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Transport and Distribution of Nutrients and Chlorophyll-*a* by Mesoscale Eddies in the Northeastern Mediterranean

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ABSTRACT

Salihoğlu, İ., Saydam, C., Baştürk, Ö., Yılmaz, K., Göçmen, D., Hatipoğlu, E. and Yılmaz, A., 1990. Transport and distribution of nutrients and chlorophyll-*a* by mesoscale eddies in the northeastern Mediterranean. Mar. Chem., 29: 375–390.

The distribution of nutrient elements and chlorophyll-*a* in the Northern Levantine Basin (NLB) were investigated in some detail and are discussed together with the physical aspects of the region in the present study. The surface circulation pattern of the NLB was studied and the structure of the relatively large-scale Rhodes cyclonic gyre, which is located between Rhodes and Cyprus, was investigated for the same time period. The most important characteristics of this cyclonic gyre are the upwelling of nutrient-rich deep waters within the gyre and the reverse phenomenon at the peripheries. Anticyclonic circulation systems generally surround the Rhodes cyclonic gyre; the permanent ones are located in the southern part of the Rhodes gyre, in the Cilician Basin, and off Iskenderun Bay. The vertical distribution of nutrients in the water column shows completely reversed trends and the nutrient gradient ranges between 300–400 m in the central parts of the anticyclonic systems. Thus downwelling processes also occur in the NLB and the formation of Levantine Intermediate Water (LIW) observed in the NLB matches the chemical data presented here. This special vertical and spatial distribution of nutrients affects the distribution of the phytoplankton population, as the patches of primary producers are aggregated in the central parts of the Rhodes gyre. This is confirmed by the chlorophyll-*a* data and the unexpected content of neuston net collection in the same region. The concentration of chlorophyll-*a* was relatively high at offshore stations, such as in the central parts of the cyclonic gyres, where zooplankton, small shrimp and fish larvae, etc., were observed in large quantities.

INTRODUCTION

The need for basic oceanographic experiments covering the Eastern Mediterranean (EM) extensively has long been recognized, in view of the insuffi-

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ciency of the past data available for the region. The recent collection of high-resolution physical, chemical and biological data during the framework of POEM (a research programme on Physical Oceanography of the Eastern Mediterranean) started in April 1986. The area covered by this research is shown in Fig. 1. Sampling and in situ data collection were carried out on board R/V "Bilim", which belongs to the Institute of Marine Sciences (METU).

Review of the regional characteristics

The Levantine Basin (LB) (Fig. 2) is the second largest basin of the EM. It is bounded by Asia Minor, and the northeast African mainland. The pas-

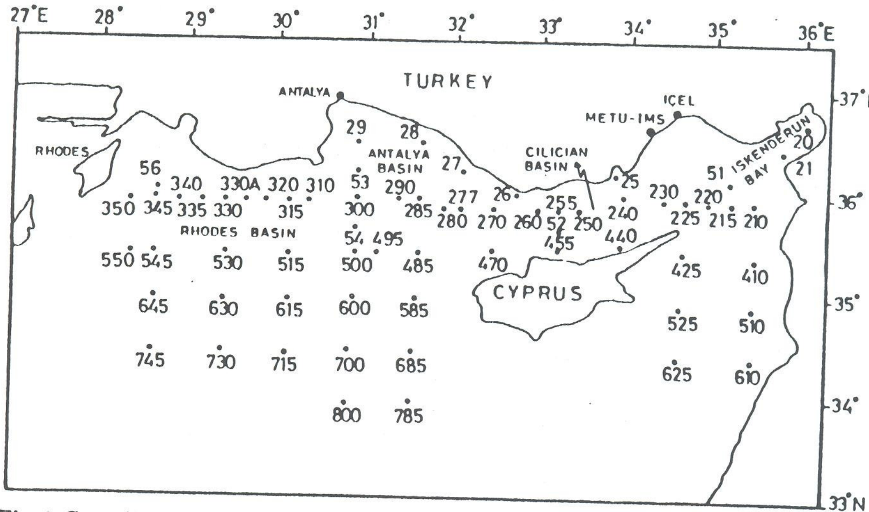


Fig. 1. Sampling stations in the Northern Levantine Basin (NLB).

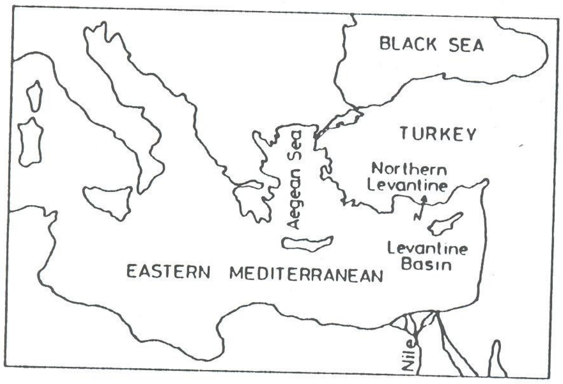


Fig. 2. Location map of the NLB.

sages of Rhodes, Scarpanto and Casos are its connection to the Aegean Sea, and connection to the Ionian Sea is through the Cretan Strait.

There exist two important water masses in the EM. The first is Levantine Intermediate Water (LIW), which affects the entire Mediterranean Sea. LIW is locally generated, especially in the northern sector of the LB and along the periphery of the Rhodes gyre (Özsoy et al., 1989). The sinking of surface water can be observed in autumn and spring, which suggests that LIW may be formed continuously in the LB, although more intensely during late winter.

In general, the LB is a region of convergence and convective sinking of high-salinity waters (Wüst, 1961). The LIW forms and flows in the reverse direction and carries relatively nutrient-rich waters towards the Atlantic Ocean. These hydrodynamics tend to dilute any nutrient input either from the atmosphere (Duce, 1986) or from the coastal shelf, as the terrigenous run-off of nutrient-rich waters is very small and the coastal shelf where the benthic-pelagic coupling for nutrient recycling is efficient is very narrow.

The second important water mass in the EM is Atlantic Water (AW) which enters from the Gibraltar Strait to balance the mass deficit of the Mediterranean. The water from the Atlantic generally circulates around the Mediterranean in an anticlockwise pattern; thus there are cyclonic gyres within both the western and eastern basins of the Northern Levantine Basin (NLB). As previously discussed by Phillippe and Harrang (1982), Ovchinnikov (1984), An-

TABLE 1

Average annual primary production values along the Turkish coasts, at different parts of the Mediterranean and the World oceans ($g\ C\ m^{-2}\ yr^{-1}$)

Location	Production	Reference
Northeastern Mediterranean (the whole basin)	24[a]	(Yılmaz, 1986)
Eastern Mediterranean	10–20	(Berman et al., 1984b)
Eastern Mediterranean	25	(Murdoch and Onuf, 1974)
Western Mediterranean	50	(Murdoch and Onuf, 1974)
Northern Levantine Basin (central parts of Rhodes cyclone)	60[a]	(Present study, 1986–1987 averages)
Northern Levantine Basin (central parts of anticyclones)	33[a]	(Present study, 1986–1987 averages)
Aegean Sea	36[a]	(Yılmaz, 1986)
The Sea of Marmara	74[a]	(Yılmaz, 1986)
Black Sea	200–250	(Sorokin, 1983)
North Sea	100	(Murdoch and Onuf, 1974)
Atlantic Ocean	69	(Koblenz-Mishke et al., 1970)
Pacific Ocean	46	(Koblenz-Mishke et al., 1970)
Indian Ocean	98	(Koblenz-Mishke et al., 1970)

[a]Primary production values estimated from chlorophyll-*a* data as described in Methodology.

TABLE 2

The concentration range of nutrient elements in the Eastern Mediterranean and the Black Sea

Nutrient		Concentration range (in μg-atom l^{-1} unit^{-1}		
		SE Mediterranean[a]	NE Mediterranean[b]	Black Sea[c]
Inorganic phosphate	U	0.0	<0.1-0.2	0.02
(PO_4-P)	L	0.35	0.2-0.4	9.92
Total oxidized nitrogen	U	0.0-0.1	<0.5-1.0	0.0
[$(NO_3+NO_2)-N$]	L	0.1-10.0	4.0-9.0	4.07
Reactive silicate	U	0.0-0.5	<1.0-1.0	10.0
[$Si(OH)_4-Si$]	L	0.5-11.0	1.0-10.0	224

[a]Israel Report (1985).
[b]Present study.
[c]Brewer and Murray (1973).
U: euphotic zone; L: aphotic zone.

ati (1984) and Özturgut (1976), the Rhodes cyclonic gyre is the permanent and relatively large-scale gyre in the region. Recent studies on the physical characteristics of the gyre systems of the NLB and the overlapping of the chemical and the biological data with these physical data showed that especially the central parts of Rhodes cyclonic gyre included patches of high quantities of phytoplankton even though they lived locally at offshore stations. The reason for this is very clear, as the Rhodes cyclonic gyre tends to homogenize water properties at its central parts through upwelling (Özsoy et al., 1989); thus the relatively nutrient-rich deep waters are carried upwards where photosynthetic activity occurs. This is confirmed by the chlorophyll-*a* and neuston results in the present study.

The previously reported data for the region are unanimous on the low production rates for the EM (Oren, 1969; Gulland, 1971; Oren et al., 1973; Sournia, 1973; Murdoch and Onuf, 1974; Berman et al., 1984b). The studies carried out by Yılmaz (1986) have also reported low production rates for the NLB. Most of these studies either were limited to neritic waters overlying the narrow continental shelf or were confined within the anticyclonic gyre systems. They generally included the measurement of nutrient elements and chlorophyll-*a* in the region (Oren et al., 1973; Azov, 1986; Berman et al., 1986). Some examples of primary production values measured directly and/or estimated from chlorophyll-*a* data along the Turkish coasts and different parts of Mediterranean and the World oceans are shown in Table 1 for comparison. This table clearly indicates the oligotrophic characteristics of the EM. The poor primary productivity of the region is the result mainly of the low levels of available nutrients which are essential for phytoplankton growth. As a consequence, the Mediterranean in general and the EM in particular can be considered as a 'marine desert' in terms of nutrients (Table 2). Black Sea nutrient levels are included in Table 2 for comparison, as this basin is considered as a 'nutrient trap', and the concentrations of all nutrients there are the highest among all seas. As is seen from Table 2, the concentration ranges of inorganic phosphate, total oxidized nitrogen (nitrate+nitrite) and reactive silicate for the upper and deeper layers obtained in the present study are in good agreement with data obtained earlier in the EM (Miller et al., 1970; Israel Report, 1985).

METHODOLOGY

In the field study a Sea Bird Model 9 CDT probe system was used, which measures seawater temperature, conductivity and dissolved oxygen simultaneously at a rate of 24 data points per second.

Nutrient concentrations were measured on board with the aid of a single-channel Technicon Autoanalyzer II. Standard Autoanalyzer methods for orthophosphate, nitrate+nitrite, and reactive silicate were used.

Spectrofluorometric measurements of chlorophyll-*a* used the acetone extracts of membrane-filtered seawater. Fluorescence intensities were obtained at 660-nm emission and 425-nm excitation wavelengths with a band-width of 60 nm by a Turner Model 430 Spectrofluorometer. Calibration was performed with concentrated acetone extracts of seawater samples which were measured spectrophotometrically. For the in situ detection of chlorophyll-*a* at sea a Navitronic Fluorometer Model Q-200 was used. The fluorometer consists of an underwater unit and a deck panel. The underwater unit contains a xenon discharge lamp which is electronically synchronized to the highly sensitive detector. The filter used in the instrument is coloured glass in combination with a narrow-band interference filter. The instrument is fitted with a depth transducer as well.

The gross primary production was estimated from the chlorophyll-*a* values using the formula of Ryther and Yentsch (1957):

$$PPt=\frac{RP}{K}\times C\times 3.7$$

where PPt is the gross primary productivity in g C m^{-2} d^{-1}, RP is the intensity of relative photosynthesis RP m^{-3} d^{-1}, C is the chlorophyll-*a* concentration in g m^{-3}, K is the average extinction coefficient in m^{-1}, and the factor 3.7 is the carbon assimilation number, which is in g C h^{-1} g^{-1} chlorophyll. The values of RP were obtained as a function of solar radiation, and the extinction coefficient was related to Secchi disk depth (d, in m) as follows:

$$K=\frac{1.7}{d}$$

RESULTS AND DISCUSSION

The water mass distribution characteristics of the NLB were studied by Özsoy et al. (1986, 1989). Seasonal aspects of thermal stratification and the formation of LIW are shown by selected temperature and salinity profiles in Fig. 3a and examples of the surface circulation patterns are illustrated in Fig. 3b, based on data obtained by the above research workers for the same sampling period. As is clearly seen from Fig. 3a, thermal stratification tends to form in April–May but is not significant, and the top 200–400 m seems to be homogeneous,

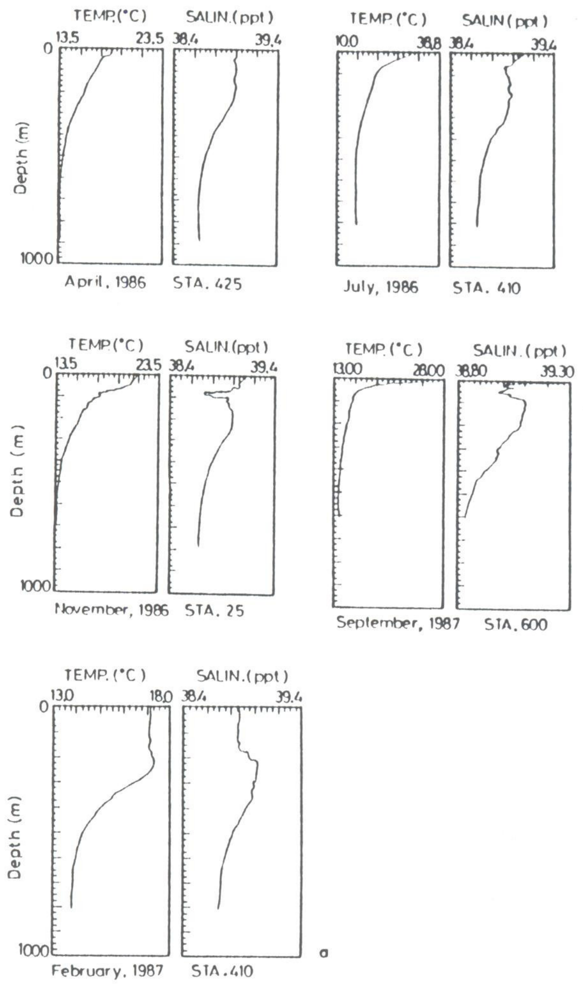
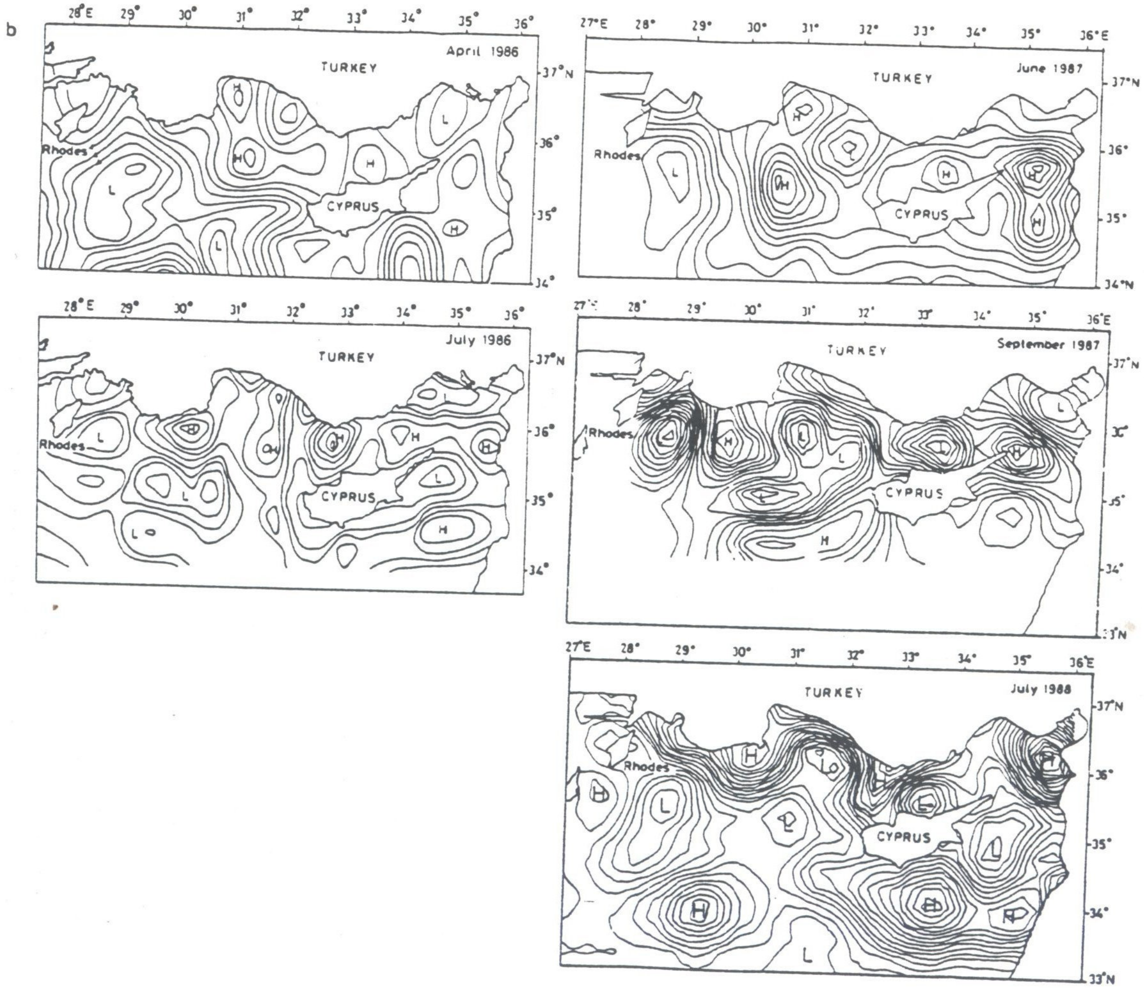


Fig. 3. (a) Temperature and salinity profiles at selected stations in the NLB. (b) Surface circulation patterns in the NLB. Cyclonic and anticyclonic systems are represented with 'L' and 'H' respectively (Özsoy et al., 1988).


b
April 1986
TURKEY
Rhodes
CYPRUS
June 1987
July 1986
September 1987
July 1988

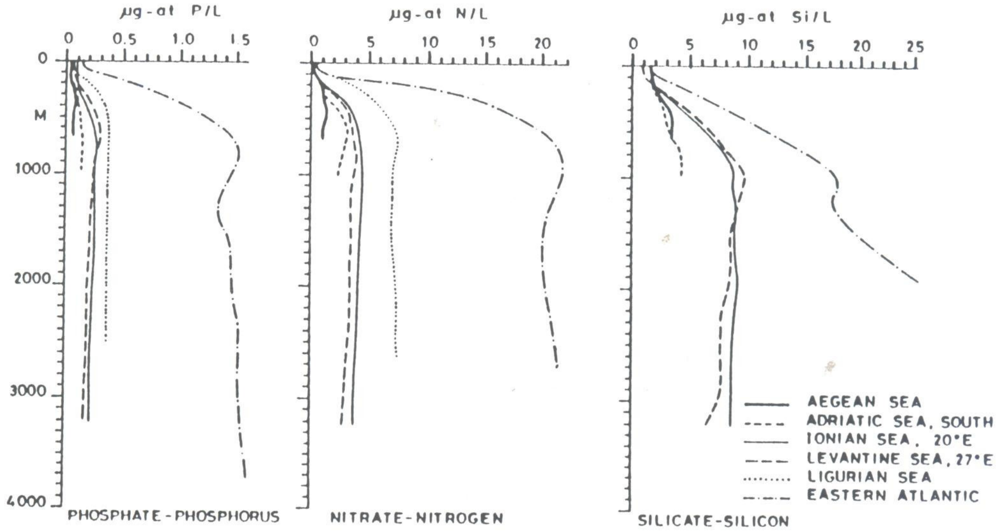


Fig. 4. Vertical distribution of inorganic phosphate, nitrate and silicate in Mediterranean and Eastern Atlantic (after McGill, 1965).

as observed in the salinity profile. In summer, the seasonal thermocline is clearer but not complete; it forms above 50 m. The presence of low-salinity AW could be observed at 75–100 m. Below this depth, high-salinity LIW occurs at around 200–300-m depth. This shape is strongly patterned in autumn; thermal stratification is strong and located around 50–100 m. AW is observed at 100-m depth and LIW is formed significantly at 200 m. In winter, the seasonal thermocline disappears and the permanent thermal stratification is observed at deeper layers (300–400 m); LIW keeps the usual structure, being located at 250–400 m.

Figure 3b represents some examples of surface circulation patterns of the NLB. The Rhodes cyclonic gyre persistently covers a large area centered upon the Rhodes Basin. At its center a cold dome with uniform properties indicates permanent upwelling (Özsoy et al., 1988). This phenomenon causes the transportation of relatively nutrient-rich deep waters to the euphotic layer and produces a high primary production. Generally, a relatively large-scale anticyclonic gyre surrounds the Rhodes gyre; the permanent and relatively small-scale gyres are also observed in offshore areas of İskenderun Bay. The LIW is locally generated in the NLB and along the periphery of the Rhodes gyre. Sinking processes for the formation of LIW can be observed continuously throughout the year, probably more intensely in late winter. Thus the anticyclonic eddies cause the surface waters to be poor in nutrient elements. On the other hand, in general, because the LIW has westward flow characteristics, the Mediterranean waters are impoverished in nutrient content, as relatively nutrient-rich deep waters are carried to the Atlantic Ocean.

In the Mediterranean the concentrations of nutrients are low and decline

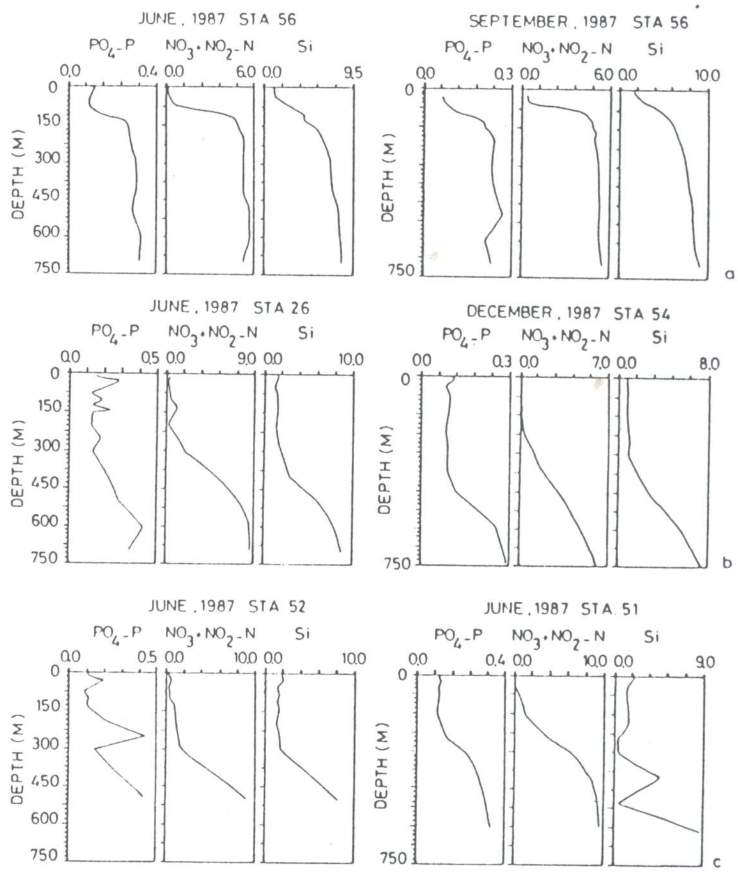
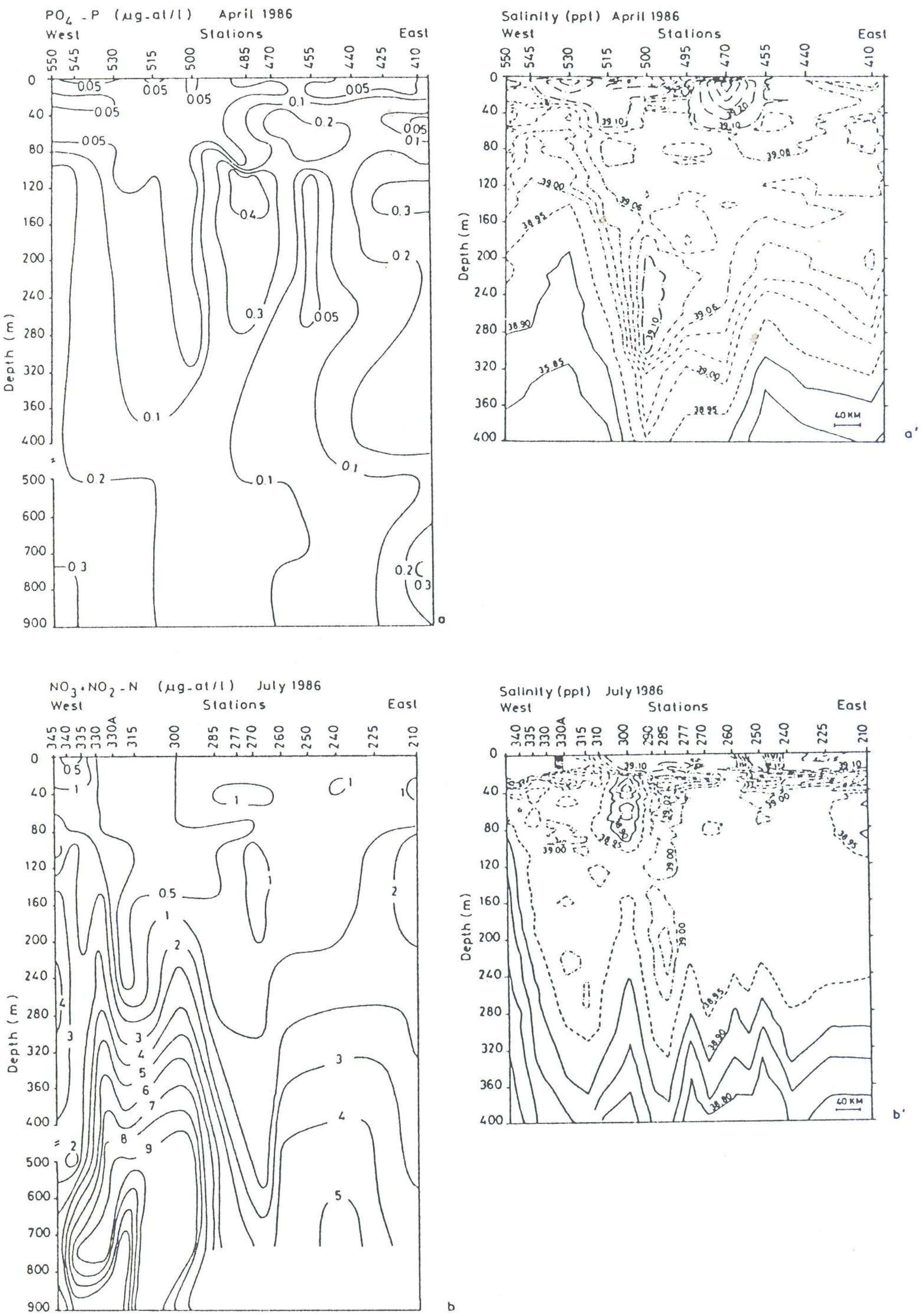


Fig. 5. Vertical distribution of inorganic phosphate, total oxidized nitrogen and reactive silicate at selected stations in the NLB. (a) Stations at the central parts of the Rhodes cyclonic gyre. (b) Stations at the peripheries of the Rhodes cyclonic gyre. (c) Stations at the central parts of the anticyclonic gyres.

towards the eastern parts. This phenomenon is presented in Fig. 4, which includes nutrient profiles for the Eastern Atlantic for comparison (McGill, 1965). The three nutrient elements, inorganic phosphate, nitrate and silicate, have their lowest concentrations at the surface. The concentration increases with increasing depth. Even in the very deep layers, the concentration of nutrients of the LB is approximately five times lower than the concentration of nutrients of the deeper layers of Atlantic Ocean. The concentration range of nutrients for the euphotic and aphotic zones in the NLB are shown in Table 2. Because the LB is a region of convergence and convective sinking of high-salinity waters, in general, the euphotic layer is low in nutrients. In spite of this situation, the present study on the vertical distribution of nutrients showed that relatively nutrient-rich deep waters are upwelling in the central parts of cyclonic gyres



PO4 - P (µg-at/l) April 1986
West
Stations
East
550 545 530 515 500 485 470 455 440 425 410
Depth (m)
a
Salinity (ppt) April 1986
West
Stations
East
550 545 530 515 500 495 470 455 440 410
Depth (m)
40 KM
a'
NO3+NO2-N (µg-at/l) July 1986
West
Stations
East
345 340 335 330 330A 315 300 285 277 270 260 250 240 225 210
Depth (m)
b
Salinity (ppt) July 1986
West
Stations
East
340 335 330 330A 315 310 300 290 285 277 270 260 250 240 225 210
Depth (m)
40 KM
b'

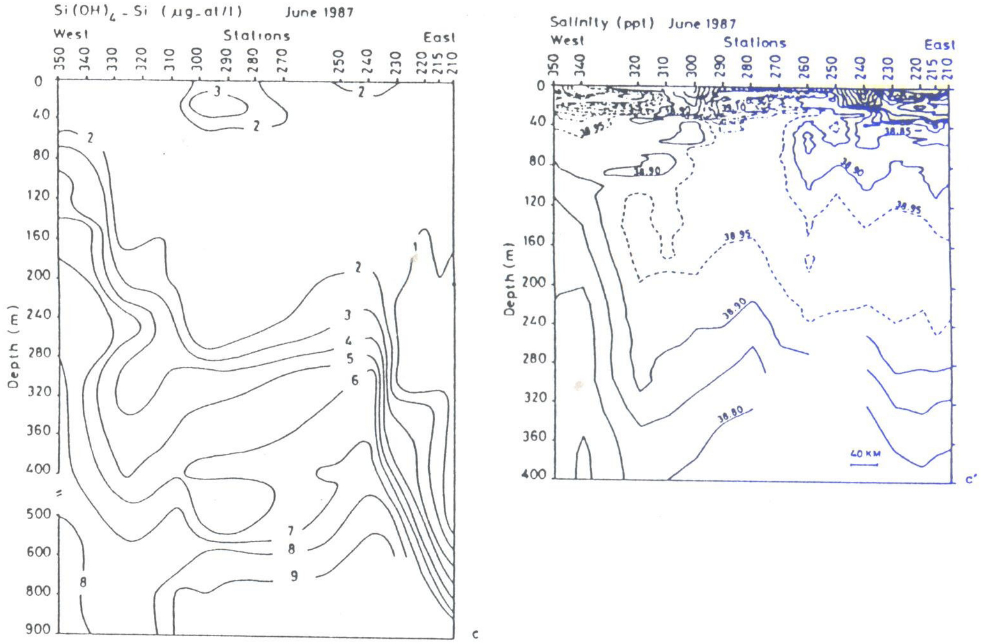


Fig. 6. Nutrient and salinity transects in an west-east direction in the NLB. April 1986: (a) inorganic phosphate, (a') salinity. July 1986: (b) total oxidized nitrogen, (b') salinity. June 1987: (c) reactive silicate, (c') salinity. (Salinity profiles; Özsoy et al., 1988).

in the NLB. This is very clearly seen in the vertical distribution of nutrients. Examples of profiles and transects, from a time series measurement from the years 1986 and 1987, are presented in Figs. 5 and 6, respectively. To show the consistent variability of nutrient and salinity at all times, a transect for each nutrient at different times is selected. The nutrient profiles obtained at station 56 (Fig. 5a), which is generally located in the centre of the Rhodes cyclonic gyre, show that the nutricline was observed very close to surface, at ~75 m. The depth of the nutricline fell to 250–300 m at the peripheries of cyclonic gyres (i.e. stations 26 and 54) and the central parts of the anticyclonic gyres (i.e. stations 51 and 52). The depth of the nutricline is dependent on the structural dynamics of water masses. The nutrient and salinity transect couples (Fig. 6), when superimposed, help to explain the phenomenon in some detail, as high nutrient concentration contours rise towards the surface at the central parts of the cyclonic systems (i.e. at stations 550, 545 and 530 in April 1986, at stations 345, 340, 335 and 300 in July 1986, and at station 340 in June 1987). The same type of vertical distribution was observed in salinity transects. The reverse trends were consistently observed at the peripheries of the gyre systems (i.e. at stations 500 and 485 in April 1986, and at station 315 in July 1986) and the central parts of the anticyclones (for example at stations 425 in April 1986,

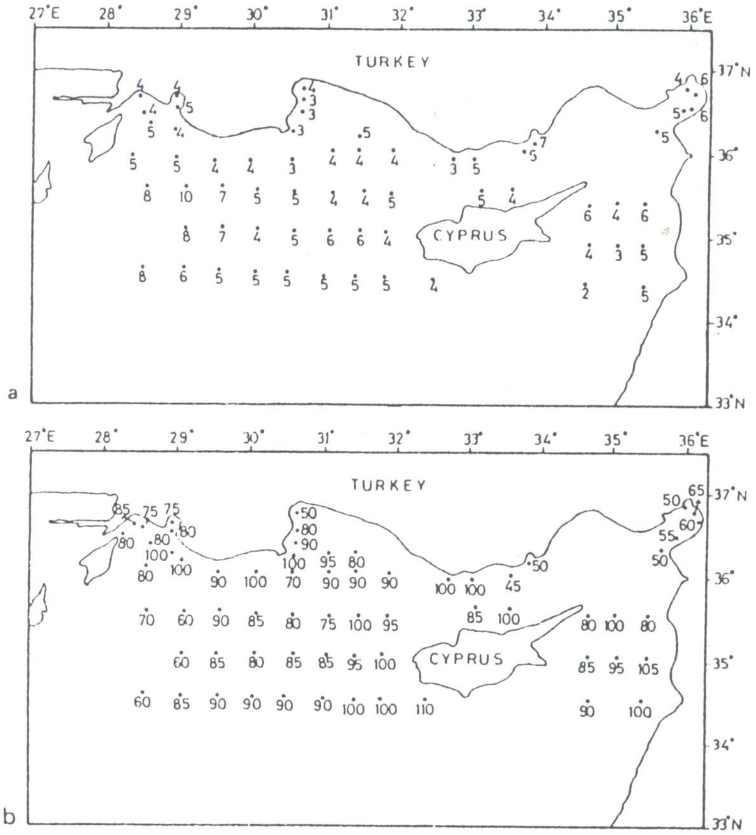


Fig. 7. (a) Relative maximum fluorescence intensities ($\times 10^{-2}$) due to chlorophyll-*a* measured by in situ fluorometer at depths illustrated in part (b), July 1988. (b) Depth (m) of maximum chlorophyll-*a*, July 1988.

at 220 in July 1986, and at 270 in June 1987), with lower concentration contours below the euphotic layer.

This is reflected in the spatial distribution of chlorophyll-*a*; the specific example of in situ relative fluorescence maximum due to chlorophyll-*a* and hence standing stock of phytoplankton is shown in Fig. 7a, and the depth of maximum fluorescence in Fig. 7b, both for the July 1988 sampling period. The point which has to be emphasized here is the exact agreement between the distribution of phytoplankton population and the dynamics of the water masses (Figs. 3a and 3b, and 7a and 7b). It is clear that when the nutricline rises to 70–75 m at the central parts of the cyclonic systems by local upwelling, the depth of maximum chlorophyll-*a* could be observed at about the same depth. At the peripheries of the cyclones and at the centers of anticyclonic systems the depth of chlorophyll-*a* maxima drops as deep as 100–110 m. On the other hand, maximum fluorescence intensities due to chlorophyll-*a* could be ob-

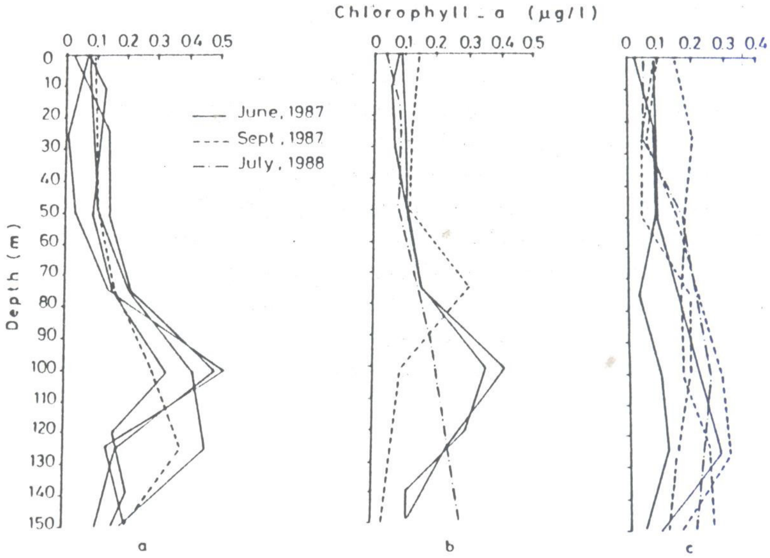


Fig. 8. Profiles from high and low chlorophyll-*a* regions in the NLB. (a) Central parts of Rhodes cyclonic gyre. (b) Central parts of anticyclonic gyres. (c) Peripheries.

TABLE 3

Maximum chlorophyll-*a* and thermocline depth

Date	Thermocline depth (m)	Depth of chlorophyll-*a* maximum (m)	No. of observations
April 1986	45–70	80–100	6
July 1986	45	115	2
November 1986	35–70	100–120	7
February 1987	Mixed	75–125	6

served at the central parts of cyclonic gyres, e.g. the Rhodes cyclonic gyre, and lower values at the peripheries and at the central parts of anticyclonic systems. Consequently, the patches of high phytoplankton populations coincide with the local upwelling areas. In other words, the distribution of phytoplankton is strongly affected by the physical dynamics of the environment. As estimated from the chlorophyll-*a* data, the primary production is found to be relatively high in the areas of local upwelling – mainly the central parts of cyclonic gyres, especially the Rhodes cyclonic gyre – where the nutrients are upwelled and available to the euphotic zone, and is half of this value at the centers of anticyclonic gyres for the same sampling period (Table 1).

The vertical profile of chlorophyll-*a*, of which some examples are shown in Fig. 8, has a characteristic shape; the deep chlorophyll-*a* maxima are common in the NLB. The depth of the chlorophyll-*a* maximum is as deep as 100 m and

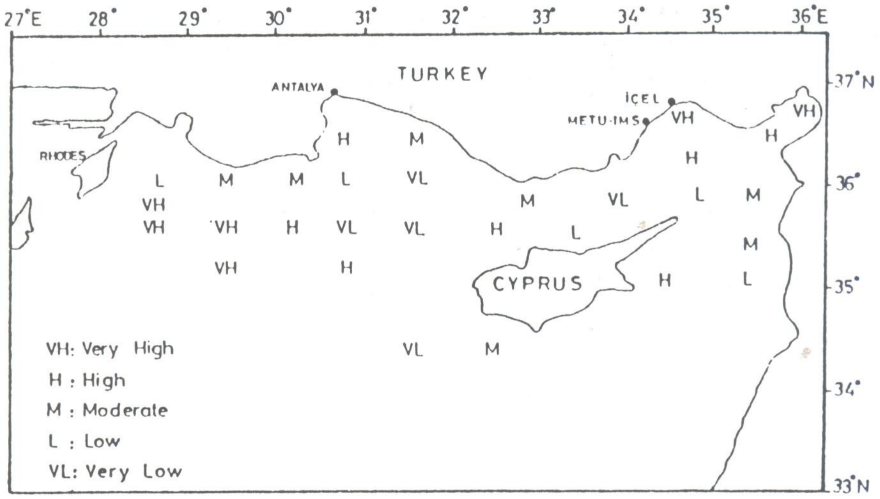


Fig. 9. Neuston net data for the surface waters of the NLB, September 1987.

is not dependent on the seasonal thermocline, as is shown in Table 3. The mesoscale eddy systems affect the vertical and spatial distribution of chlorophyll-*a* and hence the standing stock, the concentration and the depth of maximum chlorophyll-*a*. The vertical distribution of light affects the depth of maximum concentration of standing stock. In the present work, 1% of the incident solar radiation was detected in the range of 100–120 m in the NLB. In other words, the euphotic zone in the NLB is relatively deep and phytoplankton prefer to inhabit the deeper levels of the euphotic zone. On the other hand, at all seasons both for nearshore and pelagic waters, most of the chlorophyll in the EM is associated with organisms smaller than 3 μm (Berman et al., 1984a). Often these ultra-phytoplankton are relatively more numerous towards the bottom of the euphotic zone or in deep chlorophyll-*a* maxima. There is some evidence that they are adapted to low intensity of light in the green region of the spectrum (Platt et al., 1983).

The neuston net results obtained for the same time period, which are presented in Fig. 9, also confirm the above discussion. The neuston net content, collected in September 1987, was analyzed and the quantities were measured arbitrarily and comparatively. Thus the results are given on a relative basis such as high or low quantities of biological material. Qualitatively, the net contained a series of organisms such as large phytoplankton (diatoms and dinoflagellates) and zooplankton (copepoda, pteropoda, isopoda, gastropod larvae, fish larvae and surprisingly small shrimp) in its collector. Very high quantities of neuston net biological material were observed at stations located in the central parts of the Rhodes cyclonic gyre as well as in the other small-scale cyclonic gyres in the basin. Nevertheless, the important phenomenon is that those offshore stations which are physically located at the center of cyclonic gyres are productive enough to support the growth of fish and other pelagic species.

CONCLUSION

The primary productivity, as estimated by the measurement of relative fluorescence due to chlorophyll-*a* and the biological content of a neuston net, is strongly influenced by the physical dynamics of the environment through upwelling and downwelling processes in the NLB.

The Rhodes Basin, where nutrient-rich deep waters are upwelled to the euphotic zone in the central parts, seems to be relatively productive, or we could say that the EM is not as poor in terms of productivity as was concluded in the past. Thus with extensive knowledge of the behavior of the cyclonic gyres it should be possible to increase the economical potential of the region.

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