The SeaWiFS Pigment algorithm in the Black Sea

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Analysis of SeaWiFS level 2 product characterizing water leaving radiance $nLw(\lambda)$ to λ = 490, 510, and 555 nm bands has shown that indexes defined as ratio $I_{510} = \frac{nLw(555)}{nLw(510)}$ and $I_{490} = \frac{nLw(510)}{nLw(490)}$ are characterized by significant uncorrelated annual dynamics in the Black Sea. Based on this feature regional algorithm of chlorophyll *a* estimation has been developed. It has been shown there are two types of a solution at the minimum, which represent the different character of light absorption in the water of the Black Sea in the band 555nm. Analytical expressions for estimation $a_{ph}(\lambda)$ and $a_{CDM}(\lambda)$ in the band 490 nm have been derived for the both solution types. The first solution (*Deep* solution) reproduces qualitatively and quantitatively seasonal dynamics of chlorophyll *a* concentration (C_a) observed in deep-water part. The second solution (*Shelf* solution) matches positively with *in situ* C_a data in shelf zones. Analysis of stability of the *Deep* and *Shelf* solutions to variables of water optical model has been done.

Key words: visible domain, remote sensing, absorption, chlorophyll *a*, colored dissolved organic matter, cyanobacteria, *SeaWiFS*, regional algorithm, the Black Sea

Now in a earth orbit a number of high quality remote instruments such as *SeaWiFS*, *MODIS* and others which are transferred by unique data about spectral structure of ascending radiation works. After performance of procedure of atmospheric correction [21] from these data some biooptical characteristics of the top layer of water (products of the second level), for example, concentration of a chlorophyll *a* (below as C_a), in particular, are calculated. Unfortunately, the standard approach used in *NASA* [28, 29], gives the unsatisfactory quantitative and qualitative description of this parametre for the Black sea [7, 8, 10, 22]. One of the reasons consists in the raised maintenance of yellow substance in the Black Sea water [7, 14] in comparison with oceanic waters on which data standard statistical algorithm *NASA* has been adjusted. Other reason consists in the inadequate description of properties of an aerosol in those models which are used at performance of standard atmospheric correction [4, 5, 19]. Specified above the reason can lead to low accuracy of calculated water-leaving radiances , in all visible range of a spectrum. And accuracy decreases in a blue part of a spectrum, that seriously limits application of the approaches using short spectral bands (SB) [14, 20].

Now two directions of researches in parallel develop. The first of them is connected with increase of accuracy of restoration of a spectrum of the normalised water-leaving radiance, $nLw(\lambda)$ all visible range, for the account of the correct account of optical properties real an aerosol at performance of atmospheric correction. After performance of atmospheric correction such approach means use of all spectrum $nLw(\lambda)$ restoration of biooptical characteristics of the top layer of the sea. However to execute well atmospheric correction in visible area of a spectrum for the areas subject to influence of various types of aerosols, it is possible only in separate special cases. The second direction is connected with creation of regional algorithms of restoration of concentration of pigments without using of short-wave area of a spectrum [6, 7, 24, 25]. With reference to Black sea algorithms existing till now or have restrictions on seasons/areas, or low accuracy of restoration of C .

The given work concerns the second direction. In it the regional algorithm of an estimation C_a standard products of the second level of device *SeaWiFS* for Black sea will be developed. The offered approach will allow to describe correctly seasonal and spatial variability C_a higher accuracy, in comparison with other known algorithms.

Material and methods. Field measurements C_a the top layer of the sea (0 - 5), used in the given work, are presented to table 1.

Basis of satellite data daily *SeaWiFS* level 2 standard data of the spatial resolution 1x1 km in nadir *Merged Local Area Covered* (*MLAC*) and the spatial resolution 4x4 km in nadir *Global Area Covered* (*GAC*) versions 5.2 make [32]. The choice of the spatial resolution was carried out depending on a solved problem. In cases when spatial and time variability was small, satellite data *GAC*, averaged with step on time for two weeks on a spatial grid 0.035° on a longitude and 0.025° on latitude were used. If spatial variability was essential, satellite data *MLAC* were used..

Results. Since 70th years of 20 centuries, experts of department of optics of Marine Hydrophysical institute of National Academy of Sciences of Ukraine used the relation of radiation leaving the sea on two lengths of waves as the indicator of total absorption of light water in different parts of the World ocean [3]. The physical essence of this phenomenon consists that variability of bacscattering of light makes essentially weaker impact on the relation of signals on two lengths of waves, than variability of total absorption of light by sea water.

It is established [7], that the index $I_{490} = \frac{nLw(510)}{nLw(490)}$ is steady against errors of atmospheric correction and can be used for calculation of total absorption of light in the top layer of water in a deep-water part of Black sea during the summer period. Later researches have shown, that with the account of use of additional criteria this stability can be raised [4, 5]. To raise quality of satellite data output for Black Sea, following [5], from the analysis were excluded all level 2 products which or had negative value $nLw(\lambda)$ one of SB (flag 8), or were close with bright objects (flag 9) or for which procedure of search of the best pair aerosol models converged slowly (flag 20). All such situations in a standard satellite product are marked with special badges, so-called flags, that essentially facilitates procedure of their filtration. To similarly it the estimation of stability of other index $I_{490} = \frac{nLw(510)}{nLw(490)}$ use of data *SeaWiFS* (updated version 5.2) for small area in deep-water area in the southwest of Black sea for cloudless conditions for August, 13 and 15, 1998 (table 2) has been spent. Distinction between these next days consisted that on August, 15 spectra $nLw(\lambda)$ the western part of the sea had lower values in comparison with August, 13, and this difference increased with reduction λ (table 2). Besides, on the considerable area of the sea on August, 15 the flag 8 is equaled 1. According to [5], it is a sign of unsatisfactory performance of atmospheric correction. However, if the relative error $nLw(\lambda)$ these two days is more than 12 %, for indexes I_{510} and I_{490} it less than 3 % and 1 % accordingly. It means that indexes I_{510} and I_{490} are restored more reliably, than all spectrum $nLw(\lambda)$. It is necessary to notice, that spatial distribution of each index I_{510} and I_{490} practically has not changed from August, 13 till August, 15, that also points in stability of restoration I_{510} and I_{490} both in a deep-water part of the sea, and on a shelf too. Law of this effect can be revealed, analyzing variability daily *GAC* values I_{510}, I_{490}, $nLw(412)$,and $nLw(555)$, avaraged inside area 2 (table 1) on an example of 1998. On figure 1 are shown only those days in which the considered area had high provided data on the area (> 70 %). Obviously, that within a year for values of indexes I_{510} and I_{490} smooth variability while the value of $nLw(412)$ changed within several days that is a sign of bad performance of atmospheric correction is characteristic. Hence, values of indexes I_{510} and I_{490} are steadier against errors of standard atmospheric correction.

In the beginning of summer of 1998 in a deep-water part of the sea blooming coccoliths [10] which in the course of the development generate a large quantity of a small suspension has been noted. As consequence of it, during the specified period of time high values were marked $nLw(412)$ and $nLw(555)$. However, it has not affected in any way summer values of indexes I_{510} and I_{490}. It means, that the named indexes are poorly sensitive to change of light backscattering.

The analysis of seasonal variability of indexes I_{510} and I_{490} also has shown, that spring blooming 1998 [10] on time coincided with unusual behaviour of indexes I_{510} and I_{490}. From figure 1 it is visible, that while the index I_{490} then the index I_{510} decreases. During other seasons both index changed is interfaced (have the same sign on the first derivative), distinction was only in amplitude of a signal.

Thus, unlike standard algorithm of restoration C_a there are two indexes I_{510} and I_{490} which are poorly sensitive to partical backscattering of light and to errors of performance of atmospheric correction, and also between them there is no strong correlation within a year.

Proceeding from known models of optical properties of sea water [2, 23, 26], we will present an index as

$$I_{\lambda_j} = \frac{a(\lambda_j)}{a(\lambda_i)} \frac{b_b(\lambda_i)}{b_b(\lambda_j)} \frac{F_0(\lambda_i)}{F_0(\lambda_j)}, \qquad (1)$$

where $F_0(\lambda)$ is a solar constant for SB with the central wavelength λ, and

$$\begin{aligned} a(\lambda) &= a_w(\lambda) + a_{CDM}(\lambda) + a_{ph}(\lambda) \\ b_b(\lambda) &= b_{bw}(\lambda) + b_{bp}(\lambda) \end{aligned}, \qquad (2)$$

where $a(\lambda)$ и $b_b(\lambda)$ are total absorption and backscattering coefficients of light by sea water, their components with indexes *w*, *CDM*, *ph* and *p* for pure sea water, the sum detrit and yellow substance, a phytoplankton and particles, respectevly. We will consider further, that all variables and constants are specified for SB with the central wavelength λ.

In our model three assumptions are made. The first consists in that in a considered interval of wavelengths absorption by detrit and yellow substance has been united:

$$a_{CDM}(\lambda) = a_{CDM}(\lambda_0)\exp(-S(\lambda - \lambda_0)), \qquad (3)$$

where S is a variable setting spectral dependence $a_{CDM}(\lambda_0)$; λ_0 is basic wavelength, λ_0 = 490 nm.

The second consists in that the exponent of backscattering of light in sea water is described by following expression:

$$b_b(\lambda_i) = b_b(\lambda_j)\left(\frac{\lambda_j}{\lambda_i}\right)^n, \qquad (4)$$

where as a first approximation value n is the same constant for both indexes I_{510} and I_{490}. The substantiation of this assumption will be given more low.

The third, we consider, that the exponent of absorption by a phytoplankton $a_{ph}(\lambda)$ is linear function from concentration of a chlorophyll *a* (Here and in further chlorophyll *a* the sum of concentration of a chlorophyll *a* and pheothitin *a* is designated C). It means, that dimensionless constants k_{510} and k_{555} between in $a_{ph}(\lambda)$ SB 490, 510, and 555 nm are defined as:

$$k_{510} = a_{ph}(510)/a_{ph}(490)$$
$$k_{555} = a_{ph}(555)/a_{ph}(490) \qquad (5)$$

and do not depend from C.

Using the equations (1) - (5), written down for two indexes I_{490} and I_{510} it is possible to find the decision for $a_{CDM}(490)$ and $a_{ph}(490)$

$$a_{ph}(490) = -\frac{J_{490}J_{510}h_1 + J_{510}h_2 + h_3}{J_{490}J_{510}z_1 + J_{510}z_2 + z_3} \qquad (6)$$

and

$$a_{CDM}(490) = \frac{J_{490}J_{510}c_1 + J_{510}c_2 + c_3}{J_{490}J_{510}z_1 + J_{510}z_2 + z_3} \qquad (7)$$

where

$$h_1 = y_{510}a_w(555) - y_{555}a_w(510)$$
$$h_2 = y_{555}a_w(490) - a_w(555)$$
$$h_3 = a_w(510) - y_{510}a_w(490)$$

$$c_1 = k_{510}a_w(555) - k_{555}a_w(510)$$
$$c_2 = -a_w(555) - k_{555}a_w(490)$$
$$c_3 = a_w(510) - k_{510}a_w(490)$$

$$z_1 = k_{555}y_{510} - k_{510}y_{555}$$
$$z_2 = y_{555} - k_{555}$$
$$z_3 = k_{510} - y_{510}$$

$$J_{510} = I_{510}\frac{F_0(510)}{F_0(555)}\left(\frac{510}{555}\right)^n$$
$$J_{490} = I_{490}\frac{F_0(490)}{F_0(510)}\left(\frac{490}{510}\right)^n$$

$y_{510} = \exp(-S \cdot 20)$
$y_{555} = \exp(-S \cdot 65)$

For calculation of concentration of chlorophyll *a* following expression was used

$$a_{ph}(490) = A \cdot C^{B},$$

where A= 0.030 м² мг⁻¹ [18], B=1. As a result C= a_{ph}(490)/0.030.

For calculation $a_{ph}(490)$ and $a_{CDM}(490)$ on satellite data we should set solar constants, absorption by pure sea water and four unknown parametres of model: n, S, k_{510}, and k_{555}. Solar constants and absorption by pure sea water for SB *SeaWiFS* (table 3) have been chosen according to [30, 34].

The exponent coefficient n gives a spectral shape $b_b(\lambda)$. For more correct estimation of value n, according to expression (2), we should know $b_{bw}(\lambda)$ and $b_{bp}(\lambda)$. Values $b_{bw}(\lambda)$ calculated analitically [27]. All suspension, following [2], has been presented in the form of two component: a large and small suspension with *n*к = 0.3 and *n*м = 1.7 accordingly. Calculation $b_{bp}(555)$ was spent under the empirical formula (8) taken from [7, 33], on averaged for two weeks to the satellite measurements, received over Black sea from September 1997 till October, 2006. Expression for $b_{bp}(555)$ is given as:

$$b_{bp}(555) = \left\{ \begin{array}{l} 6.76 \cdot nLw(555) + 0.03 \cdot [nLw(555)]^{3} \\ + 3.40 \cdot nLw(555) \cdot (I_{510})^{3.8} - 0.84 \end{array} \right\} \cdot 10^{-3} \quad [\mathrm{m}^{-1}], \quad (8)$$

where $nLw(555)$ is in mW um^{-1} sm^{-2} sr^{-1}. As a result of calculations n by eq. (4) two histograms for the relation are received $b_b(555):b_b(510)$ at *n*к and *n*м with maxima 1.0 and 2.2 accordingly. Similar pair of histograms is received for the relation $b_b(510):b_b(490)$ maxima 1.1 and 2.2 accordingly. As we do not know a parity between small and large fractions of a suspension was average value between maxima of corresponding histograms is taken. It has appeared approximately identical and equal n = 1.5 for both relations.

Optical properties of waters of Black sea are subject to strong influence of a river input. As is known [15], the dissolved organic substance of a different origin leads to variability of value S on space. In the areas adjoining to mouth of the rivers, value of S is more, in comparison with more offshore sea areas. The analysis *in situ* the data, executed in [16, 18], has shown, that for a deep-water part of Black sea of value $S \approx$ of 0.018 nm^{-1}, in coastal areas - $S \approx$ 0.021 nm^{-1}.

Equations (6) and (7) can be written down in the form of the system consisting of two linear equations of a kind:

$$k_{510} = \alpha_i \cdot k_{555} + \beta_i,$$

where i = 1 and 2.

It is necessary to have at least two nonsingular equations to find k_{510} and k_{555}. For construction of such system of the equations, and also for the further estimation of quality of the received decision creation of a representative data set from *in situ* and satellite measurements is necessary. All *in situ* and satellite data are from area with co-ordinates 42.5 - 44°N and 31 - 33°E. Satellite data were averaged on this area for time equal approximately to two weeks for what each calendar month has been broken on two equal parts 1 and 2 (table 4). *In situ* data on time were not averaged. It has allowed to use as much as possible all *in situ* measurements which we had, and to compare calculated values of C_a with in situ C_a in a wide range of their variability – from the minimum values in summer period to its maximum values in spring blooming diatoms. Such measurements which had high coverage *in situ* data have been considered only. It means, that more than 80 % of knots of a grid (see above) should be provided by satellite measurements. Selected data cover all seasons except for winter and can reflect objectively enough all set of natural optiko-biological situations for deep-water area of Black sea (table 4).

As an example of a finding of values k_{510} and k_{555} spring (March, 26 1998) when on *in situ* to data diatom blooming [11] was observed, and summer (August, 20 1998) when measurements *in situ* have shown the minimum values C_a (table 4, points 3 and 14). The equations of lines 3 and 4 (figure 2) have been received at S =0.018 nm^{-1} and n =1.5 (the substantiation of it see above). The line 3 turns out from the equation (6) for a spring point where values of C_a, I_{490} and I_{510} are used (table 4), a line 4 - from the equation (7) for a summer point where $a_{CDM}(490)$ calculate by the empirical equation [7, 33]:

$$A_{\Sigma}(510) = 0.23 \cdot I_{510}^2 - 0.196 \cdot I_{510} + 0.049 \quad [\text{м}^{-1}],$$

where $A_{\Sigma}(510)$ is the total contribution of absorption of pigments of a phytoplankton and the sum of yellow substance and detrit $a_{ph}(510) + a_{CDM}(510)$ the SB at 510 nm. In view of low concentration of pigments during the summer period in a deep-water part of Black sea we have neglected phytoplankton absorption, considering, that $a_{CDM}(510) = A_{\Sigma}(510)$. Transition from $a_{CDM}(510)$ to $a_{CDM}(490)$ was carried out by equation:

$$a_{CDM}(490) = a_{CDM}(510) \cdot \exp\left(S \cdot (510 - 490)\right),$$

where S = 0.018 nm^{-1}. Thus, the line 4 is defined also a point of crossing of lines 3 and 4 gives required *Deep* the decision.

The basic scheme of search of the *Deep* decision is above shown. More difficult statistical approach which consisted in increase in quantity of the equations for the account of addition of similar situations from 1998 for 2007 under the scheme described above has been actually chosen. For this purpose we used the periods of spring blooming for which values of C_a equal in the range from 1.5 to 2.5 mg m^{-3}. With corresponding satellite measurements it there were analogues of a line 3 on figure 2. The equations for the lines similar to a line 4 on figure 2, turned out for $a_{CDM}(490)$ calculated for summer months and September with values of C_a from 0.1 to 0.3 mg m^{-3}. Thus, we have received the redefined system of the equations which decision has given required *Deep* the decision: k_{510} =0.745 and k_{555} =1.25 (a circle on figure 2). Such approach has allowed to smooth the noise of different character inherent both satellite and *in situ* data, and the way of a finding of the decision stated above. In addition on figure 2 lines 1 and 2 are shown. The line 1 is described by the equation:

$$k_{510} = 0.692 + 0.307 \cdot k_{555}.$$

The physical sense of this function will be explained below. The line 2 is constructed for k_{510} and k_{555} expression (5). Values of $a_{ph}(490)$, $a_{ph}(510)$ и $a_{ph}(555)$ were calculated follow by [13] where C changed in a range from 0.1 to 3 mg m^{-3}. It is obvious, that the *Deep* decision strongly differs from the decision [13].

Substituting in the equations (6) and (7) found above value of constants of model for *Deep* decision and tabular data, we will receive following formulas:

$$
\begin{aligned}
&a_{CDM}(490) = (0.00474 \cdot I_{490} \cdot I_{510} - 0.0470 \cdot I_{510} + 0.0213) \\
&/(0.804 \cdot I_{490} \cdot I_{510} - 1.08 \cdot I_{510} + 0.0487) \\
&a_{ph}(490) = -(0.0395 \cdot I_{490} \cdot I_{510} - 0.0633 \cdot I_{510} + 0.0221) \\
&/(0.804 \cdot I_{490} \cdot I_{510} - 1.083 \cdot I_{510} + 0.0487)
\end{aligned}
\qquad (9)
$$

Formulas (9) allow to estimate quantitatively values of $a_{ph}(490)$ and $a_{CDM}(490)$ on *SeaWiFS* level 2 standard products for all points laying above an isoline $a_{ph}(490) = 0$ m^{-1} in co-ordinate plane $\{I_{510}, I_{490}\}$.

To the *Shelf* decision all cases which unequely cannot be described within the limits of *Deep* decision are carried. These are satellite measurements which in co-ordinates $\{I_{510}, I_{490}\}$ are placed below an isoline $I_{490} = (1.599 - 0.557 / I_{510})$. Last expression is a direct consequence of the equation (9) under a condition $a_{ph}(490) = 0$ m^{-1}. The preliminary analysis of such satellite measurements has shown, that their geographic location, as a rule, is connected with the coastal areas subject to carrying out fresh waters. It is a northwest shelf of Black sea and Kerch strait.

For determination of the *Shelf* decision satellite and *in situ* measurements selected, proceeding from following criteria. First, it is necessary to consider specificity of such areas, namely, to minimise effects of temporol-spacial variability at an identification *in situ* and satellite measurements. For this purpose *SeaWiFS MLAC* and *in situ* measurements should be executed in the same calendar day. The area of averaging of I_{490} and I_{510} around *in situ* measurements was small and made ±0.025° on latitude and ±0.035° on a longitude that corresponds to 9 knots of our grid. The second condition consists in spatial uniformity of indexes $\sigma(I_{510}) / \langle I_{510} \rangle < 0.05$ averaging area. Satellite measurement in plane of $\{I_{510}, I_{490}\}$ applaing the condition $\sigma(I_{490})$ and $\sigma(I_{510})$ should not concern an isoline $a_{ph}(490) = 0$ m^{-1} for *Deep* decisions. Besides, such measurements in which flags 8, 9 and 20 equaled a zero were participated in averaging only, and they were in limits of *GAC* swath. These conditions allow to minimise contortions in values I_{490} andи I_{510} connected with errors of atmospheric correction. Last condition is a presence of measurements in all 9 knots of our grid. Satellite and *in situ* the data chosen by criteria described above, belong to a shelf of Bulgaria (table 5). On figure 3b their arrangement in co-ordinates in plane $\{I_{510}, I_{490}\}$ is shown.

Sampling for *Shelf* decision (table 5) is much less than sampling for *Deep* decision (table 4). Nevertheless, we have measurements (table 5) executed during two seasons within three years that will allow to define areas of possible decisions for a shelf.

The metod of finding of the *Shelf* decision is similar to a way of finding of the *Deep* decision. Differences concern values of some parametres. First, in the *Shelf* decision applied higher value of $S = 0.021$ nm^{-1}. Second, the equation (7), because of absence *in situ* measurements and empirical relationships between $a_{CDM}(\lambda)$ and satellite measurements in a shelf part of Black sea is not used. Therefore as *Shelf* decision, we considered area of a condensation of the lines constructed similarly of a line 3 on figure 2 for all measurements from table 5. Results of such build-ups and the *Shelf* decision (k_{510} =0.875 and k_{555} =0.5) are shown on figure 3a. Substituting in the equation (7) found above value k_{510}, k_{555}, S, n, and constants from table 3, we will receive for *Shelf* decision following formulas:

$$\begin{aligned} &a_{CDM}(490) = (0.0451 \cdot I_{490} \cdot I_{510} - 0.0599 \cdot I_{510} + 0.0194) \\ &/(0.132 \cdot I_{490} \cdot I_{510} - 0.281 \cdot I_{510} + 0.218) \\ &a_{ph}(490) = -(0.0387 \cdot I_{490} \cdot I_{510} - 0.0642 \cdot I_{510} + 0.0226) \\ &/(0.132 \cdot I_{490} \cdot I_{510} - 0.281 \cdot I_{510} + 0.218) \end{aligned} \quad (10)$$

Formulas (10) allow to estimate quantitatively the values of $a_{ph}(490)$ and $a_{CDM}(490)$ on standard *SeaWiFS* level 2 products for all points laying below an isoline $I_{490} = (1.659 - 0.584 / I_{510})$.

Discussion. The calculations of C_a on *Deep* and *Shelf* decisions, were compared to results of calculations on methods [25, 26, 29] on representative data sets (tables 4 and 5). Comparison of values of C_a *in situ* data and the calculated values on satellite measurements for described in [24] (figure 4a), [28] (figure 4b) models, and equation (9) for *Deep* decision (figure 4c) has shown that model [24] gives the underestimated estimations C_a spring of 1998 and autumn of 1999 and overestimated for summer 2001. Standard model *OC4v4* [28] overestimates all summer values and underestimates estimations of C_a spring of 1998, that already it was marked earlier in [14, 11]. Our model (figure 4c) describes the spring and summer periods is better, but gives the underestimated estimations of C_a autumn of 1999.

For deep-water area (№ 2 of table 1) comparison of calculations of $a_{CDM}(490)$ using the formula (9) with results of calculations of $a_{CDM}(490)$ on the procedure described above at finding of the *Deep* decision, for all summer months and September during 1997 - 2007 has shown good quantitative coincidence among themselves ($r^2 = 0.99$; N=77).

Comparison of values of C_a *in situ* observations in shelf waters with the calculated values on satellite measurements for described [24] (figure 5a), and [28] (figure 5b) models and equation (10) for *Shelf* decisions (figure 5c) has shown that all three models from a point 3 to a point 1 give the correct tendency of increase in value of C_a. However, the best results are noted for standard model [28] and *Shelf* decision. Model [24] has a systematic error.

Results of some statistical estimations, such as coefficient of correlation between *in situ* and count values of C_a, an average absolute error and an average relative error of restoration of C_a are resulted in table 6. It is visible, that the *Deep* decision is better quantitatively describes a seasonal cycle of C_a and feature of summer of 2001, in comparison with two other models in a deep-water part of the sea (tab. 6). For shelf area standard and *Shelf* decisions well describe observable variability of C_a. Unfortunately, absence any semiempirical links between standard satellite products and a_{CDM}, such as in [7], has not allowed to compare to the values of $a_{CDM}(490)$ for the *Shelf* decision by using the formula (10).

Difference *Deep* and *Shelf* decisions from the standard decision [24] and the decision offered in [28] is the most obvious if to consider these decisions in the form of isolines of C_a and $a_{CDM}(490)$ in co-ordinates in the plane of $\{I_{510}, I_{490}\}$. For this, the equations (9) and (10) have transformed in $I_{490} = \Psi(I_{510})$, that has allowed to construct in co-ordinates $\{I_{510}, I_{490}\}$ of isolines $a_{ph}(490)$ (or C_a) for *Deep* and *Shelf* decisions, respectively (figures 6 and 7). From figure 7 it is visible, that the increase of I_{490} and I_{510} leads to increase of C_a known methods [24] and [28], that for *Deep* and *Shelf* decisions (9) and (10), generally speaking, it is incorrect (figigure

6). Isolines of C_a the standard decision have qualitative similarity to isolines of $a_{CDM}(490)$ for *Deep* decision at $I_{510} < 1$ with isolines of C_a [24] at $I_{510} > 1$. Isolines of *Deep* and *Shelf* decisions remind "fan". Values of C_a in a clockwise direction for *Deep* decision and counter-clockwise for *Shelf* decision. Thus, there are essentially different two decisions for Black sea - *Deep* and *Shelf* decisions. The line 2 (figures 2 and 3) allows to see arrangement of *Deep* and *Shelf* decisions in relation to the decision [13] and to each other too. Both our decisions do not coincide with the decision [13] as in band 5 at the Black Sea phytoplankton exist additional absorption which is not present at oceanic phytoplankton [13]. It is necessary to notice, that the neighbourhood of a line 1 (figures 2 and 3a) is an area of degeneration of "fans". All points above it is this set of *Shelf* decision, all points is set of *Deep* decision more low. At the fixed values of n and S area of possible values of indexes in plane of $\{I_{510}, I_{490}\}$ are limited by isolines $a_{ph}(490) = 0$ m^{-1} and $a_{CDM}(490) = 0$ m^{-1}. As the value of S the *Deep* decision is less than a value of S for the *Shelf* decision, the combination of such pairs $\{I_{510}, I_{490}\}$ simultaneously belongs to both decisions takes place. As the analysis of satellite data has shown, such measurements, as a rule, occupy on the area rather small part in relation to all area of Black sea. For such situations there is a problem of ambiguity of a choice of the decision, however the solve of this problem in given article is not considered.

In addition six points are put on figures 6 and 7. Four points are taken from a deep-water part of the sea (the *Deep* decision, points with numbers № 14, 3, 7 and 15 from table 4): August, 1998, spring bloming of 1998, summer of 2001, both autumn of 1999, and two points on a shelf (the *Shelf* decision, points with numbers № 1 and 3 from table 5). Points from tables 4 and 5 are marked by corresponding numbers and symbols “*d*” and “*s*” which designate *Deep* and *Shelf* decisions respectively. We will notice, that on figure 7b there is no isoline of 0.2 mg м$^{-3}$, that specifies in use by a standard method of measurements $nLw(\lambda)$ at SB with λ<490 nm for calculation of this isoline. It is necessary to notice, that the spring point *d3* only within the limits of our approach can explain high values of C_a. In two other models the value of C_a in August, 1998 (the point *d14*) has higher value, than in a point *d3*. Other important difference between the *Deep* decision and decisions from [24, 28] we will consider on an example of summer of 2001 (a point *d7*). Our decision shows, that high value of $a_{CDM}(490)$ at that time took place at low, typical for summer, values of C_a. Two other decisions give the overestimated values of C_a.

The offered algorithm (the *Deep* decision), as a whole, correctly describes seasonal dynamics of surface concentration of chlorophyll *a* in a deep-water part of the sea, and only for autumn of 1999 some differences between a model estimations and the measured values of C_a are noted. The reason of it can consist in that in our model the input parametre S is constant. It is quite probable to assume presence of seasonal variability of S in a deep-water part of the Black sea. During summer and in the beginning of fall when rather weak water exchange between a shelf and a deep-water part of the sea takes place, the value of S, proceeding from the nature of an origin of the dissolved organic substance, should decrease in a deep-water part, and, hence, tend to i ocean value [15]. If the given assumption is true, as show simple calculations within the limits of our model, it and will lead automatically to higher values of C_a for the autumn period in deep-water area of the sea.

Examination of stability of *Deep* and *Shelf* decisions to input parametres of optical model of water such as n and S has been spent for intervals 0.3 – 2.5 and 0.014 – 0.023 nm^{-1} respectively. The basic conclusion of this research consists in that influence of variations of n and S significantly affects at calculations for large values of C_a. The analysis of satellite data has shown, that it is important, first of all, for shelf areas. As to our model, here we have got the same problem – a constancy of S which obviously should vary on the area and, hence, be calculated for each pixel of satellite image. As show simple estimations if for *Deep* decisions, by virtue of relatively small absolute values of indexes of I_{490} and I_{510} changes of S can be neglected, for large values of indexes, for example, in mouth areas, even little changes of S can lead to the large errors at calculations of C_a.

On a shelf as it is noted above, the best results have given a standard method and the *Shelf* decision. Proceeding from available data, both the approachs have shown approximately identical results (figures 5b, c and table 6). If to consider, that the *Shelf* decision has been successfully used for restoration on satellite measurements *SeaWiFS* of superficial concentration of a chlorophyll *a* [9] on a shelf of southern coast of Crimea (SCC) offered *Shelf* decision it is possible to expand borders on the area which is under the influence of water of Sea of Azov. However, still, it is the measurements executed during only summer period.

Optical properties of the top layer of water are directly connected with specific structure of a phytoplankton. Our approach is based on the assumption of existence of physical relation between absorption micro-and nano-dimensional groups of a phytoplankton in SB at 490 nm and absorption pico- phytoplankton (it is the most probable cianobacteria) in SB at 555 nm. The reason of existence of two decisions *Deep* and *Shelf* or is connected by that in the Black sea there are, at least, two types of kinds of cianobacteria with different spectral properties [12], or can be a consequence of the different contribution of cianobacteria in a biomass of planktonic seaweed. Investigations in September, 2005 in a northwest part of the Black sea have revealed presence of cianobacteria in shelf and deep-water zones (1900-88000 кл ml^{-1}) (Rulkova, unpublished data), however on concentration of cianobacteria the shelf zone differed from deep-water slightly. At the same time, the local maximum of absorption about 550 nm was observed only when the contribution of cianobacteria in the general biomass of phytoplankton made not less than 20 %. Such spectra with a local maximum of ~550 nm are received only in deep-water area of the sea [17]. Apparently, change of coefficient of k_{555} at transition from *Deep* to *Shelf* decision reflects share decrease phicobilins, absorbing light at 555 nm, relating other auxiliary pigments participating in absorption at 490 nm. It is connected with share reduction of cianobacteria in the general biomass of planktonic algas.

Unfortunately, there are only limit information about the concentration, species composition, size distibution, and spectral absorption properties of cianbacteria [1, 12, 17], that does not give possibility to make accurate representation about their spatial and seasonal variability in the top layer of the Black sea and, especially, about their optical properties which can have the regional features.

Conclusions. 1. Two algorithms (*Deep* and *Shelf* decisions) of an estimation of chlorophyll *a* concentration in surface layer of the Black sea are developed. The *Shelf* decision has restriction on space (areas of a southwest part of the sea and SCC) and on time (July-September). **2.** The analysis has shown higher accuracy of the *Deep* decision in comparison with existing models and approximately identical accuracy for the standard decision and *Shelf* decision. **3.** Analytical expressions for calculation $a_{ph}(490)$ and $a_{CDM}(490)$ for *Deep* and *Shelf* decisions are received; for a deep-water part of Black sea the seasonal cycle of chlorophyll *a* concentration is correctly restored; for a shelf part of the sea more expanded analysis synchronous satellite and *in situ* measurements, as on seasons so and to shelf areas is required.

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Table 1 *In situ* measured C_a in upper layer of the Black Sea

Investigator*	RV	Location	Period	Institute***	Source
Dr. Vedernikov, Dr. Demidov*	“Akwanawt”	42.89° N 31.61° E	9 Oct 1997	IO RAS	a
Dr. Churilova, Dr. Berseneva*	Monitoring, ship opportunity	42.92°-43.17° N 30.8°-31.13° E	Feb 1998 – Jun 2000	IBSS	our data
Dr. Berseneva*	“Horizont“	Western site	Jun 1998	IBSS	b
Dr. Moncheva**	“Academic“	Bulgarian shelf	23 Sep 1999 14 Sep 2000 7 Jun 2003	IO BAS	c
Dr. Yilmaz *	“Knorr“	Western site	May – Jun 2001	METU	b

Comments:
a – http://seabass.gsfc.nasa.gov [31]; b – V.Suslin has got a permission from the authors to use their data; c – data has been got with help of Dr. Yunev; * - data used for *Deep*-solution; ** - data used for *Shelf*-solution; *** IBSS – institute of Biology of the Southern Seas NAS of Ukraine,Sevastopol, Ukraine; IO RAS – Shirshov institute of oceanology, Russian Academy of Aciences, Moscow, Russian Federation; IO BAS - institute of oceanology, Bulgarian Academy of Sciences, Varna, Bulgaria; METU – Middle-eastern technical university, institute of Marine Science, Erdemli, Turkey

Table 2 Mean values (standard deviations) of *nLw*(λ) and their ratio for separated spectral bands, obtained for small area in south-western deep-waters part of the Black Sea for cloudless sky conditions using remote sensing *SeaWiFS* data on 13 and 15 August 1998

λ or λ_i / λ_j	*nLw*(λ) or *nLw*(λ_i) / *nLw*(λ_j)*	
	August, 13 1998	August, 15 1998
412	0.48 (0.08)	0.20 (0.08)
443	0.73 (0.07)	0.49 (0.07)
490	0.88 (0.07)	0.70 (0.07)
510	0.72 (0.06)	0.57 (0.06)
555	0.46 (0.05)	0.38 (0.05)
555/412	0.99 (0.18)	2.02 (0.54)
555/443	0.64 (0.07)	0.78 (0.08)
555/490	0.53 (0.03)	0.54 (0.03)
555/510	0.64 (0.03)	0.66 (0.03)
510/490	0.83 (0.01)	0.83 (0.01)

Comments: * - mean values (standard deviation) *nLw*(λ) and their ratio were estimated not taking into account flags 8,9 and 20 (about using these flags see below); λ – in nm; *nLw*(λ) – in mW cm^{-2} μm^{-1} sr^{-1}

Table 3 Solar irradiances F_0 [34] and pure sea water absorption a_w [30] in *SeaWiFS* spectral bands

λ, nm	F_0, μW cm^{-2} nm^{-1}	a_w, m^{-1}
490	193.6	0.015
510	188.41	0.0325
555	185.90	0.0596

Table 4 Representative massive of remote sensed and *in situ* data used for estimation and analysis of *Deep* solution

№	YY MM HH*	$C_a \pm \sigma(C_a)$ ** mg m^{-3}	$I_{490} \pm \sigma(I_{490})$ **	$I_{510} \pm \sigma(I_{510})$ **	*in situ* C_a *** mg m^{-3}
	spring 1998				
1	1998 3 1	0.70 ± 0.09	0.946 ± 0.016	0.634 ± 0.033	1.02
2	1998 3 1	0.70 ± 0.09	0.946 ± 0.016	0.634 ± 0.033	1.28
3	1998 3 2	0.55 ± 0.06	0.997 ± 0.043	0.556 ± 0.030	1.92
4	1998 4 1	0.50 ± 0.04	0.926 ± 0.017	0.551 ± 0.017	0.98
5	1998 4 2	0.44 ± 0.03	0.893 ± 0.020	0.536 ± 0.015	0.58
	summer				
6	2001	1.06 ± 0.21	0.911 ± 0.028	0.774 ± 0.043	0.06
7	2001 5 2	2.03 ± 0.22	1.002 ± 0.020	0.919 ± 0.029	0.11
8	2001 6 1	2.03 ± 0.22	1.002 ± 0.020	0.919 ± 0.029	0.19
	2001 6 1				
	summer				
9	1998	0.52 ± 0.03	0.808 ± 0.010	0.644 ± 0.011	0.10
10	1998 6 1	0.52 ± 0.03	0.808 ± 0.010	0.644 ± 0.011	0.21
11	1998 6 1	0.46 ± 0.02	0.785 ± 0.007	0.625 ± 0.008	0.15
12	1998 6 2	0.50 ± 0.03	0.799 ± 0.011	0.643 ± 0.014	0.21
13	1998 7 2	0.45 ± 0.05	0.774 ± 0.018	0.626 ± 0.022	0.25
14	1998 8 1	0.45 ± 0.04	0.780 ± 0.015	0.627 ± 0.024	0.17
	1998 8 2				
	fall 1997				
15	1997 10 1	1.04 ± 0.07	0.914 ± 0.011	0.770 ± 0.017	0.39
	fall 1999				
16	1999 9 1	0.74 ± 0.12	0.862 ± 0.025	0.717 ± 0.044	0.71
17	1999 10 1	0.83 ± 0.16	0.894 ± 0.042	0.728 ± 0.049	0.57
18	1999 10 1	0.83 ± 0.16	0.894 ± 0.042	0.728 ± 0.049	0.48
19	1999 10 2	0.92 ± 0.16	0.905 ± 0.024	0.744 ± 0.055	0.77
20	1999 11 1	1.05 ± 0.16	0.929 ± 0.024	0.764 ± 0.035	1.03

Comments:
* YY – year; MM – month; HH –first or second half of the month;
** mean value of satellite product of level-2 *GAC*;
*** *in situ* measured C_a (table 1), corresponding to area (42.5 - 44°N и 31 - 33°E) and date

Table 5 Representative massive of remote sensed and *in situ* data used for estimation and analysis of *Shelf* solution

№	YY/ MM/DD*	lat /lon degrees	$C_a \pm \sigma(C_a)$ ** mg m^{-3}	$I_{490} \pm \sigma(I_{490})$ **	$I_{510} \pm \sigma(I_{510})$ **	*In situ* C_a mg m^{-3}
1	1999/ 9/ 23	43.17N /28.33E	5.69 ± 0.90	1.080 ± 0.020	1.249 ± 0.060	4.79
2	1999/ 9/ 23	43.17 N/28.17E	6.06 ± 0.32	1.080 ± 0.023	1.276 ± 0.017	7.47
3	2000/ 9/ 14	42.50 N/28.00E	1.41 ± 0.05	0.940 ± 0.012	0.848 ± 0.010	0.85
4	2003/ 6/ 7	43.12 N/28.12E	2.24 ± 0.27	0.986 ± 0.017	0.949 ± 0.030	3.83
5	2003/ 6/ 7	43.30 N/28.33E	3.61 ± 0.43	1.046 ± 0.015	1.097 ± 0.039	1.33

Comments:
* DD –day, MM – month, YY – year;
** daily satellite product of level-2 *MLAC* - mean value for area around *in situ* measured data (±0.025° along latitude and ±0.035° along longitude)

Table 6 Some statistic estimations for comparison *in situ* C_a data with calculated values using representative massives

Estimation type\model	[24] Table 4/Table 5	[28] Table 4/Table 5	Our method Table 4/Table 5
Correlation coefficient	-0.37/0.78	-0.22/0.80	0.74/0.85
Mean value of absolute error, мг м$^{-3}$	0.57/3.35	0.77/1.47	0.43/1.84
Mean value of relative error, %	134/55	303/63	65/45

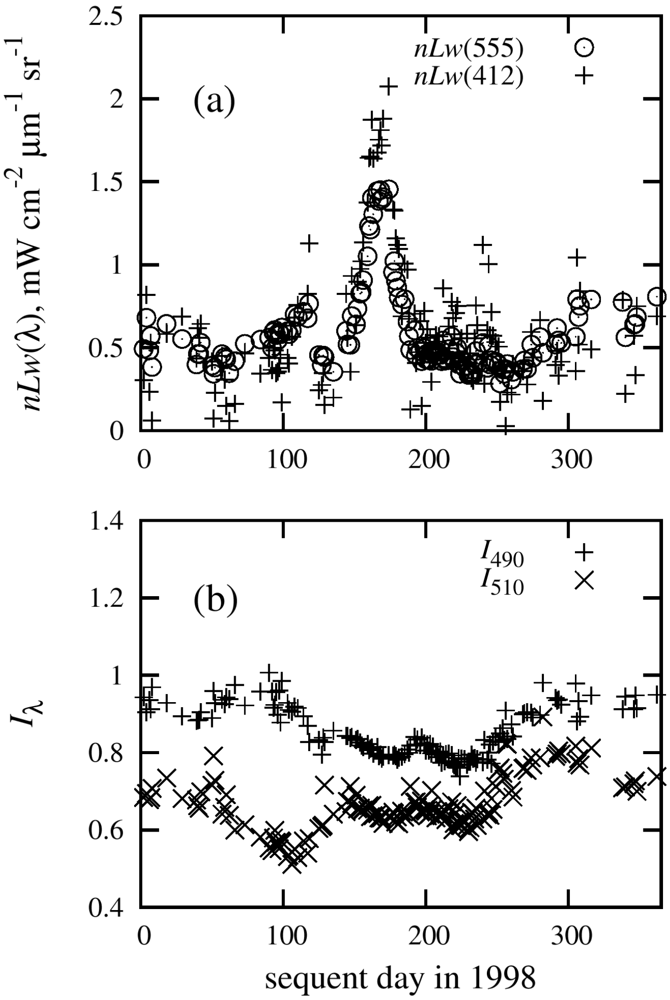

Fig. 1 Variability of $nLw(412)$ and $nLw(555)$ - (a) and I_{510} и I_{490} - (b) in 1998 for the region with coordinate 42.92 - 43.17° N, 30.8 - 31.13° E (table 1). λ is in nm

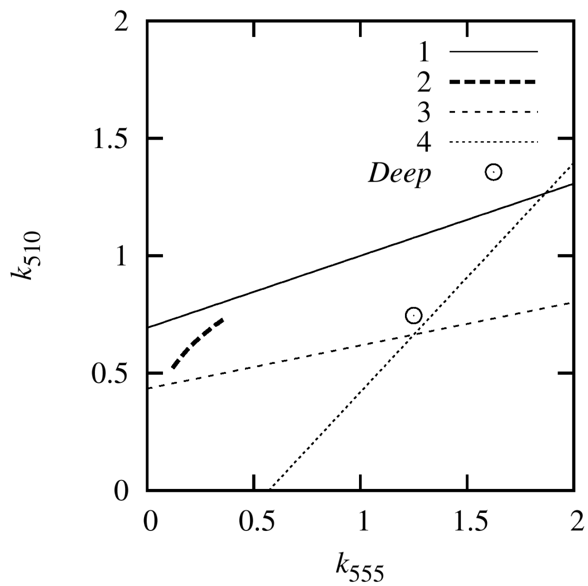

Fig. 2 Estimation of *Deep* solution: k_{510} =0.745 andи k_{555} =1.25 (circle with dot). Line 1 (solid line) described by equation $k_{510} = 0.692 + 0.307 \cdot k_{555}$, found when second derivation equals zero $k''_{\lambda} = 0$ for 490, 510 and 555 nm. Line 2 (bland dashed line) describes k_{510} and k_{555} according to equation (5), where $a_{ph}(490)$, $a_{ph}(510)$ and $a_{ph}(555)$ defined as in *Bricaud et al*., 1995 [13] , *C* varied in a range from 0.1 to 3 mg m^{-3}. Line 3 (dashed line) done according to equation (6) for third point (table 4). Line 4 (dot line) done according to equation (7) for 14th point (table 4)

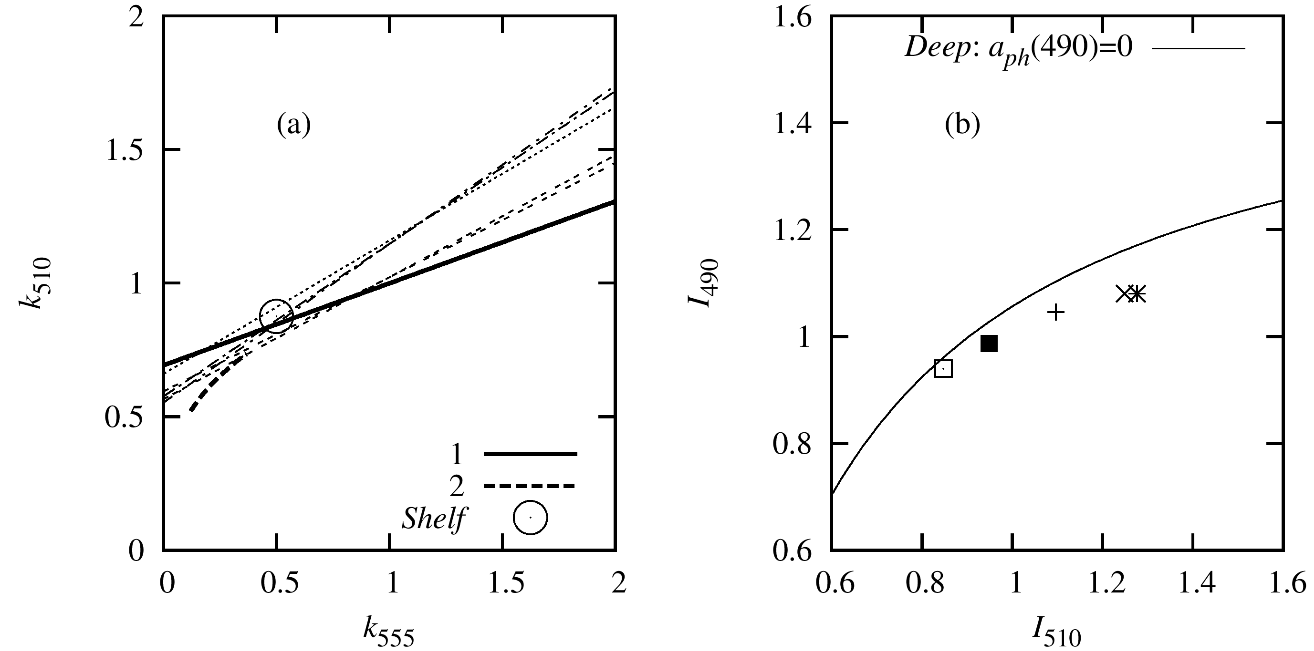

Fig. 3 Estimation of *Shelf* solution.

(a): Line 1 and 2 – the same as on fig.2. *Shelf* solution: k_{510} =0.875 and k_{555} =0.5. The other lines are done according to equation (6) for the measurements 1-5 (table 5).

(b): The measurements 1-5 (table 5) in coordinates $\{I_{510}, I_{490}\}$. Solid line – according to equation (9), when $a_{ph}(490) = 0$ m^{-1}

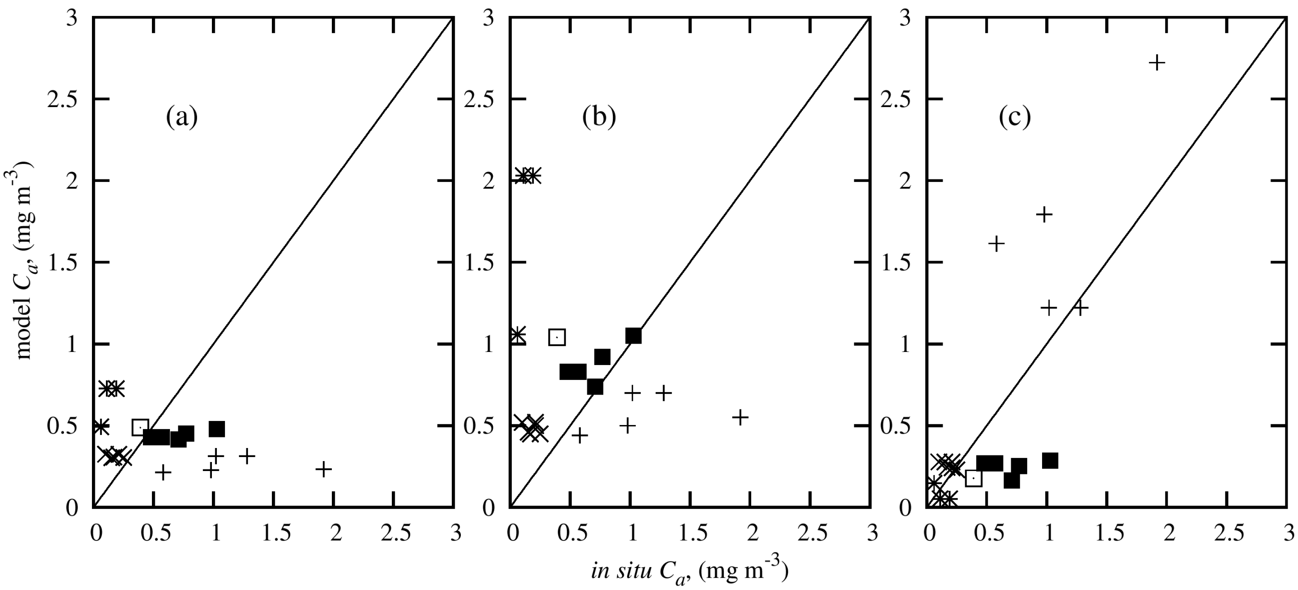

Fig. 4 Comparison of *in situ* measured C_a with calculations of C_a using satellite data (table 4) by three models: (a) – model [24]; (b) – model [28] and (c) – *Deep* solution: autumn 1997 – square ; autumn 1999 – filled square; spring 1998 - (+) ; summer 1998 - (x) ; summer 2001 - (∗)

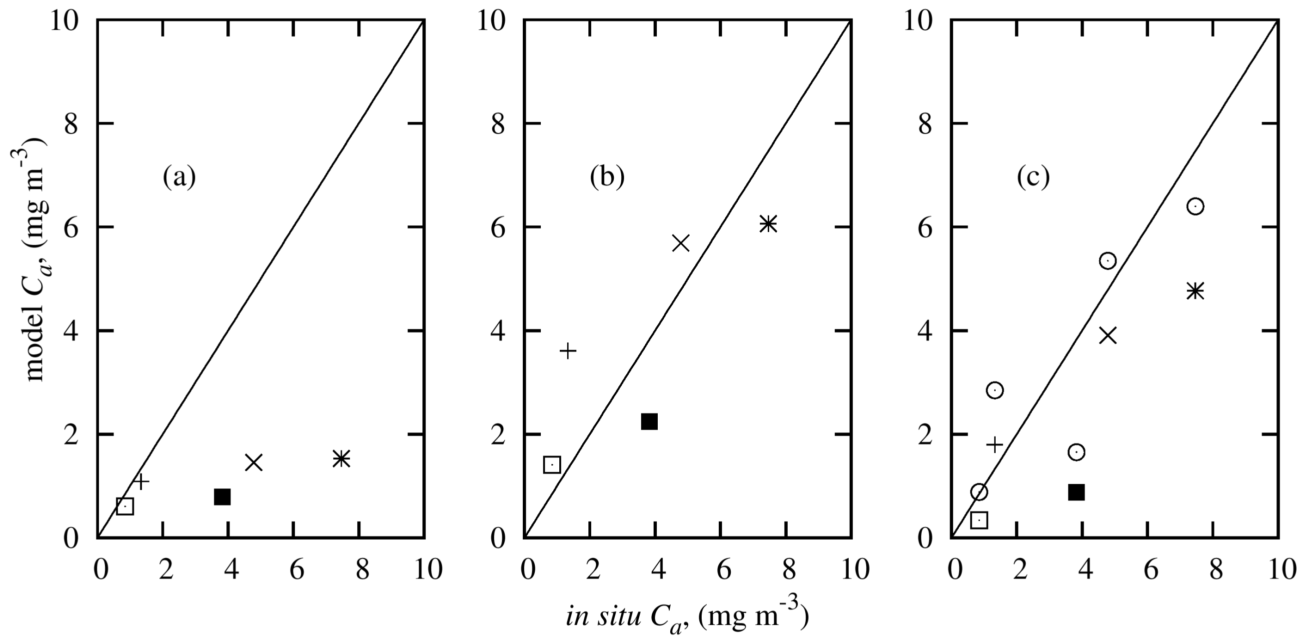

Fig. 5 Comparison of *in situ* measured C_a with calculations of C_a using satellite data (table 5) by three models: (a) – model [24]; (b) – model [28] and (c) – *Shelf* solution

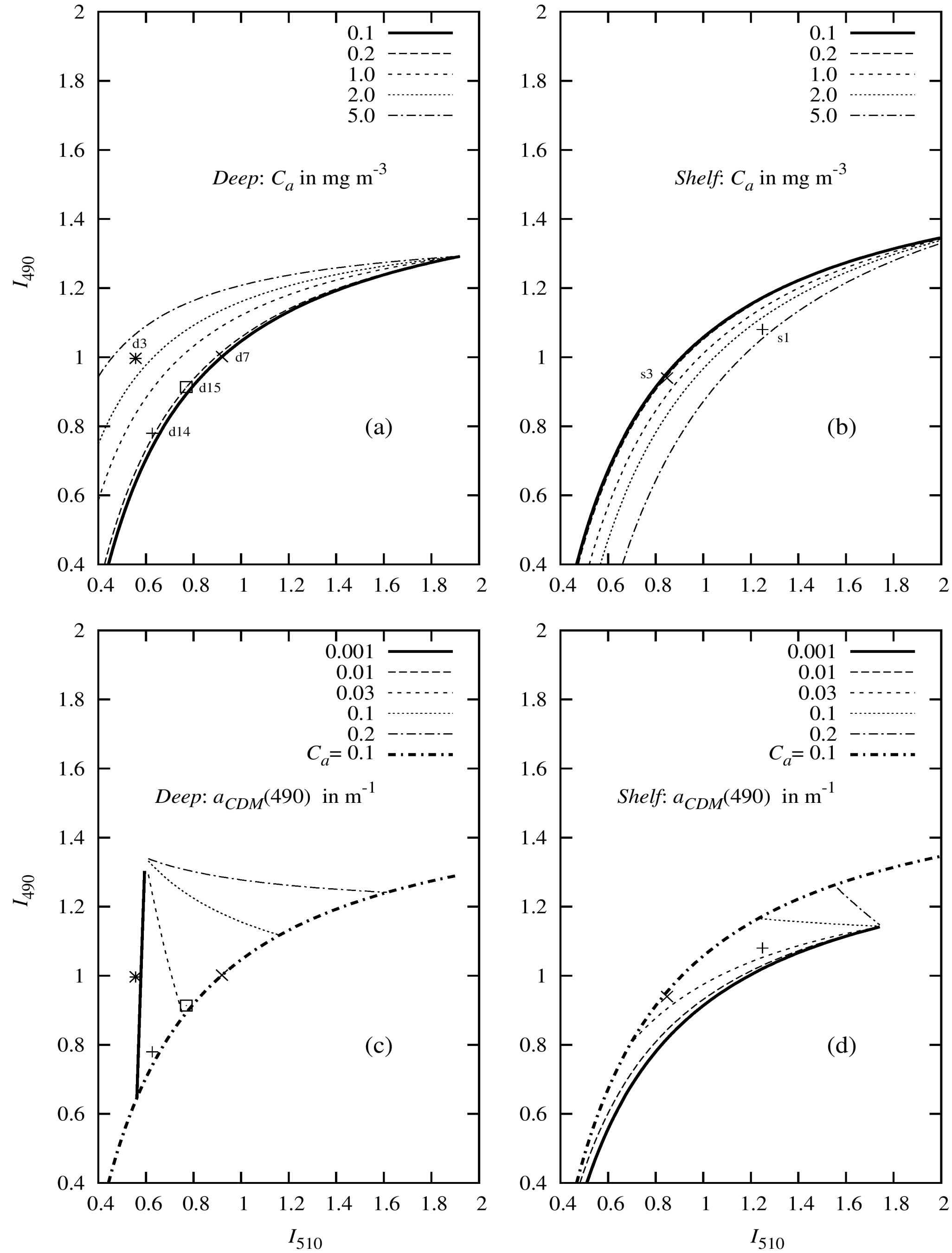

Fig. 6 *Deep* and *Shelf* solutions as isolines of C_a and $a_{CDM}(490)$ in coordinates $\{I_{510}, I_{490}\}$: (a) and (b) – isolines C_a for *Deep* and *Shelf* solution correspondently, where C_a is in mg m^{-3}; (c) and (d) – isolines of $a_{CDM}(490)$ for *Deep* and *Shelf* solution correspondently, where - $a_{CDM}(490)$ is in m^{-1}. On (c) and (d) there are isolines C_a = 0.1 mg m^{-3} for *Deep* and *Shelf* solution correspondently. On (a) and (c) there are points 3, 7, 14 and 15 from table 4 (symbols - d3, d7, d14 and d15). On (b) and (d) there are points 1 and 3 from table 5 (symbols -s1 and s3)

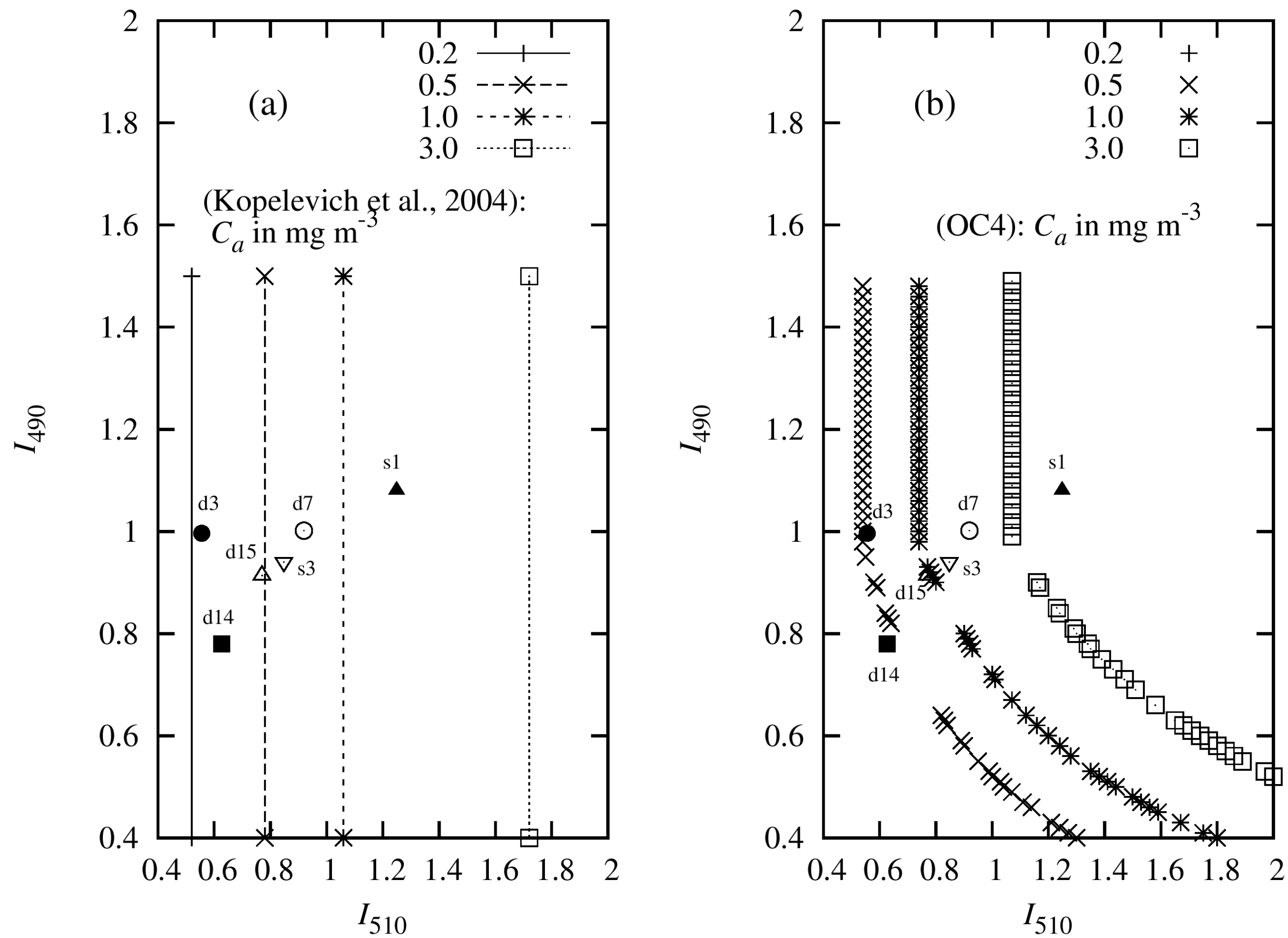

Fig. 7 Model solution [24] and [28] as isolines C_a in coordinates $\{I_{510}, I_{490}\}$, where C_a is in mg m^{-3}.
On (a) and (b) there are points 3, 7, 14 and 15 from table 4 and point 1 and 3 from table 5 (denoted as on fig. 6)