapsed since the formation of the water mass and, accordingly, a gradual loss of oxygen and gain in nutrients from the north to the south.

In fact, an important decrease of oxygen and increase of nitrates in the deep waters is observed between the north stations influenced by the AdBW (stations 10 and 50, Fig. 10) and the stations south of 39°N latitude where the

DWEM is found (stations 90, 100 and 140 in the same figure). Interestingly, in the same figure we can also distinguish a slight diminution in oxygen in the the Deep Water (DW) of the southern stations (south of 39°N latitude) in the north-south direction. For example, the deep waters at station 140 have slightly lower values than those of station 90. The summer figures are similar to those of winter (Fig. 10). These small variations can be observed also on the vertical sections of oxygen and nitrate (Fig. 6 and 7).

It is difficult to disclose in LIW a clear tendency concerning the evolution of the chemical parameters (Fig. 10 and 11). This water is situated in depths with pronounced gradients owing to biological phenomena (photosynthesis, decomposition). The LIW originates in various parts of the Levantine Sea and we expect a gain in nutrients and a loss of oxygen along its northward propagation to the Ionian Sea. In fact the comparison of LIW oxygen and nutrient content in the Levantine and the Ionian Sea shows the opposite. We believe that an explanation may be found in the contribution of the Cretan Sea to the formation of the LIW. A new source area of intermediate water was revealed during the late winter POEM-01-86 cruise over the Cretan Sea (Georgopoulos *et al.*, 1989). It is well known from previous observations that the Cretan Sea has higher oxygen and lower nutrients than the Levantine Sea. More studies are needed for the estimation of the contribution of the intermediate water formed in the Cretan Sea and the variation of the chemical composition in the different area of formation.

CONCLUSIONS

From the nutrient and oxygen data obtained over the Ionian Sea during late winter (March-April 1987) and late summer (September-October 1987) cruises it is apparent that the different scale physical phenomena dominant in the Eastern Mediterranean (thermohaline circulation, water mass formation, eddy field activity) have a significant chemical signature.

The Deep Water of the Eastern Mediterranean has very small seasonal variation in oxygen and nutrients. Conversely, the Adriatic Bottom Water has a clear evolution between winter and summer. In winter this water is younger than in summer.

Concerning spatial evolution, in the Deep Water of Eastern Mediterranean this process is related to spreading from the Ionian to the Levantine Sea.

The spatial evolution of Levantine Intermediate Water is more complex, without a clear tendency. We found no loss of oxygen and a gain in nutrients along its northward route from the Levantine to the Ionian Sea, as was expected. This can be attributed to the contribution of LIW formed in the Cretan Sea.

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