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SPATIAL AND TEMPORAL DYNAMICS OF THE PHYTOPLANKTON BIOMASS IN THE SURFACE LAYER OF THE BLACK SEA

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The spatial and temporal variability of phytoplankton biomass in the surface layer of the Black Sea during an 18-year period is analyzed, and the effect of the main currents in the sea on the spatial and temporal dynamics of phototrophic phytoplankton biomass is assessed. Regular long-term chlorophyll concentration data were used, obtained from satellite observations with SeaWiFS and MODIS-Aqua/Terra instruments in the Black Sea for 1998–2015. The role of macro- and microcirculations in the spatial and temporal variability of phytoplankton biomass is estimated. A gain in wind activity and a drop in water temperature from October to March, which lead to an increase in the depth of the mixed upper layer and the intensity of the main synoptic circulations, become a significant factor promoting winter–spring phytoplankton bloom. As revealed, a decrease in the mean water temperature in the cold season to +7…+8 °C, lasting for more than six weeks in the deepwater zone, leads to the intensive biomass development in spring. It was established that the mean phytoplankton biomass for 18 years in the western and eastern cyclonic cycles is (38.0 ± 17.8) and (37.7 ± 16.8) $\text{mg C}\cdot\text{m}^{-3}$, respectively, and in the Batumi anticyclone, (38.2 ± 18.0) $\text{mg C}\cdot\text{m}^{-3}$. As a rule, the Rim Current carries phytoplankton formed at the shelf zone along the coastline and almost does not mix with deep waters. In the cyclonic cycles, winter–spring phytoplankton bloom is observed on average for six weeks. Intensive bloom in the area of the flow of northwestern rivers, recorded in May–June, extends to the Bosporus, while in the cold season, it can penetrate into the deep-sea area in the form of micro-eddies. In winter and spring, the Sevastopol anticyclonic eddy stood out as a separate zone in terms of biomass development. The role of anthropogenic load is most significant in the coastal zone. However, the effect of coastal waters on the deep-sea area is possible in late autumn and winter.

Keywords: phytoplankton biomass, synoptic circulation, Black Sea, spatial variability of phytoplankton biomass, water temperature, depth of the mixed layer

As known, one of the key indicators of the ecological state of the marine ecosystem is the level of phytoplankton biomass. Its development and variability reflect CO_2 transport from the atmosphere to the ocean, hydrochemical regime of water bodies, and carbon cycle in them. Phytoplankton development is affected by several factors: climate, anthropogenic load, and interaction between autotrophs and heterotrophs. Phytoplankton of the Black Sea is widely studied both in coastal and deep-sea areas [Arashkevich et al., 2015; Berseneva et al., 2004; Finenko et al., 2018, 2019; Mikaelyan, 2018; Mikaelyan et al., 2015]. However, there was no analysis of spatial changes in the biomass of phototrophic plankton throughout the Black Sea. The effect of the main water circulations in the sea surface layer on the variability of phytoplankton biomass was not considered as well. Vertical convection currents of water masses, seasonal geostrophic circulations, large-scale cyclonic gyres, anticyclonic eddies, and the Rim Current form conditions for rise and transfer of nutrients and, accordingly, for formation, transfer, and localization of phytoplankton biomass in certain sites of the water area. To assess the effect of macrocirculations on the spatial distribution of phytoplankton, regular observations covering large water areas are required. Bio-optical models developed to estimate chlorophyll *a* concentration using satellite data are most convenient for solving this problem. There are various methods for establishing phytoplankton biomass [Eppley et al., 1977; Menden-Deuer, Lessard, 2000]; however, the most common technique is biomass estimation by chlorophyll *a* content. To determine phytoplankton biomass in carbon units, data on chlorophyll *a* concentration, temperature, and light conditions are required; then, chlorophyll–organic carbon ratio is calculated. In algae, this ratio depends on their taxonomic composition, light intensity, and concentration of nutrients [Finenko et al., 2003; Geider, 1987]. In our work, phototrophic phytoplankton biomass was quantified using a previously developed model [Finenko et al., 2018] allowing to calculate changes in the specific content of chlorophyll *a* in algae organic matter in various sea areas for long time series. Analysis of the spatial and long-term dynamics of phytoplankton biomass will help in assessing the effect of local and global, natural and anthropogenic factors on its variability.

The aim of the work is to analyze the spatial and temporal variability of phytoplankton biomass in the surface layer of the Black Sea over an 18-year period and assess the effect of main sea currents on the spatial and temporal dynamics of phototrophic phytoplankton biomass.

MATERIAL AND METHODS

Chlorophyll *a* concentration was calculated from satellite observations for the entire Black Sea water area for the period of 1998–2015. To estimate chlorophyll content, we applied an algorithm that was developed for the Black Sea with the inclusion of the sea brightness coefficient in three spectral channels [Suslin, Churilova, 2016]. Second-level data were obtained using the SeaWiFS (1998–2010) and MODIS-Aqua/Terra (2000–2015) instruments. The measurements were carried out on a spatial grid of 0.025° in latitude and 0.035° in longitude and averaged over a two-week period for the entire sea surface. The mean relative error in retrieving chlorophyll concentration applying the specified algorithm for the deepwater area of the Black Sea according to MODIS-Aqua/Terra and SeaWiFS data was 40% [Suslin et al., 2018].

To calculate phytoplankton biomass, we used our model developed earlier; it is based on the relationship between light absorption in the visible area of the spectrum and the specific content of chlorophyll *a* in ten species of marine planktonic algae representing different taxonomic groups [Finenko et al., 2018]. This model includes the following parameters: chlorophyll *a* concentration, intensity of solar radiation reaching the sea surface, and light absorption by algae. Phytoplankton biomass (B) in organic carbon units ($\text{mg C}\cdot\text{m}^{-3}$) was calculated by the equation:

$$B = \text{Chl}_0 / \mathit{Chl} : C,$$

where Chl_0 is chlorophyll *a* concentration in the surface layer obtained from satellite data averaged over a two-week period (1998–2015) ($\text{mg}\cdot\text{m}^{-3}$);

Chl : C is chlorophyll–organic carbon ratio in algae.

To estimate the thickness of the upper quasi-homogeneous layer and the depth of the upper mixed layer, the model from [Dorofeev, Sukhikh, 2017] was used.

The depth of the zone of photosynthesis was determined by a model including the vertical light attenuation at a wavelength of 490 nm [Suslin et al., 2017].

Values of temperature in the surface layer and intensity of photosynthetically active radiation within the range of 400–700 nm were acquired from satellite observations obtained from second-level standard satellite products: SeaWiFS for 1998–1999 (http://podaac.jpl.nasa.gov/sst/) and MODIS-Aqua/Terra for 2000–2015 (https://oceancolor.gsfc.nasa.gov/).

RESULTS AND DISCUSSION

Spatial variability of seasonal and interannual dynamics of phytoplankton biomass in the deepwater area of the Black Sea. Analysis of the long-term seasonal dynamics of biomass in the deep-sea area in 1998–2015 revealed two main, as a rule, periods of its increase: in late November–February and in mid-spring. Spatial variability of the biomass of the Black Sea phytoplankton throughout the year is presented using data from 2009 as an example (Fig. 1).

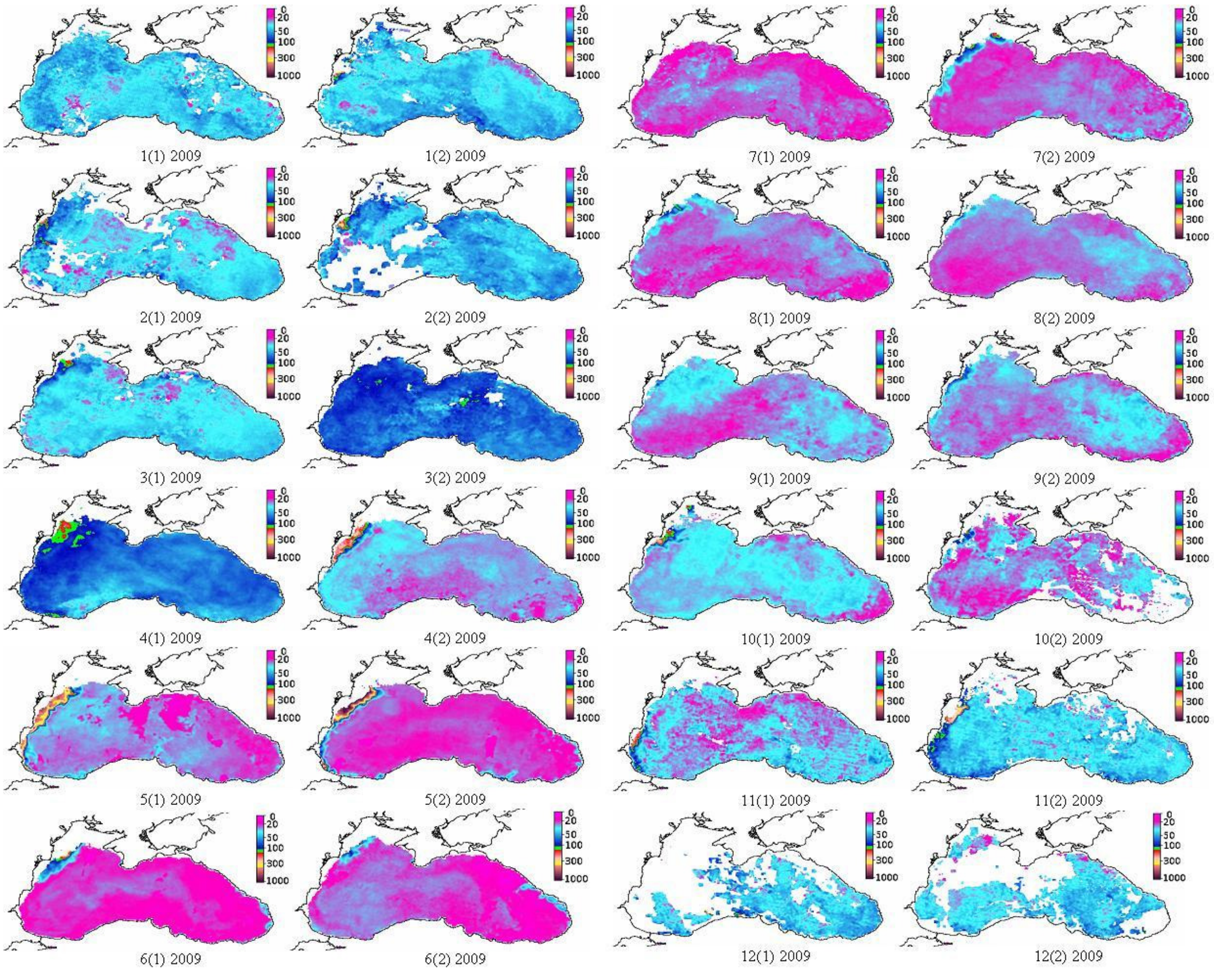

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Fig. 1. Seasonal variability of phytoplankton biomass (mg C·m^{-3}) during 2009 every first and second half of the month in the Black Sea water area

Usually, biomass values begin to increase in late October–November, and local spots of phytoplankton are observed throughout the sea. The period of wind effect in late October and November, when the depth of the mixed layer rises to 19–23 m, precedes the winter increase in phytoplankton biomass. During these months, a mosaic distribution of phytoplankton biomass values was noted almost throughout the entire sea, resulting from both macro- and microcirculations and varying in most years within the range of 20–70 mg C·m^{-3} (Figs 1, 2). An important role in the spatial distribution of phytoplankton in autumn and winter is played by the western coastal zone, from which a significant part of its biomass is transferred to the deep-sea area. The wind regime creates turbulent micro-eddies and meanders in the surface layer and transfers them in space. During the cold period, the effect of coastal sea areas on deepwater ones is most pronounced (Figs 1, 2). The water temperature in the surface layer in October–December remains relatively high compared to the temperature at depth, and the thermocline is not completely destroyed; therefore, the involvement of nutrient-rich water masses in the convection current and their entry into the euphotic layer are minor. For this reason, there is no significant increase in biomass up to December. By late December–January, convection in the surface layer, according to calculated data of satellite measurements, covers depths approximately down to 25–28 m. In December and January, the field of biomass becomes almost homogeneous throughout the sea (Fig. 2). Usually, the maximum phytoplankton biomass is recorded in January; less often, in December or February.

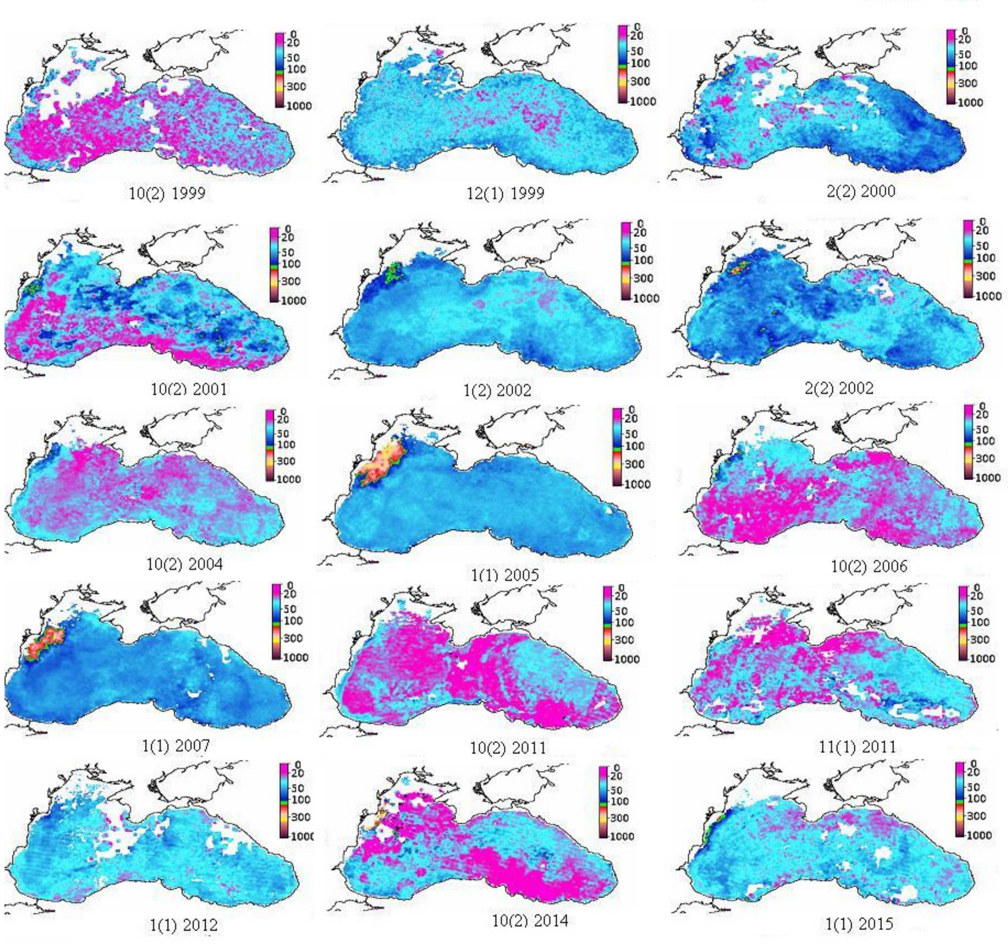

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Fig. 2. Spatial variability of phytoplankton biomass (mg C·m^{-3}) under the effect of circulations during increased mixing of water masses in autumn months and winter increase in phytoplankton biomass in the Black Sea in different years

Maximum values vary from 50 to 100 mg C·m^{-3}. On average over an 18-year period, for the entire deep-sea area, phytoplankton biomass in winter is (51.52 ± 10.08) mg C·m^{-3}. From February–early March, biomass decreases, which may be due to the involvement of phytoplankton by convection currents below the zone of photosynthesis. On most maps, it is reflected as a mosaic distribution of values over the entire surface of the Black Sea which vary within the range of 20–100 mg C·m^{-3} (Fig. 3). The maximum depth of water mixing, averaging 28–30 m, is usually observed in February. In some years, the depths of mixing in December and February exceeded 30 m in the deepwater zone and the slope of depth; for some areas, the mean values reached (36 ± 6) m. Moreover, in the western cyclonic gyre, the depths of convective mixing are higher compared to those in the eastern Black Sea. The occurrence of convective currents in the second half of February–early March can be caused, in addition to wind activity, by a decrease in water temperature and the leveling-off of the temperature gradient between the surface and deep-sea area. The mixing process involves layers from the sea depths, and this leads to an increase in concentration of nutrients in the upper mixed layer. The cold intermediate layer, which separates the upper quasi-homogeneous layer from nutrient-rich deep waters, is located at a depth of 30–100 m [Ivanov, Belokopytov, 2011]. At the same time, the upper boundary of the layer of maximum gradients of nitrate and phosphate concentration is located at 30–60 m [Krivenko, Parkhomenko, 2014]. From late March, a decrease in water temperature stops, wind activity drops, turbulent flows weaken, and irradiance increases, which leads to the spring bloom of phytoplankton. Thus, due to the rise of nutrients into the euphotic layer during convection in February–March, spring development of phytoplankton in deep-sea areas reaches its maximum values in the year, 100 mg C·m^{-3} or more.

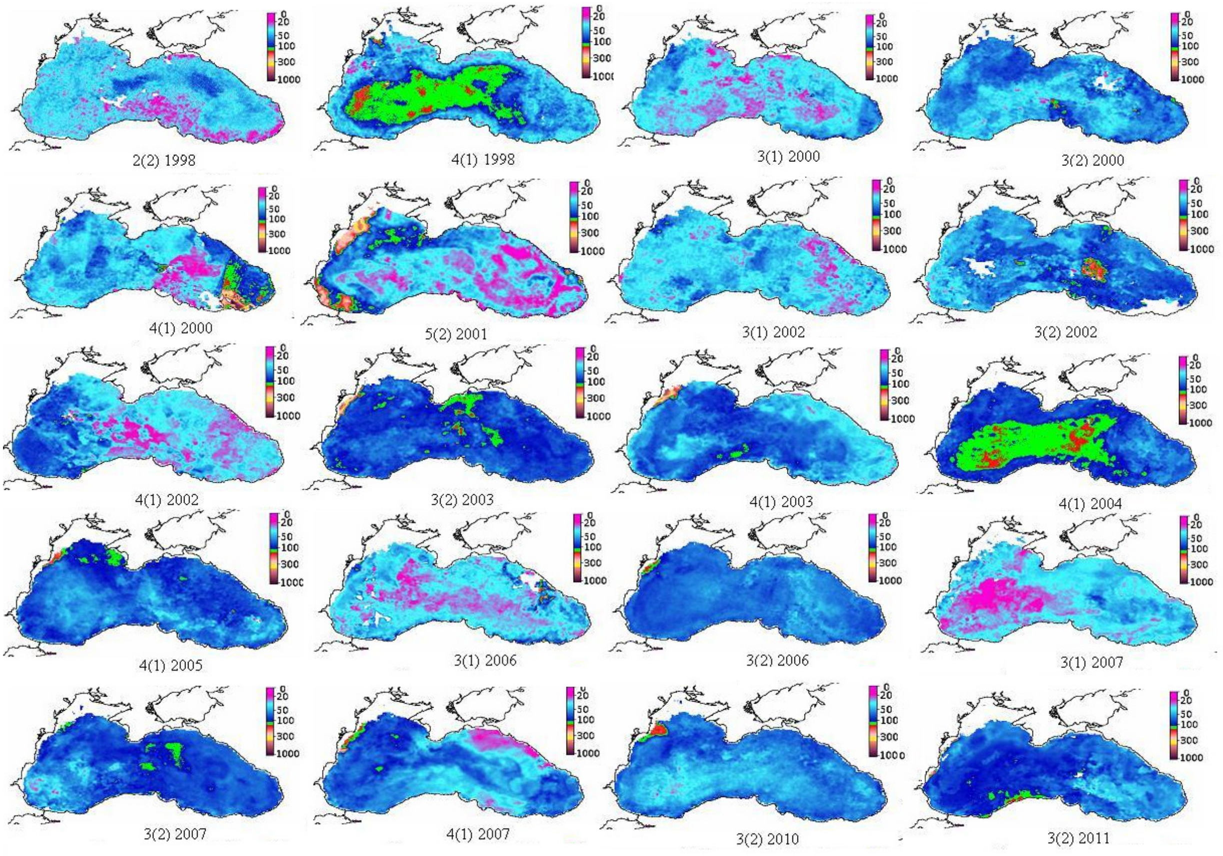

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Fig. 3. Spatial variability of phytoplankton biomass (mg C·m^{-3}) under the effect of circulations during the spring increase in phytoplankton biomass in the Black Sea in different years

During most years, the maximum values of phytoplankton biomass in spring were noted closer to centers of the cyclonic gyres. Based on the results of satellite observations averaged for the western and eastern cyclonic gyres, it was established as follows. In years with the mean water temperature in the deep-sea area during the cold season decreasing to the value below +8 °C for six weeks or more, intensive development of phytoplankton biomass is observed in spring. In years with the mean water temperatures above +8 °C or with the temperature decreasing to the value below +8 °C for no more than one month in winter, weak biomass growth is usually recorded in spring. At the same time, the spring bloom is less pronounced in years with prolonged mean water temperature below +7 °C during the cold season than in the case of a long period of winter temperature at +7…+8 °C. Therefore, conditions for convective mixing and transfer of nutrients into the zone of photosynthesis are the most favorable when the temperature in the upper quasi-homogeneous layer is leveled off with the temperature in the cold intermediate layer. At lower temperatures, cold surface waters can form zones with strong downward flows, and this leads to a deepening of the upper quasi-homogeneous layer zone well below the zone of photosynthesis. As a result, chlorophyll concentration and phytoplankton biomass decrease. In the central sea, apparently, mixing is limited by the pycnocline. Moreover, the cold intermediate layer can become denser. During this period, wind effect and dynamic processes in water masses are of high importance. Specifically, in 2003, the water temperature in winter dropped below +7 °C for two months only in the western cyclonic gyre, while in the eastern one, the decrease lasted no more than a month. Accordingly, in the center of the eastern gyre, the spring bloom was approximately twice as intense as the bloom in the western gyre. These observations indicate that the condition for intensive development of phytoplankton in spring is the mean water temperature in the range of +7…+8 °C for more than six weeks during the cold season.

From late April–May, the values of phytoplankton biomass decrease in the deepwater zone. Throughout summer and early autumn, according to data averaged for the area, those are usually within the range of 12–42 mg $C \cdot m^{-3}$. A rise in mean values in some years to 27–42 mg $C \cdot m^{-3}$ can be recognized as a weak third maximum in the seasonal dynamics of biomass. The research [Finenko et al., 2018] indicates the occurrence of three biomass maximums: the winter, spring, and summer–early autumn ones. However, the latter maximum was not annual, and the mean values for the area were below 40 mg $C \cdot m^{-3}$. In the deepwater zone, temperature and density stratifications are formed, and the exchange of water masses with shelf waters is minimum.

The effect of synoptic circulations on the distribution of phytoplankton biomass. About a month after the spring bloom, a decrease in biomass begins and gradually spreads across the water area with cyclical variations from the eastern area to the western one. Phytoplankton bloom in the deepwater zone usually lasts about a month [Finenko et al., 2018]. The cyclicity in variations in phytoplankton biomass, from two weeks to a month, can result from water movement in large cyclonic gyres, the western and eastern ones. This variability corresponds to the seasonal cycle of geostrophic circulation [Belokopytov, 2004]. The circulation is characterized by a common cyclonic movement with a variable center in the western or eastern Black Sea or with two pronounced gyres [Belokopytov, 2004]. The cyclicity observed throughout the year has a particularly noticeable effect on the variability of biomass in late autumn, winter, and spring, with the most pronounced processes of new formation and successive death of phytoplankton (Figs 2, 3). As follows from this circulation cycle, the periods we identified, with a mosaic distribution of phytoplankton biomass in November–December and February–March, occurring *prior* to the winter and spring blooms, coincide with a merger of two cyclonic gyres, shift in the center of cyclonic rotation, and general increase in speeds of currents [Ivanov, Belokopytov, 2011]. In January–February, according to hydrophysical data, the eastern gyre is more pronounced. However, increased speeds of water movement and the mixing seem to prevent phytoplankton organisms, that formed biomass during the winter bloom, from being localized separately in the cycle or in its center. Phytoplankton are usually distributed along the periphery of the gyre or spread throughout the sea. In a layer down to 200 m, the horizontal structure of currents is strongly interconnected vertically; therefore, circulation throughout the entire water column has common features [Ivanov, Belokopytov, 2011], and in these months, a seasonal correlation is registered between surface and deep currents [Korotaev et al., 2006]. This may contribute to phytoplankton distribution in the water column to greater depths and beyond the zone of photosynthesis. During the spring bloom, on the contrary, biomass is more often concentrated in the gyres. In most years, the values of phytoplankton biomass established in the eastern Black Sea spread to the western sea in late March and April (Fig. 3). For summer period, due to high stratification in the water column and low current speeds [Ivanov, Belokopytov, 2011], a homogeneous field of low concentrations of phytoplankton biomass is characteristic. However, in some months of the warm season, the transport of waters with low concentrations of phytoplankton in accordance with the centers of cyclonic rotation can be noted. Thus, according to our research, phytoplankton biomass is formed, transferred, and localized under the effect of seasonal cycles of alternating changes in intensity of the eastern and western cyclonic gyres.

It is worth noting as follows. The distribution and formation of phytoplankton biomass in the Black Sea also occur in local anticyclonic eddies along the Rim Current and the movement of large cyclonic gyres. For example, the Sevastopol anticyclonic eddy [Ivanov, Belokopytov, 2011] is distinguished as a separate zone. During the spring bloom, lower or higher phytoplankton concentrations are registered there; during the winter bloom, usually lower ones. Intensive development of phytoplankton in this zone was observed in the second half of March or in the first half of April (in 1999, 2000, 2003, 2005, 2010, 2011, and 2012). Usually, the bloom in the Sevastopol micro-gyre lasted no more than two weeks, and the biomass values were 2–2.5 times higher than in the western cyclonic gyre (Fig. 3). Only in 2013 and 2015, phytoplankton concentration in the Sevastopol anticyclonic eddy was 2 times lower than in the deepwater zone. There was one significant increase in biomass – in 2001, in the second half of May; it was presumably affected by the widespread distribution of the Danube River flood (Fig. 3). In other years, in spring, changes in the analyzed indicator occurred according to the same pattern as in the deep-sea area. In winter, in this site of the water area, a homogeneous field of biomass with a western circulation is recorded, which may indicate an intensive mixing of these two zones and a temporary disappearance of the anticyclone as a separate zone for the development of phytoplankton biomass. Over the entire study period, only in 2001, 2012, 2014, and 2015, the Sevastopol anticyclonic eddy was characterized by lower biomass values in some winter months. In summer, as a rule, it was not distinguished as a separate zone; there, concentrations of phytoplankton biomass were lower than in the deep-sea area. In the Batumi anticyclone, according to 18-year studies, the values of biomass differed from those for the rest of the deep-sea area in the first half of April 2000 and 2006, in the first half of May 2001, and in the winter of 2003. During these years, intense phytoplankton bloom occurred there against the backdrop of low biomass values in the deep-sea area. In other years, the variability of values was similar. In April 2000, there was an outbreak of phytoplankton both in the coastal zone along the East Pontic Mountains (the values reached 1,000 mg $C \cdot m^{-3}$) and in the Batumi gyre (300 mg $C \cdot m^{-3}$). In May 2001, in the shelf zone in the Batumi area, biomass increased to 200 mg $C \cdot m^{-3}$. In the indicated months in 2003 and 2006, the values did not exceed 100 mg C·m^{-3}, but were approximately twice as high as in the eastern cyclonic gyre. According to data averaged for the area over 18 years, in the western cyclonic gyre, phytoplankton biomass was (38.0 ± 17.8) mg C·m^{-3}; in the eastern cyclonic gyre, (37.7 ± 16.8) mg C·m^{-3}; and in the Batumi gyre, (38.2 ± 18.0) mg C·m^{-3}.

The importance of circulations in the occurrence of phytoplankton blooms was considered by other researchers as well [Kubryakov et al., 2019]. In August 2015, in the southeastern Black Sea, there were a sharp disturbance in the physical structure of waters and an isopycnic mixing, with the latter one caused by a shift in inertial currents under the effect of strong winds; this led to an increase in chlorophyll concentration [Kubryakov et al., 2019]. However, according to our calculations and satellite observation data (Fig. 4), in August 2015, a slight increase in phytoplankton biomass in the eastern anticyclonic gyre was registered: up to 27 mg C·m^{-3} on average for the area, against the backdrop of 13–20 mg C·m^{-3} in June and July. Only in the center of the anticyclone, the values rose to 50 mg C·m^{-3}. At the same time, there was no significant increase in biomass in the eastern sea. Phytoplankton development was the same as in most years. Over an 18-year period, the greatest increase in biomass in the deep-sea area was observed in 2001 in summer (in particular, up to 38 mg C·m^{-3} in August), but its reasons require separate analysis. Also, for the deepwater zone, a sudden outbreak of phytoplankton development was noted in late August–early September 2012 (Fig. 4).

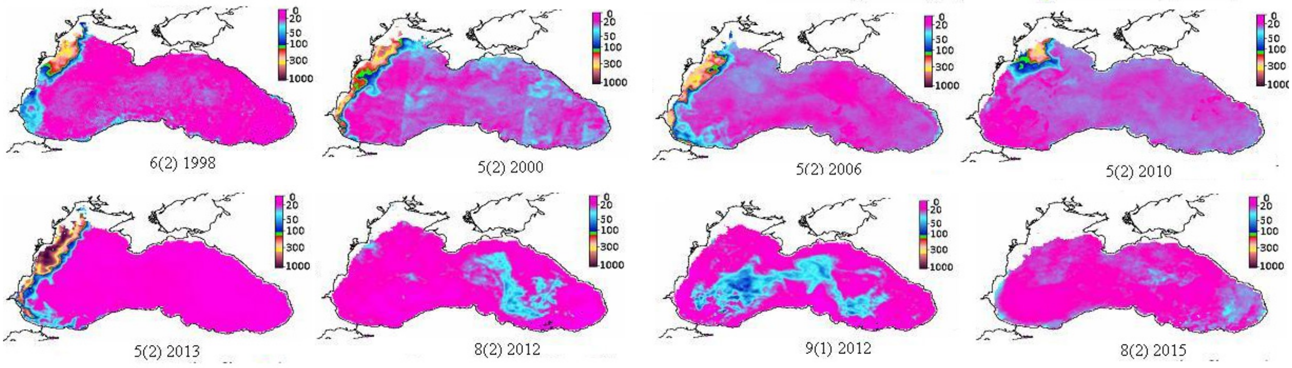

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Fig. 4. Spatial variability of phytoplankton biomass (mg C·m^{-3}) under the effect of circulations during summer months and in the Danube flood period in the Black Sea in different years

The bloom began approximately in the center of the eastern cyclonic gyre; within two weeks, it spread to the western one. Maximum values in the center of the western cyclonic gyre reached 70–80 mg C·m^{-3}. At the same time, according to data averaged for the entire area, the values did not exceed 35 mg C·m^{-3}, and this did not lead to a rise in biomass in general during summer. On the contrary, since 2012, the biomass of phytoplankton became to decrease in summer and dropped on average by 1.4 times in the deepwater zone and by 1.2–1.4 times in the slope of depth of the western Black Sea and almost along the entire shelf zone (compared to that in previous years). In the deep-sea area, over an 18-year period, negative trends in the values of phytoplankton biomass were recorded in spring and summer; no significant trends were found in winter and autumn [Finenko et al., 2019]. This decrease, as pointed out in the research [Finenko et al., 2019], is not associated with changes in temperature and light conditions. The only exceptions were the area of the Danube River drainage, where there was a rise in phytoplankton biomass by 1.3 times in recent years in summer, and the Gulf of Burgas area, with an increase by 1.14 times. Over 18 years in the Danube area, according to year-round regular two-week data, biomass rose by 33% compared to the initial level, with its high variability (when assessed by Fisher's exact test at $p \leq 0.1$). This may indicate a rise in the trophic level of this area, which is likely to result from an increase in anthropogenic load.

Typically, increased biomass values extended to the boundaries of cyclonic gyres and the slope of depth, and in some cases, to the coast of the Crimea. However, according to long-term observations, due to differences in the density and salinity of shelf waters and waters of the central Black Sea, their separation occurred, and this did not lead to an increase in phytoplankton biomass in the deep-sea area.

The role of the Rim Current in shaping the development of phytoplankton in shelf waters. In the coastal zone, mainly in the area of the Danube River drainage and somewhat less in the area of the Dniester and Dnieper rivers, from late April–May, there is a significant rise in biomass caused by spring floods. Within two months, increased phytoplankton biomass, following the direction of the Rim Current, reaches the Bosporus Strait, but, as a rule, does not spread further to the east (see Fig. 4). Most of desalinated waters is carried into the Sea of Marmara.

The period of the summer bloom on the western shelf lasted until September–October. Against the backdrop of increased concentrations, usually, there were two peaks: in May–June and in September–October (two times less one). In some cases, biomass values reached 300–1,000 mg $\mathrm{C \cdot m^{-3}}$; on average, in the area of the Danube River drainage, the values were about 100 mg $\mathrm{C \cdot m^{-3}}$ in summer. As water masses move towards the Bosporus Strait, phytoplankton biomass decreases. A re-increase in its values in the western coastal zone occurs in winter, but with lower concentrations and area of distribution than in late spring. Fairly high values of phytoplankton biomass persist there throughout the year, while the level of biomass in other coastal areas in winter is usually lower than in the deepwater zone. Changes along the southern and eastern shelves occur in most years according to the same pattern as in the deep-sea area, and phytoplankton concentrations vary within the same limits. Only the northeastern coast is characterized by the lowest biomass values throughout the year, especially in summer. This may be due to the highest speed of the Rim Current [Ivanov, Belokopytov, 2011] in this site of the water area and the low depth of the mixed layer, averaging (5.0 ± 3.7) m, according to our calculations. The maximum of chlorophyll and biomass off the Crimean and Caucasian coasts in summer occurs on average at a depth of 29 m. The maximum speed of current is observed in the surface layer, 10–25 m [Ivanov, Belokopytov, 2011]. Apparently, this leads to water stratification in terms of movement speeds and to weak stirring.

Throughout a year, especially in summer, the Rim Current [Ivanov, Belokopytov, 2011] promotes biomass distribution along the shelf zone, practically without mixing with the deep-sea area. An exception may be the formation of eddy circulations transported to the open sea in late autumn and winter. Therefore, the effect of coastal waters on the deepwater zone is possible precisely during this period. In spring, during floods, the values of phytoplankton biomass are high, and those can spread to the slope of depth; however, temperature and density differences and low wind activity prevent mixing of shelf waters and deep-sea ones.

Conclusion. The movement of the main surface currents and mixing processes play an important role in the spatial distribution of phytoplankton biomass in the Black Sea. We showed the effect of large synoptic gyres on the periodicity of bloom shift from one cyclonic gyre to another, with a duration of about a month. Deep vertical circulations of water caused by temperature and wind regimes in winter, determine the occurrence of winter and spring maximum of phytoplankton biomass. One of the key conditions for its intense bloom in the deepwater zone in spring is a drop in the mean water temperature in the cold season to +7…+8 °C for more than six weeks. These conditions contribute to an increase in vertical circulation of water masses and transfer of nutrients into the euphotic layer. According to the data of spatial changes over an 18-year period, the spring–summer bloom in the shelf zone did not go beyond the slope of depth and did not penetrate into the deep-sea area. Only in certain cases, high phytoplankton concentrations during heavy spring floods on the northwestern shelf were observed off the Crimean coast; on the southeastern shelf, those penetrated into the Batumi anticyclone. In the warm season, most of phytoplankton biomass formed at the drainage of northwestern rivers spreads to the Bosporus Strait and is carried out of the Black Sea. In autumn from October and in winter, the bloom can cover the western cyclonic gyre and contribute to phytoplankton development in the surface layer of the central Black Sea.

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ПРОСТРАНСТВЕННАЯ И ВРЕМЕННАЯ ДИНАМИКА БИОМАССЫ ФИТОПЛАНКТОНА В ПОВЕРХНОСТНОМ СЛОЕ ЧЁРНОГО МОРЯ

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Проведён анализ пространственной и временно́й изменчивости биомассы фитопланктона в поверхностном слое Чёрного моря за 18-летний период и оценено влияние основных течений в море на пространственную и временну́ю динамику биомассы фототрофного фитопланктона. Использованы регулярные многолетние данные концентрации хлорофилла, полученные по спутниковым наблюдениям с помощью приборов SeaWiFS и MODIS-Aqua/Terra за период с 1998 по 2015 г. в Чёрном море. Оценена роль макро- и микроциркуляций в пространственно-временно́й вариабельности биомассы фитопланктона. Усиление ветровой активности и снижение температуры воды с октября по март, приводящие к увеличению глубины перемешивания верхнего слоя и интенсивности основных синоптических циркуляций, становятся существенным фактором, который способствует возникновению зимнего и весеннего цветения фитопланктона. Выявлено, что понижение средней температуры воды в холодный сезон до +7…+8 °C на протяжении более чем полутора месяцев в глубоководной зоне приводит к интенсивному развитию биомассы весной. Установлено, что средняя биомасса фитопланктона за 18-летний период в западном и восточном циклонических круговоротах составляет (38,0 ± 17,8) и (37,7 ± 16,8) мг $\mathrm{C{\cdot}м^{-3}}$ соответственно, в Батумском антициклоне — (38,2 ± 18,0) мг $\mathrm{C{\cdot}м^{-3}}$. Основное черноморское течение, как правило, переносит фитопланктон, образовавшийся у шельфовой зоны, вдоль береговой линии, мало смешиваясь с водами глубоководной акватории. В циклонических круговоротах зимне-весеннее цветение фитопланктона наблюдается в среднем на протяжении полутора месяцев. Интенсивное цветение в районе стока северо-западных рек, регистрируемое в мае — июне, распространяется до пролива Босфор, тогда как в холодный сезон может в виде микровихрей проникать в глубоководную зону. В зимние и весенние месяцы Севастопольский антициклонический вихрь выделялся как отдельная зона в развитии биомассы. Роль антропогенной нагрузки наиболее существенна в прибрежной зоне. При этом влияние прибрежных вод на глубоководную зону в некоторой степени возможно поздней осенью и зимой.

Ключевые слова: биомасса фитопланктона, синоптические циркуляции, Чёрное море, пространственная изменчивость биомассы фитопланктона, температура воды, глубина перемешанного слоя