Use of SeaWiFS data to estimate water optical properties of the Black Sea

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ABSTRACT

Since 1997 the U.S. satellite sensor SeaWiFS is providing an information, that can be helpful to monitor Black Sea waters in routine operational mode. Due to the errors inherent in atmospheric correction procedures, the possibilities to determine the full spectrum of normalized spectral water-leaving radiance are very limited. At the same time the analysis shows that the use of two SeaWiFS channels at 510 and 555 nm allow us to detect many interesting features of temporal and spatial variability of the effects of absorption and scattering of light in the Black Sea.

Keywords: remote sensing, sea color, chlorophyll, absorption and scattering of light, SeaWiFS, Black Sea, coccolithophore bloom.

1. INTRODUCTION

The Black Sea is a site of significant environmental problems caused primarily by human activities in surrounding countries. Data collected by the U.S. satellite-mounted ocean color sensor SeaWiFS during about nine years provide unique possibilities for the Black Sea research. Analysis of SeaWiFS data demonstrates considerable spatial and temporal variability of optical water properties of the Black Sea. It would be very helpful to use SeaWiFS data to determine chlorophyll-a concentration C_a, but results of C_a calculations, performed using standard SeaWiFS algorithm, often significantly differ from the real values of C_a in the Black Sea. Resulting estimations of chlorophyll concentration and other properties of sea water are obtained through the complex chain of satellite data processing. Most probably, the errors in C_a estimations for the Black Sea are caused by the fact that Black Sea waters belong to the Morel's Case 2 type, while the standard algorithm was developed for Case 1 ocean waters.

Due to the errors in atmospheric correction, possibilities of determination of full spectrum of normalized spectral water-leaving radiance, $L_{WN}(\lambda)$, are very limited. At the same time, the use of two SeaWiFS bands with wavelengths $\lambda = 510$ and 555 nm allows values of absorption coefficients of all constituents of seawater at $\lambda = 510$ nm, A_Σ, and backscattering coefficient b_{bp} of suspended in water particulate matter at $\lambda = 555$ nm to be computed. Our goals are to use the large SeaWiFS data set to estimate some interesting features of variations of these optical properties, to achieve better understanding of their nature, and to reveal associated problems. Our attention is generally focused on the analysis of the open deep-water part of the sea. Properties of the coastal zones with very turbid waters are extremely complicated and demand special consideration, that is beyond this work. Nevertheless, processes in the open deep-water part of the Black sea are also rather interesting because they reflect an overall state of the sea as a whole.

The material presented below is an enhancement of several reports presented at three Conferences "Current Problems in Optics of Natural Waters" [1-3] with an addition of some new results.

2. METHODOLOGY

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The conventional model of oceanic Case 1 type waters assumes that their optical properties are correlated with the phytoplankton chlorophyll-*a* concentration C_a. In contrast to this model, Black sea water belongs to more complex Case 2 type waters, and thus other additional independent parameters are necessary to describe variations of its optical properties. In particular, it is helpful to consider the coefficients of backscattering and absorption of light by various admixtures in seawater.

Many approaches are known for satellite data interpretation in Case 2 coastal waters, but because of the errors in the atmospheric correction it is difficult to implement them because all these approaches are based on the use of multispectral measurements. The experience shows that in the Black Sea region, atmospheric conditions often do not satisfy the assumptions that are used in the standard NASA's atmospheric correction algorithm. The errors are rather small for $L_{WN}(555)$ and color ratio $I_{510} = L_{WN}(555)/L_{WN}(510)$, but are significant for $L_{WN}(412)$ and $L_{WN}(443)$.

Using the results of $L_{WN}(555)$ and I_{510} estimations it is possible to calculate the values of the absorption coefficient of all admixtures in seawater at $\lambda = 510$ nm, A_Σ , and backscattering coefficient b_{bp} of suspended in water particulate matter at $\lambda = 555$ nm.

Using a simple optical model, similar to that described by Siegel *et al.*[4], we have generated several sets of computed I_{510} values for different combinations of values of input parameters C_a , b_{bp} and a_g , corresponding to their independent variations within a rather wide range of expected intervals. Here a_g describes the combined influence of absorption by dissolved yellow substance and detrital particulate matter (below for the case of simplicity we will call this component as "yellow substance"). In the next step we have found that, within reasonable accuracy, the following approximation[5] is valid:

$$A_\Sigma = 0.230\cdot (I_{510})^2 - 0.196\cdot I_{510} + 0.049 \ [\mathrm{m}^{-1}], \qquad (1)$$

where A_Σ is the sum $a_{ph} + a_g$; a_{ph} is a phytoplankton absorption coefficient at the same wavelength 510 nm. The values of a_{ph} were estimated via C_a according to the model given by Bricaud *et al.*[6]

Similar analysis of sets of calculated values of I_{510} and $L_{WN}(555)$ allowed us to express b_{bp} in the following form:

$$b_{bp} = \{6.76\cdot L_{WN}(555) + 0.03\cdot [L_{WN}(555)]^3 + 3.40\cdot L_{WN}(555)\cdot (I_{510})^{3.8} - 0.84\}\cdot 10^{-3}. \qquad (2)$$

The values of b_{bp} and $L_{WN}(555)$ are in m^{-1} and in $\mu\mathrm{W\ nm^{-1}\cdot sr^{-1}\cdot cm^{-2}}$, respectively. Equations (1) and (2) explain an information content and physical meaning of two variables I_{510} and $L_{WN}(555)$ obtained as standard products of SeaWiFS data processing.

As noted above, for the Black Sea observations, the results of atmospheric correction in most cases are rather good for $L_{WN}(555)$ and I_{510}. This statement is supported by a number of indirect criteria, such as, for example, smoothness of spatial and temporal variations of these values regardless of sharp changes, observed in the atmosphere. At the same time, optical properties of atmospheric aerosol in the Black Sea region demonstrate very strong diversity. Therefore sometimes substantial atmospheric correction errors take place in $L_{WN}(\lambda)$ for all λ , and in the results of calculations of I_{510} and C_a as well.

As an example, it is interesting to review results of observation of the eastern part of the Black Sea made in September 12, 1998. Figure 1 schematically shows estimations of chlorophyll concentration in water and atmospheric aerosol optical thickness τ_A (for $\lambda = 865$ nm) retrieved from SeaWiFS measurements. Identical outstretched narrowing bands are distinctly observed in the spatial distribution of these two values. Within this band $L_{WN}(412) < -0.2$ $\mu\mathrm{W\cdot nm^{-1}\cdot sr^{-1}\cdot cm^{-2}}$, chlorophyll concentration exceeds 1.9 $\mathrm{mg\cdot m^{-3}}$ (in a few isolated points values of C_a reach 4–5 $\mathrm{mg\cdot m^{-3}}$), while in the surrounding area $L_{WN}(412)$ is greater than zero and $C_a \approx 0.8 - 1.0$ $\mathrm{mg\cdot m^{-3}}$. Unlike these patterns, the field of estimated chlorophyll concentration during September 10, 1998 is rather uniform with $C_a = 0.8 – 1.0$ mg· m^{-3} within the whole area of the considered region. Obviously, high correlation between values of C_a and τ_A, presented in Figure 1, and large difference of chlorophyll concentration between September, 10 and 12 are caused by the errors in atmospheric correction. It is natural to suggest that the remarkable contrasts observed in the field of τ_A (see Fig. 1,*b*) reflects specific

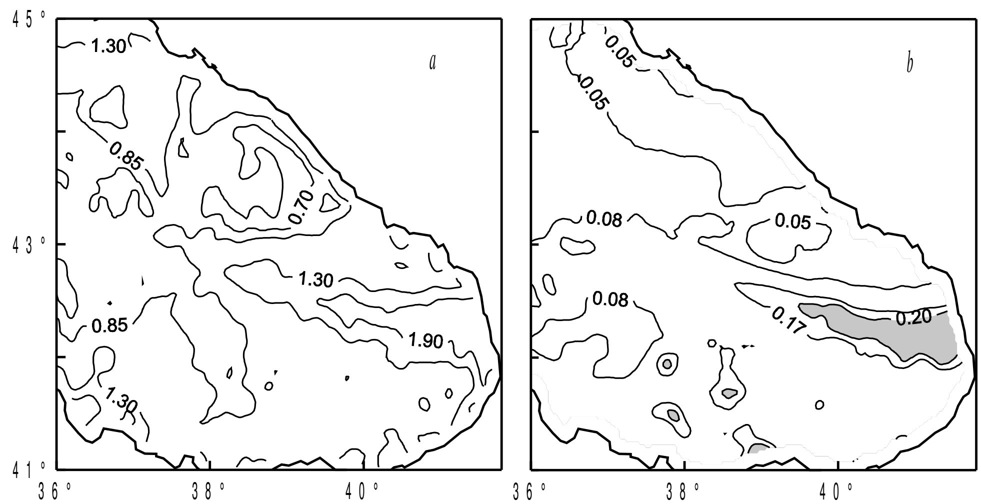


Fig. 1. Spatial distribution of C_a, mg· m^{-3}, (*a*) and aerosol optical thickness τ_A at λ =865 nm (*b*) in the eastern part of the Black Sea for September 12, 1998.

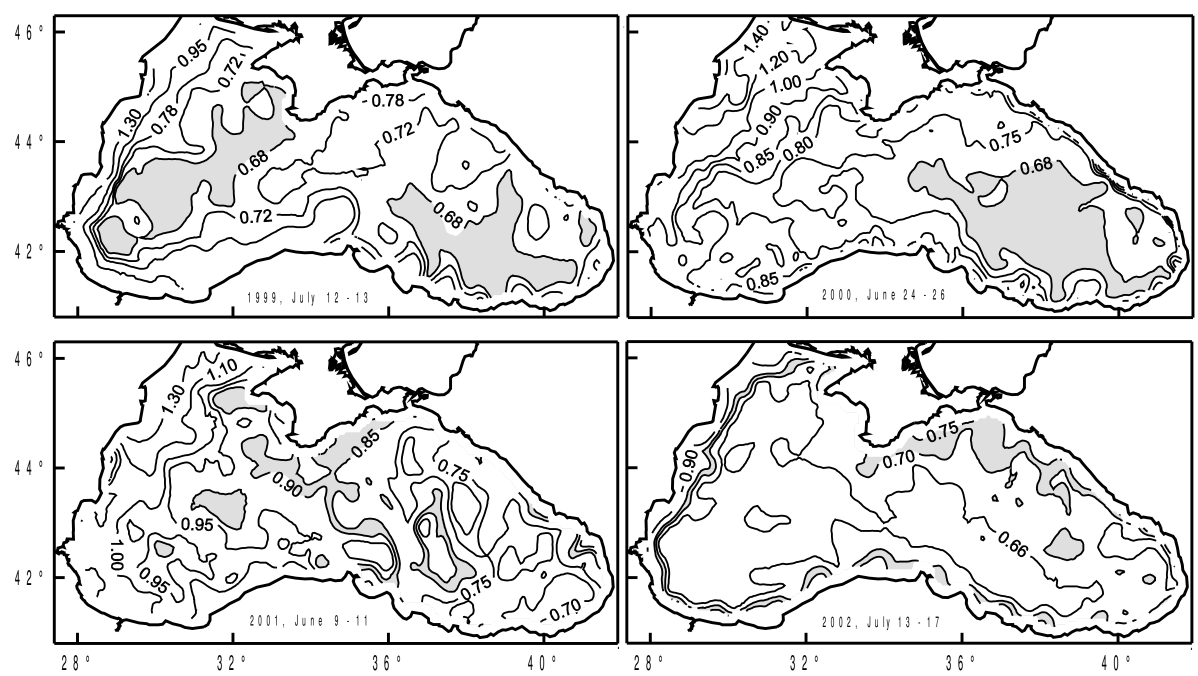


Fig. 2. Examples of I_{510} spatial distribution in summer 1999, 2000, 2001, and 2002.

process of propagation of absorbing aerosol which can not be accounted for by standard SeaWiFS atmospheric correction procedure.

The number of quality control procedures is used in the SeaWiFS data processing system for detecting various anomalous situations in which the real conditions differ from the model assumptions accepted in the algorithms. Special binary values (flags) are used to mark data whose quality (due to a variety of reasons) is under suspicion. In the context of problems considered here, the most important are the following three flags: 16 (chlorophyll not calculable), 18 (absorbing aerosol index above the threshold), and 20 (maximum number of iterations in the NIR algorithm). Our experience shows, however, that in some cases this quality control is not sufficiently effective. For instance, in the case considered above (in September 12, 1998; Fig. 1) all these flags (16, 18, 20) have not been set for the whole area of the sea, excluding a few isolated points.

In the SeaWiFS data processing system flags are included into the standard *Level-2* files and their main function consists in marking unreliable data when the final *Level-3* products are created. Usually, most significant errors in atmospheric correction influence the values of L_{WN} (412). It causes these values to be underestimated and even become negative. For these reasons the reliability of estimated values of L_{WN} (555) and I_{510} become essentially better if we implement an additional elimination of pixels that have values L_{WN} (412) < 0 or L_{WN} (412) ≈ 0. By implementing this idea to obtain results of our Black Sea investigations, we use *Level-2* data in a place of a standard *Level-3* input.

3. ABSORPTION

Expression (1) gives a simple empirical relation between I_{510} and A_Σ . Consequently, it is possible to consider both these parameters as equivalent characteristics of absorption. Table 1 presents some numerical examples of this relation. Figures 2 and 3 show examples of variations of I_{510} in space and time. Maps, presented in Figure 2, have been plotted using standard SeaWiFS *Level-2* data processing products generated by NASA GSFC (GAC data). They are based on measurements during several short summer time periods during different years. Figure 3 have been plotted from the daily observations averaged over fortnight time periods within the geographic area restricted by the following geographic boundaries: 31.0 – 33.2°E; 42.5 – 44.0°N. This testing site is rather representative because it reflects typical optical properties of water that exists in the open part of the whole sea.

Table 1. Relations between some optical parameters and two variants of estimates of chlorophyll-*a* concentration C_a.

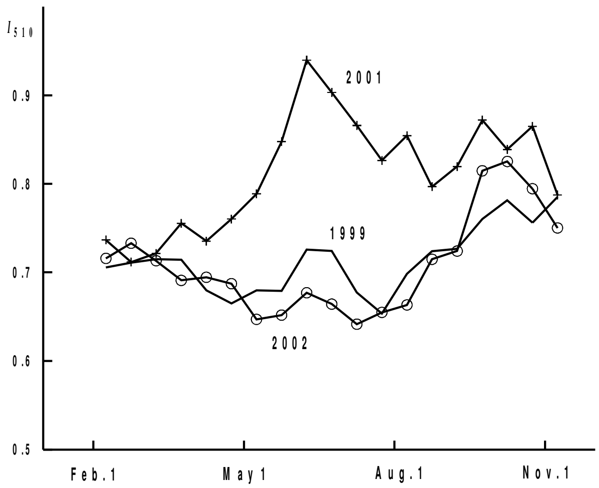
I_{510}	A_Σ , m^{-1}	$C_a(1)$, $mg \cdot m^{-3}$	$C_a(2)$, $mg \cdot m^{-3}$	$A_{ph}(1)$, m^{-1}	$A_{ph}(2)$, m^{-1}
0.62	0.016	0.38	0.23	0.009	0.006
0.74	0.030	0.83	0.41	0.016	0.009
0.90	0.059	1.6	0.80	0.025	0.015

Figures 3 and 4 show that optical properties of water in different parts of the Black Sea strongly vary in space and in time (from season to season and from year to year) reflecting complex processes in the marine ecosystem caused by the transport of various types of admixtures in water as well as by the activity of phytoplankton. One of the regions with high variations of I_{510} is located in the north-western shelf zone, where for example, I_{510} < 0.66 in July 2002, and > 0.90 in June 2000. Our attention was not concentrated on the analysis of coastal zones and river plumes with very turbid waters, so the typical interval of I_{510} variations is about 0.6 – 0.9. The corresponding values of A_Σ vary approximately from 0.015 to 0.058 m^{-1}.

In order to see the nature of these quantities it is useful to evaluate the appropriate variations of the values of a_{ph} and a_g . For this purpose we applied two alternative estimations of a_{ph} using chlorophyll-*a* concentration and then I_{510} , defined as $C_a(1)$ and $C_a(2)$ (see Table 1). The values of $C_a(1)$ correspond to the algorithm present in standard SeaWiFS data processing system[7], and the values of $C_a(2)$ correspond to the regional algorithm,[5, 8] specifically for the Black Sea conditions during the summer of 1998. This regional algorithm is based on the combined analysis of SeaWiFS data and *in situ* measurements. This regional algorithm represented by the following expression:

$$C_a = 1.13\ (I_{510})^{3.33}\ [\text{mg m}^{-3}]. \quad (3)$$

This formula generates values of C_a that are approximately two times smaller than the results of computations based on standard SeaWiFS algorithm. After obtaining estimated values of C_a, we further compute a_{ph} using the model proposed by Bricaud *et al*.[6] Evidently, chlorophyll concentration could be retrieved from I_{510} only in those cases when significant relationship exists between values of C_a, a_{ph}, and a_g. Our experience shows that in many cases regional algorithms



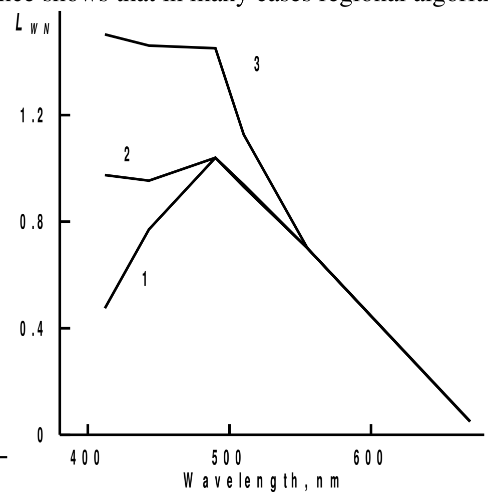


Fig. 3 (left). Changes of I_{510} in time during different years within the selected area in the open part of the Black Sea.

Fig. 4 (right). Schematic comparison of $L_{WN}(\lambda)$ spectra, μ W $nm^{-1}\cdot sr^{-1}\cdot cm^{-2}$, in the Black Sea (line 1) and in the Ocean (lines 2 and 3). Line 1 corresponds to real SeaWiFS data and *in situ* measured[13, 14] chlorophyll-*a* concentration $C_a = 0.41$ mg$\cdot$ m^{-3}. Here, ocean spectra were modeled using the empirical approximation[7] for $C_a = 0.83$ and 0.41 mg$\cdot$ m^{-3}. These two spectra were specifically scaled to adjust to SeaWiFS value in the Black Sea at λ =555 nm.

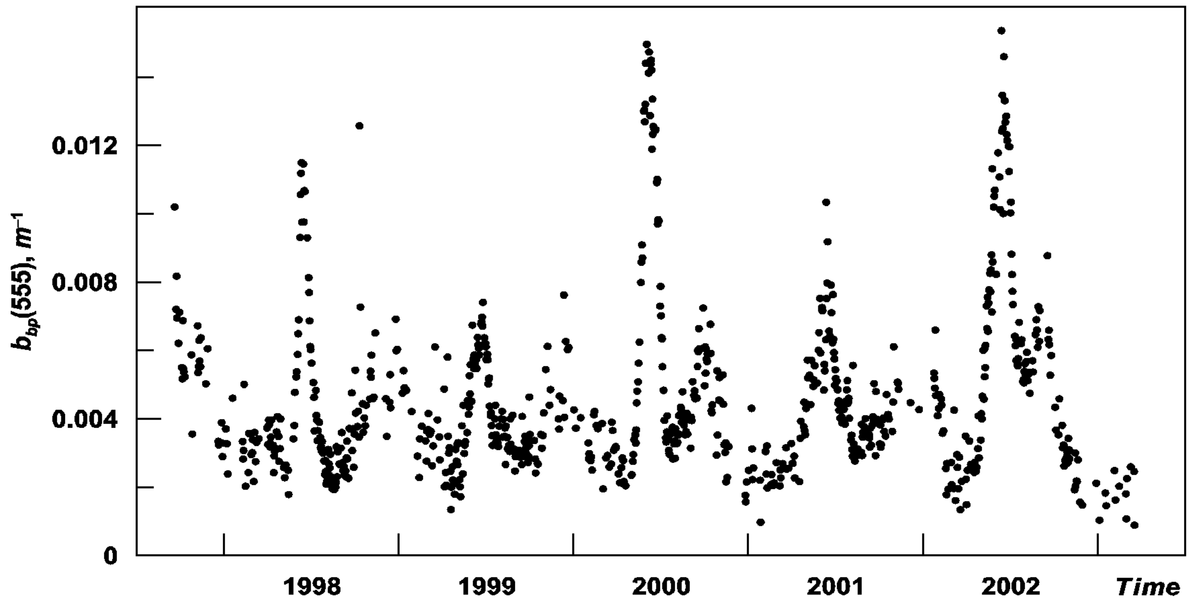


Fig. 5. Example of variations of $b_{bp}(555)$ with time.

give better results than the standard procedure. For example, in the autumn 1998 in the open part of the Black Sea, values of $C_a(1)$ are closer to *in situ* measurements presented by Berseneva *et al.*[9] than values of $C_a(2)$. It is interesting to note that in both cases of C_a determination the yellow substance (a_g) contributes more to the absorption in comparison to phytoplankton (a_{ph}).

In general, one should be ready to meet situations with very different relations between a_{ph} and a_g . For example, comparisons of the data in the open deep-water part of the sea for different years show unusually high level of I_{510} observed in the summer 2001. Within the frames of simple multi-parametric optical model this effect can be attributed to the anomalous contribution of "yellow substance" in seawater, provided that its concentration increased independently from a chlorophyll-*a* concentration of phytoplankton.

This statement, in particular, is supported by *in situ* determinations of C_a in June 2001 at several sites in the western Black Sea performed by Turkish researchers during the U.S.-Turkey Expedition aboard R/V *Knorr*.[10] Essentially, their results do not differ from usual summer level of C_a which is near 0.2–0.4 mg· m^{-3} in the open part of the Black sea. In summer 2001, the corresponding values of C_{a1} and C_{a2} are equivalent to chlorophyll-*a* concentration that occurred in the early 1990s, when a severe ecological anomaly was observed in the whole Black Sea basin.[11, 12] The effect observed in 2001 may be caused by increased contribution of a_g . This increase in a concentration of "yellow substance" is interesting in itself, but it demands special consideration which is out of the scope of our work.

Other examples of independent variability of a_g and chlorophyll-*a* concentration are related to seasonal changes of I_{510} displayed in Figure 3. In this figure, one can see that the level of I_{510} in autumn usually is higher as compared to its level in late winter and spring, while it is well known that in reality the corresponding C_a field has an opposite tendency.[9, 12]

To better understand the relative role of two components of absorption (a_{ph} and a_g), it is interesting to consider the total $L_{WN}(\lambda)$ spectra. Usually, the results of $L_{WN}(\lambda)$ estimation have questionable quality for $\lambda < 510$ nm. None the less, sometimes it is possible to select situations where standard SeaWiFS atmospheric correction procedure yields reliable results for all SeaWiFS spectral bands, and moreover it is possible to obtain indirect evidence for their reliability. An example of such an approach is described by Suetin et al.[13] where we have analyzed SeaWiFS data obtained in the vicinity of the South Coast of Crimea simultaneously with an *in situ* determination of C_a from the oceanographic platform in 2002 summer ground-truth experiment[14]. Figure 4 schematically shows the spectral dependence of $L_{WN}(\lambda)$, determined in[13], together with two relevant ocean Case 1 water spectra.

In Figure 4, all three curves are different for $\lambda < 490$ nm, and curve 3 does not coincide with the two others for $\lambda < 555$ nm. At the same time, lines 1 and 3 correspond to the same value of C_a (equal to 0.41 mg· m^{-3}), while for line 2, the concentration C_a is approximately two times higher. For $\lambda > 443$ nm, lines 1 and 2 coincide in spite of very different chlorophyll-*a* concentrations (equal to 0.41 and 0.83 mg· m^{-3}). These features of the observed spectra originate from the increased level of "yellow substance" content in Black Sea water compared to ocean waters with the same chlorophyll-*a* concentration. The corresponding model numerical evaluations are presented in the 2-d line of Table 1. In Figure 4, spectra 1 and 2 have identical values of I_{510} and A_Σ ; hence, it is easy to show that the values of a_g are equal to 0.021 and 0.014 m^{-1}, accordingly.

It is not out of place to note that all spectra shown in Figure 4, are approximated by the optical model for all SeaWiFS spectral bands with good accuracy and moreover, model estimated numerical values of a_g and C_a compare well to above mentioned evaluations (for the Black Sea spectrum they are: $a_g = 0.021$ m^{-1} and $C_a = 0.41$ mg· m^{-3}). Also, the value of $C_a = 0.41$ mg· m^{-3} coincides with the value obtained from the above mentioned formula (3) and corresponds well to the *in situ* measurements provided by Korotaev *et al.*[14] Comparisons of these results with the results[5, 8, 9] allow us to conclude that, for the considered example, the nature of light absorption is similar to the nature of light absorption that occurred in the open part of the sea in the summer of 1998.

4. BACKSCATTERING

Optical properties of the Black Sea vary in a wide range due to the influence of many different physical, bio- and geo-chemical, and other environmental processes. One of many causes of the variability consists in changes of phytoplankton species composition that takes place at a number of spatial and temporal scales. During different time intervals and in different parts of the Black Sea, the phytoplankton community is dominated by diatoms, dinoflagellates and/or coccolithophore, presented by *Emiliania huxleyi*. Such domination occurs at all seasons, but sometimes in June its amount may reach a "bloom" critical mass, and in most cases it happens in the open part of the sea. This "bloom" can produce strong optical signature.[11]

Typical examples of temporal and spatial variability of SeaWiFS-based estimations of $b_{bp}(555)$ are illustrated in Figures 5–7. In Figure 5, data were selected from the western deep-sea region bounded by the following coordinates: 31.0 – 33.2°E; 42.5 – 44.0°N. For this figure, each point represents the mean value of $b_{bp}(555)$ computed using Eq. (2) in all cloud-free pixels taken from a single image (one per day). We included here only the images with 70% or more cloudless pixels.

One can clearly see the intensive coccolithophore bloom events that occur every year in the beginning of summer, resulting in the sharp increase of light backscattering over almost entire open part of the Black Sea. The typical range of $b_{bp}(555)$ is 0.0015 – 0.015 m^{-1}. In addition to essential seasonal variability of $b_{bp}(555)$, there is also some year-to-year difference in the intensity of bloom events in different parts of the sea. For example, in the center of the sea in 1999 and 2001 the bloom intensities were weaker than in 1998, 2000, and 2002. It is interesting to note the fact that the sharp increase of b_{bp} is not accompanied by an increase in absorption of the light in the water, and usually there is no increase of chlorophyll concentration in the open part of the Black Sea in June. The reason is that the major contributor to the high values of b_{bp} observed during coccolitofore bloom events is the large amount of small detached coccoliths.

Typically in the open part of the sea, intensive blooms of *Emiliania huxleyi* occur in June, but it also can dominate the phytoplankton community in the winter.[9] Figure 7 shows examples of $b_{bp}(555)$ maps for August and January. As a rule. it is difficult to observe the Black Sea from space in winter, because of a large amount of clouds, but in January 2005, conditions were rather favorable, and the pattern with high $b_{bp}(555)$ was observed during several days in the center of the sea (Fig. 7,*b*). Note that in this area, $L_{WN}(555)$ is somewhat higher than 1.4 μ W nm^{-1}· sr^{-1}· cm^{-2}. This level is not as high as in June, however it is sufficient enough for reliable detection of appropriate contrasts by SeaWiFS imagery. In addition, a similar bloom event occurred in August 2003 (Fig. 7,*a*). Our analysis of SeaWiFS data sets shows that there were no similar patterns in other years at the end of summer and thus, this example should be considered as an anomaly for the sea condition at that time. In this case, in the central part of the sea, the values of $L_{WN}(555)$ and $b_{bp}(555)$ increased up to 1.1 μ W $nm^{-1} \cdot sr^{-1} \cdot cm^{-2}$ and 0.0065 m^{-1}, respectively.

5. SUMMARY

Our experience shows that in some situations the corresponding quality control criteria are not effective enough. For instance, in the case considered above (September, 12, 1998; Fig. 1) all SeaWiFS flags (16, 18, 20) were not set for the whole area of the sea, except for a few isolated points. In the SeaWiFS data processing system these flags are included to the standard *Level-2* files and their main function consists in rejection unreliable data when the final *Level-3* products are created. Usually, most significant errors in atmospheric correction take place in the values of $L_{WN}(412)$, causing them to be underestimated and even negative. That is why the reliability of estimated values of $L_{WN}(555)$ and I_{510} become essentially better when we include additional discarding of the pixels that have $L_{WN}(412) < 0$ or $L_{WN}(412) \approx 0$. Utilizing this idea, we apply *Level-2* data instead of usage of standard *Level-3* products in our Black sea investigations.

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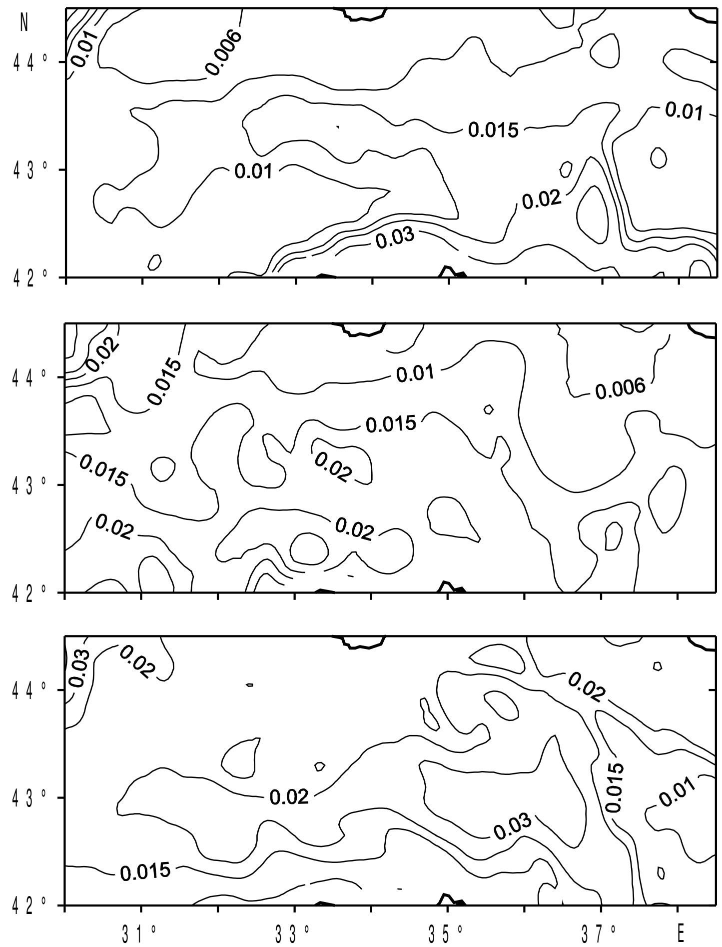

Fig. 6. Examples of $b_{bp}(555)$, m^{-1}, spatial distribution in the open part of the Black Sea; from up to bottom: June 16, 1998; June 13, 2000; June 15, 2002.

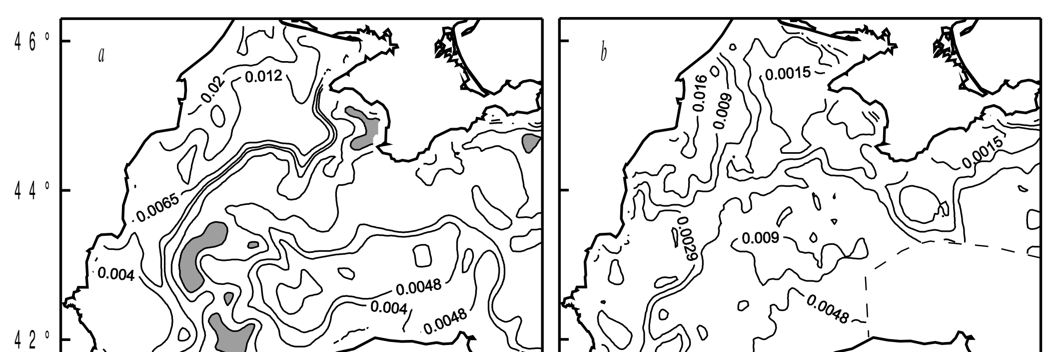

Fig. 7. Spatial distribution of $b_{bp}(555)$, m^{-1}, in August 2003 (*a*) and January 2005 (*b*). In the left map, filled areas correspond to $b_{bp}(555) < 0.0024$ m^{-1}.

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