Interannual variability of the early summer coccolithophore blooms in the Black Sea: impacts of climatic factors

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Abstract

Interannual variability of the early summer (May-June) coccolithophore blooms within surface waters of the Black Sea was studied by means of satellite-based bio-optical observations. The performance of two coccolithophore detection algorithms were tested for Black Sea conditions, and were found to provide comparable spatial patterns consistent with the corresponding true color images. An analysis of six, year-long OCTS and SeaWiFS imagery from 1997 onwards points to the presence of a major phytoplankton bloom in every early summer season. Blooms are dominated by densely populated coccolithophore algae within the entire basin, except during 2001. In the early summer of 2001, the coccolithophore activity was limited to the northeastern coastal zone, and the bloom in the rest of the basin was formed by non-coccolithophore groups, as suggested by their relatively strong chlorophyll signature. More coccolithophore over, limited coccolithophore abundance noted in the historical CZCS data suggests substantial differences in terms of spatial coverage and total biomass from the early 1980s to the late 90s. The increasing contribution of coccolithophores to the early summer phytoplankton community structure during the last decade is also consistent with the current view of dramatic shifts in taxonomic composition from diatoms to coccolithhophores and flagellates, as a part of transformations that took place in the Black Sea biogeochemistry and ecosystem structure under changing anthropogenic and climate forcing during the 1980s and 1990s, respectively.

Keywords: Black Sea, coccolithophore, SeaWiFS, chlorophyll

1. Introduction

 The present work aims to elucidate the inter-annual variability of early summer coccolithophore blooms depending on their relative abundance within mixed phytoplankton assemblages. Using the analysis of six, year-long, satellite-based bio-optical observations from the Ocean Color and Temperature Scanner (OCTS) and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) sensors since 1997, the year-to-year variations of bloom coverages detected as high reflectance patches in the data are documented, and compared with the historical observations collected by the Coastal Zone Color Scanner (CZCS) sensor in the early 1980s. The results are then interpreted within the framework of dramatic changes that took place in ecosystem structure and function during the last two decades in response to varying anthropogenic and climatic forcings (Oguz et al., 2002; Kideys, 2002). The current work, in addition, uses the Black Sea as an independent test site for assessing the performance of two different coccolithophore detection algorithms by comparing their products with the corresponding true color images.

From 1998 onwards, the daily, 8-day, and monthly average, 9 km resolution chlorophyll and normalized water leaving radiance SeaWiFS Level 3 data provided by the NASA-Distributed Active Archive Center (DAAC) are utilized in this study. These data are complemented by the OCTS data for 1997 and the CZCS data from the 1979-1985 period with comparable temporal and spatial resolutions. The radiance data were processed by the SeaWiFS Data Analysis System (SeaDAS) software v.4.3B (Baith et al., 2001). The processing of SeaWiFS data for chlorophyll concentrations involves the standard four-band OC4v4 algorithm (O'Reilly 2000) using the four available visible bands (443, 490, 510, 555 nm). The resulting chlorophyll concentrations were then calibrated according to the estimates derived from the local algorithm (Suetin et al., 2001). The calibration curve between the Suetin et al. (2001) and OC4v4 algorithms suggests an offset by a factor of two.

The standard coccolithophore mask algorithm, originally proposed by Brown and Yoder (1994) for the CZCS data, hereinafter referred to as BY algorithm, was built according to pre-specified ranges of five distinct combinations of three mean normalized water leaving radiances at 443, 510 and 555 nm for the SeaWiFS data. Their threshold values, used in the present study, are similar to values used in our previous work (Cokacar et al., 2001). For the CZCS data, the corresponding range of values for bands 440, 520 and 550 nm are taken as in Brown and Yoder (1994). The OCTS data for which no specific threshold criteria are available, on the other hand, was processed using the above limits for the SeaWiFS data.

A more recent coccolithophore detection algorithm was proposed by Gordon et al. (2001), hereinafter referred to as Getal algorithm. It differs from the BY algorithm by using the red and near infra red bands (670, 765, 865 nm) of mean normalized water leaving radiance data. The essence of this new algorithm is to minimize the influence from the absorption by chlorophyll and dissolved organic material in the visible channels in case 1 type waters. It is capable of empirically estimating calcite concentrations and thus regional coccolithophore abundance. This algorithm processes only the daily data, and is provided as a part of the NASA SeaDAS software.

2. Performance of the coccolithophore detection algorithms

The performance of the coccolithophore detection algorithms are assessed by means of two specific examples; by comparing their products with the corresponding SeaWiFS true color images. The first example is from a bloom episode on June 13, 2000 for which the true color picture is presented in Fig. 1a. Among other possible examples showing more complete bloom coverage within the basin, this true color image was chosen because it consists of considerable spatial variability characterized by three different color ranges corresponding to different levels of coccolithophore abundance. As shown, the turquoise color along the southern coast of the Black Sea refers to the densest bloom, whereas blue in the central zone and dark blue along the northern coast corresponds to moderate and weakest bloom conditions, respectively. In addition, these true color patterns also indicate how accumulations are often associated within highly rich mesoscale flow structures in the form of filaments, mush-room eddies, etc., distributed all over the basin.

Between each other the mean normalized water leaving radiance bands at 443, 510 and 555 nm for June 13, 2000 reveal similar horizontal structures (Fig 2a-c). In these figures, the regions with dark gray color represent high reflectance from coccolithophores, whereas the regions in the light gray color along the northern coast as well as in the eastern corner of the basin (cf. Fig. 2a) are characterized by weaker reflectance, with values outside the ranges specified above. The absence of dense coccolithophore communities in these regions correspond to the dark blue

color zone in the true color image shown in Fig. 1a. On the contrary, the light gray color band of the *nlw(443)* and *nlw(510)* in case 2 turbid waters along the northwestern coast (Fig. 2a,b) is related to strong absorbance (thus low radiance, below the threshold value) in these particular radiation bands due to presence of high concentrations of dissolved and particulate colored material, as shown by Holligan et al. (1983). The origin of the green to turquoise color in Fig. 1a in this coastal zone therefore differs from those in other regions of the sea and does not represent enhanced coccolithophore activity.

The close similarity between the horizontal structures of the three mean normalized water leaving radiances at 443, 510 and 555 nm (Fig. 2a-c) leads to horizontally uniform distributions of their ratios throughout the basin (Fig. 2d-f). The horizontal structure of the coccolithophore bloom represented by dark gray colors in Fig. 2g is primarily governed by the value of *nlw* at 443 nm. In other words, the most stringent criterion governing a coccolithophore bloom in the Black Sea is *nlw(443)>1.1*. Amongst the criteria assigned for the ratios, the most critical one is the lower bound of *nlw(510/555)*. Moreover, the fact that coccolithophore cell abundance is inversely related to chlorophyll concentration (e.g. Balch, et al., 1991; Head et al., 1998) is clearly noted along the northern rim of the basin. While this zone is identified by the absence of coccolithophores, its chlorophyll values greater than 0.6 mg m^{-3} (Fig. 2h), as compared to half this value within the rest of the basin, suggests the presence of some local non-coccolithophore based algae production.

The distribution of calcite concentration computed using the Getal algorithm for the same image is shown in Fig. 3. The calcite concentrations, related empirically to the backscattering coefficient at 555 nm, reveal a pattern which closely resembles the true color picture depicted earlier in Fig. 1a. The calcite distribution. identifies the turquoise color zone along the south coast of the Black Sea with the densest calcite accumulation of about 20.0 mmol m^{-3}. It gradually decreases to approximately 5.0 mmol m^{-3} towards the region along the northern coast and near the southeastern corner of the basin, marked by the absence of coccolithophores in the BY algorithm. This difference, as explained by Gordon et al. (2001), results from the capability of the new algorithm in detecting sub-bloom concentrations in regions discarded by the BY algorithm. A more substantial difference between these two algorithms emerges in case 2 waters along the northwestern coast, where the Getal algorithm gives rise to dense coccolithophore activity as opposed to the BY algorithm. This difference seems to arise since the Getal algorithm can not successfully differentiate the coccolithophore signature from dissolved and particulate organic material, as depicted by the difference between *nlw(443)* and *nlw(555)* distributions in Figs. 3a,c. The Getal algorithm is therefore mainly valid for open oceanic waters, and overestimates calcite concentrations in northwestern coastal waters of the Black Sea, where the algorithm requires some sort of filtering to introduce high absorbance at 443 nm. In fact, the BY coccolithophore detection criteria have already been included in one version of the Getal algorithm for this purpose. The detection criteria set in this particular version were, however, found to be different than those given by Brown (2000), and therefore not appropriate for our analysis. Those used in the present work were then applied to the Gental algorithm to obtain the modified calcite concentration distribution.

The second example for assessing the performance of the coccolithophore detection algorithms applies to the June 15, 2002 case for which the true color image is presented in Fig. 1b. The BY algorithm reveals basin wide coverage for coccolithophores in the Black Sea except along the western coastal zone (Fig. 4a). Once again, the Getal algorithm produces a very similar pattern of coccolithophore coverage. As in the previous example, the pixels with densest calcite concentrations (represented by dark gray color in Fig. 4b) coincide with the turquoise color spots in its true color image.

3. Interannual variability of the early-summer coccolithophore blooms

The inverse relationship between coccolithophore cell abundance and chlorophyll concentration will first be used to infer the interannual variability of the Black Sea's early summer coccolithophore blooms by means of the chlorophyll data. Fig. 5 shows distributions of the basin-averaged chlorophyll concentration obtained from the monthly OCTS and SeaWiFS data for regions of the water-column deeper than 200 m (thus neglecting the contribution of the western shelf) for the six year period from Januuary 1997 to December 2002. During the May-July periods in each of these years, represented by the gray shaded zones in Fig. 5, chlorophyll concentrations mainly varied around 0.4 ± 0.1 mg m^{-3}, and were markedly different than those around 0.8 mg m^{-3} for 2001. Superimposed on this figure is also the total number of pixels satisfying the coccolithophore bloom conditions according to the BY algorithm in the 8-day composite mean normalized water leaving radiance data. High total pixel numbers of approximately 12000 to 15000 during the first half of June, at the times of minimum monthly average chlorophyll concentrations, therefore suggest coccolithophore-rich phytoplankton blooms in 1997, 1998, 1999, and 2000.

The monthly distributions of coccolithophore coverage for June of each year formed as super-positions of pixels satisfying the bloom signature, in at least one of the four, 8-day data sets, as shown in Figs. 6a, b, d, and f indicate that the coccolithophore bloom spread uniformly over almost the entire basin during 1997, 1998, 2000 and 2002. However, the coverage is patchier in 1999 (Fig. 6c) with the total number of pixels not exceeding 10000. Moreover, a basin wide coverage in 2002 (Fig. 6f) is contradicted by the low number of pixels (less than 2000) in Fig. 5 due to cloud masking of pixels in each of the individual 8-day average data sets. Most of the regional coccolithophore patches under clouds are, on the other hand, recovered by monthly compositing (Fig. 6f). The most dramatic difference between the distributions of pixels and chlorophyll concentrations was found during the early summer of 2001. Low pixel numbers of approximately 2000 versus relatively high chlorophyll concentrations of approximately 0.8 mg m^{-3} suggest minimal contribution of coccolithophores during this particular phytoplankton bloom event with respect to other algae groups. This is further supported by the monthly coccolithophore distribution in Fig. 6e, where the population is only confines along the northeastern coast. While this particular region is characterized by monthly average chlorophyll concentration of less than 0.5 mg m^{-3} (Fig. 7), the rest of the basin without coccolithophores attains values approximately two times higher. Furthermore, the presence of high chlorophyll concentrations along the western coast (Fig. 7) is a robust characteristic feature of the Black Sea, and arises in response to high nutrient and organic material supply from the Danube and other local rivers (Oguz et al., 2002). This highly productive coastal zone is separated from the outer shelf by a sharp gradient generally coinciding with the density front of the brackish coastal current system.

4. Conclusions

Our analyses of the mean normalized water leaving radiance data indicate that both the BY and Getal algorithms result in similar coccolithophore bloom patterns in the Black Sea. Applicability of the Getal algorithm is limited only to daily Level 1 data, in contrast to the more flexible BY algorithm applied to Level 3 data sets with different temporal resolutions. The BY algorithm, on the other hand, can not yield a quantitative form of coccolithophore abundance, whereas the Getal algorithm provides a rough estimate in terms of calcite concentration using an empirical relationship derived on the basis of some bio-optical measurements.

The six, year-long (1997-2002) mean normalized water leaving radiance and chlorophyll concentration data sets indicate that the May-June bloom events constitute a robust signature of the annual phytoplankton structure, in addition to the late winter-early spring and the autumn events. In the five of these six years, this particular phytoplankton bloom structure is dominated by coccolithophore communities, whereas the other algal groups possess weaker and patchier distributions except in the early summer period of 2001 when coccolithophores were restricted only to the northeastern coast. Spatial patterns for coccolithophores, in the form of basin wide coverage, during 1998 and 2000 versus patchier coverage during 1999 and 2001 are interestingly quite similar to those reported in the eastern Bering Sea (Iida et al., 2002).

Observations of the densely populated basin wide coccolithophore blooms monitored after the advent of the OCTS and SeaWiFS sensors seem to be quite different than those provided by the CZCS data from the early 1980s. Unfortunately, the CZCS sensor was only able to provide some selected basinwide scenes during May-June, 1980-1983 for analysis of coccolithophore blooms. Application of the BY algorithm to the composite of this imagery set resulted in limited coccolithophore activity only around the periphery of the basin (Fig. 8). Our analysis suggest a robust character of this feature not varying with changes in the threshold values of the algorithm within a 25% range. These findings lead us to suggest that coccolithophores achieved distinctly different structures in terms of their abundance and horizontal extent from the early 1980s to the late 1990s. This result is also in accord with findings from other observations, and was related to the transformation of the Black Sea ecosystem in response to different environmental and climatic factors during the last two decades. For example, analyzing the long term data (1955-1994) from the Bulgarian Black Sea coast, Moncheva and Krastev (1997) noted the first appearance of intense *Emiliania huxleyi* blooms in 1983, and they have been monitored every year since 1986. Both Moncheva and Krastev (1997) and Humborg et al. (1997) explained this phenomenon by a shift in phytoplankton species composition from diatoms to coccolithophores and flagellates as a consequence of changes in the silicon to nitrogen ratio due to eutrophication as well as to a reduction in the dissolved silicate load of the River Danube following dam constructions in the early 1970s. These observations are further supported by a drastic decrease in water transparency after 1986 as a result of a 1.5-2 order of magnitude increase in coccolithophores and Peridinium populations (Vladimirov et al., 1997).

The similarities between recent coccolithophore bloom events of the eastern Bering Sea and the Black Sea may imply a global scale control operating on Coccolithophore bloom dynamics. The Bering Sea coccolithophore bloom events are found to develop as a result of a recent warming of arctic waters as a response to global warming. The Black Sea surface waters have also been subject to a temperature rise of about $2.5^{\circ}C$ since 1993, which was shown to lead to pronounced changes in its physical and biogeochemical characteristics within the second half of the 1990s (Oguz et al., 2003). In particular, enhanced stratification, a shallower mixed layer, and decreased inorganic nutrient availability are suggested to alter phytoplankton community structure in surface waters towards smaller cells with more enhanced nutrient uptake rates and light absorption characteristics as reported elsewhere (Karl et al., 2001). Coccolithophores are amongst the groups which might respond most favorably to such changes. Thus, their basin wide blooms observed by ocean color scanners after 1997 might be a consequence of climate-induced changes following the impacts of eutrophication in the 1980s.

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Figures
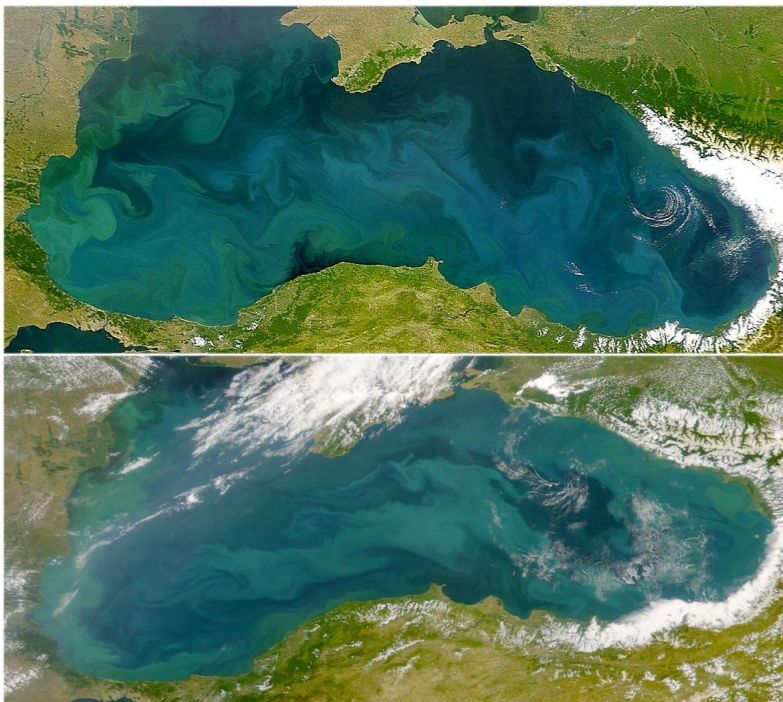
Figure 1. SeaWIFS true color images of the Black Sea during 13 June 2000 (upper) and 15 June 2002 (lower) showing coccolithophore distributions by the blue-turquoise color.
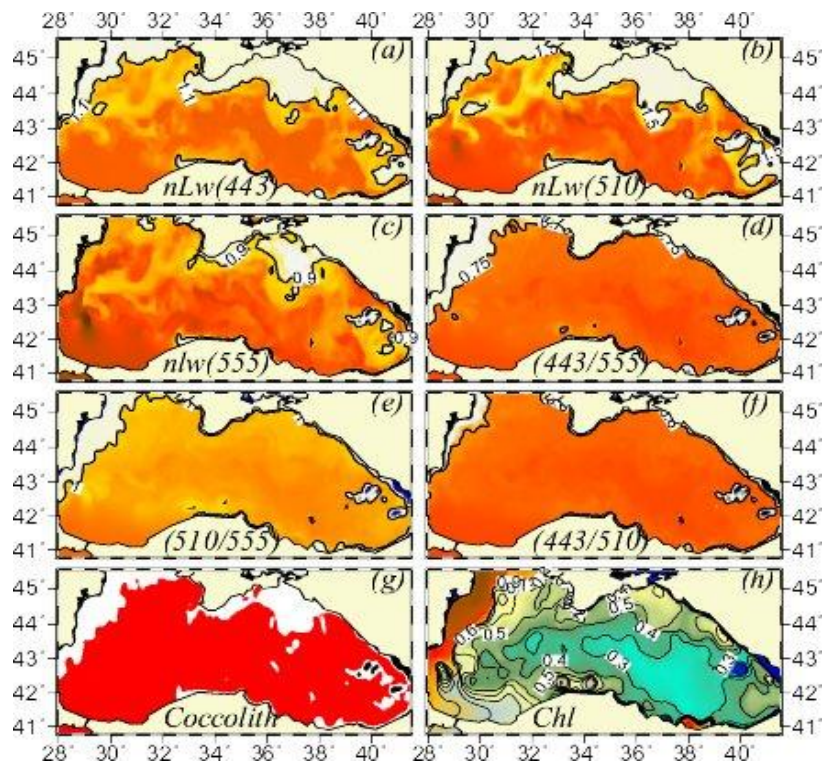
FIGURE 2. Distributions of the mean normalized water leaving radiances ($mW\ cm^{-2}\ \mu m^{-1}\ sr^{-1}$) at (a) 443 nm, (b) 510 nm, (c) 555 nm, and of their ratios for (d) 443/555, (e) 510/555, (f) 443/510, as well as the horizontal patterns of (g) coccolithophore abundance derived according to the Brown and Yoder (1994) algorithm, and (h) chlorophyll concentration ($mg\ m^{-3}$).
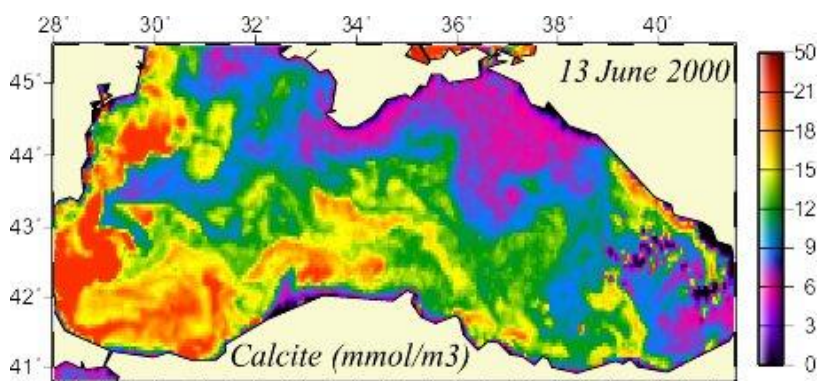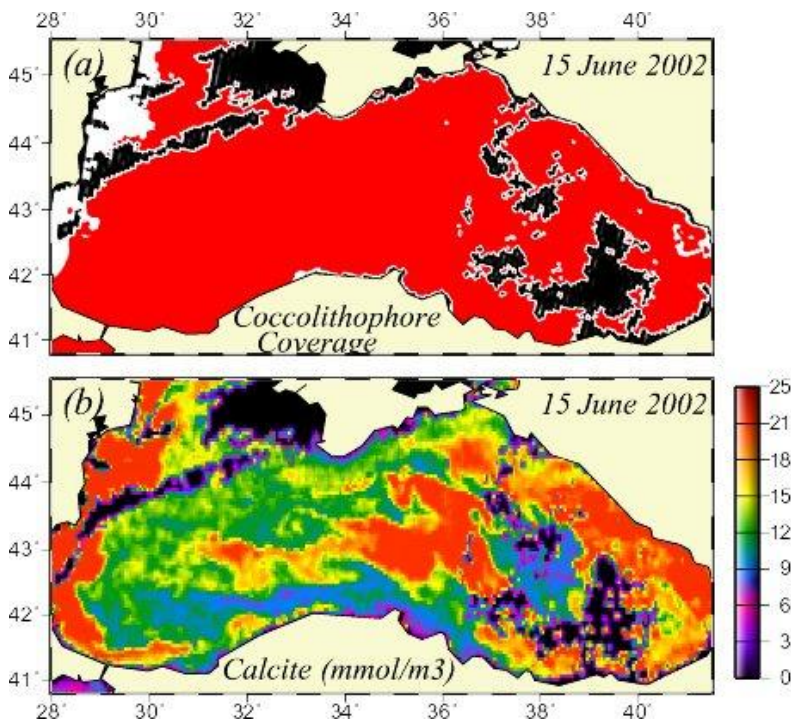

FIGURE 3. Distributions of calcite concentration (in mmol m^{-3}) in the Black Sea estimated by the Gordon et al (2001) algorithm alone (upper), and when it is combined with the Brown and Yoder (1994) algorithm (lower).

FIGURE 4. Distributions of (a) coccolithophore abundance derived according to the Brown and Yoder (1994) algorithm, and (b) calcite concentration (in *mmol m*$^{-3}$) estimated by the Gordon et al (2001) algorithm in the Black Sea. The Black color represents the cloud coverage in both figures.
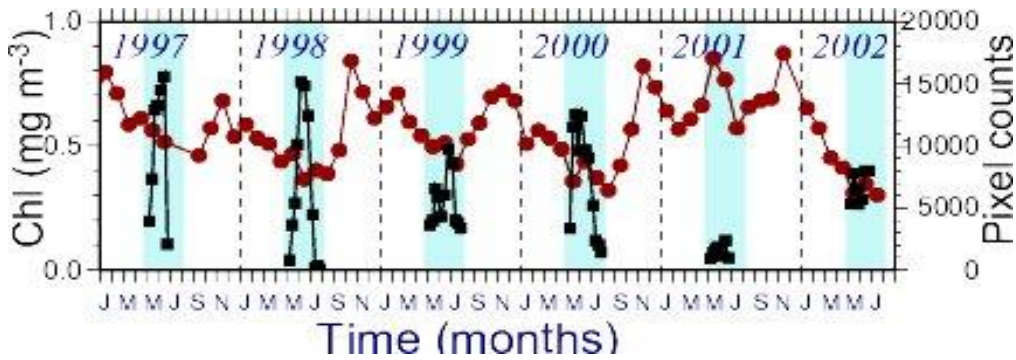

FIGURE 5. Time series of the basin-averaged, monthly chlorophyll concentration (dots) and total number of pixels having coccolithophores (squares) obtained by the application of the Brown and Yoder (1994) algorithm to 8-day average mean normalized water leaving radiance data in the Black Sea. The gray-shaded zones represent the May-July periods of the early-summer coccolithophore blooms under consideration in the present study.
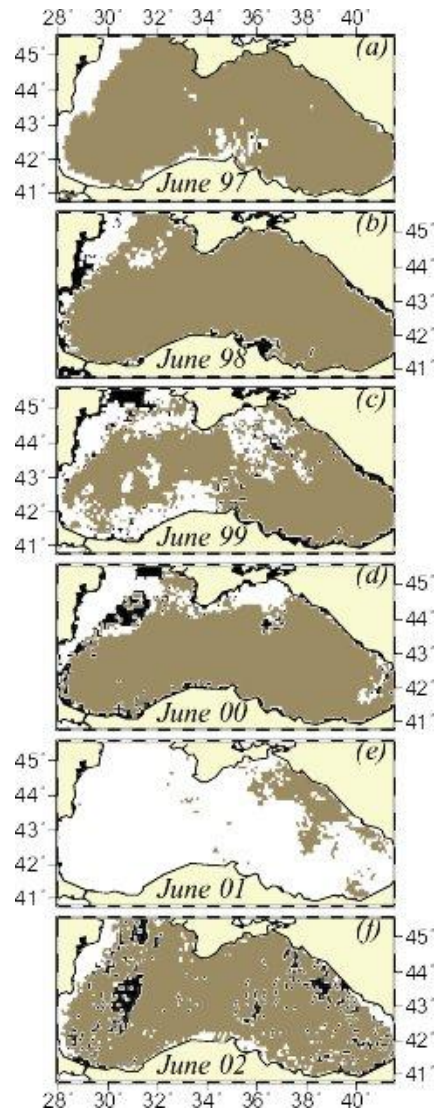
FIGURE 6. Distributions of the monthly composite coccolithophore abundance in the Black Sea derived according to the Brown and Yoder (1994) algorithm for June of (a) 1997, (b) 1998, (c) 1999, (d) 2000, (e) 2001 and (f) 2002. The regions in white color depict without coccolithophores. The Black color represents the cloud coverage.
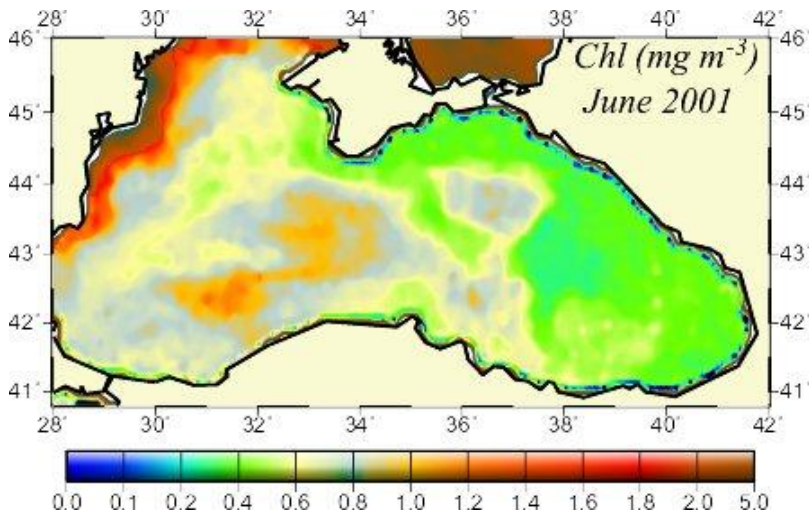
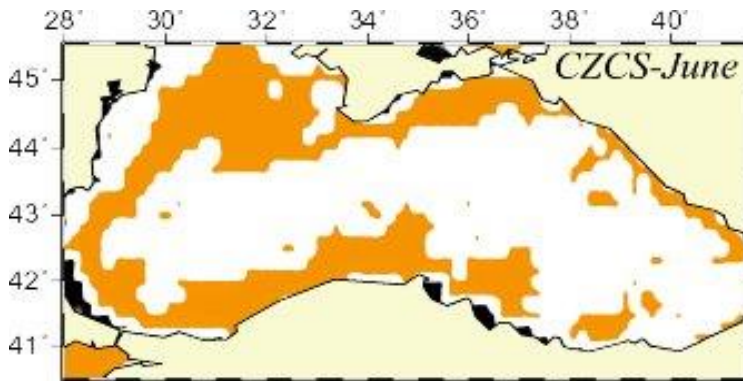FIGURE 7. The monthly average chlorophyll distribution (mg m^{-3}) in the Black Sea for June 2001.

FIGURE 8. Distribution of the coccolithophore abundance in the Black Sea obtained using all available CZCS data for June in the Brown and Yoder (1994) algorithm. The regions in white color depict without coccolithophores. The Black color represents the cloud coverage.