Structure of *Emiliania huxleyi* blooms in the Black Sea surface waters as detected by SeaWIFS imagery

Tulay Cokacar, Nilgun Kubilay, and Temel Oguz

Institute of Marine Sciences, Middle East Technical University, Erdemli, Icel, TURKEY

Abstract. The temporal and spatial characteristics of coccolithoprid *Emiliania huxleyi* blooms in the surface waters of the Black Sea are studied using the Sea-WIFS mean normalized water-leaving radiances data for 1998-2000. It is shown that the Black Sea consistently experiences high reflectance patches of coccolith platelets throughout the basin each year during the May-July period. Although the Black Sea is masked by clouds, the data also suggest enhanced activity for some period during autumn and early winter. Their spatial patterns resemble very closely the circulation system derived from the altimeter data, and exhibit pronounced differences between cyclones and anticyclones. The cyclonic cell, which covers the entire interior part of the basin, appears as a more favourable site for more intense bloom formation. This is related with its relatively shallower mixed layer thickness and stronger mixed layer average water leaving radiance.

Introduction

Blooms of the coccolithophore *Emiliania huxleyi* and their coccolith platelets have global significance. They affect radiation budgets [*Tyrrell et al.*, 1999], regulate marine carbon cycling and ocean-atmosphere CO_2 exchange through their production of $CaCO_3$ [*Holligan and Robertson*, 1996], and provide high reflectance which allows their spatial and temporal extent to be visually monitored from space.

Since the first invasion of *E. huxleyi* into the Black Sea about 2000 years ago, high carbonate content in sediment cores [*Hay and Honjo*, 1989; *Tekiroglu*, 2001] indicates that they have always been one of the predominant species in the regional plankton community. Recent measurements suggest that *E. huxleyi* blooms sometime during the late spring-summer and the autumn-early winter periods in different parts of the basin [*Sorokin*, 1983; *Benli*, 1987; *Mankovsky et al.*, 1996; *Uysal et al.*, 1998]. A signature of the Black Sea *E. huxleyi* blooms has also been traced by aerosol filter samples collected daily at a site along the Mediterranean coast of Turkey [*Ozsoy et al.*, 2000]. Changes in the methane sulfonic acid and sulfate concentrations at this site, when supported by air mass back trajectory analysis, were shown to be related to the Black Sea *E. huxleyi* bloom events. Although all these studies demonstrate occurence of the *E. huxleyi* blooms in the Black Sea, their duration, persistence, spatial extent as well as relation with circulation dynamics are for the first time reported in the present paper by analyzing the SeaWIFS time series data.

Satellite data and processing method

The data used in this study comprise the normalized water leaving radiances from the 8-day composite, 9 km resolution, Level 3 SeaWIFS imagery for the period from the beginning of September 1997 to the end of December 2000. The algorithm used to map the distribution pattern of *E. huxleyi* blooms was originally developed and used for the analyses of CZCS imagery by *Brown and Yoder* [1994], *Brown and Podesta* [1997], and later modified for SeaWIFS imagery by *Brown* [2000]. It separates the spectral signatures of coccolith platelets according to the pre-specified ranges of five distinct combinations of mean normalized water leaving radiances (nLw) at 443, 510 and 555 nm. As given by Brown (2000), we set $0.60< nLw443/nLw510 <1.15$, $0.75< nLw443/nLw555<1.85$, $1.0< nLw510/nLw555 <1.65$, $nLw443>1.1$, and $nLw555>0.9$ with radiances in units mW cm^{-2} m^{-1} sr^{-1}. The pixels satisfying all these criteria are assigned to have high concentration of coccoliths. Further details on the characteristics of these mean normalized water leaving radiances can be found in *Gordon et al.* [1988, 2001].

A set of experiments has been performed to test sensitivity of blooms to the values of these limits. Changing these numbers by ±25% did not generally lead to significant changes on spatial structure of the blooms. The most critical parameter was found to be the limiting value of $nLw443$. Its smaller values (within the 25% range) provided a wider coverage of coccoliths especially during spreading and decaying phases of the blooms. Its higher values, on the other hand, were found to be less critical for the bloom structure. Although they are included into the bloom classification algorithm, shelf areas with the total depth less than 200 m (mainly along the western coastal part of the basin) are excluded from the interpretation to avoid contamination by the high reflectances of lands or high turbidity shelf waters.

Table 1. Monthly classification of the SeaWIFS data in terms of the *E. huxleyi* distribution from September 1997 to December 2000 in the Black Sea

|	1997	1998	1999	2000
Jan.		X	BS (CL)	(CL)
Feb.		X	BS (CL)	(CL)
Mar.		X	NBS	X
Apr.		X	X	X
May	X	X EBS X	EBS EBS X	WBS BS
Jun.		BS	BS	BS
Jul.	EBS	X X BS	EBS X EBS	EBS X
Aug.		X	X	X
Sep.	WBS	X	X	WBS
Oct.	X	X	X	WBS X X
Nov.	(CL)	X X WBS	BS (CL)	(CL)
Dec.	(CL)	BS (CL)	(CL)	(CL)

The symbol "X" refers to no bloom, whereas "(CL)" means cloud coverage with a total absence of information on the *E. huxleyi* activity. "BS" signifies presence of the bloom within the entire basin, while the prefix "W", "E" or "N" implies its presence only in the western, eastern or northern part of the sea, respectively. " "BS(CL)" suggests cloud coverage over the entire basin, but some scattered data values are readily available to signify the bloom occurrence in different parts of the basin. Extension of single column information for an entire month into three subcolumns for certain months provides a more detailed, 10-days average, temporal structure of the blooms.

## Temporal and spatial characteristics of *E. huxleyi* blooms in the Black Sea

An overview of the *E. huxleyi* bloom episodes inferred from the SeaWIFS data examined within the framework of this study is shown in Table 1. For all these three years, the major bloom activity attains its most intense and widest coverage during June, and diminishes gradually within the first half of July. A similar activity also occurs in autumn months, although the blooms are traced mostly by some scattered data points irregularly distributed among clouds over the basin. The *in situ* data shown in Fig. 1 for the summer-autumn 1998 and early winter 1999 periods from the interior part of the western basin provide an independent support for the bloom occurence, and more importantly establish validity and reliability of the SeaWIFS coccolith detection algorithm. The algorithm is also checked by verifying consistency of its products with corresponding actual true color SeaWIFS images.

In 1998, the bloom initiates from the eastern basin during mid-May and spreads rapidly towards the west and occupies the entire basin by the end of the month. The bloom remains uniform throughout the sea in June (Fig. 2a), and then begins to weaken from the western to eastern basin. It, left only within the eastern basin during early July, is depleted completely around mid-July. The year 2000 summer bloom activity also exhibits a similar structure. The bloom is initiated approximately two weeks earlier, and maintains its full basin scale structure from mid-May to third week of June (Fig. 2b). Once again, it weakens gradually from the western to eastern basin during July. A notable feature for both of these two years is remarkably rapid

development of the bloom and its spreading basinwide; they all took place within about a week. In 1999, on the other hand, the bloom structure possesses a patchy character, and is confined mostly to the eastern basin. The bloom started to spread from the northern part of the eastern basin during mid-May, covered the eastern basin by the end of May, and expanded into the western basin for a short period of time toward the end of June (Fig. 2c). By mid-July, only some scattered coccolith patches remained noticeable in the eastern basin.
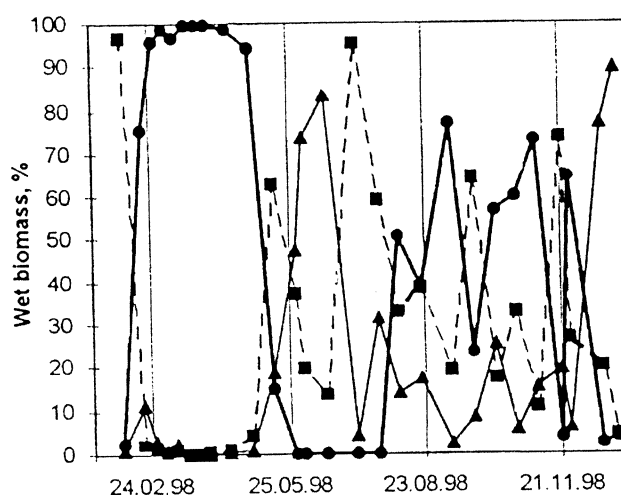
Figure 1. Relative contribution of diatoms (circles), dinoflagellates (squares) and *E. huxleyi* (triangles) to annual phytoplankton biomass structure obtained from bi-weekly surface measurements within the central part of the western basin within the region of 30-31°E, 42-43°N from February 1998 to January 1999 (after *Churlikova et al.,* [1999]).
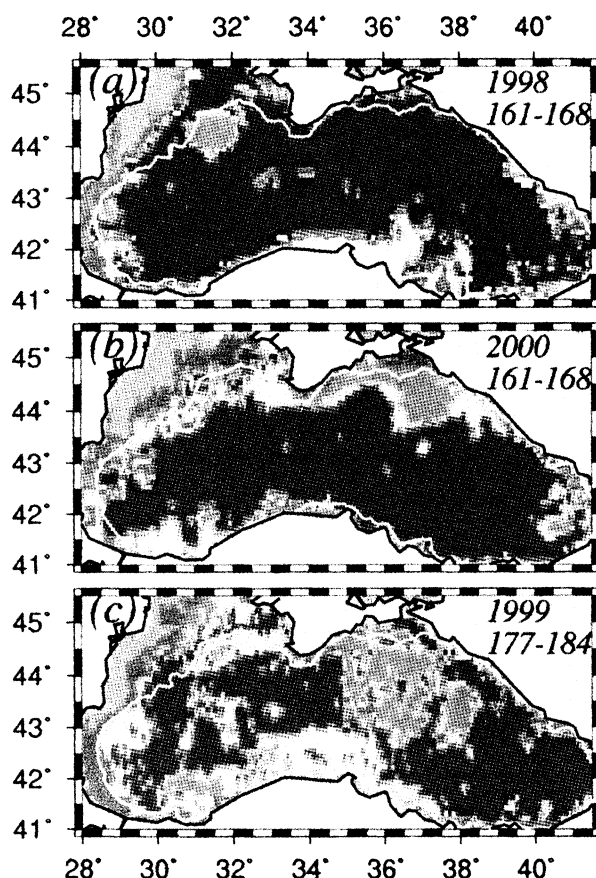
Figure 2. The coccolith distributions in the Black Sea as determined by the 8-day composite SeaWIFS data for Julian days (a) 161-168 in 1998, (b) 161-168 in 2000, and (c) 177-184 in 1999. They all correspond to the periods of most intense coccolith activity. The red color indicates the regions in which all the five criteria of the coccolith detection algorithm are satisfied. The yellow and green colors represent the regions when only four and three of these criteria are satisfied, respectively. The yellow color zones generally indicate the regions in which $nLw443$ varies between 0.9 and 1.1, and thus may be considered as the regions prone to the $E.$ $huxleyi$ bloom activity. The curve in white color represents 200 m topography contour separating the shelf from the interior basin. The regions in gray color indicate cloud coverage.

Persistency and basinwide coverage of $E.$ $huxleyi$ blooms make the Black Sea a potential regional source of calcite carbon and DMS sulfur production. The data reported by $Mankovsky$ et $al.,$ [1996] on the July 1992 $E.$ $huxleyi$ bloom measurements suggested an average value of 3850×10^6 cell m^{-3} within a 20 m layer. Using 1.1 pg DMSP cell^{-1} as used by $Brown$ and $Yoder,$ [1994] and using a surface area of 300 000 km^2 (approximately 70% of the total surface area covering the deep part of the basin), we estimate ~5700 tons of DMS sulfur production for this particular event. The calcite carbon production can be estimated to vary between the two extreme values of 0.12 and 3.9×10^6 tons depending on the assumption of 0.02 and 0.065 g calcite carbon per

cubic meter, respectively. These values are comparable with the estimates for subpolar latitudes [$Brown$ and $Yoder,$ 1994] and western south Atlantic Ocean [$Brown$ and $Podesta,$ 1997]. They therefore imply an important role of the Black Sea $E.$ $huxleyi$ blooms on the biogeochemistry, ecology and climatology of the region.

Dependence of $E.$ $huxleyi$ blooms on the circulation system

The Black Sea possesses a highly complex, eddy-dominated, predominantly cyclonic upper layer circulation system [$Korotaev$ et $al.,$ 2001]. This includes a band of strong Rim Current system encircling the basin over the steep continental slope, an interior cell composed mainly by an interconnected series of cyclonic eddies of different sizes, as well as some anticyclonic eddies on the coastal side of the Rim Current zone. While a part of these coastally-attached eddies constitutes quasi-stable/recurrent features persisting for seasonal and/or longer time scales, the overall peripheral circulation system essentially possesses a highly transient character involving a chain of eddies, meanders and fila-
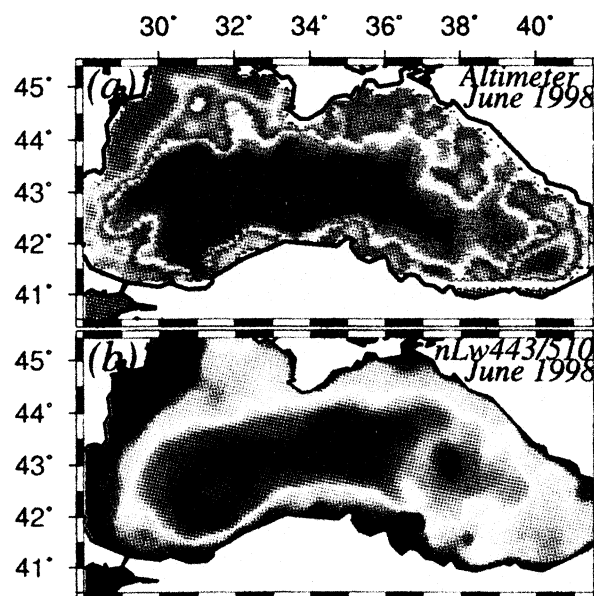
Figure 3. (a) 10-day average sea surface height anomaly field (in cm) computed from Topex-Poseidon and ERS II altimeter data for mid-June 1998. The negative values with the color range from violet to blue indicate cyclonic circulation, and the positive values with the color range from green to red indicate anticyclonic circulation. The Rim Current is shown by the grey color, (b) 8-day composite $nLw443/nLw510$ field for Julian days 161-168, 1998 (which approximately correspond to the second week of June). Red color indicates highest reflection from the cyclonic interior, whereas yellow and green colors indicate weaker reflection around the periphery (anticyclones) of the basin. Similar type spatial variability may also be inferred by other normalized water leaving radiances data. The one chosen here has no particular significance.

ments propogating cyclonically around the basin. Their translation and evolutionary characteristics introduce a major control on the mesoscale structure of the circulation system. The sea surface height anomaly field (Fig. 3a) derived from the June 1998 altimeter data reveals most of these characteristic features of the circulation system.

The mean normalized water leaving radiances data show an intimate relation between spatial patterns of the coccolith blooms and mesoscale character of the basinwide circulation system. For example, the pattern shown in Fig. 3b for the June 1998 basinwide bloom event (Fig. 2a) compares remarkably well with the altimeter data (Fig. 3a) in terms of the cyclonic cell occupying the interior part of the basin, the meandering Rim Current system around the periphery, as well as position of the coastal anticyclonic eddies. The cyclonic cell characterized by relatively shallower mixed layer (typically ≤ 20 m in June) coincides with the region of stronger mixed layer average water leaving radiances as compared to the case of anticyclonic dominated peripheral zone having deeper mixed layer of the order of ~30 m. The combination of these two features of cyclones features of cyclones makes them more favourable sites for more intense bloom formation. The presence of a persistent large scale cyclonic circulation system therefore gives the E. huxleyi blooms a basinwide character in the Black Sea. In a similar context, preferential development of E. huxleyi blooms on shallower stratification and higher light intensities was noted by Nanninga and Tyrrell [1996] using data from the N. Atlantic and elsewhere.

References

Benli, H., Investigation of plankton distribution in the southern Black Sea and its effect on particle flux, in *Particle flux in the ocean*, edited by E. T. Degens and E. Izdar, pp. 77-87, Mitteilungen des Geologisch-Palaontologischen Institutes, Universitat Hamburg, *62*, 1987.

Brown, C.W., Spatial and temporal variability of *Emiliania huxleyi* blooms in SeaWiFS imagery, paper presented at American Geophysical Union, Ocean Sciences Meeting, San Antonio, Teksas (USA), 24-28 January 2000.

Brown, C. W., J. A. Yoder, Coccolithophoroid blooms in the global ocean, *J. Geophys. Res.*, *99*, 7467-7482, 1994.

Brown, C. W., and G. P. Podesta, Remore sensing of coccolithophore blooms in the western South Atlantic Ocean, *Remote Sens. Environ.*, *60*, 83-91, 1997.

Churlikova, T. I., G. P. Berseneva, L. V. Georgieva, S. V. Stanichny, Light absorbtion by phytoplankton, detritus and dissolved organic substances during diatom and coccolithhophore blooms in the Black Sea: impact on algorithms for remote sensing, paper presented at International Association for the Physical Sciences of the Oceans (IAPSO) Symposium, Birmingham, UK, 28-30 July, 1999.

Gordon, H.R., O. B. Brown, R. H. Evans, J. W. Brown, R. C. Smith, K. S. Baker, D. K. Clark, A semianalytic radiance model of ocean color, *J. Geophys. Res.*, *93*, 10909-10924, 1988.

Gordon, H.R., G. C. Boynton, W. M. Balch, S. B. Groom, D. S. Harbour, T. J. Smyth, Retrieval of coccolithophore calcit concentration from SeaWIFS imagery, *Geophys. Res. Letters*, *28*, 1587-1590, 2001.

Hay, B. J., S. Honjo, Particle sources in the present and Holocene Black Sea, *Oceanography*, 2, 26-31, 1989.

Holligan, P. M., and J. E. Robertson, Significance of ocean carbonate budgets for the global carbon cycle, *Global Change Biol.*, *2*, 85-95, 1996.

Korotaev, G. K., O. A. Saenko, C. J. Koblinsky, Satellite altimetry observations of the Black Sea level, *J. Geophys. Res*, *106*, 917-933, 2001.

Mankovsky, V. I., V. L. Vladimirov, E. I. Afonin, A. V. Mishonov, M .V. Solovev, B. E. Anninskiy, L. V. Georgieva, O. A. Yunev, Long-term variability of the Black Sea water transparency and factors determined its strong decrease in the late 1980s, early 1990s *Technical Report, 32 pp.*, Marine Hydrophysical Institute, Sevastopol, Ukraine, 1996.

Nanninga, H. J., and T. Tyrrell, The importance of light for the formation of algal blooms by *Emiliania huxleyi*, *Mar. Ecol. Progr. Ser.*, *136*, 195-203, 1996.

Ozsoy, T., C. Saydam, N. Kubilay, I. Salihoglu, Aerosol nitrate and non-sea-salt sulfate over the eastern Mediterranean, *The Global Atmosphere and Ocean System*, 7, 185-228, 2000.

Sorokin, Yu. I. The Black Sea, in *Ecosystems of the World, 26: Estuaries and Enclosed Seas*, edited by B. H. Ketchum, Elsevier Scientific Publishing Company, pp. 253-292, 1983.

Tekiroglu, E., V. Ediger, S. Yemenicioglu, S. Kapur, E. Aka, The experimental analysis on the late quaternary deposits of the Black Sea, *Oceanologica Acta*, 24, 51-67, 2001.

Tyrrell, T., P. M. Holligan, and C. D. Mobley, Optical impacts of oceanic coccolithophore blooms, *J. Geophys. Res.*, *104*, 3223-3241, 1999.

Uysal, Z., A. E. Kideys, L. Senichkina, L. Georgieva, D. Altukhov, L. Kuzmenko, L. Manjos, E. Eker, Phytoplankton patches formed along the southern Black Sea coast in spring and summer 1996, in *Ecosystem Modeling as a Management Tool for the Black Sea*, edited by L. I. Ivanov and T. Oguz, vol 1, pp. 151-162, Kluwer Academic Publishers, Netherlands, 1998.

T. Cokacar, N. Kubilay and T. Oguz Institute of Marine Sciences, Middle East Technical University PO Box 28, Erdemli 33731, Icel, Turkey. (e-mail: tulay@ims.metu.edu.tr; kubilay@ims.metu.edu.tr; oguz@ims.metu.edu.tr)