Distribution of nutrients and chlorophyll-*a* in the Aegean Sea

Aegean Sea
Nutrients
Chlorophyll-*a*

Mer Egée
Nutriments
Chlorophylle-*a*

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ABSTRACT

The distributions of inorganic nutrients and phytoplankton chlorophyll-*a* were investigated in relation to the hydrography of the Aegean Sea. The data were collected during cruises in May and October 1992, February, May and October 1993 and July 1994, in the framework of a National Marine Measurement and Monitoring Programme for the Aegean Sea. Concentrations of nitrate +nitrite+ammonia nitrogen and phosphate phosphorus were lower than those previously reported for the Black Sea; generally lowest at the surface, they increased with depth. The highest nutrient values were in the northern part of the Aegean Sea, and may have resulted from water originating from the Black Sea. Both phosphates and silicates increased with depth to maxima of 0.16 and 4.7 µM, respectively. The concentration of chlorophyll-*a* ranged from 0.03 to 0.70 mg m^{-3}. Elemental ratios (N/P and Si/P) were calculated to be 13.6 - 36.8 and 14.0 - 48.0, respectively.

RÉSUMÉ

Répartition des nutriments et de la chlorophylle-*a* en mer Egée

La répartition des nutriments inorganiques et celle de la chlorophylle-*a* sont analysées en liaison avec l'hydrologie de la mer Egée. Les mesures ont été effectuées en mai et octobre 1992, février, mai et octobre 1993 et juillet 1994, dans le cadre du programme national d'étude et de surveillance de la mer Egée.
Les concentrations en nitrate, nitrite et phosphate sont inférieures aux valeurs citées dans la littérature sur la mer Noire ; généralement faibles en surface, elles croissent avec la profondeur. Les teneurs en nutriments sont maximales dans le nord de la mer Egée, sous l'effet probable de l'eau en provenance de la mer Noire. Les concentrations en phosphate et silicate augmentent avec la profondeur jusqu'à des valeurs maximales de 0,16 et 4,6 µM respectivement. La teneur en chlorophylle-*a* est comprise entre 0,03 et 0,70 mg m^{-3}. Les rapports calculés entre les éléments N/P et Si/P sont respectivement 13,6 - 36,8 et 14,0 - 48.

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INTRODUCTION

The Aegean Sea is one of the Eastern Mediterranean sub-basins located between the Greek and Turkish coasts and the islands of Crete and Rhodes. It has more than 2000 islands forming small basins and narrow passages, and a very irregular coastline and topography. Its area is 2×10^5 km^2, its volume 7.4×10^4 km^3 and its maximum depth is 2500 m north of Crete.

In the southeast, the Aegean Sea joins the Levantine Sea through three passages between the islands of Crete and Karpathos (Cassos strait), the islands of Karpathos and Rhodes (Karpathos strait) and Rhodes and Turkey. In the southwest, it joins the Ionian and Cretan Seas through three wide passages between the island of Crete and the Peloponnese (Laskaratos, 1983). There is considerable exchange of waters through each of these straits, thus linking strongly the water circulation in the Aegean Sea to the hydrodynamics of the Eastern Mediterranean (Ünlüata, 1986). In the north, the water mass flowing from the Black Sea through the Bosporus and the Dardanelles to the Aegean Sea is estimated to be 190 km^3/year (Ünlüata, 1986).

Three water masses can be distinguished in the Aegean Sea: Atlantic water "AW" (S: 37.5-38.9, T: 13.0-24.5), Levantine Intermediate water "LIW" (S: 38.9-39.1, T: 14.5-16.5) and Black Sea water "BSW" (S: 26.2-35.0, T: 14.5-24.0) (Metaxas, 1973; Hopkins, 1978; Pickard and Emery, 1982). Black Sea water, after mixing over the Sea of Marmara, generates a distinct surface water layer in the Aegean, especially in the north, which is characterized by low salinity. It is evident that only a very diluted amount of Atlantic water is transported into the Aegean Sea from the upper reaches of the northern Levantine. It is quite possible that with increasing northward transport of Atlantic water during winter there is a greater influx into the Aegean Sea (Ünlüata, 1986). The mechanisms whereby Aegean Sea waters exchange with the Eastern Mediterranean are not well understood, nor are those that result in influxes of Atlantic water.

Much attention has been focused recently on the ecosystems of the oligotrophic seas which constitute the majority of the world's ocean surface. A number of studies have determined the nutrient concentrations in the western, central and eastern Mediterranean Sea (Schinck, 1967; Miller *et al.*, 1970; Morcos and El-Rayis, 1973; Cescon and Macchi, 1973; Murdoch and Onuf, 1974; Weiss *et al.*, 1983; Coste *et al.*, 1984; Hydes *et al.*, 1988; Townsend *et al.*, 1988; Krom *et al.*, 1991; Souvermezoglou *et al.*, 1992; Krom *et al.*, 1992; Krom *et al.*, 1993), but very few published data are available on nutrient concentrations in the Aegean (Mc Gill, 1965; Ignatiades, 1965; Ignatiades *et al.*, 1992). The Aegean is one of the most oligotrophic parts of Mediterranean Sea, and although it is of limited productivity, waste water and river estuaries constitute nourishment areas for aggravated growth because of local nutrient additions from pollution.

In this paper, dissolved nutrient and chlorophyll-*a* data are presented from cruises of the R/V *K. Piri Reis* in the northern and southern Aegean Sea in 1992 (May, October), 1993 (February, May, October) and 1994 (July). This is the first time that a relatively complete set of such data has been presented. Dissolved nutrients have been studied in sea water samples concurrently with the analysis of high resolution physical data collected within the framework of the National Marine Measurement and Monitoring Programme.

MATERIALS AND METHODS

Area of study

A number of stations were sampled as part of six cruises of the R/V *K. Piri Reis* to this area in 1992, 1993 and 1994. Of these stations, 41 were sampled for nutrients and chlorophyll-*a*. The locations of stations are given in Figure 1.

Water samples were collected with a General Oceanics rosette, equipped with twelve 10-litre Niskin bottles. Pressure, temperature and conductivity were measured *in situ* using a Sea Bird (Model 9) CTD coupled to the rosette. The data acquired by the CTD were stored on computer for later detailed analysis. The CTD salinities were calculated using the 1978 Practical Salinity Scale Equations (1980). Sea Bird CTD sensors were calibrated by the northwest Regional Calibration Center (operating under contract to NOAA) once a year.

Sampling and analysis

Water for nutrient samples was collected as soon as the rosette was taken on board. Samples were collected in 100 ml polyethylene bottles which had been prewashed with 10% hydrochloric acid. At the time of sampling the sample bottles were rinsed twice with the sample, filled with sample, and then immediately frozen. Samples were kept continuously under deep freeze (–20 °C) until analysis. In the laboratory, the samples were thawed for 24 hours prior to determination of dissolved nutrients (Macdonald and McLaughlin, 1982). Sample determinations were generally carried out within one week of the completion of the cruise, using methods described by Strickland and Parsons (1972). At each station, the samples for nutrient analysis and physical data were taken at the following standard depths: 0, 10, 30, 50, 75, 100, 150, 200, 250, 300, 400, 500 m.

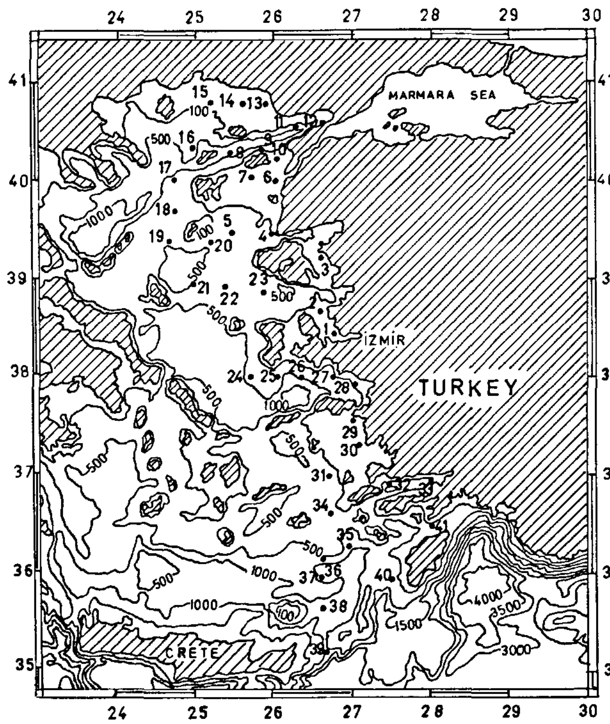


Figure 1

Location of stations in the Aegean Sea.

Samples (1000 ml) for chlorophyll-*a* determination were collected immediately after the nutrient water samples were taken. The samples were filtered onto GF/F glass fibre filters after prefiltration through a 60 micron sieve. The filters were folded into aluminium foil and immediately frozen for later analysis in the laboratory, which was within two weeks of collection. Chlorophyll-*a* was determined using the acetone extraction, fluorometric method (Strickland and Parsons, 1972).

RESULTS AND DISCUSSION

The distribution of nutrients is strongly affected by the physical dynamics of the environment. In order to understand the distribution of nutrients in the Aegean Sea, the physical characteristics of the region were first briefly reviewed.

Seasonal aspects of thermal stratification and the formation of three different water masses are shown by selected temperature and salinity profiles in Figure 2 and examples of the salinity and temperature transects (in north-south and west-east directions) in the Aegean Sea in Figure 3, based on data obtained by the research workers for the same sampling period. In winter the shallow seasonal thermocline disappears and the permanent thermal stratification is observed at deep layers; LIW retains the usual structure, being located at 200-300 m in the southern part of the Aegean Sea. Thermal stratification tends to form in May and the top 200-300 m seems to be homogeneous, as observed in the salinity profile. In summer, the seasonal thermocline forms above 50 m. The presence of low-salinity AW could be seen at 75-100 m. Below this depth, high salinity LIW occurs at around 200-400 m depth. As shown in Figure 2*a*, the thermal stratification is strong in autumn and located around 50-100 m. AW is observed at 100 m (S:38.8-38.9) and LIW is formed at 200-450 m in the southern part of the Aegean.

The prevailing winds in the Aegean in summer are northerly, dry and cold. These winds are called the Etesians, and are particularly influential in the hydrodynamics of the Aegean Sea, giving rise to intense convective movements of water. The Etesians cause upwellings along the coast of Turkey, forming a cold surface zone. They also cause a southward flow along the Greek coast and, according to Metaxas (1973), give rise to a two-gyre system: anticyclonic in the east and cyclonic in the west. In winter, Laskaratos (1983) suggests a north-westward movement in the Eastern Aegean, resulting in a well defined cyclonic gyre in the central Aegean.

The low salinity inflow from the Black Sea is very important for the Aegean circulation. Satellite imagery suggests that these low salinity waters (varying from 32.4 to 35.8) follow a cyclonic path (northwesterly route) in the Aegean in the cooler season (December to May), moving to the southwest and to the south towards Evoia and then to the southeast, exiting the Aegean through the Kithira passages (Ünlüata, 1986). A branch of the Black Sea waters moves

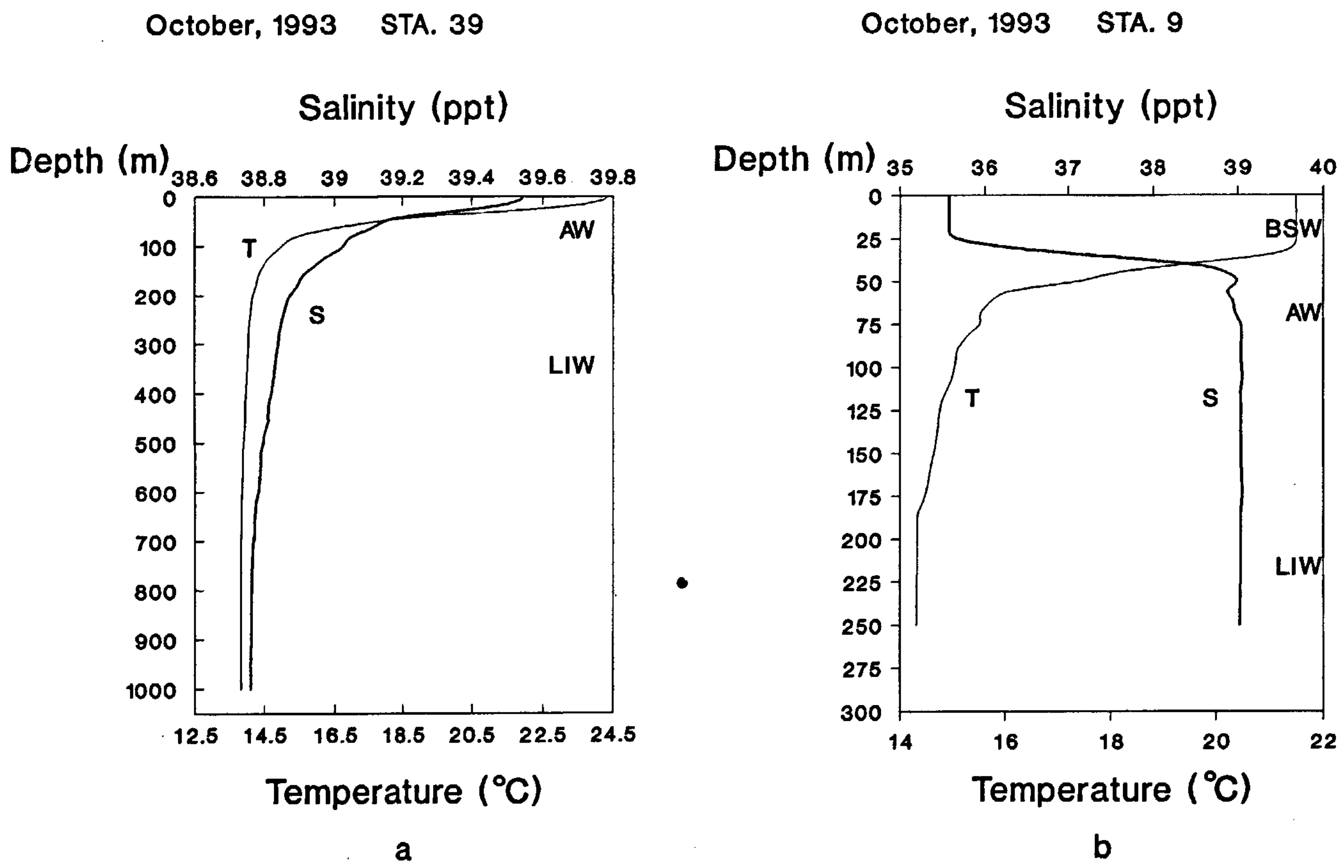


Figure 2

Temperature and salinity profiles at selected stations in the southern (a) and northern (b) Aegean Sea.

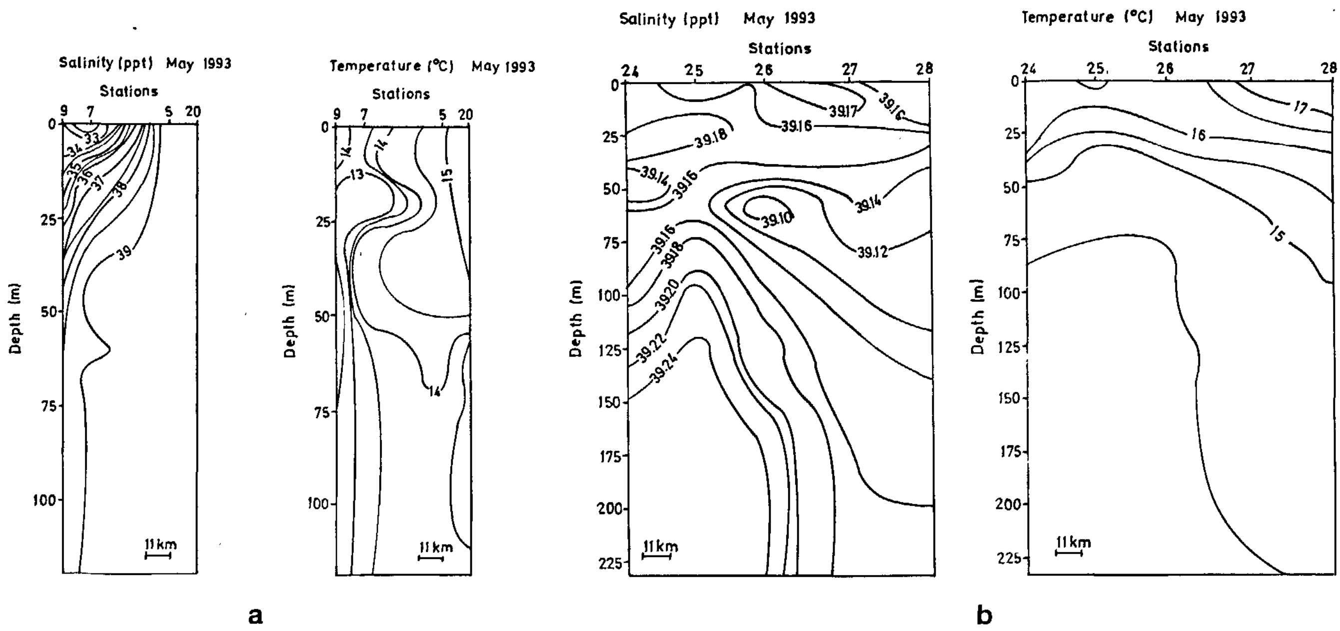


Figure 3

Temperature and salinity transects in north-south (a), west-east (b) directions in the Aegean Sea.

along the north coast of the Aegean, causing a surface or subsurface salinity minimum near Mount Athos. With the start of summer and under the influence of the Etesian winds, Black Sea water flows to the Turkish coast. In the northern Aegean, an energetic anticyclonic eddy that seems to be seasonally invariant appears in the Mount Athos basin. A well-defined eddy in the east central Aegean between the island of Chios and Turkey appears cyclonic at the surface but anticyclonic at 200 m (Metaxas, 1973; Laskaratos, 1983). Ovchinnikov's (1966) circulation map shows the same pattern.

Figure 2*b* presents an example of temperature and salinity profiles at a selected location, chosen as typical of most of the stations in the northern part of the Aegean. In winter, the seasonal thermocline is clear and forms above 25 m; the top 35 m appears to be homogenous, as observed in the salinity profile. In May, low salinity is measured above 30 m and the thermocline forms at 30-35 m at station 9 due to the influence of Black Sea water in the northern Aegean (Fig. 3). In summer, the thermocline is formed above 50 m and the top 100 m seems to be homogenous, as seen in the salinity profile. In autumn, thermal stratification is strong and located around 30-50 m.

Nutrient concentrations decline from west to east in the Mediterranean: this phenomenon is presented in Figure 4, which includes nutrient profiles for the eastern Atlantic for comparison (McGill, 1965). Examples of profiles and transects are presented in Figures 5 and 6, respectively. The nutrient profiles obtained (in May 1993) at station 20, which is located in the northern part of the Aegean, show that the nutricline was very close to the surface, at ~ 40 m (Fig. 5*a*). The depth of the nutricline fell to ~ 100 m at station 31 (in May 1993) in the southern part of the Aegean Sea (Fig. 5*b*). The nutrient transects in Figure 6 show that the distribution of the inorganic phosphate, nitrate and silicate have their lowest concentrations at the surface and increase with increasing depth. The sampling stations have the highest values for ammonium concentrations (0.32-0.95 µM) in surface waters, changing very slightly with increasing depth. Generally, the concentrations of phosphorus in surface waters of the Aegean are extremely low: expressed as values for orthophosphate, they amount to

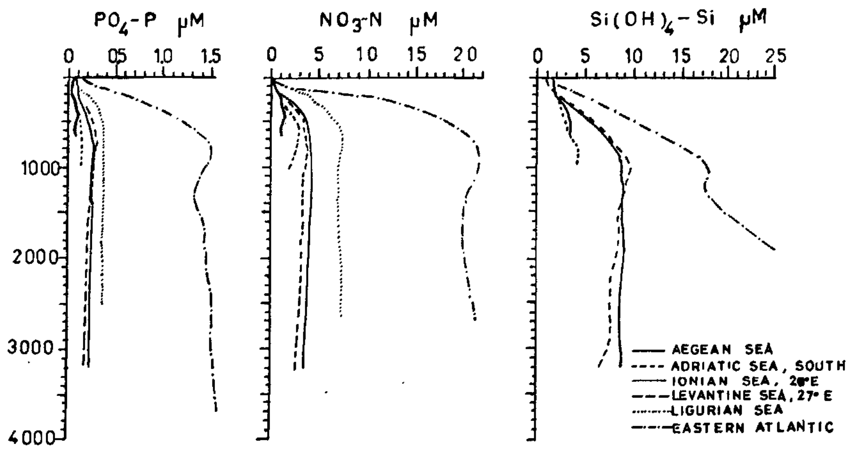


Figure 4

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

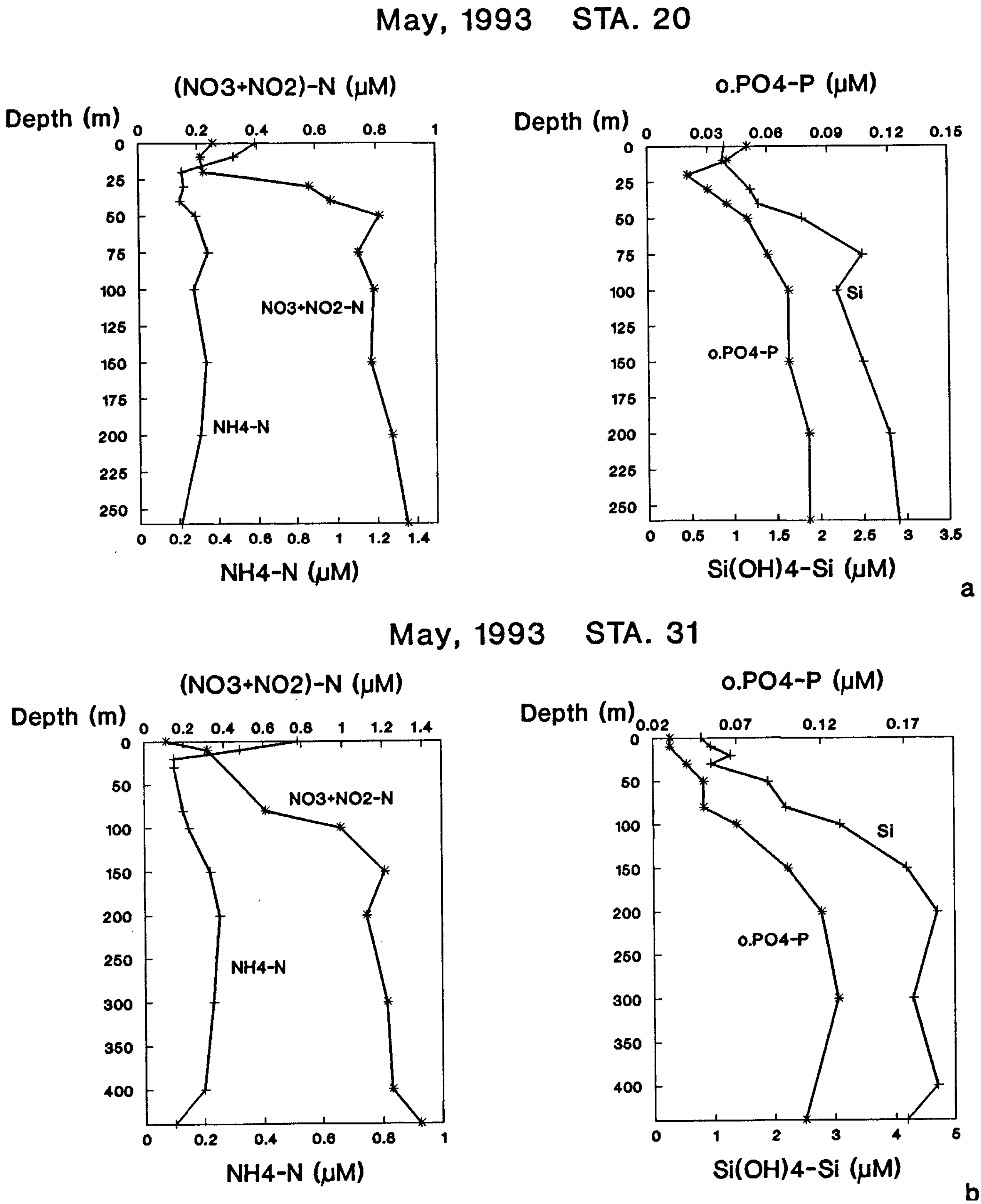


Figure 5

Vertical distribution of dissolved nutrients at selected stations in the northern (a) and southern (b) Aegean Sea. May 1993.

0.01-0.15 µM, confirming previous observations (McGill, 1965). Average natural concentrations of orthophosphate in euphotic layers of productive temperate waste waters are around 0.3 µM o.P-PO_4, and are significantly lower after periods of phytoplankton bloom. Values for the Mediterranean Sea are typically below 0.05 µM in the euphotic zone and at most 0.3 µM in the deepest waters (Stirn, 1988).

The northern part of the Aegean Sea has the highest values (0.16 µM) of orthophosphate, in contrast with the southern

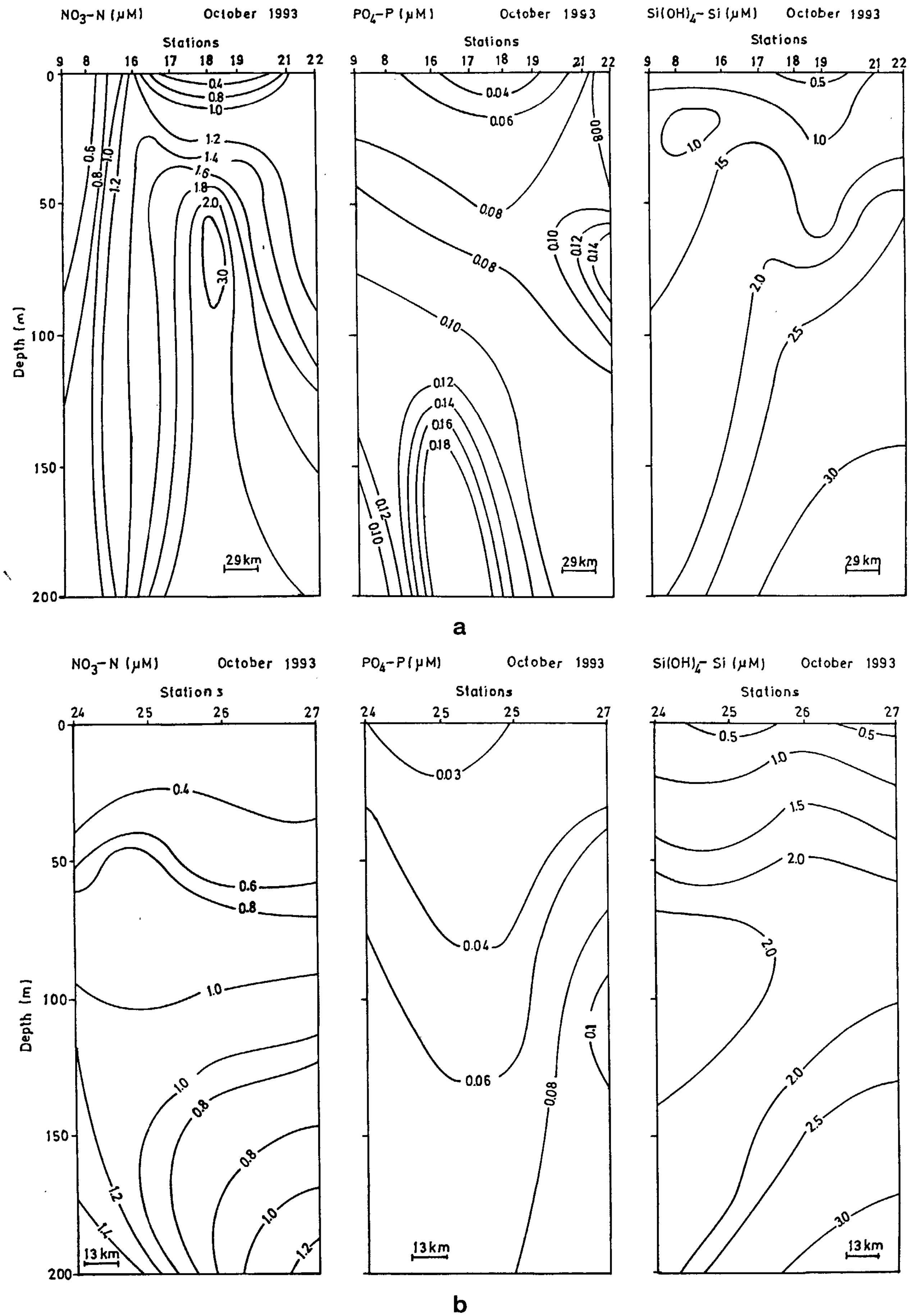


Figure 6
Inorganic phosphate, nitrate and silicate transects in the northern (a) and southern (b) Aegean Sea. October 1993.

Table 1

Summary statistics of the raw data in the northern and southern parts of the Aegean Sea.

	NO_3-N	NO_2-N	NH_4-N	o.PO_4-P	Si	TIN	N/P	Si/P
Northern Aegean Sea								
Sample size	183	196	176	160	167	160	109	119
Mean (μM)	0.84	0.04	0.34	0.07	1.65	1.21	21.5	25.4
S.deviation	0.58	0.03	0.15	0.03	0.74	0.57	5.1	7.9
S.error	0.04	0.002	0.01	0.002	0.06	0.04	0.49	0.73
Minimum	0.10	0.01	0.10	0.02	0.30	0.18	13.6	14.0
Maximum	2.80	0.13	0.95	0.16	3.80	3.05	36.8	48.0
Southern Aegean Sea								
Sample size	134	147	134	123	134	125	92	88
Mean (μM)	0.78	0.03	0.28	0.06	1.83	1.11	20.9	30.6
Standard deviation	0.55	0.02	0.15	0.03	0.97	0.49	5.1	8.0
Standard error	0.05	0.002	0.01	0.003	0.08	0.04	0.53	0.85
Minimum	0.10	0.01	0.10	0.01	0.30	0.44	13.7	15.0
Maximum	2.90	0.11	0.80	0.14	4.70	2.82	36.0	48.0

Aegean (0.08 μM), in the surface water. This might be due to the low salinity water originating from the Black Sea. The phosphate concentration of this basin presents very small variations. Minimum levels (0.01 μM) are usually recorded during spring and late summer when phytoplankton growth peaks, and maximum levels occur during winter under destratified conditions.

Sampling stations located in the northern part of the Aegean Sea had the highest values of total inorganic nitrogen (TIN, calculated as sum of NH_4-N, NO_2-N, NO_3-N), in contrast with the southern Aegean, and ranged between 0.18-3.05 and 0.44-2.82 μM, respectively (Tab. 1). The higher values of TIN which were recorded in the northern Aegean are in agreement with the results reported by Ignatiades (1965).

Considering the generally oligotrophic nature of the Mediterranean Sea, the decisive role of phosphorus in limiting pelagic productivity appears indisputable. The N:P ratio is as a rule significantly higher than the assimilatory optimal (N:P = 15:1) in conformity with Redfield's ratio N:P = 16:1 (Redfield *et al.*, 1963) and N:P ratio is usually

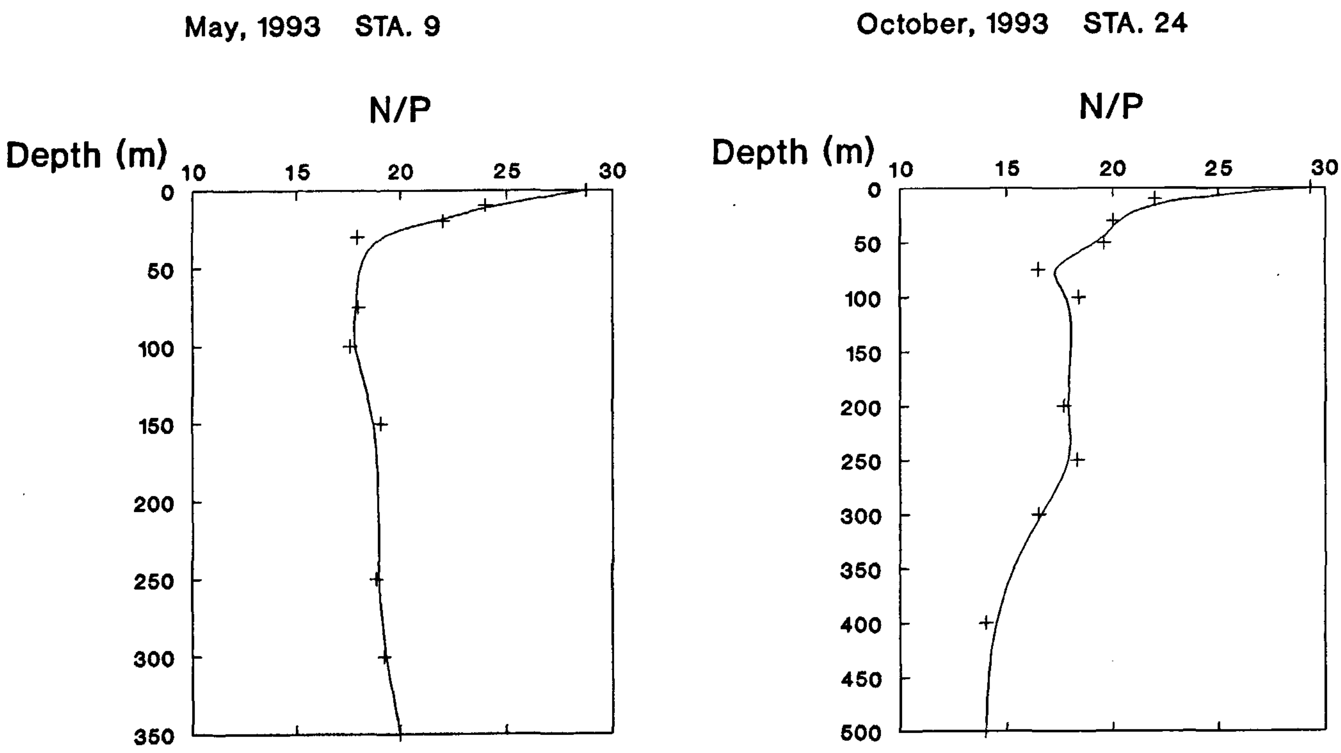


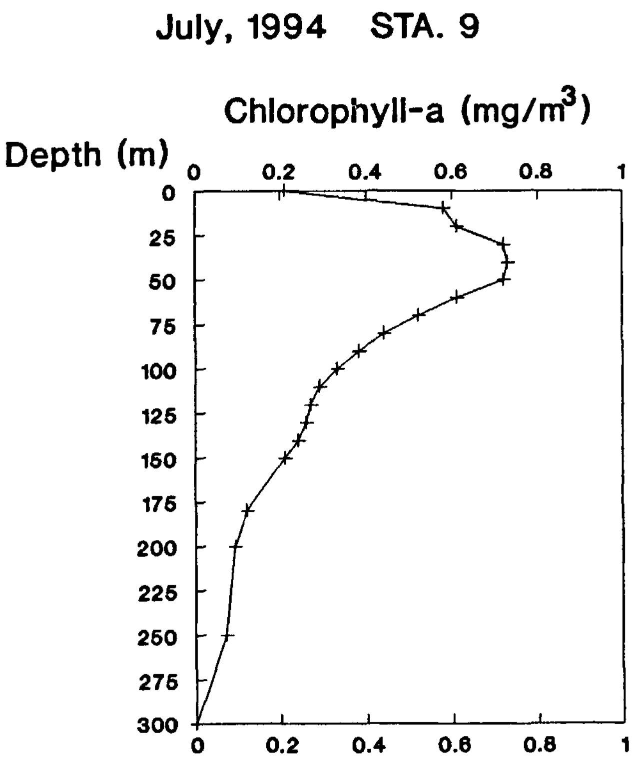
Figure 7

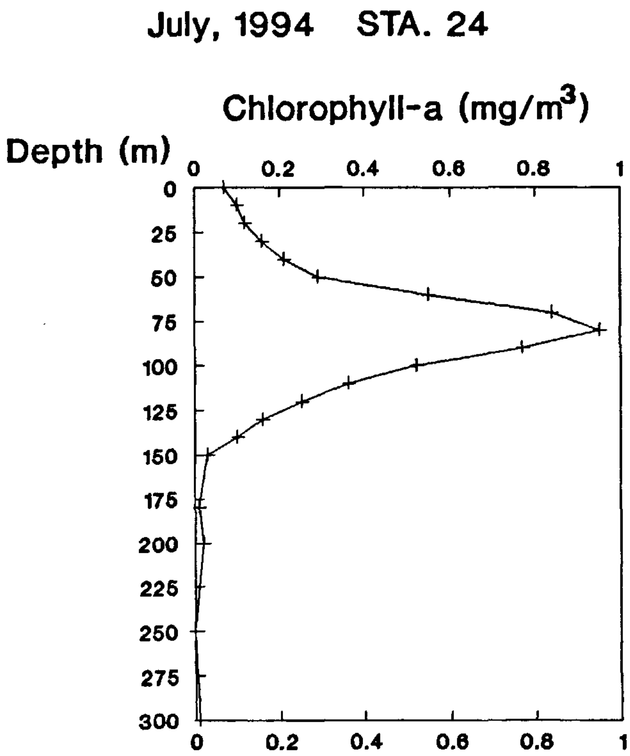
Vertical profiles of elemental ratio (N/P) at two selected stations in the Aegean Sea.

Table 2

*Relative maximum fluorescence intensities due to chlorophyll-*a *measured by fluorometer and depth of maximum chlorophyll-*a, *July 1994.*

Station	Max fluor. intensities	Depth of max fluor.(m)
4	0.11	78
5	0.13	77
7	0.15	48
8	0.09	69
9	0.10	48
10	0.15	55
11	0.15	80
16	0.09	58
17	0.08	76
18	0.09	85
19	0.11	86
20	0.14	77
21	0.14	84
22	0.14	86
23	0.10	84
24	0.11	82
25	0.10	90
26	0.11	85
27	0.10	68
28	0.10	53
30	0.08	77
31	0.10	84
32	0.08	79
33	0.08	88
34	0.10	95
35	0.11	93





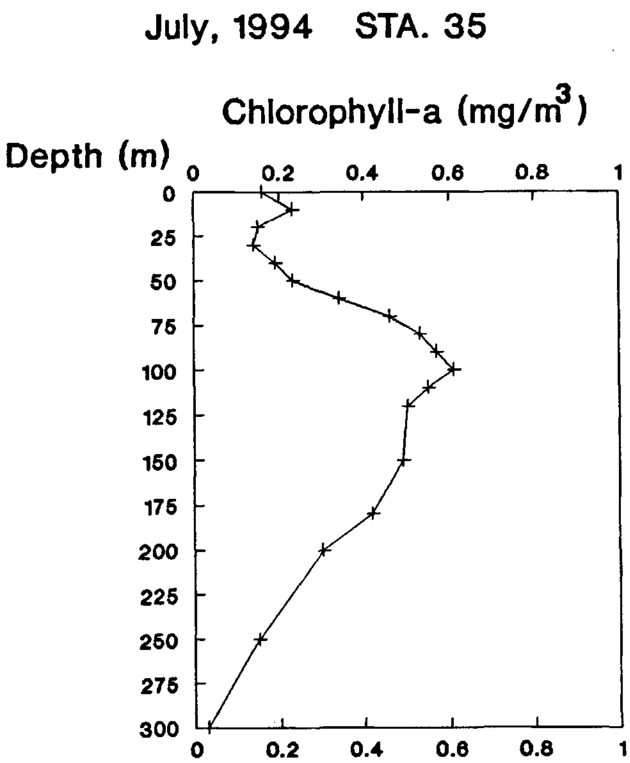


Figure 8

*Vertical profiles of chlorophyll-*a *at (Sta. 9, 24, 35) considered typical examples of the northern, central and southern parts of the Aegean Sea.*

above 19:1, as shown in Table 1 which presents the summary statistics of nutrient and N:P ratios. The stations in the northern Aegean have an N:P ratio of 21.50, while the ratio at stations in the southern part of the Aegean is 20.95 owing to the different characteristics of the water masses. Some examples of N/P vertical profiles are shown in Fi-

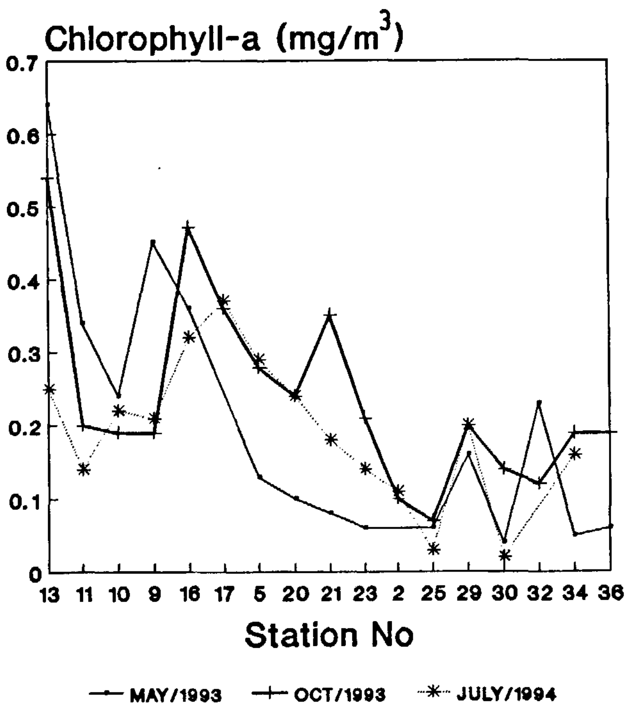


Figure 9

*Spatial distribution of chlorophyll-*a *at selected stations in the Aegean surface waters.*

Table 3

*Average chlorophyll-*a *(mg m^{-3}) values along the Turkish coasts in different parts of the Mediterranean and the world ocean.*

Location	Chlorophyll-*a*	
The Sea of Marmara	1.3-1.7	(Tugrul *et al.*, 1986)
Black Sea	1.1-1.6	(Grasshoff, 1971)
Northern Aegean Sea	0.1-0.8	(IMST, 1990; IMST, 1991)
Southern Aegean Sea	0.1-0.4	(IMST, 1990; IMST, 1991)
Pasific Ocean	0.04-0.14	(Beers *et al.*, 1982)
Eastern Mediterranean	0.02-0.12	(Berman *et al.*, 1984a; Berman *et al.*, 1984*b*; Berman *et al.*, 1986)
Atlantic Ocean	0.15	(Trees *et al.*, 1986)
North Sea	1.85	(Gieskes and Kraay, 1980)
Northeastern Med.	0.01-0.15	(Salihoglu *et al.*, 1990)

gure 7. As is clearly seen in Figure 7, the N/P ratio decreases with increasing depth due to the increasing concentration of phosphorus.

The concentrations of silicates increased slightly with depth from values of 0.3-1.5 µM at the surface to values of 2-4 µM in deep water. The average Si:P ratios for the northern and southern parts of the Aegean are 25.36 and 30.60, respectively (Tab. 1). Si:P ratios are also much higher than Redfield's ratio Si:P = 15:1. Similar values for the Si:P ratio have been reported for the Ionian, Tyrrhenian and Aegean Seas (Mc Gill, 1965; Pastouzo, 1971; Friligos, 1983; Povero *et al.*, 1990).

The specific example of *in situ* relative fluorescence maximum due to chlorophyll-*a* and hence the standing stock of phytoplankton, and the depths of maximum fluorescence are shown in Table 2, both for the July 1994 sampling period in the Aegean Sea. It is clear that when the nutricline rises to 40 m in the northern and is situated at -100 m at the southern parts of the Aegean, the depth of maximum chlorophyll-*a* could be observed at about the same depths. The vertical profiles of chlorophyll-*a*, some examples of which are shown in Figure 8, have a characteristic shape; the depths of the chlorophyll-*a* maximum are 40-50 and 90-100 m for the northern and southern parts of the Aegean Sea, respectively.

The spatial distribution of chlorophyll-*a* is shown in Figure 9 for the surface waters at selected stations. The concentrations of chlorophyll-*a* ranged between 0.06-0.64 (in May), 0.07-0.70 (in October) and 0.03- 0.37 (in July) mg m^{-3}.

Some published examples of chlorophyll-*a* data along the Turkish coast and from different parts of Mediterranean and the world ocean are presented in Table 3. These data clearly demonstrate the oligotrophic nature of the Aegean Sea. The very low primary productivity of the region is the result mainly of low levels of available nutrients which are essential for phytoplankton growth. Consequently, the Mediterranean in general, and the southern Aegean Sea in particular, can be described as "marine deserts" in terms of nutrient and chlorophyll-*a* concentrations.

CONCLUSIONS

The distributions of nutrient and chlorophyll-*a* during 1992 (May-October), 1993 (February-May-October) and 1994 (July) cruises in the Aegean Sea have been investigated with reference to the hydrographic structure, and compared with other reported distributions in the Eastern Mediterranean. We have attempted to demonstrate the importance of the horizontal circulations in controlling the vertical distribution of these variables. The influx of Black Sea water into the northern Aegean varies seasonally and has the highest concentration of nutrients, in contrast to the southern part of the Aegean. The deep water of the Aegean Sea shows very slight seasonal variations in nutrients. Nutrient minimum values throughout the Aegean occurred in spring as a result of high productivity. Thus, nutrient distribution in the Aegean is defined not only by oceanographic and meteorological factors but also by biological cycles of the organic matter in the sea. The spatial and vertical distribution of nutrients affects the distribution of phytoplankton, as confirmed by the chlorophyll-*a* data in the Aegean Sea (between 0.03-0.70 mg m^{-3}).

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