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Review article

# Phytoplankton Blooms in the Surface Layer of the Deep-Open Black Sea: Analysis of Methods and Research Results Based on Satellite Data

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*Abstract*
*Purpose*. The purpose of the article is to analyze the studies of phytoplankton blooms in the deep-open Black Sea based on satellite bio-optical data obtained using various algorithms. Satellite data are used due to the lack of *in situ* monitoring programs for studying the spatiotemporal variations of phytoplankton blooms in this region, and the use of different algorithms results in conflicting conclusions. The presented analysis summarizes the available results.
*Methods and Results.* The examined publications have demonstrated the evolution of research on phytoplankton blooms in the deep-open Black Sea from the application of satellite-derived chlorophyll *a* concentration ($\mathrm{Chl}_{\mathrm{sat}}$) to the use of satellite-derived phytoplankton biomass in carbon units ($\mathrm{C}_{\mathrm{sat}}$). $\mathrm{C}_{\mathrm{sat}}$ is obtained from $\mathrm{Chl}_{\mathrm{sat}}$ concentration data and *in situ* seasonal changes in the carbon-to-chlorophyll *a* ratio ($\mathrm{C : Chl}_a$). Determination of $\mathrm{Chl}_{\mathrm{sat}}$ concentration in the Black Sea using standard NASA algorithms (*OC*2 and *OC*4) results in errors of up to 500% and requires the development of regional algorithms, which take into account the specificity of bio-optical parameters in the given basin. The iterative statistical algorithm identifies the blooms as biomass outliers exceeding the 99th percentile of the base seasonal values. The $\mathrm{C : Chl}_a$ ratio varies from 46 (February) to 195 (September). The seasonal maximum shifts from December–January, typical of $\mathrm{Chl}_{\mathrm{sat}}$ concentration, to September–November, typical of $\mathrm{C}_{\mathrm{sat}}$ biomass, i.e., to the actual timing of phytoplankton bloom in the deep-open Black Sea. Bloom thresholds vary by month: 90 (August), 120 (September), and 105 mg C·m$^{-3}$ (October–November). During the post-eutrophication period (since the mid-1990s), the phytoplankton biomass decreased, and winter-spring blooms disappeared.
*Conclusions.* The significant difference in the seasonal dynamics of $\mathrm{Chl}_{\mathrm{sat}}$ concentration and $\mathrm{C}_{\mathrm{sat}}$ biomass indicates that satellite-derived chlorophyll *a* concentration corresponding to the period of operation of the *SeaWiFS and MODIS-Aqua/Terra* ocean color satellite scanners (the post-eutrophication period) is not an acceptable indicator of biomass and cannot be used for studying the patterns of phytoplankton bloom and their mechanisms. One of the solutions to this problem consists in recalculating $\mathrm{Chl}_{\mathrm{sat}}$ concentration into $\mathrm{C}_{\mathrm{sat}}$ biomass using the $\mathrm{C : Chl}_a$ ratio and the algorithm with iterative bloom event extraction.

**Keywords:** subject field overview, chlorophyll *a* concentration, phytoplankton biomass, seasonal changes, interannual changes, long-term changes, phytoplankton bloom, iterative algorithm, Black Sea, regional bio-optical algorithms, satellite methods

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## Introduction

Phytoplankton bloom is a natural phenomenon known since ancient times [1]. It can occur regularly (for example, the spring bloom in the North Atlantic [2]) or episodically throughout the year, as on the northwestern Black Sea shelf prior to the early 1970s [3]. With the onset of anthropogenic eutrophication in the second half of the 20th century, increased nutrient inputs (mainly from river runoff) into marine ecosystems, including the Black Sea, substantially raised the frequency and intensity of phytoplankton blooms in coastal waters [4–11]. This leads to a significant increase in algal biomass, whose subsequent decay intensifies the flux of suspended organic matter from the photosynthetic zone into deeper layers, where bacterial decomposition occurs. As a consequence, dissolved oxygen concentrations decrease in those layers, promoting hypoxia in the near-bottom shelf layer (oxygen concentration in seawater falls below 2.0 $ml \cdot l^{-1}$), which is extremely detrimental to both pelagic and benthic organisms and causes the so-called fish-kill events [4].

Another negative consequence of anthropogenic eutrophication in the coastal waters of the western and northwestern Black Sea was a substantial increase in the frequency and intensity of “red tides” – blooms of toxic dinoflagellates that discolor seawater and lead to mass mortality of fish, invertebrates, birds, and mammals [4, 11]. To study this phenomenon in the coastal areas of the Black Sea, in addition to *in situ* measurements, remote sensing methods were employed, namely aerial surveys [12–14]. An observer on board an aircraft could see from the air the spread of river waters over the sea surface and zones of “red tides”, map these observations, and relay information to a research vessel that would proceed to the exact coordinates provided to investigate the bloom area across the entire chain of ecological processes – from hydrology and hydrochemistry to hydrobiology. Today, small unmanned aerial vehicles (UAVs) [15] have taken over from aerial surveys for coastal research. Their significantly lower cost compared to manned aircraft and high functional capabilities make UAVs one of the key tools in modern coastal biological research.

In the deep-open Black Sea, for a long time only sparse *in situ* biomass determinations of individual algal species were available for studying phytoplankton blooms, which were identified by the authors as “blooms” on the grounds that they exceeded the biomass of other algae several-fold (for example, blooms of the diatoms *Nitzschia delicatissima* [16] and *Nitzschia delicatula* [17]). A major advance in studies of the spatiotemporal changes in phytoplankton characteristics and mechanisms driving their intensive development in this part of the Black Sea was the use of chlorophyll *a* ($Chl_a$) concentration calculated from satellite optical data ($Chl_{sat}$), which was traditionally regarded as an acceptable indirect indicator of phytoplankton biomass [18, 19].

The high spatiotemporal resolution of $Chl_{sat}$ measurements allowed the use of statistical methods for data analysis. However, the definition of blooms was often based on subjective, inconsistent, and arbitrary criteria, substantially affecting the results and conclusions of studies [20]. As will be evident from the present analysis of phytoplankton bloom research in the Black Sea, this situation persists in most cases to the present day.

There is a widely accepted qualitative definition of “bloom”: “An algal bloom is simply an acceleration of phytoplankton growth that leads to an increase in its biomass” [21, p. 83]. However, qualitative descriptions (“exceptional”, “unusual”, or “anomalous”) lack quantitative expression, leading to widespread confusion in defining the phenomenon [22]. Thus, the quantitative threshold criteria for exceptional phytoplankton blooms in [23], which exceed $Chl_a$ concentrations of 100 $mg \cdot m^{-3}$, are unacceptable for mesotrophic and oligotrophic waters.

The iterative algorithm [24], based on the 1984 conclusion of the International Council for the Exploration of the Sea (ICES) that a “bloom” constitutes a deviation from the normal phytoplankton biomass cycle [25], allows the objective identification of bloom events as outliers exceeding the 99th percentile of the prediction interval for the baseline seasonal changes. Application of this algorithm eliminates subjective and arbitrary threshold criteria for quantitative bloom assessment: bloom events are extracted from phytoplankton biomass data statistically, independently of regional and seasonal scales of biomass variability. The iterative algorithm has been successfully applied to study phytoplankton blooms using monitoring *in situ* data on chlorophyll *a* and phytoplankton biomass data from various regions of the Baltic Sea [24, 26], and in eight coastal regions of North America and Europe [27].

The aim of the present work is to analyze studies of phytoplankton blooms in the deep-open Black Sea, which evolved from the use of $Chl_{sat}$ concentration obtained by various algorithms based initially on oceanic and then on Black Sea data (studies prior to 2021), to the use of satellite-derived phytoplankton biomass (starting from 2021).

## Materials and methods

The review analyzes published works devoted to satellite studies of phytoplankton blooms in the deep-open Black Sea. The time coverage spans the period from the availability of CZCS (Coastal Zone Color Scanner) data (1978–1986) through publications of 2025. Studies are reviewed that use data from the CZCS radiometer and algorithms developed for it; data from the SeaWiFS (Sea-viewing Wide Field-of-view Sensor) and MODIS-Aqua/Terra scanners, processed using standard algorithms of the US National Aeronautics and Space Administration (NASA) (*OC*2, *OC*4); regional algorithms for the Black Sea (MHI RAS algorithm [28, 29] and IO RAS algorithm [30, 31]); the transition from $Chl_{sat}$ concentration to phytoplankton biomass in carbon units ($C_{sat}$), calculated from $Chl_{sat}$ concentration and using seasonal carbon-to-chlorophyll *a* ($C : Chl_a$) ratios obtained *in situ* [32, 33]; and the iterative statistical algorithm for identifying blooms [24].

The analysis is based on publications listed in the references, without a formalized quality assessment, consistent with the objectives of a subject field review.

## Results

### Phytoplankton bloom research prior to 2021

*Studies based on CZCS data* (1978–1986). The first studies of seasonal and interannual changes in $Chl_{sat}$ concentration in the surface layer of the Black Sea [34–36] were conducted using the CZCS algorithm, based on empirical equations derived by statistical regression applied to a dataset of "radiance–chlorophyll *a*" data obtained in the Gulf of Mexico and off the western and eastern coasts of the USA [37]. The $Chl_{sat}$ concentration values in the deep-open Black Sea for the cold season (October–April), which were several times higher than those for the warm season (May–September), were interpreted by the authors [34–36] as the result of winter–spring phytoplankton blooms. In their view, this was corroborated by the high biomass of the diatom *Nitzschia delicatula*, obtained *in situ* in the surface layer in February–March 1991 [38].

*Launch of SeaWiFS and application of standard NASA algorithms*. After a ten-year gap (since 1986) in the operation of radiometers providing $Chl_{sat}$ data, SeaWiFS began operating in September 1997. To obtain $Chl_{sat}$, NASA developed two standard bio-optical algorithms: *OC*2 [39] and *OC*4 [40]. *OC*2 is an empirical cubic polynomial equation relating the remote sensing reflectance ($R_{rs}$) at two spectral wavelengths ($\lambda$) (490 and 555 nm) to *in situ* measured values of $Chl_a$; *OC*4 is also an empirical equation relating $R_{rs}$ to $Chl_a$, but as a fourth-order polynomial in which four wavelengths $\lambda$ are used: 443, 490, 510, and 555 nm.

The author of the first study of the seasonal cycle of $Chl_{sat}$ concentration in the surface layer of the deep-open Black Sea from September 1997 to March 2000 [41] used the old CZCS algorithm and also identified two periods for each seasonal cycle over the three-year period: a warm period with low $Chl_{sat}$ values and a cold period with high values. He noted that the cold season of 1998/1999 was characterized by higher $Chl_{sat}$ values over a longer period and concluded that an unusually intense phytoplankton bloom occurred from autumn 1998 through spring 1999. However, this conclusion was inconsistent with *in situ* data [42] and was corrected by the author of [43] only after reprocessing satellite data with allowance for regional atmospheric conditions, i.e., after atmospheric correction, $Chl_{sat}$ became close to the concentration obtained *in situ* [42].

In subsequent studies [44–50], data from the SeaWiFS and MODIS-Aqua/Terra radiometers, processed using NASA algorithms [39, 40], were used to study the seasonal and interannual variability of $Chl_{sat}$ concentration in the deep-open Black Sea. However, the obtained results also did not correspond to *in situ* measurements. The most illustrative example is a study in which high $Chl_{sat}$ values, calculated using NASA algorithms in the surface layer of the deep-open Black Sea at the end of August 2015 (~ 5 $mg \cdot m^{-3}$ and above) and persisting until November, were interpreted by the authors as an anomalous phytoplankton bloom that covered almost the entire eastern part of the basin for over three months and was caused "by the action of several successive strong storms that amplified each other" [48, p. 22].

Without analyzing in detail the meteorological, physical, and hydrochemical conditions that have prevailed in the deep-open Black Sea since the mid-1990s to the present – conditions that determine phytoplankton characteristics, primarily biomass and bloom frequency [51] – one can cite at least two well-known facts (known at the time of publication of [48]) indicating the erroneous nature of such high $Chl_{sat}$ concentration values in the surface layer of the deep-open Black Sea (~ 5 $mg \cdot m^{-3}$ and above) and, accordingly, the erroneous conclusion drawn by the authors.

First, according to data on long-term changes in $Chl_a$ in the surface layer of the deep-open Black Sea from May to September [51, 52], obtained *in situ* by standard methods in various Black Sea countries, even at the peak of anthropogenic eutrophication in July 1992, $Chl_a$ values did not exceed 2.4–2.5 $mg \cdot m^{-3}$, averaging (1.0 ± 0.7) $mg \cdot m^{-3}$. High $Chl_a$ values (5 $mg \cdot m^{-3}$ and above) in the surface layer during the summer–autumn season after the mid-1990s were recorded only on the inner shelf (depths less than 50 m) off the Danube River mouth [53]. The constant nutrient input from Danube runoff onto the inner shelf even during the post-eutrophication period is incomparably higher than the nutrient flux assumed by [48] into the surface layer from below in the deep-open Black Sea as a consequence of several successive strong storms in August 2015, which, according to the authors, sustained an anomalous phytoplankton bloom in this part of the Black Sea over the subsequent three months.

Secondly, already in the late 1990s and early 2000s, results of studies were published addressing the application of the empirical equations *OC*2 and *OC*4, developed for ocean Case 1 waters [39, 40], to Case 2 waters, including Black Sea waters, which differ from ocean waters in the relationship between the absorption coefficient of phytoplankton pigments and that of colored organic matter [54–57]. These studies showed that such application typically leads to substantial errors of up to 500% and more. The standard NASA *OC*2 and *OC*4 algorithms are applicable only to ocean waters (*OC* – Ocean Color chlorophyll algorithms), which has been repeatedly emphasized in IOCCG (International Ocean Colour Coordinating Group) reports [18, 58, 59].

*Regional algorithms for the Black Sea*. The only solution to this problem, as emphasized in all the articles and reports cited above, is the development of bio-optical algorithms for obtaining $Chl_{sat}$, which would account for the specific features of bio-optical parameter formation in a given region. The first regional algorithm for Black Sea data from 1978–1986 [60] consisted of regression equations for directly comparing $Chl_{sat}$ data obtained using the CZCS algorithm [37] with *in situ* data. Regression equations were calculated for six subregions of the Black Sea (including various shelf and deep-water areas) and accounted for subregional and seasonal differences. The resulting new $Chl_{sat}$ concentration values allowed estimation of their spatial–seasonal variability in the Black Sea averaged for the period 1978–1986, but could not be used for phytoplankton bloom studies due to the poor quality of CZCS data in terms of their spatiotemporal coverage of the Black Sea area.

Subsequently, regional algorithms were developed for SeaWiFS and MODIS-Aqua/Terra $Chl_{sat}$ concentration in the Black Sea: the MHI algorithm (Marine Hydrophysical Institute, Sevastopol) [28, 29] and the IO algorithm (Shirshov

Institute of Oceanology, Moscow) [30, 31]. These algorithms account for the specific features of bio-optical parameter formation in the Black Sea. Using data on $\mathrm{Chl_{sat}}$ concentration obtained using the MHI and IO regional bio-optical algorithms, studies were conducted of its seasonal and interannual dynamics, as well as the mechanisms of phytoplankton blooms in the deep-open Black Sea [61–63]. These studies identified two characteristic maxima of $\mathrm{Chl_{sat}}$: a main winter–spring peak in February–March and a weaker autumn peak in November. These peaks were interpreted by the authors as algal blooms on the assumption that $\mathrm{Chl_{sat}}$ concentration peaks correspond to phytoplankton biomass maxima and reflect blooms. The authors [61–63] also proposed various mechanisms promoting intensive phytoplankton development in November and February–March, based on the assumption that nutrients are supplied to the euphotic layer from deep waters through erosion of the seasonal thermocline (November) or winter convection (February–March).

The present work does not discuss in detail the results obtained using $\mathrm{Chl_{sat}}$ concentration derived from regional algorithms [61–63], since later studies [32, 33], based not on $\mathrm{Chl_{sat}}$ but on satellite-derived phytoplankton biomass ($\mathrm{C_{sat}}$), fundamentally changed the prevailing understanding of the seasonality of phytoplankton biomass and blooms, as well as of the mechanisms sustaining these blooms in the deep-open Black Sea.

## Phytoplankton bloom research starting from 2021 (transition to phytoplankton biomass)

In [32, 33], to obtain phytoplankton biomass, $\mathrm{Chl_{sat}}$ concentration was used, calculated, as in [61], using the MHI regional algorithm [28, 29], along with *in situ* data on seasonal changes in the $\mathrm{C : Chl}_a$ ratio. The MHI algorithm is based on the use of $R_{\mathrm{rs}}$, measured at three wavelengths λ (490, 510, and 555 nm for SeaWiFS and 488, 531, and 547 nm for the MODIS-Aqua/Terra scanners), and their ratios, the so-called spectral channel ratios $I_\lambda$ ($I_{490} = R_{\mathrm{rs}}(510)/R_{\mathrm{rs}}(490)$ and $I_{510} = R_{\mathrm{rs}}(555)/R_{\mathrm{rs}}(510)$ for SeaWiFS; $I_{488} = R_{\mathrm{rs}}(531)/R_{\mathrm{rs}}(488)$ and $I_{531} = R_{\mathrm{rs}}(547)/R_{\mathrm{rs}}(531)$ for MODIS-Aqua/Terra). The use of three $R_{\mathrm{rs}}$ values and two spectral channel ratios for each satellite ocean color scanner allows the separation of absorption associated with the phytoplankton component from that of colored organic matter within the total light absorption coefficient, and estimation of the relationship between the phytoplankton absorption component ($a_{\mathrm{ph}}$) at a wavelength of 490 nm ($a_{\mathrm{ph}}(490)$) and $\mathrm{Chl}_a$ concentration, measured *in situ*.

The use of the $\mathrm{C : Chl}_a$ ratio for recalculating $\mathrm{Chl_{sat}}$ into phytoplankton biomass ($\mathrm{C_{sat}}$) in [32, 33] was motivated by: 1) substantial seasonal changes in $\mathrm{C : Chl}_a$ depending on phytoplankton species composition, light intensity, and nutrient concentration in the environment [64, 65]; 2) the pronounced seasonality of these factors in the deep-open Black Sea [66]; 3) the three- to six-fold increase in this ratio in summer compared to winter on the Black Sea shelf [67].

Studies [32, 33] showed that:

1) the $\mathrm{C : Chl}_a$ ratio in the deep-open Black Sea has a unimodal character and varies from 46 (average for February) to 195 (average for September) (Fig. 1, *a*), i.e. close to the shelf data [67];

2) applying the obtained seasonal $\mathrm{C : Chl}_a$ values (Fig. 1, *a*) to $\mathrm{Chl_{sat}}$ concentration and applying the iterative algorithm [24] yielded data on the

seasonal changes in bloom events and baseline $C_{\mathrm{sat}}$ biomass values in the deep-open Black Sea and made it possible to compare phytoplankton biomass with seasonal changes in $\mathrm{Chl}_{\mathrm{sat}}$ (Fig. 1, *b*).

In Fig. 1, *b*, a notable shift in the seasonal maximum is visible: from December–January, typical of $\mathrm{Chl}_{\mathrm{sat}}$ concentration, to September–November, typical of the base $C_{\mathrm{sat}}$ biomass. Similar differences between the seasonal dynamics of chlorophyll *a* and phytoplankton biomass have been recorded in the North Sea [68] and Mediterranean Sea [64], in the subtropical gyre of the North Pacific Ocean [69], and on the northwestern Black Sea shelf [70]. All the data obtained, including those for the deep-open Black Sea (Fig. 1, *b*), indicate that the uncritical use of chlorophyll *a* concentration as an indicator of phytoplankton biomass can lead to an incorrect representation of the seasonal dynamics of phytoplankton biomass and algal blooms, as well as of the mechanisms sustaining them.

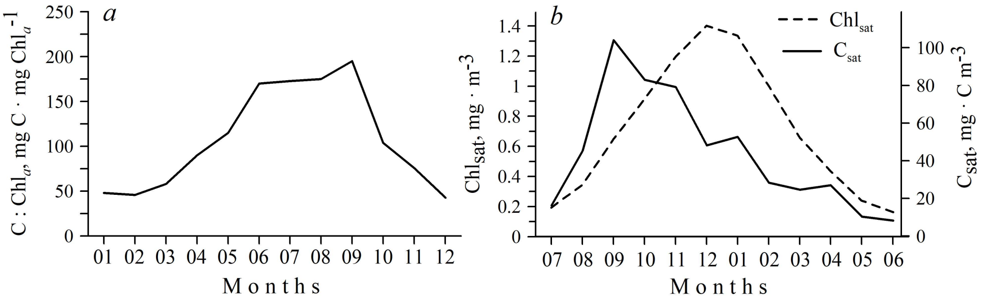


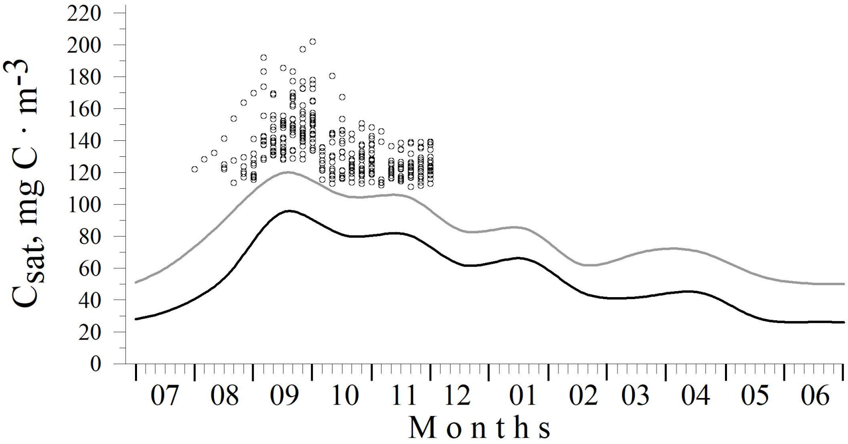
**Fig. 1.** Seasonal changes in the deep-open Black Sea: *a* – the C : $\mathrm{Chl}_a$ ratio obtained from the data for 1988–2013; *b* – the $\mathrm{Chl}_{\mathrm{sat}}$ concentration and base $C_{\mathrm{sat}}$ biomass values according to the data for 1998–2018. Adapted from [32]

Analysis of the seasonal changes in $C_{\mathrm{sat}}$ (Fig. 2) showed that blooms in the surface layer of the deep-open Black Sea are characteristic not only of the September phytoplankton biomass maximum, but also of October–November, with lower baseline $C_{\mathrm{sat}}$ biomass values, and of August, with considerably lower values compared to October–November. Thus, these data indicate that blooms in the deep-open Black Sea are not confined to the seasonal phytoplankton biomass maximum, as was assumed in previous studies [61–63].

Different bloom threshold criteria were obtained for different months: 90, 120, and 105 mg $\mathrm{C{\cdot}m^{-3}}$ for August, September, and October–November, respectively. Consequently, there are no uniform bloom threshold criteria even within a single region and a single bloom season in the deep-open Black Sea.

Moreover, analysis of the long-term changes in phytoplankton biomass and bloom frequency (based on $C_{\mathrm{sat}}$), as well as their relationship with natural factors [33], showed that the studied phytoplankton characteristics underwent substantial changes as a result of climate change combined with changes in the physical and chemical characteristics of the deep-open Black Sea over the past 60 years [71–76].

The pre-eutrophication period (approximately up to the early 1970s) was characterized by low phytoplankton biomass and virtually no blooms in the surface layer throughout the year, whereas nutrient inputs from land and an increased nitrate concentration gradient in the layer between the deep nitrate maximum and the euphotic layer, along with low winter temperatures during the intense eutrophication phase (mid-1980s – early 1990s), promoted high phytoplankton biomass and algal blooms in late summer–autumn and late winter–early spring. In the subsequent post-eutrophication period (mid-1990s – present), due to oligotrophication of the Black Sea and warming, phytoplankton biomass decreased, bloom events in August–September became less frequent, and blooms in late winter–early spring disappeared.



**F i g. 2.** Seasonal changes in phytoplankton biomass ($C_{sat}$) from July to June (1998–2022) in the deep-open Black Sea, based on the data divided into base distribution and blooms. Adapted from [33]. Circle is the five-day average $C_{sat}$ value of bloom for the entire study period; black curve is the calculated average seasonal base $C_{sat}$ biomass; gray curve is the 99th percentile of prediction interval for the base seasonal variation separating the bloom and non-bloom data

Studies [32, 33] propose various mechanisms promoting phytoplankton blooms in the open Black Sea. The most likely are migrations of large diatoms to deeper layers to harvest nitrates in late summer and autumn, and the supply of nutrients to the surface layer from depth through convective mixing during the cold season. The realization of these two mechanisms depends on the physical and chemical characteristics of the open Black Sea, as well as on the climatic conditions in a given interannual period.

## Conclusion

The review of methods and results of phytoplankton bloom research in the deep-open Black Sea based on satellite data allows the following conclusions:

1. Satellite-derived chlorophyll *a* concentration for the period of operation of the SeaWiFS and MODIS-Aqua/Terra ocean color scanners, which coincides with the post-eutrophication period, is not an acceptable indicator of phytoplankton biomass and cannot be used to study phytoplankton bloom patterns and the mechanisms promoting blooms during this period. One solution to this problem is to convert this chlorophyll *a* concentration into phytoplankton biomass, as was done in studies that used for this purpose *in situ* seasonal changes in the carbon-to-chlorophyll *a* ratio.

2. Satellite-derived chlorophyll *a* concentration should be calculated only using a regional algorithm that accounts for the specific features of bio-optical parameter formation in the Black Sea, since the standard NASA (*OC*2 and *OC*4) algorithms, developed for ocean waters, introduce substantial errors when applied to Black Sea waters (up to 500% and more). Another solution to the problem of using chlorophyll *a* concentration in studies of phytoplankton bloom patterns in the sea surface layer may be the development of a regional algorithm for obtaining phytoplankton biomass directly from satellite optical data, bypassing the calculation of satellite-derived chlorophyll *a* concentration, as has been done for the Atlantic and the Mediterranean Sea.

3. Identification of bloom events from phytoplankton biomass data should not be based on arbitrary and subjective criteria, but should employ statistically sound methods that distinguish baseline values characterized by a normal distribution from bloom values characterized by deviations from the normal phytoplankton biomass cycle.

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