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Satellite-detected early summer coccolithophore blooms and their interannual variability in the Black Sea

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Abstract

Interannual variability of the prevalent early summer coccolithophore blooms within surface waters of the Black Sea was studied by means of satellite-based bio-optical observations. Two coccolith detection algorithms, tested for the Black Sea conditions, were found to provide comparable spatial coccolith patterns consistent with the corresponding true color images. Reliability of the algorithms is also supported by several sets of time-series measurements in different parts of the basin. An analysis of 6 year-long series of OCTS and SeaWiFS images from 1997 onwards shows major phytoplankton bloom activity every year in early summer. These blooms are often dominated by dense populations of coccolithophores but with some year-to-year variations in their spatial coverage, intensity, duration and timing of their maximum expanse over the basin. Moreover, limited coccolith coverage noted in the historical CZCS data may imply an increasing contribution of coccolithophores to the summer phytoplankton community from the early 1980s to 1990s. It is consistent with almost an order of magnitude increase in phytoplankton production, and the current view of dramatic shifts in taxonomic composition from diatoms to coccolithophores and dinoflagellates, as a part of transformations that took place in the Black Sea biogeochemistry and ecosystem structure under changing anthropogenic and climate forcing.

Keywords: Black Sea; Coccolithophone bloom; *Emiliana huxleyi*; Remote-sensing; Interannual variability

1. Introduction

Coccolithophores in general and their most abundant and dominant species *Emiliania huxleyi* in particular are the main calcifying organisms giving rise to extensive blooms from the tropics to arctic seas (Brown and Yoder, 1994). In temperate and sub-arctic latitudes, they grow in warm and nutrient depleted shallow surface mixed layers of highly stratified waters following termination of the spring diatom blooms. They are most commonly observed in different parts of the North Atlantic Ocean such as the Gulf of Maine (Balch et al., 1991; Towsend et al., 1994), the Nova Scotia shelf (Brown and Yoder, 1993), the eastern North Atlantic (Holligan et al., 1993; Balch et al., 1996), the northern North Sea (Robertson et al., 1994; van der Wal et al., 1995; Head et al., 1998),

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Norwegian Fjords (Kristiansen et al., 1994), off Bermuda Island (Haidar and Thierstein, 2001), the Bay of Biscay (Lampert et al., 2002). Massive coccolithophore blooms have also been observed recently in polar seas as reported for the eastern Bering Sea (Sukhanova and Flint, 1998; Vance et al., 1998; Olson and Strom, 2002; Iida et al., 2002; Murata and Takizawa, 2002) and the Weddell Sea (Winter et al., 1999). Their presence in the Black Sea goes back 2000 years BP as monitored by white laminated layers of calcium carbonate in sediment cores (Tekiroglu et al., 2001). Some aspects of temporal and spatial characteristics of *E. huxleyi* blooms in the Black Sea have been documented with the SeaWiFS ocean color data (Cokacar et al., 2001; Kubilay et al., 2002). Their weekly global spatio-temporal distributions are provided by satellite ocean color data since September 1997 by C.W. Brown at http://orbit-net.nesdis.noaa.gov/orad2/doc/ehux_www.html, and described by Iglesias-Rodriguez and Debora (2002). As inferred from these global patterns, the Black Sea appears to be the only enclosed basin subject to *E. huxleyi* blooms almost every year.

Coccolithophores constitute a key component of the ocean-atmosphere sulfur cycle through the release of dimethysulfide (DMS), known as the main natural source of atmospheric sulfur and thought one of the key regulators of present-day climate (Charlson and Wigley, 1994; Holligan et al., 1993; Simo, 2001; Burkill et al., 2002). Two other by-products of coccolithophore blooms are the export flux of calcium carbonate into the deep ocean and the release of CO_2 into surface waters. This sinking biogenic carbonate flux constitutes about 60% of the total burial flux of carbon to the world's sediments (Honjo, 1996), often comparable to the burial of newly produced organic carbon, especially in oligotrophic and mesotropic areas (e.g. Westbroek et al., 1993). Free CO_2 released during calcification partially escapes to the atmosphere, and therefore constitutes a source for atmospheric CO_2 (Buitenhuis et al., 2001).

As a complement to our ongoing studies devoted to identifying characteristics of the Black Sea ecosystem using satellite-derived ocean color data (Cokacar et al., 2001; Oguz et al., 2002), the present work aims to elucidate the inter-annual variability of coccolithophores, which are identified by their distinct spectral characteristics due to strong reflection by their calcite plates, or coccoliths, detached primarily during the senescence phase of blooms. Using the analysis of 6 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) since 1997, we document the year-to-year variations of bloom coverage and compare them with the historical observations collected by the Coastal Zone Color Scanner (CZCS) sensor in the early 1980s. In addition we use 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.

2. Data processing methods

From 1998 onwards, the daily, weekly (8-day), and monthly, 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 standard coccolithophore mask algorithm, originally proposed by Brown and Yoder (1994) for the CZCS data, hereafter referred to as the BY algorithm, was built according to pre-specified ranges of five distinct combinations of three normalized water leaving radiances, at 443, 510 and 555 nm, for the SeaWiFS data. Their threshold values, provided by Brown (2000), form a slightly improved version of those provided by the NASA standard algorithm, which were reported to be unsatisfactory to simulate observed bloom structure and evolution in the Bering Sea (Iida et al., 2002). Their ranges of values, used in the present study, are similar to values used in our previous work (Cokacar et al., 2001), and are given by *nlw(443)>1.1*, *nlw(555)>0.9, 1.15> nlw(443/510) >0.60, 1.85> nlw(443/555) >0.75, 1.65> nlw(510/555)>1.0*, expressed in units of $\mathrm{mW\,cm^{-2}\,\mu m^{-1}\,sr^{-1}}$. For each particular image, only the pixels satisfying all these criteria are accepted to represent coccolithophore bloom conditions. This algorithm therefore does not provide standing stock estimates. 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 with the above limits used for the SeaWiFS data.

A more recent coccolithophore detection algorithm was proposed by Gordon et al. (2001), hereafter referred to as the Getal algorithm. It differs from the BY algorithm by using the red and near infra red bands (670, 765, 865 nm) of 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 indirectly pointing to relative changes in regional coccolithophore abundance. The algorithm processes only the daily data, and is provided as a part of the NASA SeaDAS software.

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 differ by a factor of two when compared to the estimates derived from a local algorithm (Suetin et al., 2001). In the final processing, chlorophyll concentrations from the OC4v4 algorithm were thus divided by two to yield their more conservative estimates. Even in the case of such local corrections, chlorophyll concentrations may still have some level of uncertainty. However, they are not critically important in the present study since we are interested only in relative differences of chlorophyll concentrations in the regions with and without coccolithophore blooms. Field measurements (e.g. van der Wal et al., 1995) suggest that coccolithophore dominated phytoplankton blooms tend to have weaker chlorophyll signature as compared to those dominated by other photosynthetic phytoplankters.

3. Observational support for *E. huxleyi* blooms

The algorithms described above were based on bio-optical observations from the North Atlantic (Holligan et al., 1983; Balch et al., 1996). The threshold values were specified originally from these data by Brown and Yoder (1994) and improved later by Brown (2000). They were found to be compatible with more recent estimates provided by the measurements in the eastern Bering Sea during July–August 1998 and 2000 (Iida et al., 2002). These algorithms are currently utilized as standard tools for satellite-based identification of *E. huxleyi* blooms over the globe (e.g. Iglesias-Rodriguez and Debora, 2002). Their implementation in individual basins may have limitations. In some cases they may even falsely identify spectral signature of other environmental properties as *E. huxleyi* blooms. A specific field program dedicated to exploring bio-optical characteristics of coccolithophore blooms and subsequent verification of the current satellite detection algorithms for the Black Sea conditions has not been possible up to now. Nevertheless, some field measurements exist to support the reliability of the algorithms. They were performed at approximately bi-weekly intervals from a passenger vessel operating between Istanbul (Turkey) and Sevastopol (Crimea) during January 1998–June 2000 (T. Churlikova, personal communication). The measurement site is located inside the box of 30–31°E, 42–43°N within the central part of the western basin. An in-depth analysis of this data set will be provided by T. Churlikova and her co-workers elsewhere. Here, the coccolithophore cell counts per liter as well as their percentage of the total phytoplankton biomass, as the averages of measurements carried out each month, are given in Table 1, in columns A. They are further supported by additional measurements within the southern Black Sea during March–April 1998, July 2000 (Eker-Develi and Kideys, 2003), and May–June

Table 1
Coccolithophore cell counts per liter (upper values) and coccolithophore percentage of the total phytoplankton biomass (lower values in parantheses) during 1998–2001

	1998		1999		2000		2001	
	A	B	A	B	A	B	A	B
January	199 (0)							
February	6268 (7)		40787 (28)					
March	1415 (1)	18400 (42)	36438 (27)					
April	853 (0.5)	45766 (22)	47337 (32)					
May	87315 (33)		14880 (26)		**982857** **(86)**			74987 (25)
June	**917419** **(79)**		100578 (49)		98648 (73)			132234 (57)
July	18488 (18)		36933 (18)			88272 (87)		
August	22995 (16)		4479 (4)					
September	1986 (5)		1236 (3)					
October	28289 (15)		5648 (9)					
November	122147 (13)		39272 (27)					
December	473489 (83)		1752 (7)					

Two different data sets are shown for each year. Those shown in columns A represent the averages of measurements carried out within the central part of the western basin each month at approximately bi-weekly intervals by T. Churlikova and co-workers. Those shown in columns B represent the averages of all stations in specific field surveys performed within the southern Black Sea by A. Kideys and co-workers. Two specific bloom cases, during June 1998 and May 2000, are indicated by bold characters.

2001 (Soydemir et al., 2003). Their values, as averages of all stations performed in each of these surveys are also provided in Table 1, in columns B.

The data (Table 1) suggest that *E. huxleyi* population remains at sub-bloom level most of the year, typically less than 100,000 cell l^{-1} and less than 25% of the total phytoplankton biomass. The only exceptions are June 1998 and May 2000, during which monthly averaged cell counts increase an order of magnitude and approach values slightly less than 1 million l^{-1}, and therefore may be accepted to reflect bloom conditions. As will be shown elsewhere by T. Churlikova and her co-workers, individual measurements (not the monthly averages as given here) in fact reveal higher cell counts, on the order of several millions l^{-1}. These periods of enhanced coccolithophore population are consistent with those presented by the satellite-retrieved coccolith data in Section 5. Moreover, the coccolithophore cell count of about 100,000 at the same measurement site during June 1999 (non-bloom case) will also be shown to agree with the absence of coccoliths in the western basin as indicated by the satellite data. Similarly, non-bloom level cell counts measured during May–June 2001 support the absence of coccolithophore bloom occurrence predicted from the SeaWiFS radiance data.

The historical data based on the measurements performed during the late 1980s and early 1990s also support development of *E. huxleyi* blooms within the surface mixed layer (0–20 m) in various parts of the Black Sea. For example, 4.7×10^6 and 30.7×10^6 *E. huxleyi* cells l^{-1} were reported within Romanian sector of the northwestern shelf during summer months (June–July August) of 1990 and

1994, respectively (Mihnea, 1997). Similar measurements further south along the Bulgarian sector of the western coast indicated *E. huxleyi* cells of $1.0–1.5 \times 10^6$ l^{-1} during summers of 1986, 1989, 1992, 1993, and of $10–50 \times 10^6 l^{-1}$ during summers of 1987, 1988 and 1990 (Moncheva and Krastev, 1995). Moreover, measurements within the northern part of the Black Sea during 1990 and 1992 revealed areal average of *E. huxleyi* cells of $\sim 2 \times 10^6 l^{-1}$ (Mankovsky et al., 1996). In particular, during 8–27 July 1992, *E. huxleyi* cells varied in the range $1.4 \times 10^6–9.8 \times 10^6$ at 15 stations to the north of 43.5°N bounded by the longitudes of 31°E on the west and 40°E on the east. The phytoplankton data set covering the interior Black Sea during 1985–1995 period compiled by L. Georgieva and A. Mikaelyan (personal communication) also supports coccolithophore blooms during May–June, whereas their contribution to overall phytoplankton abundance was negligible during the rest of the year.

4. Performance of the coccolithophore detection algorithms

Two coccolithophore detection algorithms were checked whether their products agree 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 coccolith 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 coccolith accumulation. In addition, this true color pattern indicates how accumulations are often associated with complex mesoscale flow structures in the form of filaments, mushroom eddies, etc., distributed all over the basin.

The 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 gray color represent high reflectance from coccoliths, whereas the regions in white 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 less than the lower limits specified above. The absence of coccolith accumulation in these regions (Fig. 2d) is marked by the dark blue color zone in the true color image shown in Fig. 1a. Moreover, chlorophyll values greater than $0.6\,mg\,m^{-3}$ in these regions (Fig. 2e), as compared to half of this value within the rest of the basin, suggest the presence of some local non-coccolithophore algae. In contrast, the white color band of the *nlw(443)* and *nlw(510)* along the northwestern coast (Fig. 2a and b) is related to strong absorbance (thus low water leaving radiance, below the threshold value) by high concentrations of dissolved and particulate colored material. They are introduced from the River Danube and other local rivers as well as high rate of almost continuous primary production taking place within the coastal and inner shelf waters of the northwestern Black Sea (Zaitsev and Mamaev, 1997). This anthropogenically derived high biogenic activity along the western coast is further evident in the high chlorophyll concentrations ($>1\,mg\,m^{-3}$) in Fig. 2e. The origin of the green to turquoise color in Fig. 1a in this coastal zone should therefore differ from those in other regions of the sea and represents a mixture of free or attached coccoliths and high concentrations of particulate material. Except filaments and offshore jets occasionally developed, this coastal zone, however, has a limited exchange with the outer shelf and interior waters of the western Black Sea due to the presence of a sharp density front associated with the brackish coastal current system (Oguz et al., 2002). Moreover, it has been suggested that 78% of the detrital load of fluvial input to the Black Sea is deposited near the mouth of the Danube River (Brewer and Spencer, 1974). Dissolved and particulate colored material content within the interior cyclonic cell of the Black Sea is thus expected to be much lower (Coban-Yildiz, 2003), and certainly diminishes towards the eastern basin. This is particularly true for the late spring and early summer period within the surface mixed layer when most of the biological production take place below the seasonal thermocline. The contribution of organic material thus should not introduce a significant source of error for the

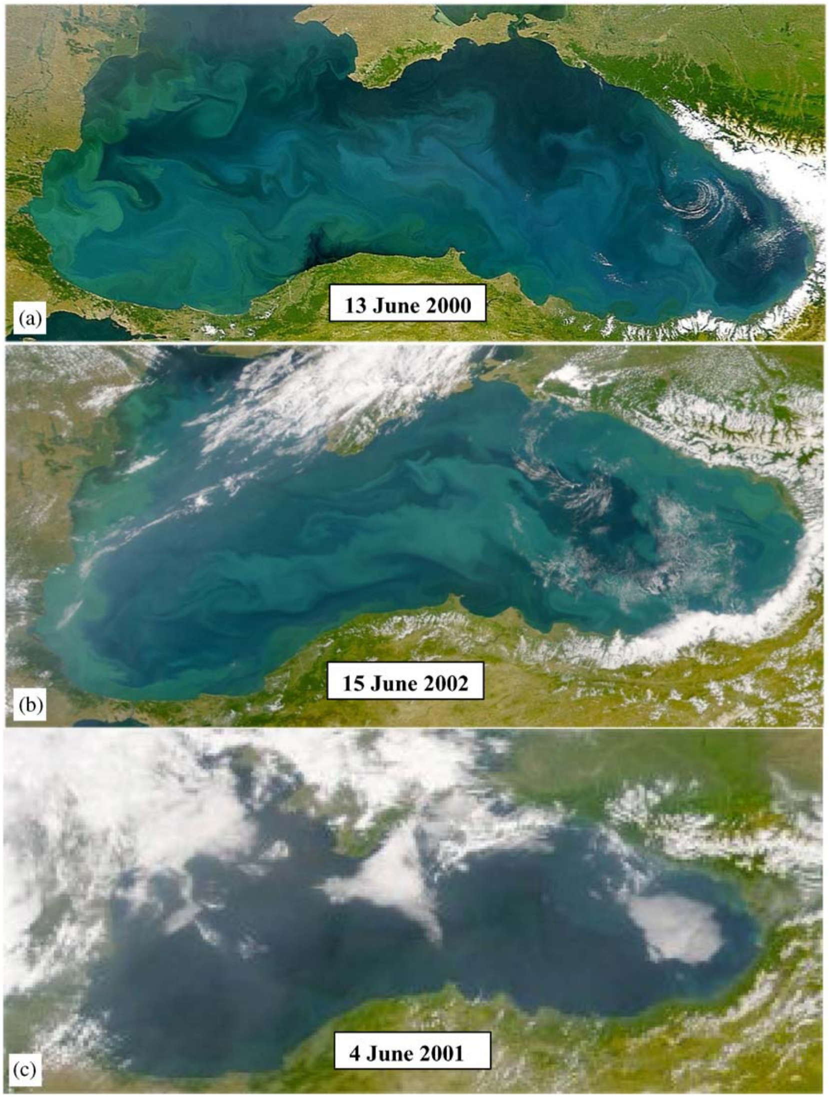

Fig. 1. SeaWIFS true color images of the Black Sea during (a) 13 June 2000 (upper), (b) 15 June 2002 (middle), and (c) 4 June 2001 (lower). Coccoliths are marked by the turquoise color in the upper and middle images. The distinct color change in the lower image corresponds to the conditions of no dense coccolith development. They are generated by from radiances at 412 nm (blue), 555 (green) and 670 nm (red) bands.

satellite-based detection of large-scale characteristics of the early summer coccolithophore activity in offshore waters of the Black Sea.

The distribution of calcite concentration computed with the Getal algorithm for the same image is shown in Fig. 2f. The calcite concentrations, related empirically to the backscattering coefficient at 555 nm (Gordon et al., 2001), 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 by 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

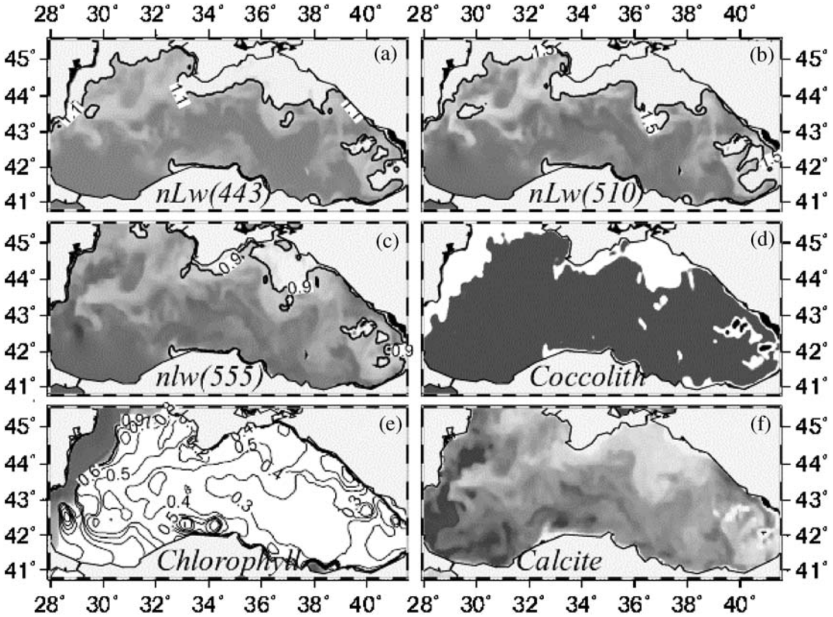

Fig. 2. Distributions of the mean normalized water leaving radiances (mW cm^{-2} μm^{-1} sr^{-1}) for June 13, 2000 at (a) 443 nm, (b) 510 nm, (c) 555 nm; the regions in gray color represent high reflectance from coccoliths whereas the regions in white, separated by contours of the threshold reflectance values, indicate the absence of dense coccolith patches, (d) distribution of coccolith coverage derived according to the Brown and Yoder (1994) algorithm, which classifies pixels into bloom (in gray), non-bloom classes (in white), and cloud coverage is shown in black, (e) chlorophyll concentration (mg m^{-3}) plotted with contour interval of 0.1 mg m^{-3}; the region shaded in dark gray along the western coast represents chlorophyll concentrations larger than 1.0 mg m^{-3}, and (f) distribution of calcite concentration (in mmol m^{-3}) estimated by the Gordon et al. (2001) algorithm.

by the absence of coccoliths in the BY algorithm. This difference, as explained by Gordon et al. (2001), results from the capability of the new algorithm to detect sub-bloom concentrations in regions where they were not detected 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 coccolith activity as opposed to the BY algorithm. This difference seems to arise because the computation of calcite concentration in the Getal algorithm is based solely on *nLw(555)* and this radiation band alone can not distinguish the coccolith signature from that of dissolved and particulate organic material, as depicted by the difference between *nlw(443)* and *nlw(555)* distributions in Figs. 2a and c. Thus, the Getal algorithm should overestimate coccolith concentrations in northwestern coastal waters of the Black Sea and require some sort of filtering to introduce the effect of high absorbance at 443 nm. In fact, the BY coccolithophore detection criteria have been recently implemented in the Getal algorithm of the NASA standard SeaDAS system. The threshold criteria provided were different than those employed in our present work and therefore were not utilized here.

The second example for assessing the performance of the coccolithophore detection algorithms is the June 15, 2002 case, for which the true color image is presented in Fig. 1b. The BY algorithm reveals basinwide coverage for coccoliths in the Black Sea except along the western coastal zone (Fig. 3a). Once again, the Getal algorithm produces a very similar pattern of coccolith coverage with densest calcite concentrations (represented by dark gray color in Fig. 3b) coinciding with the turquoise color spots in its true color image. As in the previous case, however,

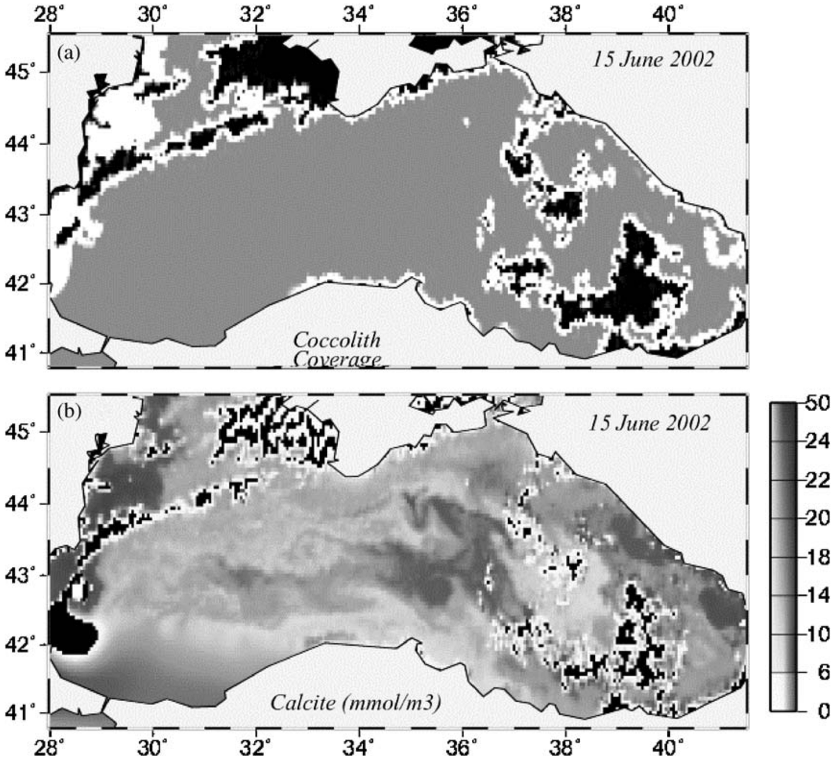

Fig. 3. Distributions of (a) coccolith coverage derived according to the Brown and Yoder (1994) algorithm, which classifies pixels into bloom (in gray), non-bloom classes (in white), and (b) calcite concentration (in mmol m^{-3}) estimated by the Gordon et al. (2001) algorithm in the Black Sea during 15 June 2002. Black represents the cloud coverage in both figures.

the algorithms give rise to contradictory results in the northwestern coastal zone.

The distinct true color signature (hence distinct radiative properties) of the coccoliths may be demonstrated by comparing the two particular true color images shown in Fig. 1a and b with the one shown in Fig. 1c representing the conditions of no coccoliths on 4 June 2001. The latter image reflects the post-bloom conditions with relatively high particulate organic matter concentration (Coban-Yildiz, 2003) measured during the R.V Knorr cruise, 20 May–10 June 2001 following a non-coccolithophore-dominated phytoplankton bloom that took place during the first half of May. The distinct color changes between the images presented in Fig. 1a and b and that in Fig. 1c provide the visual identification of a satellite-detected coccolithophore-dominated bloom and its difference from the spectral characteristics of high particulate matter accumulation in surface waters.

5. Interannual variability of the early summer coccolithophore blooms

The monthly classification of the SeaWiFS data in terms of *E. huxleyi* distribution from September 1997 to December 2000 presented by Cokacar et al. (2001) has already indicated high reflectance patches of coccolith platelets each year during May–July (see Table 1 in Cokacar et al., 2001). In situ measurements described in Section 3 also reveal this period as the major coccolithophore (preferentially *E. huxleyi*) bloom activity of the year. Here, the analysis presented by Cokacar et al. (2001) is extended to cover the weekly (8 day) variations of coccolith coverage and subsequently

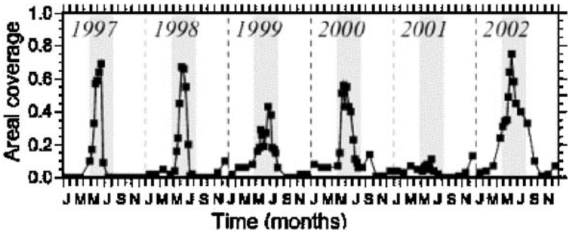

Fig. 4. Time series of the areal coccolith coverage as a percentage of the total area of the basin during the 1997–2002 period in the Black Sea. The gray-shaded zones represent the May–July period in which coccolithophore blooms occur.

bloom characteristics of the coccolithophorid *E. huxleyi* during September 1997–July 2002 by plotting time series variations of the areal coverage of coccoliths with respect to the total surface area of the Black Sea (Fig. 4). The entire data set is shown to document appreciable coccolithophore bloom activity only during the summer season with some interannual variability in terms of bloom coverage and duration. The lack of coccolith signature during the rest of the year generally implies non-bloom level coccolithophore activity; the analysis is not however reliable during autumn and winter months due to large cloud coverage over the basin. The years 1997, 1998 and 2002 are shown to be characterized by about 70% coverage, suggesting almost basinwide events except along the coastal zone (primarily north-western shelf) excluded by the detection algorithm. The coccolith coverage reaches its maximum in 1997 after mid-May, following bloom initiation during the first half of May. In 1998, maximum coverage occurred within the first two weeks of June and decayed gradually towards the end of the month, and coccoliths diminished throughout the basin by the beginning of July. Slightly less coccolith coverage, around 60% of the total surface area of the sea, took place during the same period of the year 2000. The bloom initiation shifted earlier towards the beginning of May, and the widest coccolith coverage throughout the basin occurred by mid-May.

The summer of 1999 exhibits even smaller coccolith coverage and hence a more limited coccolithophore bloom. The maximal areal extent of coccoliths attained approximately 40% of the basin within the first half of June decreasing towards the end of July. The summer 2002 bloom event is a unique case of extended coccolithophore bloom activity persisting longer than in other years examined by the satellite ocean color data. The noise in the data as well as cloud masking hindered a precise determination of the actual coccoliths coverage during the summer of 2002. In fact, patchy turquoise color regions can be spotted among clouds for the whole summer of 2002 by visual inspection of the daily true color images available at http://www.nrlmry.navy.mil/aerosol/satellite/seawifs/med/. This feature is also evident in Fig. 5 by scattered white pixels.

The coccolith coverage was only 10% of the basin during May–July 2001. It is a genuine response and does not arise as an artifact of cloud masking. Chlorophyll concentration of approximately 0.8 mg m^{-3} (Fig. 6), higher than in other years during the same period, indicates development of a phytoplankton bloom dominated by other algae groups instead of coccolithophores. This is further supported by the shallower euphotic zone thickness of 25 m (instead of 50 m under normal conditions), and 3–4-fold increase in the surface mixed layer particulate organic carbon (POC) concentrations observed by the R.V *Knorr* measurements performed during 20 May–10 June 2001 within the western Black Sea (Coban-Yildiz, 2003). The values around 10–15 of the POC to PON (particulate organic nitrogen) ratio also indicate non-coccolithophore dominated algae production since this ratio should be much higher for coccolithophore blooms (Paasche, 2002).

Fig. 5 gives monthly distributions of coccolith coverage for June of each year formed by four weekly data sets as superpositions of pixels satisfying the bloom signature in at least one of them. As shown in Figs. 5a, b, d and f, they spread uniformly over almost the entire basin during 1997, 1998, 2000 and 2002. Note that most of the regional coccolithophore patches which were under clouds in each of the individual 8-day images during 2002 are recovered by monthly compositing (Fig. 5f). The monthly coccolith distribution for June 2001 (Fig. 5e) suggests only a limited coccolithophore bloom development confined, as an isolated patch, along the

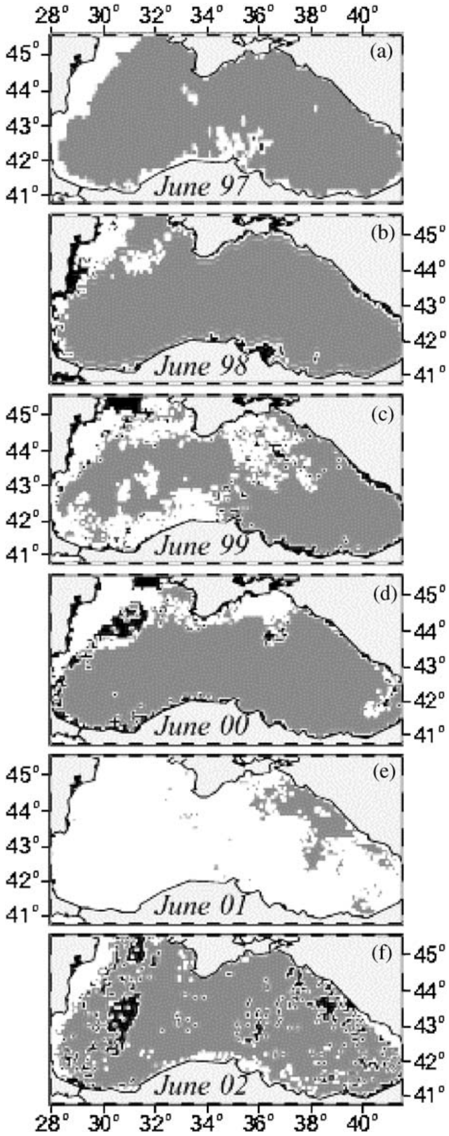

Fig. 5. Distributions of the monthly composite coccolith coverage in the Black Sea derived according to the Brown and Yoder (1994) algorithm for June of (a) 1997, (b) 1998, (c) 1999, (d) 2000, (e) 2001 and (f) 2002. The regions in white depict absence of coccoliths. Black represents the cloud coverage. Except June 2001, coccolithophore bloom events emerge as a robust signature of the annual phytoplankton structure each summer during the 1997–2002 period.

northeastern coast. Note that, while this particular region is characterized by monthly average chlorophyll concentration of less than 0.4 mg m^{-3} (Fig. 6); the rest of the basin, without coccoliths, attains chlorophyll concentrations approximately twice this value.

6. Discussion

Our analyses 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 to daily Level 1 data, in contrast to the more flexible BY algorithm, which can be applied to Level 3 data sets with different temporal resolutions. The BY algorithm, on the other hand, can not yield a quantitative form of coccolith abundance, whereas the Getal algorithm provides a rough estimate of calcite (coccolith) concentration using an empirical relationship derived from bio-optical measurements.

The 6 year-long (1997–2002) normalized water leaving radiance and chlorophyll concentration data sets indicate that the May–June coccolithophore bloom events constitute a robust signature of the annual phytoplankton structure, in addition to the late winter–early spring and the autumn events. Five of the six bloom events are mainly dominated by coccolithophores. The other algal groups possess weaker and patchier distributions except in the early summer period of 2001, when coccolithophores are confined to the northeastern coast.

Total duration of the summer coccolithophore bloom events as well as timing of their peak periods also undergo year-to-year variations. The lack of a comprehensive measurement program over the entire spring–summer period over several consecutive years, however, makes unable to identify factors leading to these year-to-year variabilities. Existing studies (e.g. Tyrrell and Taylor, 1996; Paasche, 2002) have already suggested that intensity and duration of vertical exchange across the seasonal thermocline, photoinhibition and changes in local radiation characteristics, zooplankton selective grazing, local nutrient structure and nitrogen to phosphorus content can introduce considerable variability in the formation and duration of coccolithophore blooms. On the basis of monthly composite images

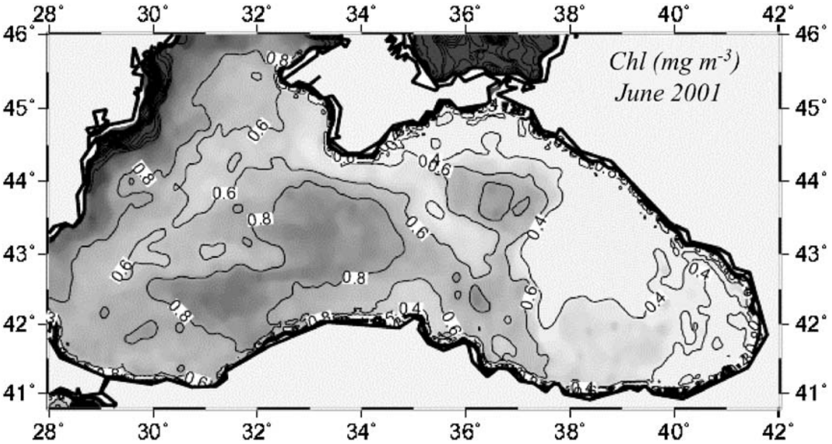

Fig. 6. The monthly average chlorophyll distribution (mg m^{-3}) in the Black Sea for June 2001. The region with low chlorophyll concentrations (<0.4 mg m^{-3}) in the northeastern sector corresponds to the isolated coccolith patch shown in Fig. 5e.

of classified coccolithophorid blooms and global climatological maps of physical variables and nutrient fields, Iglesias-Rodriguez and Debora (2002) identified stability of water column, high incident irradiance and relatively low nutrient concentrations as three major driving forces that determine the prevalence of coccolithophorid blooms versus other marine phytoplankters. They suggested coccolithophorid bloom development preferentially in areas of low turbulence, under semi-oligotrophic conditions with decreasing nitrate concentrations. Temporal shifts in the formation and evolution of the previous late-winter and spring bloom events may also affect structure of a subsequent coccolithophore bloom.

Observations of the basinwide 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 the analysis of coccolithophore blooms. Application of the BY algorithm to the composite of this imagery set resulted in coccolithophore activity limited to the periphery of the basin (Fig. 7). Our analysis further suggested 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 coccolithophore blooms achieved distinctly different structures in terms of their horizontal extent from the early 1980s to the late 1990s. Confinement of coccolithophore blooms to peripheral surface waters may be a consequence of more limited nutrient availability in the early 1980s prior to transformation of the ecosystem into highly eutrophic form with 3–4-fold increase in the total nitrogen content and more intense and frequent phytoplankton blooms. Under such oligotrophic conditions, the surface mixed layer waters of the interior Black Sea could not provide sufficient regenerated nutrients to support coccolithophore or other phytoplankton production during late spring and early summer, following the late winter diatom bloom. The anticyclonically dominated peripheral waters characterized by deeper mixed layer and more nutrient supply from the subsurface nutrient pool might constitute more favorable regions for promoting coccolithophore blooms as compared to the inner cyclonic cell, when other environmental conditions are satisfied.

Field measurements also support increasing contribution of coccolithophores to summer phytoplankton assemblages during the 1990s. Analyzing the long-term data (1955–1994) from the Bulgarian Black Sea coast, Moncheva and Krastev (1997) noted the first appearance of intense *E. huxleyi* blooms in 1983, and they have been monitored every year since 1986. Moncheva and

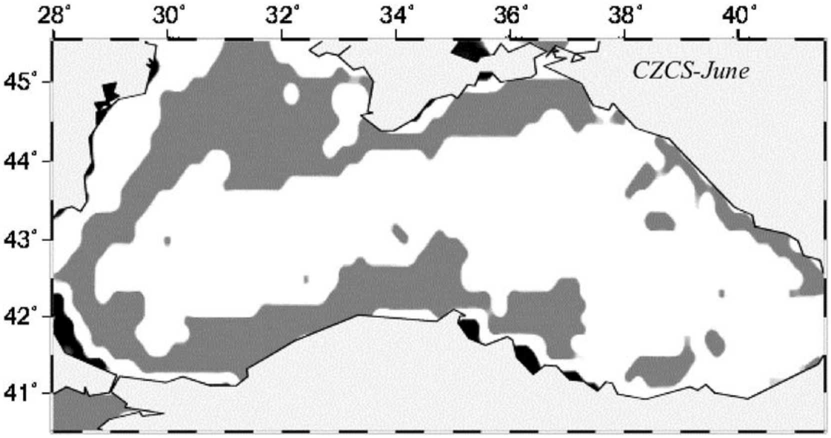

Fig. 7. Distribution of the coccolith coverage in the Black Sea obtained from all available CZCS data for June within the Brown and Yoder (1994) algorithm. The regions in white depict in the absence of coccolithophores, suggesting that the coccolithophore activity is limited to the periphery of the basin in the early 1980s, prior to transformation of the ecosystem into more eutrophic form. Black represents the cloud coverage.

Krastev (1997) and Humborg et al. (1997) explained this phenomenon by a shift in phytoplankton species composition from diatoms to coccolithophores and dinoflagellates 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 construction in the early 1970s. Similar ecological changes have been reported for the interior basin away from the direct influence of the anthropogenic load (Mikaelyan, 1997).

The similarity between recent coccolithophore bloom events of the eastern Bering Sea and the Black Sea is striking. They both reveal basinwide coverage during 1998 and 2000 versus patchier coverage during 1999 and 2001. If not coincidence, they may imply a global scale climate-driven 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°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 also be favored by climate-induced changes in addition to the impacts of eutrophication in the 1980s.

The Black Sea may be listed as the second most important region of the world oceans, after the North Atlantic Ocean, in terms of persistence, temporal extent and spatial coverage of the coccolithophore blooms. Because of its controlled nearly enclosed environment and presence of both cases 1 and 2 types of water masses, it may serve as an ideal study site to conduct research on improvement of coccolith detection algorithms and a better mechanistic understanding of the role of coccolithophores on the global carbon and sulfur cycles.

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