Primary production, availability/uptake of nutrients and photo-adaptation of phytoplankton in three interconnected regional seas: Black Sea, Sea of Marmara and Eastern Mediterranean

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1. Introduction

Black Sea: **In addition to natural processes, the increasing input of nutrients from the rivers and the discharge of wastes especially in the NW shelf are the main sources of nutrients (Cociasu *et al.*, 1996) in the coastal Black Sea. In the open ecosystem, primary production is mainly sustained by the influx of nutrients from the oxic/suboxic lower layers by vertical mixing which is limited due to the presence of a strong pycnocline at 50-200m. (Yilmaz *et al*, 1998). Coastal region is P-limited while N-limited production occurs in the central Black Sea. In addition to common spring and autumn blooms, recently, additional summer blooms have frequently been observed in the entire basin (Yilmaz *et al.*, 1997).**

The Sea of Marmara: **Nutrient budget of the Marmara upper layer and thus the primary production in the basin is dominated by the inputs both from natural (input from the subhalocline waters by vertical mixing and the Black Sea inflow) and land-based sources (domestic/industrial wastes especially by the city of Istanbul) (Polat *et al.*, 1998). Mediterranean waters possess relatively low concentrations of nutrients before they enter the Marmara deep basin and then the concentrations increase nearly ten-fold during their sojourn in the basin (Polat *at al.*, 1998). In terms of primary production, the Sea of Marmara ranks among the eutrophicated seas (Polat *et al.*, 1998).**

Eastern Mediterranean: **Nutrient supply to the Eastern Mediterranean euphotic layer is limited both from its deep layer and from external sources; majority of the rivers and the Atlantic inflow principally feed the western basin. The permanent nutricline is located between specific density surfaces throughout the basin (Yilmaz and Tugrul, 1998) and it is shallower in the cyclonic Rhodes Gyre (RG) and coincides with the lower boundary of the euphotic zone (EZ); but it is far below the EZ in the peripherial zones of RG and in anticyclonic eddies. The eastern Mediterranean waters are very clear and oligotrophic (Chl-a is <0.5 µg L^{-1} and primary production is as low as 45 mgC m^{-2} d^{-1}) and P-limited. (Ediger and Yilmaz, 1996; Robarts *et al*., 1996).**

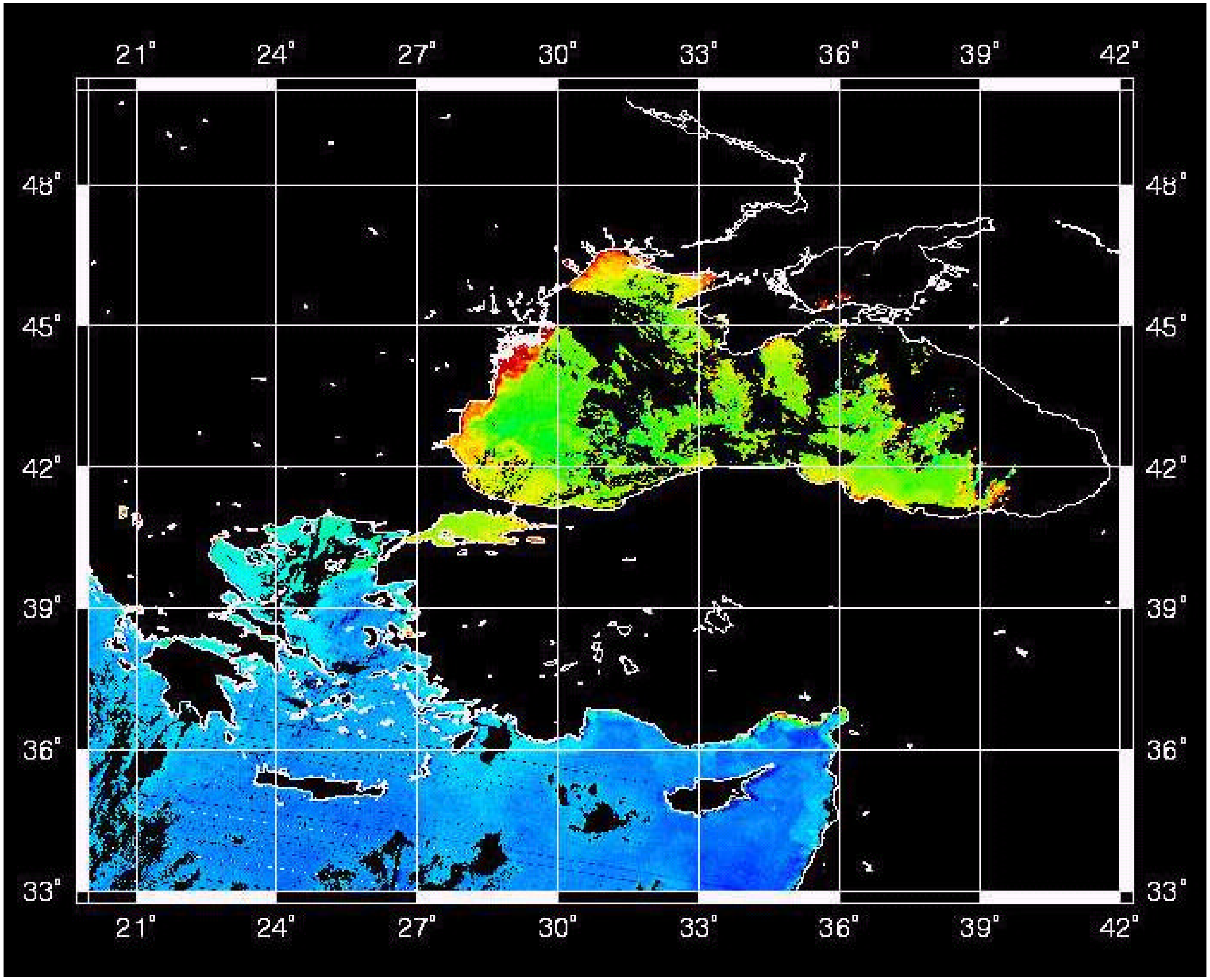

Fig. 1. Sea WiFS measured Chlorphyll-a distribution showing different trophic states

of the three interconnected regional seas surrounding Turkey (23.09.1999)

2. Results and Discussion:

The Black Sea: A permanent halocline is present at s_t=14.8-14.5 (shoaling in the central cyclones, 50m and deepening in the coastal regions, >200m) in the Black Sea. Surface layer down to the upper pycnocline is well oxygenated and then DO decreases steeply to ~20 µM at s_t=15.5. Below oxycline, DO declines to <5 µM at s_t=16.0 and can no longer be detected at s_t=16.2 where H_2S concentration becomes detectable (<3 µM). This DO-deficient layer is called suboxic layer (SOL). Anoxic layer (AL) is consistently observed at density surfaces of >16.2 with H_2S concentration increasing steadily with depth (Fig. 2).

Below EZ, nutrient concentrations increase with increasing density down to the base of the oxycline. The NO_3 profile displays a well defined maximum (~7.5 µM) at s_t=15.5 then it declines to ~0.1 µM at the SOL-AL interface due to the denitrification processes. NH_4 is always below detection limit in the EZ and this feature is prominent down to s_t=16.2; then it increases steadily with depth. PO_4 increases within the oxycline, yielding a broad maximum in the upper SOL, then it declines steeply in the central cyclones, forming a pronounced minimum at s_t=16.0. This feature is less marked in the nearshore regions. PO_4 always increase steeply within the sulphidic water interface and reach peak values of 5-8 µM at s_t = 16.2. Si increases steadily below the EZ with increasing density (Fig. 2).

A relatively shallow EZ located above the main pycnocline is the characteristic of the Black Sea. The Chl-a concentration is generally low in the upper EZ and a subsurface Chl-a maximum coincides with the fluorescence maximum observed near the base of the EZ. A secondary maximum may appear in nearshore waters at very low light level (<0.3 µE m^{-2} s^{-1}) or below 0.1 % of surface light. In late winter, Chl-a shows almost uniform vertical distribution. The POM concentrations of the EZ are relatively high and they decrease markedly below EZ to background levels in the SOL. The POM profiles display peak

values in the upper boundary of sulphide-bearing waters and the deep layer particulate maxima are more pronounced for PP, especially in the Rim current where a fine particle layer (mainly of non-biogenic origin) selectively enriched with phosphorus. C/Chl-a ratio declines at the base of the EZ due to less organic carbon synthesis per Chl-a by shade-adapted cells. The Black Sea seston is rich in carbonaceous compounds with N/P ratio ranging between 9-27 (Fig. 2, Table 1).

The highest primary productivity rates are always observed in the upper EZ and the rates drop to insignificant values at 1% LD. There is capacity for potential production far below the EZ (<%0.1 LD) in the Black Sea; a secondary deep Pot-PP maximum at the same depths of deep fluorescence maximum is observed in the nearshore regions. PPt rates and Chl-a concentrations are nearly uniform in the EZ during winter period-early spring period. Virtually, no difference is present between the light adaptation characteristics of the samples and thus P-I curve characteristics for whole EZ during winter when the upper water column is well mixed. The P-I curves from near surface exhibit high maximum production rates (P_{max}) and light saturation constant (I_k) but low initial slope during stratification seasons (Fig. 2, Table 1).

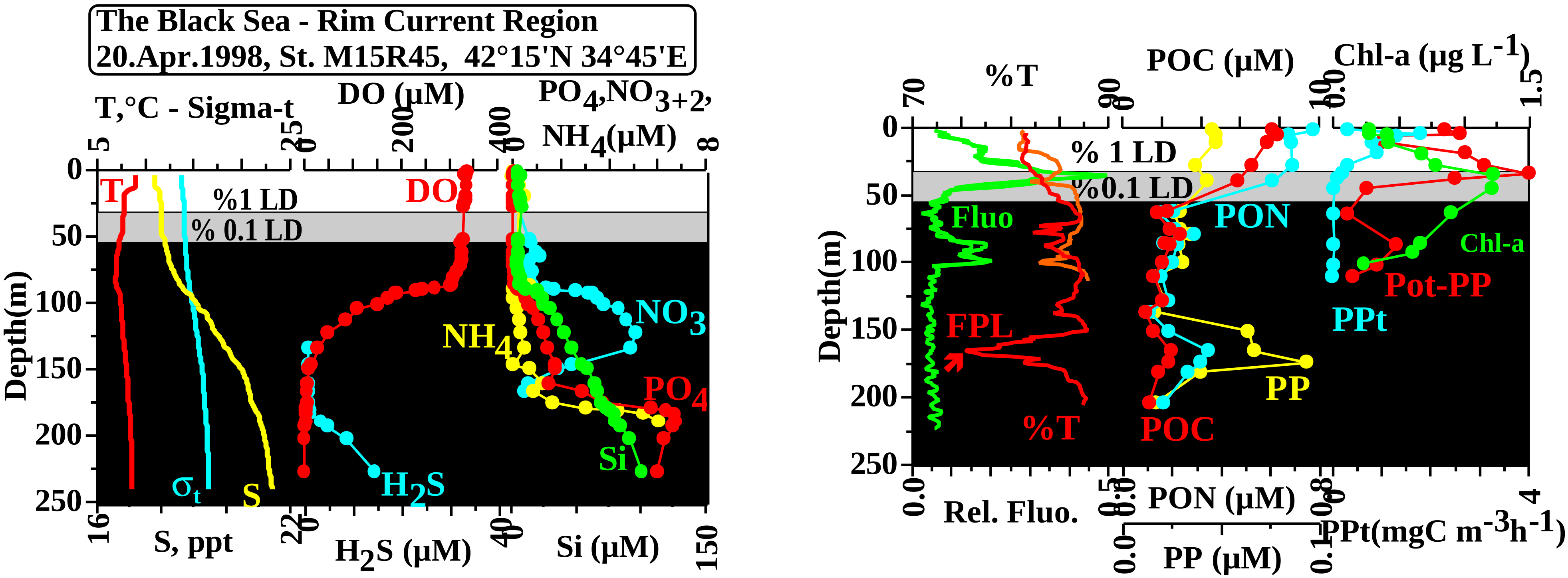

Fig. 2. Vertical distribution of hydrographical and bio-chemical parameters in the Black Sea (T:Temperature; S:Salinity; σ_t:Sigma-theta; DO: Dissolved Oxygen; Fluo: *In situ* Fluorescence; %T:Light Transmission; FPL: Fine Particle Layer; POC,PON,PP: Particulate Organic Carbon, Nitrogen, Particulate Phosphorus; Chl-a:Chlorophyll-a; PPt: Primary Production; Pot-PP: Potential (Max) Production;%1 LD: %1 Light Depth: Upper boundary of Euphotic Zone(EZ) %0.1 LD: %0.1 Light Depth: Lower boundary of EZ

The Sea of Marmara: **The less saline Black Sea origin waters occupy merely the upper 20m of the Marmara Sea and the Mediterranean origin subhalocline waters possess nearly constant temperature, salinity and density throughout the basin. The upper layer is well oxygenated opposite to its lower layer; the permanent and strong halocline drastically limits the ventilation. The Mediterranean waters possess relatively low nutrient and nearly saturated levels of DO before they enter the deep Marmara basin, but during its stay of 6-7 years, DO declines to about 30-75 µM in the eastern basin (Polat *et al.*, 1998) (Fig. 3).**

Nutrient concentrations are relatively low in the upper layer where NO_3/PO_4 molar ratio estimated as <2-4 (Polat *et al.*, 1998). The nutrient concentrations in the lower layer are as high as 8-10 µM for NO_3+NO_2, 0.8-1.2 µM for PO_4 and 35-40 µM for Si, changing very little with depth and the NO_3/PO_4 molar ratio remains constant at 8-10. The nutricline coincides with the halocline in the Sea of Marmara (Fig. 3).

The bottom of the EZ coincides with the halocline in the Sea of Marmara; thus primary production is limited to the upper layer. A subsurface Chl-a maximum is located in the upper EZ. POM concentrations in the EZ are relatively higher than those in the Black Sea and no apparent POM accumulation is observed within the pycnocline. Pycnocline also limits particle snow to the subhalocline waters. The N/P ratios(7-12) of seston are as low as in the Mediterranean, being consistent with the NO_3/PO_4 ratios of the Marmara subhalocline water. The highest primary production rates are always determined in the upper few meters of the EZ. The rate decreases rapidly with depth and drops to very low levels at 1% LD. Pot-PP values are in good agreement with the *in situ* fluorescence and Chl-a data. P-I curve characteristics are similar to those from the Black Sea (Fig. 3, Table 1).

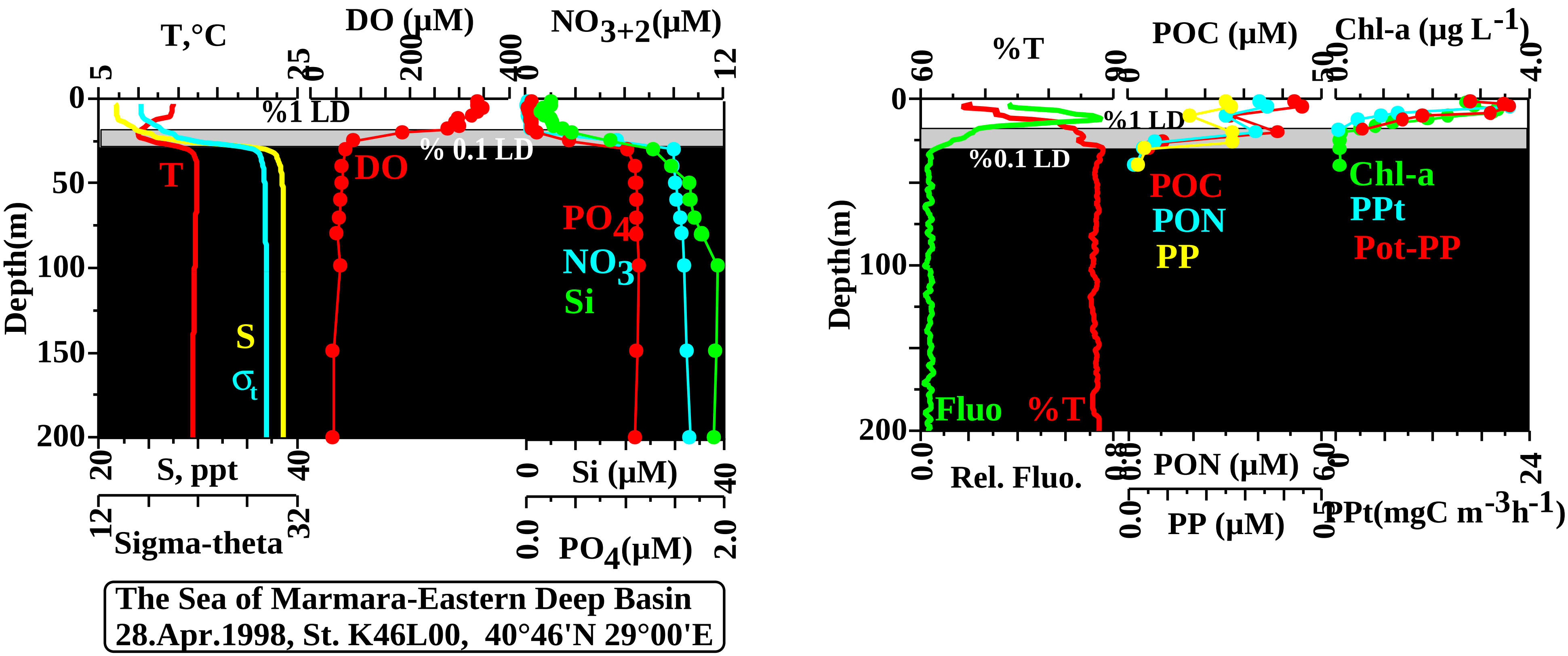

Fig. 3. Vertical distribution of hydrographical and biochemical parameters in the Sea of Marmara (See Fig. 2 for symbols)

Eastern Mediterranean: **During the thermal stratification period (an example is given for Rhodes Gyre, RG; Fig. 4), the warm and salty surface waters are separated from the less saline Levantine Deep Water (LDW) and the seasonal thermocline is established at 25m. Temperature and salinity of LDW decrease very slowly with depth while the density remains almost constant at 29.15 for all seasons. The upper water column is well oxygenated down to the upper boundary of the nutricline. The DO maximum due to the photosynthetic activity is pronounced, sharp and located at the shallower depths in the RG. The deep water of the NE Mediterranean is also rich in oxygen; the concentration range between 180-200 µM.**

The nutricline forms quasi-permanently at the base of the EZ and the base of the nutricline is determined by the depth of the LDW masses upwelling in the RG. If LDW reaches as far as the surface, the nutricline disappears as occurred in the severe winters of 1992 and 1993 (Yilmaz and Tugrul, 1998). The average concentrations of nutrients in the LDW are determined as 0.2 µM for PO_4, 5.5 µM for NO_3 + NO_2 and 7-8 µM for Si and the NO_3/PO_4 molar ratio is as high as 28. In anticyclonic regions, the layer below the EZ down to the top of the main nutricline is relatively poor in nutrients when compared with the LDW values (Yilmaz and Tugrul, 1998). This layer coincides with the Levantine Intermediate Waters (LIW) and the main nutricline is established at the permanent halocline formed within the LIW-LDW interface and far below the EZ (Fig. 4).

The average EZ is determined as 70m in the Rhodes basin which is thicker (95m, Ediger and Yilmaz, 1996) in the anticyclonic eddies. The deep Chl-a maximum (DCM) is common feature of eastern Mediterranean, it forms at shallower depths (70m) in the cyclonic RG and in general the depth of DCM coincides with the nutricline. The profiles of Chl-a are consistent with *in situ* fluorescence; with peak values at or just above the 1 % LD. The DCM forms at greater depths (80-95m) in the peripherial

regions of RG and in anticyclonic eddy systems and it is located at the base of the EZ which is far above the main nutricline. In contrast to the Black and Marmara Seas, POM concentrations reach the peak values at the base of the EZ when the surface layer is seasonally stratified and thus, depleted in nutrients available for photosynthesis. This causes a very high POC/Chl-a ratio at the near surface and relatively low ratio at the DCM depth. The average EZ concentrations of POC, PON and PP are at least 3-4 times less than the values in the Black and Marmara seas, whereas nearshore data are comparable with the seston content of deep Black Sea. Unexpectedly, N/P ratios of POM are very low (7-9) in the coastal region but slightly increase to levels of 10-15 in the open sea. The deep fluorescence maximum coincides with the Pot-PP maximum, both of which are more pronounced in the RG than in the periphery. It is also worth to note that, unlike the Black Sea and the Sea of Marmara, not only the Pot-PP values, but also the PPt rates are significant at the DCM depth. A distinguished feature of the P-I curves obtained from the NE Mediterranean, is the high production rates per unit Chl-a, implied by high P_{max} values for the near surface and for the DCM depth. In the majority of the P-I curves from the upper part of the EZ, photo-inhibition is not detected while PPt and the Chl-a data indicate that photo-inhibition is an important factor, limiting primary production at the upper few meters, since the irradiance level is significantly high in the NE Mediterranean. The initial slope of P-I curve from DCM depth is relatively high when compared with those of P-I curves from the Black and Marmara seas (Fig. 4, Table 1).

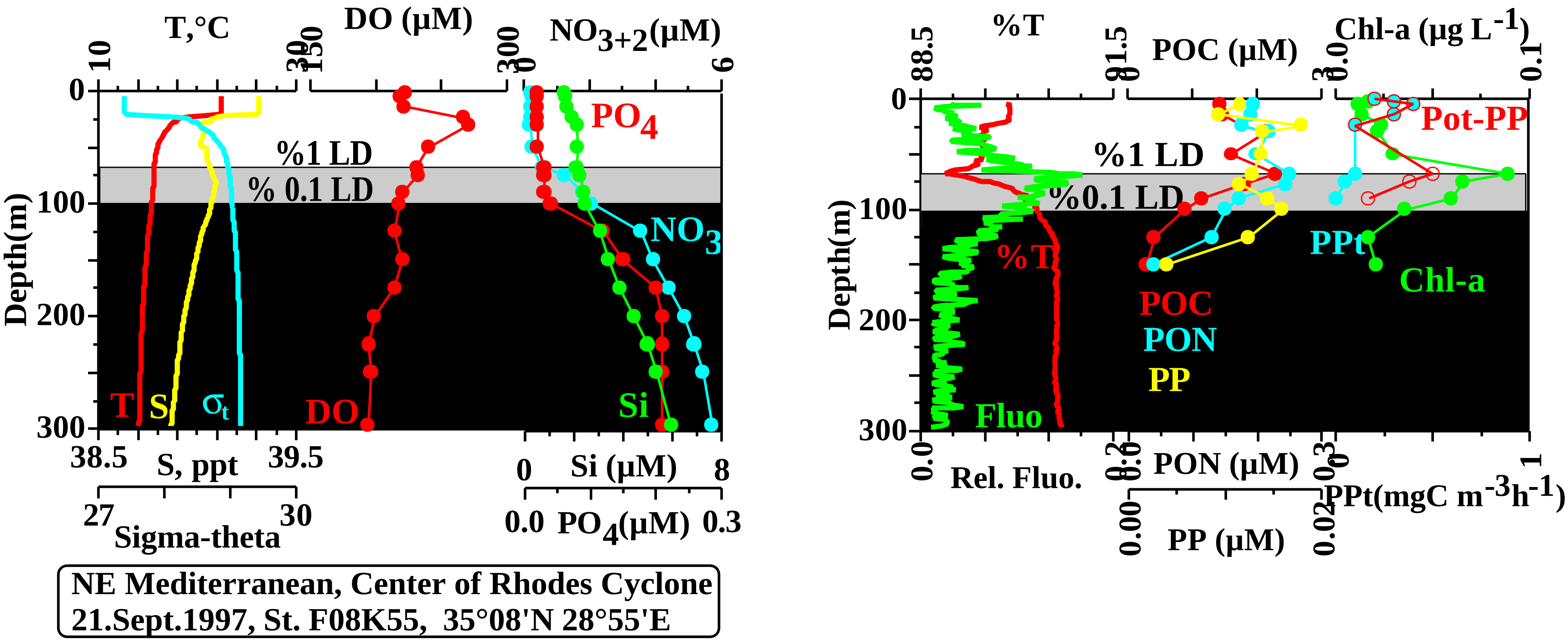

Fig. 4. Vertical distribution of hydrographical and biochemical parameters in the NE Mediterranean(See Fig.2 for symbols)

Table 1. Comparison of the three interconnected regional seas surrounding Turkey: Survey along the eutrophic and oligotrophic ecosystems

Parameter	*The Black Sea*	*Marmara Sea*	*NE Mediterr.*
Secchi Disc Depth (m)	9.3±1.6	6.5±0.7	20.9±3.5
Euphotic Zone (EZ) (1% Light Depth, m)	29.6±4.9	16.3±3.9	76.8±10.5
Attenuation Coefficient, K_d (m^{-1})	0.16±0.03	0.26±0.02	0.07±0.01
Surface Chl-a(μg L^{-1})	0.30±0.22	1.39±1.32	0.03±0.02
Max Chl-a(μg L^{-1})	0.74±0.37	2.2±1.1	0.14±0.11
Integr. Chl-a(μg L^{-1}) (Down to 1% LD)	14.2±5.8	26.8±19.7	3.2±1.4
C/Chl Ratio (Surface-1% LD)	586-139	310-165	2148-327
POC (μM) (Open-Coastal)	7.2-14.5	13.4-28.9	1.7-11.2
PON (μM) (Open-Coastal)	0.7-1.3	1.1-2.9	0.2-1.0
PP (μM) (Open-Coastal)	0.06-0.09	0.11-0.24	0.01-0.07
Primary Production (mgC m^{-2} d^{-1})	487±184	1521±465	194±143
P_{max}(mgC $mgChl^{-1}$ h^{-1}) (Surface-1% LD)	13.2-5.4	21.8-4.3	23.5-11.8
Light Saturation Constant, I_k(μE m^{-2} s^{-1}) (Surface-1% LD)	195-78	200-55	164-57
Initial Slope of P-I Curve α [d^{-1} $(Wm^{-2})^{-1}$] (Surface-1% LD)	0.01-0.05	0.04-0.05	0.01-0.1

Conclusion:

The bulk of primary production is accomplished in the upper euphotic zone (down to approximately 10% light depth) in the Black Sea and the Sea of Marmara, although Chl-a and fluorescence maxima are located at around 1% light depth. In contrast, in the NE Mediterranean, phytoplankton in the vicinity of the DCM at ~1% light depth have the largest share in the total primary production in the water column. Secondary Chl-a maxima has been observed far below the euphotic in the nearshore regions in the Black Sea.

Organic carbon synthesis per unit Chl-a in phytoplankton cells increases with the increasing temperature of the upper euphotic zone, but decreases with the increasing Chl-a content of each cell. P-I curves indicate that the light adaptational characteristics of the phytoplankton populations from the upper and lower layers of the euphotic zone vary significantly. This variation becomes more evident when the seasonal thermocline is steep.

The Black and Marmara seas are ranked in the meso-trophic (eutrophic in the coastal areas) and eutrophic respectively. Eastern Mediterranean is not as oligotrophic as previously reported if one takes into account the Rhodes Cyclonic Gyre in the NE basin.

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