THE DYNAMICS OF NUTRIENT ENRICHMENT AND PRIMARY PRODUCTION RELATED TO THE RECENT CHANGES IN THE ECOSYSTEM OF THE BLACK SEA

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Abstract

During the spring period of 1998, light penetrated into the upper 25-35m, with an attenuation coefficient varying between 0.1 and 0.5 m^{-1}. The chlorophyll-a (Chl-a) concentrations for the euphotic zone ranged from 0.2 to 1.4 $\mu g\ l^{-1}$. Coherent sub-surface Chl-a maxima were formed near the base of the euphotic zone and a secondary one was located at very low level of light in the Rim Current region. Production rates varied between 450 and 690 $mgC/m^2/d$ in this period. The chemocline boundaries and the distinct chemical features of the oxic/anoxic transition layer (the so-called suboxic zone) are all located at specific density surfaces; however, they exhibited remarkable spatial variations both in their position and in their magnitude. Bioassay experiments (using extra NO_3, NH_4, PO_4 and Si) performed during Spring 1998 cruise showed that under optimum light conditions the phytoplankton population is nitrate limited in the open waters. Phosphate seems to control the growth in the Rim Current regions of the southern Black Sea. Si concentration also influenced the phytoplankton growth since the majority of the population was determined as diatom.

1. INTRODUCTION

The Black Sea is a relatively large, deep, landlocked anoxic basin and there exists a permanent and strong halocline at depths of >50-200 m, shoaling in the central cyclones and deepening in the coastal regions. Continuous downward transport of biogenic particles from the productive surface layer, combined with limited vertical ventilation through the permanent halocline are the major reasons for the anoxic conditions in the deep waters. The presence of cyclonically meandering Rim Current along the peripheries of the basin partly isolates coastal waters from the interior waters. The Black Sea is further unique possessing very narrow shelf along more than half of its margin, except northwestern shelf area.

In addition to natural biochemical processes forming the anoxia in the deep waters, the increasing input of nutrients and organic matter from land-based sources during the last two decades, generated dramatic changes in the Black Sea ecosystem, especially in the wide northwestern shelf [1-5]. Long-term modifications and collapses of the biological structure of the ecosystem have been well documented [3,6,7]. However, the lack of good quality historical data of high resolution impairs understanding of how the recent anthropogenic inputs and climatic changes have influenced nutrient and organic carbon pools of the Black Sea. Nevertheless, comparison of the limited earlier measurements with the high-resolution data obtained since 1988 has enabled several workers to address the magnitude of the long-term changes in the nutrient and oxygen profiles from the upper layer down to the sulphide-bearing waters of the deep basin [9 - 15]. Similar changes have been observed in the nutrient chemistry of the waters of the northwestern shelf [5].

Primary production in the Black Sea displays two phytoplankton maxima throughout the year; the major one occurs in early spring while a secondary peak appears in autumn [16,17]. Recently, additional summer blooms have frequently been observed in both the coastal and open waters [18,19,20,21]. Primary production is relatively low in the open sea (50-200 gC m^{-2} y^{-1}) compared to the northwestern shelf area (up to 400 gC m^{-2} y^{-1}) [2,17], where there are riverine discharges of nutrients[5]. Since input of nutrients from the anoxic layer through the permanent pycnocline is limited both by denitrification and by oxidation-reduction processes occurring in the oxic/anoxic transition layer, since the major nutrient source for the open system is the input from the nutricline [22]. New production in the open waters of the Black Sea is therefore dominated by the input from the nutricline, riverine input via surface circulations and atmospheric transport probably being of secondary importance; consequently the rates of new production in the Black Sea are low [22,23].

2. RESULTS AND DISCUSSION

Area of Study: The station network for Spring 1998 cruise is illustrated in Fig. 1. Previous studies clearly demonstrate the physical oceanography of the Black Sea upper layer to be dominated by the quasi-permanent cyclonic gyres in the eastern and western halves of the basin. The two gyres are separated from a series of anticyclonic eddies in the coastal zone by the cyclonically undulating Rim Current [24]. The influence of the freshwater input, mainly from the Danube, Dnepr and Dnester rivers at the northwestern shelf, can be traced down to the Bosphorus region [20]. The stations were selected according to such physical structures.

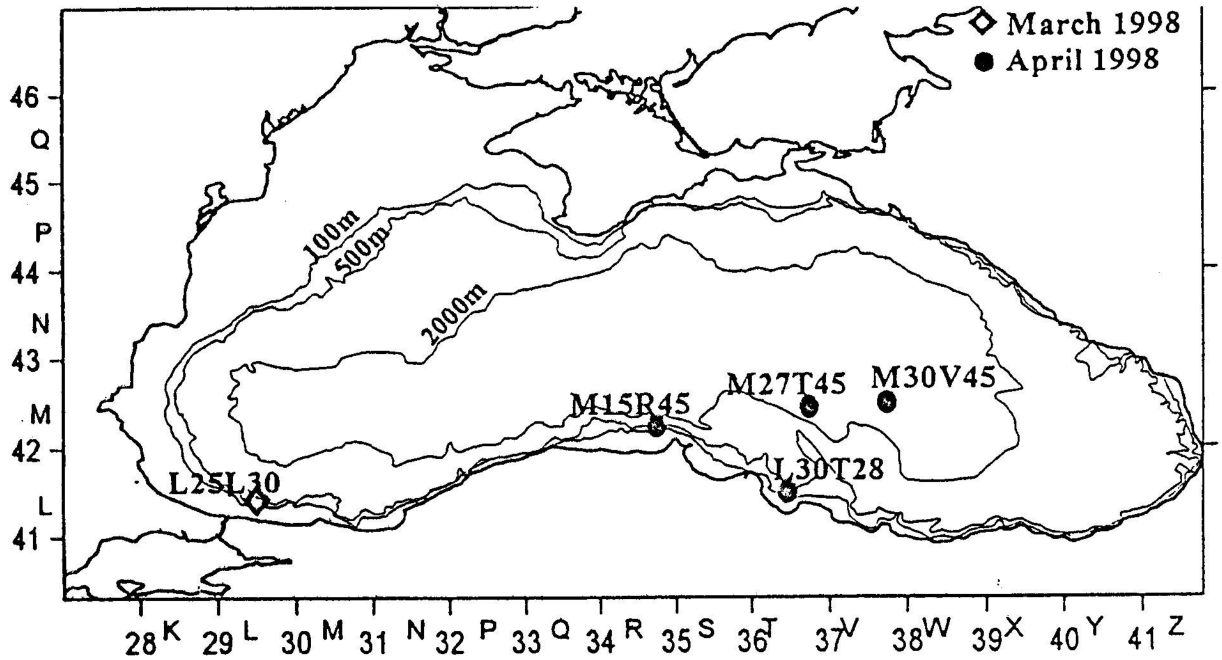

FIG. 1.Station network for the spring 1998 cruise

Hydrographic Structure: The profiles of Temperature, Salinity, Density (Sigma-theta = σ_t) and Light Transmission from the southern Black Sea demonstrate that a nearly isohaline and relatively cool, isothermal water mass exists below the seasonal pycnocline (Fig. 2). This prominent and persistent feature of the Black Sea, termed as the Cold Intermediate Layer (CIL), possesses a temperature minimum which is characterized by the 8 °C limiting isotherms [24]. The thickness of the CIL is larger (up to 100m) in the anticyclonic regions (ACYC) than in the cyclonic regions (CYC) (about 50m). The σ_t =14.8 isopycnal surface defines not only the temperature minimum within the

CIL but also the upper boundary of the permanent pycnocline in the Black Sea [10]. In the CIL, the salinity varies slightly from nearly 18.5 to 20.1 ppt. The profiles illustrated in Fig. 2 show that, in March 1998, when the surface waters cool down to 7 °C, the upper layer is thoroughly homogenized - by convective mixing down to the σ_t = 14.7-14.8 isopycnal surfaces. With the advent of heating in the early spring, the surface temperatures rise to 12-13°C and then CIL becomes topped by a warm surface layer (Fig.). Below the CIL the temperature gradually rises from 8 °C to 8.7 °C at the base of the permanent pycnocline; this is observed at different depths for different regions. The subhalocline waters posses similar temperatures at similar density surfaces over the basin though isohalines appear at different depths from the deep to the coastal region. The light transmission is between 75-90% down to the lower boundary of the CIL and it increases to higher percentages or transmission down to σ_t =16.0-16.2 where the fine particle layer is located with low transmission.

Chemical Properties. The chemical profiles down to the anoxic waters were plotted relative to water density and depth as a vertical scale for selected stations. (Fig. 3.) AS recently indicated, composite profiles from hydrodynamically different regions exhibit characteristically similar vertical features below the euphotic zone down to the upper anoxic layer when the vertical scale is density [14,15,22].

Dissolved Oxygen (DO). Fig.3 shows the surface layer down to the temperature minimum the CIL to be nearly saturated with dissolved oxygen(DO=300-350 μM). The concentrations decrease steeply in the upper depths of the permanent pycnocline from 300 μM at the σ_t =15.5 surfaces, these surfaces defining the upper and lower boundaries of the main oxycline. As recently indicated [25], the oxycline commences at greater density surfaces (σ_t =14.4-14.5)but at shallower depths 950-60m) in cyclonic regions than in the frontal zones of the Rim Current or in anticyclonicregions where the onset is located at σ_t =114.2-14.3 970-100m) Below the main oxycline DO declines slowly to <20μM at σ_t =15.9-16.0 and can no longer be detected at the σ_t =16.15-16.20 density surfaces where sulphide concentrations are 1-3 μM (Fig. 3). This DO-deficient water, formed within the oxic/anoxic transition layer with DO <20 μM and H_2S <1 μM, is called the suboxic zone. Sulphide-bearing waters were consistently observed at density surfaces of >16.15-16.2 over the entire deep basin. In the upper anoxic layer, the H_2S concentration increased steadily with depth, showing insignificant spatial or temporal variation at any density surface.

Phosphate (PO_4) and T-NO_x (NO_3+NO_2) Distributions: As previously emphasised [15,21], the surface waters of the southern Black Sea are always poor in nutrients during the seasons when these waters are stratified. In the late spring 1998 when the seasonal stratification has started to established, concentrations in the euphotic zone were less than 0.5 μM for T-NO_x (mainly NO_3), 0.35 μM for phosphate and 5 μM for Silicate. The nutrient data from previous years [21,26] together with modelling studies [23] indicate that intense vertical mixing in winter provides input from the nutricline which may increase surface nitrate concentrations 5-10-fold. Composite profiles of T-NO_x and phosphate indicate that, below the euphotic zone, nutrient concentrations increase with increasing density down to the base of the main oxycline (Fig. 3). The nitrate concentrations display a well-defined maximum of 5-8 μM at 15.5 density surface defining the upper boundary of the suboxic zone where DO concentrations decrease to 20-30 μM. In the suboxic zone, due to denitrification, nitrate concentrations decline steadily to 0.1-0.2 μM at the suboxic/anoxic interface. Nitrate then becomes reduced by sulphide in the upper anoxic waters until to undetectable levels. Phosphate concentrations increase within the oxycline to a maximum in the upper suboxic zone or at the σ_t = 15.6-15.7 isopycnal surfaces. Below this broad maximum, phosphate concentrations decline steeply in the cyclonic regions, forming a pronounced minimum (0.05-0.10 μM) at the σ_t = 15.9-16.0 isopycnal surfaces. This feature is less marked in coastal regions and it is nearly imperceptible within the Rim Current region. Nevertheless, throughout the deep basin phosphate profiles always increase steeply within the sulphidic water interface and reach peak values of 6-8 μM at σ_t = 16.2 isopycnal surface. Phosphate concentrations decrease slightly in the upper anoxic layer and then increase again slightly with depth. The occurrence throughout the deep basin of the marked maximum at the sulphidic boundary probably results from dissolution of phosphate-associated Fe- and Mn-oxides in the anoxic waters [13,27]. Silicate concentration increase steadily below the euphotic zone with increasing depth and density.

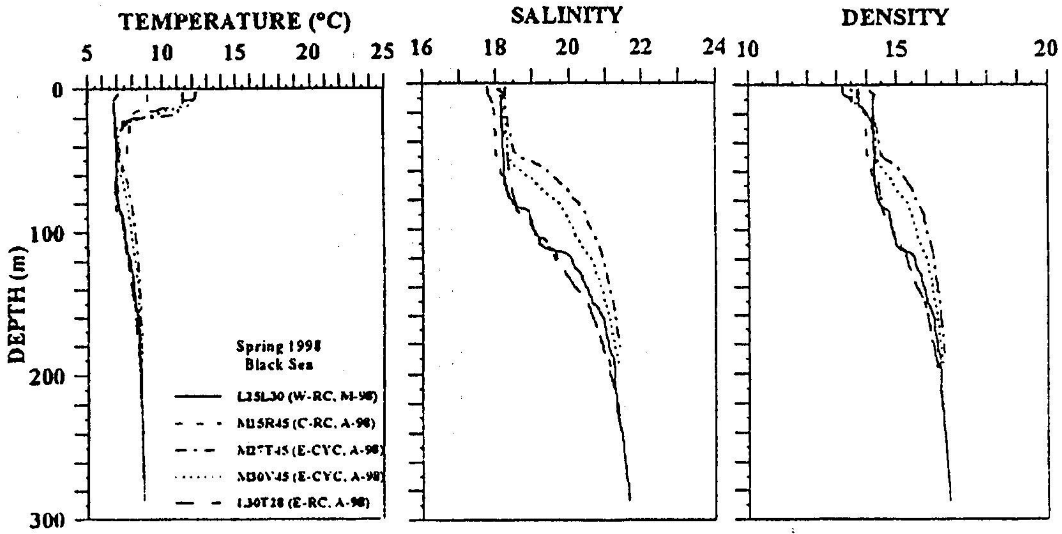

FIG. 2. Potential Temperature (°C), Salinity and Sigma-theta (Density) Profiles in the southern Black Sea for Spring 1998 period

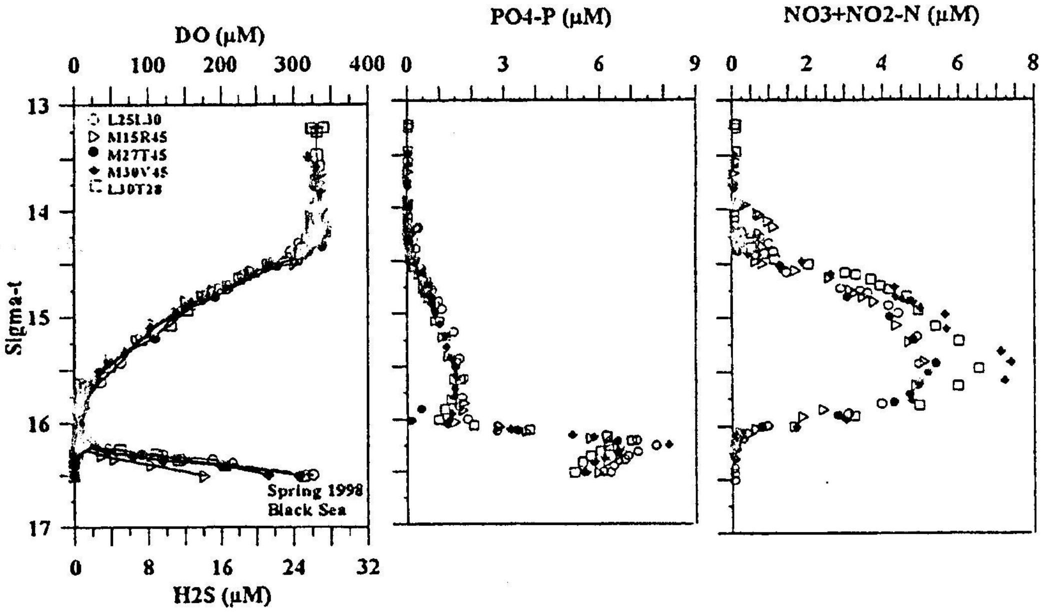

FIG. 3. Vertical profiles of Dissolved Oxygen (DO)-H2S and Dissoved Nutrients (PO4-P a NO3+NO2-N) in the southern Black Sea for spring 1998 period

Primary Productivity and Related Parameters: The observed light penetration in the upper water column of the southern Black Sea during spring 1998 period indicated the thickness of the euphotic zone (defined as the depth of 1% of the surface light) to range between 25 and 35 m (Fig. 4). The less energetic, high wavelength component of the incoming light was absorbed in the upper surface layer (the top 10m), where the highest (downward) attenuation coefficient (K_d = 0.2-1.2 m^{-1}) was calculated. Below this layer the solar light penetrated with a constant K_d, which varied regionally between 0.1 and 0.3m^{-1}. The highest estimated K_d values were observed in the Rim Current region where the phytoplankton biomass and the photosynthetic production rates are relatively high.

Chl-a and in situ fluorescence data from different regions of the southern Black Sea are displayed in Fig.4. The concentrations in the euphotic zone were generally low (<0.5 μg/L) with the lowest values in the surface mixed layer, and a subsurface Chl-a maximum was formed near the base of the euphotic zone and below the seasonal thermocline or at a certain density surface σ_t = 14.25-14.5 having a concentration values up to 1.5 µg/L. In the central gyres where the upper boundary of nutricline is shallower, the subsurface maxima was fallowed by a sharp decrease while the chlorophyll-a profiles (as well as in situ fluorescence) have shown a secondary deep maximum in the Rim Current region. The deep secondary maxima were located at very low level of light (at 0.1-0.3 µE/m^2/s). In March 1998, chlorophyll-a showed almost uniform vertical distribution with 0.8 µg/L concentration.

Primary productivity profiles were similar throughout the southern Black Sea; the highest rates, which varied regionally between 1 and 5 mgC m^{-3} h^{-1} (or 10 and 50 mgC/m^3/d), were always determined in the upper euphotic zone down to the 10 % light intensity depth or the top 10-15m of the water column. Below this layer, the rate decreased markedly with depth and dropped to negligible rates at the 1% light intensity depth (Fig. 4).

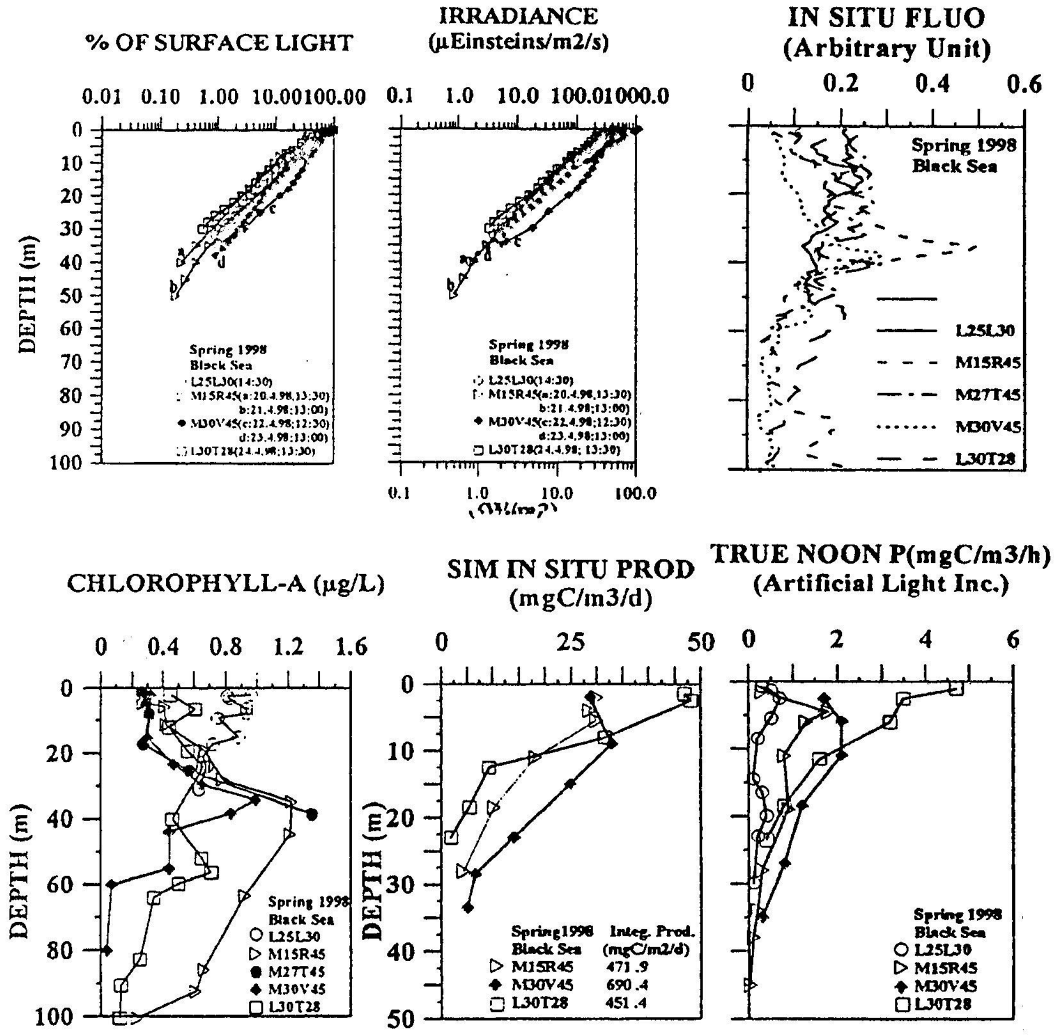

FIG 4. Vertical distribution of downward light in situ flourescence, chlorophyll-a and carbon production rates for Spring 1998 period

In order to determine the maximum rates of production, under adequate light intensity, samples taken from different depths of the euphotic zone were exposed to the full artificial light conditions in the incubator. The estimated maximum rates, were comparable with the surface values and the subsurface maxima of photosynthetic production rates coincided with the subsurface Chl-a maxima. The secondary but relatively weak peak of photosynthetic carbon production rates were observed at the same depths of deep secondary fluorescence maxima (as deep as 70-90m). The population living here was determined mostly as diatoms (E. Eker, unpublished data) and though the presence of very low level of light they were photosynthetically active. Such secondary maxima were

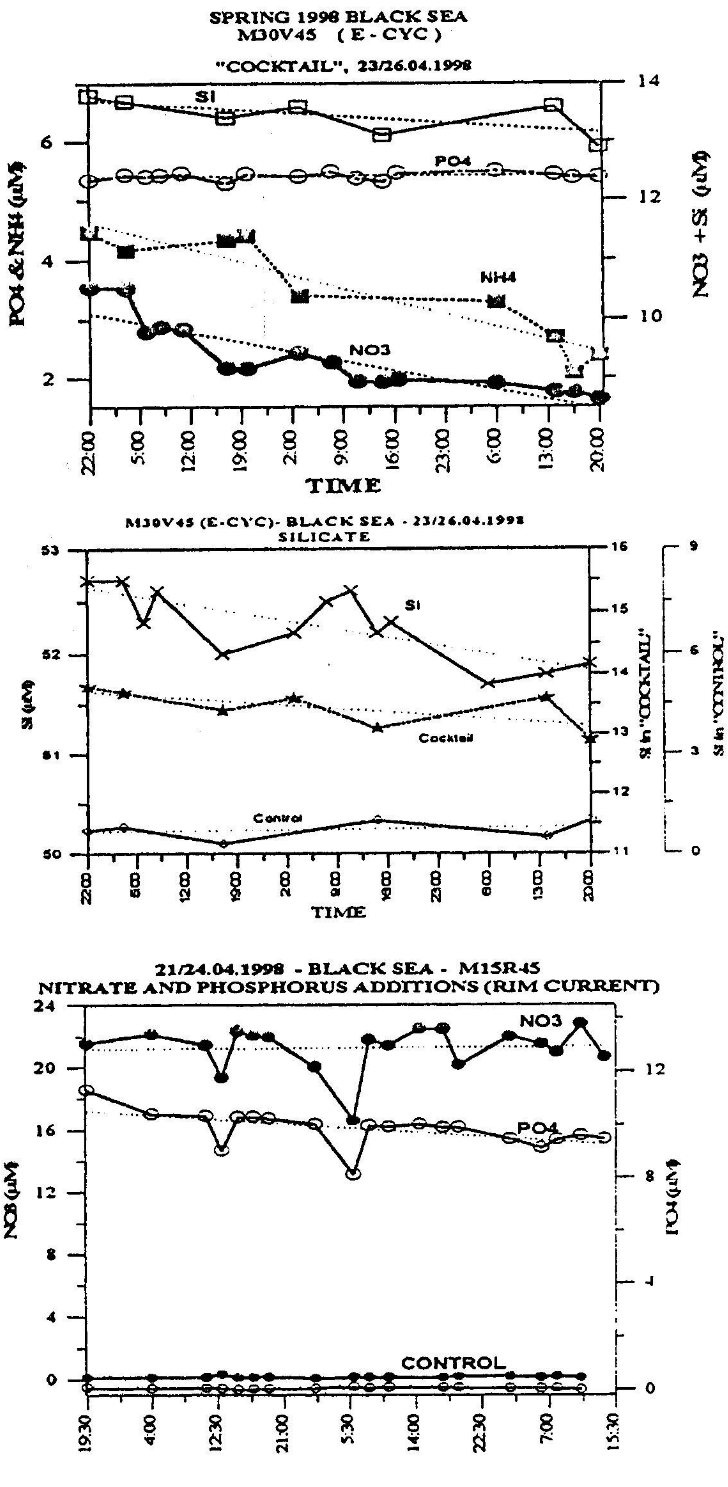

FIG. 5 .Bioassay experiments performed during Spring 1998 cruise

not observed in the central cyclones. The depth-integrated production rates ranged from 450 to 690 $mgC/m^2/d$ in the southern Black Sea for the late spring period while very low level of daily production (<50 $mgC/m^2/d$) was recorded in the Rim Current region in March 1998. The highest depth-integrated production rate was 0.7 $gC/m^2/d$ in this region in Spring 1998 which is lower than the values already known for the NW shelf and off the Romanian coast for the 1970-1980 period [2] and very similar to those of the central Black Sea given for the late 1980 and early 1990s [17].

Bioassay experiments (using extra NO_3, NH_4, PO_4 and Si) performed during Spring 1998 cruise showed that under optimum light conditions the phytoplankton population is nitrate limited in the open waters. Phosphate seems to control the growth in the Rim Current regions of the southern Black Sea. Si concentration also influenced the phytoplankton growth since the majority of the population was determined as diatom (Fig. 5).

3. DISCUSSION

Coastal waters of the Black Sea are principally fed by the riverine input whereas the cyclonically dominated open ecosystem is mainly controlled by the influx of nutrients from the oxygenated lower layers by vertical diffusion and wind induced mixing processes that is much effective in winter. However, the input from the anoxic layer is limited due to the presence of a permanent halocline in the Black Sea. Halocline coincides with the suboxic zone where intense denitrification and redox-dependent processes also limit nitrogen and phosphorus input to the productive layer. In comparison, the role of atmospheric sources of nutrients appears to be marginal [28]. The f-ratio has therefore been estimated to be as low as 0.1 [13,22] and in such systems the f-ratio is mainly determined by the availability of ammonia [29].

As a result of as yet undefined processes, the upper CIL down to the temperature minimum depth in the Rim Current is enriched with nitrate but drastically poor in phosphate. There are thus very high N/P ratios in the upper nutricline and an apparent shift in the nutricline onset in the CIL. Since these P-limited CIL waters are mixed vertically with the surface waters in winter and early spring,bloom in such areas is limited by phosphorus. Nitrate-limited production occurs in the central gyres due the low N/P ratios of the chemocline established just below the euphotic zone. The relatively high atomic N/P ratios of POM indicate that the anomalously low ratio of nitrate/phosphate in the oxic/anoxic interface of the entire deep basin is due to nitrate removal via denitrification, greatly exceeding P-export from the suboxic waters [21].

On the other hand changes recently observed in the Black Sea such as the reduction in dissolved silicate load of Danube River by about two-thirds since dam constructions in the early 1970s, concominant decrease in witertime Si concentartion by more than 60% in the central areas [30], increase in nitrate concentrations in the NW shelf waters [4] and above the pycnocline in the whole Black Sea [13,14] significantly influenced the ecosystem of the lower trophic levels.

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