Phytoplankton fluorescence and deep chlorophyll maxima in the Northeastern Mediterranean

In situ fluorescence
Chlorophyll-*a* maxima
Light transparency
Circulations
Northeastern Mediterranean

Fluorescence *in situ*
Maximum de chlorophylle *a*
Transparence à la lumière
Circulations
Méditerranée du Nord-Est

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ABSTRACT

Two expeditions in the northeastern Mediterranean by the R/V *Bilim* (in July 1988 and March 1989) scanned an area of about 3 x 10^5 km^2 to determine, *in situ*, the relative fluorescence intensities of the upper layer waters. The *in situ* fluorescence intensities exhibited a fair correlation with the discrete chlorophyll-*a* concentrations when the concentrations exceeded 0.1 µg/L. Light intensities indicated that the euphotic zone had an average thickness of 100 m in the open waters. The deep chlorophyll-*a* maxima (DCM) at the bottom of the euphotic zone usually coincided with the maxima observed by *in situ* fluorometry and were a prevalent characteristic of the oligotrophic northeastern Mediterranean. The formation, maintenance and location of the DCM were controlled by the changes in light attenuation and nutrient concentrations occurring in the anticyclonic and cyclonic gyres. Accordingly, DCM with relatively high chlorophyll concentration formed at shallower depths in late winter (*e.g.* 50 m for March, 1989) whilst in summer DCM possessed lower chlorophyll concentrations and were found as deep as 100 m in the anticyclonic regions. Although the depths of the maximum fluorescence intensity varied in space and time, they remained within a relatively narrow range of isopycnal surfaces, namely, from 28.8 to 29.0 in March 1989, and from 28.6 to 29.0 in July 1988; the appearance of maximum fluorescence intensities at larger density values but at shallower depths in late winter is principally the result of lower light intensity, available nutrients and hydrological changes in the upper layer.

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RÉSUMÉ

Fluorescence due au phytoplancton et profondeur maximum de chlorophylle en Méditerranée du Nord-Est

Au cours des deux campagnes, effectuées (en juillet 1988 et mars 1989) en Méditerranée du Nord-Est à bord du navire océanographique *Bilim*, une aire de 3 x 10^5 km^2 d'environ a été étudiée pour déterminer *in situ* les intensités relatives de fluorescence des eaux de la couche supérieure. Les intensités de fluorescence *in situ* montrent une raisonnable corrélation avec les concentrations discrètes de chlorophylle-*a* à des profondeurs choisies lorsque les concentrations ont dépassé 0,1 µg/l. Les intensités lumineuses ont indiqué que la zone euphotique a une épaisseur moyenne de 100 m dans les eaux du large. Les profondeurs maximales de chlorophylle (PMC) au bas de la zone euphotique ont généralement coïncidé avec le niveau maximum observé par fluorométrie *in situ*; elles sont une caractéristique répandue dans la Méditerranée oligotrophique du Nord-Est. La formation, le maintien et la localisation de PMC étaient contrôlés par les changements dans l'atténuation de la lumière et les concentrations des sel nutritifs qui se trouvent dans des tourbillons cycloniques et anticycloniques. En conséquence, de grandes PMC, avec une relativement haute concentration de chlorophylle, formées dans de faibles profondeurs vers la fin de l'hiver (par exemple 50 m pour mars 1989), alors qu'en été les PMC ont eu des concentrations de chlorophylle plus basses et ont été trouvées jusqu'à la profondeur de 100 m dans les régions anticycloniques. Bien que les profondeurs de l'intensité maximale de fluorescence varient avec le temps et l'espace, elles restent à l'intérieur d'une distance relativement étroite de la surface isopycne, à savoir 28,8 à 29,0 en mars 1989 et 28,6 à 29,0 en juillet 1988 ; son apparition dans des densités plus grandes, mais à des profondeurs plus faibles vers la fin de l'hiver, est généralement liée à une plus faible intensité de la lumière, à la disponibilité des sels nutritifs et aux changements hydrologiques dans la couche supérieure.

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INTRODUCTION

The eastern Mediterranean is oligotrophic because of the limited supply of nutrients to the photosynthetically active layer (McGill, 1961; Sournia, 1973; Murdoch and Onuf, 1974; Coste *et al.*, 1984; Béthoux and Copin-Montégut, 1988; Dugdale and Wilkerson, 1988). Recent oceanographic surveys covering the whole basin have indicated the existence of a series of interconnected quasi-permanent anticyclonic and cyclonic gyres in the Levantine Basin of the Mediterranean (Özsoy *et al.*, 1989; 1991; 1993). Nutrient distributions in this area are strongly associated with the hydrographic features (Salihoglu *et al.*, 1990; Krom *et al.*, 1991; Krom *et al.*, 1992). In the anticyclonic regions, the nutricline and the relatively nutrient-rich Levantine deep waters are situated too deeply to be able to supply sufficient nutrients into the euphotic zone to maintain phytoplankton growth. However, in cyclonic regions, which constitute a relatively small portion of the basin, the nutricline can rise to the base of the euphotic zone so that, especially in winter months, nutrients are introduced into the productive zone from the nutricline by vertical mixing. Indeed, the major source of the nutrients in the anticyclonic regions of the Levantine basin is the input from the nutrient-deficit aphotic layer down to the nutricline by vertical mixing only in winter as also stated by Krom *et al.* (1992), resulting in a late winter-early spring bloom in the surface waters but depletion of inorganic nutrients in the euphotic zone throughout most of the year. Thus, primary productivity is expected to be very low in the anticyclonic regions during most of the year. Similarly, chlorophyll concentrations will also be low and the peak concentrations will be found at the bottom of the euphotic zone; the so-called Deep Chlorophyll Maxima (DCM), being a prevalent feature of the Mediterranean and other oligotrophic seas (Dowidar, 1984; Berman *et al.*, 1984 *a*; 1984 *b*; Berman *et al.*,1986; Salihoğlu *et al.*, 1990 and Krom *et al.*, 1991). Until recently, there has only been limited information on the formation and maintenance of DCM in these nutrient-poor areas. This feature of an oligotrophic sea is principally the result of the chlorophyll content per phytoplank-

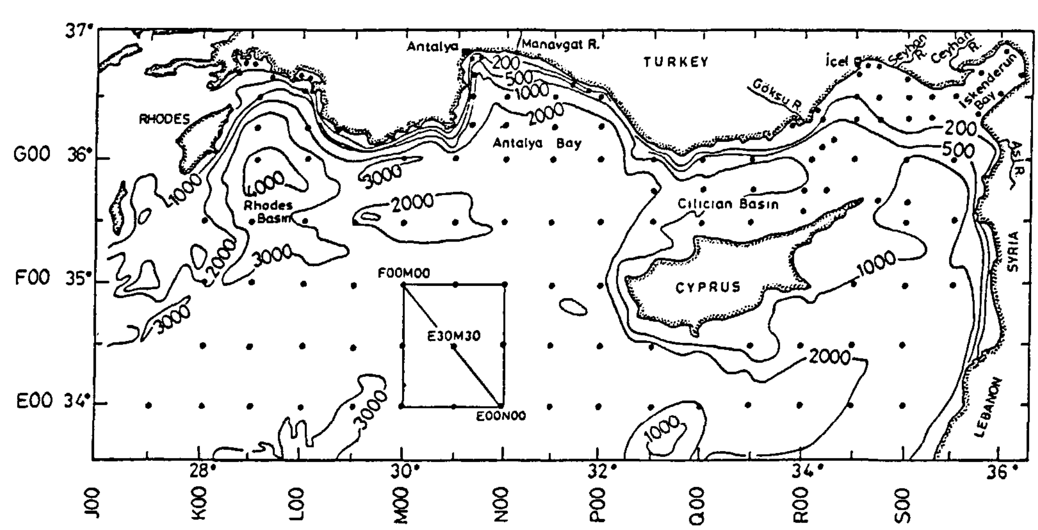


Figure 1

Map showing the locations of stations visited in the northeastern Mediterranean during the July 1988 and March 1989 R/V Bilim *cruises (the depth contours are in metres).*

ton cell increasing with depth in the lower euphotic zone, a factor which produces misleading estimates of algal biomass in the water column (Chisholm *et al.*, 1988; Li and Wood, 1988; Li *et al.*, 1992). In the past, the lack of data on the spatial and seasonal distribution of phytoplankton in the northeastern Mediterranean has prevented us from defining the relatively productive regions of the Levantine basin. Recently, however, the hydrodynamic circulations derived from CTD measurements, together with the nutrient and chlorophyll data collected systematically in the basin since 1986 (admittedly at limited number of stations) suggest that the relatively high chlorophyll-*a* concentrations and the DCM recorded in the cyclonic regions may partly account for an increased biomass, as shown by Estrada (1985) for the western Mediterranean. The temporal and spatial variations of chlorophyll-*a*, the occurrence of DCM and the correlation of both with that of algal biomass in the oligotrophic seas could be studied extensively on the basin scale provided that *in situ* fluorescence recorded by an adequate sensor is principally of chlorophyll origin. In this report we examine the correlation between the discrete chlorophyll-*a* data and *in situ* relative fluorescence intensities which were measured in different seasons between 1988 and 1989 together with simultaneous determinations of the nutrient and hydrophysical characteristics of the northern Levantine Basin.

MATERIALS AND METHODS

R/V *Bilim* made two cruises, in July 1988 and March 1989 in the eastern Mediterranean between longitudes 28°00' and 36°00' E, and latitudes 34°00' and 36°45' N. The locations of the stations are shown in Figure 1. Relative *in situ* fluorescence intensities were recorded using a Navigator Q-200 fluorometer. The fluorescence and depth signals were digitized by a Tecmar A/D converter interface and recorded on board ship on an IBM PC. A broad band excitation filter in the blue region was used and the emission detector was a long-wave pass filter with a cut off at 665 nm. A xenon discharge lamp, used as the light source, was electronically synchronized to the highly sensitive (silicon photodiode) detector. The detection limit for the fluorescence measurements was 50 ng/L in terms of chlorophyll-*a* concentration and/or 0.01 (arbitrary units) in terms of relative fluorescence. Water samples at selected depths were collected using a General Oceanics "go-flow", 12-bottle rosette. Samples for chlorophyll-*a* were filtered through 0.45 µ pore size membrane filters and kept frozen (maximum one month) until analysis. The standard fluorometric method, having a detection limit of 10 ng/L, was followed to measure the chlorophyll contents of the samples (Strickland and Parsons, 1972). Nutrient concentrations were measured using a Technicon multi-channel autoanalyzer according to the methods described in the Technicon operating manual which were principally very similar to those described in Strickland and Parsons (1972) and detection limits were 0.05 and 0.02 µM for nitrate and phosphate respectively. A selenium photocell combined with the *in situ* fluorometer was used to measure light penetration relative to the surface incident light at depths down to 150 m. A Sea-Bird Model 9 CTD probe was used for collection of hydrographic data to a depth of 1 000 m.

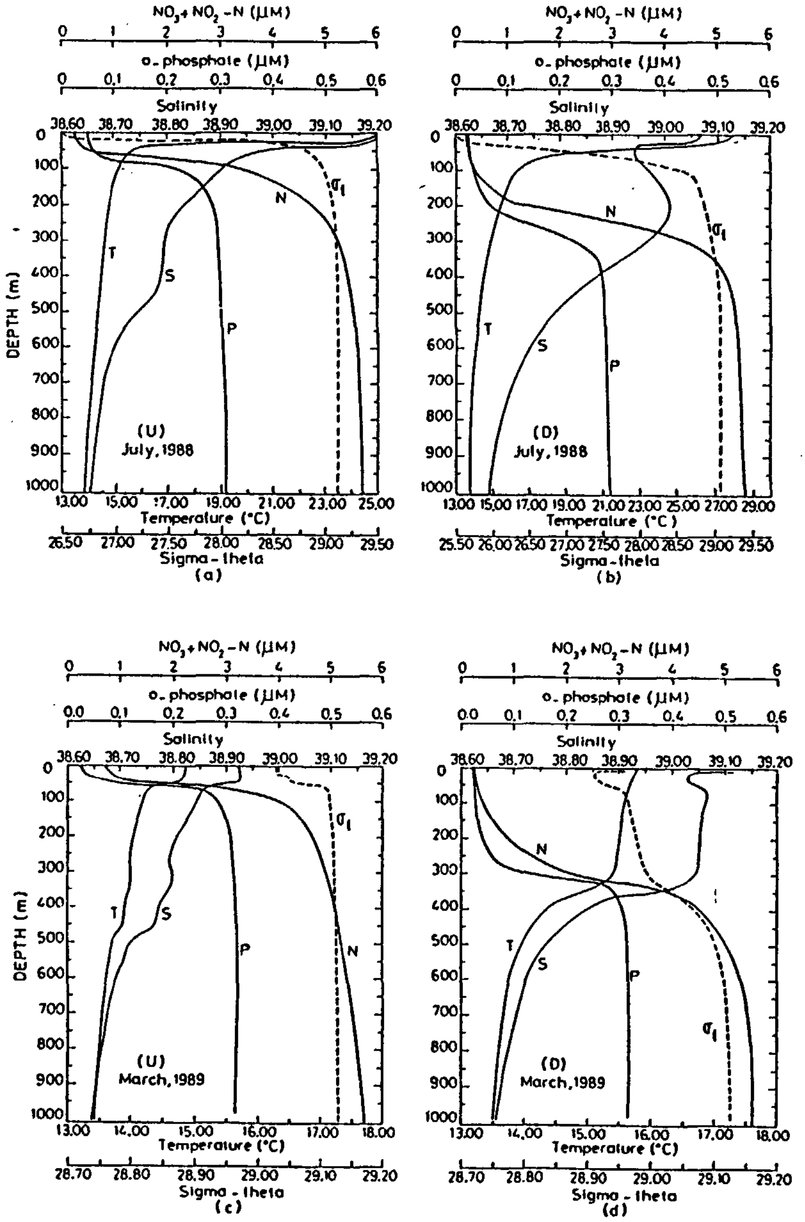
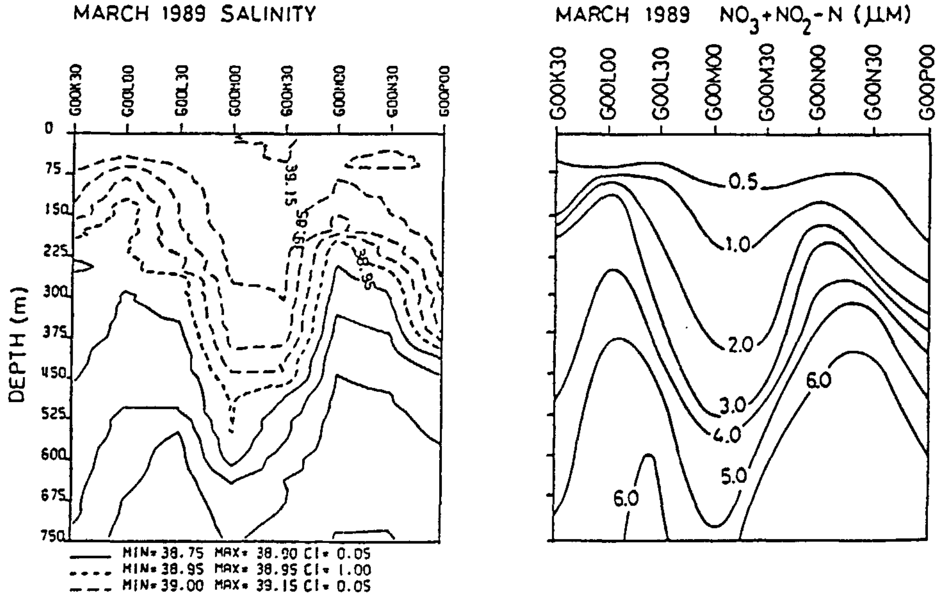


Figure 2

Typical depth profiles of temperature (T, °C), salinity (S), Sigma-theta (σ_t), orthophosphate (PO_4-P, µM) and total oxidized nitrogen ($NO_3^+NO_2^-N$, µM) in the northeastern Mediterranean: a) station F30K30, Rhodes cyclonic (U) region, July 1988,; b) station G15N30, Antalya anticyclonic (D) region, July 1988; c) station F00K30, Rhodes cyclonic (U) region, March 1989; d) stationG10N30, Antalya anticyclonic (D) region, March 1989.

Figure 3

Longitudinal transects of salinity and total oxidized nitrogen ($NO_3^+NO_2^-N$, µM) for March 1989.



RESULTS AND DISCUSSION:

Nutrients

Concentrations of nutrients in the surface waters were low during the summer of 1988 due to their earlier consumption by photosynthesis and their low rate of supply. In the euphotic zone, the average phosphate concentration was generally less than 0.05 µM, whilst the average nitrate concentration, which attained a level of 0.6 µM in March 1989, was only 0.2 µM during the previous summer. Similar seasonal variations of nutrient concentrations in the upper layer during 1990-1991 have been reported by Yilmaz *et al.* (1994). In the water column, below the euphotic zone, the nutrient distribution is strongly associated with the physical dynamics of the eastern Mediterranean as has also been shown by Salihoğlu *et al.* (1990), Krom *et al.* (1992) and Yilmaz *et al.* (1994). As shown in Figure 2 the vertical distributions of phosphate, (nitrate + nitrite), temperature, salinity and sigma-theta varied regionally and seasonally. In July 1988, for example, the nutricline was formed at shallower depths (< 100 m) near the bottom of the euphotic zone in the cyclonic Rhodes gyre whereas it was as much as 250-350 m deep in the anticyclonic gyre formed in Antalya Bay. The regional variations in the hydrochemical properties of the basin can be seen in the alongshore transects of (nitrate + nitrite) and salinity plotted in Figure 3 for March 1989. The thickness and depth of the nitracline were determined by the hydrographic features; for instance, the 2 µM nitrate contour was raised from 400 m in the anticyclonic region to 75 m in the Rhodes cyclonic region. As stated above, the depth of the nutricline, formed by the mixing of the Levantine intermediate and deep waters, was observed to vary in space and time; its upper and lower boundaries, however, always appeared at isopycnal surfaces of 29.0-29.05 and 29.15 respectively, independent of the geographical location of the basin (Yilmaz *et al.*, 1994). Close inspection of the present nutrient and physical data confirm the establishment of the nutricline between the above isopynocal surfaces. The supply of nutrients from the deep waters by the winter mixing was much more efficient in the cyclonic gyres, where the nutricline was relatively shallow, than in the anticyclonic gyre. Furthermore, the molar nitrate/phosphate ratio in the Levantine deep waters was much larger (N:P = 27-28) than the ratios observed in the open ocean (Krom *et al.*, 1991; Yilmaz *et al.*, 1994). The input of nutrients from the deep waters through the nutricline can therefore be expected to be deficient in inorganic phosphate.

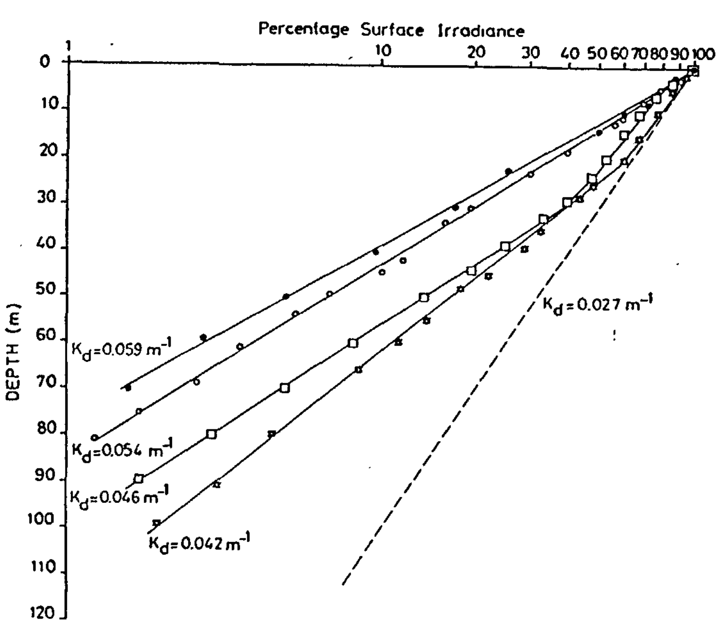


Figure 4

Variation of light intensity (logarithmic scale) with depth in the northeastern Mediterranean. Light attenuation coefficients, $Kd(m^{-1})$, calculated for each profile, are also indicated on the plots. The broken line represents the light penetration in clear sea water with an extinction coefficient of $Kd = 0.027\ m^{-1}$ (after Smith and Baker, 1978). (□):station F30L00, Rhodes cyclonic region, July 1988; (✻):station G15S00, Iskenderun anticyclonic region, July 1988; (●):station F00L00, Rhodes cyclonic region, March 1989; (○):station G15N30, Antalya anticyclonic region, March 1989.

Optical properties

The low content of particulates and the high transparency of Mediterranean waters were confirmed by measurements of the penetration of light in the northeastern Mediterranean. As Figure 4 shows, in July 1988, 1 % of the intensity of the surface light could be observed at depths of 115 m in anticyclonic regions of the northeastern Mediterranean but only down to 100 m deep in the cyclonic Rhodes gyre. In March 1989, the depths coresponding to 1 % of the surface light were 85 and 75 m for anticyclonic and cyclonic regions, respectively. The downward attenuation coefficient, K_d, calculated from measurements of light intensity in off-shore waters was found to range between 0.035 and 0.065 m^{-1} with an average value of 0.045 m^{-1} (*see* Fig. 4); these values are in good agreement with data given by Megard and Berman (1989) for the southeastern Mediterranean. The change in the slopes of the light profiles at around 25 m in July 1988 coincided with the depth of the seasonal thermocline. Figure 4 also shows that the euphotic zone (defined as the layer from the surface to the 1 % light depth) becomes thin in winter and enlarges to a maximum thickness of 120 m in summer, depending on the location. The relative shallowness of the nutricline in the cyclonic region always limited the thickness of the euphotic zone, whereas this limiting factor became noticable in the anticyclonic regions only during the late winter-early spring bloom period. In brief, the thickness of the euphotic zone varied between 40 and 70 m in coastal areas and from 70 to 120 m in offshore areas, with an average value of 100 m for offshore northeastern Mediterranean waters.

Fluorescence and chlorophyll *a*

The relative *in situ* fluorescence intensities (RFI) measured in the northeastern Mediterranean in July 1988 and March 1989 were compared with the discrete chlorophyll-*a* (CHL) measurements obtained at selected stations. As shown in Figure 5, a significant correlation existed between the depth profiles of RFI and CHL obtained at the same location provided the CHL concentrations exceeded 0.1 µg/L. The plot of CHL as a function of RFI from measurements throughout the basin (Fig. 6) confirms the suggested correlation ($r = 0.57$, $n = 59$). The large variations in the values of RFI obtained for similar CHL values in plankton poor waters may have derived from non-living fluorescent organic materials of various origins as well as from the change with depth in the ratio of the mean fluorescence per cell to the chlorophyll-*a* per cell of photosynthetic organisms (Li *et al.*, 1992). Nevertheless, the coincidence of the depths of DCM with those observed in the RFI profiles at most of the stations in the northeastern Mediterranean strongly suggests the *in situ* fluorescence values recorded at the DCM depths to have been principally of planktonic origin. However, the peak values recorded by both methods may have been the result of an increase in either the biomass of the planktonic species or in the chlorophyll (thus fluorescence intensity) present per cell at the DCM depths. As shown recently by Chisholm *et al.* (1988), Li and Wood (1988) and Li *et al.* (1992), planktonic organisms living at the bottom of the euphotic zone contain more chlorophyll per cell and yield more fluorescence intensity per cell than in the upper waters. They also observed that the composition of the species inhabiting the bottom of the euphotic zone differed from the composition in well-illuminated upper layers. The POC concentrations measured recently in the study area during both summer and winter periods (D. Ediger and C. Polat, unpublished data) suggest that during mixing seasons (March 1989 for the present case) when the euphotic zone was relatively rich in nutrients, the DCM was partly the result of an increase in the planktonic biomass. A similar argument was given by Estrada (1985) for the origin of DCM in the western Mediterranean.

Some specific examples of the deep fluorescence maxima (DFM) due to chlorophyll are illustrated in Figure 7. As the

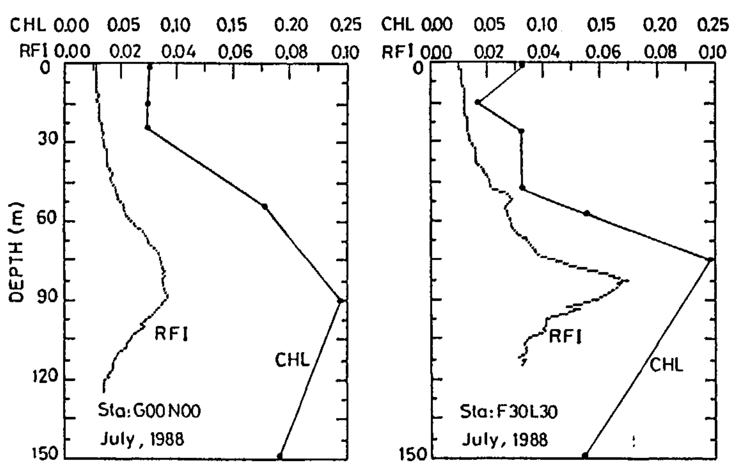


Figure 5

Typical profiles of in situ *relative fluorescence intensities (RFI, arbitrary unit) and chlorophyll-*a *(CHL, µg/L) at selected stations in the northeastern Mediterranean.*

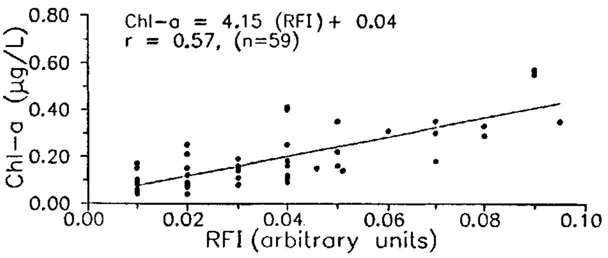


Figure 6

*Correlation between the discrete chlorophyll-*a *concentrations (CHL, µg/L) and* in situ *relative fluorescence intensities (RFI,arbitrary unit) measured during the July 1988 and March 1989 cruises in the northeastern Mediterranean.*

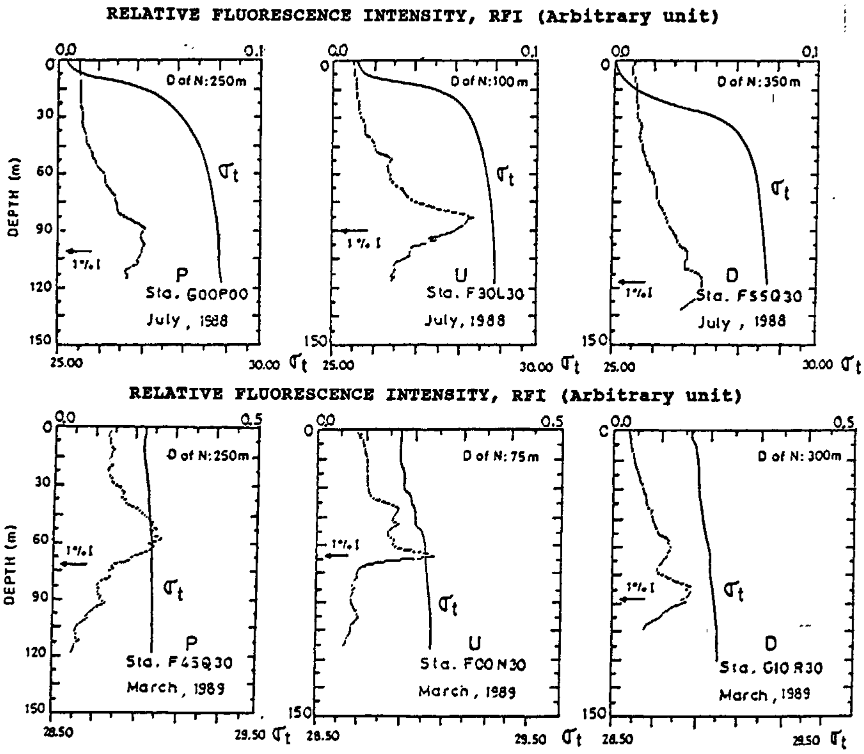


Figure 7

Continuous in situ *profiles of relative fluorescence intensities and water density (sigma-theta) at selected stations from peripheries(P), cyclonic(U), and anticyclonic(D) regions in the northeastern Mediterranean. The arrows indicate the depth of 1 % of the surface light and "D of N" stands for the top of the nutricline.*

RFI profiles for summer show, there was no noticeable change in RFI at the depth of the seasonal pycnocline; DFM were always observed at the bottom of the euphotic zone. Such features were also prevalent during winter though deep convective mixing rendered the euphotic layer homogeneous (*see* Fig. 7). Significantly, the depth of the DFM coincided with the depth of the DCM and was always observed to be close to the nutricline in cyclonic regions, whereas, in anticyclonic regions, it was always found at the bottom of the euphotic zone, the nutricline appearing below 250 m as indicated in Figure 7. Light intensity appears to be of little consequence to the depth of the DCM and solar light as weak as 1 % of the surface intensity seems to be sufficient for the occurrence and maintenance of DCM and DFM. The principal results of basin-wide fluorescence and discrete chlorophyll-*a* measurements in the northeastern Mediterranean are summarized in the Table. The depth of deep fluorescence maxima (DFM) varies both in space and in time, being found at greater depths with an average value of 88 m in the anticyclonic regions in summer whereas it appears at shallower depths with a mean depth of about 52 m in late winter. The maximum RFI (x 10^{-2}, arbitrary unit) measured at these depths ranged between 3 and 8 (mean = 5, n = 61) for July 1988 and from 7 to 35 (mean = 14, n = 40) for March 1989. RFI in the near-surface waters were in the range from below detection limit to 5 for summer and to 10 for winter. As also shown in the Table, the average chlorophyll-*a* concentrations measured at the depth of the DCM were not only two-three times as large as those in the surface waters, but a similar ratio also appeared between the average values of the late winter and summer periods.

Table

*Relative fluorescence intensity (RFI, x 10^{-2}, arbitrary unit) in the near-surface waters, at its maximum (DFM) and the depth at which DFM occurred; and chlorophyll-*a *concentration (CHL, µg/L) at the surface and at its maximum (DCM) in the northeastern Mediterranean.*

	July 1988				March 1989			
Parameter	Min.	Max.	Ave.	n	Min.	Max.	Ave	n
RFI(surface)	BDL	5	2	63	BDL	10	5	40
RFI(at DFM)	3	8	5	61	7	35	14	40
Depth of DFM	55	120	88	59	35	90	52	40
CHL(surface)	0.04	0.14	0.07	9	0.01	0.42	0.18	14
CHL(at DCM)	0.16	0.41	0.26	8	0.23	0.92	0.51	14

BDL: Below Detection Limit.

The spatial distribution of relative fluorescence intensities of the deep fluorescence maximum (DFM) and the surface circulation patterns in the basin for July 1988 and March 1989 are illustrated in Figure 8. Since the larger part of the basin waters had very low RFI in summer, smaller than the detection limit of the instrument, its spatial distribution in the surface waters could not be plotted. Nevertheless, measurable values exceeding 0.1 units were recorded in the northeastern part of the Levantine Basin, in the Bay of Iskenderun and in the region surrounding the bay where the sizeable Ceyhan and Seyhan rivers flow into the basin and then in cyclonic regions and their neighbourhood (*see* Fig. 1 for their locations). As shown in Figure 8, the most pronounced DFM for summer were found in the cyclonic Rhodes gyre, at 50-60 m, and its peripheries. Intensities of the DFM were also high in the vicinity of another cyclonic gyre present in the basin to the east of Cyprus in the region of the Iskenderun Bay. Few patches of high RFI were also observed in the anticyclones to the south of the Rhodes gyre and Cyprus below 110 to 120 m. The location of the DFM in the pelagic system was entirely consistent with the behaviour of the circulation system controlling the supply of nutrients to the euphotic

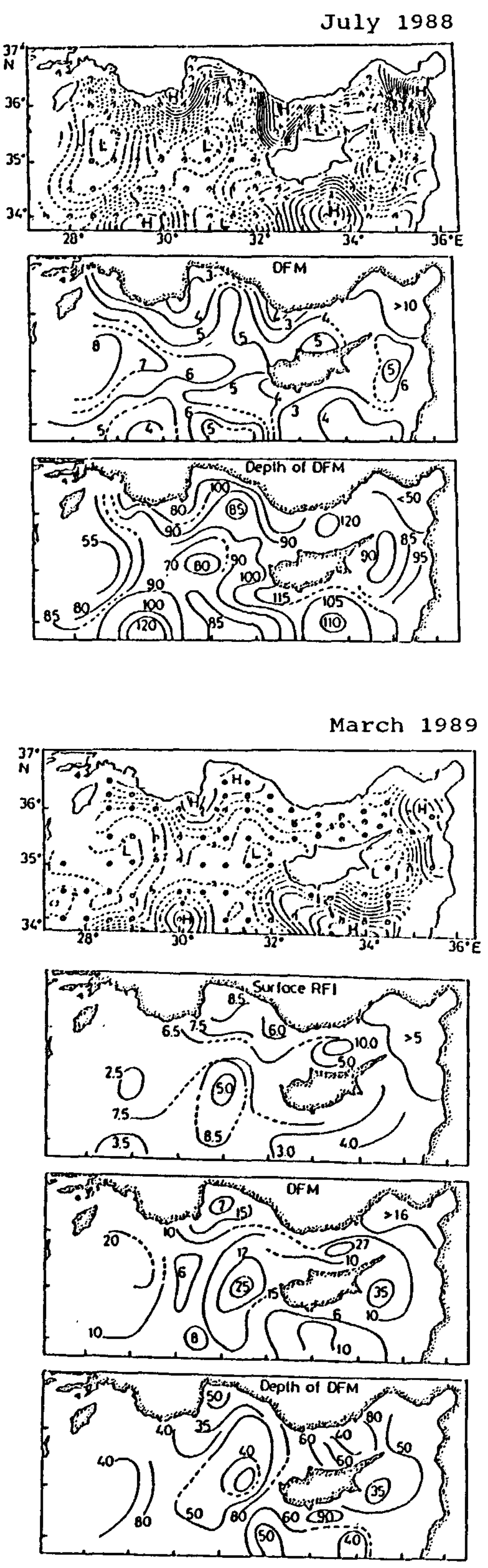


Figure 8

Circulations in the northeastern Mediterranean, showing cyclonic (L, low pressure) and anticyclonic (H, high pressure) systems in July 1988 (after Ozsoy et al.*, 1991); and in March 1989 (after Ozsoy* et al.*, 1993) and spatial distribution of* in situ *relative fluorescence intensities (RFI, X 10^{-2}, arbitrary unit) in the surface waters, deep fluorescence maxima (DFM, X 10^{-2}, arbitrary unit) and depth of DFM (in metres) for the same sampling periods.*

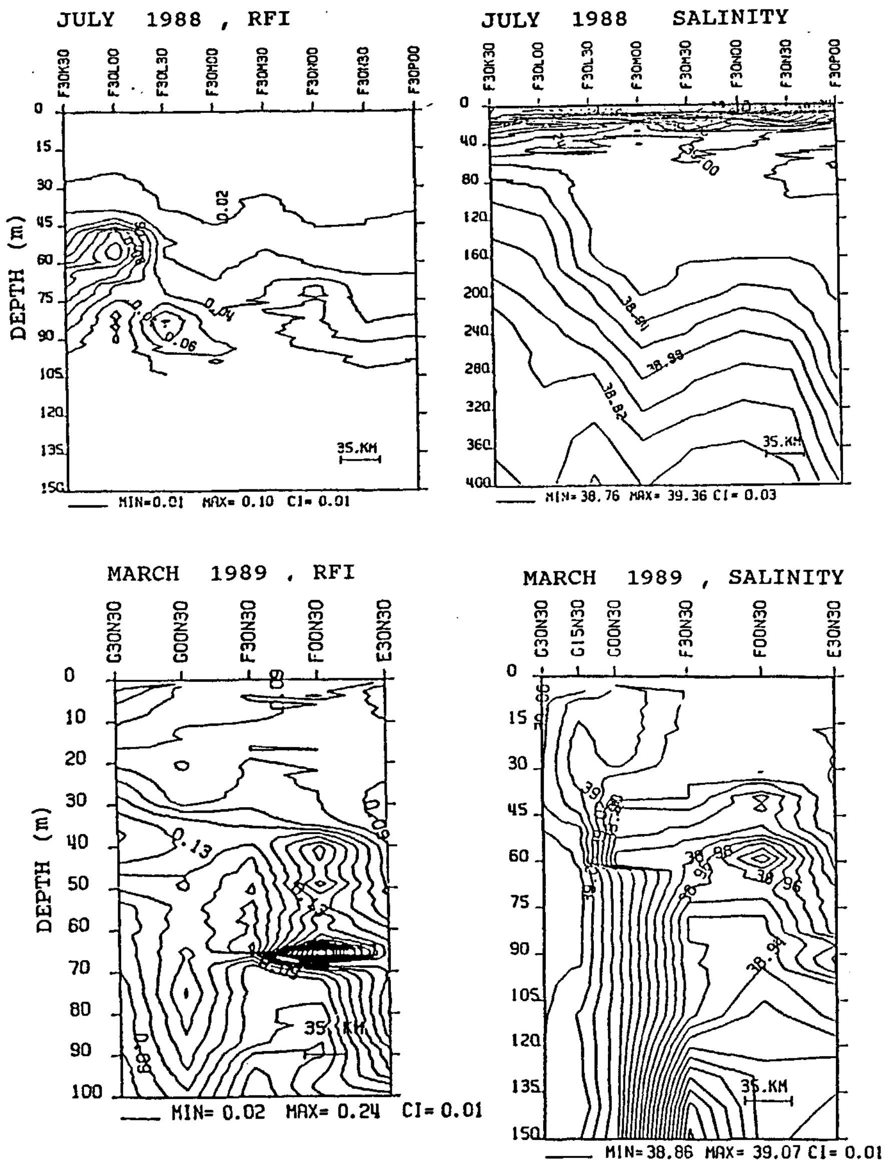


Figure 9

Relative fluorescence intensity (RFI, arbitrary unit) and salinity transect couples in west-east and north-south directions in the northeastern Mediterranean for July 1988 and March 1989 sampling periods.

zone. As stated above, the summer DFM values most probably represent the occurrence and maintenance of specific planktonic species having relatively high fluorescencence per cell, rather than the larger biomass at these depths. In March 1989, the physical and biochemical data are representative of conditions for the early spring bloom. Thus, as seen in Figure 8, the maximum values of RFI in the surface waters, two-three times as intense as in July 1988, were observed in the region between western Cyprus and Antalya Bay. The relative intensities at the deep fluorescence maxima (DFM) were most intense at the centres of two cyclones, one located in the Rhodes basin to the west of Cyprus and the other immediately to the east of Cyprus. The depths of deep fluorescence maxima (DFM), shallower than those observed in July 1988, generally ranged from 35 to 60 m, though at some locations the maximum was observed at 80-90 m depths (Fig. 8). The shallowing of the depth of DFM in late winter was due principally to the decrease in light intensity limiting the lower boundary of euphotic zone and, to some extent, to the relative enrichment of the euphotic zone with nutrients by the deep-winter mixing.

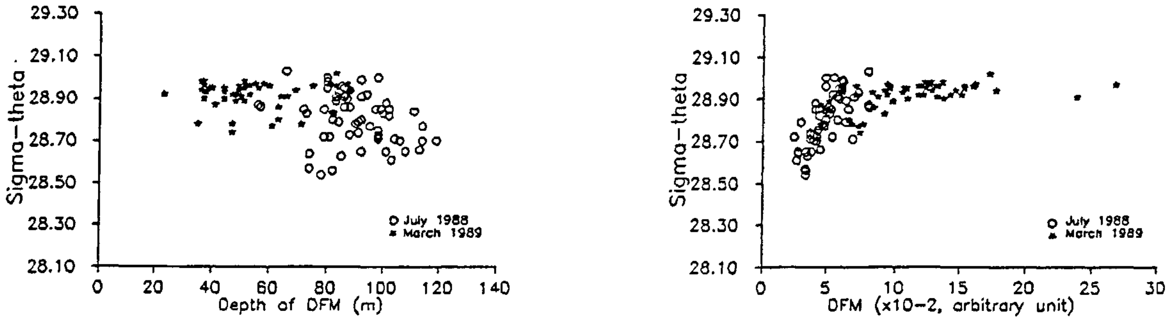


Figure 10

Correlation between the changes in the water density (Sigma-theta) values and the depth of deep fluorescence maxima (DFM) and DFM itself (x 10^{-2}, arbitrary unit) measured in the lower euphotic zone of the northeastern Mediterranean for July 1988 and March 1989 sampling periods.

The agreement between the relative fluorescence intensity and salinity transects demonstrates the coincidence of the fluorescence data with the salinity fields and some examples of these transects are presented in Figure 9. The fluorescence contours show nearly the same trend as the isohalines. The upwelling at the centre of the Rhodes gyre tends to homogenize the water properties and provide nutrients for the growth of planktonic species at the relatively shallow depths of 60-70 m (*see* Fig. 9, station F30L00 for July 1988 and station F00N30 for March 1989). On the other hand, at the peripheries of the cyclones and at the central parts of anticyclones the waters downwell and the surface waters become poor in nutrient elements from late spring to late autumn. Thus, highly fluorescent planktonic species inhabit the bottom of the euphotic zone (*see* Fig. 9, station F30M00 for July 1988 and station G00N30 for March 1989).

The interrelationship of the physical and chemical data we have been describing is encapsulated in Figure 10 which shows plots of water density *versus* the depth of DFM and DFM itself in the upper layer of the northern Levantine Basin. It is clear from these graphs that, irrespective of the region where the data were collected, although, for reasons that have already been described, the DFM were at greater depths in summer than in late winter, these fluorescence maxima inevitably appeared within a relatively narrow range of isopycnal surfaces; namely, from σ_t =28.8 to 29.0 in March, 1989 and from 28.6 to 29.0 in July 1988. The same trend was observed for the depth of nutricline and the top of the nutricline always found to be established at 29.00-29.05 isopycnal surfaces whatever the geographical location (Yilmaz *et al.*, 1994).

CONCLUSIONS:

Measurements of *in situ* fluorescence intensity in the photosynthetic zone appear to provide a rapid method for determining the relative spatial and temporal variations of chlorophyll concentrations in the northeastern Mediterranean. In fact, the deep chlorophyll maximum is a prevalent feature of the oligotrophic basin waters; its occurrence and maintenance are independent of the seasonal stratification in the surface waters but dominated by the 1 % light depth which varies seasonally between 50 and 120 m. Moreover, the spatial distribution of the depth of maximum fluorescence is closely associated with the circulations and hydrochemical regimes of the basin; the maximum is formed at depths close to the nutricline in the cyclonic regions and at the bottom of the euphotic zone in the anticyclonic regions where the nutricline is established below 250 m. Interestingly, the DFM appears within a relatively narrow range of isopycnal surfaces whose depths in the upper layer are determined by circulations and winter mixing.

Acknowledgements

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