Original Russian Text © I. V. Kovalyova, V. V. Suslin, 2022,
published in MORSKOY GIDROFIZICHESKIY ZHURNAL, Vol. 38, Iss. 4 (2022)

Integrated Primary Production in the Deep-Sea Regions of the Black Sea in 1998–2015

I. V. Kovalyova [1], ✉, V. V. Suslin [2]

[1] *A. O. Kovalevsky Institute of Biology of the Southern Seas, Russian Academy of Sciences, Sevastopol, Russian Federation*
[2] *Marine Hydrophysical Institute of RAS, Sevastopol, Russian Federation*
✉ *ila.82@mail.ru*

Abstract
Purpose. The work is aimed at estimating monthly changes in the integrated primary production in the deep-sea zone of the Black Sea in 1998–2015 using mathematical modeling based on the satellite measurements.
Methods and Results. Based on the *SeaWiFS* and *MODIS* satellite observations, the integral primary production was calculated using the model modified by the authors. The algorithm developed in the Marine Hydrophysical Institute, RAS based on the *in situ* measurements performed in 1997–2015, was used for reconstructing the chlorophyll *a* concentration by the satellite measurements in the spectrum visible range. The applied sea brightness coefficients for three wavelengths 490, 510 and 555 nm permitted to take into account the colored solute absorption; they are weakly sensitive to the errors of atmospheric correction and to the light backscattering by suspension. The integral primary production was calculated using the Behrenfeld and Falkowski adapted model that had included the phytoplankton physiological parameters derived from the *in situ* data for the Black Sea. The data on seasonal variability of the fortnight-averaged primary production values for the central part of the Black Sea in 1998–2015 are presented.
Conclusions. Over 18 years, in the deep-sea zone (below 500 m), productivity in the water column averaged 157–158 gC · $m^{-2} \cdot year^{-1}$. In course of an annual cycle, three periods of increase in the integral primary production, namely the winter-spring, summer and late autumn ones were observed. No productivity trends were noted over the time period under study. The decline of indicators was recorded after 2008. In the eastern and western deep-sea regions, the characters of the primary production changes were similar. The productivity values obtained for 1998–2015 are consistent with those of the previous studies. In the Black Sea, observed are the alternating periods of increase and decrease in the production indicators that is conditioned mainly by climatic effects.

Keywords: primary production, Black Sea, phytoplankton, model calculations, satellite observations

Acknowledgements: the authors thank Ph.D. (biol.) Professor Z. Z. Finenko for participating in discussion of the results. The study was carried out within the framework of the state assignment of the Federal Research Center IBSS on theme No. 121041400077-1 “Functional, metabolic and toxicological aspects of existence of hydrobionts and their populations in biotopes with different physical-chemical regimes”, and partially within the framework of the state assignment on theme No. FNNN-2021-0003 “Development of operational oceanology methods based on interdisciplinary research of processes of the marine environment formation and evolution and on mathematical modeling using data of remote and contact measurements” (“Operational oceanology” code).

For citation: Kovalyova, I.V. and Suslin, V.V., 2022. Integrated Primary Production in the Deep-Sea Regions of the Black Sea in 1998–2015. *Physical Oceanography*, 29(4), pp. 404-416. doi:10.22449/1573-160X-2022-4-404-416

DOI: 10.22449/1573-160X-2022-4-404-416

Introduction

The study of phytoplankton productivity – the first link in the trophic chain of aquatic ecosystems – is one of the important tasks in oceanology. The process of photosynthesis is a key part of the biogeochemical cycle, during which carbon dioxide and oxygen are exchanged between the ocean and the atmosphere, which affects the climate. Estimates of productivity indices over long periods are required for predicting the ecological state of the basins' ecosystem. The integral primary production in the water column, which reflects the total neoplasm of organic matter in the photosynthesis layer, is of particular interest. Such studies for the Black Sea were carried out earlier [1–11] using both direct radiocarbon measurements and calculated ones involving satellite observations. The complexity of carrying out direct measurements of integral primary products, which require a large time and material costs, has caused such studies to be minimized. Therefore, the main array of direct measurement data was obtained mainly in the past century. To date, computational methods are mainly used with the inclusion of more accessible characteristics of phytoplankton in the models, as well as data from satellites. At the same time, satellite measurements enabled us to take research to a new level and became an impetus for the intensive development of computational models and research on a global scale.

Many works have been devoted to the modeling of integral primary production in the World Ocean and in the Black Sea [3, 8, 10–15]. However, the assessment of integral primary production in various areas of the Black Sea, in contrast to productivity in the surface layer, was carried out infrequently both in the past century [1, 3, 16] and after 2000 [5, 7, 8, 11, 17]. Therefore, an urgent task is to analyze the variability of the integral primary production values using model calculations and satellite data over the past two decades.

Materials and methods of research

The satellite level-2 data (*SeaWiFS\R2018.0\MLAC\Level-2, MODIS-Aqua\R2018.0\LAC\Level-2* and *MODIS-Terra\R2018.0\LAC\Level-2*), which include measurement time, geographic reference, the at-surface spectral remote-sensing reflectances, the concentration of chlorophyll *a* calculated on the basis of an algorithm developed at Marine Hydrophysical Institute of the Russian Academy of Sciences (for *SeaWiFS* and *MODIS*) [18, 19]. The average relative error in reconstructing the chlorophyll *a* concentration according to the algorithm applied was ~ 30% [20]. Measurements by satellite scanners were carried out with a spatial resolution of ~ 1 km in nadir for *MODIS* and ~ 4 km for *SeaWiFS*. The chlorophyll *a* concentration was obtained on a spatial grid of 0.025° in latitude and 0.035° in longitude. Measurements with *SeaWiFS* satellite scanner were carried out in 1998–2008 with *MODIS-Aqua* and *MODIS-Terra* instruments in 2008–2015 (Available at: https://oceancolor.gsfc.nasa.gov/). Data on the surface layer temperature for 1998–2000 period are taken from the website http://podaac.jpl.nasa.gov/sst/, for 2000–2015 period – from the website https://oceancolor.gsfc.nasa.gov/. Data on photosynthetically active radiation (PAR) reaching the sea surface are taken from the website https://oceancolor.gsfc.nasa.gov/ for three *SeaWiFS* [1] and *MODIS-Aqua/Terra* [2] optical scanners.

The chlorophyll *a* concentration and the indicator of diffuse attenuation of light obtained from images of different scanners were calculated using a single algorithm [18, 19]. The difference in the calculation of the values was that the use of constants (indicators of light absorption by pure seawater, the ratio of phytoplankton absorption indicators, absorption of dissolved organic matter, solar constant), since different scanners had a different set of spectral channels within the range of 480–560 nm. The accuracy of the reconstructed satellite product of chlorophyll *a* concentration was considered to be the same [20].

The calculation of the integral primary production was carried out according to the Behrenfield and Falkowski model adapted for the Black Sea [21]:

$$PP = P_{opt}^{B}\, DL\, Chl_0\, Z_{eu} \frac{0.66 E_0}{E_0 + 4.1}, \tag{1}$$

where PP is a net integral daily primary production (mgC·m^{-2}·day^{-1}); P_{opt}^{B} is a the maximum hourly rate of photosynthesis, normalized for chlorophyll (mgC·mgChl^{-1}·h^{-1}); DL is a daylight duration (h); Chl_0 is a chlorophyll *a* concentration in the surface layer (mg·m^{-3}); Z_{eu} is an euphotic zone depth (m); E_0 is an the amount of solar energy falling on the surface of the sea (mole quanta·m^{-2}·day^{-1}). The essence of the adaptation was to use the calculated parameters included in the equation obtained for the Black Sea phytoplankton from the expedition data [3].

The euphotic zone depth was calculated using the power equation obtained for the Black Sea [22]:

$$Z_{eu} = 7.0 / (k_d(490))^{0.69} + 3.0, \tag{2}$$

where k_d (490) is the diffuse light attenuation index (m^{-1}), calculated using an algorithm adapted for the Black Sea [23]. The developed method of calculating k_d (490) takes into account the “blooming” of diatoms and thus better describes the seasonal variation. The error of equation (2) is ~ 20% [23].

According to the results given in [4], P_{opt}^{B} average values for temperatures of 5–26°C with one-degree interval were calculated. According to the obtained data, the general equation relating P_{opt}^{B} to temperature (T) is calculated [13]:

$$P_{opt}^{B} = a \exp\left(bT\right), \tag{3}$$

where $a = 1.4 \pm 0.2$ and $b = 0.06 \pm 0.01$ are dimensionless coefficients. The determination coefficient for equation (3) $r^2 = 0.77$, the significance level

---

[1] NASA. Ocean Color WEB. 2022. [online] Available at: https://oceancolor.gsfc.nasa.gov/data/10.5067/ORBVIEW-2/SEAWIFS/L2/OC/2018/ [Accessed: 05 July 2022].

[2] NASA. Ocean Biology Distributed Active Archive Center. 2022. [online] Available at: https://oceancolor.gsfc.nasa.gov/ data/10.5067/AQUA/MODIS/L2/OC/2018/ [Accessed: 06 July 2022], Available at: https://oceancolor.gsfc.nasa.gov/data /10.5067/TERRA/MODIS/L2/IOP/2018/ [Accessed: 05 July 2022].

[3] Kovalyova, I.V., 2017. [*Modeling of Seasonal and Long-Term Variability of Primary Phytoplankton Production in the Black Sea*]. Thesis Cand. Biol. Sci. Sevastopol, 147 p. (in Russian).

$p < 0.0001$. However, equation (3) will be less accurate if the depth of chlorophyll *a* maximum and the photosynthesis maximum coincide or when the chlorophyll *a* maximum is in the surface layer and decreases sharply with depth. In this case, according to the calculated data, the production will be somewhat overestimated [3]. The model error in this form for the Black Sea is less than 30%. When comparing the calculated and measured radiocarbon data, $r^2 = 0.77 - 0.88$ for the specified model [13].

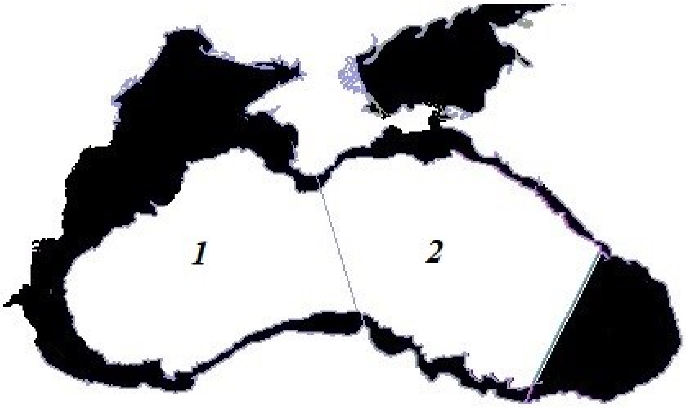
Estimation of statistical indicators was carried out using the programs *SigmaPlot*, *Grapher*, *Excel*.

For the Black Sea basin, the *SeaWiFS* scanner gave one scene per day, *MODIS-Aqua* and *MODIS-Terra* – from one to two scenes per day. In this paper, the period 1998–2015 is considered: in 1998–2000, the daily coverage of the Black Sea was one image, from 2000 to July 2002 – from two to three images, from July 2002 to December 2008 – from three to five images, in 2009–2015 – from two to four images. In this regard, a period of two weeks was chosen for averaging the data, which is a compromise solution when choosing between the amount of second-level data and the percentage of filling the Black Sea water area with data in cloudy conditions.

On average, during 1998–2015, the availability of two-week data on the space, taking into account clouds, depended on the season: from March to October – 70% and higher, from November to February – 40% and higher. A detailed analysis of the availability of satellite products is given in [19].

According to the *SeaWiFS*, *MODIS-Aqua*, and *MODIS-Terra* scanners, for each grid cell covering a region, the average value of the corresponding regional product (chlorophyll *a* concentration, the indicator of vertical attenuation of light at a wavelength of 490 nm) for a two-week period was calculated, and then the spatial average was determined. To find the combined (merge) product, the average value was calculated for all scanners that worked during the time period under consideration [3].

Calculations were carried out for the deep-water area of the Black Sea (from 500 m) (Figure).



F i g u r e. The Black Sea regions under study: *1* – deep-sea part including the western cyclonic gyre; *2* – deep-sea part including the eastern cyclonic gyre

Results

Calculations of primary production in the water column for the Black Sea deep-water part have been carried out. The average values for every two weeks over an 18-year period are presented in Table 1.

Table 1

Values of integral primary production <*PP*> (mgC·m^{-2}·day^{-1}) in the Black Sea deep-sea regions averaged over 1998–2015 for the first (*1*) and the second (*2*) halves of a month, standard deviation (*SD*), minimum (*PP*$_{min}$) and maximum (*PP*$_{max}$) values of integral primary production

Month	Region *1*				Region *2*			
	<*PP*>	*SD*	*PP*$_{min}$	*PP*$_{max}$	<*PP*>	*SD*	*PP*$_{min}$	*PP*$_{max}$
January (*1*)	390	85	261	539	409	80	291	559
January (*2*)	380	77	253	603	400	99	293	704
February (*1*)	339	42	266	441	374	51	258	457
February (*2*)	388	95	251	626	389	91	221	549
March (*1*)	320	71	204	482	344	76	216	496
March (*2*)	688	197	392	1149	701	179	318	990
April (*1*)	679	282	366	1450	568	222	222	1105
April (*2*)	343	168	178	872	319	131	168	680
May (*1*)	334	118	173	726	320	89	182	522
May (*2*)	322	78	178	467	306	64	188	408
June (*1*)	348	73	213	450	351	75	245	452
June (*2*)	413	91	252	547	399	67	274	517
July (*1*)	511	90	330	657	471	83	294	617
July (*2*)	536	84	367	683	532	78	349	622
August (*1*)	565	72	442	676	547	76	389	653
August (*2*)	526	60	382	656	540	62	429	647
September (*1*)	470	75	379	649	479	59	375	640
September (*2*)	437	79	328	593	442	61	366	602
October (*1*)	404	78	301	610	406	70	259	551
October (*2*)	369	62	261	497	371	46	296	448
November (*1*)	376	75	224	546	374	68	272	483
November (*2*)	434	96	260	597	412	100	244	614
December (*1*)	439	104	279	645	440	100	274	591
December (*2*)	384	53	258	470	413	94	245	628

In these areas, the maximum primary production was observed during the spring “blooming” in the second half of March – the first half of April. According to non-average data, productivity mainly increased in these months, but in some years “blooming” could begin in February. Also, in the cold period (January – March), in isolated cases, quite high values of *PP* maximum values were recorded. These increases are mainly due to high concentrations of chlorophyll *a*.

The second pronounced maximum was observed in July – August. In the range of variations during this period, the minimum values of production were at a fairly high level, as well as the maximum, although below the values of the spring period. The summer peak may be associated with a high assimilation rate, high temperature, and illumination.

The occurrence of a weak autumn peak can be noted in late November – early December, it is caused, apparently, by increased wind exposure and precipitation, contributing to an increase in convective fluxes of nutrients into the euphotic layer in still relatively warm water. After this maximum, with the onset of a period of minimal illumination and a decrease in water temperature, a short-term decrease in primary production occurred. Since January, integral primary production has been gradually increasing again.

According to the averaged data, in the eastern region, the winter values of integral primary production before the beginning of spring “blooming” are higher than in the western one; since April, on the contrary, in the western region the average productivity is higher, despite the synchronous decrease in average values to minimum values in May – early June. Until the beginning of August, the values of the average integrated production in the western deep-sea region are slightly higher than in the eastern one. At the end of August – September, there is a more noticeable increase in the eastern region, after which the productivity in the water column changes approximately the same in the two districts. However, if we consider the annual dynamics based on two-week data, it can be noted that on the scale of the averaged water areas, regular changes of zones with high production are clearly not traced. In the western region, the average annual values are slightly higher than in the eastern region, but in general, during the year in these areas, production indicators change approximately the same.

Thus, the primary production annual cycle in the water column according to the averaged two-week data for 1998–2015 has two characteristic peaks – winter-spring, and summer, as well as the third – weak autumn peak. At the same time, the dynamics of values in different years may change, somewhat shifting the main peaks of maxima and minima in terms of timing and duration. And also in rare cases, depending on the complex influence of factors, non-characteristic peaks or minima in productivity dynamics may appear in the water column.

The trends of integrated primary production were evaluated based on regular two-week data for 18 years. The sample of such data corresponds to a normal distribution (according to the Shapiro-Wilk criterion). The slope angle of the linear regression of the seasonal cycle of phytoplankton productivity was analyzed, and coefficients using the least squares method (LSM) were obtained. In addition, anomalies were determined for each year as the difference between the half-month average and the long-term average, as well as the coefficients of regression equations (Table 2). The following statistical indicators were used: Fisher criterion, Student criterion, and significance level ($p < 0.1$). According to the results of the analysis of seasonal variations based on two-week data for the deep-water part of the Black Sea, as well as on calculations of anomalies of seasonal changes in integral primary production over 18 years, we did not find a statistically significant trend. There were no statistically significant trends in shorter time intervals (1998–2008) with a positive slope of the regression line. A downward trend was observed in two districts after 2008 (with a significance level of $p < 0.005$), which may be due to the climatic features of recent years and warm winters. However, this did not affect the overall trend over the 18-year period.

Table 2

Coefficients of linear regression $y = c + ax$, statistical indicators for the seasonal values (PP), anomalies (PP_{an}), and PP variations over 2009–2015 (PP^*) in assessing the trend of integral primary production

Type of data	*c*	*a*	SD_a	*F*	*t*	*p*
Region *1*						
PP	438.6	-0.026	0.057	0.202	0.451	0.653
PP_{an}	5.9	-0.027	0.041	0.452	0.672	0.502
PP^*	480.9	-0.630	0.214	8.664	2.943	0.004
Region *2*						
PP	438.1	-0.040	0.051	0.609	0.780	0.436
PP_{an}	9.0	-0.041	0.036	1.307	1.143	0.254
PP^*	480.0	-0.687	0.213	10.368	3.220	0.002

Note. SD_a is a standard deviation for coefficient a; F is the Fisher criterion; t is the Student criterion for coefficient a; p is probability.

Thus, it can be concluded that in 1998–2015, the trend of integrated primary production was not observed in the deep-water zone. In 1998–2008 period, with a weak upward trend, a statistically significant trend was absent. The decline occurred mainly after 2008, which indicates the alternation of short cycles of increasing and decreasing productivity.

Discussion of the results

In the seasonal dynamics of integral primary production described in early studies, in the deep-sea areas in February – April, as a rule, the winter-spring maximum stood out [3, 4, 8, 17]. Depending on the number of measurements and the number of years included in the averaging, as well as on the dimensions of the studied water area, the average values varied approximately within the range of 500–750 $\text{mgC}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ [1, 3, 4]. According to scattered measurements carried out in expeditions in 1960–1991, the “blooming” was observed in February – March. However, in different years, the winter-spring development of phytoplankton did not occur in the same way. According to [7, 10], in the 80s, the increase in integrated production reached its maximum in March; according to [8, 16], in 1998–2004, according to calculated data, the increase occurred in March – early April. Studies of the phytoplankton biomass development seasonal dynamics also indicated the period of "blooming" in February – April [14, 24]. Phytoplankton biomass has a direct relationship with primary production, but the phytoplankton biomass dynamics, primary production in the surface layer, and integral primary production may not coincide, since additional factors affect each of the indicators. The late winter and spring periods of "blooming" are associated with the intensive development of diatoms [25].

Based on the results of modeling and generalization of satellite observation data for 1998–2015 (Table 1) from the second half of March to the beginning of April, the spring maximum of integral productivity, averaging 568–701 $\text{mgC}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$, was noted. An increase in productivity by average values was also observed in January and the end of February, but it was lower than in spring since winter peaks were not every year and occurred depending on a significant increase in the chlorophyll *a* concentration. The obtained values of productivity in the water column (Table 1) for January, are close to the values (350–430 $\text{mgC}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$) determined by the radiocarbon method in the 70s and 90s [2, 4, 17], whereas the February average values, according to our data for 1998–2015, were slightly lower. The minimum productivity in the photosynthesis zone in May – early June is also consistent with the data of *in situ* expedition studies [4]. According to the average data, after 1998 it is higher than in the 80s.

According to our data, from July to the beginning of September, the second maximum of integrated phytoplankton production is observed with the highest values in late July – August. According to the results of the works [4, 8, 16, 17], an increase in primary production in the summer period, associated with the "blooming" of coccolithophorids and dinoflagellates, which since the 90s began to develop more intensively in the central part of the sea [3], was noted. The range of variations in the values was similar to our data (Table 1) for June – July. However, in August – September, the average values, according to our calculations (565–437 $\text{mgC}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$, respectively), were approximately 1.5 times higher compared to the literature data [4], although according to later studies obtained by calculation, this difference turned out to be less [8, 16]. Each year of the considered period, summer "blooming" occurred in different ways (varying within the range of 294–683 $\text{mgC}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ in both regions), in some years it could be practically absent in these months. According to some data [26, 27], since the 2000s, in the Black Sea from July to September, an intense "blooming" of *Pseudosolenia calcaravis* diatoms, which develops at low concentrations of nutrients, took place.

Primary production in a water column in summer is largely determined by temperature and illumination, which results in a second productivity maximum at low chlorophyll *a* concentrations. The temperature gradient keeps the phytoplankton community within the euphotic zone. Due to the established stratification in the water column, the number of nutrients providing phytoplankton production is determined mainly by the number of substances that remained after the winter convection period. They penetrated from the deep layers of the sea and were not consumed during the spring "blooming". In addition, the phytoplankton primary production can also be determined during this period by regenerative production, i.e. the substances excreted by heterotrophic organisms. Therefore, the maxima and minima within the variation range differ slightly, which can be seen by small standard deviations for these months (Table 1). The extreme maximum values of productivity values in summer are lower than in winter and spring. It should also be assumed that since the 80–90s there has been a restructuring of the phytoplankton community, as a result of which the annual dynamics of integrated primary production have changed somewhat, including in the summer period.

According to the averaged data for 18-year period, in the late September – October a decrease in values took place, and then from the second half of November – a slight increase, which in other studies stands out as the autumn maximum [4, 8, 16]. In the autumn period, mainly diatoms and dinoflagellates also developed [28]. However, the autumn maximum usually does not last long. In different years it can be observed from the first half of November to the first half of December. A further decline in productive indicators occurs in the second half of December. The values of the integral primary production for October – December, calculated according to the model (1) adapted by us and obtained in the works [1, 4, 8, 16], are consistent. Some studies indicate lower productivity values in the water column for December [4], which may be due to the peculiarity of the processes occurring in individual years, and the amount of data collected, as well as the averaging area. Satellite observations provide regular measurements with high coverage density, which is problematic to do on expeditions. The areas where data is averaged, the regularity of the averaged data, and the analyzed years are also important. When compared, all this affects the differences in the values obtained in different studies. The lack of expeditionary research on integrated primary products in recent years does not allow us to objectively compare the data of calculations and measurements and introduce the required corrections to correct the model. However, the research we carried out and published in the works [2, 4, 8, 16, 17], according to their estimates, are close to each other.

The average annual value for an 18-year period, according to our calculations using satellite data, for the western deep-water region is 433.1 $mgC \cdot m^{-2} \cdot day^{-1}$, for the eastern 429.5 $mgC \cdot m^{-2} \cdot day^{-1}$, i.e. 157–158 $gC \cdot m^{-2} \cdot year^{-1}$. These production values are higher than in the previously cited studies [1, 4, 5], but somewhat lower (170–186 $gC \cdot m^{-2} \cdot year^{-1}$) than in the 1998–2004 studies [16]. It can be assumed that the calculations (Table 1), carried out according to a model adapted for the Black Sea, may overestimate primary production since photoinhibition of the phytoplankton photosynthesis rate is not taken into account. According to the results of verification of the model we used, an overestimation of the integral primary production in comparison with its measured values is possible up to 30% [13], apparently mainly due to overestimation in summer and early autumn. Based on the fact that no reliable positive productivity trends were found in the water column, it follows that primary production has not increased over the past 18 years. And in 2008–2015 its slight decrease was observed, approximately by 1 $gC \cdot m^{-2} \cdot year^{-1}$ in each region for 7 years. Therefore, the obtained primary production estimates can be comparable with the estimates from [14, 25], taking into account the scale of the averaged water area, the coverage density of the analyzed measurements, and the method of determining the values of integral products.

For example, the analysis of satellite data for 1998–2008 [5] also revealed no reliable productivity trends in the photosynthesis layer, although the nature of variations in primary production was similar. In this study, other areas of averaging in the deep part of the sea were used, and the depth of the photosynthesis zone was determined by the connection with the chlorophyll *a* concentration, which somewhat underestimated the values; the rest of the calculations were carried out according to the model we used in this work. The nature of trends in 1998–2008 according to the new calculations, it was similar to the previous one for these years, while the average production values in the water column turned out to be higher. The equation we used to calculate the depth of the photosynthesis zone, which includes the diffuse attenuation coefficient of light, is more accurate. The above highlights the importance of the scales of the averaged areas in comparison and is one of the reasons for the differences in the final averages. When analyzing the processes taking place in the ecosystem and identifying characteristic trends, it is also important to carry out assessments in one way.

The analysis of interannual variations and trends of integral primary production indicates a change in the periods of indicators' increasing and decreasing. In the 80s and early 90s, an increase in production characteristics [5, 9, 24] took place, and since the mid-90s – their decline. During 1998–2008 statistically significant trends were absent, although there was a tendency for an increase in integral primary production, after 2008 its decline began. The revealed variations are most associated with climatic cycles, temperature changes, and wind effect. Similar cycles were considered in [29].

Comparing the western and eastern deep-sea areas, it should be noted that the primary production values and their changes were approximately at the same level. The increase in the 18–year average integral productivity in January – April in the eastern part of the sea was more significant than in the western part, and in April – August in the western part was more significant than in the eastern part, this is consistent with the seasonal cycle of geostrophic circulation calculated from climatic thermohaline fields [30]. Such a change in the periods of strengthening of the western and eastern cyclonic gyres probably contributes to an increase in the nutrient flux from the deep layers of the sea and leads to a slight increase in productivity in the water column (Table 1).

Conclusion

According to model calculations using satellite observations, monthly values of integrated primary production for the eastern and western deep-water areas of the Black Sea for 1998–2015 averaged over a two-week period are estimated and presented for the first time. According to the averaged data for 18 years, the primary production values in the water column were 157–158 $gC \cdot m^{-2} \cdot year^{-1}$ in two regions. In the seasonal dynamics of productivity, the most significant are winter-spring and summer maximums, as well as weak autumn one. The obtained values are in good agreement with the data of other studies carried out earlier for other time intervals. Statistically significant trends in integrated primary production in the deep-water zone have not been observed for 18 years. The downward trends after 2008 are observed. An alternation of short periods of increase and decrease in production indicators takes place. The strengthening of cyclonic gyres, according to seasonal cycles of geostrophic circulations, leads to a slight increase in the average integral primary production in the corresponding area.

REFERENCES

1. Vedernikov, V.I. and Demidov, A.B., 1993. Primary Production and Chlorophyll in the Deep Regions of the Black Sea. *Oceanology*, 33(2), pp. 229-235 (in Russian).
2. Vedernikov, V.I. and Demidov, A.B., 1997. Vertical Distribution of Primary Production and Chlorophyll during Different Seasons in the Deep Regions of the Black Sea. *Oceanology*, 37(3), pp. 376-384.
3. Vedernikov, V.I. and Demidov, A.B., 2002. Long-Term and Seasonal Variability of Chlorophyll and Primary Production in the Eastern Regions of the Black Sea. In: A. G. Zatsepin and M. V. Flint, 2002. *Multidisciplinary Investigations of the Northeastern Part of the Black Sea*. Moscow: Nauka, pp. 212-247 (in Russian).
4. Demidov, A.B., 2008. Seasonal Dynamics and Estimation of Annual Primary Production of Phytoplankton in the Black Sea. *Oceanology*, 48(5), pp. 664-678. doi:10.1134/S0001437008050068
5. Kovaleva, I.V., 2014. [Interannual and Seasonal Changes in the Concentration of Chlorophyll *a* and Primary Production in the Deepwater Section of the Black Sea]. *Hydrobiological Journal*, 50(3), pp. 38-50 (in Russian).
6. Finenko, Z.Z., 2001. Primary Production of the Black Sea: The Ecological and Physiological Characteristics of a Phytoplankton. *Ecology of the Sea = Ekologiya Morya*, 57, pp. 60-67 (in Russian).
7. Finenko, Z.Z., Suslin, V.V. and Churilova, T.Y, 2010. Estimation of phytoplankton productivity in the Black Sea based on satellite data. *Doklady Biological Sciences*, 432(1), pp. 233-236. https://doi.org/10.1134/S0012496610030191.
8. Finenko, Z.Z., Suslin, V.V. and Churilova, T.Ya., 2009. The Regional Model to Calculate the Black Sea Primary Production Using Satellite Color Scanner SeaWiFS. *Marine Ekological Journal = Morskoj Ehkologicheskij Zhurnal*, 8(1), pp. 81-106 (in Russian).
9. Yunev, O.A., 2009. Eutrophication of the Deep-Water Part of the Black Sea: Long-Term Changes in the Annual Primary Production of Phytoplankton. In: *Monitoring Systems of Environment*. Sevastopol: MHI, pp. 407-413 (in Russian).
10. Yunev, O.A., Vedernikov, V.I., Basturk, O., Yilmaz, A., Kideys A.E., Moncheva, S. and Konovalov, S.K., 2002. Long-Term Variations of Surface Chlorophyll *a* and Primary Production in the Open Black Sea. *Marine Ecology Progress Series*, 230, pp. 11-28. doi:10.3354/meps230011
11. Agirbas, E. and Bakirci, M., 2021. Size-Fractionated Primary Production in the South-Eastern Black Sea. *Oceanologia,* 64(2), pp. 244-266. doi:10.1016/j.oceano.2021.11.002
12. Churilova, T., Kryvenko, O., Suslin, V., Efimova, T. and Moiseeva, N., 2016. Primary Production of the Black Sea: Spectral Approach. *Marine Biological Journal*, 1(3), pp. 50-53. doi:10.21072/mbj.2016.01.3.08
13. Kovalyova, I.V., 2010. Comparison of Calculation Algorithms of Primary Production in the Black Sea on Concentration of Chlorophyll in Surface Layer, to Intensity Radiation of Sun and Temperature. *Marine Ekological Journal = Morskoj Ehkologicheskij Zhurnal*, 9(2), pp. 62-73 (in Russian).
14. Finenko, Z.Z., Churilova, T.Ya and Suslin, V.V., 2011. [Estimation of Phytoplankton Biomass and Primary Production in the Black Sea from Satellite Data]. In: V. N. Yeremeyev, A. V. Gaevskaya, G. E. Shulman, Ju. A. Zagorodnyaya, eds., 2011. *Biological Resources of the Black Sea and Sea of Azov*. Sevastopol: EKOSI-Gidrofizika. Chapter 7.1, pp. 221-236 (in Russian).

15. Oguz, T., Dippner. J.W. and Kaymaz, Z., 2006. Climatic Regulation of the Black Sea Hydro-Meteorological and Ecological Properties at Interannual-to-Decadal Time Scales. *Journal of Marine Systems*, 60(3–4), pp. 235-254. doi:10.1016/j.jmarsys.2005.11.011

16. Yunev, O.A., 2011. Eutrophication and Annual Primary Production of Phytoplankton in the Deep-Water Part of the Black Sea. *Oceanology*, 51(4), 616. https://doi.org/10.1134/S0001437011040199

17. Stelmakh, L.V., Yunev, O.A., Finenko, Z.Z., Vedernikov, V.I., Bologa, A.S. and Churilova, T.Y., 1998. Peculiarities of Seasonal Variability of Primary Production in the Black Sea. In: L. I. Ivanov and T. Oguz, 1998. *Ecosystem Modeling as a Management Tool for the Black Sea*. NATO Science Partnership Subseries: 2. Dordrecht: Springer. Vol. 47, issue 1, pp. 93-104.

18. Suslin, V.V., Churilova, T.Ya. and Sosik, H.M., 2008. The SeaWiFS Algorithm of Chlorophyll a in the Black Sea. *Marine Ekological Journal = Morskoj Ehkologicheskij Zhurnal*, 7(2), pp. 24-42 (in Russian).

19. Suslin, V.V. and Churilova, T.Ya., 2016. A Regional Algorithm for Separating Light Absorption by Chlorophyll-*a* and Coloured Detrital Matter in the Black Sea, Using 480-560 nm Bands from Ocean Colour Scanners. *International Journal of Remote Sensing*, 37(18), pp. 4380-4400. doi:10.1080/01431161.2016.1211350

20. Suslin, V.V., Churilova, T.Ya., Lee, M., Moncheva, S. and Finenko, Z.Z., 2018. Comparison of the Black Sea Chlorophyll-*a* Algorithms for SeaWifs and MODIS Instruments. *Fundamentalnaya i Prikladnaya Gidrofizika*, 11(3), pp. 64-72. doi:10.7868/S2073667318030085

21. Behrenfeld, M.J. and Falkowski, P.G., 1997. A Consumer's Guide to Phytoplankton Primary Productivity Models. *Limnology and Oceanography*, 42(7), pp. 1479-1491. https://doi.org/10.4319/lo.1997.42.7.1479

22. Suslin, V.V., Slabakova, V.K. and Churilova T.Ya., 2017. Diffuse Attenuation Coefficient for Downwelling Irradiance at 490 nm and Its Spectral Characteristics in the Black Sea Upper Layer: Modeling, *in Situ* Measurements and Ocean Color Data. In: SPIE, 2017. *Proceedings of SPIE*. Vol. 10466: 23rd International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics, 104663H. doi:10.1117/12.2287367

23. Suslin, V.V. and Churilova, T.Ya., 2010. Simplified Method of Calculating of Spectral Diffuse Beam Attenuation Coefficient in the Black Sea Upper Layer on the Basis of Satellite Data. In: MHI, 2010. *Ekologicheskaya Bezopasnost' Pribrezhnykh i Shel'fovykh Zon i Kompleksnoe Ispol'zovanie Resursov Shel'fa* [Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources]. Sevastopol: ECOSI-Gidrofizika. Iss. 22, pp. 47-60 (in Russian).

24. Krivenko, O.V. and Parkhomenko, A.V., 2010. Temporal and Spatial Variability of Phytoplankton Biomass in the Black Sea from 1948 to 2001. *Marine Ekological Journal = Morskoj Ehkologicheskij Zhurnal*, 9(4), pp. 5-24 (in Russian).

25. Finenko, Z.Z. and Krupatkina, D.K., 1993. Primary Production in the Black Sea during Winter-Spring Period. *Okeanologiya*, 33(1), pp. 97-104 (in Russian).

26. Stel'makh, L.V., Babich, I.I., Tugrul, S., Moncheva, S. and Stefanova, K., 2009. Phytoplankton Growth Rate and Zooplankton Grazing in the Western Part of the Black Sea in the Autumn Period. *Oceanology*, 49(1), pp. 83-92. doi:10.1134/S000143700901010X

27. Bryantseva, Yu.V. and Gorbunov, V.P., 2012. Spatial Distribution Phytoplankton Basic Parameters at the Northern Black Sea. *Optimization and Protection of Ecosystems*, (7), pp. 126-137 (in Russian).

28. Mikaelyan, A.S., Mosharov, S.A., Kubryakov, A.A., Pautova, L.A., Fedorov, A. and Chasovnikov, V.K., 2020. The Impact of Physical Processes on Taxonomic Composition, Distribution and Growth of Phytoplankton in the Open Black Sea. *Journal of Marine Systems*, 208, 103368. doi:10.1016/j.jmarsys.2020.103368

29. Platt, T., 1986. Primary Production of the Ocean Water Column as a Function of Surface Light Intensity: Algorithms for Remote Sensing. *Deep Sea Research Part A. Oceanographic Research Papers*, 33(2), p. 149-163. doi:10.1016/0198-0149(86)90115-9

30. Ivanov, V.A. and Belokopytov, V.N., 2013. *Oceanography of the Black Sea*. Sevastopol: ECOSI-Gidrofizika, 211 p.

About the authors:

Ilona V. Kovalyova, Research Associate, Department of Ecological Physiology of Algae, A.O. Kovalevsky Institute of Biology of the Southern Seas of RAS (2 Nakhimova ave, 299011, Sevastopol, Russia), Ph.D. (Biology), **ORCID ID: 0000-0001-5430-2002**, **Scopus Author ID: 56405274600**, **WoS ResearcherID: AAB-4397-2019**, ila.82@mail.ru

Vyacheslav V. Suslin, Leading Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya str., 299011, Sevastopol, Russia), Ph.D. (Phys.-Math.), **Spin-code: 1681-7926**, **ORCID ID: 0000-0002-8627-7603, Scopus Author ID: 6603566261, ResearcherID: B-4994-2017, AuthorID: 825673, SPIN-code: 1681-7926,** slava.suslin@mhi-ras.ru

Contribution of the co-authors:

Ilona V. Kovalyova – idea of the work; processing of primary data received from satellites and calculated indicators required for the model; calculation of the integral primary production, depth of the photosynthesis zone, maximum hourly rate of photosynthesis; calculation of statistical indicators; processing and registration of final results; analysis of the results; and writing the paper

Vyacheslav V. Suslin – satellite data extraction; obtaining primary results for the Black Sea required for model calculations; calculation of the concentration of chlorophyll *a* and the diffuse attenuation coefficient of light; correction of final text of the paper

All the authors have read and approved the final manuscript.
The authors declare that they have no conflict of interest.