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ФОТОСИНТЕТИЧЕСКИ АКТИВНАЯ РАДИАЦИЯ НА ДНЕ СЕВЕРО-ЗАПАДНОГО ШЕЛЬФА ЧЁРНОГО МОРЯ НА ОСНОВЕ РЕГИОНАЛЬНЫХ МОДЕЛЕЙ И СПУТНИКОВЫХ ДАННЫХ И ЕЁ МЕЖГОДОВАЯ ИЗМЕНЧИВОСТЬ

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Предложен и реализован алгоритм оценки фотосинтетически активной радиации, достигающей дна черноморского шельфа. Двухнедельные, среднемесячные и среднемноголетние карты фотосинтетически активной радиации с сентября 1997 по 2018 г. построены на основе региональных спутниковых продуктов и региональных спектральных особенностей оптически активных веществ с учётом их профилей, которые получены в результате статистического анализа многолетних измерений био-арго буями. Результаты количественной оценки фотосинтетически активной радиации, достигающей дна черноморского шельфа, представлены в виде двухнедельных карт с пространственным разрешением 2.5 × 2.5 км по долготе и широте за период с января 1998 по декабрь 2018 г. на сайте blackseacolor.com на странице http://blackseacolor.com/browser3.html. Анализ межгодовой изменчивости фотосинтетически активной радиации на дне шельфа для шести небольших выделенных районов (Филлофорное поле Зернова, Каркинитский залив, в центре на свале глубин, около Одессы, устья р. Дунай и Западного Крыма) показал, что в отдельных районах для летних месяцев наблюдается устойчивый рост фотосинтетически активной радиации на дне шельфа, в то время как для зимних месяцев он отсутствует. Оцениваемая точность восстановления фотосинтетически активной радиации на дне шельфа находится на уровне 50%.

Ключевые слова: фотосинтетически активная радиация, Чёрное море, шельф, региональный спутниковый продукт, вертикальная структура оптически активных веществ.

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PHOTOSYNTHETICALLY AVAILABLE RADIATION AT THE BOTTOM OF THE NORTHWESTERN SHELF OF THE BLACK SEA BASED ON REGIONAL MODELS AND SATELLITE OCEAN COLOR PRODUCTS AND ITS INTERANNUAL VARIABILITY

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Algorithm of assessment of photosynthetically available radiation near the bottom of the Black Sea shelf was developed and validated. Two-weekly, monthly, and long-term average maps of photosynthetically available radiation were obtained for the period from September 1997 to 2018, based on regional satellite ocean color products and regional spectral bio-optical properties of opti-

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cally active substances, which profiles were obtained with statistical analysis of long-term measurements from profiling Bio-Argo floats. Estimates of the photosynthetically available radiation near the bottom of the Black Sea shelf are presented on two-weekly maps with a spatial resolution of 2.5 km by 2.5 km of longitude and latitude for the period from January 1998 to December 2018 on the website at http://blackseacolor.com/browser3.html. Interannual variability of photosynthetically available radiation near the shelf bottom was analyzed for six small designated areas: Zernov's Phyllophora field, Karkinitsky Bay, in the center of the shelf slope zone, near Odessa, the mouth of the Danube River and Western Crimea. The analyses for summer months revealed an increase of photosynthetically available radiation near the shelf bottom in some areas during the period from 1998 to 2018. However, it was not observed for the winter months. The accuracy of the photosynthetically available radiation assessment is ~50%.

Key words: photosynthetically available radiation, Black Sea, shelf, regional oceancolor product, IOPs profile.

1. Introduction

Short-wave solar radiation (200–4000 nm) is one of the essential factors of the Black Sea ecosystem. Its component — photosynthetically available radiation from 400 to 700 nm (PAR) is utilized in photosynthesis [1], affects the thermodynamic properties of seawater due to its absorption by the upper layers and the seabed on the shelf [2], which makes an assessment of the maximum depths of algae and seagrass distribution on the Black Sea shelf possible [3]. Earlier, for the Black Sea, a semi-empirical spectral model of penetrating PAR was used, which was described in [4, 5]. Afterward, two important events happened. First, several Bio-Argo floats were launched in the Black Sea that provide bio-optical characteristics' profiles, namely: the chlorophyll-a concentration, C_a; the backscattering coefficient of suspended particles, b_{bp}; and the concentration of the colored component of the dissolved organic substances, CDOM (Colored dissolved organic matter) [6]. Second, the Optics Department of the Marine Hydrophysical Institute of RAS created instruments that made it possible to measure horizontal irradiation and PAR in the Black Sea, including its northwestern shelf [7, 8].

Modern regional models that reconstruct the bio-optical characteristics from satellite and profile data, using statistical processing of Bio-Argo floats measurements, provide the solution of the PAR evaluation problem at the bottom of the north-western shelf of the Black Sea. Acknowledging that the main obstacle for obtaining useful information from satellites at "visible" wavelengths of the spectrum are clouds, mitigation of this natural limitation was found in the combination of satellite information obtained from several satellite instruments (SeaWiFS, MERIS, MODIS-Aqua/Terra). The purpose of this work is to describe and implement the newly developed methodology for calculating PAR at the bottom of the Black Sea shelf.

2. Initial data and methods

The second level satellite data (i. e., the results of standard atmospheric correction with a set of masks and flags of the current processing versions) of the four color scanners SeaWiFS (1997–2010), MERIS (2002–2012), MODIS-Aqua (2002–2018)/Terra (2000–2018) over the Black Sea for the entire period of their work [9–12] were used. The merged (data from four satellite instruments) three products — the absorption coefficient of colored detrital matter in the spectral channel of 490 nm, $\left(a_{\mathrm{CDM}}(490) = a_{\mathrm{CDOM}}(490) + a_{\mathrm{NAP}}(490)\right)$, where a_{NAP} the absorption coefficient of non-algal particles), C_a and $b_{bp}(555)$ were obtained in spatial resolution of 2.5 × 2.5 km (of longitude and latitude) and with two week averaging (first and second half of the month) [13].

The presented sequential scheme for calculating PAR includes the boundary conditions obtained by regional satellite algorithms, the calculation of the profiles of optically active substances using the results of the long-term measurements of Bio-Argo floats analyses, followed by the calculation of the spectral scattering and absorption coefficients, based on which the spectral diffuse attenuation coefficient of light is retrieved as a function of depth.

Boundary conditions. Spectrum of quantum irradiation par(λ, 0^-), expressed through the spectrum of energy irradiation, appears as $\mathrm{par}(\lambda,0^-) = E_d\left(\lambda,0^-\right)/h\nu = \left[\lambda E_d\left(\lambda,0^-\right)\right]/hc,$ where h is the Planck constant, ν is the frequency, and c is the speed of light. Consequently, quantitative changes par(λ, 0^-) using integral values of PAR just beneath the sea surface (PAR(0^-)) can be calculated as follows:

$$\mathrm{par}(\lambda,0^-) = (\lambda/hc)\left[(E_d(\lambda,0^-))/\mathrm{PAR}(0^-)\right]\mathrm{PAR}(0^-) = \left[\lambda w(\lambda)/hc\right]\mathrm{PAR}(0^-), \quad (1)$$

where the function $w(\lambda) = E_d\left(\lambda,0^-\right)/\mathrm{PAR}\left(0^-\right)$ is the spectral energy irradiation normalized to PAR(0^-), par is wavelength-dependent spectral quantum irradiation; PAR is integral of quantum irradiation in the range from 400 to 700 nm, wavelength independent. Apparently, $w(\lambda)$ depends on lighting conditions i. e. on the height of the Sun and cloudiness. In our case, its numerical values were taken from the study [14]. PAR(0^-) was calculated by the formula

$\mathrm{PAR}(0^-) = 0.96 \times \mathrm{PAR}(0^+)$. Data source of PAR($0^+$) is a standard satellite product [15]. Note that it is possible to replace the satellite standard product PAR(0^+) with downward short-wave radiation at sea level calculated according to the regional meteorological model [16]. The work [17] shows that both products' accuracy is 10–15%, compared with direct measurements. Here, we use only the standard satellite product PAR(0^+) composed of averaging measurements taken from one to four scanners depending on the period in question. The particulate backscattering coefficient $b_{\mathrm{bp}}(\lambda_1,0)$, at λ_1 = 555 nm, can be calculated in two different ways with comparable quality of the resulting product, described in [18–19]. We used the method [18]. Values of the $a_{\mathrm{CDM}}(\lambda_0, 0)$, λ_0 = 490 nm and chlorophyll-*a* concentrations $\mathrm{C}_a(0)$ are calculated by the regional bio-optical algorithm [20].

Profiles of optically active substances. In this work, we used measurements from three Bio-Argo floats for the period from 2013 to 2018. With these data, the average values of the profiles and the first two eigenvectors as functions of the current day in the year were obtained for each of the three bio-optical parameters ($a_{\mathrm{CDM}}(490)$, C_a and $b_{\mathrm{bp}}(555)$). Both average profiles' values and the first two eigenvectors obtained with statistical analysis of Bio-Argo buoy profiles depended on the current day in the year and did not depend on a specific year. Vertical profiles were restored using the current day upper layer data (obtained using regional satellite algorithms), which were adjusted to the average profile and the first two eigenvectors for the corresponding current day in the year.

For each of the three parameters, the average vector was calculated $(\vec{m})$ and the first two eigenvectors ($\vec{v_1}$ и $\vec{v_2}$). In our case, a vector has 14 components, each of which belongs to one of 14 depths with a step of 5 m in the upper layer 0–70 m. The values of the components are obtained with statistical analysis of the corresponding matrices comprising profiles recorded within a fixed period, ±10 days of the current day in the year, in increments of 10 days starting from January 1. Furthermore, each matrix contains profiles from all floats and from different years. For each specific point on the surface of the sea (x, y) and current day of the year t_0 coefficients α and β for the first two eigenvectors were determined by the method described in [21]. Thus, the vertical profile of the corresponding parameter for the current day in the year (t_0) was calculated by the following expression (2):

$$\begin{aligned} a_{\mathrm{CDM}}(\lambda_0,z) &= m_a(z,t_0) + \alpha\left(t_0,a_{\mathrm{CDM}}(\lambda_0,0)\right)\cdot v_{1a}(z,t_0) + \beta\left(t_0,a_{\mathrm{CDM}}(\lambda_0,0)\right)\cdot v_{2a}(z,t_0),\\ b_{\mathrm{bp}}(\lambda_1,z) &= m_b(z,t_0) + \alpha\left(t_0,b_{\mathrm{bp}}(\lambda_1,0)\right)\cdot v_{1b}(z,t_0) + \beta\left(t_0,b_{\mathrm{bp}}(\lambda_1,0)\right)\cdot v_{2b}(z,t_0),\\ \mathrm{C}_a(z) &= m_c(z,t_0) + \alpha\left(t_0,\mathrm{C}_a(0)\right)\cdot v_{1c}(z,t_0) + \beta\left(t_0,\mathrm{C}_a(0)\right)\cdot v_{2c}(z,t_0). \end{aligned} \tag{2}$$

The second index below the eigenvector denotes the corresponding parameter: *a* is a_{CDM}, *c* is C_a, *b* is b_{bp}. The number "0" in the variables for the coefficients α and β relates to a surface data by a satellite product.

The spectral characteristics of optically active substances, considering their profiles, were calculated using equations (3)—(10):

for the absorption coefficient of colored detrital matter [22]

$$a_{\mathrm{CDM}}(\lambda,z) = a_{\mathrm{CDM}}(\lambda_0,z)\cdot\exp\left(-S\cdot(\lambda-\lambda_0)\right). \tag{3}$$

where λ_0 = 490 nm and S = 0.018 nm^{-1};

for the particulate backscattering coefficient [23]

$$b_{\mathrm{bp}}(\lambda,z) = b_{\mathrm{bp}}(\lambda_1,z)\cdot\left(\frac{\lambda}{\lambda_1}\right)^{-n_p}, \tag{4}$$

where λ_1 = 555 nm and n_p = 0.8;

for phytoplankton absorption coefficient [24]

$$a_{\mathrm{ph}}(\lambda,z) = a^*_{\mathrm{ph}}(\lambda)\cdot\mathrm{C}_a(z), \tag{5}$$

where $a^*_{\mathrm{ph}}(\lambda) = A(\lambda)\cdot\mathrm{C}_a^{B(\lambda)}$, while $A(\lambda)$ and $B(\lambda)$ are functional dependencies for the Black Sea shelf reported in the studies [25–29]. Spectral characteristics of pure seawater, coefficient of absorption and scattering of light, $a_w(\lambda)$ and $b_{\mathrm{bw}}(\lambda)$ are from [30, 31].

PAR at the depth z, further PAR(z), were derived as follows:

$$\mathrm{PAR}(z) = \int_{400nm}^{700nm}\mathrm{par}(\lambda,z)\,d\lambda, \tag{6}$$

where PAR(bottom) at $z = bottom$, , and par(λ, z) [32]

$$\mathrm{par}(\lambda,z+\Delta z) = \mathrm{par}(\lambda,z)\cdot\exp\left(-K_d(\lambda,z)\cdot\Delta z\right); \tag{7}$$

Spectrum of $K_d(\lambda, z)$ as a function of z

$$K_d(\lambda, z) = 1.2 \cdot \left(a(\lambda, z) + b_b(\lambda, z)\right), \quad (8)$$

where $a(\lambda, z)$ is the seawater absorption coefficient

$$a(\lambda, z) = a_w(\lambda) + a_{\mathrm{CDM}}(\lambda, z) + a_{\mathrm{ph}}(\lambda, z), \quad (9)$$

where $a_w(\lambda)$, $a_{\mathrm{CDM}}(\lambda, z)$, and $a_{\mathrm{ph}}(\lambda, z)$ are coefficient of light absorption by pure water, colored detrital matter and phytoplankton, and $b_b(\lambda, z)$ is backscattering by seawater

$$b_b(\lambda, z) = b_{\mathrm{bw}}(\lambda) + b_{\mathrm{bp}}(\lambda, z), \quad (10)$$

where $b_{\mathrm{bw}}(\lambda)$ and $b_{\mathrm{bp}}(\lambda, z)$ are backscattering coefficients of pure seawater and suspended particles [35].

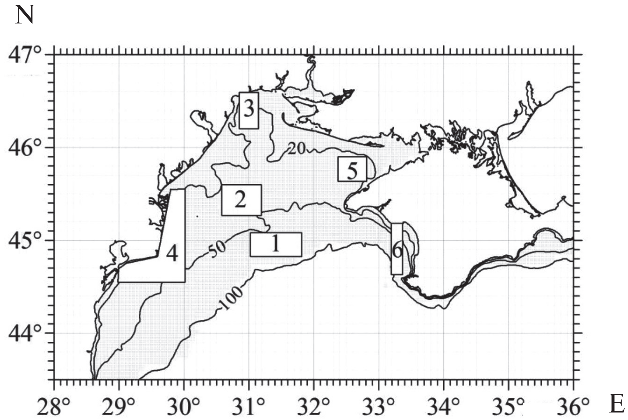

Fig. 2. A bathymetric map of the northwestern shelf of the Black Sea and the location of areas for PAR interannual variability analyses. 1 — Central region (shelf border); 2 — Zernov's Phyllophora field; 3 — Odessa; 4 — the Danube River; 5 — the Karkinitsky Bay; 6 — Western Crimea.

3. Results and discussion

Examples of resulting two-weekly, monthly, and long-term average (1997—2018) PAR maps at the bottom of the Black Sea shelf and a bathymetric shelf map are shown in fig. 1 (see Inset) and fig. 2. A full set of two-weekly PAR maps of the Black Sea shelf for the period from January 1998 to December 2018 is available at http://blackseacolor.com/browser3.html. The correlation coefficient between the PAR at the bottom of the shelf (fig. 1) and bathymetry (fig. 2) is in the range from –0.96 to –0.80, which indicates the spatial heterogeneity of the optical properties of seawater and their effect on the PAR that reached the bottom of the shelf.

Here are some advantages of the new approach to PAR modelling in comparison to the previous methods [5, 6]. Firstly, there is a significant decrease in the time step for the reconstruction of the vertical profiles of optically active substances that appears to be 10 days compared to six months. Also, the new method profile $b_{\mathrm{bp}}(z)$ differs from $C_a(z)$ qualitatively, while both profiles are similar to each other in previous methods. The next important difference is that z doesn't determine the profile $a_{\mathrm{CDM}}(z)$ completely. The latter two are the result of the statistical processing of long-term observations by Bio-Argo floats [21]. Equation (8) has an error of about 20—30%, considering the error of the profiles [36, 37]. The PAR(0+) reconstruction, with semimonthly averaging from the available satellite data, is estimated at 10—15%. Therefore, our accuracy assessment of the PAR at the bottom of the shelf is at the 50% level.

To analyze the spatial and long-term variability of PAR on the Black Sea shelf, we used surface and bottom monthly average PAR maps. The coefficients α and β of the regression equation $y = \alpha \cdot x + \beta$ were obtained by the least-squares method after subtracting the average seasonal cycle derived for the entire considered period.

Table 1

Coefficients of the linear regression equation (or trend) for time series of monthly mean PAR values on the surface and at the bottom for some areas of the northwestern shelf of the Black Sea for the period from 1998 to 2018

Region	Coordinates / number of grid nodes 0.025° × 0.035° (latitude × longitude)	Regression Equation Parameters $y = \alpha \cdot x + \beta$: $\alpha/\beta/t$* January — February July — August	
		At the surface (0+)**	At the shelf bottom***
Central region (shelf border)	31–31.8: 44.8–45.1/252	–0.0845/169.7/Insign 0.1008/–202.3/Insign	0.0107/–21.60/Insign 0.0480/–96.56/0.01
Zernov's Phyllophora field	30.5–31.2: 45.25–45.55/210	–0.092/185.5/0.10 0.1361/–273.3/0.05	0.0101/–20.31/Insign 0.0478/–96.15/0.01
Odessa	30.8–31.2: >46.3/122	–0.0747/150.01/0.05 0.1128/–226.43/0.05	0.00057/–1.1707/Insign 0.0113/–22.70/0.10
The Danube River	29–30: 44.6–45.5/434	–0.0793/159.23/0.10 0.1450/–291.13/0.01	–0.0097/19.50/Insign 0.0167/–33.62/0.05
The Karkinitsky Bay	32.4–32. 8:45.6–45.9/142	–0.0349/70.02/Insign 0.0775/–155.53/Insign	0.00334/–6.738/Insign 0.0237/–47.50/0.10
Western Crimea	33.2–33.4: 44.6–45.2/108	–0.017/34.30/Insign 0.053/–105.78/Insign	0.0101/–20.38/Insign 0.022/–43.91/0.01

*level of statistical significance of the coefficient α according to Student's t-test (Insignificant)
**x is the year, y is the value of interannual variability of PAR [E m^{-2} d^{-1}].
***x is the year, y is the value of interannual variability of lg(PAR [E m^{-2} d^{-1}]).

The statistical significance of the coefficient α was calculated using Student's t-test. An analysis of the interannual variability of PAR at the surface and at the bottom of the sea shelf for six designated areas (fig. 2) showed that for the period from 1998 to 2018 in these areas, for the summer months (July–August), a statistically significant steady increase in PAR at the bottom of the shelf is observed; while for the winter months (January–February), it is absent. For three of these areas (the Zernov Phyllophora field, near Odessa, the mouth of the Danube River), this growth coincides with the statistically significant increase in PAR at the sea surface (table 1, figs. 3 and 4). In general, this agrees with the independent results obtained in the Black Sea study [38], and associated with the manifestations of long-term weather anomalies in certain regions of the planet, the reasons for which are not clear until now.

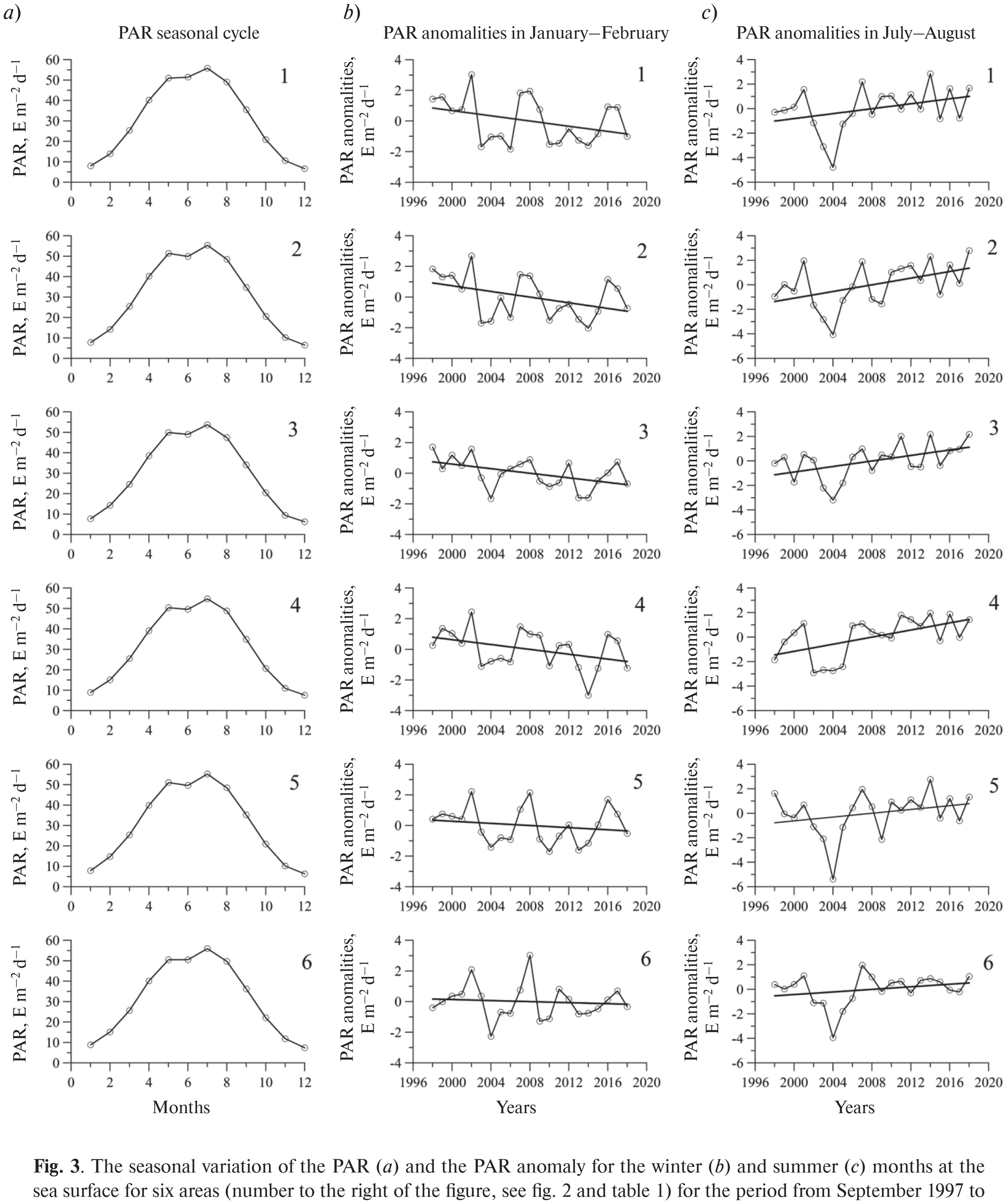

Fig. 3. The seasonal variation of the PAR (*a*) and the PAR anomaly for the winter (*b*) and summer (*c*) months at the sea surface for six areas (number to the right of the figure, see fig. 2 and table 1) for the period from September 1997 to December 2018.

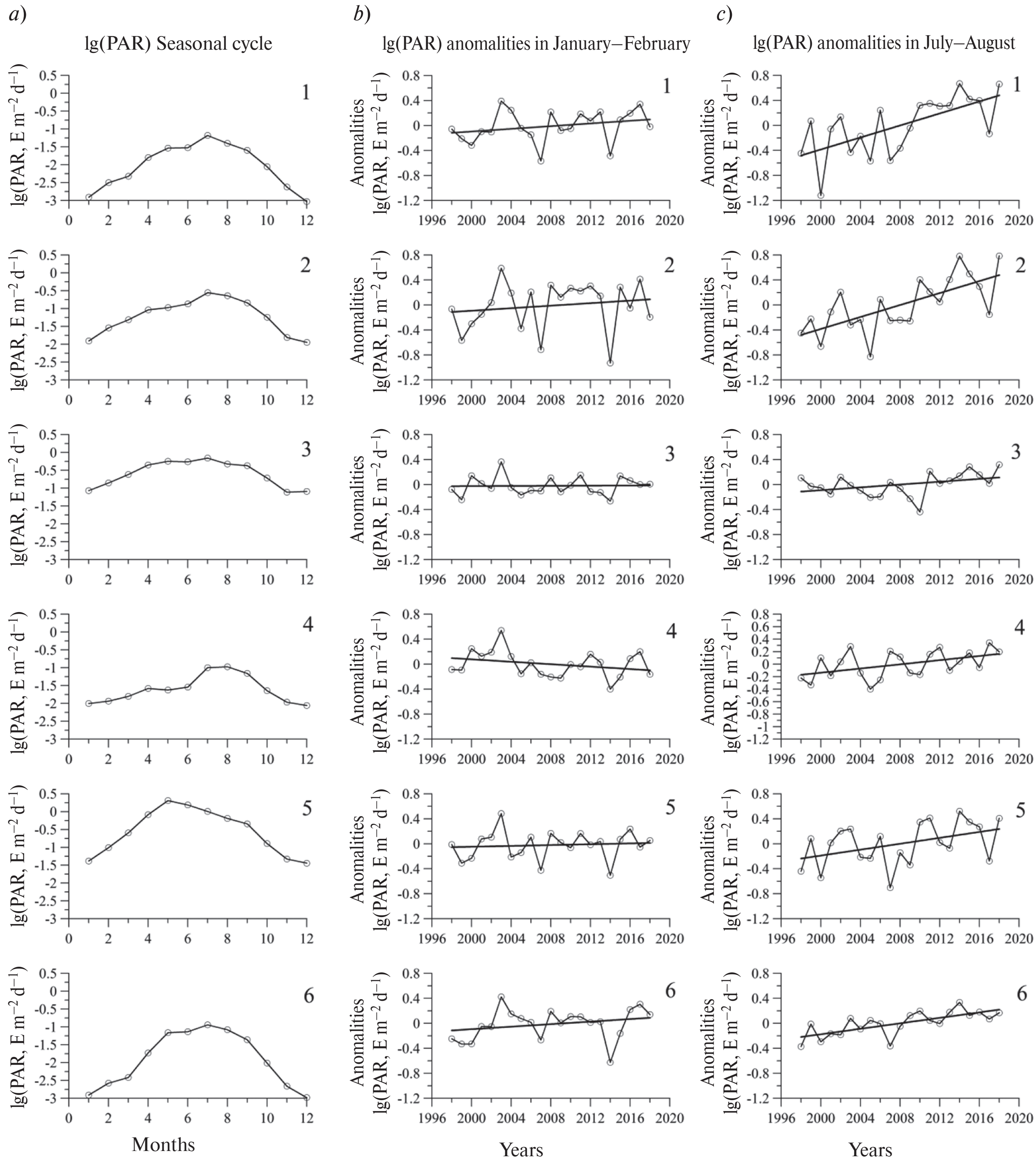

Fig. 4. Seasonal variance of the PAR in log-scale (left column) and the PAR anomaly for the winter (central column) and summer (right column) months at the bottom of the sea shelf for six areas (number to the right of the figure, see fig. 2 and table 1) for the period from September 1997 to December 2018.

4. Conclusion

New algorithm for evaluating photosynthetically available radiation reaching the bottom of the Black Sea shelf was developed and described in details (all steps of solution). Based on this algorithm, maps of PAR near the bottom of the Black Sea shelf were obtained for the first time, that were used to reproduce a long-term series of the parameter with a two-weekly step and a spatial resolution of 2.5 × 2.5 km of longitude and latitude from September 1997 to 2018. The analyses of the interannual variability of the PAR at the shelf bottom for six small designated regions (Zernov's

Phyllophora field, the Karkinitsky Bay, Central region (shelf border), near Odessa, the mouth of the Danube River, and Western Crimea) revealed that in the summer months (July–August) there is a steady increase in PAR at the bottom of the shelf in some areas; however, it is not observed in the winter months (January–February). The main explanation of the phenomena is the increase of PAR at the surface of the sea, which results in coinciding significant PAR trends at the surface and the bottom of the sea for independently studied sea areas.

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Suslin V.V., Churilova T.Ya., Latushkin A.A., Shokurova I.G., Shokurov M.V., Moiseeva N.A., Efimova T.V., Pryahina S.F. Photosynthetically available radiation at the bottom of the northwestern shelf of the Black Sea based on regional models and satellite ocean color products...

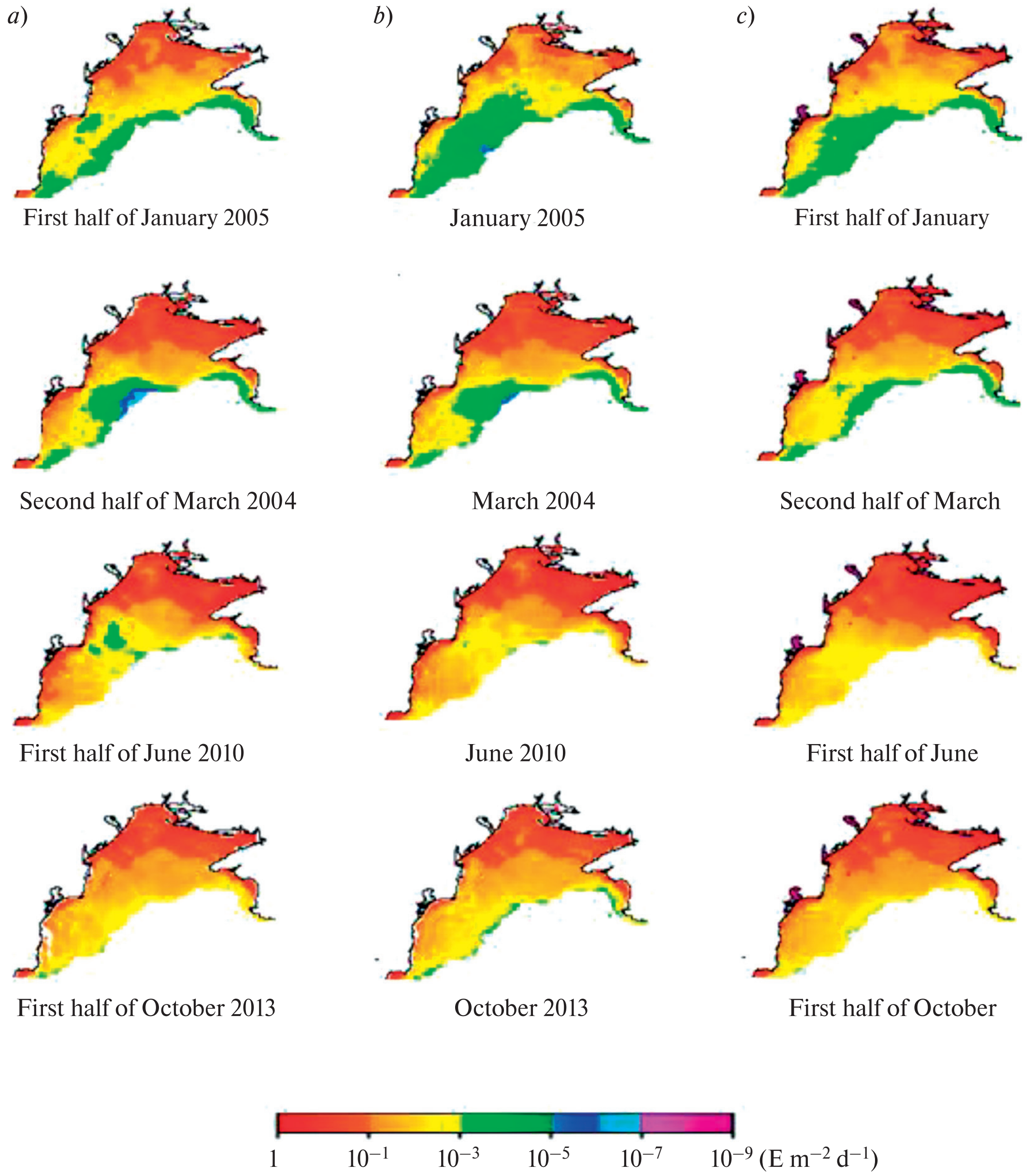

Fig. 1. Examples of PAR near the bottom of the Black Sea shelf ($E\times m^{-2}\times day^{-1}$) from top to bottom: two-weekly average (*a*) first half of January 2005, second half of March 2004, first half of June 2010, first half of October 2013; monthly average (*b*) January 2005, March 2004, June 2010, October 2013; long-term (20 years) two-weekly average (*c*) first half of January, second half of March, first half of June, first half of October.