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Studies of chlorophyll-a levels in the North Aegean Sea using SeaWiFS data

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ABSTRACT: The hydrographical characteristics of the North Aegean Sea (NAS) have been studied using in-situ data and thermal NOAA AVHRR data. Lately, efforts to simulate the circulation patterns in the NAS have also been performed. Thus, it has been found that the discharge of water of Black Sea origin (BSW) affects extensive areas of the NAS surface waters. Another meso-scale phenomenon is the extensive upwelling south of the mouth region of the strait of the Dardanelles. The knowledge of the water quality situation is, however, small.

This paper will describe the use of SeaWiFS ocean color satellite data in order to study the water quality situation in the NAS in terms of chlorophyll-a levels and patterns, especially in relation to the discharge of the BSW, which is rather rich in nutrients and with enhanced levels of chlorophyll. The latter could also act as a “tracer” for the influence of the BSW and for the movement of water masses. The analysis of ocean color satellite data in terms of chl-a is strongly dependent on the atmospheric correction and two different algorithms have been studied, the one in the SeaDAS software package and the MUMM approach. Moreover, two slightly different chlorophyll algorithms have been compared, SeaDAS 3.3 and 4.0 respectively. Results from published data on in-situ measured chl-a levels in the NAS have been compared with MUMM satellite data.

It is shown that SeaDAS 3.3, SeaDAS 4.0 and MUMM derived chl-a levels from three locations in the NAS agree fairly well. Conclusive results from the comparison with in-situ chl-a data are difficult to obtain, one reason being possible bio-fouling of the in-situ apparatus. However, it seems as if SeaWiFS MUMM data gives significantly higher chl-a levels during extended periods. Analysis of SeaWiFS data from 1999 clearly shows that enhanced chl-a levels exist during the whole year in the northern part of NAS, approximately north of the island of Limnos with especially high levels during December to April/May (levels of about 0.5 – 1.1 mg/m^3). There is a fairly distinct boundary to the water masses to the south with chl-a levels of about 0.2 – 0.4 mg/m^3 during the whole year. A seasonal transport pattern of the BSW water from the Dardanelles' mouth region is evidenced by the chl-a patterns and is similar to the ones observed using NOAA SST data. A seasonal cycle of the maximum chl-a concentrations at the mouth of the Dardanelles is also found, highest levels (1-3 mg/m^3) during January-March.

1 INTRODUCTION

The North Aegean Sea (NAS) is part of the Mediterranean Sea and is bordered by Greece and Turkey and the Cyclades islands to the south (Fig.1). The W-E length scale is about 270 km and the N-S scale about 350 km. The Black Sea is connected to the NAS via the Sea of Marmara and the strait of the Dardanelles. The flow in the latter has a strongly stratified two-layer character with the upper layer, with water of Black Sea origin (BSW), flowing to the NAS and with the lower layer transporting dense, high salinity Mediterranean water towards the Sea of Marmara. The hydrographical situation in the surface waters of NAS is significantly affected by the discharge of BSW, see for instance Zodiatis (1994) according to whom a surface layer of a depth of up to 40 m is characterized by BSW. Thermal NOAA AVHRR satellite data, Jönsson (2000), using SST as a “tracer” for water masses and water movements give evidence of the influence of the BSW and also clearly indicate the seasonal variation of the transport pattern of the BSW. The upper layer monthly average flow at the mouth of the Dardanelles is estimated at 5,000 – 15,000 m^3/s, Kourafalou & Barbopoulos (2001) with the highest values in April-July. The width of the strait at the mouth is about 13 km and the upper layer depth of the order

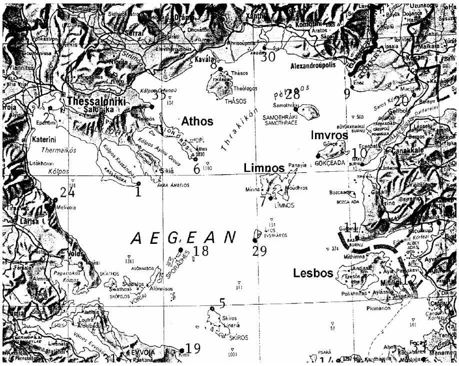

Figure 1. North Aegean Sea with the mouth of the strait of the Dardanelles SE of the island of Imvros

of 10 m, Oguz & Sur (1989). Moreover, Zodiatis (1994) has reported, on the basis of CTD measurements, evidence of extensive upwelling south of the mouth of the Dardanelles in summer/early autumn, a phenomenon which is also visible in NOAA images, Jönsson (2000).

The BSW is characterized by enhanced pollution levels and will thus affect the surface water quality in extensive areas of the NAS but fairly little is known about the basin scale conditions. The purpose of this paper is to study the water quality situation in the surface waters of NAS in terms of chl-a levels using SeaWiFS ocean color data from 1998-2001. Firstly, the properties of SeaWiFS derived chl-a data are discussed by comparing results from the application of different algorithms for atmospheric correction and chl-a derivation. Secondly, some comparison is made between satellite derived chl-a levels and results from on-going in-situ point measurements in the NAS. Thirdly, results from the determination of the basin scale surface distribution of chl-a levels in the NAS are discussed. Fourthly, the seasonal variation of the maximum chl-a levels at the mouth of the Dardanelles is described. Finally, a comparison is made between NOAA AVHRR SST data and SeaWiFS chl-a data from the upwelling area off the Turkish coast.

2 ANALYSIS OF SATELLITE DATA

SeaWiFS ocean color satellite data are obtained in six visible and near infrared channels with a spatial resolution of about 1,1 km at nadir. As the atmospheric conditions in the NAS area are often favorable, a large number of useful SeaWiFS scenes (more than a hundred) have been downloaded on a regular basis from the data archive at NASA GSFC, USA. The analysis of the SeaWiFS data is essentially a two-step procedure (besides the raw data calibration). Atmospheric correction is the first step and a very important one as about 80-90 % of the satellite signal is due to atmospheric effects (molecular, aerosol scattering etc). The original “black pixel” method, i.e. assuming no water leaving radiance in the two NIR bands 765 nm and 865 nm respectively, and developed for case 1 (oceanic) waters has been shown to give erroneous results, especially in case 2 (coastal) waters or in situations with enhanced chl-a levels whereby too high chl-levels were obtained and/or some water areas were not analyzed. This method is used in the SeaDAS 3.3 and 4.0 software, Fu et al (1998). Instead, the L1A SeaWiFS data have been atmospherically corrected using the MUMM method (from the Belgian Management Unit of the North Sea Mathematical Models), see Ruddick et al (2000). Basically, this method assumes that the ratio of 765 nm:865 nm aerosol reflectances and water-leaving reflectances are spatially homogeneous and can be considered as calibration parameters. The latter one is assumed to be independent of region and time and is put at 1.72. The former one (eps78) can be estimated for each image and will normally vary between 1.0 and 1.15. A simplified MUMM approach is possible using a fixed eps78 instead of calculating it. In this way the calculation time is significantly reduced and this method was used, with eps78=1.05, for the analysis of the SeaWiFS scenes in this paper. After the atmospheric correction step, water-leaving radiances are obtained which are used as inputs to chl-a algorithms, one for SeaDAS 3.3 and another one for MUMM and SeaDAS 4.0, O,Reilly et al (2000) where the latter one is given by:

$$\mathrm{chl} = \exp(2.303(0.366 - 3.067\mathrm{R} + 1.930\mathrm{R}^2 + \\ + 0.649\mathrm{R}^3 - 1.532\mathrm{R}^4))$$

where chl = chl-a concentration in mg/m3 and R = maximum of $^{10}\log$ of ratios of normalized water leaving radiances for 443/555, 490/555 and 510/555 nm respectively.

The effect of different eps78 values in the MUMM software and for the subsequent SeaDAS 4.0 chl-a determination was investigated for a few locations in the NAS, table 1. It is obvious that an increasing eps78 value diminishes the chl-a value, the effect being stronger the higher the chl-a concentration is.

Table 1. Effect of different eps78 values on the derived chl-a concentrations (mg/m^3) for four different locations, loc1,..,loc4, in the NAS.

eps 78	loc1	loc2	loc 3	loc4
1.03	0.978	0.853	0.523	0.177
1.08	0.833	0.785	0.481	0.173
1.15	0.833	0.653	0.433	0.173
1.22	0.833	0.665	0.338	0.173

3 COMPARISON BETWEEN DIFFERENT CHL-A ALGORITHMS

The derived chl-a concentrations for two locations in the NAS (a low chl-a area in the southern part and a high chl-a area in the mouth region of the Dardanelles) were compared for SeaDAS 3.3, 4.0 and MUMM respectively. Fig.2 shows the results. The

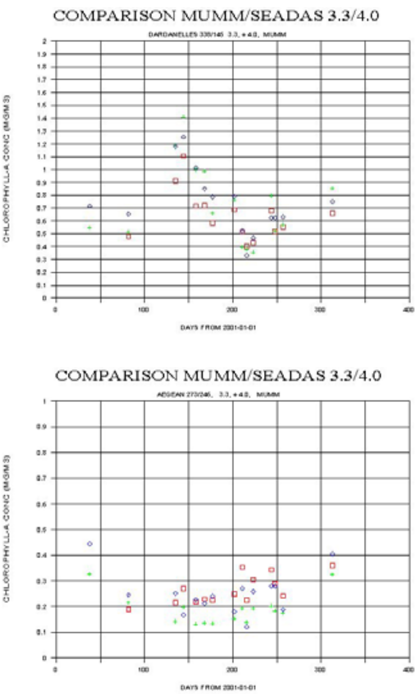

Figure 2. Comparison between chl-a algorithms SeaDAS 3.3 (□ red), 4.0 (+, green), MUMM (◊, blue) for the Dardanelles mouth region (top) and the offshore area in the southern part of NAS (bottom)

magnitudes of the differently deduced chl-a levels are the same. For instance: SeaDAS 3.3, 4.0, MUMM = 1.1, 1.4, 1.26 mg/m^3 respectively (Dardanelles) and 0.22, 0.14, 0.25 mg/m^3 respectively (offshore, southern part). There might be some tendency for MUMM to enhance low chl-a levels (less than about 1 mg/m^3) but for practical purposes the three algorithms seem to be fairly equal.

4 COMPARISON OF IN-SITU DATA AND SEAWIFS DERIVED DATA

Continuous measurements of chl-a are on-going at a few fixed locations in the NAS within the Greek POSEIDON project (2002) and are published on the Internet. One measurement station is located between the island of Limnos and the peninsula of Athos (lat 39.96 N, long 24.72 E). Fig 3. shows a comparison of these in-situ data with SeaWiFS MUMM derived data from the closest pixel for the period 2000-2001. It should be stressed that in-situ data sometimes vary considerably during the day, thus average values during the day have been used for the comparison. Unfortunately, in-situ data for part of this period were not available to the author. It is evident from Fig.3 that it is difficult to assess the

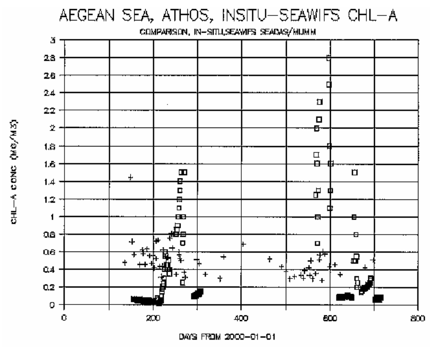

Figure 3. Comparison between in-situ chl-a (Athos, NAS) and SeaWiFS MUMM derived chl-a concentrations. Squares (□) in-situ, crosses (+) SeaWiFS. Horizontal axis: days from 2000-01-01, vertical axis: chl-a conc (mg/m^3)

accuracy of the SeaWiFS data. They are almost entirely contained in the interval 0.3-0.6 mg/m^3 whereas in-situ data at times are very low (≈ 0.05 mg/m^3) and at other times very high (2-3 mg/m^3). One could think of different reasons for the discrepancy: the rapid variation of the chlorophyll concentration during the day, malfunctioning of the in-situ system at times (bio-fouling for instance), inappropriate chl-a algorithms, the incompatibility between the spatial scales for in-situ data (point measurement) and satellite data (km scale) respectively. A general conclusion is that an assessment of SeaWIFS chl-a data requires field studies specifically dedicated to this purpose.

5 BASIN SCALE CHL-A CHARACTERISTICS

The BSW discharging into the NAS has got a significantly lower salinity (≈ 23-27 psu) and thus a lower density than the surface waters of the Aegean Sea (≈ 39 psu). This fact implies that the BSW water will remain in the surface waters of the NAS even after strong mixing with the NAS water has taken place. Thus, according to literature, Zodiatis (1994), Kourafalou & Barbopoulos (2001), a thin layer (depth of the order of 40 m) of low salinity water exists in extensive areas of the NAS associated with the BSW discharge and one could expect that the water quality of the BSW will influence this upper, low salinity layer. As the chl-a contents of the BSW is considerably higher than for the NAS surface water, implying enhanced levels of nutrients for algal growth, one could assume that enhanced chl-a conditions would prevail in this above-mentioned BSW-associated upper layer in the NAS. Figs. 4a-f show a series of six SeaWiFS MUMM chl-a scenes

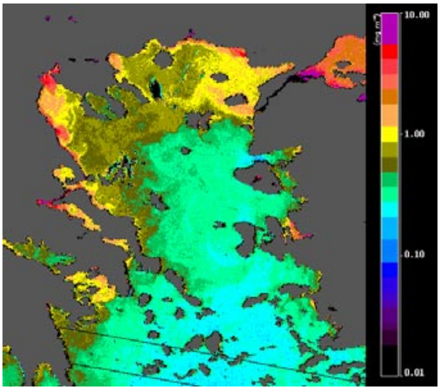

Figure 4a. SeaWiFS MUMM chl-a, 1999-01-17 at 10.36 GMT. Color scale 0-10 mg chl-a/m^3

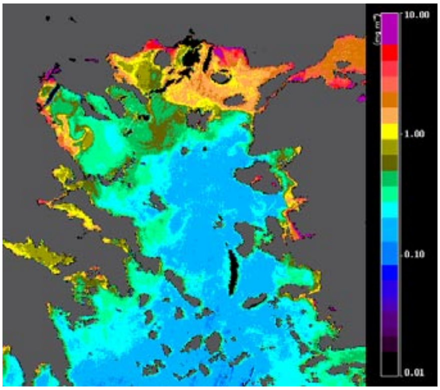

Figure 4b. SeaWiFS MUMM chl-a, 1999-04-18 at 10.38 GMT. Color scale 0-10 mg chl-a/m^3

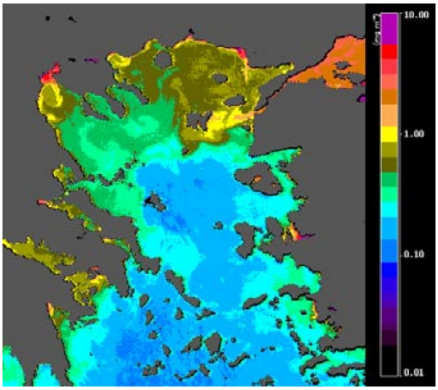

Figure 4c. SeaWiFS MUMM chl-a, 1999-06-15 at 10.49 GMT Color scale 0-10 mg chl-a/m^3

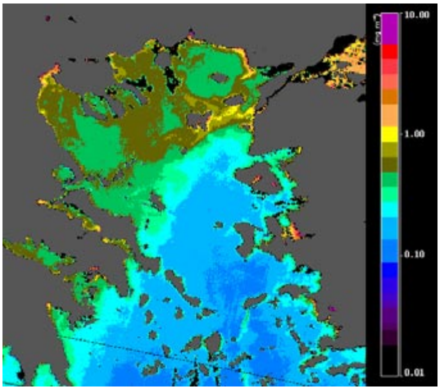

Figure 4d. SeaWiFS MUMM chl-a, 1999-08-25 at 10.40 GMT. Color scale 0-10 mg chl-a/m^3

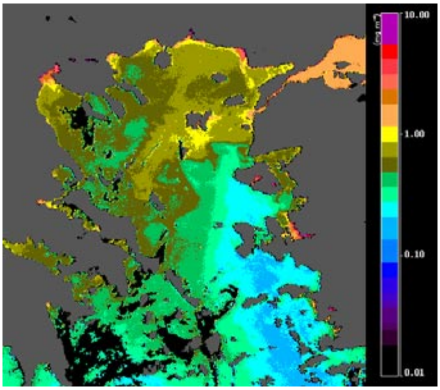

Figure 4e. SeaWiFS MUMM chl-a, 1999-09-30 at 10.54 GMT. Color scale 0-10 mg chl-a/m^3

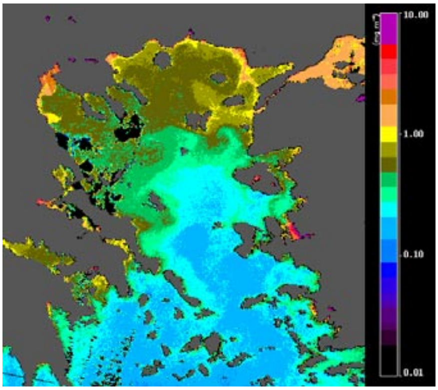

Figure 4f. SeaWiFS MUMM chl-a, 1999-10-29 at 10.56 GMT. Color scale 0-10 mg chl-a/m^3

from different seasons of the year 1999. In the first place, the six scenes in Fig. 4 clearly show that there are basically two different surface water masses in the NAS during the whole year, one water mass roughly located north of the island of Limnos with enhanced chl-a levels and one water mass in the southern part (bluish or greenish) with low chl-a levels. Moreover, the six scenes indicate that chl-a levels in the northern part are especially high during Jan-April. One could also notice that the eastern part (east of the Halkidiki peninsula) of the area north of Limnos has especially high chl-a levels, which of course is natural due to the location of the Dardanelles. Thus, Fig.4a shows a level of about 1.5 mg chl-a/m^3 in the eastern part whereas the levels in the western part are of the order of 0.4 mg chl-a/m^3. Levels in the south (bluish) amount to about 0.15 mg chl-a/m^3. Fig. 4e, however, eastern part , has got a level of about 0.6-0.7 mg chl-a/m^3, western part about 0.5 mg chl-a/m^3 and the southern part 0.2-04 mg chl-a/m^3.

In order to study the chl-a levels of the northern and southern surface water masses in a more systematic way, the average chl-a levels were determined in two large areas, Fig. 5, for all the SeaWiFS scenes from 1999 (more than 40 scenes). In Fig. 5 the red rectangle corresponds to the northern, enhanced chl-a area and the green rectangle to a southern, low chl-a area mainly unaffected by BSW and representative for the Aegean Sea surface waters. Fig. 6 shows the results of this averaging process. Squares correspond to the northern, red rectangle and crosses correspond to the southern, green rectangle. In the first place it is very obvious that the chl-a concentration is significantly higher in the northern rectangular area during the whole year with levels of 0.5–1.1 mg/m^3 to be compared with levels of 0.2–0.4 mg/m^3 in the southern rectangular area. Moreover, there is a rather distinct seasonal variation of the chl-a levels, especially in the northern part with the most enhanced levels from about December to about April/May. This fact does not seem to correlate positively with the discharge characteristics of the upper layer of the Dardanelles. As stated in the introduction, the maximum discharges occur in April to July. Thus, one might put forward the hypothesis that the especially enhanced chl-a levels in the northern NAS might be correlated with the chl-a levels of the discharge of the BSW into the NAS. In order to check this hypothesis long-term studies of the maximum chl-a levels at the mouth of the Dardanelles were performed using SeaWiFS scenes from 1998-2002.

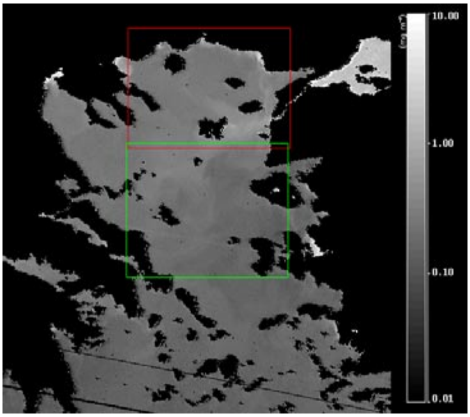

Figure 5. Areas for determination of the average chl-a conc in SeaWiFS scenes from 1999. Red rectangle: enhanced chl-a level affected by the BSW. Green area: mainly unaffected Aegean surface water

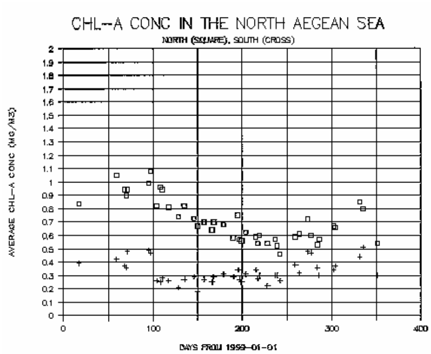

Figure 6. Average chl-a conc in the two areas depicted in Fig 5. Squares: red rectangle, BSW affected waters. Crosses: Green rectangle, unaffected Aegean Sea surface water. Vertical axis: chl-a conc (mg/m^3). Horizontal axis: days from 1999-01-01, i.e. results from one year

6 MAXIMUM CHL-A LEVELS AT THE MOUTH REGION OF THE DARDANELLES

The SeaWiFS scenes from 1998 up to 2002 were analyzed (MUMM) as to the maximum chl-a concentration along a N-S transect (longitude 26.10^0) 5 km off the mouth of the Dardanelles strait. Fig. 7 shows the result from the analysis of 143 scenes. There is an obvious seasonal variation of the chl-a

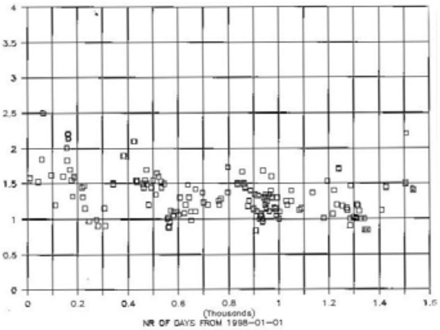

Figure 7. Maximum chl-a concentration along a N-S transect 5 km off the mouth of the Dardanelles strait in the NAS. Horizontal axis: number of days (in thousands) from 1998-01-01, i.e. about 1500 days. Vertical axis: chl-a conc from 0-4 mg/m^3 according to SeaWiFS, MUMM

level with the peaks in approximately late February to early/middle March (conc of the order of 2 mg chl-a/m^3) and minima in approximately August/September (conc somewhat less than 1 mg chl-a/m^3). According to the analysis in paragraph 5, based on Fig.6, the especially enhanced levels of chl-a in the northern part of the NAS (red rectangle in Fig.5) occur from December to April/May. The maximum chl-a level at the mouth region of the Dardanelles occurs approximately in the middle of this time period which is a strong indication that chl-a concentration in the BSW and not the discharge rates is the most relevant factor for the enhanced chl-a levels in the northern NAS.

7 UPWELLING AREA

A previous study, Jönsson (2000), using NOAA AVHRR SST data has shown that there is an extensive upwelling area off the Turkish coast south of the mouth region of the Dardanelles during late summer/autumn, characterized by low surface water temperatures. This phenomenon is most probably related to the prevailing northerly winds during this period of the year. Fig. 8 shows an example of the upwelling (magenta area) off the Turkish west coast and south of the mouth region of the Dardanelles.

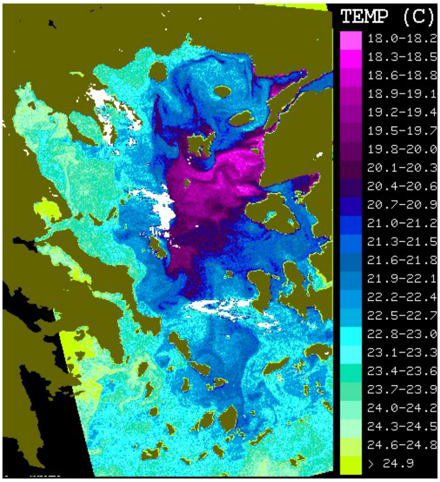

Figure 8. NOAA AVHRR SST image from 1997-09-11 at 1208 GMT, N-14. Magenta colors correspond to 21-22 ^{0}C and bluish colors 18-19 ^{0}C. Notice the cold upwelling area south of Limnos (magenta)

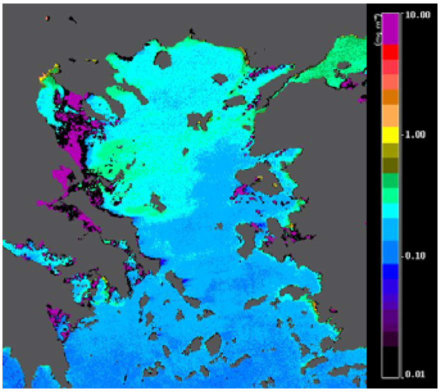

Figure 9. CZCS chl pigment concentration (SeaDas 3.3) in the NAS. Scene from 82-09-04. Chl pigment concentrations 0-10 mg/m^3) with blue about 0.2 mg chl-a/m^3. Notice the low chl-a levels at the upwelling area off the Turkish coast, south of Limnos

The scene is a NOAA AVHRR SST image (N-14) from 1997-09-11 at 1208 GMT with magenta colors representing 18-19 ^{0}C and bluish colors representing 21-22 ^{0}C. Thus, the scene indicates the very distinct feature of the upwelling area with surface water temperatures deviating from the ambient surface waters with about 2-3 ^{0}C. A comparison with a CZCS chl pigment image from the same period of the year, 1982-09-04, but from a different year, Fig. 9, clearly shows that there is no enhanced chl concentration in the upwelling area. A further comparison could be made with a SeaWiFS image, also from the same period of the year but from a different year, Fig. 4e.

There is also in this latter case no sign of any specific enhanced chl-a feature in the upwelling area. Thus, one could draw the conclusion that the upwelling, which takes place every year during approximately the same period, is not characterized by any change in the water quality in terms of chl-a levels. This fact indicates that the water, brought the surface layer by the upwelling phenomenon, is not rich in nutrients, stimulating the growth of algae.

8 CONCLUSIONS

HRPT SeaWiFS ocean color data have been analyzed in terms of chl-a concentration in the North Aegean Sea (NAS) with special emphasis on the effect of the discharge of water of Black Sea origin (BSW) via the strait of the Dardanelles. The analysis of the satellite data basically rests on algorithms for atmospheric correction and for chl-a derivation respectively. Two different algorithms for the atmospheric correction were studied (SeaDAS and MUMM respectively) as well as two slightly different chl-a algorithms (SeaDAS 3.3 and 4.0 respectively). Derived chl-a levels in a few selected locations in the NAS did not differ significantly (less than order of magnitude) for the different cases. The further analysis of chl-a conditions in NAS was based on MUMM for atmospheric correction and SeaDAS 4.0. Comparison between published in-situ chl-a levels and SeaWiFS derived levels was difficult to evaluate, probably due to uncertainties about the functioning of the in-situ system. Basin scale chl-a characteristics based on SeaWiFS data from 1999 showed that the northern part of the NAS (approximately north of Limnos) consistently had significantly higher chl-a levels (0.5–1.1 mg/m^3) than the southern part (0.2–0.4 mg/m^3). This fact is interpreted as an effect of the BSW discharge through the Dardanelles strait. Further analysis of the maximum chl-a levels in the mouth region of the Dardanelles during 1998-2002 showed that there is a seasonal variation with peak levels in late February to early/middle March. As the especially enhanced chl-a levels in the northern NAS occurred from approximately December to April/May one might conclude that this is a strong indication that the water quality (and not the discharge rate) of the BSW discharge is the main reason for the influence of the BSW on the surface water characteristics of the northern NAS. Finally, it was shown that the extended upwelling area off the Turkish coast, south of the Dardanelles, is not accompanied by enhanced chl-a levels which is an indication of the low nutrient levels of the deeper water layers brought to the surface layer.

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